LHC Physics

with ATLAS and CMS

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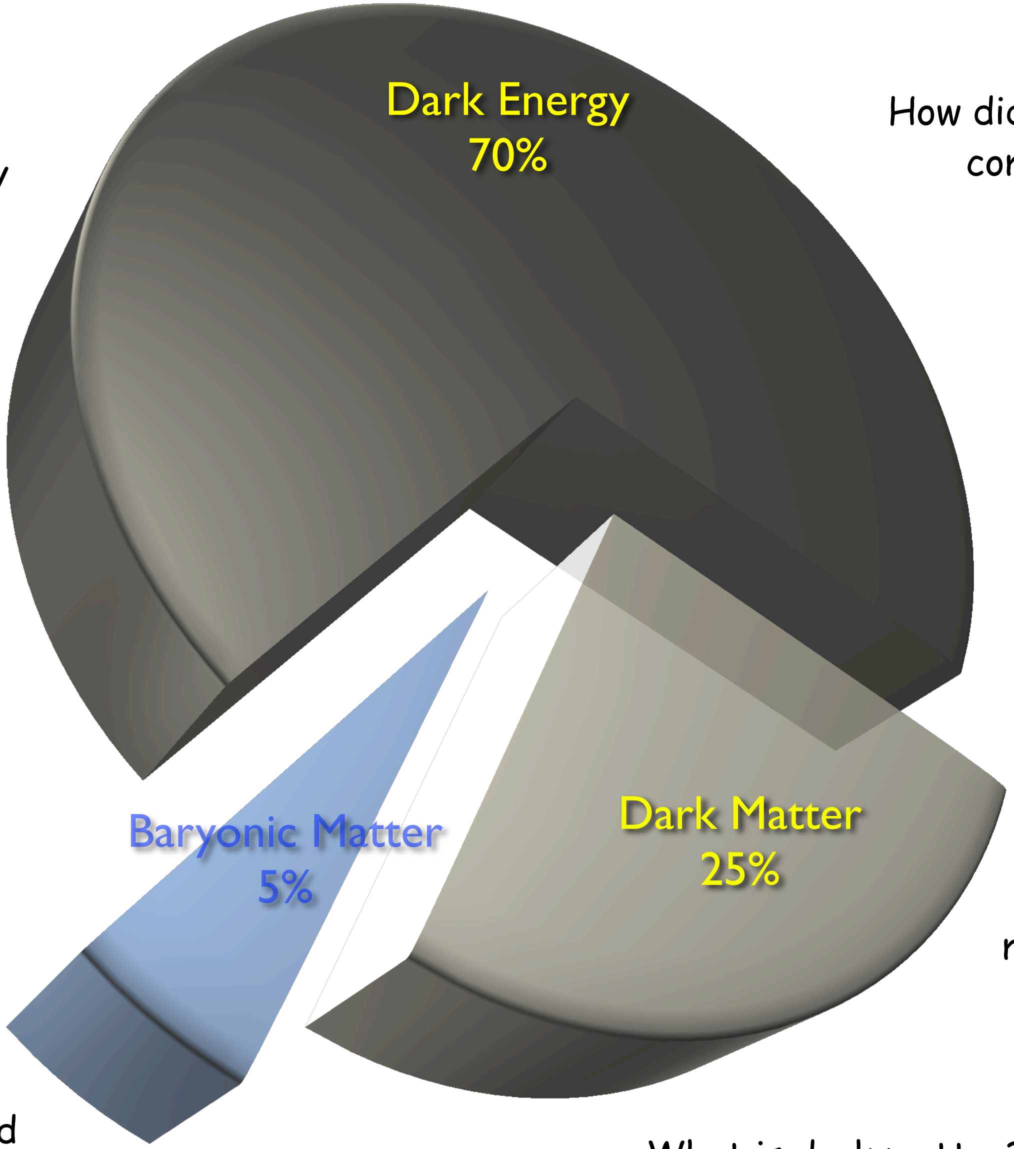
The Big Questions



How can we solve
the mystery of dark energy?

Why are there so many
kinds of particles?

Do all forces
become one?

What are neutrinos
telling us?

What happend
to the antimatter?

How did the universe
come to be?

Are there extra
dimensions of space?

Are there undiscovered
principles of nature?

Can we make dark
matter in the laboratory?

What is dark matter?

Introductory Remarks

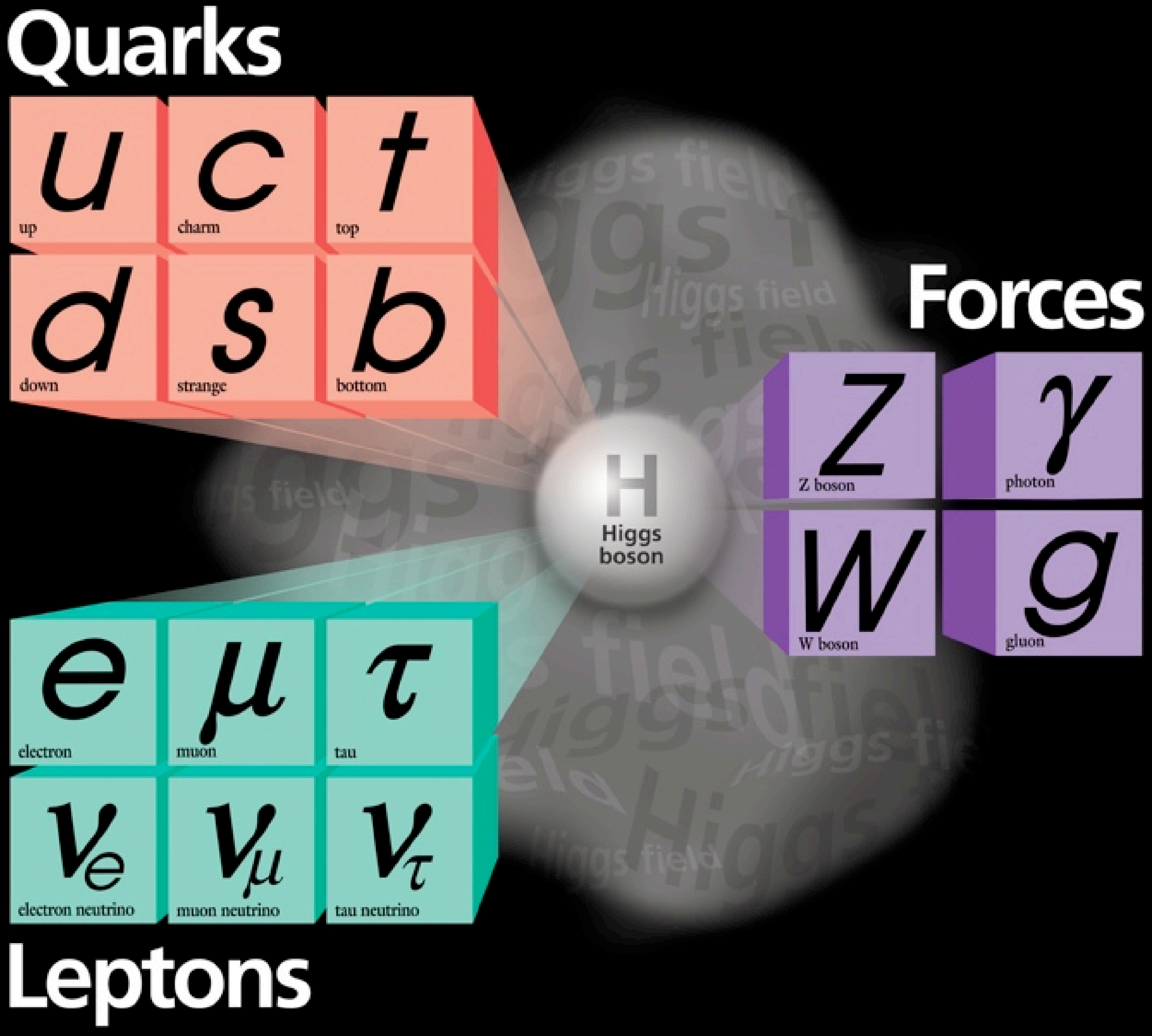
What do we know ...

... what do we not know
... and what to expect

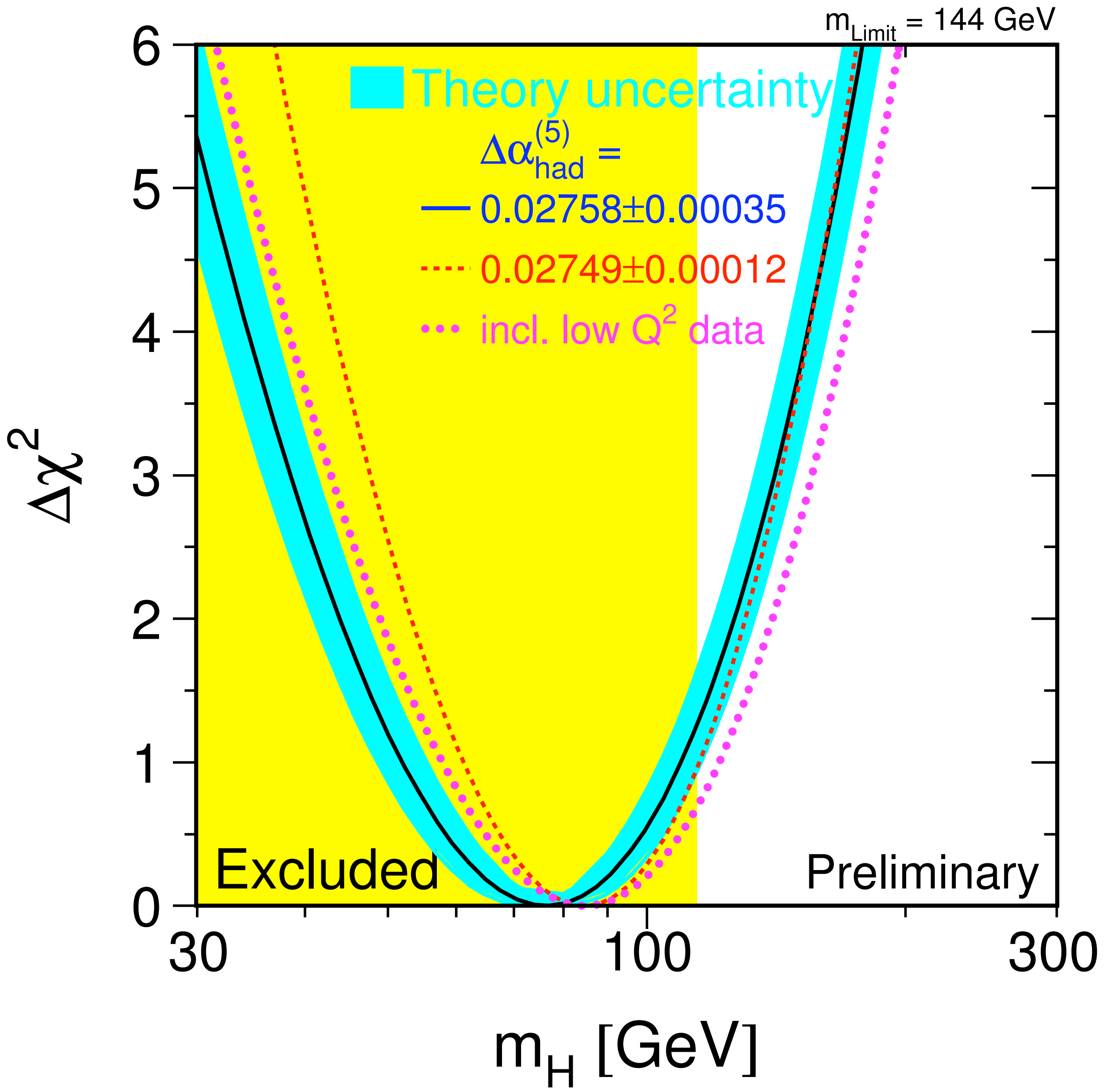
ATLAS
Mini Black Hole Event

The Standard Model

A Particle Physicist's view of the world



Our Knowledge about the Higgs



EW-Fits:

$M_H = 76^{+33}_{-24}$ GeV

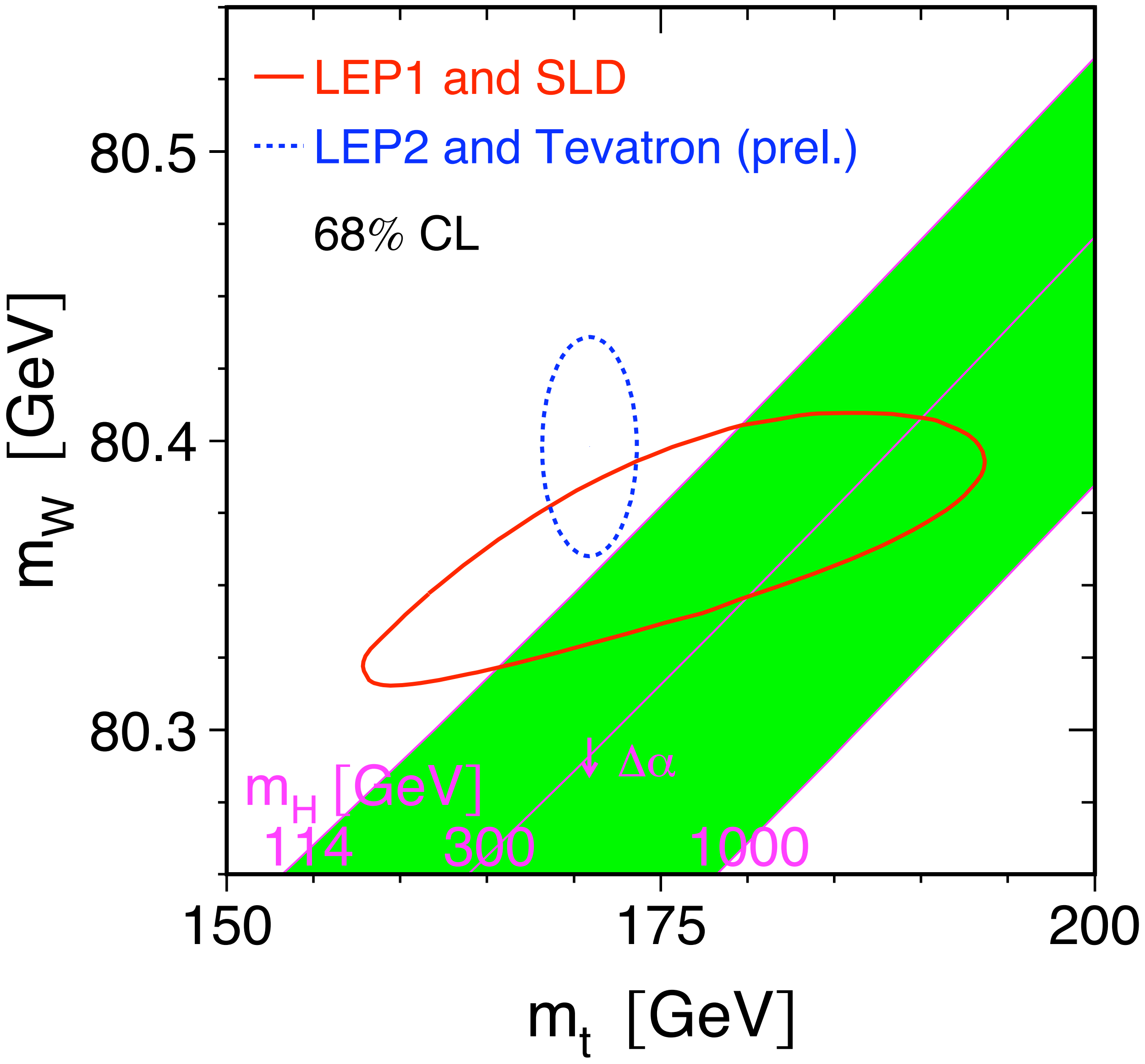
$M_H < 144$ GeV @ 95% CL

From direct search at LEP:

$M_H > 114$ GeV

[Updated: Spring 2007]

Our Knowledge about the Higgs



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$M_H = 76^{+33}_{-24}$ GeV

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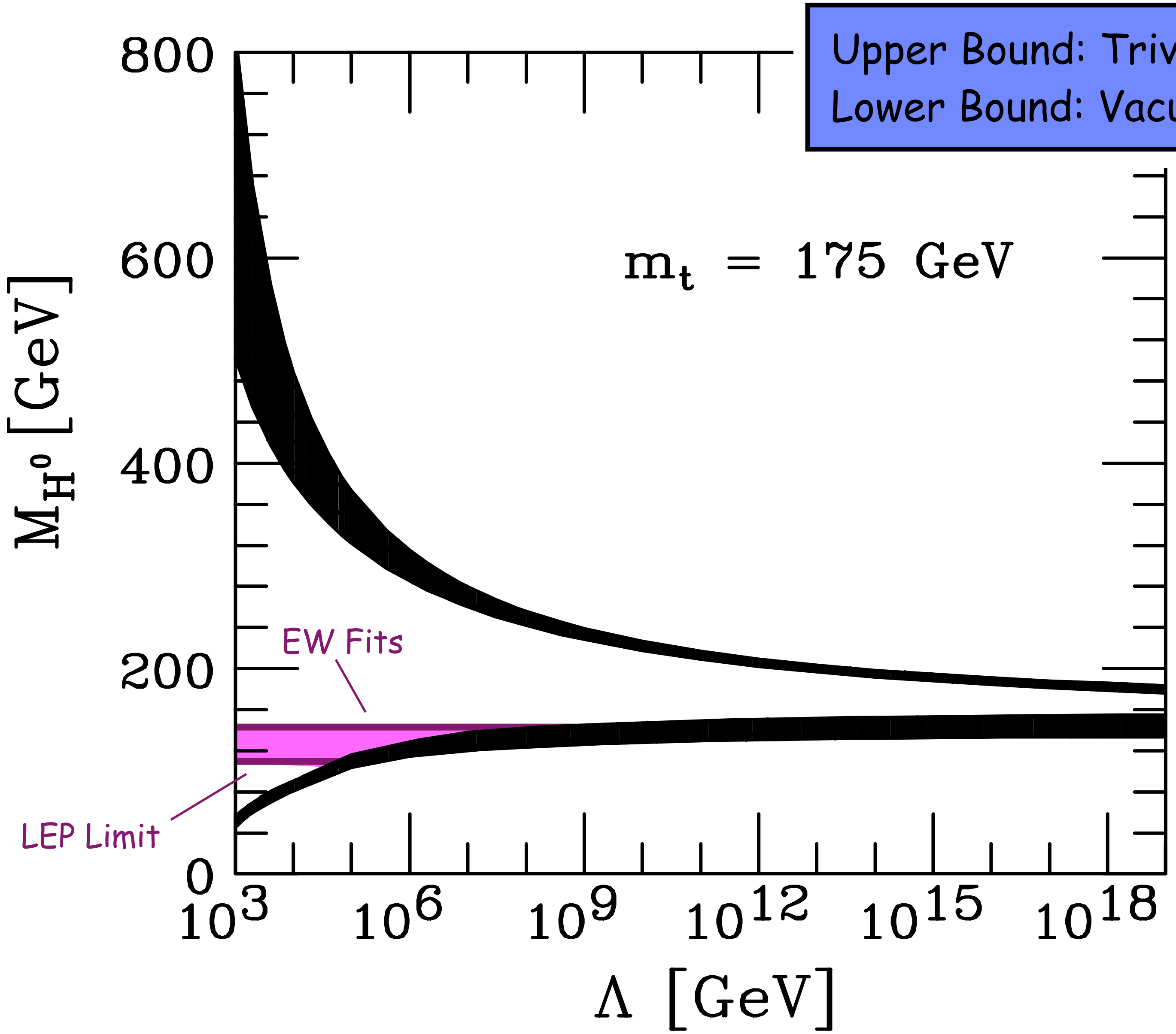
Consequences of a Light Higgs

Is new physics just around the corner?

Upper Bound: Triviality
Lower Bound: Vacuum stability

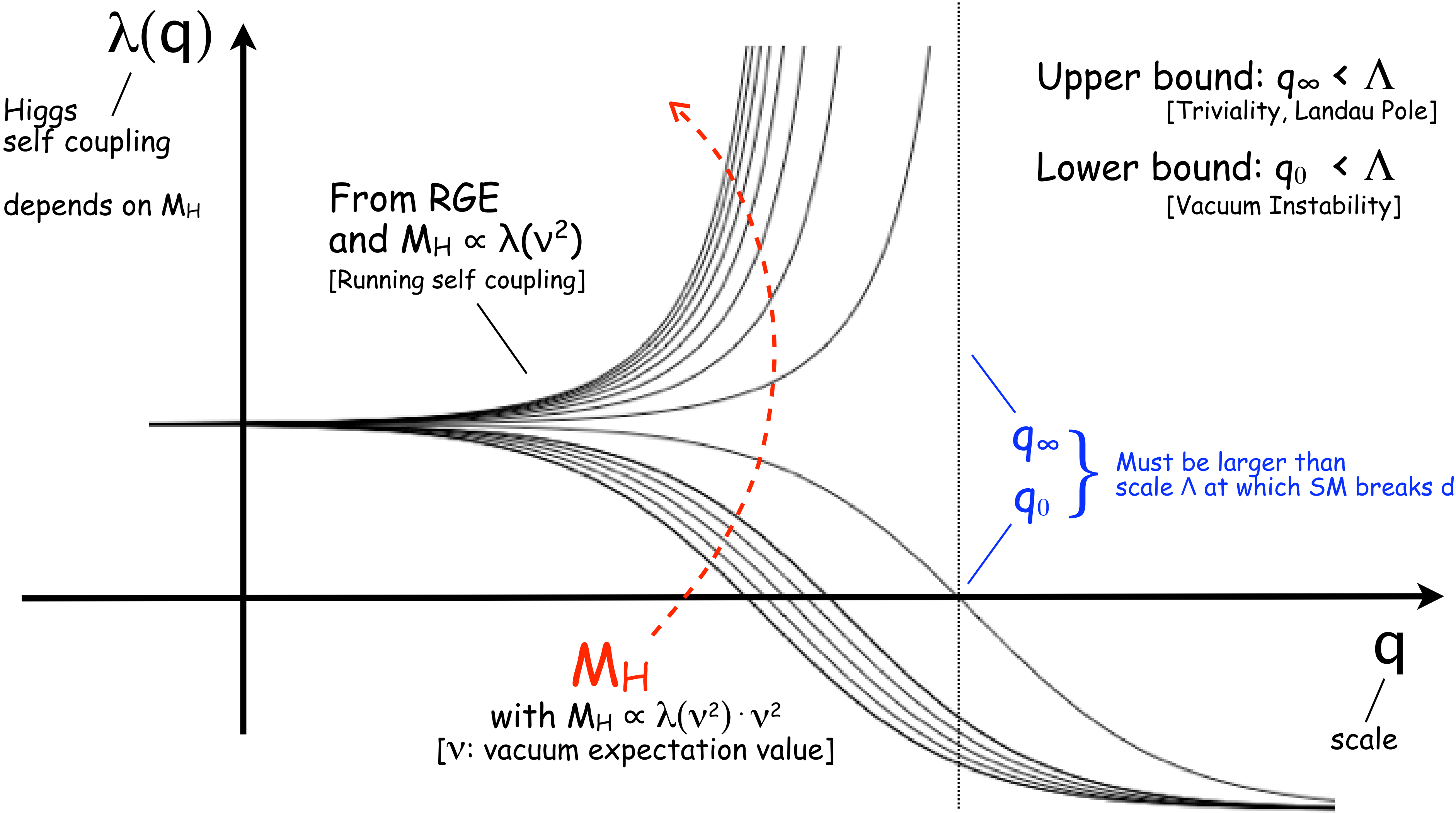


Scale Λ:

energy scale at which physics beyond the SM sets in

Triviality and Vaccum Instability

Where the Higgs bounds come from



Higgs self coupling

depends on M_H

From RGE
and $M_H \propto \lambda(v^2)$
[Running self coupling]

Upper bound: $q_\infty < \Lambda$
[Triviality, Landau Pole]

Lower bound: $q_0 < \Lambda$
[Vacuum Instability]

q_∞
q_0
Must be larger than
scale Λ at which SM breaks down

M_H
with $M_H \propto \lambda(v^2) \cdot v^2$
[v: vacuum expectation value]

Consequences of a Light Higgs

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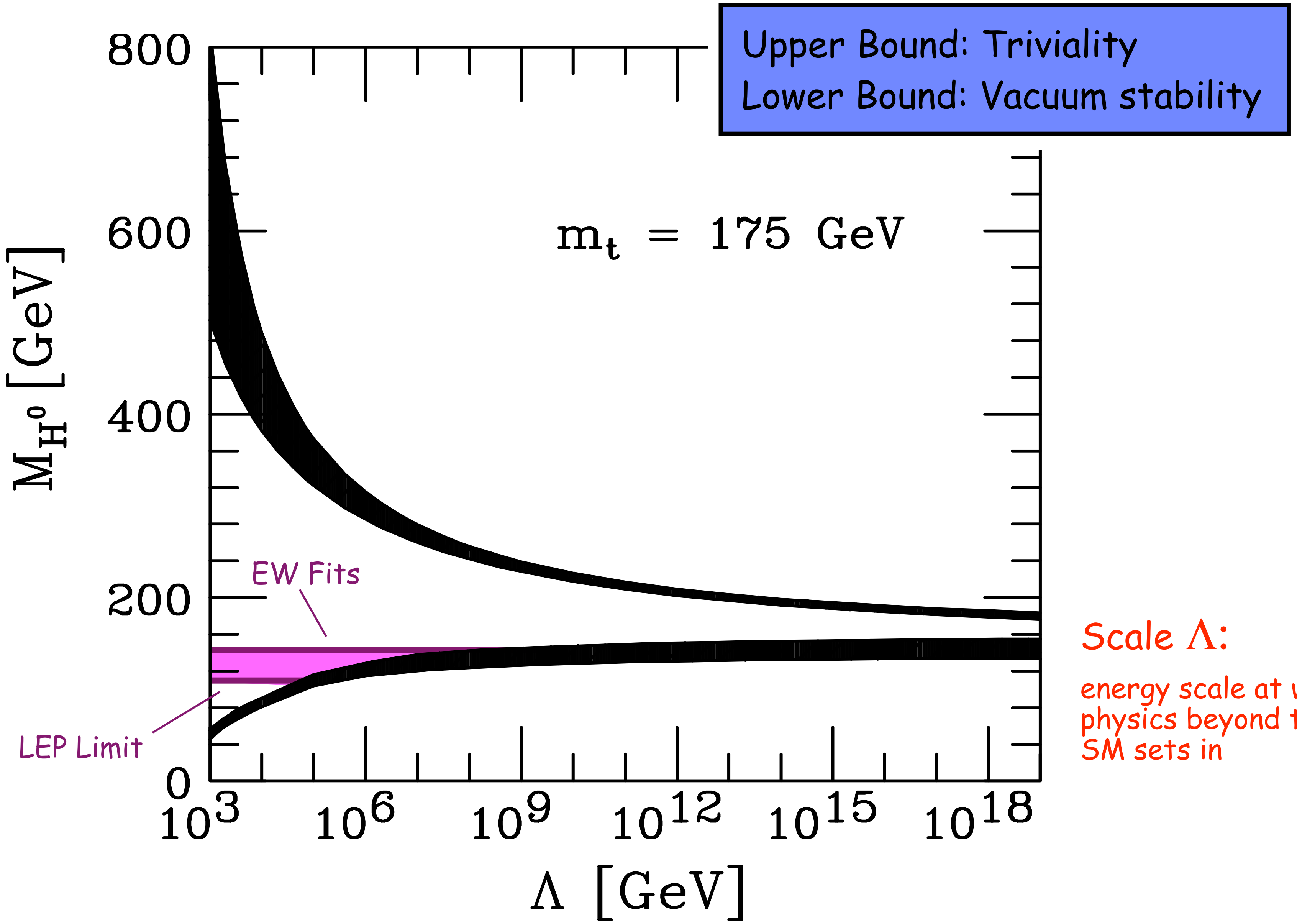

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Consequences of a Light Higgs

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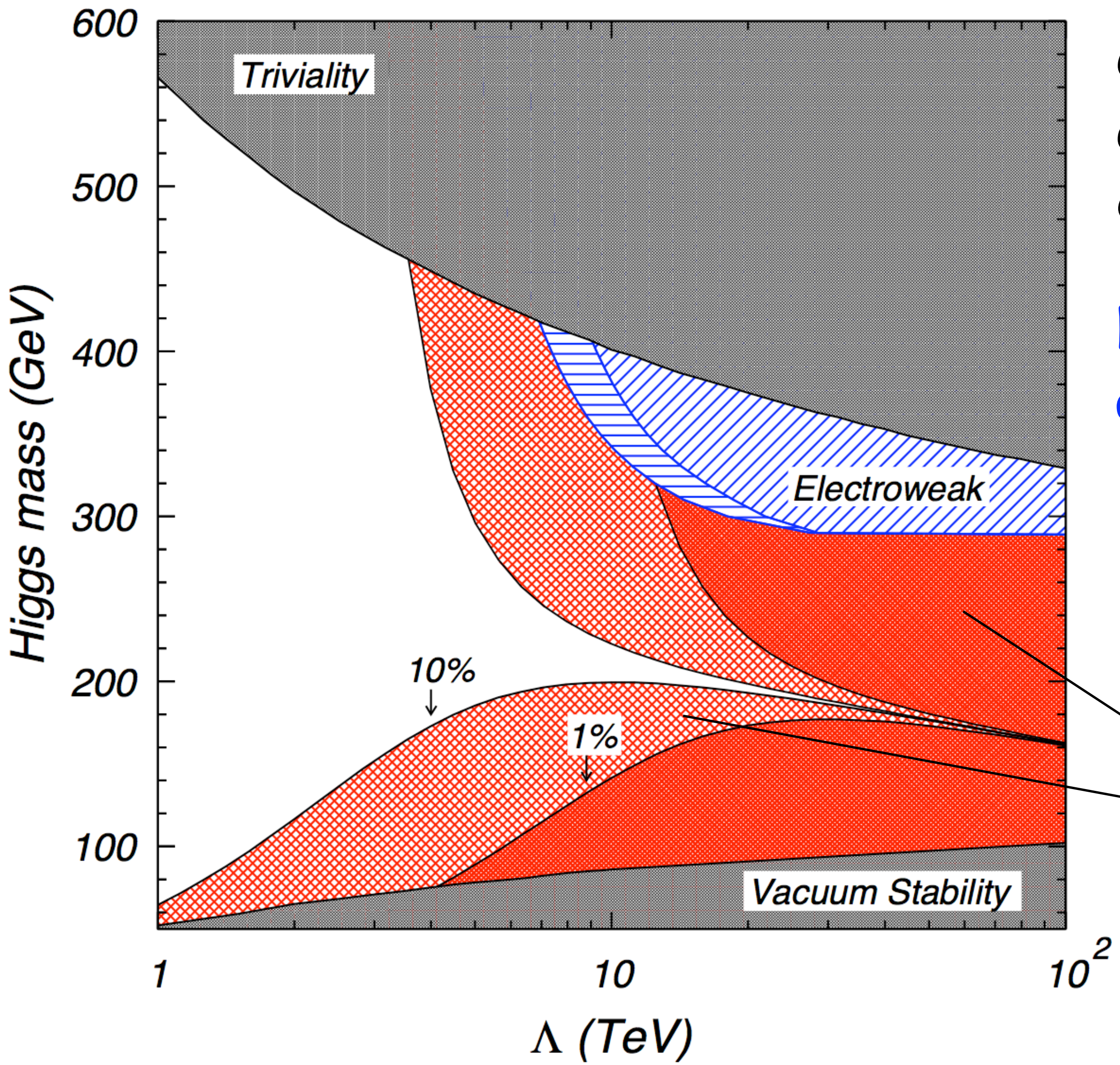


Constraints
even harder when
considering fine-tuning

New physics at
a few TeV?

Excluded to
avoid fine-tuning

What Theorists Think About

There exists a large number of models which predict new physics at the TeV scale accesible at the LHC:

- Grand Unified Theories (SU(5), O(10), E6, ...)

  embed SM gauge group in larger symmetry
- Supersymmetry (SUSY - around since a long time)
- Extended Higgs sector

  e.g. in SUSY models
- Leptoquarks
- New heavy gauge bosons
- Technicolour
- Compositeness
- Extra dimensions

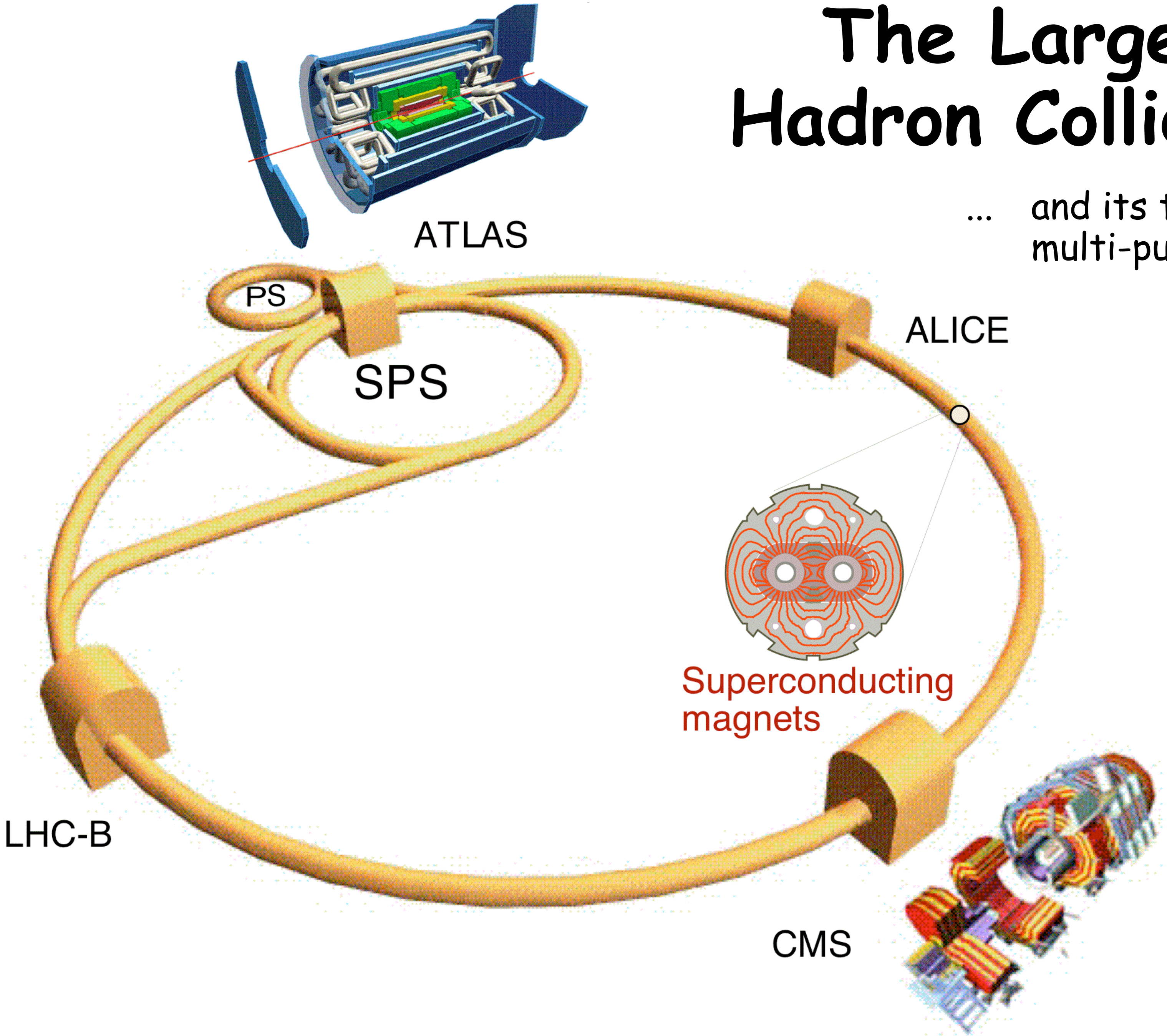
Any of this is what the LHC hopes to find ...

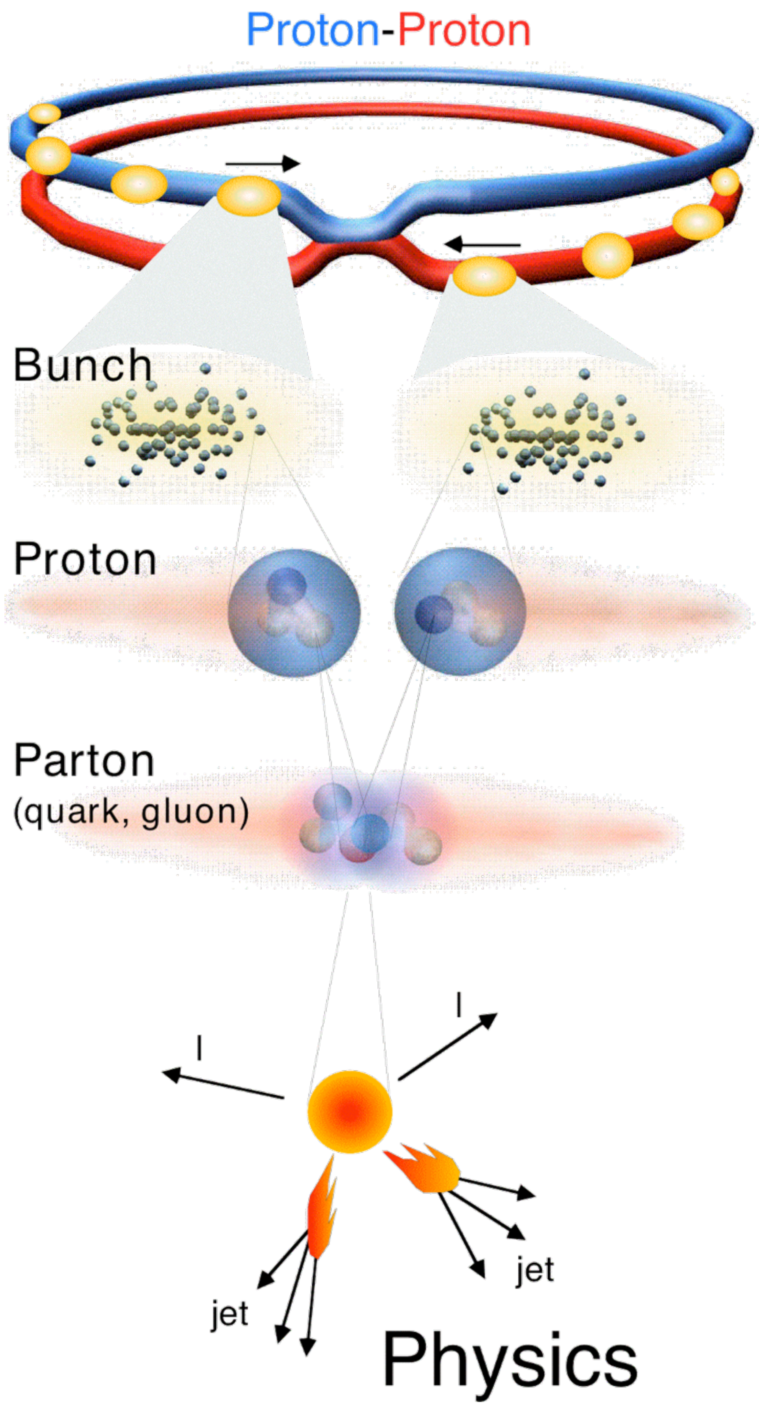
... appart from the Higgs

The Experimental Challenge of the LHC Experiments

The Large Hadron Collider

... and its two
multi-purpose experiments





The LHC:

Some Numbers

relevant for ATLAS and CMS

2835 x 2835 proton bunches
distance: 7.5 m [25 ns]

10^{11} protons/bunch
bunch crossing rate: 40 MHz

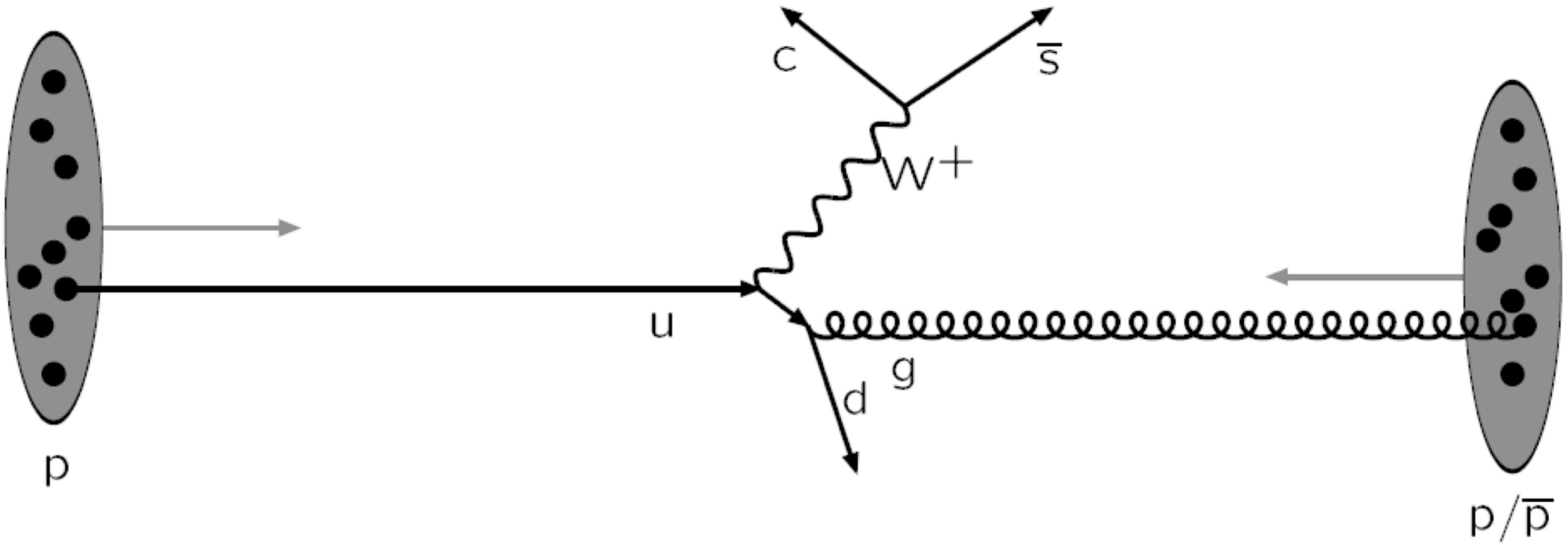
10^9 pp-collisions/sec

[i.e.: 23 pp-interactions/bunch crossing.]

Dominant Interactions:
gluon-gluon, quark-quark and
quark-gluon scattering

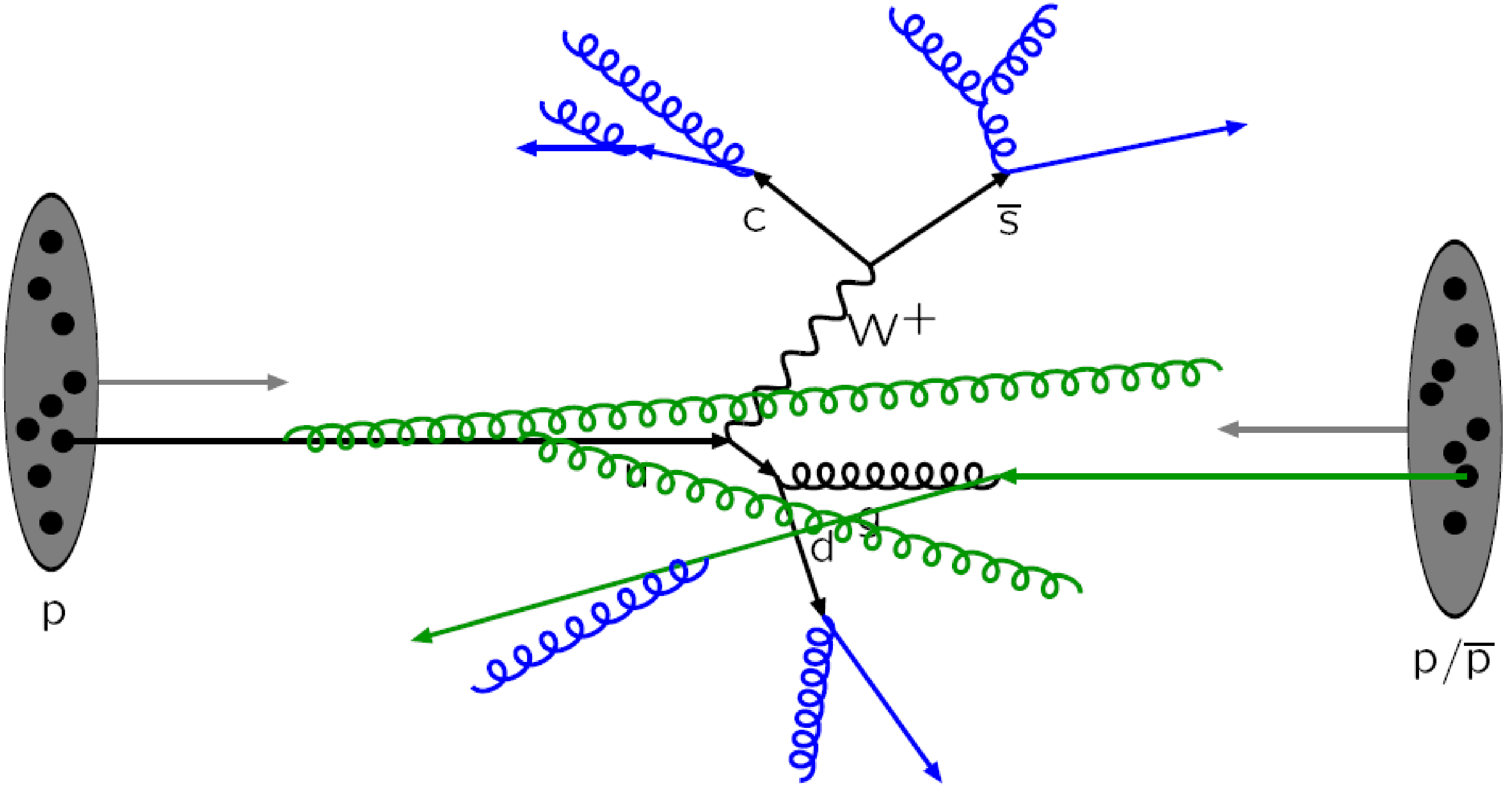
Proton-Proton Scattering @ LHC

- Hard interaction: qq, gg, qg fusion



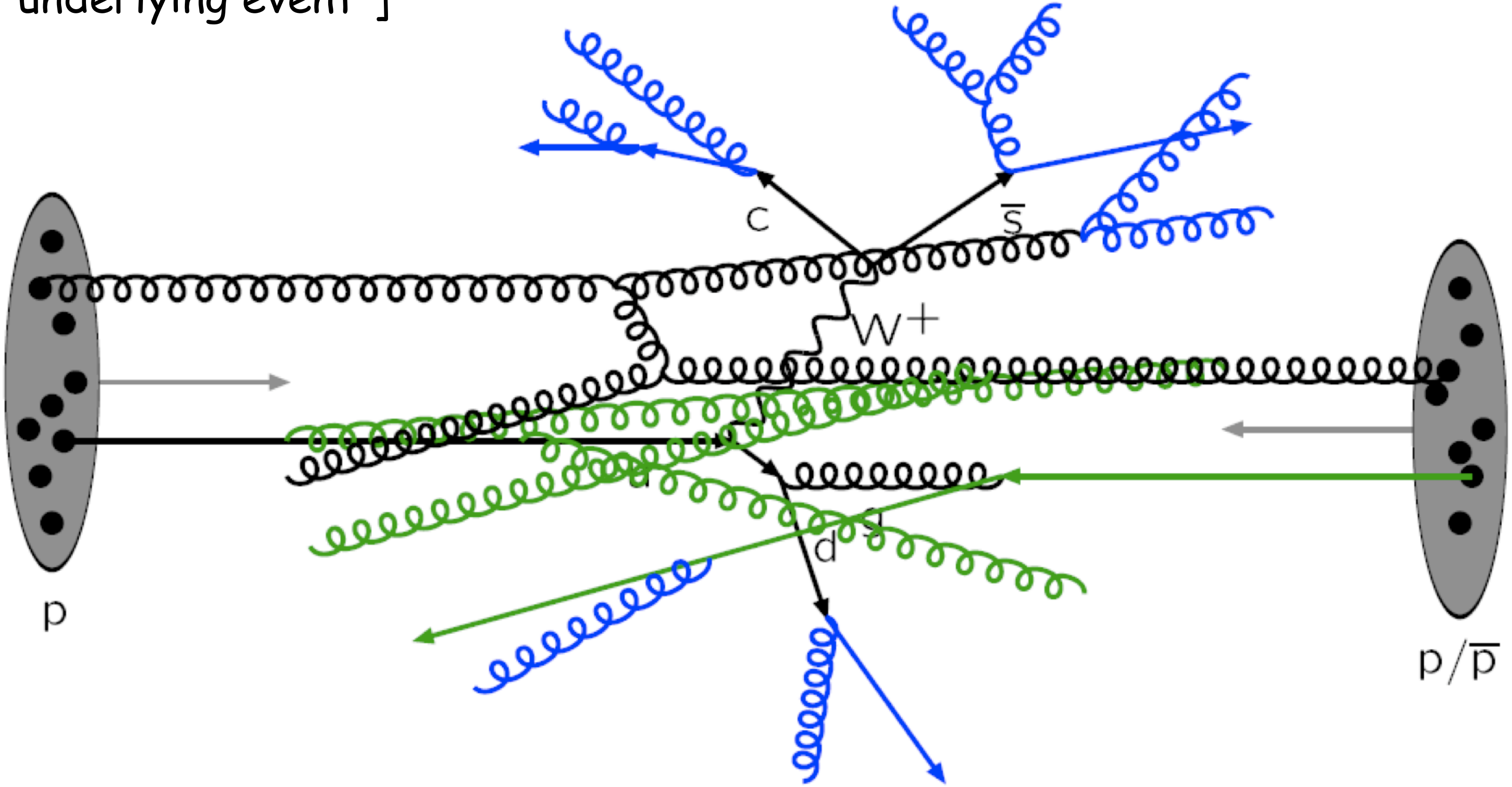
Proton-Proton Scattering @ LHC

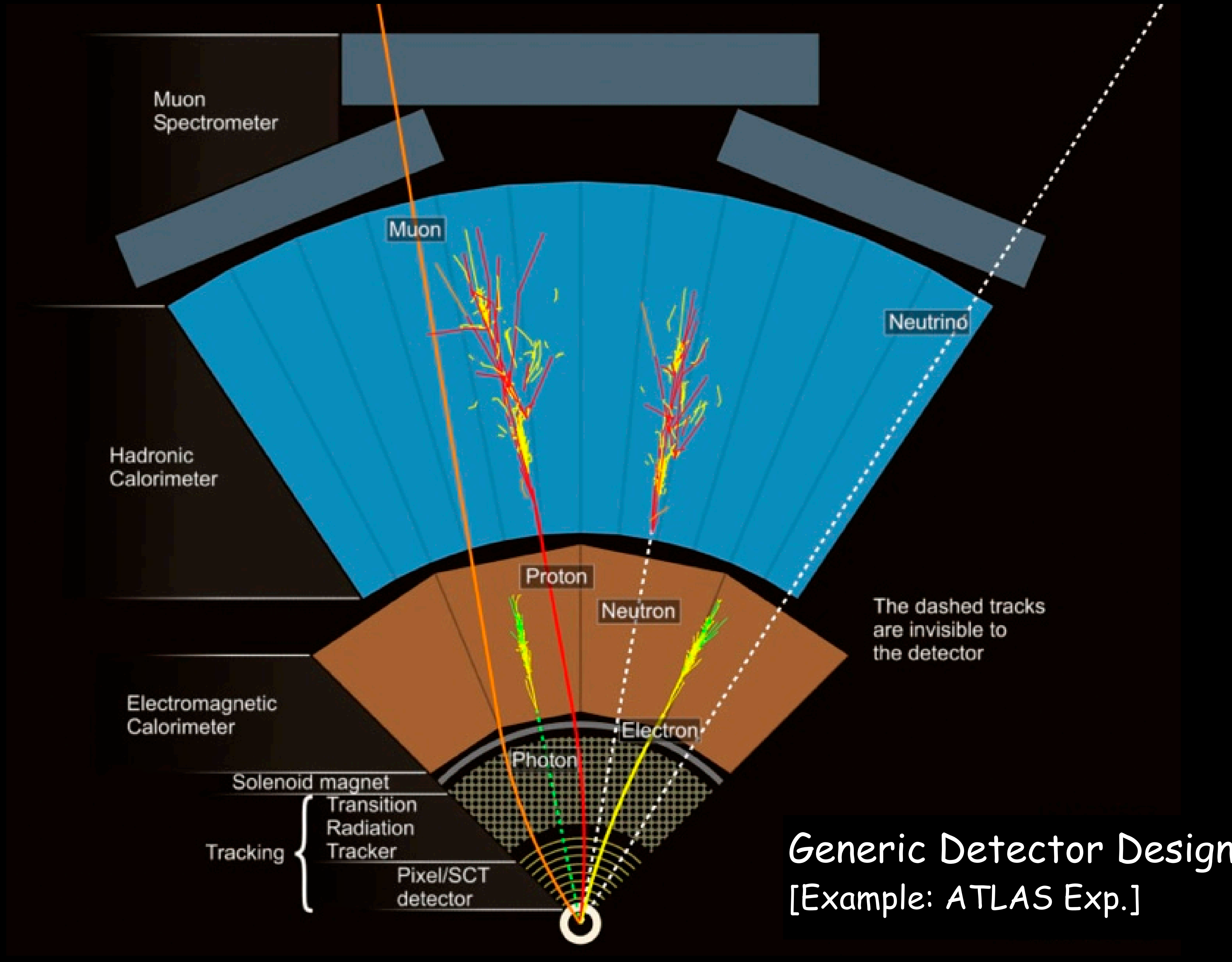
- Hard interaction: qq, gg, qg fusion
- Initial State Radiation (ISR)



Proton-Proton Scattering @ LHC

- Hard interaction: qq, gg, qg fusion
- Initial State Radiation (ISR)
- Secondary Interaction
  [“underlying event”]



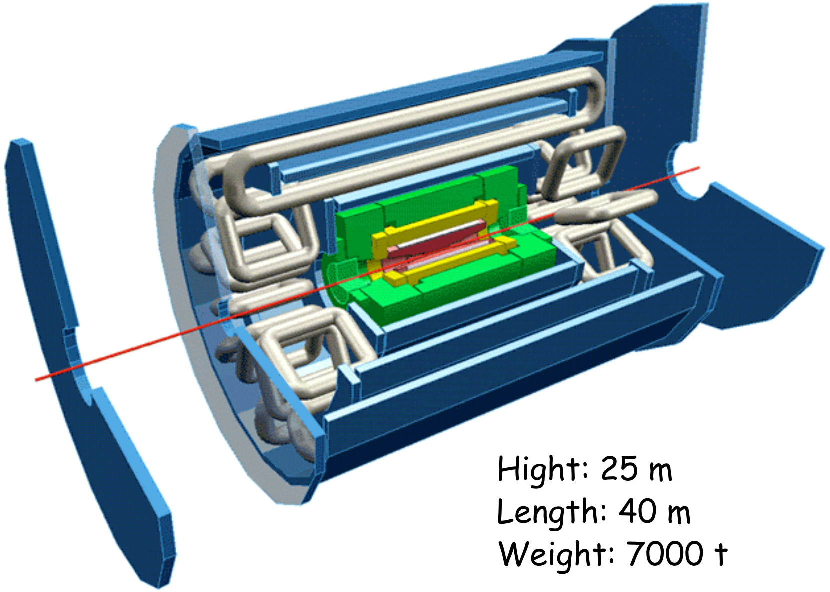


Generic Detector Design

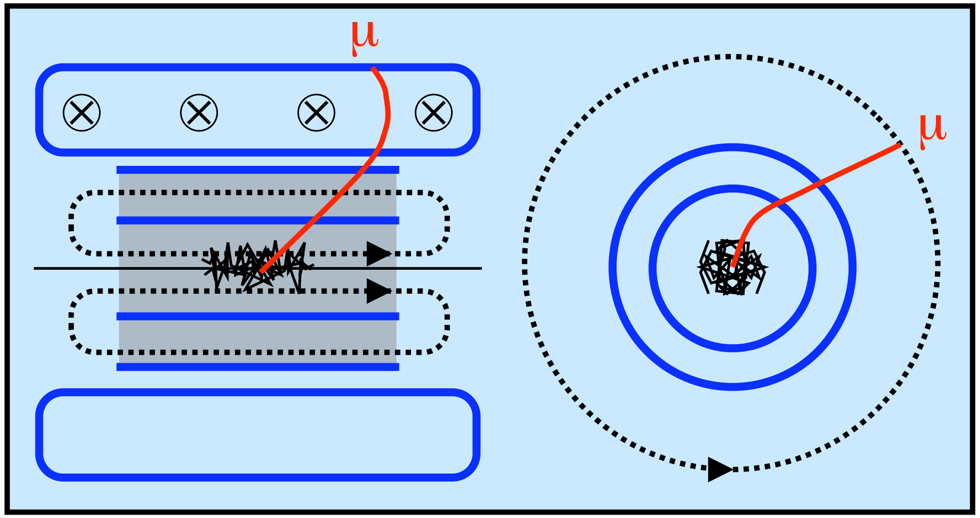
[Example: ATLAS Exp.]

Two Basic Architectures

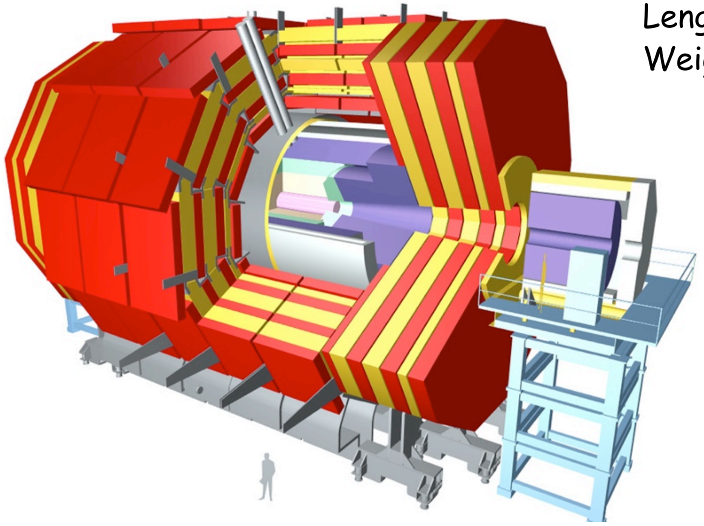
ATLAS: A Toroidal LHC ApparatuS



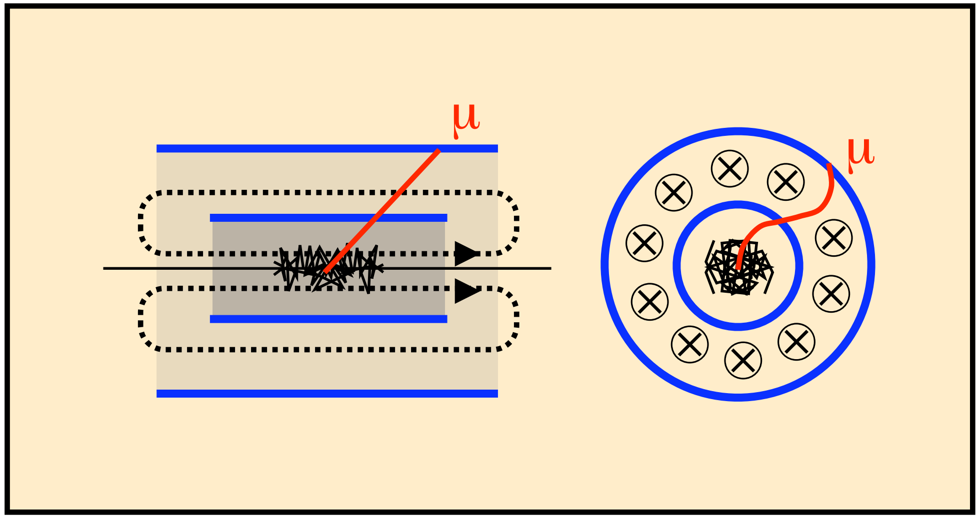
Hight: 25 m
Length: 40 m
Weight: 7000 t



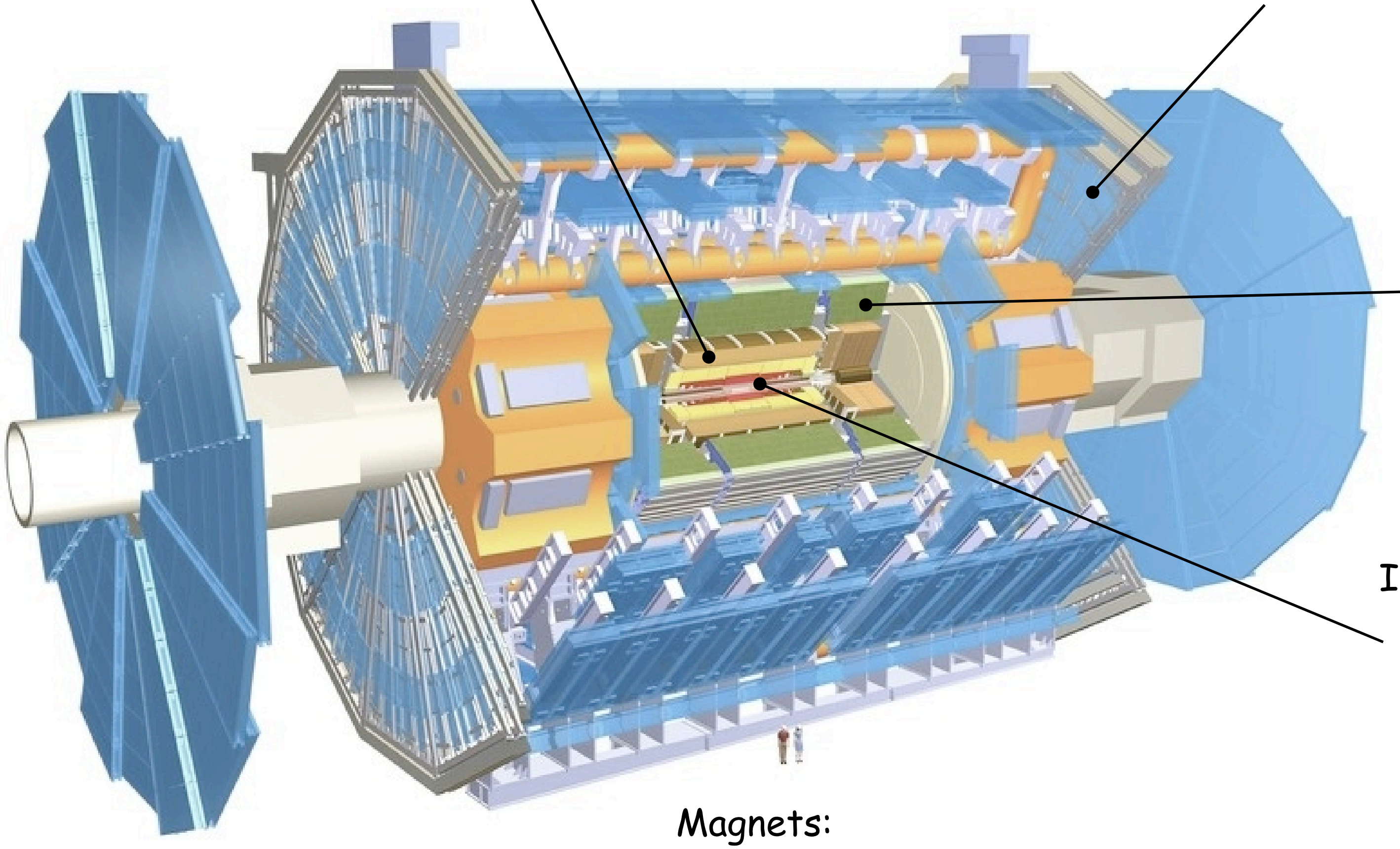
CMS: Compact Muon Solenoid



Hight: 15 m
Length: 22 m
Weight: 12500 t



The ATLAS Detector



EM Calorimeters: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$

excellent e/γ identification
good energy resolution (e.g. for $H \rightarrow \gamma\gamma$)

Prescision Muon Spectrometer: $\sigma/p_t \approx 10\%$ @ 1 TeV

fast trigger response
good momentum resolution
(e.g. $A/Z' \rightarrow \mu\mu$, $H \rightarrow 4\mu$)

Hadron Calorimeter:

$\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$

good jet resolution
good missing E_T resolution
(e.g. $H \rightarrow \tau\tau$)

Inner Detector:

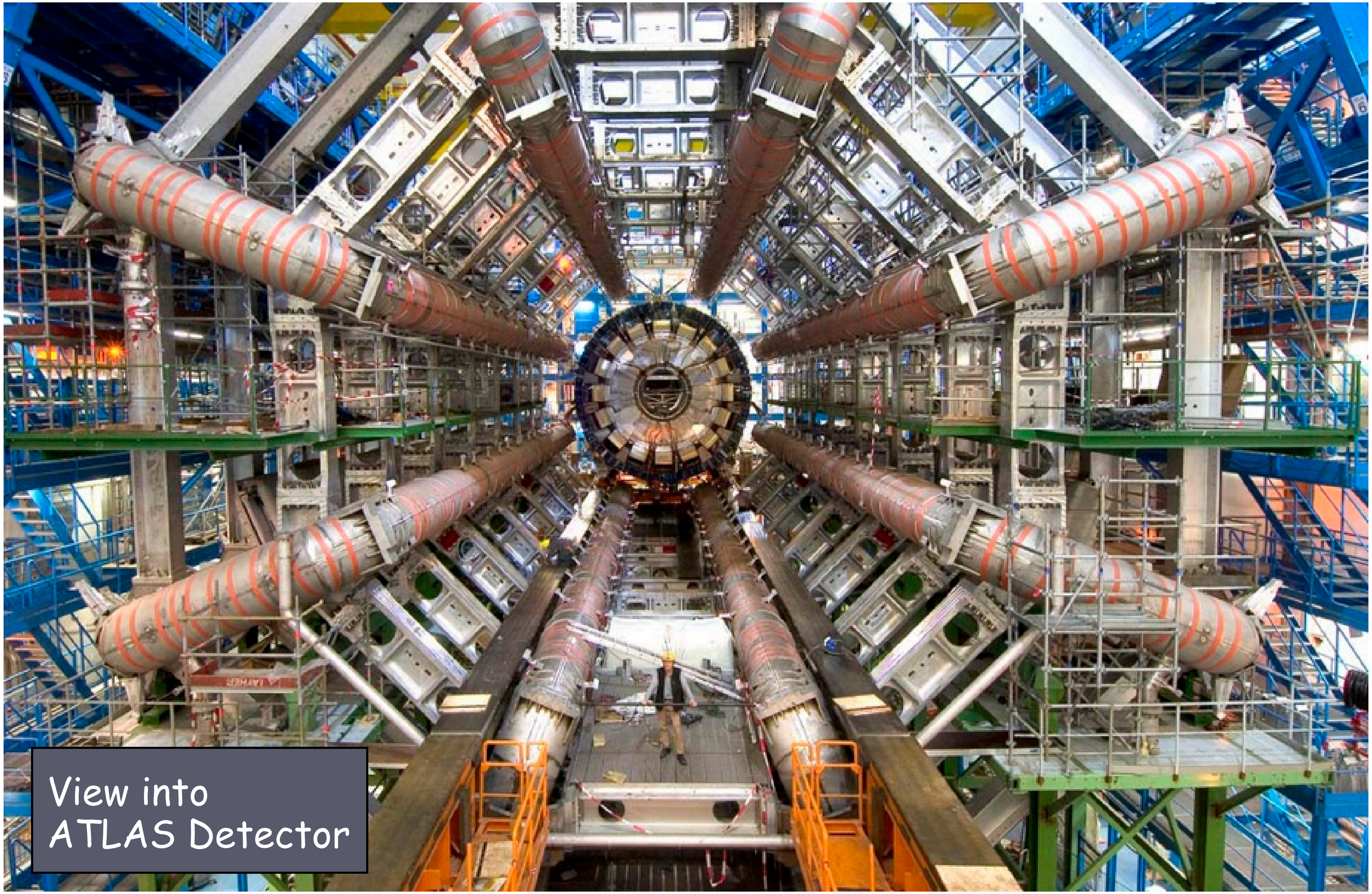
Si Pixel & strips; TRT
$\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$

good impact parameter res., i.e.
$\sigma(d_0) \approx 15\ \mu m$ @ 20 GeV
(e.g. $H \rightarrow bb$)

Magnets:

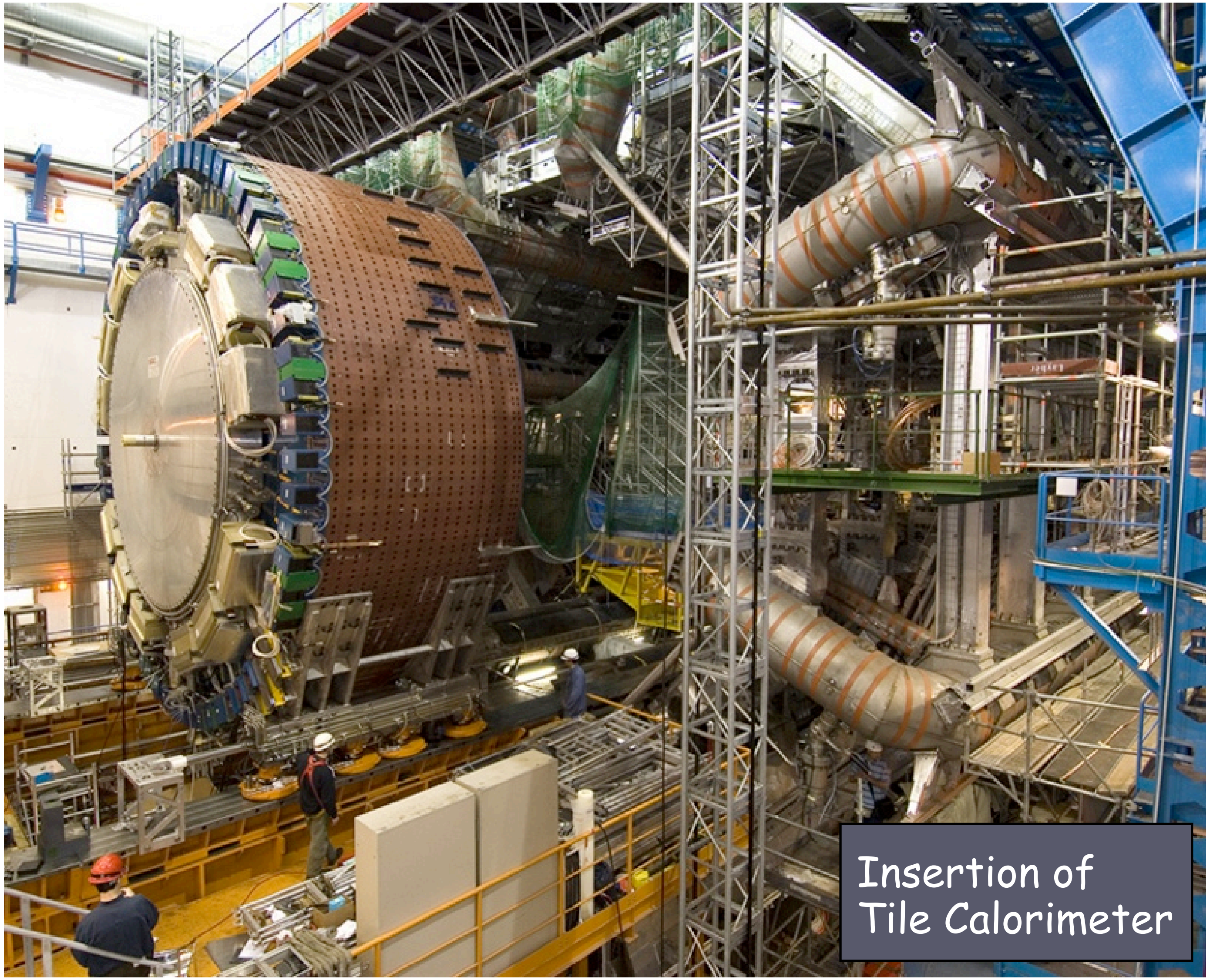
Solenoid (inner detector): 2 T
Toroid (muon spectrometer): 0.5 T

ATLAS October 2005



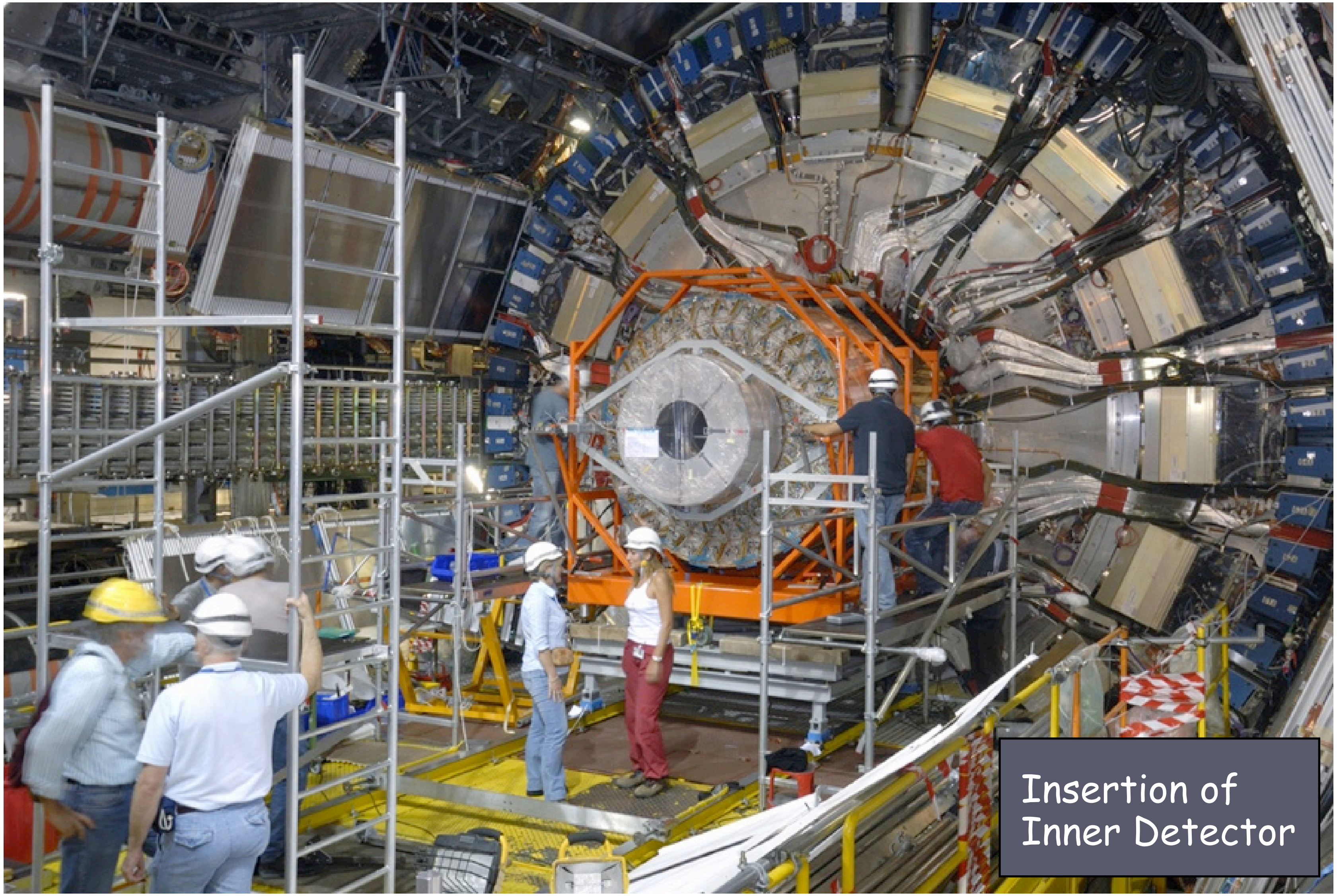
View into
ATLAS Detector

ATLAS July 2006



Insertion of Tile Calorimeter

ATLAS August 2006



Insertion of Inner Detector

The CMS Detector

Inner Detector:

$\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$

[vergl. ATLAS $\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$]

EM Calorimeters:

$\sigma/E \approx 3\%/\sqrt{E} \oplus 0.5\%$

[vergl. ATLAS: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$]

Hadron Calorimeter:

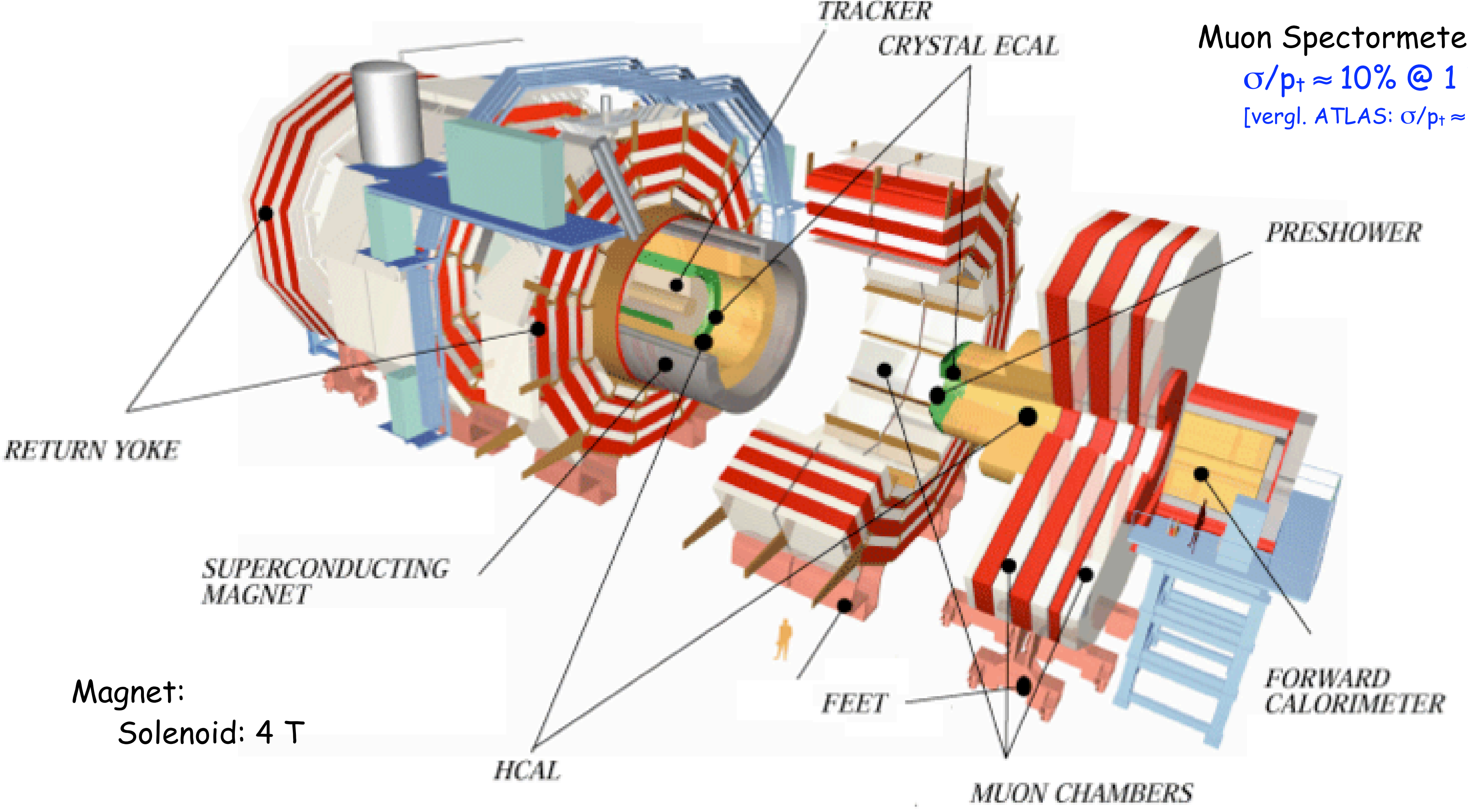
$\sigma/E \approx 100\%/\sqrt{E} \oplus 5\%$

[vergl. ATLAS: $\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$]

Muon Spectormeter

$\sigma/p_t \approx 10\%$ @ 1 TeV

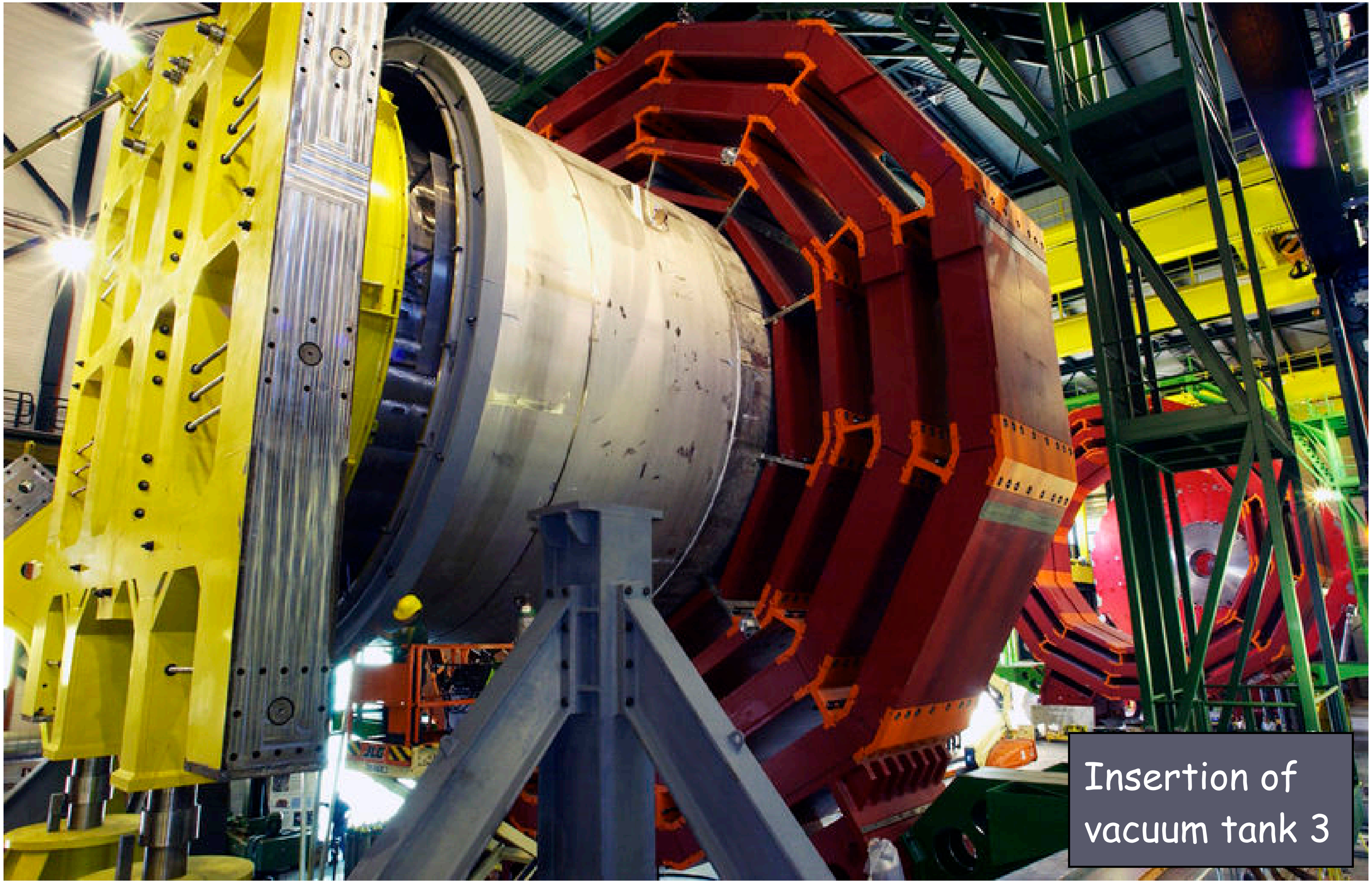
[vergl. ATLAS: $\sigma/p_t \approx 10\%$ @ 1 TeV]



Magnet:

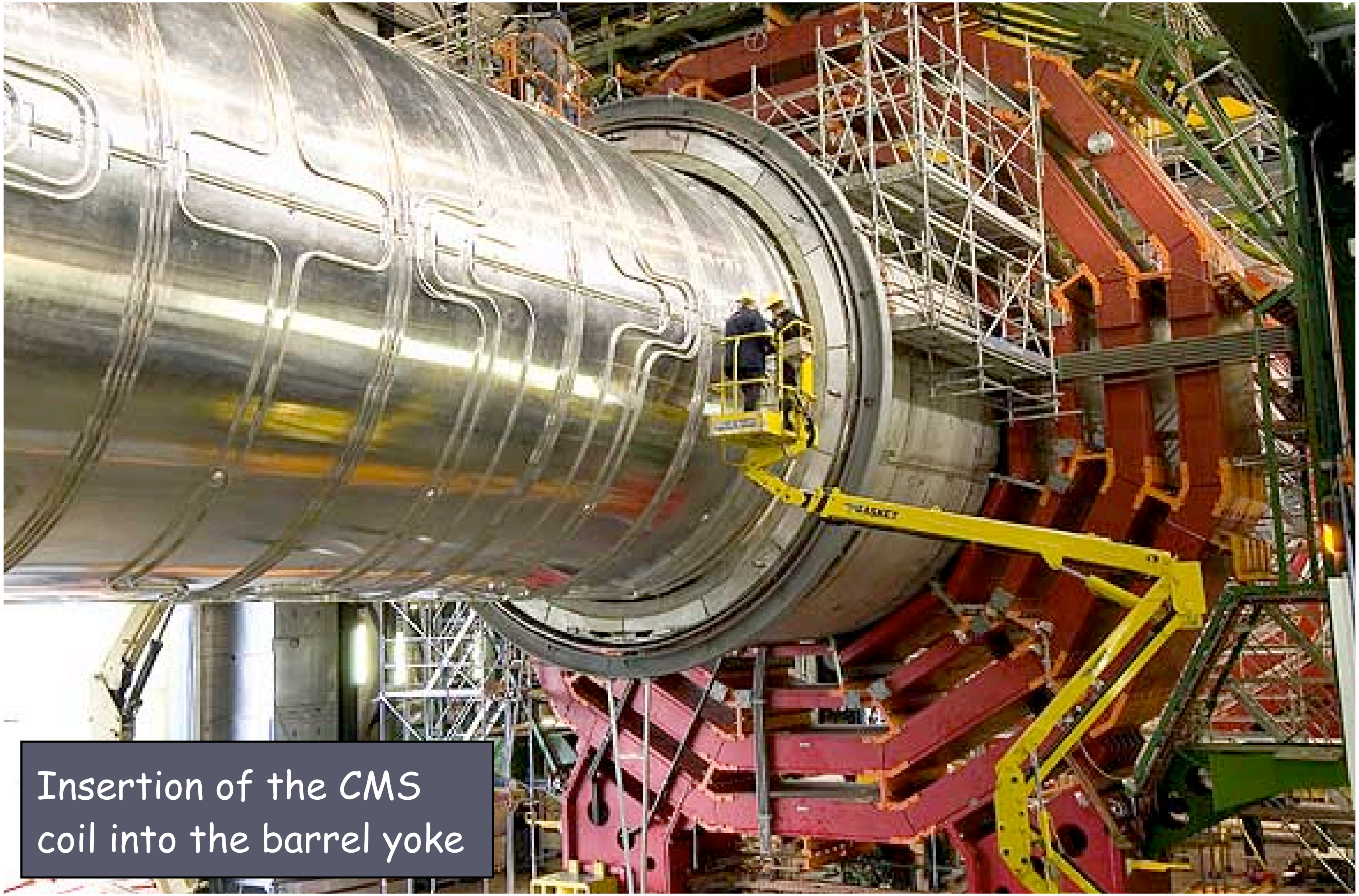
Solenoid: 4 T

CMS June 2002



Insertion of vacuum tank 3

CMS September 2005



Insertion of the CMS coil into the barrel yoke

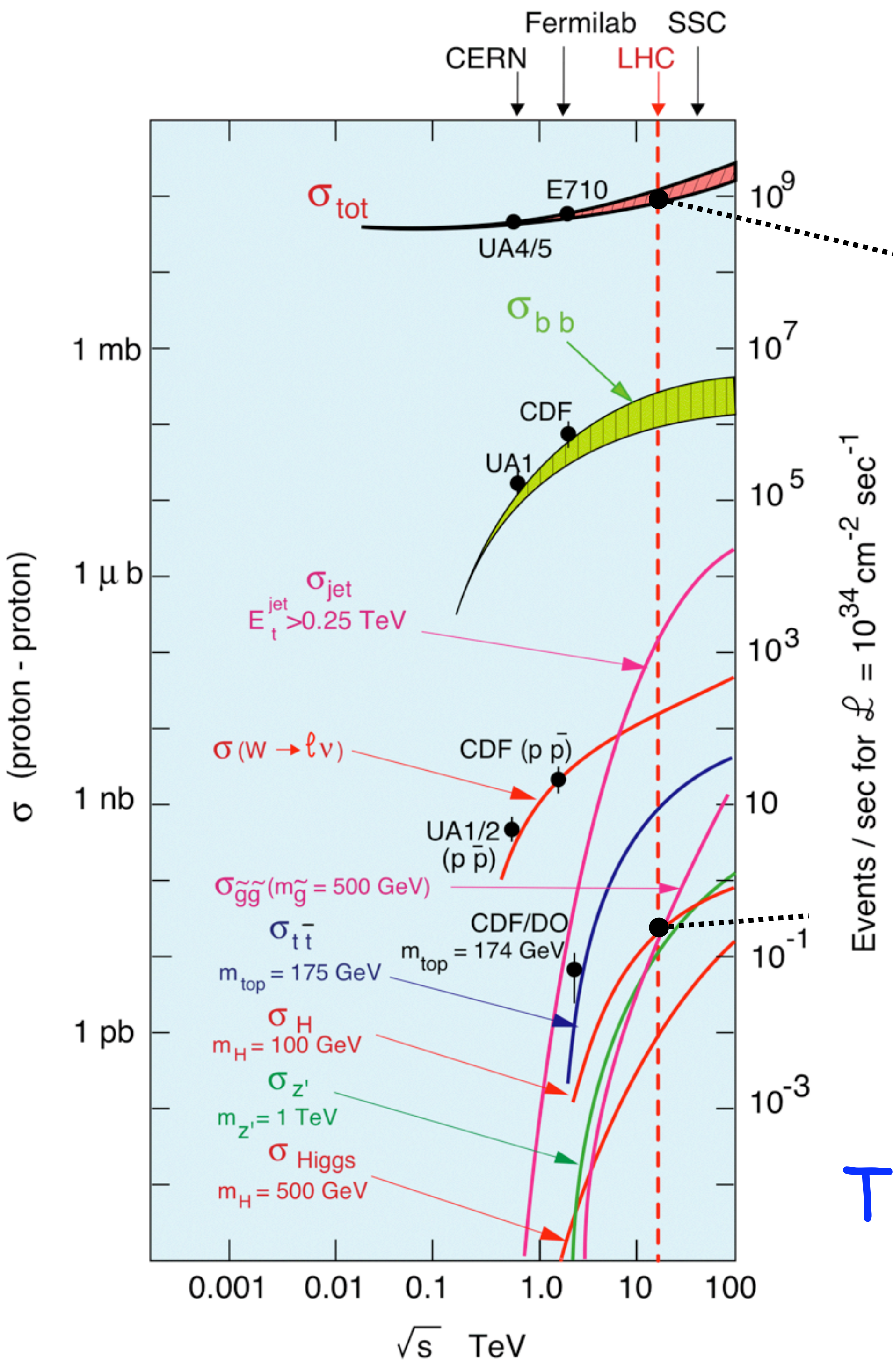
CMS February 2007

Central Section arrives underground

ATLAS vs. CMS

Silicon pixels; Silicon strips; Transition Radiation Tracker; 2 T magnetic field	Inner Detector	Silicon pixels, Silicon strips, 4 T magnetic field
Lead plates as absorbers; active medium: liquid argon; outside solenoid	Electrom. Kalorimeter	Lead tungsten ($PbWO_4$) crystals; both absorber and scintillator; inside solenoid
Central region: Iron absorber with plastic scintillating tiles; Endcaps: copper and tungsten absorber with liquid argon	Hadronic Calorimeter	Stainless steel and copper with plastic scintillating tiles
Large air-core toroid magnet; muon chambers: drift tubes and resistive plate chambers; 0.5 T magnetic field	Muon Chambers	Magnetic field from return yoke (solenoid field: 4 T); muon chambers: drift tubes and resistive plate chambers

A Needle in a Haystack



10^9 Events/sec

[1 Mbyte/Event]

10^{10}

Efficient
rate reduction needed
[Storage rate: 100 Hz]

10 Events/min

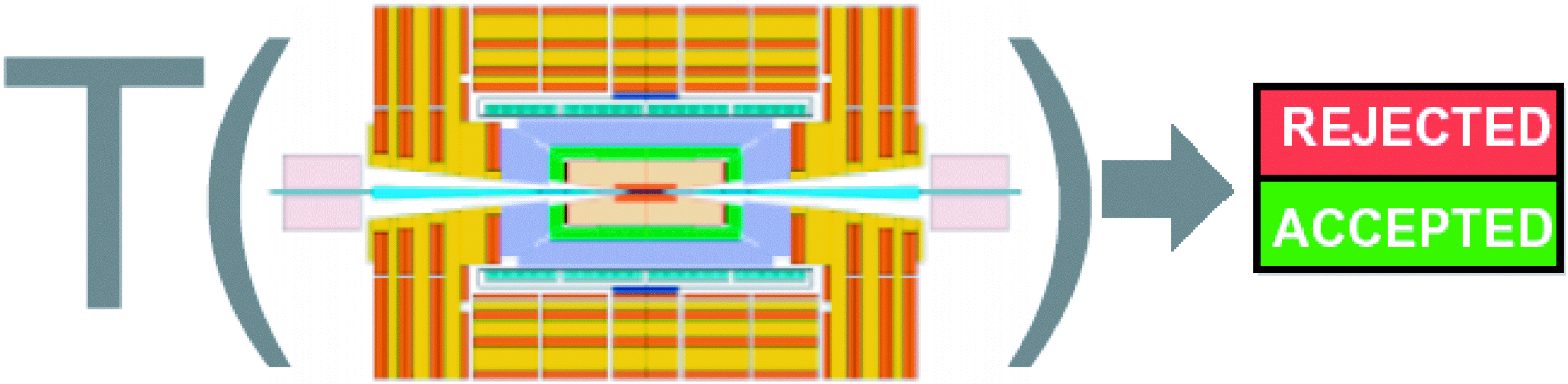
[$m_H \approx 100$ GeV]

with 0.2% $H \to \gamma\gamma$
1.5% $H \to ZZ$

Trigger !

Challenge 1: Fast Trigger System

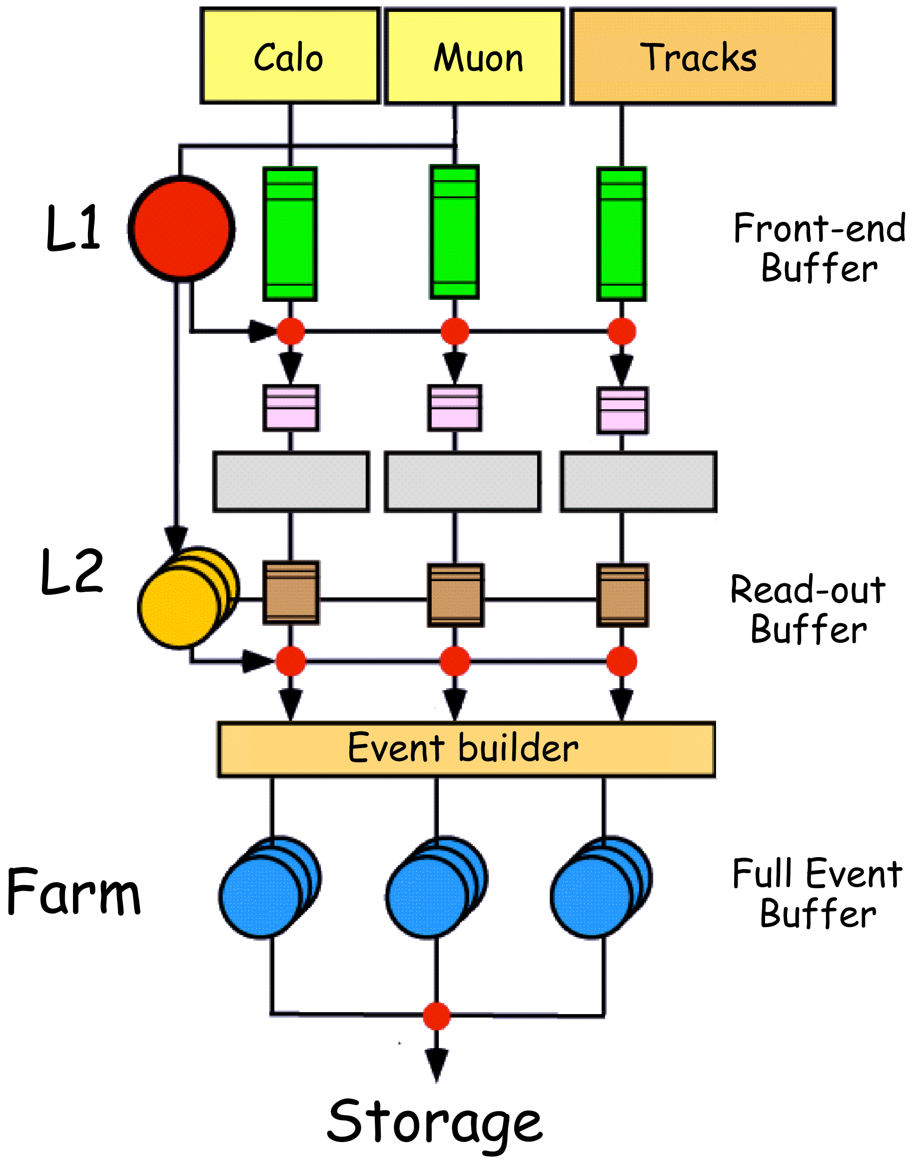
Fast selection of interesting Events
Number of necessary decisions: 40 million/sec



Function T(...) is highly complex
Detector data not directly available ➥ Stepwise decision

→ Trigger Levels

Challenge 1: Fast Trigger System



40 MHz

LEVEL-1 TRIGGER

- Hardware-Trigger [FPGAs & ASICs]
- Information from Calorimeter & muon system; low granularity
- 2 µs latency [2.5 µs piplines]

~75 kHz

LEVEL-2 TRIGGER

- Regions-of-Interest
- In principle full information of all subdetectors; high granularity
- O(10 ms) decision time

~2 kHz

EVENT FILTER

- Complete detector information
- Full event reconstruktion
- O(1 s) decision time

100 Hz

Example: The ATLAS L1 Trigger/DAQ system

LHC pp-Interaction Rate

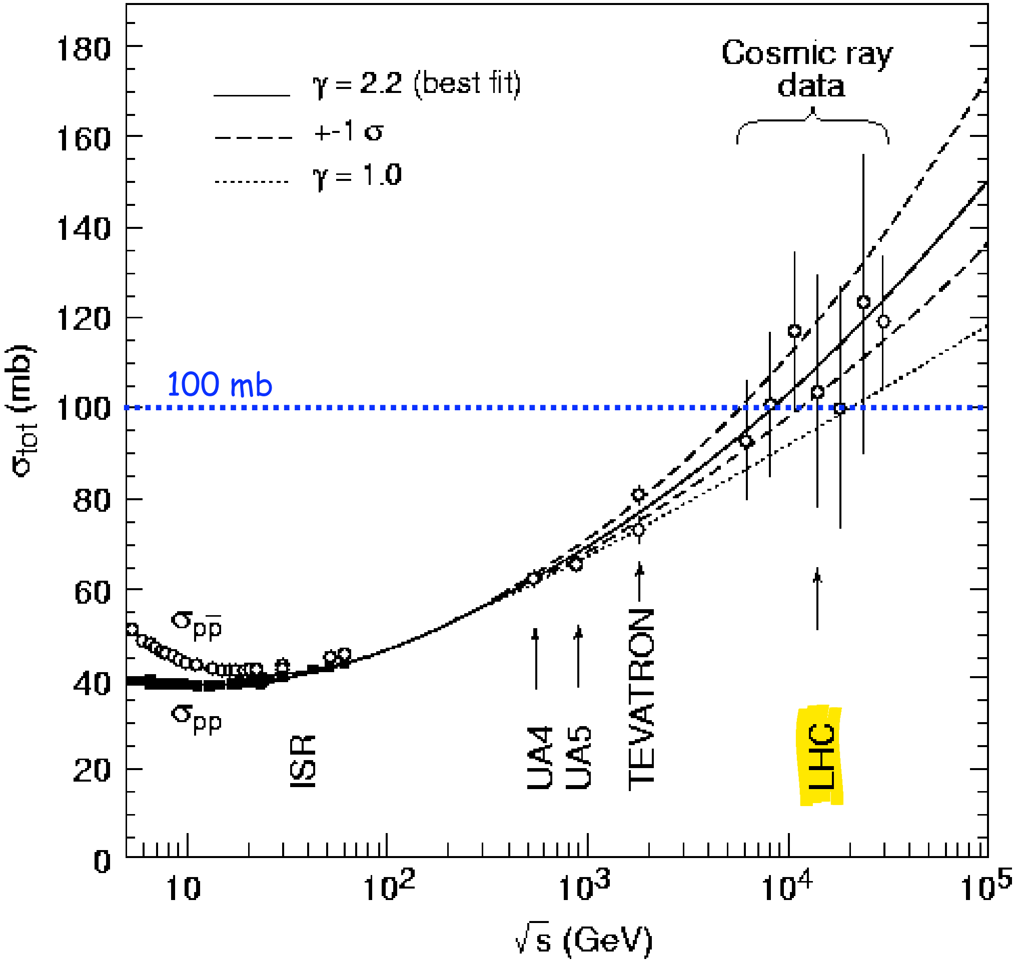
Luminosity:

$L = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
$= 10^{7}$ Hz/mb

Cross section:

$\sigma \approx 100$ mb

➥ $N = L\sigma \approx 1$ GHz



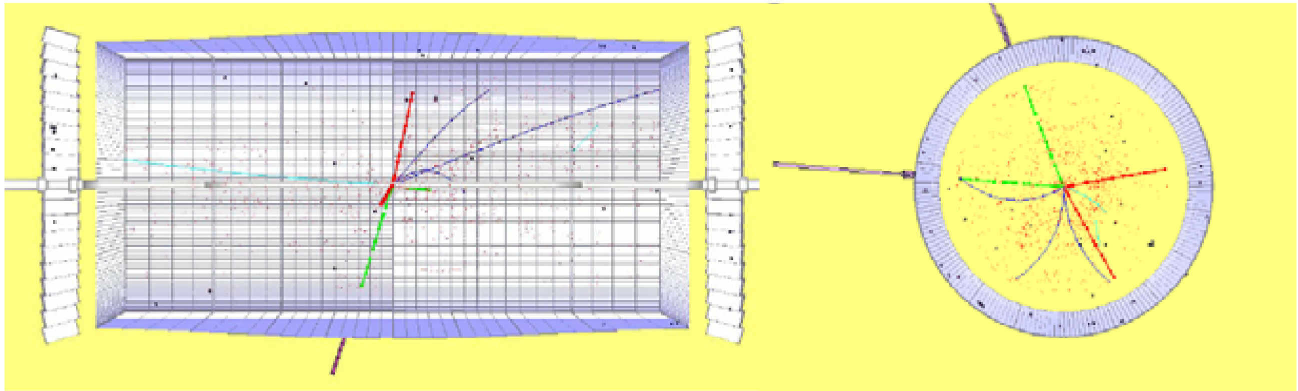
However:

Bunch crossing rate: 40 MHz

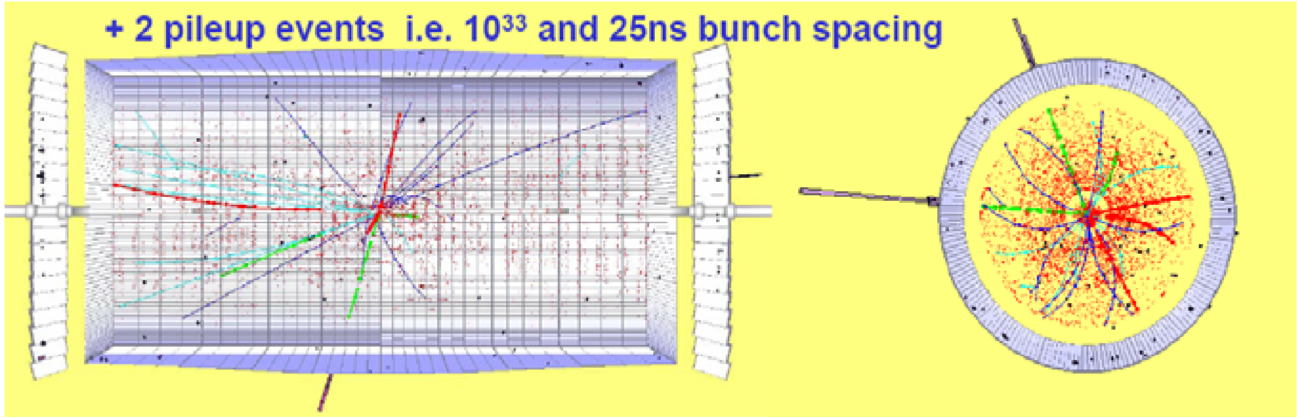
∴ Interactions/crossing ~ 25

This is a
real challenge !

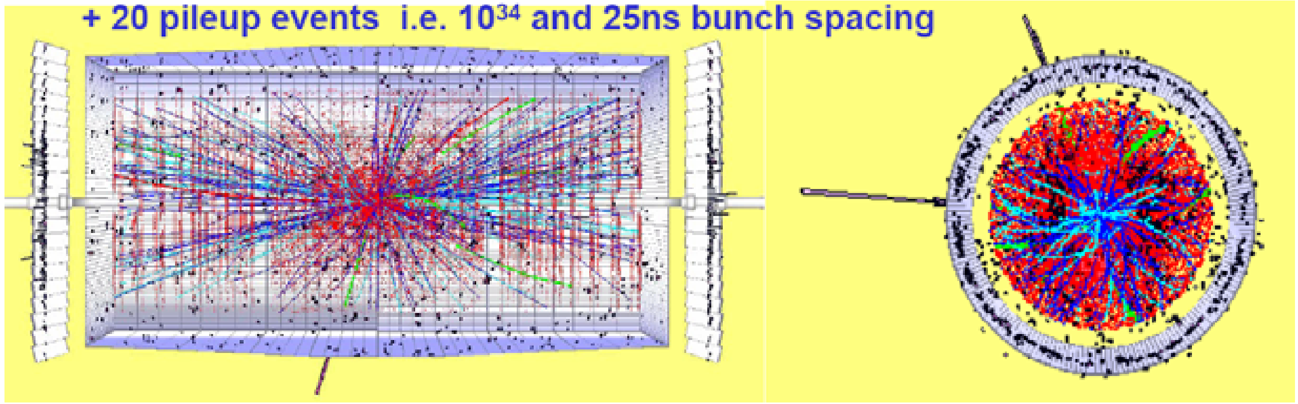
Challenge 2: Pile-up Events



Example: Z → μμee
[Golden Higgs Decay]



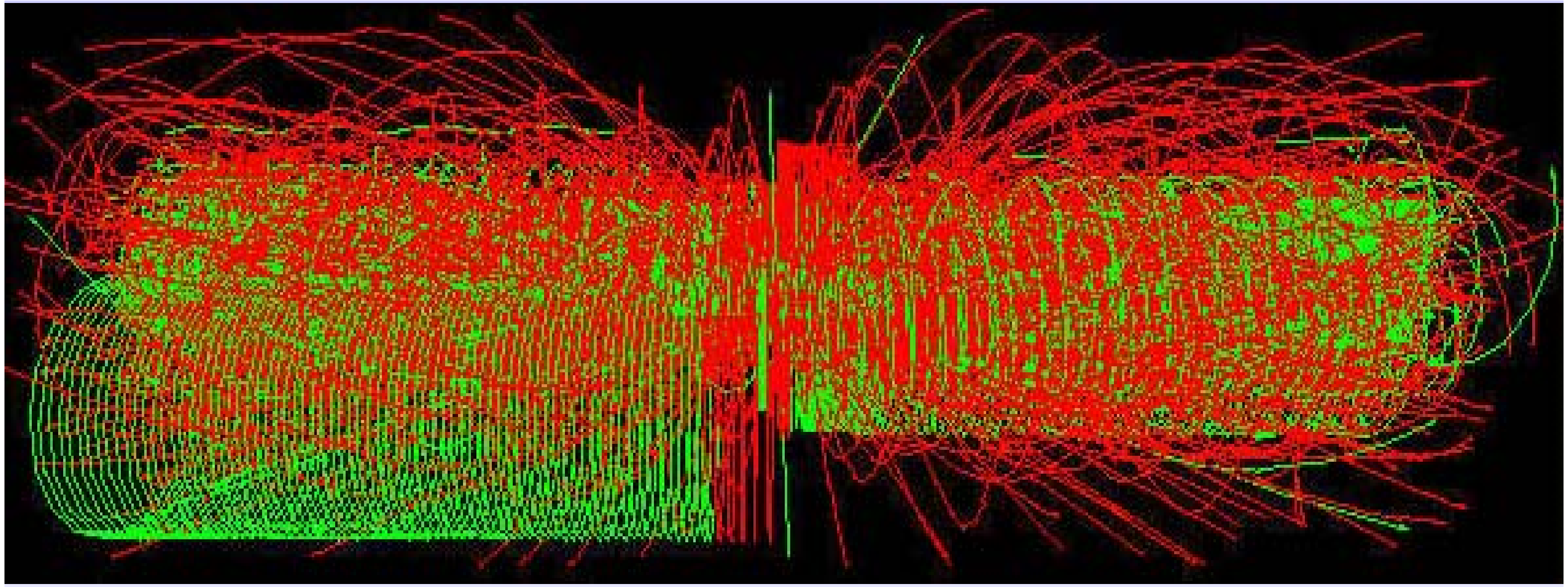
Low lumi
[First year]



High lumi
[Later ...]

Needs a good
understanding
of the detector

Challenge 2: Pile-up Events



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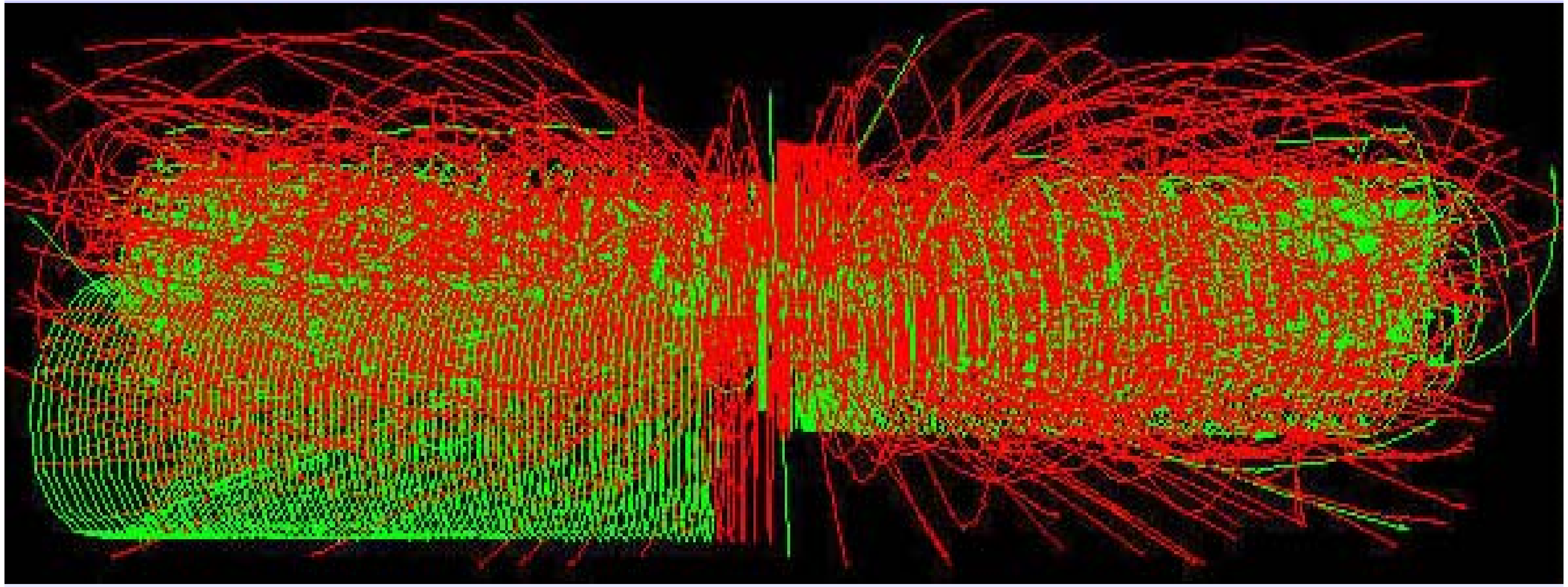
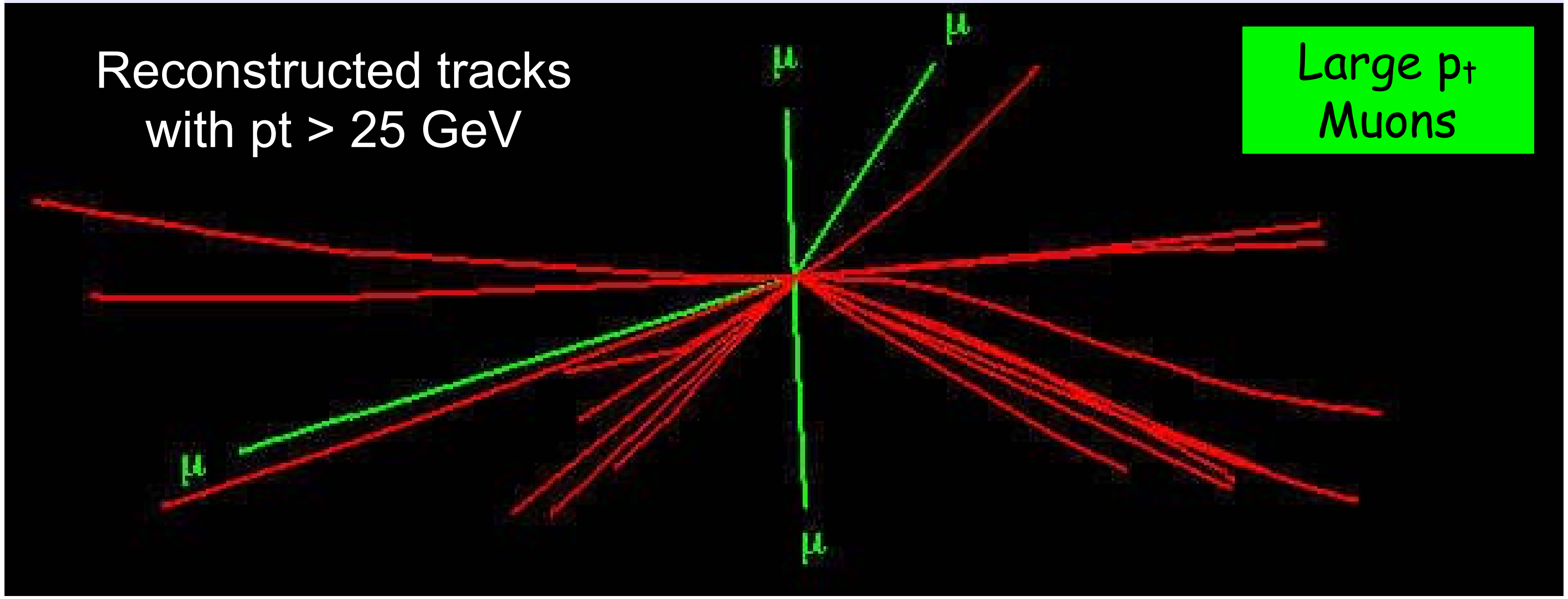
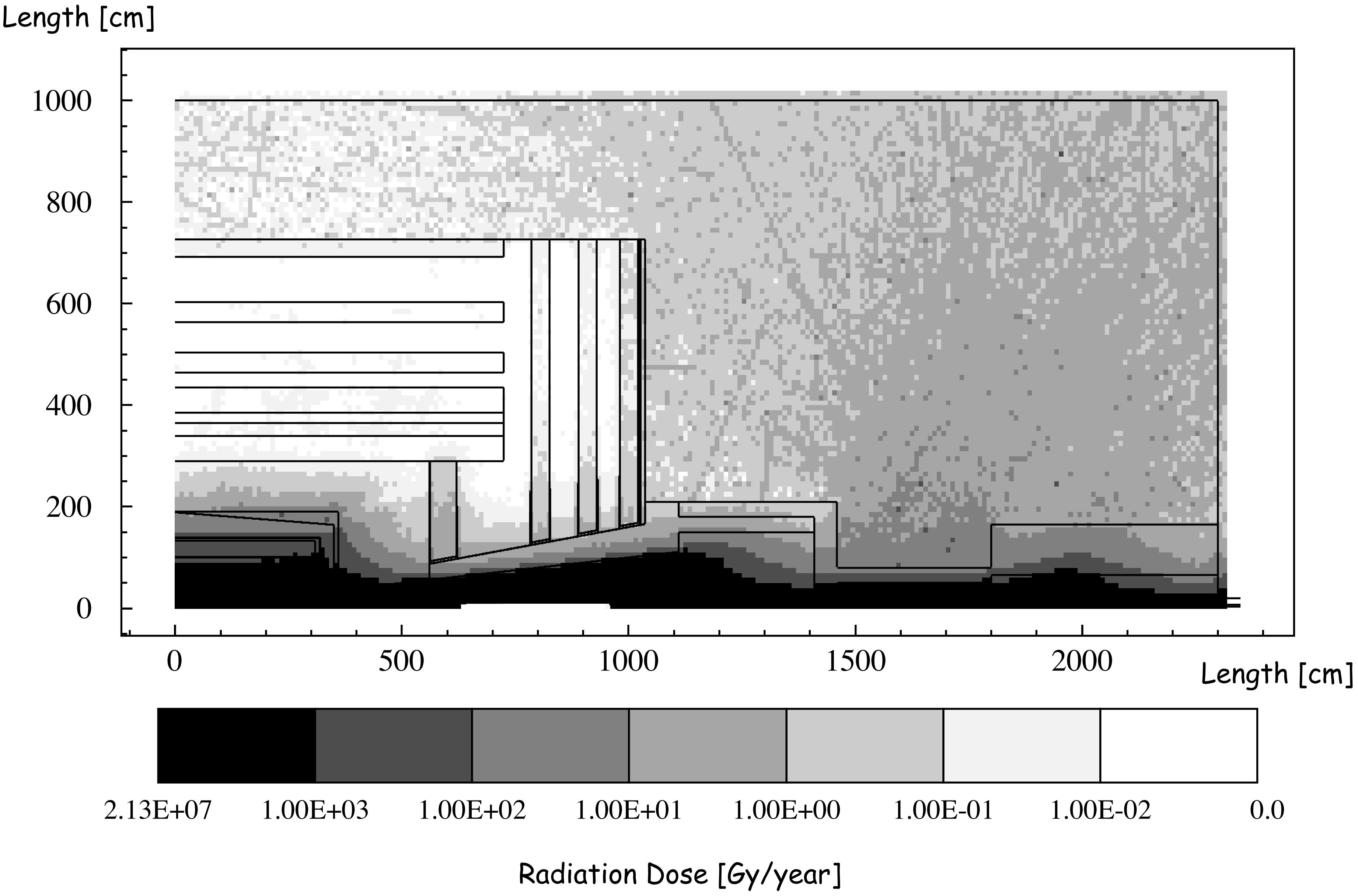




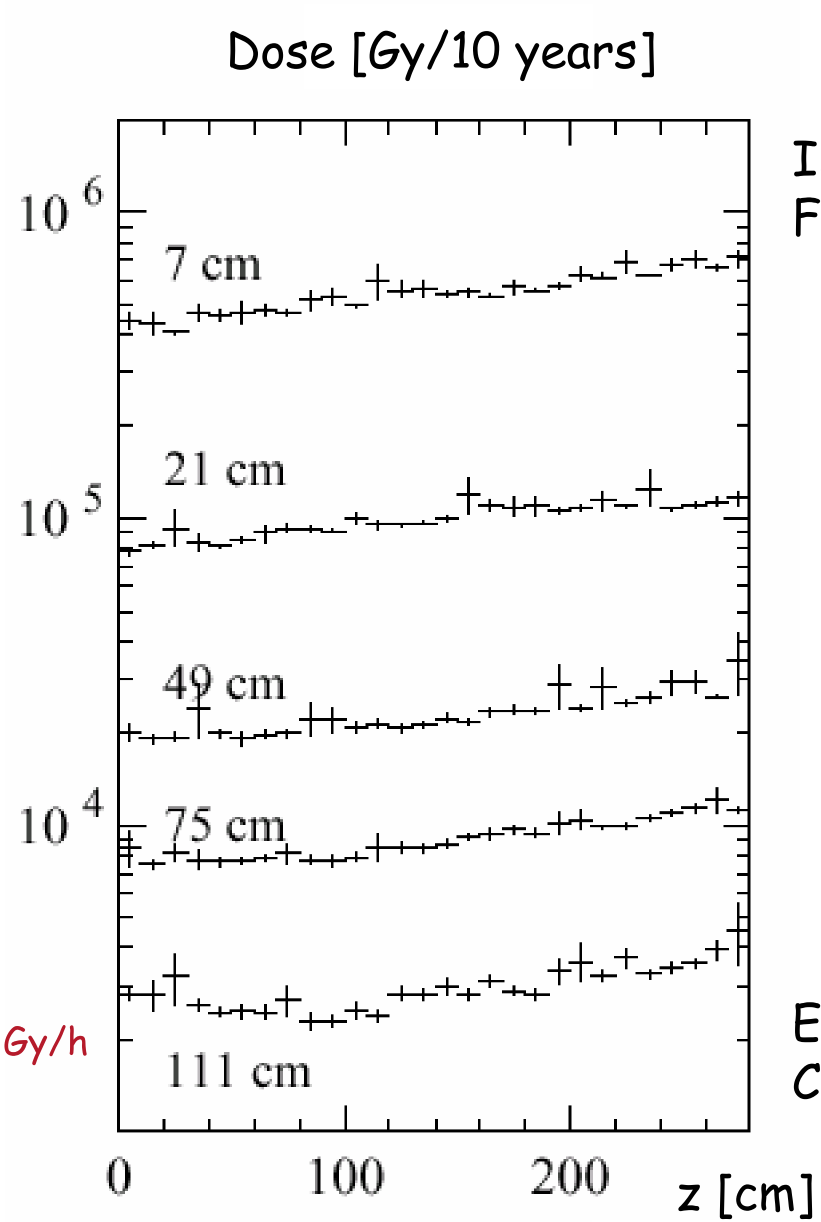
Reconstructed tracks
with pt > 25 GeV

Large p_t
Muons

Challenge 3: Radiation Environment



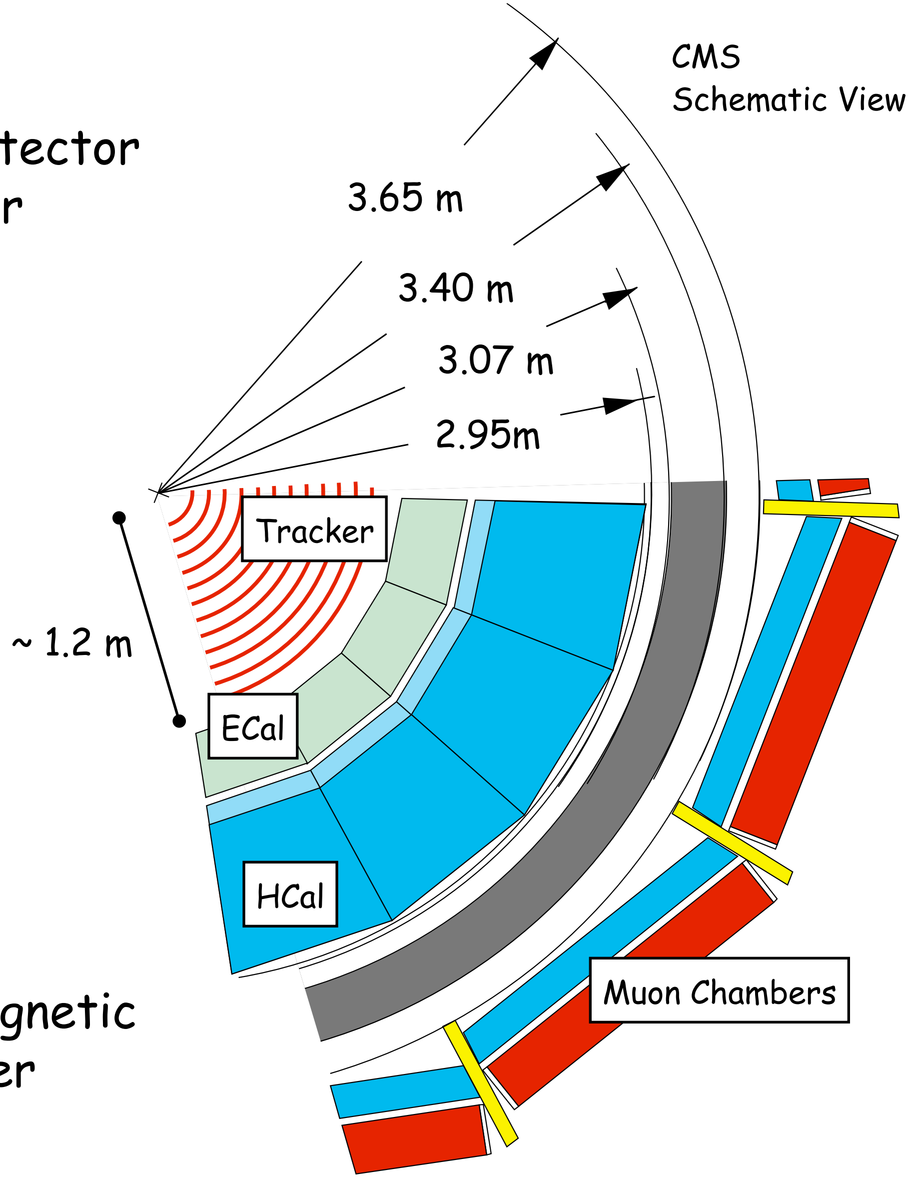
Challenge 3: Radiation Environment



Innter Detector First Layer

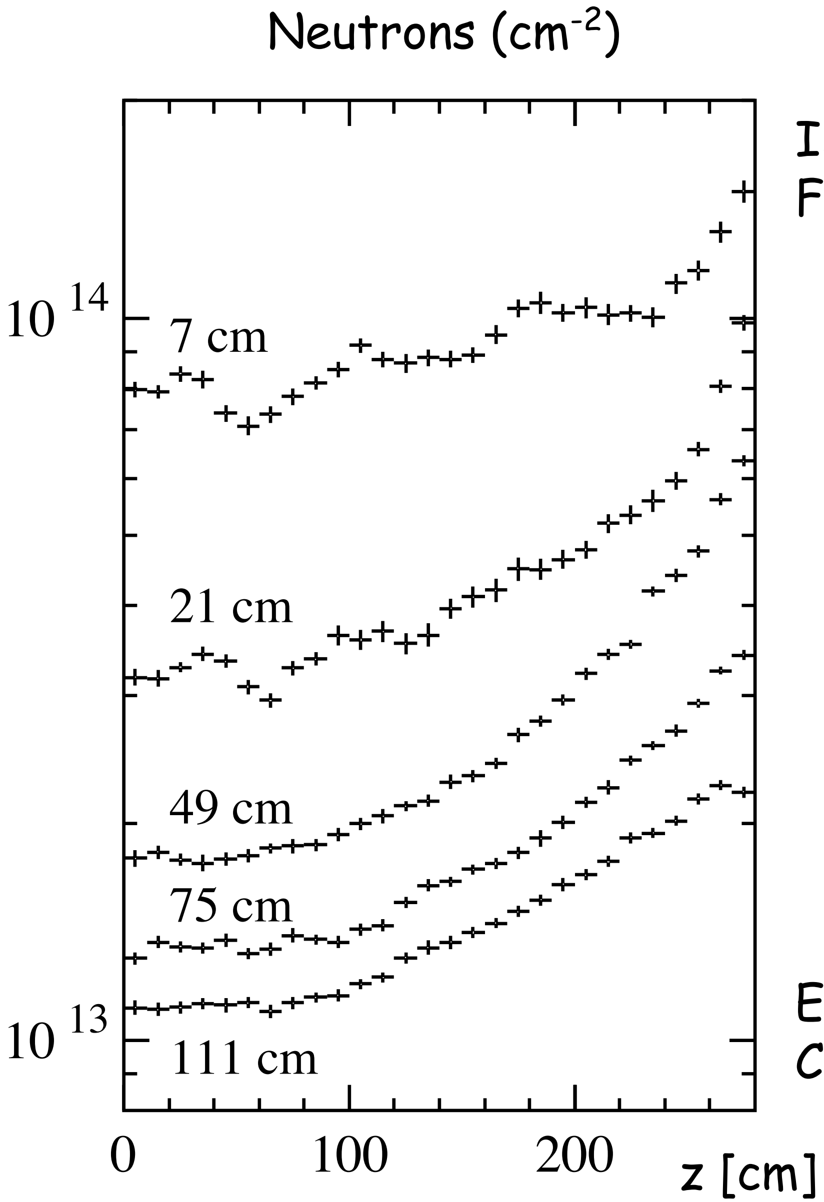
Electromagnetic Calorimeter

Note:
~.15 Gy/h



Lethal Dose: < 10 Gy

Challenge 3: Radiation Environment



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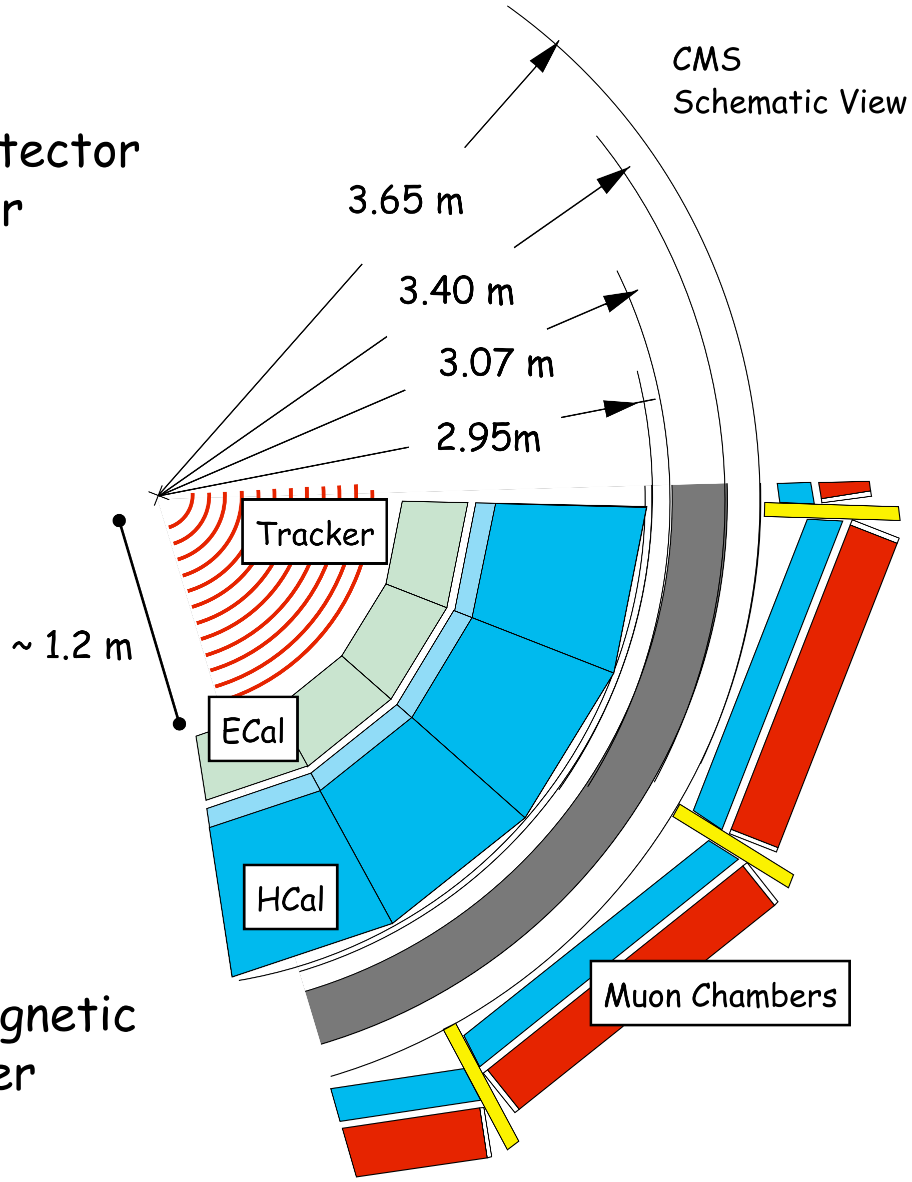
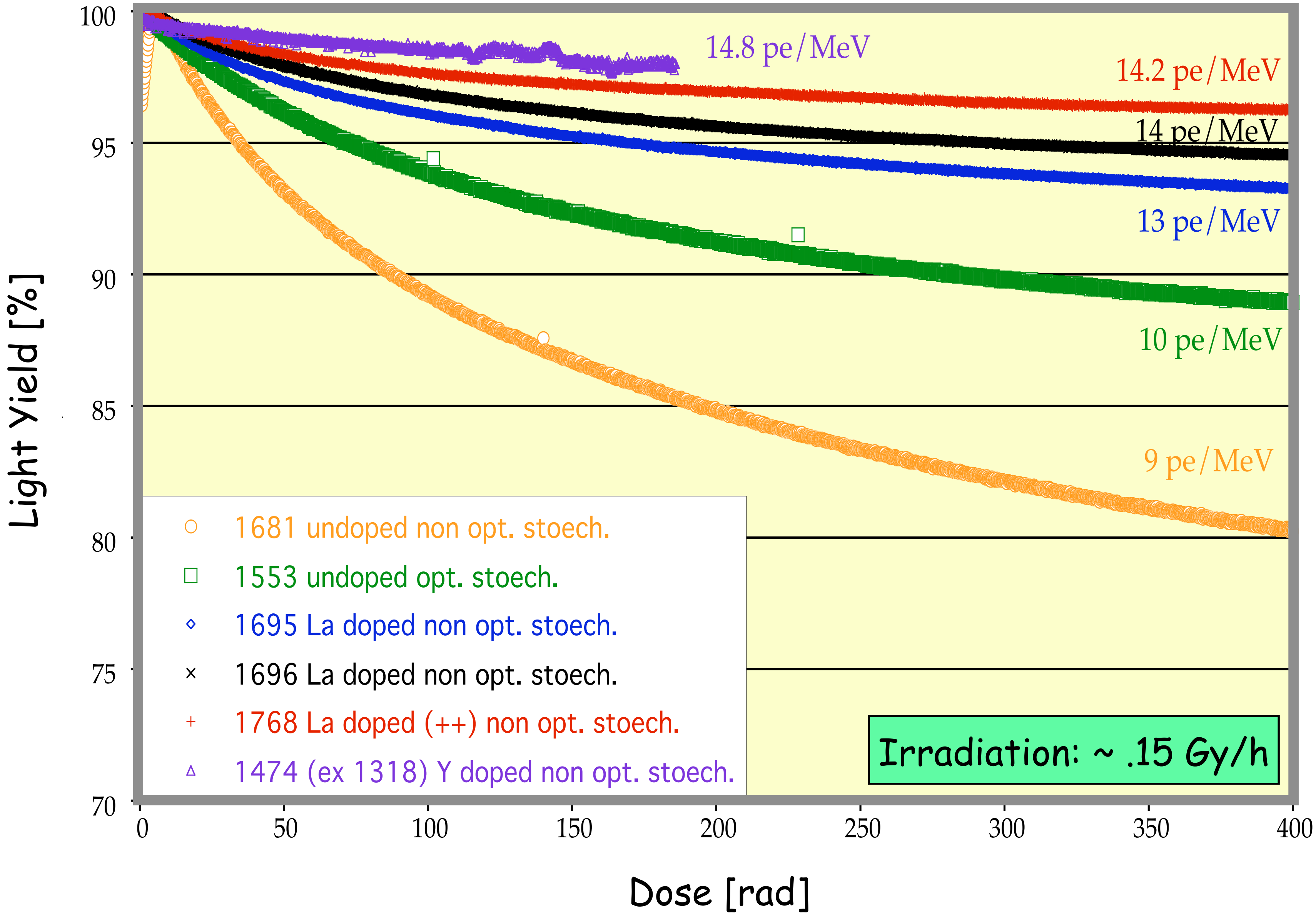


Lethal Dose: < 10 Gy

Example 1

Light Yield CMS ECAL Crystals



Transparency loss must be monitored for 0.5% energy resolution

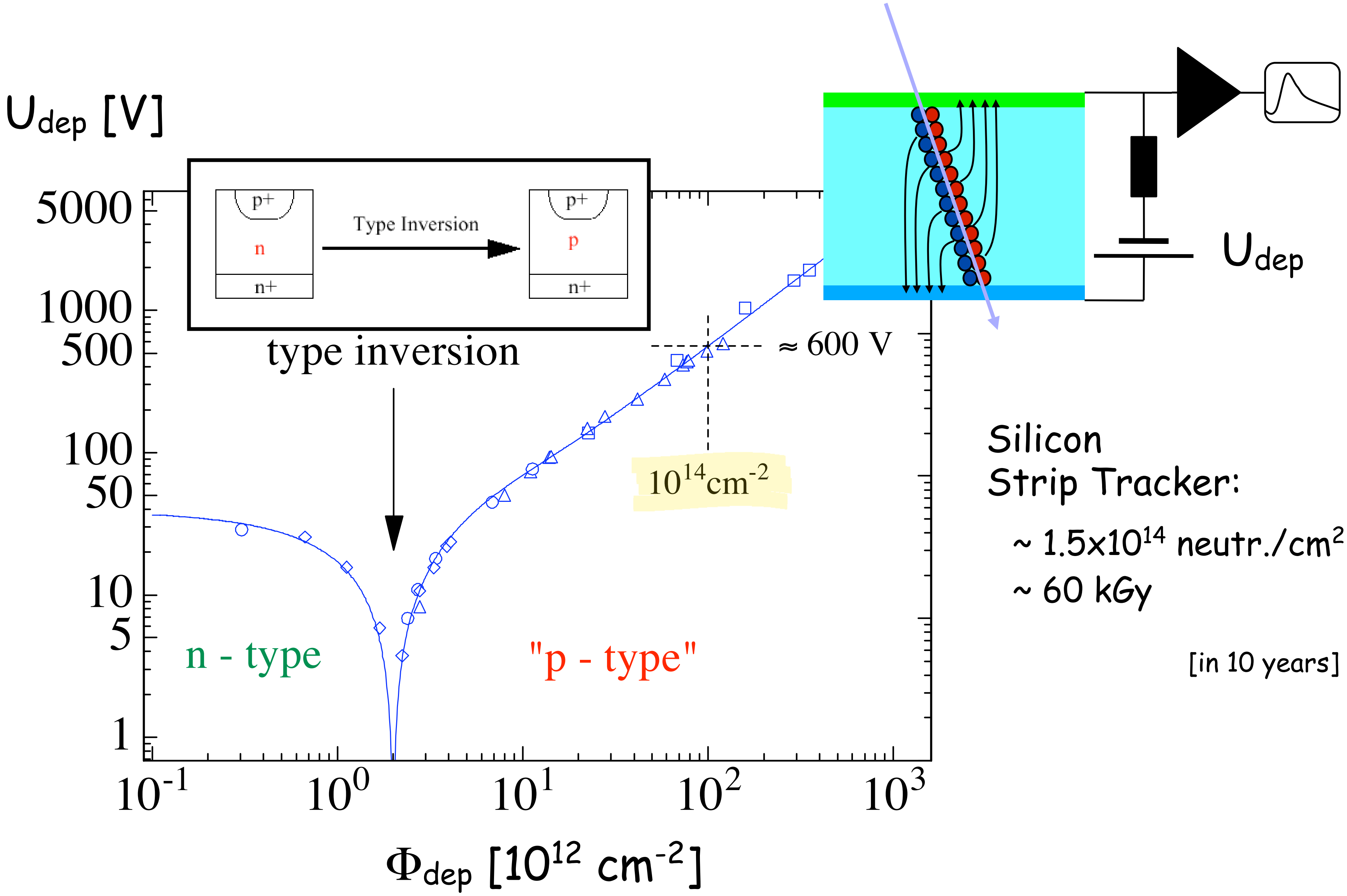
Fast laser monitoring system

Control at per mille level

4 Gy
[~ 1 day]

Example 2

Silicon Tracker Depletion Voltage



Silicon
Strip Tracker:

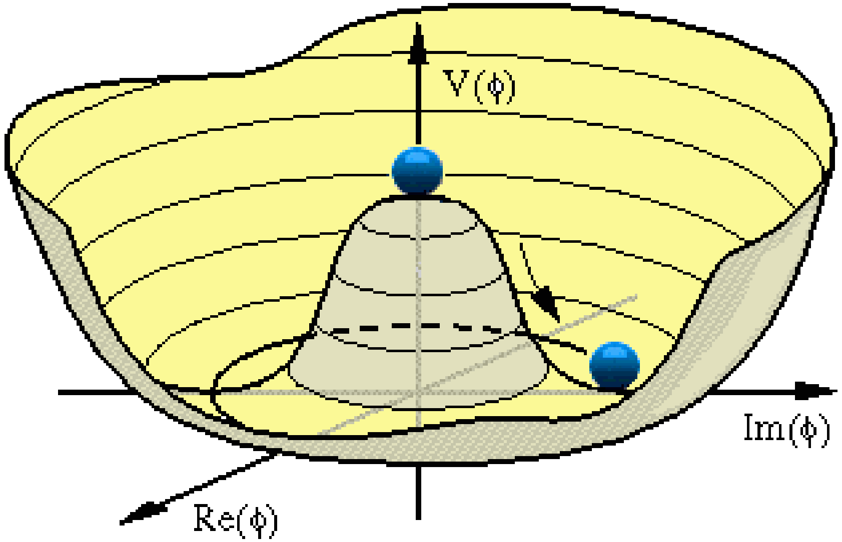
~ 1.5×10^{14} neutr./cm^2

~ 60 kGy

[in 10 years]

The Missing Piece

Searching the Higgs



The Standard Model Lagrangian

and elementary particle masses

kinetic & self-coupling
of gauge bosons

kinetic energy
of fermions

interaction between
fermions & fields

$$\boxed{\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^\mu\partial_\mu\psi + e\bar{\psi}\gamma^\mu A_\mu\psi}$$

SM Lagrangian without Higgs

where:

$$eA_\mu = \frac{g_s}{2}\lambda_\nu G^\nu_\mu + \frac{g}{2}\vec{\tau}\,\vec{W}_\mu + \frac{g'}{2}Y B_\mu$$

$$F_{\mu\nu}F^{\mu\nu} = G_{\mu\nu}G^{\mu\nu} + W_{\mu\nu}W^{\mu\nu} + B_{\mu\nu}B^{\mu\nu}$$

But: SU(2)$_L$ x U(1)$_Y$ symmetry forbids „ad hoc“ introduction of extra masses terms:

Fermions: $m\bar{\psi}\psi$

Bosons: $m^2 A_\mu A^\mu$

destroy gauge
invariance !

The Standard Model Lagrangian

and elementary particle masses

kinetic & self-coupling of gauge bosons

kinetic energy of fermions

interaction between fermions & fields

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But: $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ symmetry forbids „ad hoc“ introduction of extra masses terms:

Fermions: $m\bar{\psi}\psi$

Bosons: $m^2 A_{\mu}A^{\mu}$

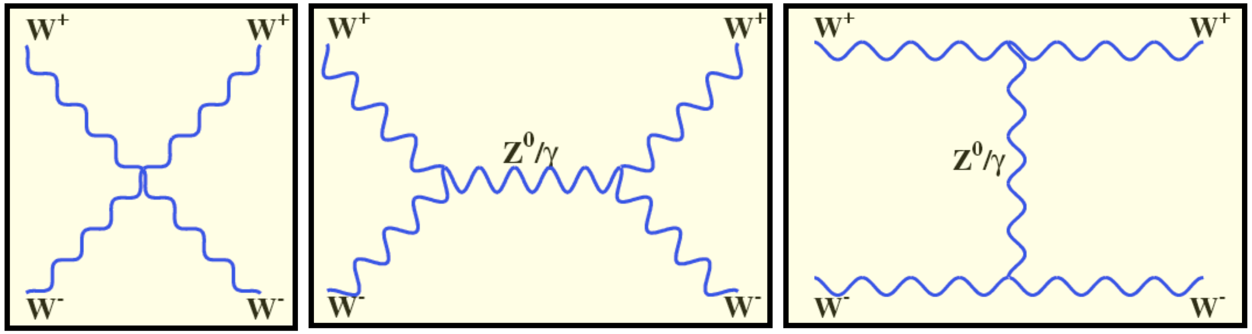
destroy gauge invariance !

But: particles do have mass

The Standard Model Lagrangian

WW scattering and unitarity violation

$F_{\mu\nu}F^{\mu\nu}$-term contains self couplings between gauge bosons.



massive gauge bosons: 2 transverse d.o.f. + 1 longitudinal d.o.f.
massless gauge bosons: 2 transverse d.o.f.

∴ WW → WW possible; cross section:

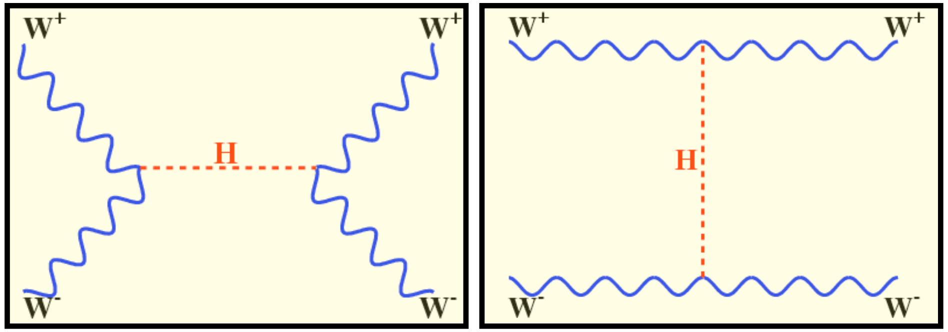
$$\sigma_{W_L W_L} \sim E_{cm}^2$$

$W_L W_L$ scattering probability becomes larger than unity for $E_{cm} > 1.2$ TeV ...
Violation of unitarity if force remains weak at this scale ...

To restore unitary it needs some scalar boson "H" with

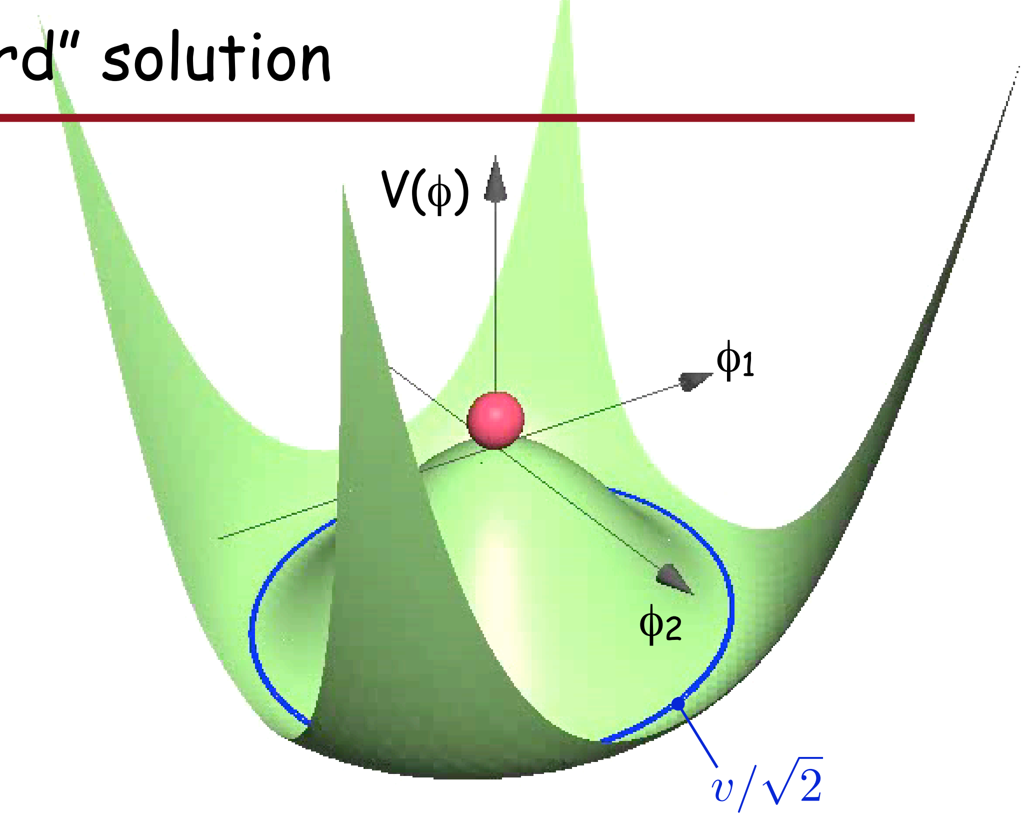
$$\left.\begin{array}{ll} g_{HWW} & \sim M_W \\ g_{Hff} & \sim M_f \\ M_H & < 1\ \text{TeV} \end{array}\right\} \sigma \to \text{const}$$

for large energies



The Higgs-Kibble Mechanism

The “standard” solution



Introduce new doublet of complex scalar fields (4 degrees of freedom) with ‘mexican hat’ potential:

$$V(\phi) = -\mu^2|\phi^\dagger\phi| + \lambda|\phi^\dagger\phi|^2$$

$$\text{with} \;\; \mu, \lambda > 0$$

Lagrangian of scalar field:

$$\mathcal{L}_\phi = (\partial_\mu\phi^\dagger)(\partial^\mu\phi) - V(\phi)$$

Coupling to bosons via transistion to covariant derivative.
Coupling to fermions via “ad-hoc” introduction of “Yukawa” coupling.

$$\mathcal{L}_\phi = (D_\mu\phi^\dagger)(D^\mu\phi) - V(\phi) \quad \text{with} \quad D_\mu = \partial_\mu + ieA_\mu$$

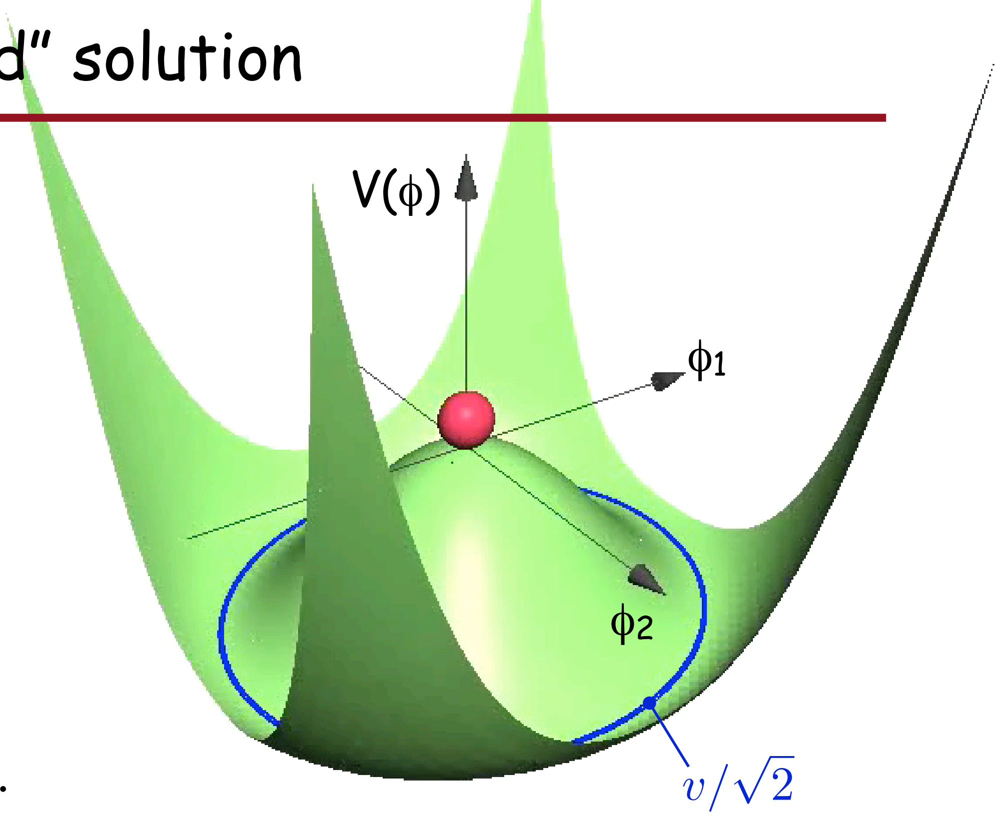
$$\mathcal{L}_{\text{Yuk}} = c_f(\bar{\psi}_L\psi_R\phi + \bar{\psi}_R\psi_L\phi)$$

Introduction into SM Lagrangian maintains invariance under $SU(2)_L$ x $U(1)_Y$ gauge transformation

The Higgs-Kibble Mechanism

The “standard” solution

Introduce new doublet of complex scalar fields (4 degrees of freedom) with ‘mexican hat’ potential:



$$V(\phi) = -\mu^2|\phi^\dagger\phi| + \lambda|\phi^\dagger\phi|^2$$

$$\text{with } \mu, \lambda > 0$$

Spontanous symmetry breaking:

System falls in to minimum of V at $\phi \neq 0$.

This results in:

- Three massless excitations along valley → 3 longitudinal d.o.f for $W^\pm$ and Z
- One massive exciation out of valley → 1 d.o.f for „physical“ Higgs boson

Higgs field has two components: $\phi = v + H$.

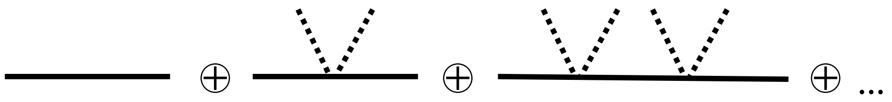
1. omnipresent, constant background condensate v = 247 GeV (from G_F)
2. Higgs boson H with unknown mass $M_H = \mu \cdot \surd 2 = (\lambda v)^{\frac{1}{2}} \cdot \surd 2$

Mass generation

and the couplings to the higgs boson

Interaction with „ether" v=247 GeV:

$M_V \sim gv$ (gauge coupling)
$m_f \sim g_f v$ (Yukawa coupling)



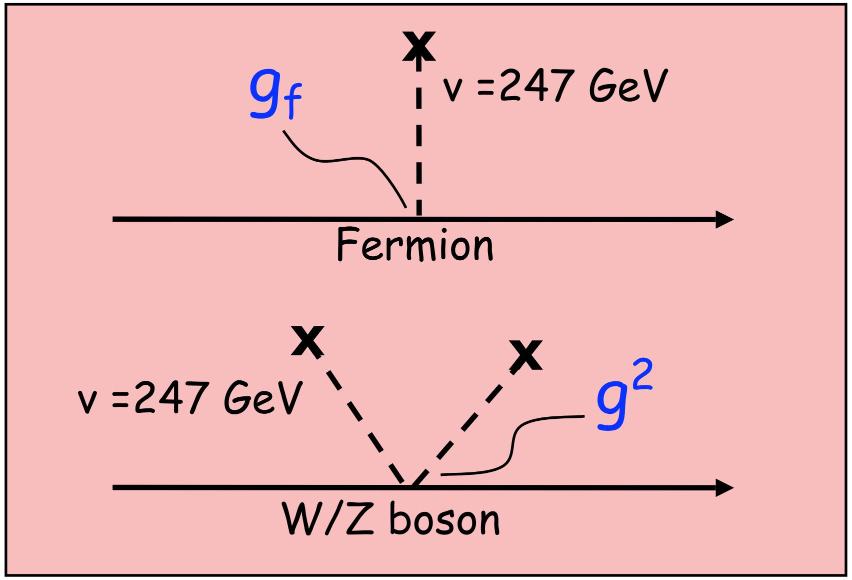
$$\left(\frac{1}{q^2}\right) \qquad \left(\frac{gv}{\sqrt{2}}\right)^2\left(\frac{1}{q^2}\right) \qquad \left(\frac{gv}{\sqrt{2}}\right)^4\left(\frac{1}{q^2}\right)$$

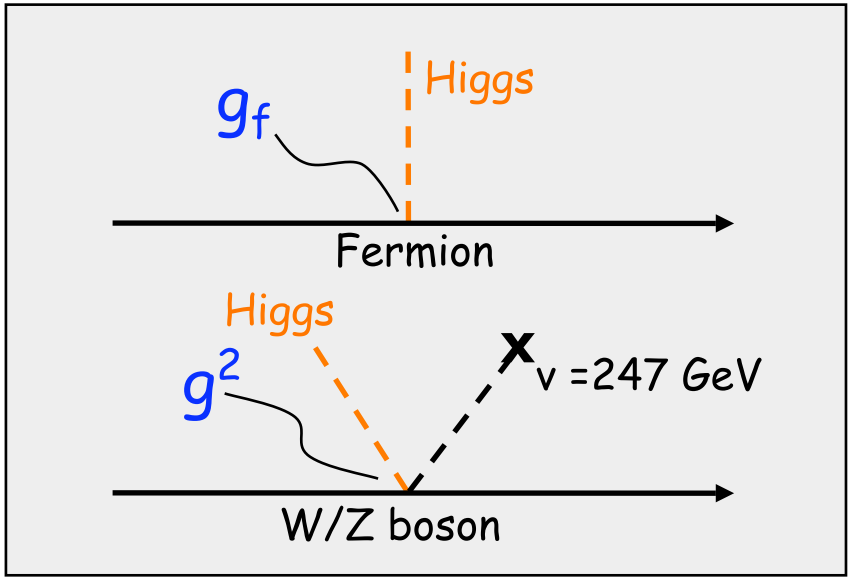
... =

$$\frac{1}{q^2 - M^2} \quad \text{where} \quad M^2 = g^2\frac{v^2}{2}$$

Interaction with Higgs boson H:

Fermions: $g_f \sim m_f/v$
W/Z bosons: $g_V \sim M_V^2/v = g^2 v$





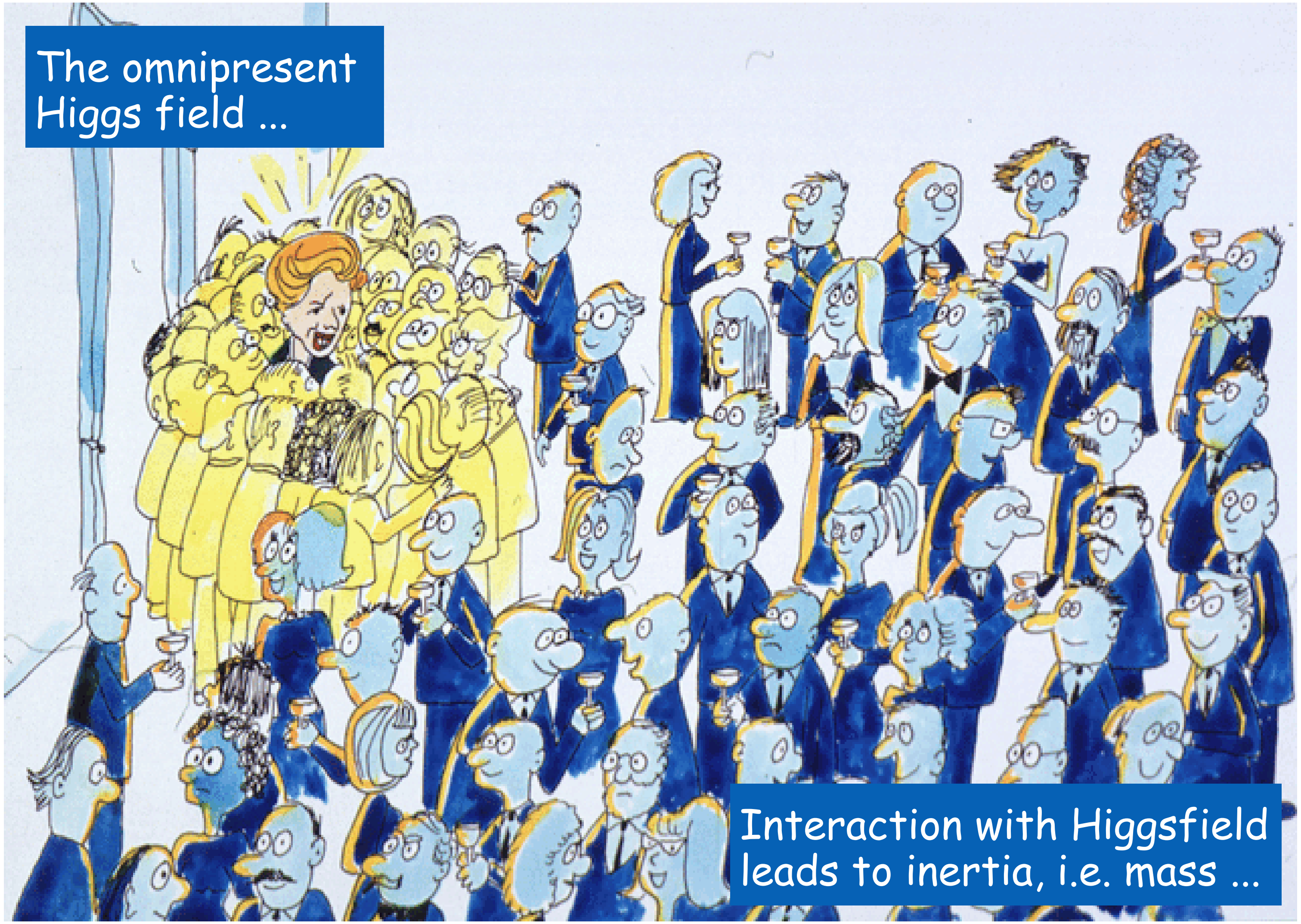
A Simple Picture

Generation of particle masses

The omnipresent Higgs field ...

A Simple Picture

Generation of particle masses

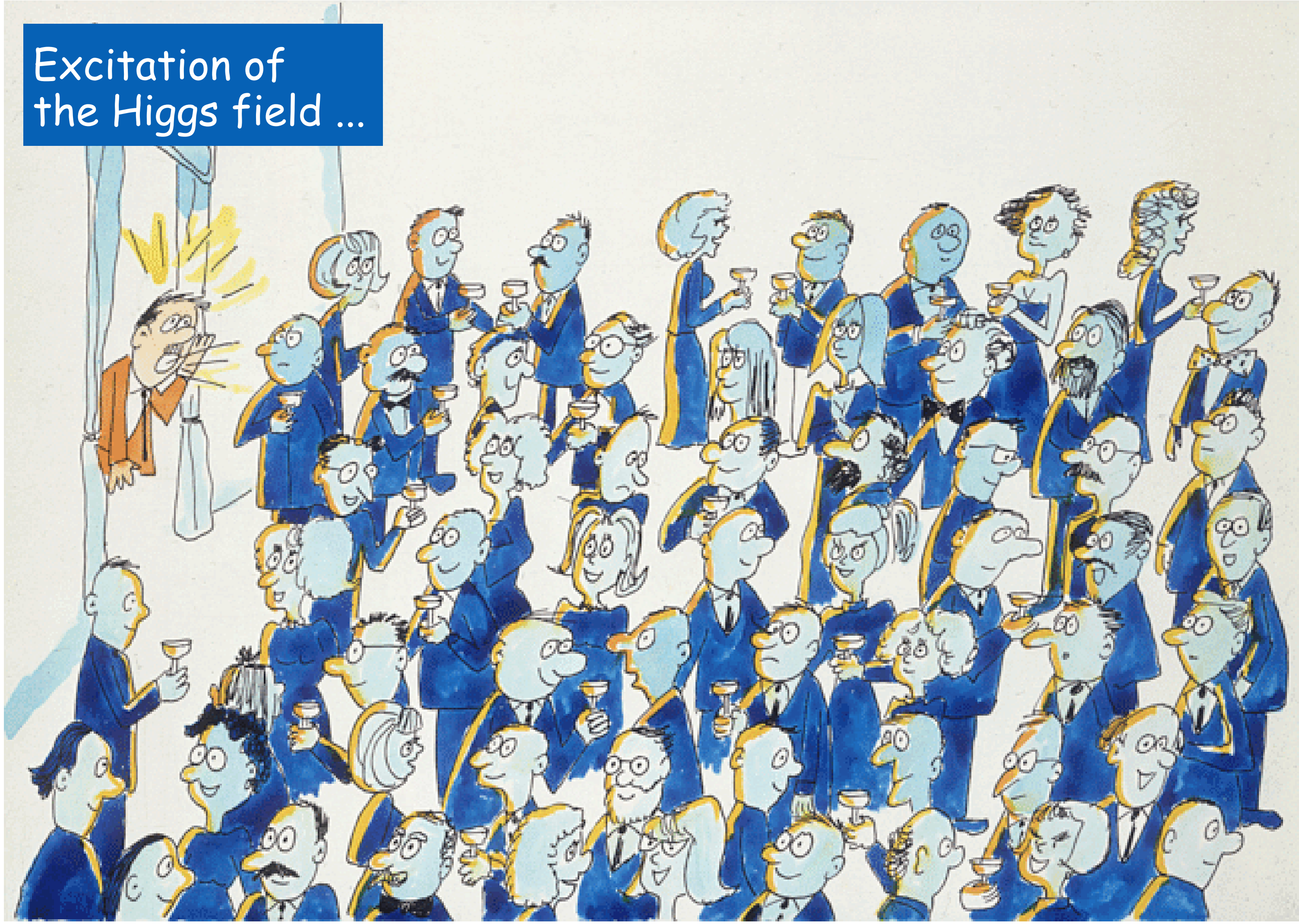


The omnipresent Higgs field ...

Interaction with Higgsfield leads to inertia, i.e. mass ...

A Simple Picutre

Generation of the Higgs mass



Excitation of the Higgs field ...

A Simple Picutre

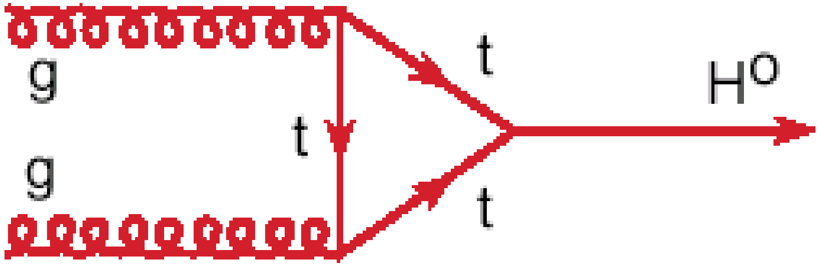
Generation of the Higgs mass

Excitation of
the Higgs field ...

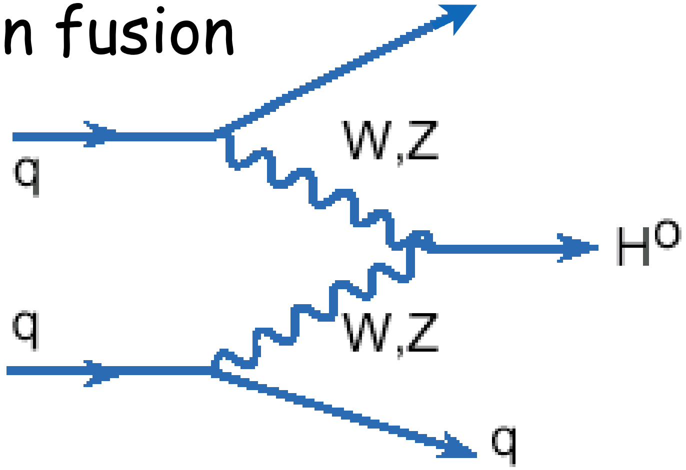
... results in
massive Higgs boson.

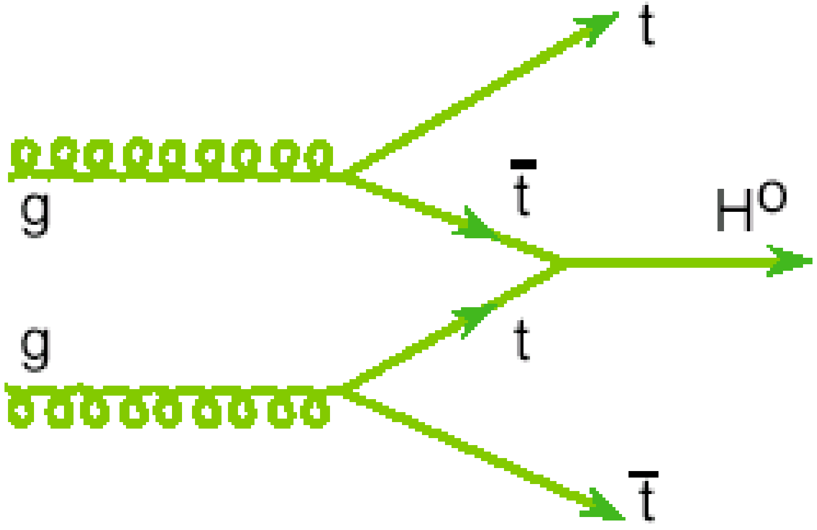
Higgs Production Mechanisms

1. Gluon fusion

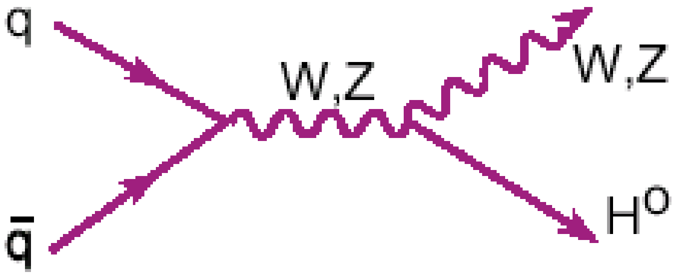


2. Vector
boson fusion



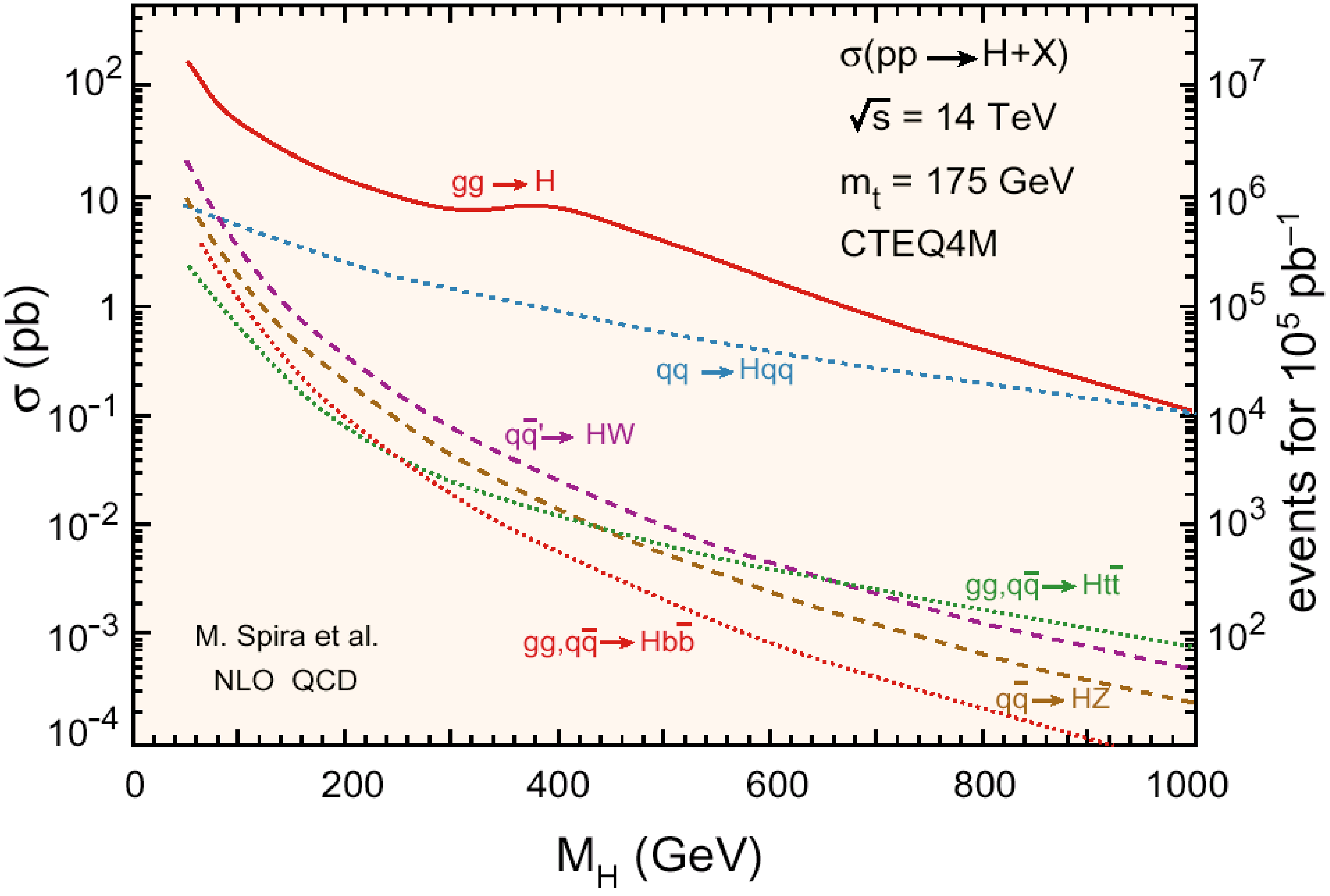


3. $t\bar{t}$-fusion

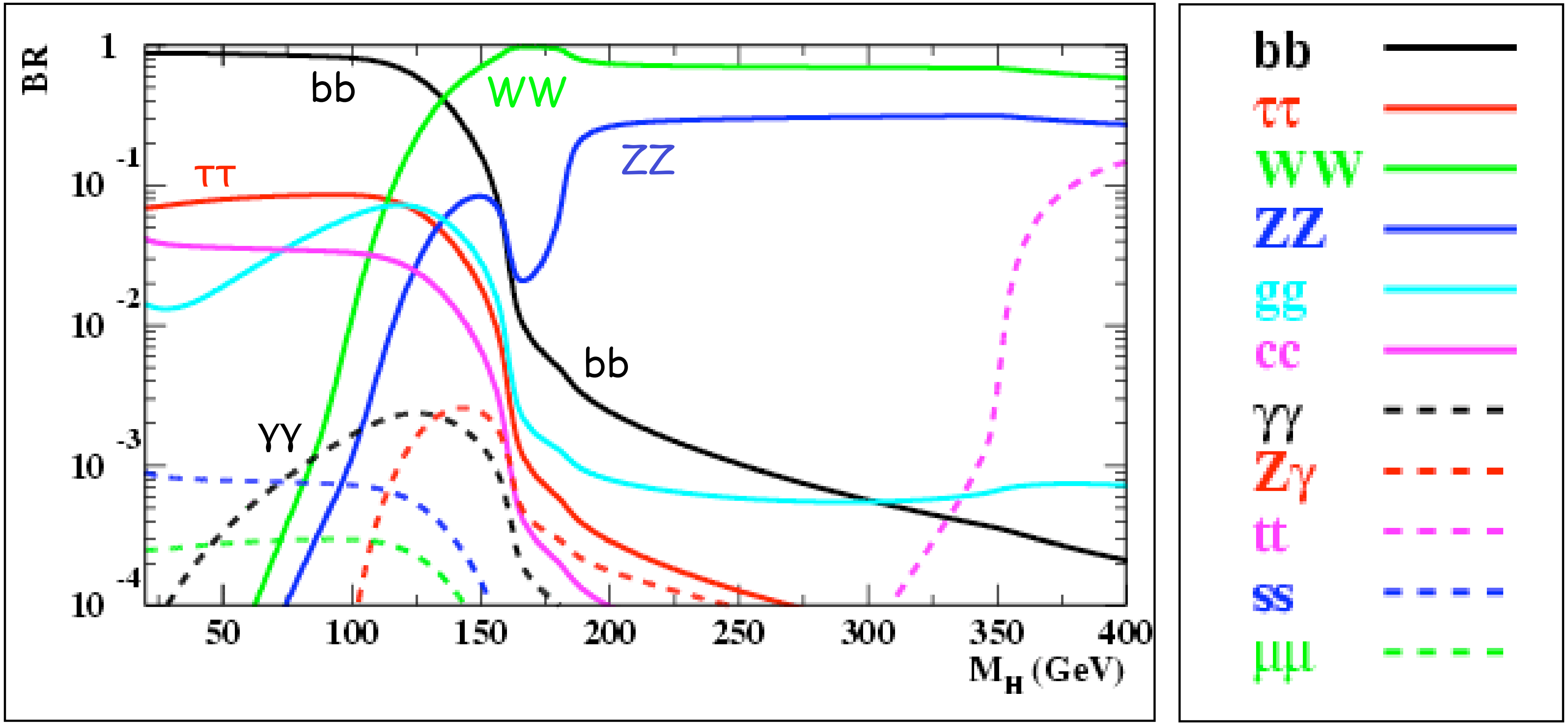


4. Associated
production

Higgs Production Cross Sections



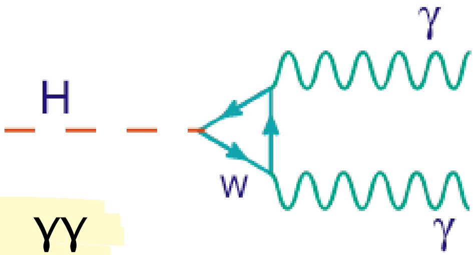
Higgs Boson Decays



For M < 135 GeV: H → bb, ττ dominant

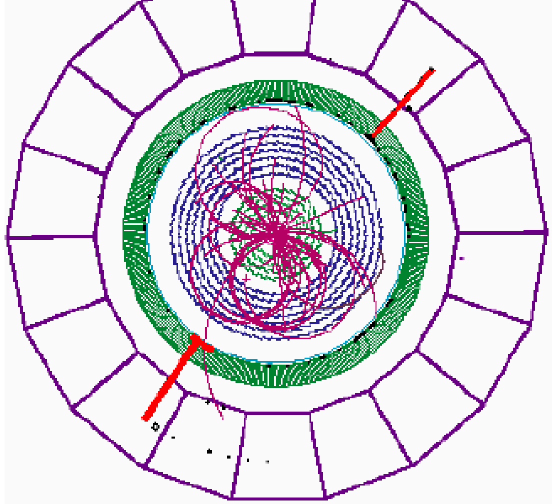
For M > 135 GeV: H → WW, ZZ dominant

Tiny but also important: H → γγ

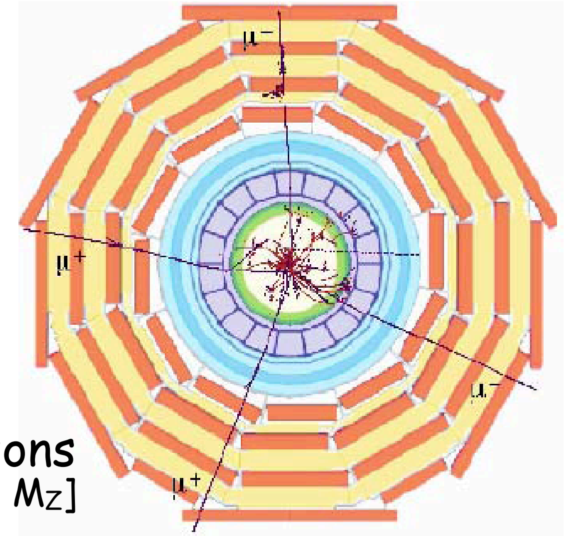


Higgs Searches @ LHC: Examples

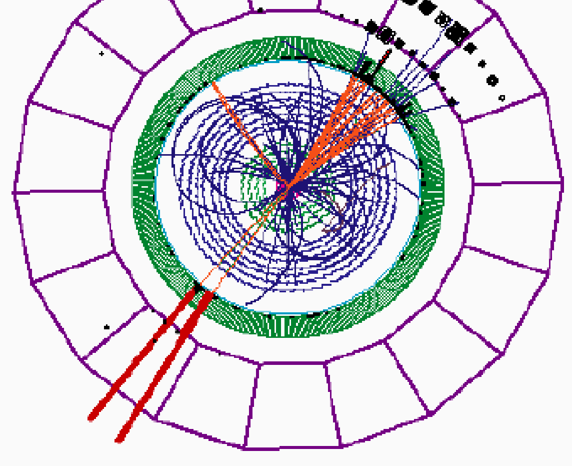
Two high-energy photons

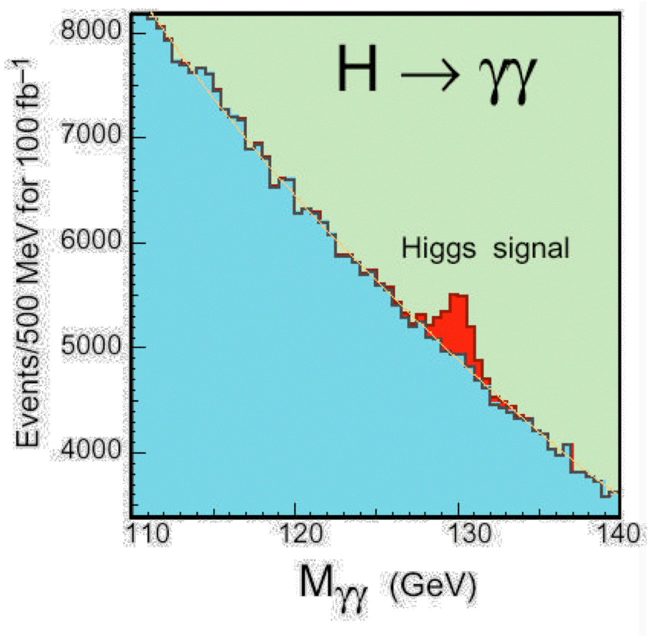


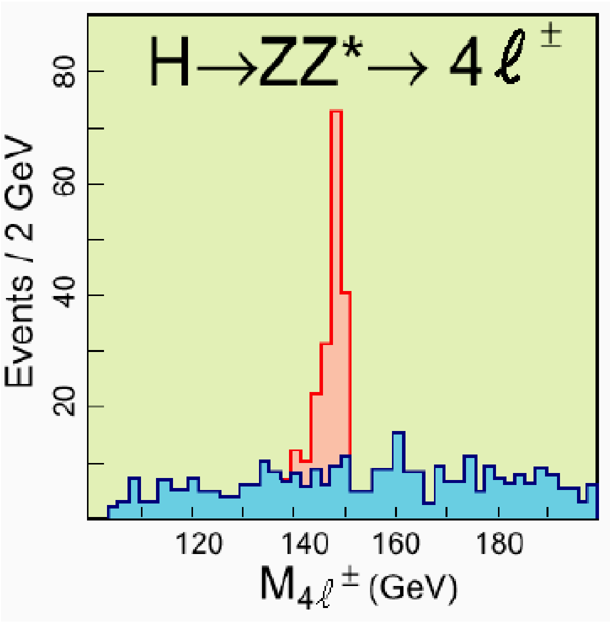
4 muons
[$M_{\mu\mu} = M_Z$]

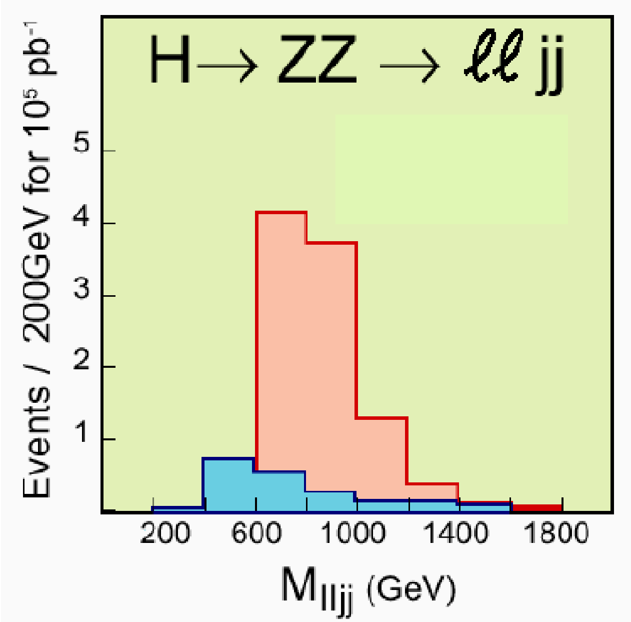


2 eletrons
2 jets



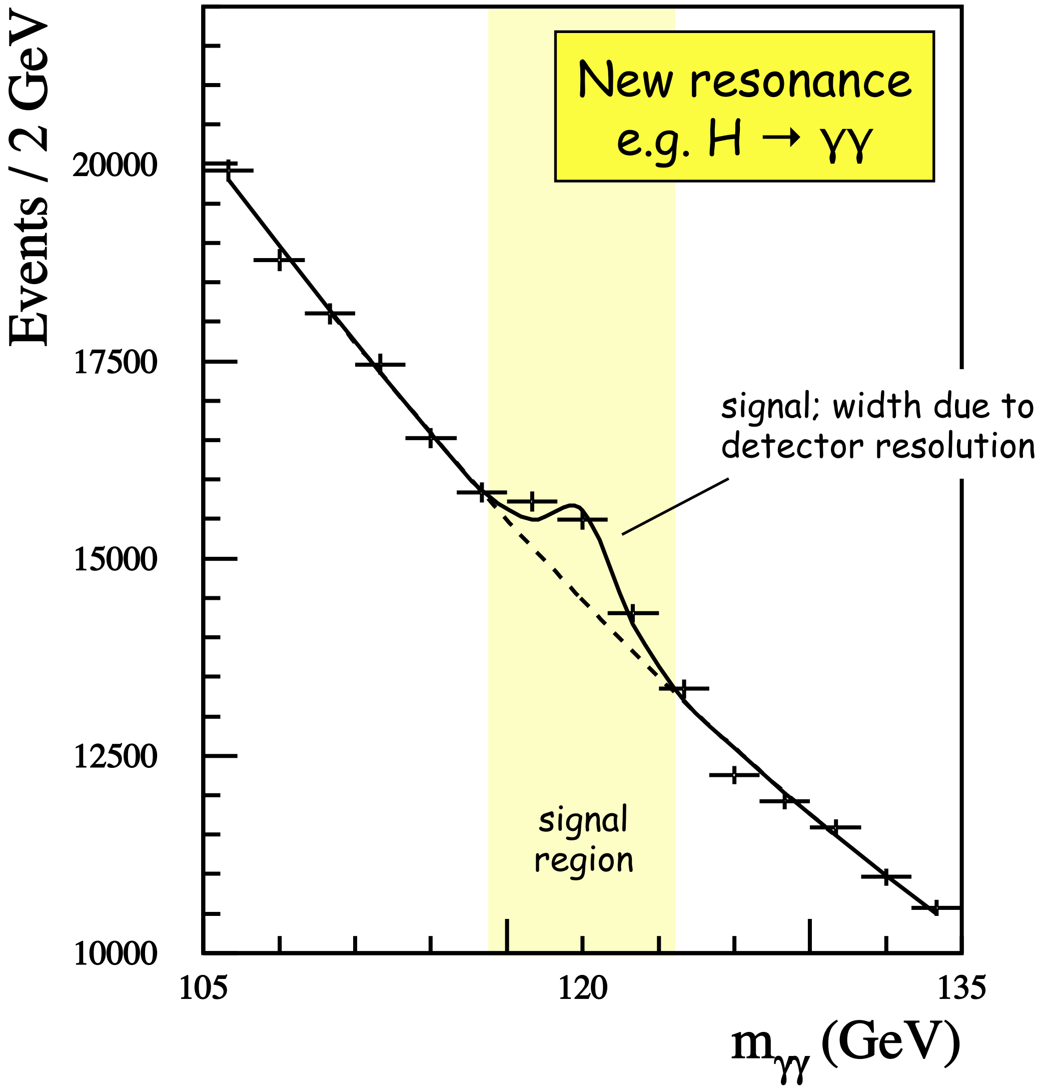






How to Make a Discovery

Signal significance



Signal significance:

$$S = \frac{N_S}{\sqrt{N_B}}$$

N_S: # signal events
N_B: # background events

... in peak region

S > 5:

Signal $N_S = N_{tot} - N_B$ is 5 times larger than uncertainty $\sqrt{N_B}$ on background;

Gaussian probability that background fluctuates upward by more than 5σ:

$$P_{5\sigma} = 10^{-7}.$$

Discovery!

Maximizing the Significance S

1. Choose channels with low SM background

not possible: H → bb ... without associated production ...
possible: H → γγ ... despite of small branching ratio ...
H → ZZ ... with at least one Z decaying leptonically ...
ttH → bb ... via additional top selection ...

2. Optimize detector resolution

Example: mass resolution σ_m increases by a factor of 2;
thus: peak region has to be increased by a factor 2 and
number N_B of background events increases by factor of 2

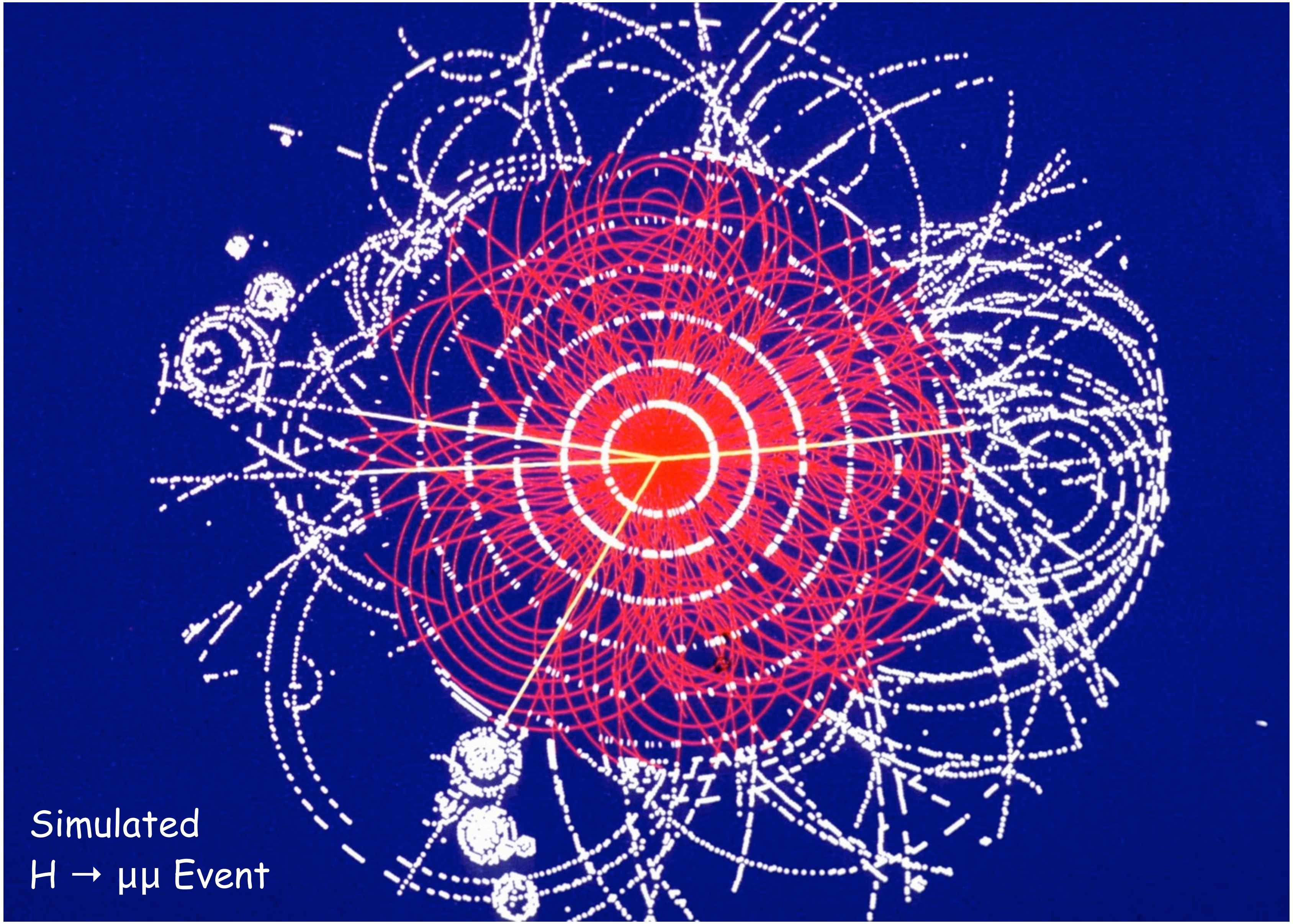
$S = N_S/\sqrt{N_B}$ decreases by $\sqrt{2}$ ➞

$$\boxed{S \sim \frac{1}{\sqrt{\sigma_m}}}$$

3. Maximize luminosity L

$$\left.\begin{array}{ll} \text{Signal:} & N_S \sim L \\ \text{Background:} & N_B \sim L \end{array}\right\} \rightarrow \boxed{S \sim \sqrt{L}}$$

The Golden Channel: H → 4ℓ



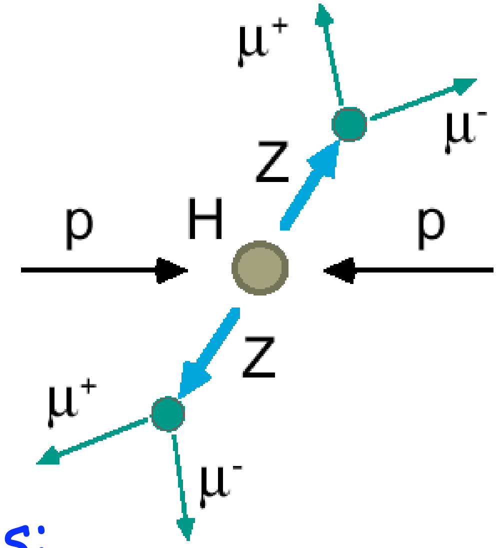
The Golden Channel: $H \to 4\ell$

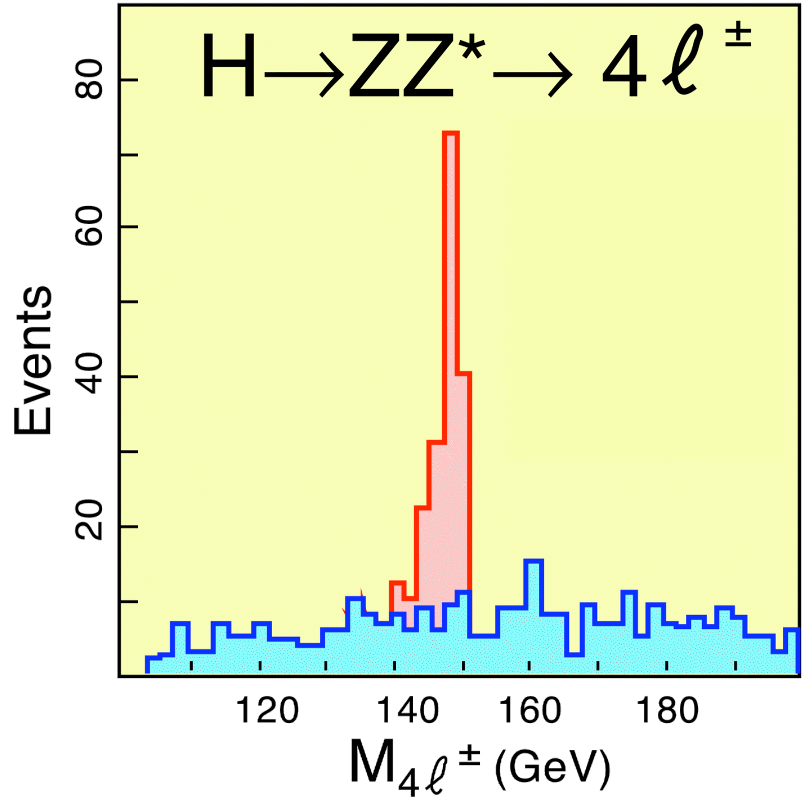
Signal: $\sigma \cdot BR = 5.7$ fb [$m_H = 100$ GeV]

Discovery potential:
130 - 600 GeV

Selection cuts:

isolated leptons within $|\eta| < 2.5$,
$P_{T(1,2)} > 20$ GeV and $P_{T(3,4)} > 7$ GeV
one lepton pair around Z mass





Main backgrounds:

Top production:
[$\sigma \cdot BR = 1300$ fb]

$tt \to Wb\,Wb \to \ell\nu\; c\ell\nu\; \ell\nu\; c\ell\nu$

Associated Z-production:

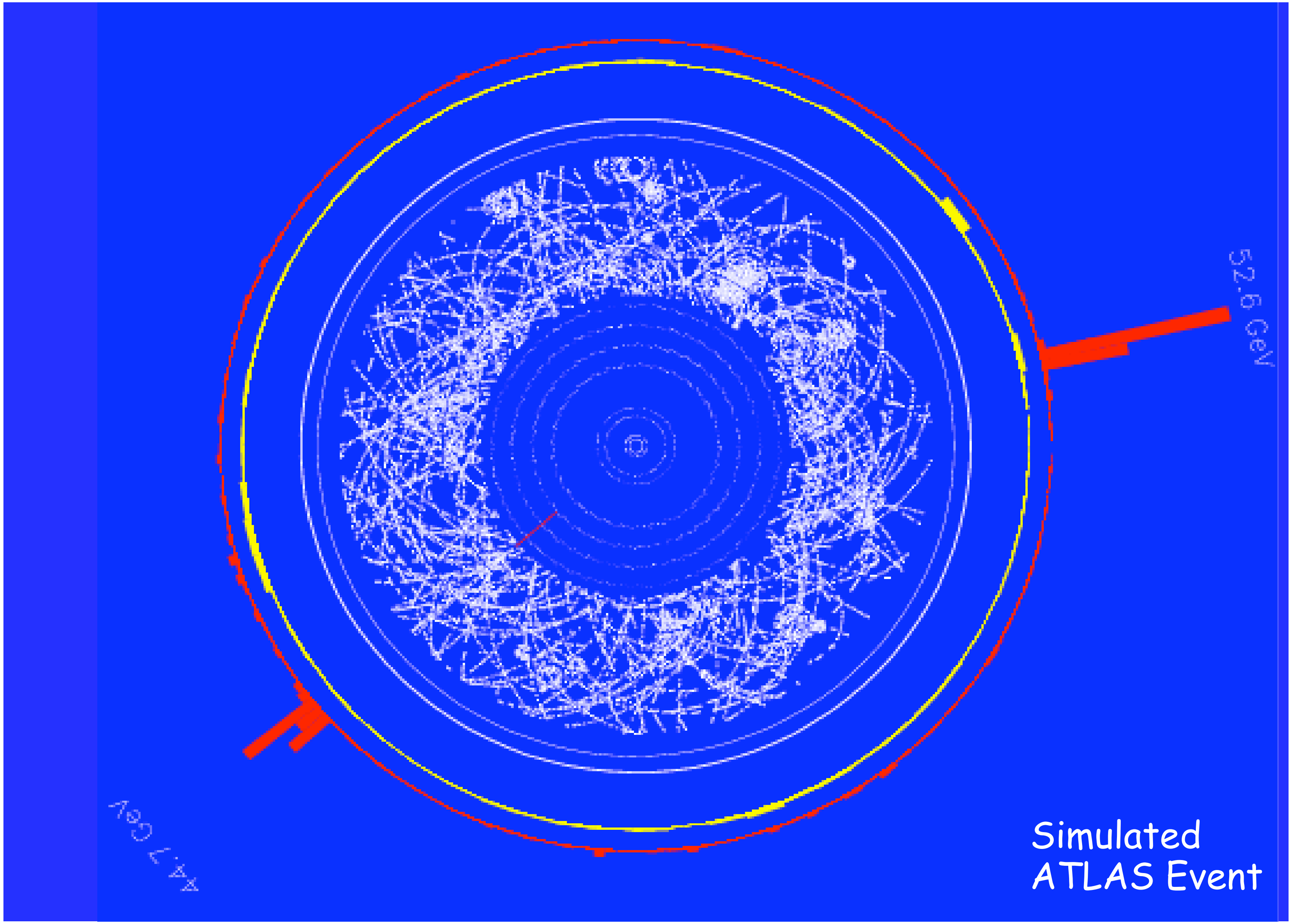
$Z\,bb \to \ell\ell\; c\ell\nu\; c\ell\nu$

Background rejection:

Leptons: non-isolated (inside jet)
not from primary vertex

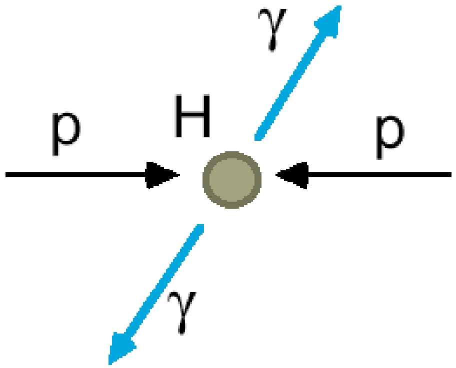
Very clean; remaining: ZZ continuum

The hard one: H → γγ



Simulated
ATLAS Event

The hard one: $H \rightarrow \gamma\gamma$



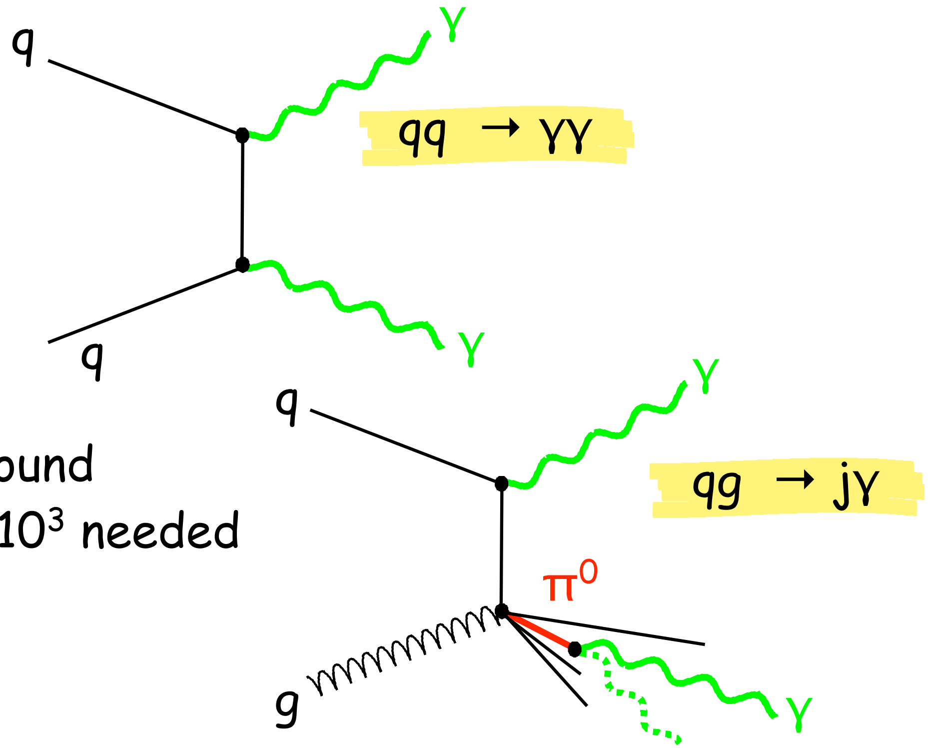
Signal: $\sigma \cdot BR \approx 50$ fb [$m_H = 100$ GeV]

Discovery potential: < 150 GeV

very demanding channel due to huge irreducible background ...

very harsh requirements on calorimeter performance (acceptance, E and θ resolution, separation of γ from jets and π^0)

Two main backgrounds:



2γ-production: irreducible background

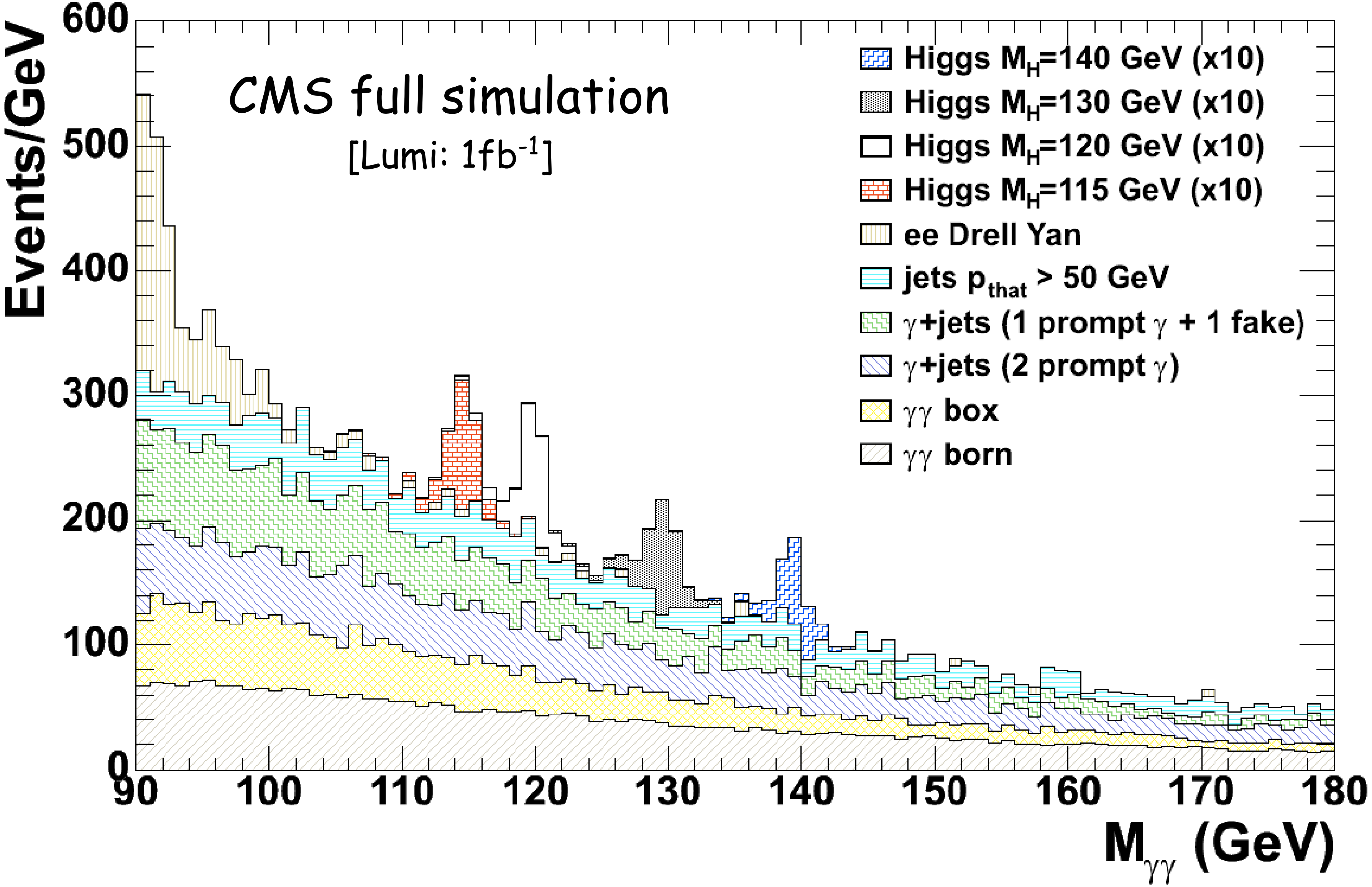
$\sigma_{\gamma\gamma} \sim 2$ pb/GeV and $\Gamma_H \sim$ MeV

implies $\sigma(m_{\gamma\gamma})/m_{\gamma\gamma} \sim 1\%$

γj and jj production: reducible background

$\sigma_{\gamma j+jj} \sim 10^6\ \sigma_{\gamma\gamma}$; jet rejection of $> 10^3$ needed

The hard one: H → γγ

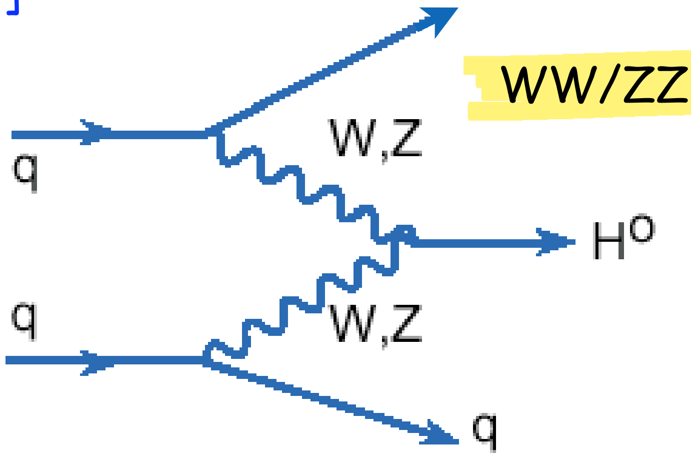


The Vector Boson Fusion Channel

Motivation: Improve low mass discovery potential

Improve measurement of Higgs boson paramters

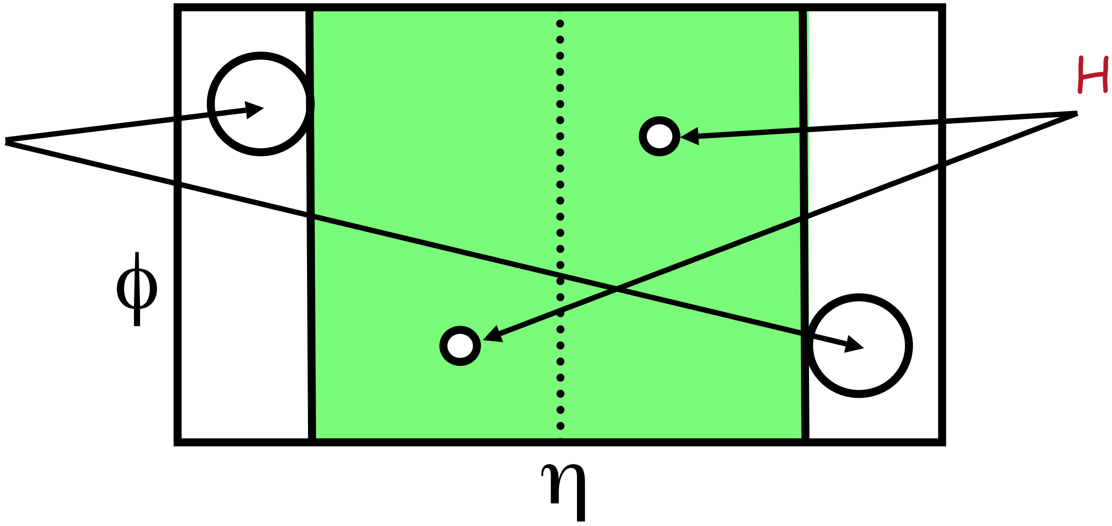
[Coupling to bosons, fermions]



WW/ZZ-fusion

Distinctive signature:

- two forward jets (tagging jets)
- little (jet) activity in central region (central jet veto)



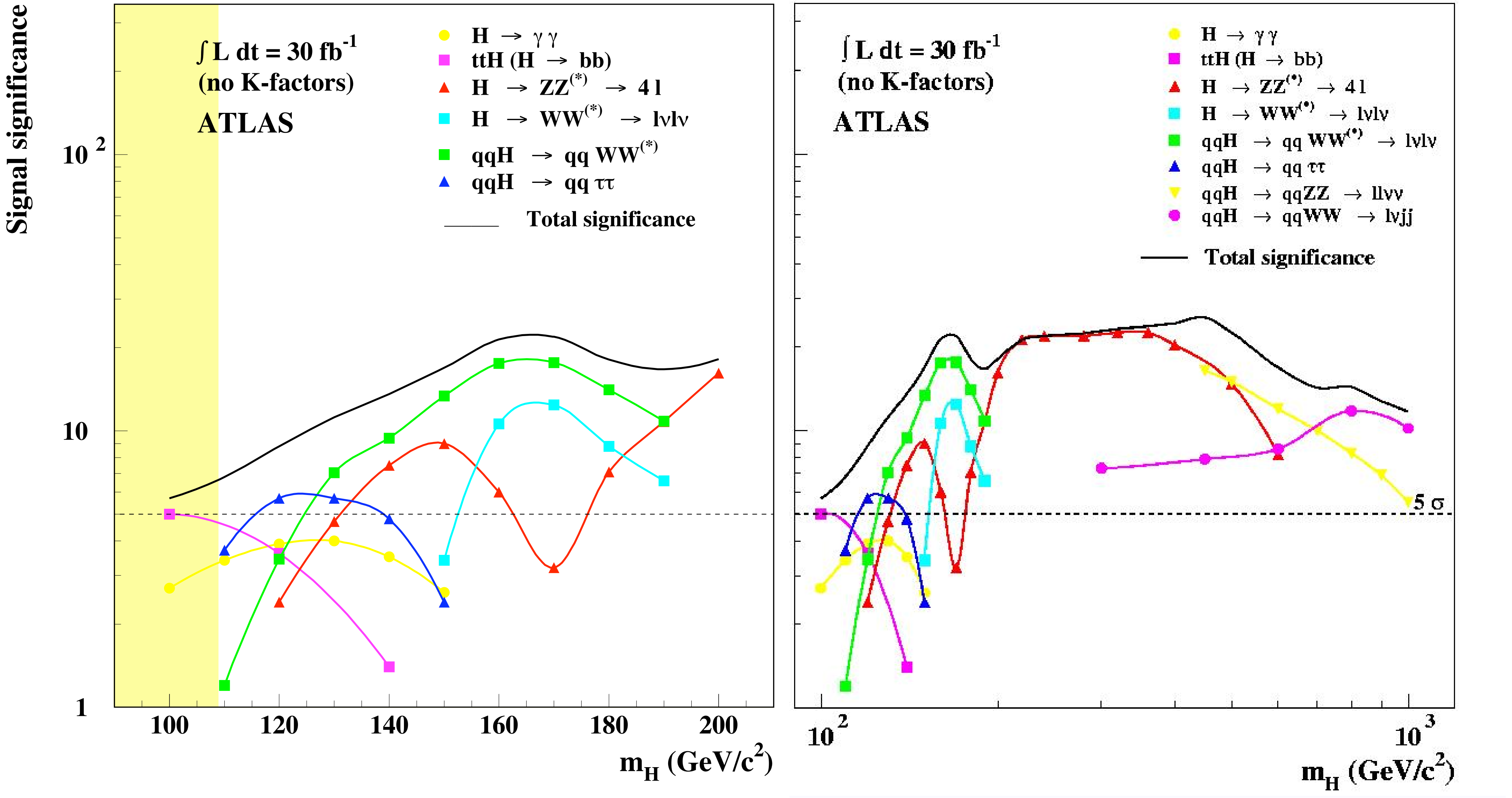
Tagging jets

Higgs decay products

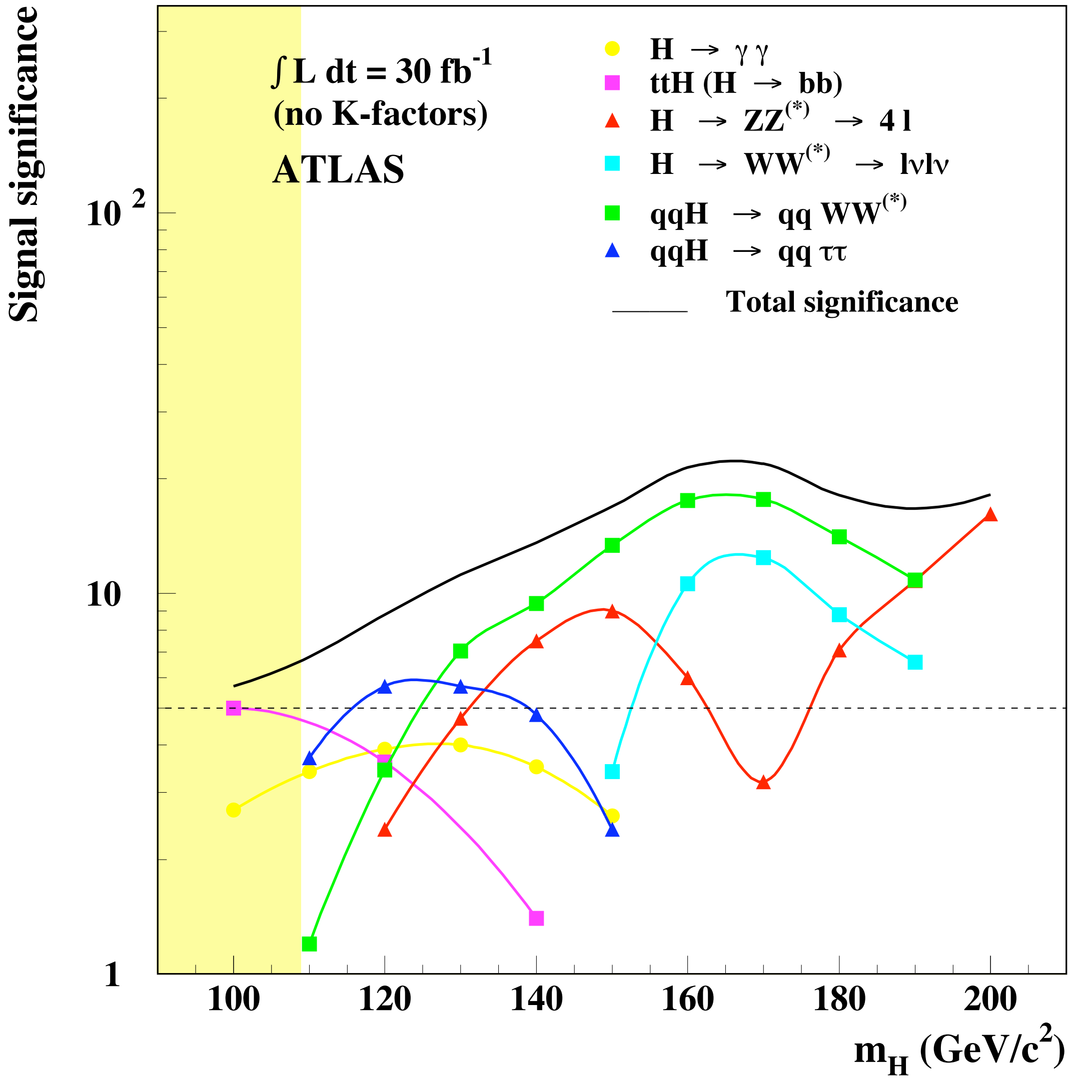
Higgs: Background Systematics

Channel	Main background	S/B	Bkg. sys for 5s	Proposed technique/comments
H->γγ	Irreduc. γγ Reducible qγ	**3-5%**	**0.8%**	Side-bands (bkg shape not known a priori)
ttH H->bb	ttbb	**30%**	**6%**	Mass side-bands Anti b-tagged ttjj ev.
H->ZZ*-> 4 lep	ZZ->4l Reducible tt, Zbb	**300-600%**	**60%**	Mass side-bands Stat Err <30% 30fb^{-1}
H->WW*->llνν	WW*, tW	**30-150%**	**6-30%**	No mass peak Bkg control region and extrapolation
VBF channels In general	Rejection QCD/EW	**Study forward jet tag and central jet veto**		Use EW ZZ and WW QCD Z/W + jets
VFB H->WW	tt, WW, Wt	**50-200%**	**10%**	Study Z,W,WW and tt plus jets
VBF H->ττ	Zjj, tt	**50-200%**	**10-40%**	Mass side-bands Beware of resolution tails

LHC: Higgs Discovery Potential



LHC: Higgs Discovery Potential



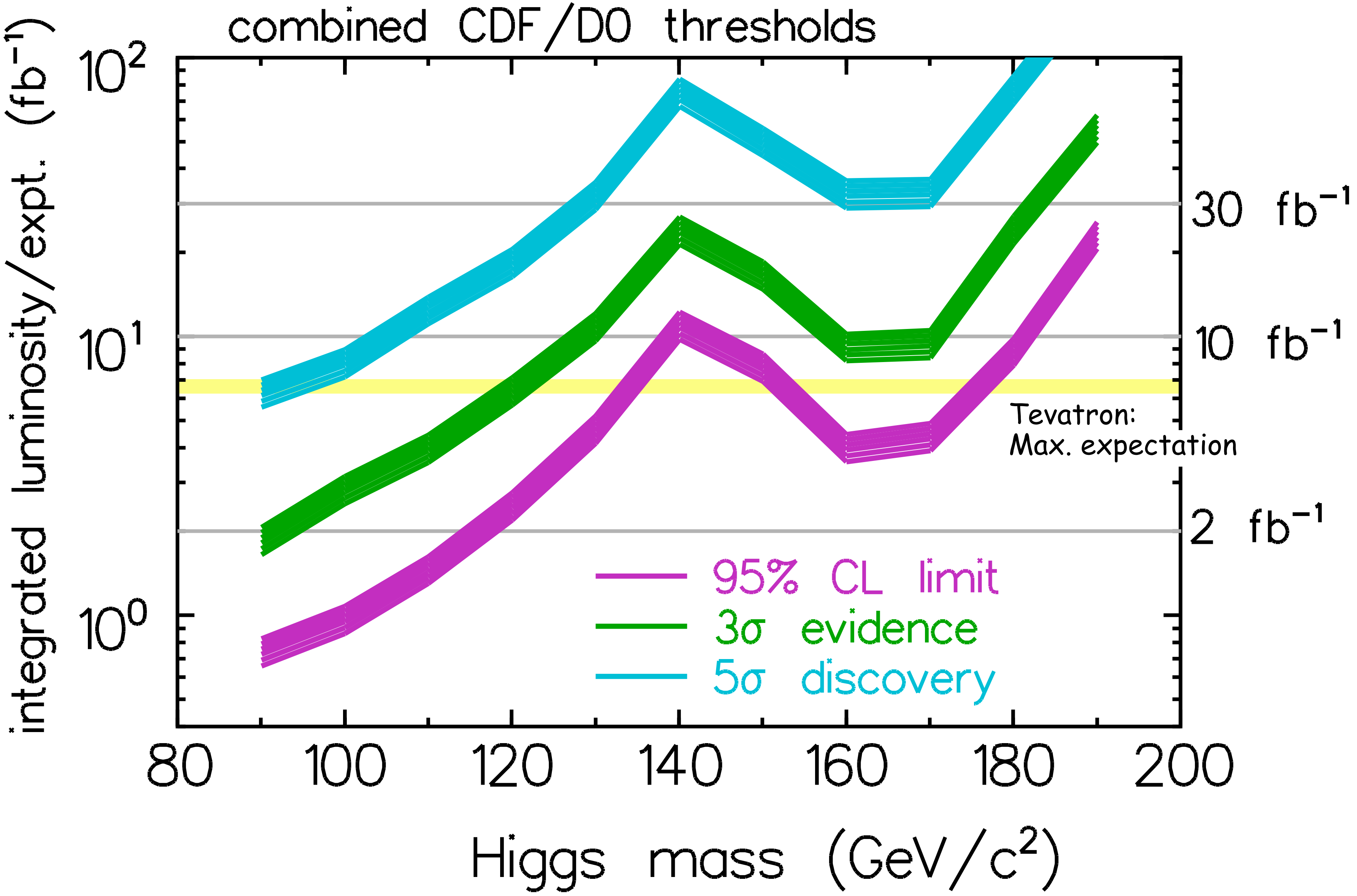
Full mass range can already be covered after a few years at low luminosity

Several channels available over a large range of masses

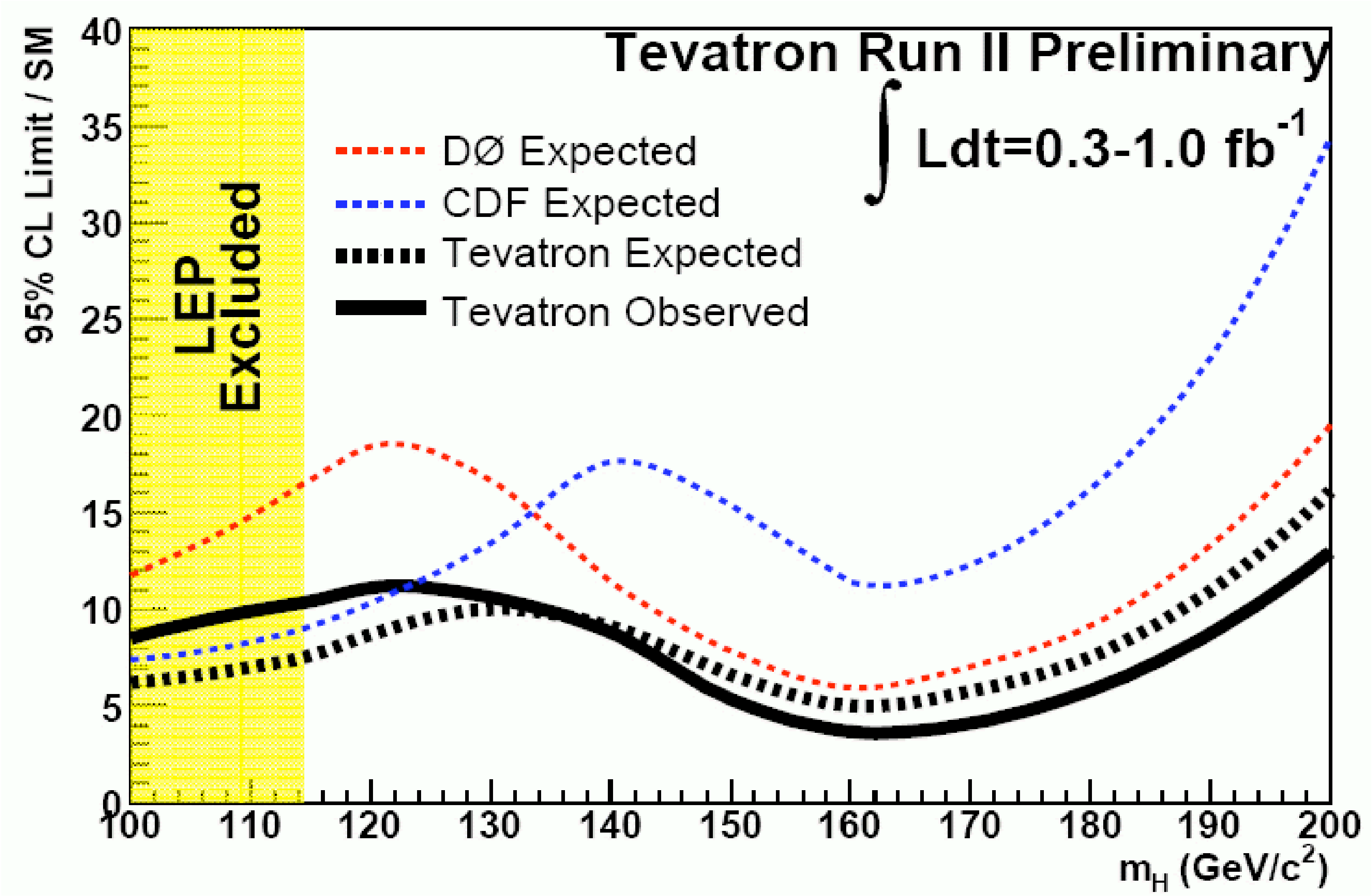
Low mass discovery requires combination of three of the most demanding channels

Comparable situation for the CMS experiment

Tevatron: Higgs Discovery Potential

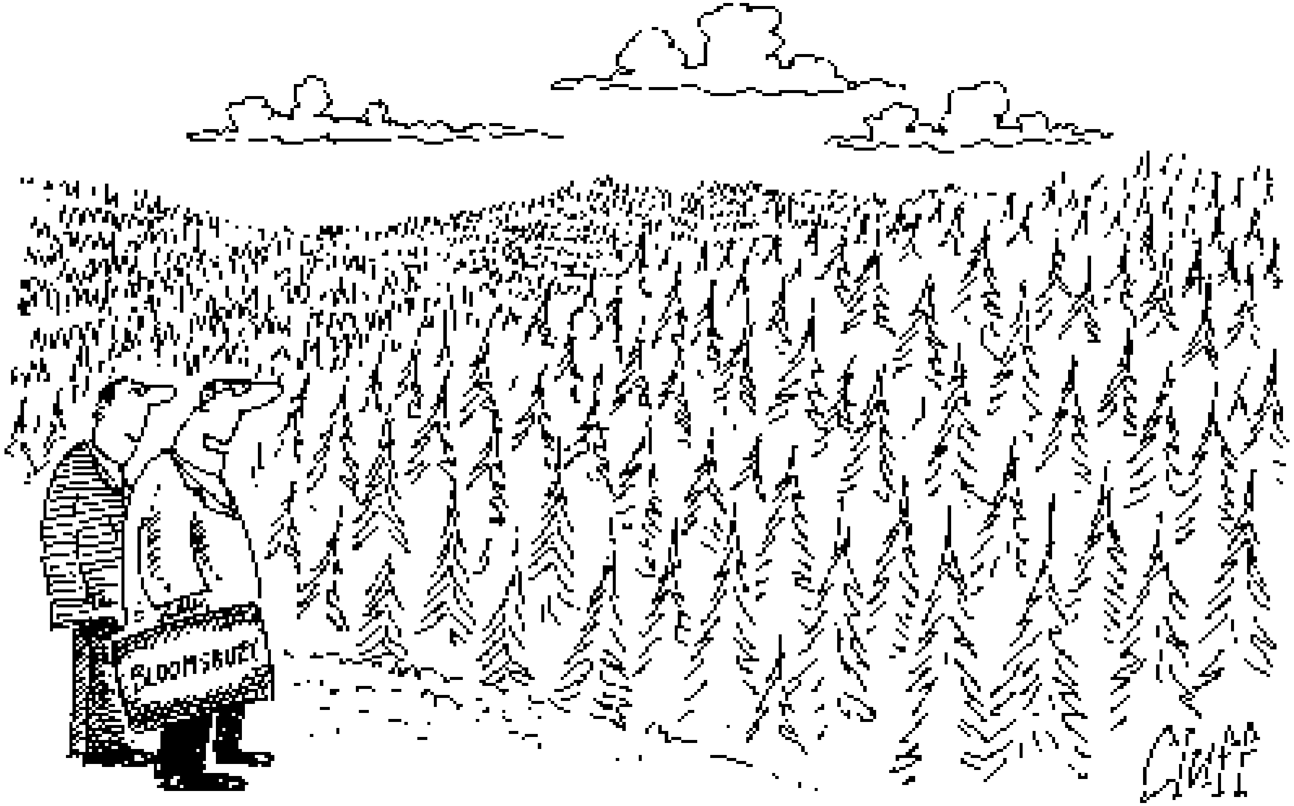


Tevatorn: Recent Results



New Physics Scenarios

Supersymmetry



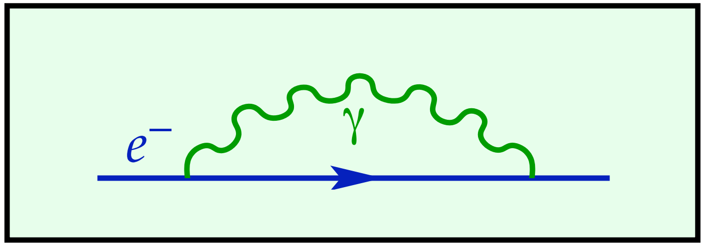
"One day, all of these will be supersymmetric phenomenology papers."

Motivation

Electrons in classical Electrodynamics

Electromagnetic self-energy:

$$\Delta E_C = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}$$



QED: Photon exchange ⇔ Coulomb law

Self-energy must be part of electron mass:

$$(m_e c^2)_{observed} = (m_e c^2)_{bare} + \Delta E_C$$

Experiment: $r_e < 10^{-17}$ cm → $\Delta E_C > 10$ GeV

$m_e = 511$ keV $= 0.511$ MeV

$$(m_e c^2)_{bare} = (m_e c^2)_{observed} - \Delta E_C$$

$$= 0.511 \text{ MeV} - 10000 \text{ MeV}$$

$$= -9999.489 \text{ MeV}$$

"fine-tuning problem"

Classical Electrodynamic not valid vor $\Delta E_C > m_e c^2$, i.e. for $d < 2.8 \cdot 10^{-13}$.

[from $d < e^2/4\pi\epsilon_0\, m_e c^2$]

Motivation

Electrons in Quantum Electrodynamics

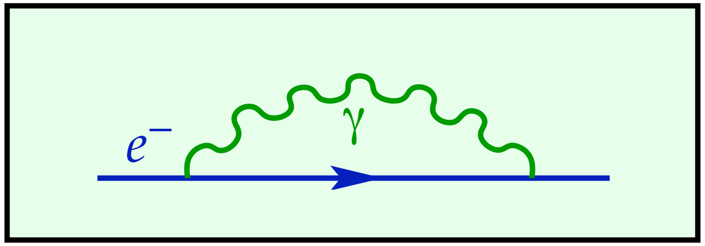
Description of self-energy in Quantum Electrodynamics via photon exchange.

Introduction of positron ...
cure of “fine-tuning problem” via vacuum fluctuations.

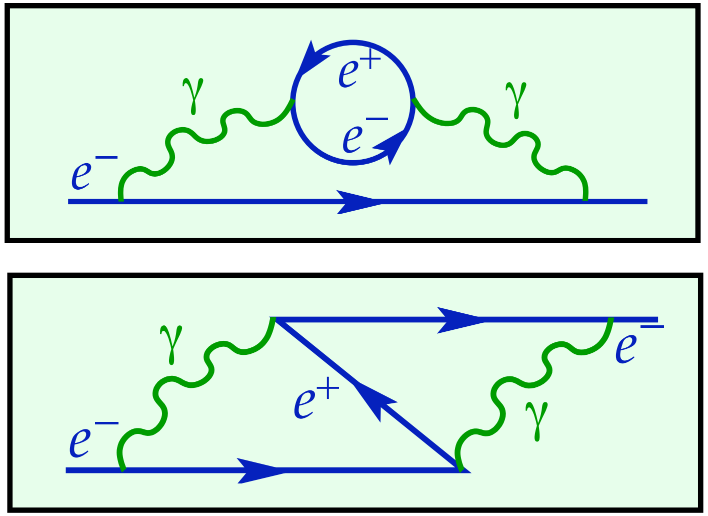
∴ Modify physics at

$d \sim c\Delta t \sim 200 \cdot 10^{-13}$ cm

with $\Delta t \sim \hbar/\Delta E \sim \hbar/2m_ec^2$



QED: Photon exchange ⇔ Coulomb law



Vacuum fluctuations: e^+e^--pair production

➡ $$\Delta E_{Pair} = -\frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e} + \ldots$$

$$\Delta E = \Delta E_C + \Delta E_{Pair} = \frac{3\alpha}{4\pi} m_e c^2 \log\frac{\hbar}{m_e c r_e}$$

smaller
self-energy !

Motivation

Electrons in Quantum Electrodynamics

Description of self-energy in Quantum Electrodynamics via photon exchange.

Introduction of positron ...
cure of “fine-tuning problem” via vacuum fluctuations.

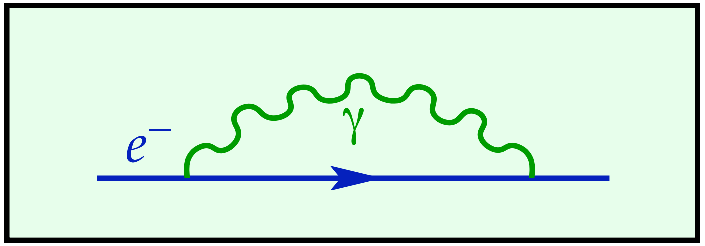
∴ Modify physics at

$d \sim c\Delta t \sim 200 \cdot 10^{-13}$ cm

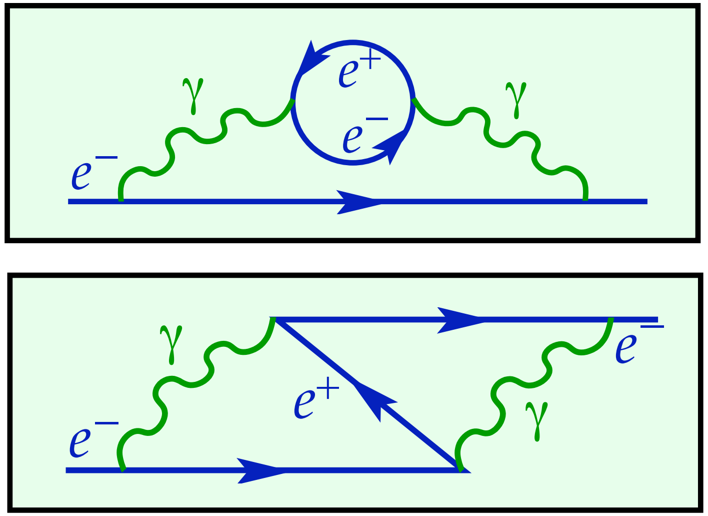
with $\Delta t \sim \hbar/\Delta E \sim \hbar/2m_e c^2$

Doubling d.o.f. & symmetry result in divergence cancellation.

➡ “Naturally” small mass correction.



QED: Photon exchange ⇔ Coulomb law



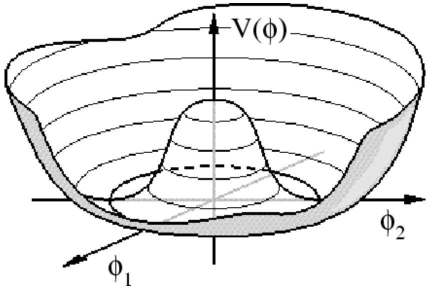
Vacuum fluctuations: e^+e^--pair production

$$(m_e c^2)_{observed} = (m_e c^2)_{bare}\left[1+\frac{3\alpha}{4\pi}\log\frac{\hbar}{m_e c r_e}\right]$$

max. 9%
even @ $r_e = 1/M_P$

Motivation

Supersymmetry and the Higgs self-energy

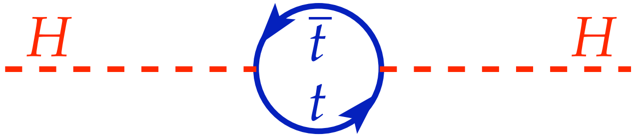


Higgs self-energy:

$$V = -\mu^2|H|^2 + \lambda|H|^4$$

$$M_H = \sqrt{2}\mu$$

Self-energy correction through top-loops:



Higgs-Top coupling

$$\Delta\mu^2_{\text{top}} = -6\frac{h_t^2}{4\pi^2 r_H^2} + \ldots$$

"Higgs radius"

- ➥ Standard Model not applicable for d < 10^{-17} cm; i.e. above a scale Λ > 2 TeV ...

Solution: double d.o.f. introducing boson partners for each fermion; results in loop corrections with opposite sign.

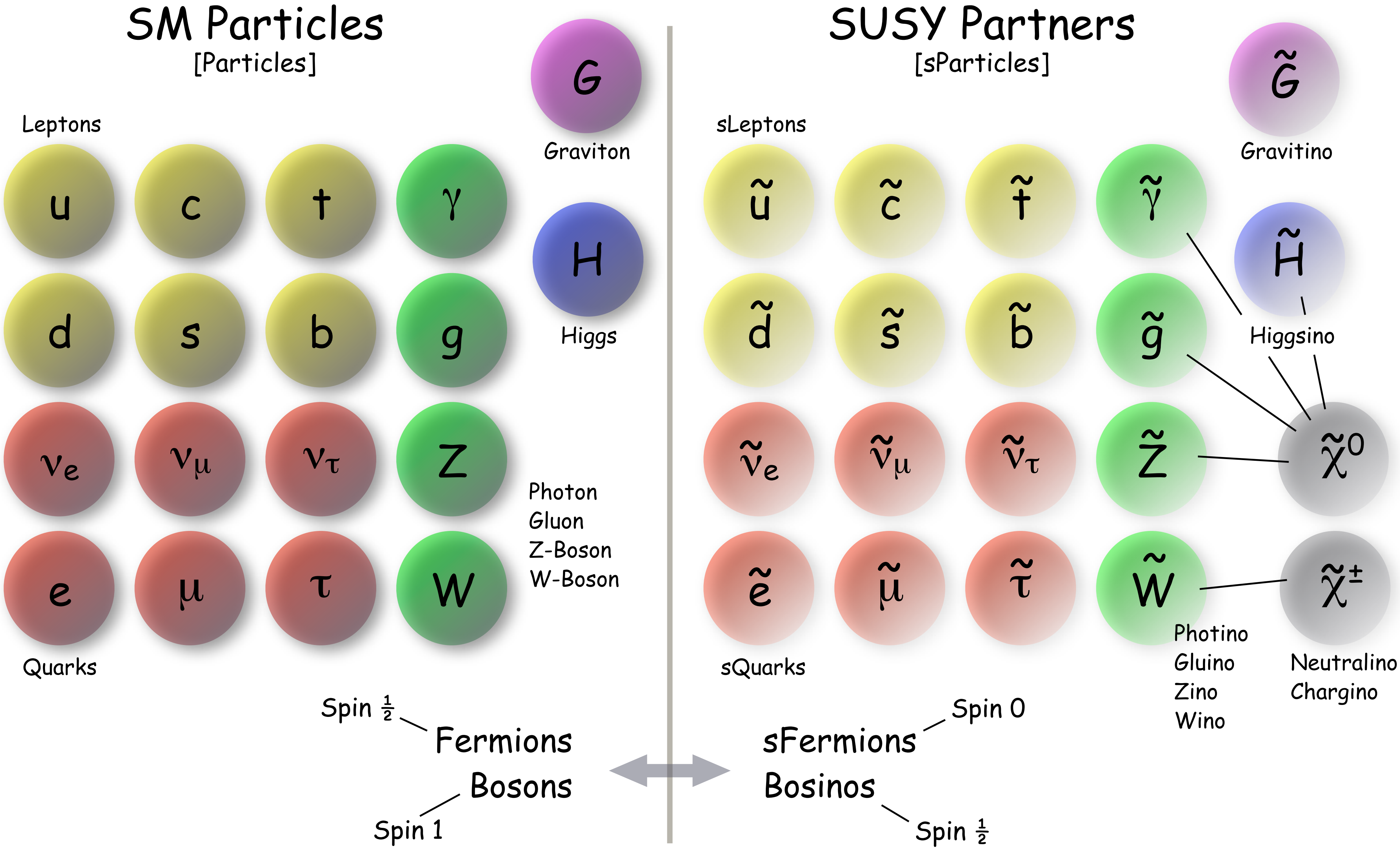
$$\Delta\mu^2_{\text{stop}} = +6\frac{h_t^2}{4\pi^2 r_H^2} + \ldots$$

Remaining correction:

$$\Delta\mu^2_{\text{top}} + \Delta\mu^2_{\text{stop}} = -6\frac{h_t^2}{4\pi^2 r_H^2}(m_{\tilde{t}}^2 - m_t^2)\log\frac{1}{r_H^2 m_{\tilde{t}}^2}$$

- ➥ "Naturalness" argument: $m_{\tilde{t}}$ not much larger than m_t, i.e. $m_{\tilde{t}}$ in TeV range.

Supersymmetric Particle Spectrum



SM Particles
[Particles]

SUSY Partners
[sParticles]

Leptons

Quarks

Graviton

Higgs

Photon
Gluon
Z-Boson
W-Boson

sLeptons

sQuarks

Gravitino

Higgsino

Photino
Gluino
Zino
Wino

Neutralino
Chargino

Spin ½ — Fermions

Bosons — Spin 1

sFermions — Spin 0

Bosinos — Spin ½

Minimal Supersymmetric Models

- Extension of the Standard Model
  - Supersymmetric partner for each SM particle
  - 2 Higgs doublets
    - Minimal structure to guarantee cancellations of anomalies
    - Two Higgs field needed to give masses to 'up' and 'down' type quarks in a consistent way
- New quantum number: R-parity R_p
  - Particles : $R_p = +1$
  - S-Particles : $R_p = -1$
    - R_p-conservation circumvents proton decay; conservation of B-L

$$\boxed{R_p = (-1)^{B+L+2S}}$$

- Motivation of SUSY
  - Avoid divergent quantum corrections to Higgs mass
  - Allows for unification of gauge couplings
  - Existence of lightest supersymmetric particle (LSP); candidate for dark matter

Broken Supersymmetry

- Supersymmetry is not an exact symmetry

  ... as SUSY particles are not observed at low masses

- Needs model(s) for (soft) symmetry breaking

  Most models assume "hidden" sector ...

  Hidden sector: particles neutral to SM gauge group

  Visible sector: MSSM particle spectrum

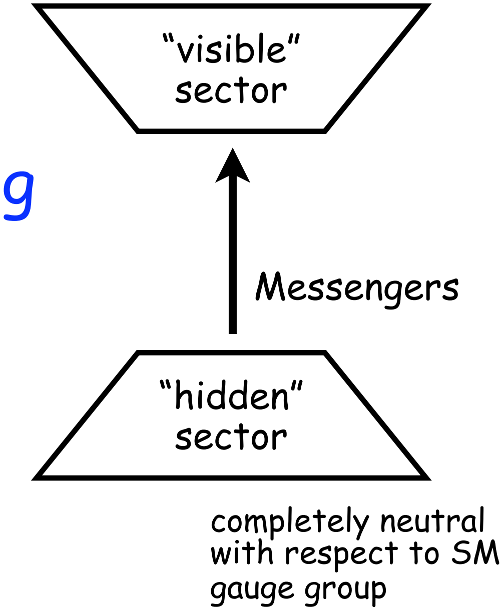
  SUSY breaking occurs in the hidden sector

  Transmitted to MSSM by specific mechanism:

  Gravity Mediated Supersymmetry Breaking (mSUGRA, cMSSM)
  Gauge Mediated Supersymmetry Breaking (GMSB)
  Anomaly Mediated Supersymmetry Breaking (AMSB)

  LSP: Neutralino

  LSP: Gravitiono



- SUSY breaking leads to extra parameters

  Unconstrained models: 105 parameters (Masses, couplings, phases)

  Constrained models: 4 or 5 parameters, assuming SUSY breaking scheme

  Examples: mSugra, cMSSM ...

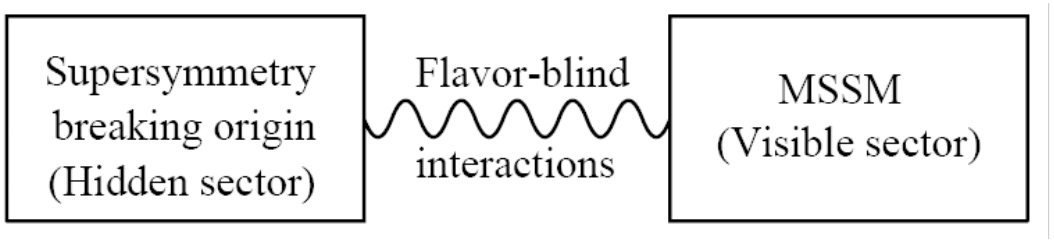
mSUGRA – A Constrained Model

- Unification assumption

  Assume universal masses for all bosons and fermions at the GUT (Grand Unification Theory) scale

- Symmetry breaking assumption

  Model where breaking is mediated by gravity



Supersymmetry breaking origin (Hidden sector)

Flavor-blind interactions

MSSM (Visible sector)

Results in

- 5 remaining parameters

  m_0: universal boson (scalar) mass

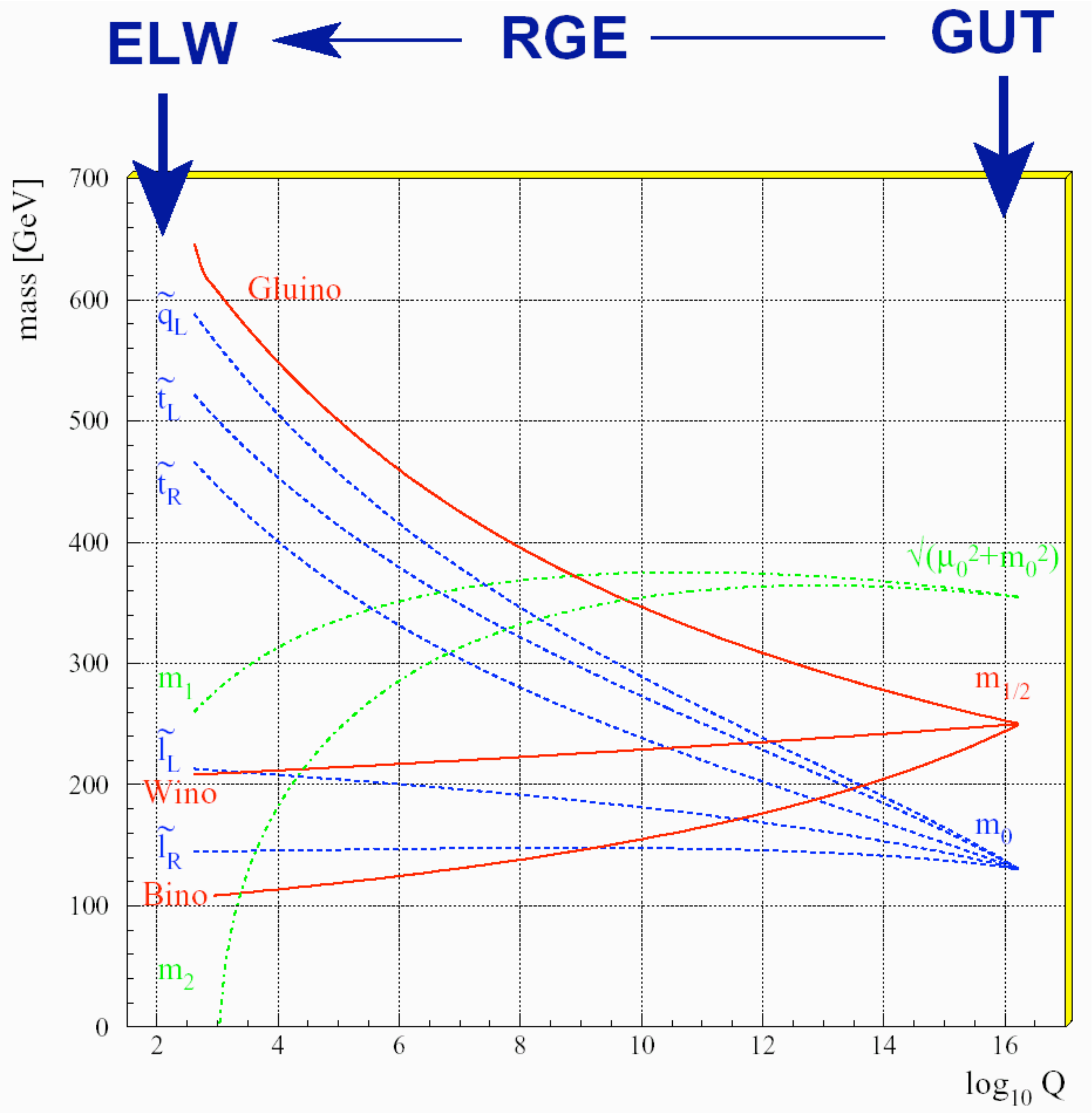
  $m_{\frac{1}{2}}$: universal gaugino mass

  A_0: universal trilinear coupling

  $\tan\beta$: ratio of the two Higgs VEVs (vacuum expectation values)

  $\mathrm{sgn}(\mu)$: sign of the higgsino mass parameter

mSUGRA Mass Spectrum



Running masses:

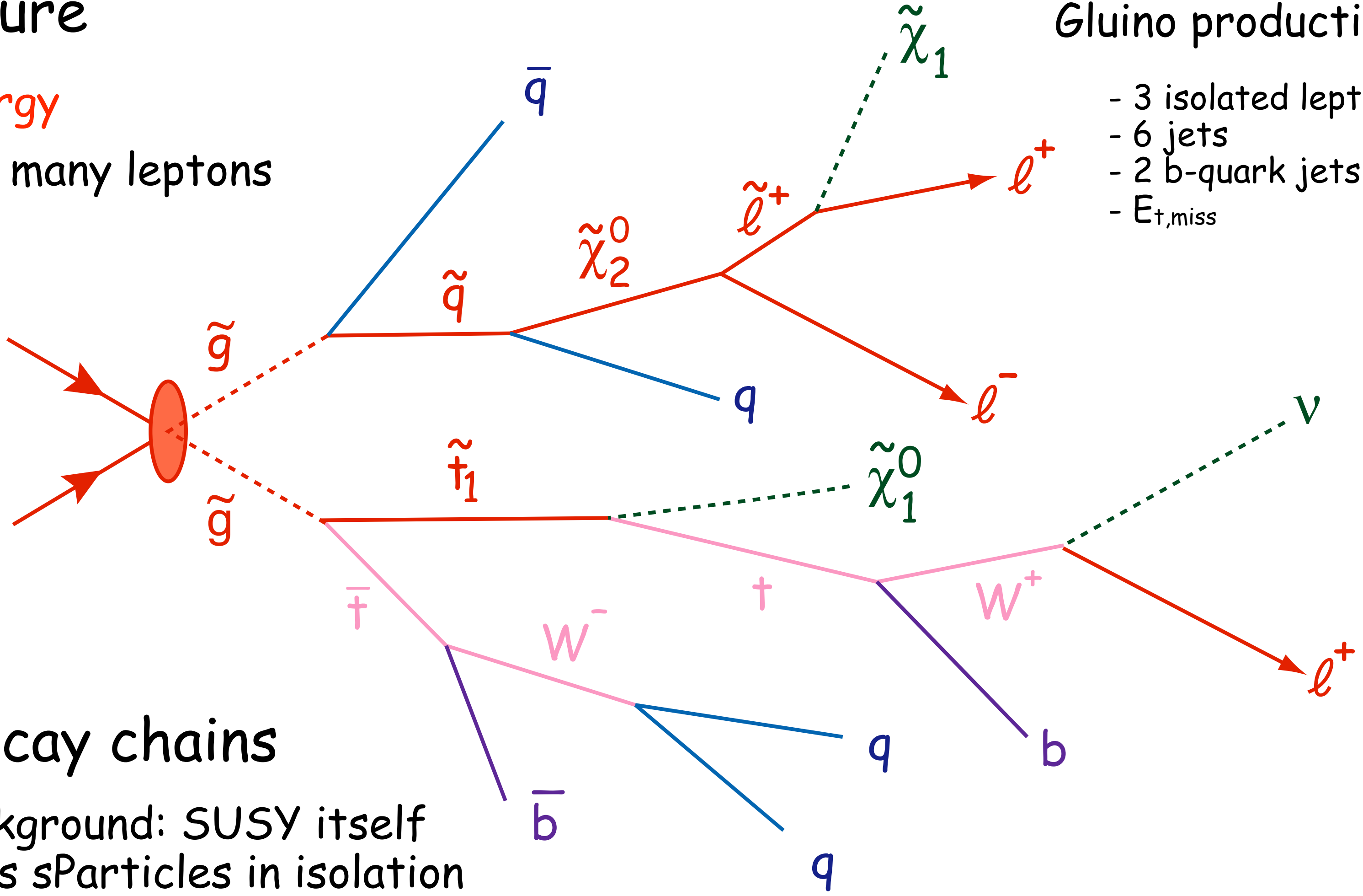
Universal Masses at GUT scale lead to Sparticle masses at EW scale via RGE evolution

SUSY Production and Decay

Pairwise production

Clear Signature

- missing energy
- events with many leptons and jets.



Example:
Gluino production

- 3 isolated leptons
- 6 jets
- 2 b-quark jets
- $E_{t,miss}$

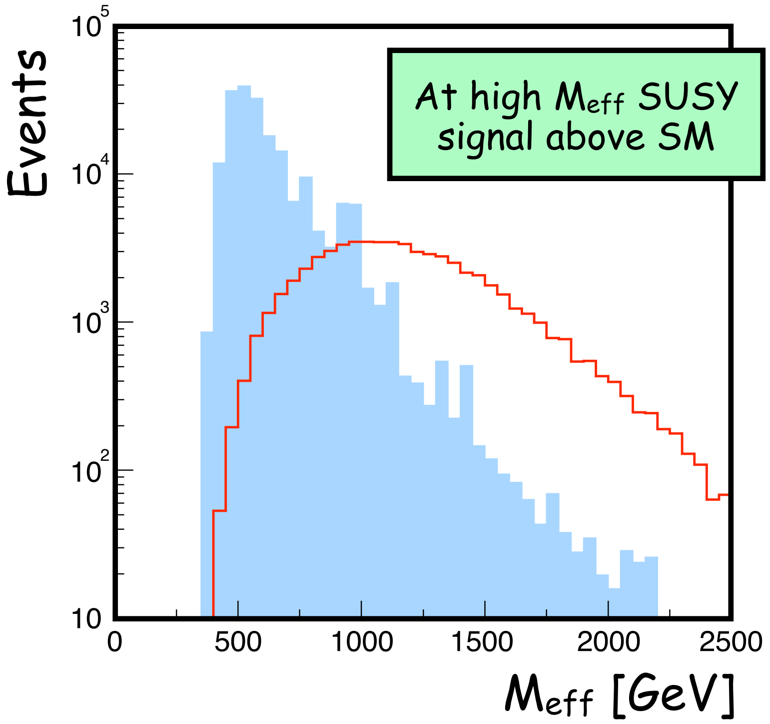
But: Long decay chains

- dominant background: SUSY itself
- cannot discuss sParticles in isolation
- use consistent model for simulation

mSUGRA: Discovery Potential

- Select: ≥ 4 jets, $E_{T,\text{miss}}$
- Reconstruct effective mass

$$M_{\text{eff}} = \sum_{i=1}^{4} |P_{T,i}| + |E_{T,\text{miss}}|$$

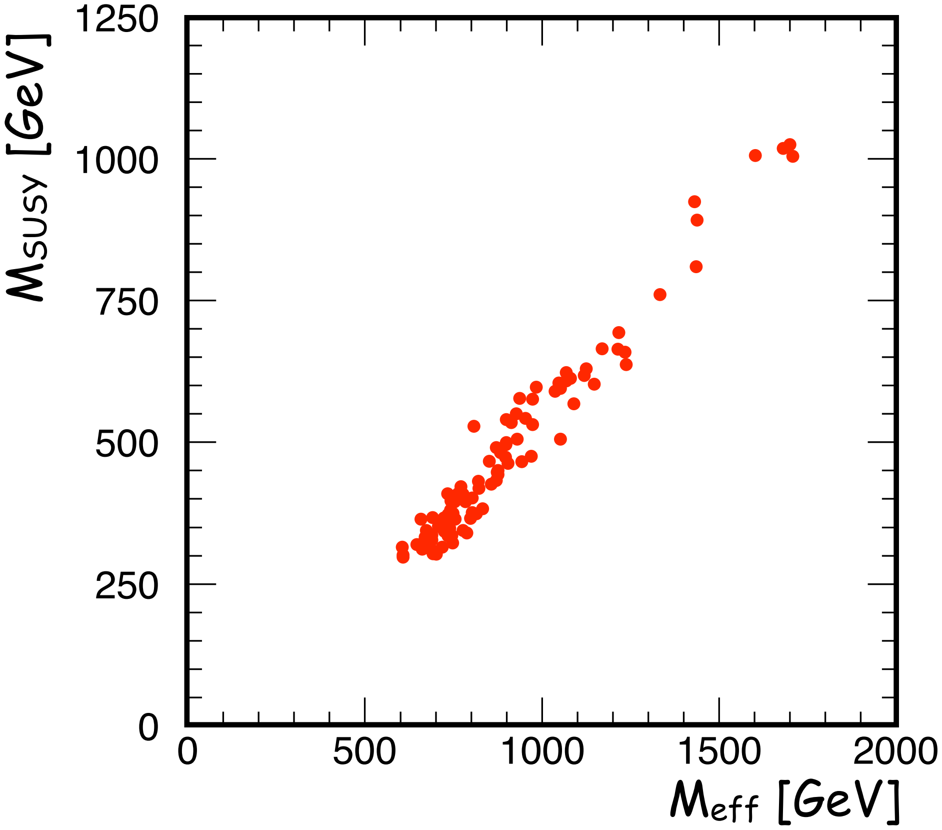


At high M_{eff} SUSY signal above SM

Inclusive signature for squarks and gluinos up to 2.5 TeV

Effective mass approximates

M_{SUSY}: "mass scale of SUSY breaking"
[mSUGRA: $M_{\text{SUSY}} = \min(M_u, M_g)$]

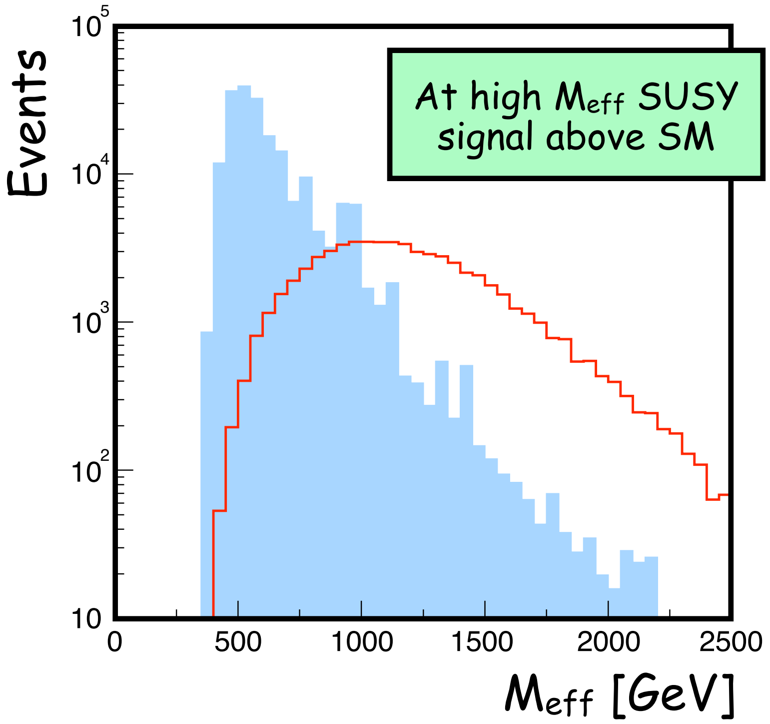


Peaking M_{eff} distribution correlates well with M_{SUSY}

mSUGRA: Discovery Potential

- Select: > 4 jets, $E_{T,\text{miss}}$
- Reconstruct effective mass

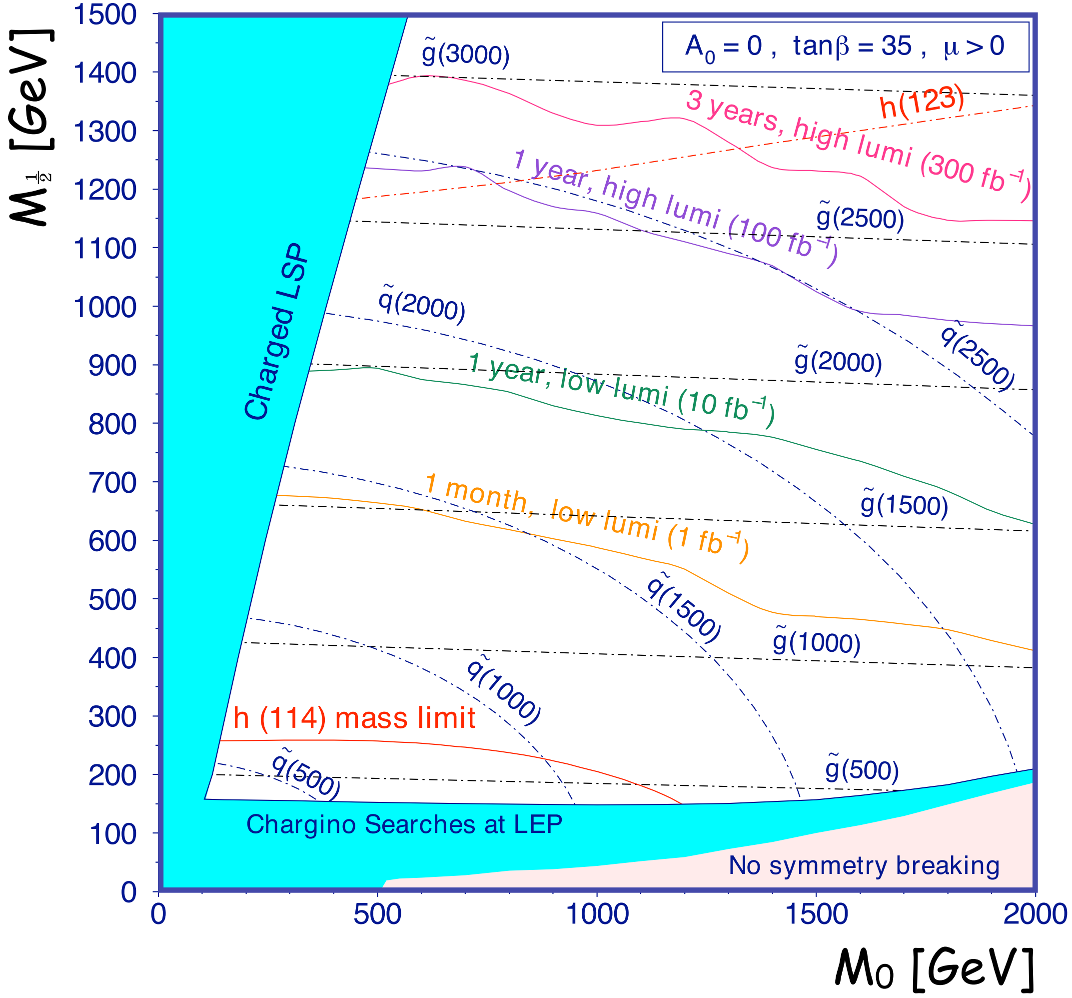
$$M_{\text{eff}} = \sum_{i=1}^{4} |P_{T,i}| + |E_{T,\text{miss}}|$$



At high M_{eff} SUSY signal above SM

Inclusive signature for squarks and gluinos

mSUGRA reach in $E_{T,\text{miss}}$ + jets final state



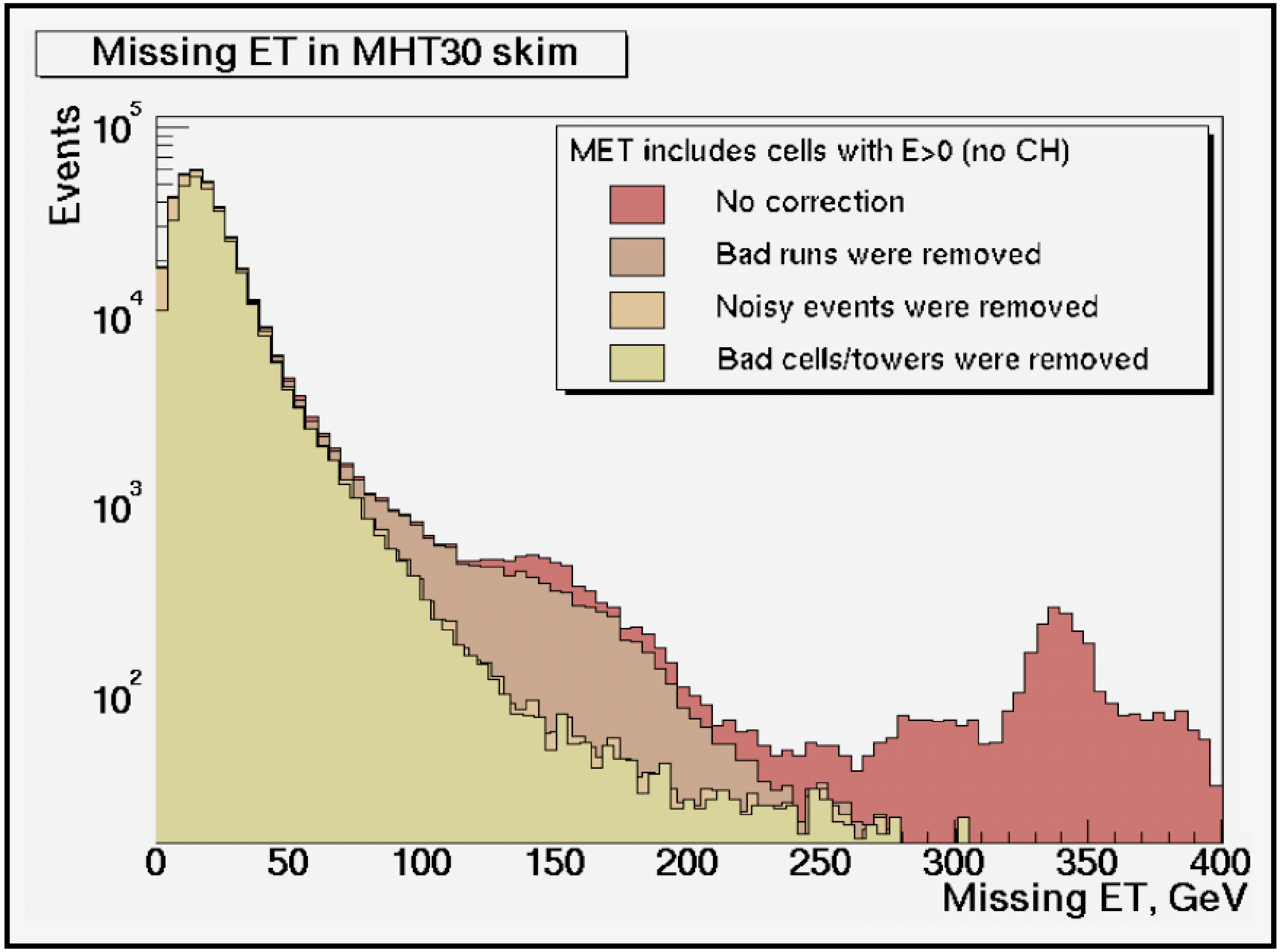
Early discovery potential for squarks and gluinos up to TeV scale

Experimental Challenge: $E_{T,miss}$

Most important SUSY signature: $E_{T,miss}$
Requires precise control of instrumental effects ...

Partial List:

- machine background
- beam-gas events
- hot cells
- regions with poor jet response
- displaced vertices
- and many more ...

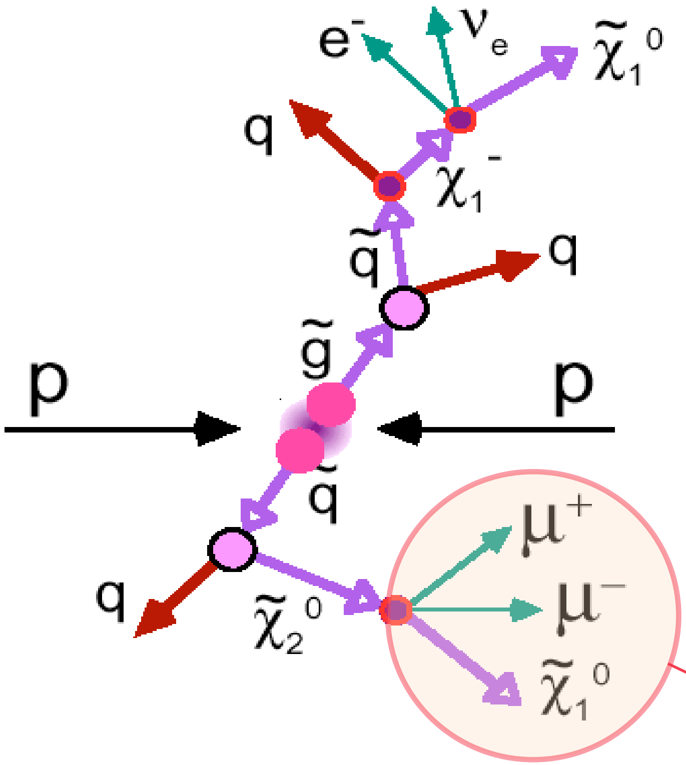


Experimental Challenge: $E_{T,\text{miss}}$

Simulated jet event [E_T>500 GeV)]
with ΔE_T^{miss} > 250 GeV
(compared to true E_T^{miss})

[jet leakage, jet punch-through, fake muons via cracks, …]

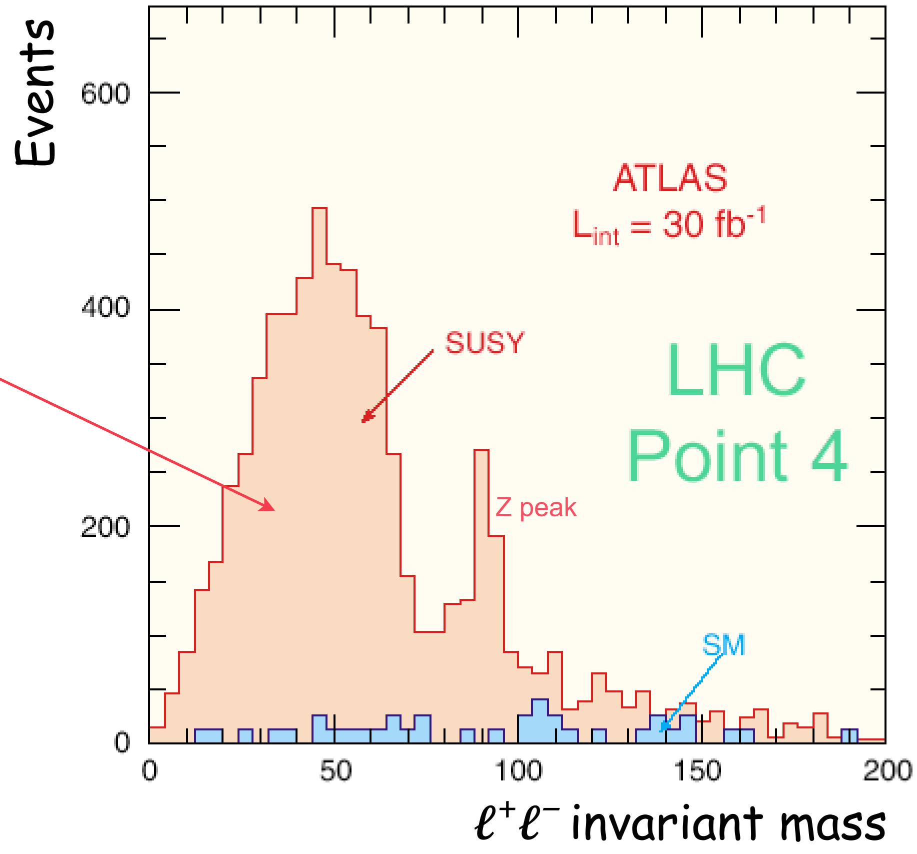
Determining sParticle Properties



Reconstruction of decay chains

Need to take unobserved LSPs into account

Need to identify specific decay chain
[SUSY is background to SUSY]



Example for approach

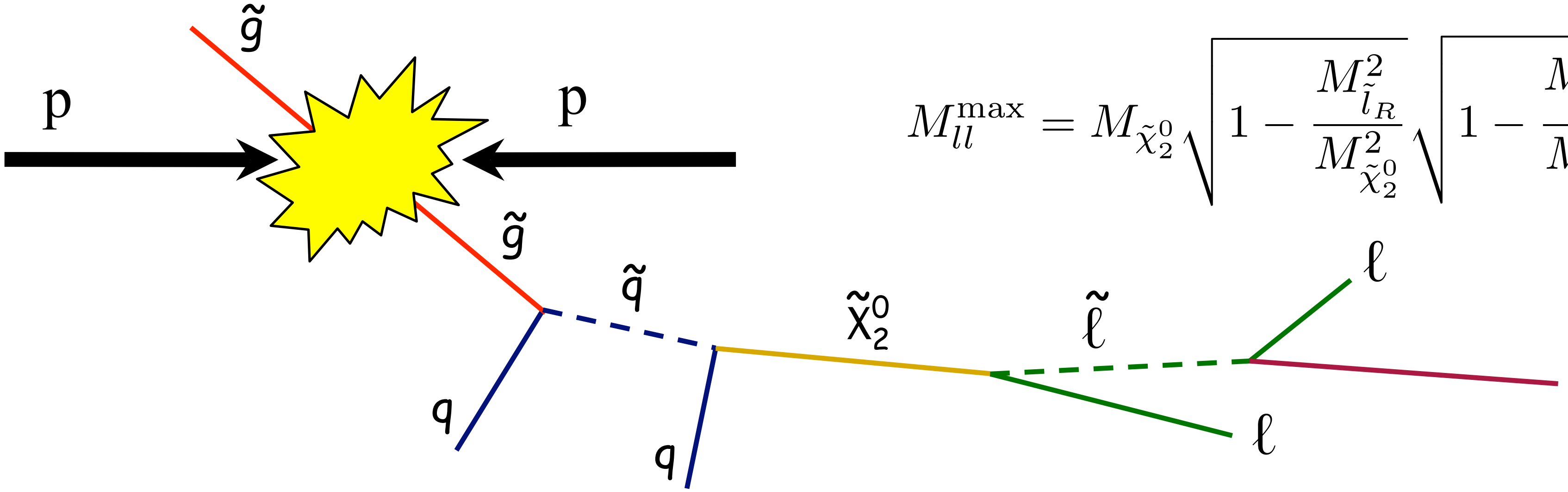
Consider decay $\chi_2^0 \to \chi_1^0 \ell^+ \ell^-$

But: contribution $\chi_2^\pm \to \chi_1^\pm Z$

Endpoint in $\ell^+\ell^-$ invariant mass
determines mass difference χ_2^0 - χ_1^0

Kinematic Endpoint Analysis

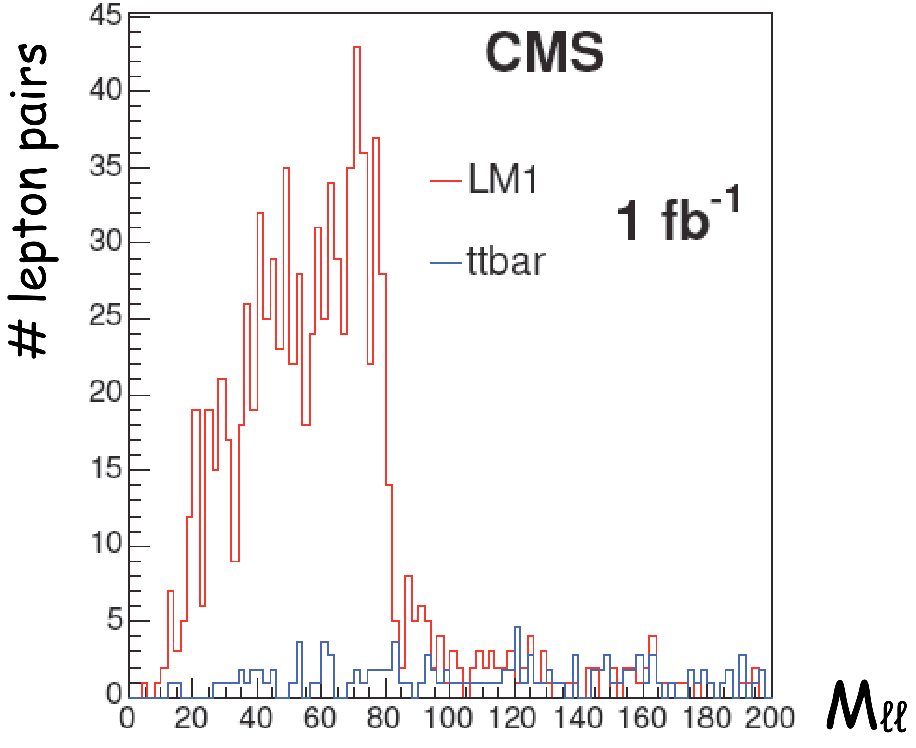
$$M_{ll}^{\max} = M_{\tilde{\chi}_2^0}\sqrt{1-\frac{M^2_{\tilde{l}_R}}{M^2_{\tilde{\chi}_2^0}}}\sqrt{1-\frac{M^2_{\tilde{\chi}_1^0}}{M^2_{\tilde{l}_R}}}$$



$$M_{lq}^{\max} = \sqrt{\frac{(M^2_{\tilde{q}_L}-M^2_{\tilde{\chi}_2^0})(M^2_{\tilde{\chi}_2^0}-(M^2_{\tilde{l}_R})}{M^2_{\tilde{\chi}_2^0}}}$$

$$M_{lqq}^{\max} = \sqrt{\frac{(M^2_{\tilde{q}_L}-M^2_{\tilde{\chi}_2^0})(M^2_{\tilde{\chi}_2^0}-(M^2_{\tilde{\chi}_1^0})}{M^2_{\tilde{\chi}_2^0}}}$$

$$M_{qq}^{\max} = \ldots$$



Determine SUSY masses from endpoints of $M_{\ell\ell}$, $M_{\ell q}$ and $M_{\ell qq}$ ...

Further SUSY Models

- R-parity violation

  Introduces couplings between lepton and quarks ("Leptoquarks")

  Leads to lepton number violation

- Gauge mediated symmetry breaking (GSMB)

  Phenomenology

  Gravitino is the lightest supersymmetric particle (LSP); m < 1 keV

  Possible existence of long lived NLSP (stau, slepton)

  Important signature: $\chi_1^0 \rightarrow \gamma G$

- NMSSM (next to minimal ...)

  Non-universal mass, i.e. more paramters ...

- Split SUSY

  Heavy scalars, light higgs, higgsinos and gauginos;
  signature: long lived gluinos (➡ displaced vertex, stopped gluinos)

...

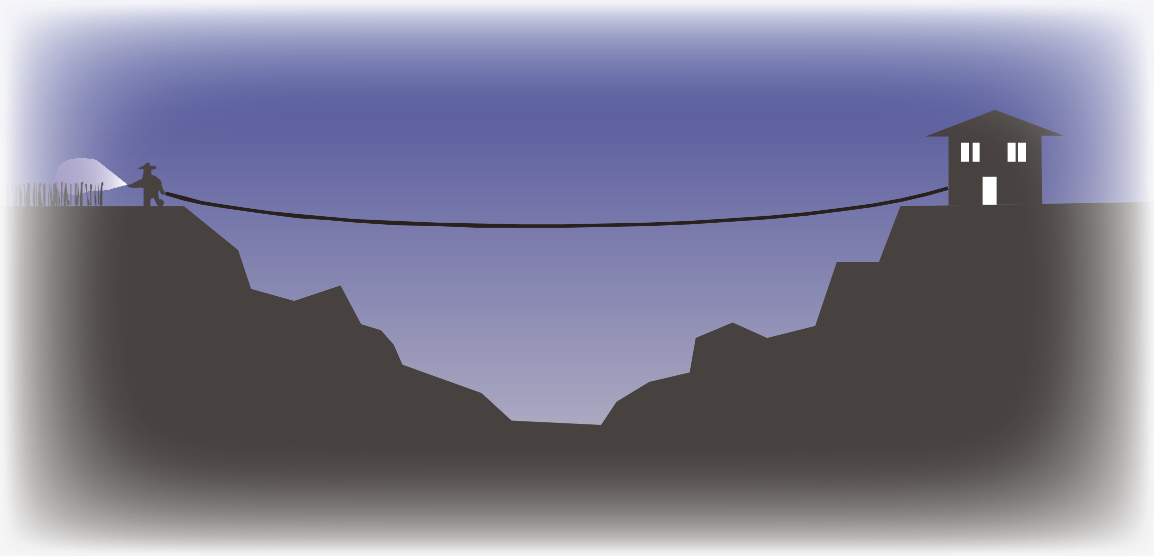
New Physics Scenarios

Extra Dimensions

Extra Dimensions - A Simple Picture

Our world:

3 space-dimensions
1 time-dimension



Extra Dimensions - A Simple Picture

Our world:

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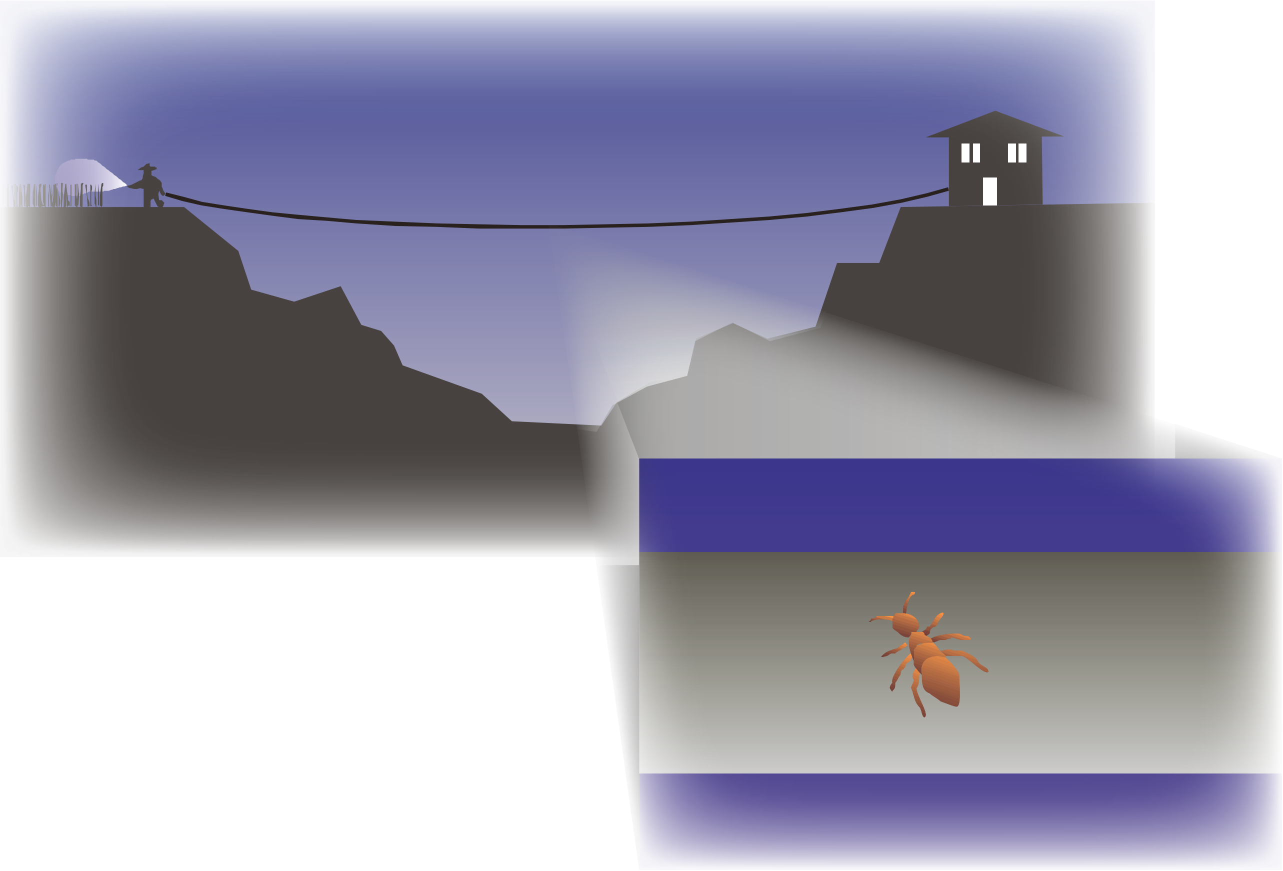
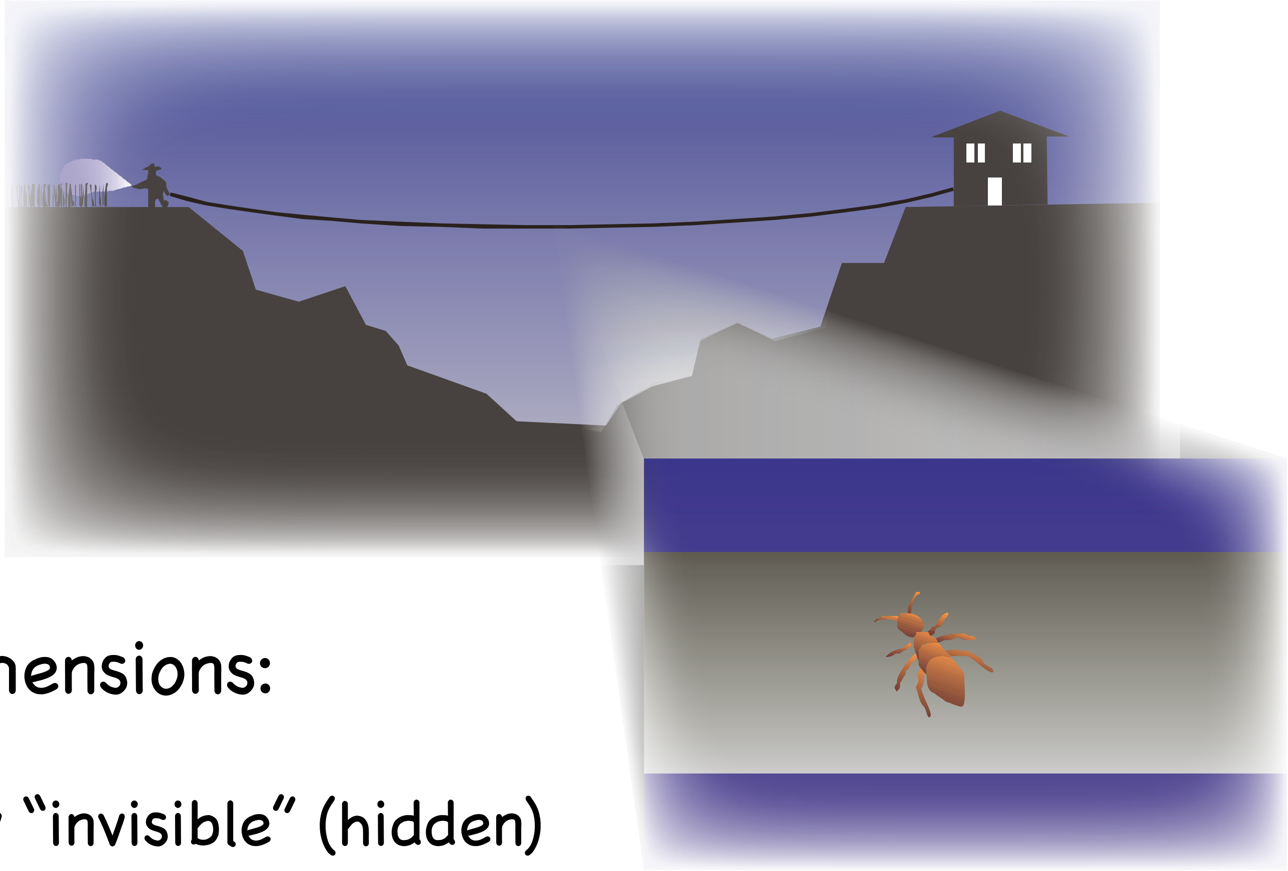
1 time-dimension



Extra Dimensions – A Simple Picture



Our world:

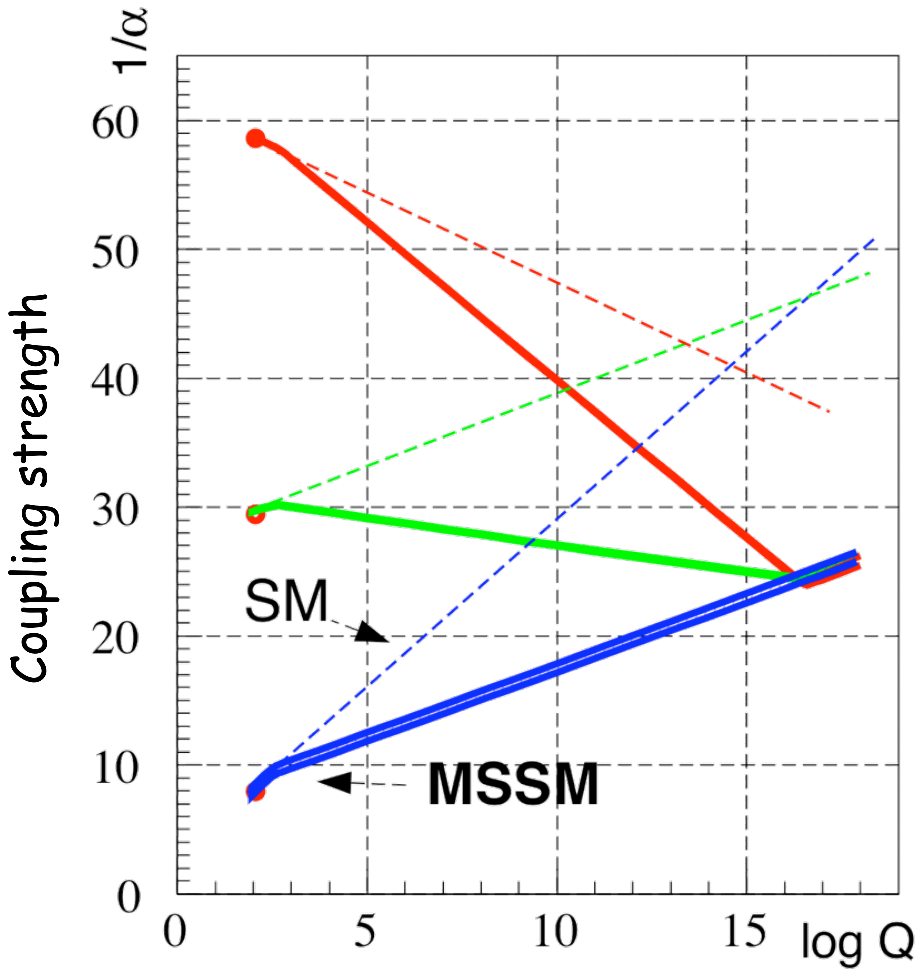
3 space-dimensions
1 time-dimension

Extra dimensions:
[if they exist]

obviously “invisible” (hidden)
i.e. must have final size
must be of small extension

Motivation

The Hierarchy Problem



Electroweak scale: 10^2 GeV

Scale of the higgs field, which gives mass to the heavy gauge bosons W and Z

GUT scale: 10^{16} GeV

Unification scale where strong, weak and, electromagnetic forces are of equal strength [Extrapolation: Supersymmetry]

Planck scale: 10^{19} GeV

Scale at which quantum fluctuations destroy space time structure.

The Standard Model of elementry particles does not explain the hierarchy problem

Extra Space-Dimensions

and the law of gravity

Law of Gravity:

3-dim.

$$F(r) = G_{(3)} \frac{mM}{r^2} \propto \frac{1}{r^2}$$

(n+3)-dim.

$$F(r) = G_{(3+n)} \frac{mM}{r^{2+n}} \propto \frac{1}{r^{2+n}}$$

Gauß' Law:

$$\oint \vec{F_G} d\vec{S} \sim M$$

$$\Rightarrow F_G \cdot S \sim M$$

$$F_G \sim M/S$$

S: n-dim. Surface
[2-dim.: $S=4\pi r^2$]

Conflict with every day life?

Compactified Dimensions

Extra dimensions with final size

---

r » R:

$$\oint \vec{F}_G d\vec{S} = \int_0^R \oint \vec{F}_G d\vec{r} dL \sim mM$$

$$\Rightarrow \quad F_G \sim \frac{mM}{r^2 R}$$

4-dim.

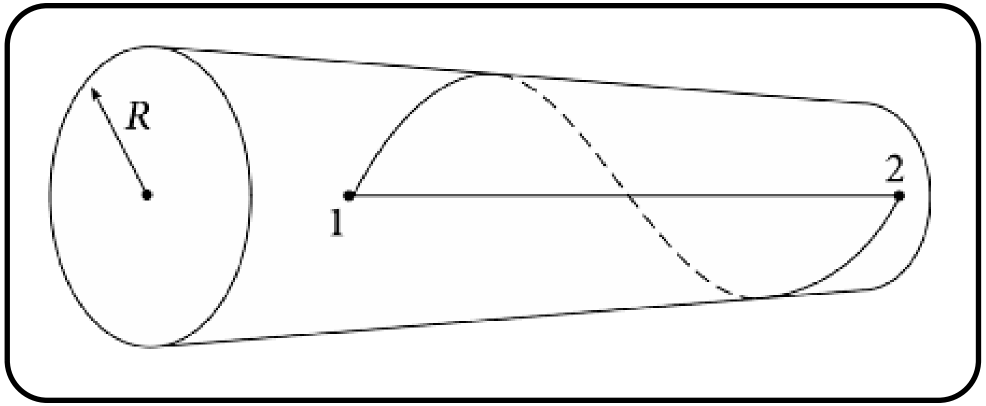
$$F(r) = \underbrace{\frac{G_{(3+n)}}{R^n}}_{G_{(3)}} \frac{mM}{r^2} \propto \frac{1}{r^2}$$

3+n-dim.

r « R:

$$F(r) = G_{(3+n)} \frac{mM}{r^{2+n}} \propto \frac{1}{r^{2+n}}$$

3+n-dim.



SM interactions tested up to r ~ 10^{-18} m

But gravity ...
only tested down to about 0.1 mm

No conflict ...

if only gravity 'lives' in extra dimensions

Hierarchy Problem

An explanation through extra dimensions

The real Planck Scale:

i.e. energy scale at which gravity gets 'strong'

$$M_{\text{Pl}} = \sqrt{\frac{\hbar c}{G_{(3)}}} \sim 10^{19}\text{GeV} \Leftrightarrow G_{(3)} = \frac{\hbar c}{M_{\text{Pl}}^2}$$

Planck Mass
Gravitational constant

$$M_{\text{S}} = \sqrt[n+2]{\frac{(\hbar c)^{n+1}}{c^{2n} G_{(3+n)}}} \Leftrightarrow G_{(3+n)} = \frac{(\hbar c)^{n+1}}{c^{2n} M_{\text{S}}^{n+2}}$$

"True"
Planck Scale: M_S

$$M_{\text{Pl}}^2 \sim G_{(3)}^{-1} \sim G_{(3+n)}^{-1} R^n \sim M_{\text{S}}^{2+n} R^n$$

R,n large → M_S small

Possible Size and Number

of extra space dimensions

To solve the
hierarchy problem

Choose $M_S \sim 1$ TeV

$M_{Pl} \sim 10^{16}$ TeV

$$M_{\rm Pl}^2 \approx M_{\rm S}^{2+n} R^n$$

Planck Mass

$$R \approx \frac{1}{M_{\rm S}} \left(\frac{M_{\rm Pl}}{M_{\rm S}} \right)^{\frac{2}{n}}$$

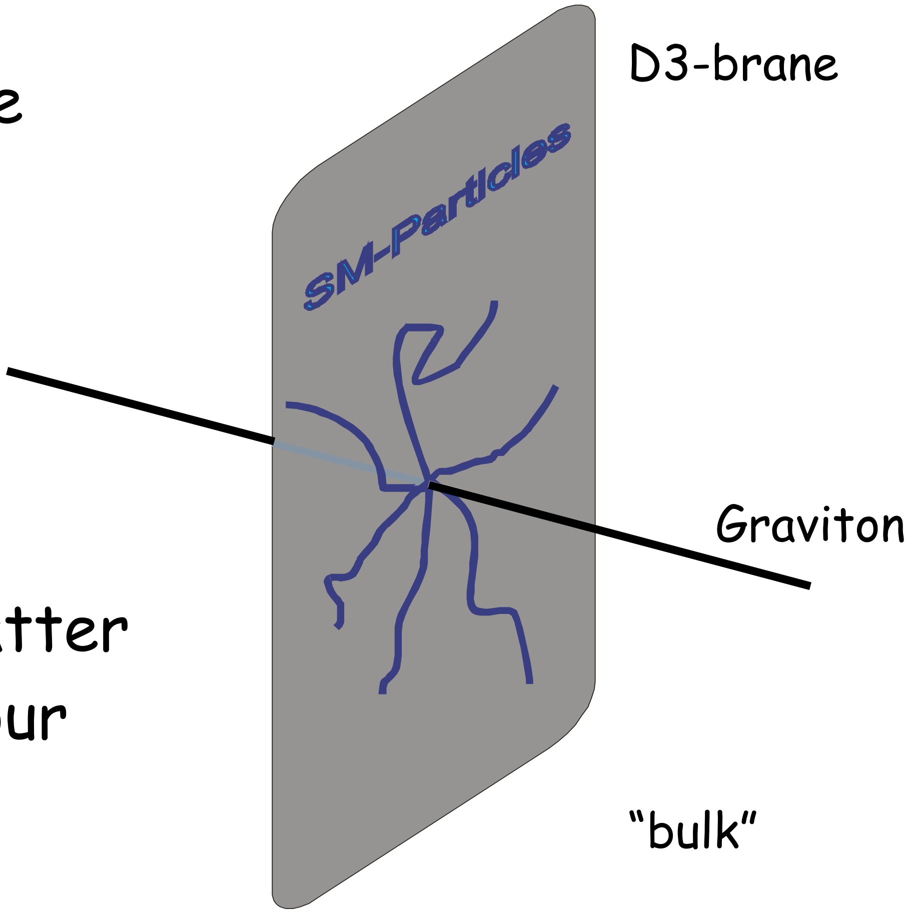
Size

n	$R \approx 10^{\frac{30}{n}-18}\mathrm{cm} \times \left(\frac{1\mathrm{TeV}}{M_{\rm EW}}\right)^{1+\frac{2}{n}}$
1	70 AU
2	1.0 mm
3	1.0 nm
4	10 pm
...	
7	3.7 fm

Large Extra Dimensions

[Arkani-Hamed, Dvali, Dimopoulos]

- n compactified extra space dimensions with size R
- gravity in all n+3 space dimensions
- SM interactions and all matter particles are confined to our 3-dimensional world.



Extra Dimensions

Consequences for particle physics

Missing energy in particle reactions

[Graviton emission into hidden space dimensions]

Change of cross sections

[Exchange of virtual gravitons]

New Particles

[Kaluza-Klein excitations]

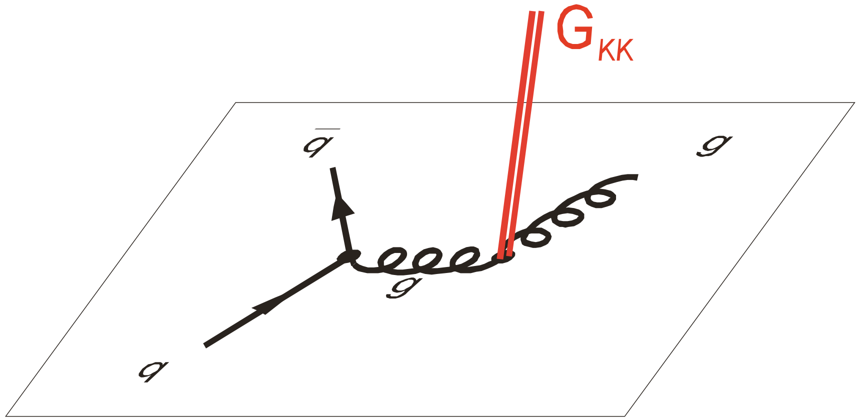
Production of Mini Black Holes

[End of short distance physics]

Signatures for Extra Dimensions

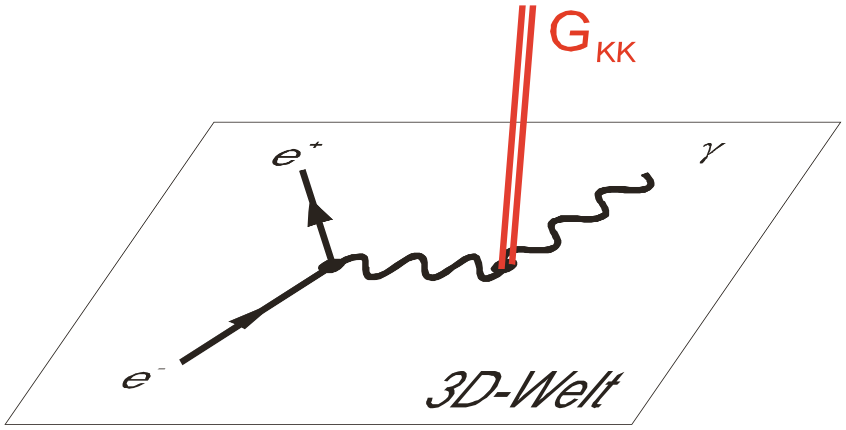
Missing Energy in Particle Reactions

In particle reactions produced gravitons leave our 3D-world (3D-brane) and are thus not detected.



qq-signature (e.g. LHC):

- high-energy Monojet
- missing energy

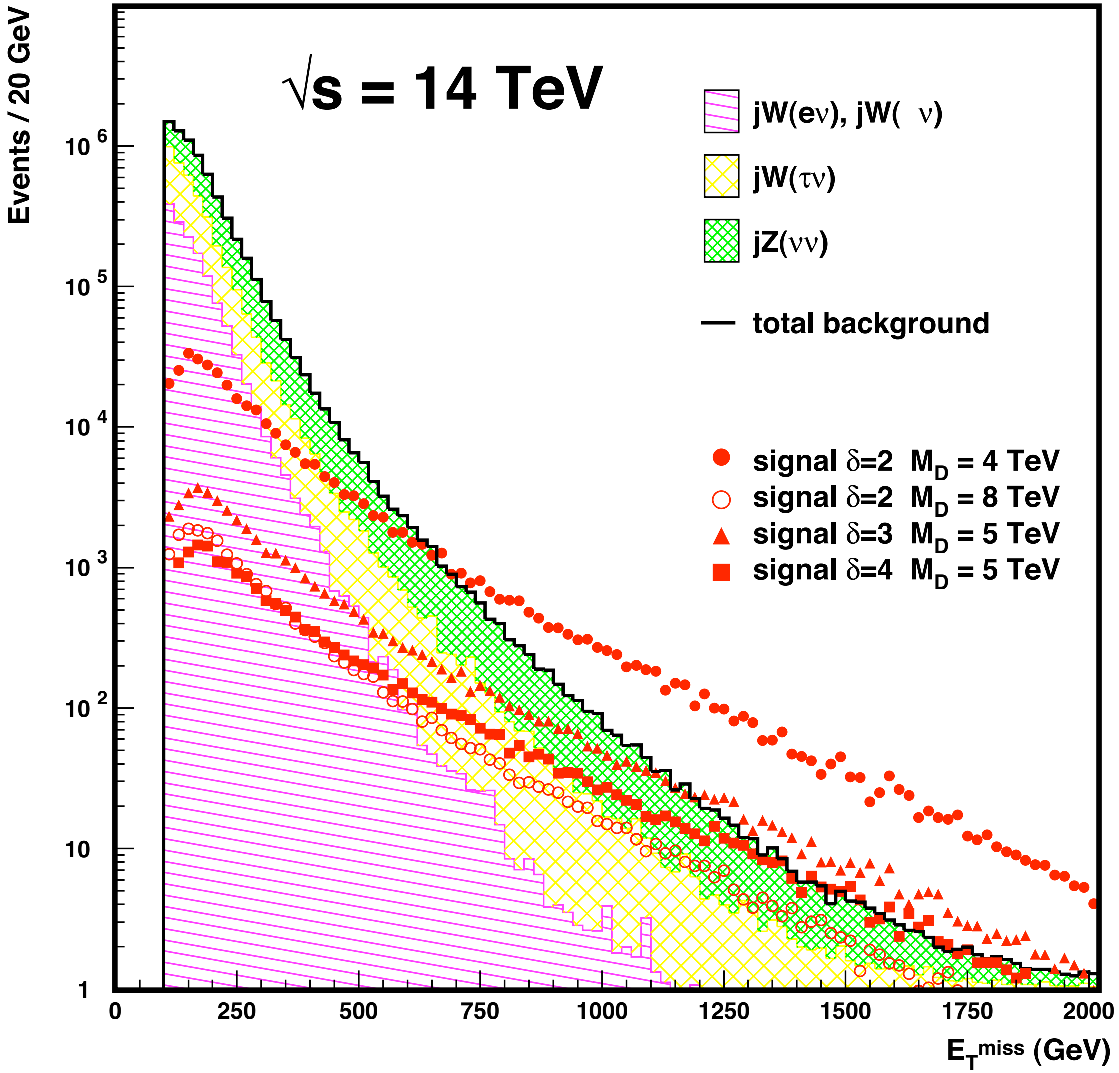


e^+e^--signature (e.g. ILC):

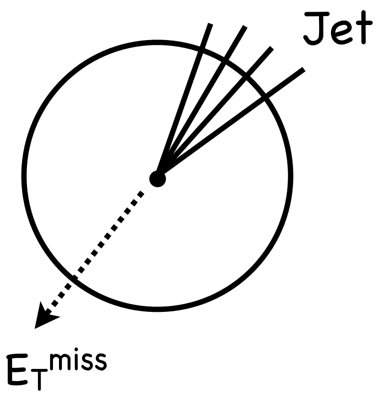
- single photon
- missing energy

Signatures for Extra Dimensions

Monojets + $E_{T,miss}$



Clear Signature:

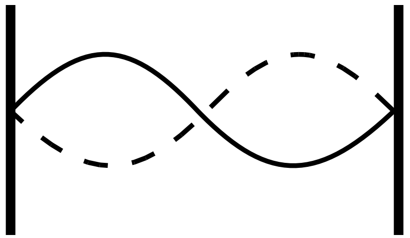


Increased Monojet rate at large $E_{T,miss}$

Kaluza-Klein Modes

Extra dimension final size → quantized energies

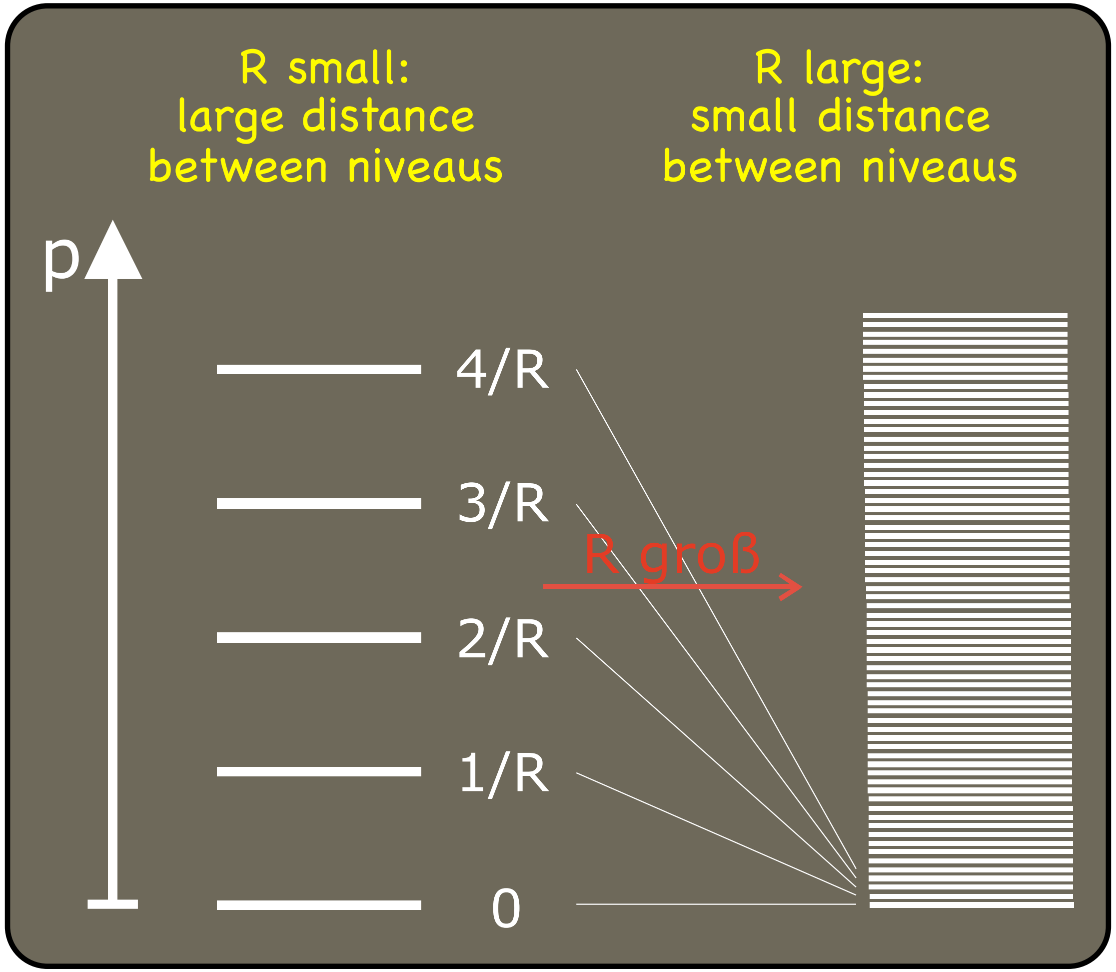
1-Dim. Box



$$p_5 = \frac{n}{R}$$

$$\begin{aligned} E^2 &= p^2 + p_5^2 + m^2 \\ &= p^2 + \frac{n^2}{R^2} + m^2 \end{aligned}$$

Mass states
in 3D-world

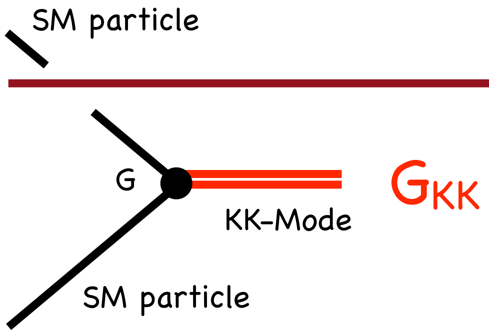


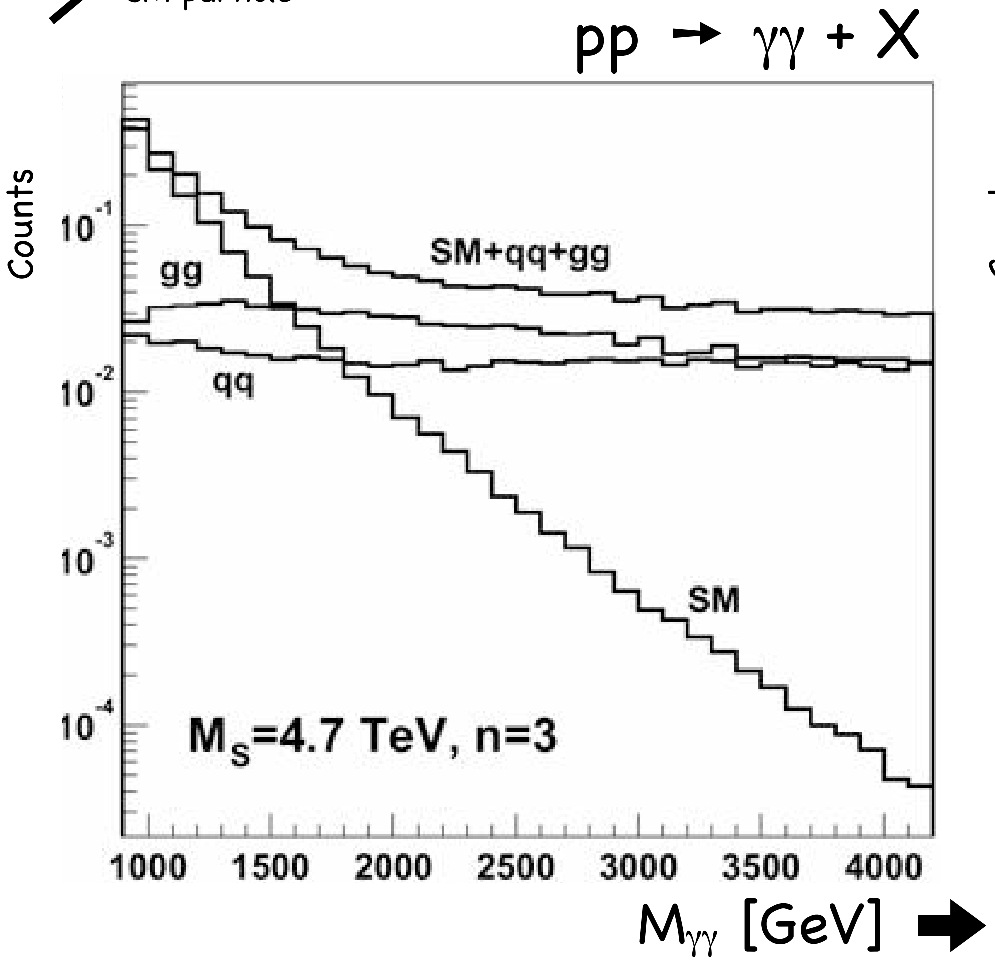
R small:
large distance
between niveaus

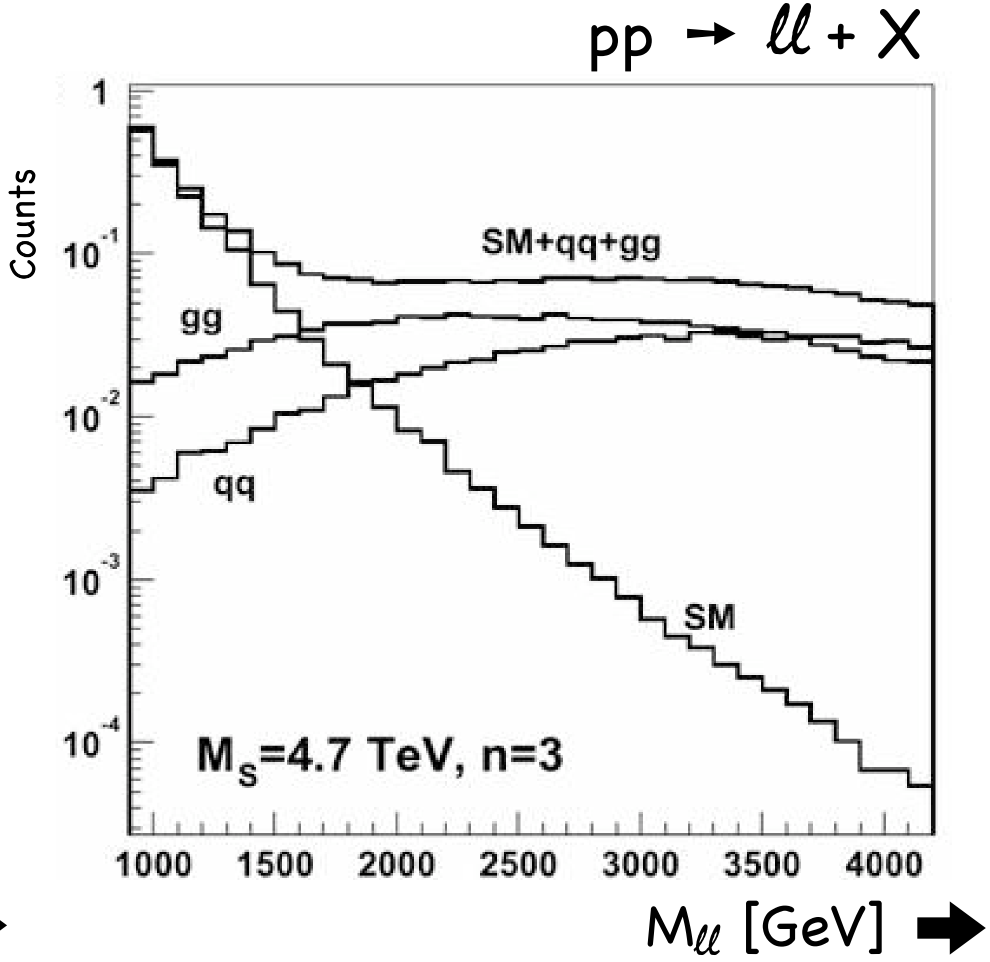
R large:
small distance
between niveaus

Kaluza-Klein Modes

Experimental Consequences I



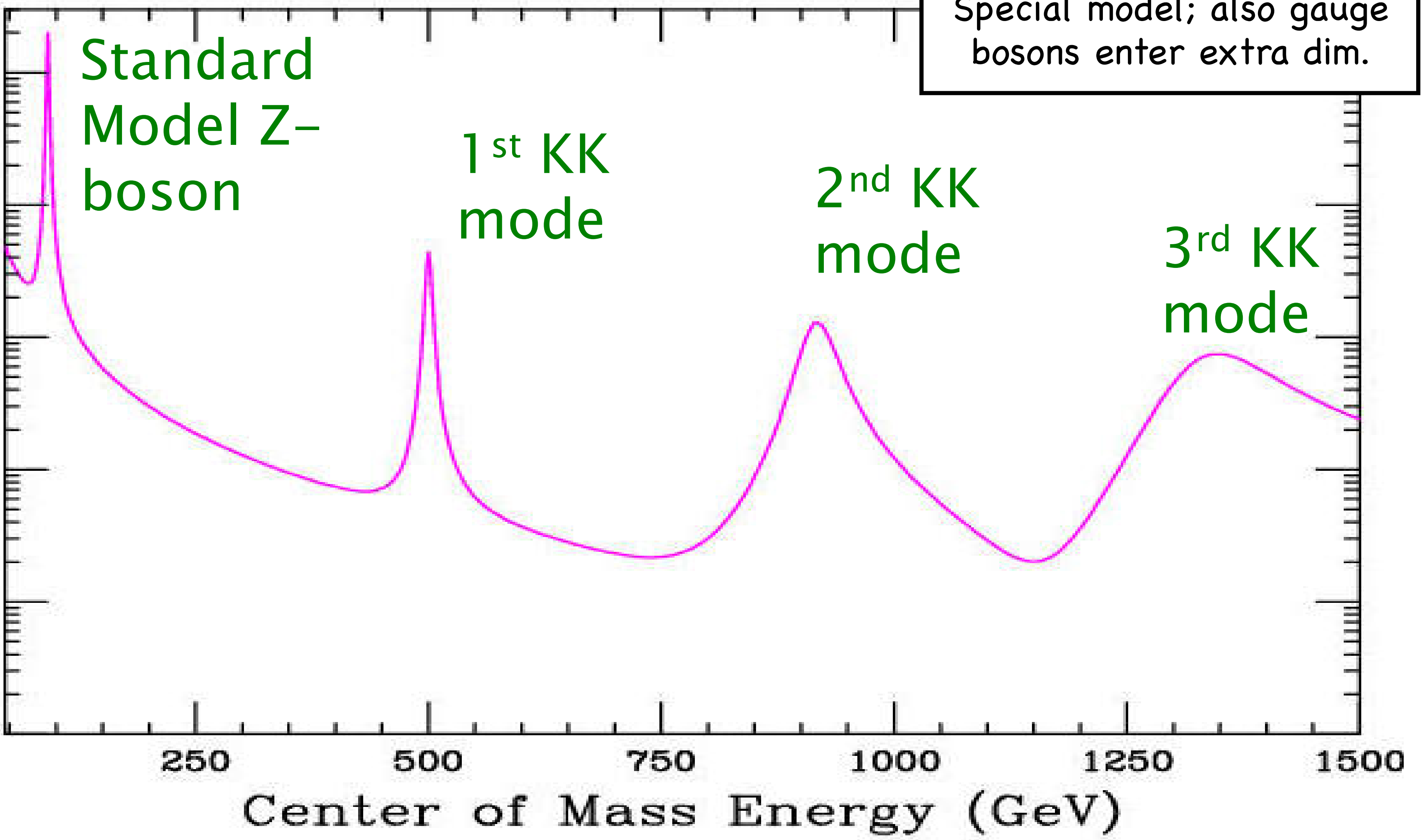

pp → γγ + X


pp → ℓℓ + X

Kaluza-Klein Modes

Experimental Consequences II

Special model; also gauge bosons enter extra dim.



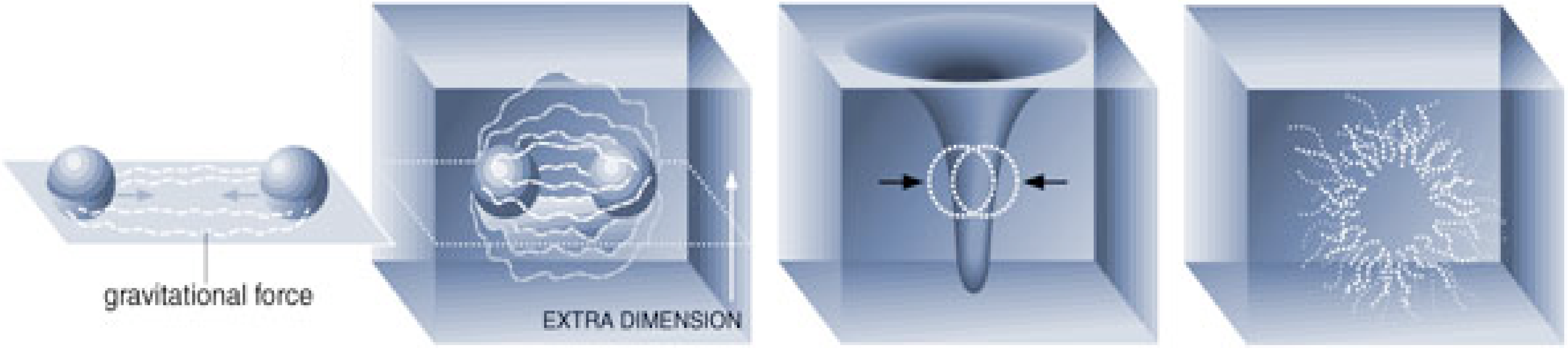
Mini Black Holes

Production and Decay

$$r_{\mathrm{BH}} \approx \frac{1}{M_S}\left(\frac{M_{\mathrm{BH}}}{M_S}\right)^{\frac{1}{n+1}}$$

M_S small → r_{BH} large

$E_{cms} > M_S$, $b < r_{BH}$ → black hole



particle collision

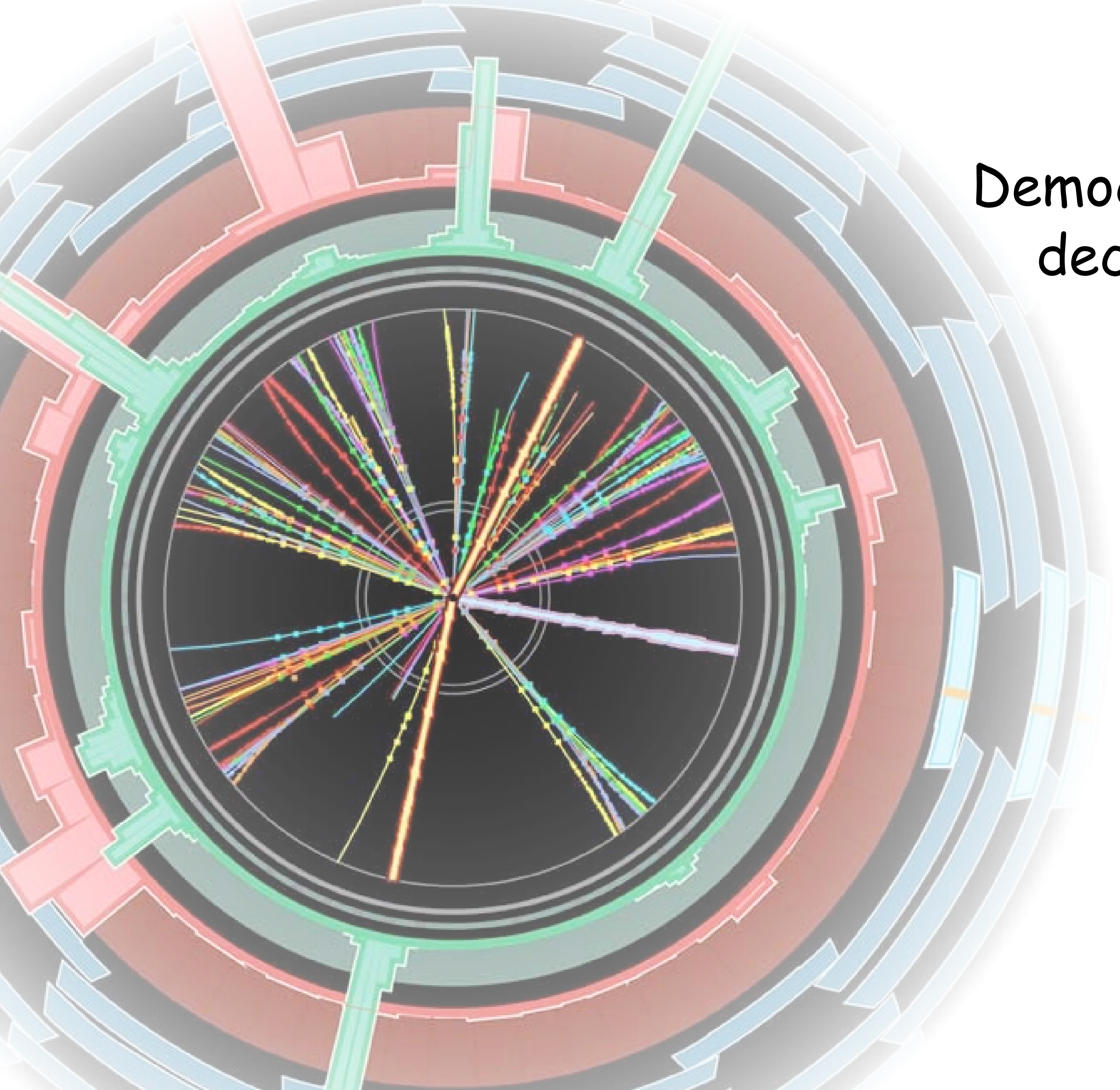
ED become relevant

birth of a mini black hole

evaporation via Hawking Rad.

Mini Black Holes

Experimental Signature



q/g : ℓ : W/Z : ν/g : H : γ
72% : 11% : 8% : 6% : 2% : 1%

Democratic
decay into SM particles

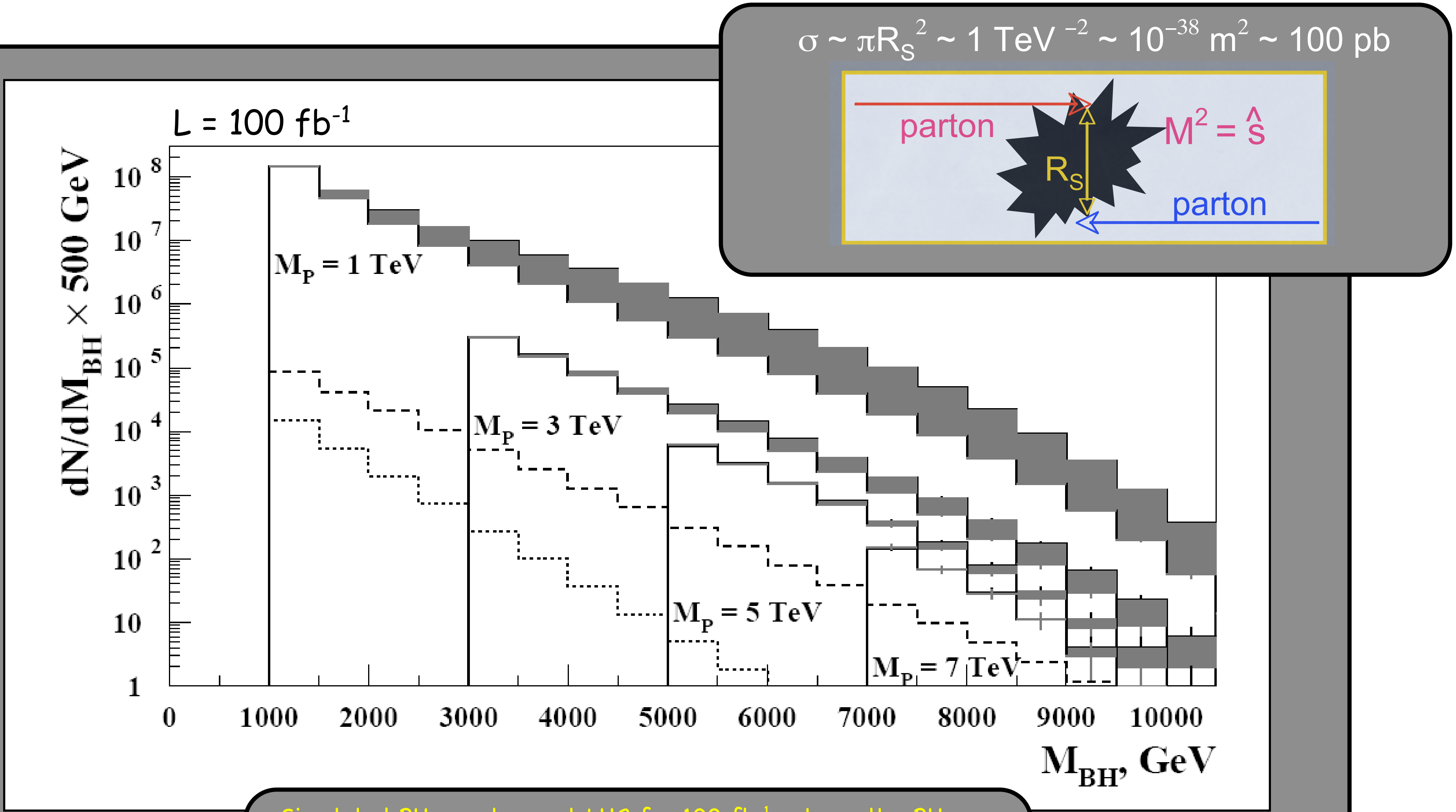
[Emparan et al., hep-th/0003118]

- High multiplicity
  [e.g. M_{BH} = 10 TeV: 50 part. with E ~ 200 GeV]
- Spheric Events
  [production at high x without Boost]
- Electrons and muons with high energy

Mini Black Holes

Cross Section

$\sigma \sim \pi R_S^2 \sim 1\ \text{TeV}^{-2} \sim 10^{-38}\ \text{m}^2 \sim 100\ \text{pb}$



Simulated BH spectrum at LHC for 100 fb^{-1}, where the BH was selected by an elektron or Photon in the final state.

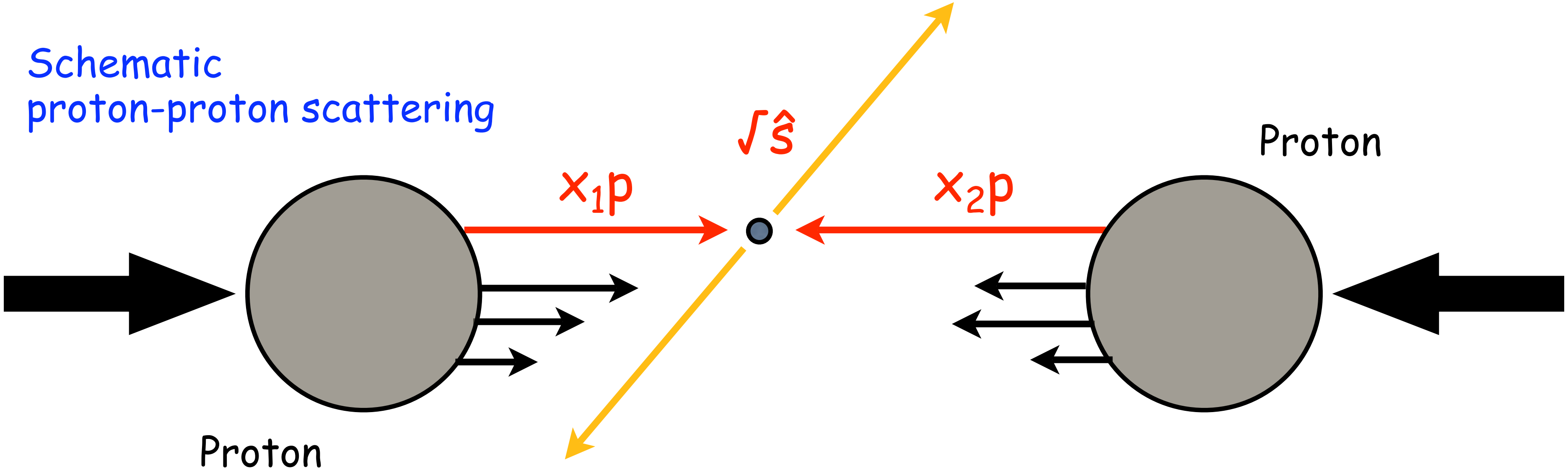
Prerequisites

Parton Densities and the LHC

Hadron-Hadron Interactions

Basic kinematic variables

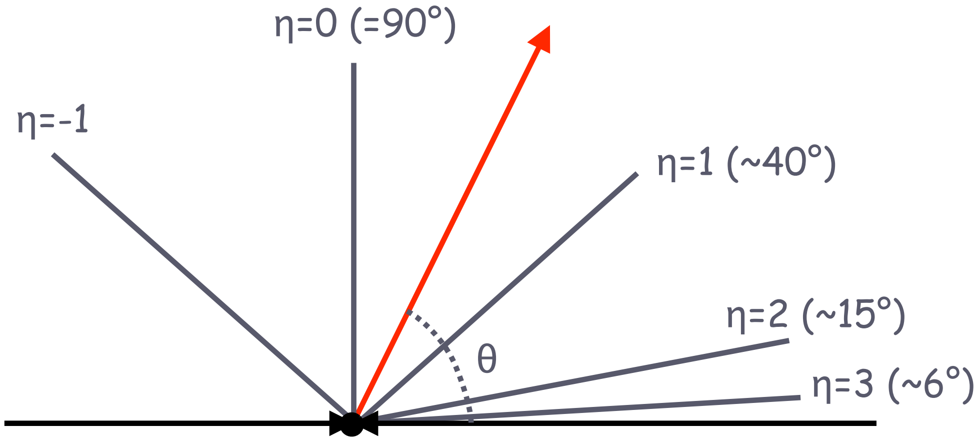
Schematic
proton-proton scattering



Relevant kinematic variables:

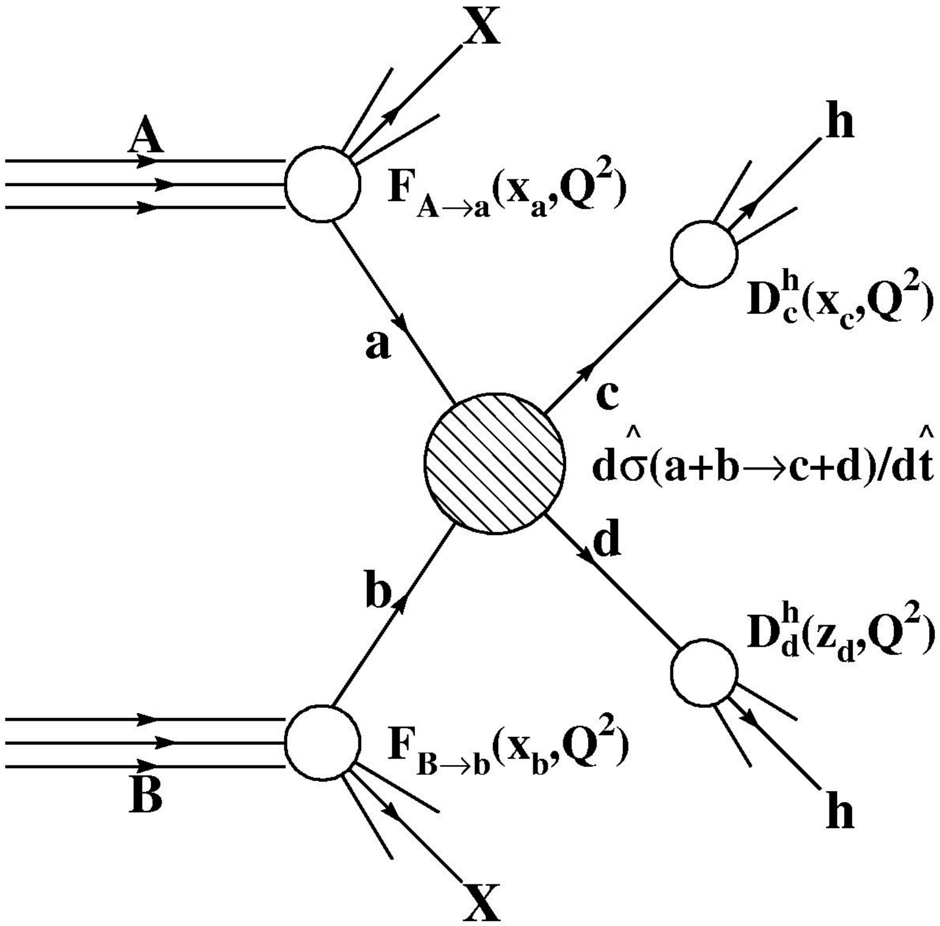
- Transverse momentum: p_T
- Rapidity: $y = \frac{1}{2}\ln (E-p_z)/(E+p_z)$
- Pseudorapidity: $\eta = -\ln \tan \frac{1}{2}\theta$
- Azimuthal angle: φ

Pseudorapidity



Hadron-Hadron Interactions

How to caculate cross sections



Hard Process: ab → cd

can be calculated ...

... but:

a,b partons inside A,B

ATLAS CMS: protons

c,d fragment into ...

Needs:

parton densities

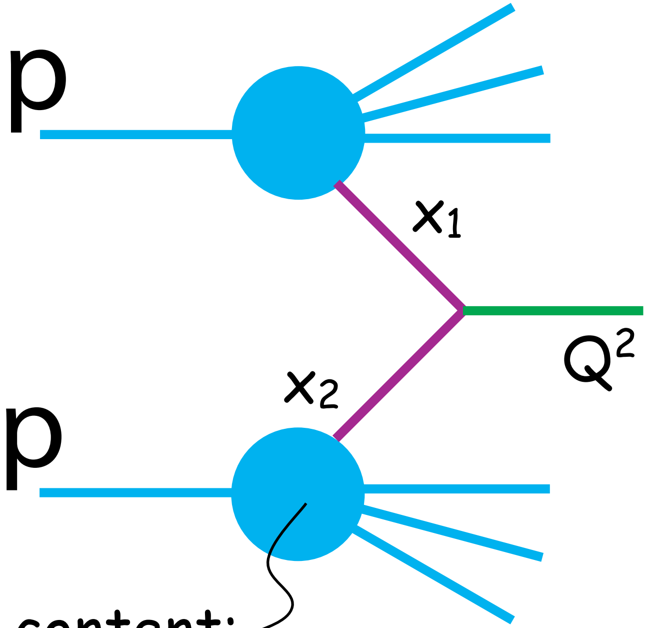
fragmentation functions

Caclulable

$$\sigma = \sum_{a,b} \int dx_a dx_b f_a(x_a,Q^2) f_b(x_b,Q^2) \hat{\sigma}_{ab}(x_a,x_b)$$

To be measured

Proton Structure in one Slide

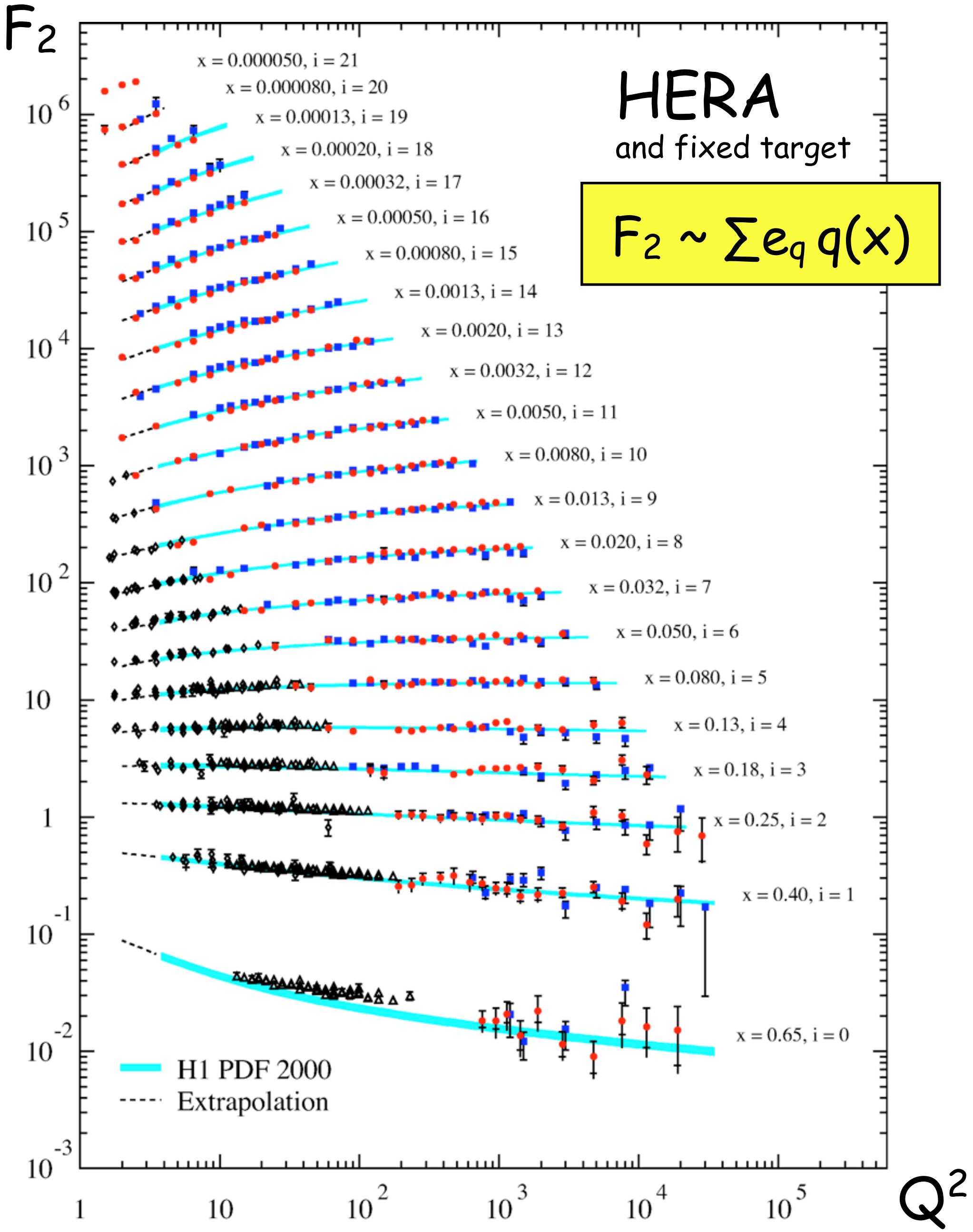


Parton content:

$f(x,Q^2) = q(x,Q^2)$ or $g(x,Q^2)$

$x_{1,2}$: fractional momentum of parton involve in hard process

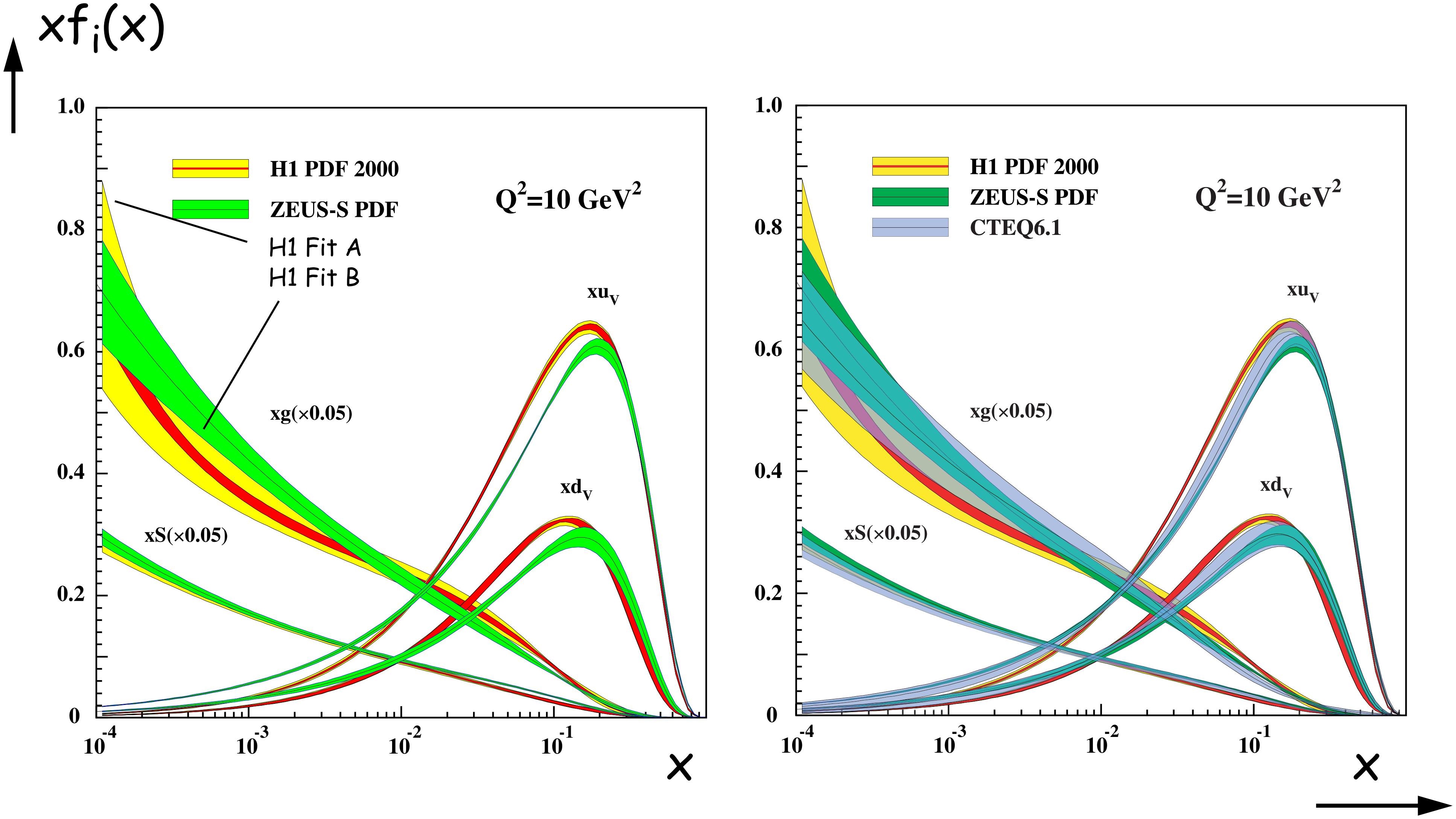
Q^2 : scale; spacial resolution

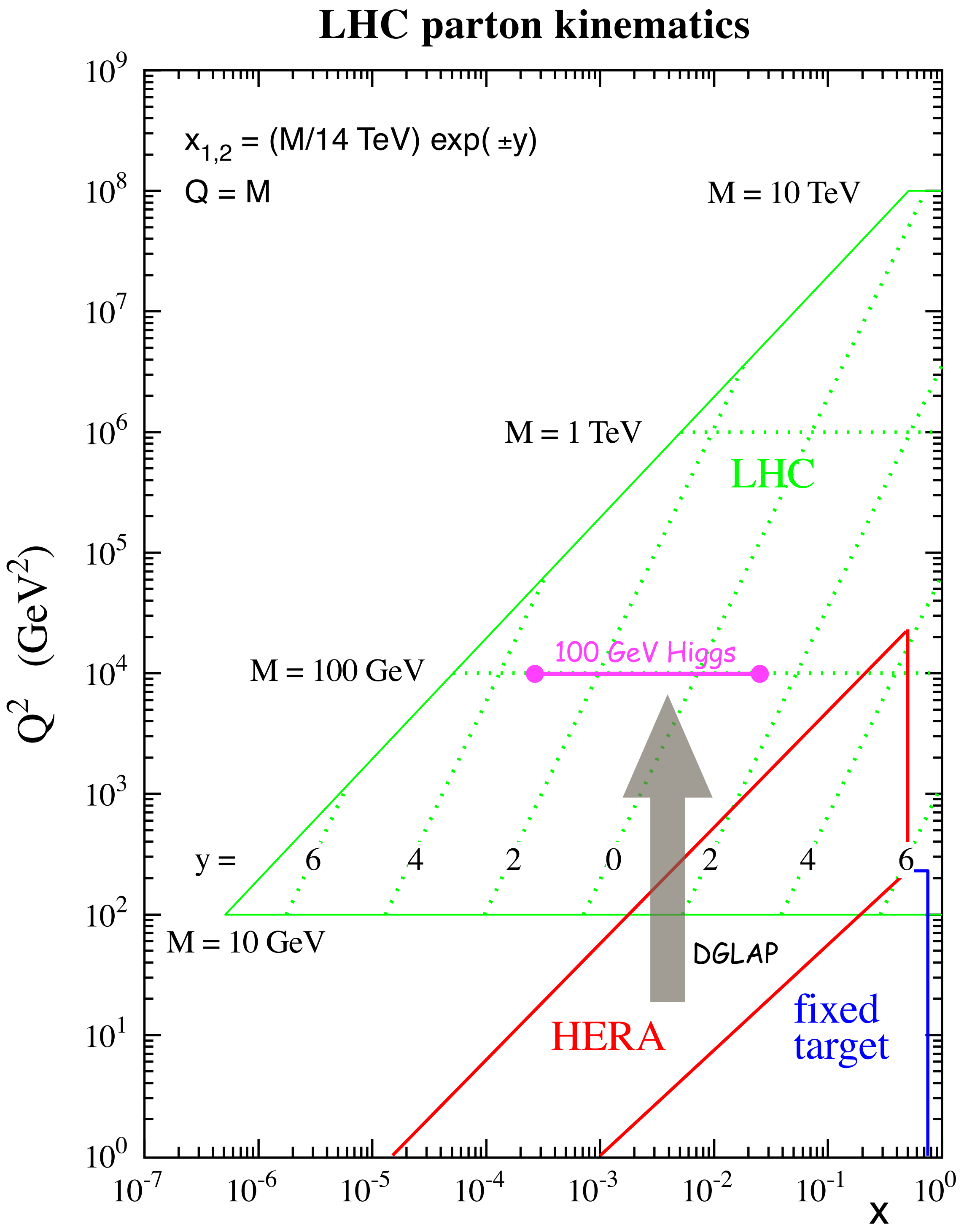


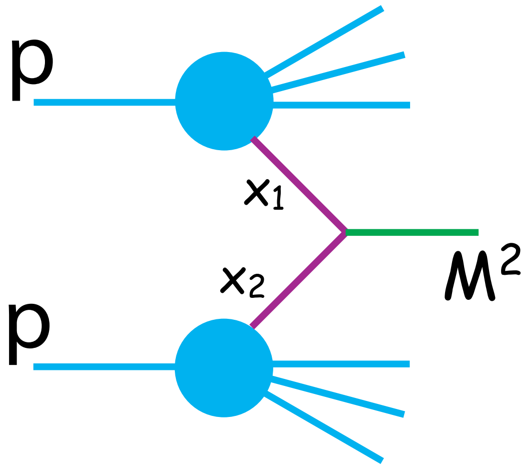
HERA
and fixed target

$F_2 \sim \sum e_q\, q(x)$

Parton Densities – HERA Results




LHC parton kinematics

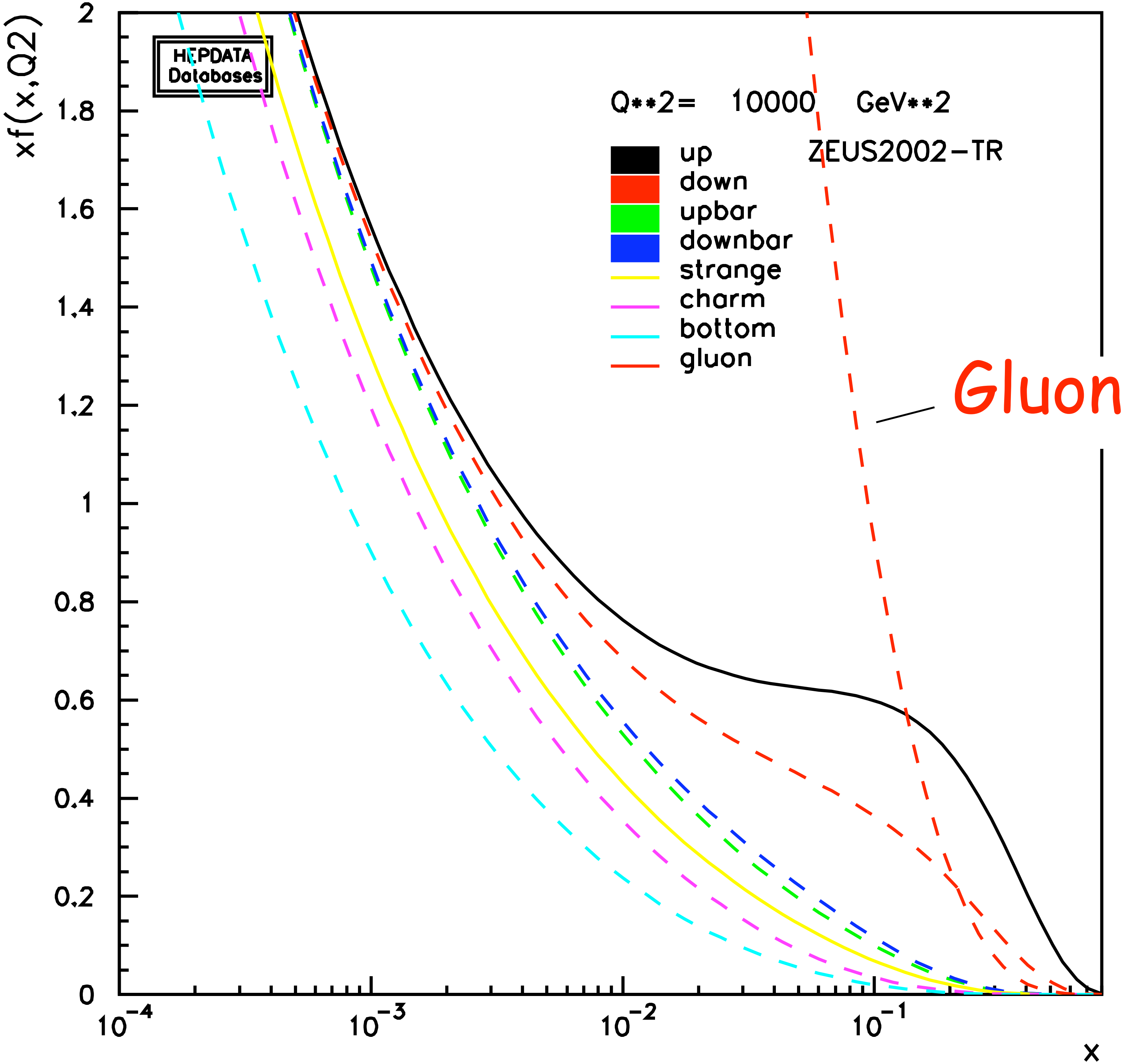


$$M^2 = x_1 x_2\, s$$

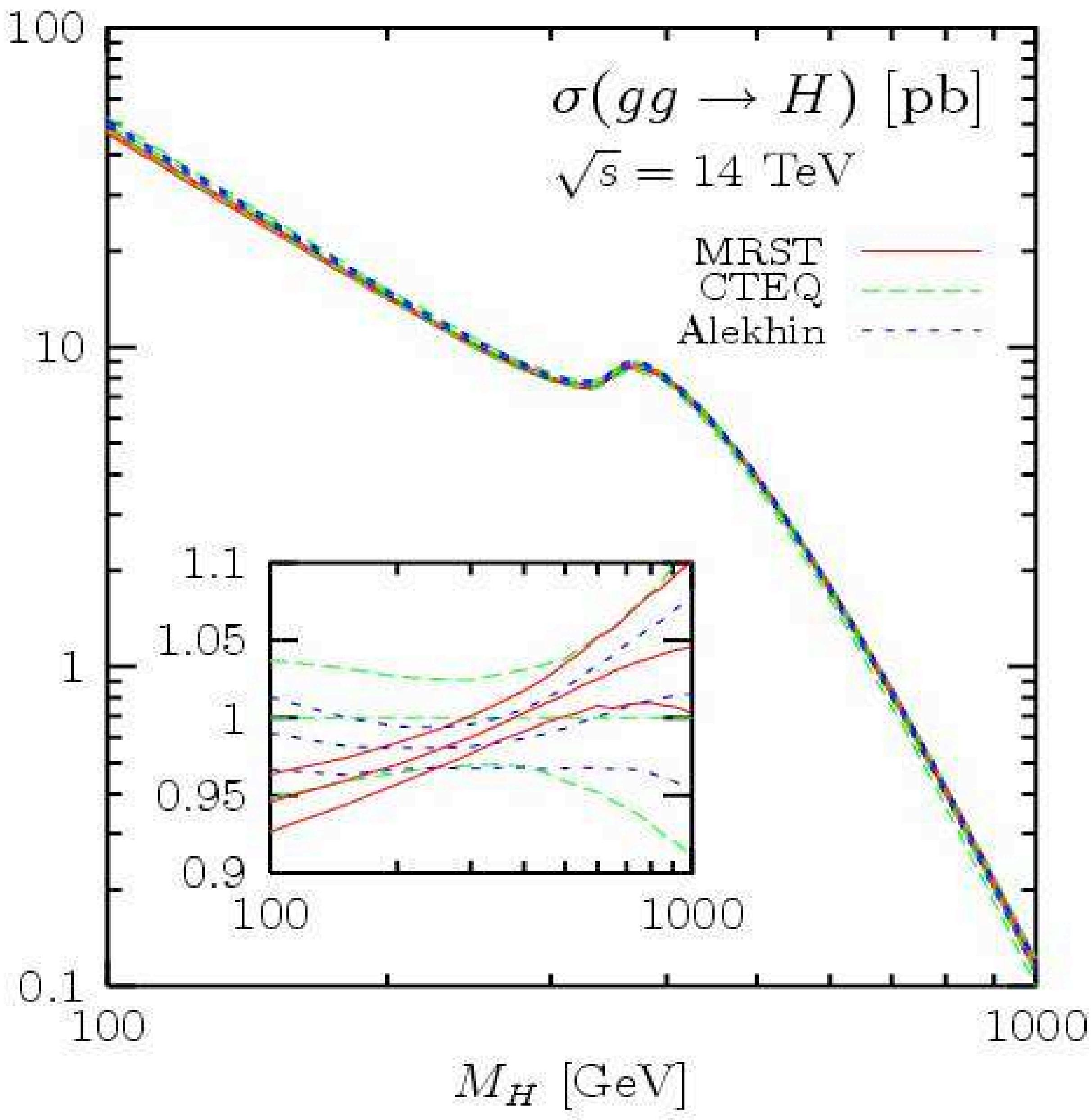
i.e. to produce a particle with mass M
at LHC energies ($\sqrt{s}$ = 14 TeV)
$\langle x \rangle = \sqrt{x_1 x_2} = M/\sqrt{s}$
[$x_1 = x_2$: mid-rapidity]

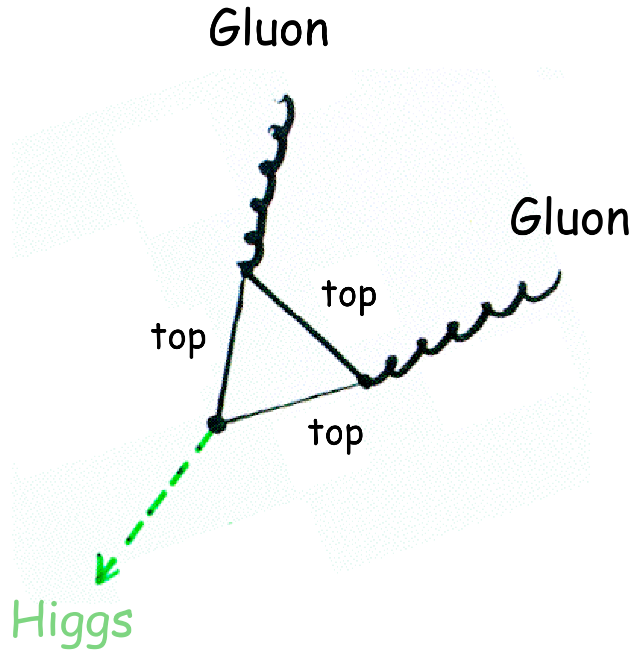
LHC needs:

- knowledge on parton densities
- extrapolation over orders of magnitude


HEPDATA Databases
Q**2= 10000 GeV**2
ZEUS2002-TR
up
down
upbar
downbar
strange
charm
bottom
gluon
xf(x,Q2)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x

Gluonen

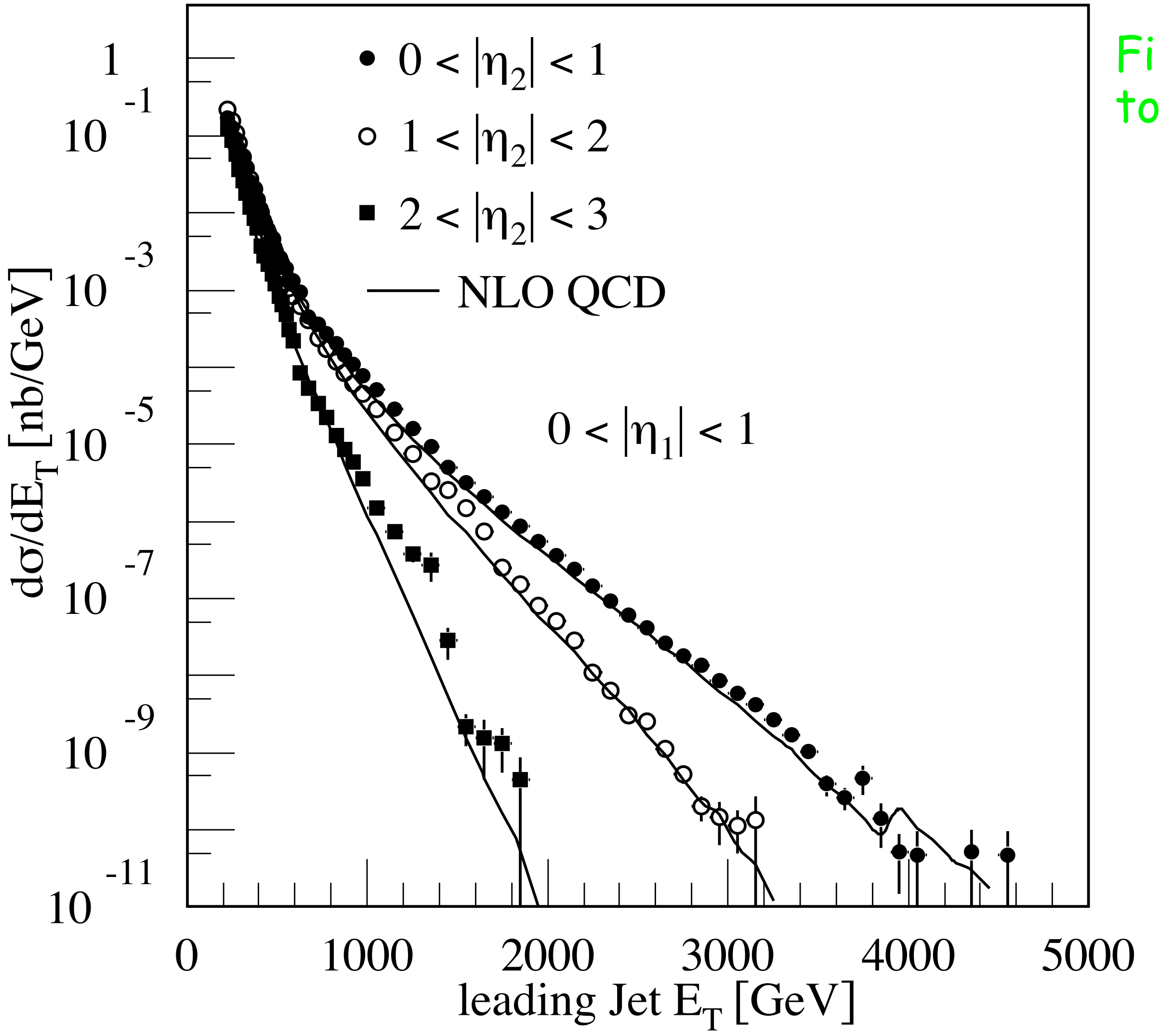




Simple spread of existing PDFs gives a 5-10% uncertainty on the Higgs cross section.

Jet Spectrum @ LHC

ATLAS TDR: Inclusive Jet E_T



First plot
to be made at LHC

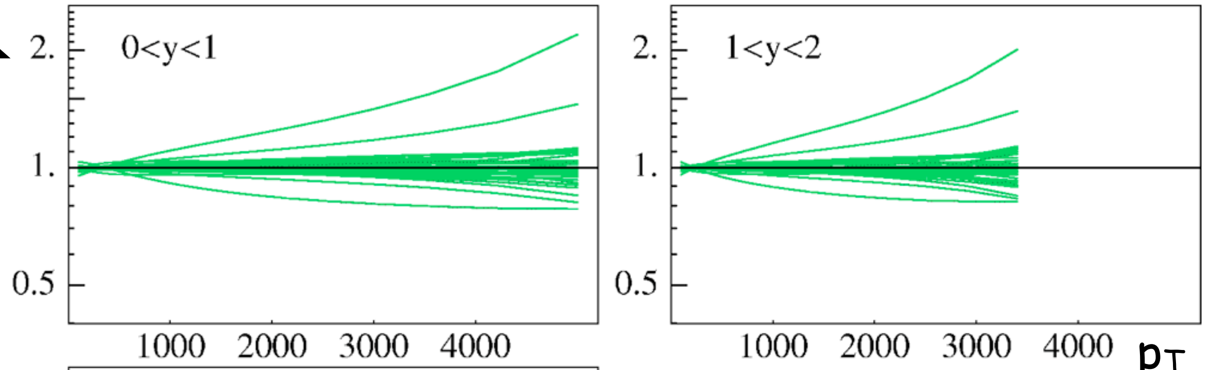
Sensitive to:

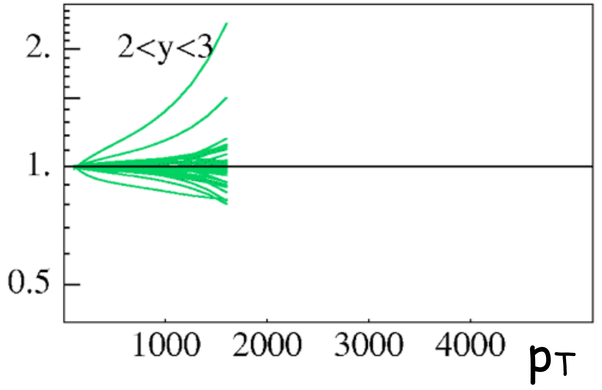
- Parton distribution functions
- Detector performance
  [Energy scale and resolution]
- New Physics

Inclusive Jet Cross Section @ LHC

[D.Stump et al., JHEP 10 (2003) 046]

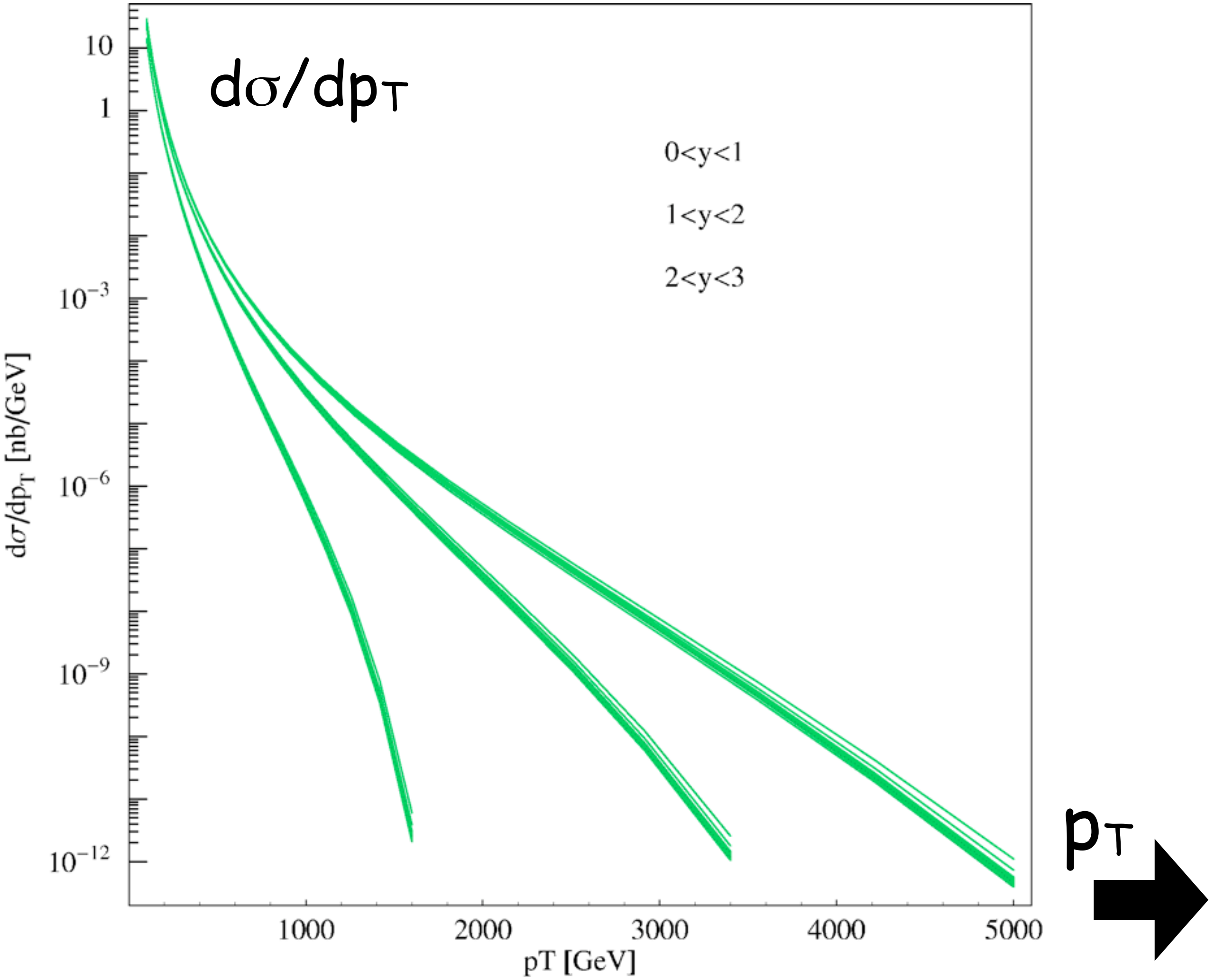
Relative Uncertainty [compared to CTEQ 6.1M]





Mid-rapidity:
100 % uncertainty
@ E_T ~ 5 TeV

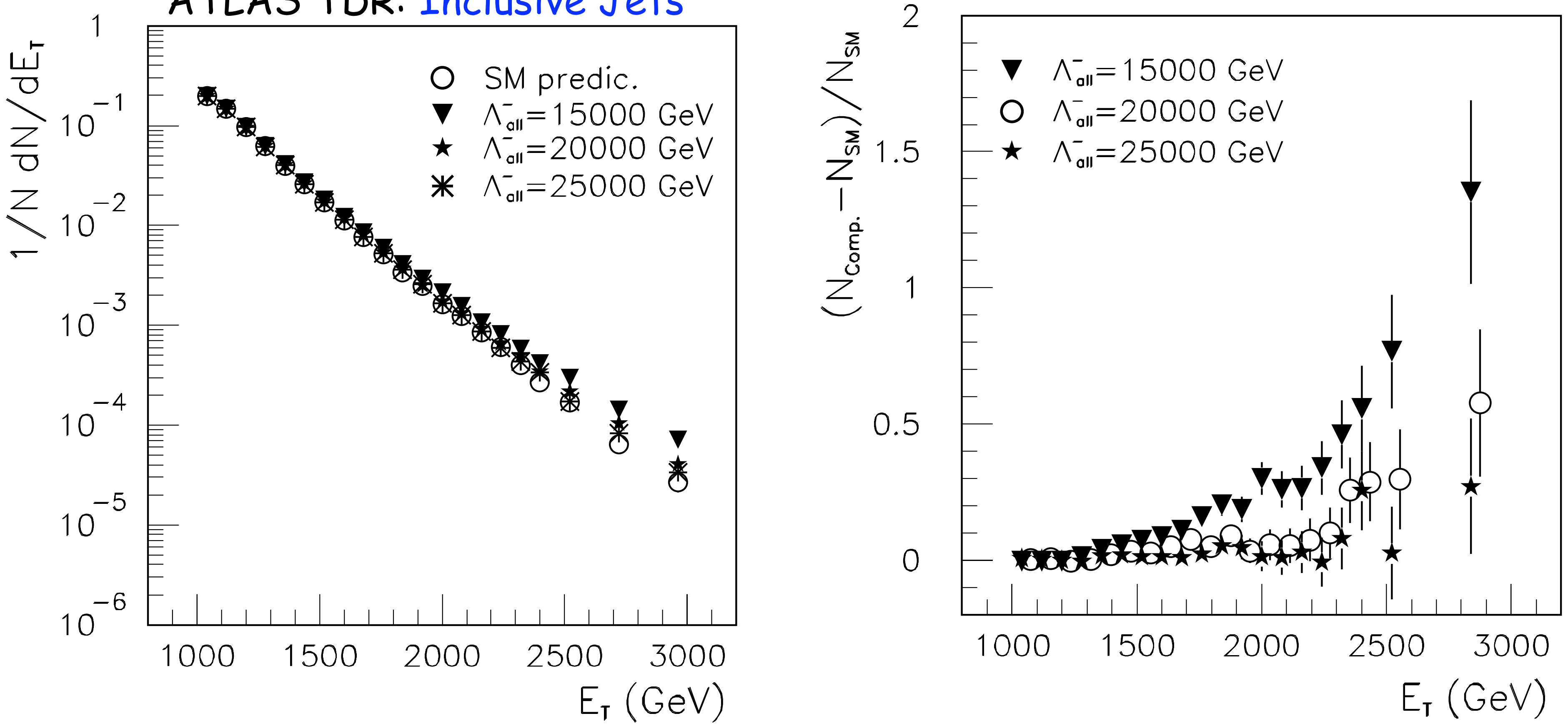
Forw. jets:
100 % uncertainty
@ E_T ~ 2 TeV



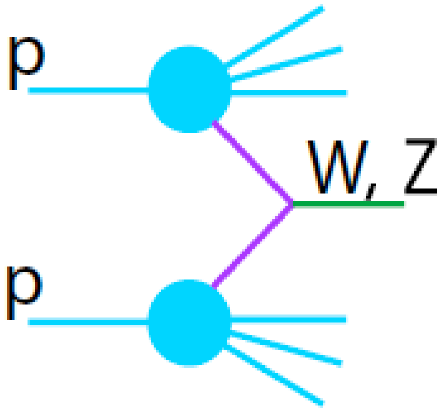
Quark Substructure [Compositeness]

Expectation: Enhancement of σ_{jet} at high E_T

ATLAS TDR: Inclusive Jets



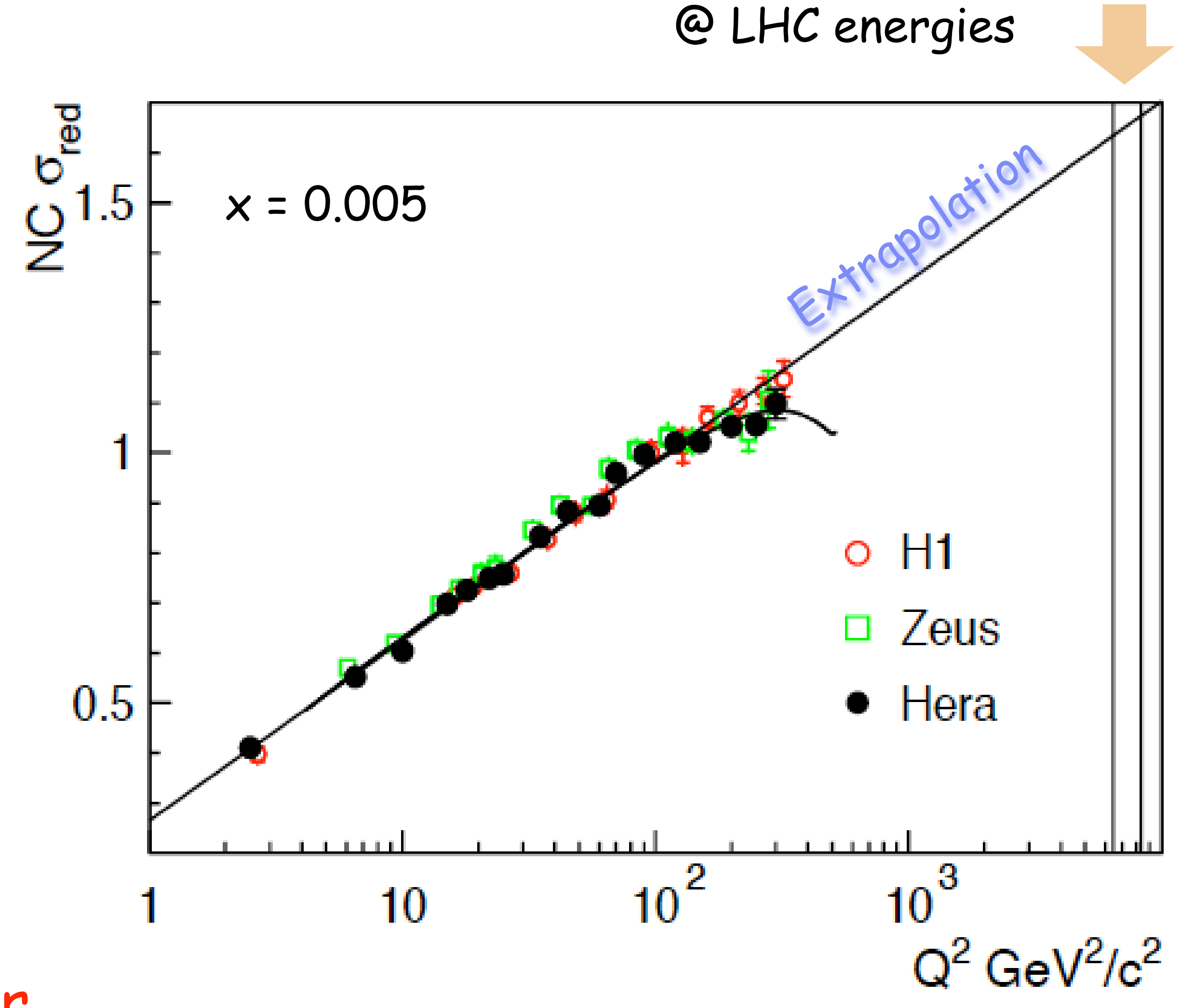
W and Z Production @ LHC



pp → W + X
pp → Z + X

Considered
as luminosity monitor

Q^2 for W/Z production
@ LHC energies

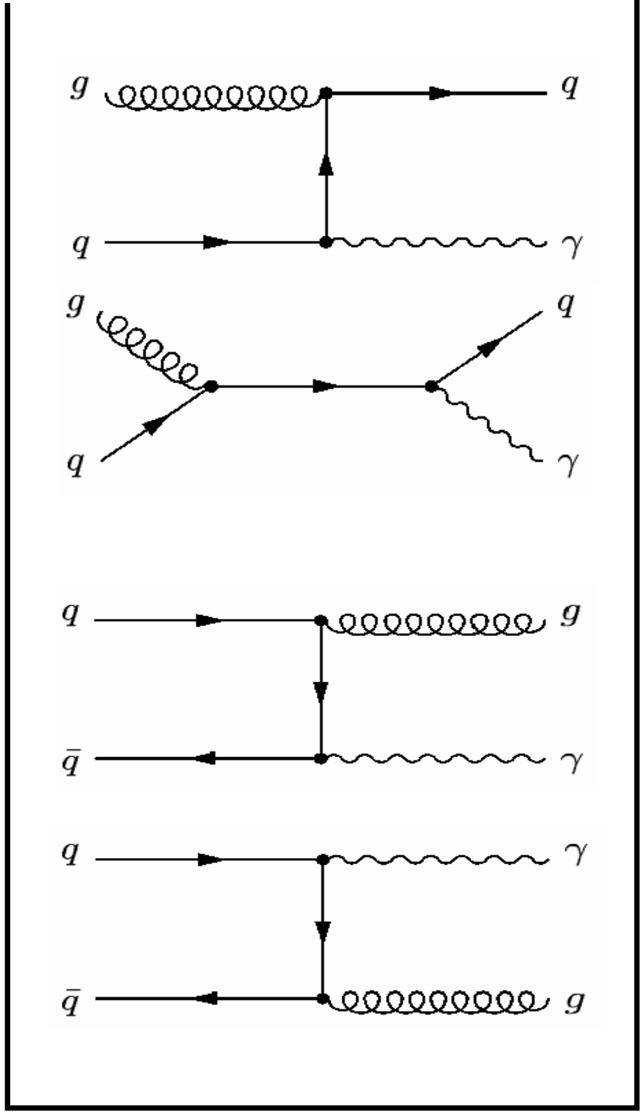


Parton Densities

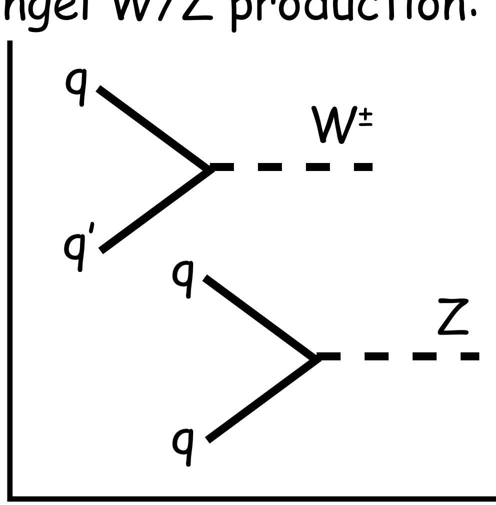
Determination @ LHC

Vector Boson Production

Direct γ-production:



Singel W/Z production:



W production: $\begin{cases} u\bar{d} \to W^+ \\ d\bar{u} \to W^- \end{cases}$
(main contributions)

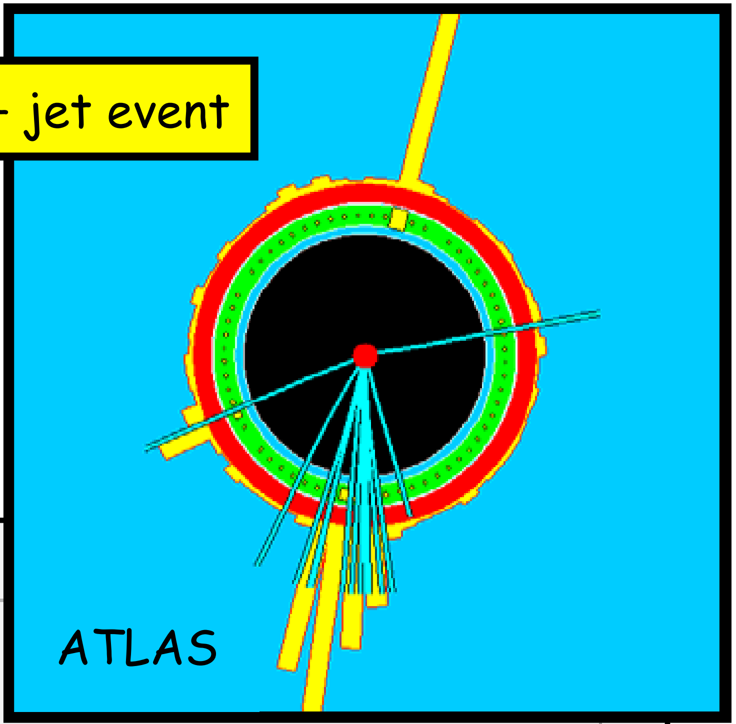
Z production: $\begin{cases} u\bar{u} \to Z \\ d\bar{d} \to Z \end{cases}$
(main contributions)

- At LHC energies these processes take place at low values of Bjorken-x
- Only sea quarks and gluons are involved
- At EW scales sea is driven by the gluon, i.e. x-sections dominated by gluon uncertainty

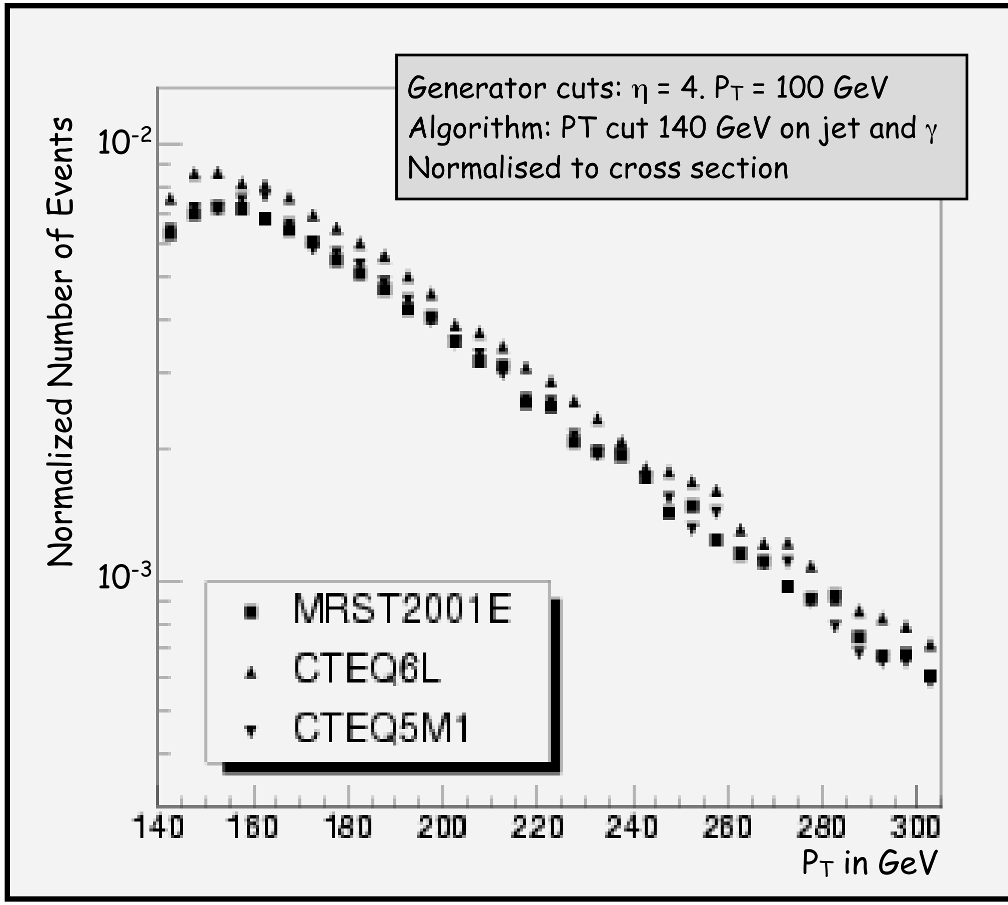
➥ Constraints on sea and gluon distributions

Direct γ Production

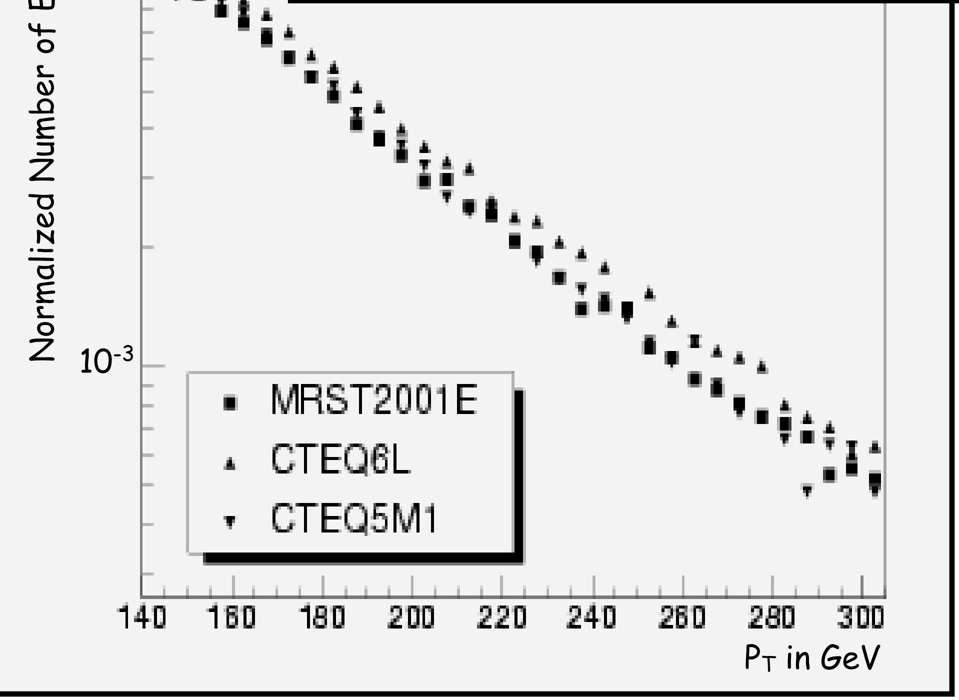
Sensitive to PDF differences
CTEQ - MRST: ± 16 -18 % disagreement
Needs good understanding of detector



γ + jet event

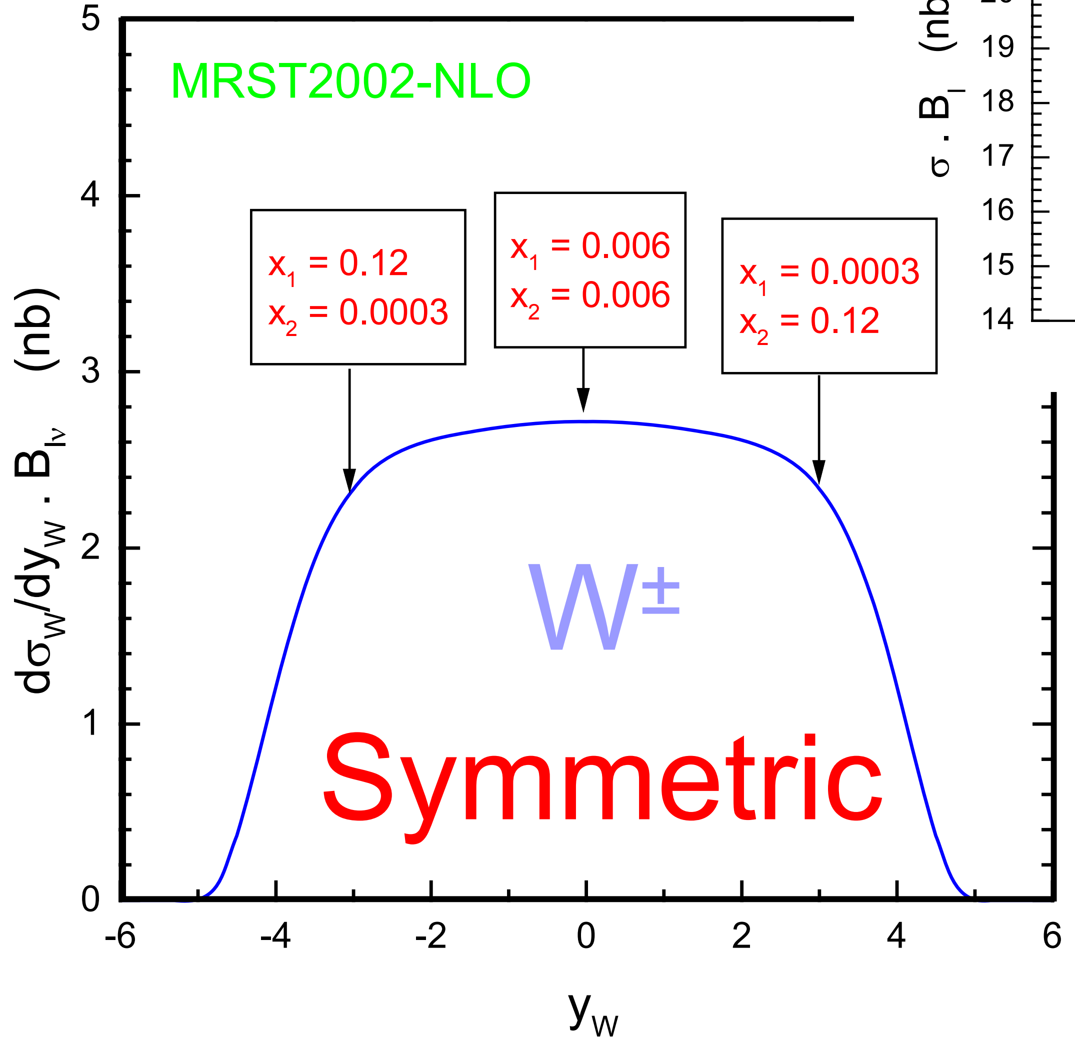


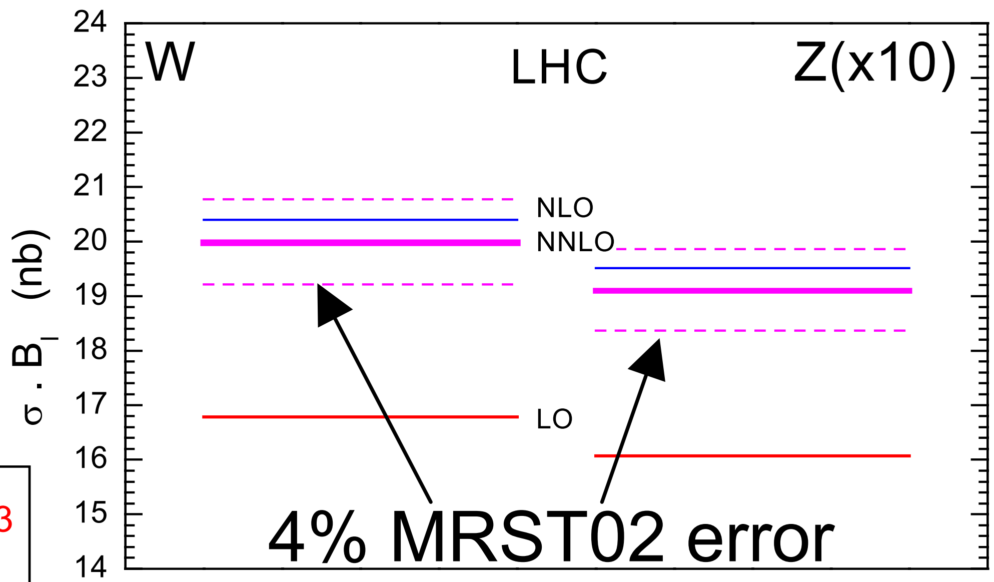
Generator cuts: η = 4. P_T = 100 GeV
Algorithm: PT cut 140 GeV on jet and γ
Normalised to cross section



Single W and Z Production

W± rapidity distribution



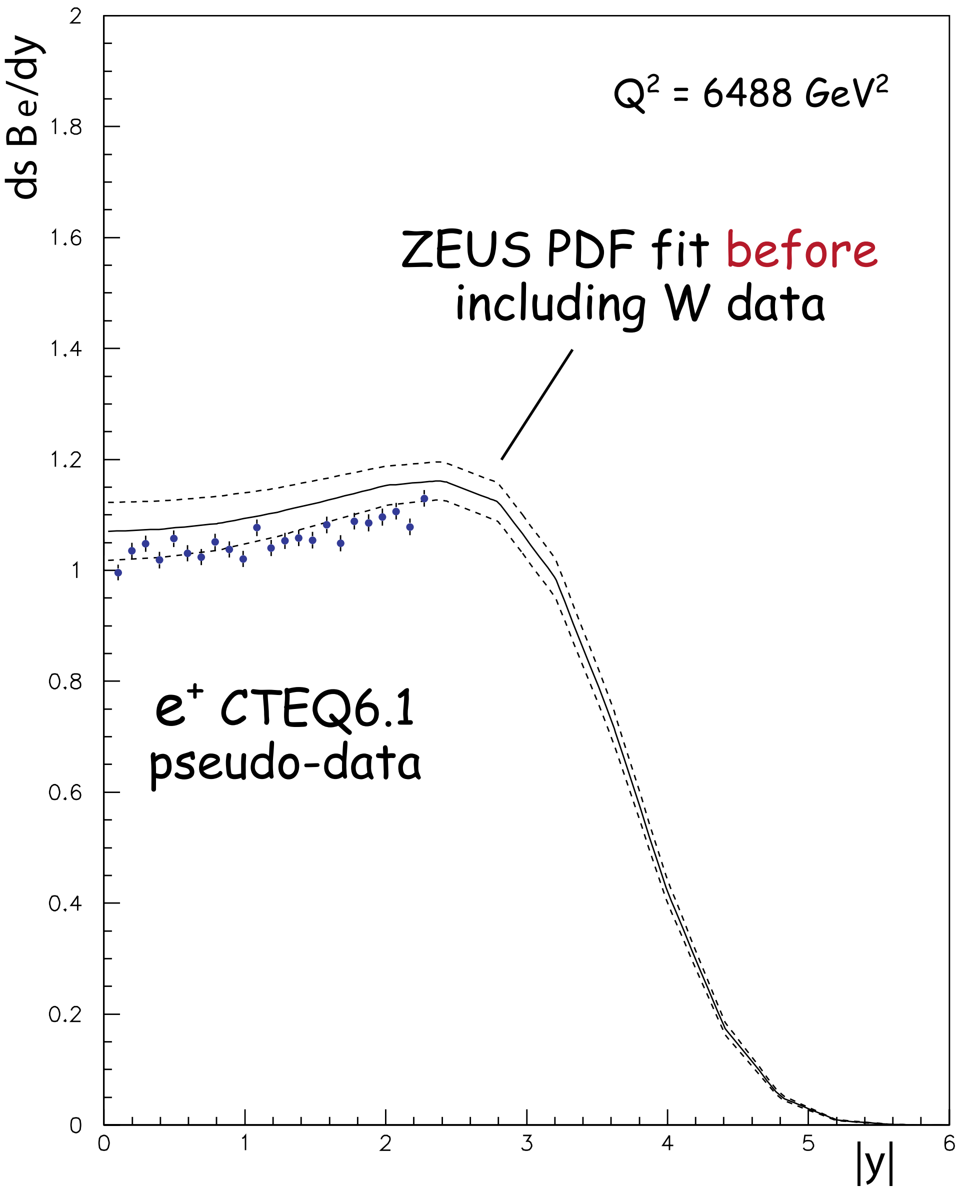


W± total cross section

Theoretical uncertainty dominated by PDFs

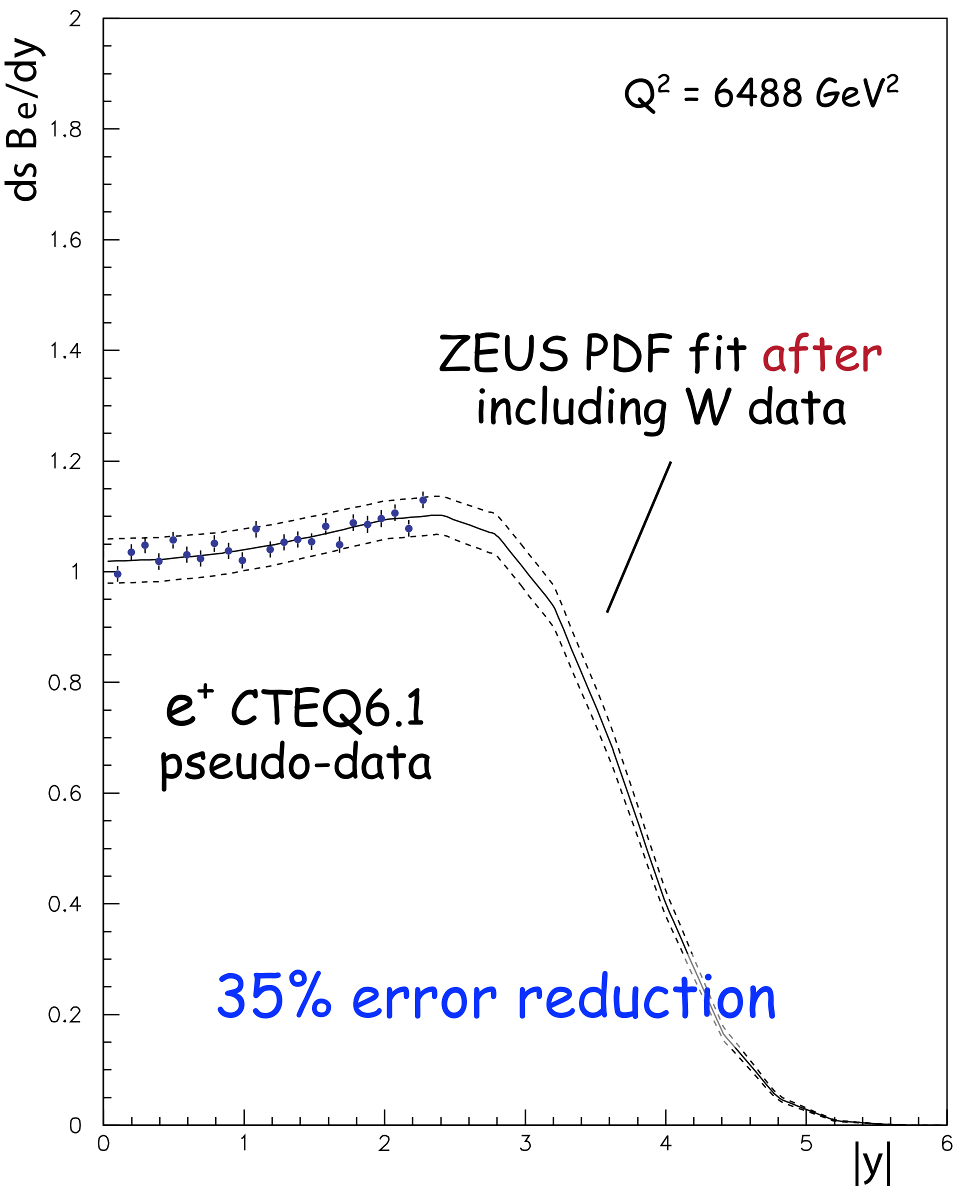
Extra input from LHC measurements

Effect on PDFs of LHC W data



ZEUS PDF fit before including W data

e^+ CTEQ6.1 pseudo-data



ZEUS PDF fit after including W data

e^+ CTEQ6.1 pseudo-data

35% error reduction

Concluding Remarks

LHC Challenges

High Rates: triggering, pile-up, radiation ...

LHC Prerequisites

Understanding of detector performance,
SM backgrounds, parton densities ...

LHC Hopes

Higgs, SUSY, Extra Dimensions...

There are exciting times ahead ...

... starting 2008 !!

End of Lecture

Thanks to:

Karl Jakobs
Victor Lendermann
Markus Schumacher
Stefan Tapprogge

... and many others, who – knowing or unknowingly – provided their slides to me.