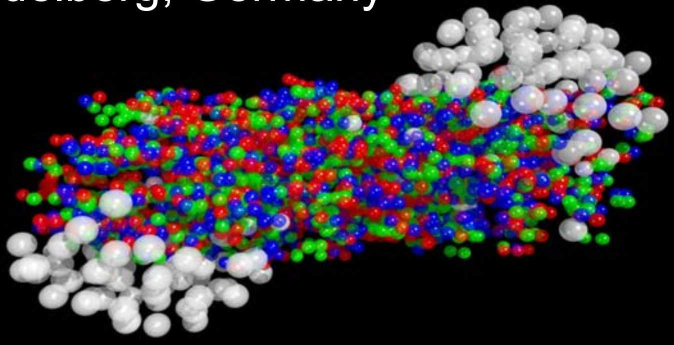
Heavy Ion Physics with ALICE (part I)

Raimond Snellings

XVIII Heidelberg Physics
Graduate Days 10th -13th
April, 2007
Heidelberg, Germany



XVIII. HEIDELBERGER GRADUIERTENKURSE PHYSIK

10. – 13. April 2007

an der Fakultät für Physik und Astronomie der Universität Heidelberg

Die Kurse richten sich an fortgeschrittene Studenten, insbesondere an Doktoranden und Diplomanden. Ziele sind die Erweiterung des physikalischen Allgemeinwissens und die Vermittlung spezieller Kenntnisse und Techniken.

Vormittagskurse (Di.-Fr., 9:30-12:30 Uhr):

Noncommutative Geometry	***Thomas Schücker*** Université de Provence, Marseille
Experiments with ultra-cold Fermi gases	***Selim Jochim / Henning Moritz*** MPI-K, Heidelberg / ETH Zürich
PVLAS Experiment	***Holger Gies / Andreas Ringwald*** ITP, Uni Heidelberg / DESY, Hamburg
Publizieren und Präsentieren mit LaTeX	***Marion u. Joachim Lammarsch*** Psycholog. Inst./URZ, Uni Heidelberg
LHC: Physics, Machine, Experiments	***H.C. Schultz-Coulon / U. Uwer*** KIP / PI, Universität Heidelberg ***R. Schmidt / R. Snellings*** CERN, Genf / NIKHEF, Amsterdam

Nachmittagskurse (Di.-Fr., 14:00-17:00 Uhr):

Calorimeters in High Energy and Nuclear Physics	***Roman Pöschl*** LAL, Orsay
Effective actions	***Gerald Dunne*** University of Connecticut
Cosmic Microwave Background	***Rachel Bean*** Cornell University
Atmosphärische Elektrizität	***Ulrich Finke*** FH Hannover
Einführung in die Physik der Röntgenstreuung	***Christian Gutt*** DESY, Hamburg

Festkolloquium (Donnerstag, 12.04.2007, 17:30 Uhr, gHS, Philosophenweg 12):

“Dunkle Materie, Dunkle Energie (finstere Gedanken) - Moderne Entwicklungen in der Kosmologie”

Hanns Ruder
Universität Tübingen

Anmeldung und weitere Informationen im Internet unter
http://gradkurs.uni-hd.de/

Mit Unterstützung von d-fine DFG

Content

- What do we want to study?
  - QCD at high density and temperature
- How?
  - Heavy-ion accelerators, experiments, collision characterization
- What are our probes and observables?
  - I cover only part of the probes and observables
- What does the near future hold for us?
  - The LHC heavy-ion program and ALICE the dedicated heavy-ion detector

Quantum Chromo Dynamics

- Theory of the strong interaction
  - Part of the standard model
  - Quarks carry a strong interaction charge (color)
  - Color comes in three types (e.g. red, green and blue)
    - Anti quarks carry anti-color
  - Quarks interact among themselves via the exchange of color field quanta, so called gluons
  - Gluons also carry a color charge, which is unlike QED were the photon is neutral (the theory is non-abelian)
- All known hadrons are color singlet’s
  - Baryons are qqq, mesons qq_{bar} states (anti-baryon $q_{bar}q_{bar}q_{bar}$)
  - No free quarks have ever been observed

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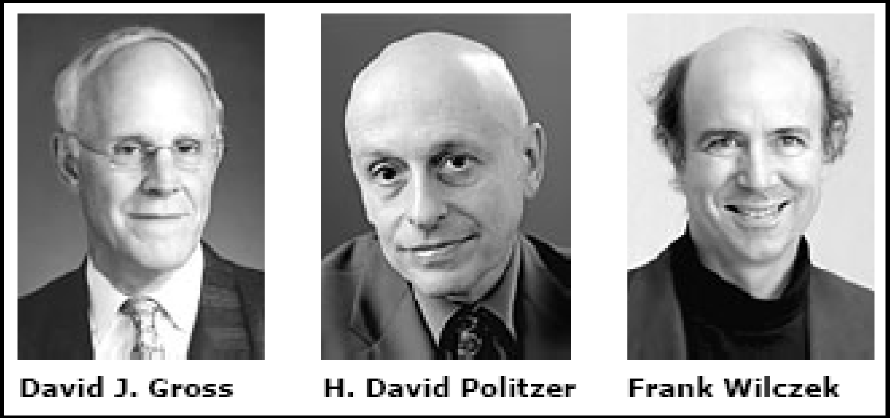
Asymptotic freedom



$$\alpha\left(q^2\right) = \frac{\alpha_0}{1+\alpha_0 \frac{\left(33-2n_f\right)}{12\pi} \ln\left(\frac{-q^2}{\mu^2}\right)}$$

- QCD is an asymptotic free theory
  - At short distance the potential is of type:

$$V_{short} = -\frac{4}{3}\frac{\alpha_s(r)}{r}$$

  - The coupling constant is running but depends on *r* in such a way that:

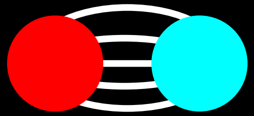
$$\lim_{r\to 0} \alpha_s(r) = 0$$

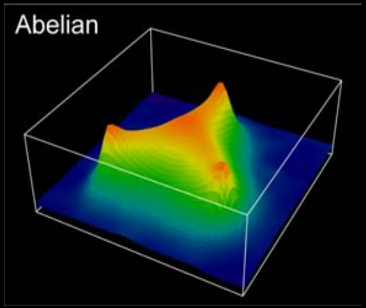
- Perturbation theory can be applied at short distances/high momentum transfer, source of much of our current knowledge

Non perturbative: confinement

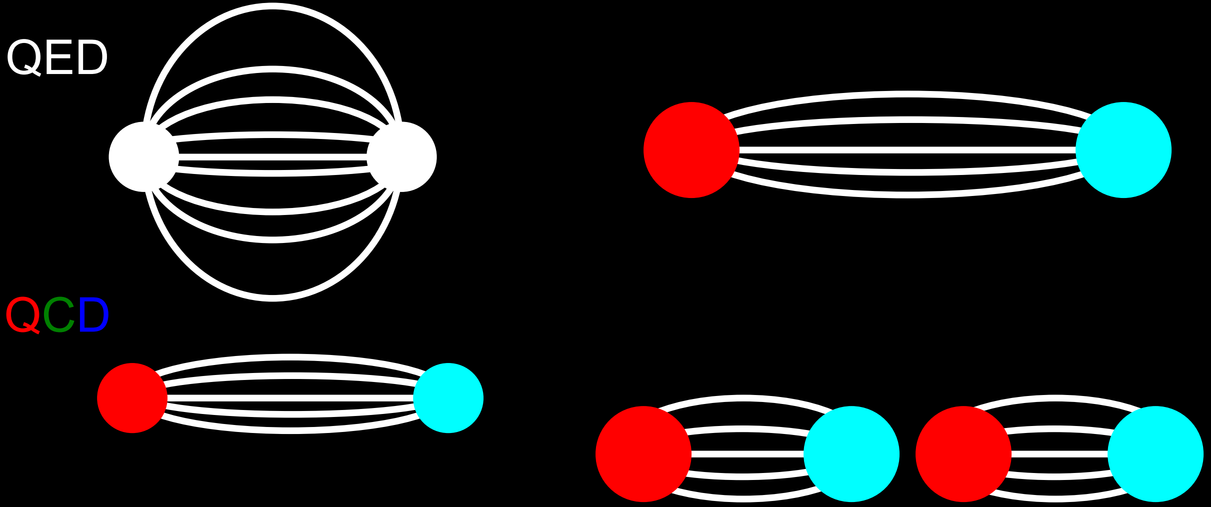
- In QCD, the field lines are compressed into flux tubes or “strings” of constant cross-section leading to a long-distance potential which grows linearly with *r*:

$$V_{long} = kr \qquad \text{with } k \approx 1\ \text{GeV/fm}$$





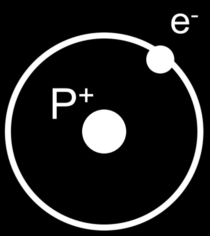
G. Schierholz *et al.*



Non perturbative: constituent quark mass

- Confined quarks (inside a proton or meson) acquire an additional mass dynamically due to the confining effect of the strong interaction
  - bare mass u and d ~ few MeV, s ~ 150 MeV

hydrogen atom

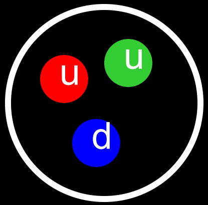


M_e = 0.5 MeV/c²

M_P = 938 MeV/c²

M_H = 932 MeV/c²

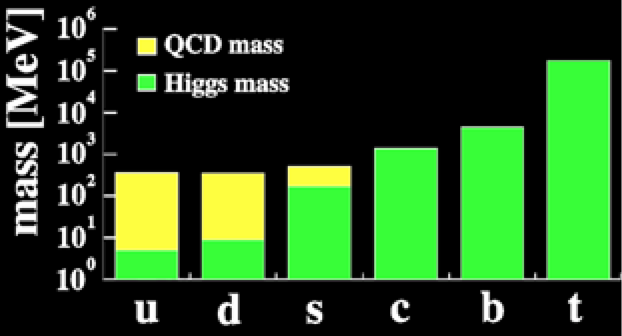
proton



M_u = 3 MeV/c²

M_d = 6 MeV/c²

M_P = 938 MeV/c²



- Deconfinement is expected to be accompanied by restoration of masses to their bare masses
  - m(u,d) 350 MeV → few MeV, m(s) 500 MeV → 150 MeV
- Referred to as partial chiral symmetry restoration (symmetry only exact for massless particles)

The QCD Lagrangian

(j,k = 1,2,3 color; q = u,d,s flavor; a = 1,..,8 gluon fields)

$$\mathsf{L}_{qcd} \quad i \quad {}^{-j}_{\ \ q} \quad (\mathrm{D}\ )_{jk} \quad {}^{k}_{q} \qquad m_q \quad {}^{-j}_{\ \ q} \quad {}^{k}_{q} \quad \tfrac{1}{4} G^{a} \ G_{a}$$

$$\quad q \qquad\qquad\qquad\qquad q$$

Gauge inv. derivative:

$$\mathrm{D} \qquad i\tfrac{1}{2} g_s \ {}_{a}G^{a}$$

Free quarks

$$G^{a}_{\mu\nu} \quad \underbrace{G^{a} \qquad G^{a}}_{\text{Gluon kinetic energy term}} \quad \underbrace{g_s f_{abc} G^{a} G^{a}}_{\text{Gluon self-interaction}}$$

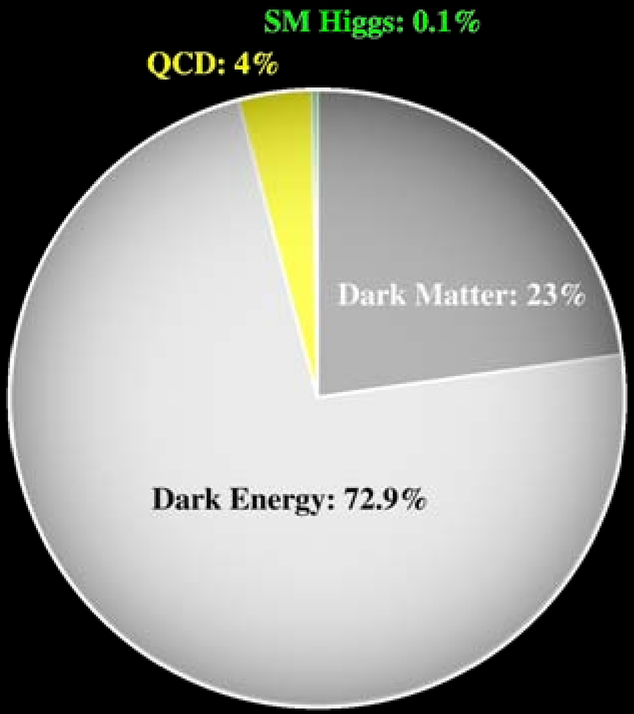
qg-interactions
SU(3) generators:

$$_1\begin{pmatrix}0&1&0\\1&0&0\\0&0&0\end{pmatrix} \quad _2\begin{pmatrix}0&i&0\\i&0&0\\0&0&0\end{pmatrix} \quad _3\begin{pmatrix}1&0&0\\0&1&0\\0&0&0\end{pmatrix} \quad _4\begin{pmatrix}0&0&1\\0&0&0\\1&0&0\end{pmatrix}$$

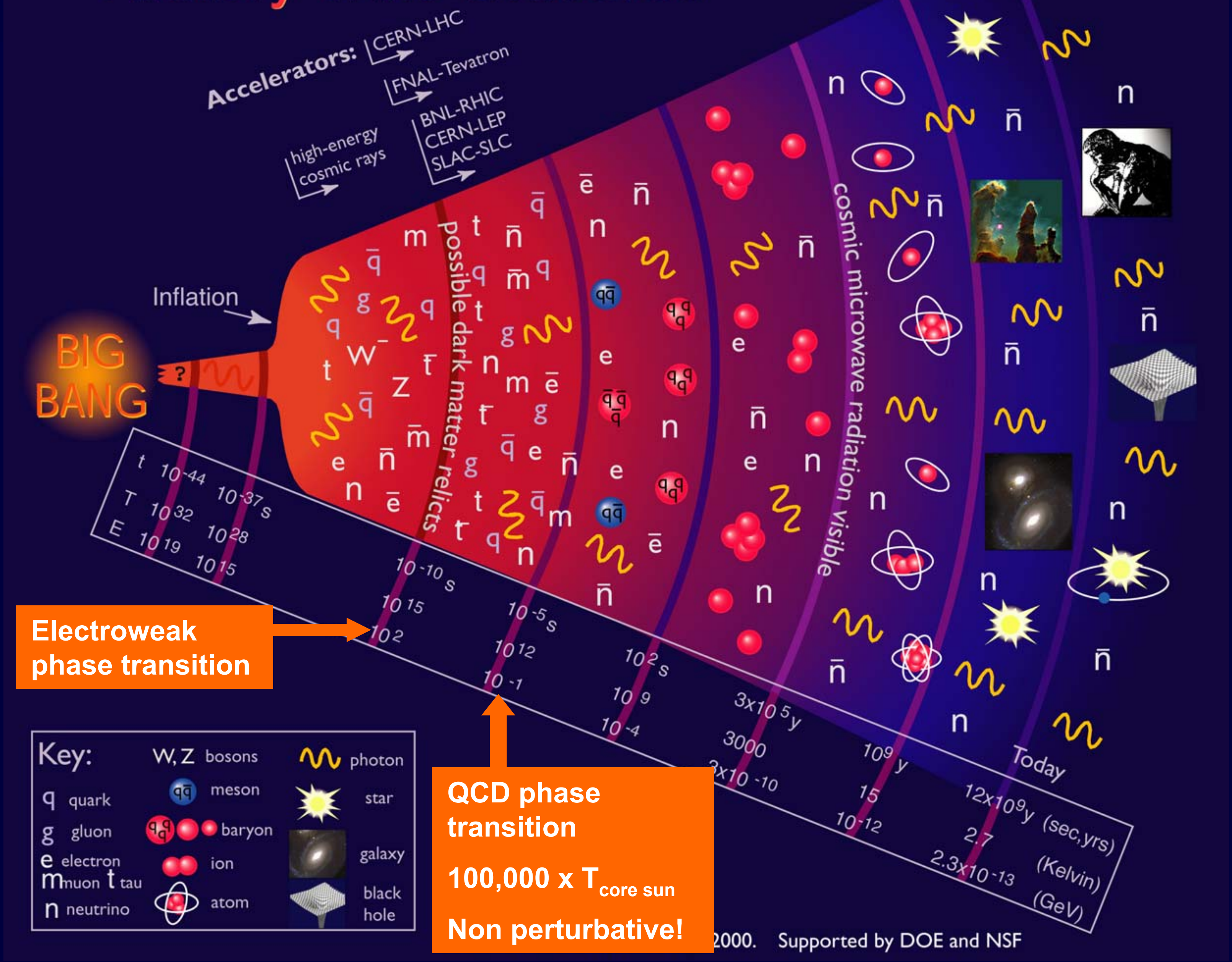
$$_5\begin{pmatrix}0&0&i\\0&0&0\\i&0&0\end{pmatrix} \quad _6\begin{pmatrix}0&0&0\\0&0&1\\0&1&0\end{pmatrix} \quad _7\begin{pmatrix}0&0&0\\0&0&i\\0&i&0\end{pmatrix} \quad _8\ \frac{1}{\sqrt{3}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&2\end{pmatrix}$$

What is the Universe made of ?

- Elementary particles make up 0.1% of the mass in the universe
  - SM Higgs mechanism
- Composite particles (hadrons) can account for ~ 4%
  - QCD chiral symmetry breaking
- Dark Matter 23%
- Dark Energy 72.9%
- The ~ 4% are still not understood very well, and the other 95% are a complete mystery!



History of the Universe



Electroweak phase transition

QCD phase transition

100,000 x $T_{\text{core sun}}$

Non perturbative!

Equation of State and degrees of freedom

ideal QGP: $$P_{\mathrm{QGP}} = \frac{1}{3}\varepsilon_{\mathrm{QGP}} = g\frac{\pi^2}{90}T^4$$

$$\frac{\varepsilon}{T^4} = g\frac{\pi^2}{30}$$

- Energy density for g massless degrees of freedom

$$\boxed{\frac{\varepsilon}{T^4} = 3\cdot\frac{\pi^2}{30}}$$

- Hadronic matter (T< 150 MeV, π^+,π^- and π^0)

$$\frac{\quad}{T^4} \qquad 2_{\mathrm{spin}}\;\; 8_{\mathrm{gluons}} \qquad \frac{7}{8}\;\; 2_{\mathrm{flavors}}\;\; 2_{\mathrm{quark/anti\text{-}quark}}\;\; 2_{\mathrm{spin}}\;\; 3_{\mathrm{color}} \qquad \frac{{}^{2}}{30}$$

$$\boxed{\frac{\varepsilon}{T^4} = 37\cdot\frac{\pi^2}{30}}$$

- Quark Gluon Plasma (T>200 MeV)
- $\varepsilon_{\mathrm{QGP}}$=2.5 GeV/fm^3 for T = 200 MeV

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Finger physics: QGP and the bag model

- Confinement due to bag pressure *B* (from the QCD vacuum):

$$B^{1/4} \approx 200\mathrm{MeV}$$

- Deconfinement when thermal pressure is larger than bag pressure:

$$P_{\mathrm{QGP}} = \frac{1}{3}\varepsilon_{\mathrm{QGP}} = g\frac{\pi^2}{90}T^4,$$

$$T_c = \left(\frac{90B}{37\pi^2}\right)^{1/4} = 140\ \mathrm{MeV}\ (\mathrm{for}\ B^{1/4} = 200\ \mathrm{MeV})$$

- Crude estimate!

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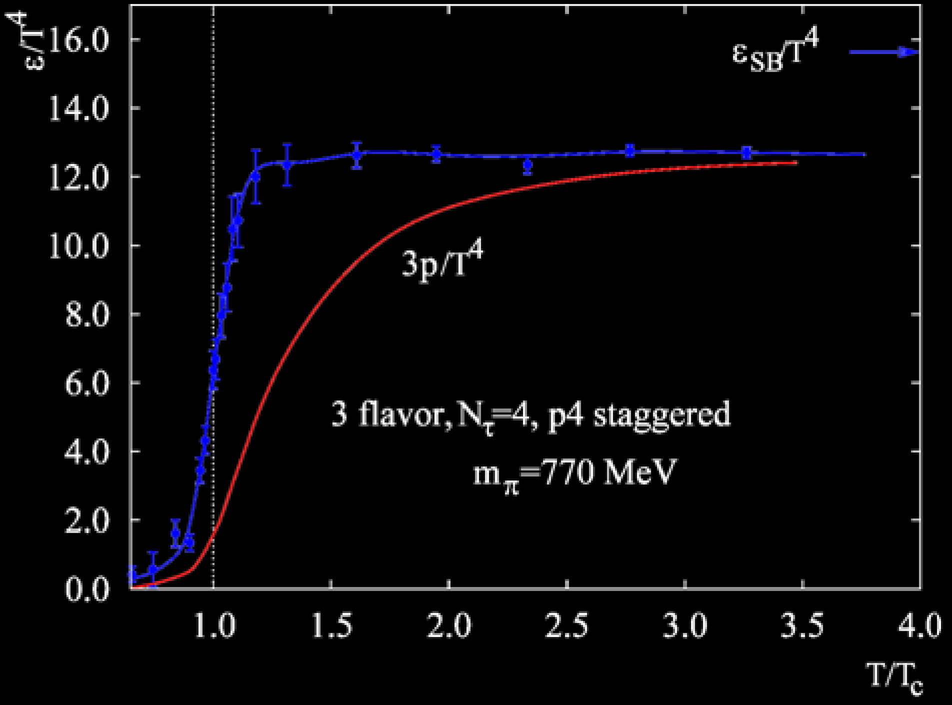
QCD on the lattice



F. Karsch, E. Laermann and A. Peikert, PLB 478 (2000) 447

T_c ~ 170 MeV,

$\varepsilon_C = 0.6$ GeV/fm^3

- perturbation theory not applicable
  - lattice QCD calculate bulk properties
- at the critical temperature a strong increase in degrees of freedom
  - color!
- not an ideal gas!
  - residual interactions
- At phase transition $dp/d\varepsilon$ decreases rapidly!!

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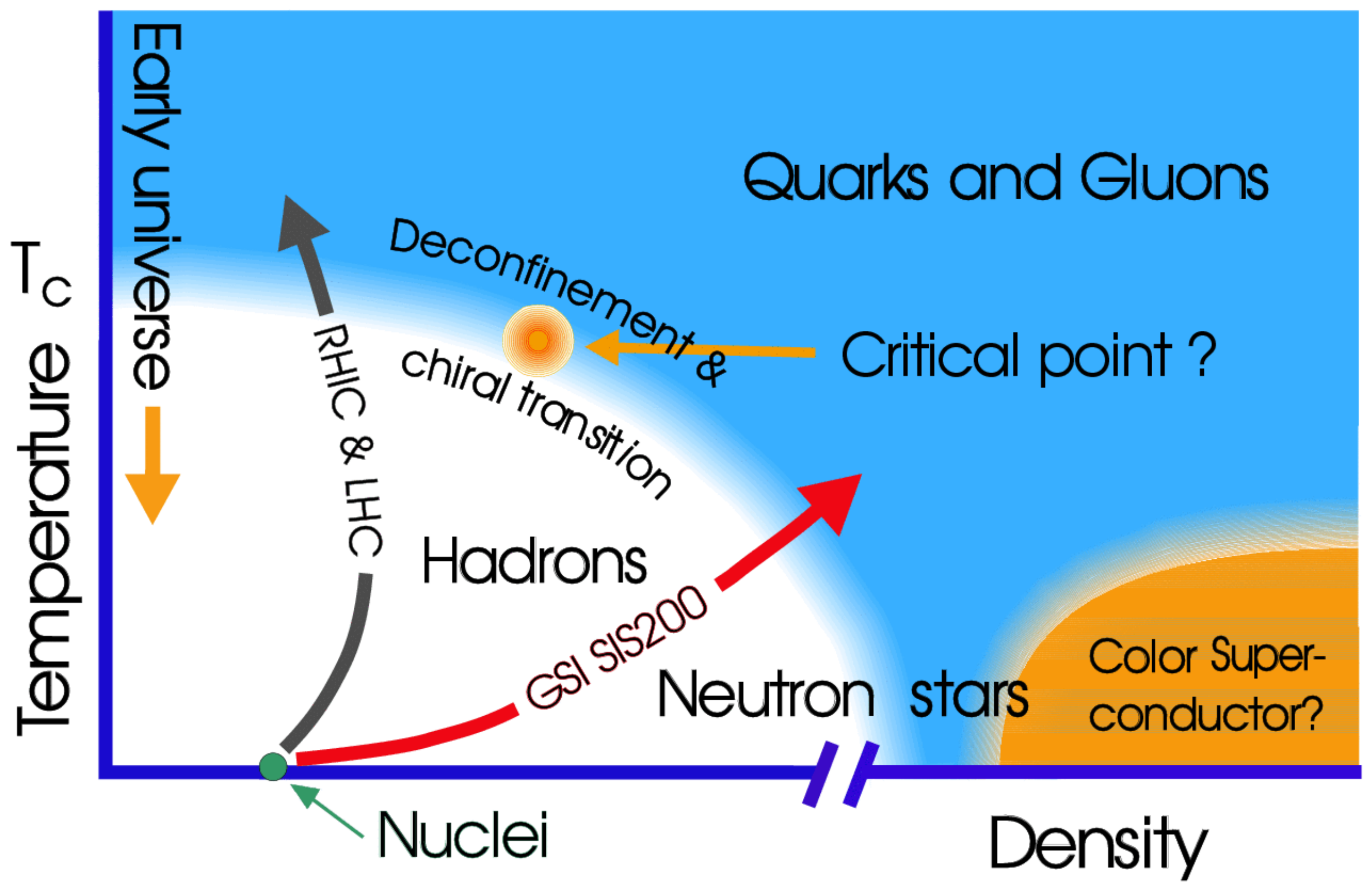
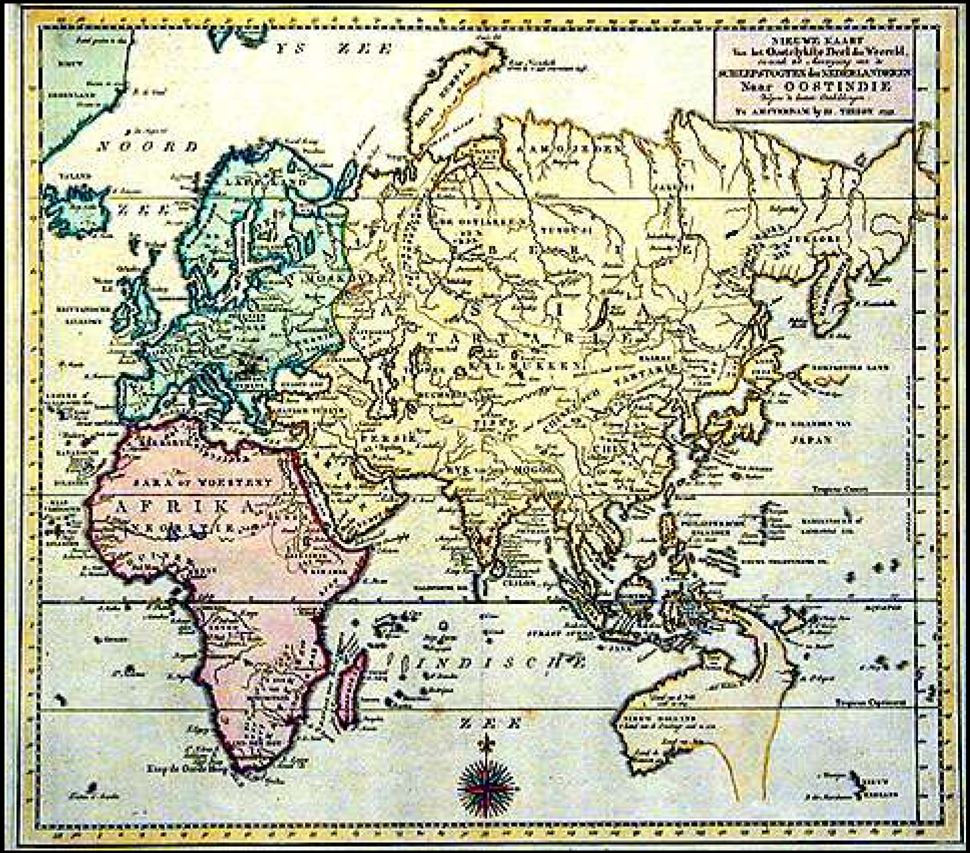
Our current map of the QCD landscape



Based on Krishna Rajagopal and Frank Wilczek: Handbook of QCD

- Theory view of phases in QCD matter

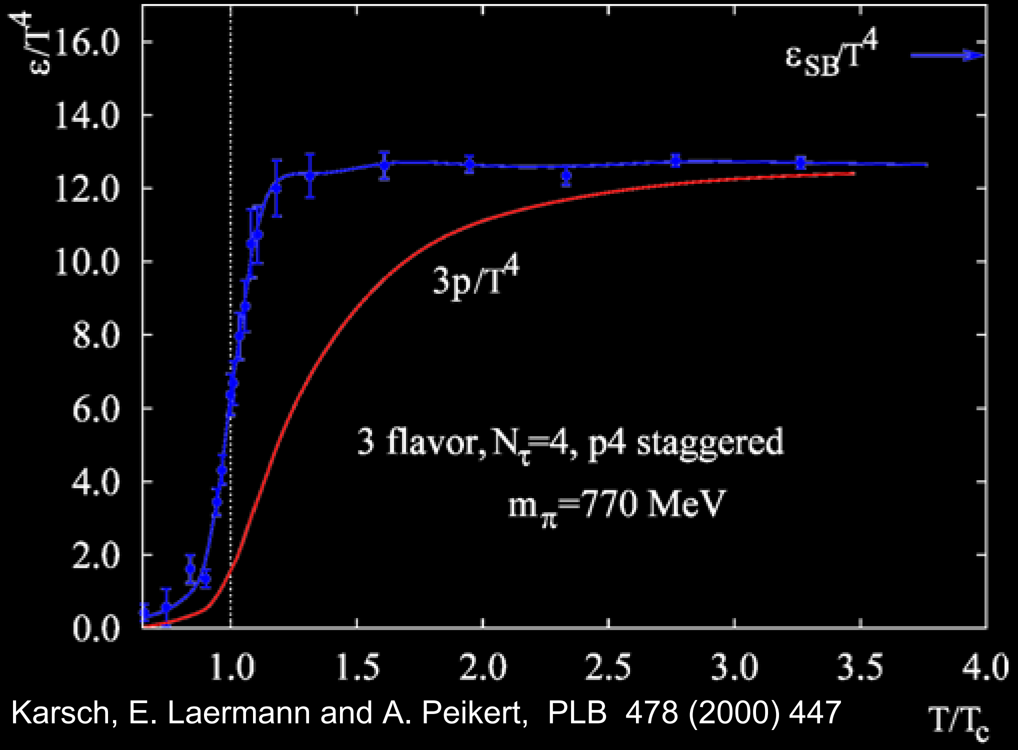
Mappamundi 1452



The map anno 2007

Understanding QCD and the early universe

- QGP properties are in principle calculable from the QCD Lagrangian using lattice QCD

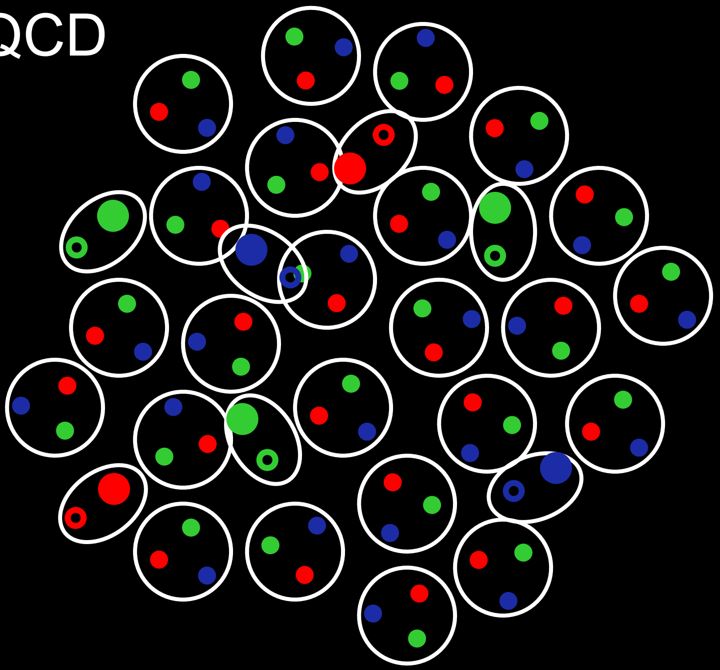


F. Karsch, E. Laermann and A. Peikert, PLB 478 (2000) 447

ε/T^4 ~ # degrees of freedom

- How to make a connection with experiment?

Animation: Mike Lisa

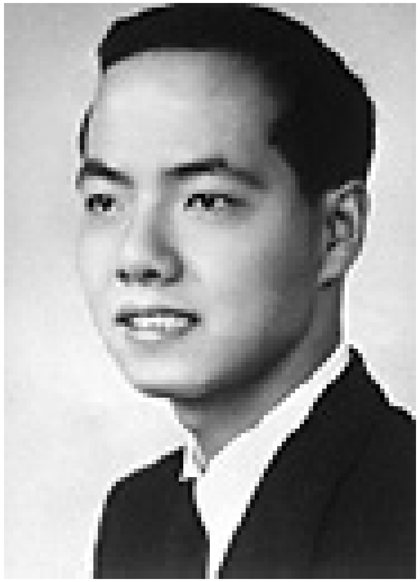


- Heating the matter
- Compressing the matter
  - deconfined matter with color degrees of freedom

The vacuum

"In high-energy physics we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions

In order to study the question of 'vacuum', we must turn to a different direction; we should investigate some bulk phenomena by distribution high energy over a relatively large volume"



Tsung-Dao Lee

T.D. Lee

Rev. Mod. Phys. 47 (1975) 267.

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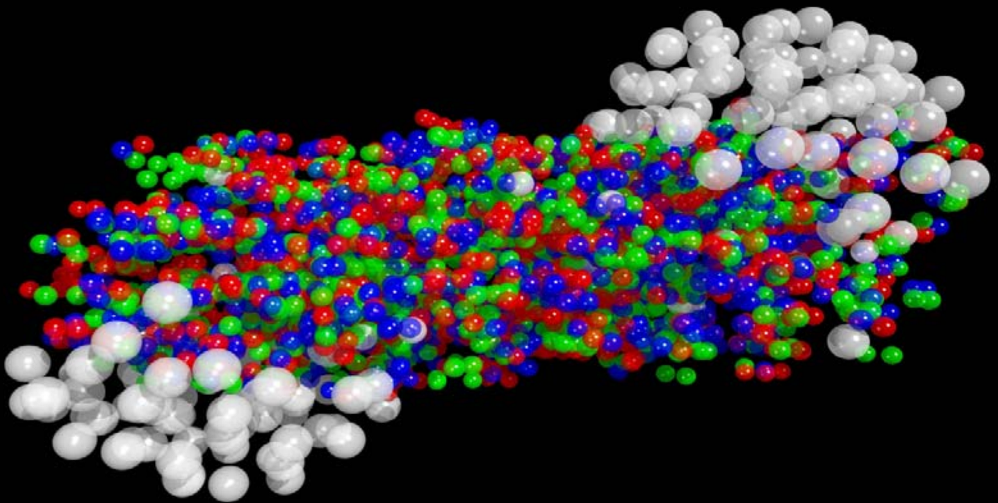
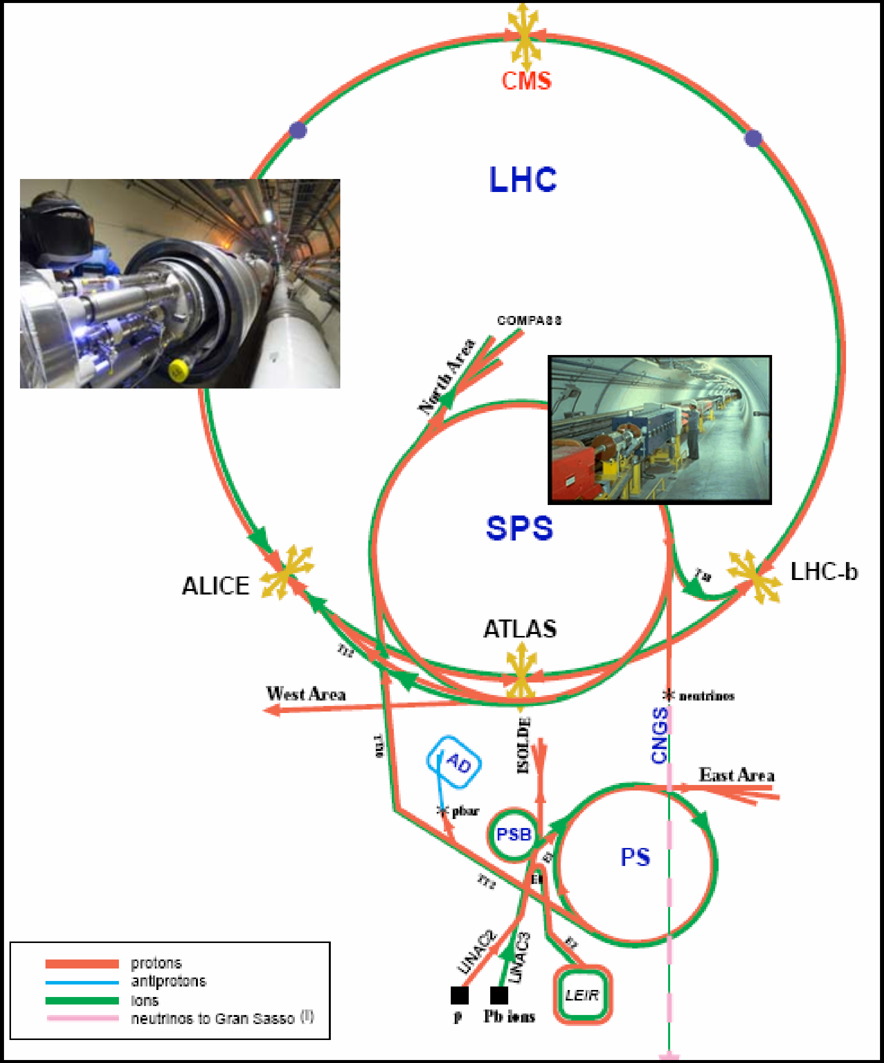
Understanding the phase transition

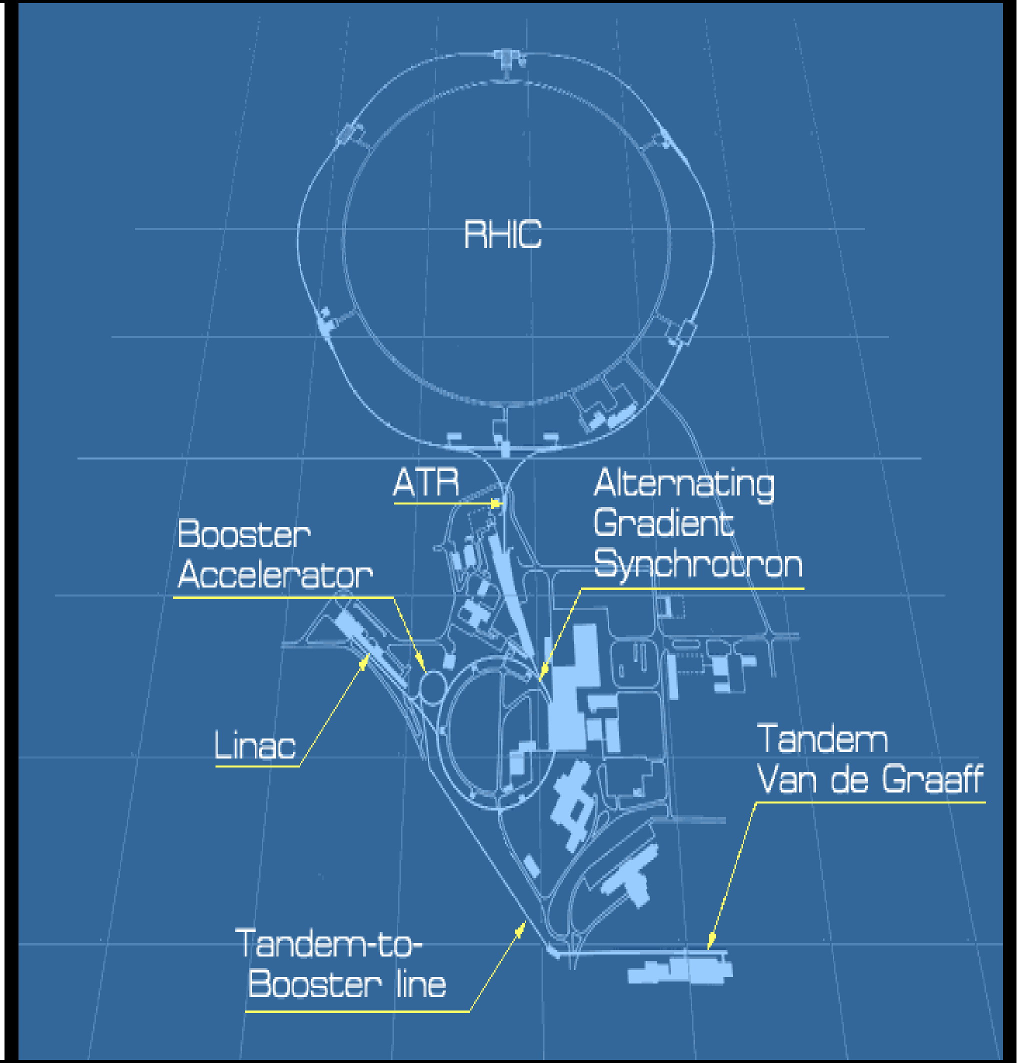
- From the experiments we like to get a measurement of:
  - The effective number of confined degrees of freedom, g_H, at T_c
  - The change in number of acting degrees of freedom, $g_{QGP} - g_H$
  - The vacuum pressure, *B*, or latent heat

How?
The accelerators and the experiments



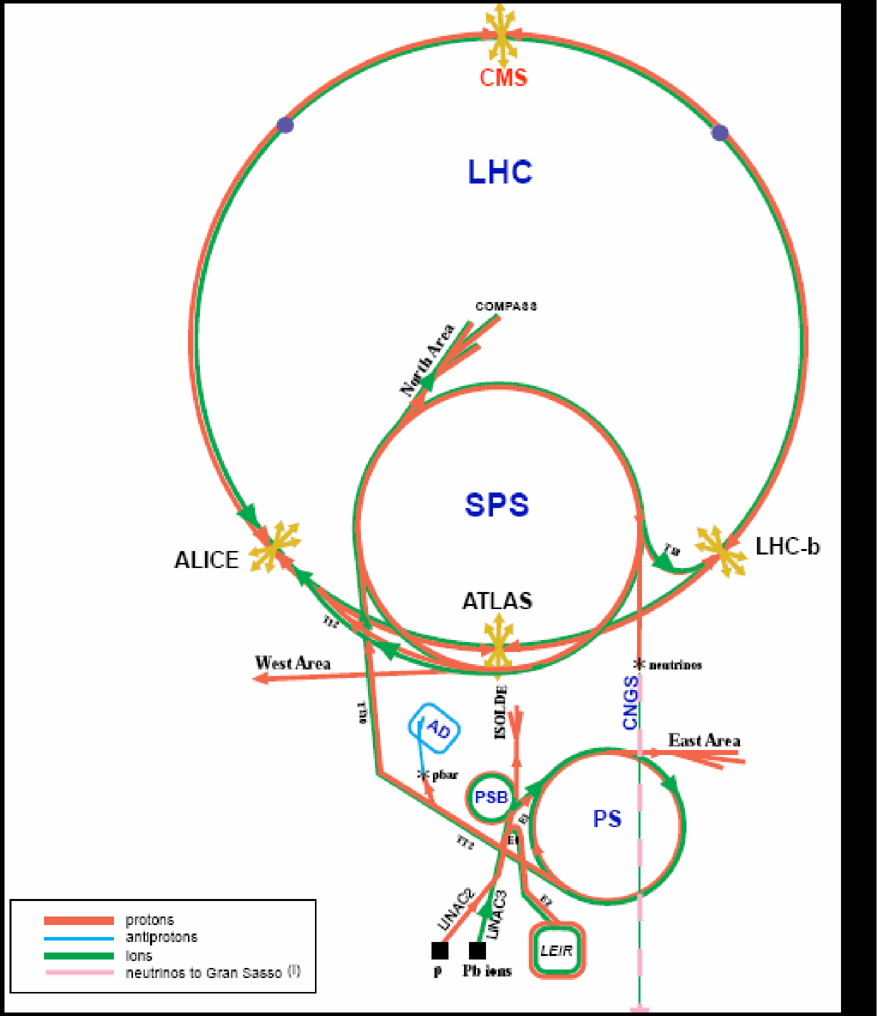
CERN and Brookhaven National Laboratory





Lead collisions at CERN

- Accelerate Pb ions
    - ECR source: Pb^{27+}
    - RFQ: Pb^{27+} to 250 A keV
    - Linac3: Pb^{27+} to 4.2 A MeV
    - Stripper: Pb^{53+}
    - PS Booster: Pb^{53+} to 95 A MeV
    - PS: Pb^{53+} to 4.25 A GeV
    - Stripper: Pb^{82+} (fully ionized)
    - SPS: Pb^{82+} to 158 A GeV
    - LHC: Pb^{82+} to 2.76 A TeV



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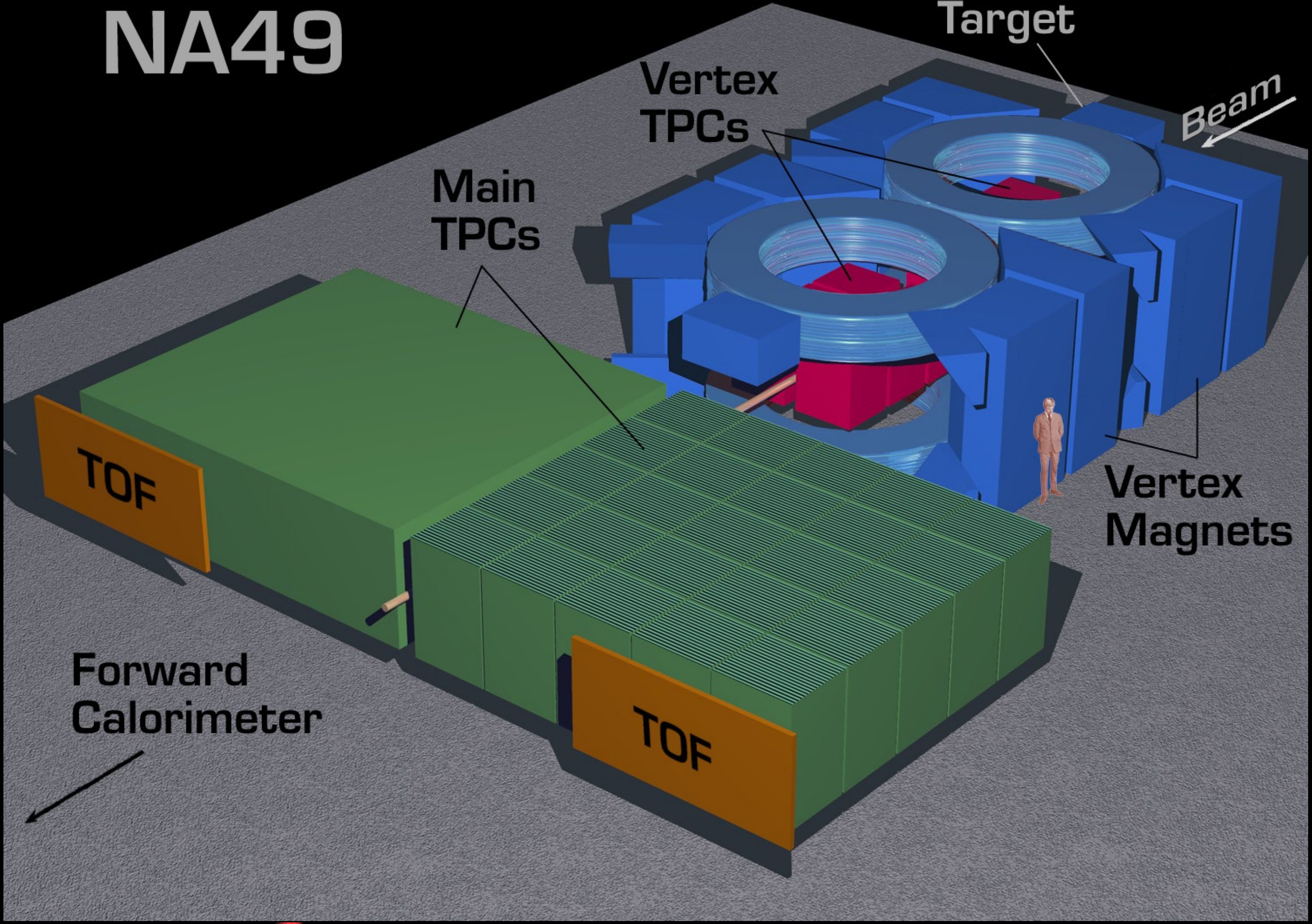
SPS detector example: NA49



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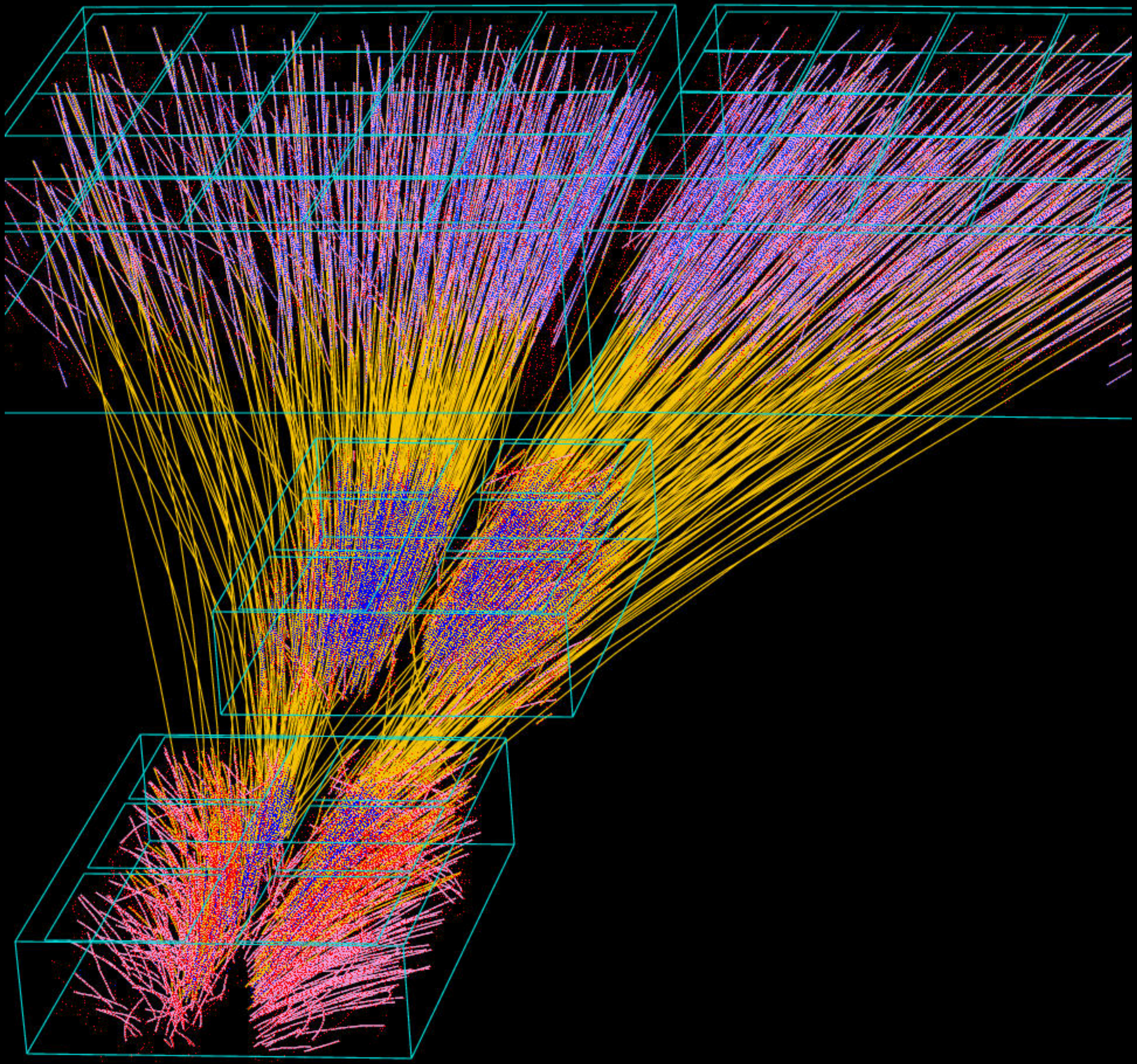
NA49 event display



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The Relativistic Heavy Ion Collider

- 3.83 km circumference
- Two independent rings
    - 120 bunches/ring
    - 106 ns crossing time
- Capable of colliding ~any nuclear species on ~any other species
- Energy:
    - ➔ 200 GeV for Au-Au (per N-N collision)
    - ➔ 500 GeV for p-p
- Luminosity:
    - Au-Au: 2×10^{26} cm^{-2} s^{-1}
    - p-p : 2×10^{32} cm^{-2} s^{-1} (*polarized*)

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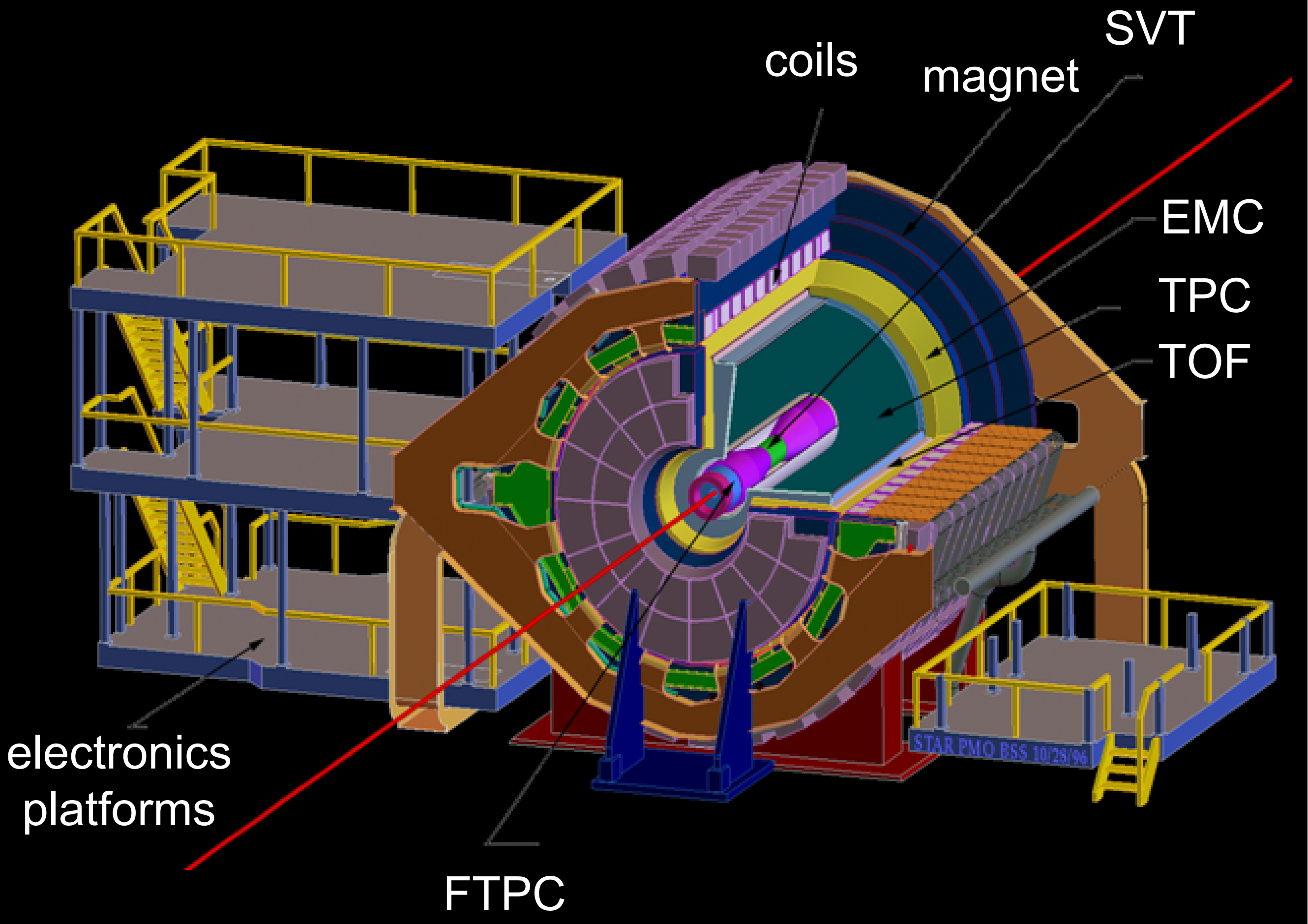
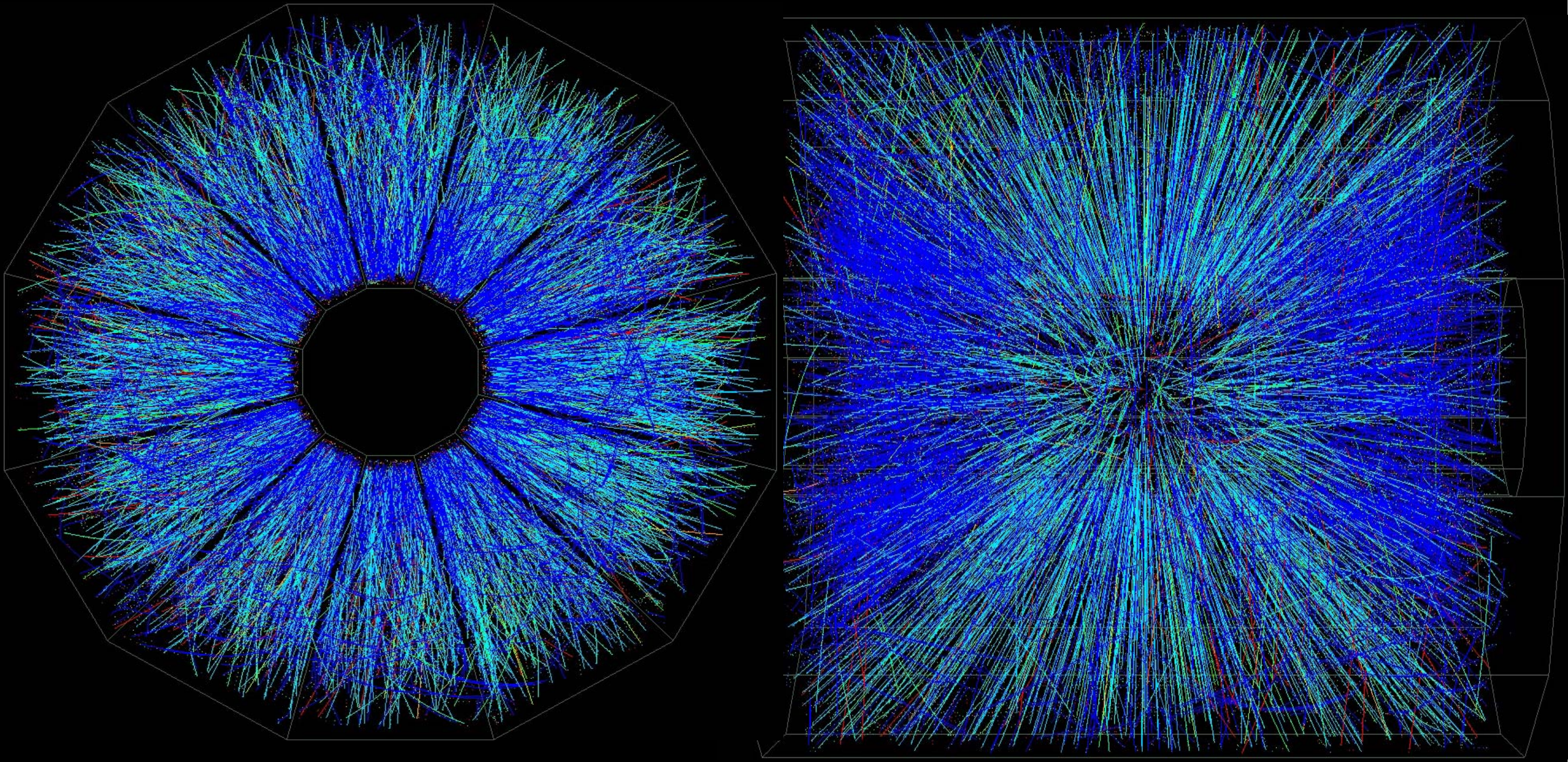
RHIC detector example: STAR

- Hadronic Observables over a Large Acceptance
  - Event-by-Event Capabilities
- Solenoidal magnetic field
- Large coverage Time-Projection Chamber
- Silicon Tracking, RICH, EMC, TOF



The STAR detector



Online Level 3 Trigger Display

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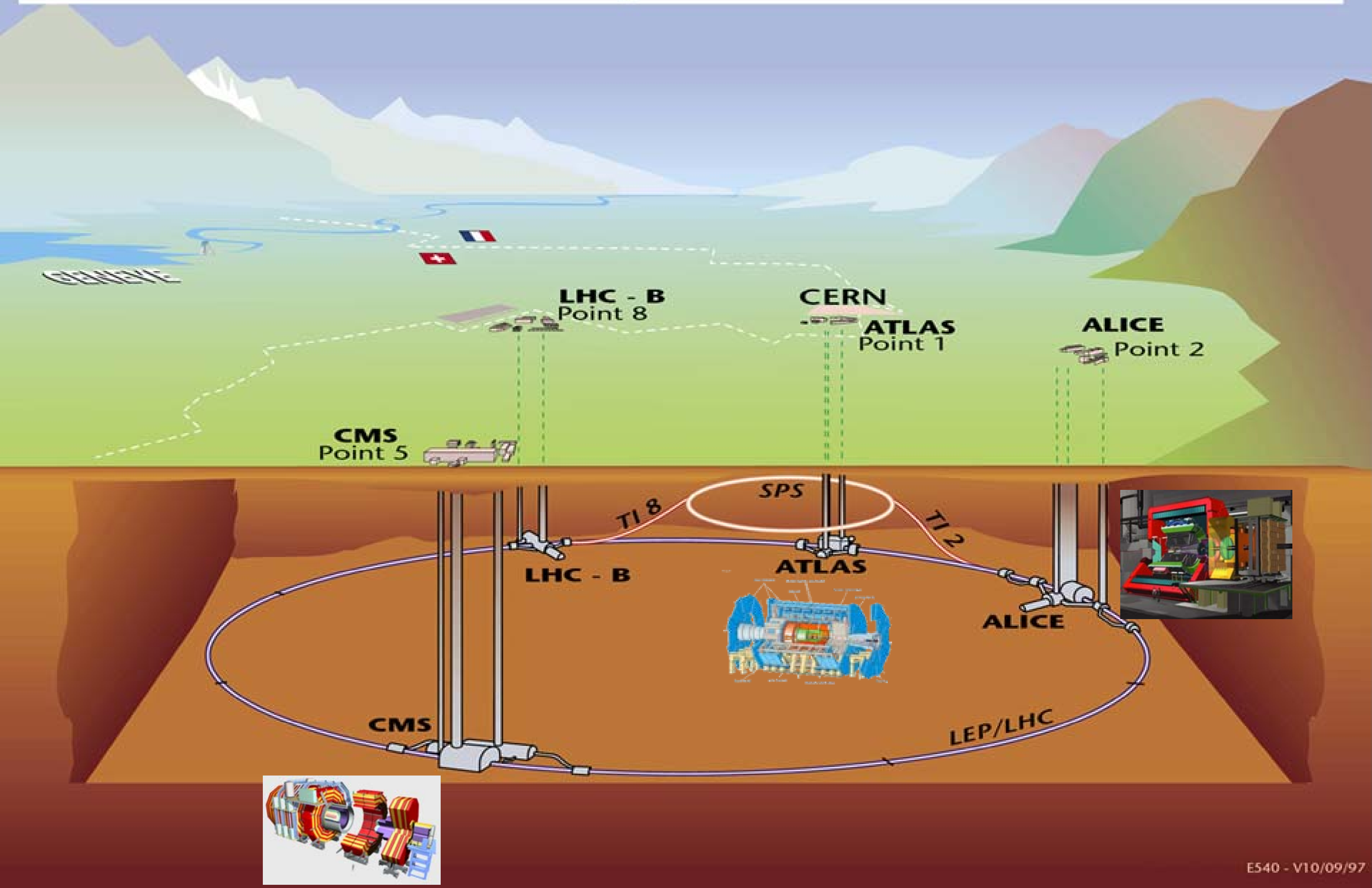
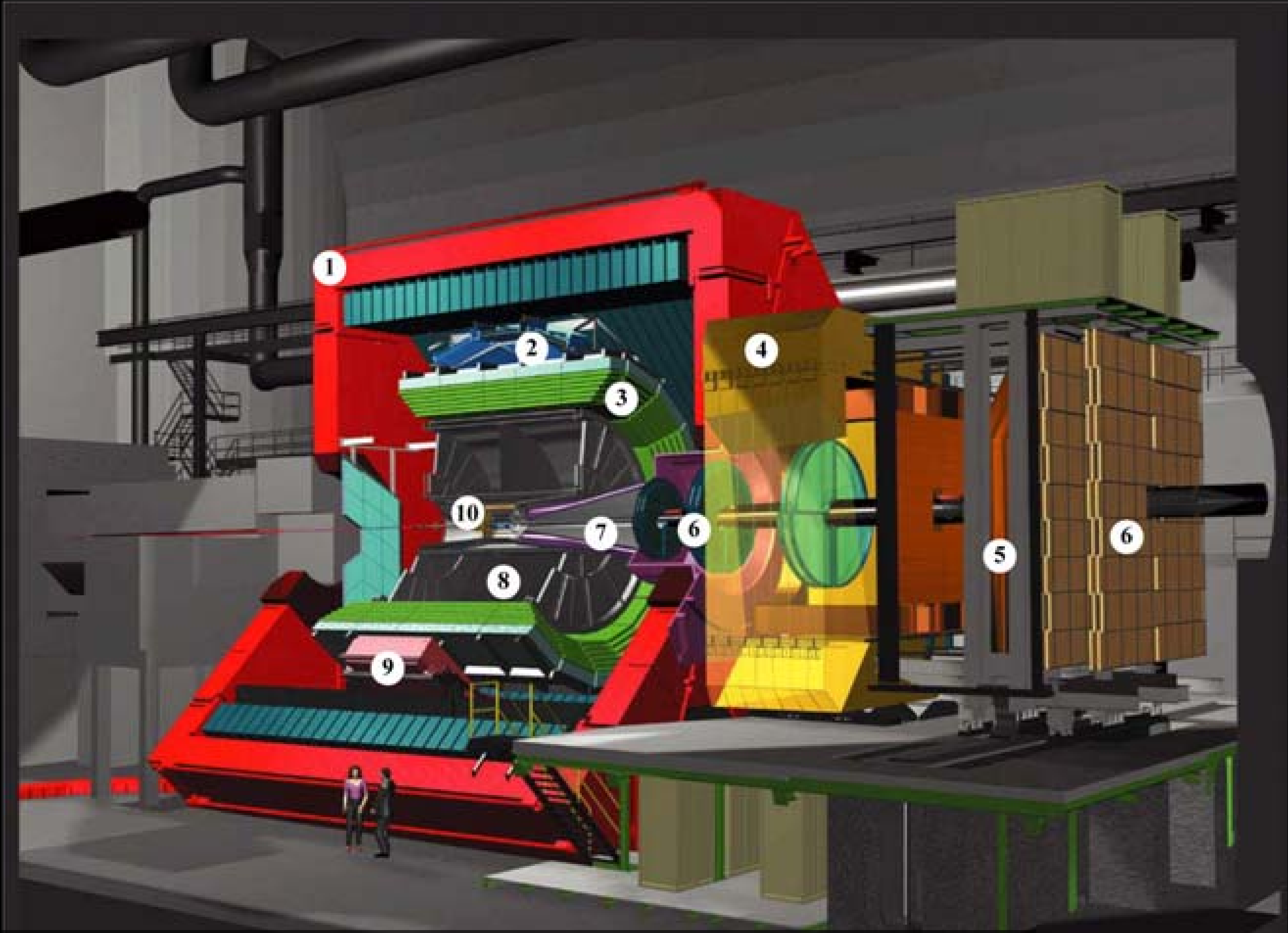
The Large Hadron Collider (LHC)

The Large Heavy ion Collider (LHC)

Overall view of the LHC experiments.



The ALICE detector

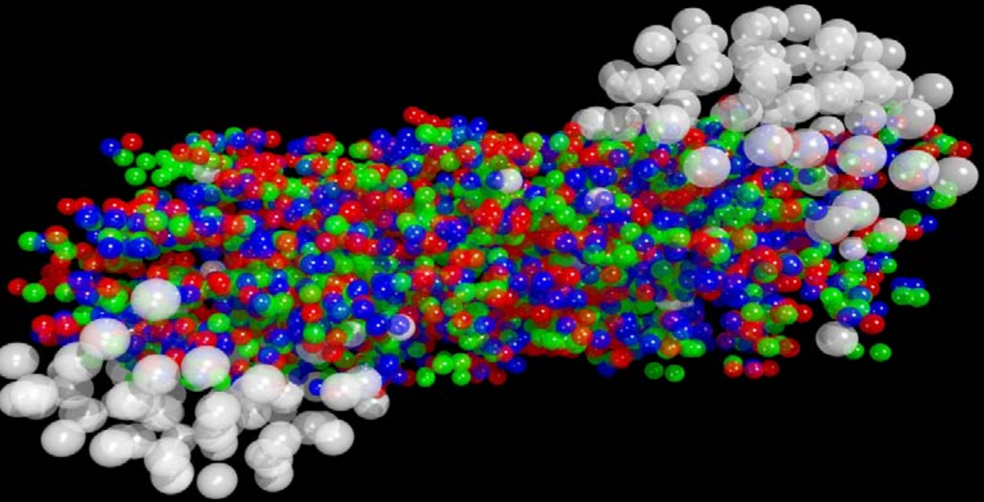


1) L3 MAGNET
2) HMPID
3) TOF
4) DIPOLE MAGNET
5) MUON FILTER
6) TRACKING & TRIGGER CHAMBERS
7) ABSORBER
8) TPC
9) PHOS
10) ITS

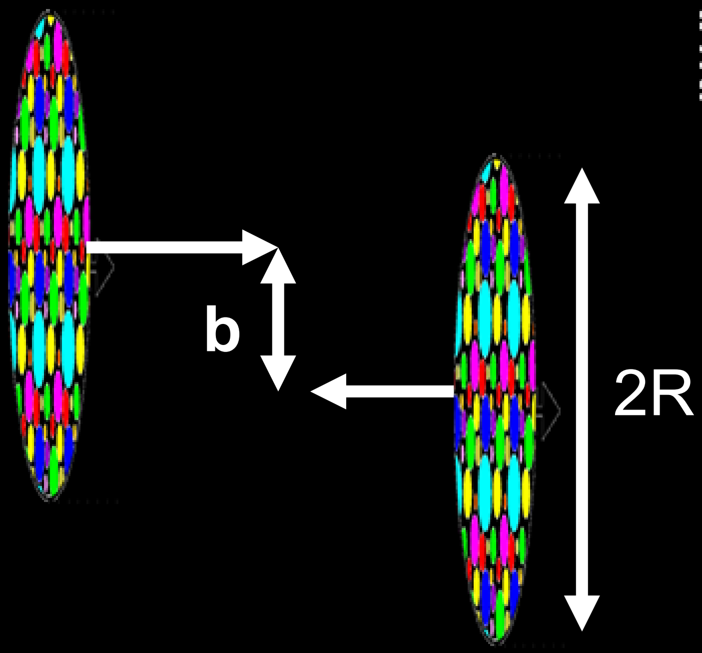
ALICE Collaboration:

~ 1000 people, 30 countries, ~ 80 Institutes

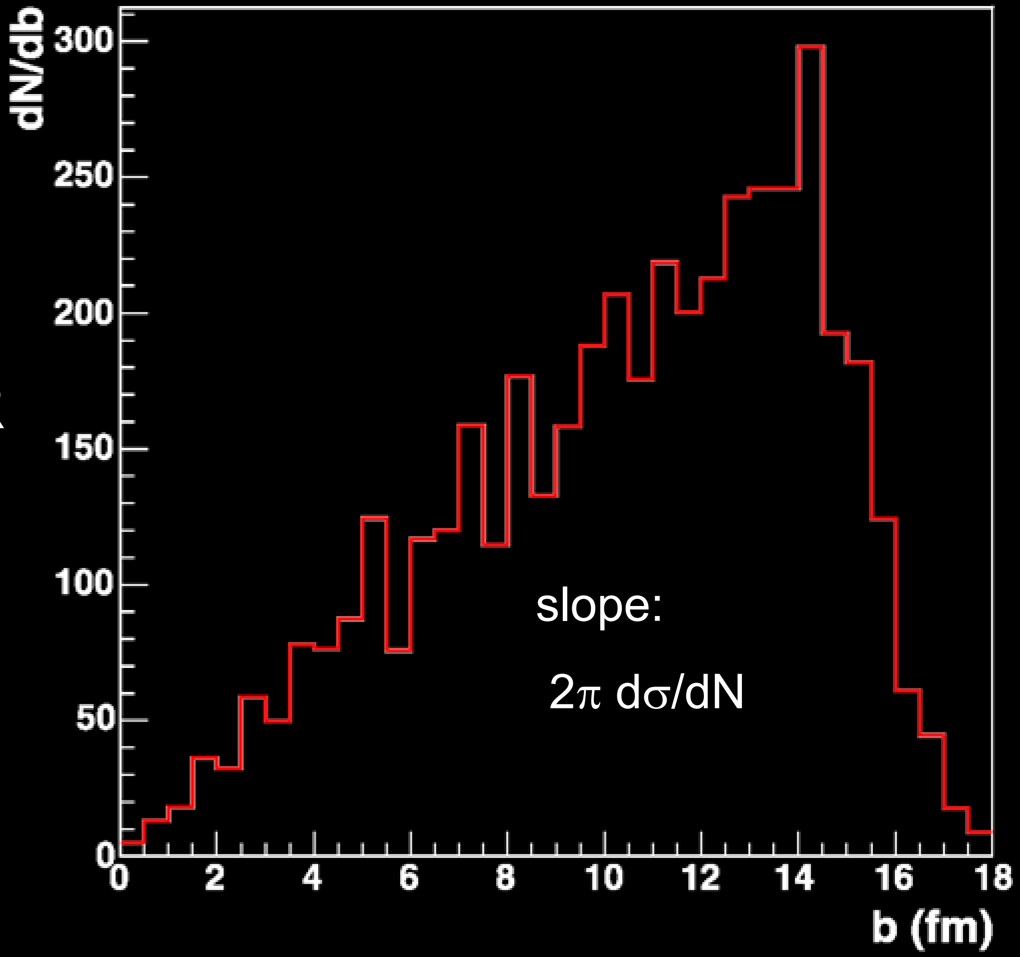
How?
Event Characterization



Impact parameter distribution



- impact parameter **b**
  - perpendicular to beam direction
  - connects centers of the colliding ions

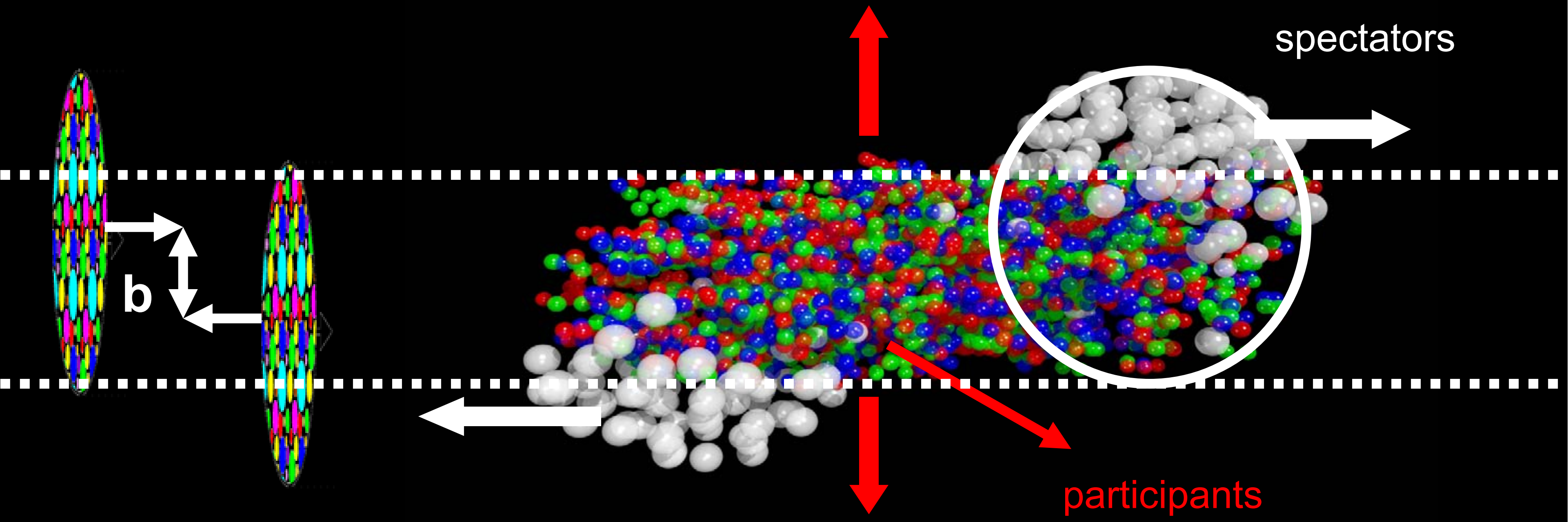


slope:

$2\pi\, d\sigma/dN$

$$d\sigma = 2\pi b\, db$$

Centrality determination (I)



- Centrality characterized by:
  - N_{part}, $N_{wounded}$: number of nucleons which suffered at least one inelastic nucleon-nucleon collision
  - N_{coll}, N_{bin}: number of inelastic nucleon-nucleon collisions

Glauber Model Calculations

- Nuclear density from Wood-Saxon distribution

$$\rho(r)=\frac{\rho_0\left(1+wr^2/R^2\right)}{1+e^{(r-R)/a}}$$

Nucleus	A	R	a
Au	197	6.38	0.535
Pb	208	6.68	0.546

- Nucleons travel on straight lines, no deflection after NN collision
- NN collision cross section from measured inelastic cross section in p+p
- NN cross section remains constant independent of how many collisions a nucleon suffered

√S (GeV)	$\sigma_{in,pp}$ (mb)
20	32
200	42
5500	~70

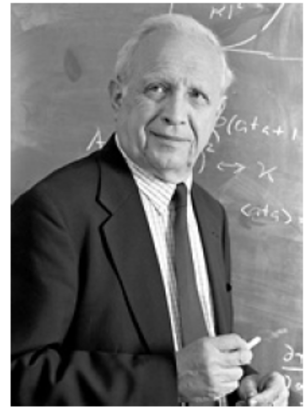
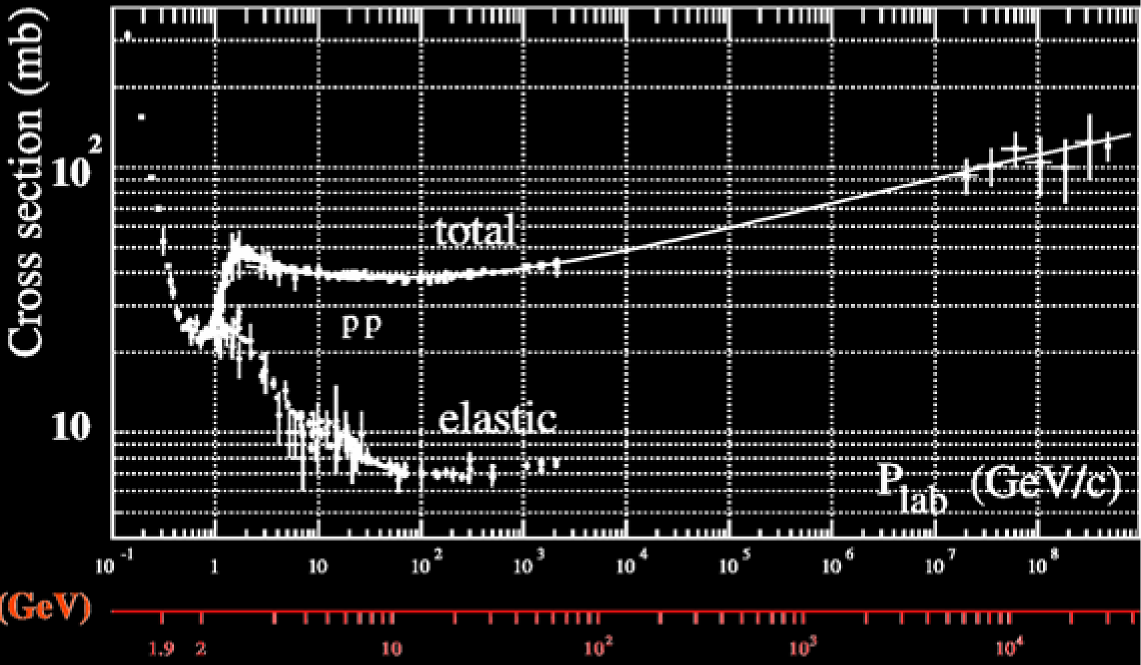


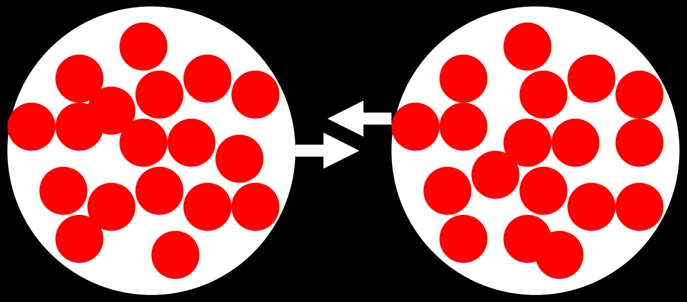
Photo: J.Reed

Roy J. Glauber



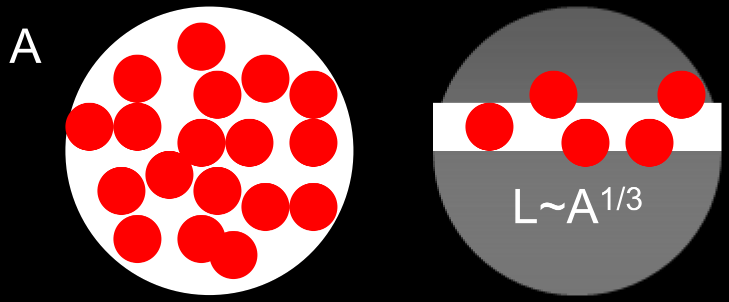
Wounded nucleons and binary collisions

Wounded nucleon scaling

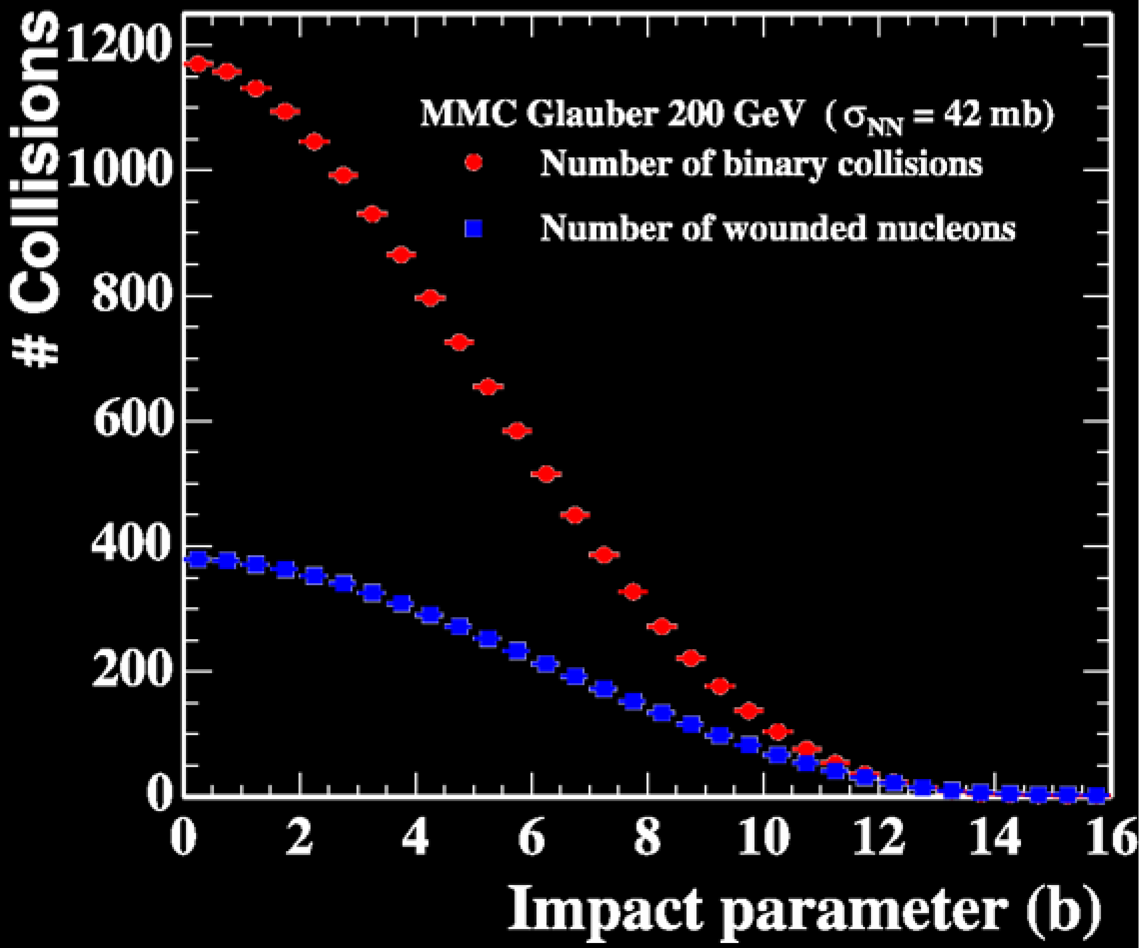


Number of participating nucleons scales with volume ~ 2A

Binary scaling

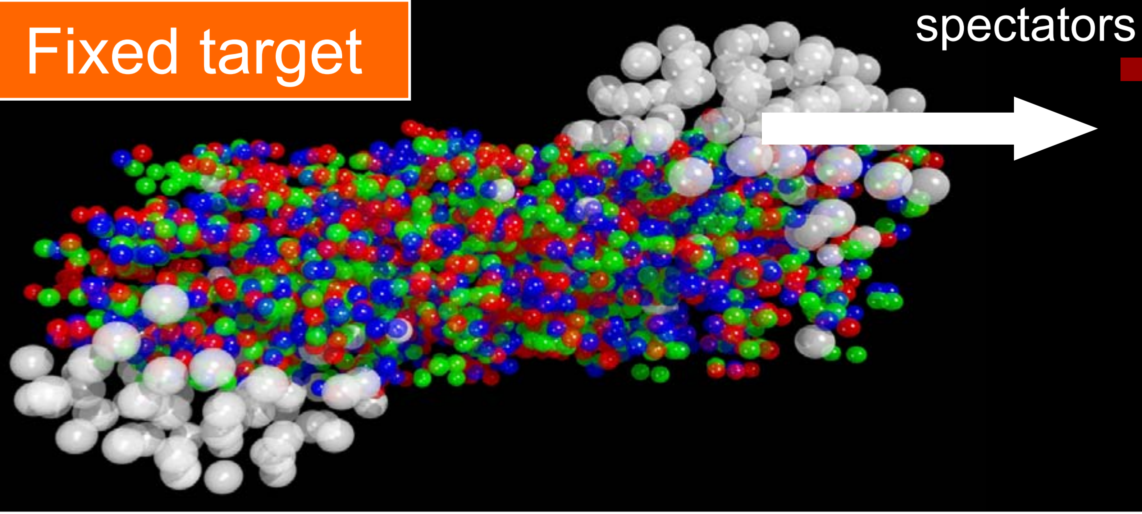


Number of NN collisions, point like, scales with ~ A$^{4/3}$



Centrality determination (II)

Fixed target

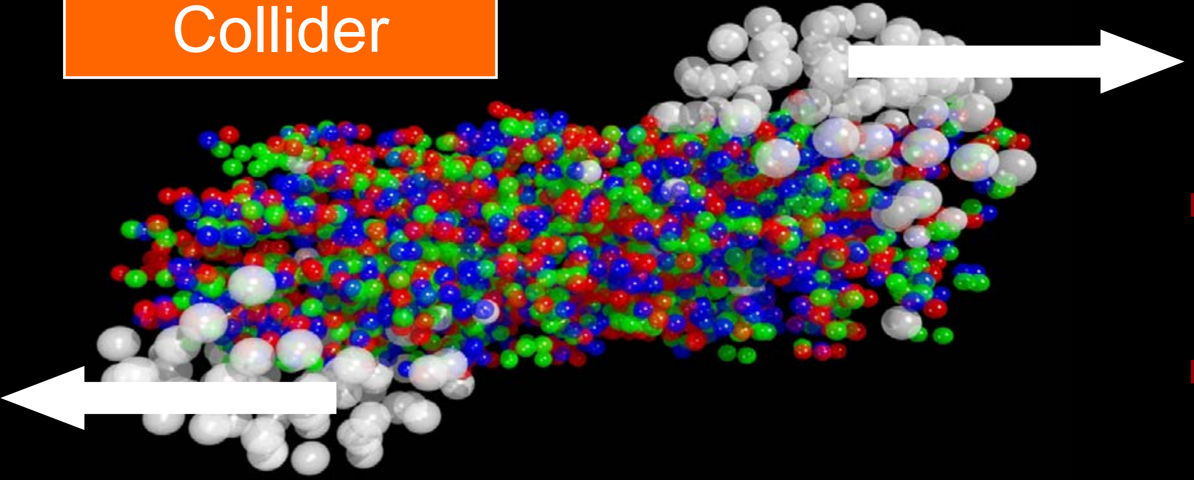


- Zero-Degree-Calorimeter (ZDC) measures energy of all spectator nucleons

$$N_{\text{spec}} \approx E_{\text{ZDC}} / \left(E_{\text{beam}} / A\right),$$

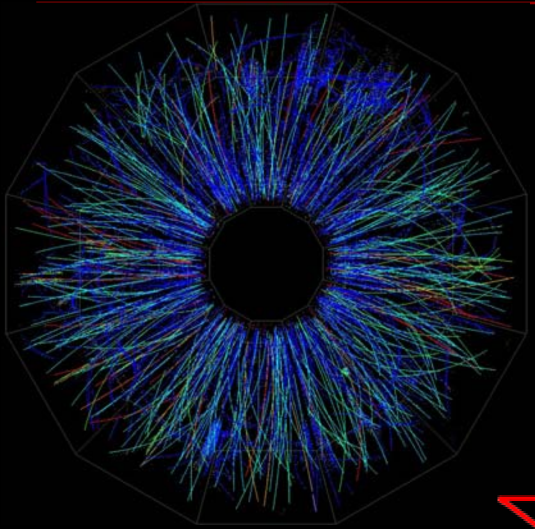
$$N_{part} \approx 2\cdot\left(A - N_{\text{spec}}\right)$$

Collider



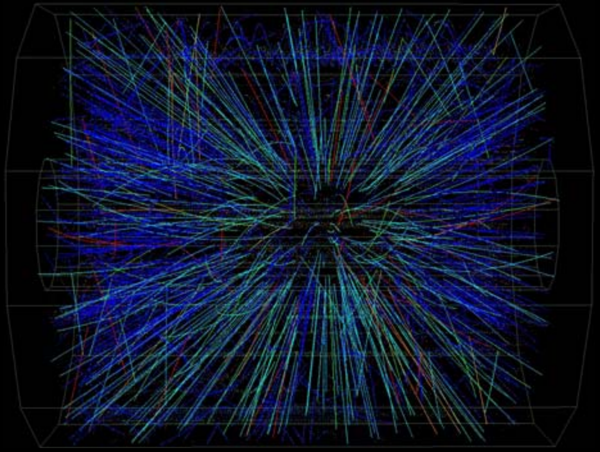
- Zero-Degree-Calorimeter (ZDC) measures energy of all <u>unbound</u> spectator nucleons
- Charged fragments (p, d, and heavier) are deflected by accelerator magnets
- E_{ZDC} small for very central and very peripheral collisions, ambiguous

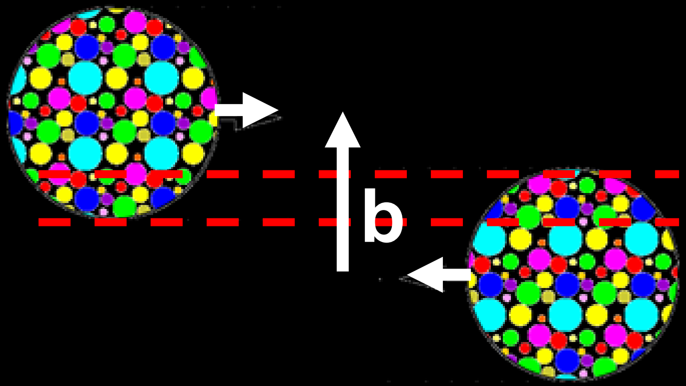
Centrality determination (III)



Peripheral Event

From real-time Level 3 display





- peripheral collisions, largest fraction cross section
- many spectators
- “few” particles produced

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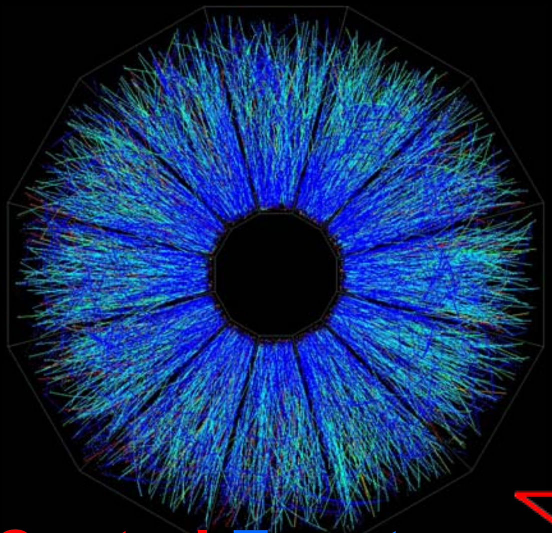
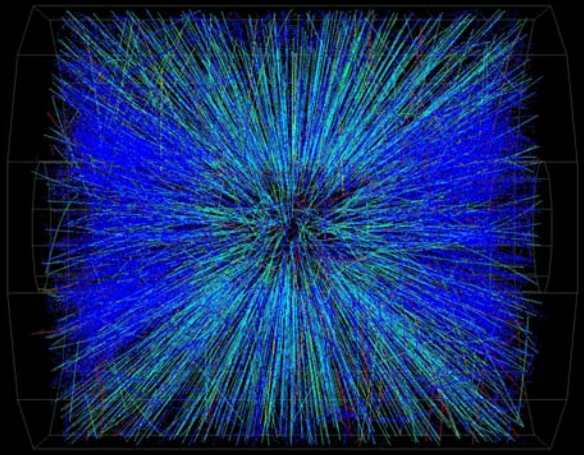
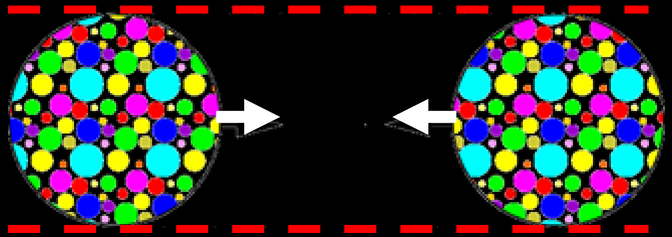
Centrality determination (IV)



Central Event

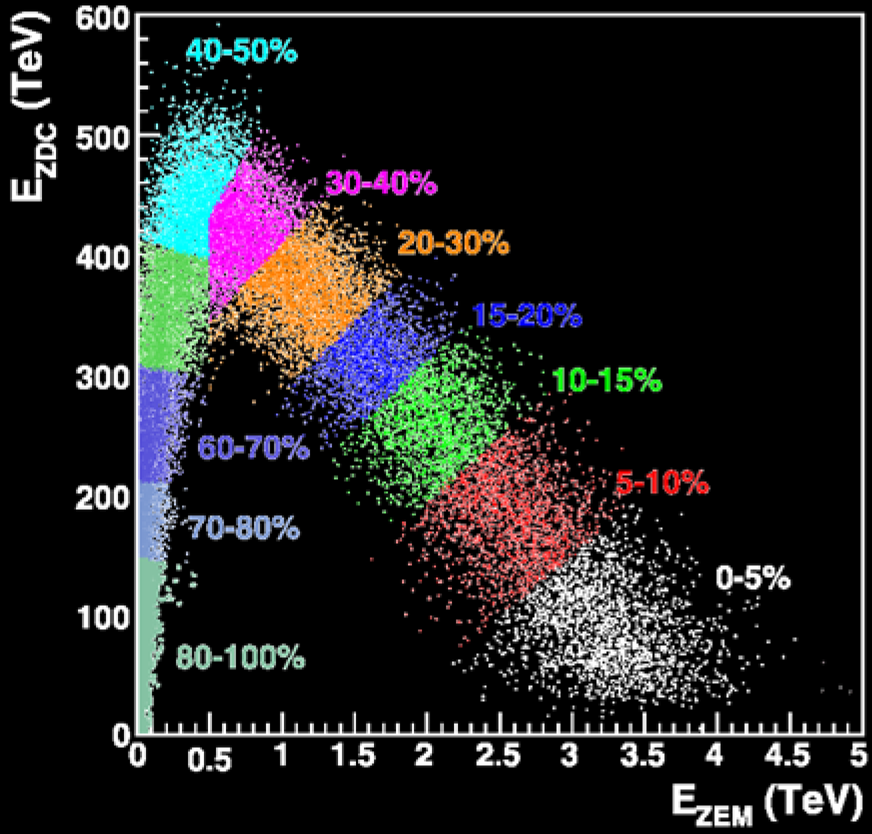
From real-time Level 3 display

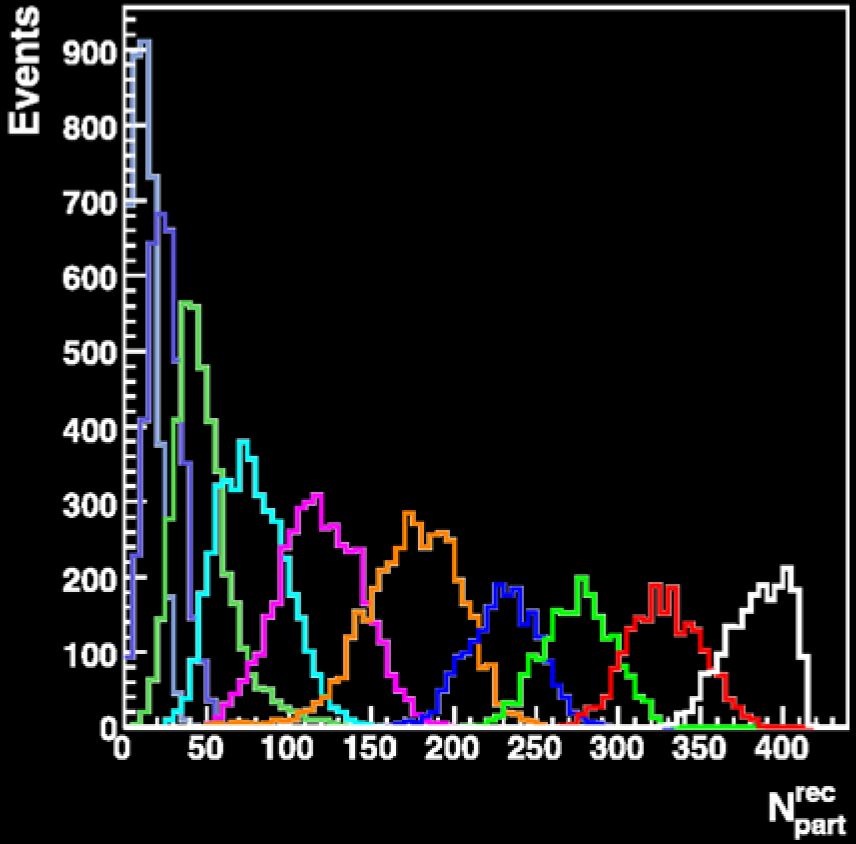




- impact parameter **b** = 0
- central collisions, small cross section
- no spectators
- many particles produced

Centrality determination in ALICE

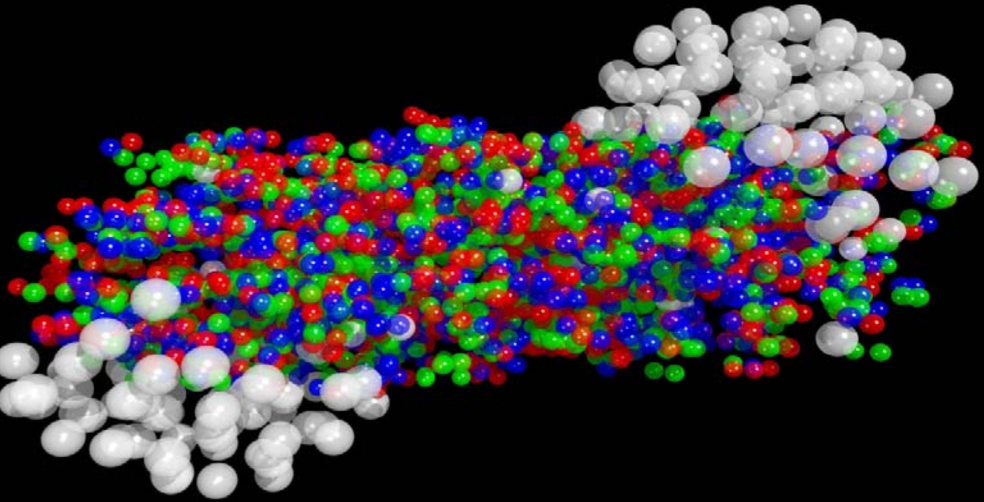




- Determine the magnitude of the impact parameter

$\%\sigma_{tot}$	$<N_{part}>$	$<b>$
0-5	386	2.48
20-30	177	7.85
60-70	25	12.66

Kinematics



Energy and Momentum

Invariants:

$$I \qquad g \quad x \;\; x \qquad x \;\; x$$

$$x \qquad ct, x, y, z \qquad x \;\; x \qquad c^2 t^2 \quad x^2 \quad y^2 \quad z^2,$$

momentum and energy:

$$\vec{p} \qquad m\vec{v}, \;\; E \qquad mc^2,$$

energy momentum four vector:

$$p \qquad \frac{E}{c}, p_x, p_y, p_z \quad ,$$

$$g_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

energy momentum relation:

$$E^2 \quad p^2 c^2 \quad m^2 c^4$$

Rapidity, pseudo-rapidity and m_T

$$\vec{p}_T \qquad \vec{p}_x \qquad \vec{p}_y$$

$$\mathrm{m}_\mathrm{T}^2 \qquad m^2 \qquad p_T^2$$

$$y = \frac{1}{2}\ln\left(\frac{p_0 + p_z}{p_0 - p_z}\right)$$

$$e^y \qquad \sqrt{\frac{p_0 \quad p_z}{p_0 \quad p_z}},$$

$$e^{\ \ y} \qquad \sqrt{\frac{p_0 \quad p_z}{p_0 \quad p_z}},$$

$$p_0 \qquad m_T \cosh y, \qquad \mathrm{p}_\mathrm{z} \qquad m_T \sinh y$$

$$\mathrm{m}_\mathrm{T}^2 \qquad m^2 \qquad p_T^2$$

Under a Lorentz transformation, with β along *z*, rapidity's add-up

Rapidity distributions are boost-invariant: d*N*/d*y* = d*N*/d*y*'

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

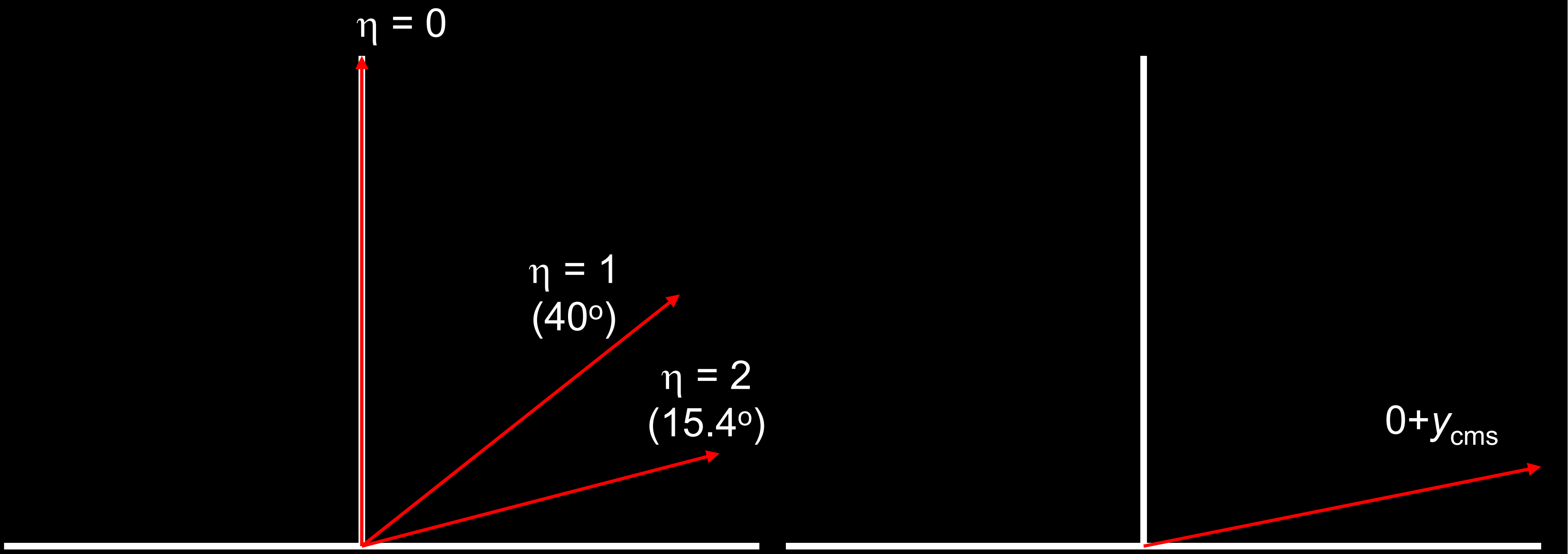
$$\eta = \frac{1}{2}\ln\left(\frac{|\mathbf{p}| + p_z}{|\mathbf{p}| - p_z}\right),$$

$$e^\eta = \sqrt{\frac{|\mathbf{p}| + p_z}{|\mathbf{p}| - p_z}},$$

$$e^{-\eta} = \sqrt{\frac{|\mathbf{p}| - p_z}{|\mathbf{p}| + p_z}},$$

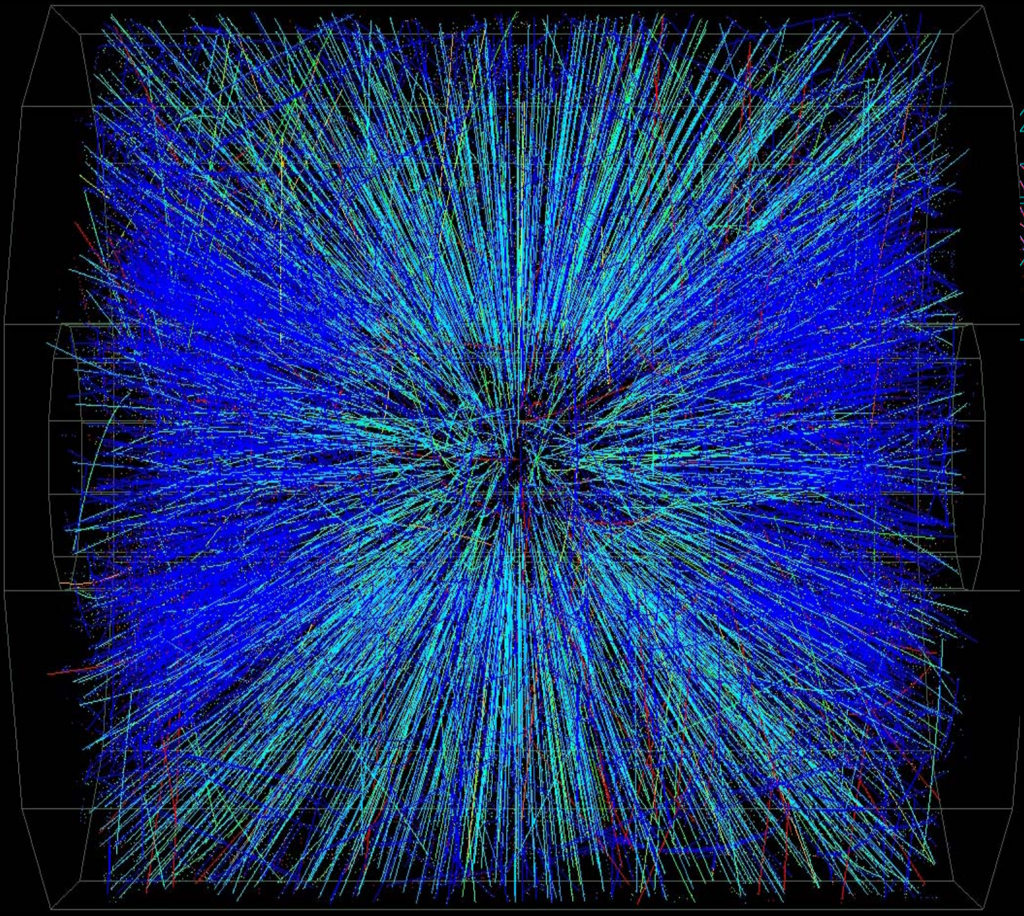
$$|p| = p_T \cosh\eta, \qquad \mathrm{p}_\mathrm{z} = p_T \sinh\eta$$

Rapidity in fixed target and collider

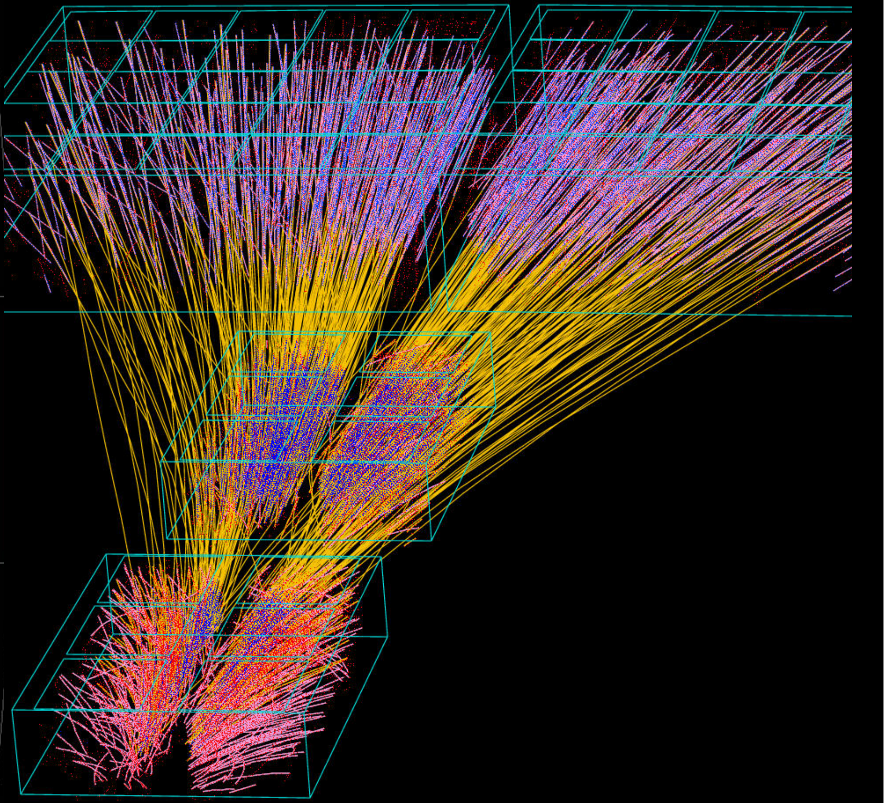


- In fixed target particles boosted with center of mass rapidity

Rapidity in fixed target and collider

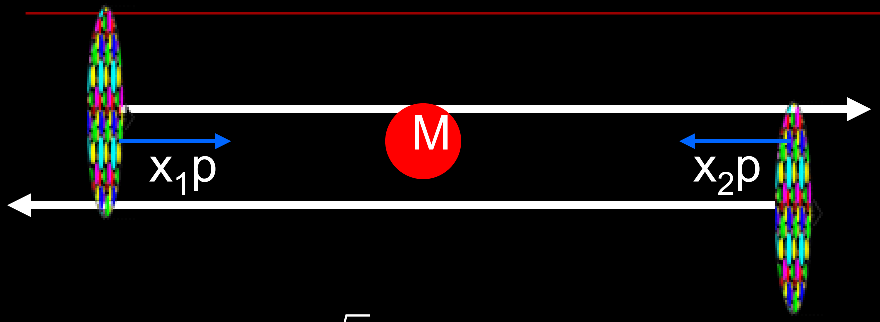


STAR, Au+Au 130 GeV RHIC
collider



NA49, Pb+Pb 17 GeV SPS
fixed target

Light-cone variables and rapidity



collision energy: $\sqrt{s}$

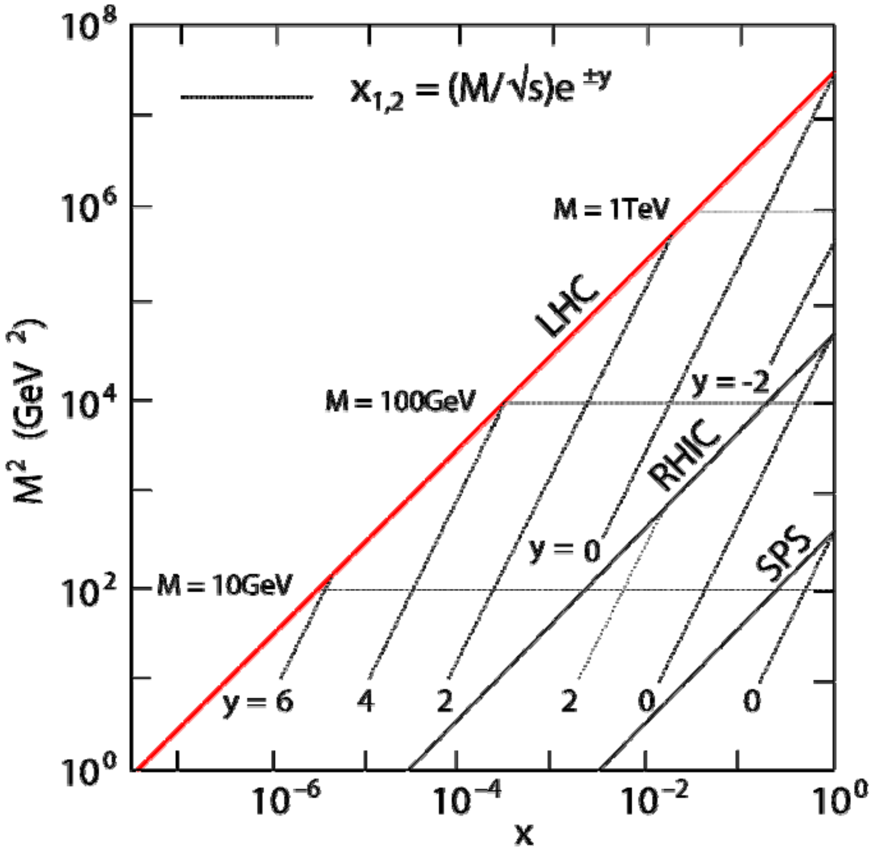
parton momenta: $p_1^\mu = x_1\sqrt{s}/2(1,0,0,1)$

$$p_2^\mu = x_2\sqrt{s}/2(1,0,0,-1)$$

invariant mass: $M^2 = (p_1 + p_2)^2 = x_1 x_2 s$

rapidity: $y = \frac{1}{2}\ln\left(\frac{p_0 + p_z}{p_0 - p_z}\right) = \frac{1}{2}\ln\left(\frac{x_1}{x_2}\right)$

$$x_1 = \frac{M}{\sqrt{s}}e^{y}, \quad x_2 = \frac{M}{\sqrt{s}}e^{-y}$$



- Higher beam energy gives larger range in x
- Forward rapidity probes smaller x
- Smaller invariant mass probes smaller x

Invariant cross section

- Differential cross section:

$$a+b\rightarrow {\color{red}c}+{\color{blue}X}$$

differential cross section: $\dfrac{d^3\sigma}{d^3p_c}$

d^3p is not Lorentz invariant: $\dfrac{d^3p}{E}$ is Lorentz invariant

$$p_z = m_T \sinh y, \quad \mathrm{d}p_z = m_T \cosh y \ \mathrm{d}y = E\mathrm{d}y,$$

$$\frac{d^3p}{E} = dp_x dp_y dy \text{ Lorentz-invariant for boost along z}$$

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Invariant cross section (II)

$$E\frac{d^3\sigma}{d^3\mathrm{p}}=\frac{d^3\sigma}{dp_x dp_y dy}=\frac{\mathrm{d}^3\sigma}{p_T dp_T d\phi dy}$$ "invariant cross section"

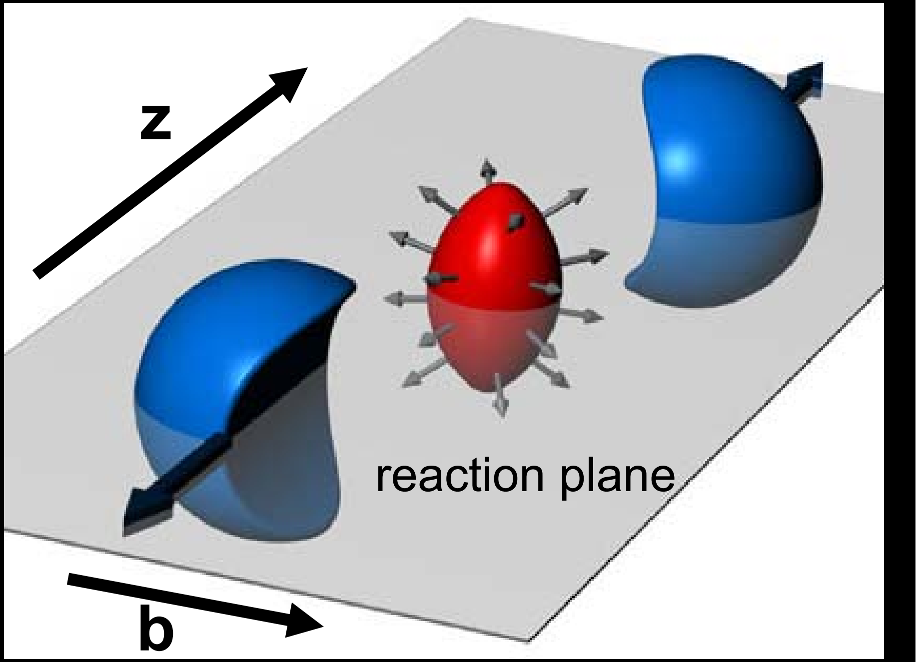
other variants (integrating over ϕ):

$$\frac{1}{2\pi p_T}\frac{d^2\sigma}{dp_T dy}=\frac{1}{\pi}\frac{d^2\sigma}{d\left(p_T^2\right)dy}=\frac{1}{\pi}\frac{d^2\sigma}{d\left(m_T^2\right)dy}=\frac{1}{2\pi m_\mathrm{T}}\frac{d^2\sigma}{dm_T dy}$$

The reaction plane

- **The reaction plane**
  - Spanned by the beam direction and the impact parameter **b**

$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3\mathrm{p}}=\frac{\mathrm{d}^3N}{p_t\mathrm{d}p_t\mathrm{d}y\mathrm{d}\left(\phi-\Psi_{\mathrm{R}}\right)}$$



The almond shape of the created quark gluon plasma in non-central collisions leads to an azimuthal dependence of the observables sensitive to the medium properties

- Determine the direction of the impact parameter

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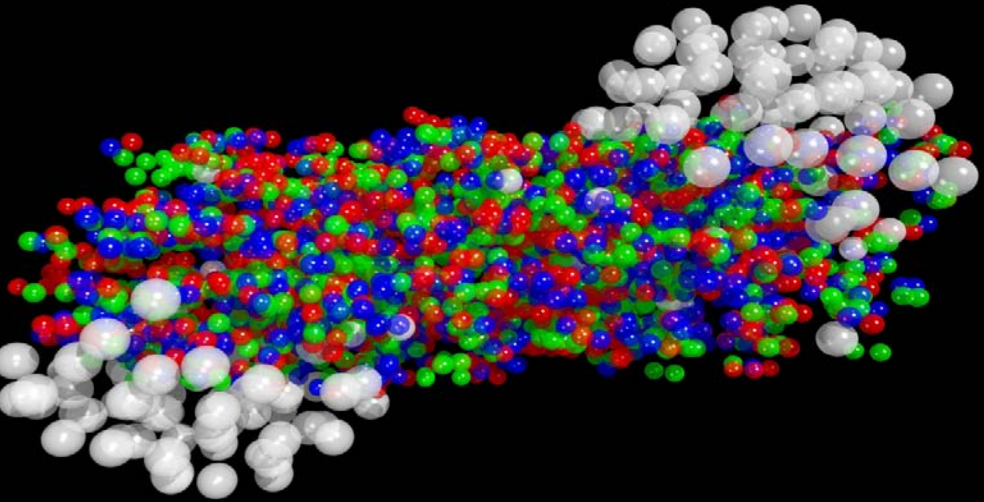
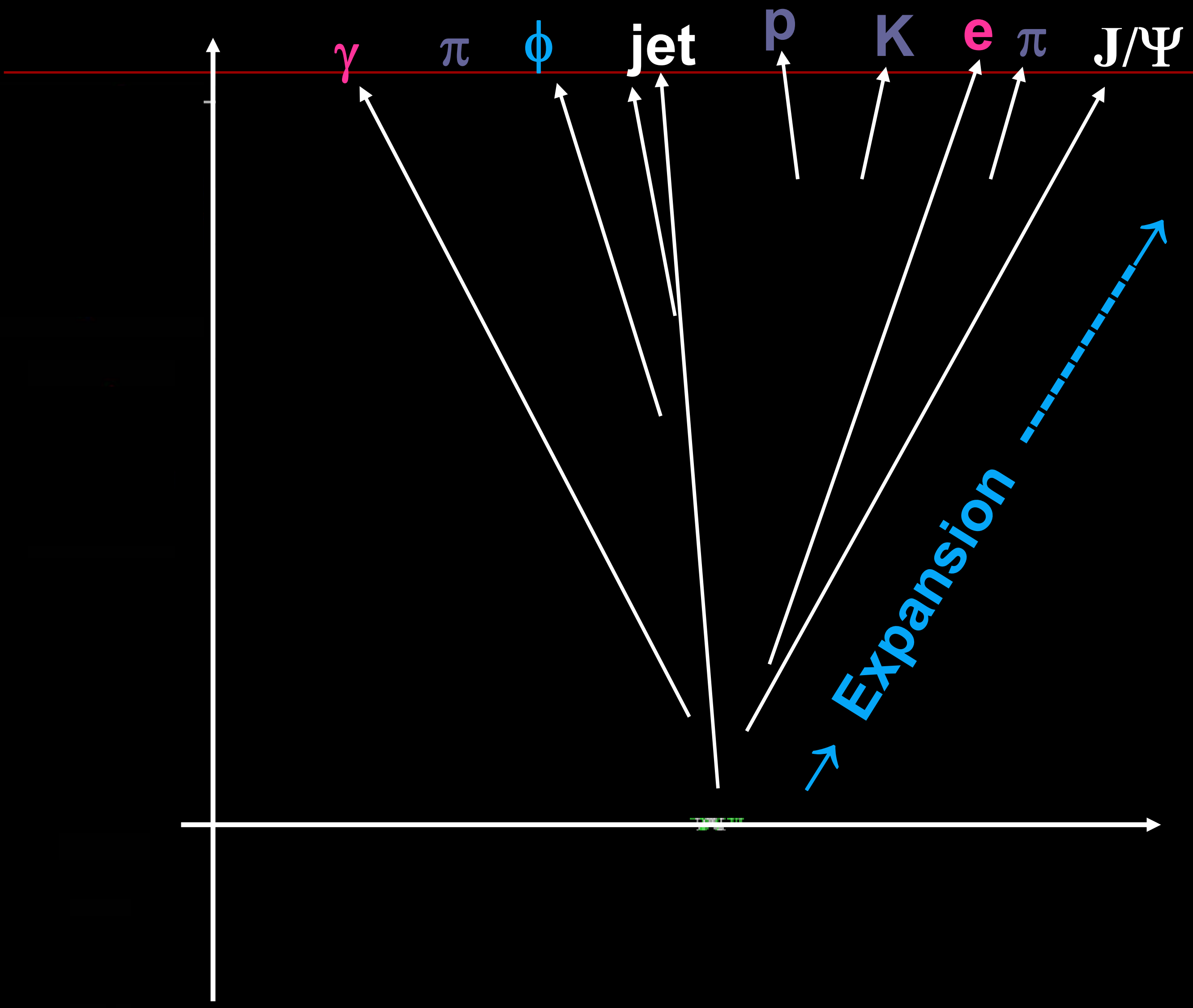
What are our probes and observables?



Schematic Time Evolution



Freeze-out

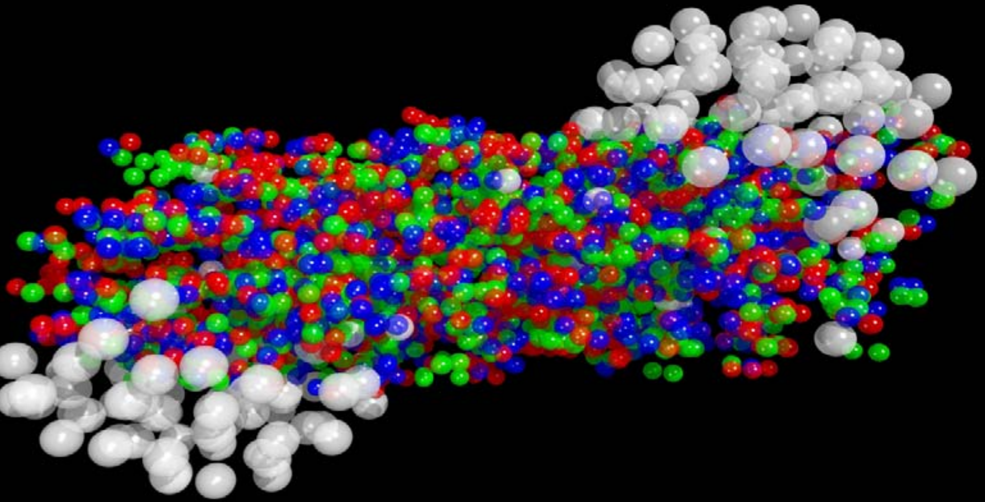
Hadronization

QGP?

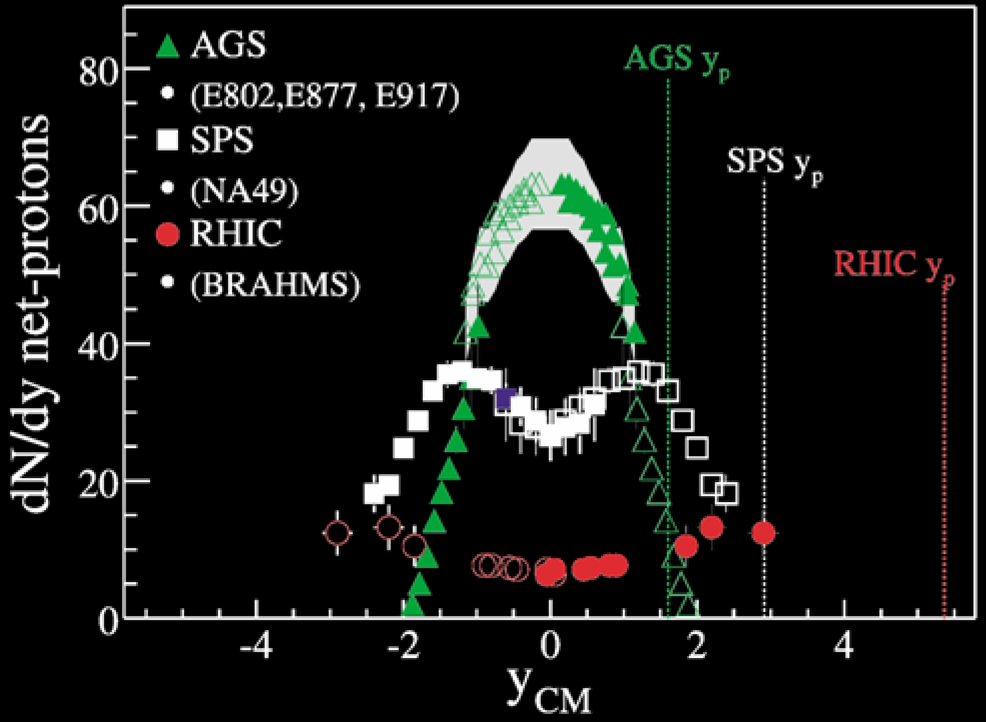
Thermalization?

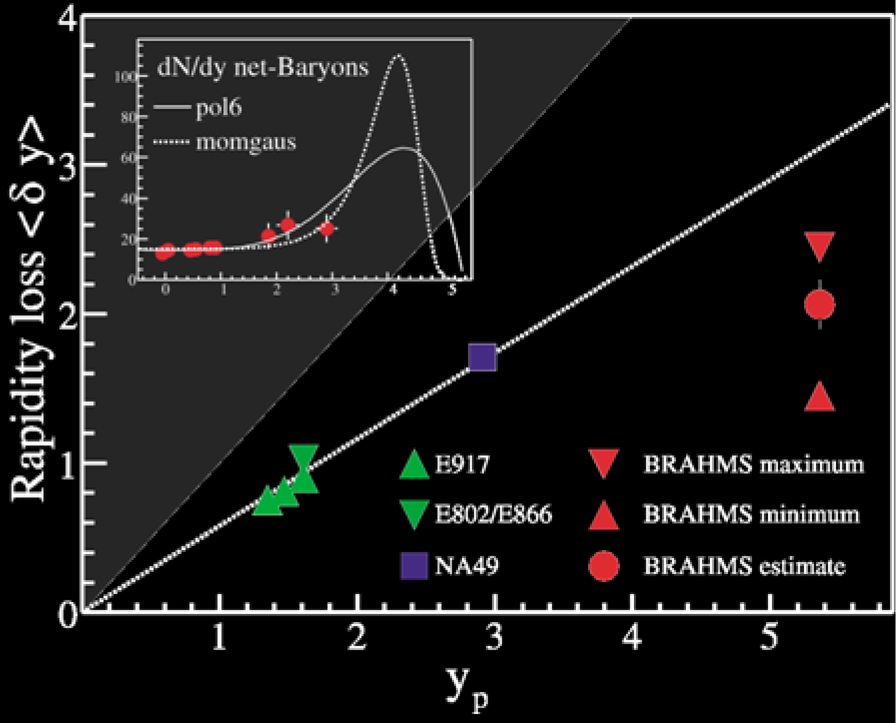
Hard Scattering

Initial conditions



Available Energy: Baryon-stopping



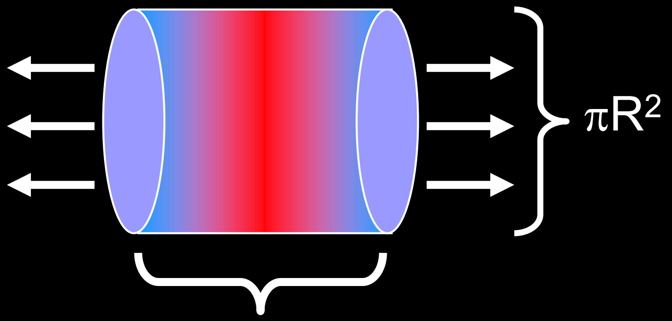


- In pp collisions 50% of beam energy available for particle production
- In AA collisions 70-80% of incoming energy available for particle production (in accordance with expectations from pA)

Transverse Energy and Energy Density

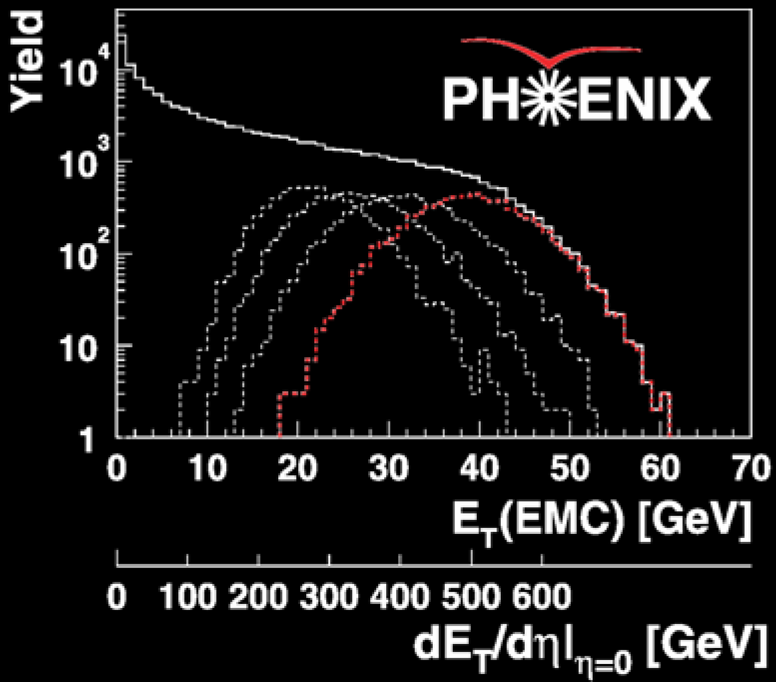
- Bjorken energy density estimate

$$\boxed{\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}}$$



$dz = \tau_0 dy$

$$\boxed{\varepsilon_{BJ} = 4.6\,\mathrm{GeV/fm^3}}$$

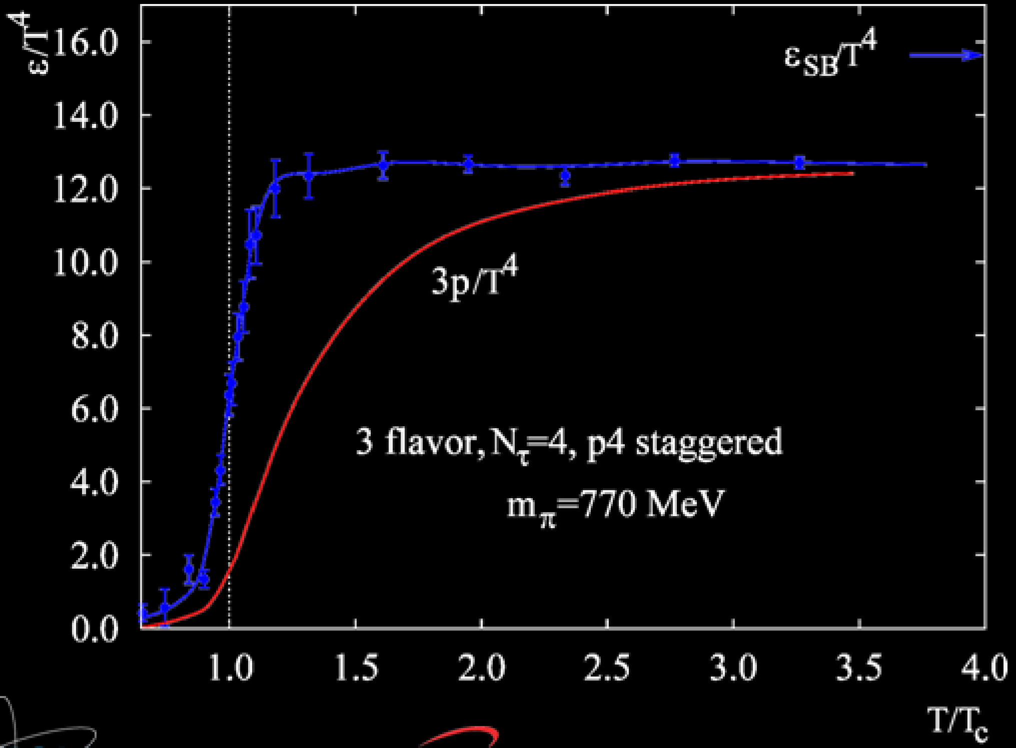


$$\boxed{\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2\ \mathrm{GeV}}$$

- Much larger than the critical energy density!!

QGP probes and observables

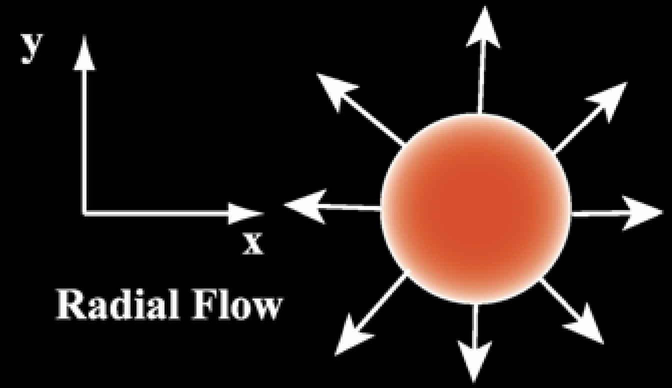
- At the SPS and at RHIC the initial conditions are already favorable for QGP formation!
- What are the QGP signatures?

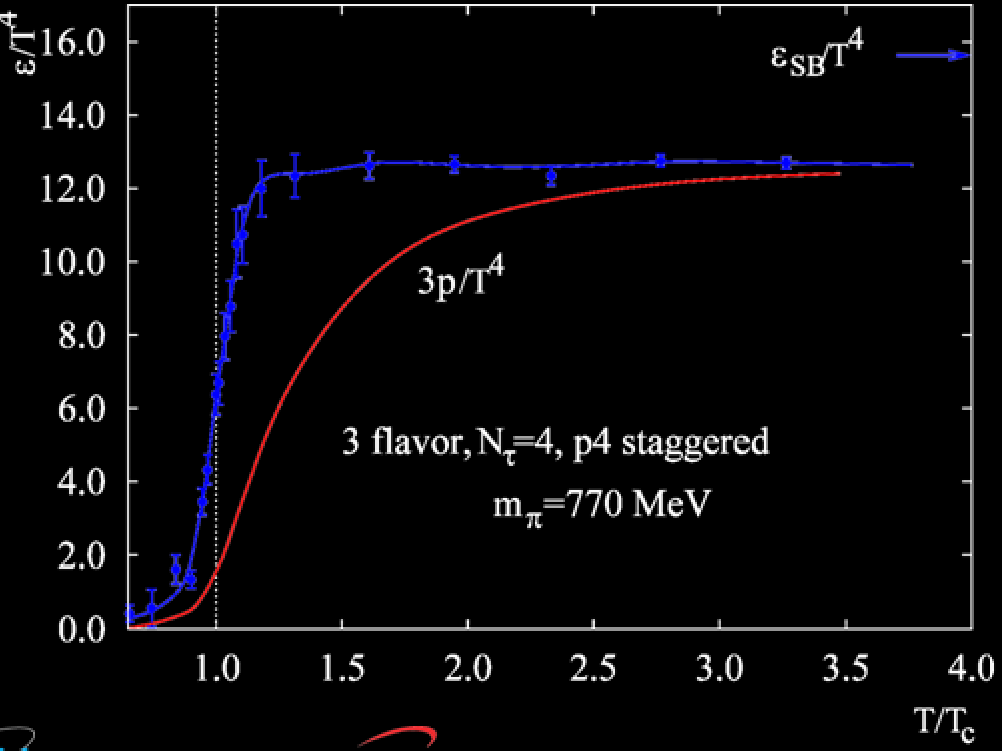


- What have we learned about the nature of the phase transition?
- What have we learned about the properties of the QGP medium?

Collective Motion (the QCD pressure gradient)

- Only type of collective transverse motion in central collision (b=0) is radial flow.
- Integrates pressure history over complete expansion phase





$$P_{\text{QGP}} \qquad \frac{1}{3} \quad {}_{\text{QGP}} \qquad g\frac{{}^{2}}{90}T^{4}$$

$$\text{velocity of sound } C_s \qquad \sqrt{\frac{dP}{d}}$$

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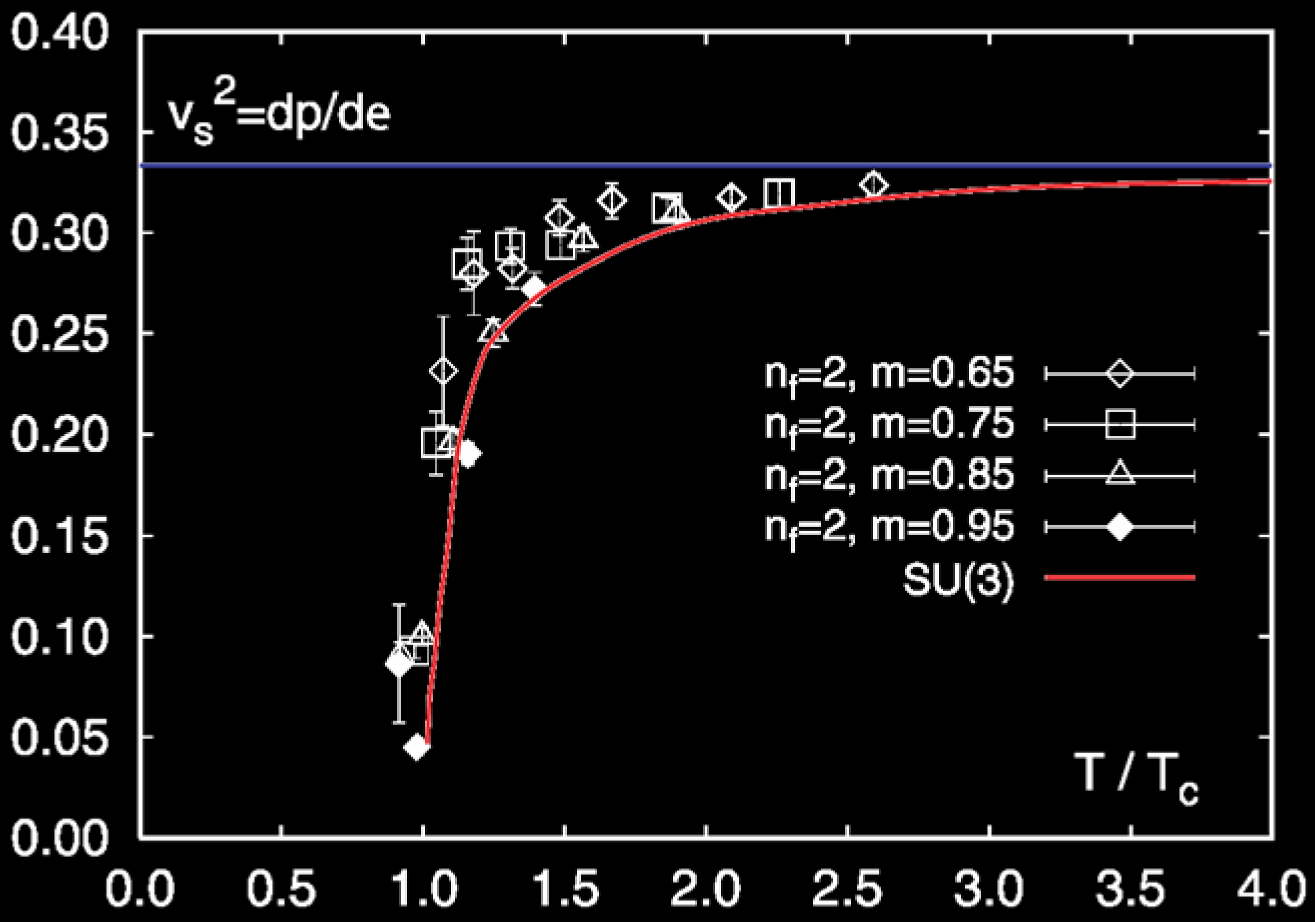
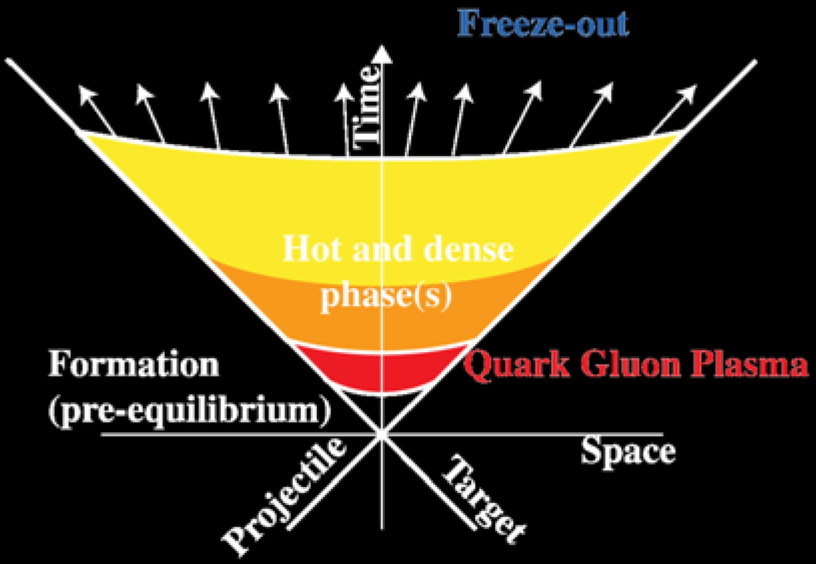
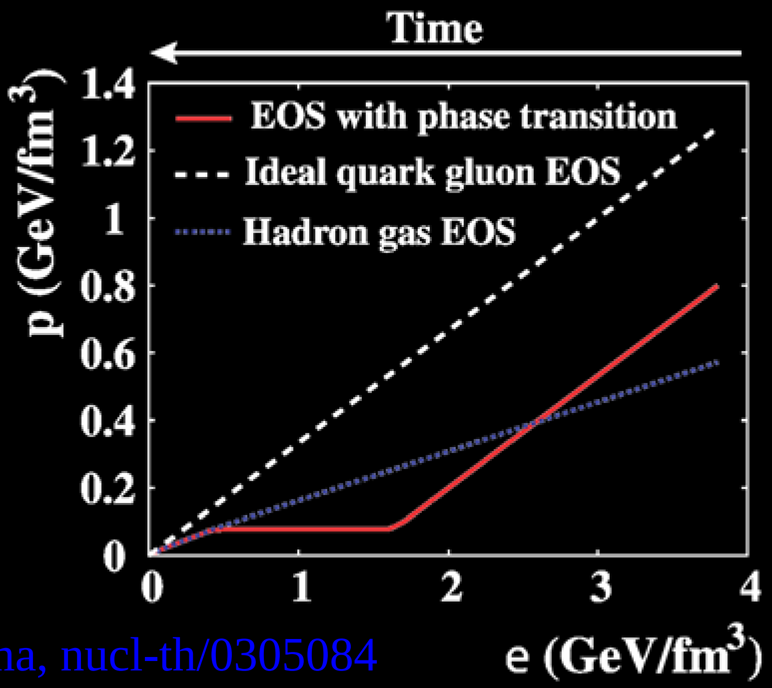
Velocity of sound on the lattice



F. Karsch and E. Laermann, arXiv:hep-lat/0305025

Velocity of sound

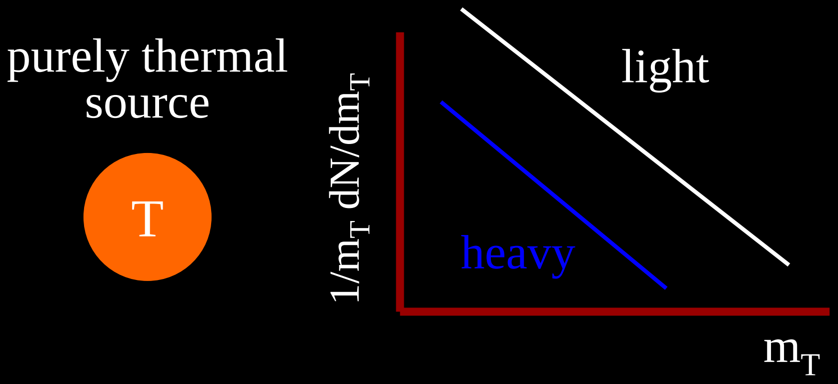


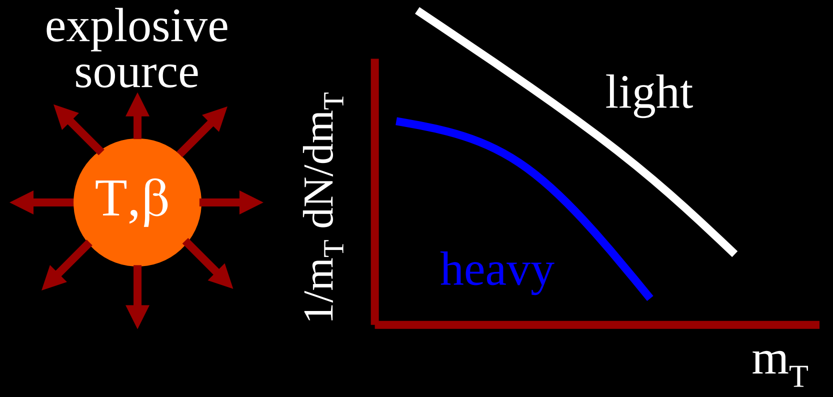


P.F. Kolb and U. Heinz, in Quark Gluon Plasma, nucl-th/0305084

- Velocity of sound $C_s = (dp/d\varepsilon)^{1/2}$ different magnitude for system of quarks and gluons and hadronic matter. Minimum in velocity of sound during phase transition so called softest point
- The collective flow probes the magnitude of the velocity of sound and the relative time spend in various phases

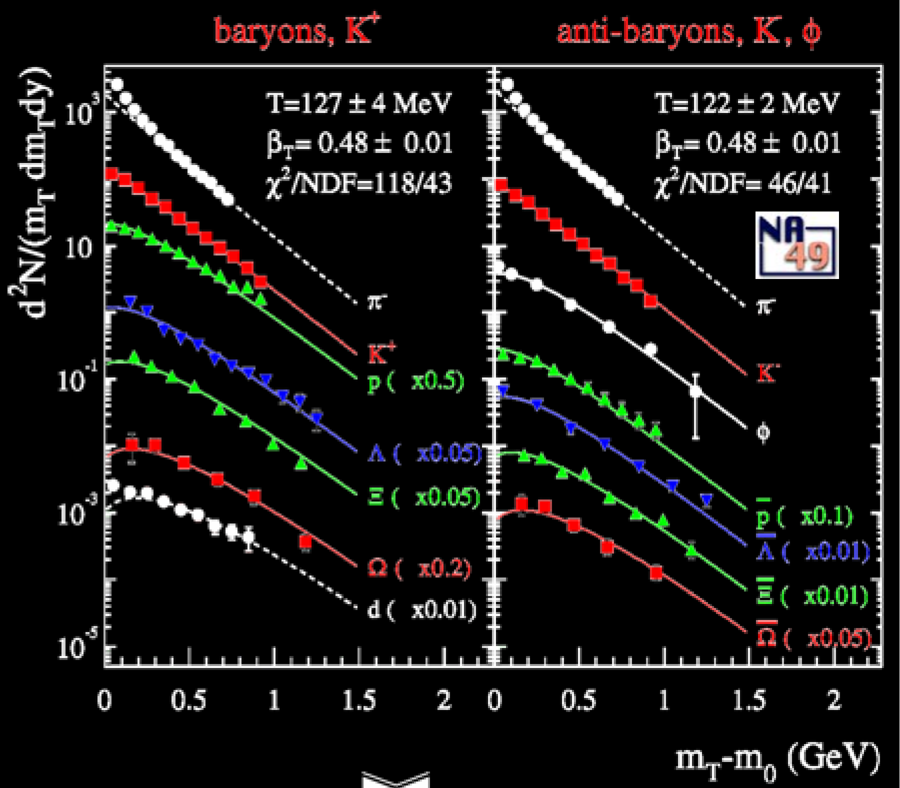
Identified Particle Spectra





$$\frac{dN}{m_T\, dm_T} \propto e^{-m_T/T}$$

- In p-p at low transverse momenta the particle yields are well described by thermal spectra (m_T scaling)
- Boosted thermal spectra give a very good description of the particle distributions measured in heavy-ion collisions



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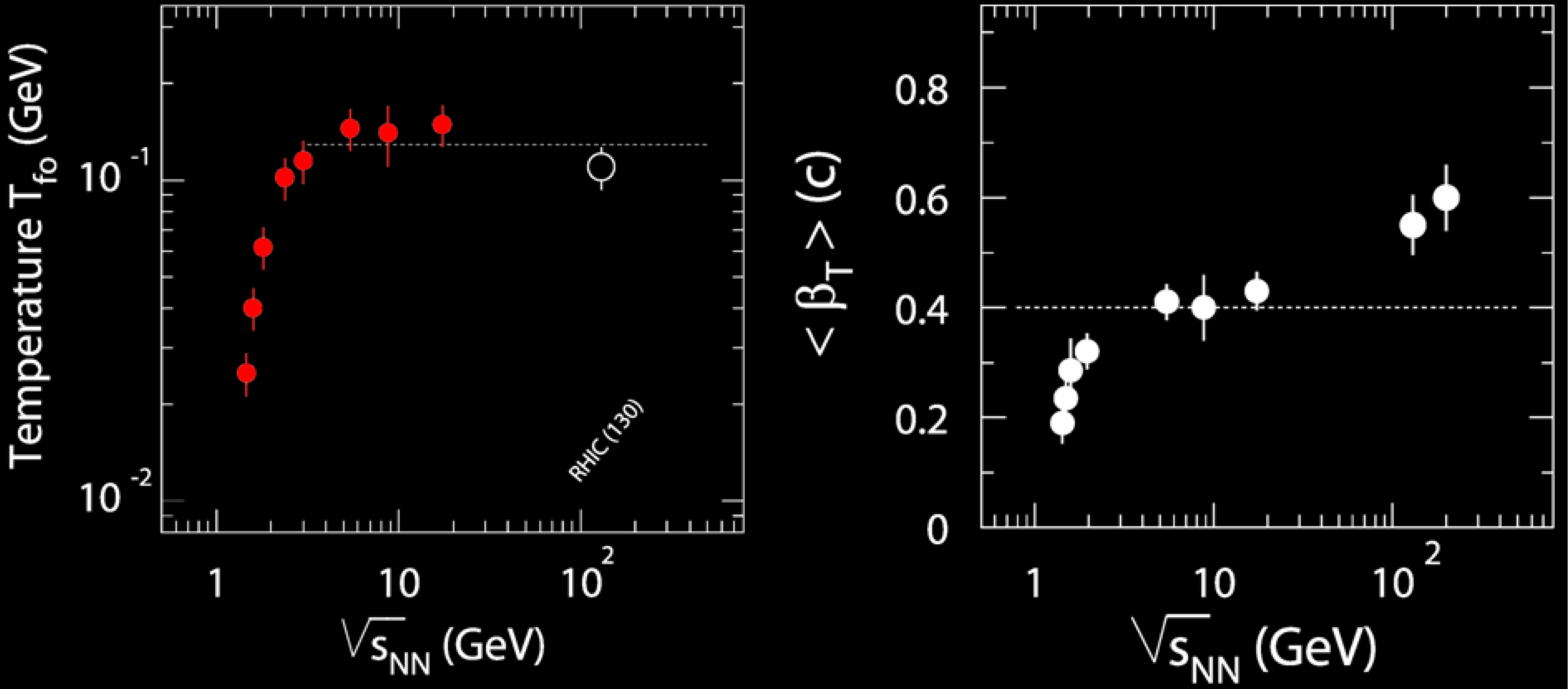
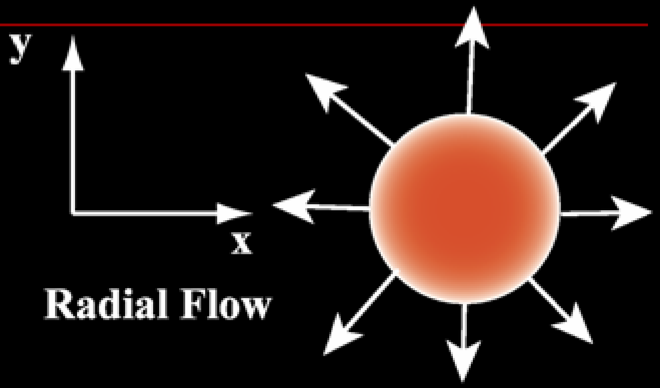
Temperature and Flow

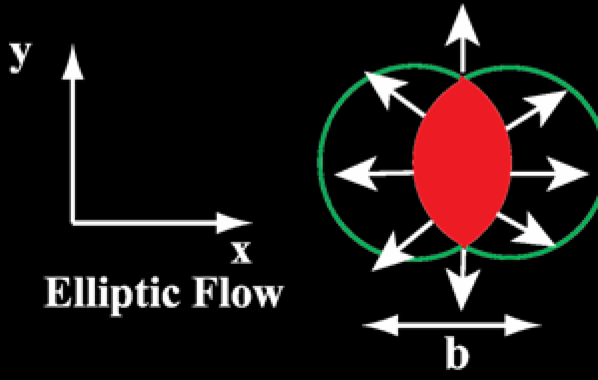


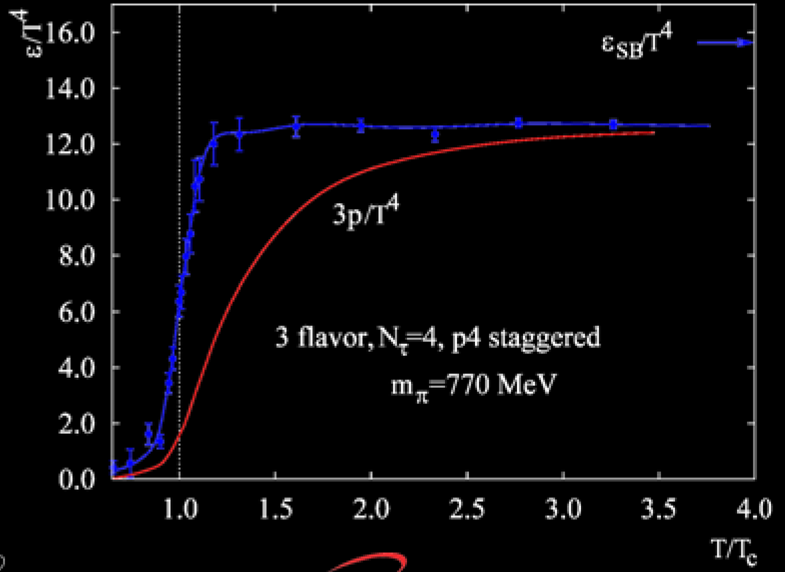
- Strong collective motion, particularly at RHIC energies, due to large thermal pressure
- Smooth behavior as function of beam energy, no sign of dramatic softening of the EoS

Collective Motion

- Only type of collective transverse motion in central collision (b=0) is radial flow.
- Integrates pressure history over complete expansion phase
- Elliptic flow, caused by anisotropic initial overlap region (b > 0)
- More weight towards early stage of expansion (the QGP phase)







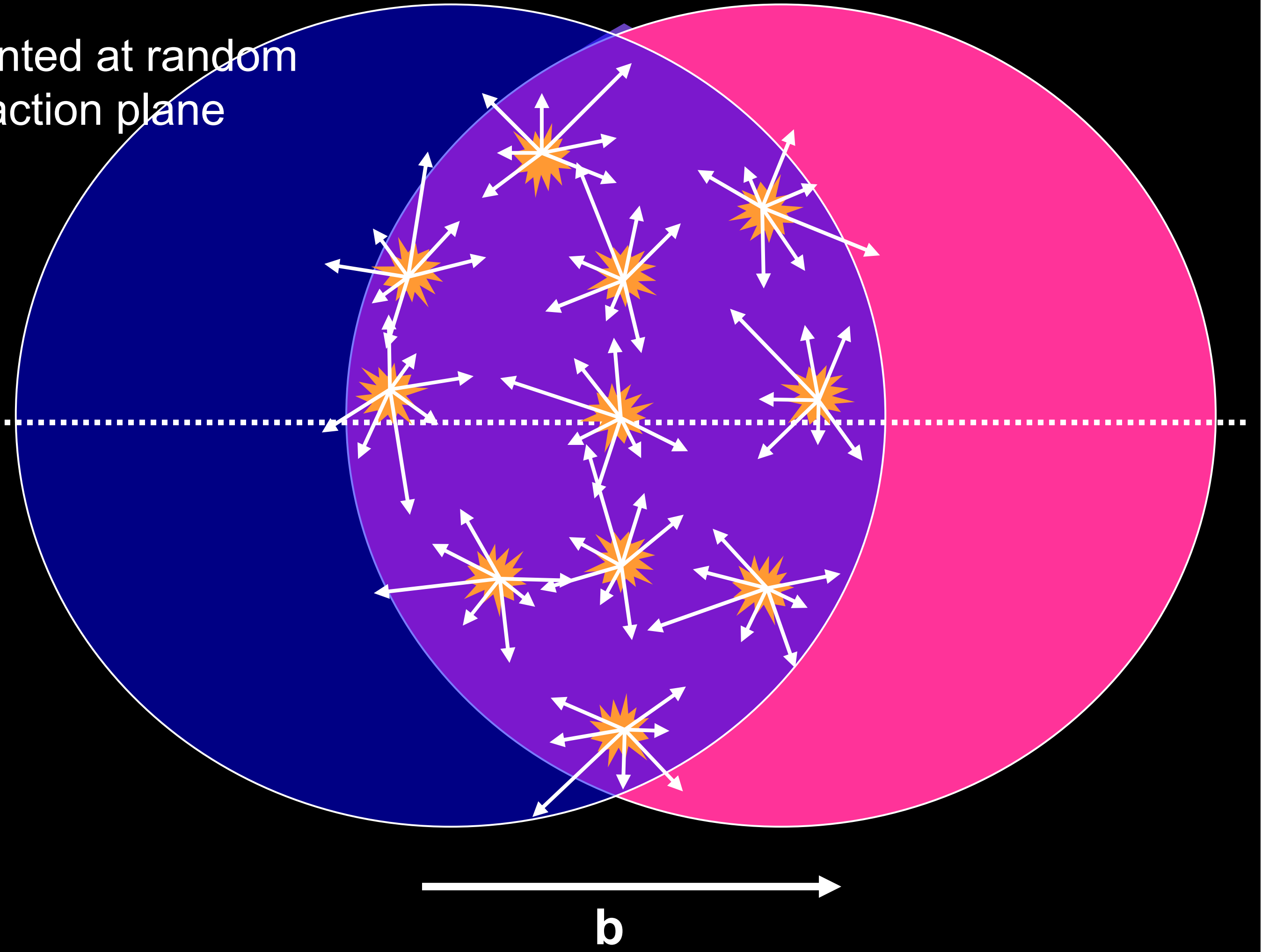
$$P_{\mathrm{QGP}} \quad \frac{1}{3} \quad {}_{\mathrm{QGP}} \quad g \frac{{}^{2}}{90} T^4$$

$$C_s \quad \sqrt{\frac{dP}{d}}$$

Forming a system and thermalizing

Animation: Mike Lisa

1) Superposition of independent p+p:



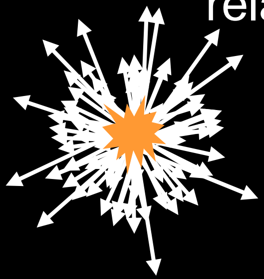
momenta pointed at random relative to reaction plane

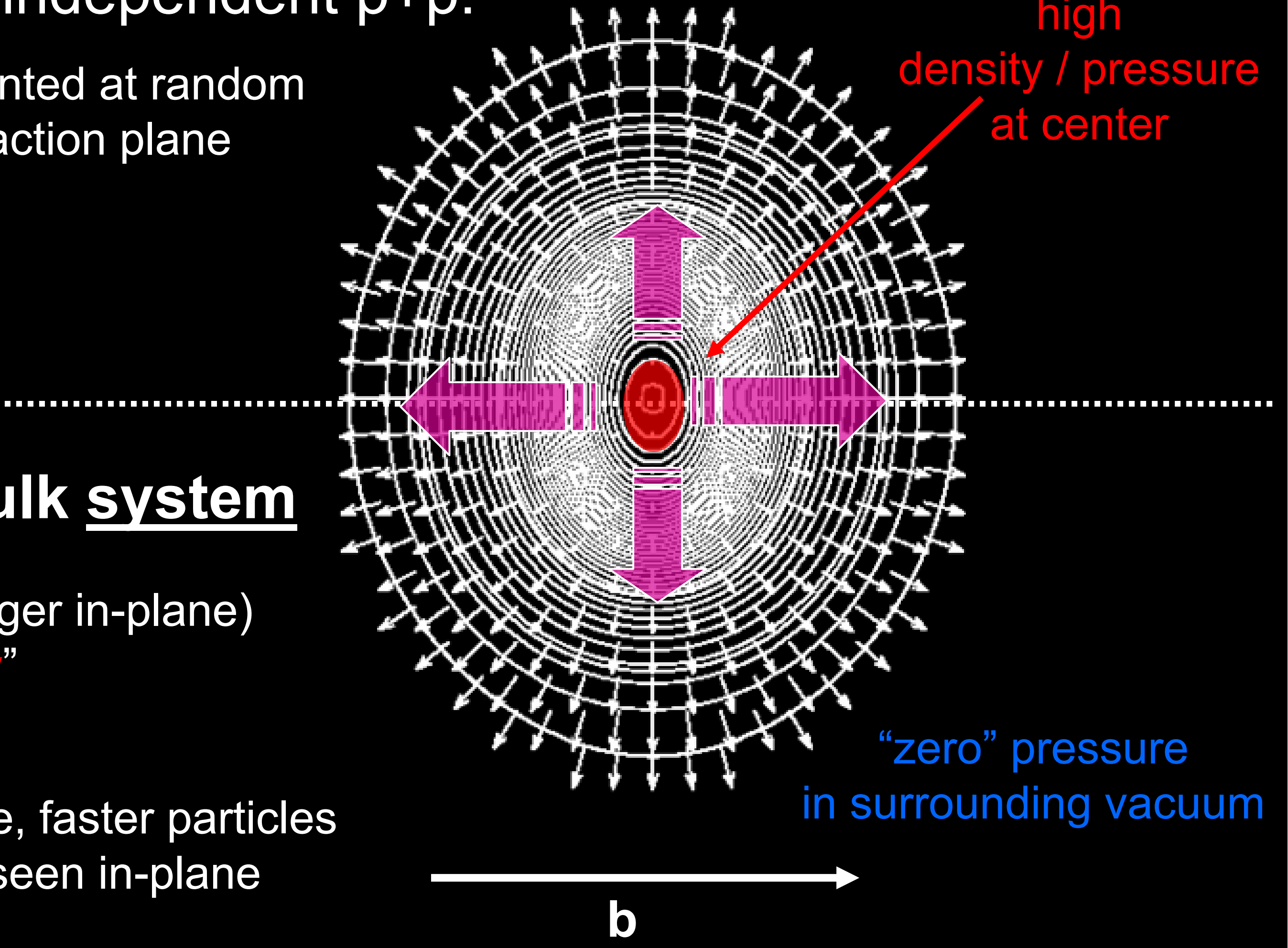
Forming a system and thermalizing

Animation: Mike Lisa

1) Superposition of independent p+p:

momenta pointed at random
relative to reaction plane



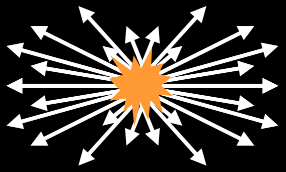


high
density / pressure
at center

"zero" pressure
in surrounding vacuum

2) Evolution as a **bulk <u>system</u>**

Pressure gradients (larger in-plane)
push bulk "out" → "flow"

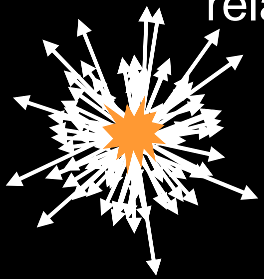


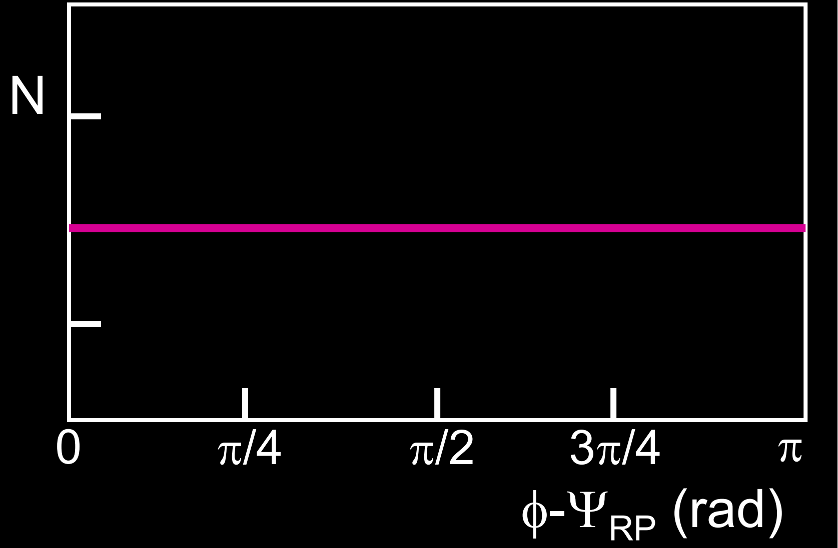
more, faster particles
seen in-plane

How does the system evolve?

1) Superposition of independent p+p:

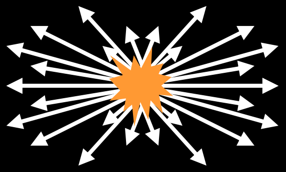
momenta pointed at random relative to reaction plane



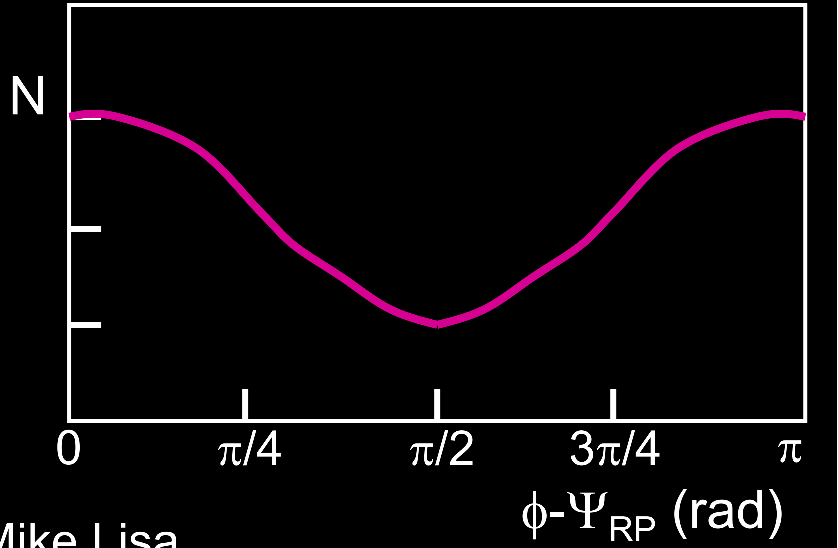


2) Evolution as a **bulk** **<u>system</u>**

Pressure gradients (larger in-plane) push bulk “out” → “flow”



more, faster particles seen in-plane



Animation: Mike Lisa

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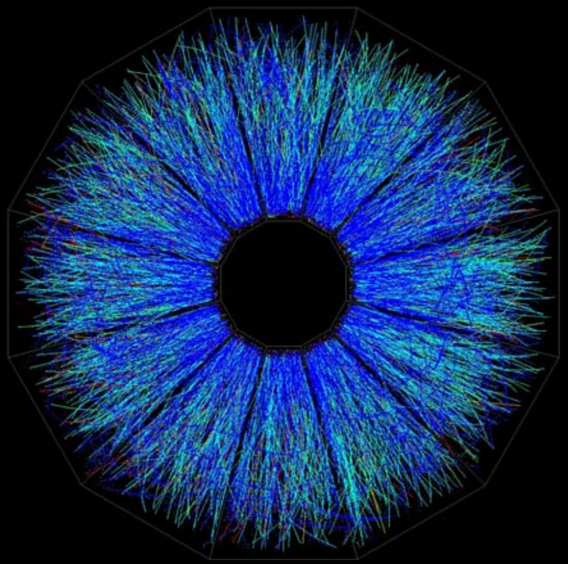
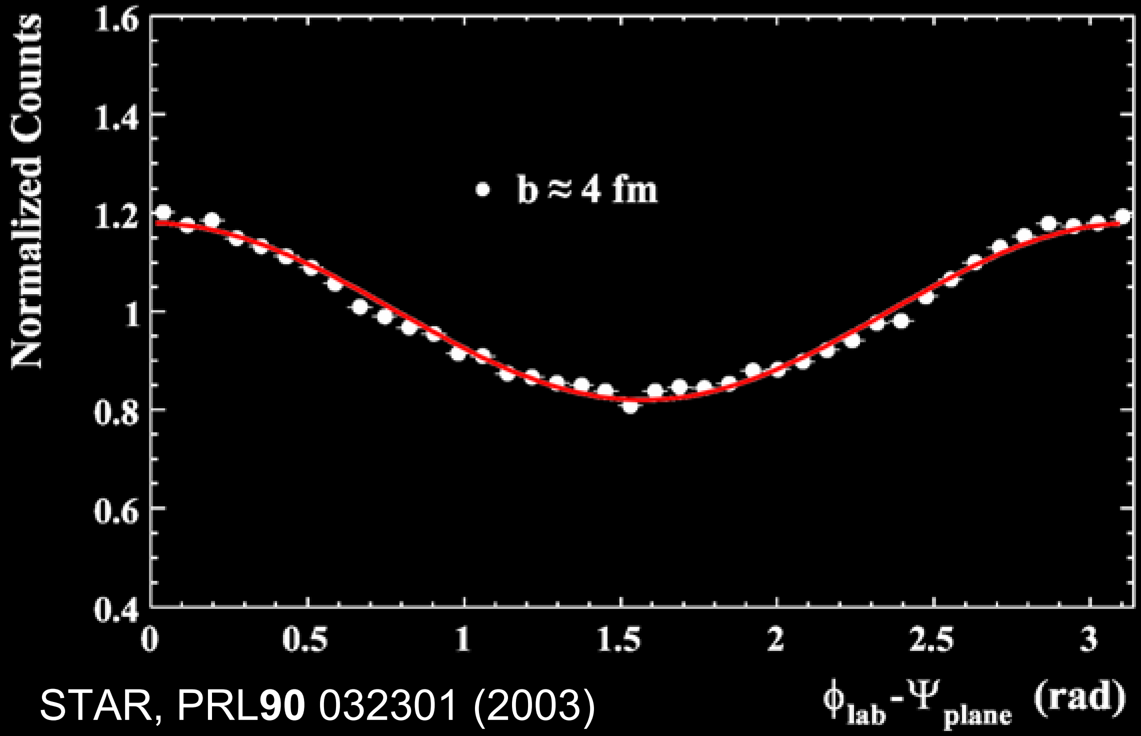
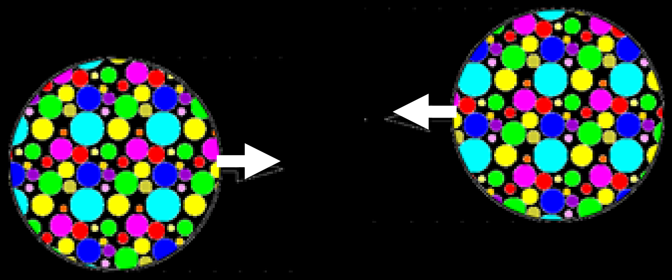
Measurements in STAR at RHIC

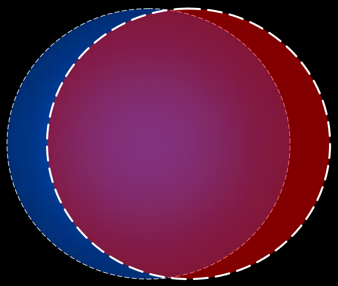


“central” collision



STAR, PRL**90** 032301 (2003)





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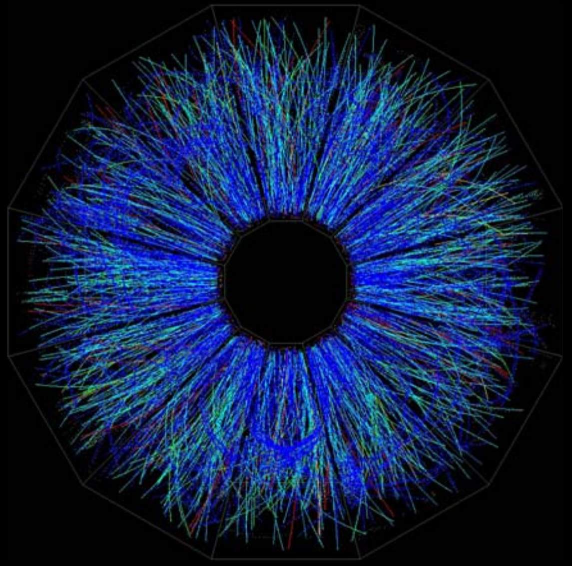
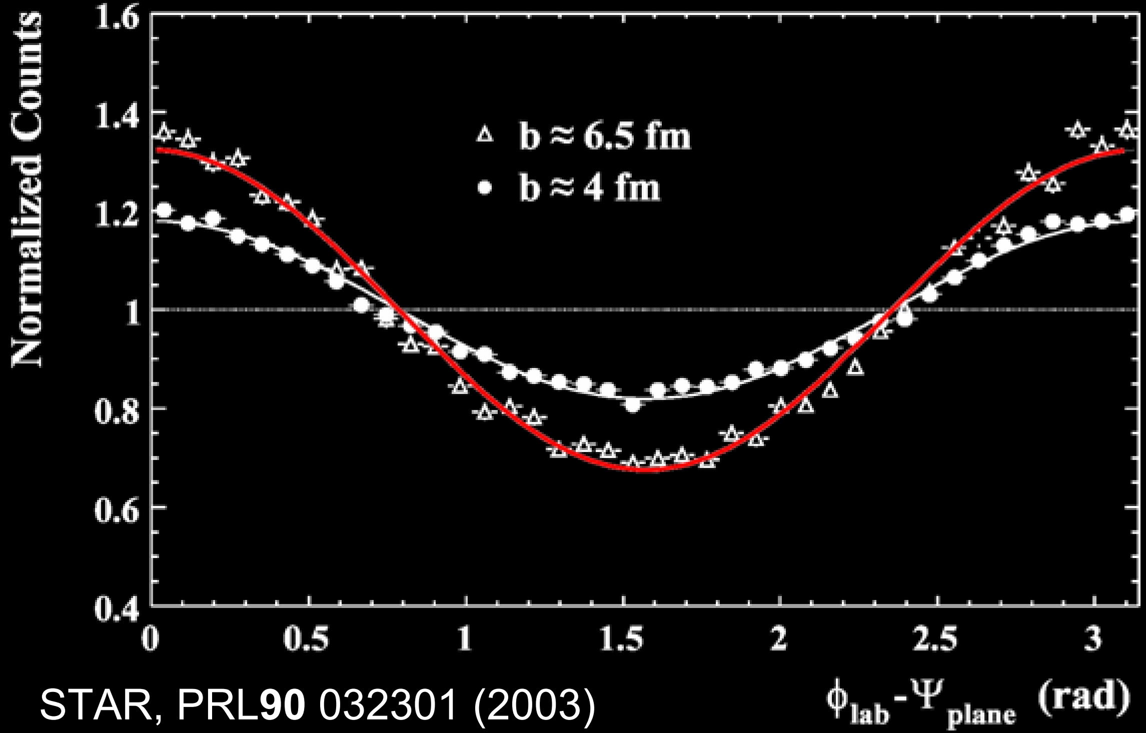
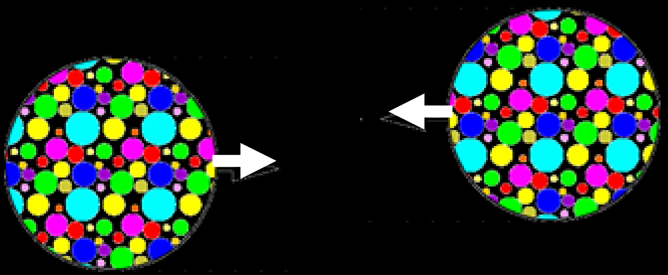
Measurements in STAR at RHIC

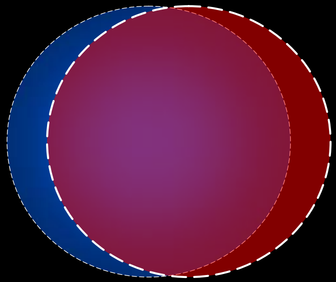


“mid-central” collision

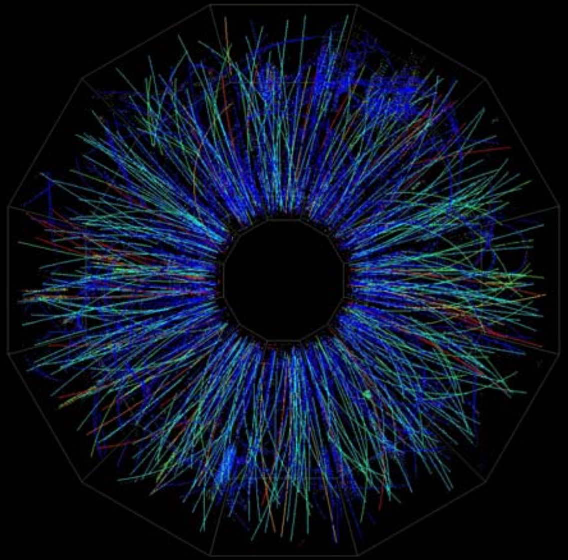


STAR, PRL**90** 032301 (2003)

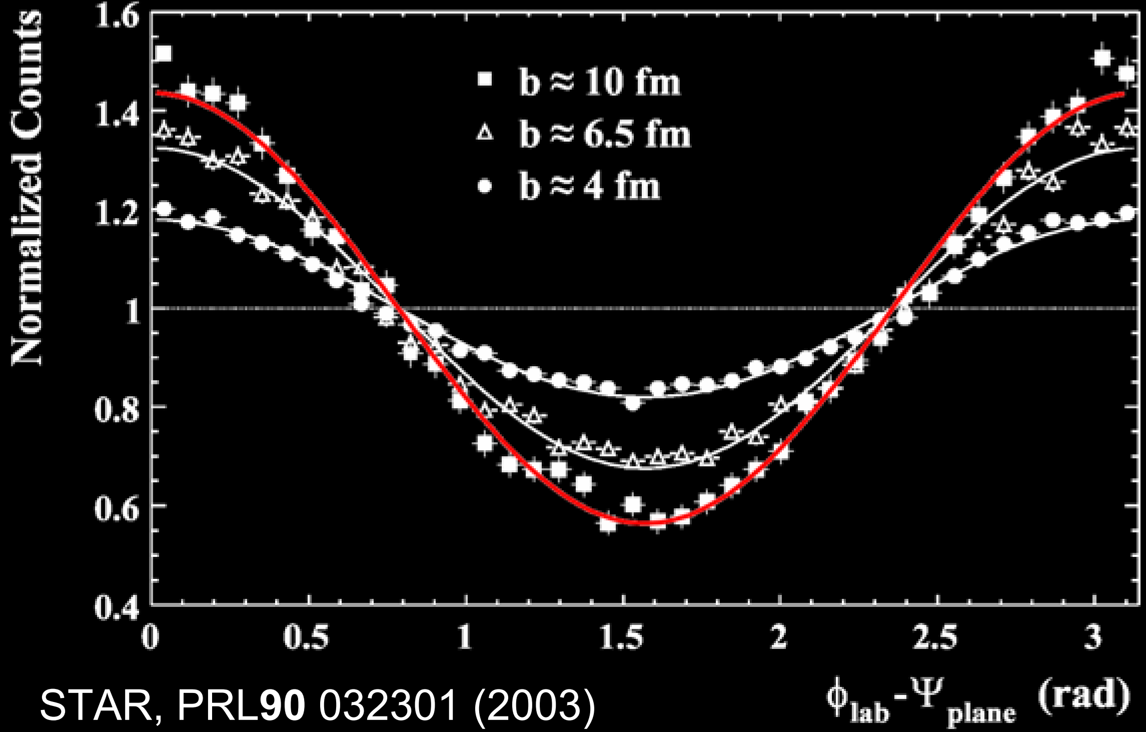




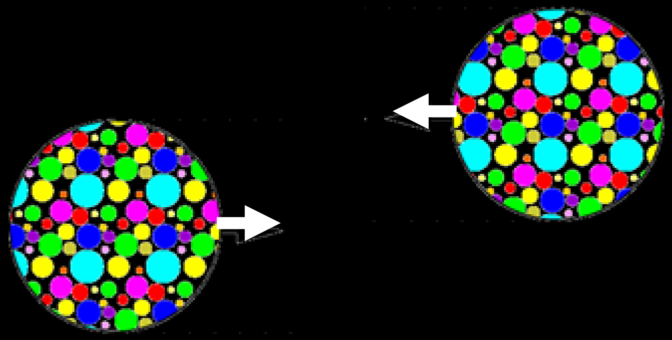
Measurements in STAR at RHIC

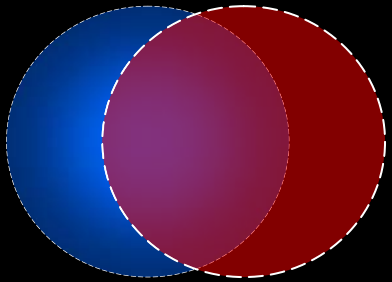


“peripheral” collision



STAR, PRL**90** 032301 (2003)





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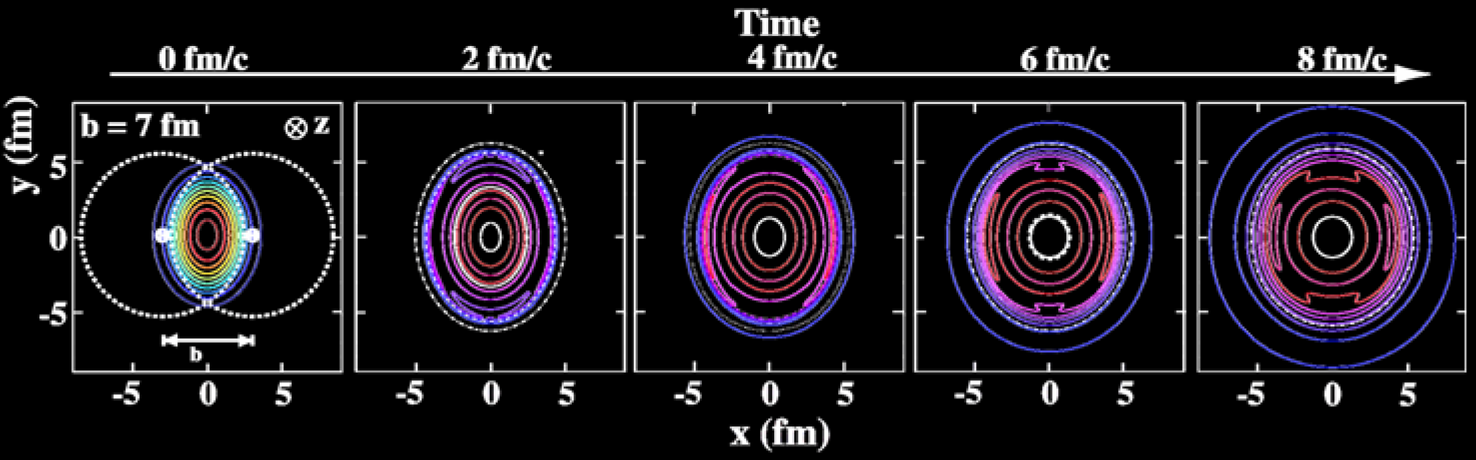
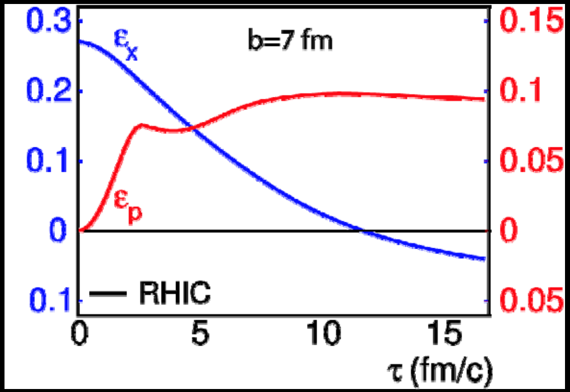
A Hydrodynamic description

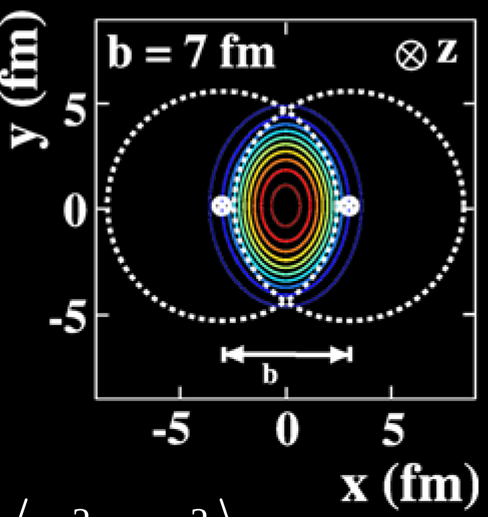




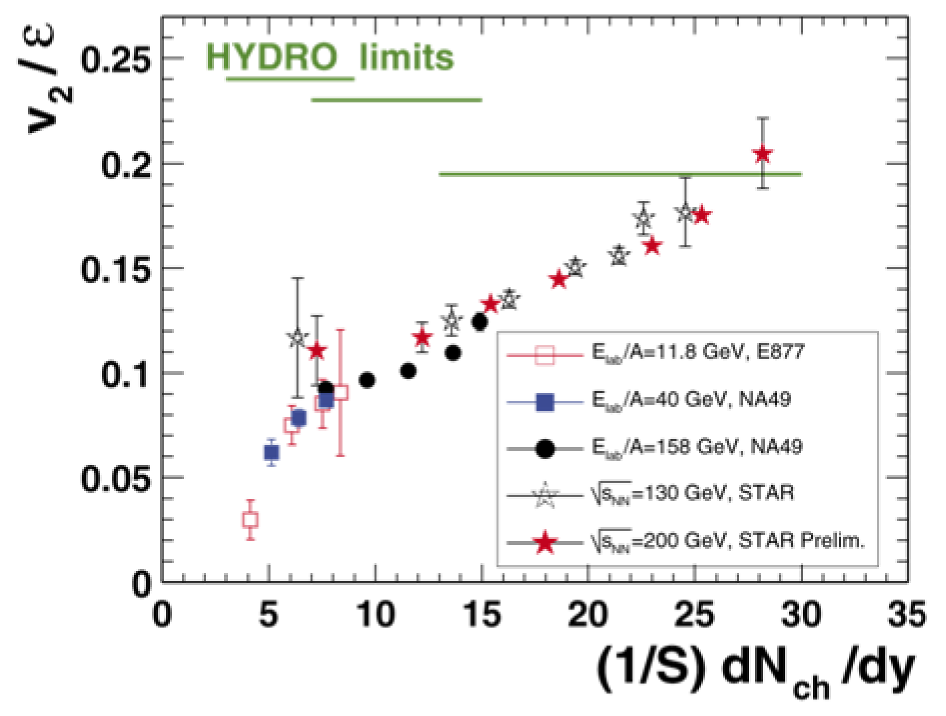
- Multiple interactions lead to thermalization -> limiting behavior ideal hydrodynamic flow
- The driving force of elliptic flow dominates at “early” times
- The QGP if created exists in the early part of the system evolution

P.F. Kolb and U. Heinz, in Quark Gluon Plasma, nucl-th/0305084

Energy dependence of flow



$$\varepsilon \equiv \frac{\left\langle y^2 - x^2 \right\rangle}{\left\langle y^2 + x^2 \right\rangle}$$

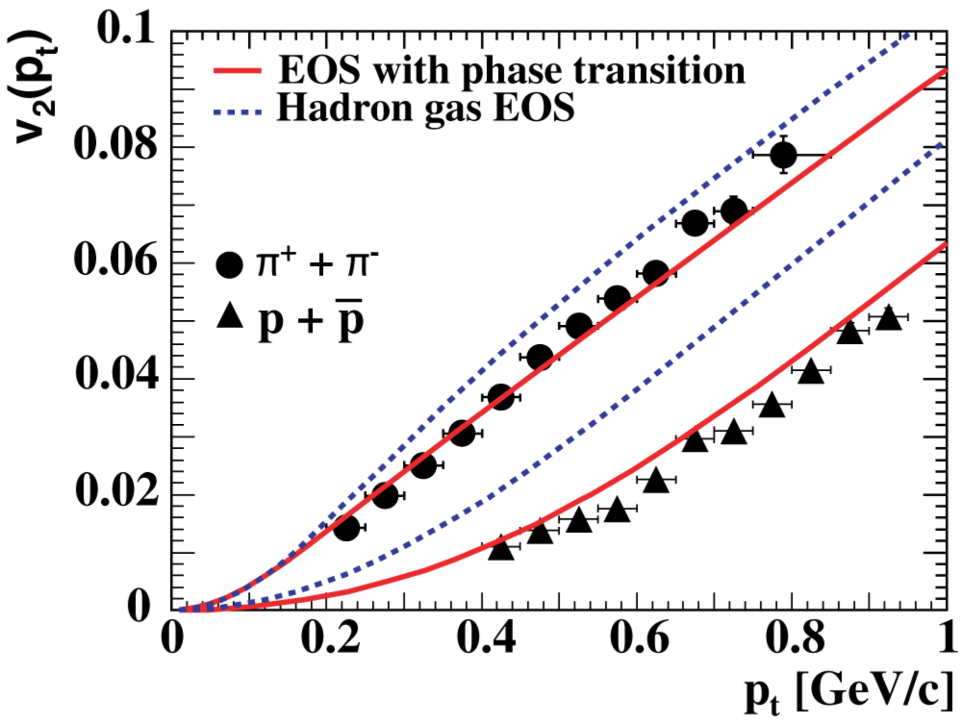


- At RHIC observed flow for the first time consistent with ideal hydrodynamics!!

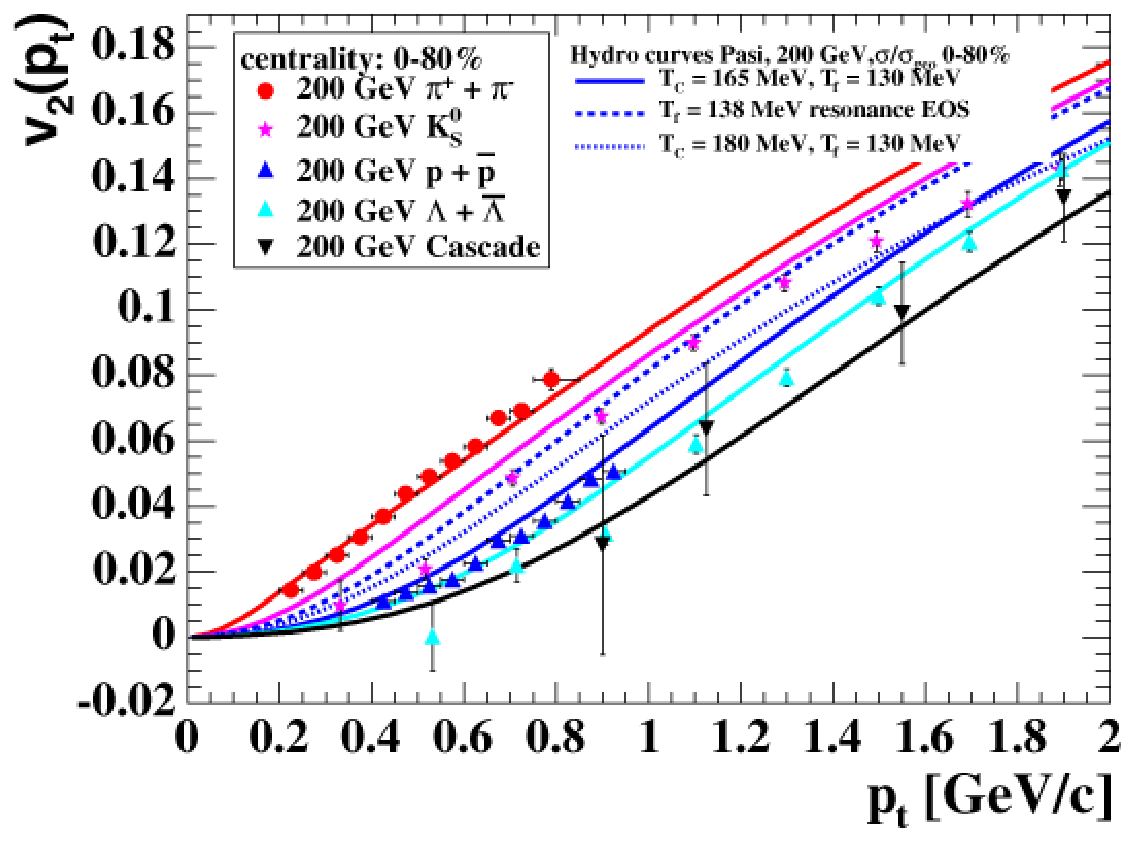
Mass dependence

Hydro calculation: P. Huovinen *et. al.*

- Identified particle elliptic flow at low p_t
- Heavier particles more sensitive to the EoS
- Mass dependence in accordance with collective flow. QGP equation of state (phase transition) provides best description



Mass dependence



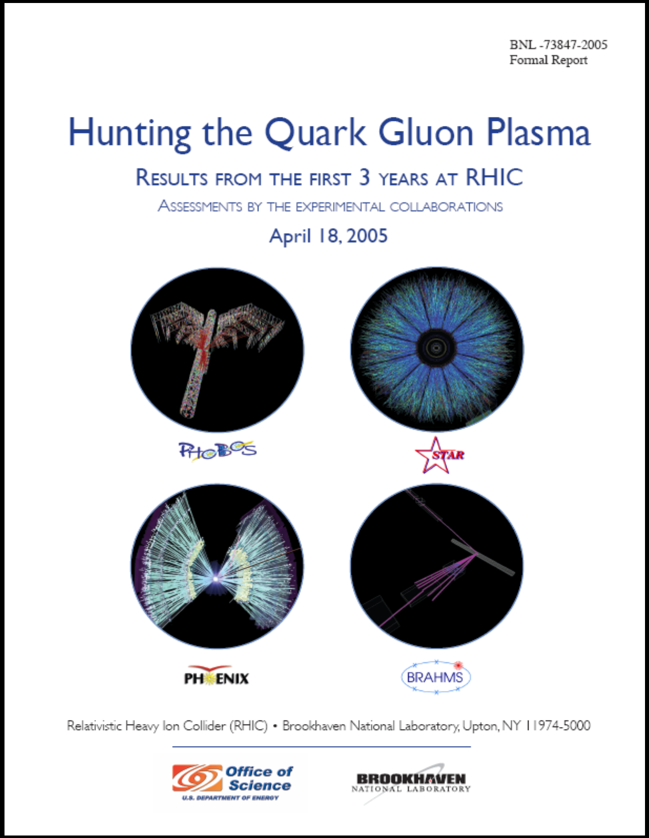
- pions to Cascade follow the mass dependence at low-p_t
- Ideal hydro provides a reasonable description (common velocity and common freeze-out!)

Experimental summary of the first 3 years and the BNL statement

RHIC Scientists Serve Up “Perfect” Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005



BNL -73847-2005
Formal Report

Hunting the Quark Gluon Plasma

RESULTS FROM THE FIRST 3 YEARS AT RHIC

ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

April 18, 2005

Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

Office of Science U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

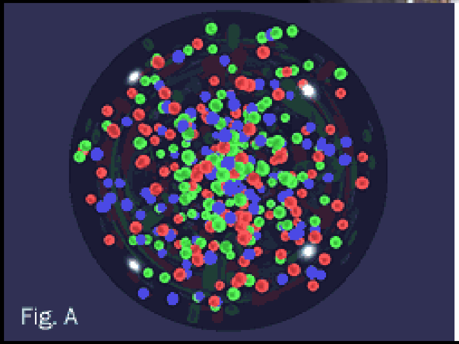


Fig. A

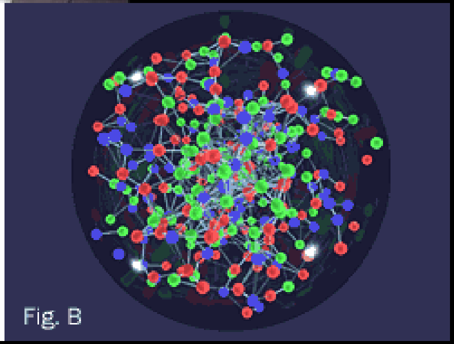


Fig. B

In the press

Science

Iran Daily April 20, 2005 4

Early Universe Liquid-Like

New results from a particle collider suggest that the universe behaved like a liquid in its earliest moments, not the fiery gas that was thought to have pervaded the first microseconds of existence, AP reported.

By revising physicists' concept of the early universe, the new discovery offers opportunities to better learn how subatomic particles interact at the most fundamental level. It may also reveal intriguing parallels between gravity and the force that holds atomic nuclei together, physicists said Monday at a Tampa, Fla., meeting of the American Physical Society.

"There are a lot of exciting questions," said Sam Aronson, associate director for high energy and nuclear physics at Brookhaven National Laboratory, which is located on Long Island about 65 miles east of New York city.

Between 2000 and 2003 the lab's Relativistic Heavy Ion Collider, known as RHIC, repeatedly smashed the nuclei of gold atoms together with such force that their energy briefly generated trillion-degree temperatures. Physicists think of the collider as a time machine, because those extreme temperature conditions last prevailed in the universe less than 100 millionths of a second after the big bang.

Everything was so hot then that quarks and gluons, which are now almost inextricably bound into the protons and neutrons inside atomic nuclei, were thought to have flown around like BBs in a blender.

But by reproducing the conditions of the early universe, RHIC has shown that unconstrained quarks and gluons don't fly away in all directions so much as squirt out in streams.

"The matter that we've formed behaves like a very nearly perfect liquid," Aronson said.

When physicists talk about a perfect liquid, they don't mean the best glass of champagne they ever tasted. The word "perfect" refers to the liquid's viscosity, a friction-like property that affects a fluid's ability to flow and the resistance to objects trying to swim through it. Honey has a high viscosity; water's viscosity is low. A perfect liquid has no viscosity at all, which is impossible in reality but useful for theoretical discussions.

Theoretical physicists have recently proposed that material swallowed by black holes might also have extremely low viscosity. That notion, based on a branch of mathematical physics known as string theory, has led some physicists to hypothesize that there might be a deeper connection between what happens in a black hole and what goes on when two gold nuclei collide at RHIC.

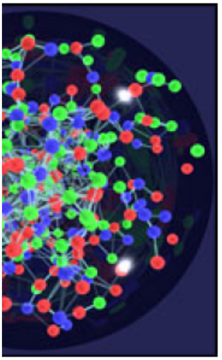
When physicist talk about a perfect liquid, they don't mean the best glass of champagne they ever tasted. The word "perfect" refers to the liquid's viscosity

New State o

Physicists
Laboratory annou
created what appe
out of the building
and gluons. The re
findings--which co
composition of the
big bang--today in
American Physica

There are four coll
PHENIX, PHOBO
Brookhaven's Rela
(RHIC). All of them
interacting beams of gold ions smash into one
another at great velocities, resulting in thousands of subatomic collisions every second. When the researchers analyzed the patterns of the atoms' trajectories after these collisions, they found that the particles produced in the collisions tended to move collectively, much like a school of fish does. Brookhaven's associate laboratory director for high energy and nuclear physics, Sam Aronson, remarks that "the degree of collective interaction, rapid thermalization and extremely low viscosity of the matter being formed at RHIC make this the most nearly perfect liquid ever observed."

e'

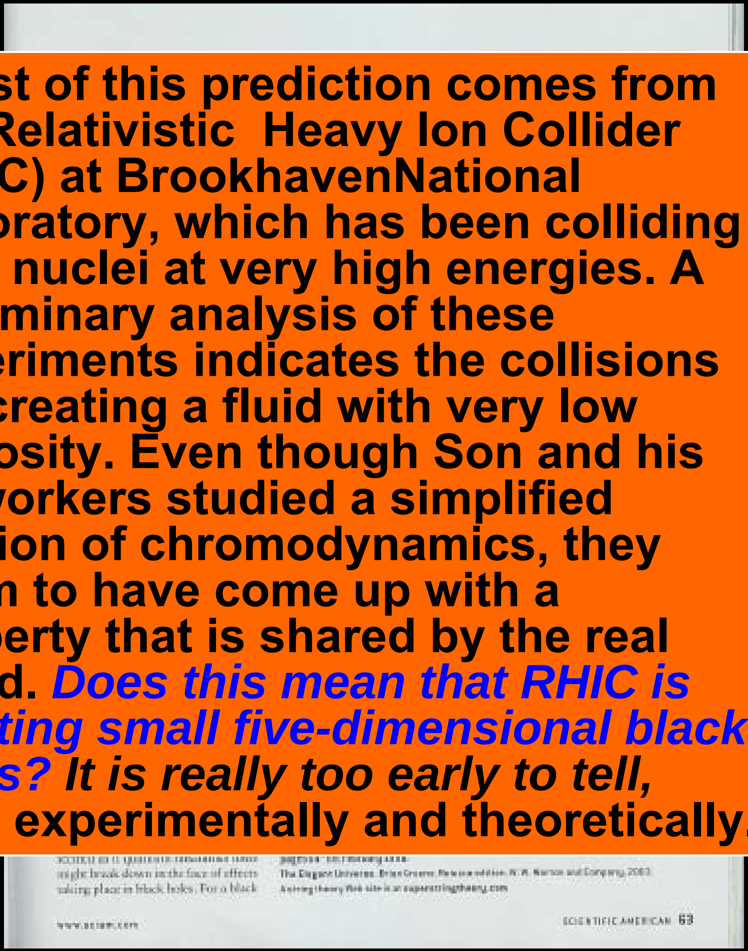


The impression is of matter that is more strongly interacting than predicted

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

AdS/CFT



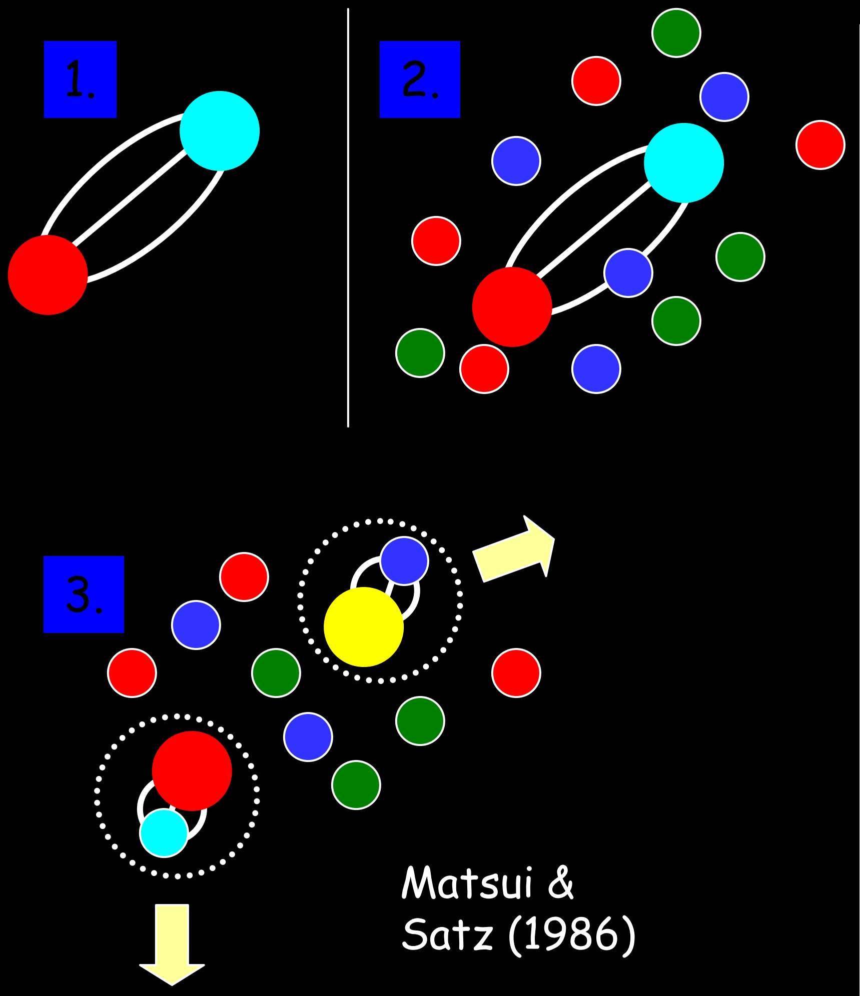
A test of this prediction comes from the Relativistic Heavy Ion Collider (RHIC) at BrookhavenNational Laboratory, which has been colliding gold nuclei at very high energies. A preliminary analysis of these experiments indicates the collisions are creating a fluid with very low viscosity. Even though Son and his co-workers studied a simplified version of chromodynamics, they seem to have come up with a property that is shared by the real world. *Does this mean that RHIC is creating small five-dimensional black holes? It is really too early to tell,* both experimentally and theoretically.

November, 2005 Scientific American “The Illusion of Gravity” J. Maldacena

Charmonium suppression (I)

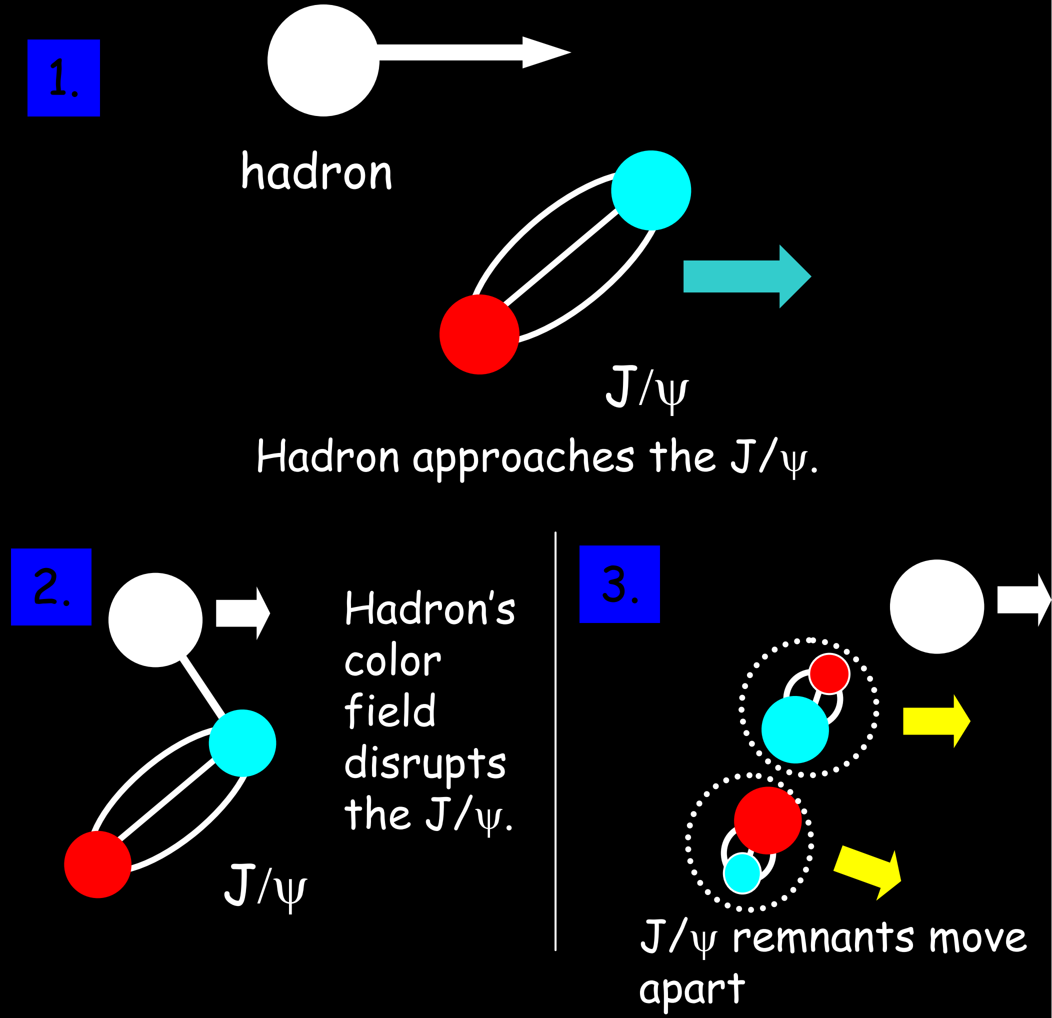
- QGP signature predicted by Matsui and Satz, 1986
- In the plasma phase the interaction potential is expected to be screened beyond the Debye length λ_D (analogous to e.m. Debye screening)
- Charmonium (cc_{bar}) and bottonium (bb_{bar}) states with $r > \lambda_D$ will not bind; their production will be suppressed

Other sources of J/Ψ suppression



Matsui & Satz (1986)

Debye screening of the J/ψ



Hadron approaches the J/ψ.

Hadron's color field disrupts the J/ψ.

J/ψ remnants move apart

Co-movers suppressing the J/ψ

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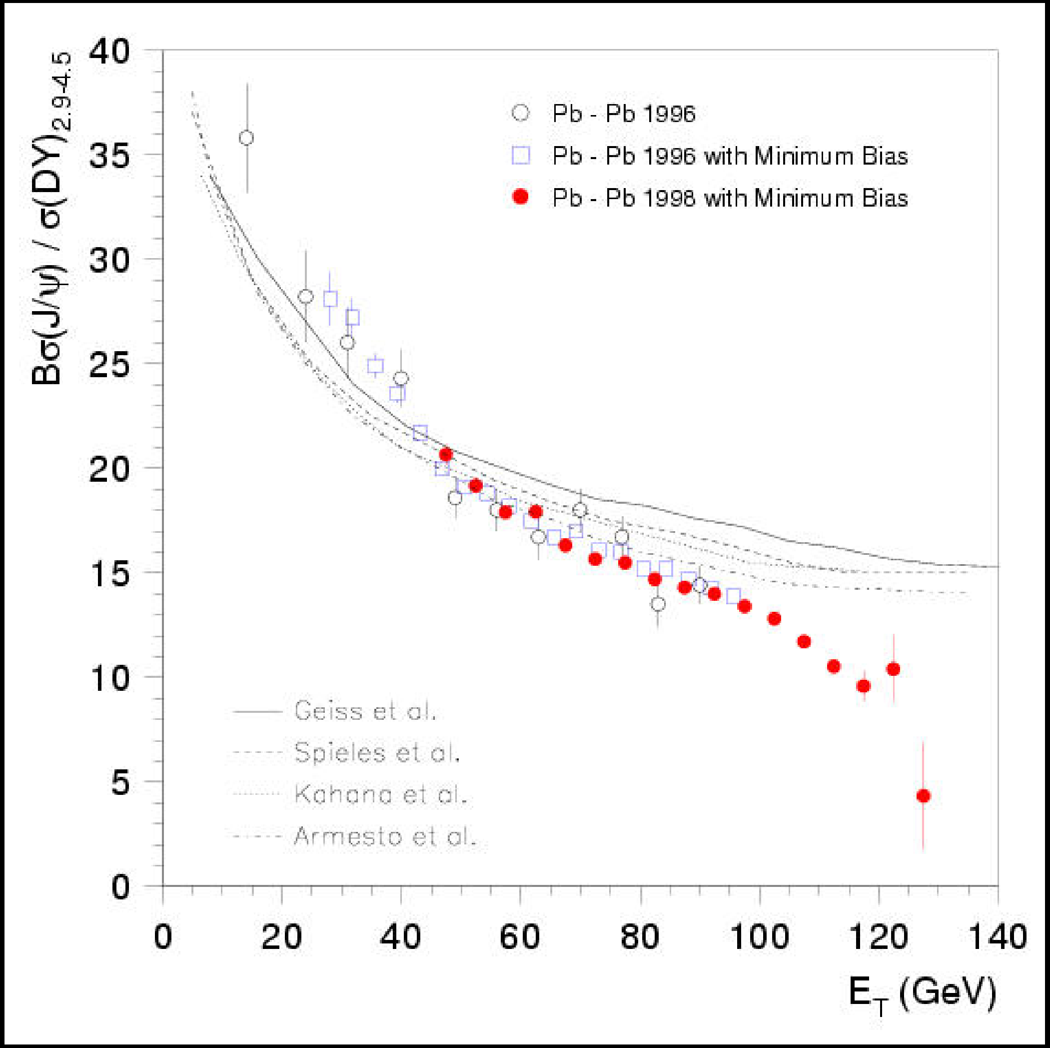
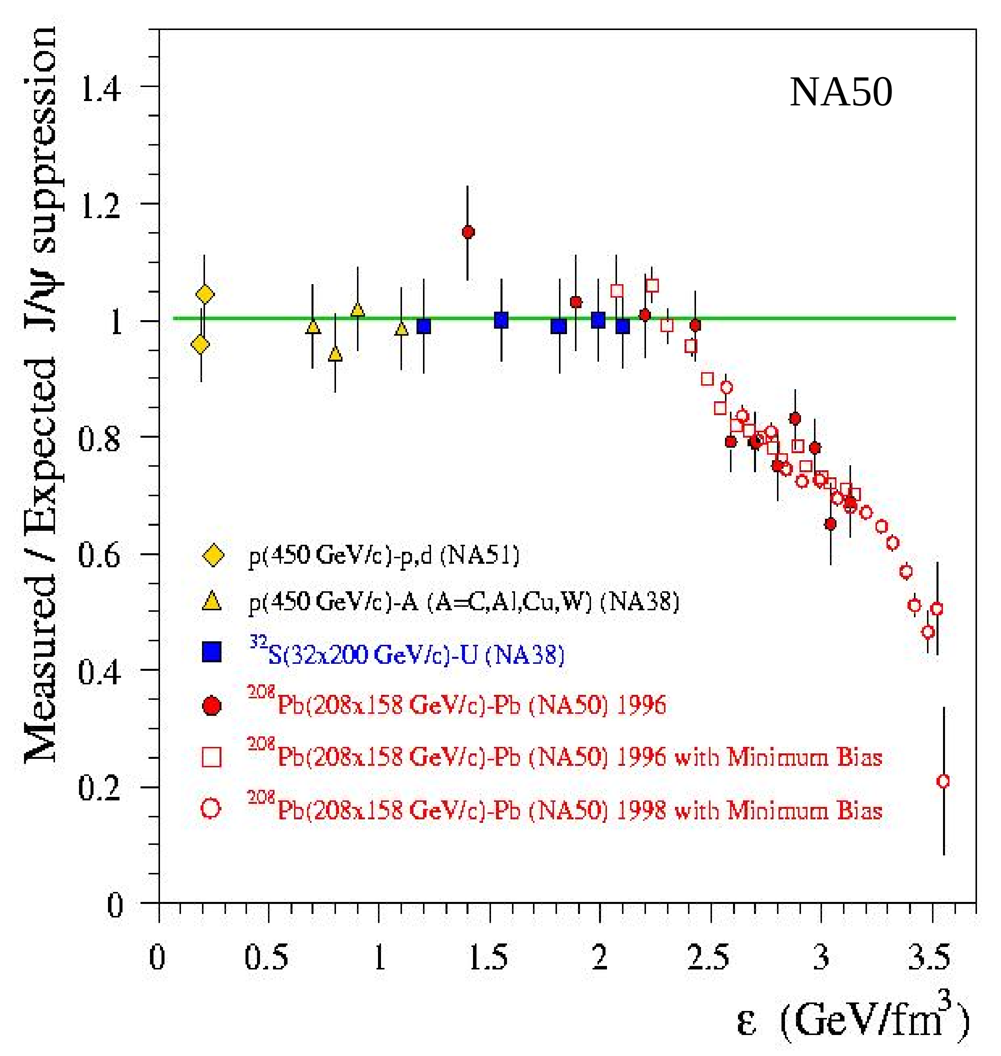
Hadronic J/Ψ dissociation



- Before
  - Before the J/ψ formation
  - Color-octet precursor interacts strongly, even with cold nuclear matter
  - Gives rise to the observed A-dependence: $\sigma \sim A^{0.92}$
- During
  - While the J/ψ is in the nuclear medium
  - This is the Debye screening signature of Matusi and Satz
- After
  - As the hadrons escape the collision zone
  - Co-movers can disrupt or destroy J/ψ's after they have exited the nuclear medium

The J/Ψ measurement at the SPS



- Measured/expected J/Ψ suppression versus estimated energy density
  - Anomalous suppression sets in at ε~ 2.3 GeV/fm^3
  - Double step was interpreted as successive melting of the χ_C and of the J/Ψ

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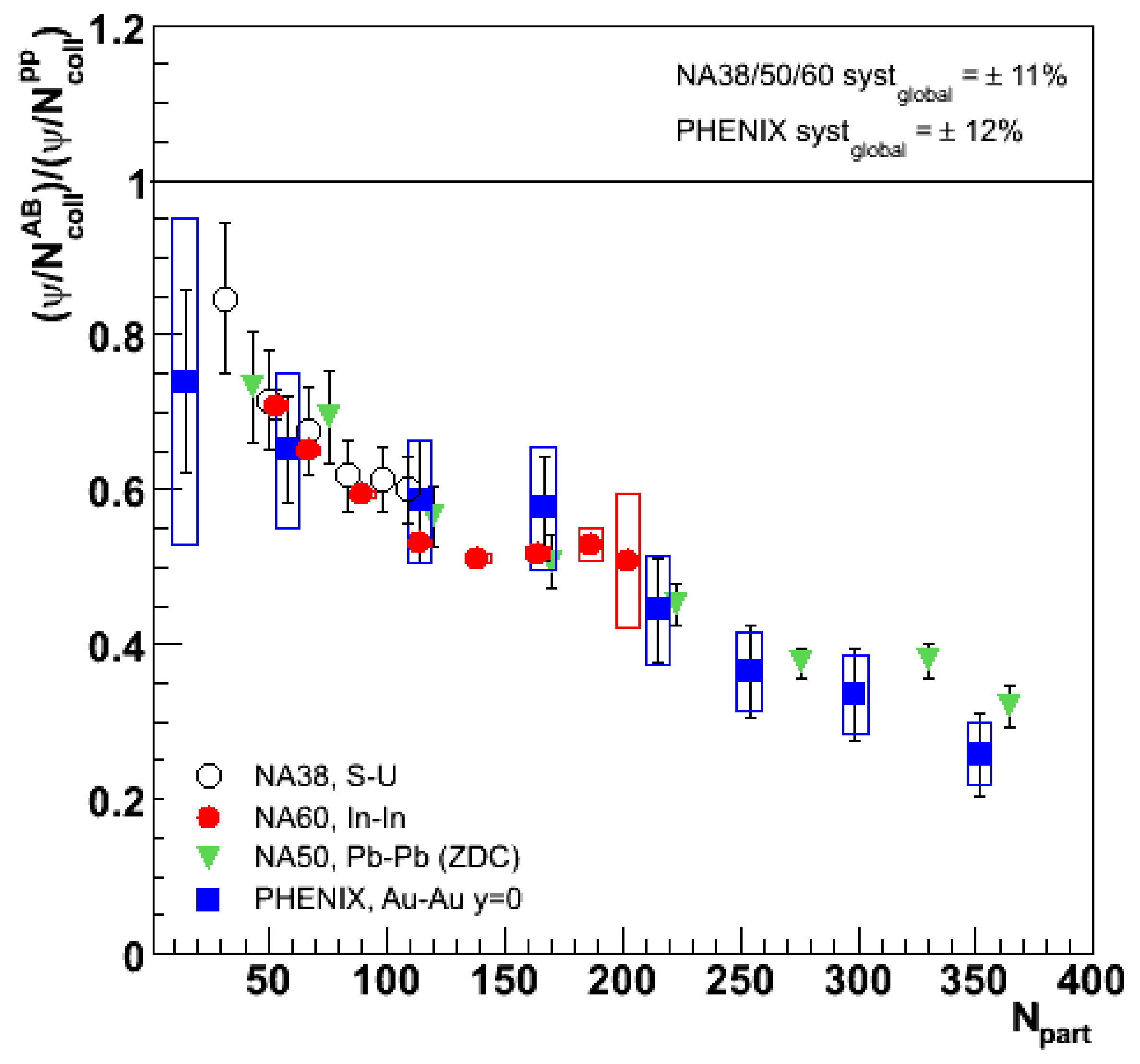
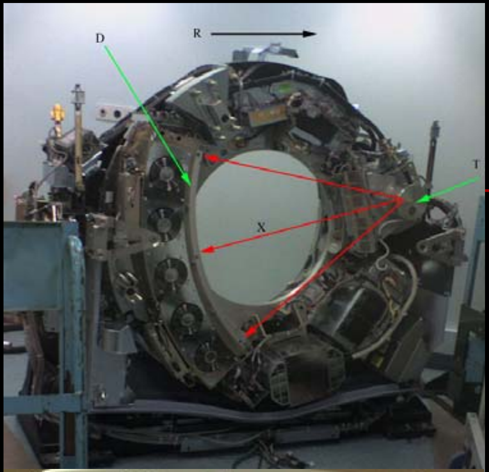
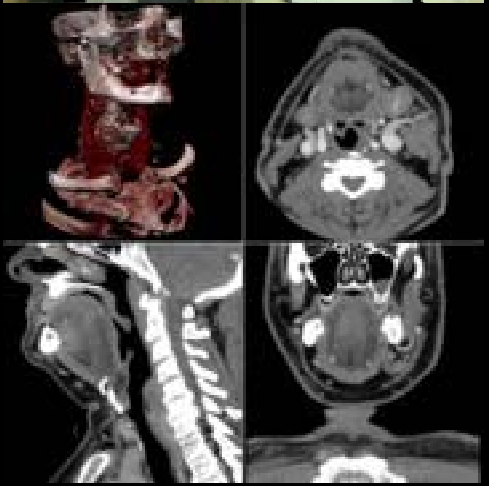
The J/Ψ measurement at RHIC

- Suppression pattern almost the same as at the SPS???
- J/Ψ production at RHIC is more complicated due to possible contributions from coalescence
- Matching energy dependence is a challenge to theory!

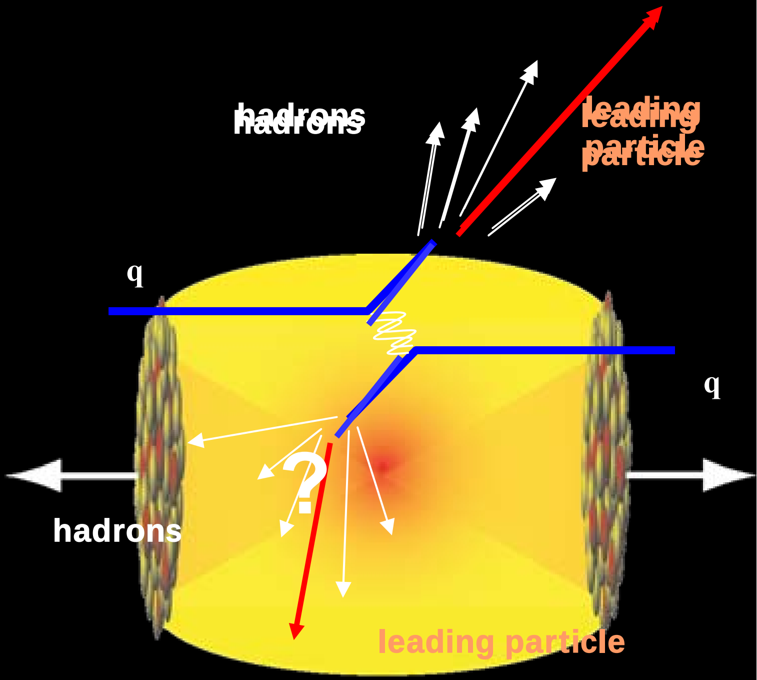






Hard Probes and Gluon Density

- Like to make a snapshot of the early phase of the collision
- Need well calibrated source
- Particles from the source (probes) needs to interact with the medium (in a controlled fashion)


schematic view of jet production

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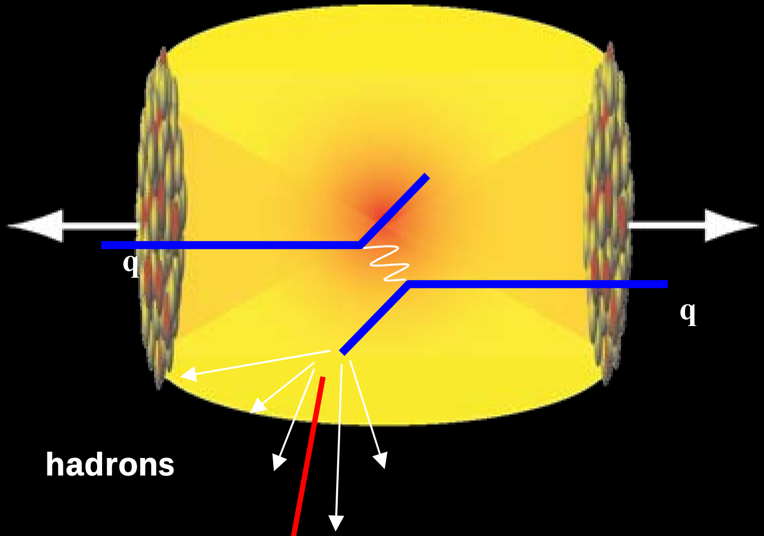
Jet Quenching: the initial color density



leading particle

Thick plasma (Baier et al.):

$$\Delta E_{BDMS} = \frac{C_R \alpha_s}{4}\hat{q}L^2\tilde{v}$$

$$\hat{q} = \frac{\mu^2_{Debye}}{\lambda_{glue}} \propto \alpha_S \rho_{glue}$$

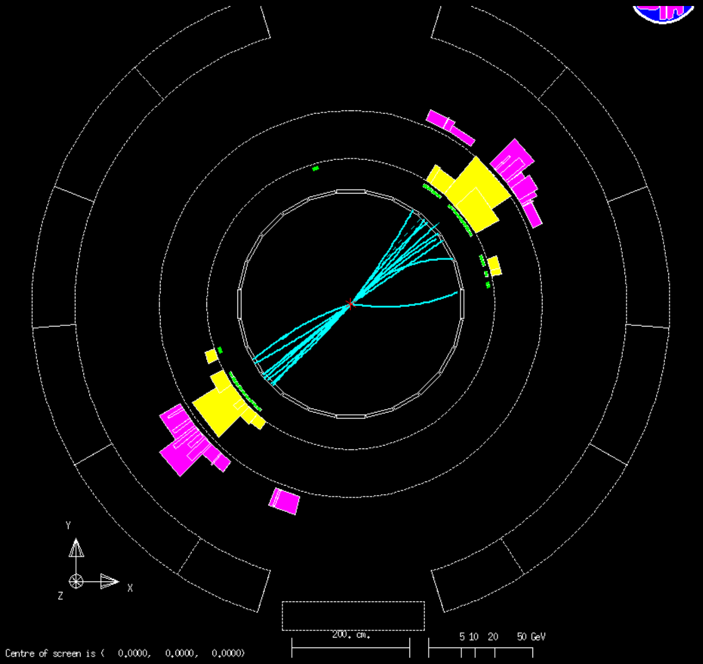
$$\Delta E_{GLV} = C_R \alpha_S^3 \int d\tau \tau \rho_{glue}\left(\tau, r\left(\tau\right)\right) Log\left(\frac{2E_{jet}}{\mu^2 L}\right)$$

Thin plasma (Gyulassy et al.):

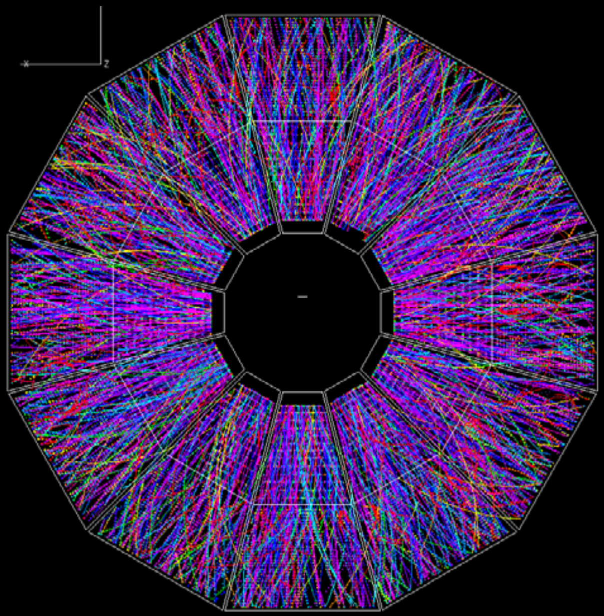
Radiated gluons decohere due to multiple interactions with the medium
This energy loss depends on the traversed path length and gluon density at the early phase

Jets in a heavy-ion environment

Jets in e^+e^-



Jets from Au + Au at 200 GeV

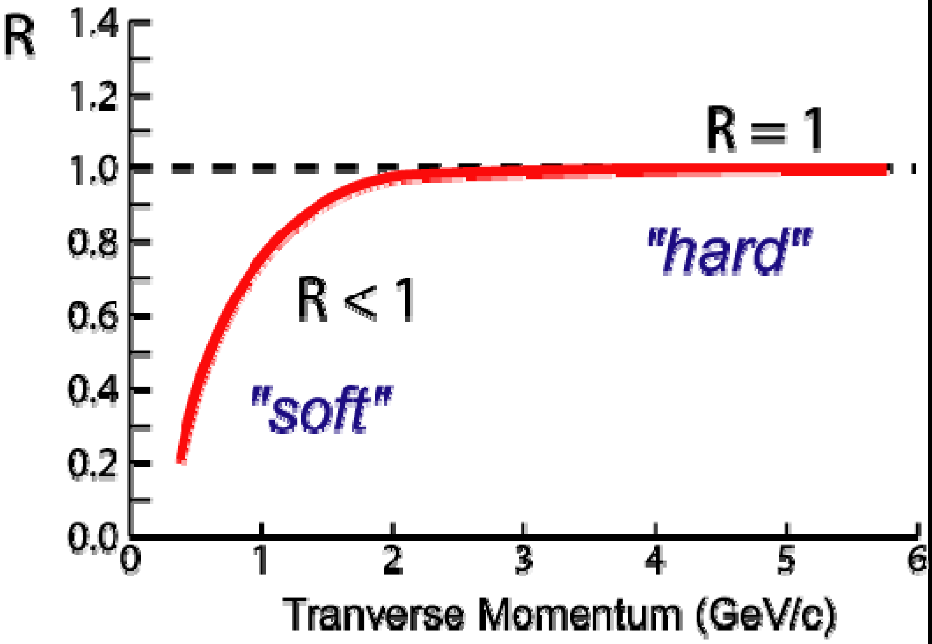


- Heavy ion collisions are a complicated environment to do full jet reconstruction

Construct simple observables (I)

- We measure: Yield(p_t) in AA and nucleon-nucleon
- Create Ratio:

$$R(p_t) = \frac{Yield_{Au+Au} / \langle N_{\text{binary}} \rangle}{Yield_{\text{nucleon-nucleon}}}$$

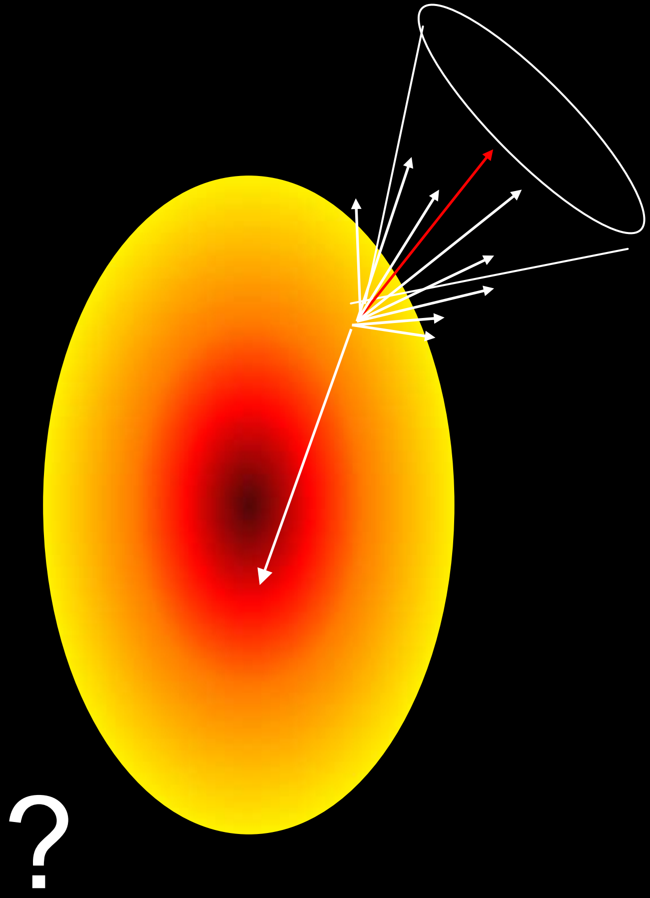


If no “nuclear effects”:
◆ R < 1 in regime of soft physics
◆ R = 1 at high-p_t where hard scattering dominates

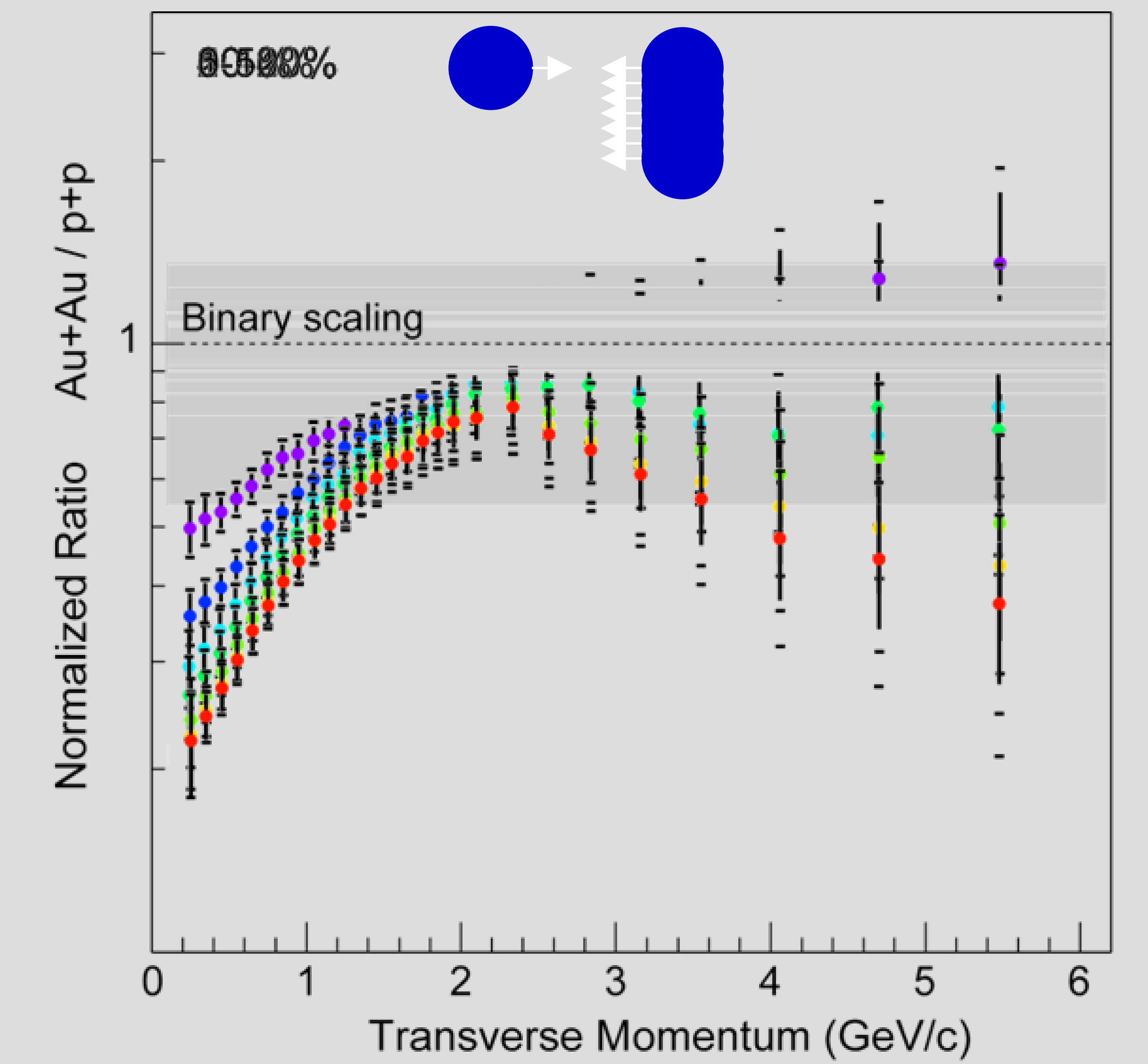
Suppression:
◆ R < 1 at high-p_t

Construct simple observables (III)

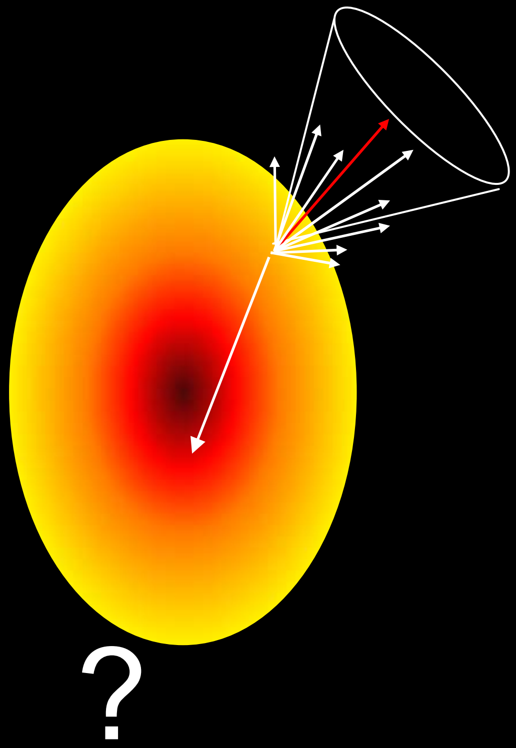
- Azimuthal jet correlations

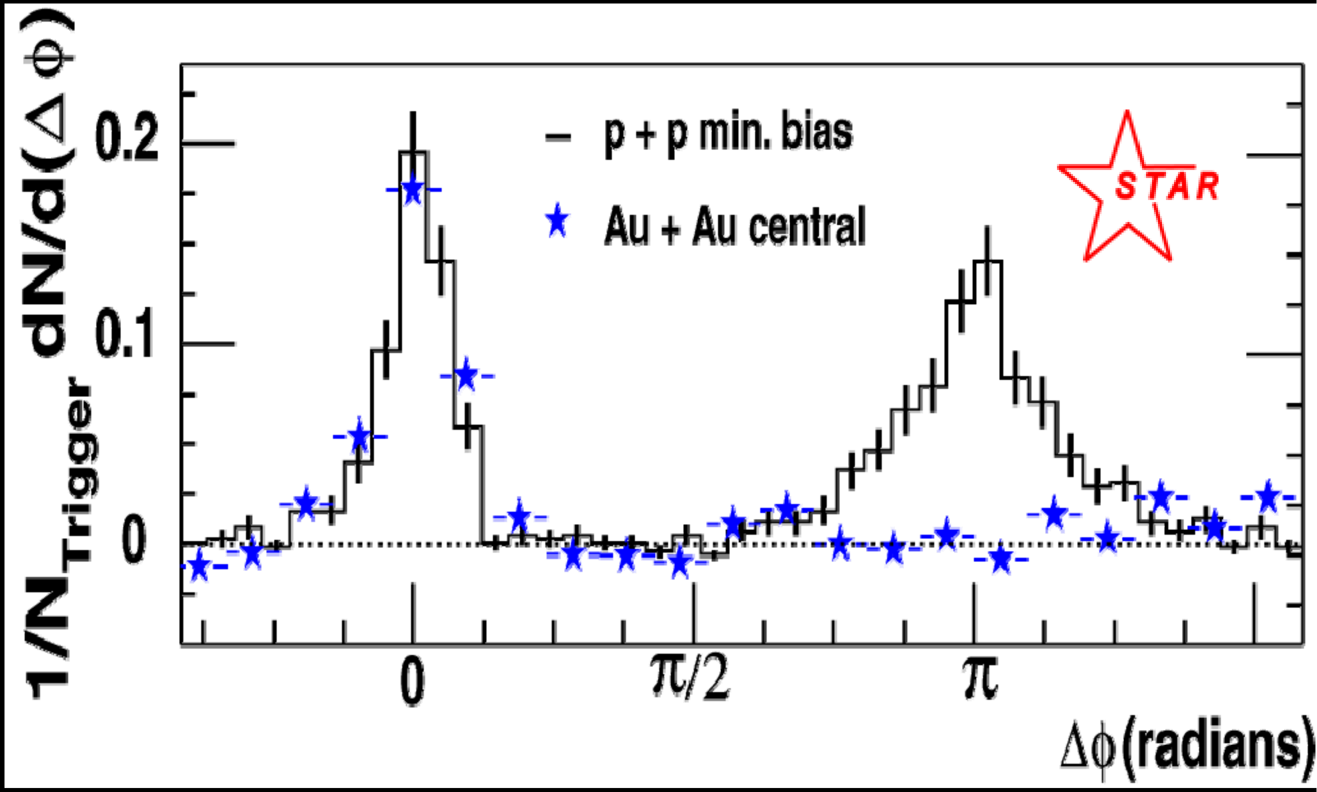


Compare p+p to Au+Au



Azimuthal jet-like correlations





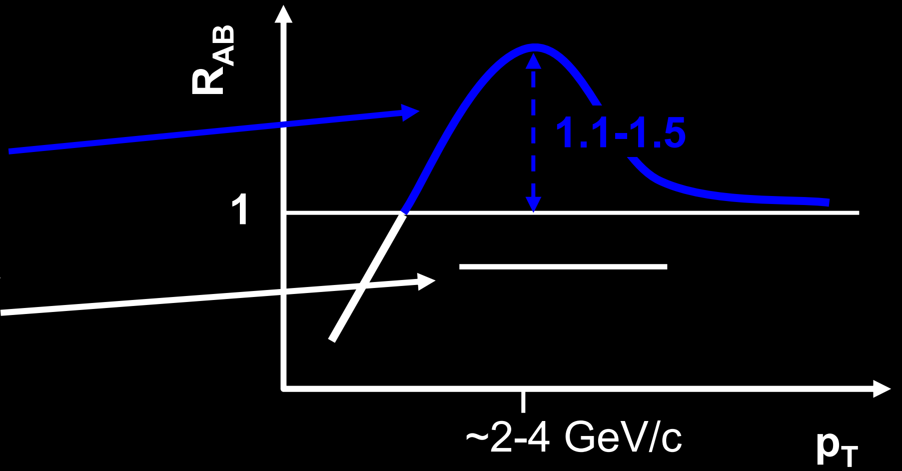
- The away side jets disappears completely!!
- Very dense system > 50x nuclear matter

What to expect in d+Au?

Inclusive spectra

If Au+Au suppression is final state

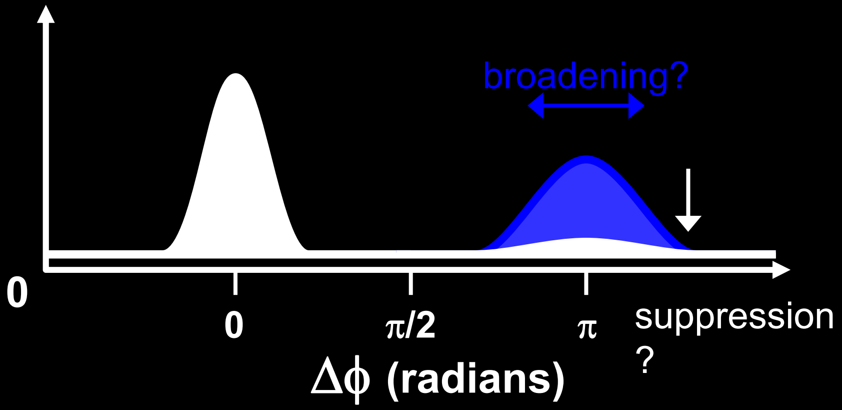
If Au+Au suppression is initial state (KLM saturation: 0.75)



High p_T hadron pairs

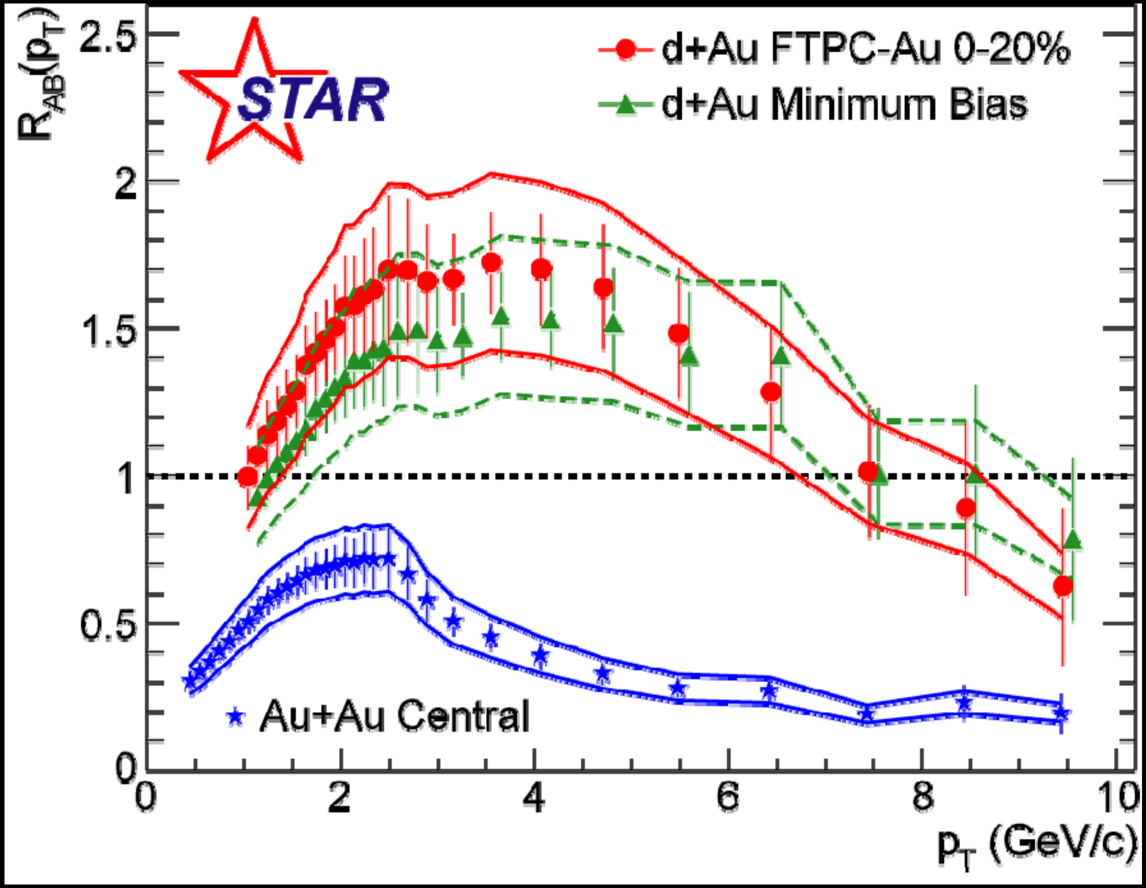
pQCD: no suppression, small broadening due to Cronin effect

saturation models:
suppression due to mono-jet contribution?



All effects strongest in central d+Au collisions

d+Au



- Ratio is enhanced in d+Au collisions, opposite to Au+Au
- Suppression is a final state effect!

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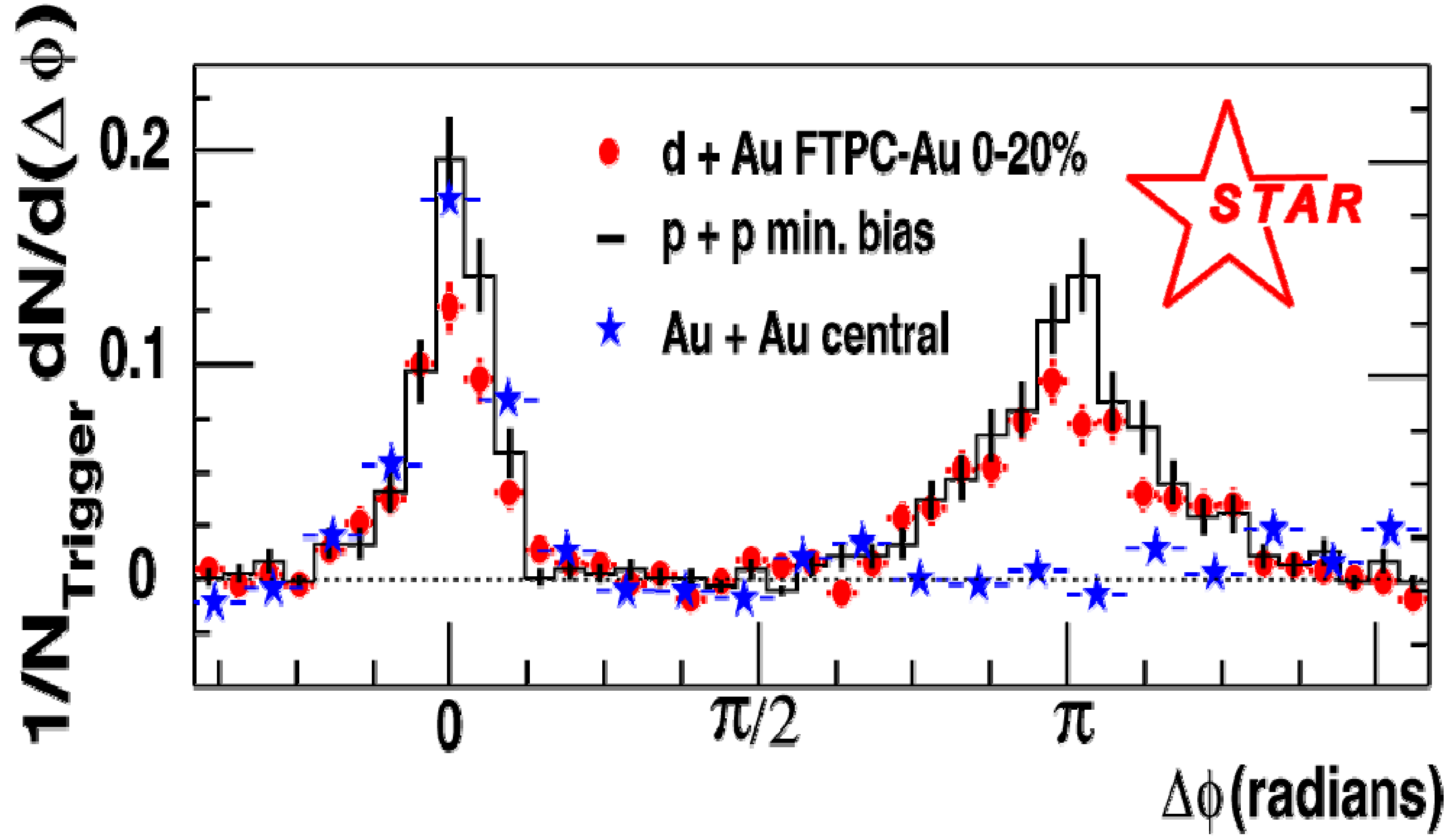
Back to back in d+Au



- Correlation in d+Au resembles p+p and is very different from Au+Au
- Suppression is a final state effect!

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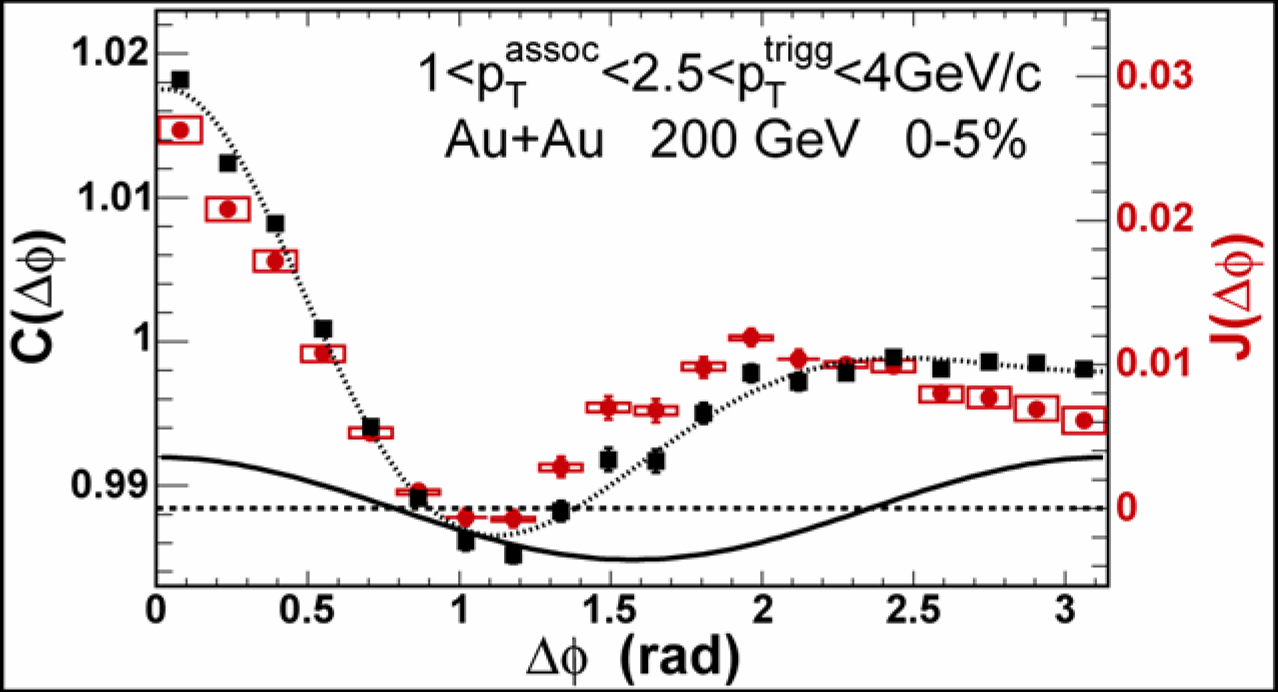
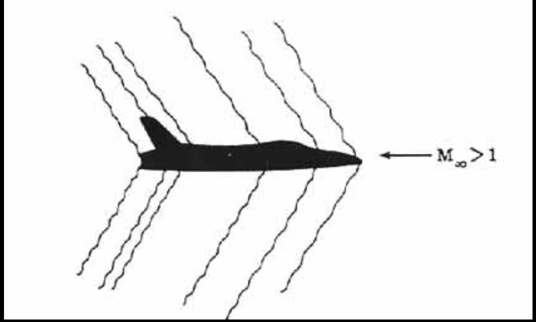
What happens with the away side jet?

PHENIX Preprint: nucl-ex/0611019

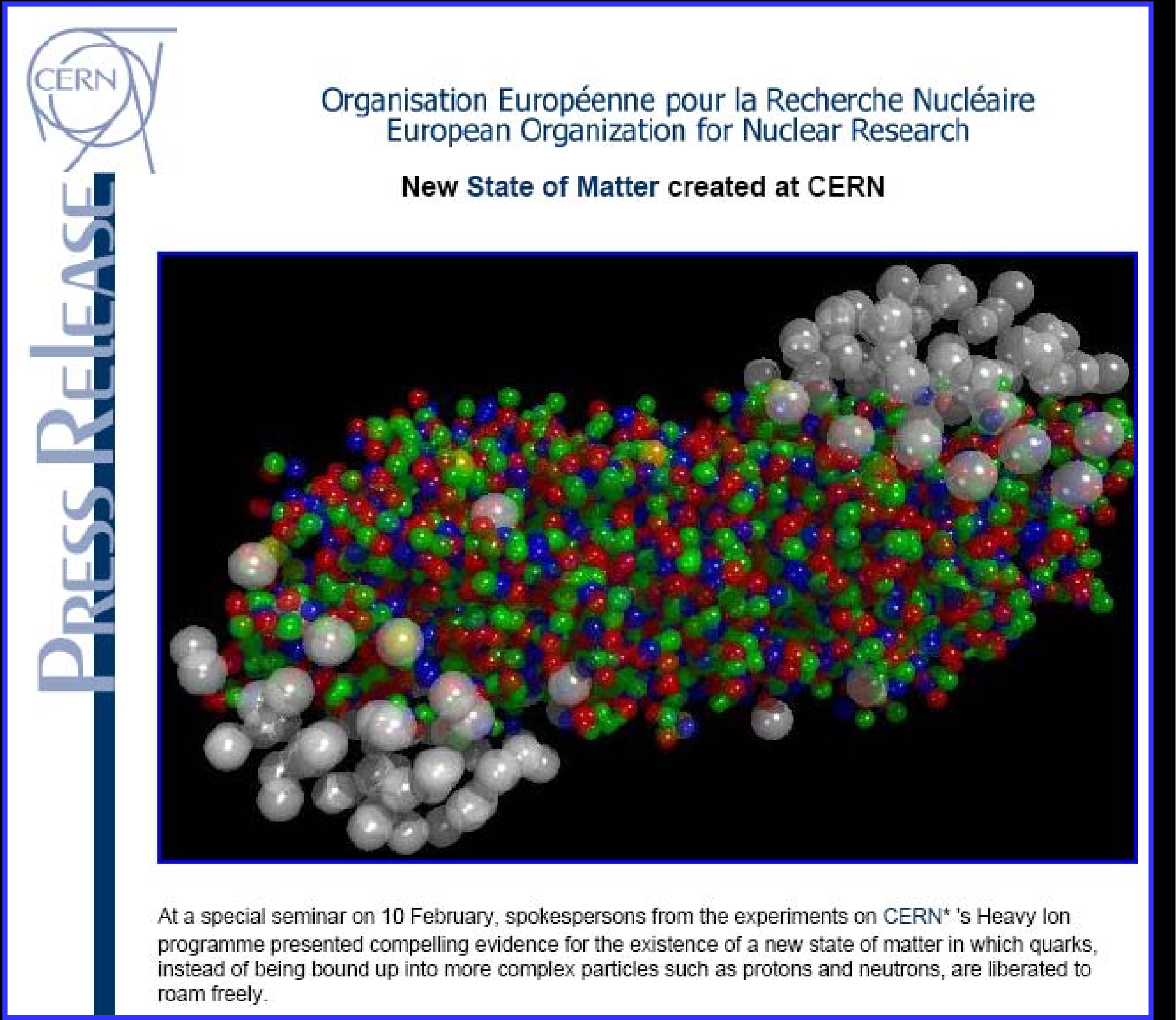




- Lively debated topic in the community
  - many uncertainties
  - Could provide alternative access to velocity of sound in the medium!

From SPS, RHIC to the LHC

- SPS
  - Observed many of the signatures predicted for QGP formation
  - CERN announced a new state of matter



Press Release

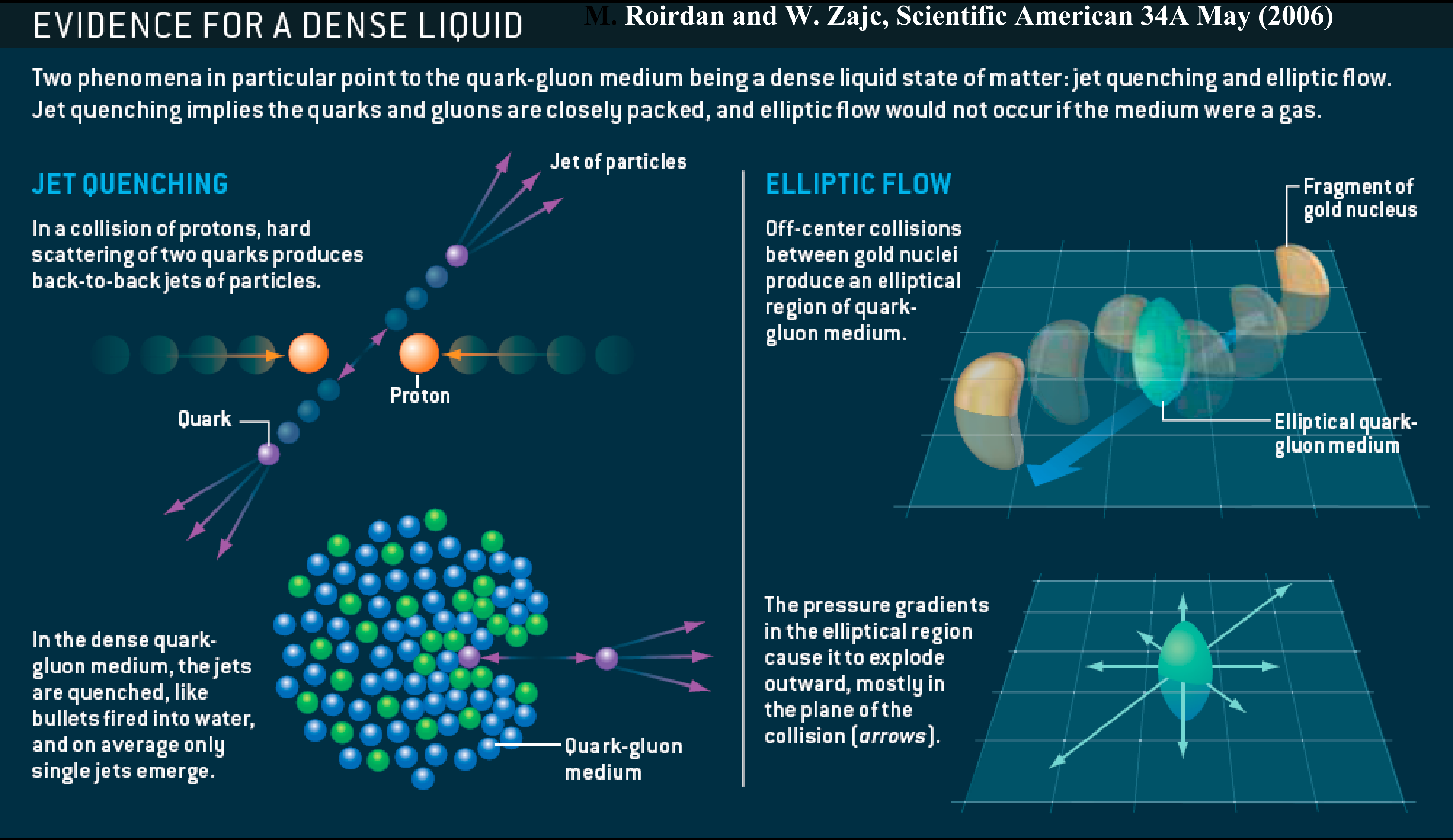
Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

New State of Matter created at CERN

At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

From SPS, RHIC to the LHC

M. Roirdan and W. Zajc, Scientific American 34A May (2006)



EVIDENCE FOR A DENSE LIQUID

Two phenomena in particular point to the quark-gluon medium being a dense liquid state of matter: jet quenching and elliptic flow. Jet quenching implies the quarks and gluons are closely packed, and elliptic flow would not occur if the medium were a gas.

JET QUENCHING

In a collision of protons, hard scattering of two quarks produces back-to-back jets of particles.

In the dense quark-gluon medium, the jets are quenched, like bullets fired into water, and on average only single jets emerge.

ELLIPTIC FLOW

Off-center collisions between gold nuclei produce an elliptical region of quark-gluon medium.

The pressure gradients in the elliptical region cause it to explode outward, mostly in the plane of the collision (*arrows*).

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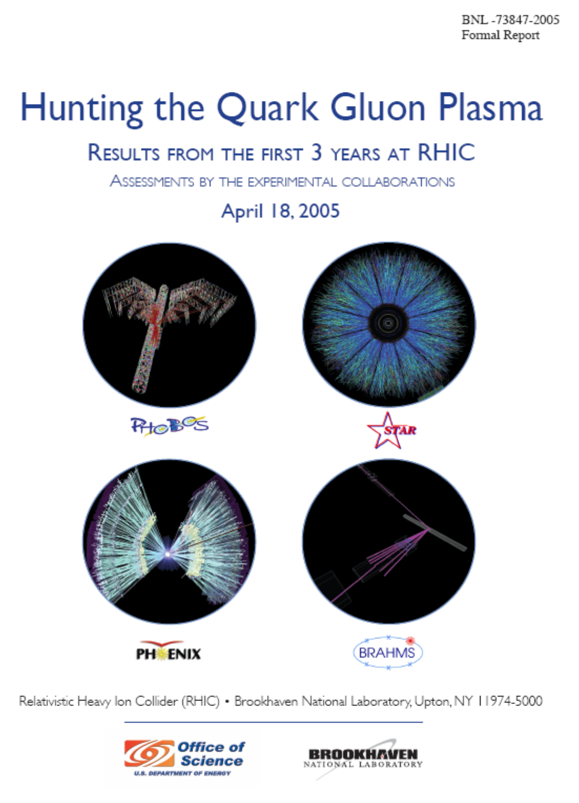
April 18, 2005



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Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

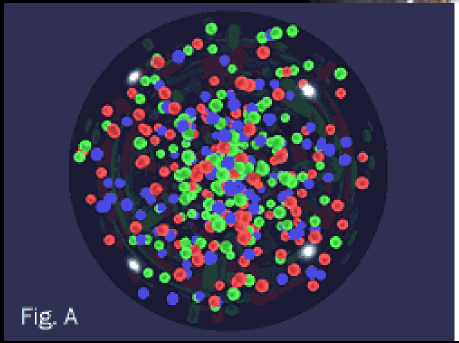

Fig. A

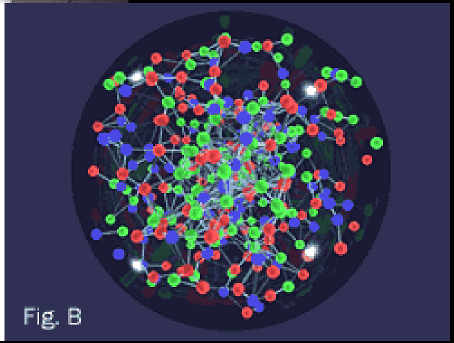

Fig. B

Heavy Ions at the LHC?

- Assume the QGP has been discovered at lower energies (the current evidence is rather strong) why go to the LHC?

- The task of characterizing the QGP has just begun: “precision” measurements
  - The LHC energy opens up many new ways to probe the system
- Confirm current interpretations: continue discovery phase
  - Understanding energy loss mechanism
  - Energy dependence of the J/Ψ “suppression”
  - New initial state: color glass condensate?
- Be prepared for surprises!!

From SPS, RHIC to the LHC

	SPS	RHIC	LHC	
$\sqrt{s_{NN}}$ (GeV)	17	200	5500	
dN/dy	500	850	1500-4000	
τ^0_{QGP} (fm/c)	1	0.2	0.1	
T/T_c	1.1	1.9	3-4	Hotter
ε (GeV/fm^3)	3	5	15-60	Denser
τ_{QGP} (fm/c)	≤2	2-4	≥10	Longer
τ_f (fm/c)	~10	20-30	30-40	
V_f(fm^3)	few 10^3	few 10^4	Few 10^5	Bigger

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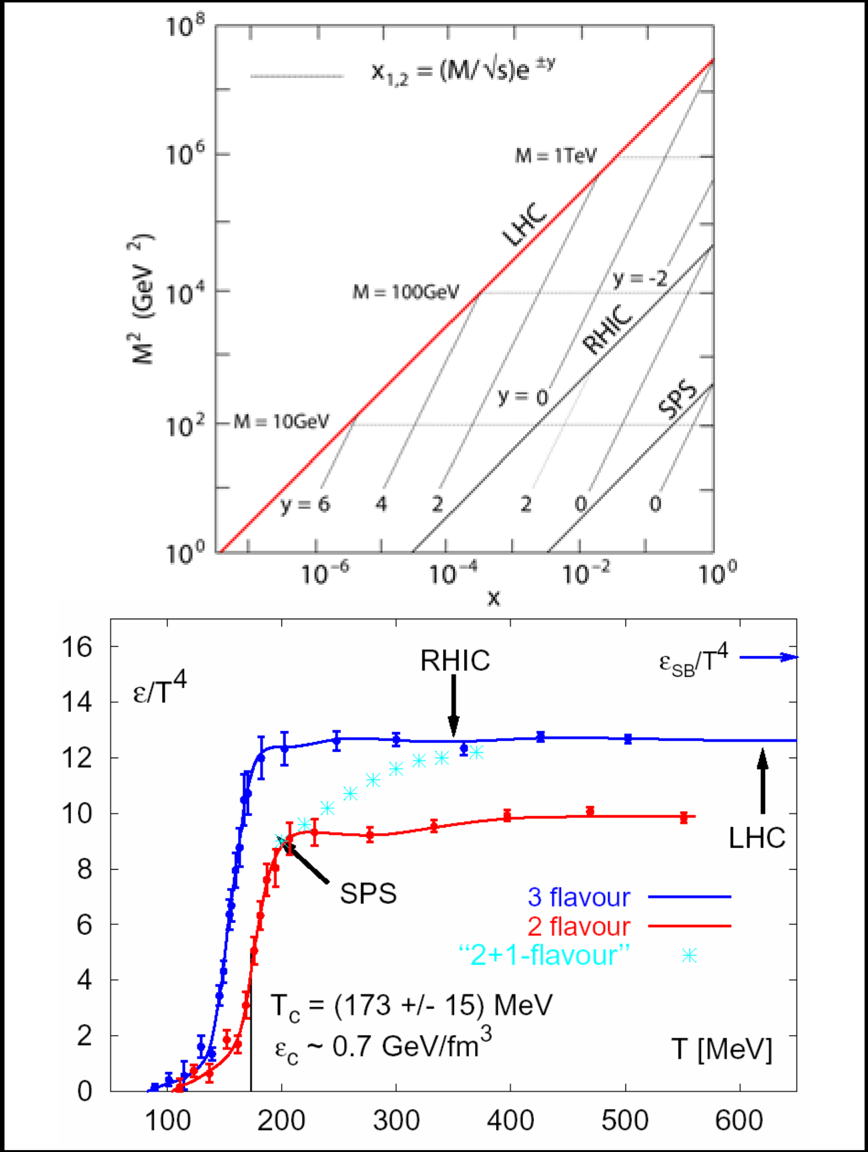
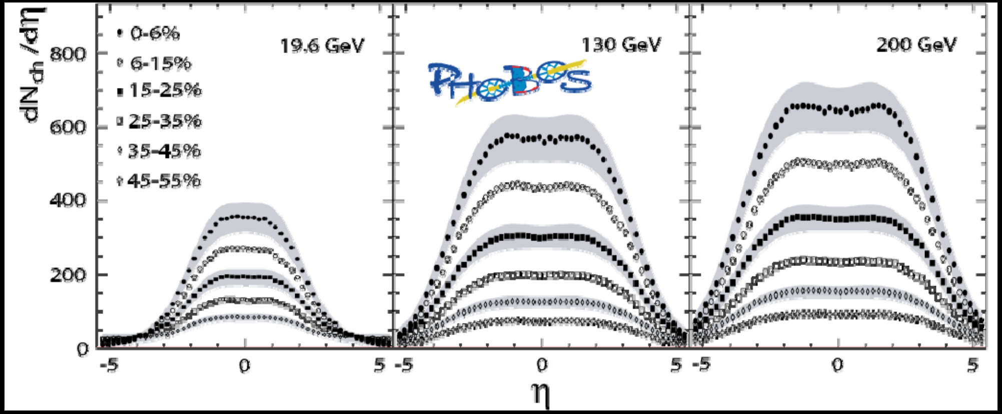
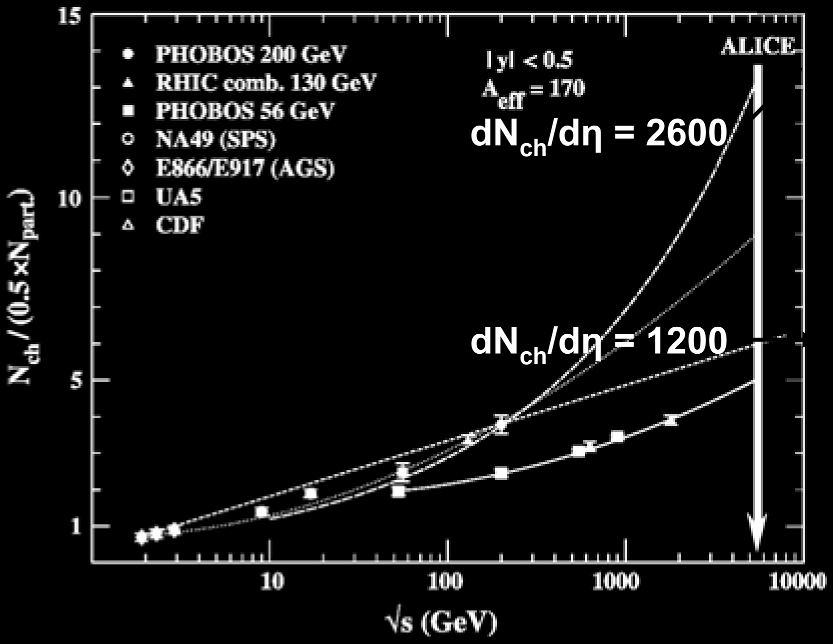
From SPS, RHIC to the LHC

- Not just super sized, a new regime!
  - high density pdf's (saturized) determine particle production
  - parton dynamics dominate the fireball expansion
- with new tools
  - hard processes contribute significantly to the cross section
  - weakly interacting hard probes become available
- Allows for detailed understanding of the QGP
- and possibly surprises



Particle Yields and Energy Density





$dN_{ch}/d\eta = 2600$

$dN_{ch}/d\eta = 1200$

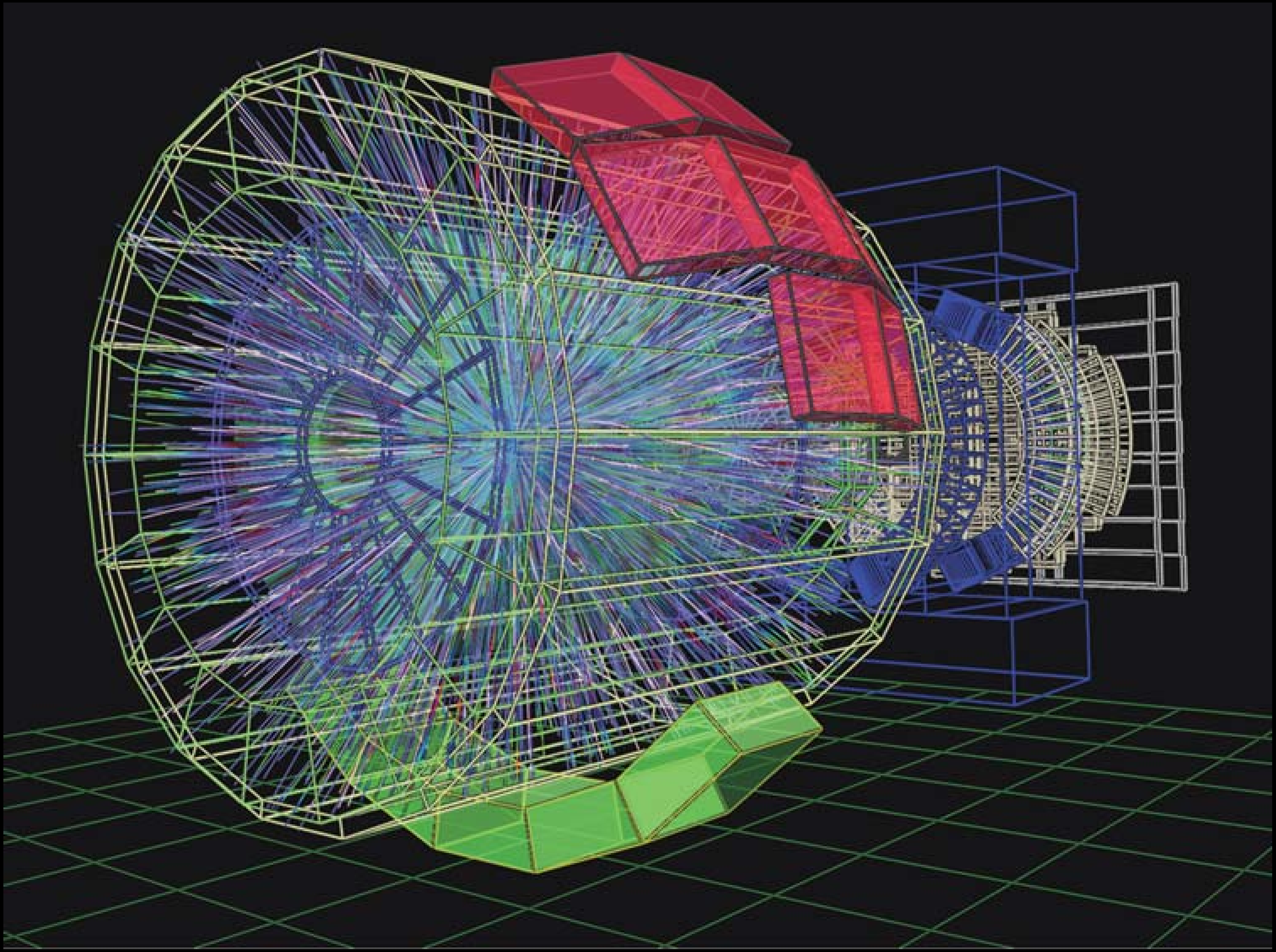
$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

$$\frac{dE_T}{dy} = \langle m_T\rangle \frac{3}{2}\frac{dN_{ch}}{dy} \quad \text{at } y = 0\,; \frac{dN_{ch}}{dy} = \left(1-\frac{m^2}{\langle m_T\rangle^2}\right)^{-1/2}\frac{dN_{ch}}{d\eta}$$

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\langle m_T\rangle \frac{3}{2}\left(1-\frac{m^2}{\langle m_T\rangle^2}\right)^{-1/2}\frac{dN_{ch}}{d\eta}$$

- Bjorken energy density estimate from charged particle density
- 3-10x increase of ε_{Bj} at the LHC
- Large uncertainty due to large uncertainty in particle production

ALICE Event



4/13/2007

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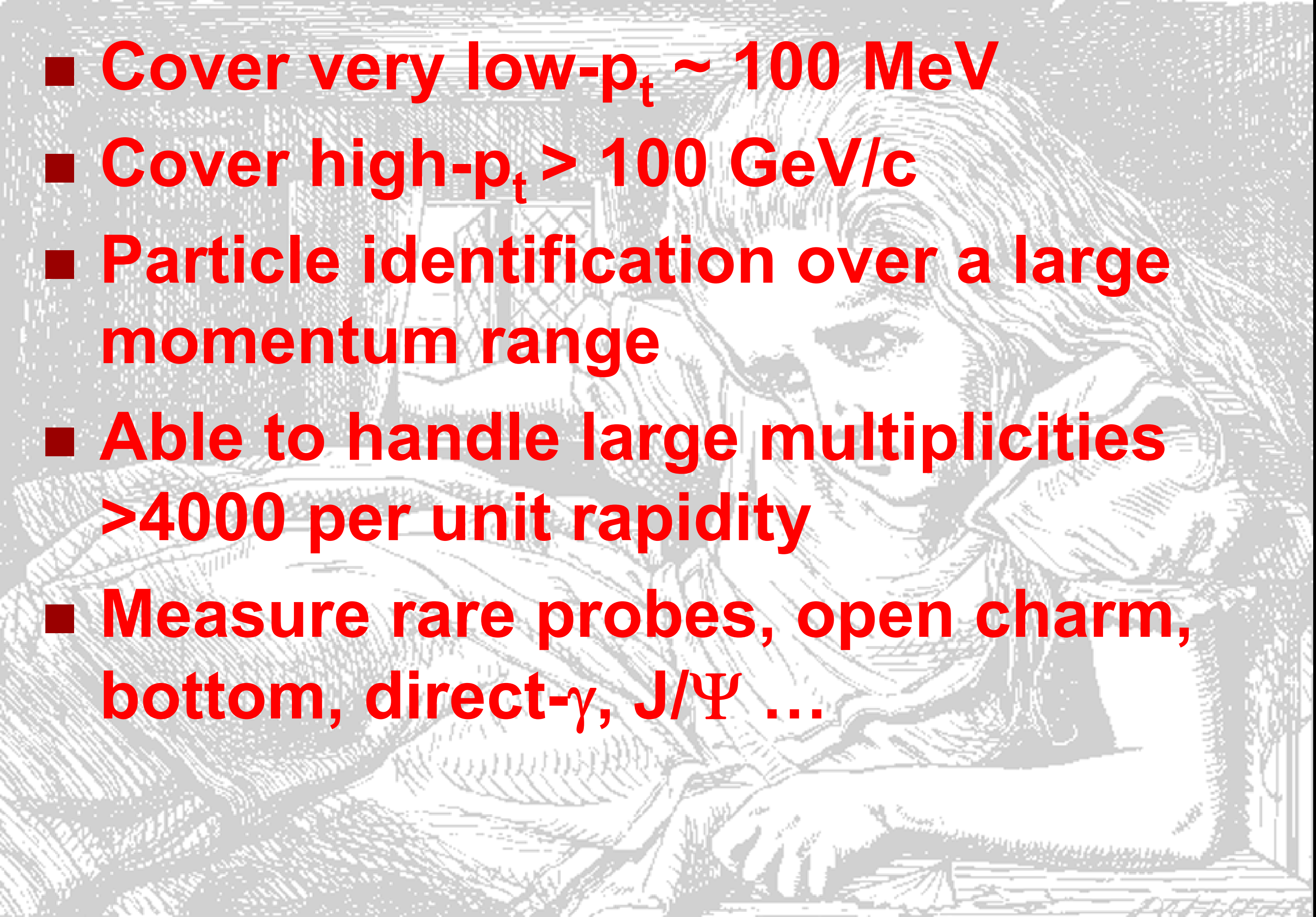
ALICE detector design



- **Cover very low-p_t ~ 100 MeV**
- **Cover high-p_t > 100 GeV/c**
- **Particle identification over a large momentum range**
- **Able to handle large multiplicities >4000 per unit rapidity**
- **Measure rare probes, open charm, bottom, direct-γ, J/Ψ …**

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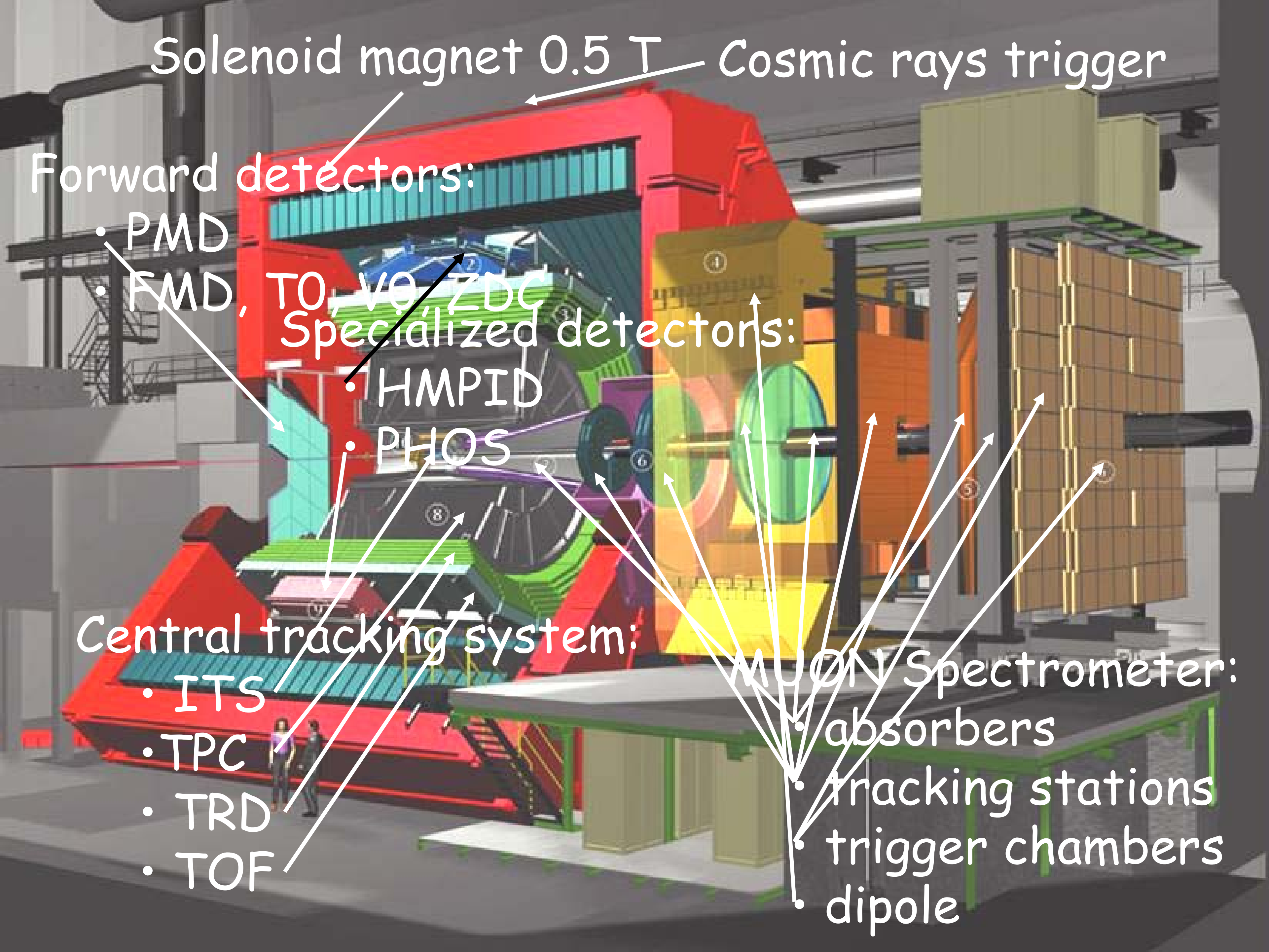


Solenoid magnet 0.5 T

Cosmic rays trigger

Forward detectors:

- PMD
- FMD, T0, V0, ZDC

Specialized detectors:

- HMPID
- PHOS

Central tracking system:

- ITS
- TPC
- TRD
- TOF

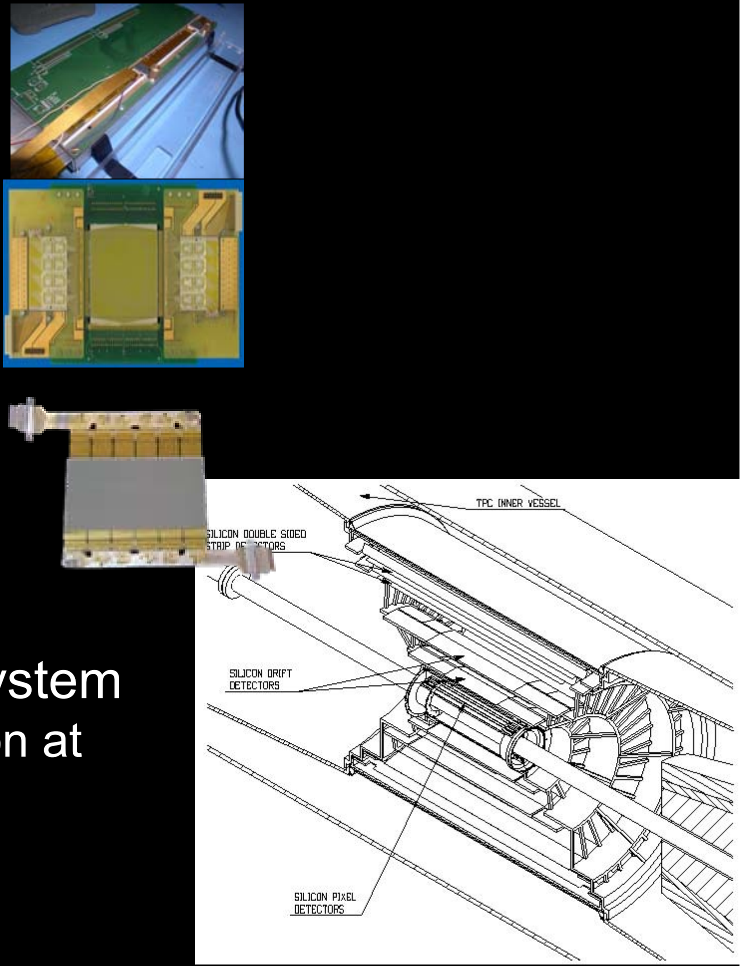
MUON Spectrometer:

- absorbers
- tracking stations
- trigger chambers
- dipole

The inner tracking system

low mass: 7 % X_0

6 layers		R	σ rϕ	σ Z
Layer 1	pixels	4 cm	12 μm	100 μm
Layer 2	pixels	8 cm	12 μm	100 μm
Layer 3	drift	15 cm	38 μm	28 μm
Layer 4	drift	24 cm	38 μm	28 μm
Layer 5	double sided strip	38 cm	17 μm	800 μm
Layer 6	double sided strip	43 cm	17 μm	800 μm



- The ITS is the center of the ALICE tracking system
  - needed to get reasonable momentum resolution at higher p_t
  - needed to reconstruct secondary vertices
  - needed to track low momentum particles

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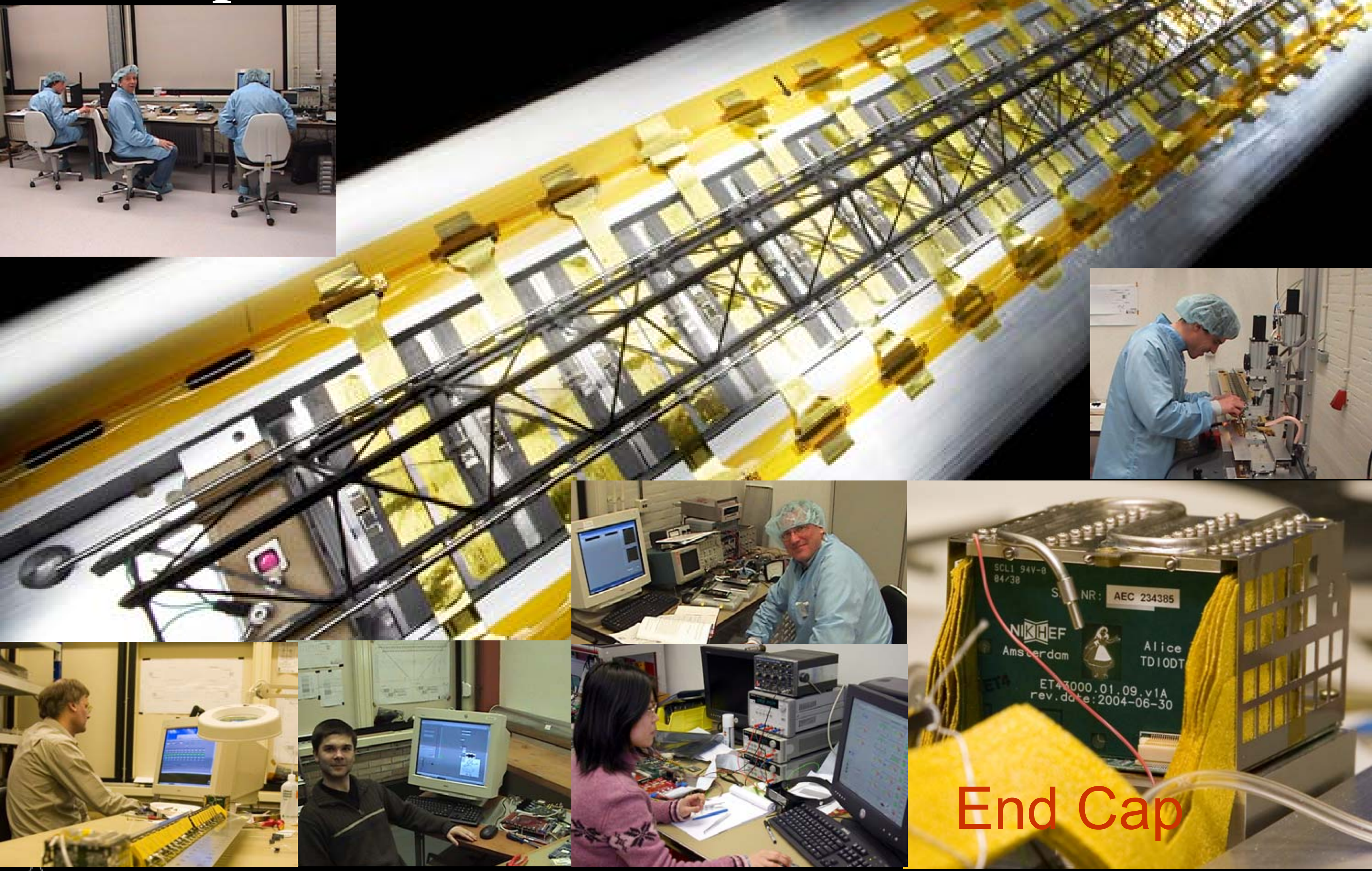
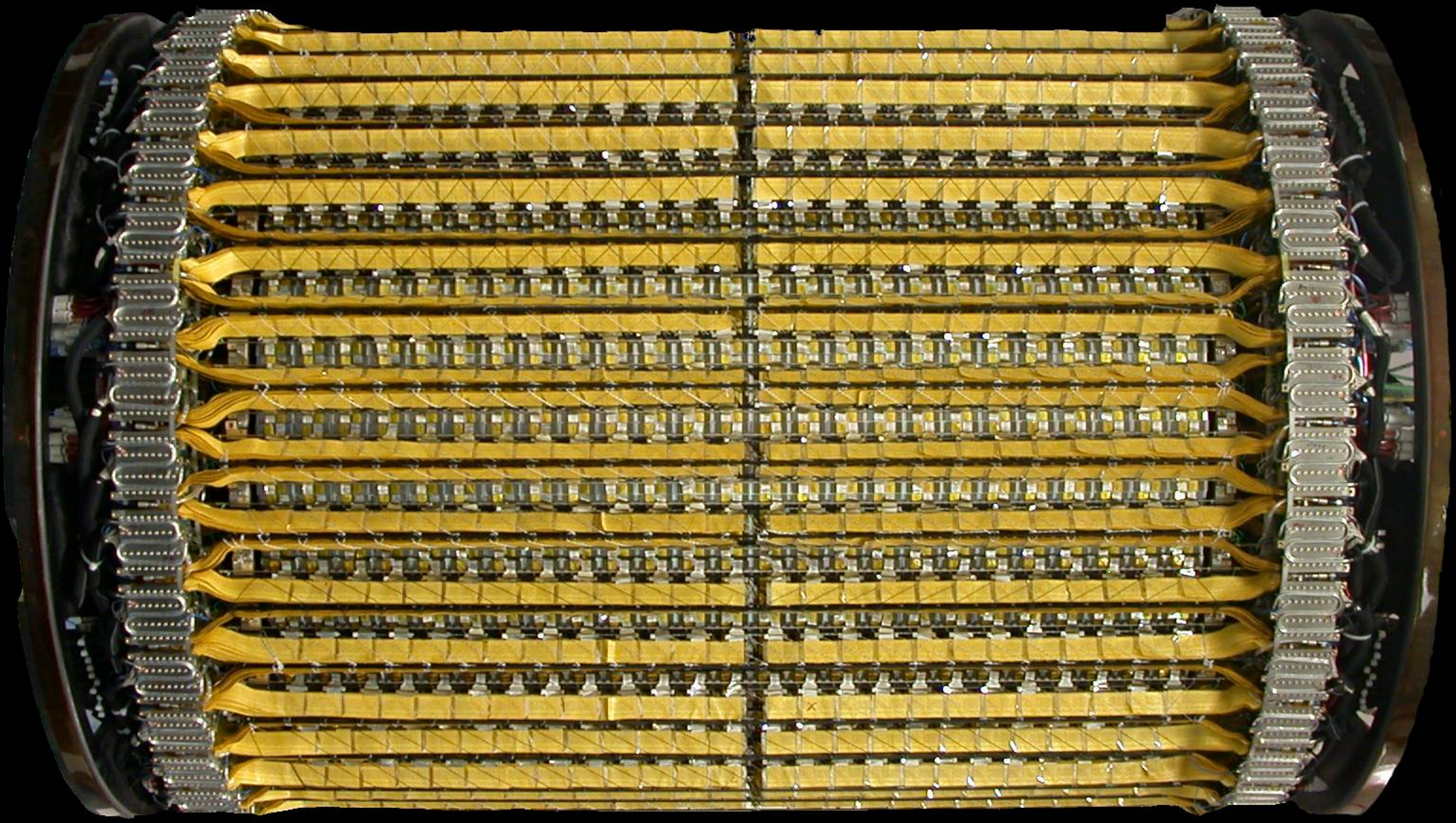
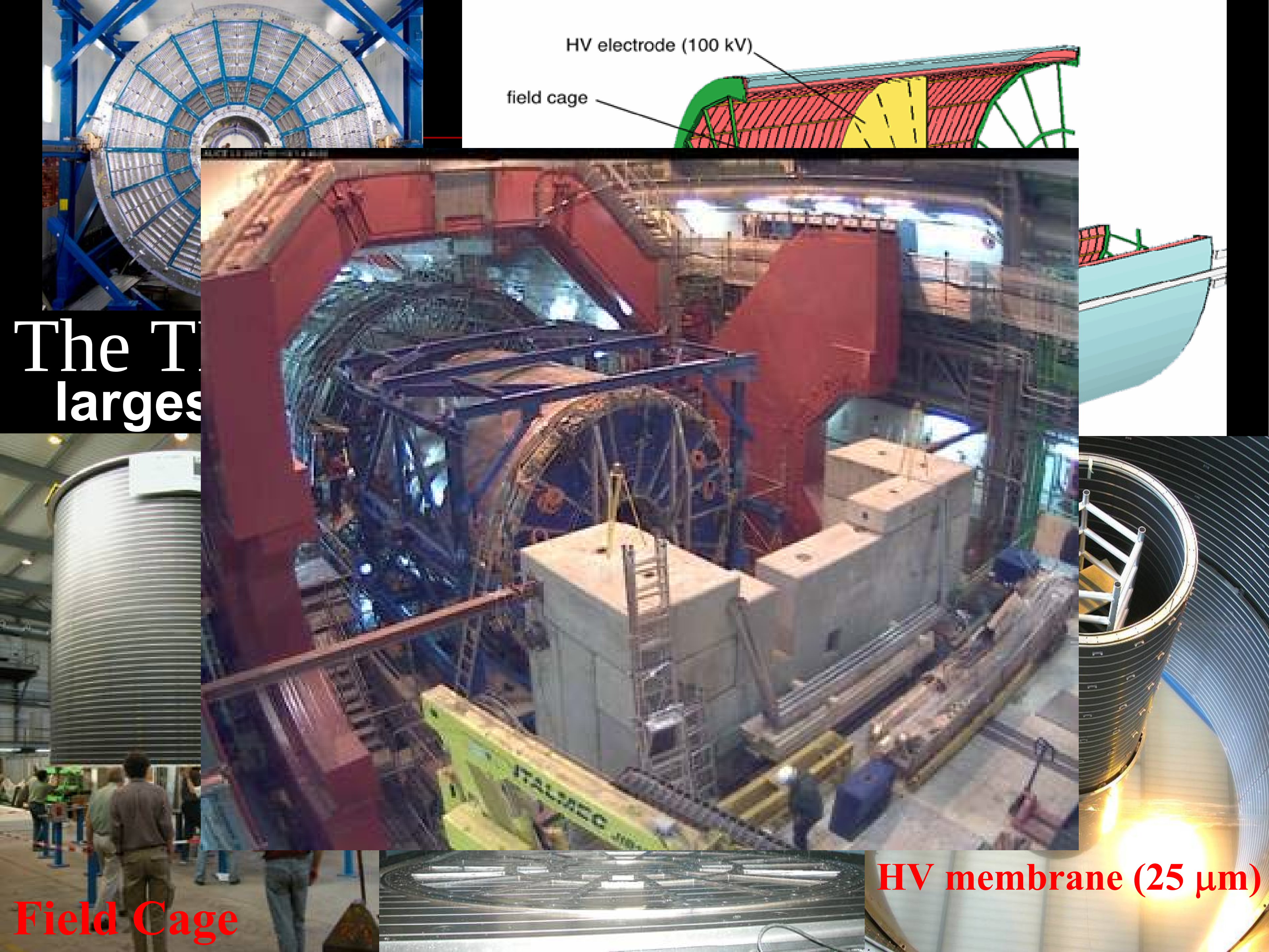
Completed SSD Ladder



End Cap

Completed SSD

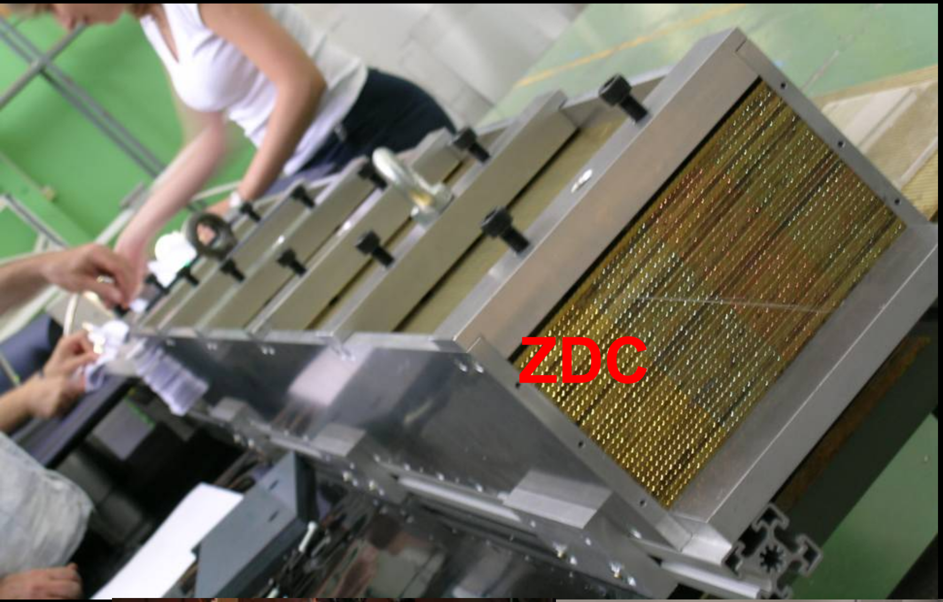


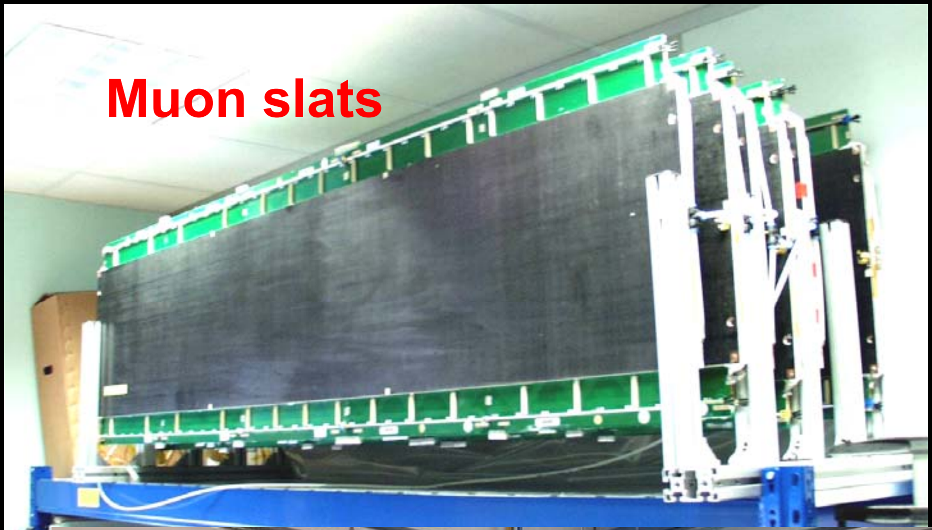


The T

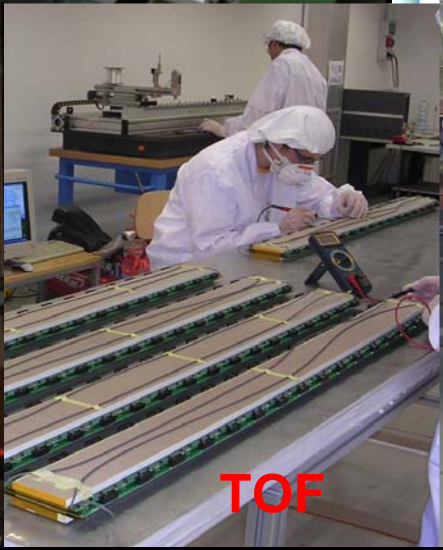
larges

A few other detectors


ZDC


Muon slats


TRD


TOF


PHOS PbWO$_4$ Crystals

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Tracking I

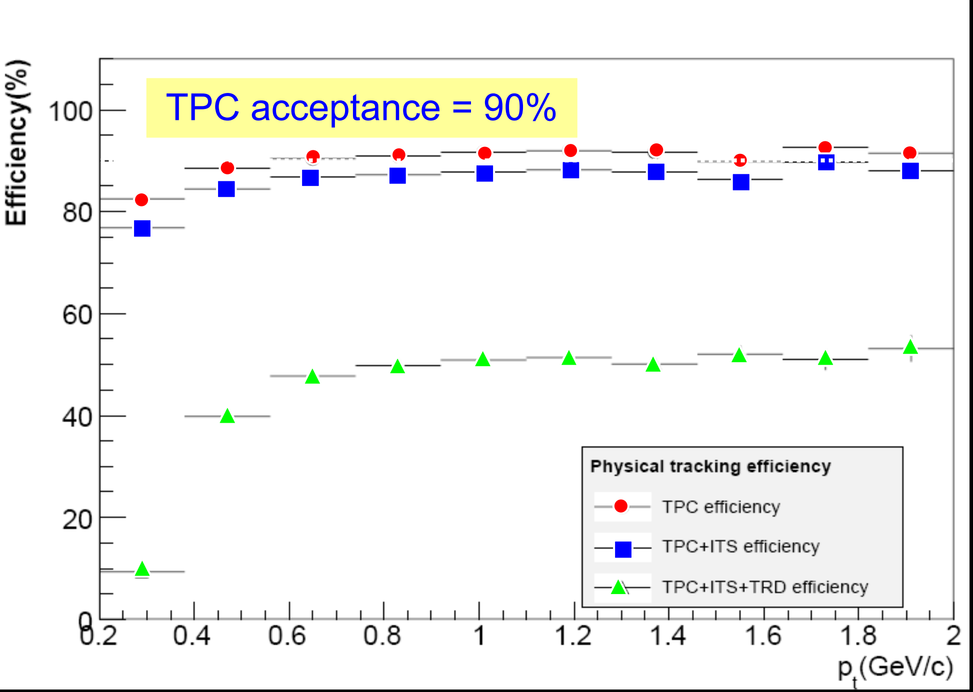
- robust, redundant tracking from 0.1 to 100 GeV/c
  - ☐ modest soleniodal field (0.5 T) => easy pattern recognition
  - ☐ long lever arm => good momentum resolution
    - (BL^2 : Alice ~ CMS > Atlas !)
  - ☐ small material budget: < 10% X_0 — vertex -> end of TPC
  - ☐ **Silicon Vertex Detector** (ITS) — 4 cm < r < 44 cm
    - stand-alone tracking at low p_t — (**6 layers**, ~9 m^2)
  - ☐ **Time Projection Chamber** (TPC) — 85 cm < r < 245 cm

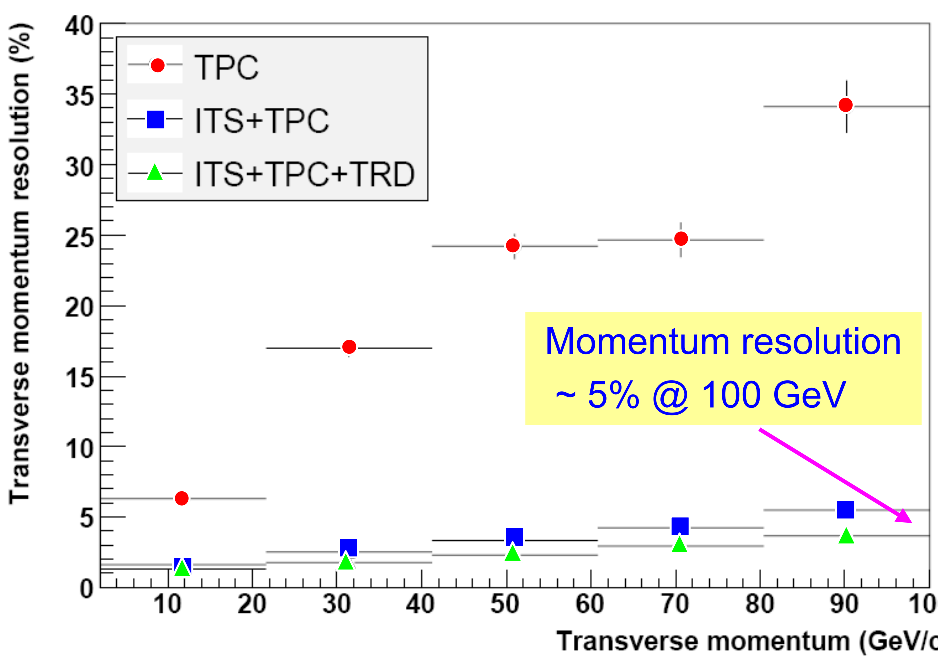
    (l=1.6m, **159 pad** rows)
  - ☐ **Transition Radiation Detector** (TRD) — 290 cm < 370 cm

    (6x3 cm tracks)

Tracking II

- full GEANT simulation: central Pb-Pb, **dN_{ch}/dy = 6000**
  - ☐ very little dependence on dN_{ch}/dy up to 8000 (important for systematics !)





Momentum resolution ~ 5% @ 100 GeV

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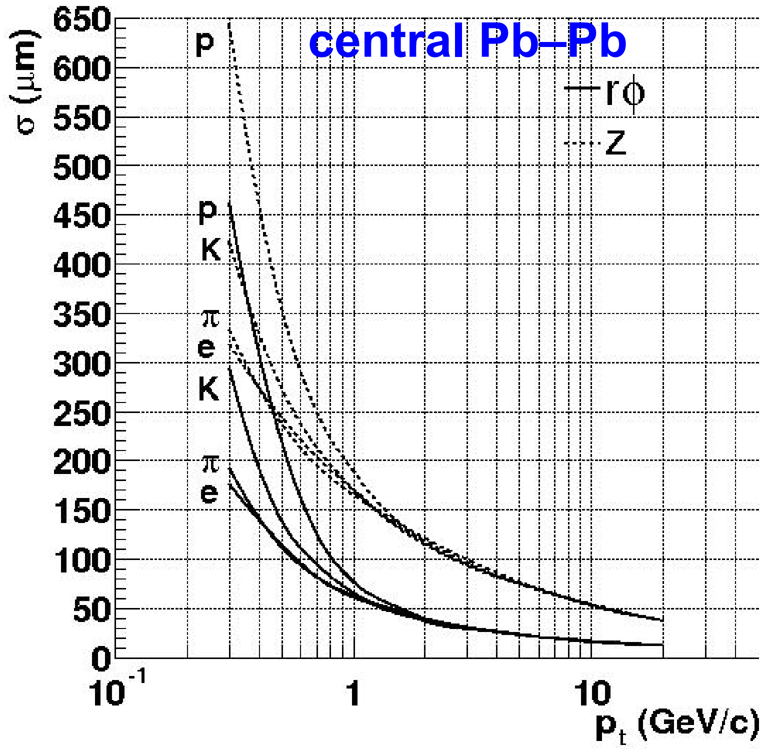
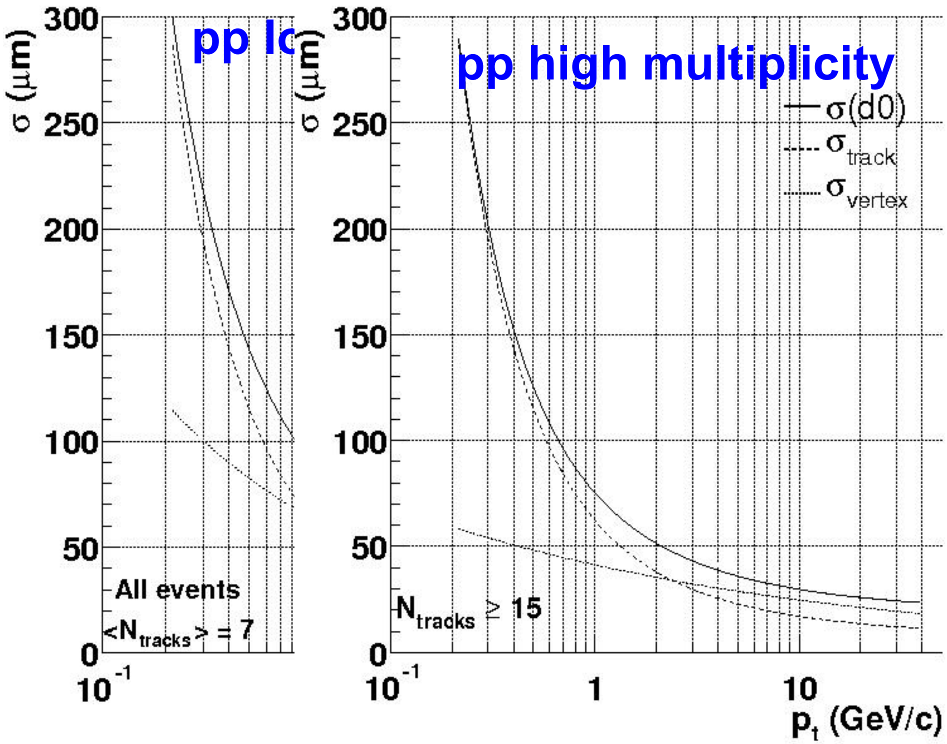
Impact Parameter Determination



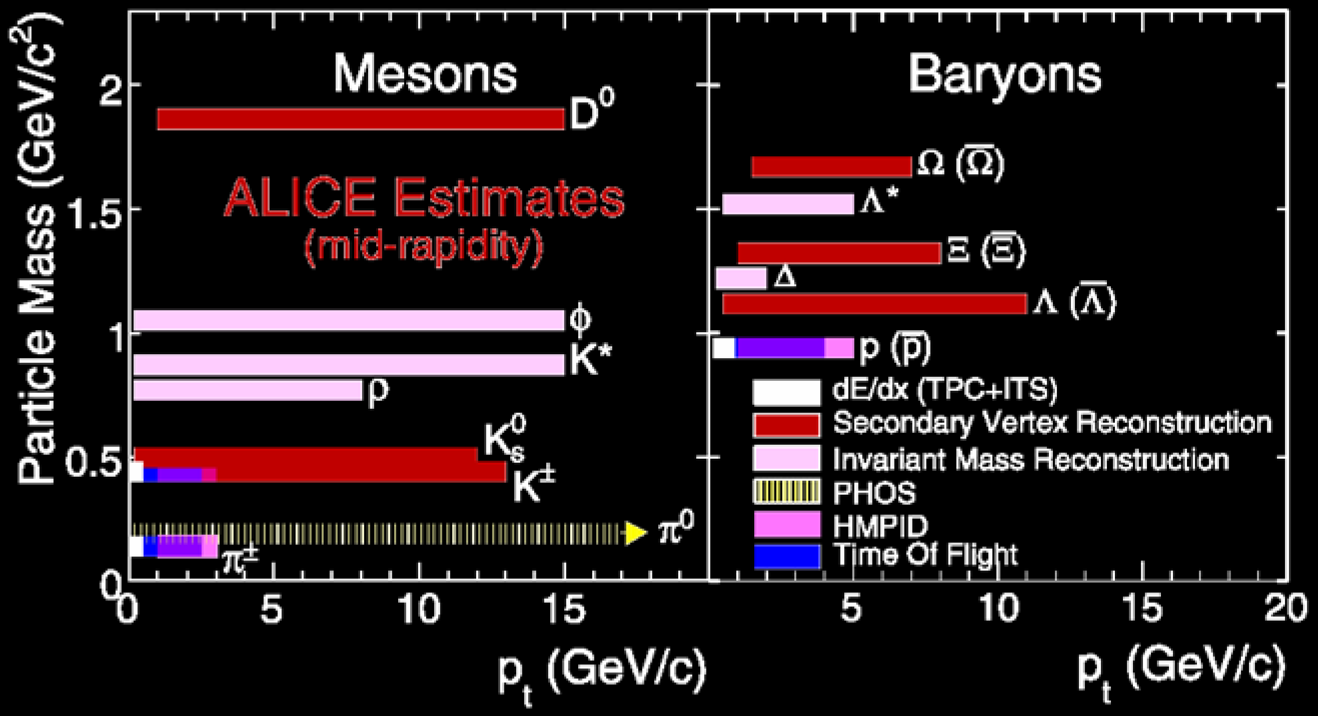


For low-multiplicity events (i.e. pp) the contribution from primary-vertex resolution is not negligible
Full reconstruction with primary tracks has to be used

Impact parameter resolution is crucial for the detection of short-lived particles - charm and beauty mesons and baryons

At least one component has to be better than 100 μm (cτ for D^0 meson is 123 μm)

Particle Identification



stable hadrons (π, K, p): 100 MeV < p < 5 GeV   (few 10 GeV)

dE/dx in silicon (ITS) and gas (TPC) + Time-of-Flight (TOF) + Cerenkov (RICH)

decay topology (K^0, K^+, K^-, Λ)

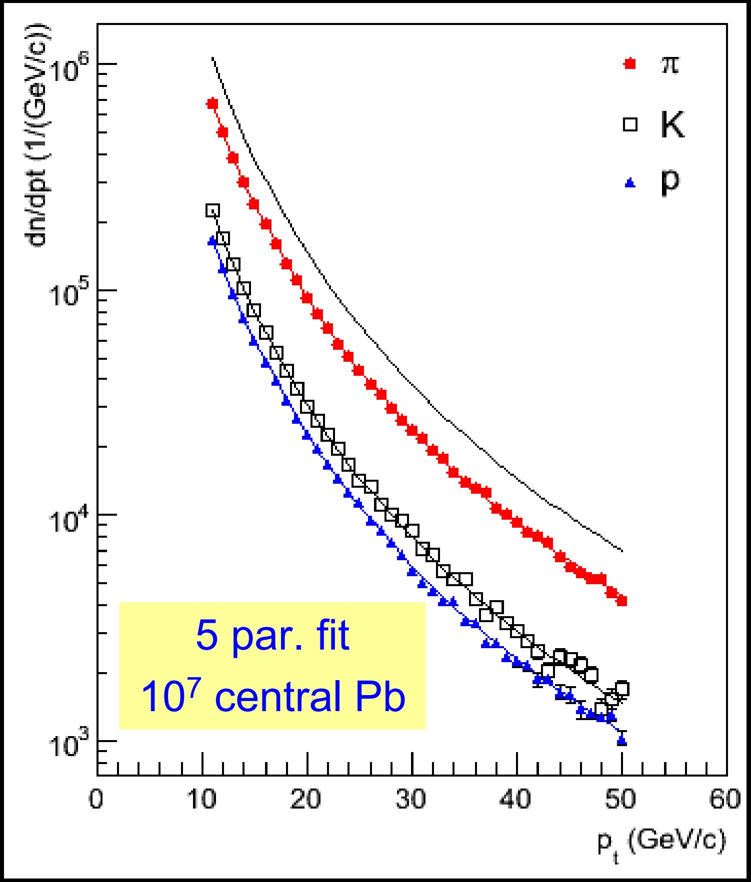
K and Λ decays up to at least 10 GeV

leptons (e, μ), photons, π^0, η

electrons in TRD: p > 1 GeV, muons: p > 5 GeV, π^0 in PHOS: 1 < p < 80 GeV

PID at very high momentum

- TPC dE/dx
  - 5.5% (pp) -> 6.5% (central Pb)
- π, K, p spectra up to ~ 50 GeV/c!!!
  - limited by statistics
  - requires good systematics (calibrate with data)



5 par. fit

10^7 central Pb

Jets at the LHC

- At LHC >90% of the particle production from hard collisions, jet rates are high at energies at which jets can be reconstructed over the large background from the underlying event
- More than 1 jet > 20 GeV per central collision (more than 100 > 2 GeV!)
- Reach to about 200 GeV
- Provides lever arm to measure the energy dependence of the medium induced energy loss

1 month of running	
$E_T >$	N_{jets}
50 GeV	**2.0×10^7**
100 GeV	**1.1×10^6**
150 GeV	**1.6×10^5**
200 GeV	**4.0×10^4**

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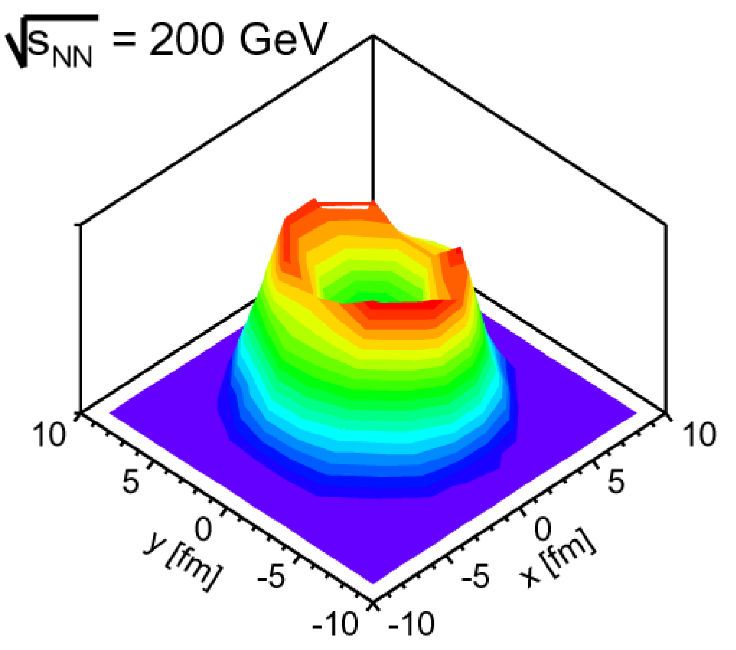
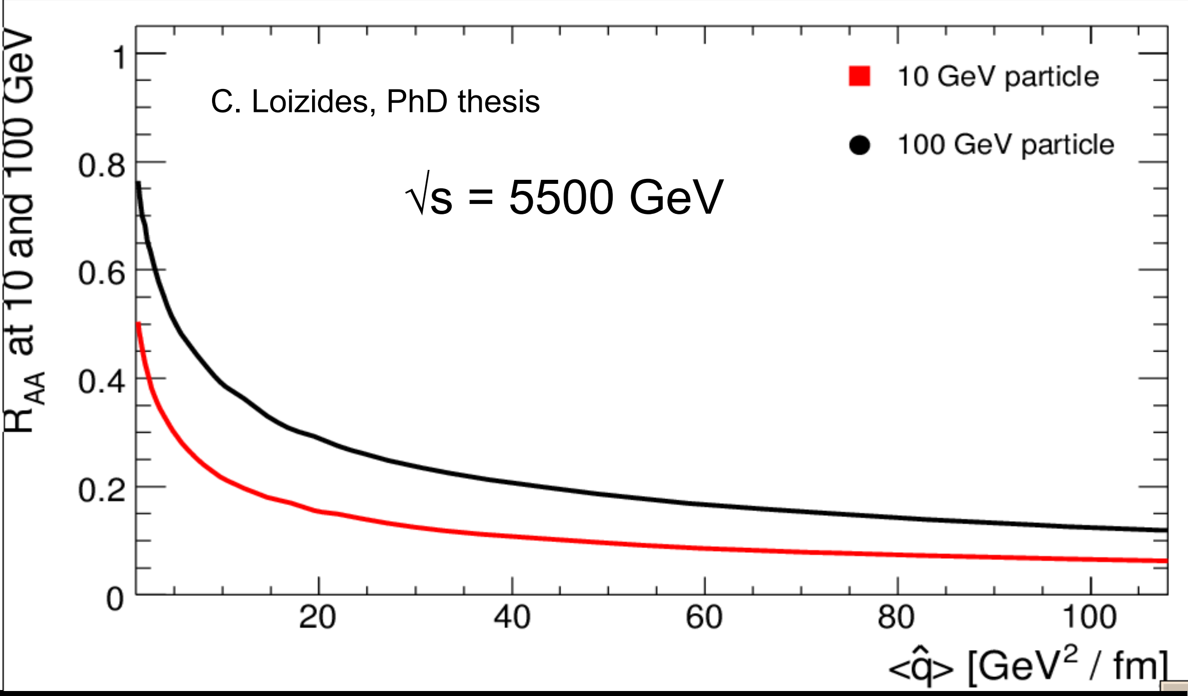
R_{AA} at RHIC and at the LHC



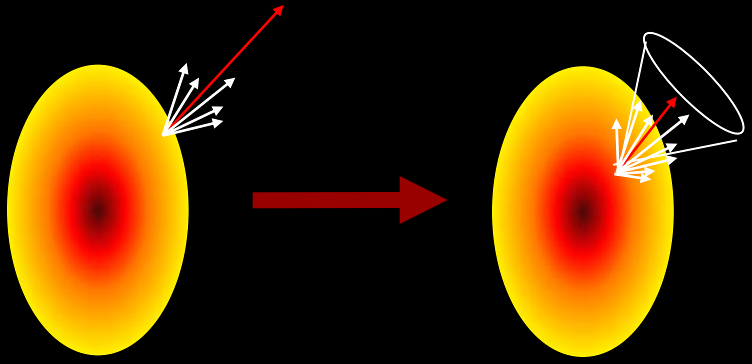


A. Dainese, C. Loizides, G. Paic, Eur. Phys. J. C38(2005) 461

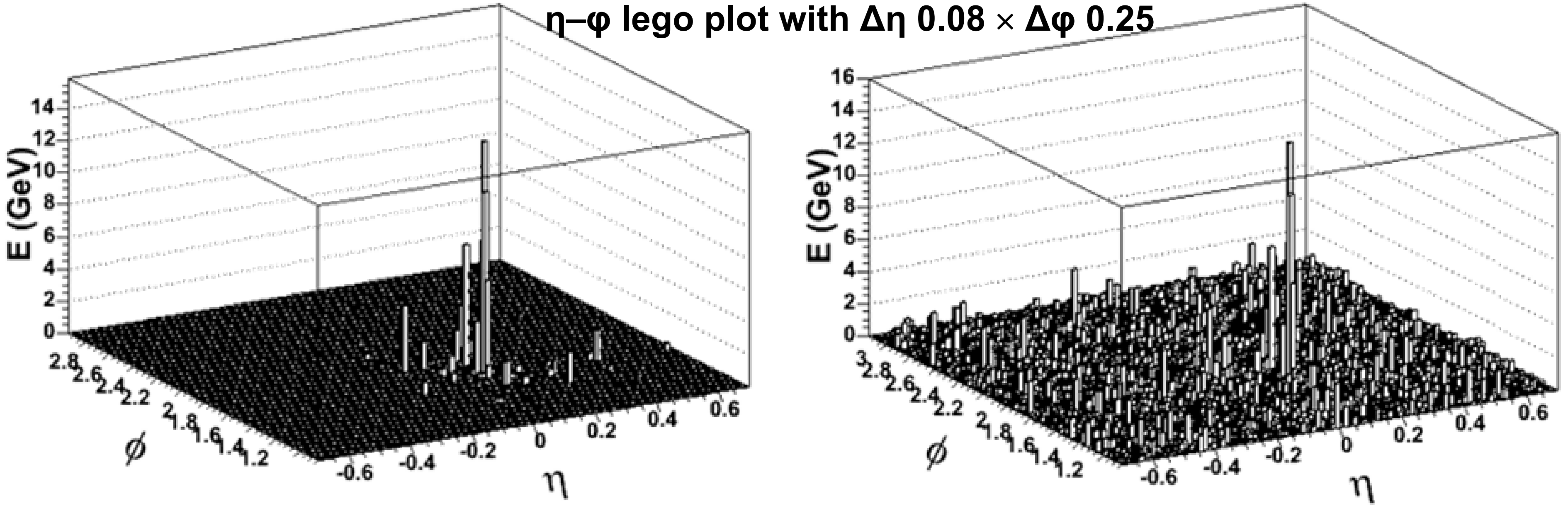
- R_{AA} at RHIC: very strong jet quenching lead to strong surface bias
- R_{AA} at the LHC also rather insensitive to the density of the medium

Less biased jet modifications

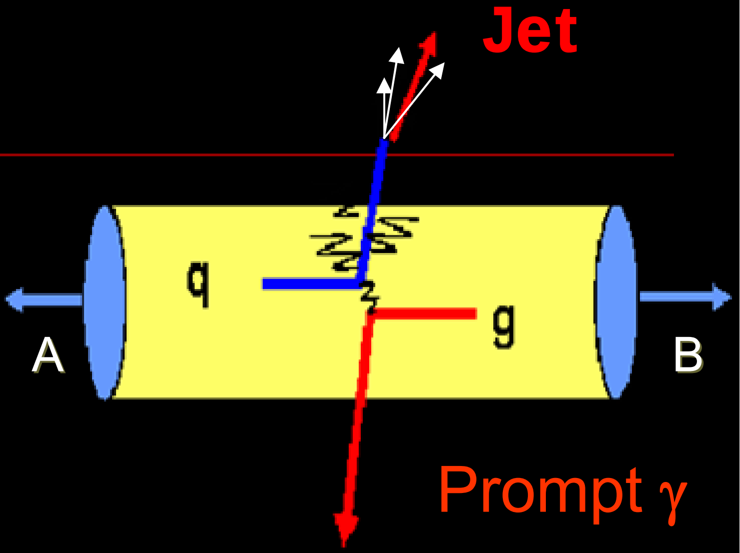
- Fully reconstructed jets
  - modification of the leading hadron
  - additional hadrons from gluon radiation
  - transverse heating



η–φ lego plot with Δη 0.08 × Δφ 0.25



Photon-tagged jets



- Why γ-jet ?
  - Medium effects redistribute ($\propto \hat{q}L$) the parton energy, E_{jet}, inside the hadron jet (multiplicity, k_T).

- Redistribution can be best measured in the Fragmentation Function... If we know E_{jet}.
- HI environment hinders precise reconstruction of E_{jet}.

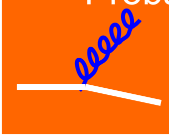
Measure $E_\gamma = E_{jet}$.

penetrading probes: heavy quarks

	SPS PbPb Cent	RHIC AuAu Cent	LHC pp	LHC pPb	**LHC PbPb Cent**
N_{cc}/evt	0.2	10	0.2	1	**115**
N_{bb}/evt	-	0.05	0.007	0.03	**5**

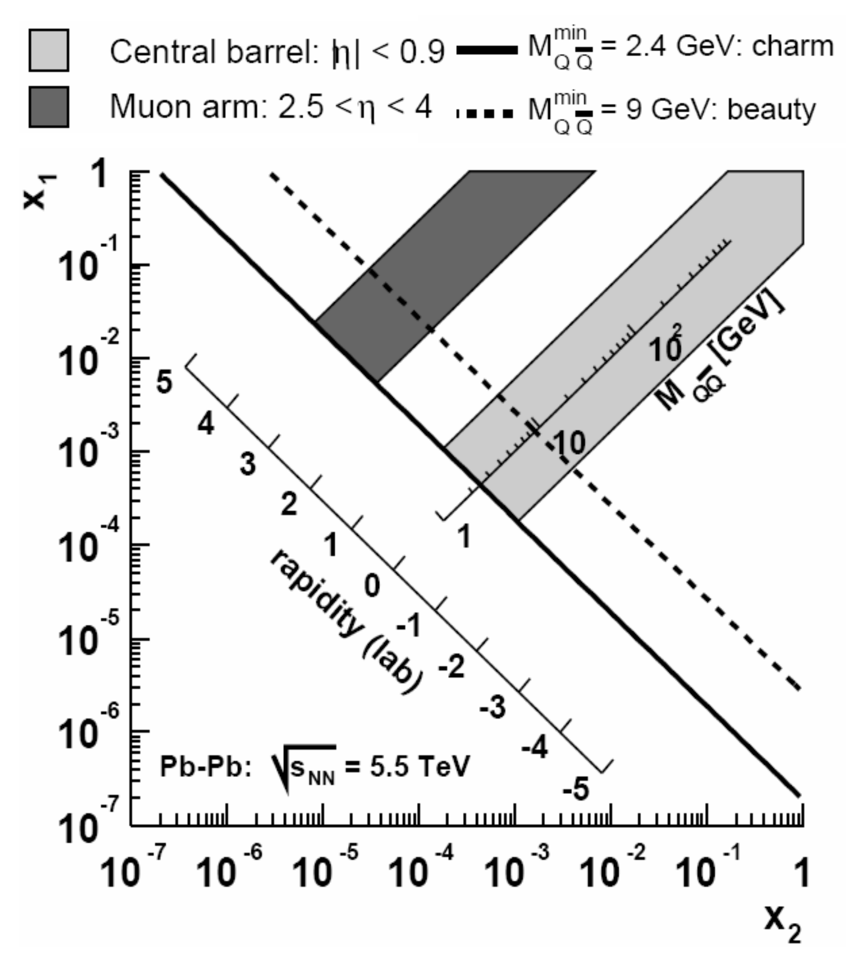
- produced early and calculable: $\tau \propto 1/m_C$
- Relatively long lifetime: $\tau_{decay} \gg \tau_{QGP}$
- detailed test of parton energy loss
  - dead cone effect

Probability:



$$\propto \frac{1}{[\theta^2 + (m_Q / E_Q)^2]^2}$$

  - In medium dead cone implies less energy loss
- probes small x (10^{-3} –10^{-5})



Proton-proton physics with ALICE

- The ALICE detector works even better for pp collisions, because of the low occupancy (10^{-4} to 10^{-3}), even if there is a significant number of events overlapping.

- The first physics with ALICE will be proton-proton collisions, which correspond to a major part of the ALICE programme for several reasons:
  - to provide **“reference” data** to understand heavy ion collisions. In a new energy domain, each signal in HI has to be compared to pp;
  - For **genuine proton-proton physics** whenever ALICE is unique or competitive; note that ALICE can reach rather “high” p_T, up to ~ 100 GeV/c, ensuring overlap with other LHC experiments.
  - The **possibility of taking proton data at several center of mass energies** (**0.9 TeV, 2.4 TeV, perhaps 5.5 TeV, and 14 TeV**), will provide ALICE with the possibility to understand the evolution of many of the properties of pp collisions as a function of the center of mass energy, and also to add to the measurements from previous experiments using proton-antiprotons.

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Summary

- The LHC is the next chapter in heavy ion physics and a step above and beyond existing facilities
- ALICE will be ready for data taking at the first pp run
- The LHC will be the place to do frontline physics after 2007!

The LHC for heavy-ions

Running parameters

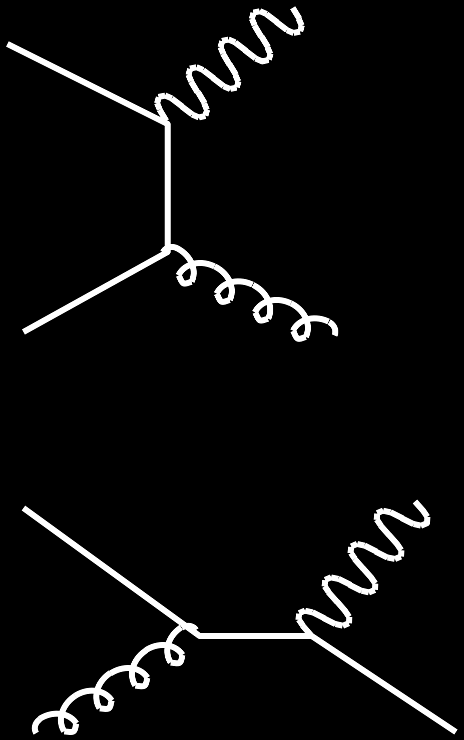
Collision system	$\sqrt{s_{NN}}$(TeV)	$\mathcal{L}_0$ (cm^{-2}s^{-1})	$\langle\mathcal{L}\rangle/\mathcal{L}_0$(%)	Run time (s/year)
pp	14.0	10^{34} *		10^7
PbPb	5.5	10^{27}	50	10^6 **
pPb	8.8	10^{29}		10^6
ArAr	6.3	10^{29}	65	10^6

*$\mathcal{L}_{max}$(ALICE) = 10^{31} ** $\mathcal{L}_{int}$(ALICE) ~ 0.5 nb^{-1}/year

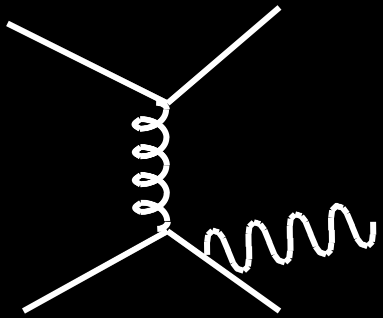
Thermal photons

- A hot QGP will emit photons
- Once emitted, photons leave system
- But any hot system, QGP or hadrons, will emit photons
  - if contained in box, cannot use photon spectrum to distinguish QGP vs. hadrons
  - if T_{photon} >200 MeV unlikely to be from hadrons
  - closer analogy is box with transparent walls
    - photons not in thermal equilibrium
- photons extremely difficult to measure
  - large background of e.g. $\pi^\circ \rightarrow \gamma\gamma$

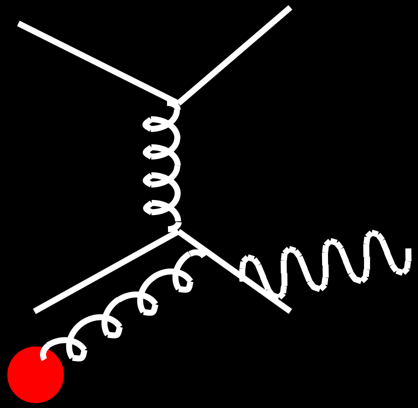
“Direct” photons



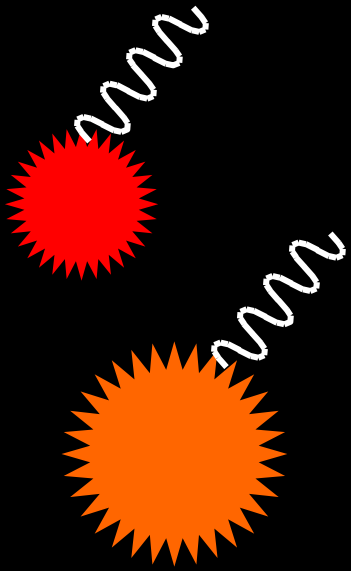
prompt



fragmentation



induced

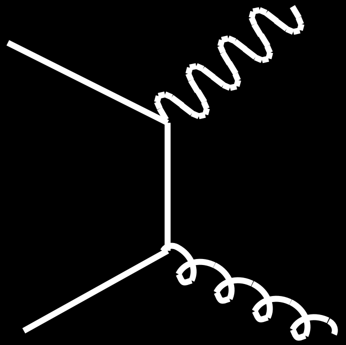


thermal radiation

QGP/Hadron gas

Quark-anti-quark annihilation

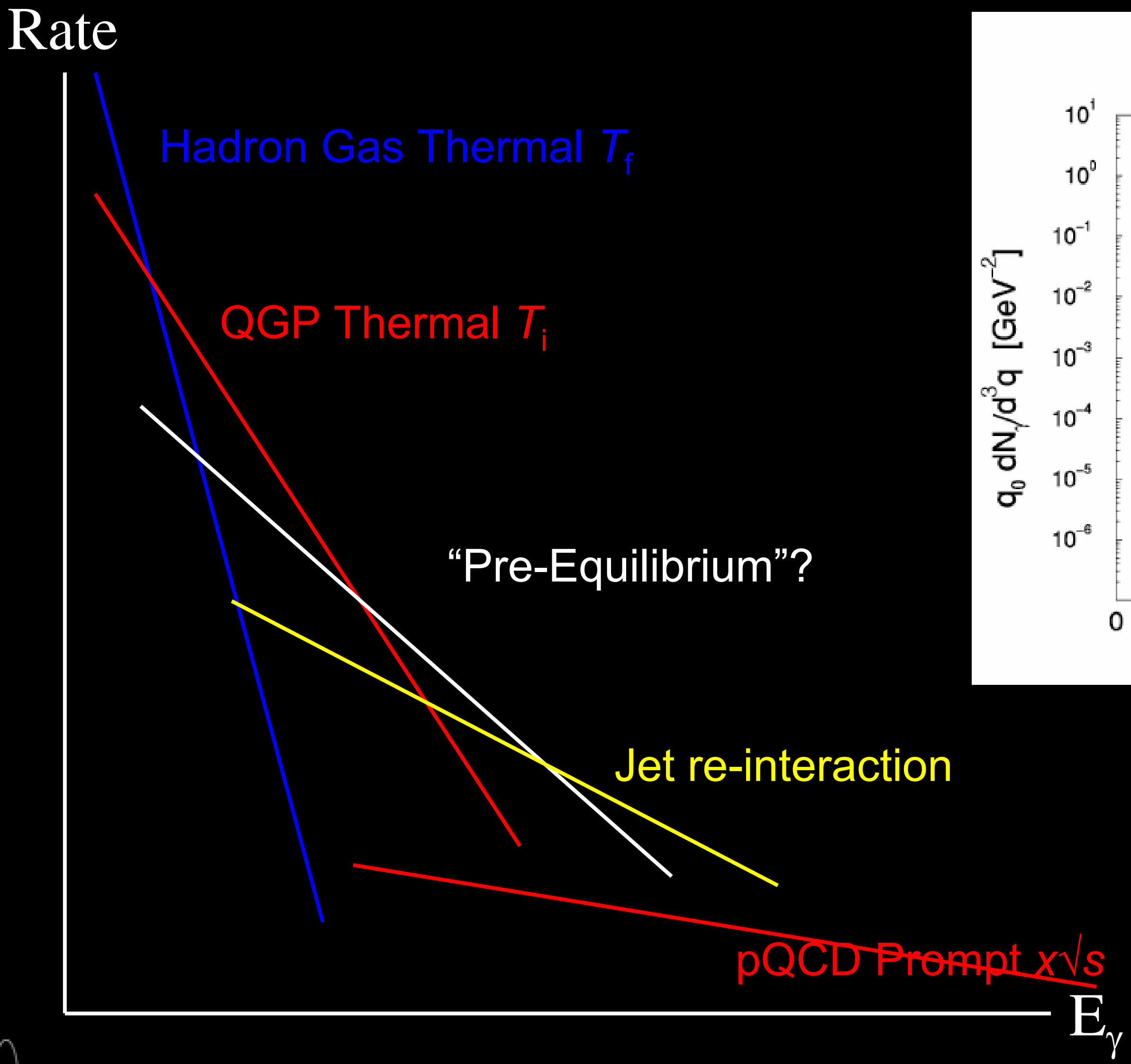
- QGP processes to create direct photons:

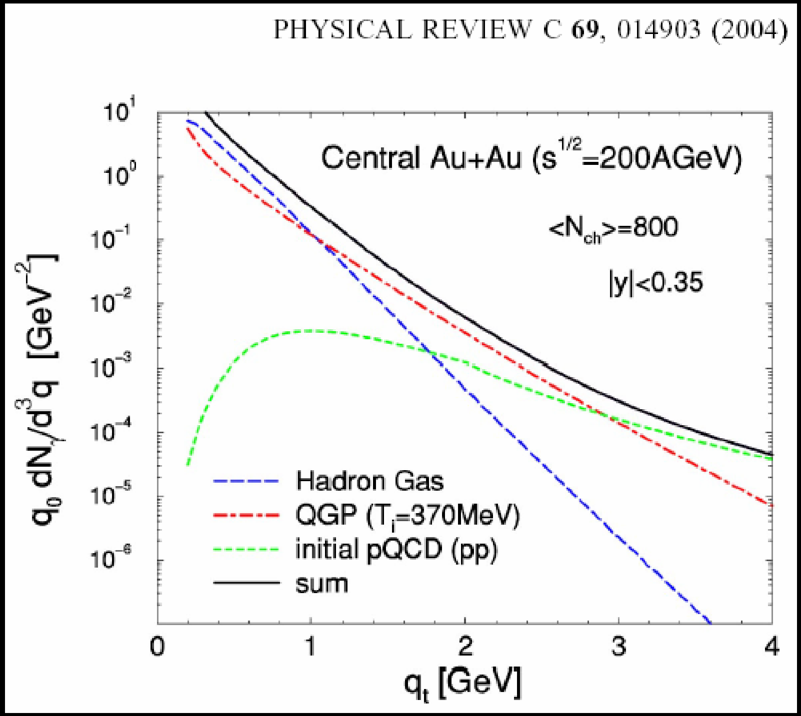


$$E_\gamma \frac{dN}{d^4x d^3p} = \frac{N}{2(2\pi)^3} \int \frac{d^3p_1}{(2\pi)^3 2E_1} \frac{d^3p_2}{(2\pi)^3 2E_2} \frac{d^3p_3}{(2\pi)^3 2E_3} (2\pi)^4 \delta^4(p_1 + p_2 + p_3 - p) \times \left|\overline{M}\right| f_1(E_1) f_2(E_2)[1 \pm f_3(E_3)]$$

- sensitive to distribution of quarks, f(E)
- matrix element - QED and QCD vertex

Direct photons sources and theory

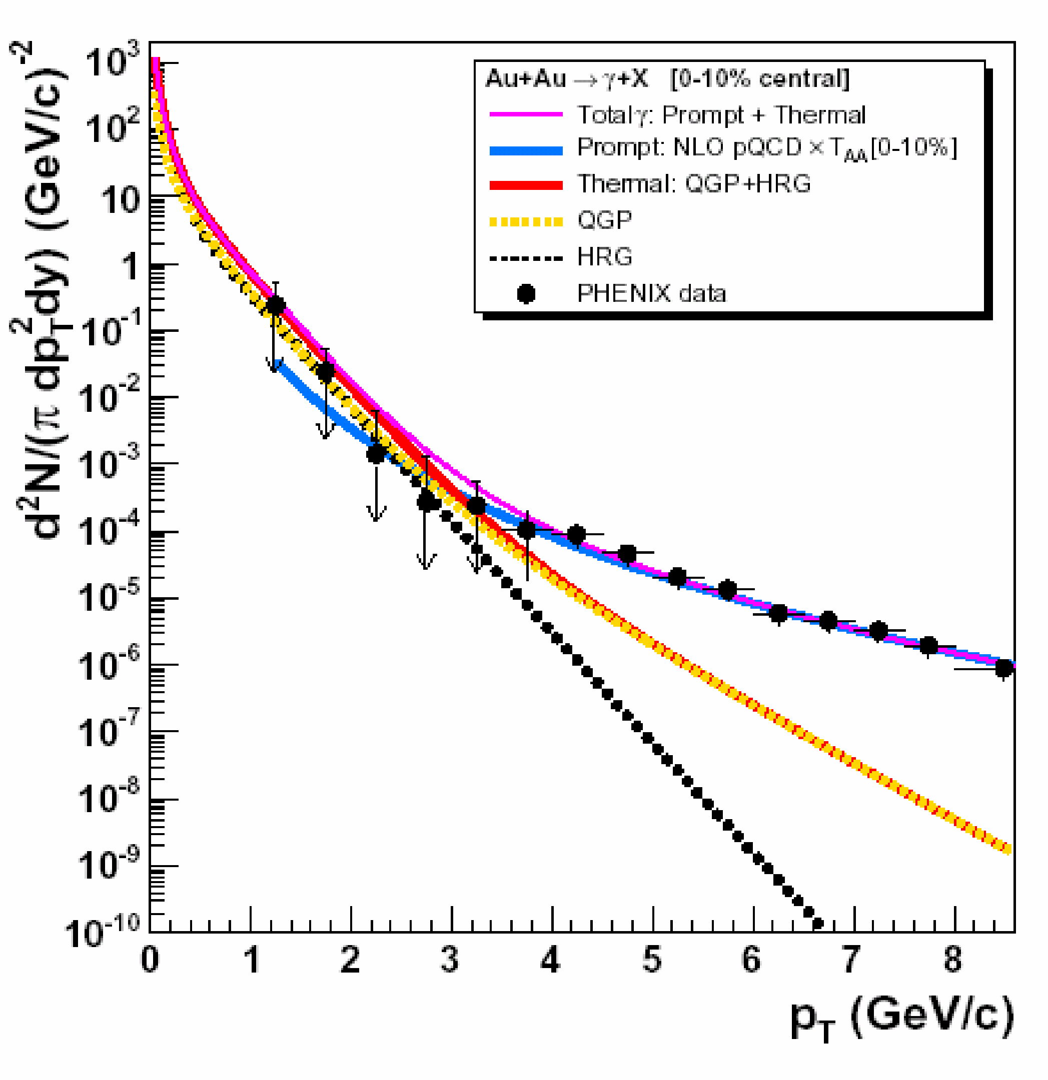




Turbide, Rapp, Gale

Final-state photons are the sum of emissions from the entire history of a nuclear collision.

Direct photons at RHIC



- Hydrodynamical predictions for thermal γ (HRG + QGP) plus prompt NLO pQCD prediction yields.
- Consistent with thermal with QGP with T_0 of 590MeV.
- Measured γ yield is consistent with NLO pQCD prediction with or without thermal contribution (large uncertainties)
- NLO pQCD works too well!? Fragmentation γ contributions are large (~50% at 3 GeV/c, 35% at 10 GeV/c). Why not modified?

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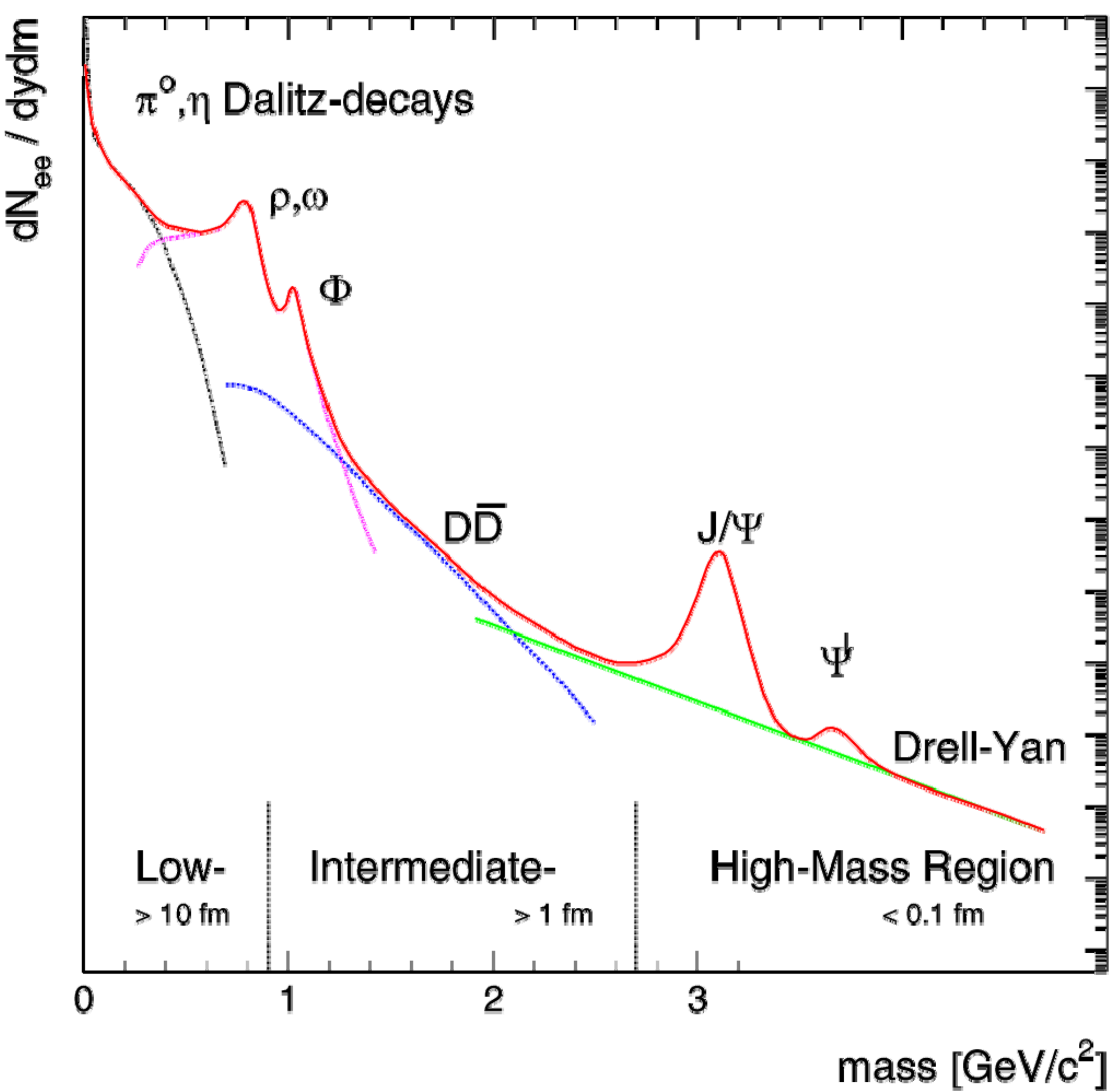
Dilepton yield

- Complicated cocktail!



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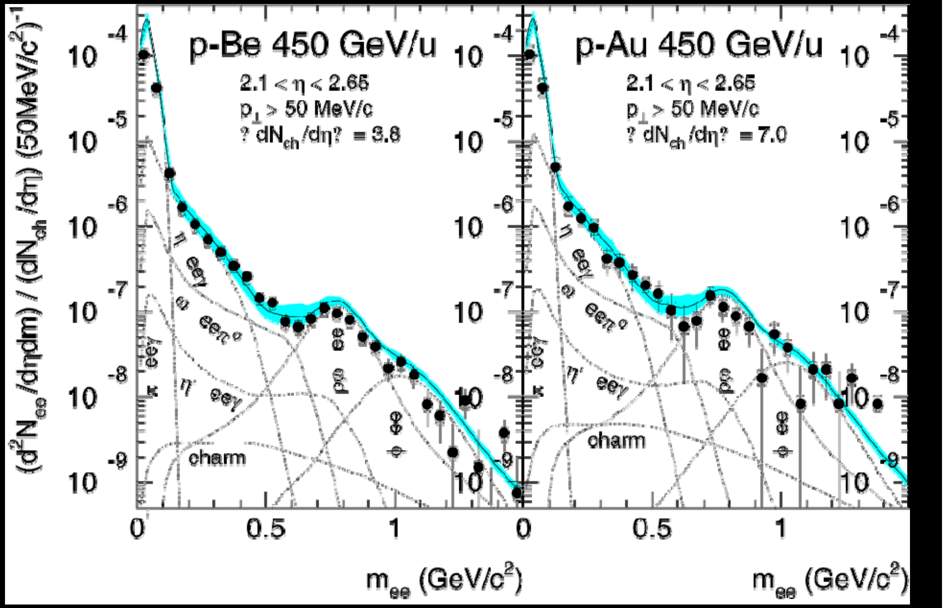
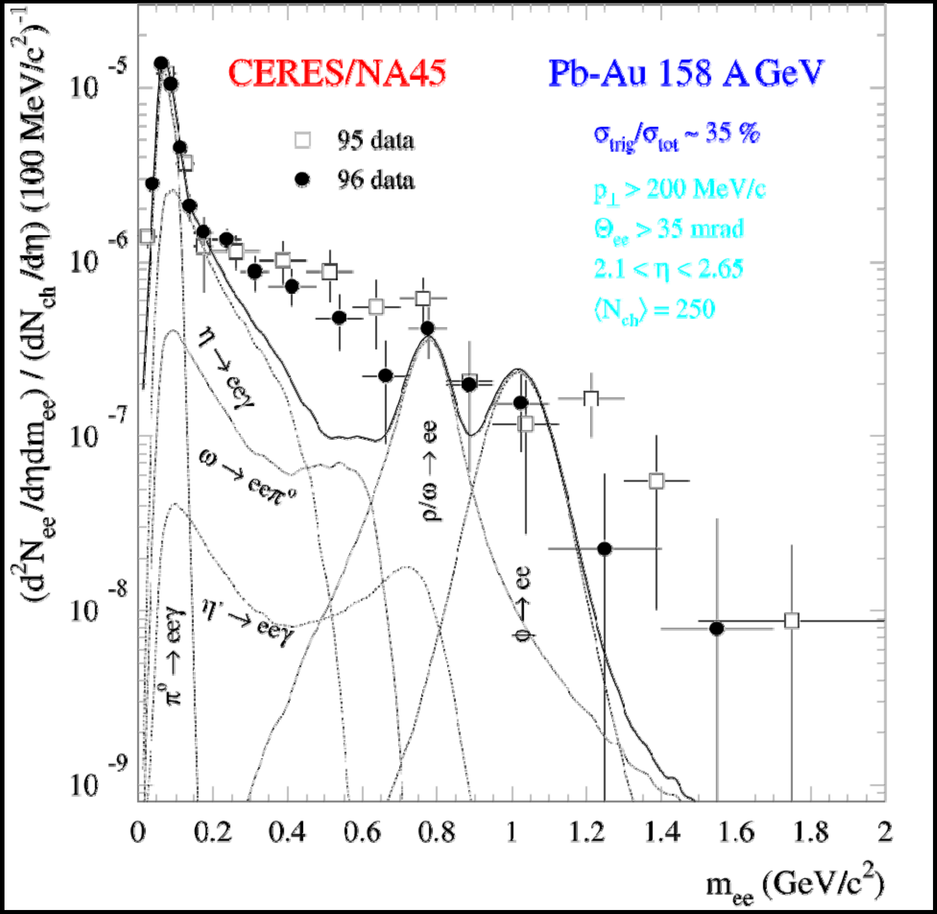
The medium modification of the ρ





- Described by models incorporating mass modification either broadening or shift in mass
- Recent NA60 results show that the ρ is broadened but not shifted in mass

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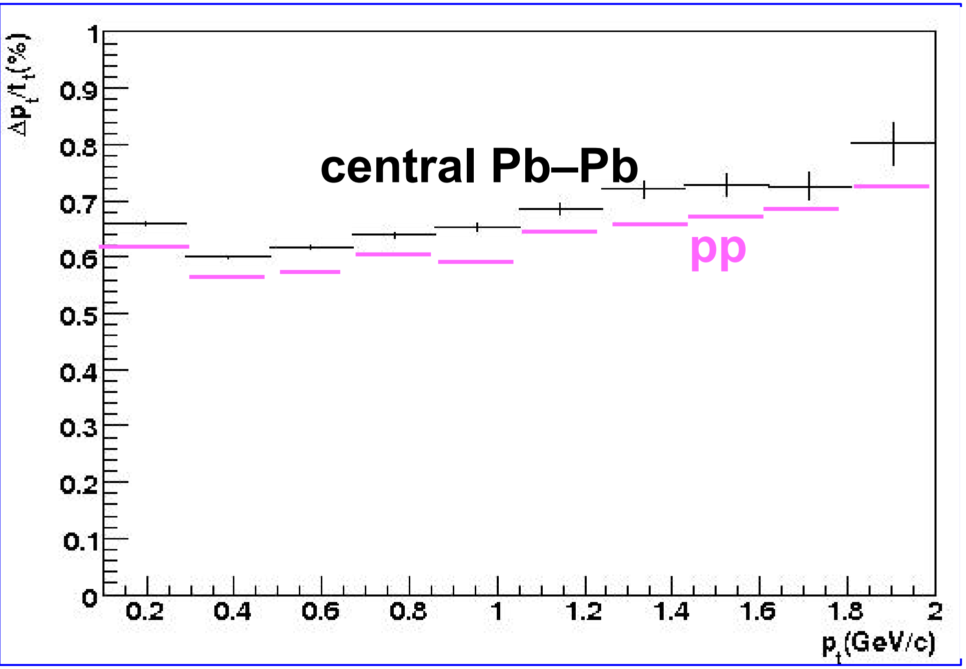
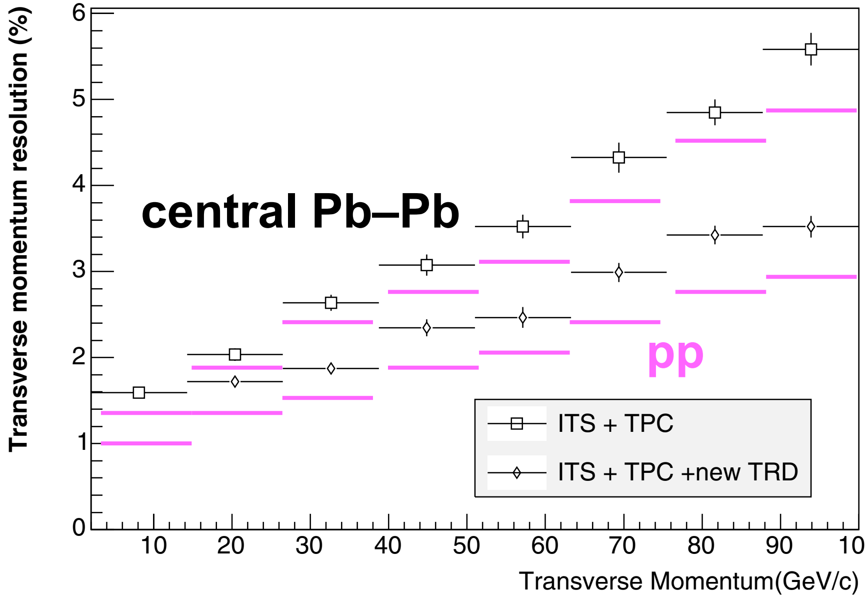
Momentum resolution





at low momentum dominated by

- **ionization-loss fluctuations**
- **multiple scattering**

at high momentum determined by

- **point measurement precision**
- **and the alignment & calibration**

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Reminder: Action

- Classical Lagrangian: $L \quad T \quad V$

$$\tfrac{1}{2}m(v_x^2 \quad v_y^2 \quad v_z^2) \quad V(x,y,z)$$

- Derivatives:

$$\frac{L}{x} \quad \frac{V}{x} \quad F_x \qquad \frac{L}{v_x} \quad mv_x \quad p_x$$

- Hamilton principle:

$$S \quad \frac{L}{x} \quad \frac{d}{dt} \quad \frac{L}{v_x} \quad 0 \qquad F_x \quad \frac{dp_x}{dt} \quad m$$

Euler-Lagrange equation

- Action:

$$S \quad {}_{t_1}^{t_2} \, dtL(q,\dot{q},t)$$

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Reminder: Fields in action

- Variation of action:

$$S \qquad {}_{t_1}^{t_2} dtL(q,\dot{q},t)$$

$$S \qquad \frac{L}{q} \quad \frac{d}{dt} \quad \frac{L}{\dot{q}} \qquad 0$$

- Replace coordinates by fields (require that the fields and their derivatives vanish at infinity)

$$q \qquad x,t$$

$$\dot{q} \qquad x,t \qquad \frac{x,t}{x}$$

- Lagrangian density and action

$$L \qquad d^3x\,\mathrm{L} \qquad x,t\ , \qquad x,t\ ,t$$

$$S \qquad {}_{t_1}^{t_2} dtL \qquad d^4x\,\mathrm{L} \qquad x,t\ , \qquad x,t\ ,t$$

- After some algebra, the equation of motion

$$\frac{\mathrm{L}}{} \qquad \frac{\mathrm{L}}{} \qquad 0$$

Reminder: The QCD Lagrangian

(*j*,*k* = 1,2,3 color; *q* = u,d,s flavor; *a* = 1,..,8 gluon fields)

$$\mathsf{L}_{qcd} \quad i \underset{q}{} \quad \bar{}^{\,j}_{q} \quad (\mathrm{D}\ )_{jk} \quad {}^{k}_{q} \qquad \underset{q}{} \quad m_q \quad \bar{}^{\,j}_{q} \quad {}^{k}_{q} \qquad \tfrac{1}{4} G^{a}\ G_{a}$$

Gauge inv. derivative:

$$\mathrm{D} \qquad i\tfrac{1}{2} g_s \ {}_{a} G^{a}$$

Free quarks

$$G^{a}_{\mu\nu} \qquad \underbrace{G^{a} \qquad G^{a}}_{\text{Gluon kinetic energy term}} \qquad \underbrace{g_s f_{abc} G^{a} G^{a}}_{\text{Gluon self-interaction}}$$

qg-interactions SU(3) generators:

$$_1\begin{matrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{matrix} \qquad _2\begin{matrix} 0 & i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{matrix} \qquad _3\begin{matrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{matrix} \qquad _4\begin{matrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{matrix}$$

$$_5\begin{matrix} 0 & 0 & i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{matrix} \qquad _6\begin{matrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{matrix} \qquad _7\begin{matrix} 0 & 0 & 0 \\ 0 & 0 & i \\ 0 & i & 0 \end{matrix} \qquad _8\ \frac{1}{\sqrt{3}}\begin{matrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 2 \end{matrix}$$

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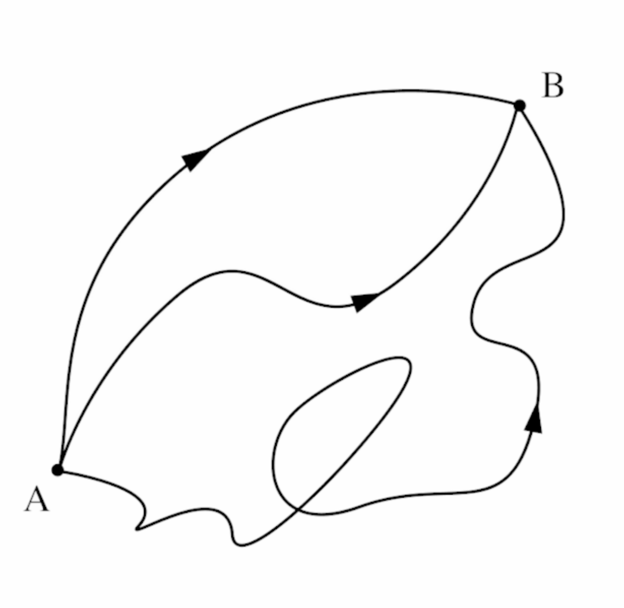
Quantum mechanics and path integrals

$$\text{Amplitude}[(\mathrm{x}_{\mathrm{a}},\mathrm{t}_{\mathrm{a}}) \qquad (\mathrm{x}_{\mathrm{b}},\mathrm{t}_{\mathrm{b}})] \qquad \left\langle x_b \middle| e^{\;iH(t_b \;\; t_a)} \middle| x_a \right\rangle$$

- Quantum mechanical law of motion
  (Developed by Feynman)
- Probability amplitude sum over all histories

$$Z(b,a) \qquad\qquad e^{\frac{iS}{\hbar}}$$

all paths



- All paths contribute with equal amplitude only with different phases
- Similar histories provide interference
- Classical limit: stationary action δS=0

Partition function

$$1)\ \mathrm{Amplitude}[(x_a,t_a) \qquad (x_b,t_b)] \qquad \left\langle x_b \middle| e^{\;iH(t_b \quad t_a)} \middle| x_a \right\rangle$$

$$2)\ \mathrm{Amplitude}[(x_a,t_a) \qquad (x_b,t_b)] \qquad \underset{\text{all paths}}{} \quad e^{\;\frac{iS_M}{\hbar}}$$

- 2 Can be calculated on a discrete lattice
- Similarities with partition function

$$Z \qquad \underset{x_a}{} \left\langle x_a \middle| e^{\quad H} \middle| x_a \right\rangle \;, \qquad 1/kT$$

- take t_b = -iβ and t_a=0; perform path integral as loop x_a -> x_a

QCD Thermodynamics

- Thermodynamic properties can be obtained from the partition function using the QCD Lagrangian

$$Z\ \ V,T,\ \ _f \qquad DA\ D\,\bar{}\,D\ \ e^{S_E}$$

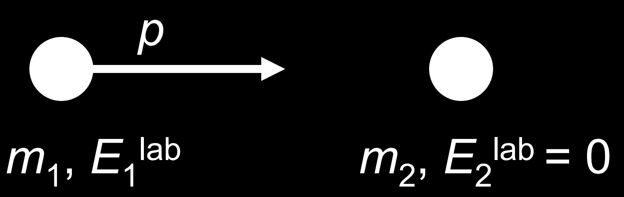
- On a lattice V = $(N_s a)^3$ and T = 1/ $N_t a$ where a is the lattice spacing and N_s , N_t the spacing in space and time of the lattice

$$\frac{p}{T^4} \quad \frac{1}{VT^3}\ln\ Z\ \ T,V,\ \ _f$$

$$\frac{\quad 3p}{T^4} \quad T\frac{\mathrm{d}}{\mathrm{d}T}\ \frac{p}{T^4} \qquad \text{at fixed} \quad /\mathrm{T}$$

Fixed target versus collider-experiments

fixed target



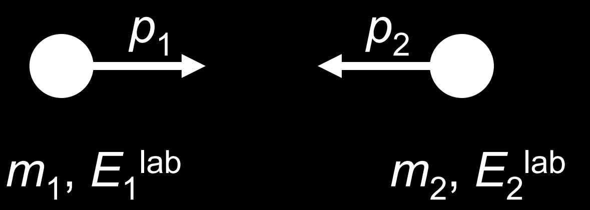
p

m_1, E_1^{lab}

$m_2, E_2^{\text{lab}} = 0$

$$\sqrt{s} = \sqrt{m_1^2 + m_2^2 + 2E_1^{\text{lab}} m_2}$$

collider



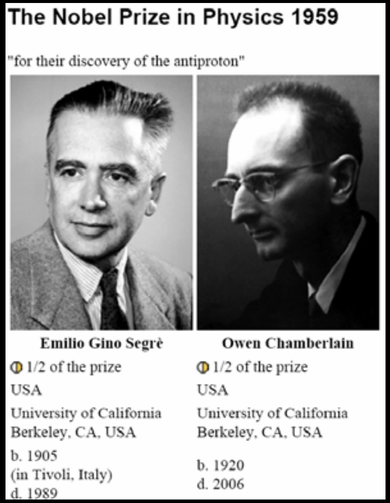
p_1

p_2

m_1, E_1^{lab}

m_2, E_2^{lab}

$$\sqrt{s} = \sqrt{m_1^2 + m_2^2 + 2E_1^{\text{lab}} E_2^{\text{lab}} + 2p_1^{\text{lab}} p_2^{\text{lab}}}$$



The Nobel Prize in Physics 1959

"for their discovery of the antiproton"

Emilio Gino Segrè	**Owen Chamberlain**
◑ 1/2 of the prize	◑ 1/2 of the prize
USA	USA
University of California Berkeley, CA, USA	University of California Berkeley, CA, USA
b. 1905 (in Tivoli, Italy) d. 1989	b. 1920 d. 2006

The Berkeley Bevatron

$$p + p \rightarrow p + p + p + \bar{p}$$

$$E_1^{\text{lab}} = \frac{(4m_p)^2 - 2m_p^2}{2m_p} = 7m_p$$

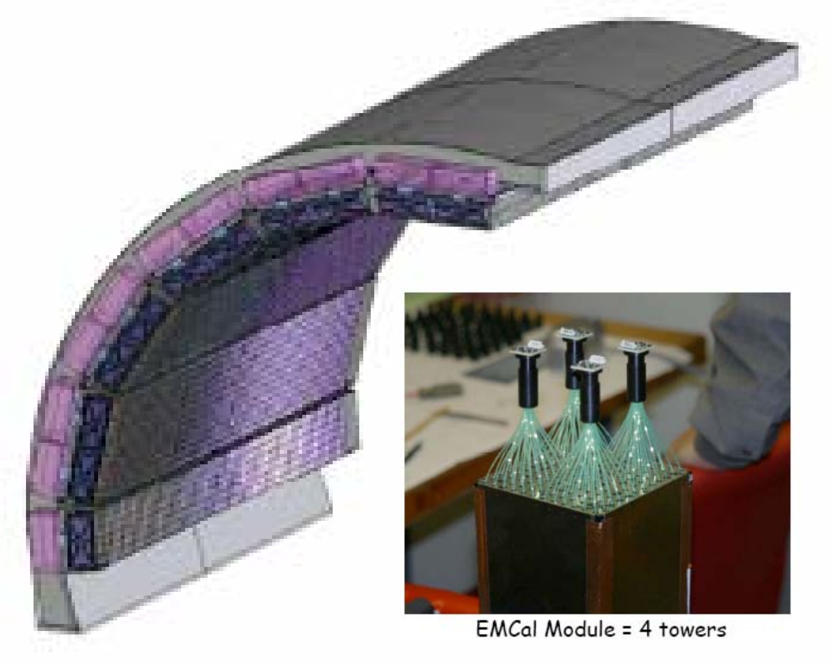
EMCAL

Lead-scintillator sampling calorimeter
Shashlik fiber geometry
Avalanche photodiode readout

Coverage: $|\eta|<0.7$, $\Delta\phi=110°$
~13k towers ($\Delta\eta \times \Delta\phi \sim 0.014 \times 0.014$)
Depth ~21 X_0
Design resolution: $\sigma_E/E \sim 1\% + 8\%/\sqrt{E}$

- Upgrade to ALICE
- ~17 US and European institutions

Current expectations:
- 2009 run: partial installation
- 2010 run: fully installed/commissioned


EMCal Module = 4 towers

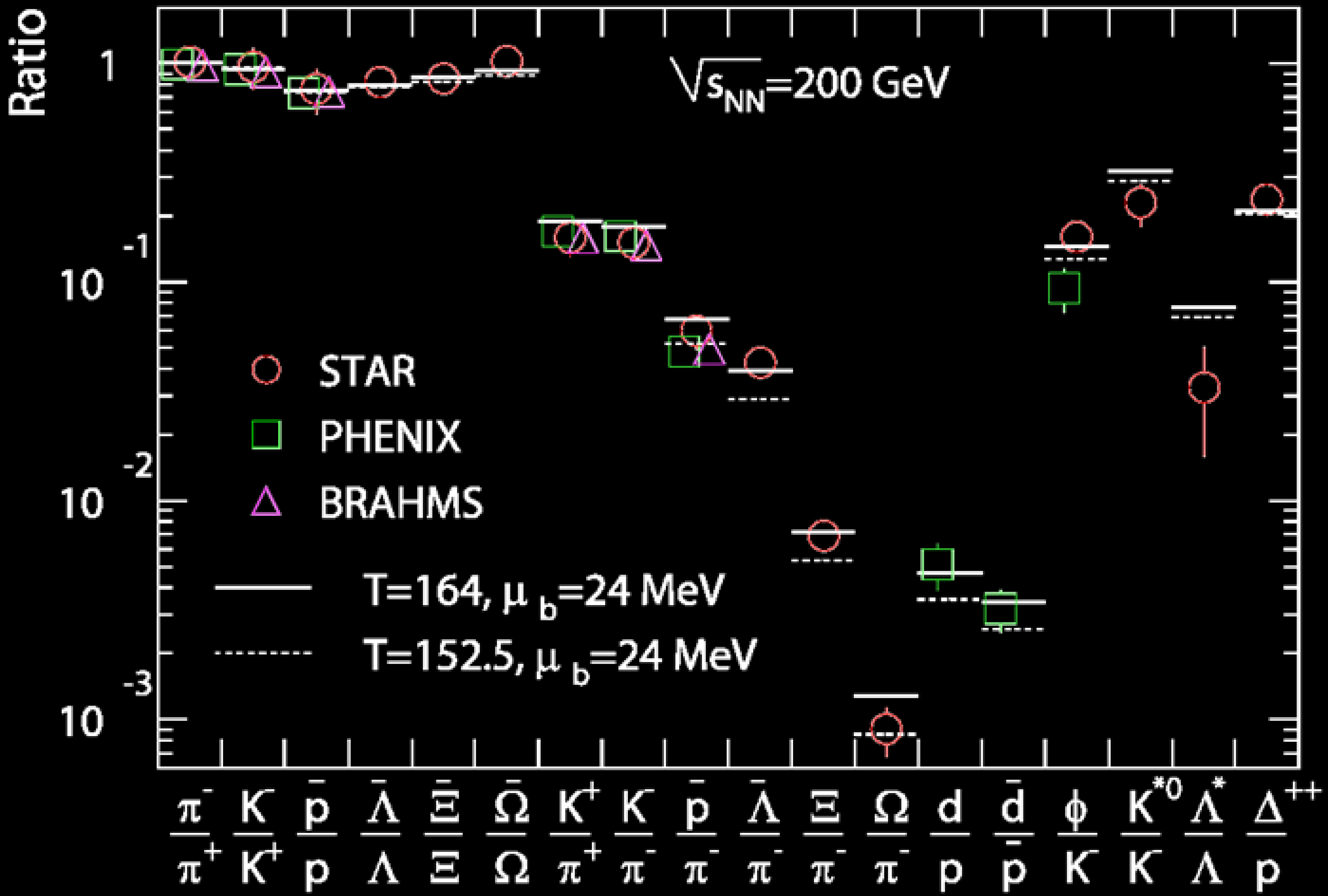
Observed particle abundances and T_{ch}

- Assume chemically equilibrated system at freeze-out (constant T_{ch} and μ)
- Composed of non-interacting hadrons and resonances
- Given T_{ch} and μ 's, particle abundances (n_i's) can be calculated in a grand canonical ensemble

$$n_i = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2\,dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}, \quad E_i = \sqrt{p^2 + m_i^2}$$

- Obey conservation laws: Baryon Number, Strangeness, Isospin
- Short-lived particles and resonances need to be taken into account

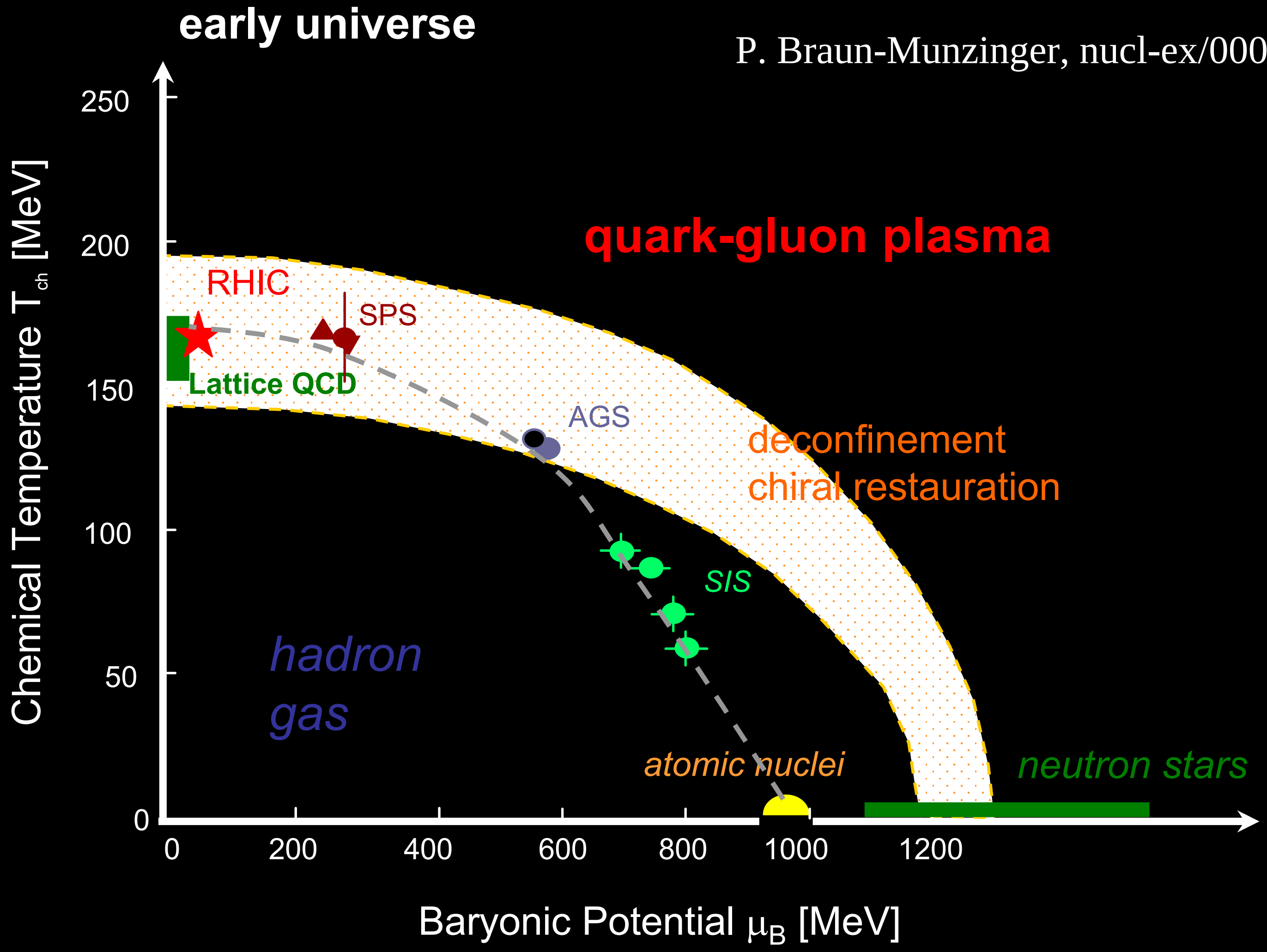
Integrated identified particle yields



- Thermal model fits rather well
- Works rather well in $e^+ e^-$ and proton-proton collisions as well, except for strange particles

The phase diagram revisited

P. Braun-Munzinger, nucl-ex/0007021



$v_2(p_t)$ and particle mass: some details

- On what freeze-out variables does it depend (simplification)?
  - The velocity difference in and out of plane (due to difference in pressure gradient)
  - But also
    - The freeze-out temperature
    - The transverse flow at freeze-out
    - The spatial eccentricity at freeze-out

Hydro Motivated Fit (blast-wave)

$$v_2(p_t) = \frac{\int_0^{2\pi} d\phi_b \cos(2\phi_b) I_2(\alpha_t) K_1(\beta_t)(1+2s_2\cos(2\phi_b))}{\int_0^{2\pi} d\phi_b I_0(\alpha_t) K_1(\beta_t)(1+2s_2\cos(2\phi_b))}$$

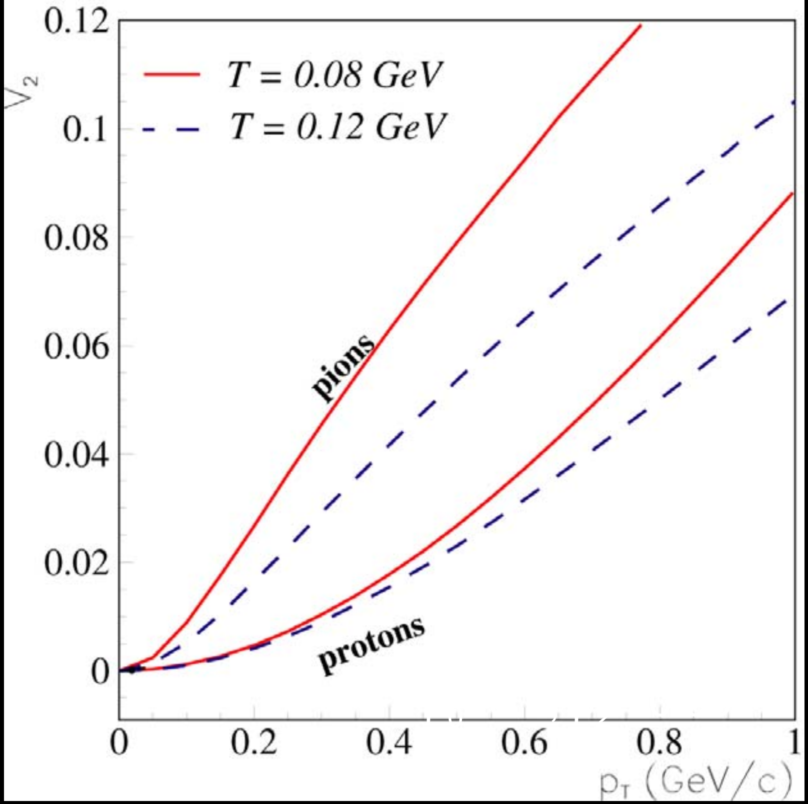
$$\alpha_t(\phi_b) = (\frac{p_t}{T_f})\sinh(\rho(\phi_b)) \qquad \beta_t(\phi_b) = (\frac{m_t}{T_f})\cosh(\rho(\phi_b))$$

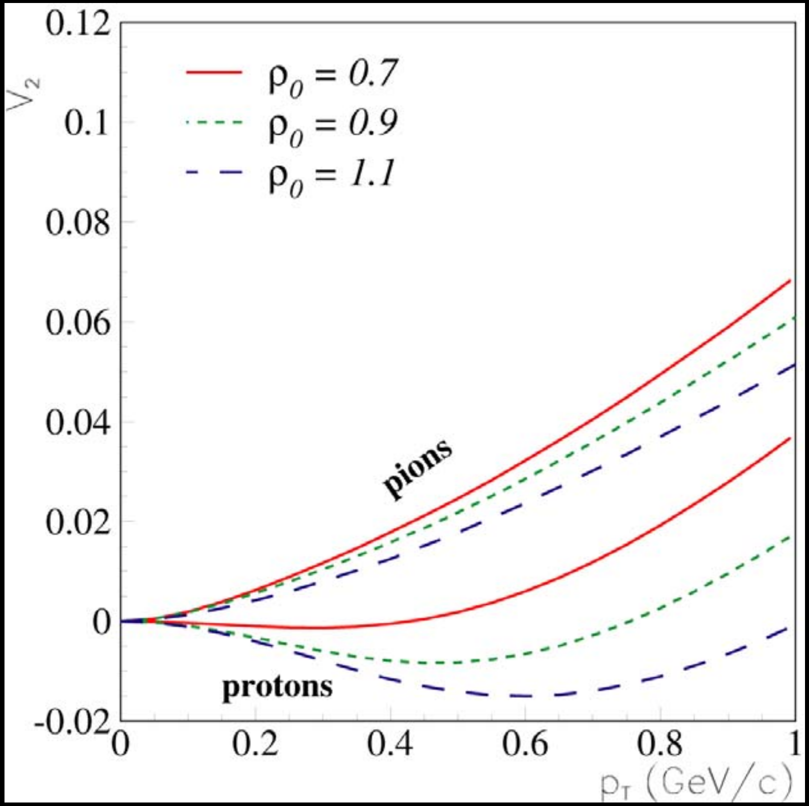
$$\rho(\phi_b) = \rho_0 + \rho_a \cos(2\phi_b)$$

More recent and extended approach in: F. Retiere and M.A. Lisa Phys.Rev.C70:044907,2004

STAR Phys. Rev. Lett. 87, 182301 (2001)

The effect of freeze-out temperature and radial flow on v_2

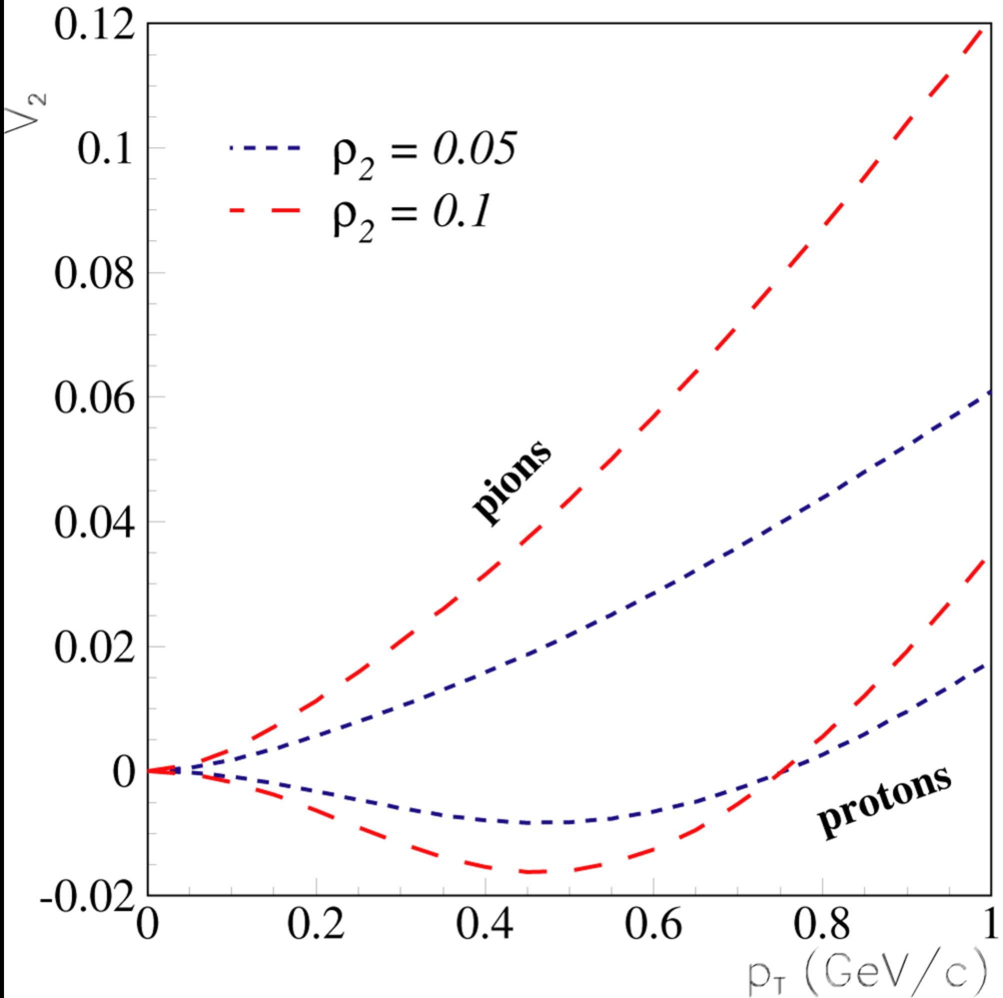




- **Light particle $v_2(p_t)$ very sensitive to temperature**
- **Heavier particles $v_2(p_t)$ more sensitive to transverse flow**

F. Retiere and M.A. Lisa, Phys.Rev.C70:044907,2004

The effect of the azimuthal asymmetric flow velocity and shape



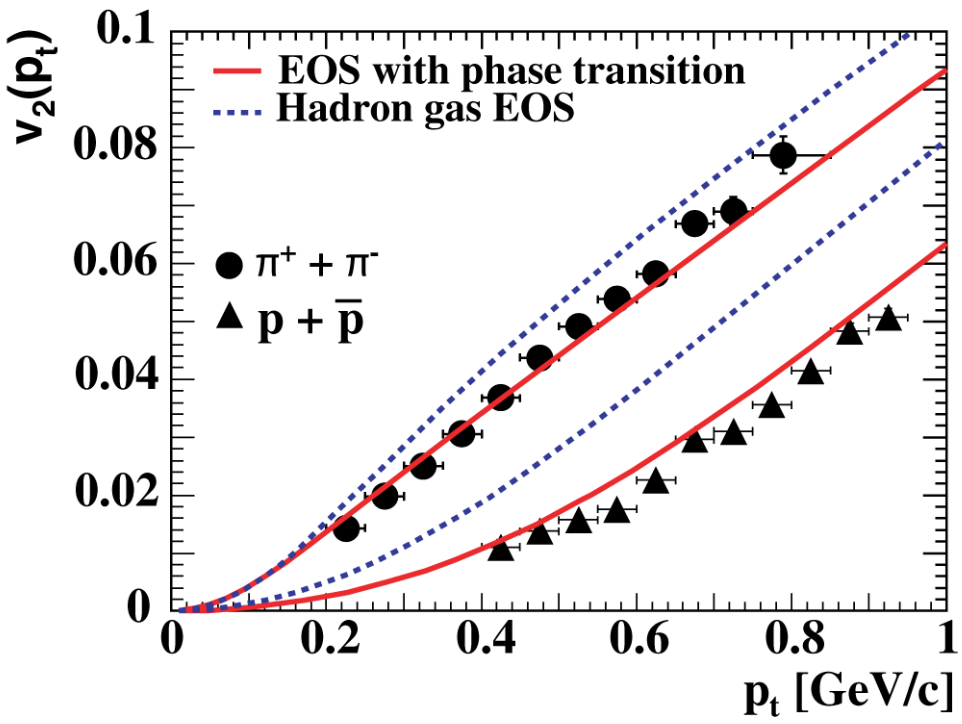
- Larger value of the difference in collective velocity in and out of the reaction plane leads to larger slope of $v_2(p_t)$ above ~ $\langle p_t \rangle$ of the particle

F. Retiere and M.A. Lisa, Phys.Rev.C70:044907,2004

Mass dependence

Hydro calculation: P. Huovinen *et. al.*

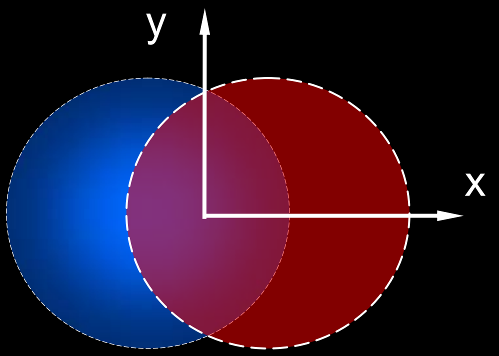
- Identified particle elliptic flow at low p_t
- Mass dependence in accordance with collective flow. QGP equation of state (soft EoS, in this calculation due to phase transition) provides best description



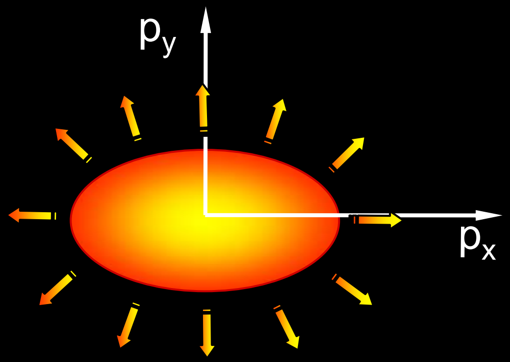
$$v_2 \quad \langle \cos 2(\quad _i \quad \quad _r) \rangle , \quad _i \quad \tan^{\ 1}\left(\frac{p_y}{p_x}\right)$$

elliptic flow an unique probe!

coordinate space



Momentum space



- Non central collisions coordinate space configuration anisotropic (almond shape). However, initial momentum distribution isotropic (spherically symmetric).
- Only interactions among constituents (mean free path small) generate a pressure gradient which transforms the initial coordinate space anisotropy into the observed momentum space anisotropy
- Multiple interactions lead to thermalization -> limiting behavior hydrodynamic flow

$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3\mathrm{p}} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_t\mathrm{d}p_t\mathrm{d}y}\left(1+2\sum_{n=1}^{\infty} v_n(p_t,y)\cos\left(n(\phi-\Psi_r)\right)\right)$$

$$\boxed{v_2 = \left\langle \cos 2(\varphi-\Psi_r)\right\rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)}$$

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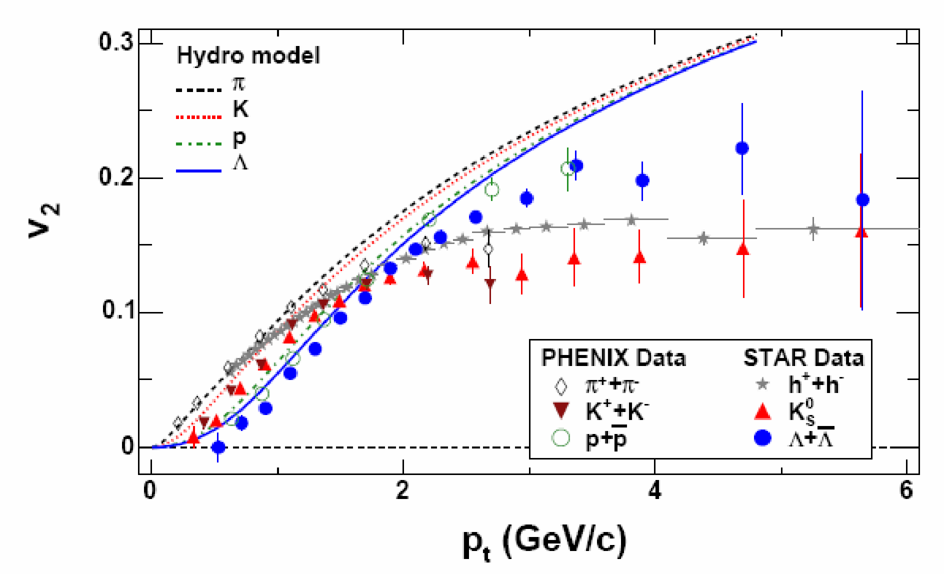
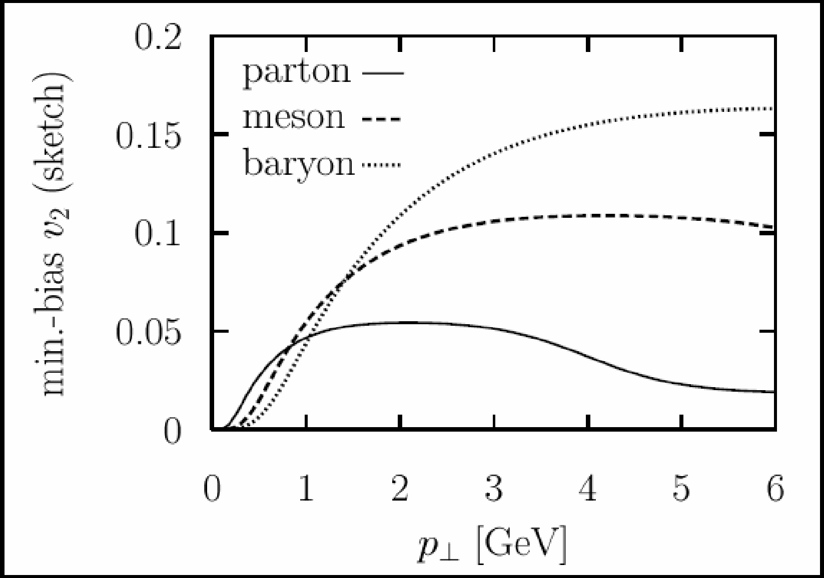
Identified particle elliptic flow at higher p_t one of the surprises at RHIC



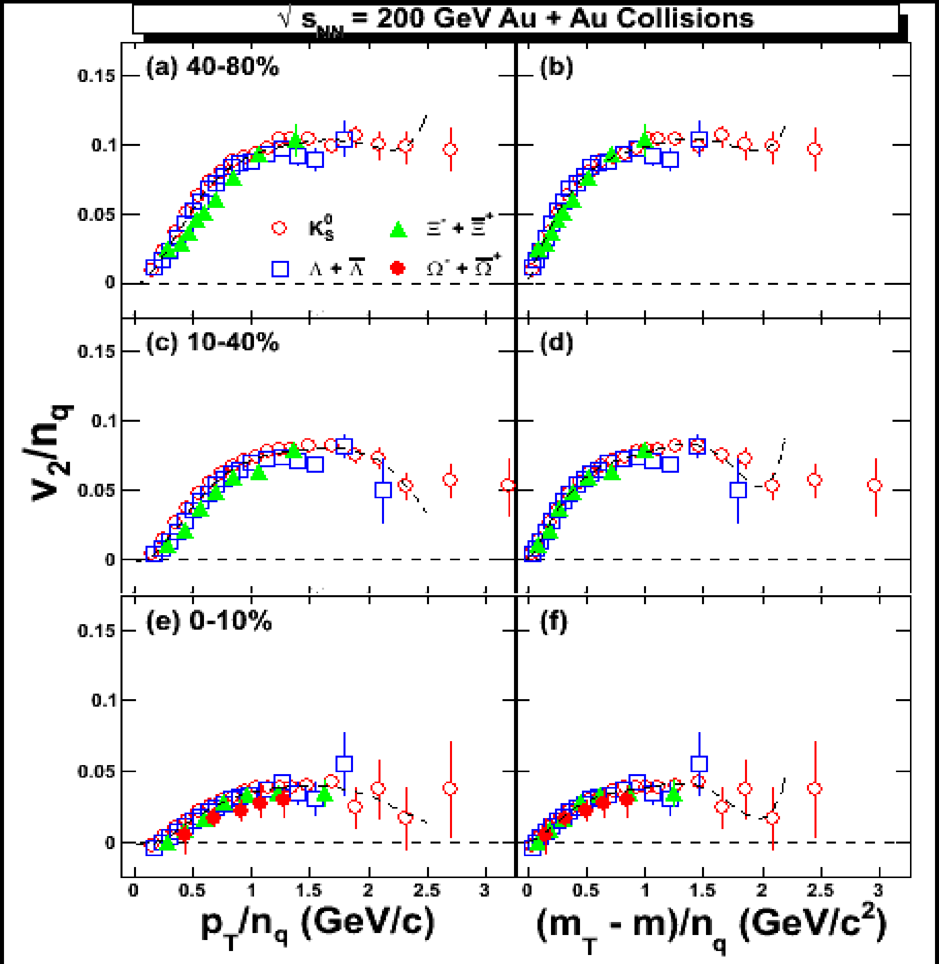


Baryon/meson scaling at intermediate transverse momenta: fits in coalescence picture.

Evidence of parton degrees of freedom!

D. Molnar and S. Voloshin, Phys.Rev.Lett. 91 (2003) 092301

Number of constituent quark scaling



Baryon/meson scaling at intermediate transverse momenta: fits in coalescence picture.

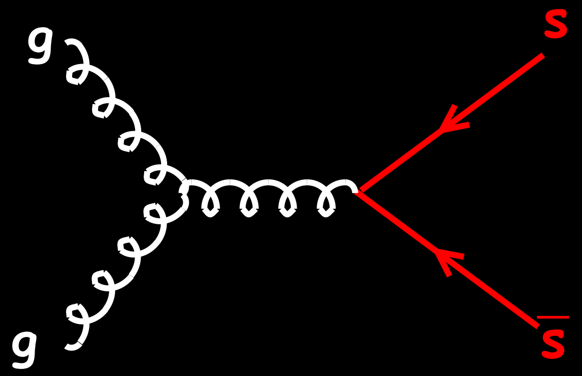
Evidence of parton degrees of freedom!

Strangeness enhancement

- QGP signature proposed by Rafelski and Muller, 1982
- The masses of deconfined quarks are expected to be about 350 MeV lower compared to confined
- m_s(constituent) ~ 500 MeV → m_s(current) ~ 150 MeV
- T_c ~ 170 MeV strange quark should be a sensitive probe

Strangeness production in a QGP

- Copious strangeness production by gluon fusion:



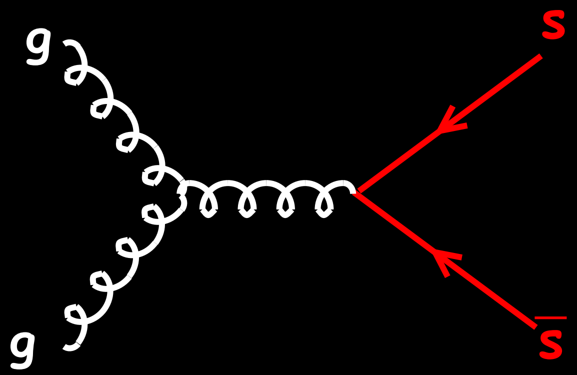
$$T \approx m_s = 150 \text{ MeV}$$

$$N(s) \propto \exp\left(-\frac{m_s}{T}\right)$$

- In a system which is baryon rich (i.e. an access of quarks over anti-quarks), the enhancement can be further enhanced due to Pauli blocking of light quark production

Strangeness abundances in a QGP

- The QGP strangeness abundance is enhanced
- The strange quarks recombine into hadrons (when the QGP cools down and hadronizes)
- The abundance of strange hadrons should also be enhanced
- This enhancement should be larger for particles of higher strangeness content



E(Ω^-) >	E(Ξ^-) >	E(Λ)
(sss)	(ssd)	(sud)

Strangeness abundances in a hadron gas

- In a relatively long lived strongly interacting hadronic system strangeness can also be enhanced
- These hadronic processes are relatively fast and easy for kaons and Λ, but progressively harder for particles of higher strangeness
- The production of multi-strange baryons is expected to be sensitive to deconfinement

$$\pi + \pi \rightarrow K + \bar{K}$$

$$\pi + N \rightarrow \Lambda + K$$

E(Ω^-) <	E(Ξ^-) <	E(Λ)
(sss)	(ssd)	(sud)

only 2→2 processes considered!!

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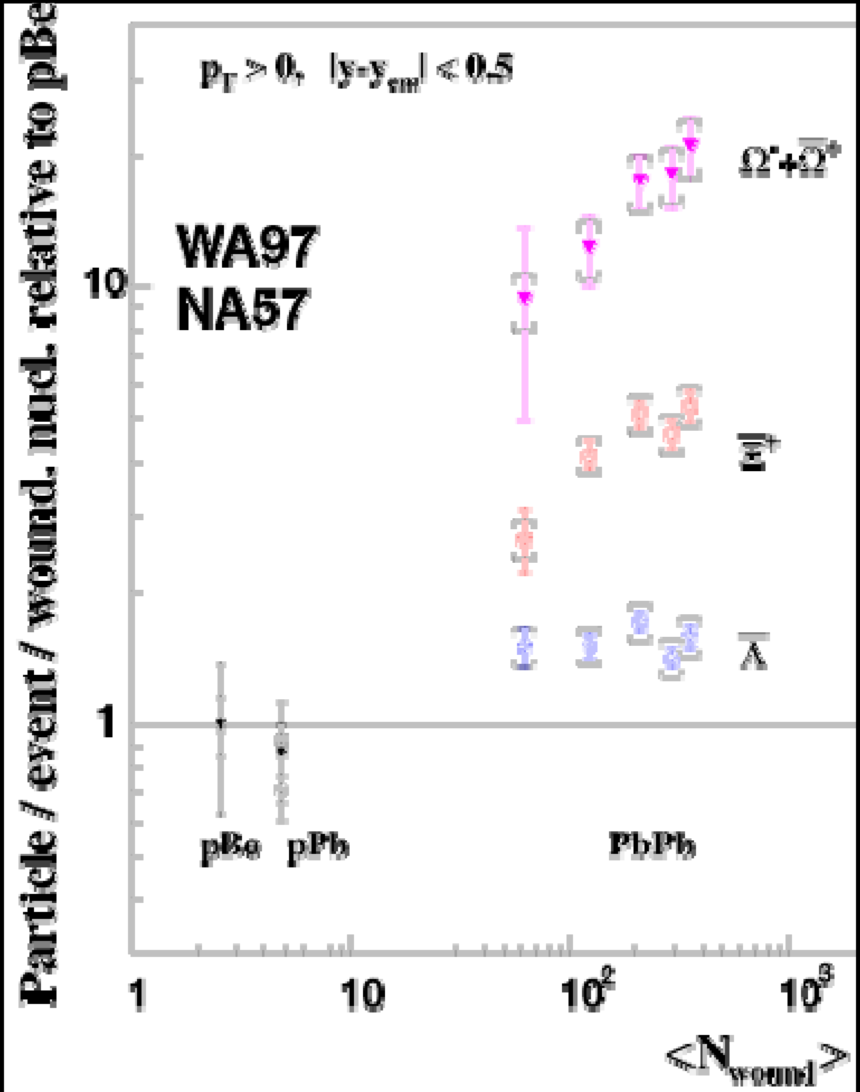
Strangeness measurement at the SPS

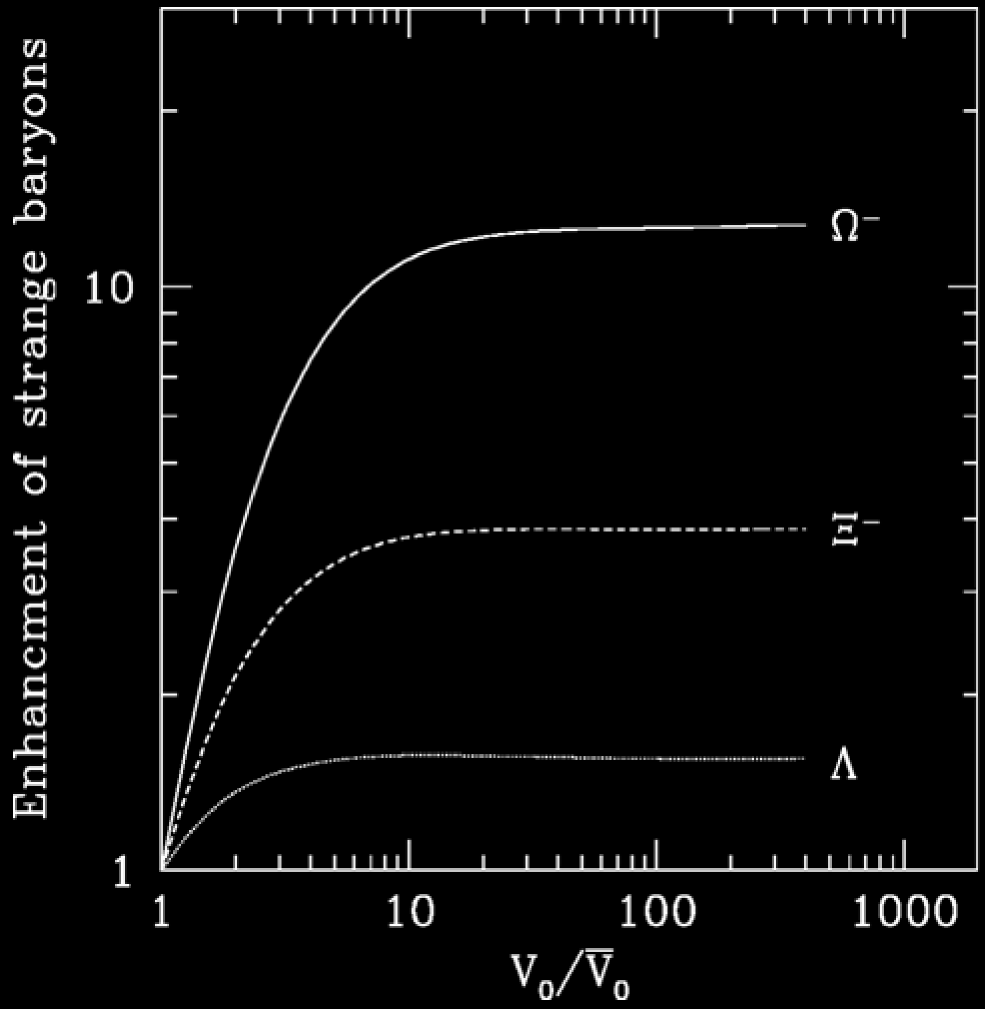


- Enhancement: yield per participant relative to yield per participant in p-Be

$$E_{\Omega^-} = \frac{\left(N_{\Omega^-} / \left\langle N_{\text{wounded}} \right\rangle\right)_{Pb+Pb}}{\left(N_{\Omega^-} / \left\langle N_{\text{wounded}} \right\rangle\right)_{p+Be}}$$

- Ω more than a factor 20 enhanced
- Relative order follows QGP prediction

Canonical suppression of strangeness



- Successful description of strangeness production in heavy ion collisions with a thermal model using a grand canonical ensemble
- For small systems exact strangeness conservation becomes important, canonical ensemble, reduces available phase space

S. Hamieh, K. Redlich A. Tounsi, PL B486 (2000) 61

Charmonium suppression (II)

- λ_D depends on temperature, thus which states are suppressed depends on temperature
- Charmonium suppression key signature of deconfinement!!!
- cc_{bar} and bb_{bar} bound states are particularly sensitive probes because the probability of combining an uncorrelated pair at the hadronization stage is small
- In fact, at the SPS the only chance of producing a cc_{bar} bound state is shortly after the pair is produced. Debye screening destroys this correlations

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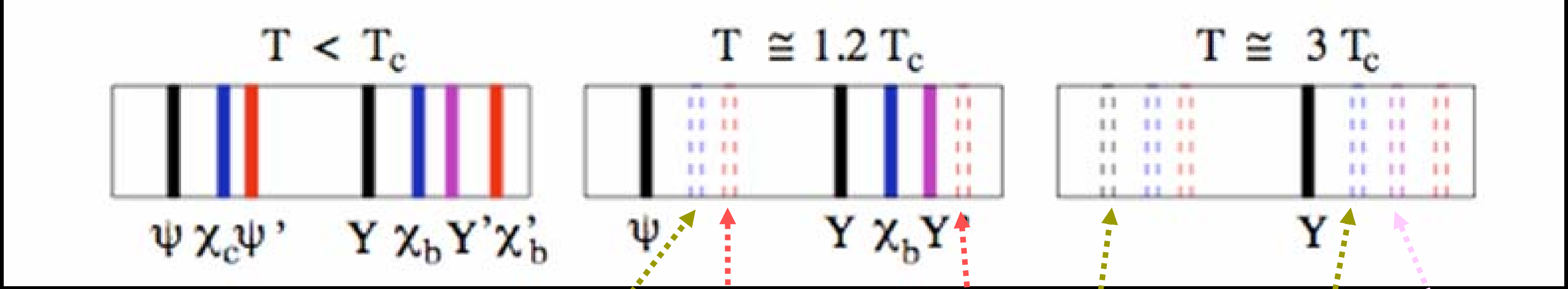
Quarkonium: thermometer dense QCD

Quarkonium Physics



Satz, HP2006

$T_{RHIC} > T_{melt}(\chi_c)$, $T_{melt}(\Psi')$, $T_{melt}(\Upsilon(3S))$

$T_{LHC} > T_{melt}(J/\Psi)$, $T_{melt}(\chi_b)$, $T_{melt}(\Upsilon(2S))$

$T_{melt}(\Psi') < T_{melt}(\Upsilon(3S)) < T_{melt}(J/\Psi) \approx T_{melt}(\Upsilon(2S)) < T_{RHIC} < T_{melt}(\Upsilon(1S))$?

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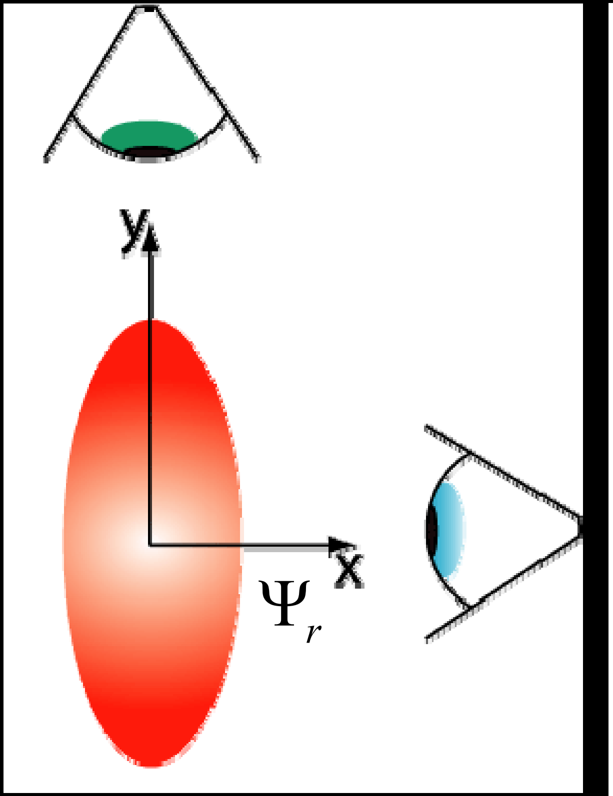
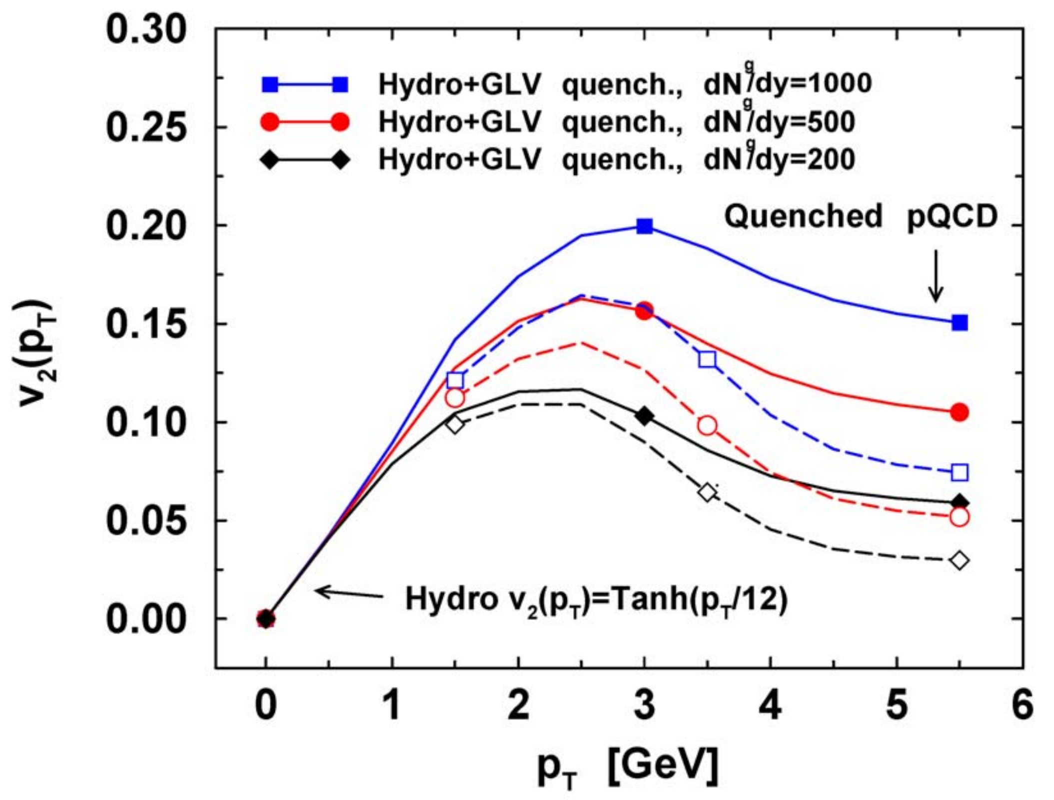
Construct simple observables (II)

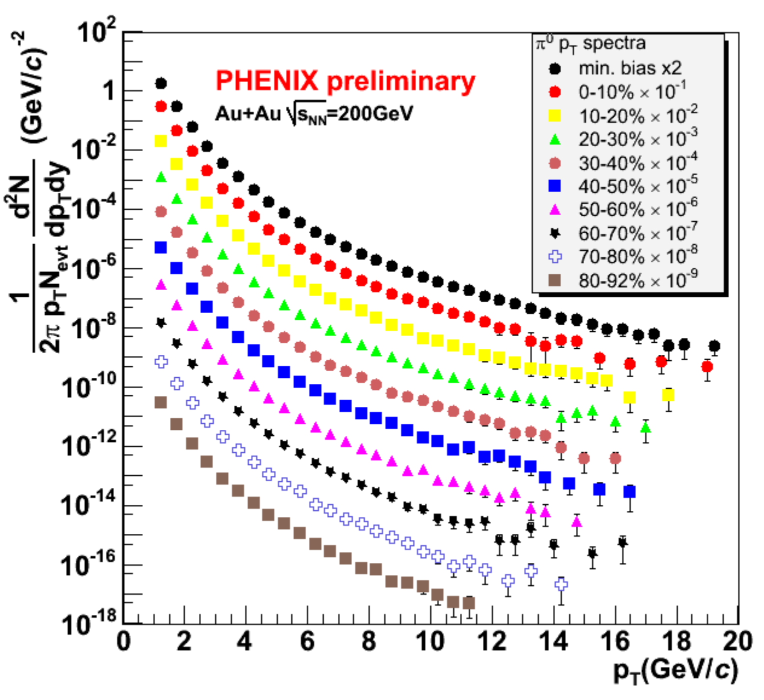


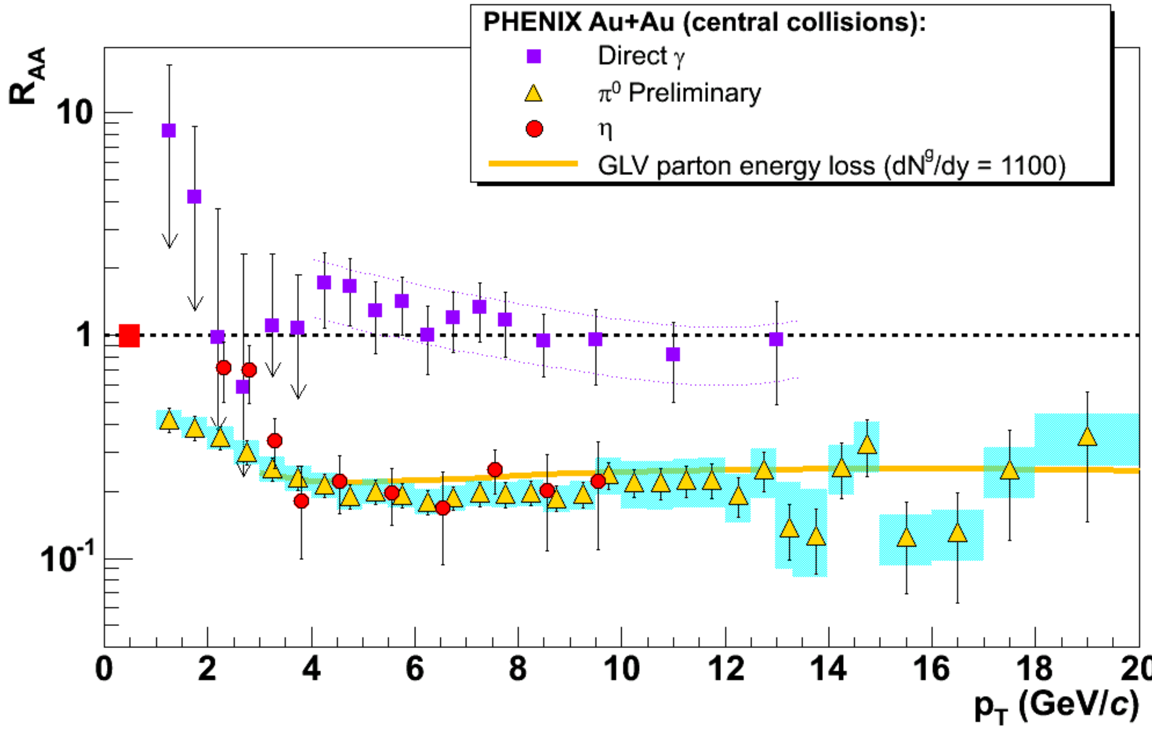


$$v_2 \quad \langle \cos 2(\qquad\quad _r) \rangle$$

M. Gyulassy, I. Vitev and X.N. Wang
PRL 86 (2001) 2537

R_{AA} at RHIC; direct photons





- One of the big RHIC discoveries: strong suppression of high-p_t particles