From Detector Design
to the
Higgs Boson at the LHC

Outline:

- The Physics @ LHC
- The Detector Design
- Measuring Leptons
- Commissioning for Physics
- Expected Performances for SM Higgs

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CNRS-IN2P3, France

Avant-Propos

Destiny is no matter of chance. It is a matter of choice
W.J. Bryan

Everything seems theoretically impossible … until it is done
R. Heinlein

Truly great madness can't be achieved without significant intelligence
H. Tikkanen

All great achievements require time.
D. J. Schwartz

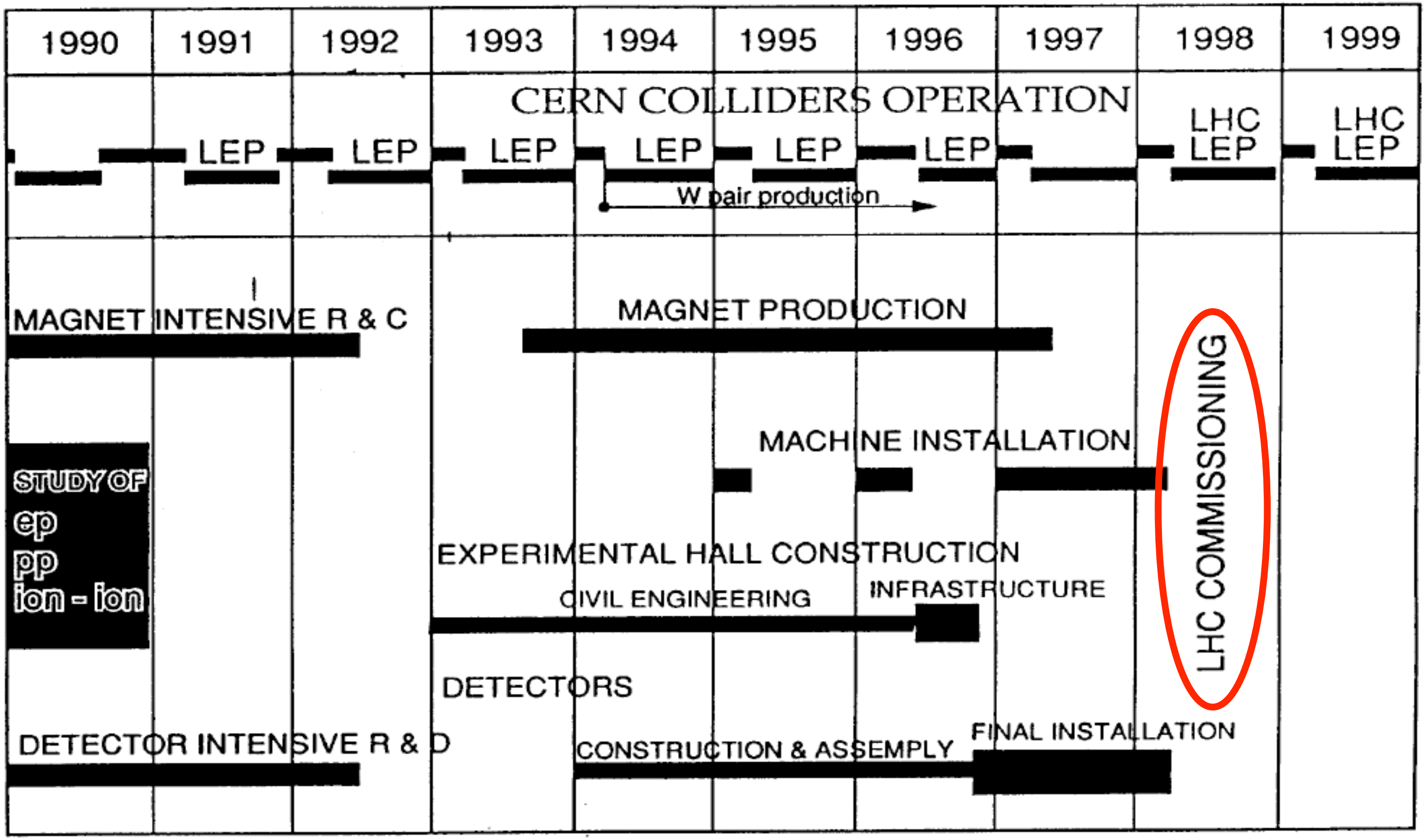
Nobody said it was easy
No one ever said that it would be this hard
Coldplay, « The Scientist »

The Physics @ LHC

… where it all started

1989

First meetings of the proto-collaborations in 1989 …



C. Rubbia - Large Hadron Collider Workshop, Aachen 1990

Figure 18 – Construction schedule of the LHC

You are NOT here !!!

The Standard Model and Beyond

Polytechnique

- EWK and Strong interactions: Yang-Mills quantum field theory with **SU(3)×SU(2)×U(1)** local gauge symmetries

Symmetries ↔ Gauge bosons

- SM Chiral Structure ↔ need a symmetry breaking to generate mass e.g. « Higgs » mechanism : spontaneous symmetry breaking preserves renormalisability in EWK sector while giving mass to the Z and W

- Fermions acquire mass by interacting with the Higgs scalar field

SM: arbitrary couplings of elementary fermions to the Higgs

The SM is remarkably confirmed in experiments ! … but:
- family replica, masses and quark flavour mixing remain unexplained
- the EWSB from a Higgs scalar field remains unproven
- the Higgs boson mass itself is left as a parameter

Unitarity Constraints

The Higgs boson allows to regulate calculations at high energies

$$A\left(W_L^+W_L^- \to Z_L Z_L\right) = \frac{G_F E^2}{8\sqrt{2}\pi}\left(1 - \frac{E^2}{E^2 - m_H^2}\right)$$

To avoid unitarity violation (scattering propability > 1 !)

Without Higgs ⇒ SM limited to E < 1.2 TeV

SM applicable ⇒ M_H < 780 GeV/c^2

… or else there must ∃ new physics at the O(TeV) to regulate the scattering amplitudes

HEP Physics in 1989

- The $W^{\pm}$ and the Z^0 electroweak bosons have been discovered (UA1/UA2)
- Experiments at LEP I are just taking their very first data and TeVatron experiments are publishing their first W boson paper at $\sqrt{s}$ = 1.8 TeV !
- With their latest 1988/89 data, the UA1 & UA2 experiments extend the top quark search only up to $M_{top} \approx M_W$

See: "Status of top quark searches at hadron colliders and present mass limits"
UA1 Collaboration, Nucl. Phys. Proc. Suppl. 13 (1990) 178

- There is very little known about the Higgs boson mass

See : "The Mass of the Top Quark from Electroweak Radiative Corrections "
J.R. Ellis and G.L. Fogli, Phys. Lett. B213 (1988) 526

Measurements of low-energy neutral current parameters and vector boson masses are sensitive to the top quark mass m_t via one-loop radiative corrections in the Standard Model. Assuming the Higgs mass $M_H = M_Z$, the combination of present data imposes m_t < 153 GeV at the 68.3% C.L. or m_t < 185 GeV if m_c is left free. The upper limit on m_t is only weakly sensitive to M_H. The overall $\chi 2$ increases slightly with M_H, but there is no significant upper bound on M_H.

PLB 213 (1988) 526

The Higgs Boson

Recall: 1 doublet of Higgs fields ⇒ 1 physical boson (CP-even)
M_H is a free parameter … $M_H^2 = 2\lambda v^2$; $v \sim 246$ GeV

Theory Constraints:

Unitarity:

$$M_H < 700 - 800\ GeV/c^2$$

"Triviality" (Higgs self-coupling remains finite :)

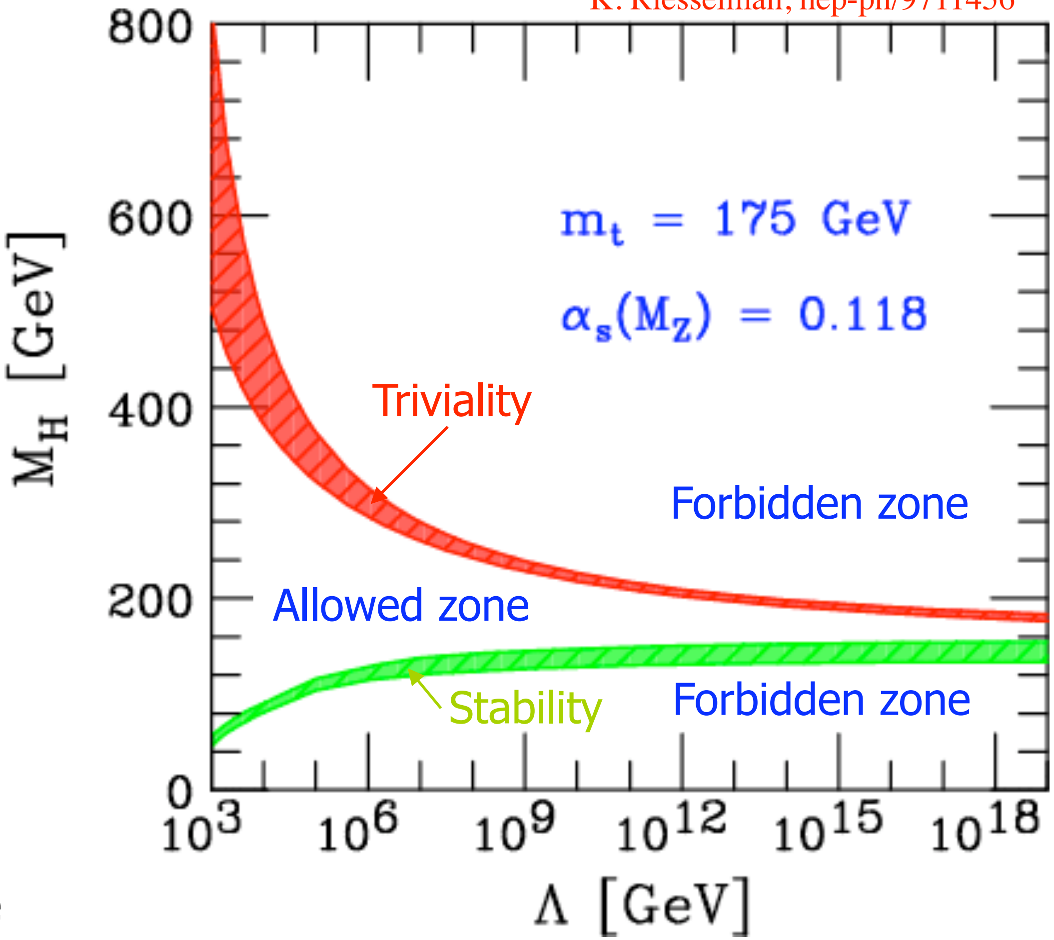
$$M_H^2 < \frac{4\pi^2 v^2}{3\ln(\Lambda/v)}$$

"Stability" of vacuum:

$$M_H^2 > \frac{4m_t^4}{\pi^2 v^2}\ln(\Lambda/v)$$

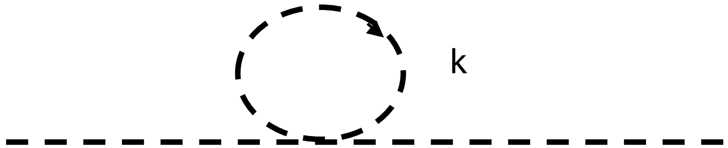
Λ = cut-off scale

K. Riesselman, hep-ph/9711456



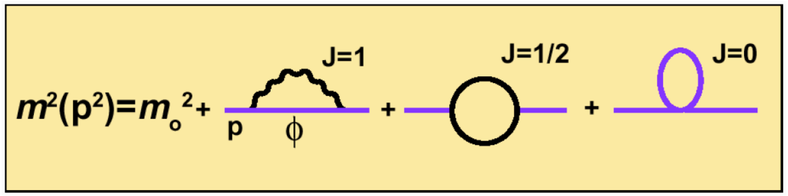
The Instability of the Mass M_H

General problem: the introduction of a scalar field in a quantum field theory generates quadratic divergencies as soon a one introduces a cut-off Λ



$$m^2 = m_0^2 + \alpha\lambda \frac{\Lambda^2}{16\pi^2}$$

e.g. If the SM is valid as an effective theory up to a « mass scale » Λ for new physics, M_H unavoidably receives radiative corrections from loops involving the top quark, the gauge bosons or from self-couplings …



$M_H^2 \rightarrow M_H^2$ (bare) + c Λ^2

$$\partial M_H = \frac{3}{8\pi^2}\lambda_t^2\Lambda^2$$ … from top quark

$$\partial M_H \propto a_W \Lambda^2$$ … des bosons de jauge

$$\partial M_H \approx \frac{\lambda}{16\pi^2}\Lambda^2$$ … du boson de Higgs

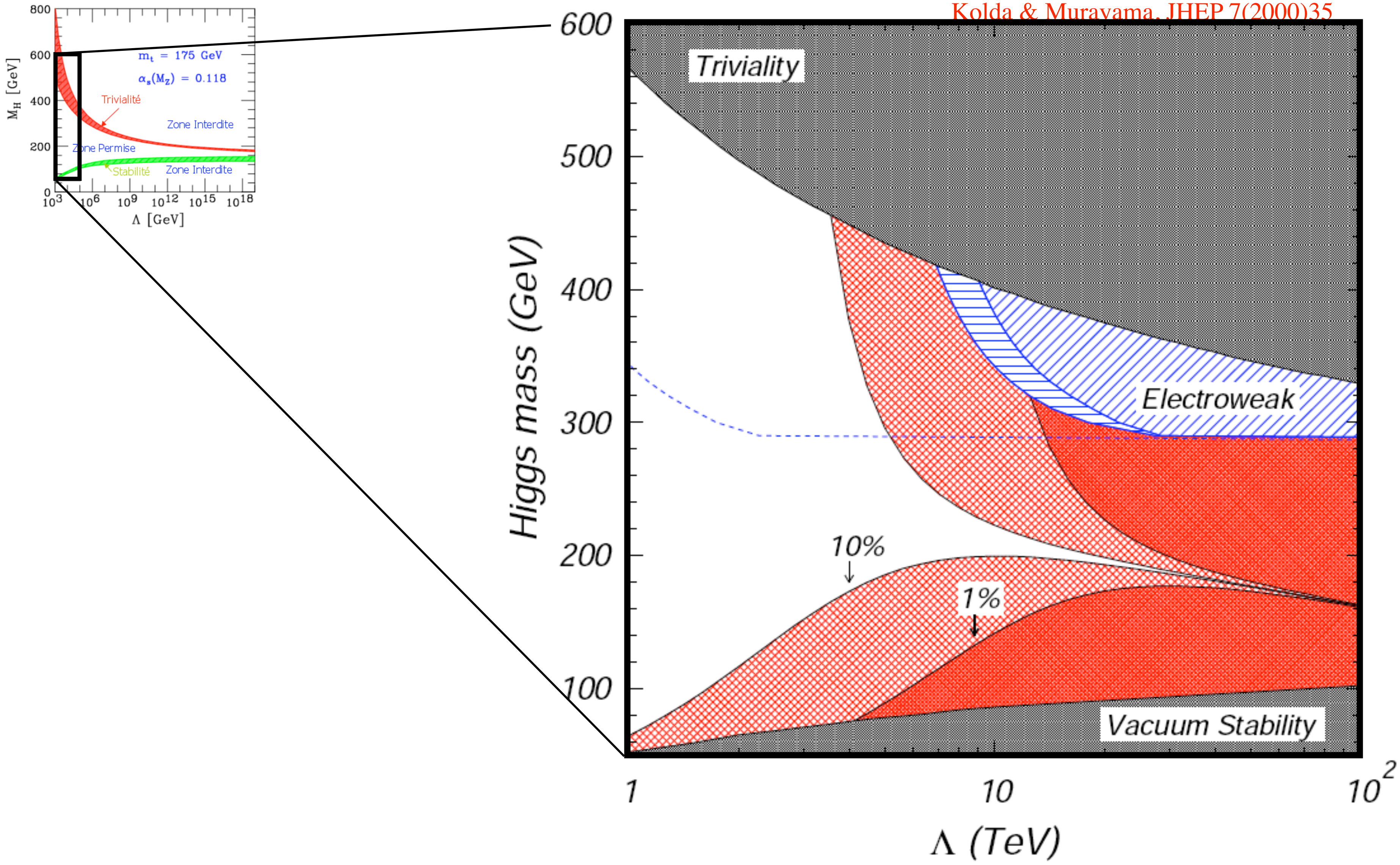
Dramatic problem if $\Lambda \sim M_{GUT}$

The difference scales between the Fermi scale and the scale for new physics (e.g. at M_{GUT}) is not natural !

Corrections of O(100) GeV at O(1) TeV already for $\Lambda \sim$ 10 TeV !

$\Rightarrow$ Fine tuning to keep $M_H \sim$ O(100) GeV

"Fine-Tuning"


800
600
400
200
0
M_H [GeV]
m_t = 175 GeV
$\alpha_s(M_Z)$ = 0.118
Trivialité
Zone Interdite
Zone Permise
Stabilité
Zone Interdite
10^3 10^6 10^9 10^{12} 10^{15} 10^{18}
Λ [GeV]
Kolda & Murayama, JHEP 7(2000)35
Triviality
Electroweak
10%
1%
Vacuum Stability
Higgs mass (GeV)
600
500
400
300
200
100
1
10
10^2
Λ (TeV)

"Fine-Tuning"

"Triviality" bound

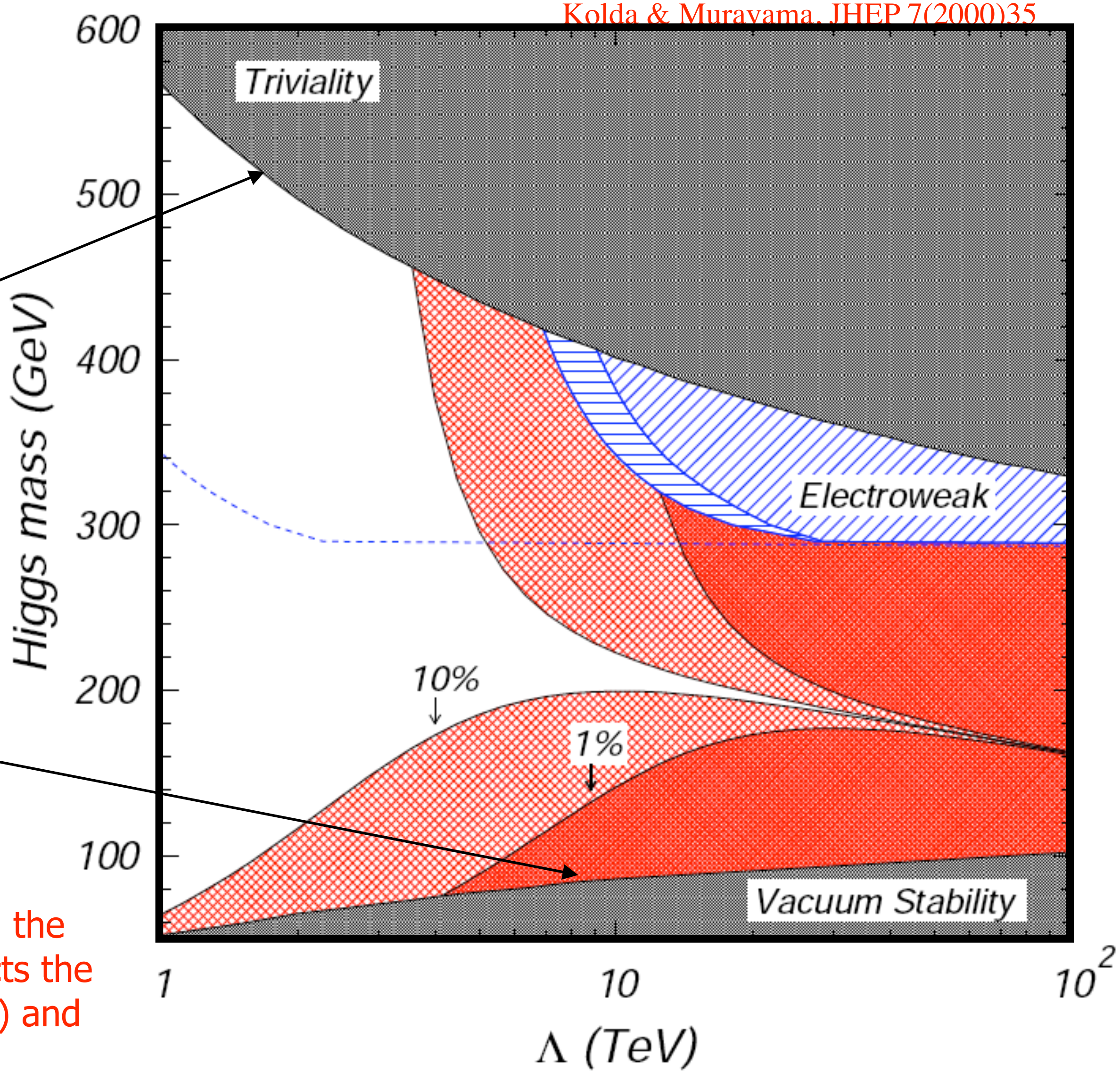
Higgs self-coupling remains finite

$$M_H^2 < \frac{4\pi^2 v^2}{3\ln(\Lambda/v)}$$

"Vacuum Stability" bound

$$M_H^2 > \frac{4m_t^4}{\pi^2 v^2}\ln(\Lambda/v)$$

Kolda & Murayama, JHEP 7(2000)35



Note: In a model with spontaneous EWSB, the instability w/r to radiative corrections affects the <v> ⇒ also concern gauge bosons (Z, W±) and fermions (quarks et leptons)

When it was all simple … one fundamental equation:

$$3 \oplus 2 = 5$$

When it was all simple … one fundamental equation:

$$3 \oplus 2 = 5$$

gluons ↔ SU(3)
transformation of 3 objects among themselves

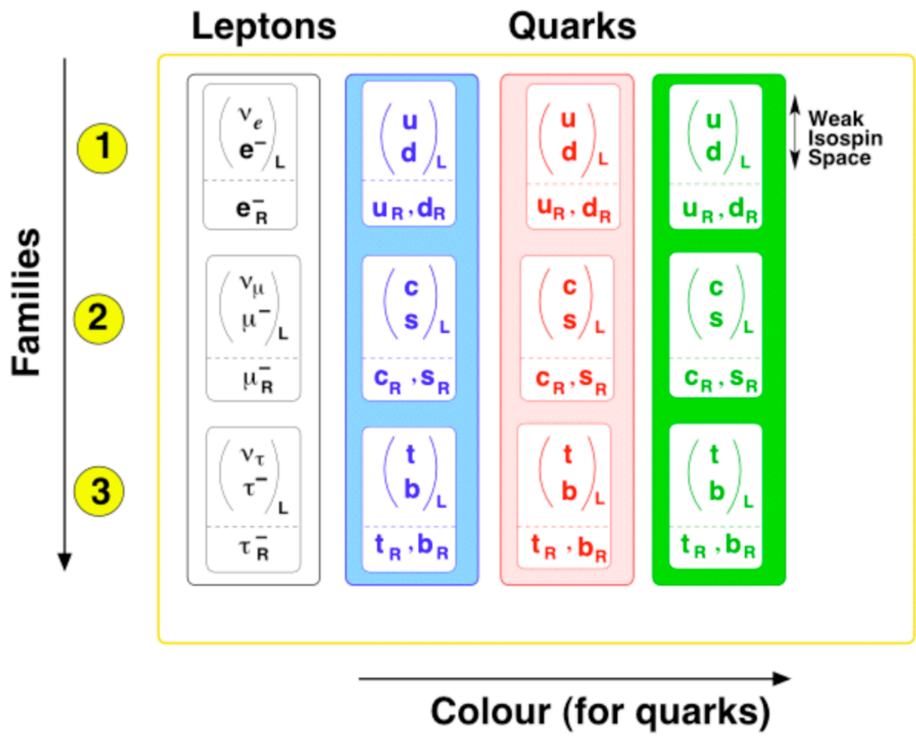
γ, Z, W± ↔ SU(2)xU(1)
Transformations of 2 objects among themselves

=

SU(5)
transformation of 5 objects among themselves !

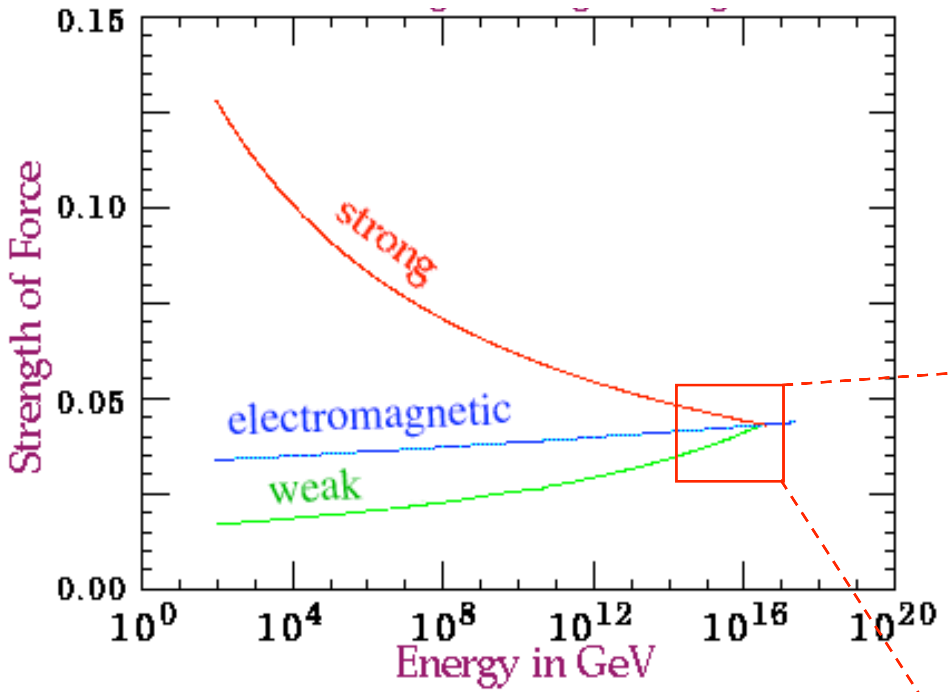
SU(5) possesses a fundamental representation of dimension 5 and a representation of dimension 10.
The "dimension" is the # of entities you can put in a representation:

5+10 = 15 = # constituents / family (!)



Toward Grand Unification

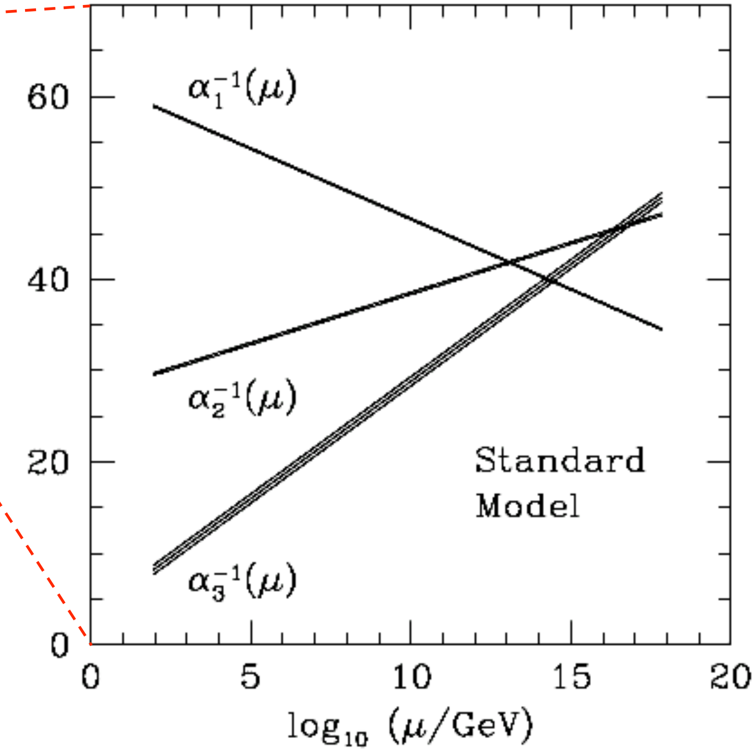
Evolution of the couplings



Couplings evolve

↑ E (↓ distance)

and meet at very high scales … almost !



The Standard Model hints towards a grand unification of fondamental interactions !
(the SM requires the «Higgs »)

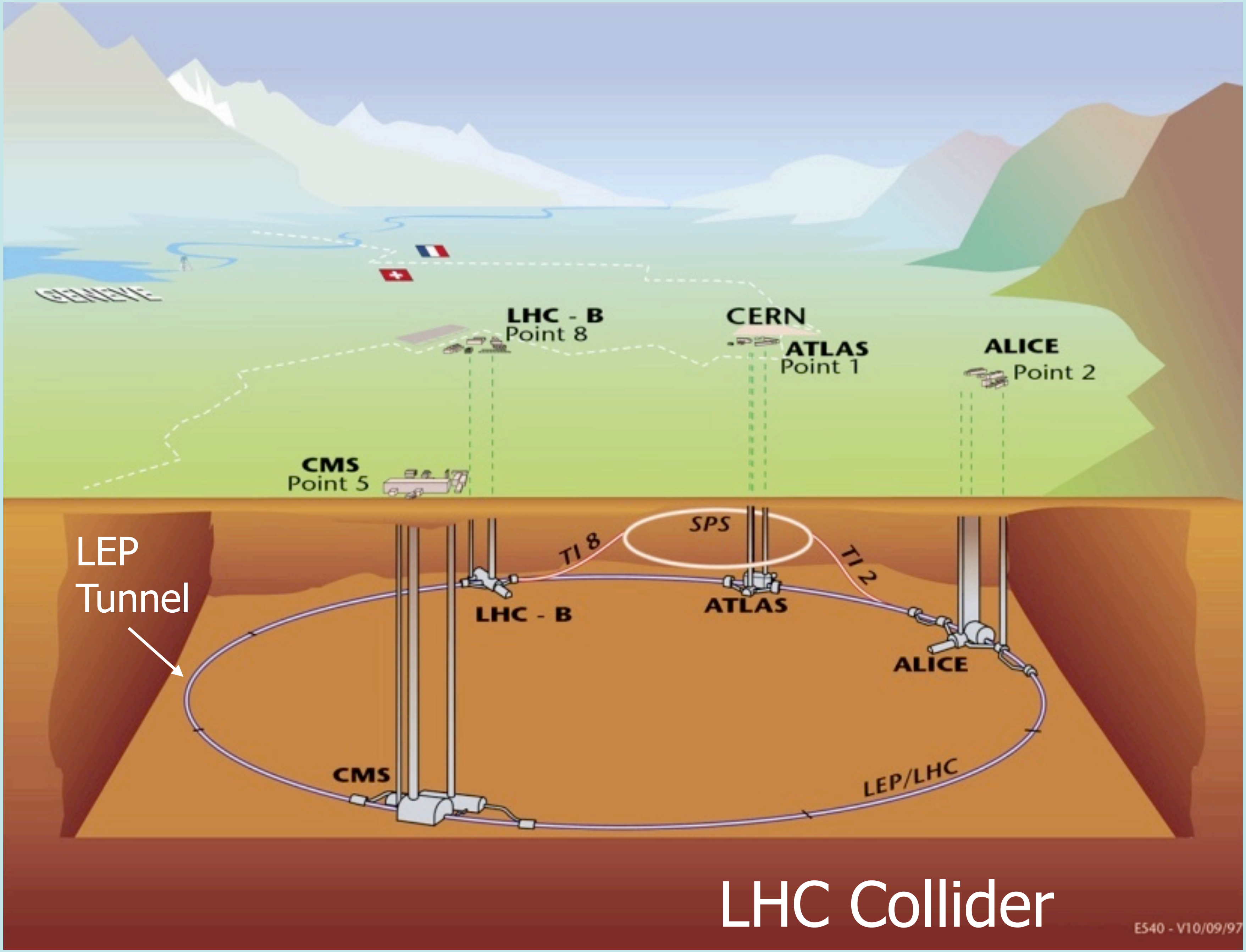
Physics @ LHC

The essential physics motivations back in 1989:

Electroweak Symmetry Breaking

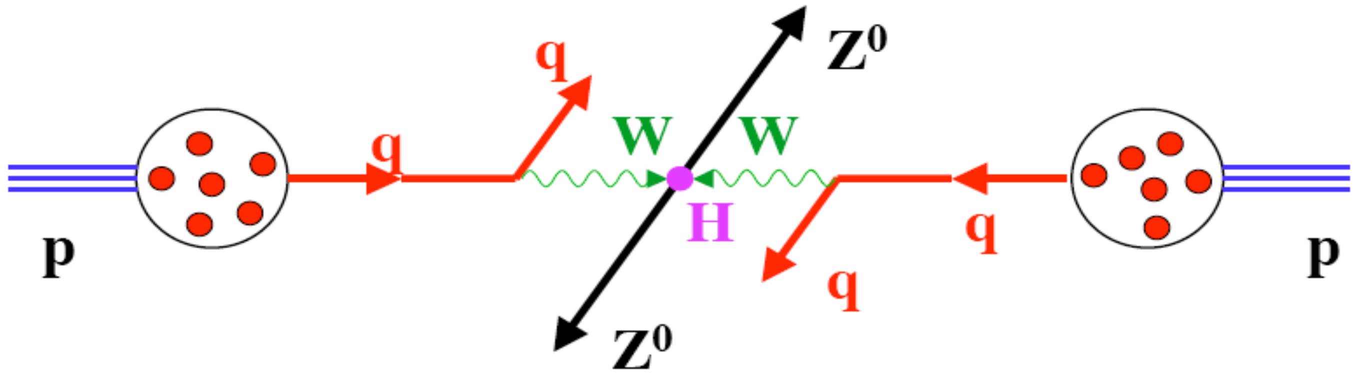
Hierarchy of Fundamental Interactions

Unification and Extended Symmetries


GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
LEP
Tunnel
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
LHC Collider
ES40 - V10/09/97

The Large Hadronic Collider

- A broad band exploratory machine
- May need to study W_L-W_L scattering at c.m. energy of ~ 1 TeV



Need $E_W \sim 500$ GeV $\Rightarrow$ q ~ 1 TeV $\Rightarrow$ $\sqrt{s_{pp}} \sim 14$ TeV

- May need to study a Higgs boson physics at a $M_H \sim 0.8$ TeV

Event rate = $\mathcal{L}\, \sigma$ Br
e.g. H ~ 0.8 TeV; $H \rightarrow ZZ \rightarrow 4l$
Events/year ≥ 10 $\Rightarrow (10/10^7) \times 1/(10^{-37}\ 10^{-3}) = L \sim 10^{34} cm^{-2}\ s^{-1}$

Physics & The LHC Detectors

Polytechnique

The essential physics motivations back in 1989:

Electroweak Symmetry Breaking

e.g. SM Higgs ⇔ High Luminosity*, √s ~14 TeV

γ's or isolated leptons

* pile-up ! … more than 20 min. bias events superimposed

Hierarchy of Fundamental Interactions

e.g. SUSY to stabilize the Higgs mass vs GUT/Planck scales

⇔ multijets and missing PT

Unification and Extended Symmetries

e.g. Z'-like resonances at the TeV

⇔ measurements at very high momentum

The Experiments at the LHC

The basic design considerations

There are issues of **cost / feasability** … sociology/politics

And of course you want the **best possible** … this and that etc.

But in fact it is driven before and above all by the:

Choice of the Magnet !

(Momentum Measurement Range)

The LHC Detectors

The Magnet

NEEDS: Measure narrow resonance states at masses of few TeV
$\Leftrightarrow$ e.g. the sign of single μ's for momenta of up to O(TeV)

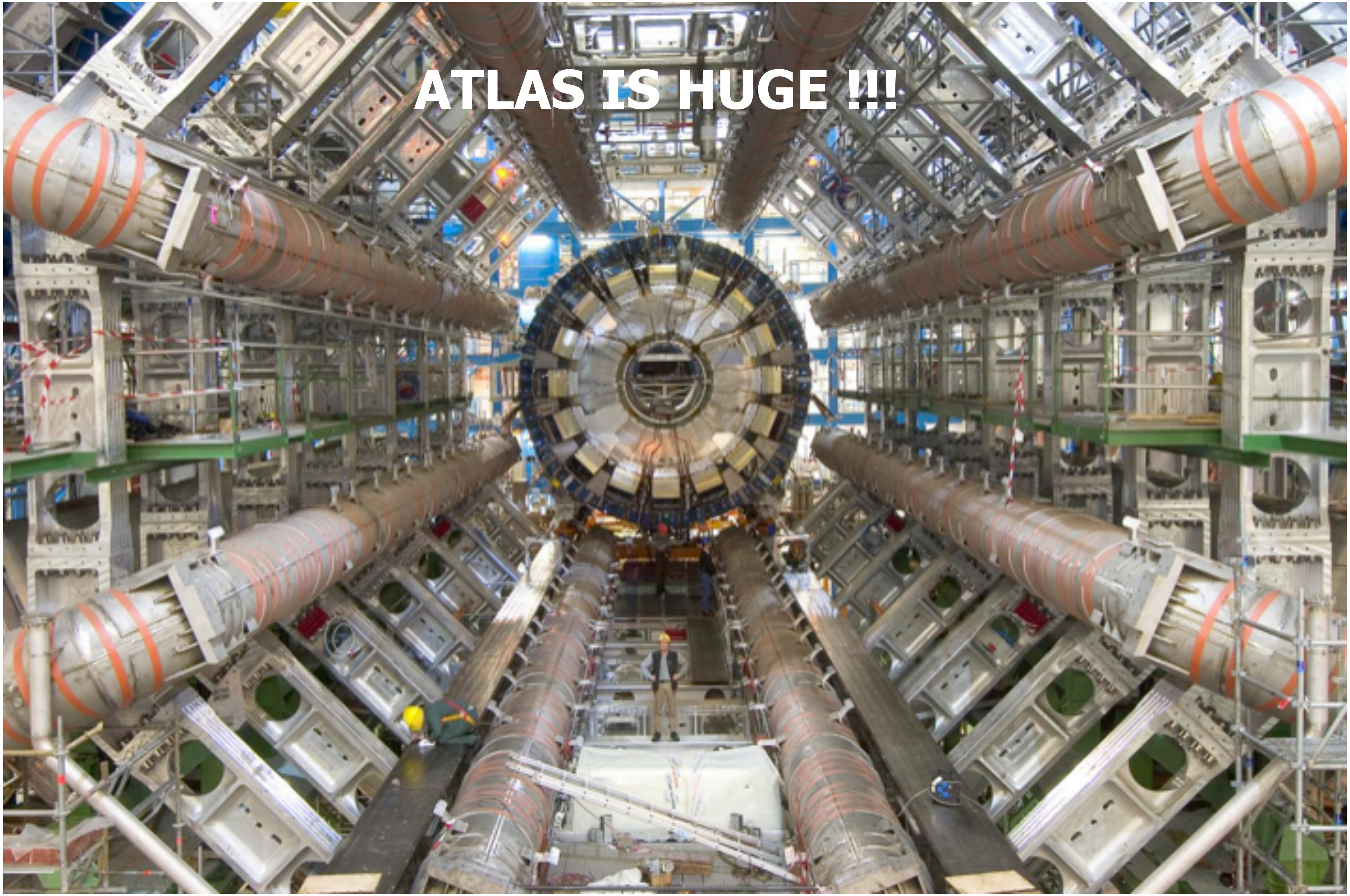
Requires enough bending power to distinguish tracks at the O(100) μm for a lever arm (radius) of O(1) m $\Rightarrow$ $\Delta P/P \sim 10\%$ and B ~ few Tesla

Solenoid — Field lines parallel to the Z beam axis (particles bend in the transverse plane)

Allows for a compact detector … but excellent $\Delta P_\mu/P_\mu$ resolution requires inner tracker and degrades towards small θ

Toroid — Field lines are circles in transverse plane centered on beam line (muons bend in a plane defined by beam axis and muon position)

Excellent stand alone $\Delta P_\mu/P_\mu$ resolution … but very large volume required and need internal solenoid for vertexing purposes


ATLAS IS HUGE !!!

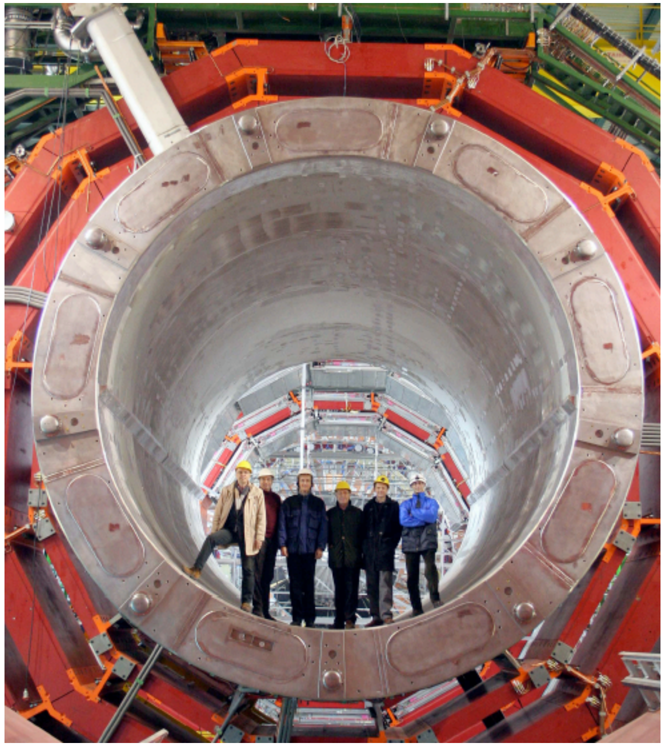
The SCAMLAST Experiment

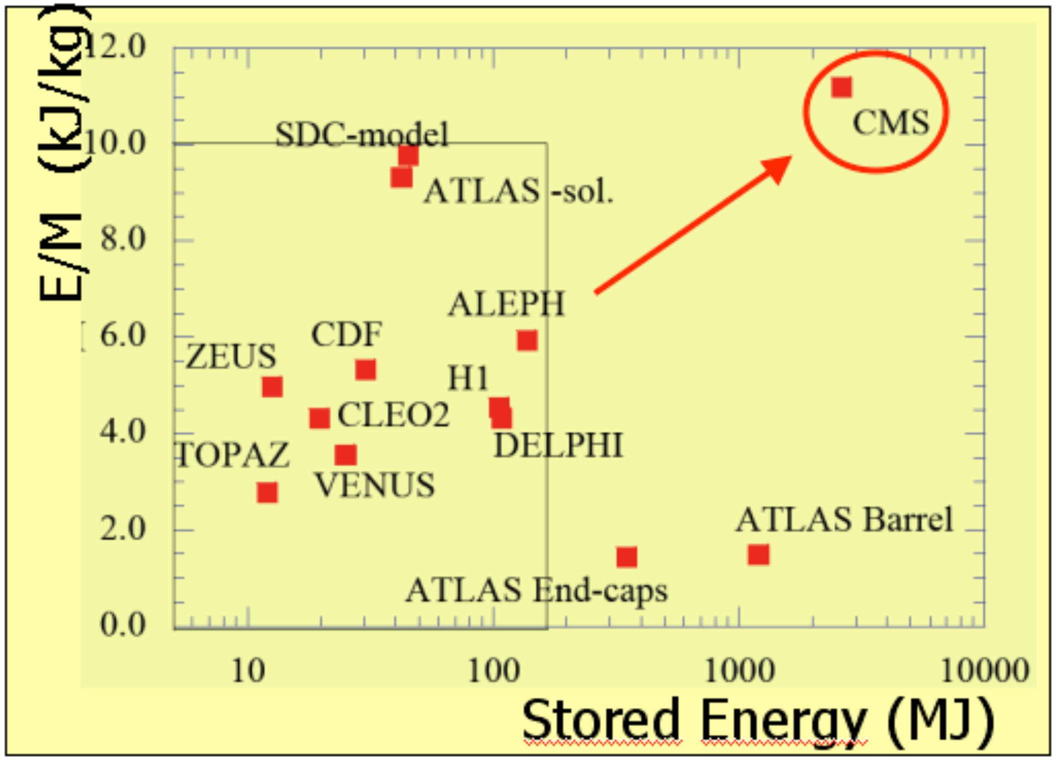
No one seriously considered such a scam …

The LHC Detectors
The CMS Magnet

The CMS magnet is 6m in diameter and 13m long (12 000 Tonnes)
[L/R ratio ajusted for best possible momentum resolution in forward region]

Refrigerated superconducting niobium-titanium coils (-268.5ºC)





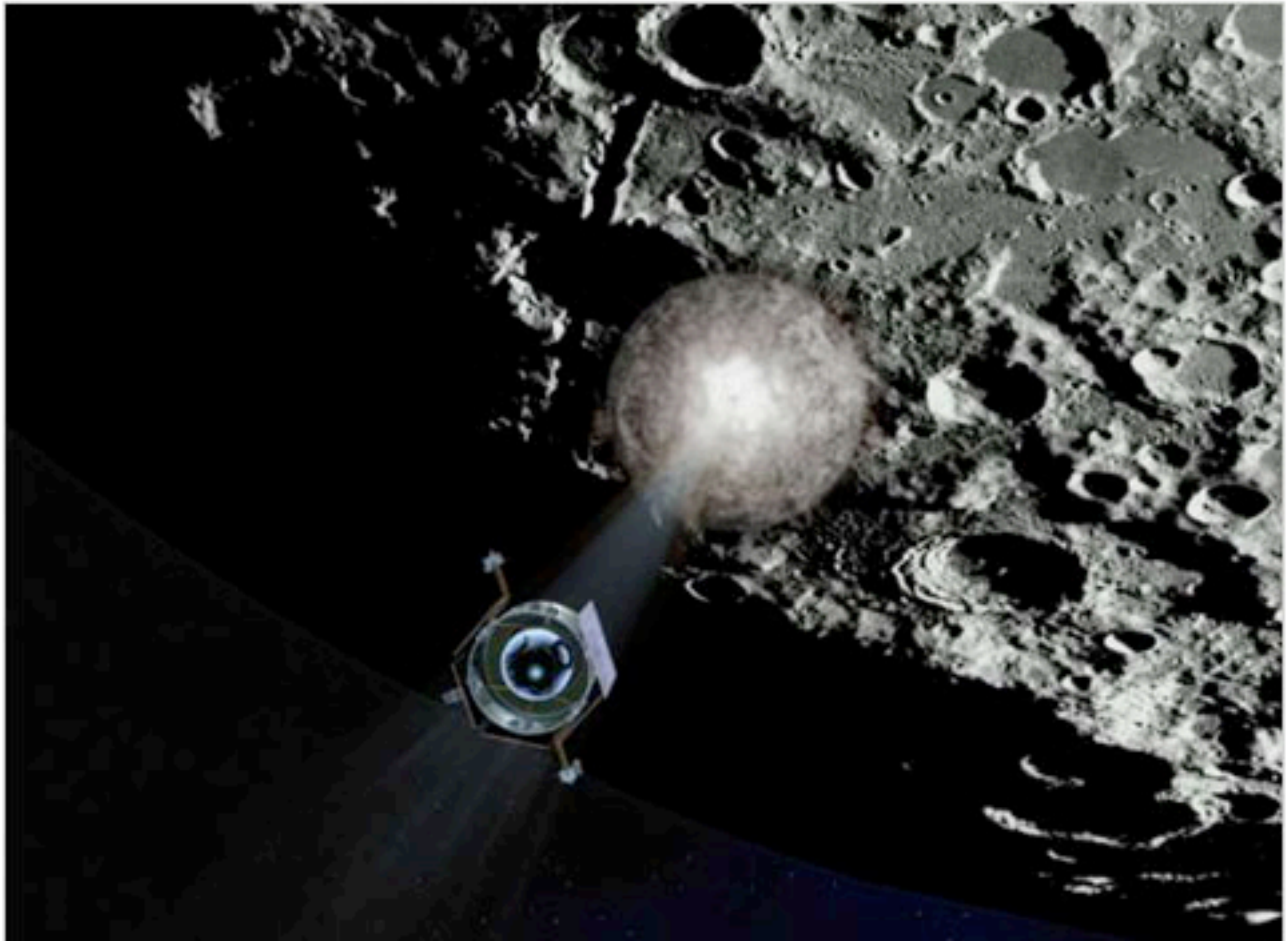
The operating current for 3.8 T is 18,160 A ($\Rightarrow$ 2.3 GJ of stored energy*** !)

*** Equivalent to 1/2 a tonne of TNT !
Enough energy to melt ~ 15 tonnes of Gold !

The New York Times News Blog

October 8, 2009, 12:00 PM

NASA Prepares to Bombard Moon



Energy release:

O(1) Tonne of TNT !

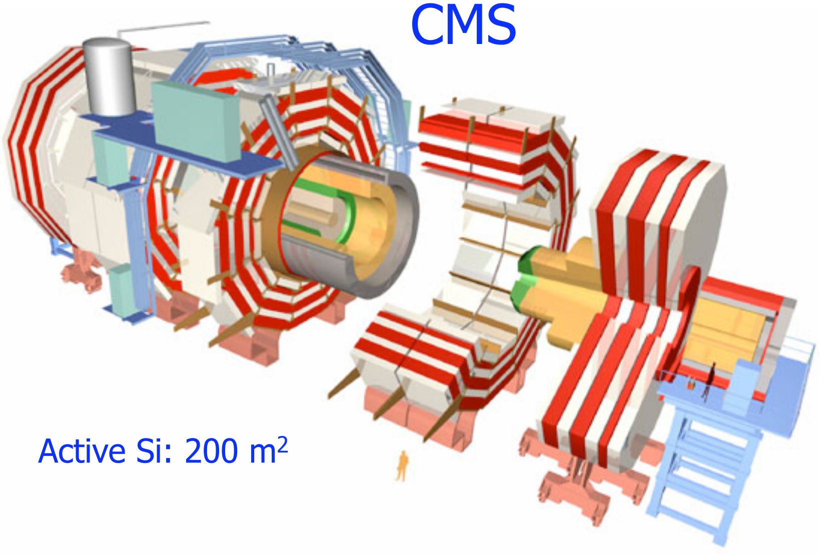
350 tons of dust in a « cloud » reaching 10 Km !

NO good Photographs provided by NASA !

Plenty of water discovered on the moon !

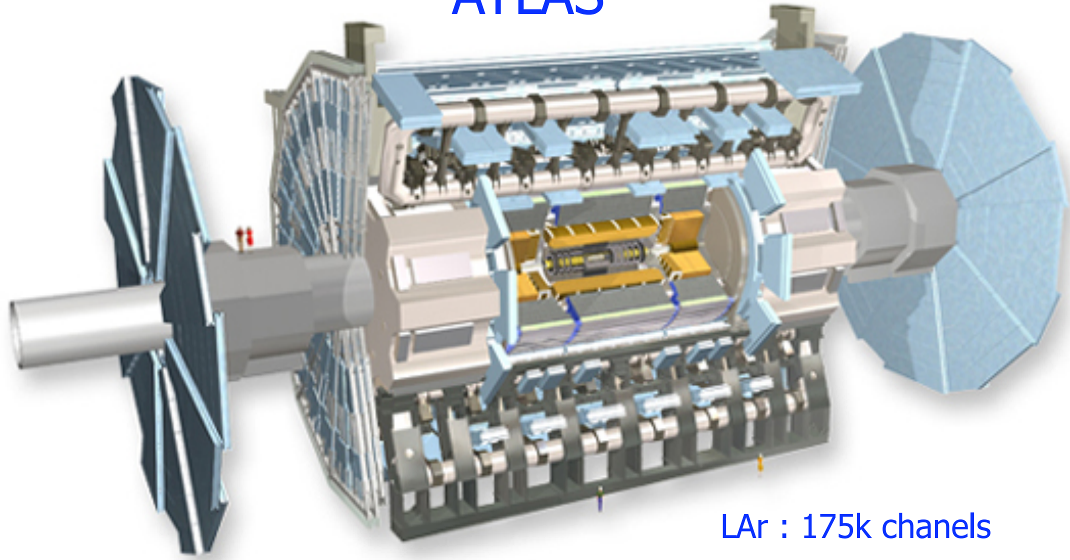
The LHC Experiments

CMS



Active Si: 200 m²

ATLAS



LAr : 175k chanels

Tracking $|\eta| < 2.5$, B = 4T

- Si pixels and strips

Calorimetry $|\eta|^{em} < 2.5$ $|\eta|^{had} < 5$

- EM: homogeneous $PbWO_4$ crystals
- HAD: Cu-Zn/scint. + Fe/Quartz

Muon Spectrometer $|\eta| < 2.7$

- Solenoïd return yoke instrumented

Tracking $|\eta| < 2.5$, B = 2T

- Si pixels and strips
- Transition radiation detector

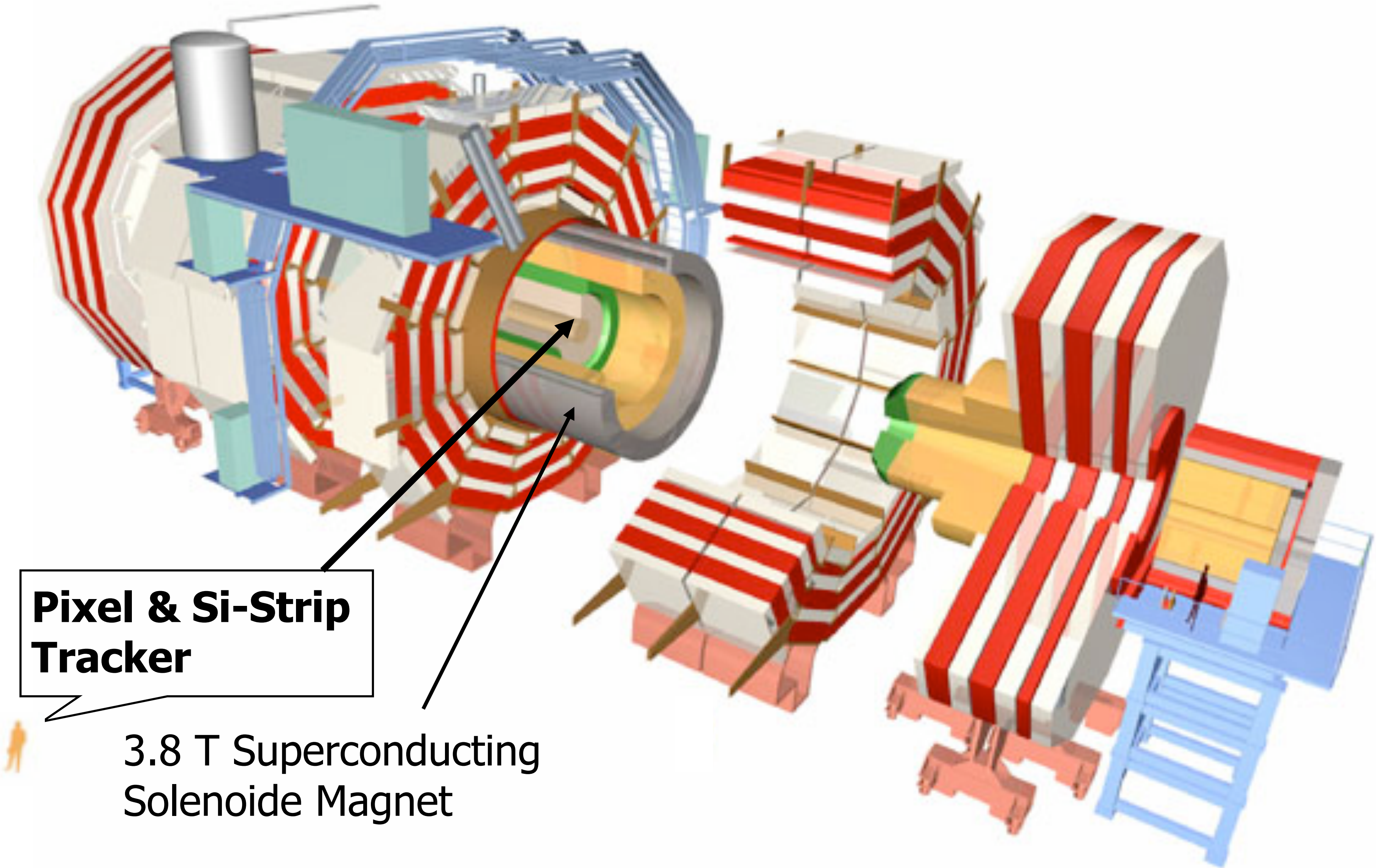
Calorimetry $|\eta| < 5$

- EM: sampling; Pb/LAr accordeon
- HAD: Sampling Fe/scint. + Cu-W/LAr

Muon Spectrometer $|\eta| < 2.7$

- Air-core toroids with muon chambers

The LHC Detectors
The CMS Tracker



What Tracker ?

NEEDS:

Measure charged particles track charge and momentum and match track to the interaction vertex … covering maximal acceptance

Aim: O(10) % momentum resolution at ~ 1 TeV
O(1) % momentum resolution at ~100 GeV

Measured displaced vertices and cope with particle density

CMS Strategy: rely on a minimal number measurement layers each with robust and clean coordinate determination

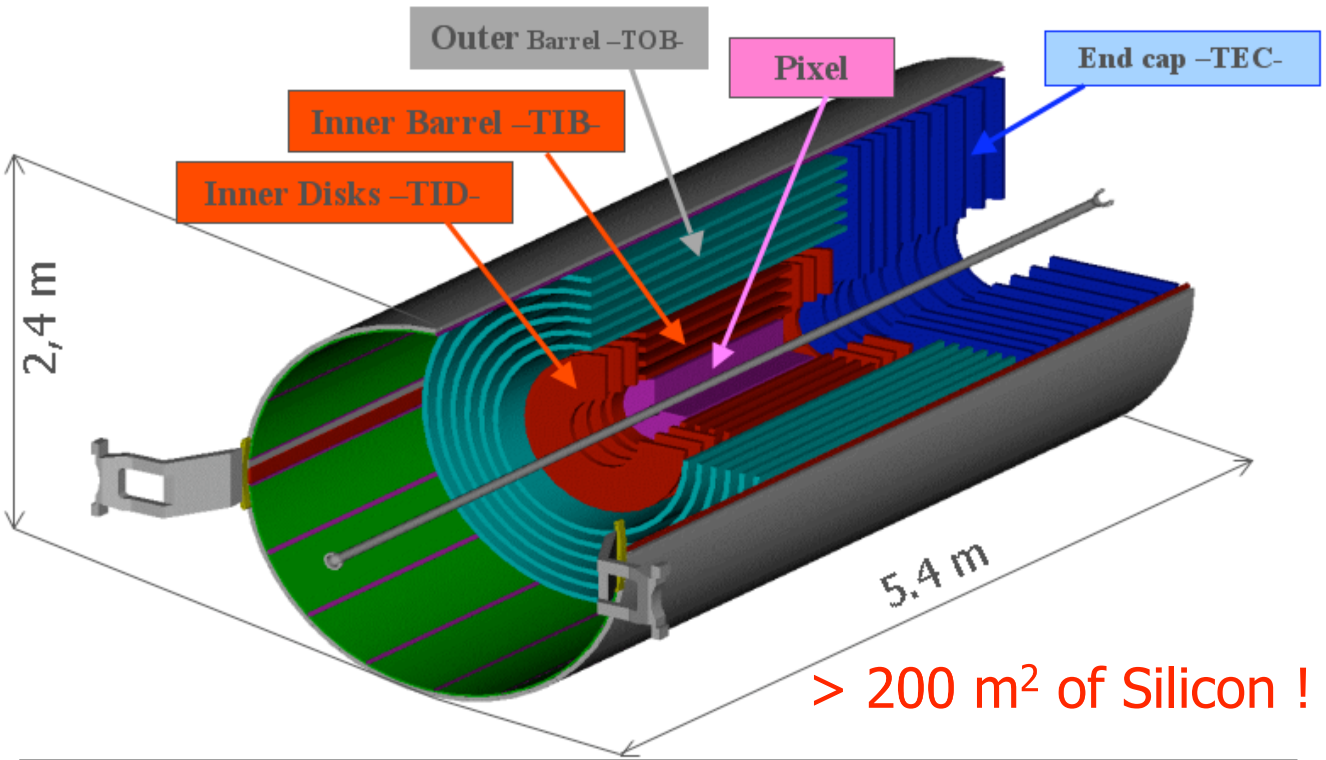
⇒ fine granularity (pixel technology) for inner layers

⇒ barrel and end-cap geometry

The LHC Detectors

The CMS Si Tracker

Pixel detector and a Silicon microstrip tracker:



> 200 m² of Silicon !

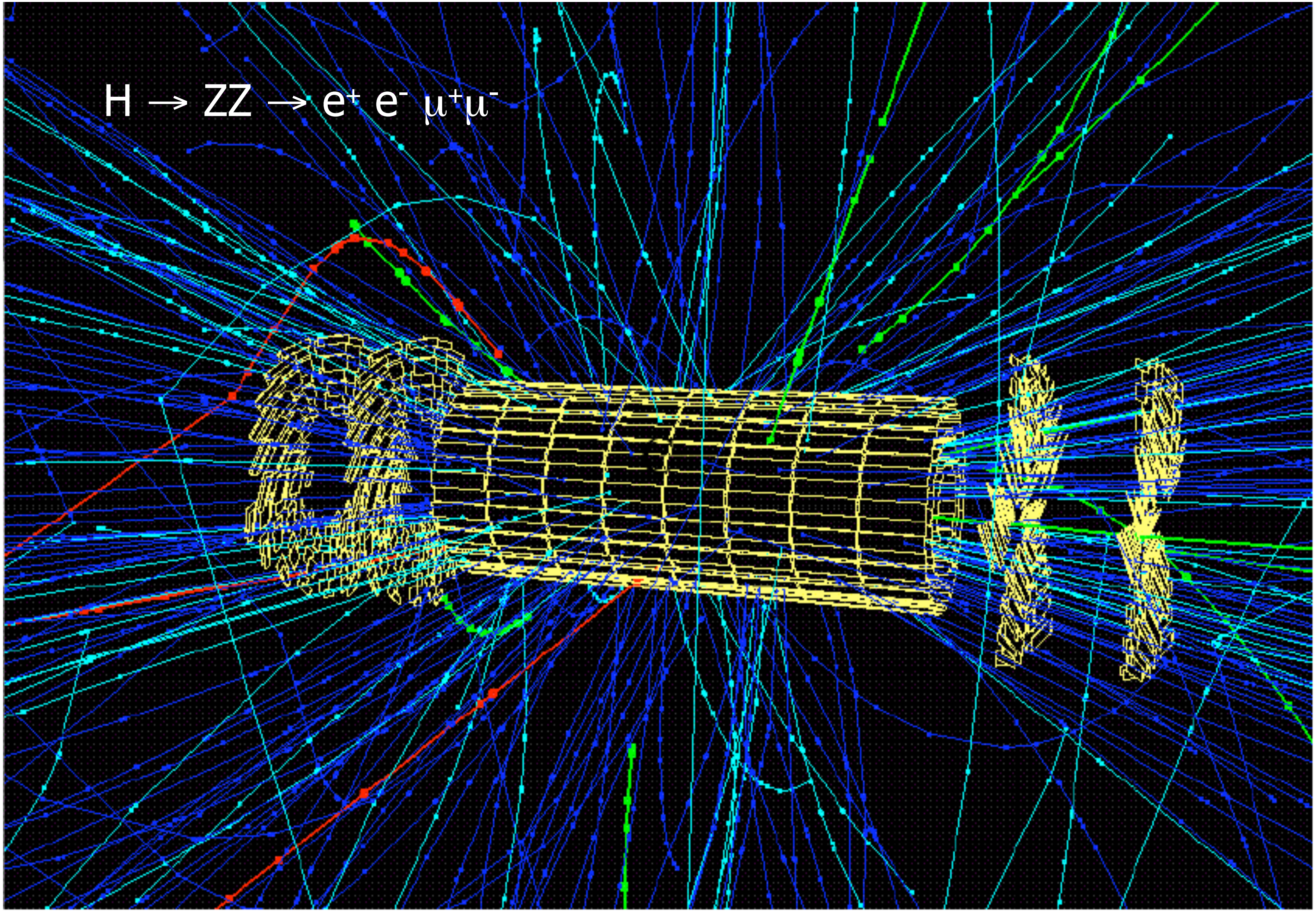
PIXEL DETECTOR

- Provides seeds for the particle tracks
  e.g. Kalman Filter reco.
- Responsible for good vertexing
  e.g. Impact parameter or DCA to interaction VTX
- Help determine Z coordinates of events
  suppresses pile-up; $\sigma_{VTX} \sim 5$ cm
- Event topology info. for High Level Trigger

SILICON μ-STRIP

- Track measurement with best possible ΔP/P and high efficiency from P ~ GeV/c to TeV/c
- Fine granularity (low occupency) for track isolation

Volume ≈ 24 m³ T° ≈ –10 ⁰C
Dry atmosphere … for years !


$H \rightarrow ZZ \rightarrow e^+ e^- \mu^+\mu^-$

VERTEXING

- Many interesting events contain B-mesons with a lifetime « τ » of a few ps ⇒ flight path $c\tau$ of a few x 100 μm ...
- Events containing such high P_T B-mesons can be found e.g. by calculating an "impact parameter" (⊥ distance to the beam axis).
- B-tagging efficiency depends mainly on R_{min} and spatial resolution of pixel inner layer ...

4cm is the closest we can get ⇒ **need ~ 20 μm** inner layer spatial resolution

TRACKING

- Reconstruct a Z′-like O(1TeV) resonance in $\mu^+\mu^-$ with $\Delta M_{Z'}/M_{Z'} \sim 1$ %

  ⇒ $\Delta P_t / P_t \sim 0.1 {*} P_t$ (P_t in TeV)

12 layers with (pitch/ √ 12) spatial resolution and 110 cm radius give a momentum resolution of

$$\frac{\Delta p}{p} \approx 0.12 \left(\frac{pitch}{100\mu m}\right)^1 \left(\frac{1.1m}{L}\right)^2 \left(\frac{4T}{B}\right)^1 \left(\frac{p}{1Tev}\right)$$

⇒ **need typical "pitch" of order 100 μm** in φ coordinate

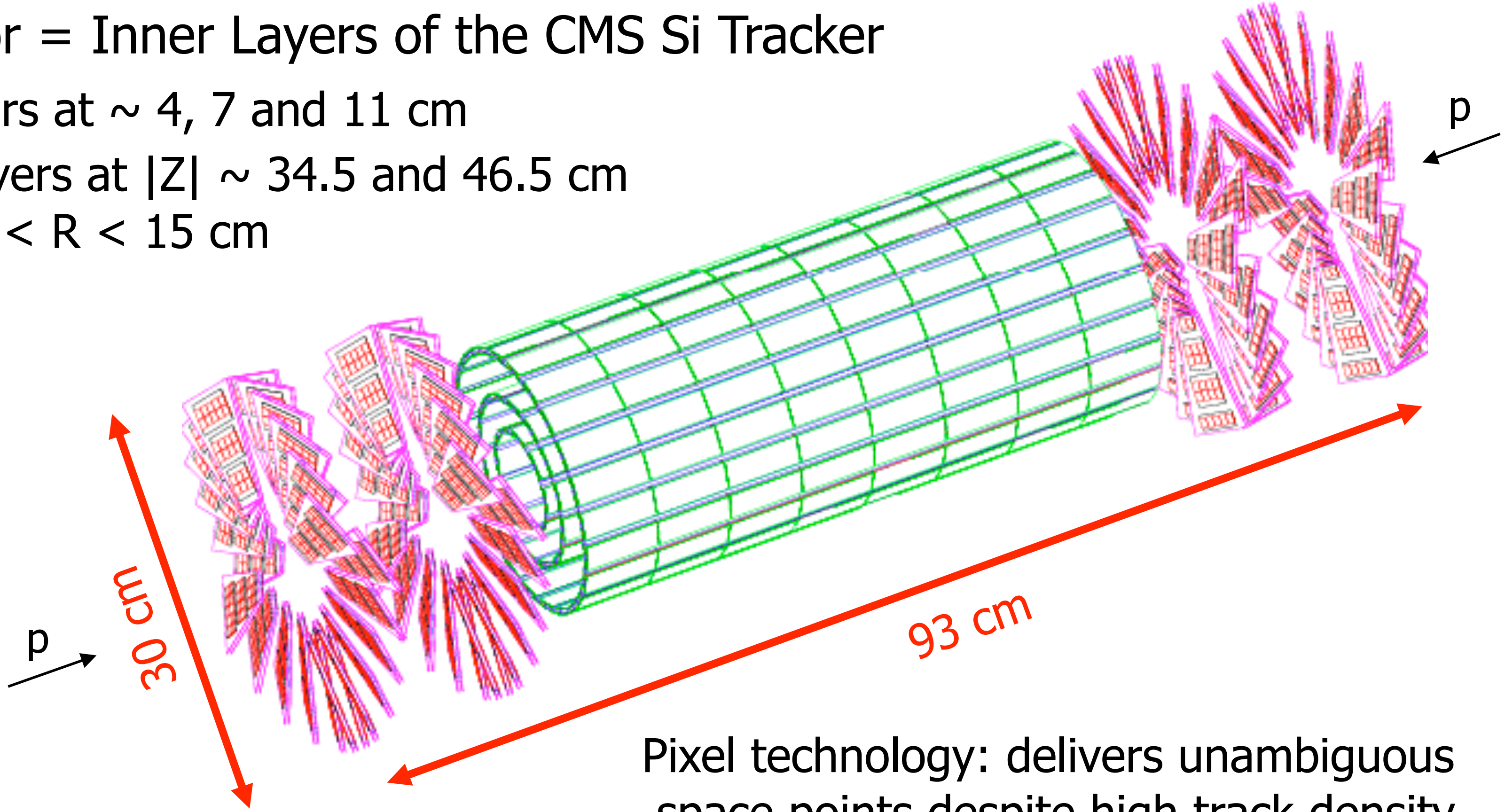
- efficient & clean track reconstruction ⇒ needs occupancy below few %

The LHC Detectors

The CMS Si-pixel Detector

Pixel Detector = Inner Layers of the CMS Si Tracker

- 3 Barrel Layers at ~ 4, 7 and 11 cm
- 2 End-cap layers at |Z| ~ 34.5 and 46.5 cm covering 6 < R < 15 cm



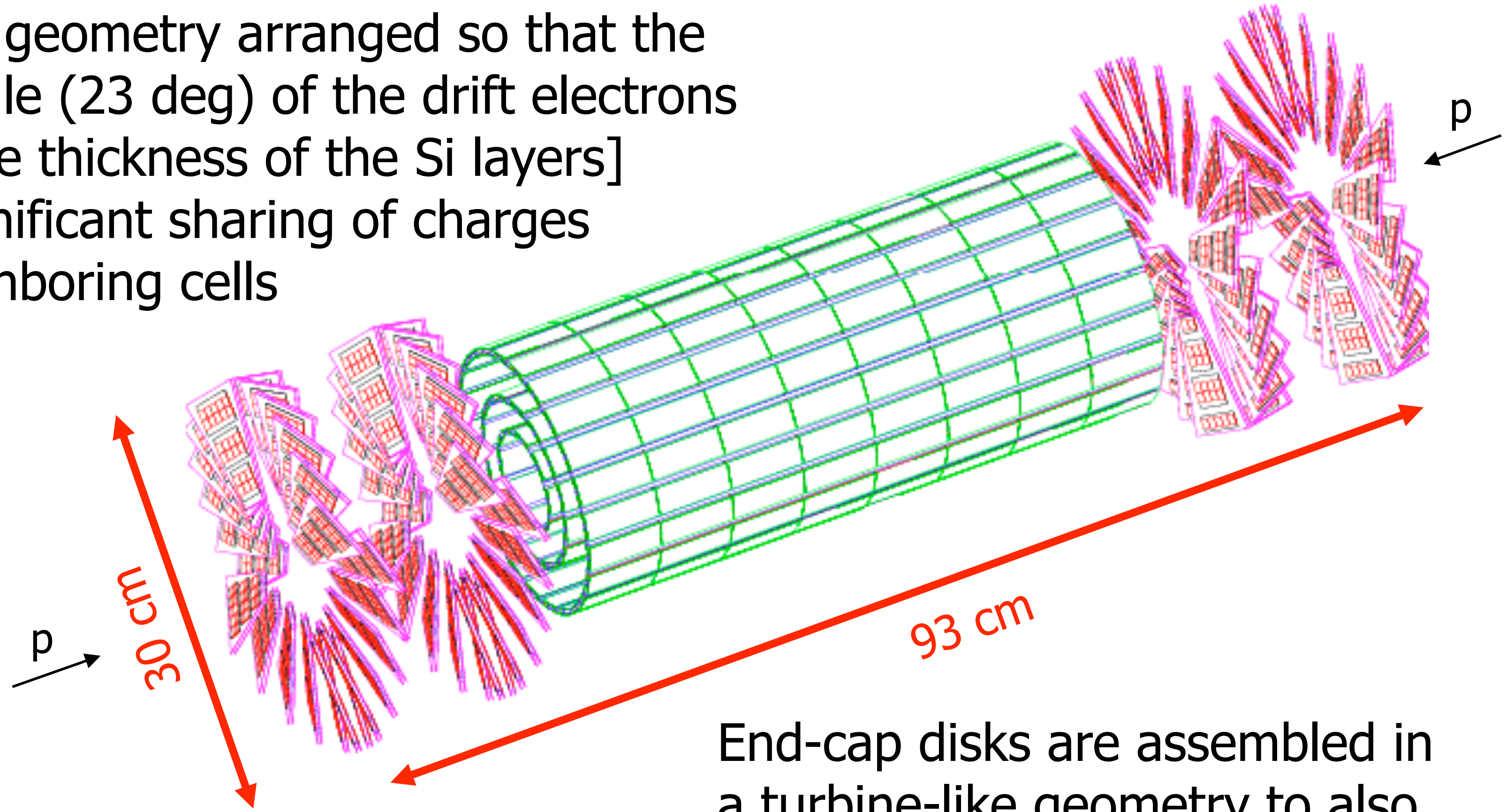
Total area ~ 1 m^2
66 million pixels of 100 x 150 μm^2

Pixel technology: delivers unambiguous space points despite high track density environment
Occupancy ~ 10^{-4} despite up to 20 MHz/cm^2 of particles … thanks to fine granularity and 40 MHz readout

The LHC Detectors

The CMS Si-pixel Detector

Barrel pixel geometry arranged so that the Lorentz angle (23 deg) of the drift electrons [through the thickness of the Si layers] induces significant sharing of charges across neighboring cells



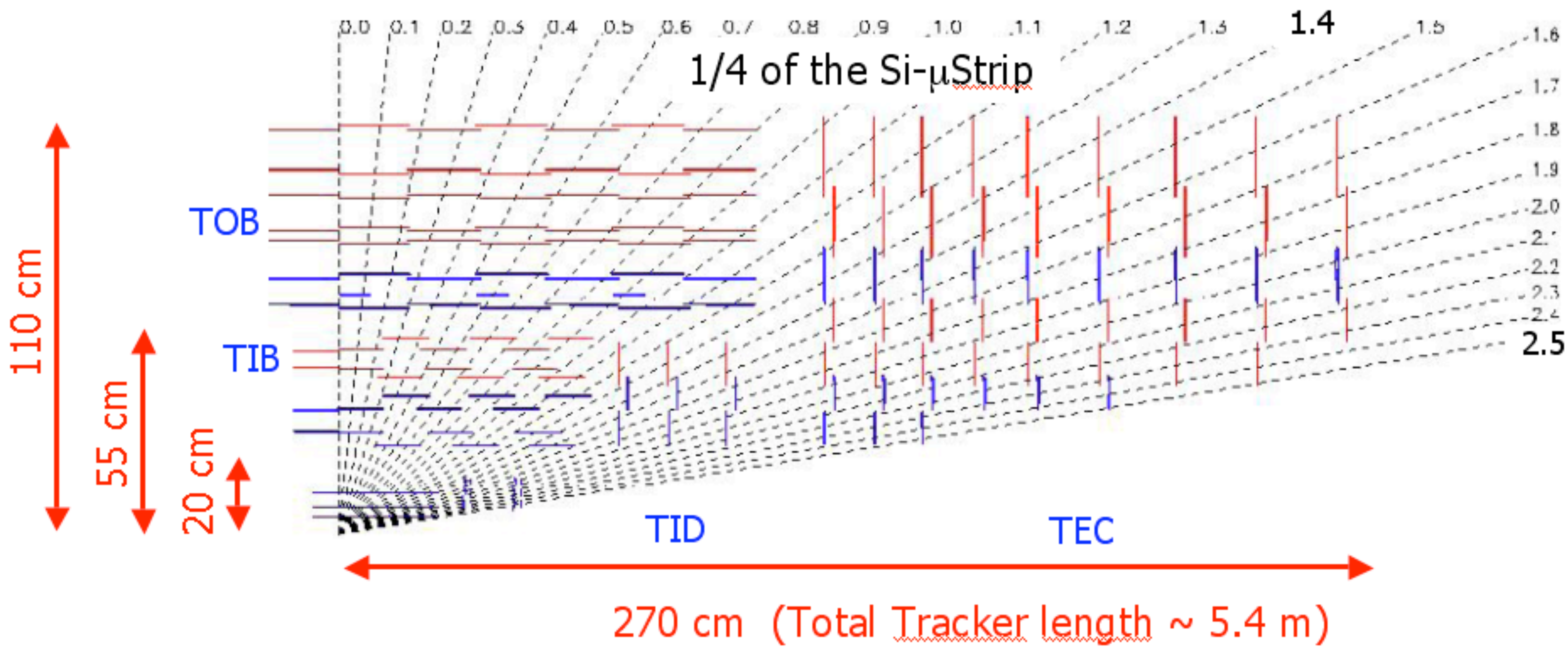
End-cap disks are assembled in a turbine-like geometry to also profit from the Lorentz effect !

Spatial resolution of ~ 10 (15) μm in ϕ (Z) coordinates

The LHC Detectors

The CMS Si-μStrip Detector

Polytechnique



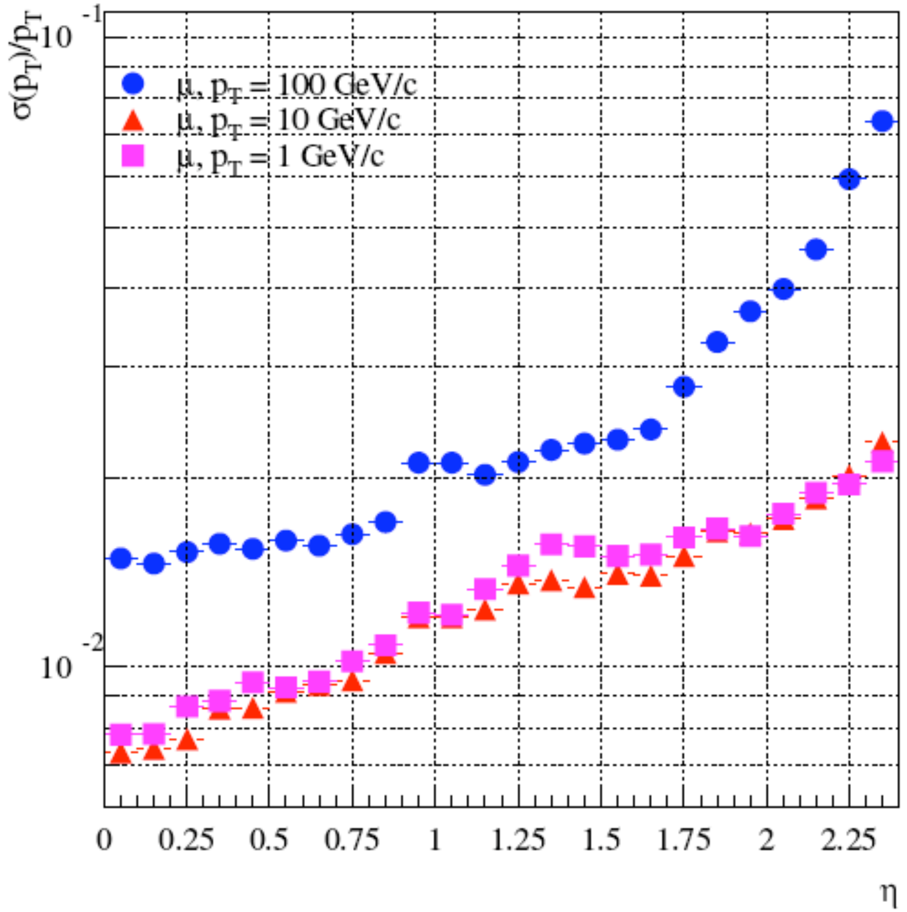
20 < r < 55 cm = Intermediate region

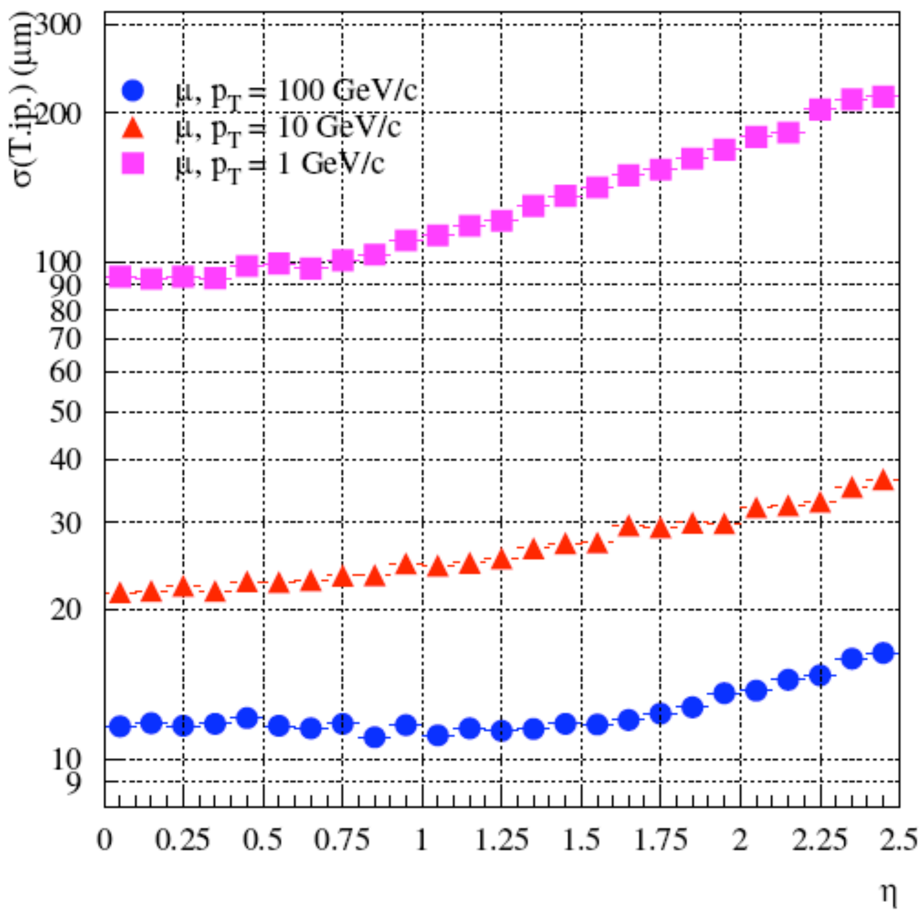
Cell size of 10 cm x 80 μm occupancy 2-3 % / LHC

55 < r < 110 cm = Outer region

Cell size of 25 cm x 180 μm occupancy ~ 1 % / LHC

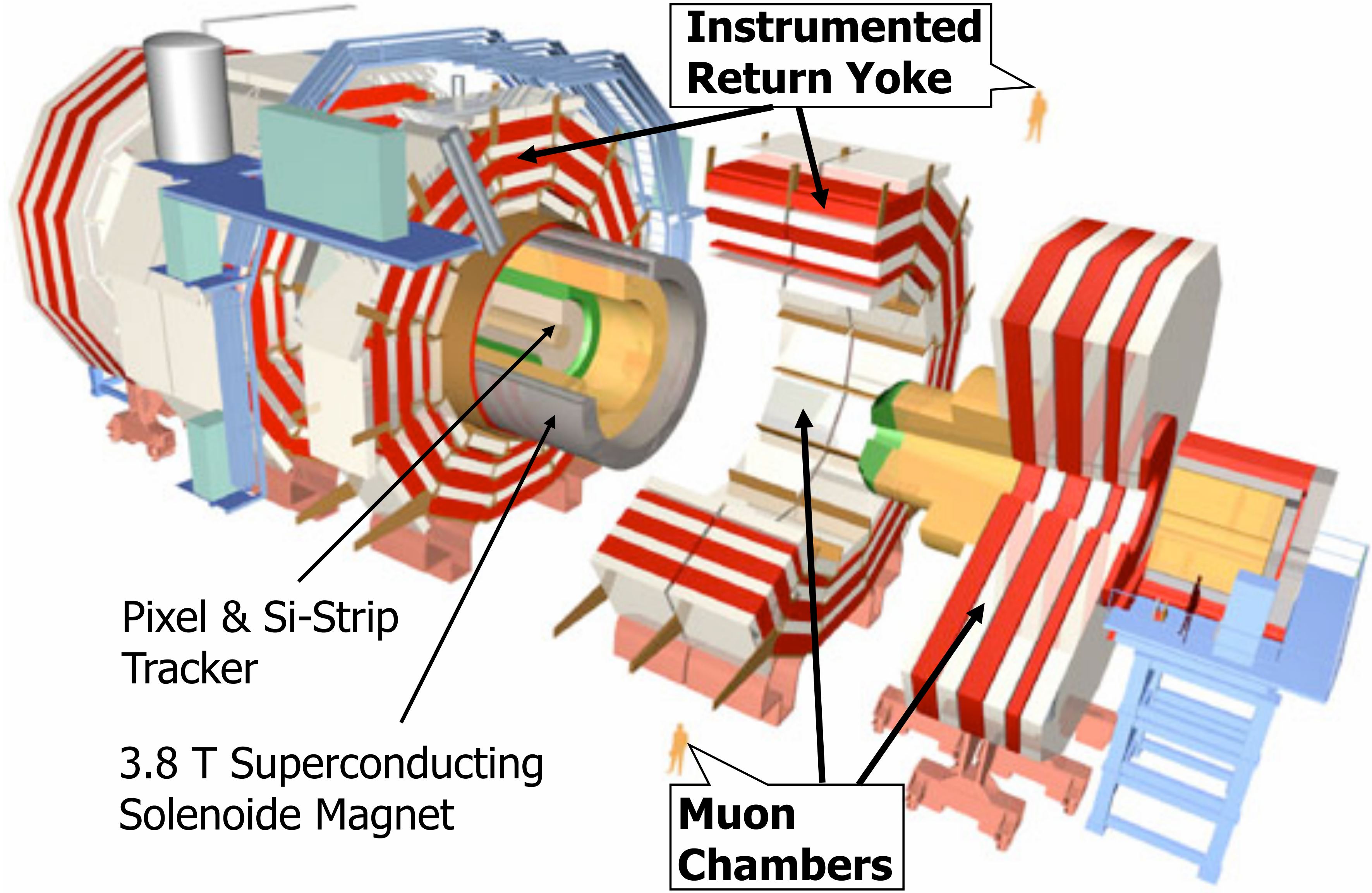
Illustration of expected performance:



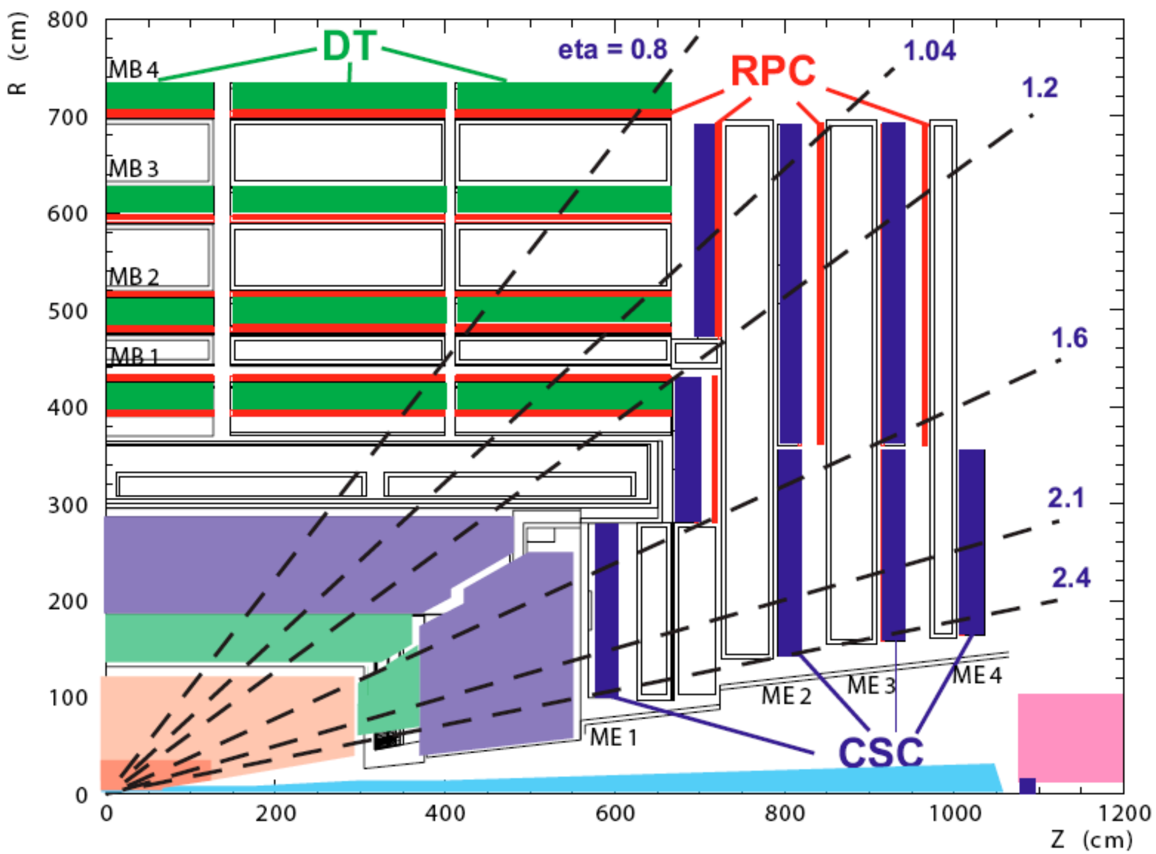


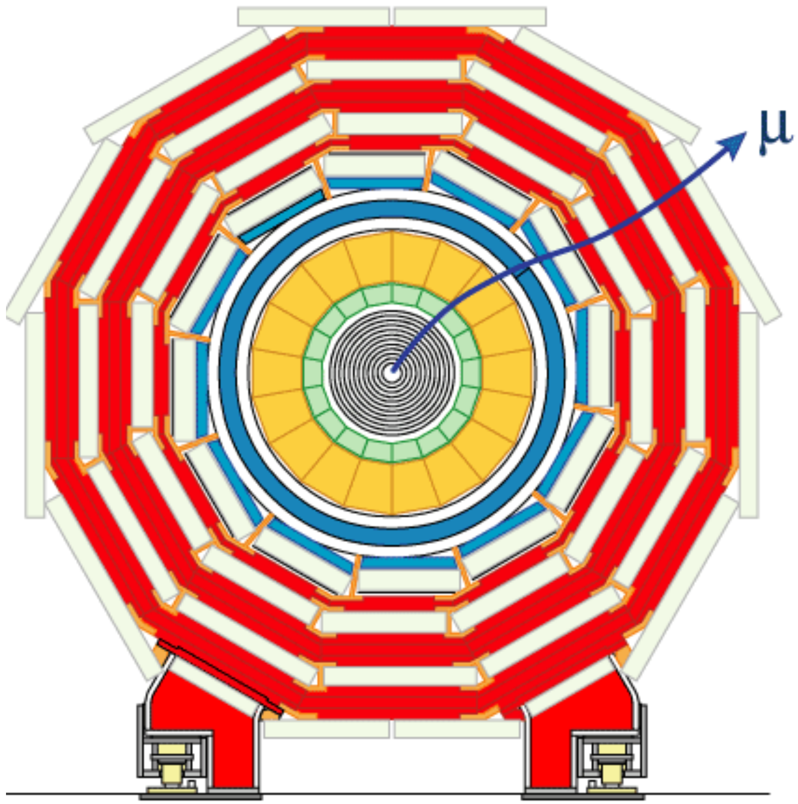
The LHC Detectors

The Compact Muon Spectrometer



The CMS Muon Detector





DT: drift tubes

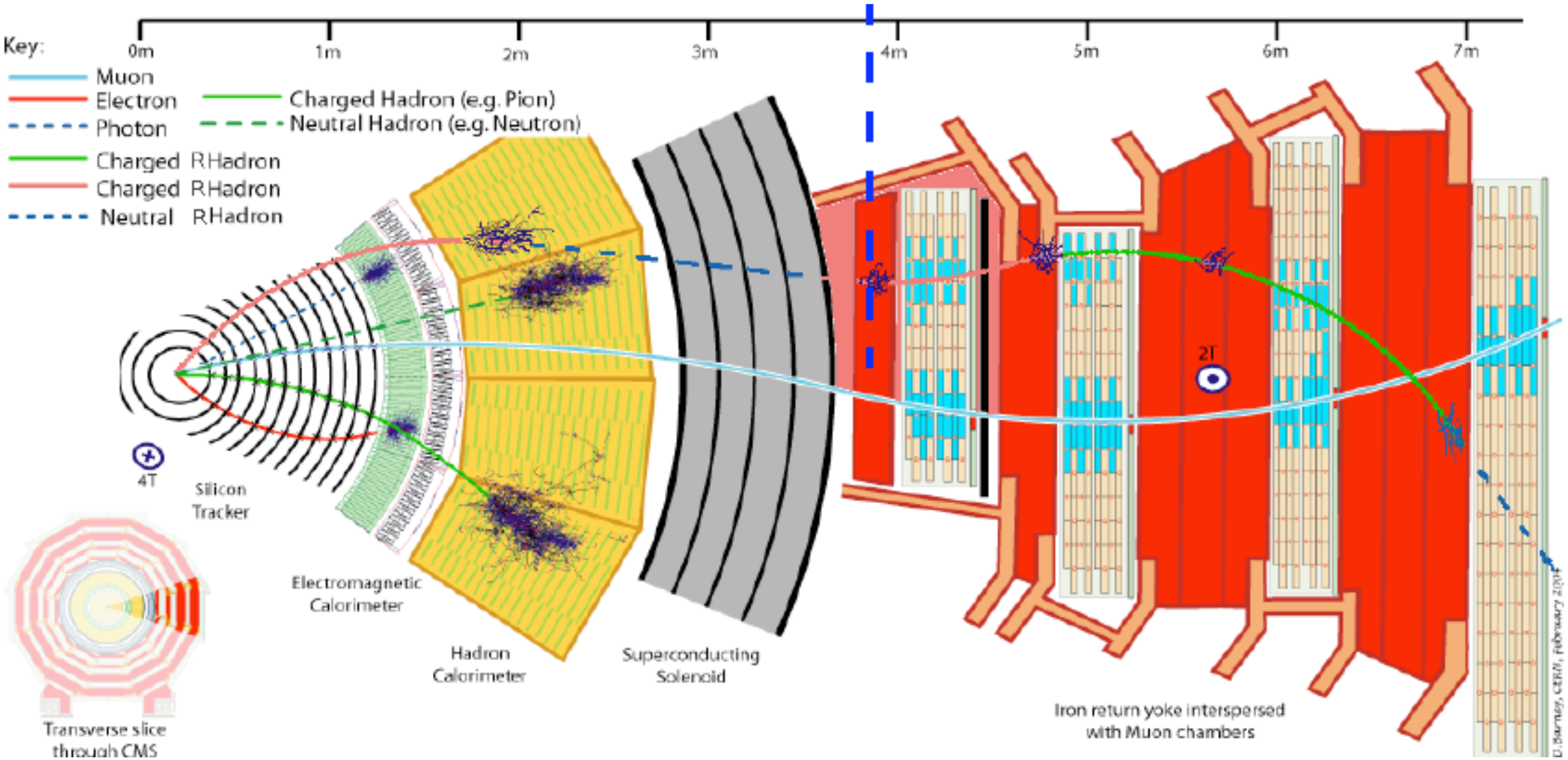
Hits with 100-200 μm resolution

RPC : Resistive Plate Chambers - fast response (3 ns)

CSC: MWPC with Cathode Strip Readout - fast response from wire groups

The LHC Detectors

The CMS Muon Detector



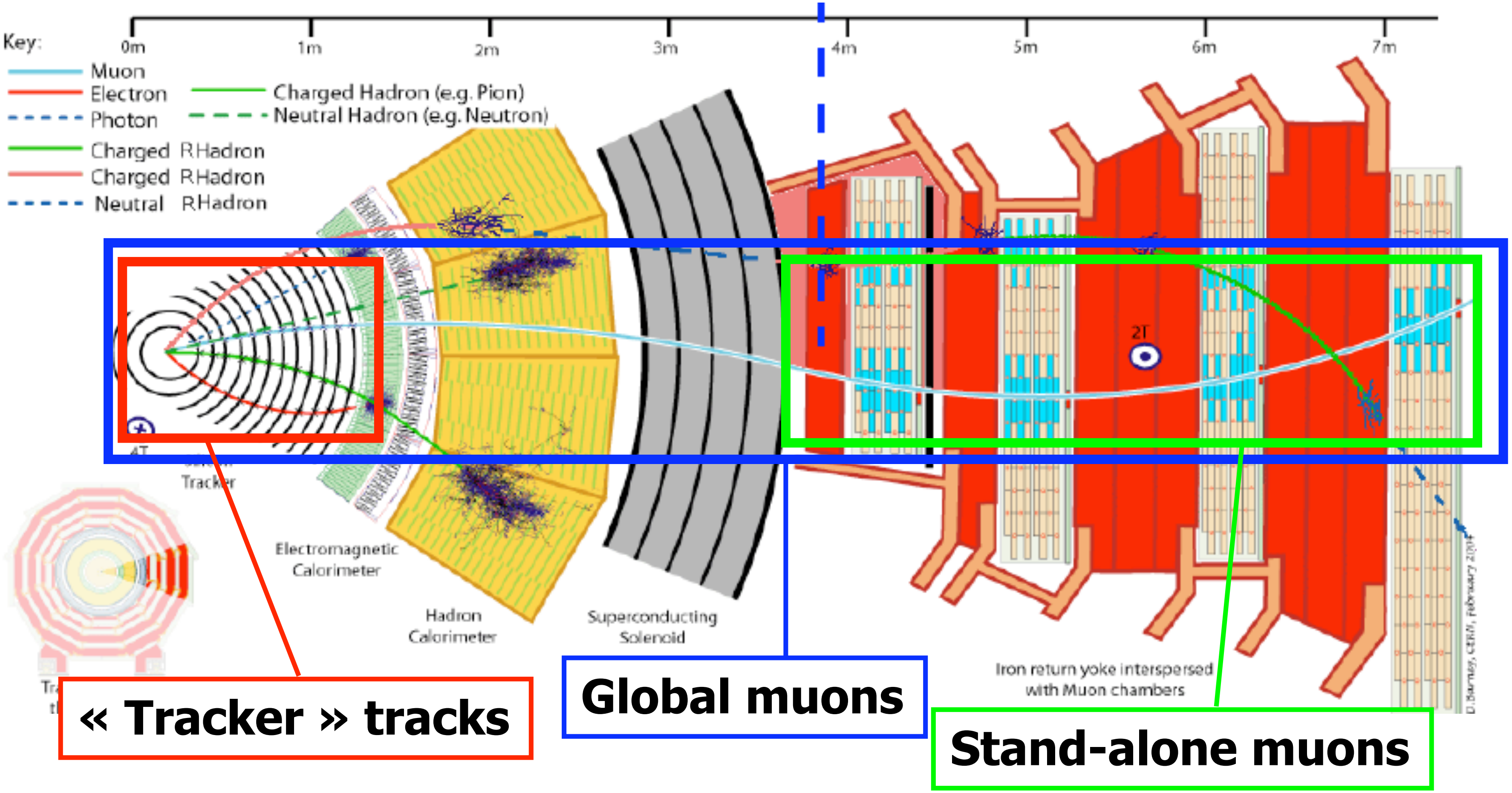
~ 120 X_0 in front of the muon chambers

Combined tracker-muon spectrometer ID and reconstruction

$$\frac{\Delta p}{p} \propto \frac{\sqrt{X_0}}{BL}$$

The LHC Detectors

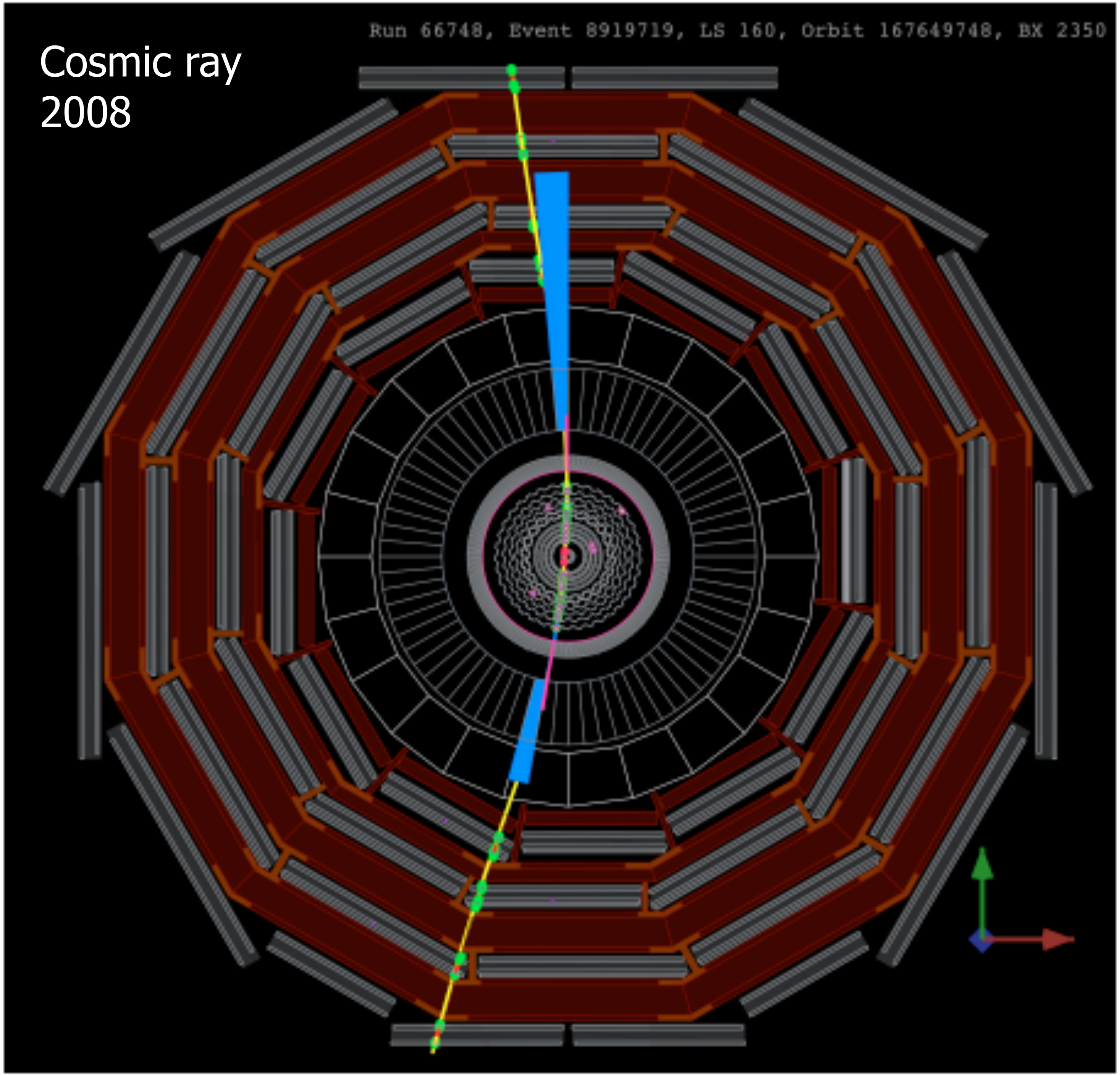
The CMS Muon Detector

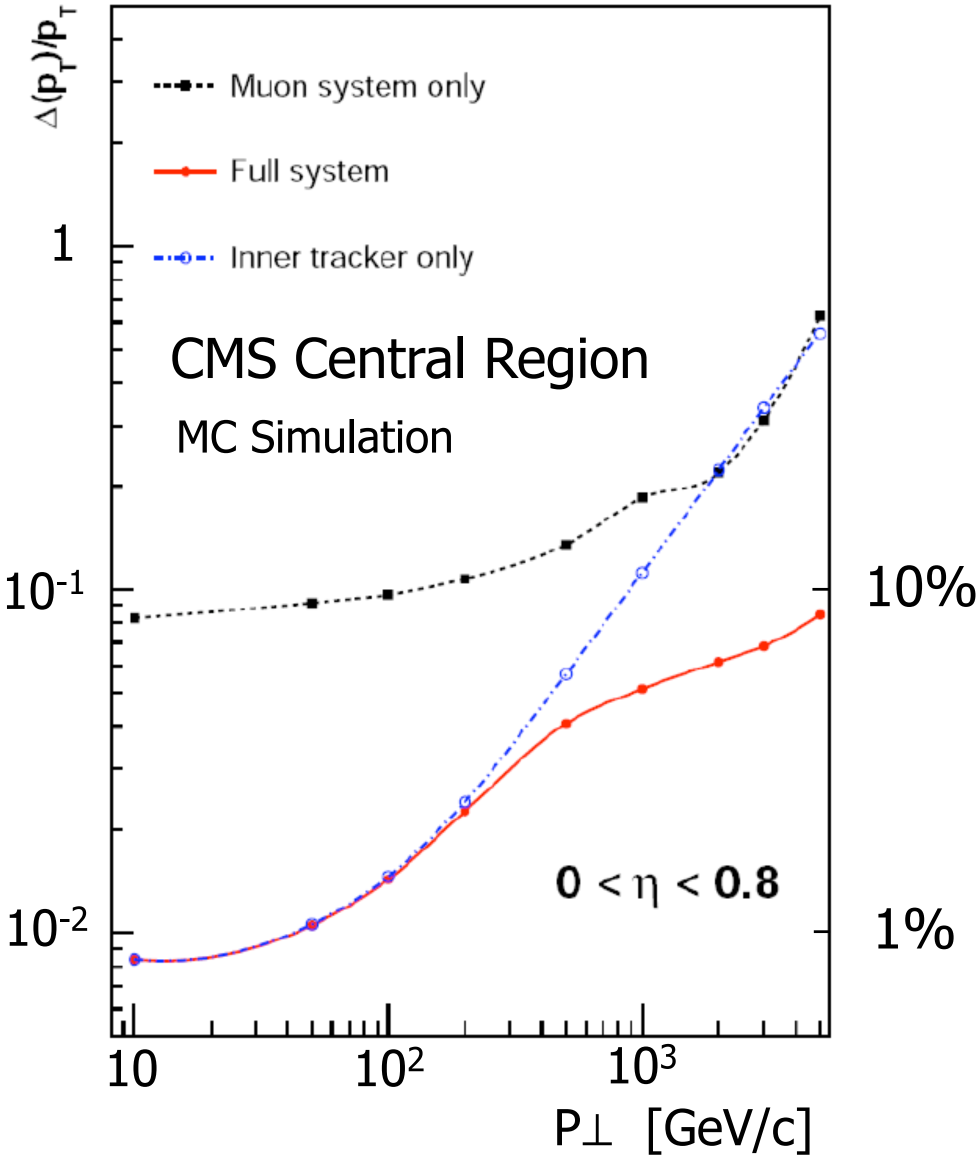


Two Approaches combined for analysis:

« outside-in »: fit muon hits and search for combatible tracker-track = Global Muon

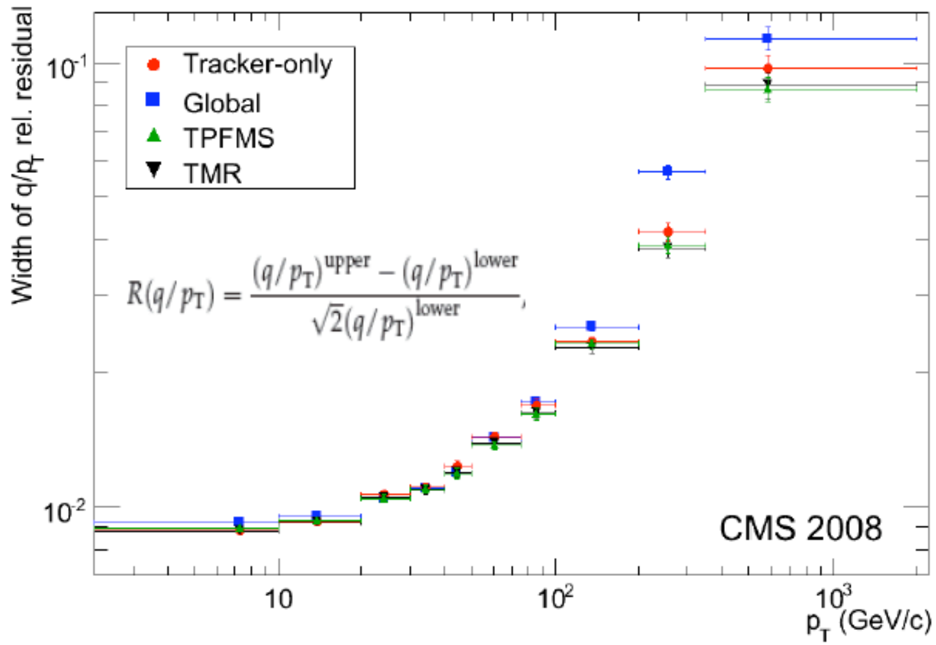
« inside-out »: match tracker tracks with mu segments = Muon Track


Run 66748, Event 8919719, LS 160, Orbit 167649748, BX 2350
Cosmic ray
2008



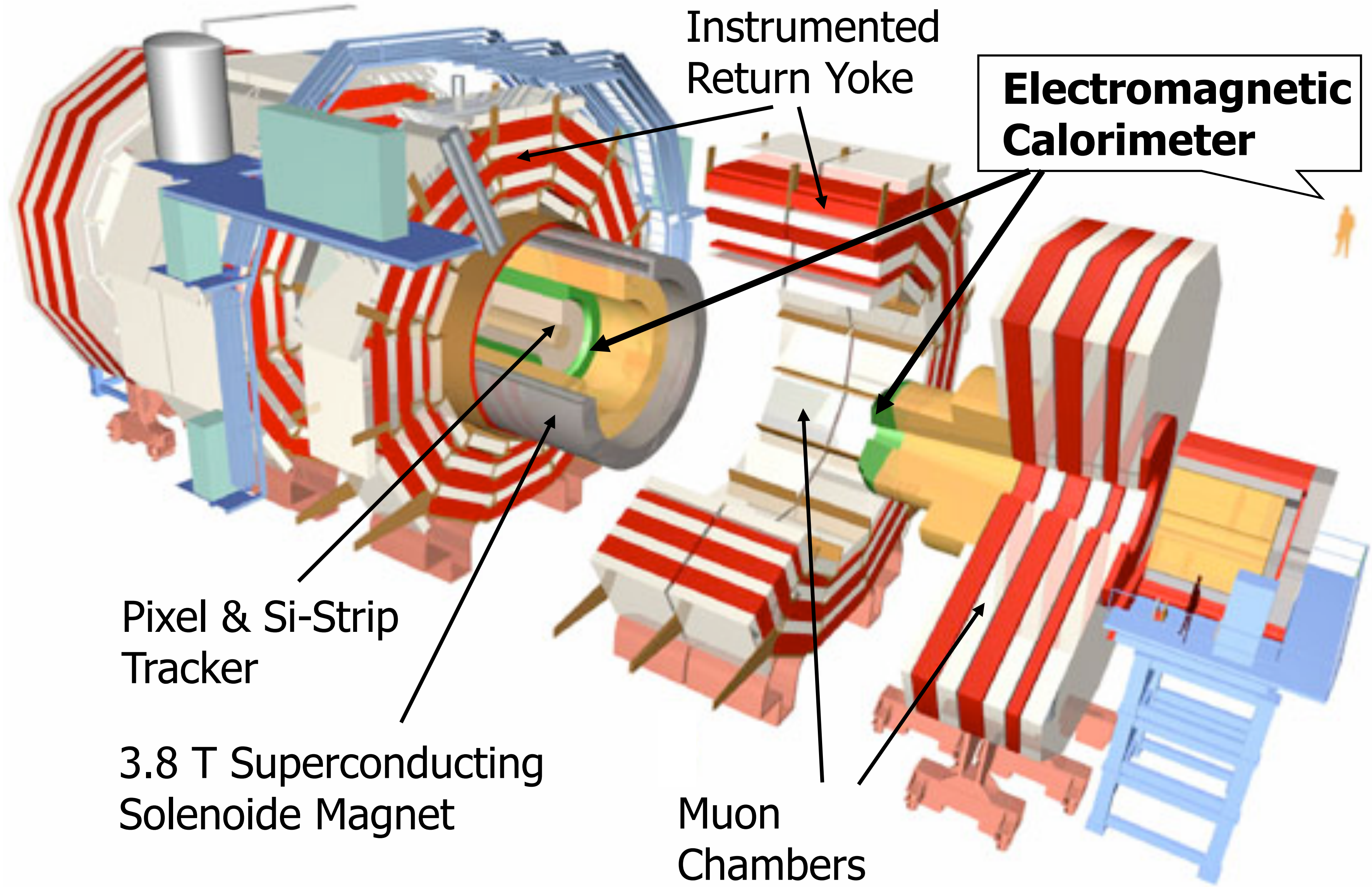
Momentum resolution expected better than 10% for mult-TeV muons ! …

Confirmed with … cosmic data:



The LHC Detectors

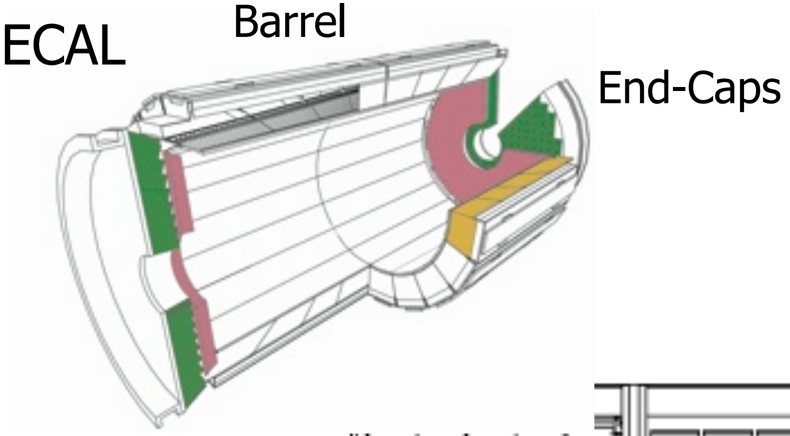
The Compact Muon Spectrometer



The LHC Detectors

The CMS Electrpmagnetic Calorimeter

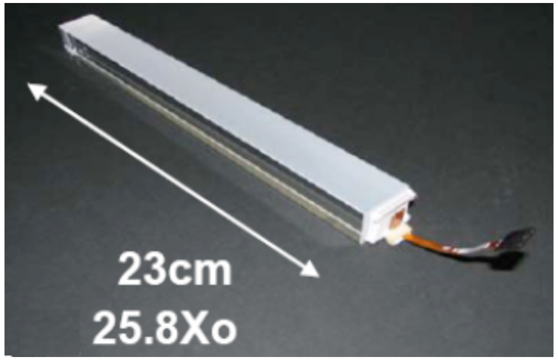
ECAL

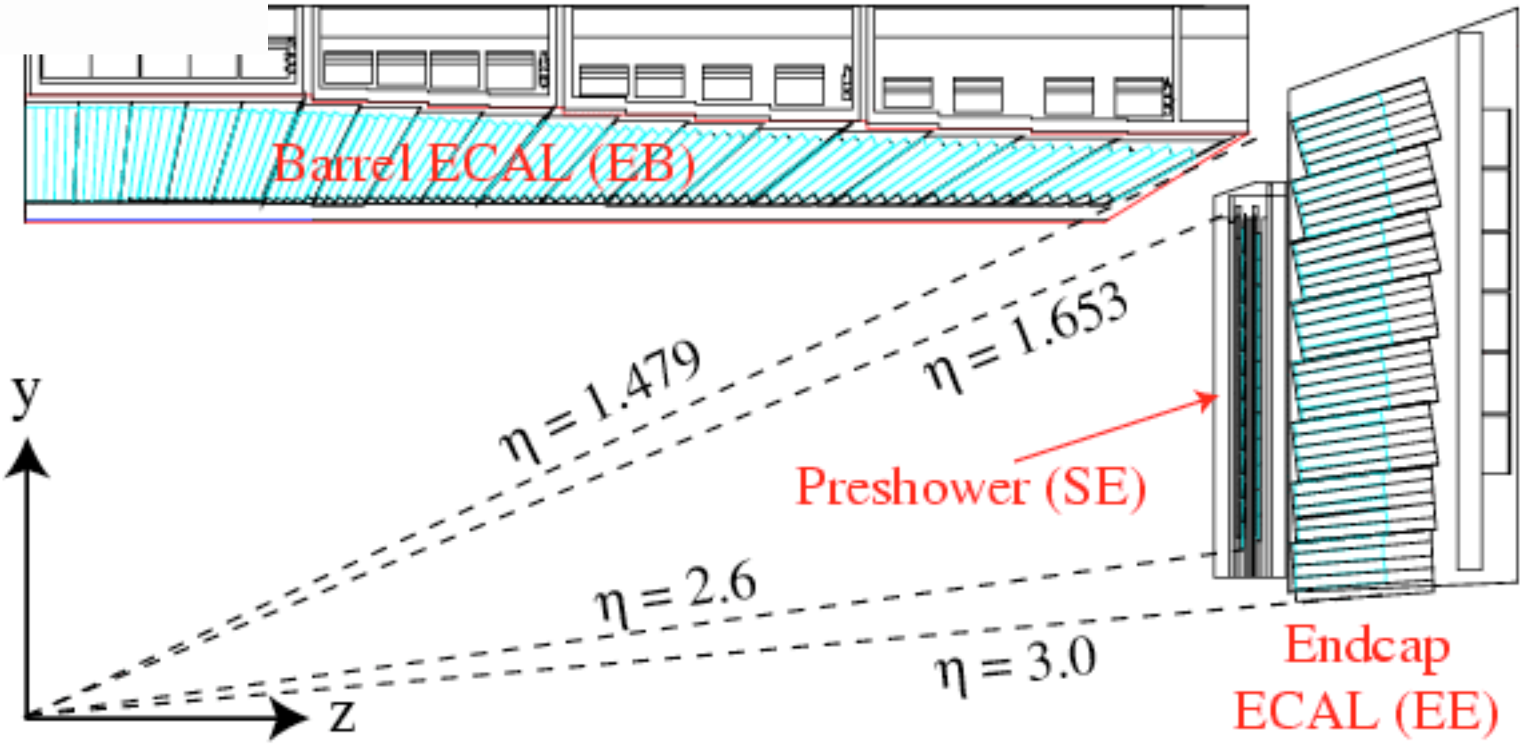


PbWO4 crystals

X_0 = 0.89 cm

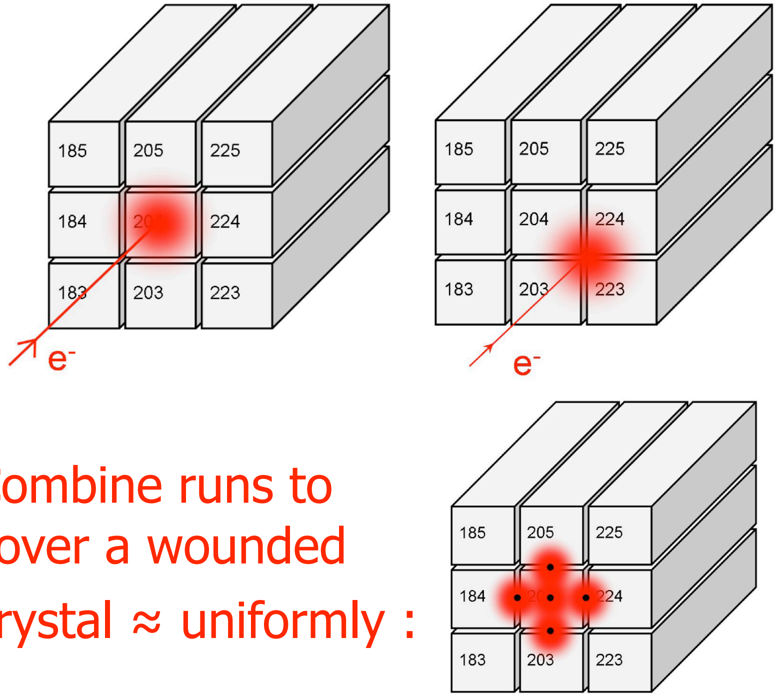
R_M = 2.10 cm



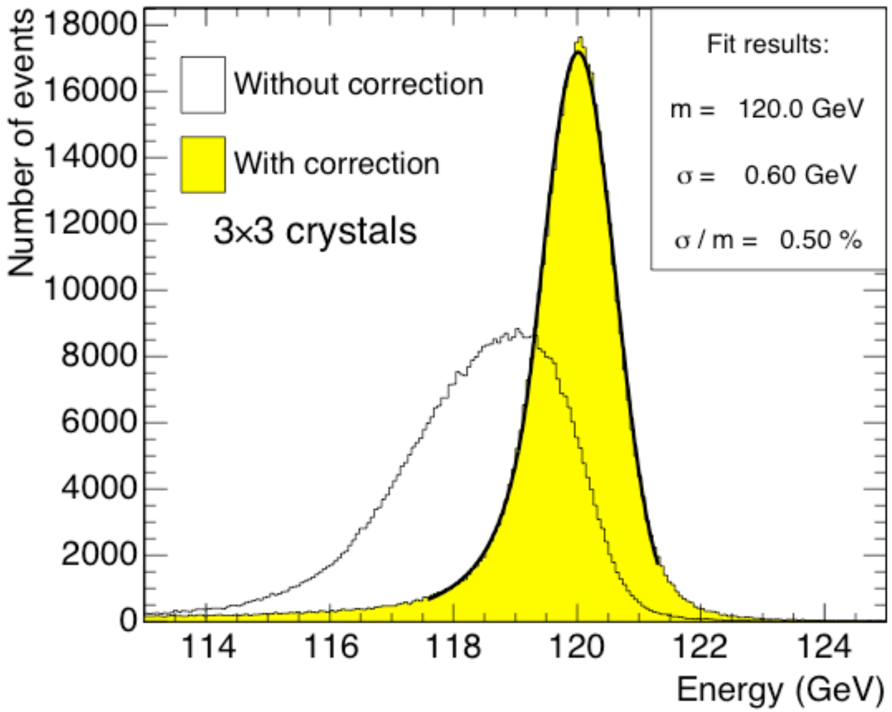


Energy Resolution: Uniform Incidence

⇒ **Study of containment corrections performance: Energy resolution 3x3**
→ 30k events runs @ 120 GeV
→ Beam directed in many positions → combining data sets



Combine runs to cover a wounded crystal ≈ uniformly :



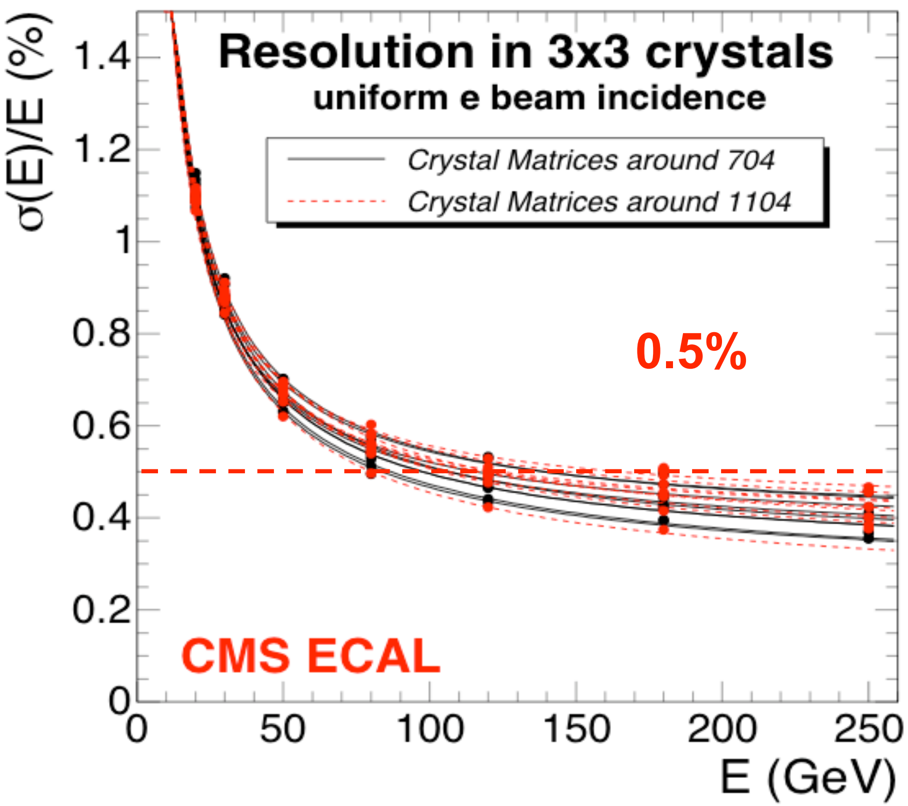
⇒ **Good performance of the containment corrections for uniform incidence: 0.50% E resolution recovered at 120 GeV**

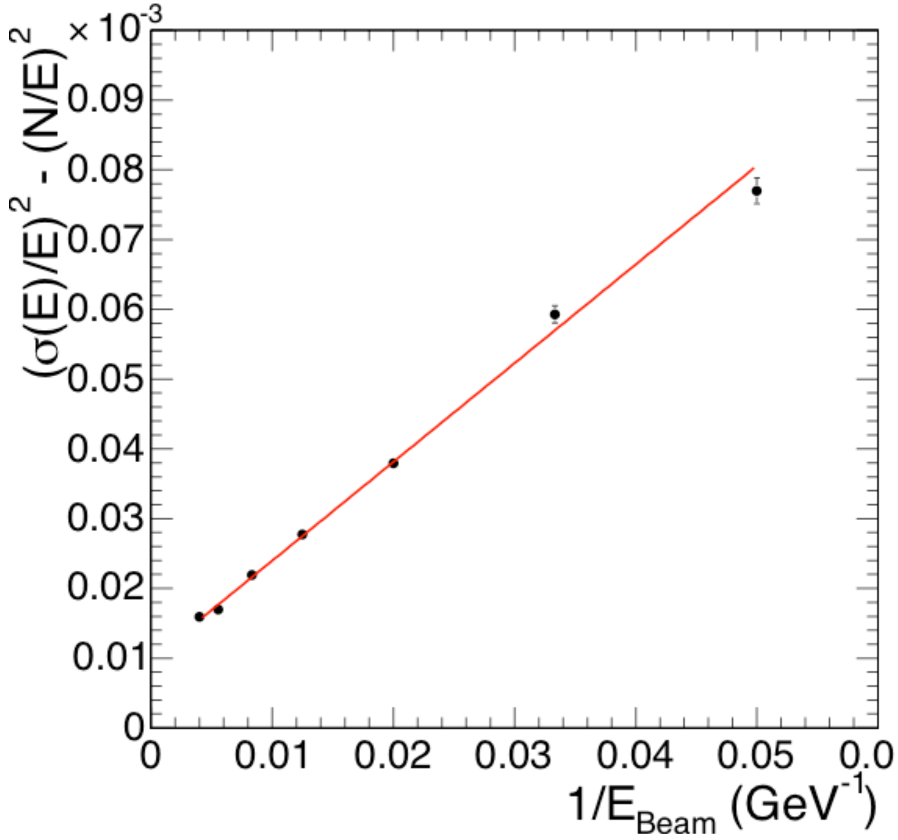
Cluster containment: CMS Note 2006/045

E Resolution vs Incident Ee

Polytechnique

Uniform Incidence





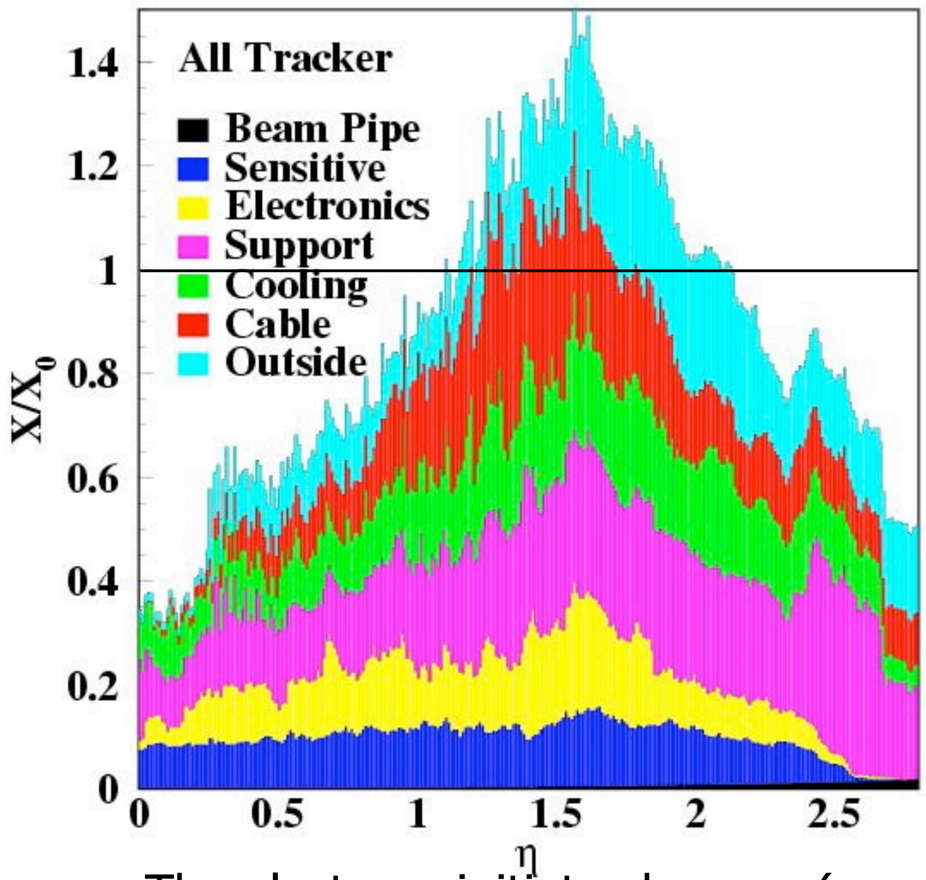
$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.125}{E}\right)^2 + (0.30\%)^2$$

Stochastic Noise Constant

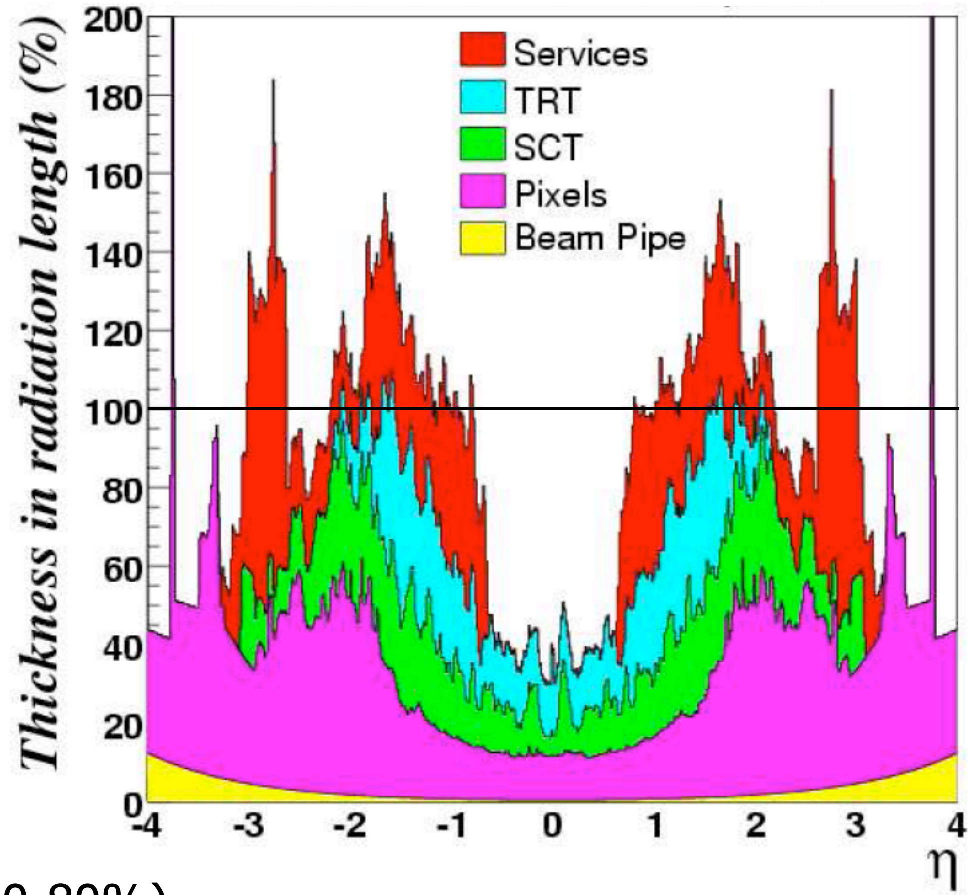
E Resolution: CMS Note 2006/140

Not so … transparent !

CMS



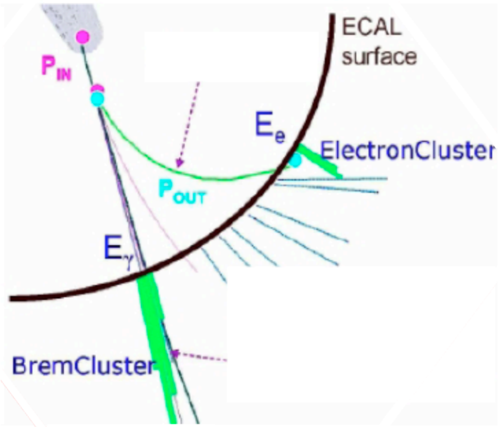
ATLAS



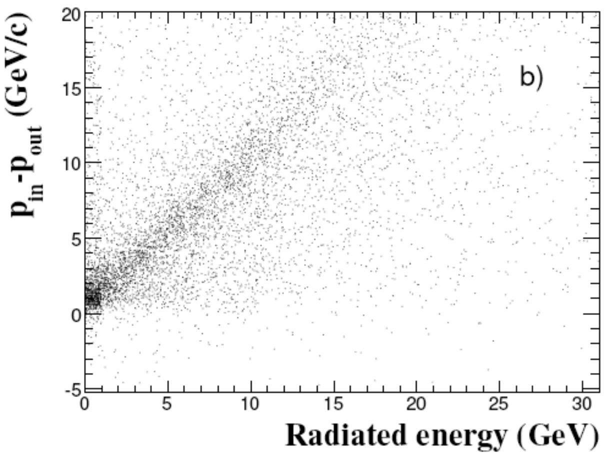
The electrons initiate showers (e.g. 40-80%)

⇒ Identification and efficiency problems, charge mis-identification

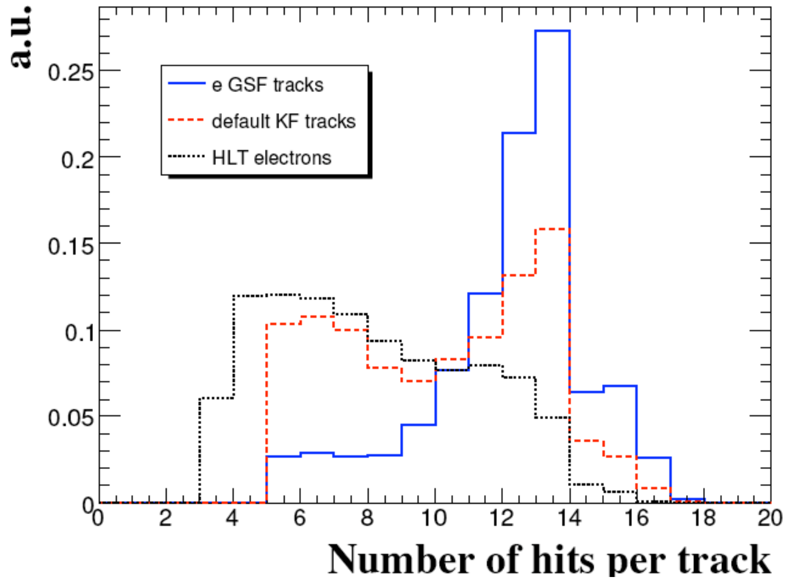
The photons convert (e.g. 20-40%) in e+e- pairs before reaching the ECAL



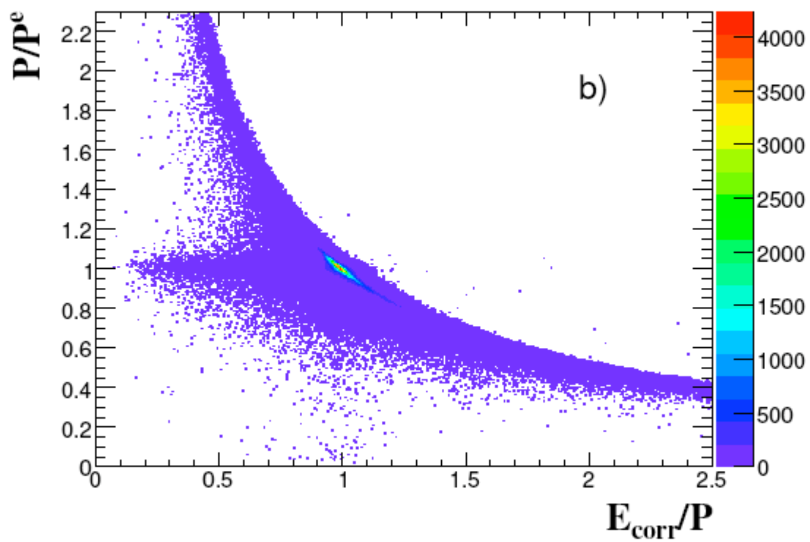
ECAL surface
P_IN
E_e
ElectronCluster
P_OUT
E_γ
BremCluster



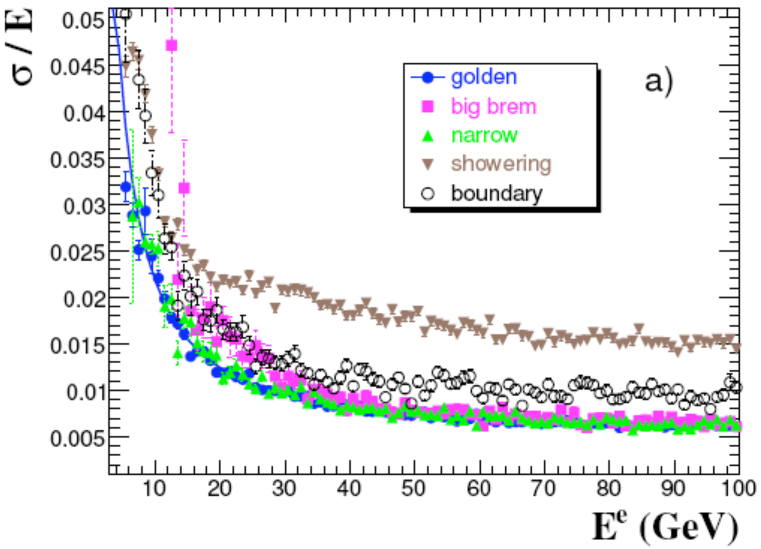
b)
p_in-p_out (GeV/c)
Radiated energy (GeV)



a.u.
e GSF tracks
default KF tracks
HLT electrons
Number of hits per track

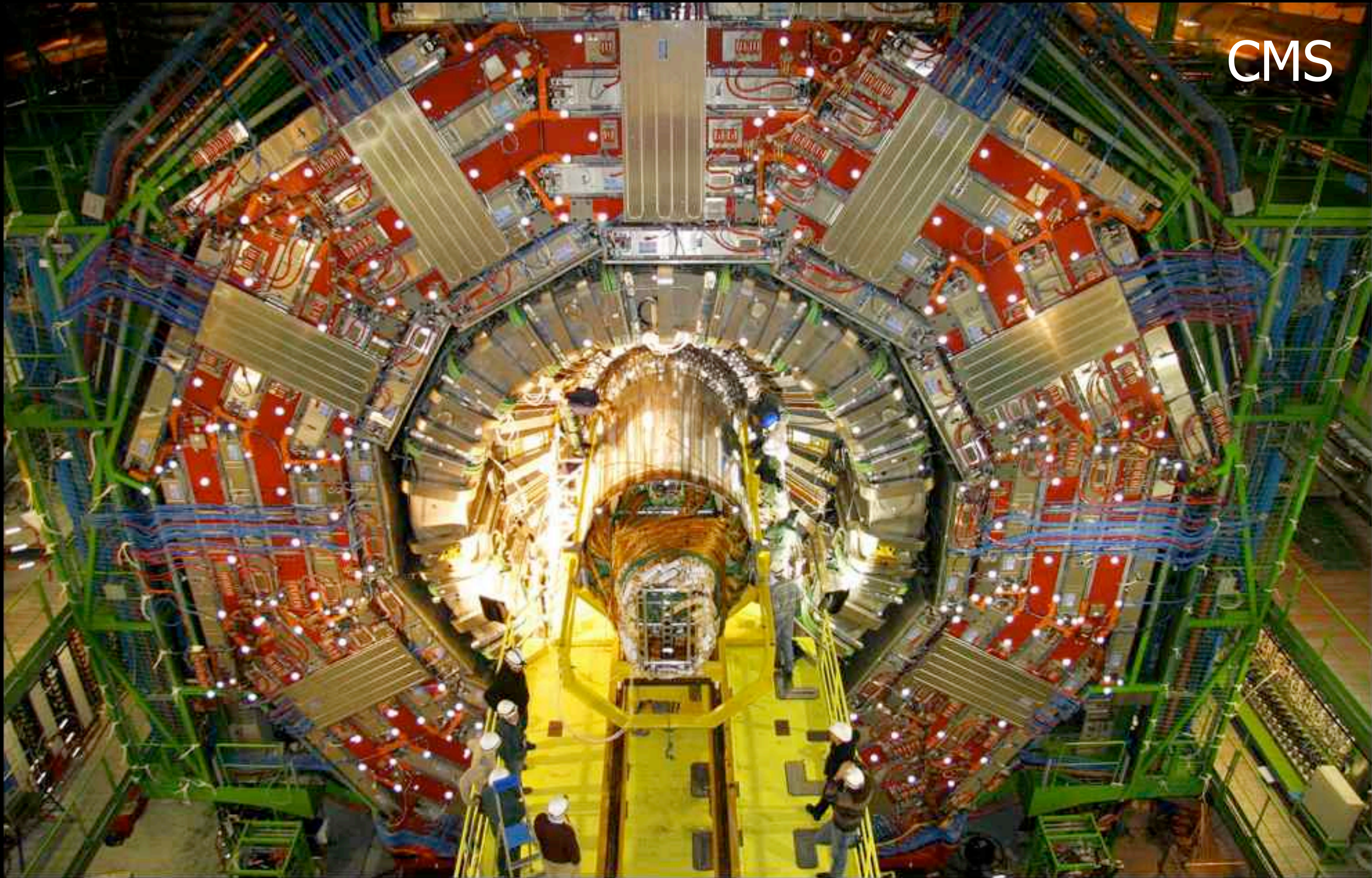


P/P^e
b)
E_corr/P



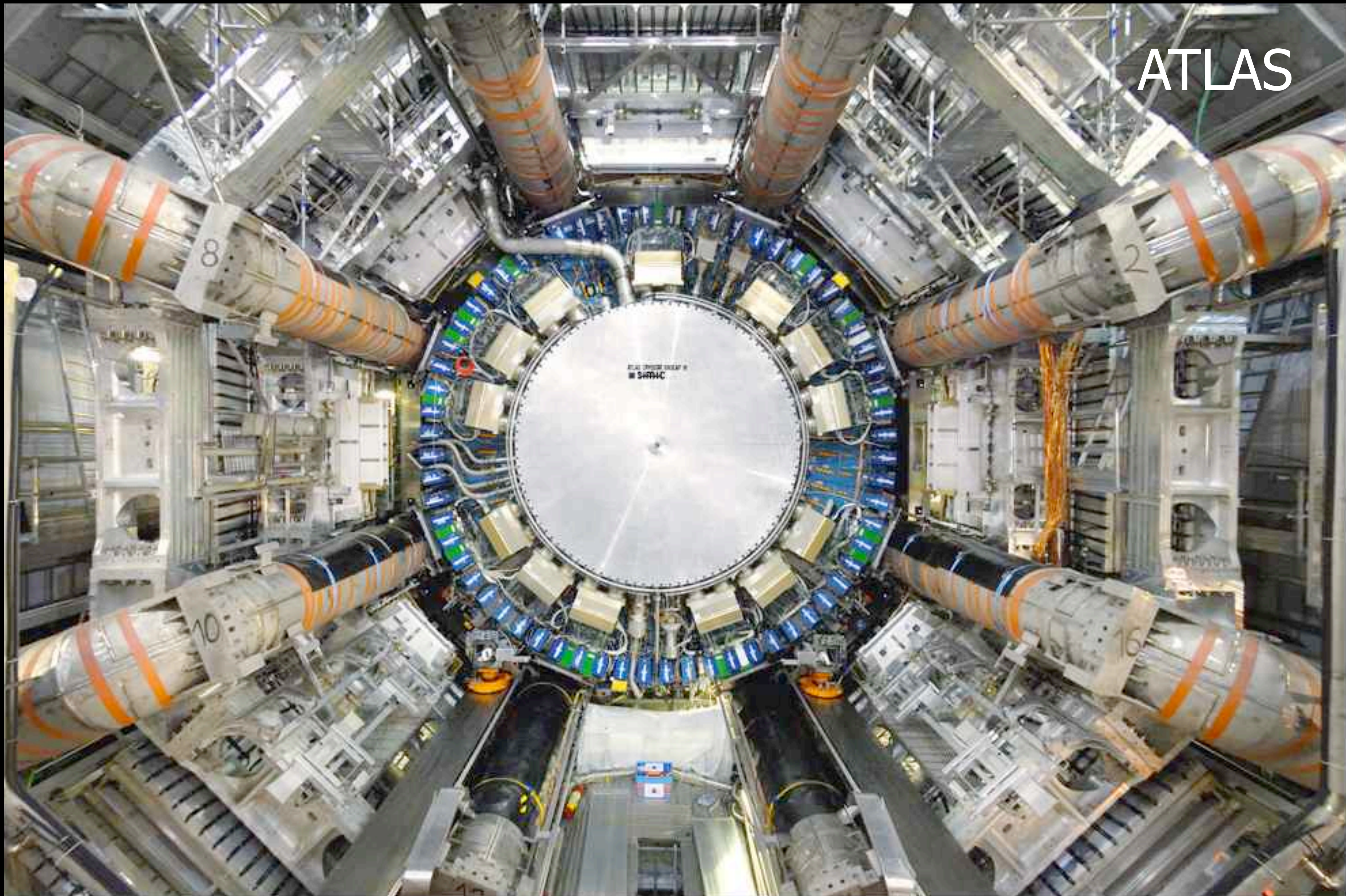
σ / E
golden
big brem
narrow
showering
boundary
a)
E^e (GeV)

From dream to reality:



Installation of the world's largest silicon tracking detector in the CMS experiment. (Michael Hoch, © CERN)

From dream to reality:



View of the ATLAS detector during July 2007 (Claudia Marcelloni, © CERN)

The World and HEP Physics

… awaiting for LHC Start

2009

The World has Changed
a Lot
in the last 20 Years !


New York
9/11 2001
Microsoft Windows 95
ITALY
World
Champion
2006
1997
OK COMPUTER
RADIOHEAD
IN / RAINBOWS
The
END
USSR 1991
2004
Tian'anmen
1989
RADIO HEAD
2008
Google
TV On The Radio
DEAR SCIENCE
DOLLY
Tsunami
2004
20
20 EURO
FRANCE
World Champion
1998
Berlin 1989
1999
... the clone
1996
Irak 2003

The HEP Science has
Progresses a Lot
in the last 20 Years !

EWK & QCD Physics @ HERA
The Manificient SM

Structure Functions at HERA

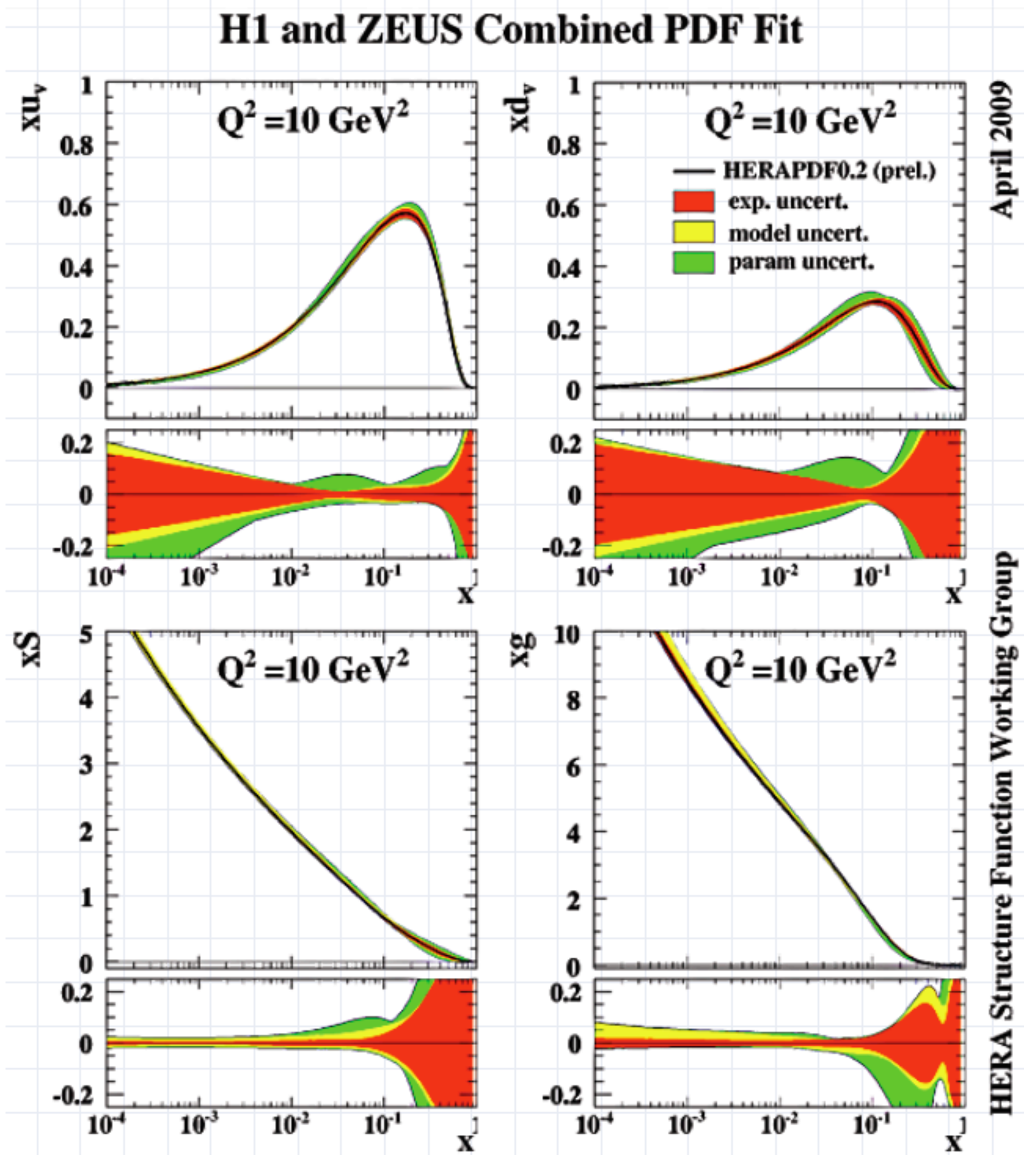
DG1 Talk: Andreï Nikiforov

QCD analysis of the HERA combined data [HERAPDF0.2]

Fully consistent account of experimental, modeling and parametrization errors !

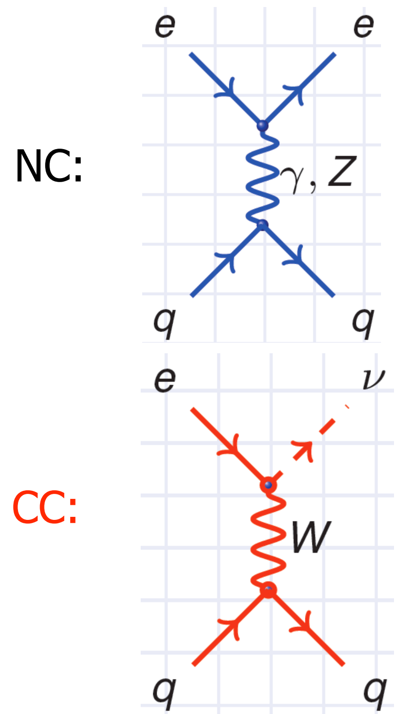
• Accurate xS and xg at low x due to precise measurement of F2

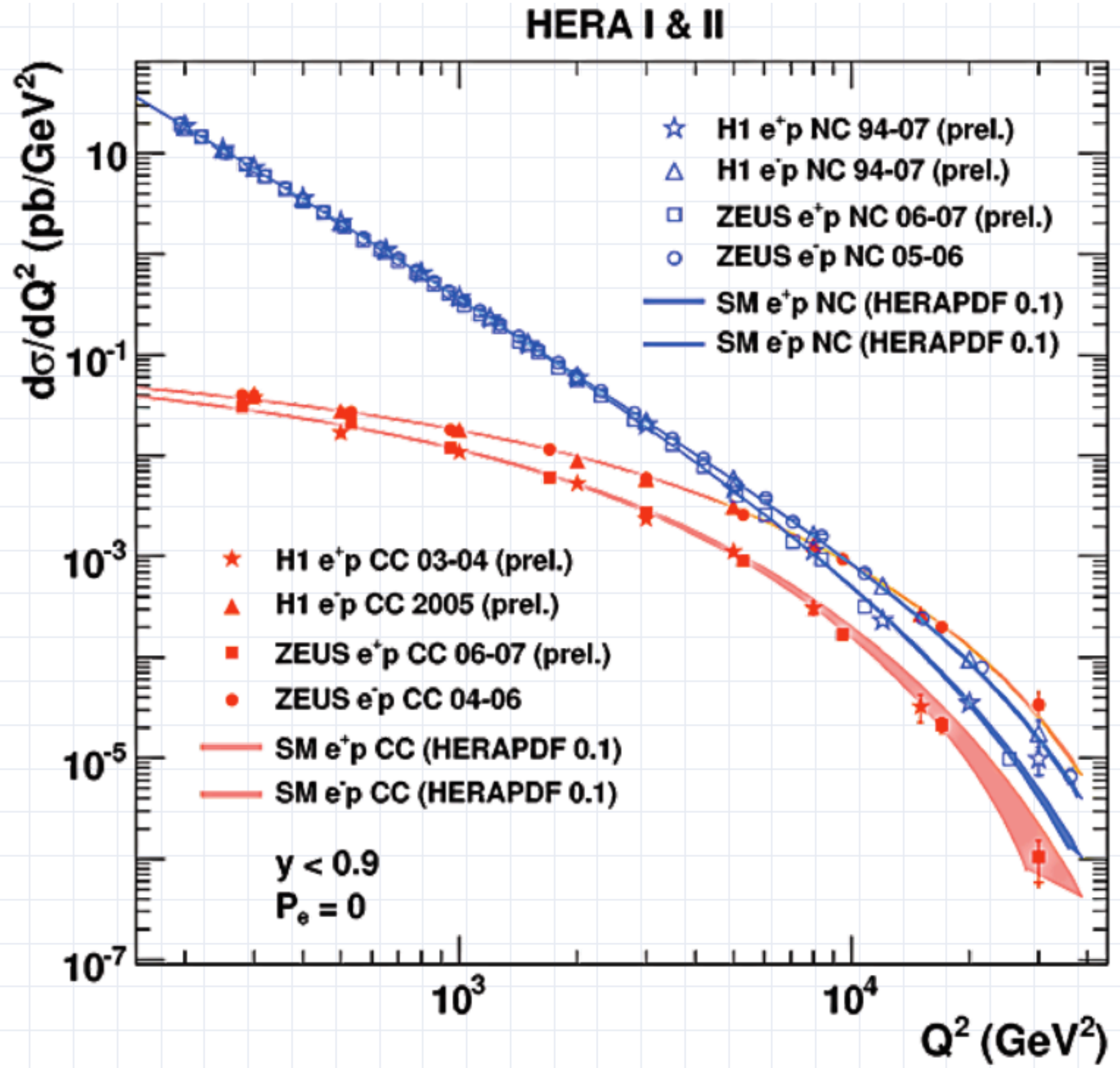
• Constraints on pdf's for valence quarks at high x [relevant e.g. for BSM searches at the LHC] and for the gluons at low x [relevant for Higgs boson searches at the LHC]



Electroweak Physics at HERA

DG1 Talk: Andreï Nikiforov

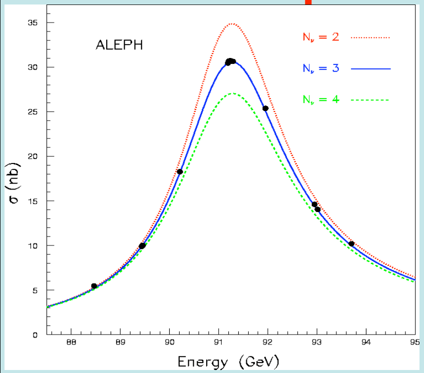
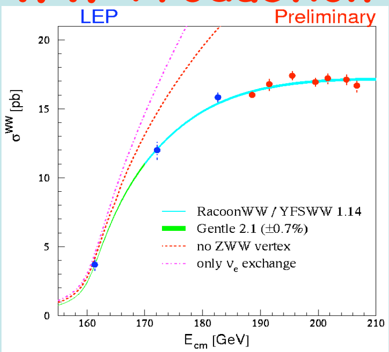
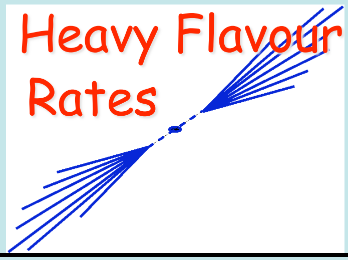




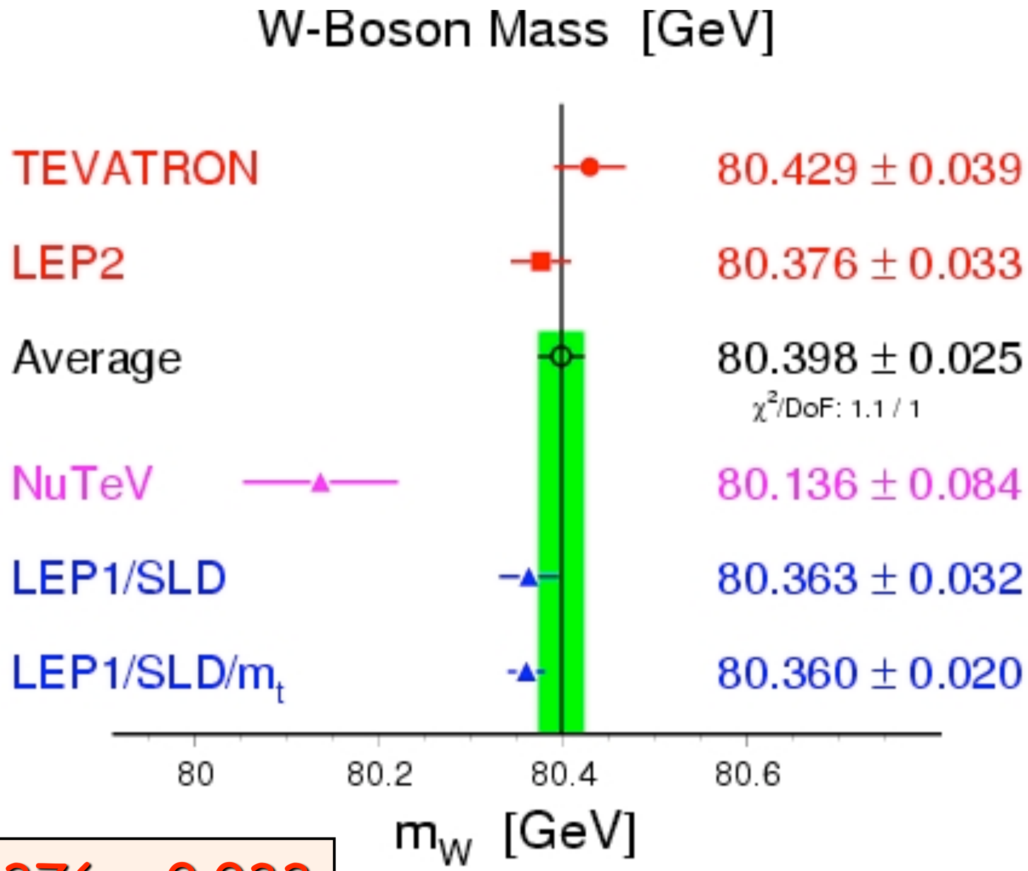
- Manifest EWK unification at $(M_{W,Z})^2$ scale !
- Good agreement with HERAPDF0.1 over a large kinematic range

Electroweak Physics @ LEP
The Manificient SM

Precision Electroweak Observables at LEP

<table>
<tr><th>Experiment</th><th>Observable</th><th>Main technology</th><th>Precision</th><th>Physics output</th></tr>
<tr><td>Z Lineshape

</td><td>m_Z
Γ_Z
σ_{peak}
$R_l = \frac{\Gamma_{hadron}}{\Gamma_{lepton}}$</td><td>Absolute beam energy
(+ ISR QED calculations)
Relative beam energy
(+ ISR ...)
Absolute luminosity
Final state identification</td><td>2.10^{-5}
10^{-3}
10^{-3}
$1.2.10^{-3}$</td><td>Input!
$\Delta\rho$, α_s, N_ν
N_ν
α_s, m_{top}</td></tr>
<tr><td>WW Production

</td><td>m_W</td><td>-Absolute
*Beam energy
* Jet angles
-Final state
Identification
-</td><td>5.10^{-4}</td><td>m_H vs m_{top}</td></tr>
<tr><td>Heavy Flavour
Rates
</td><td>$R_b = \frac{\Gamma_{b\bar{b}}}{\Gamma_{hadron}}$
$R_c = \frac{\Gamma_{c\bar{c}}}{\Gamma_{hadron}}$</td><td>b-tagging
(Vertex detector)
c-tagging (mostly SLD)</td><td>3.10^{-3}
2%</td><td>m_{top}</td></tr>
</table>

W Mass Measurements



$m_W(LEP) = 80.376 \pm 0.033$

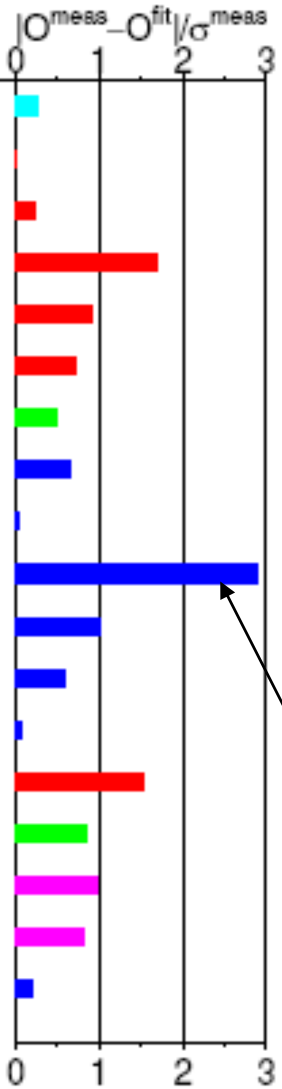
Systematics: Beam energy, FSI

- Good consistency with hadron colliders
- Fair consistency with Z data (LEP/SLD).

Global Fit of the Standard Model

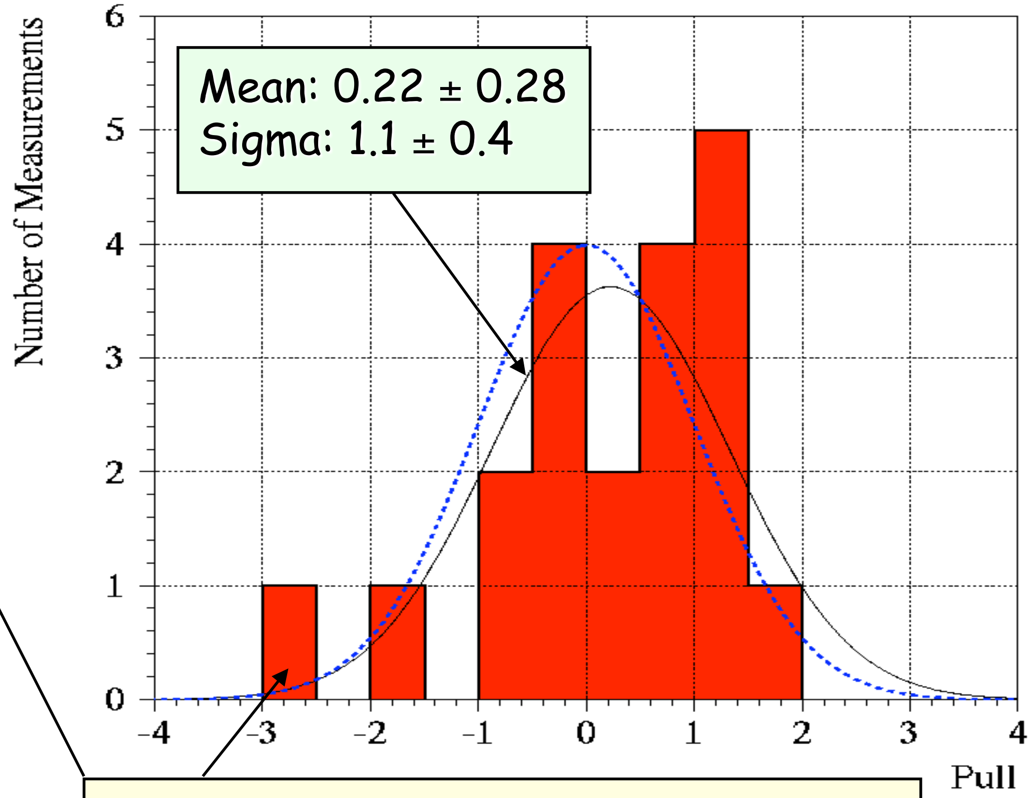
Polytechnique

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3



Internal Consistency of the SM ?

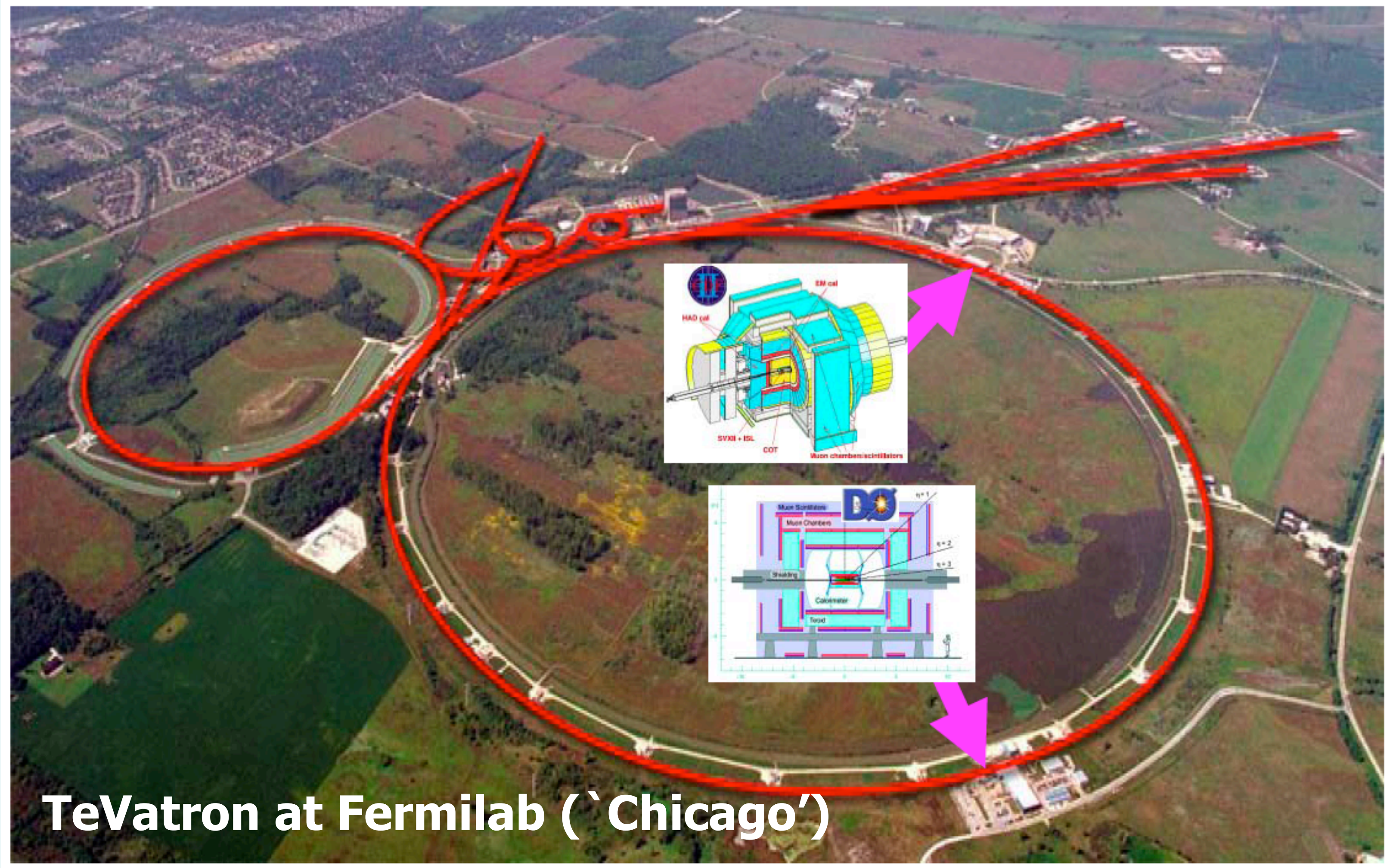
Pull distribution = Normal Gaussian ?



Largest discrepancy (-2.9σ) well inside statistical expectation;

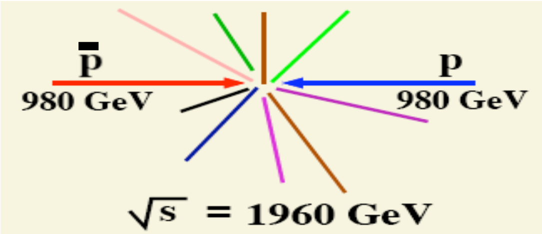
χ^2 probability = 8%. Just fine.

Z/W and Top Physics @ Tevatron



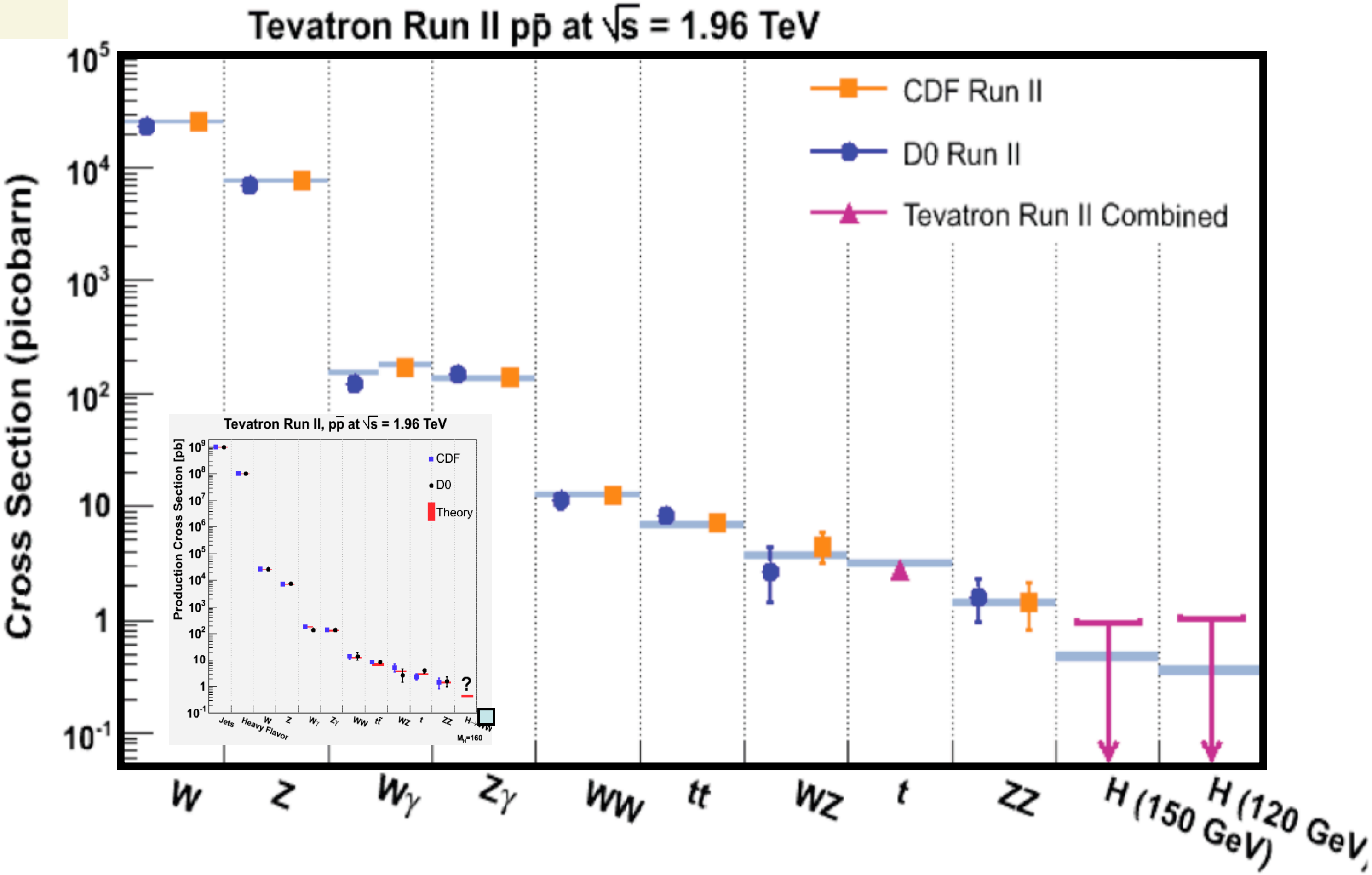
The SM Ladder at the TeVatron

DG1 Talk: Massimo Casarsa

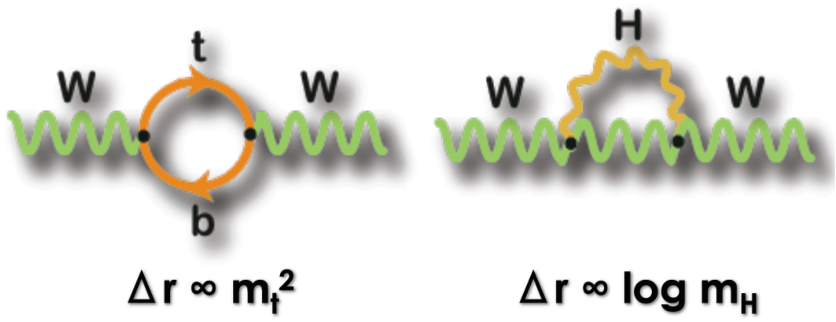


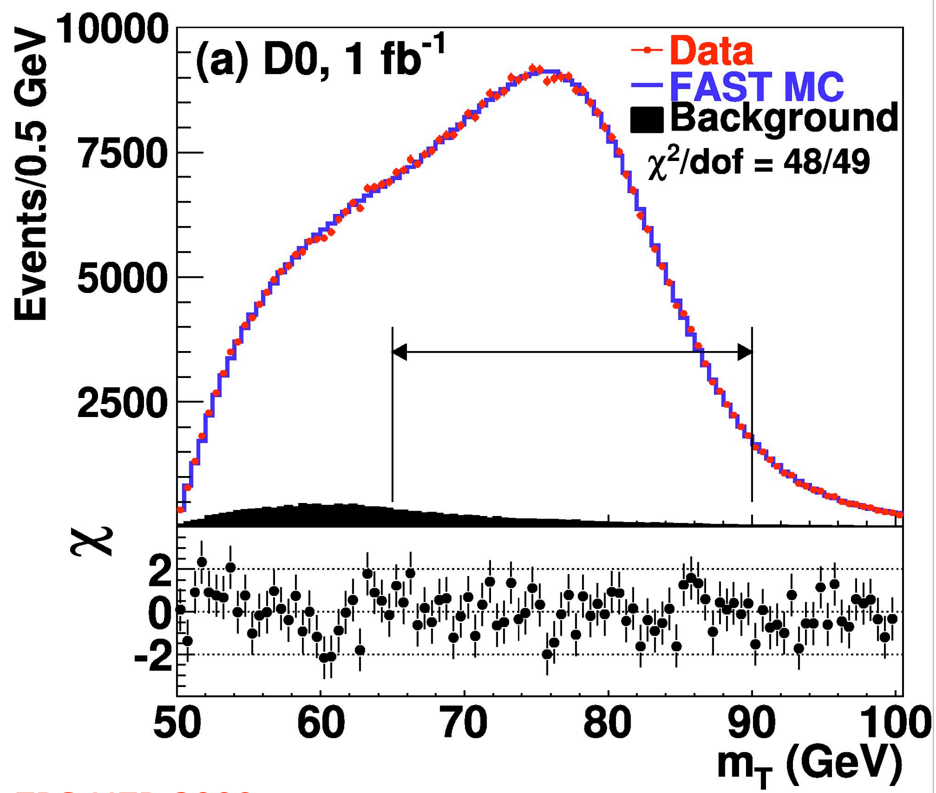
CDF and D0 experiments have explored the SM down 10 orders of magnitude … arriving in sight of the Higgs

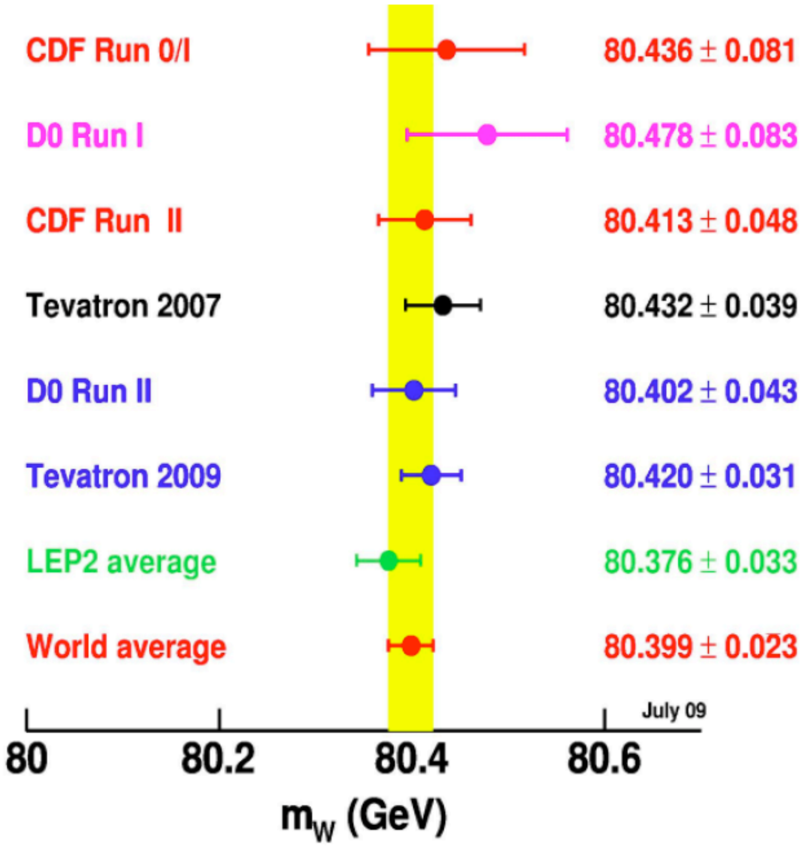
Cross-section processes of O(1) pb are now directly probed !



W Mass Measurement







EPS HEP 2009

Tevatron Average:

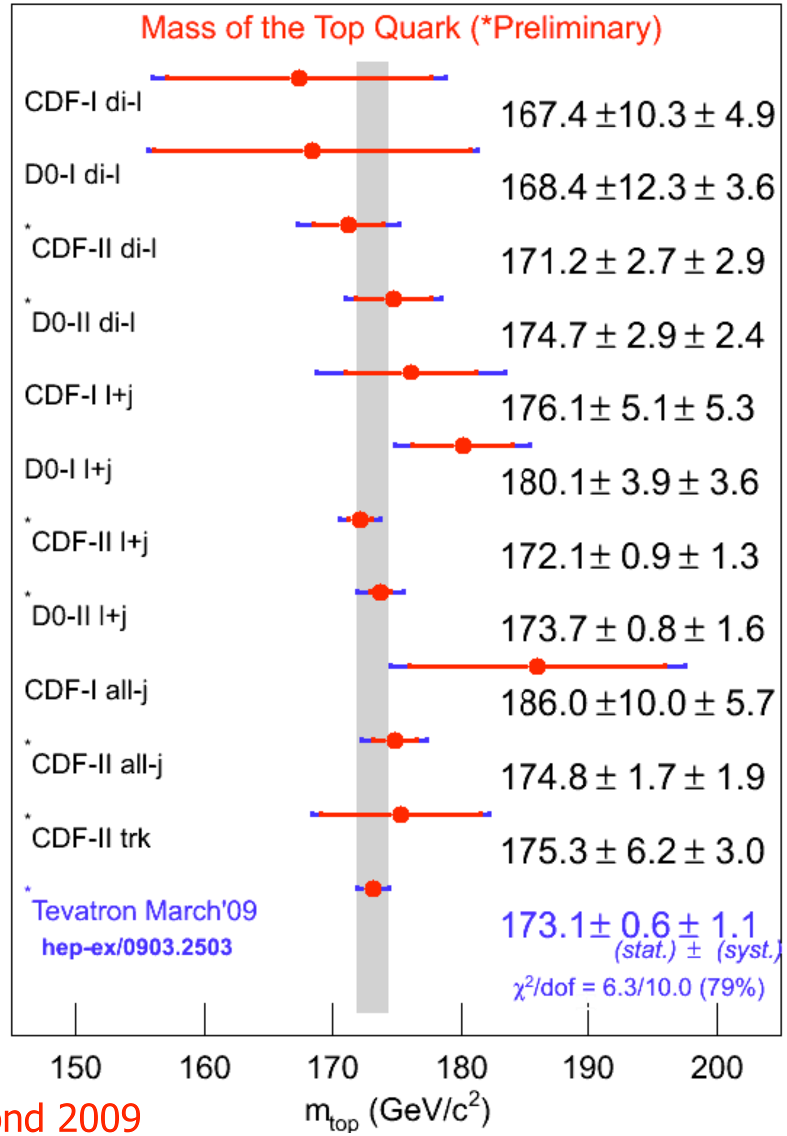
$M_W = 80.420 \pm 0.031$ GeV

World Average:

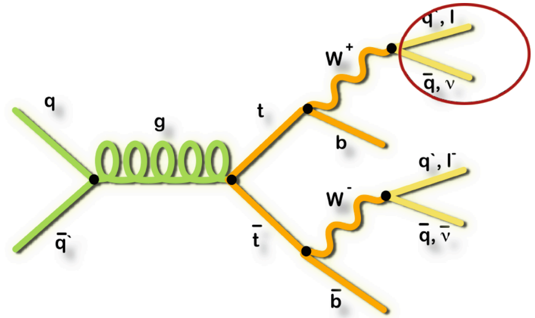
$M_W = 80.399 \pm 0.023$ GeV

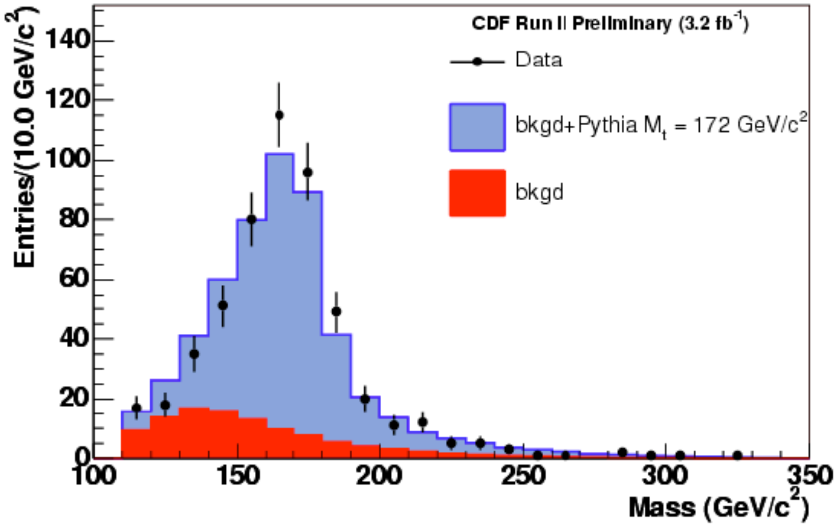
Top Mass Measurement

Polytechnique



Moriond 2009





Tevatron Average:

M_{top} = 173.1 ± 1.3 GeV

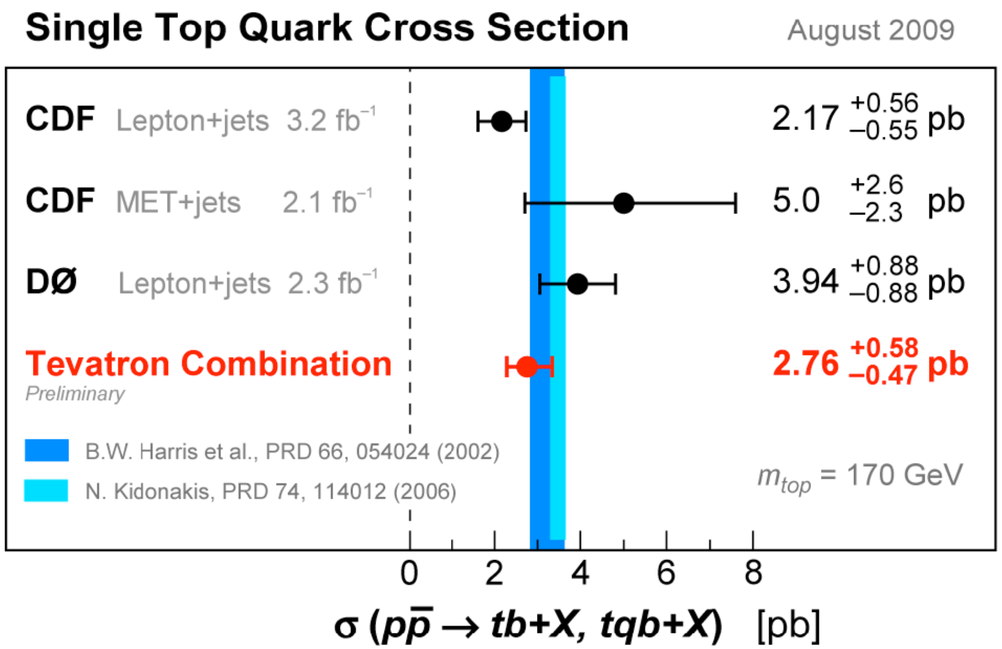
1.3 = 0.6 (stat.) ⊗ 1.1 (syst.)

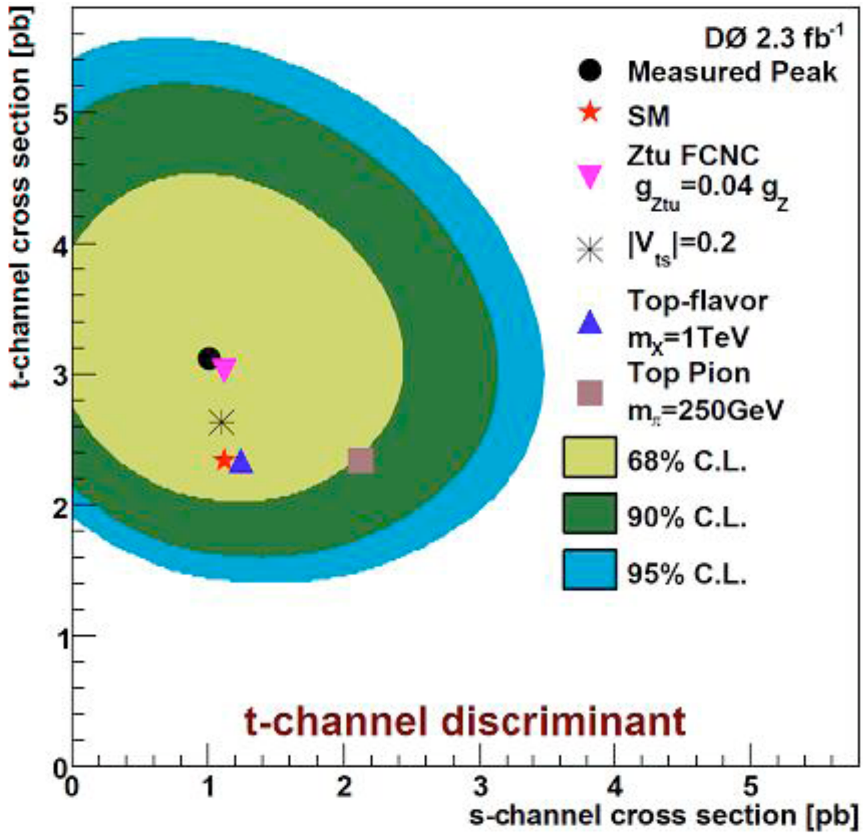
ΔM/M < 1% !!! ΔM ∝ 1/ √ L !!!

Single TOP @ Tevatron

Observation of single top production by D0 and CDF at ~ 5 σ significance

[A benchmark for the multivariate analysis techniques otherwise used for the SM Higgs boson searches]





Tevatron 3.2 fb^{-1}

| Vtb | = 0.91 ± 0.08 (stat. ⊗ syst.)

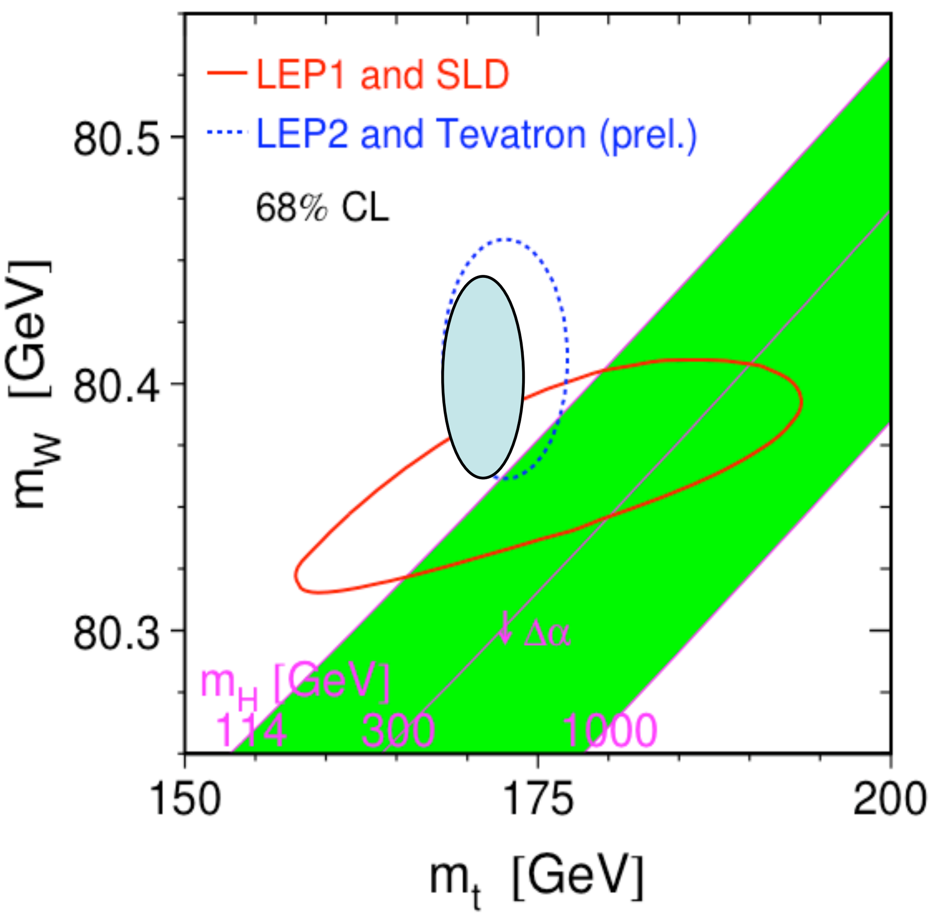
LP2009

Precision Measurements … and M_H

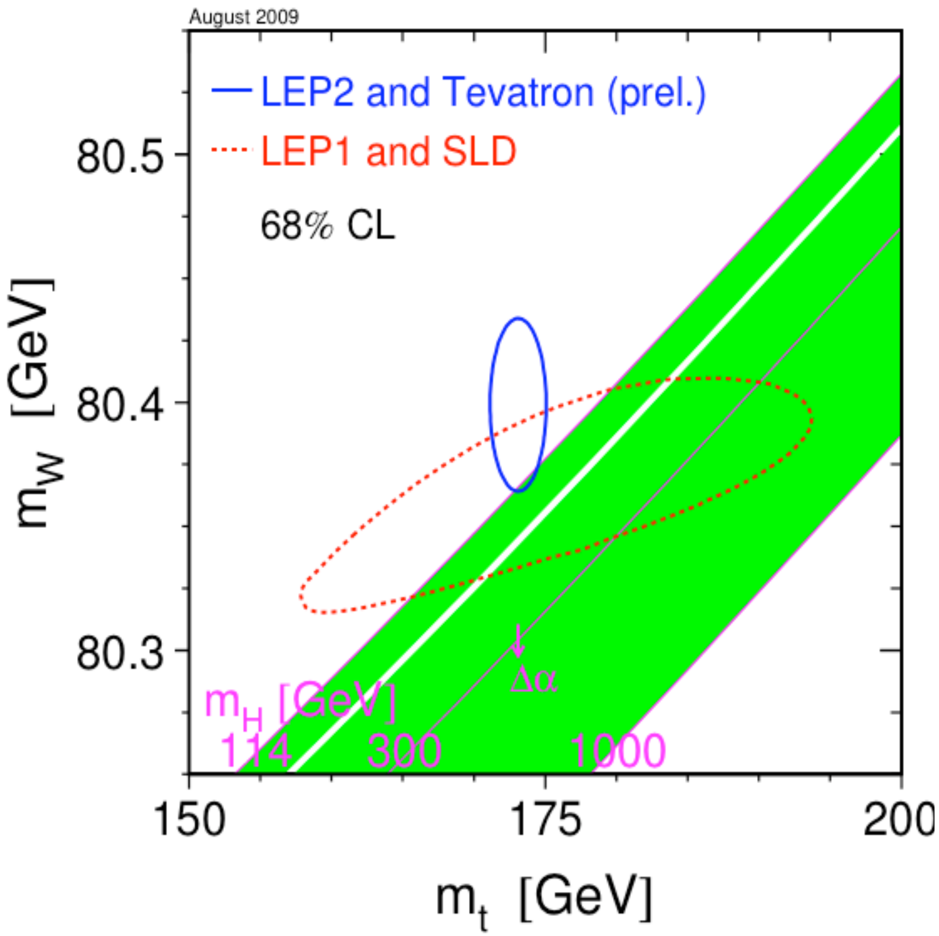
DG1 Talk: Massimo Casarsa

Polytechnique

EPS HEP 2007



LP 2009



Best 'fit' $M_H = 76^{+33}_{-24}$ GeV/C²

Too light ! .. Physics beyond SM ?

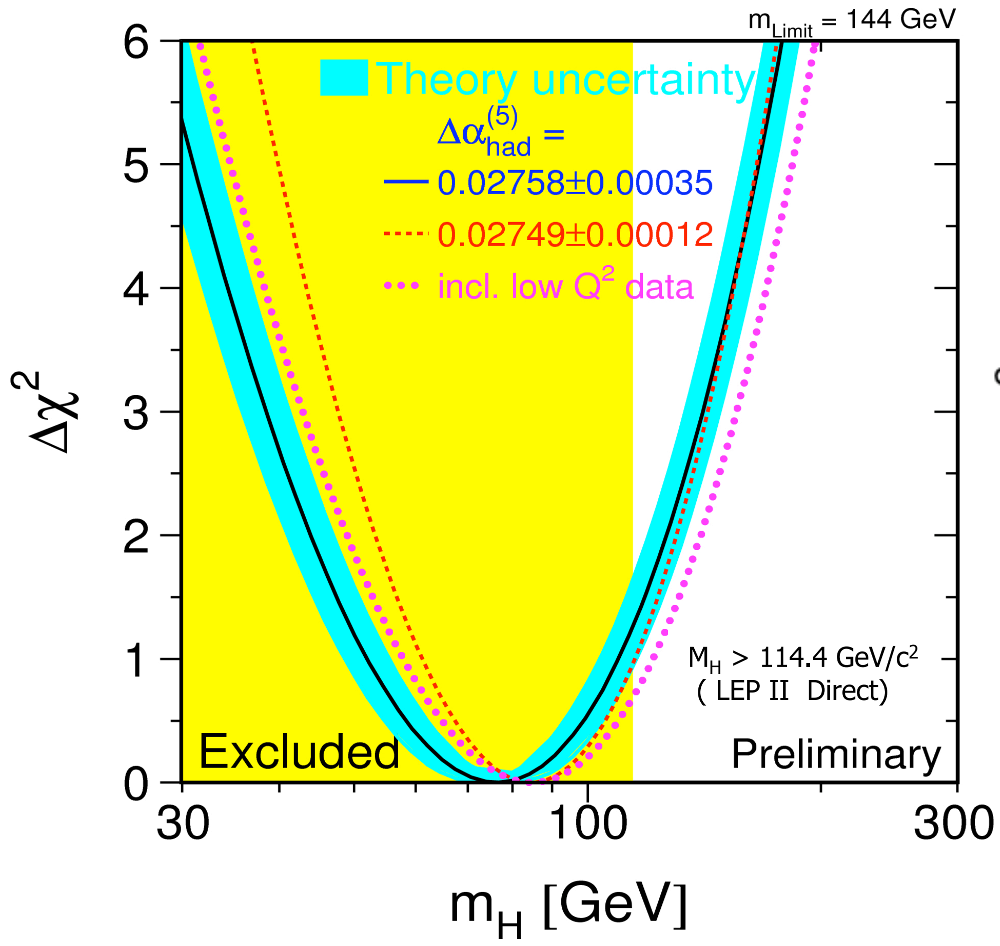
⇒ priority = precision on M_W

Constraints on the SM-like Higgs boson

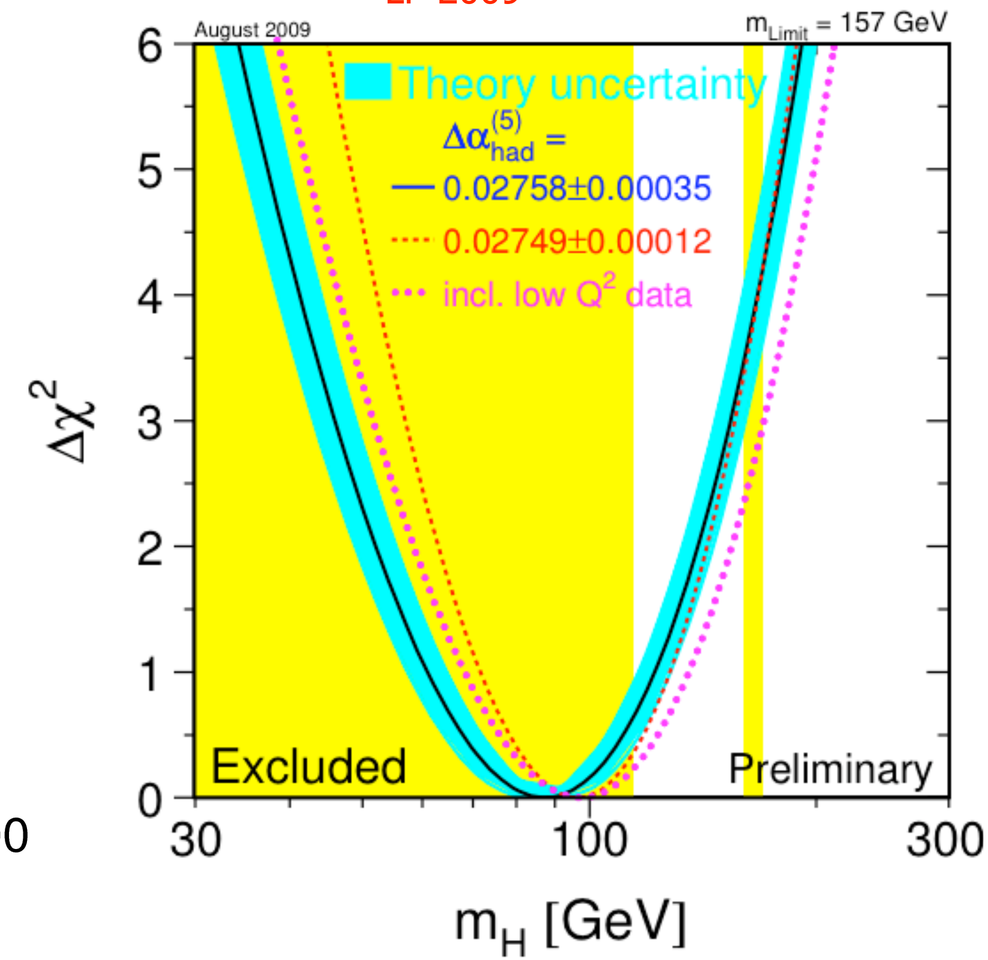
Precision Measurements ... and M_H

Polytechnique

EPS HEP 2007



LP 2009



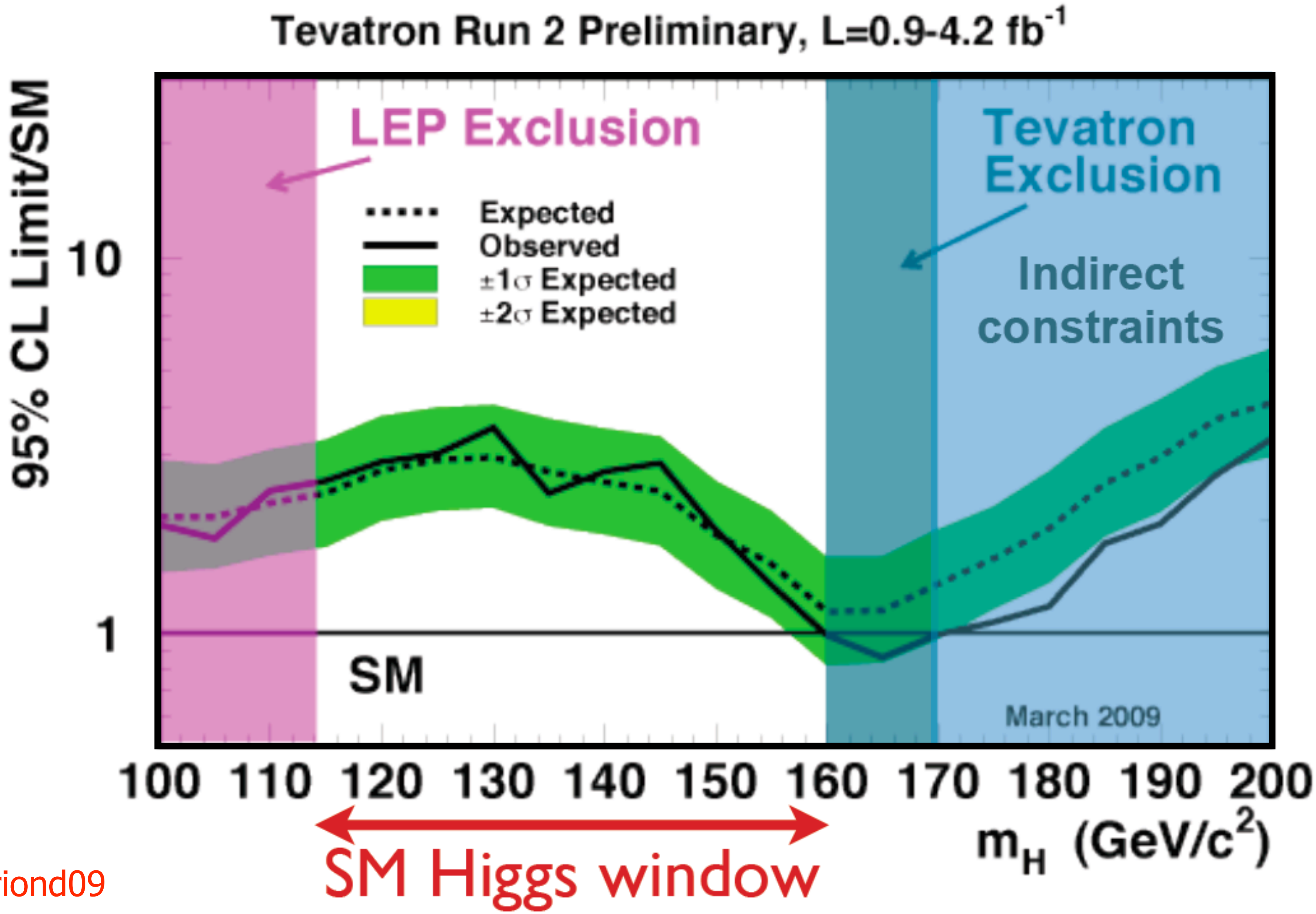
M_H < 182 GeV/c² at 95% CL

("single sided" pour M_H > 114 GeV/C²)

M_H < 186 GeV/c² at 95% CL

("single sided" pour M_H > 114 GeV/C²)

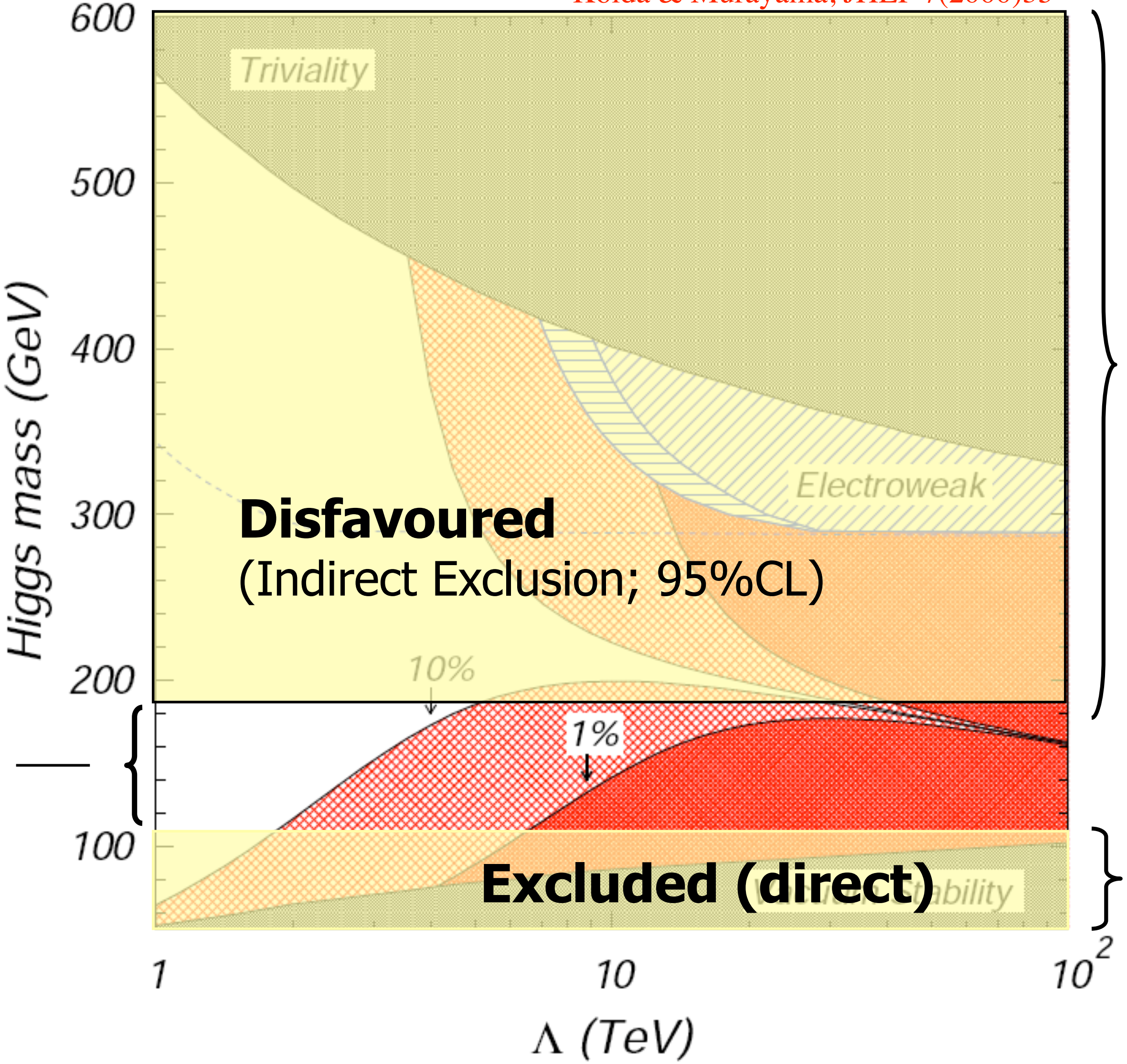
SM Higgs Search at the TeVatron



Moriond09

Higgs Boson and "Fine-Tuning"

Kolda & Murayama, JHEP 7(2000)35



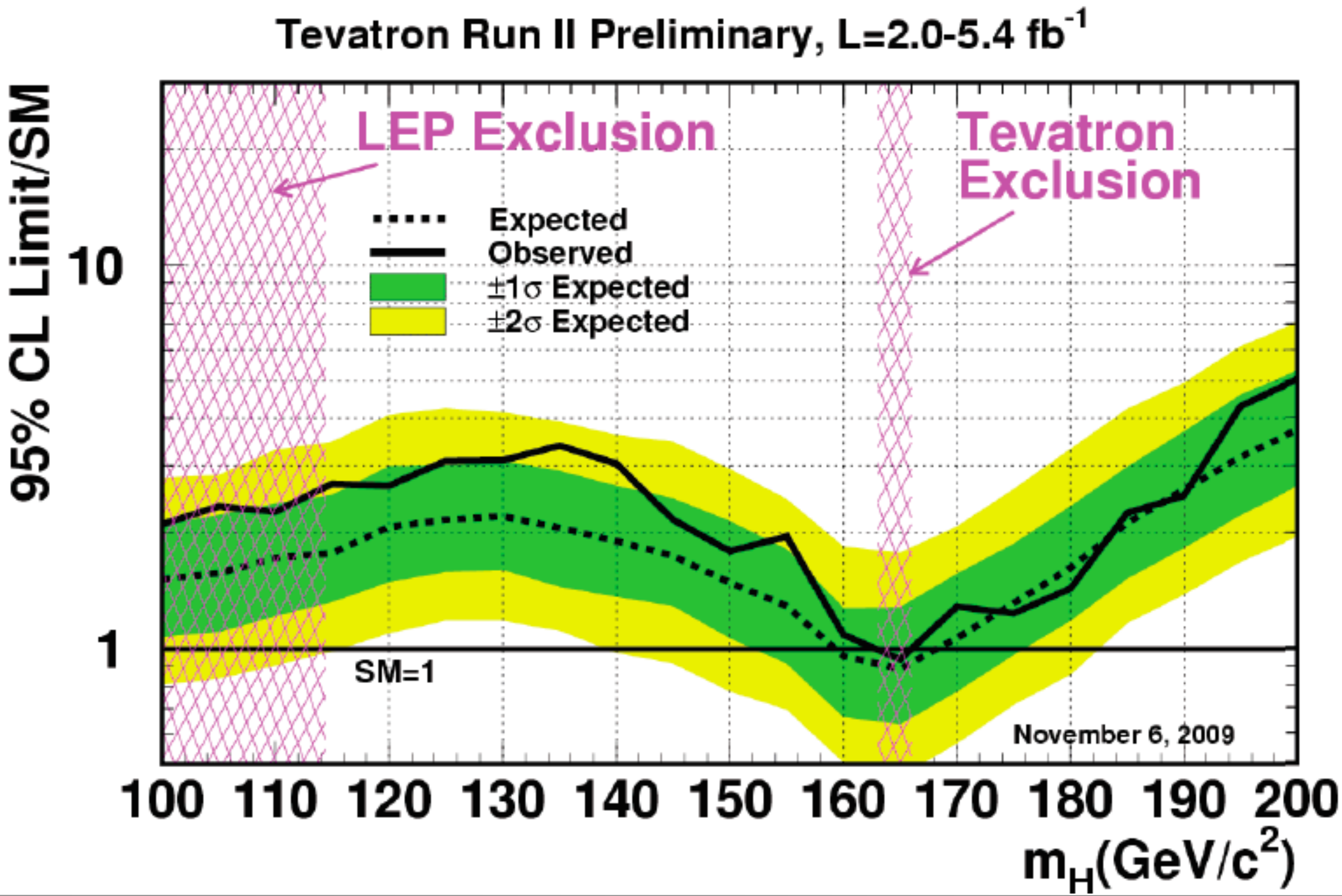
Domain favoured by experiments

$M_H > 2\,M_Z$ Disfavoured by indirect contraints (radiative corrections)

M_H excluded by direct searches at LEP

SM Higgs Search at the TeVatron

New update (last week at HCP2009)



And Meanwhile the Universe has become much more complicated !

Physics @ LHC

The HERA, LEP and Tevatron collliders have seen the triumph of the Standard Model ! … but the essential physics motivations remain as back in 1989:

Electroweak Symmetry Breaking

Hierarchy of Fundamental Interactions

Unification and Extended Symmetries

But in absence of BSM discoveries, it seems that everything as become possible and LHC must be ready for surprises

Meanwhile the universe has become much complicated (dark Matter, dark energy, neutrino masses … !)

Who is protecting a scalar mass ?

Bosons	Fermions	Vectors
$\phi \rightarrow \phi + a$	$\psi \rightarrow e^{ia\gamma_5}\psi$	$A_\mu \rightarrow A_\mu + \partial_\mu a$
no $m^2\phi^2$	no $m\bar{\psi}\psi$	no $m^2 A_\mu A^\mu$
Spontaneous Global Symmetry Breaking	Chiral Symmetry	Gauge Symmetry

} Symmetry

LITTLE HIGGS **SUPERSYMMETRY** **HIGGS-GAUGE Unif.**

M_H

TECHNICOLOR **HIGGSLESS** **EXTRA DIMENSIONS**

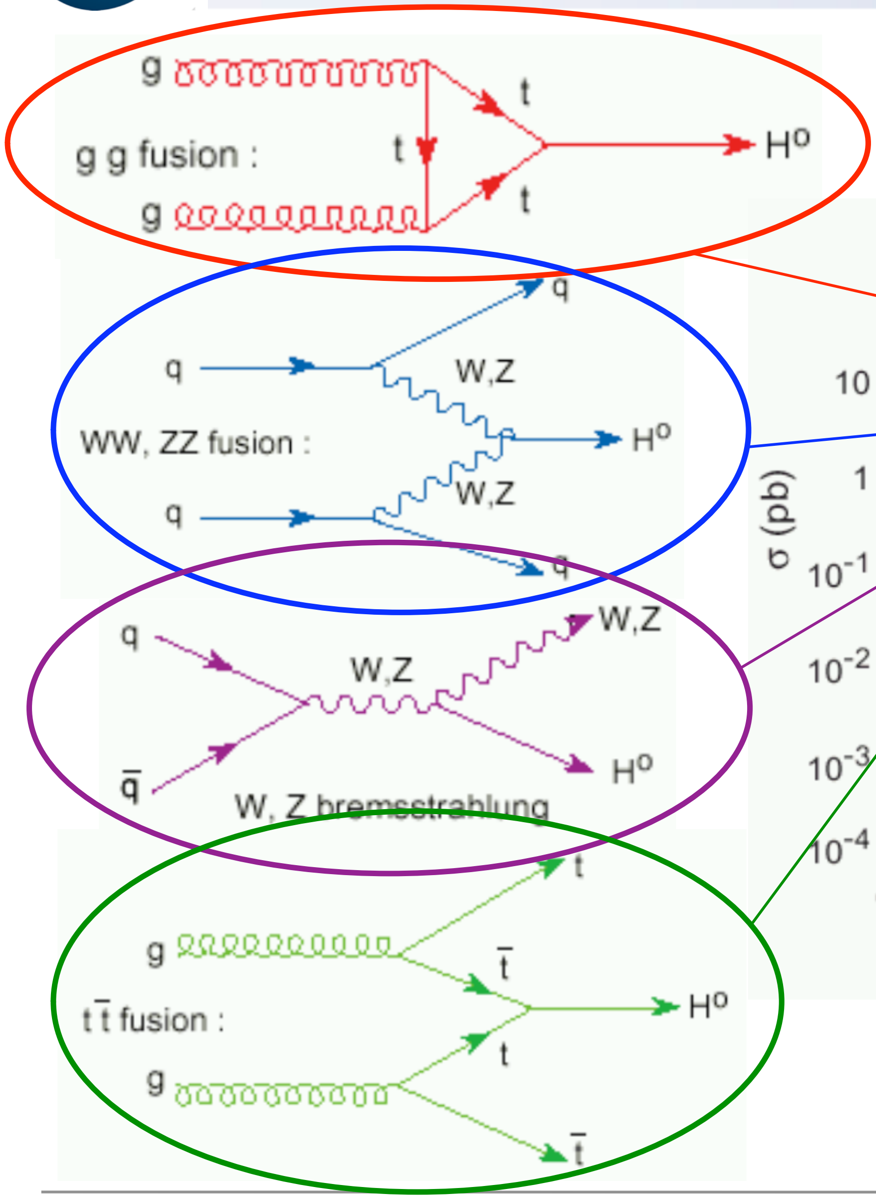
Breaking EWK dynamically	Delayed Unitarity Violation	Fondamental "Planck" scale at the TeV

} Dynamics

Early physics & prospects for the

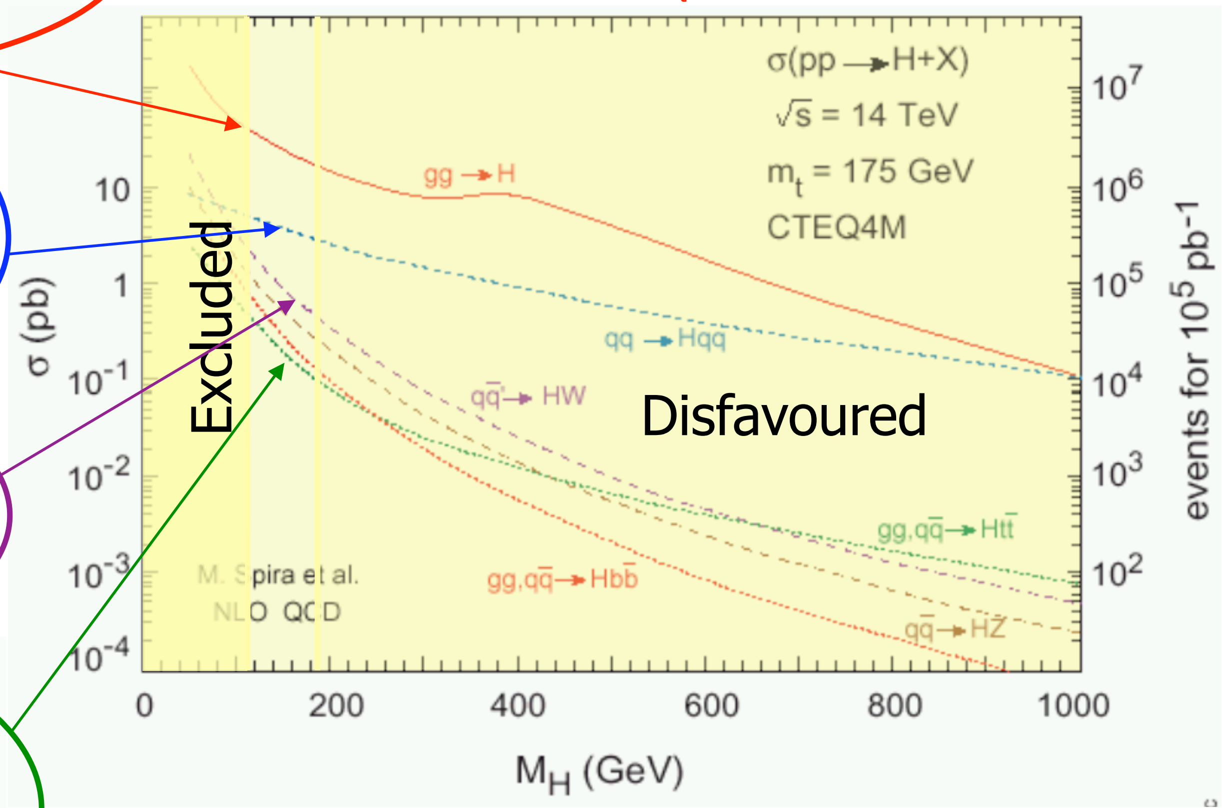
SM Higgs @ LHC

Production Modes and Cross-sections



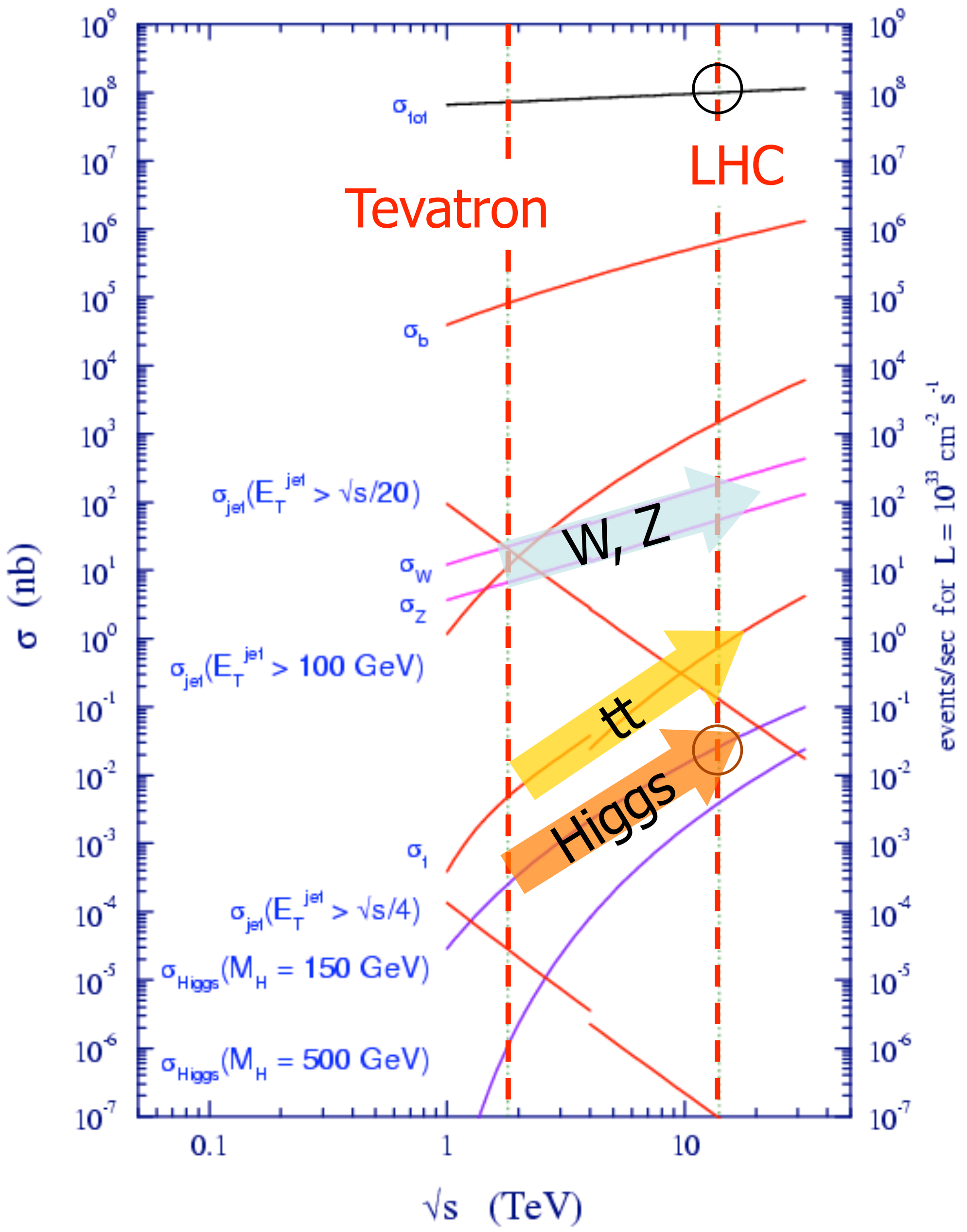
H^0 Production

CTEQ6M, M_t=175 GeV used for PTDR



BSM Physics can change these in a major way !!! (e.g. bbH in MSSM)

Evolution of the Cross-Sections



e.g. SM gg → H avec H → ZZ*, WW*

$\sigma \times BR \times \varepsilon_{acc.} \sim 50 \times$ Tevatron

Ratio of Higgs to EW cross-sections favorable !

Ratio of EW cross-sections to QCD favorable ! [background "candles"]

Relative increase of the t t background

e.g. H → ZZ* → 4l l=e,μ

$M_H = 150$ GeV/c^2

$\sigma_{H \to ZZ^*} \times BR \times \varepsilon_{acc.} \sim O(10)$ fb

$\sigma_{QCD} \sim 10^{14}$ fb

Need a "inhuman" reduction of 10^{13} !

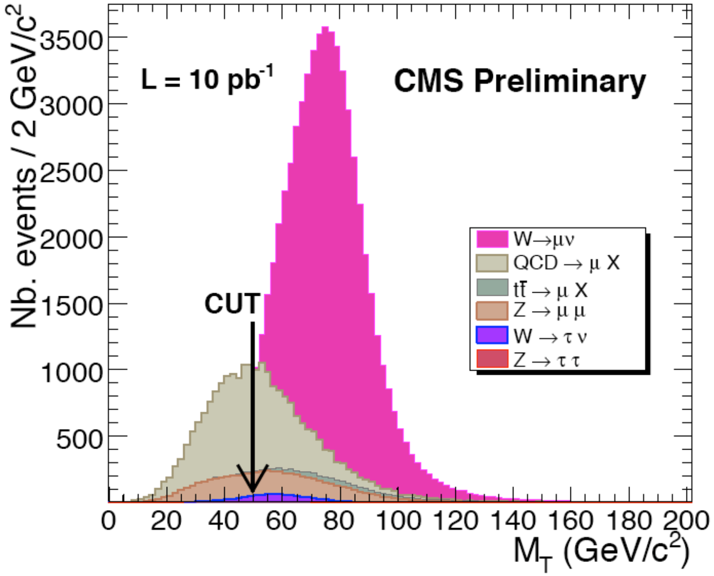
Higgs @ LHC ⇒ state of the art of "hadron collider" and "rare decay techniques"

SM Commissioning with First Data
10 pb^{-1}

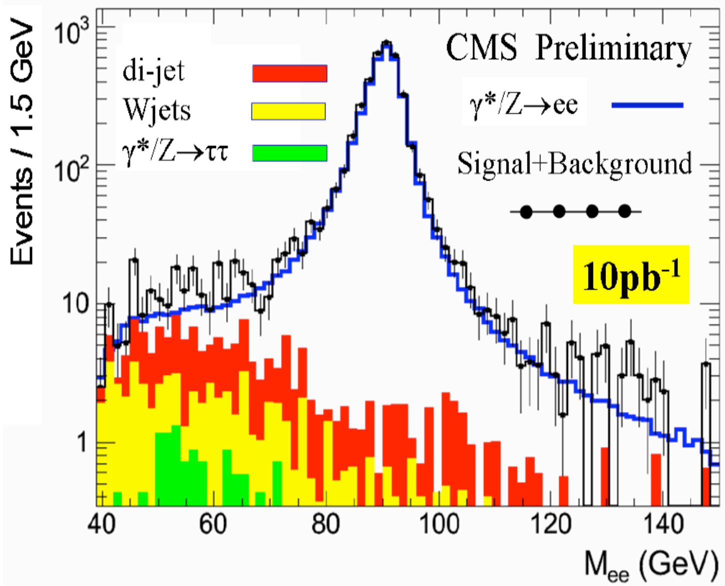
Monte Carlo

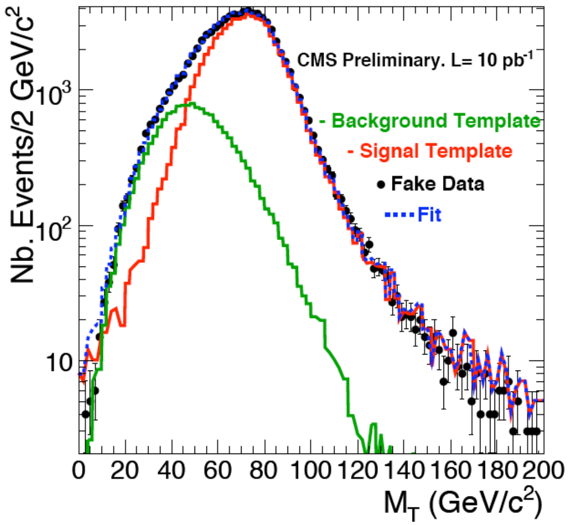
Polytechnique

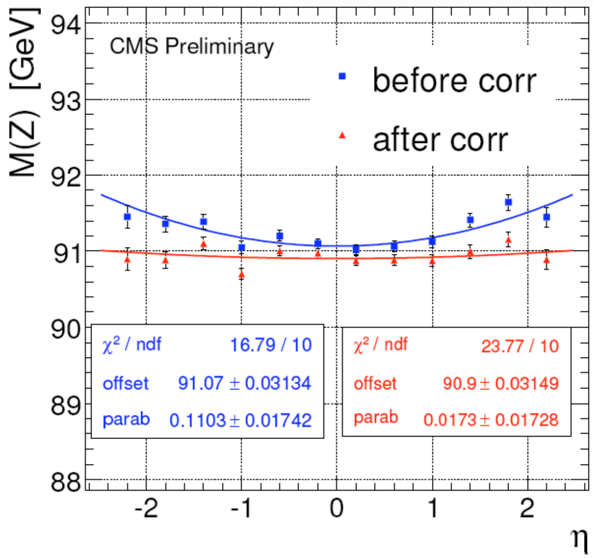
W



Z







Cross-section “Measurements”

$\sigma_W \times BR(W \to e\nu)$	19.97 ± 0.25 nb

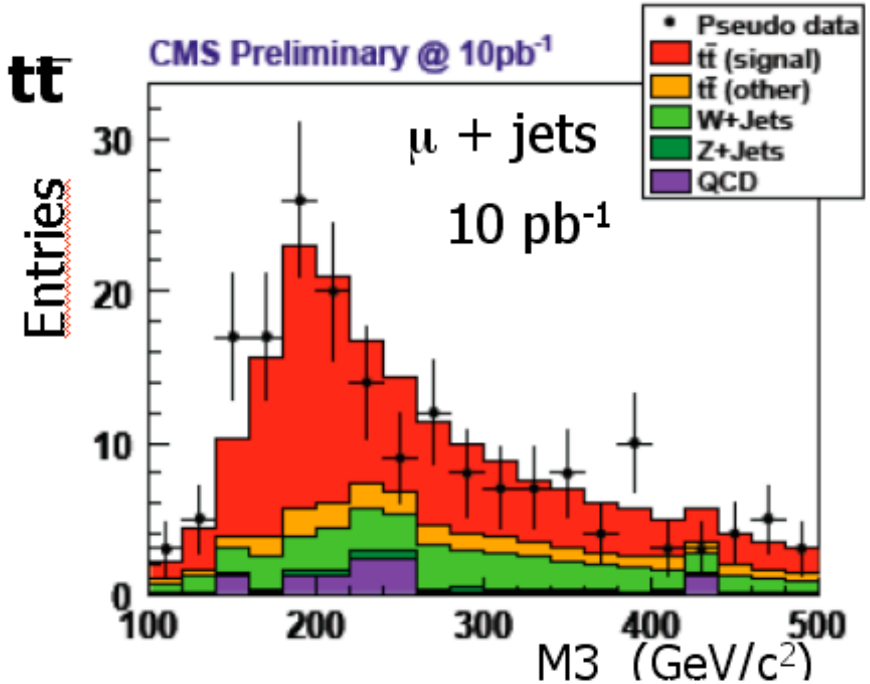
“SM expectation”: 19.78 nb

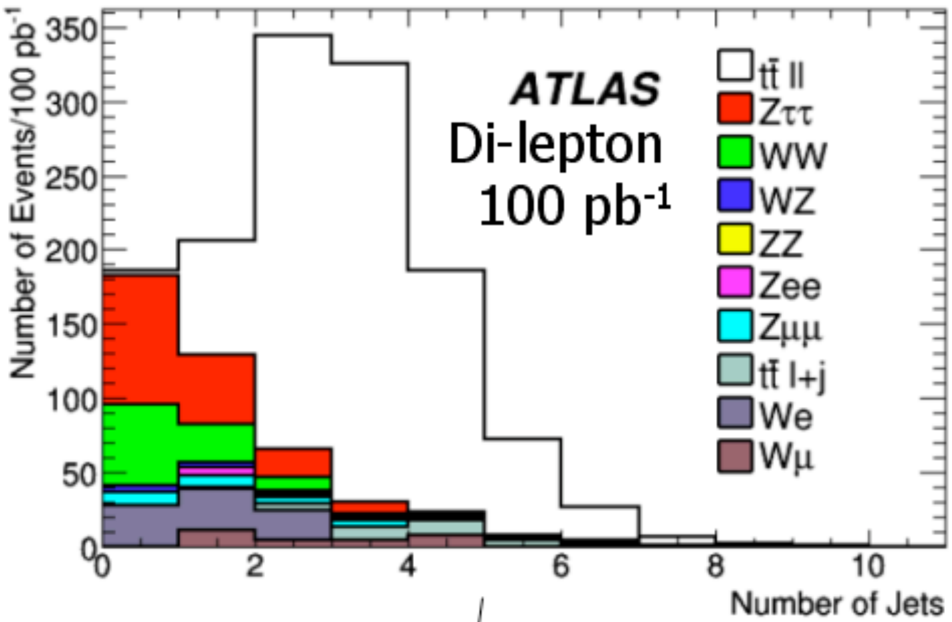
$\sigma_{Z/\gamma^*} \times BR(Z/\gamma^* \to e^+e^-)$	1775 ± 34 pb

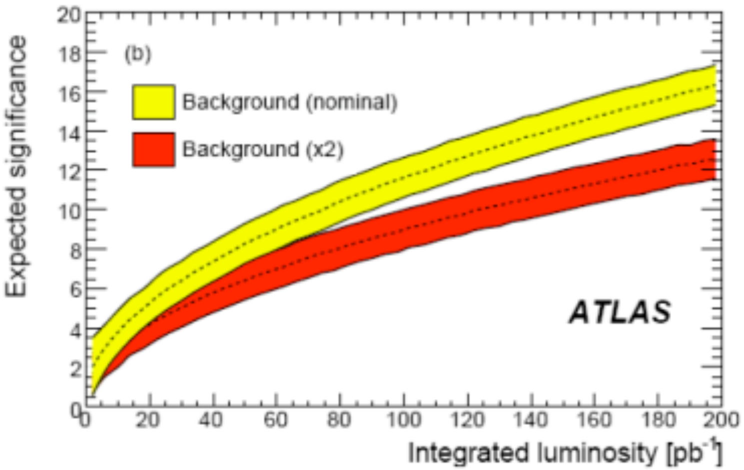
“SM expectation”: 1787 pb

SM Commissioning with First Data
10- 100 pb^{-1}

Monte Carlo







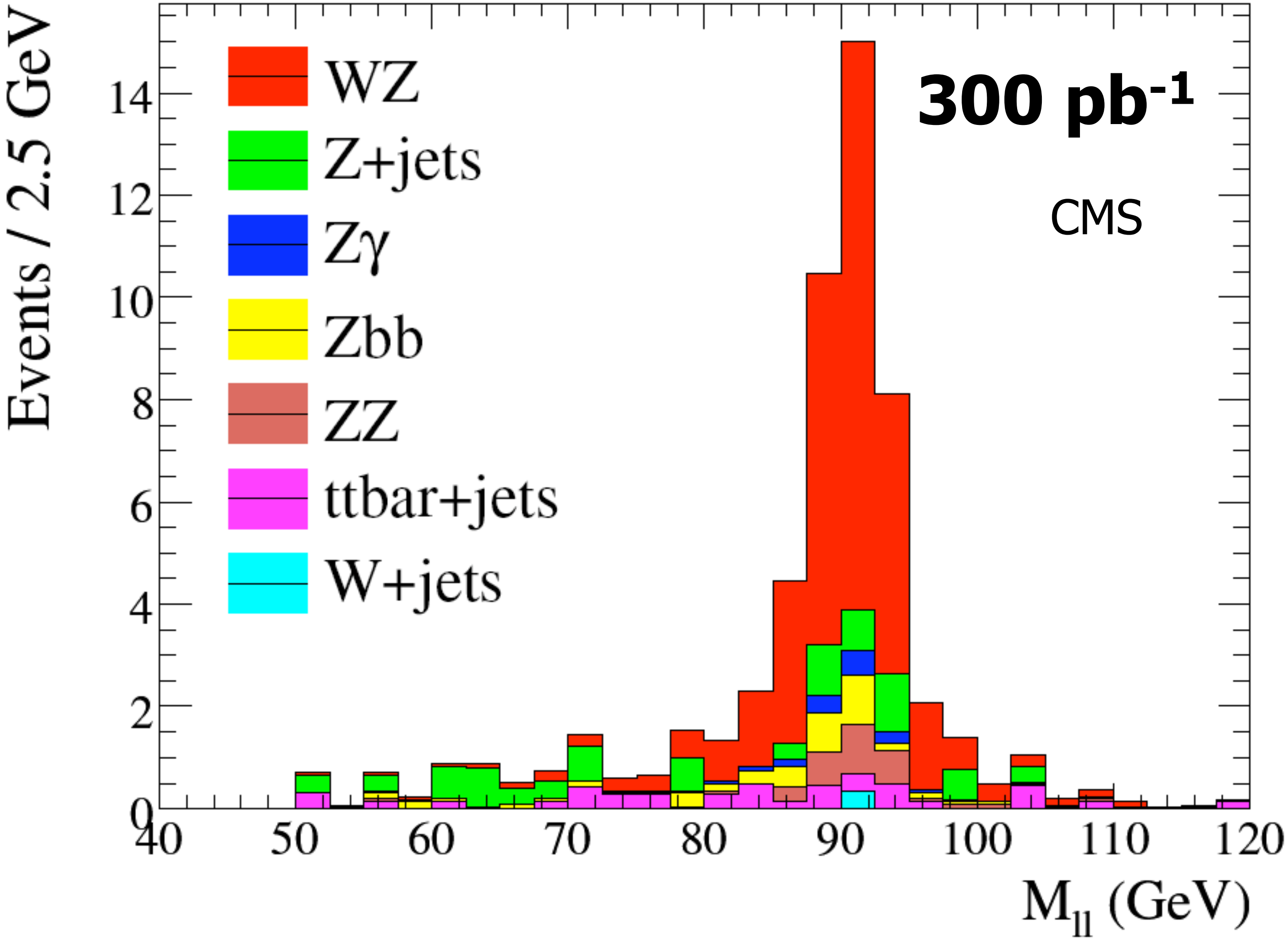
Expected Precision for the cross-section in the di-lepton channel for 100 pb^{-1}

$\Delta\sigma/\sigma$ = 4(stat) ± 4(syst) ± 2(pdf) ± 5(lumi) %

SM Commissioning with Early Data

Monte Carlo

WZ



Observability

Polytechnique

A. Djouadi, hep-ph/0503172

$M_H \leq 145$ GeV

$H \to b\bar{b}$

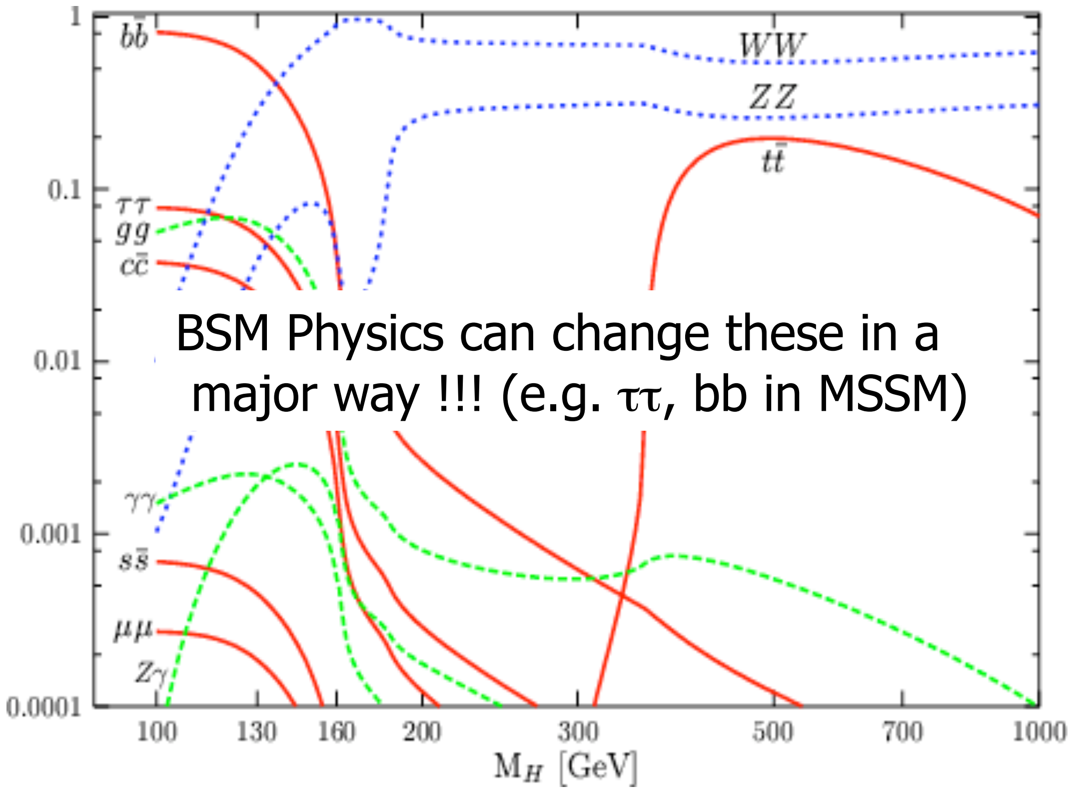
Dominant mode … but crippling QCD background … may be exploitable in the associated mode $H \to t\bar{t}$?

$H \to \tau^+\tau^-$

Exploitable at low M_H in the VBF production mode

$H \to \gamma\gamma$

Complementary mode at low M_H via loop diagrams, low *BR* but excellent γ/Jet (γ ID, γ Iso., $M_{\gamma\gamma}$) separation



BSM Physics can change these in a major way !!! (e.g. $\tau\tau$, bb in MSSM)

$M_H > 125$ GeV

$H \to WW^{(*)}$

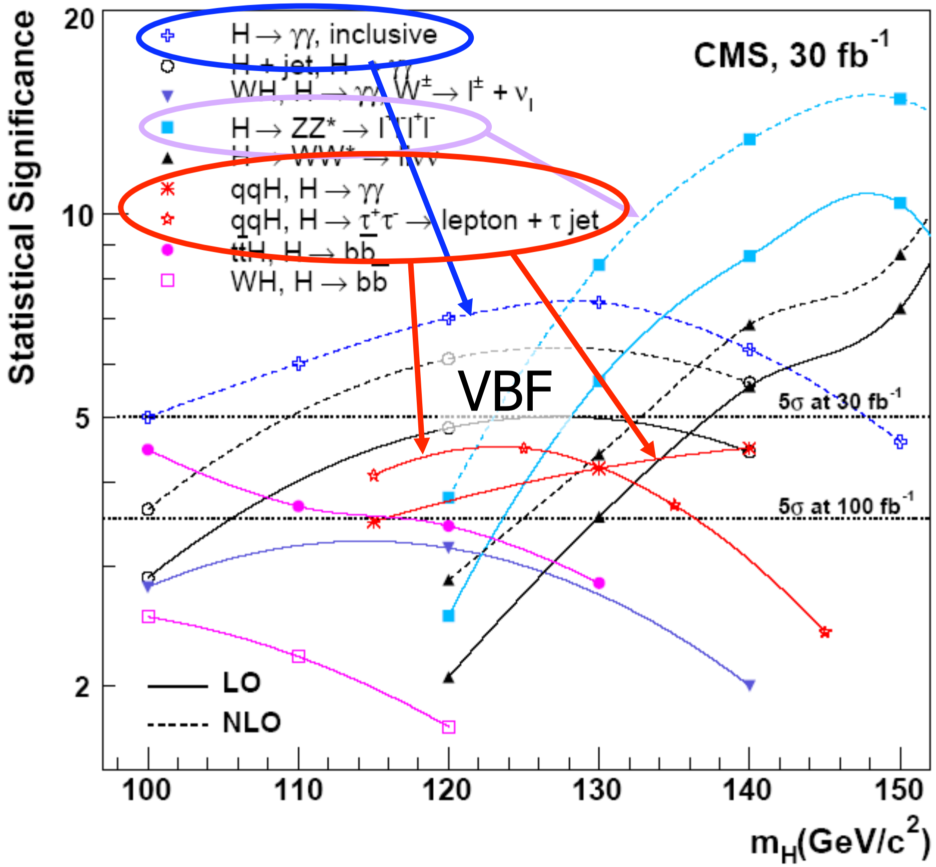
Dominant mode, $l^+\nu l^-\bar{\nu}$ channel optimal for $M_H = 2\, M_W$; $l^+\nu qq'$ channel exploitable at large MH or through VBF

$H \to ZZ^{(*)}$

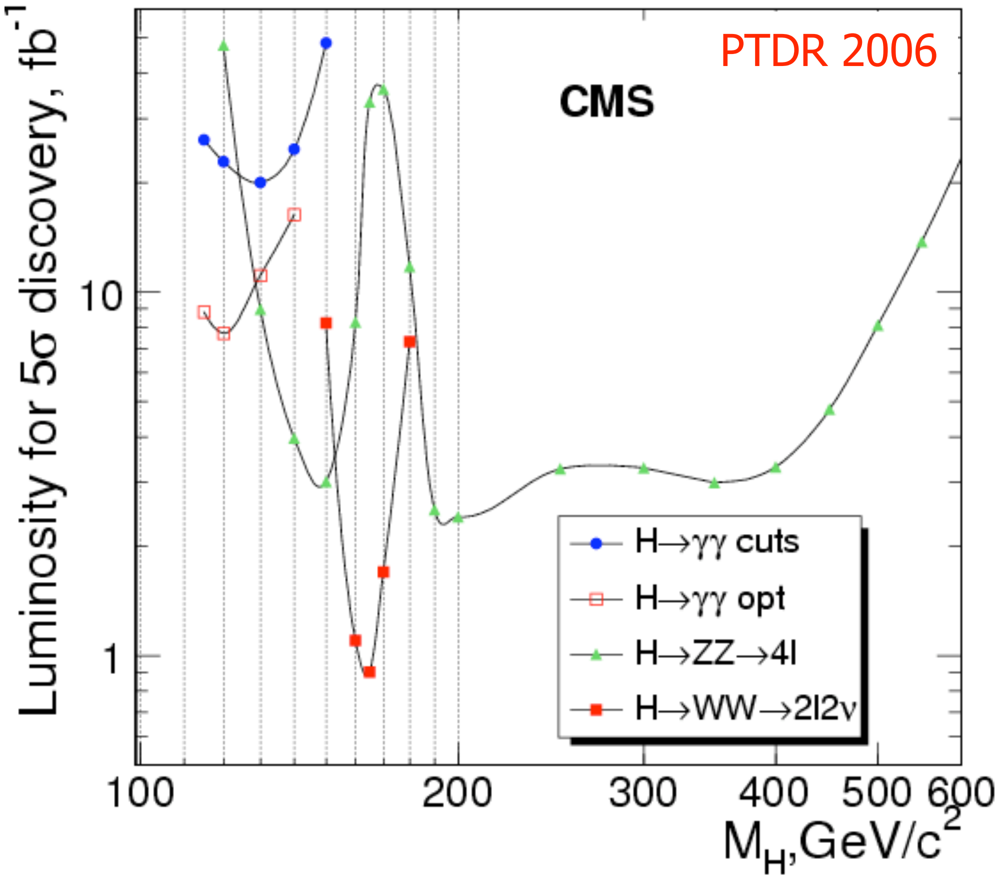
Small *BR* but "golden mode" for a discovery $l^+l^-\, l^+\, l^-$

e.g. Discovery Reach (Overview)

Polytechnique

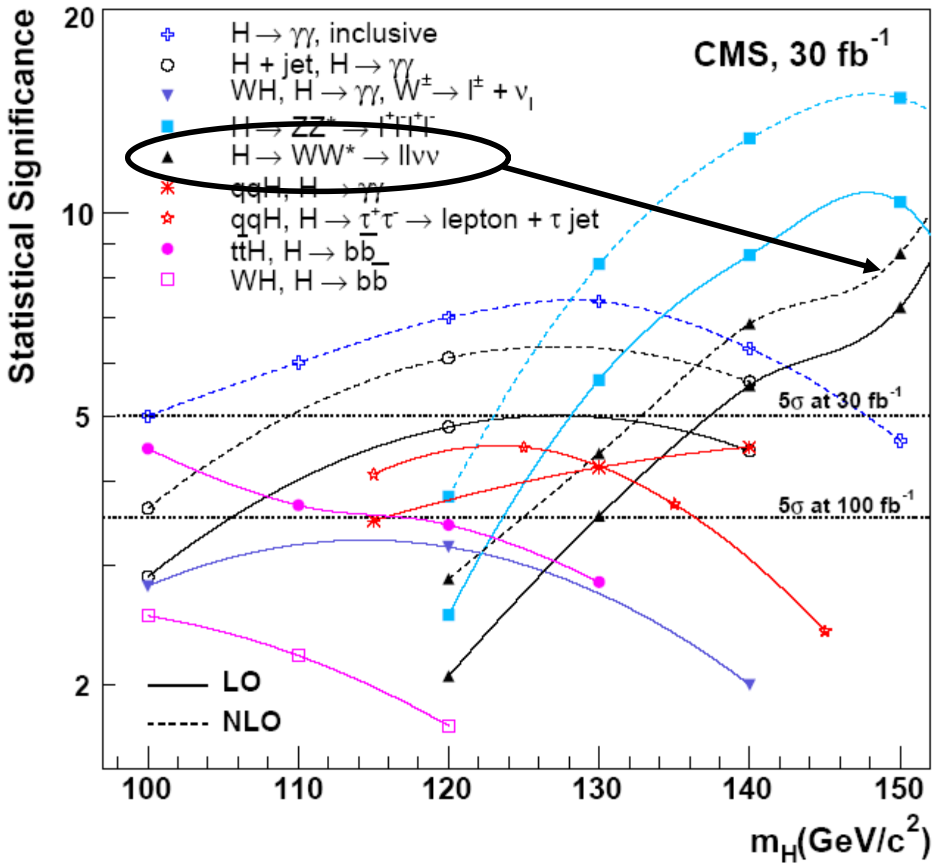


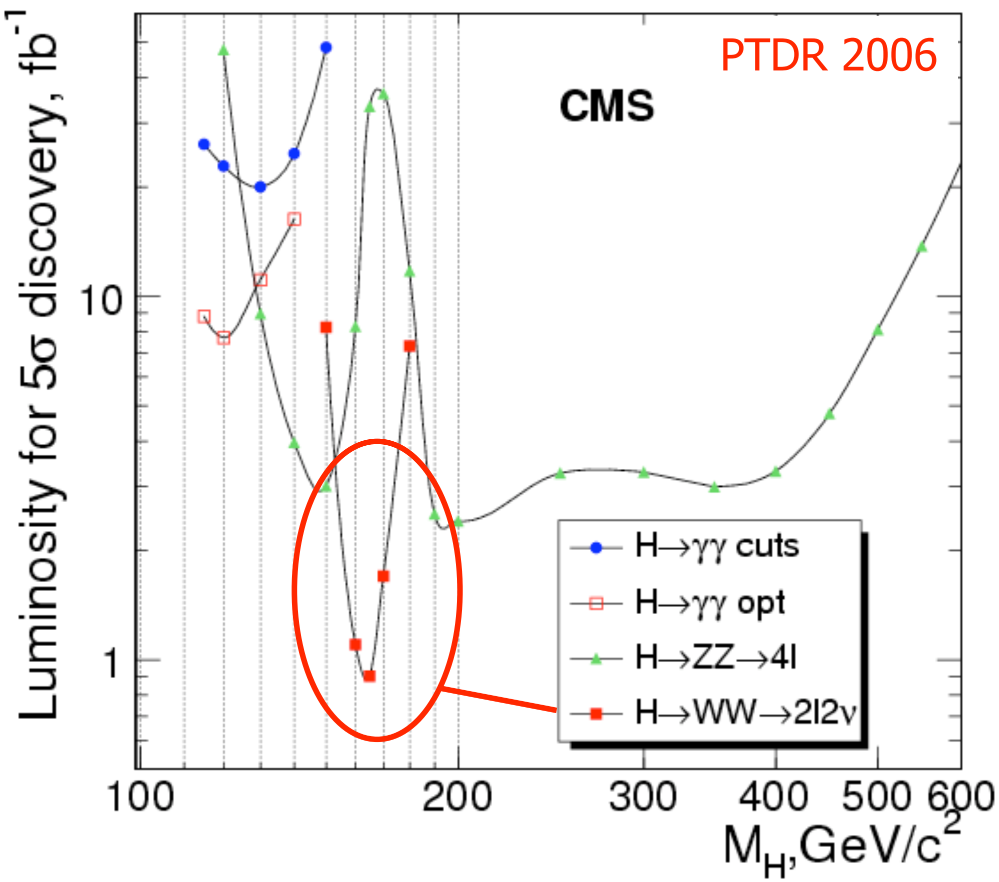
Inclusive Channels:



e.g. Discovery Reach (Overview)

Inclusive Channels:

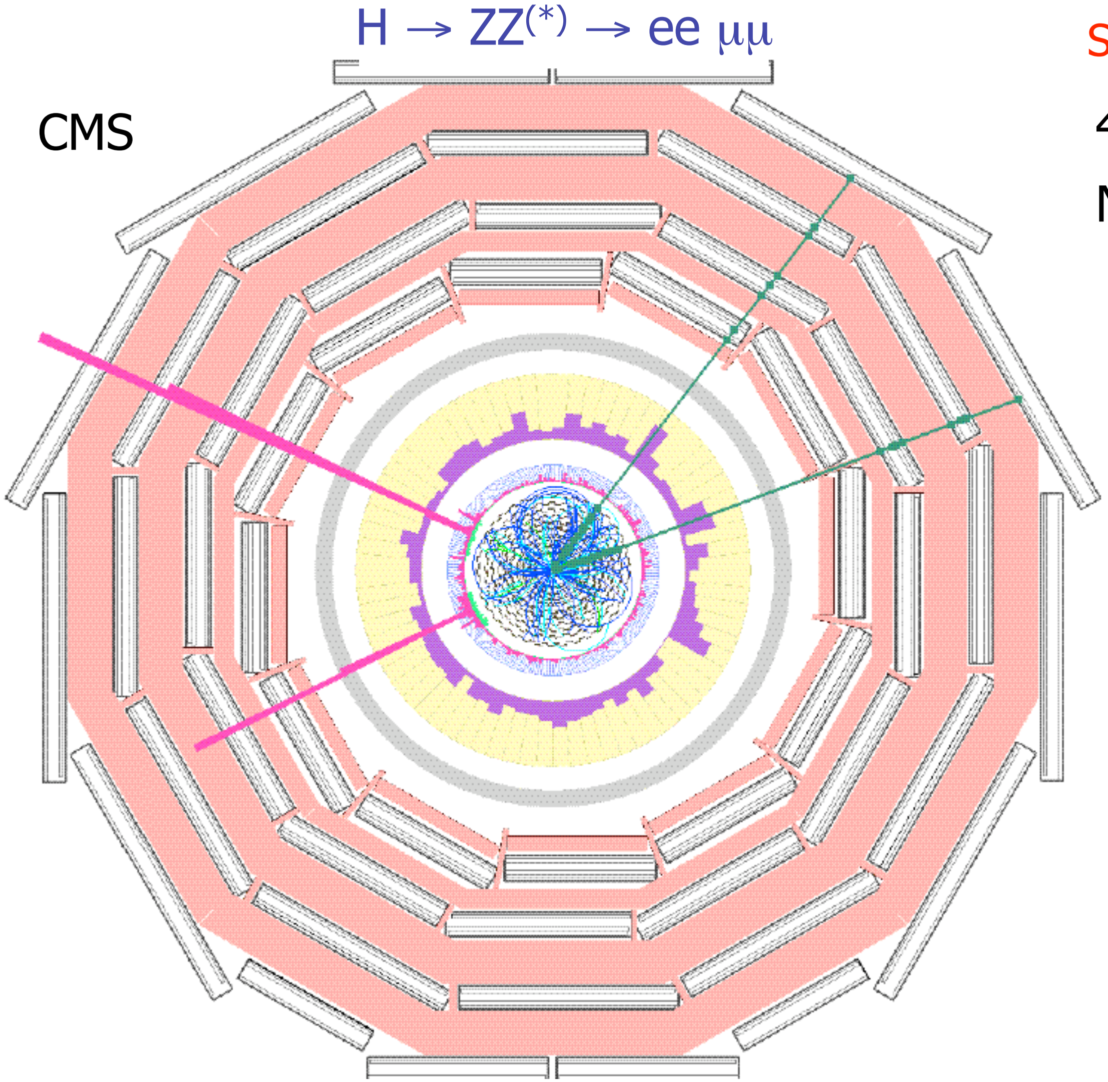




The ``Golden Mode'' : $H \rightarrow 4l$

Inclusive Modes

Polytechnique



Signal:

$4e$, 4μ, $2e2\mu$ (2x)

Narrow resonance, low background

Background:

Reducible: $t\bar{t}$, $Zb\bar{b}$
Irreducible: continuum $ZZ^{(*)}$

Selection:

4 isolated emerging from primary vertex
2 pairs of matching flavours and opposite signs

caution: ε^4
Beware of lepton efficiency at very low P_T !!!

$H \rightarrow ZZ^* \rightarrow 4l$

Polytechnique

Clear signal with M_H resonance as most significant observable
[also sensitivity to SCP quantum numbers via angular distributions]

Main experimental challenge:
Preserve highest possible signal detection efficiency (given very low $\sigma \times \beta$)
$\Leftrightarrow$ High efficiency for isolated and identified low PT leptons ($\propto \varepsilon^4$!)

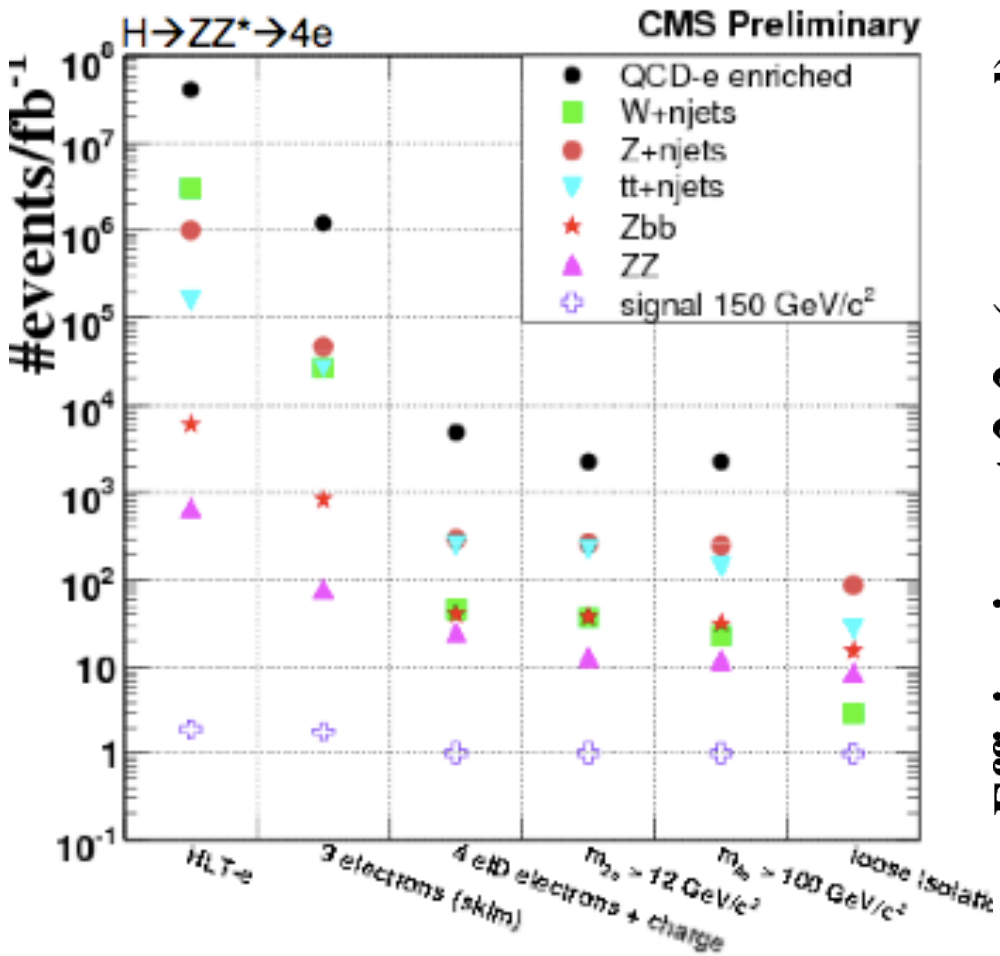
Dedicated strategy for the suppression of fake background
[and the control of systematics]

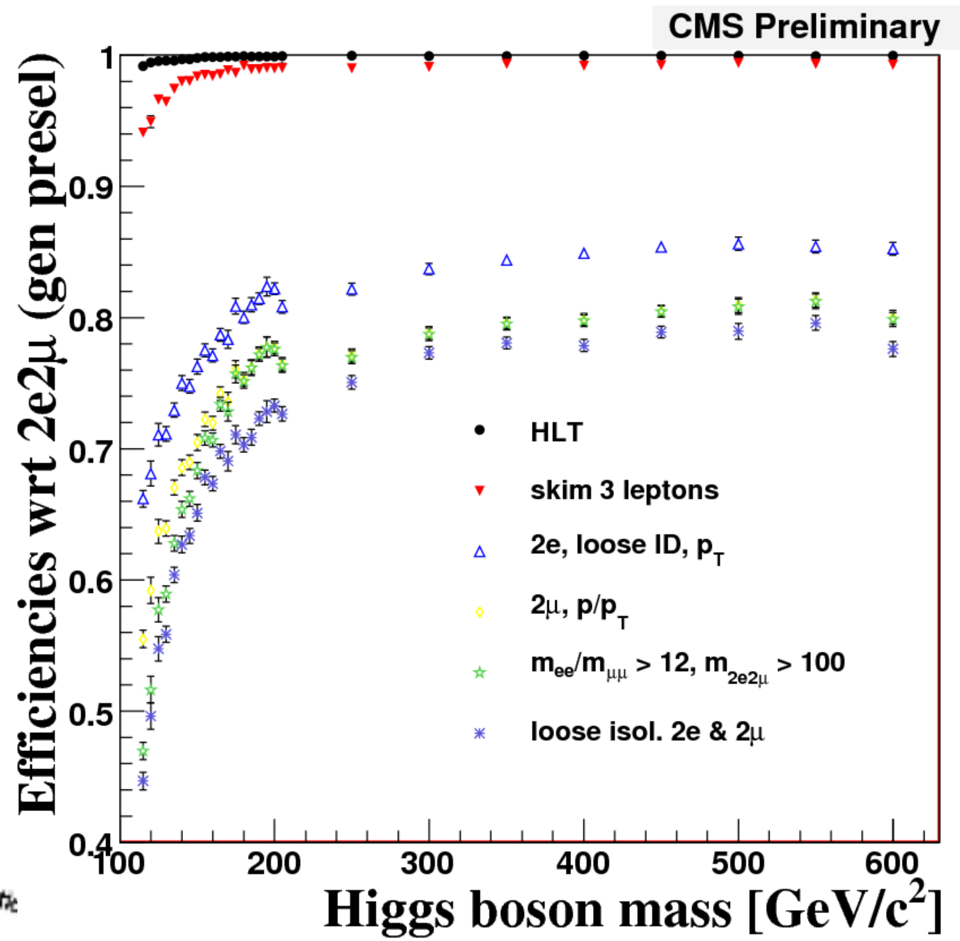
Background sources:	Experimental tools:
QCD multijets / Z + jets	Multileptons, loose ID and Iso. matching pairs (flavour and signs)
$Zb\bar{b}$, $t\bar{t}$ (WbWb)	Tigher iso. and vertex requirements on « b » legs (sources of fake primary leptons);
$ZZ^{(*)}$ continuum	ZZ observation and measurement of $d\sigma/dM_{4l}$ lineshape Normalisation to single Z for early discovery $\sigma_{syst} \sim 8\%$ $R = (\sigma_{ZZ\rightarrow 4e} * \varepsilon_{4e} * \int Ldt) / (\sigma_{Z\rightarrow 2e} * \varepsilon_{2e} * \int Ldt)$

H → ZZ* → 4l

Data Reduction

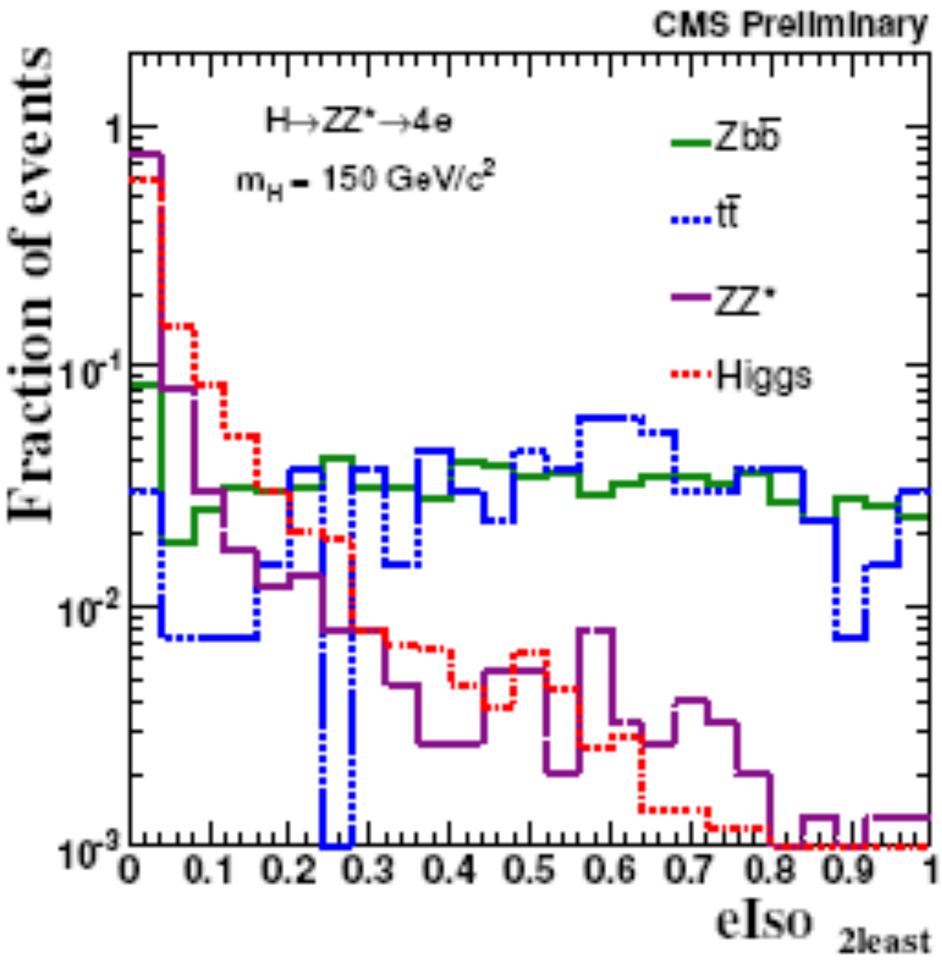
Polytechnique

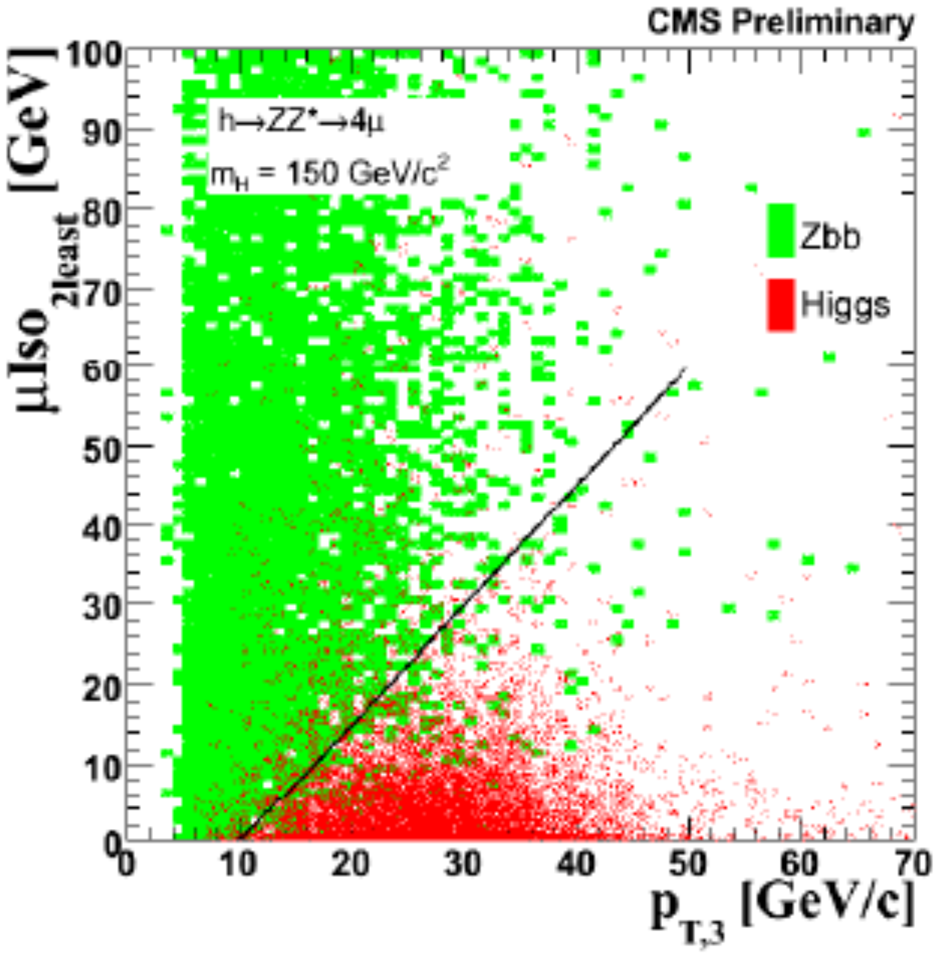




$H \rightarrow ZZ^* \rightarrow 4l$

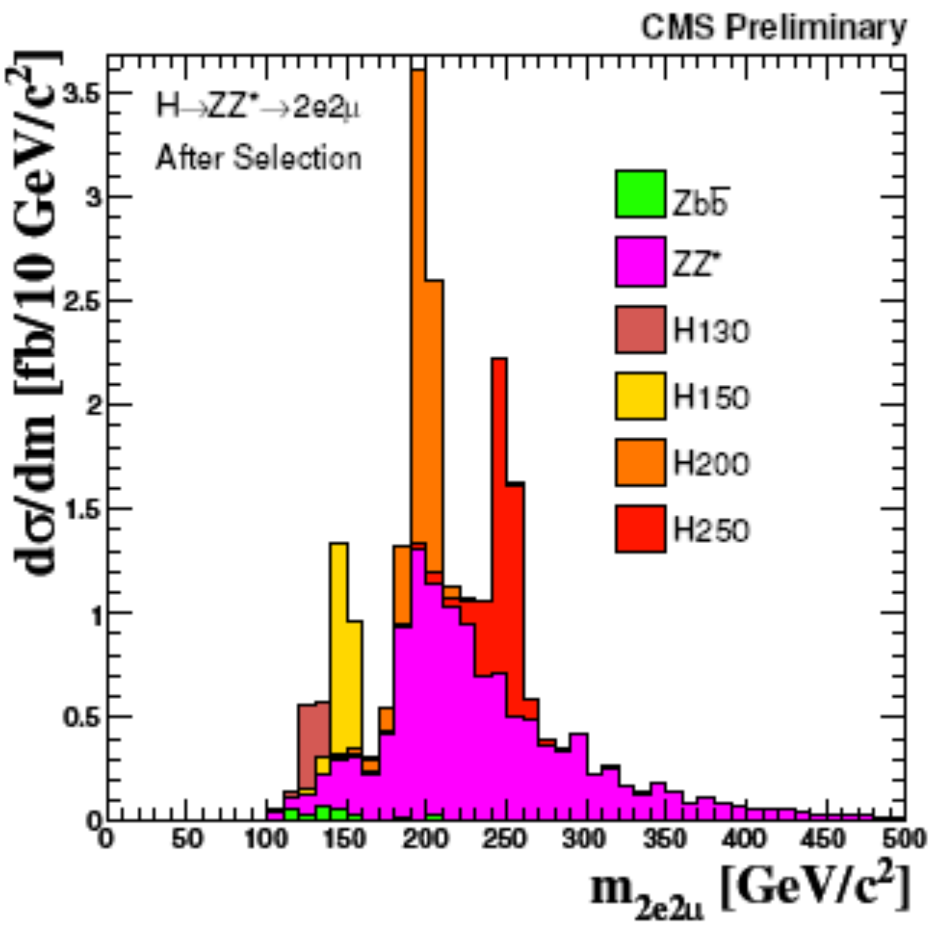
Event Selection

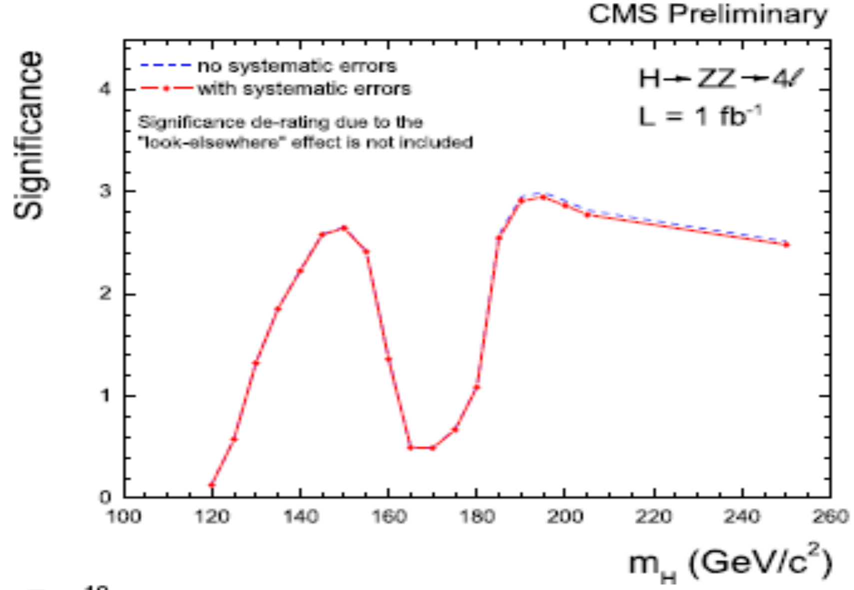


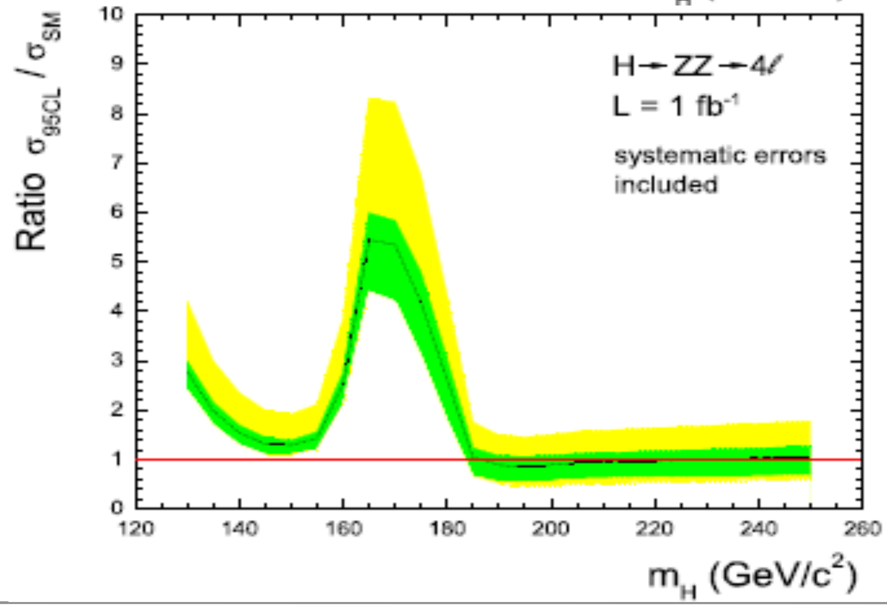


H → ZZ* → 4l

Results

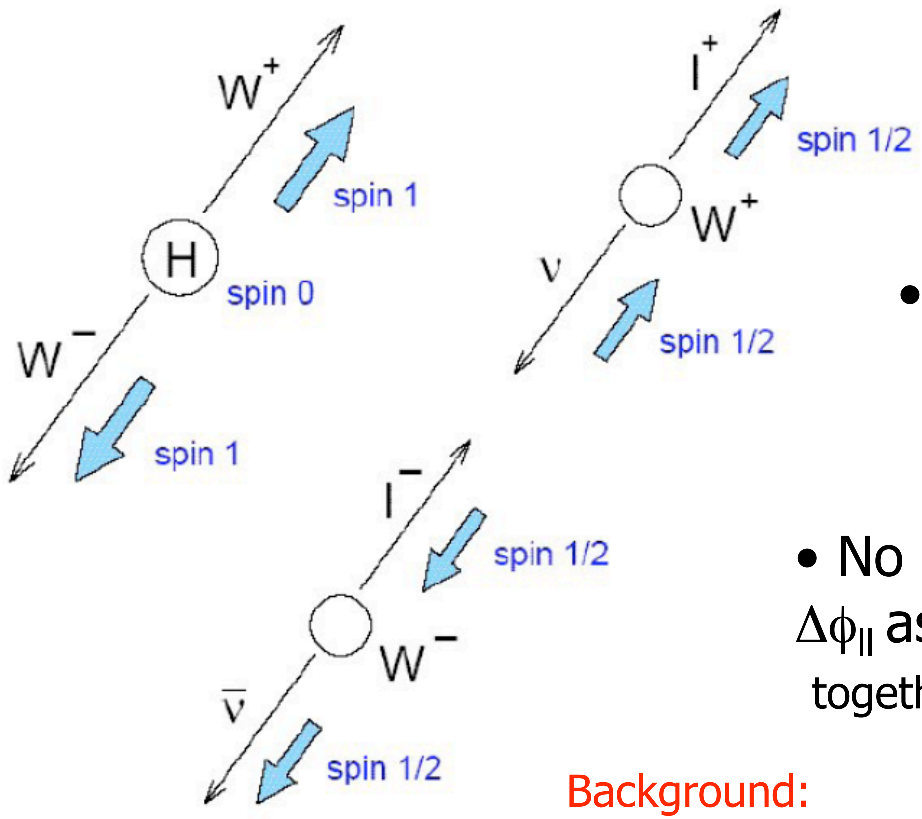






$H \rightarrow WW^{(*)} \rightarrow 2l2\nu$

Inclusive Modes



- SM Higgs can be discovered or excluded via $H \rightarrow WW^*$ over a wide mass range

- Best channel for early discovery at $M_H \sim 2M_W$
  [M_H ~ 165 GeV excluded at Tevatron 95% CL]

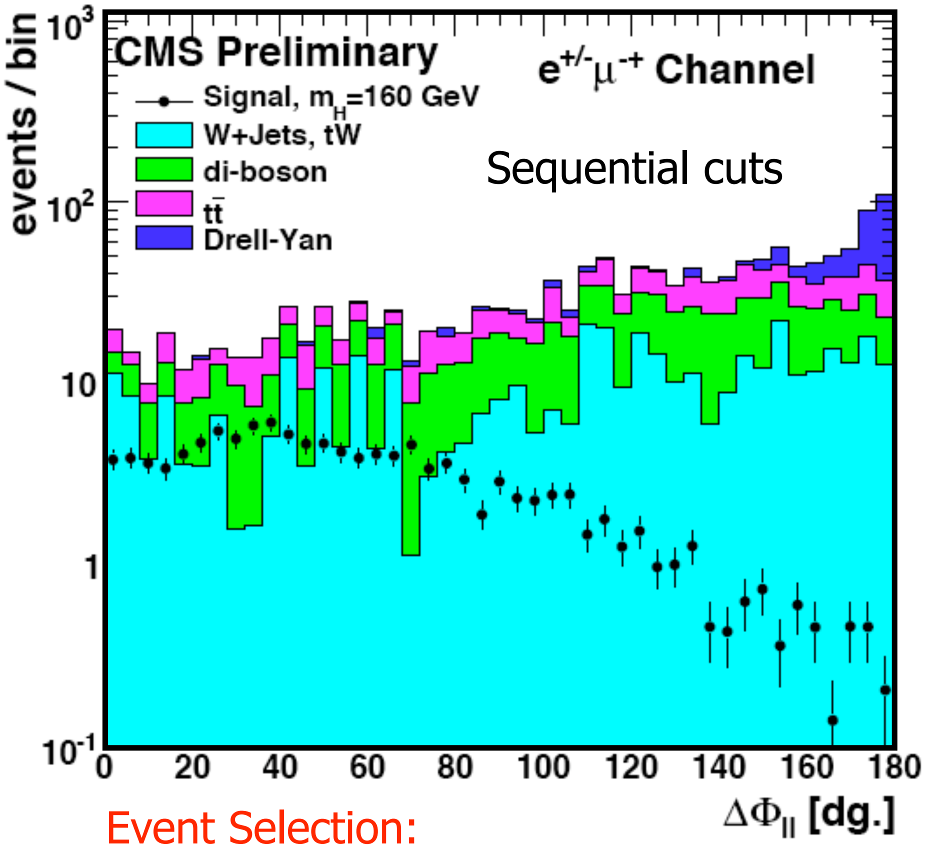
- No observable resonance peak
  $\Delta\phi_{ll}$ as most significant observable
  together with $M_{\perp}^{ll}$

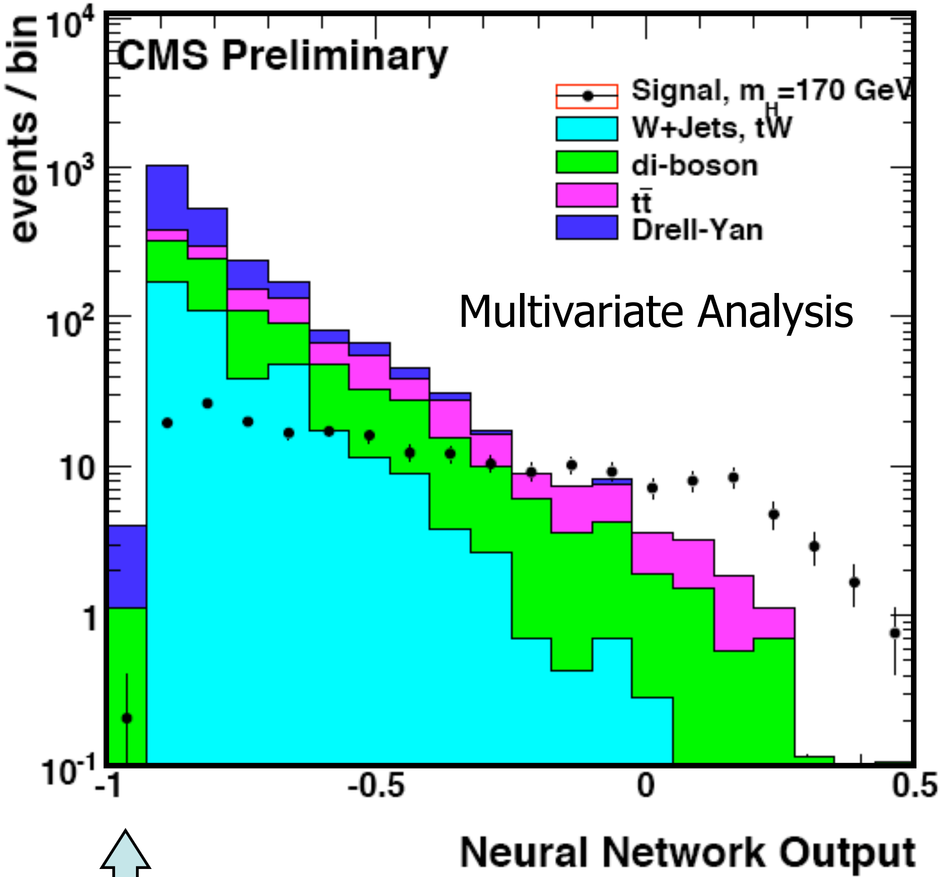
Background:		M_H=160	WW*¨Cont.	tt
	σ_{NLO}	2.3 pb	114 pb	840 pb

Reducible tt, Wbt, W+jet(s) with fake leptons
Irreducible WW* continuum

Main challenge: data-driven control of background systematics

$H \to WW^{(*)} \to 2l2\nu$





Event Selection:

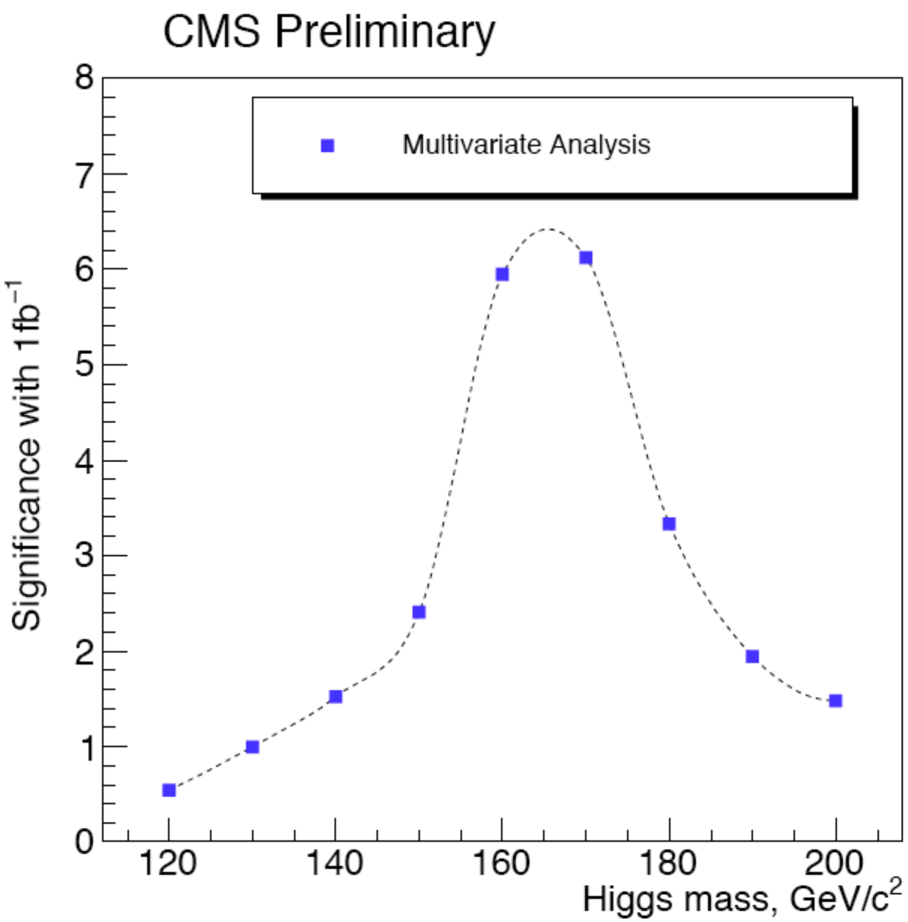
2 iso. leptons ± at high enough PT
mid-range E_t^{miss}, Max M_{ll}
Central jet veto
Small $\Delta\phi_{ll}$ (e.g. $\Delta\phi_{ll} < 45°$)

Better exploit correlations and multi-dimensional space of discriminating observables

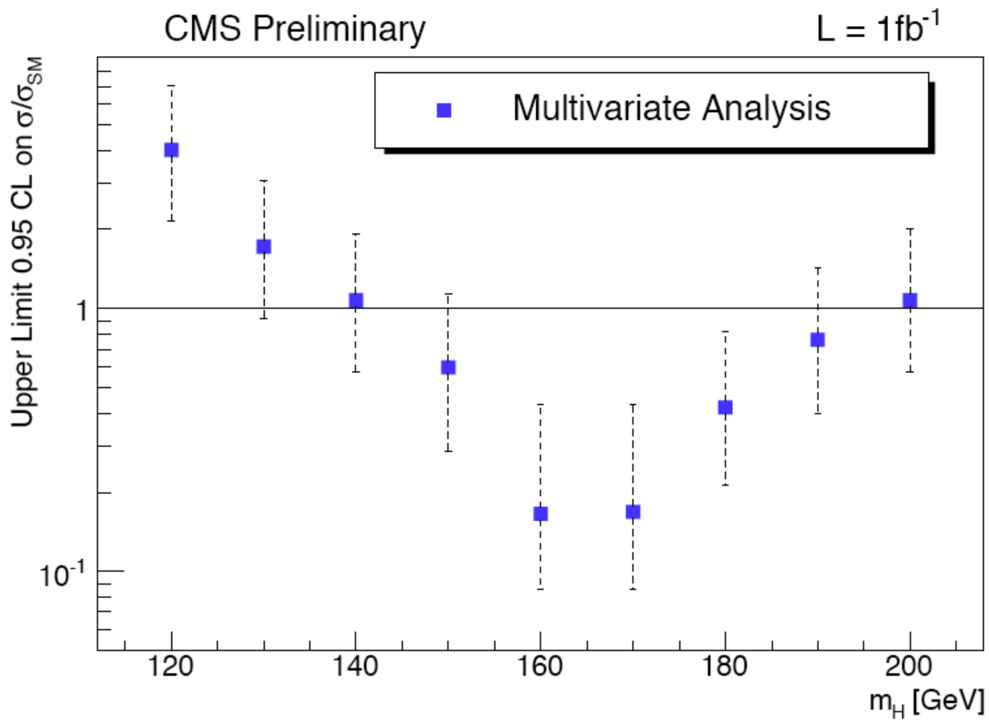
$H \to WW^{(*)} \to 2l2\nu$

Results

Discover ?



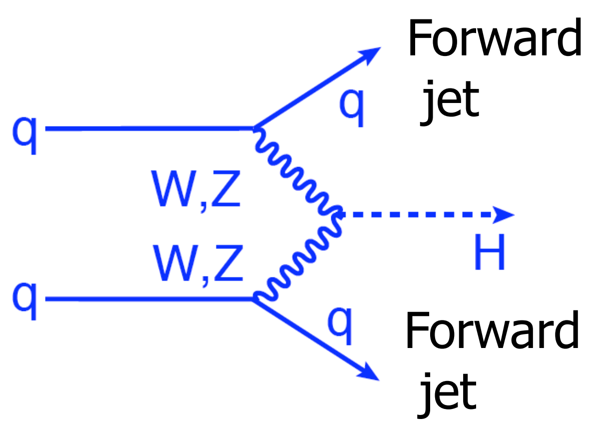
Exclude ?

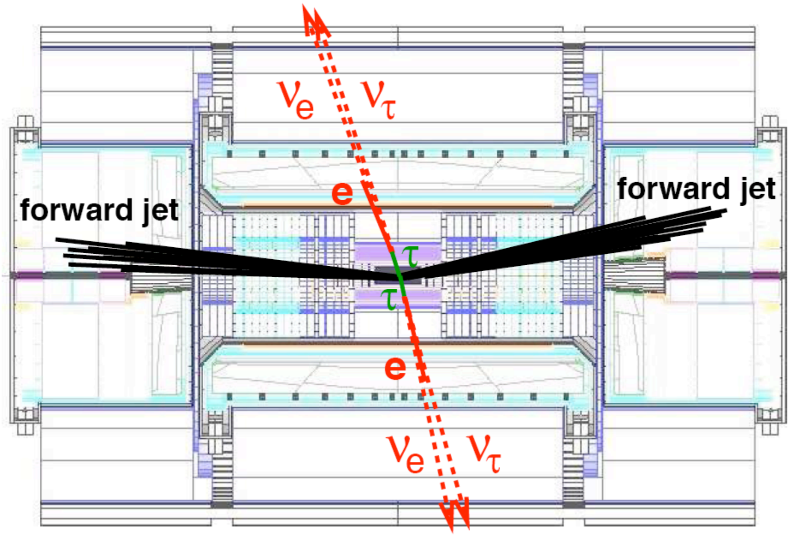


Vector Boson Fusion (VBF)

Polytechnique

Zeppenfeld et Rainwater (1997)





Forward (quark) jet tags + jet veto in central region)
Higgs boson decay products in central region (trigger)
Higgs boson gets a P_T kick ⇒ τ's generally not back-to-back

Modes studied

qq (V V*) → qq'H;

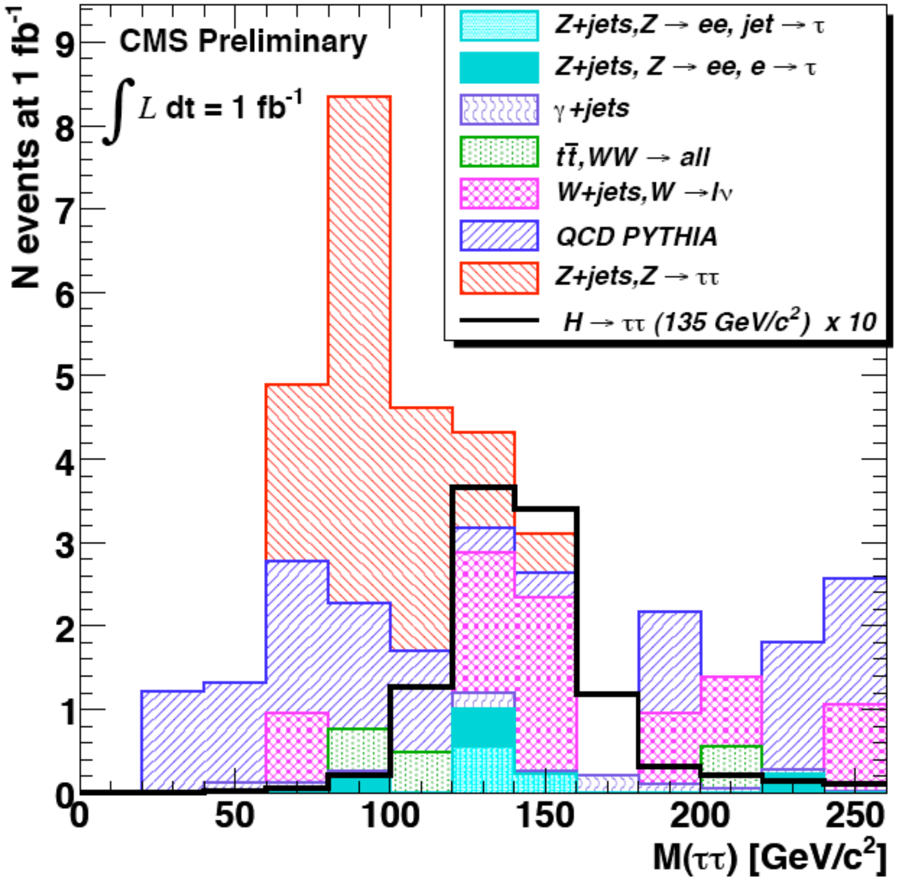
H → $\tau^+\tau^-$ → ($l^+\nu$☒ν) (l^- ν☒ν)

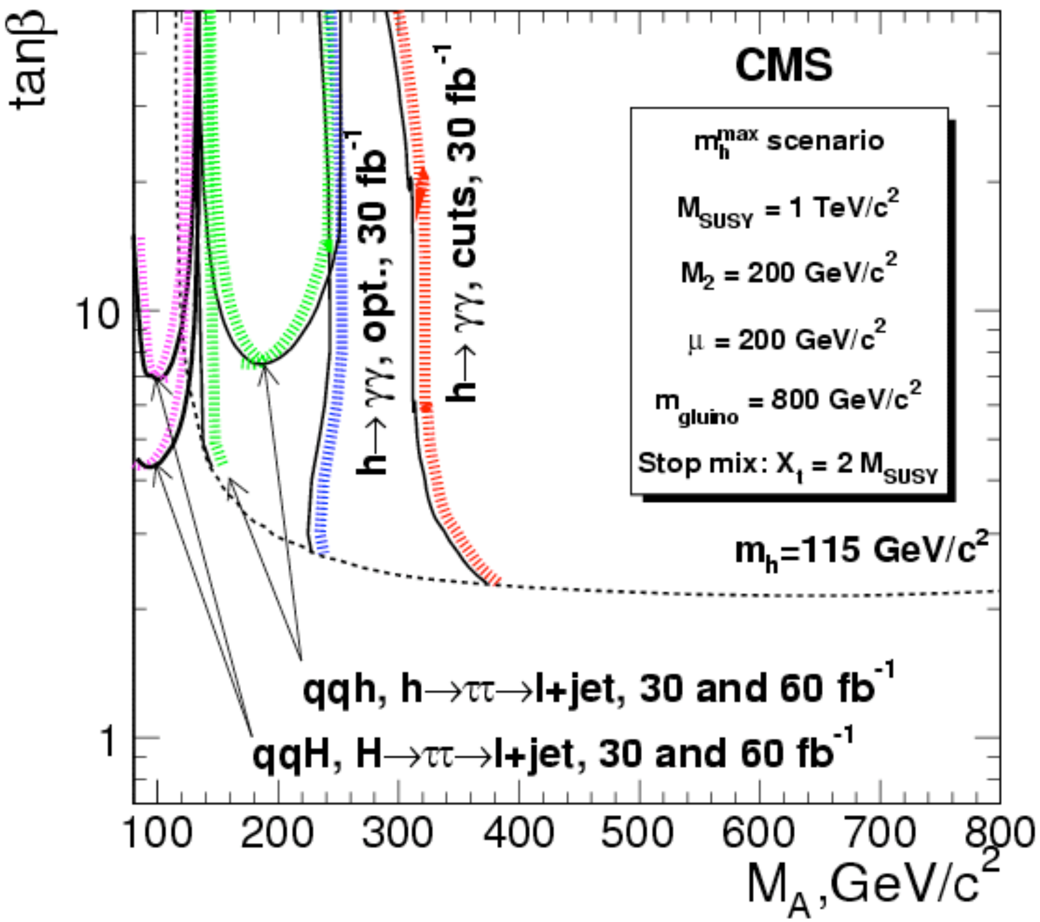
→ ($l^+\nu$☒ν) (jet ν)

$M_{\tau\tau}$: possible via e.g. collinear approx., i.e. assuming all τ decay productes aligned with τ (best if τ's are not themselves acollinear)
$M_{\tau\tau}$ resolution depends on E_T^{miss}

Best with particle flow techniques

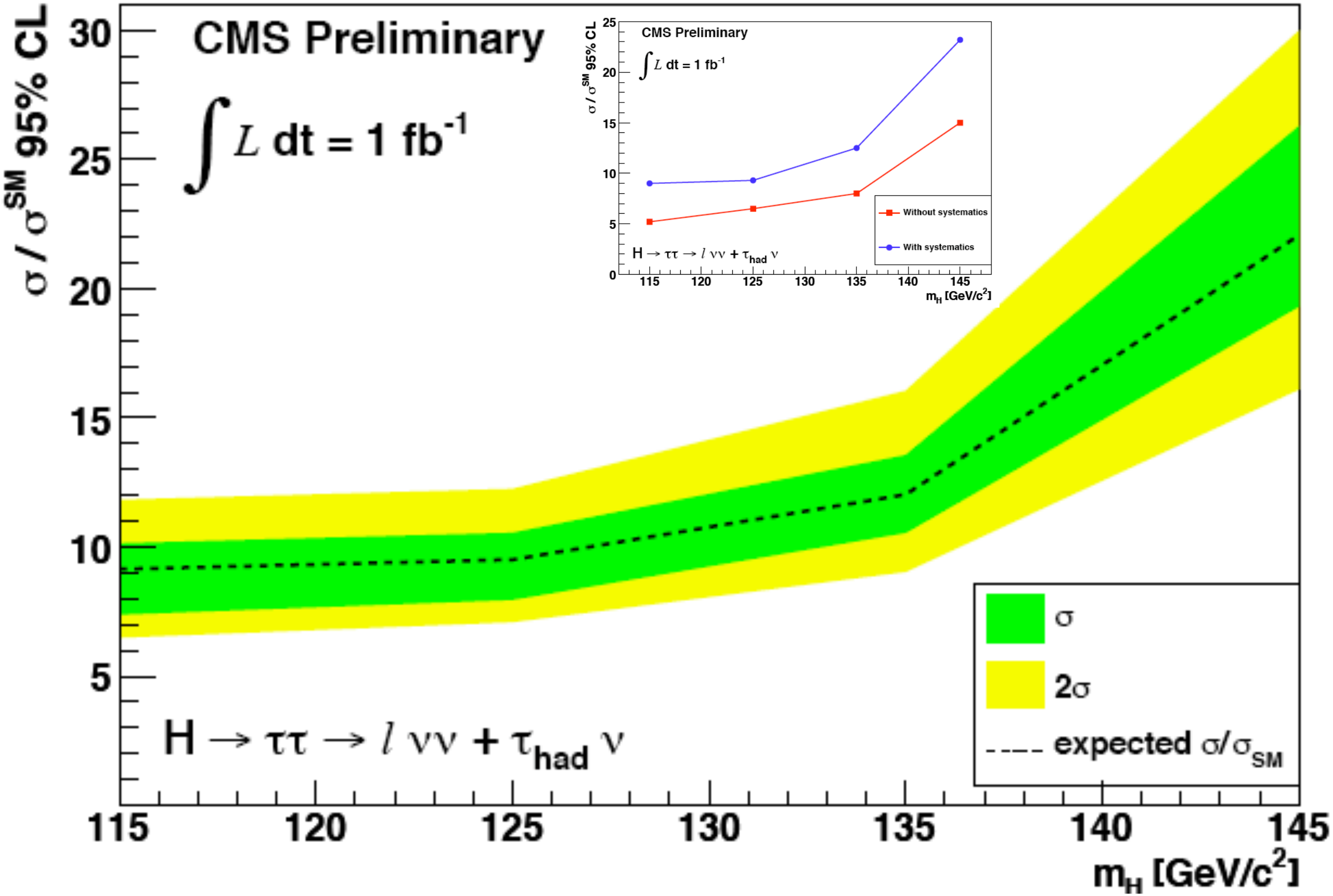
VBF H → 2tau


CMS Preliminary
∫ L dt = 1 fb-1
N events at 1 fb-1
Z+jets,Z → ee, jet → τ
Z+jets, Z → ee, e → τ
γ +jets
tt̄,WW → all
W+jets,W → lν
QCD PYTHIA
Z+jets,Z → ττ
H → ττ (135 GeV/c2) x 10
M(ττ) [GeV/c2]


tanβ
CMS
mhmax scenario
MSUSY = 1 TeV/c2
M2 = 200 GeV/c2
μ = 200 GeV/c2
mgluino = 800 GeV/c2
Stop mix: Xt = 2 MSUSY
h→ γγ, opt., 30 fb-1
h→ γγ, cuts, 30 fb-1
mh=115 GeV/c2
qqh, h→ττ→l+jet, 30 and 60 fb-1
qqH, H→ττ→l+jet, 30 and 60 fb-1
MA,GeV/c2

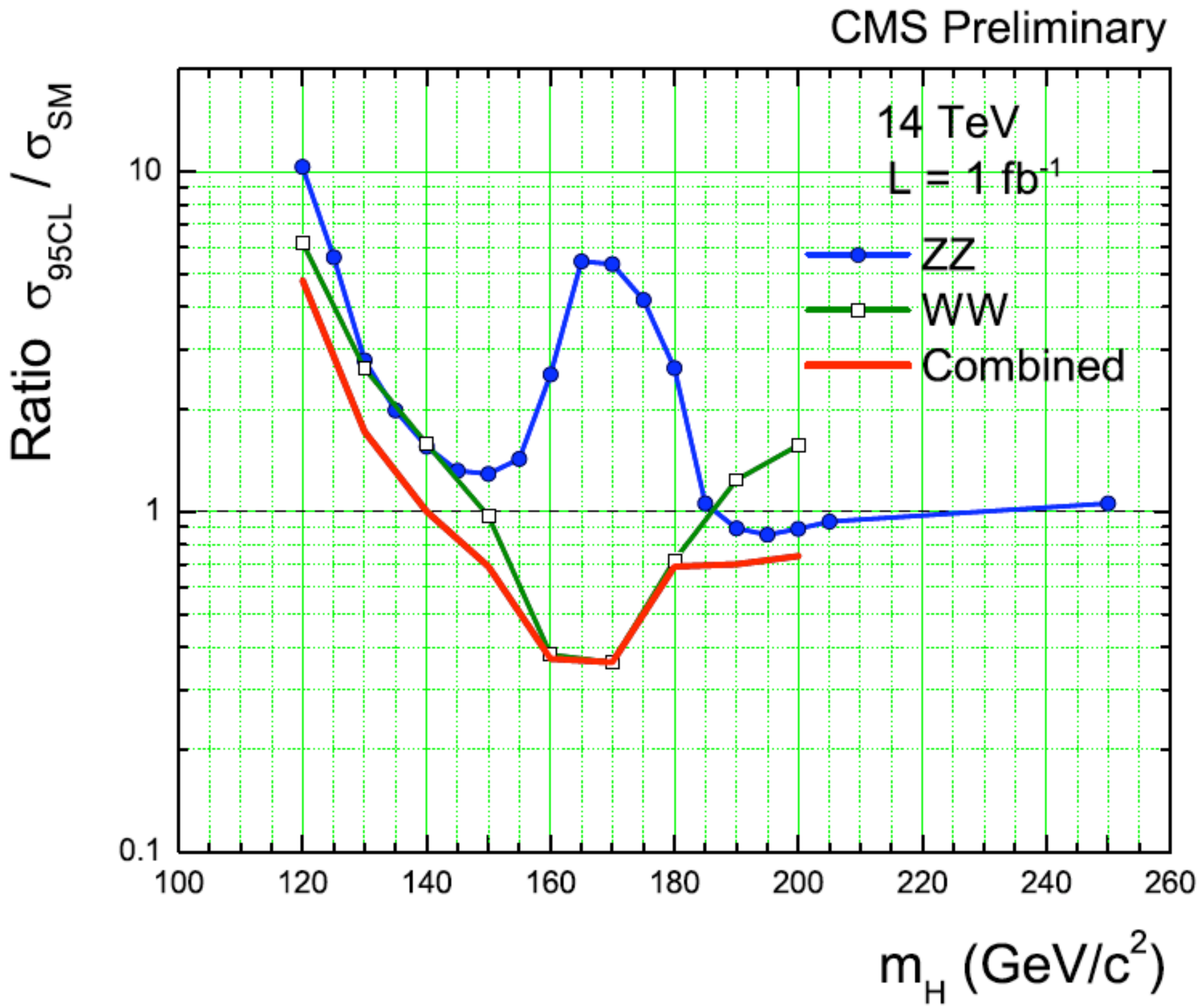
VBF H → 2tau

Exclusion Limits



Expected Reach for the SM Higgs

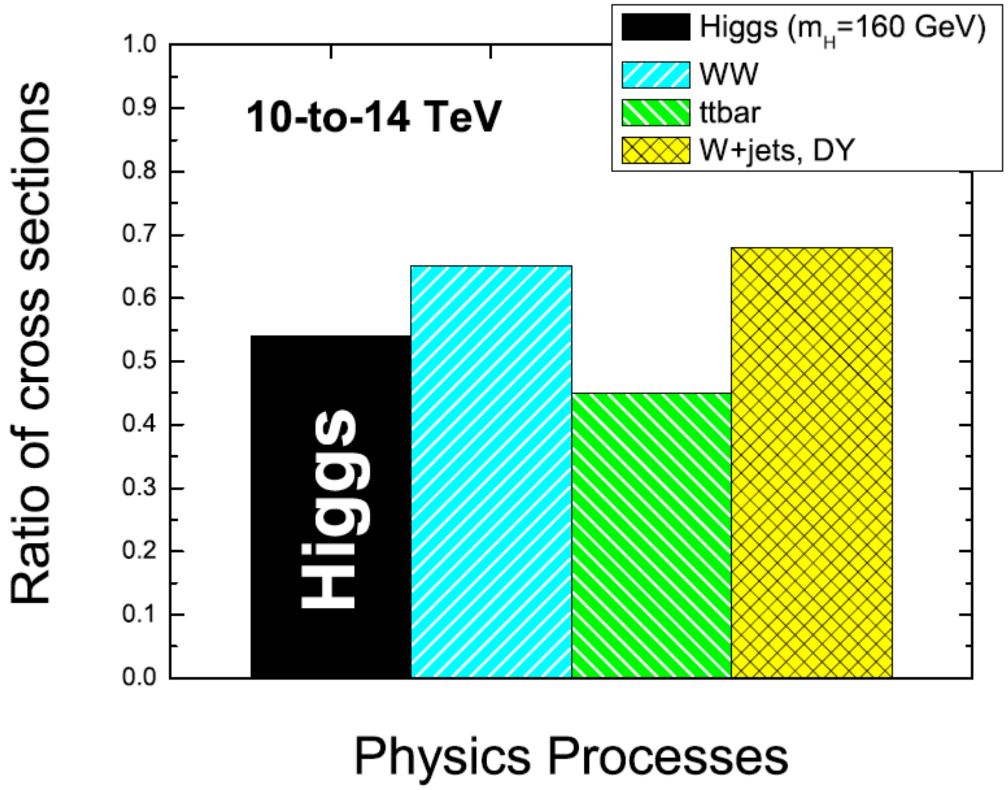
Intermediate Mass Range

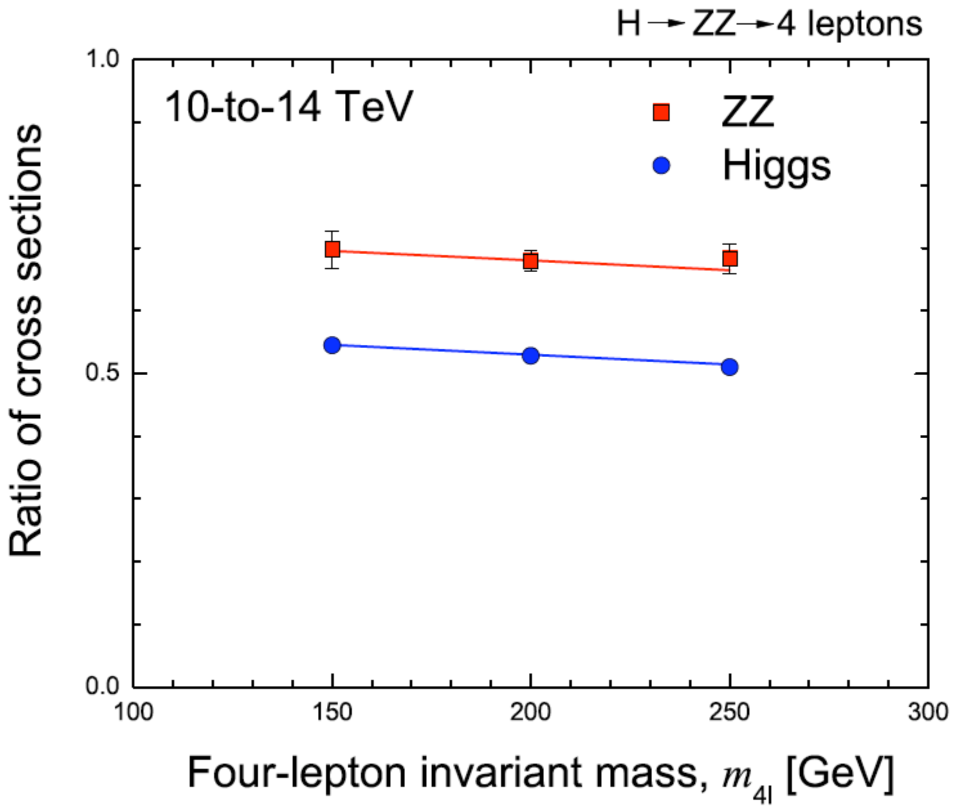


NOTE;
Expect on average 3 to 4 signal events at M_H ~ 150 GeV for < 0.5 event of background in peak region !!

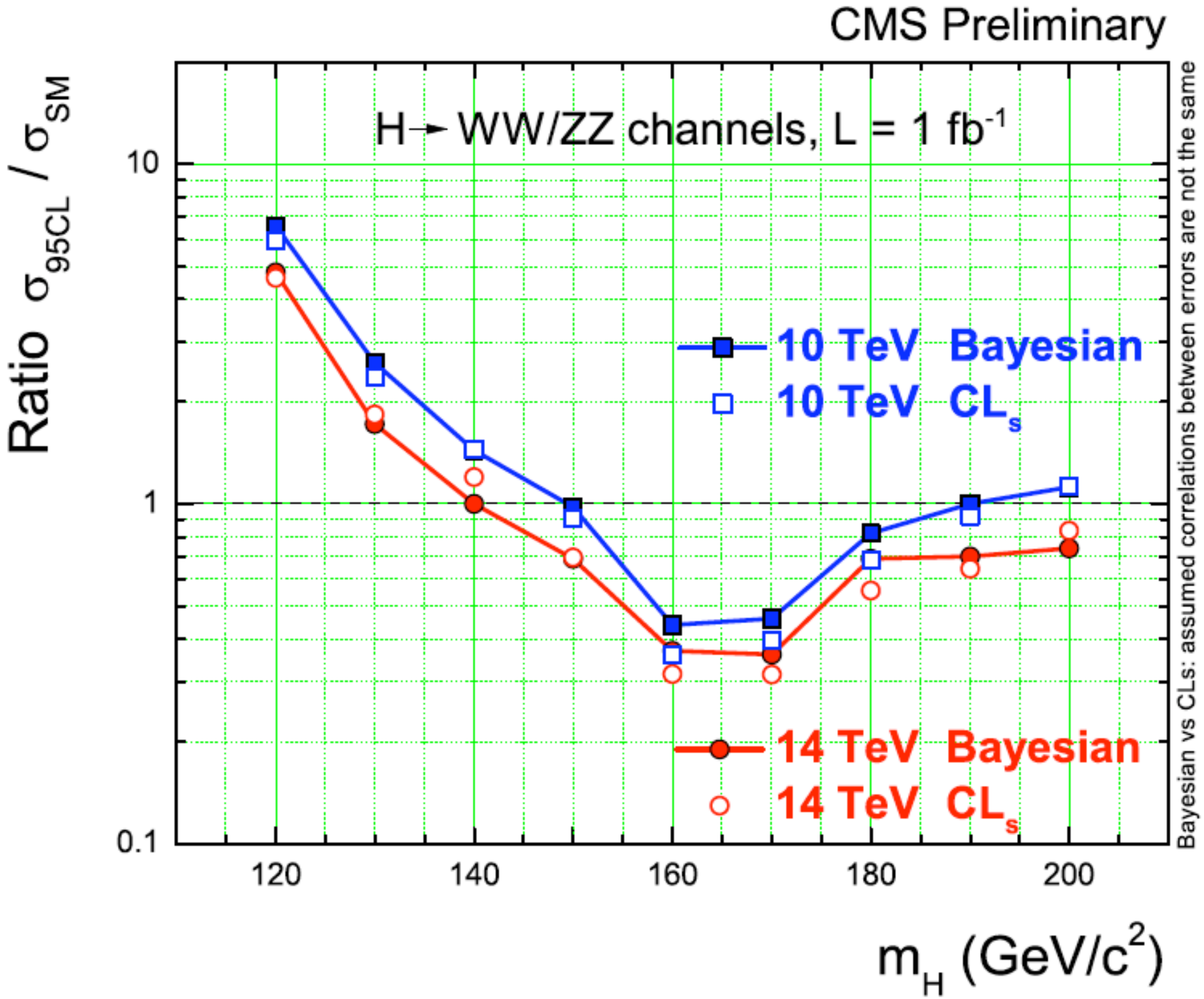
2 to 3σ fluctations seen in both CMS & ATLAS at the same M_H could be already pretty exciting !!!

Cross-sections vs $\sqrt{s}_{pp}$



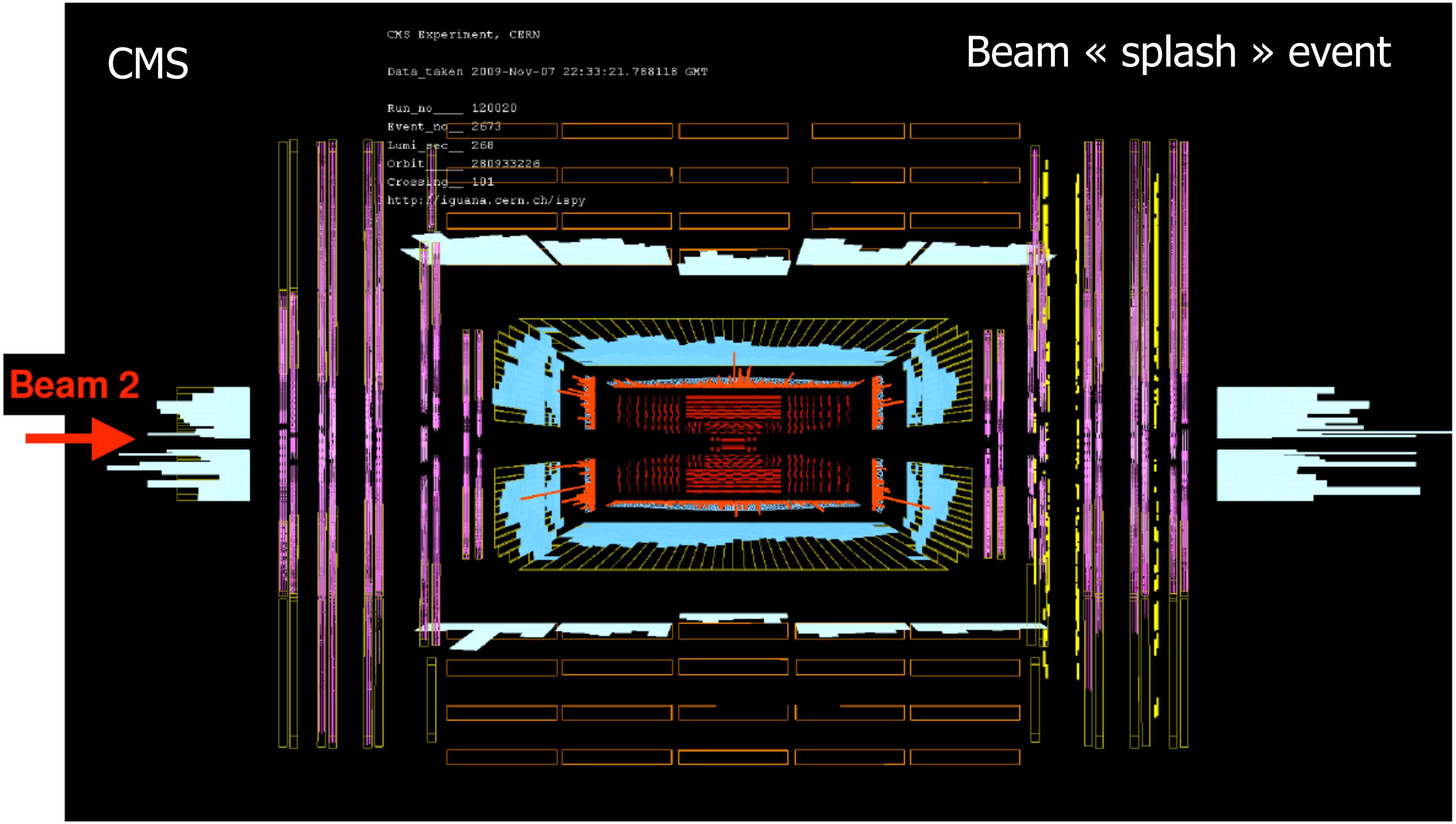


Expected Reach vs $\sqrt{s}_{pp}$



Conclusions

20 years later … the beam is now circulating in the LHC !!!



Conclusions

- 20 years later … the beam is now circulating in the LHC !!!
  … awaiting first collisions at $\sqrt{s}$ = 900 GeV (possibly 2.2 TeV)
  … preparing for $\sqrt{s}$ = 7 TeV (possibly 10TeV) in 2010 !

  [press conference on-going at CERN !]

- The experiments are ready and partly commisionned using cosmics (and beam splash) events, and complete baseline analysis strategies have been deployed from early QCD, to Electroweak Z/W and top … down to the Higgs, SUSY and beyond

- The sensitivity for a Higgs discovery in a LHC experiment is roughly 10 x (40 x) that of a TeVatron experiment for $\sqrt{s}$ = 7 TeV (10 TeV)

- The LHC experiment with takeover and extend the searches for the Higgs(es) and new physics beyond the TeVatron