Polytechnique

Electroweak Symmetry Breaking
and the
Higgs Boson(s) at the LHC

Outline:

- The Physics @ LHC
- The Detector Design
- Commissioning for Physics
- Search for the SM Higgs boson
- Higgses in SUSY and Beyond

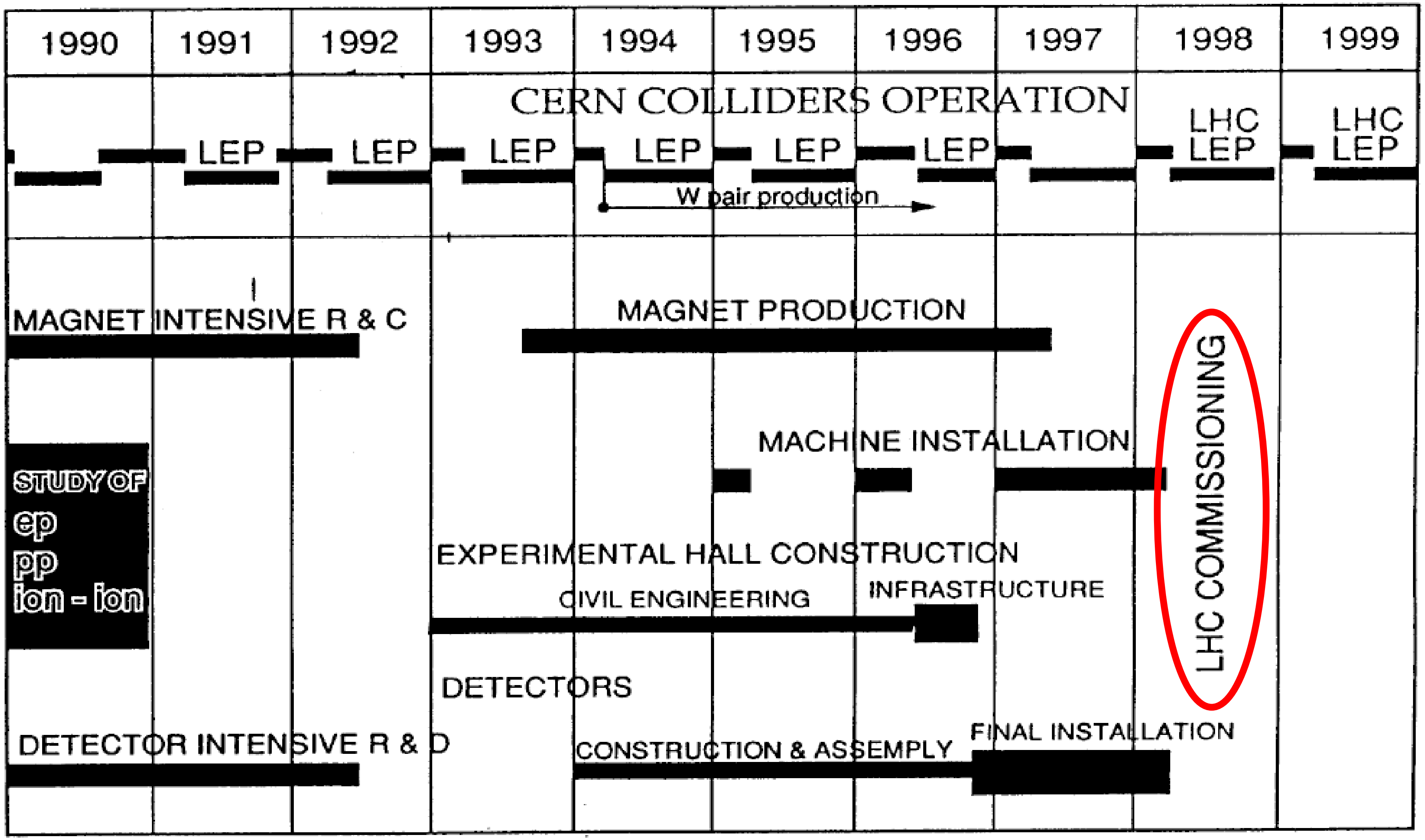
Yves Sirois
LLR Ecole Polytechnique, Palaiseau
CNRS-IN2P3, France

The Physics @ LHC

… when it all started

1989

First meetings of the LHC proto-collaborations in 1989 …



C. Rubbia - Large Hadron Collider Workshop, Aachen 1990

Figure 18 – Construction schedule of the LHC

You are NOT here !!!

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 Standard Model and Beyond

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- 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

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

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

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 :)

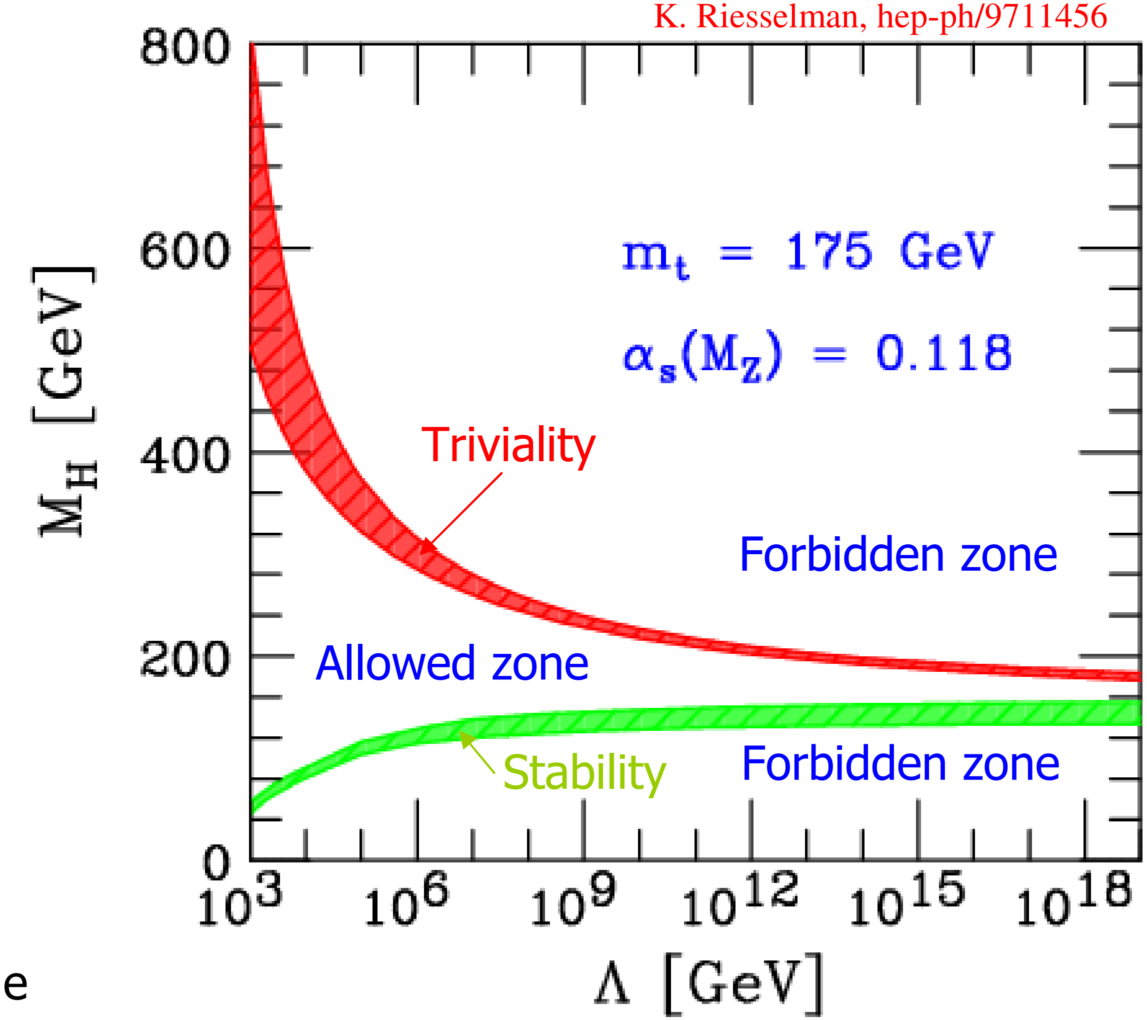
$$M_H^2 < \frac{4\pi^2 v^2}{3\ln(\Lambda/v)}$$

"Stability" of vacuum:

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

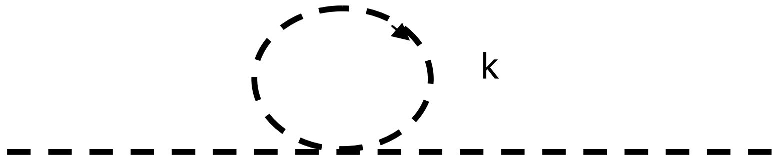
Λ = cut-off scale

K. Riesselman, hep-ph/9711456



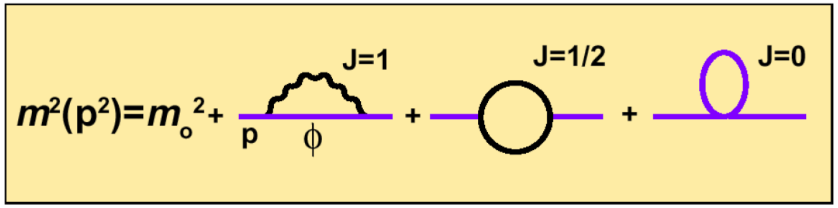
The Instability of the Mass M_H

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 …



$$M_H^2 \rightarrow M_H^2\,(\text{bare}) + c\,\Lambda^2$$

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

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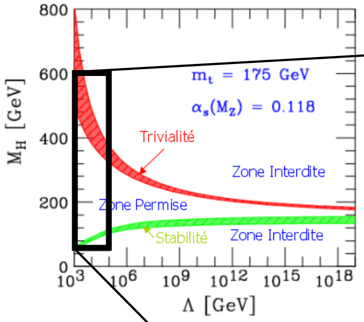
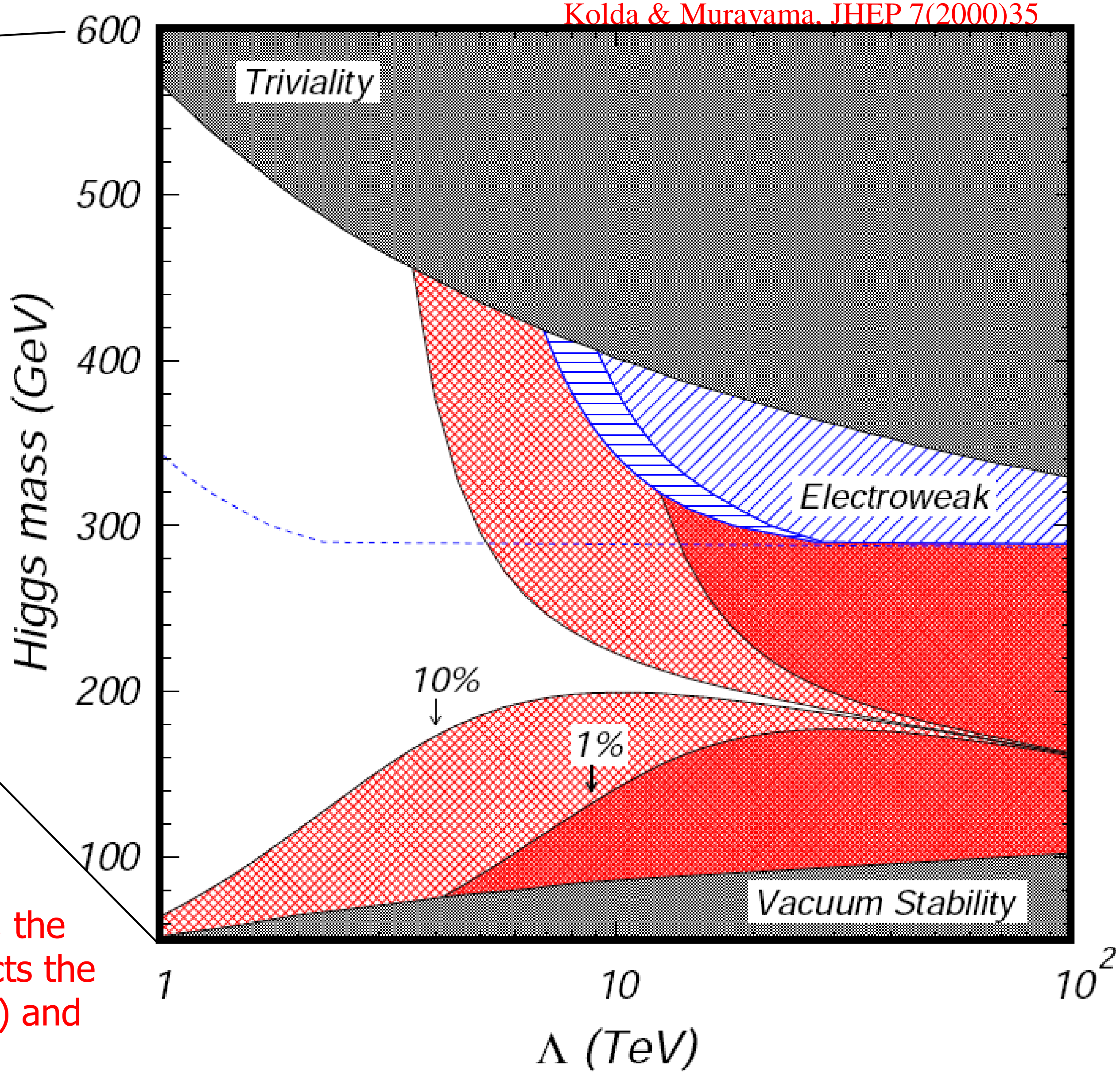


Kolda & Murayama, JHEP 7(2000)35



The difference between the Fermi scale and the scale Λ for new physics is not natural !

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

When it was all simple … one fundamental equation:

$$\boxed{3 \oplus 2 = 5}$$

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

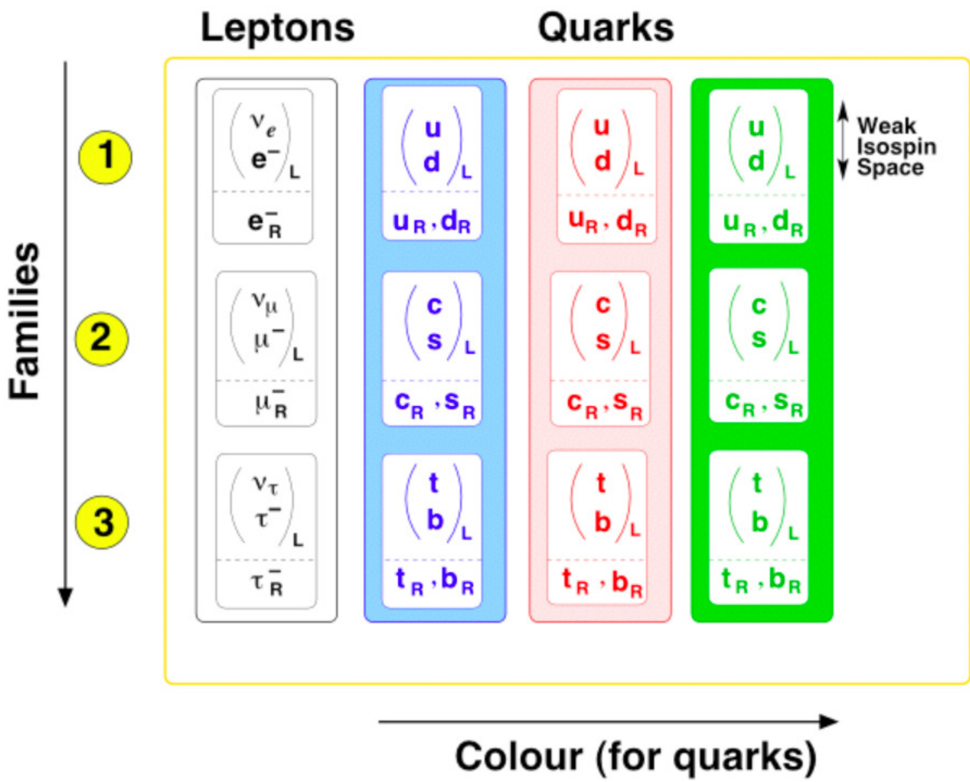
γ, Z, $W^{\pm}$ ↔ SU(2)xU(1)
Transformations of 2 objects among themselves

=

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

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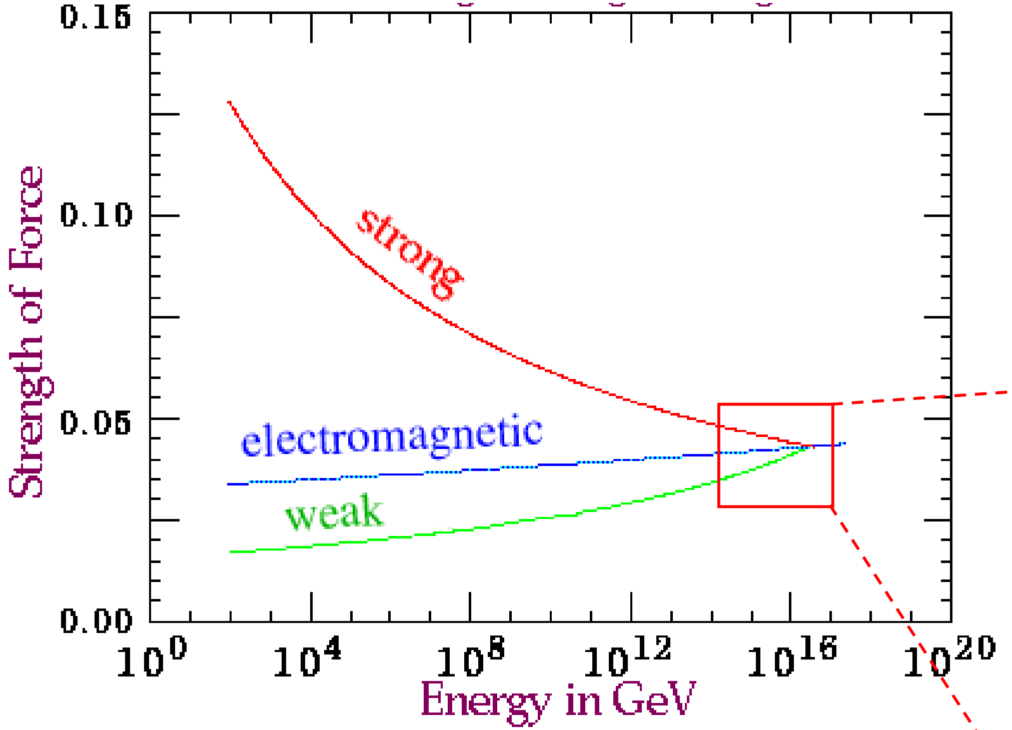
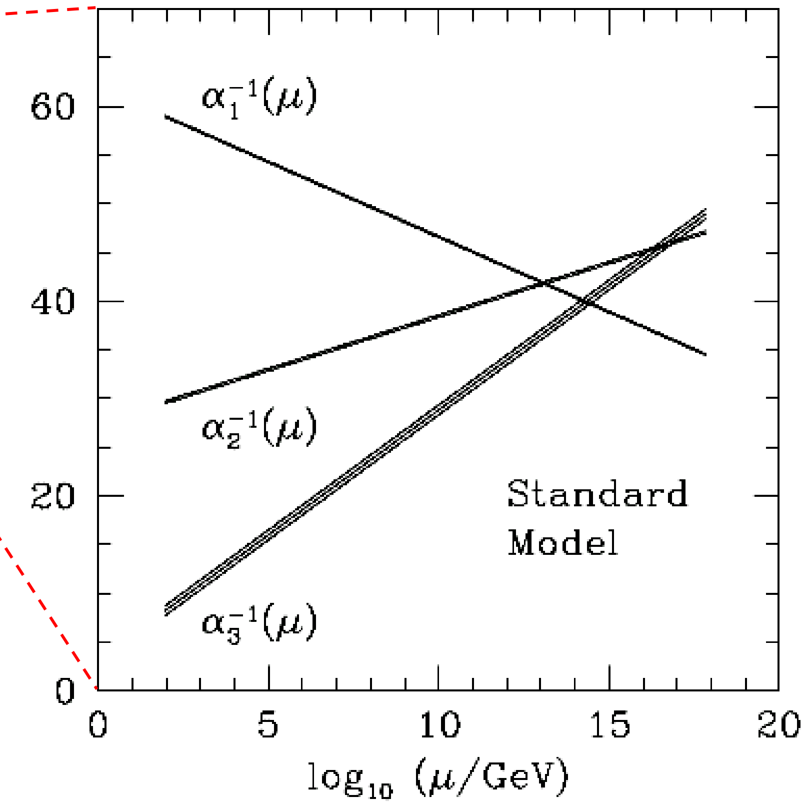
Evolution of the couplings



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 »)

Supersymmetry & Hierarchy

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SUPERSYMMETRY = fondamental symmetry between bosons and fermions
Ordinary fermions and bosons do not match: SUSY must be broken !

$\Rightarrow \exists$ "mirror" of the ordinary matter = the supersymmetric matter

Unknown Supersymmetry Breaking Mechanism $\Rightarrow$ free parametres

MSSM	Soft SUSY breaking	105 parametres
mSUGRA	Gravity Mediated SUSY Breaking (Unification at the GUT)	5 Parametres
etc.		

The lightest supersymmetric particle ("LSP") is generally considered to be stable (if R-parity est strictly conserved) $\Rightarrow$ **candidate for dark matter**

Natural solution to the Hierarchy problem :

The contributions of the fermions to the quadratic divergences cancel the contributions of the bosons !

Higgs Bosons and Minimal Models

Standard Model:

1 doublet of Higgs fields … 1 physical scalar boson H (CP-even)

M_H is a free parameter of the theory

$M_f = \lambda_f <\phi>$; $<\phi> \equiv v/\sqrt{2}$; $v = (\sqrt{2}\, G_F)^{-1/2} \sim 246$ GeV

Minimal Supersymmetric Standard Model:

2 doublets* of Higgs fields … 5 physical Higgs bosons

2 Scalars	h^0, H^0	CP= +1	$R_p = +1$
1 Pseudoscalar	A^0	CP= –1	$R_p = +1$
2 Charged	H^+, H^-	CP= +1	$R_p = +1$

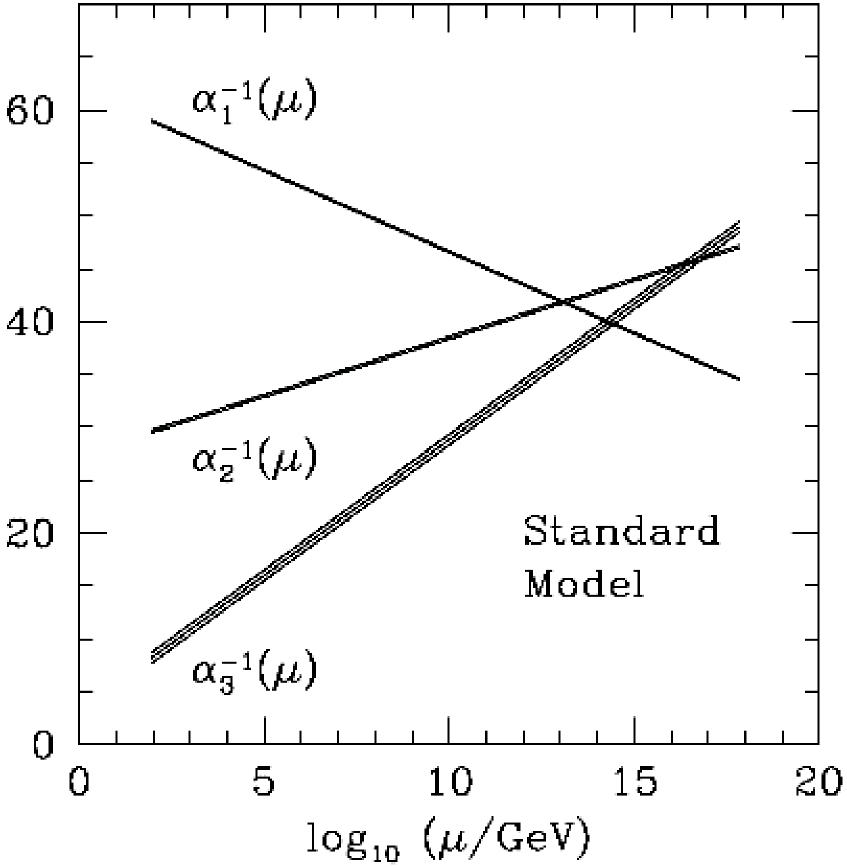
At the Born approximation:

The Higgs sector of the MSSM is entirely determined by two fundamental parameters of the theory ! E.g. M_A and $\tan\beta$ ($\equiv v_2/v_1$)

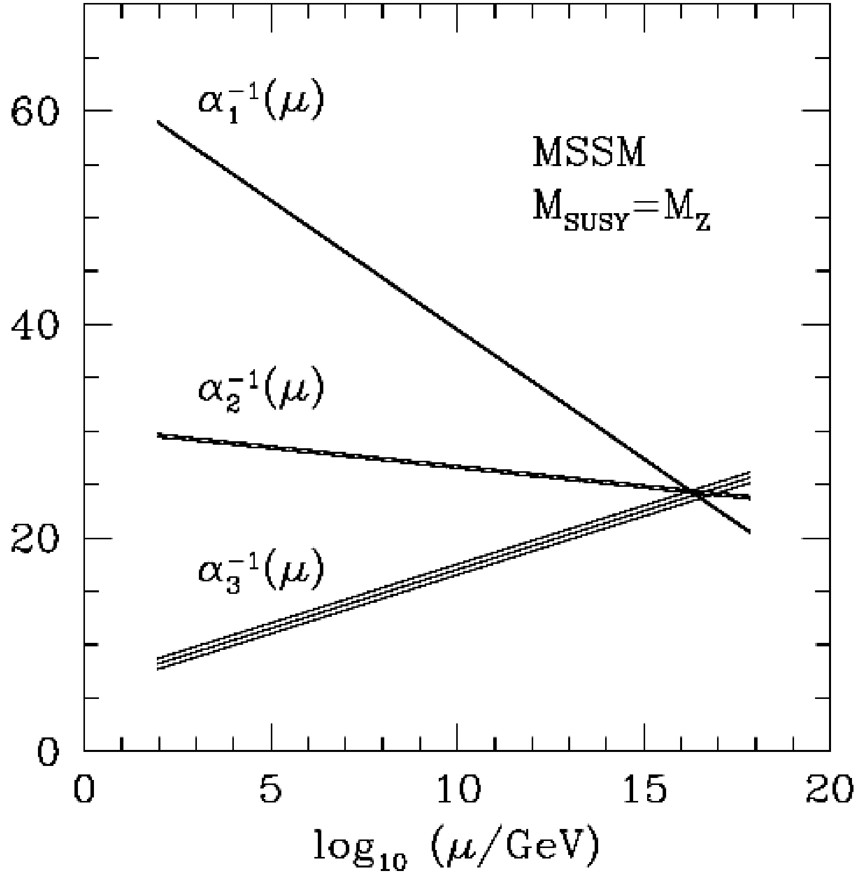
* Required for anomaly cancellation and breaking the gauge invariance

Supersymétrie et Grande Unification

Besides providing a solution to the Hierarchy problem, supersymmetry seems able to effectively allow for a realisation of the Grand Unification !



Standard Model



Supersymmetry

Note: M^{GUT} [SU(5)] < M_{GUT} [SUSY] $\leftrightarrow$ M_{PLANCK}

Physics & The LHC Detectors

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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

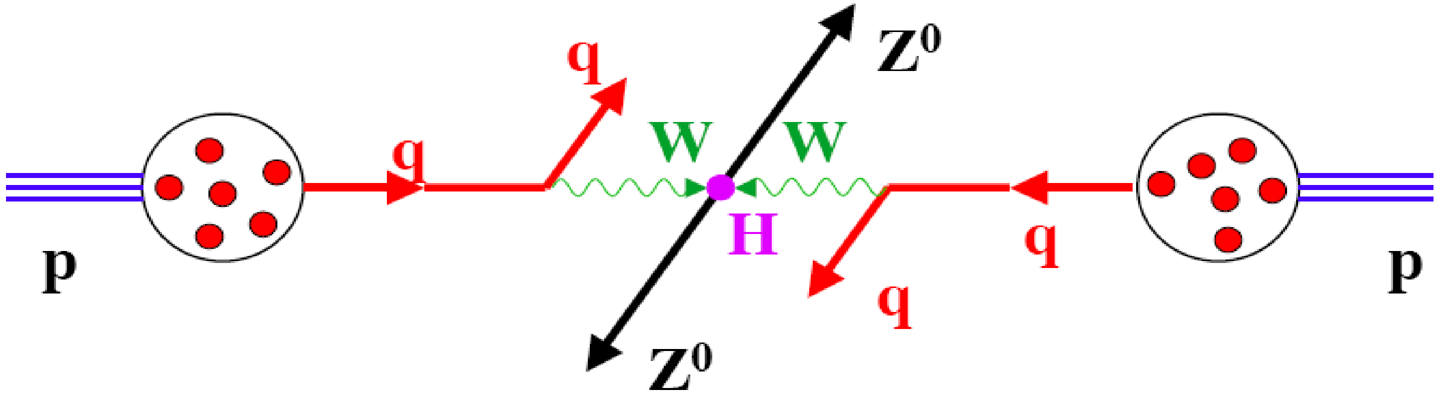
Unification and Extended Symmetries

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

⇔ measurements at very high momentum

A Large Hadronic Collider

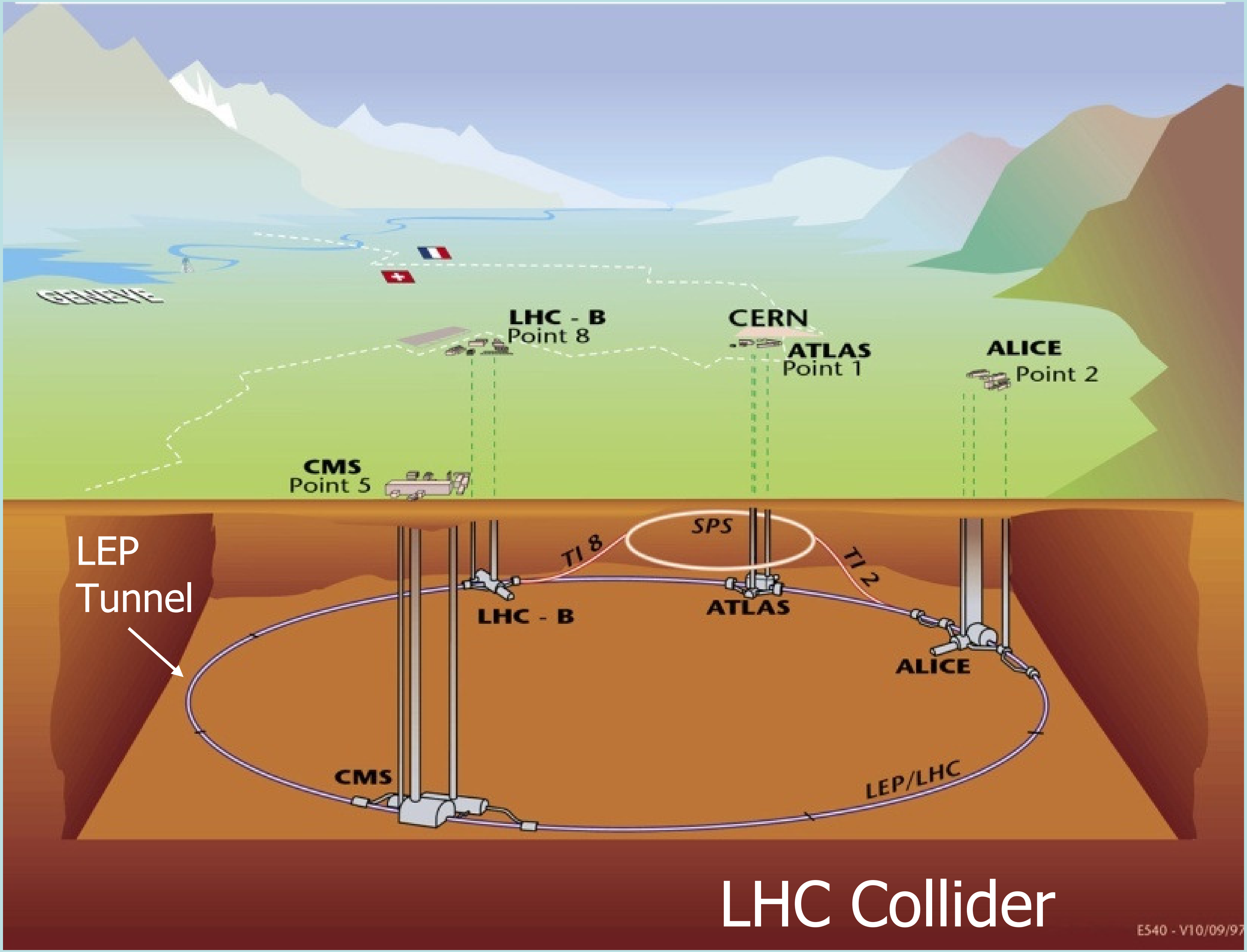
- A broad band exploratory machine
- May need to study W_L-W_L scattering at c.m. energy of ~ 1 TeV



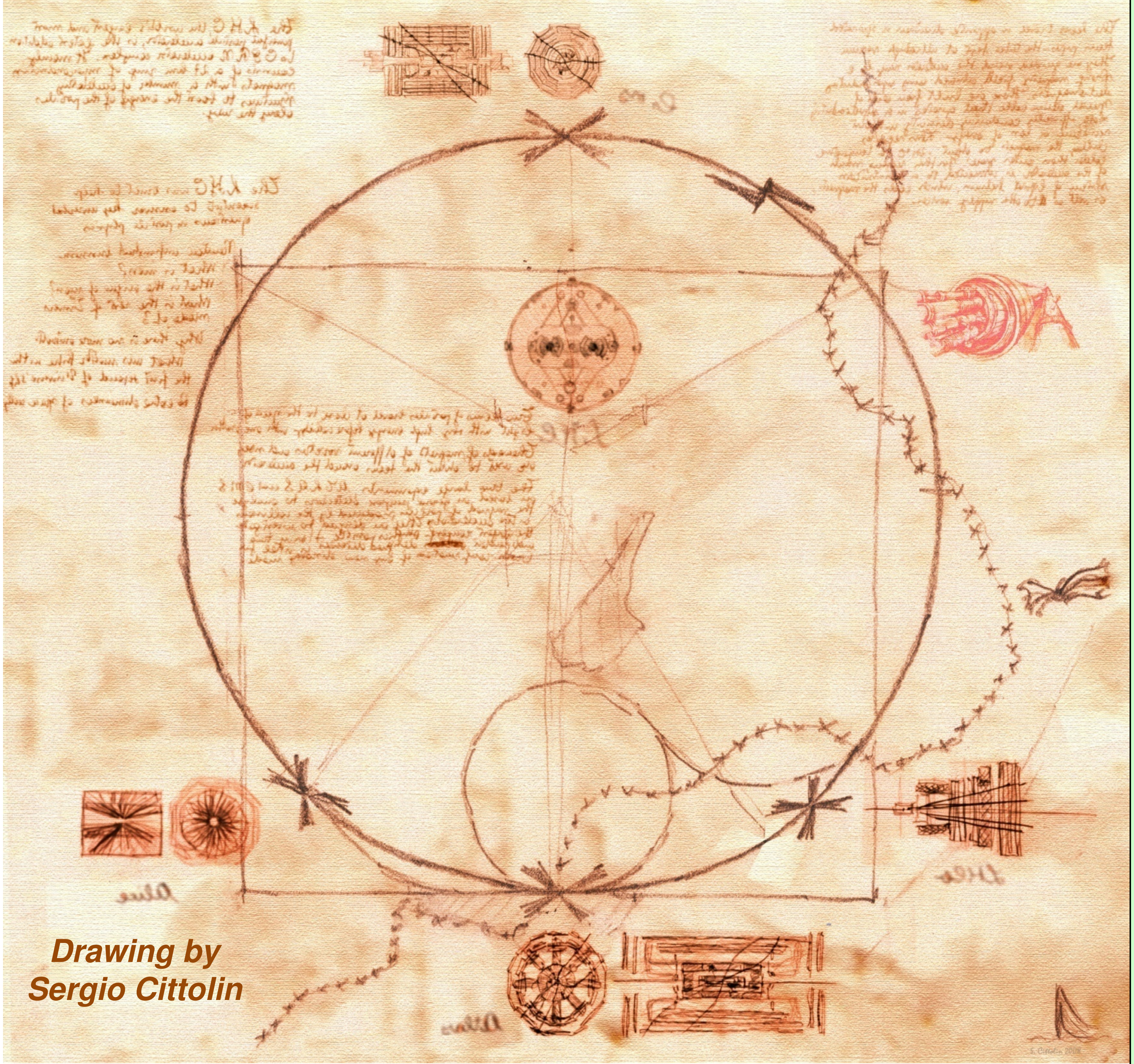
Need $E_W \sim 500$ GeV $\Rightarrow$ q ~ 1 TeV $\Rightarrow$ $\sqrt{s_{pp}} \sim 14$ TeV

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

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



LHC Collider



Drawing by Sergio Cittolin

CMS & ATLAS experiments at the LHC

20 years

From Design to experiments at the LHC

The LHC Detectors

The Magnet

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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)

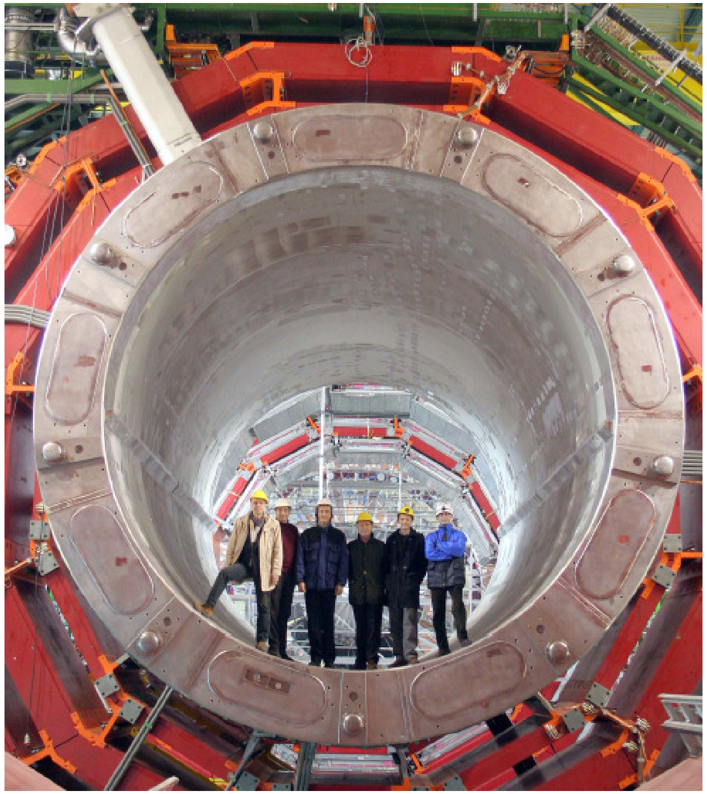
Excellent stand alone $\Delta P\mu/P\mu$ resolution … but very large volume required and need internal solenoid for vertexing purposes

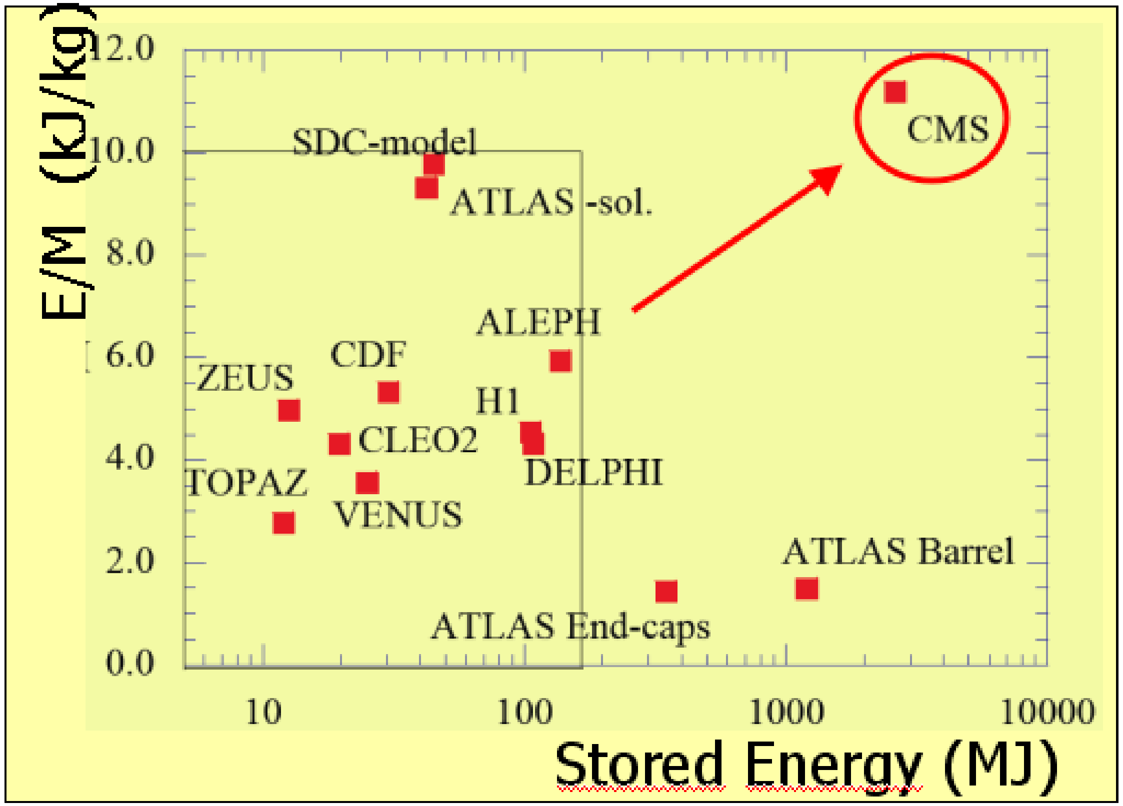
The LHC Detectors

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]

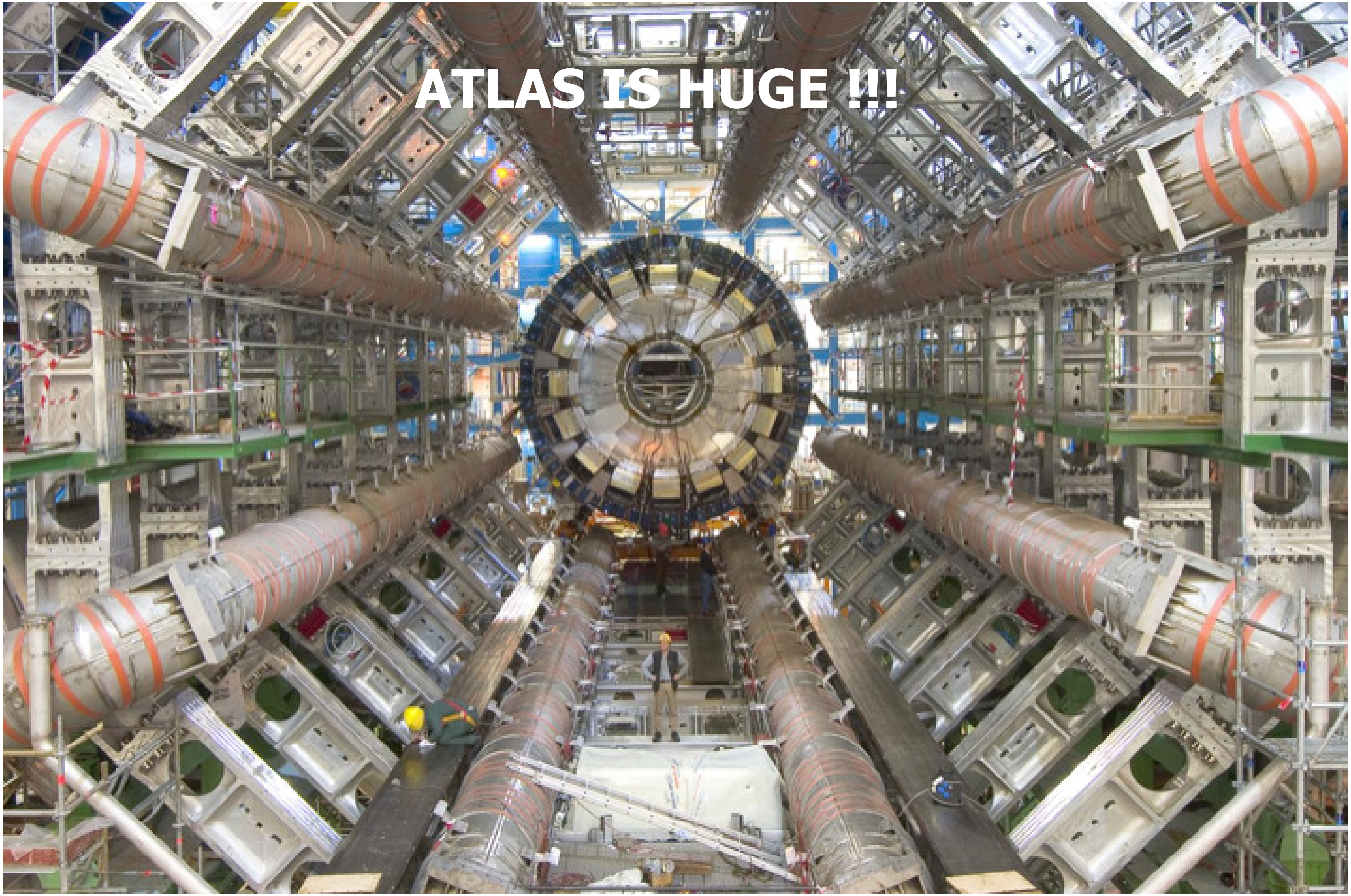
Refrigerated superconducting niobium-titanium coils (-268.5ºC)





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

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

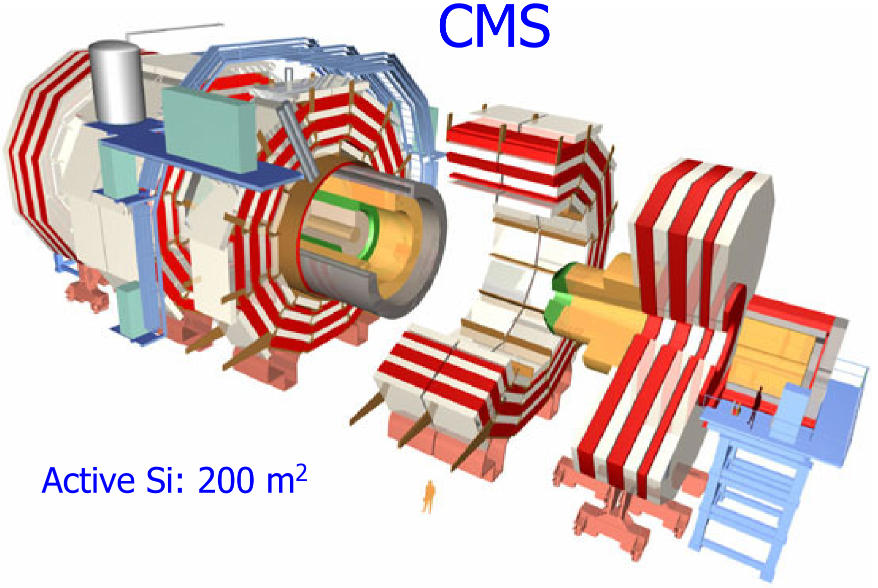

ATLAS IS HUGE !!!

The SCAMLAST Experiment

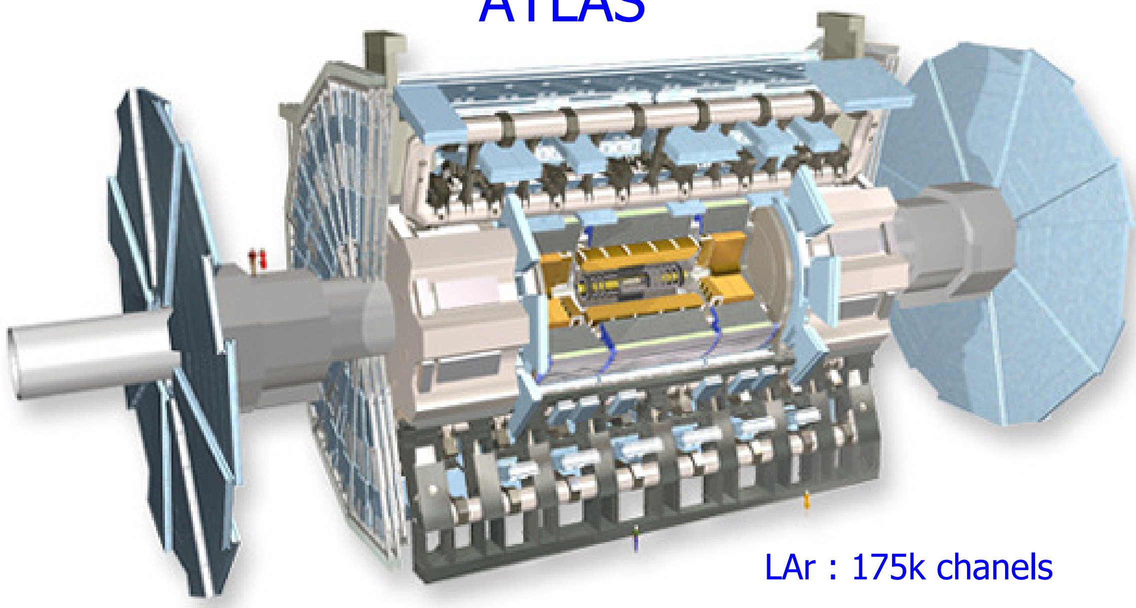
No one seriously considered such a scam …

The LHC Experiments

CMS



ATLAS



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

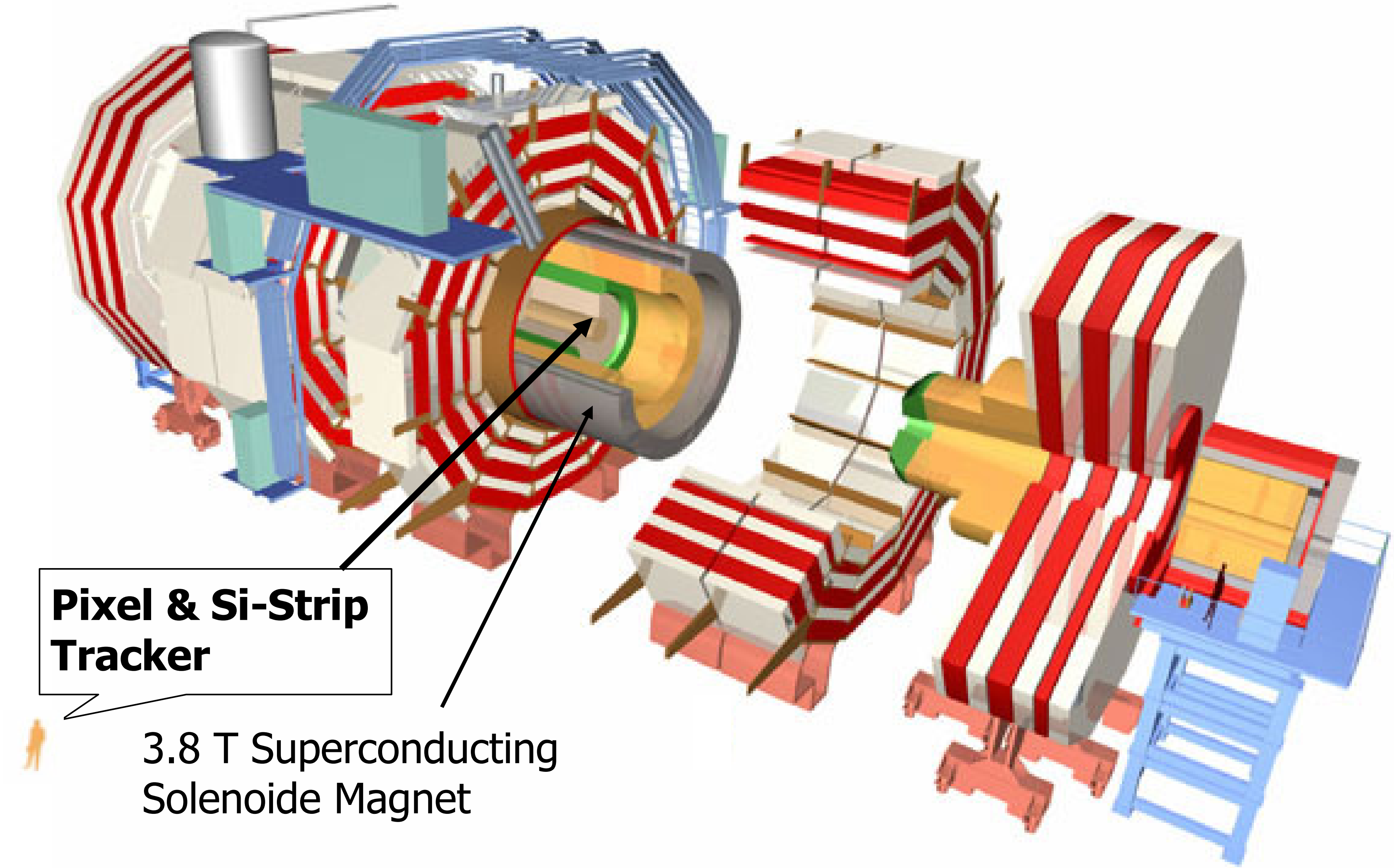
Tracking $|\eta| < 2.5$, B = 2T
- Si pixels and strips
- Transition radiation detector

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



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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

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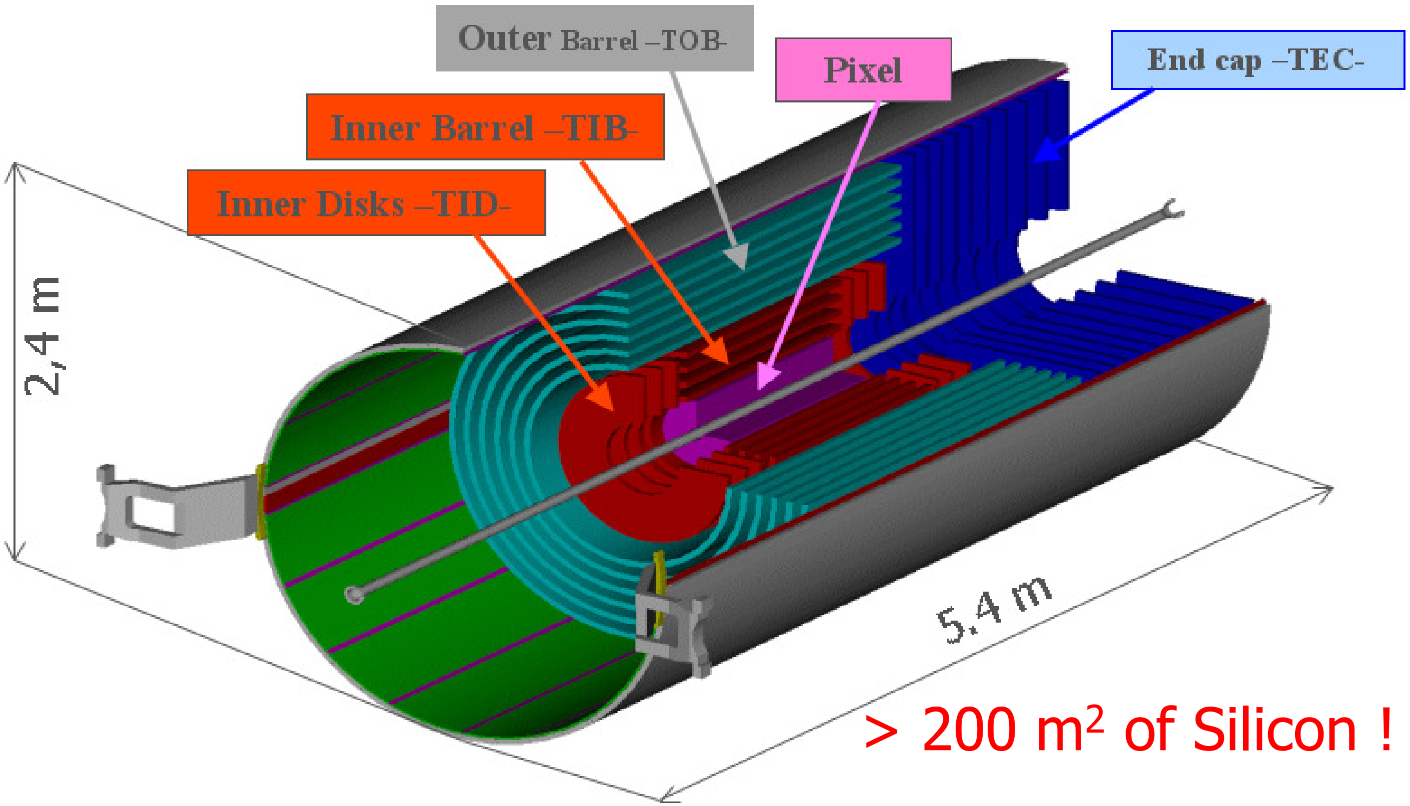
Pixel detector and a Silicon microstrip tracker:



> 200 m^2 of Silicon !

PIXEL DETECTOR
- Provides seeds for the particle tracks

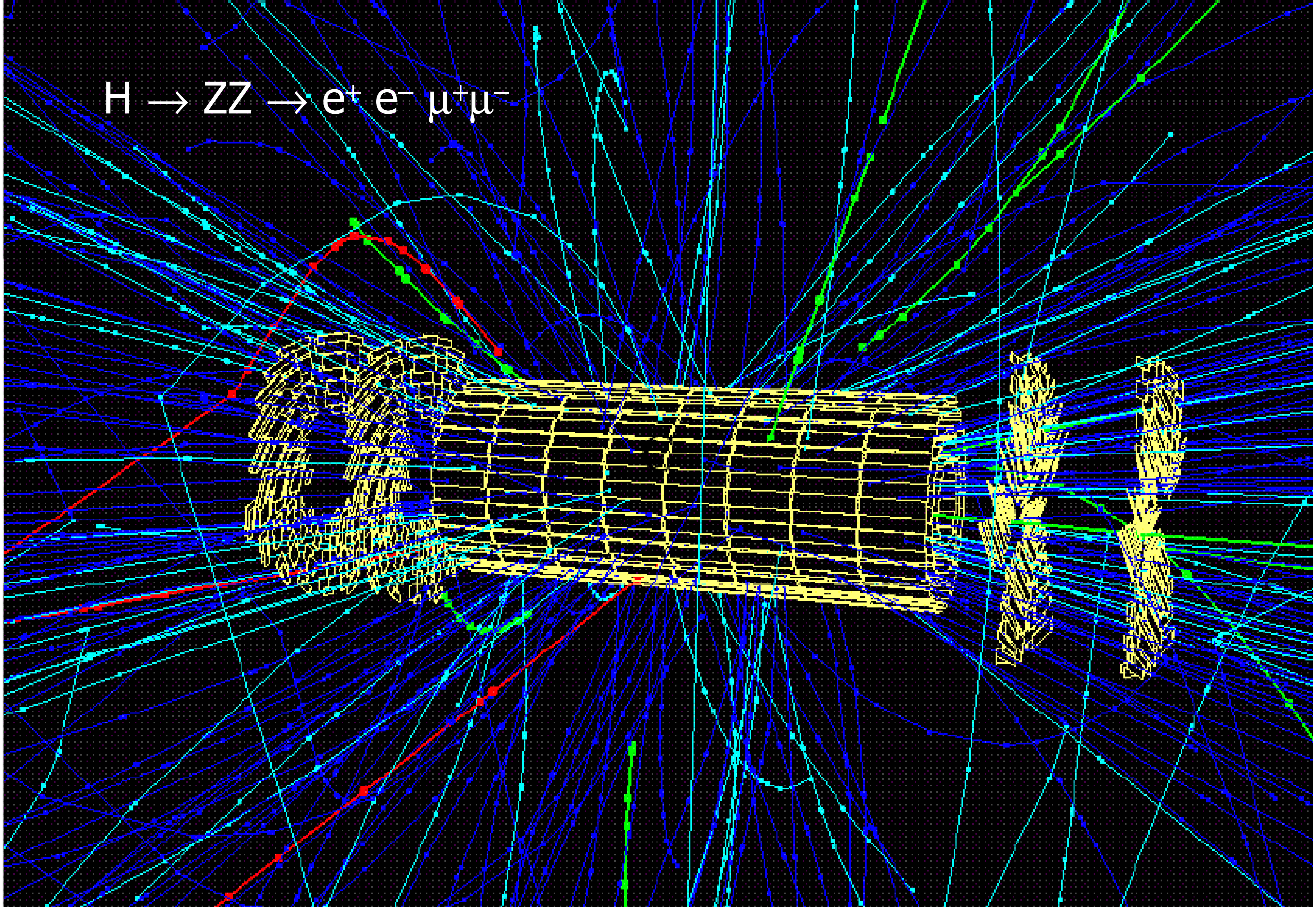
  e.g. Kalman Filter reco.
- Responsible for good vertexing

  e.g. Impact parameter or DCA to interaction VTX
- Help determine Z coordinates of events

  suppresses pile-up; σ_{VTX} ~ 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 m^3 T° ≈ –10 ^{0}C
Dry atmosphere … for years !

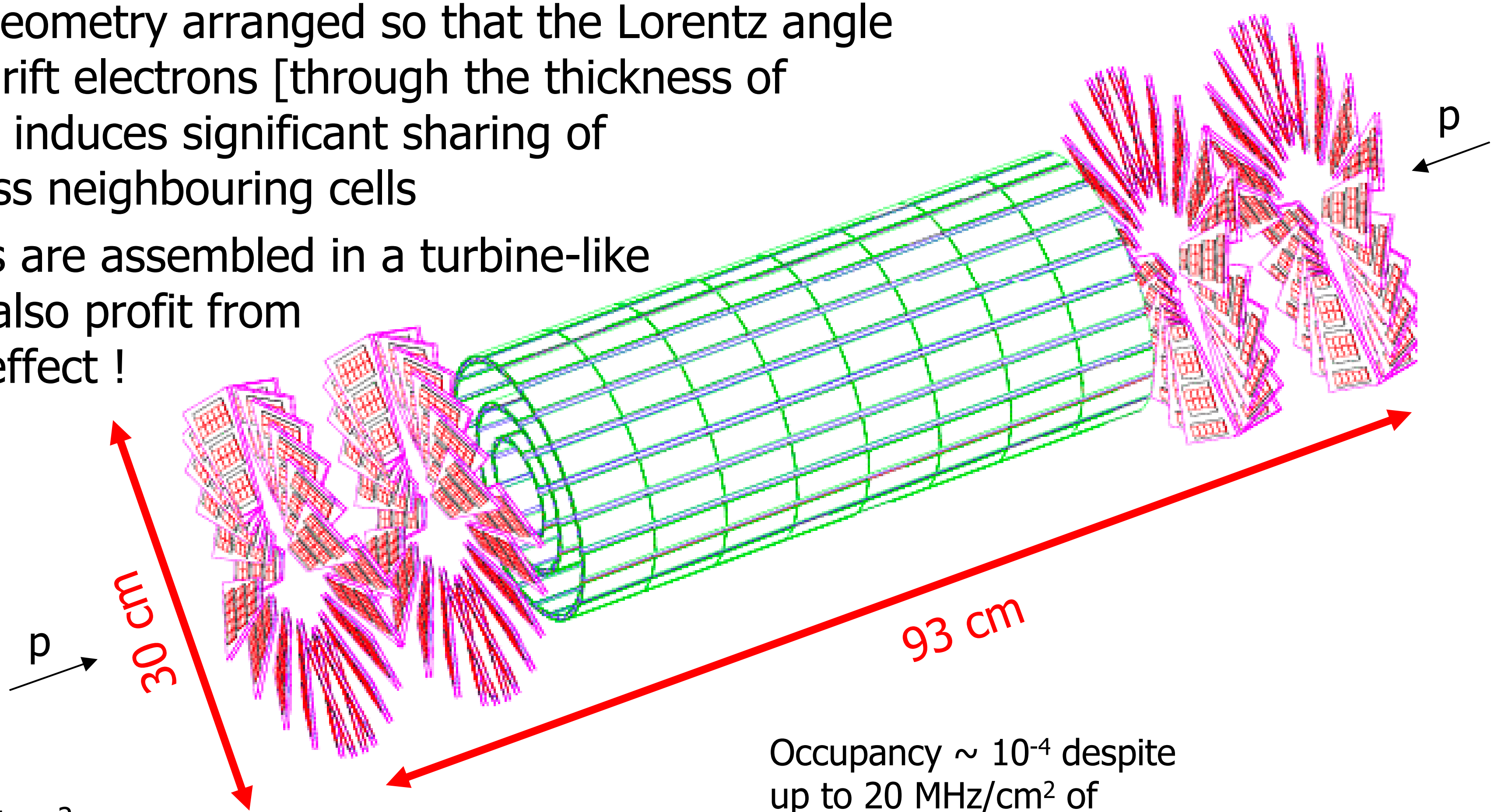

$H \to ZZ \to e^+ e^- \mu^+\mu^-$

The LHC Detectors

The CMS Si-pixel Detector

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

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



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

Occupancy ~ 10^{-4} despite up to 20 MHz/cm^2 of particles … thanks to fine Granularity and 40 MHz readout

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

The LHC Detectors

The Compact Muon Spectrometer

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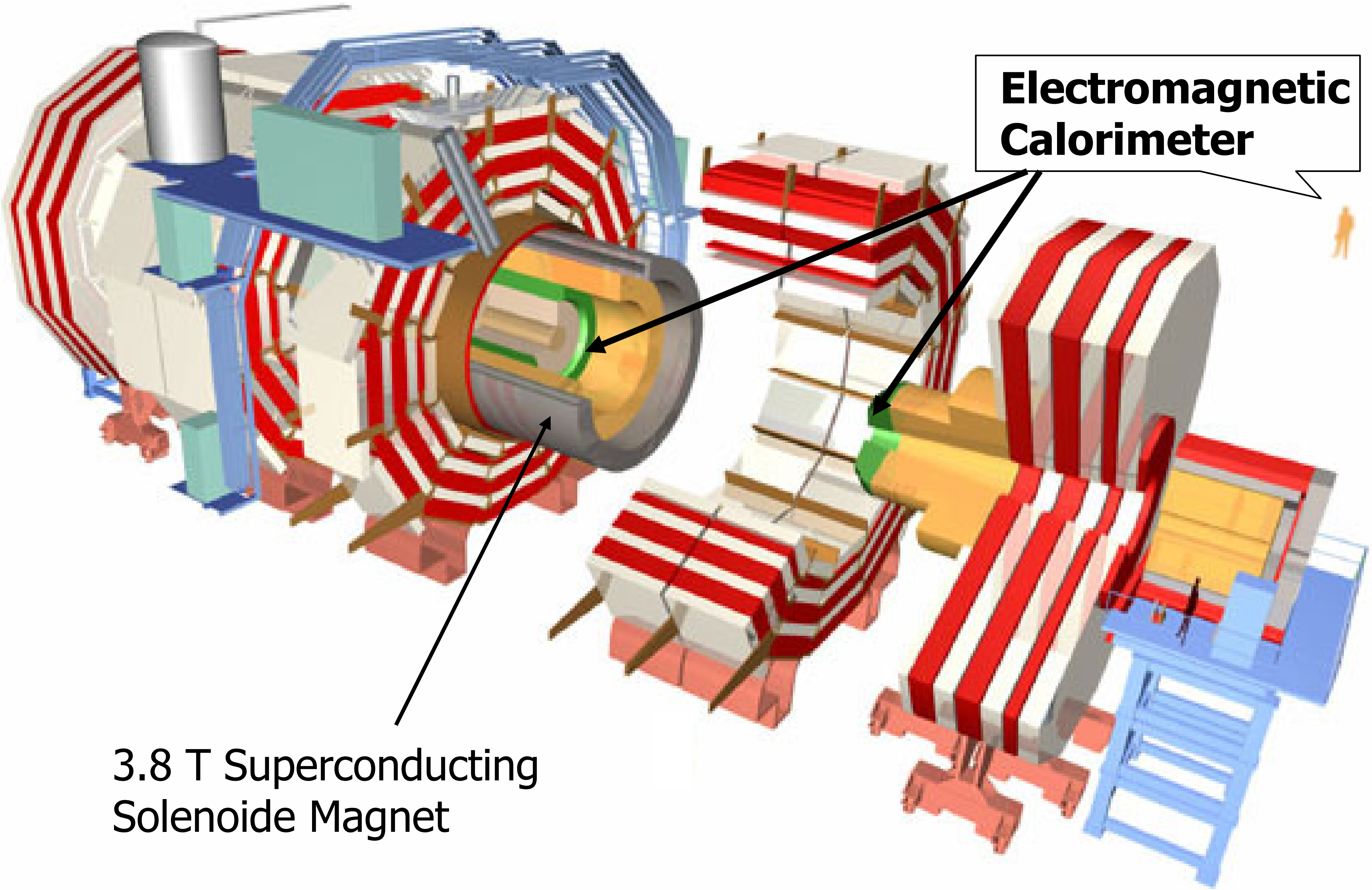
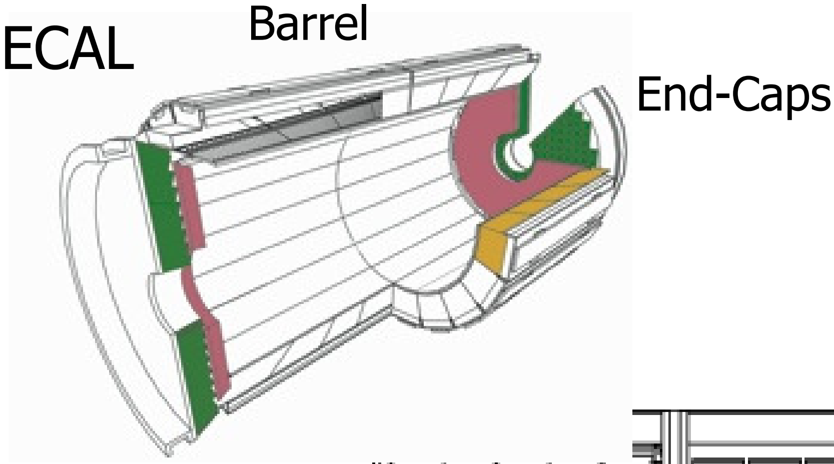
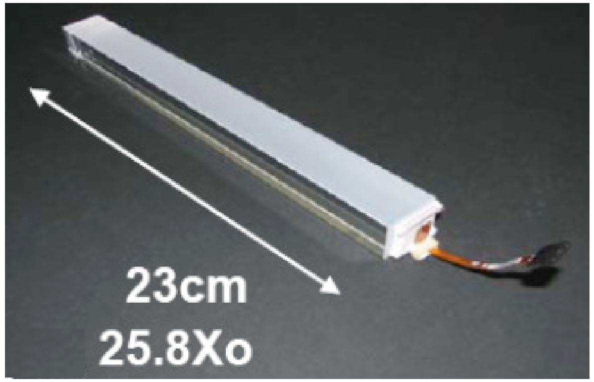


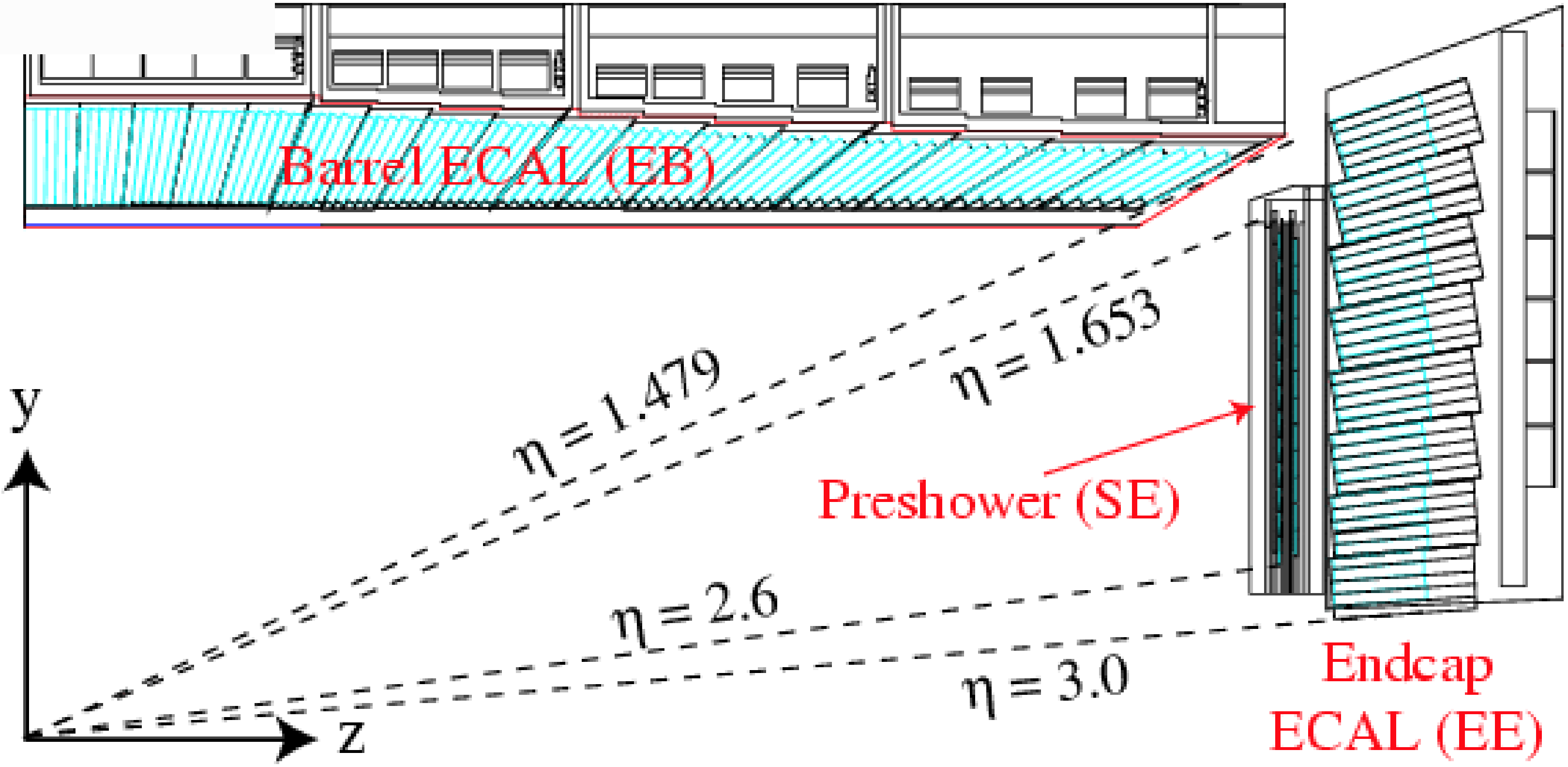
The LHC Detectors

The CMS Electrpmagnetic Calorimeter



PbWO4 crystals
X_0 = 0.89 cm
R_M = 2.10 cm





E Resolution vs Incident Ee

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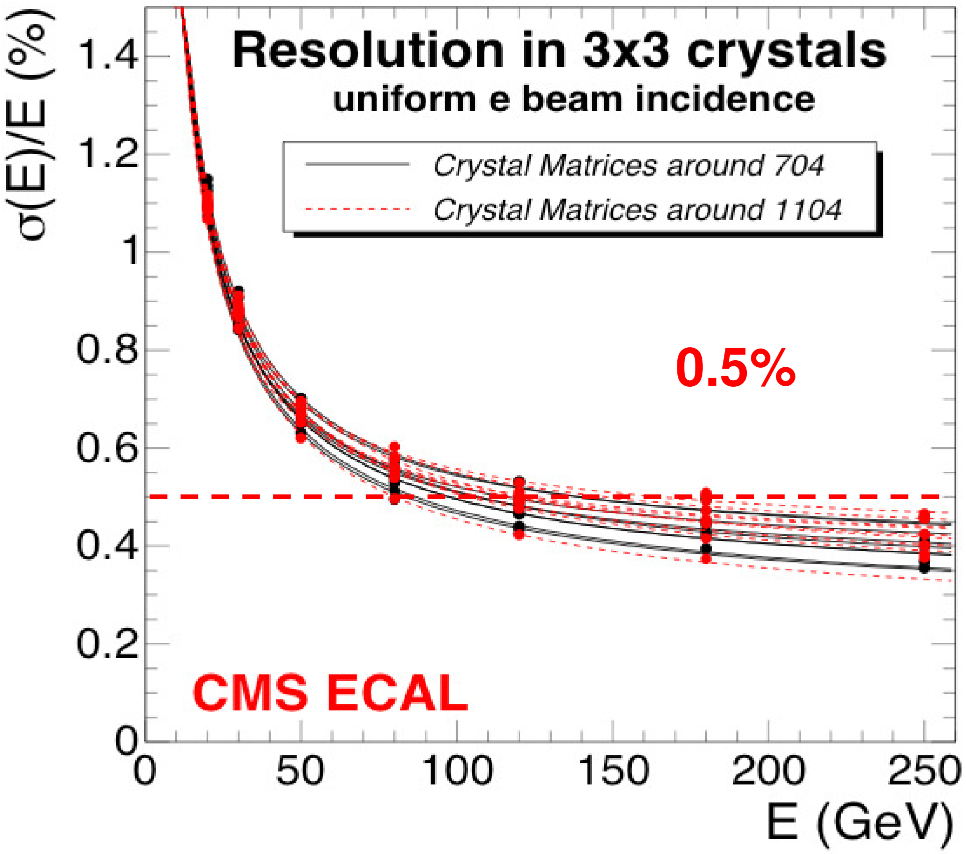
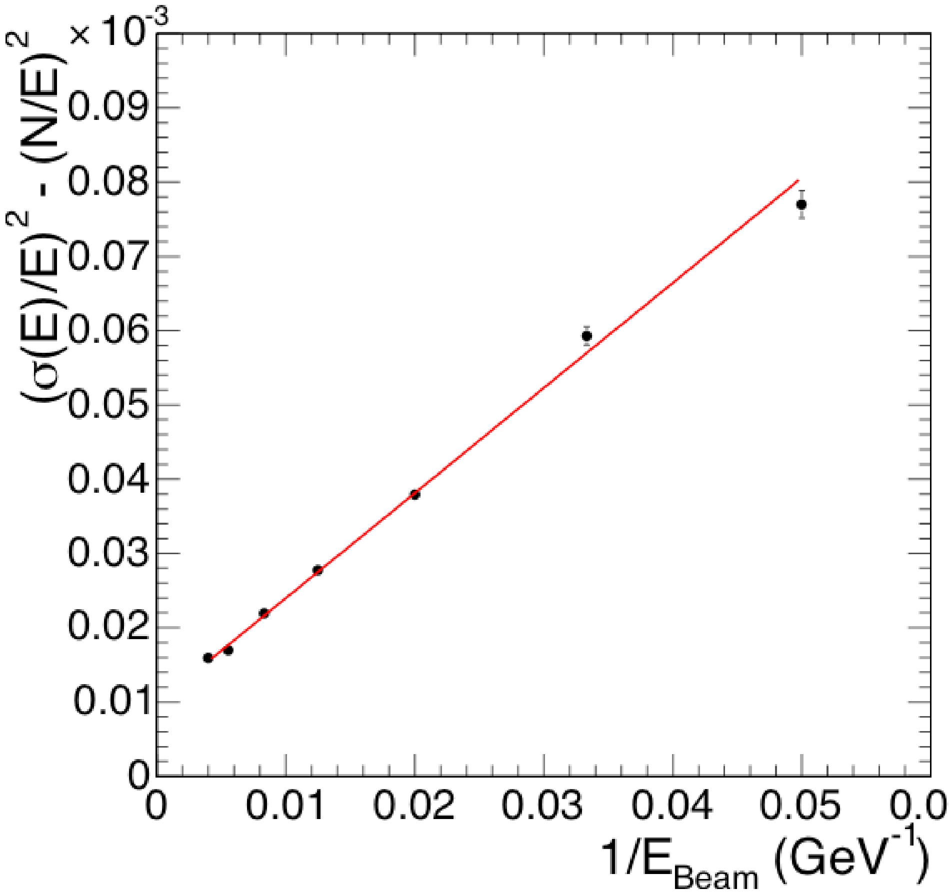
Uniform Incidence





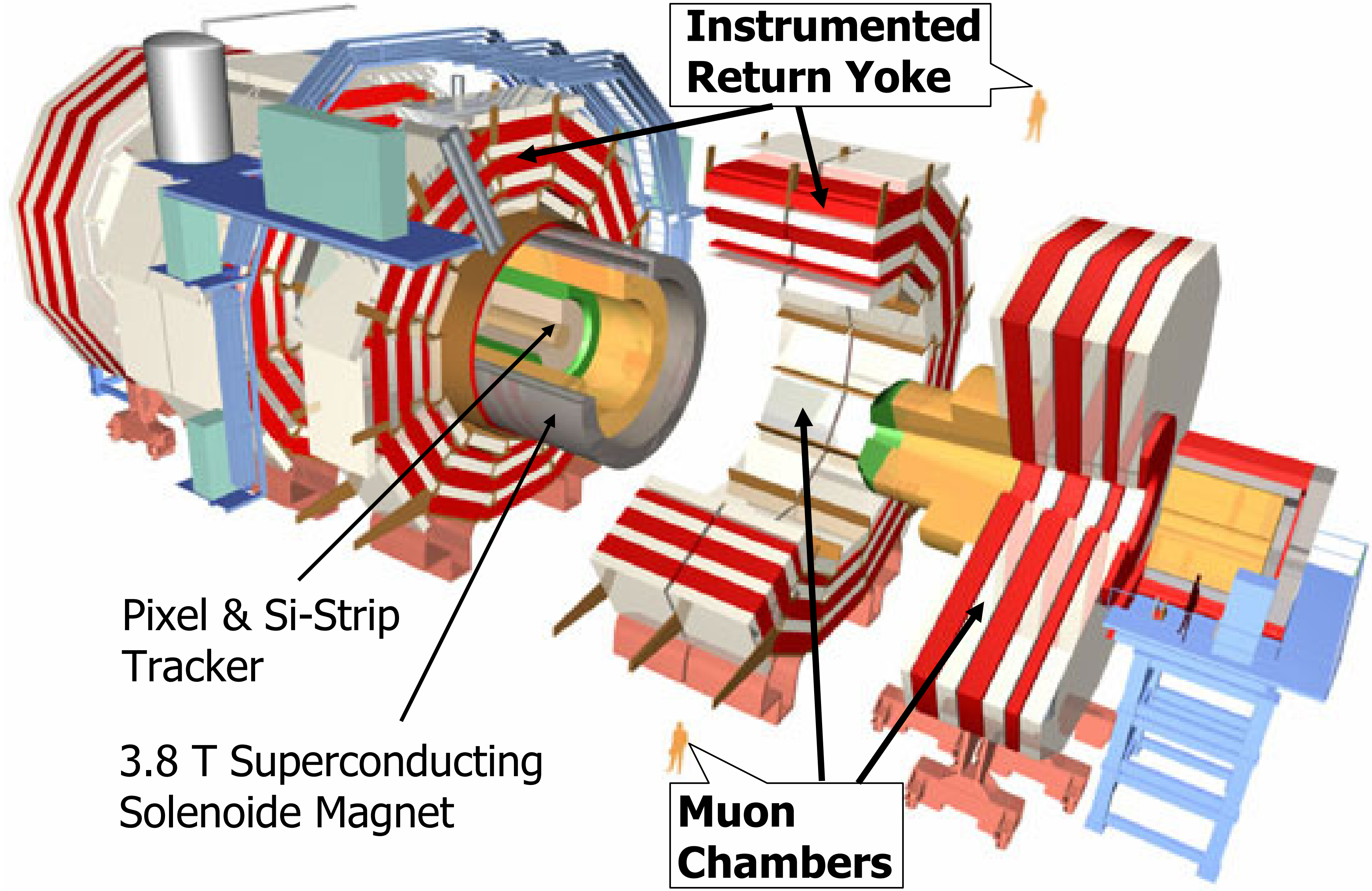
$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.125}{E}\right)^2 + (0.30\%)^2$$

Stochastic Noise Constant

E Resolution: CMS Note 2006/140

The LHC Detectors

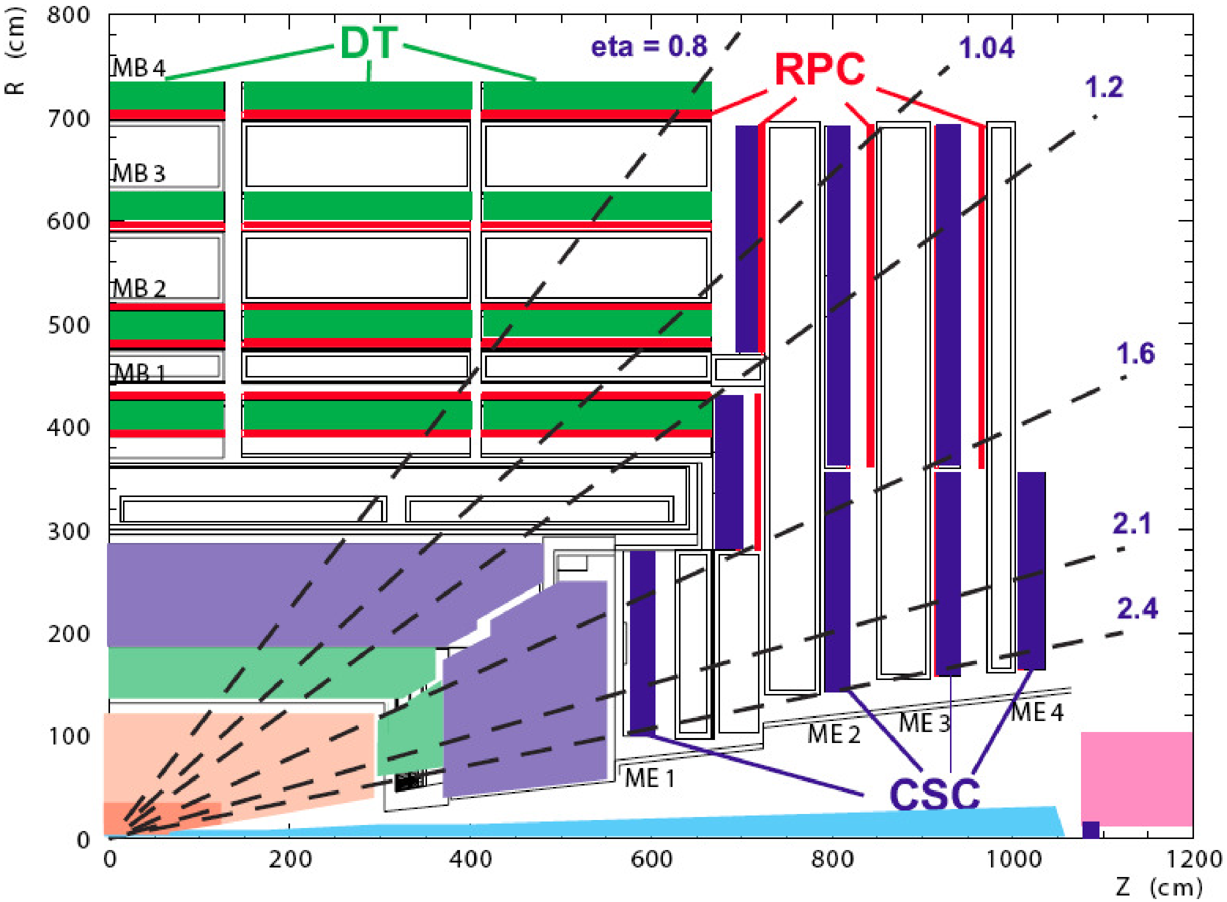
The Compact Muon Spectrometer

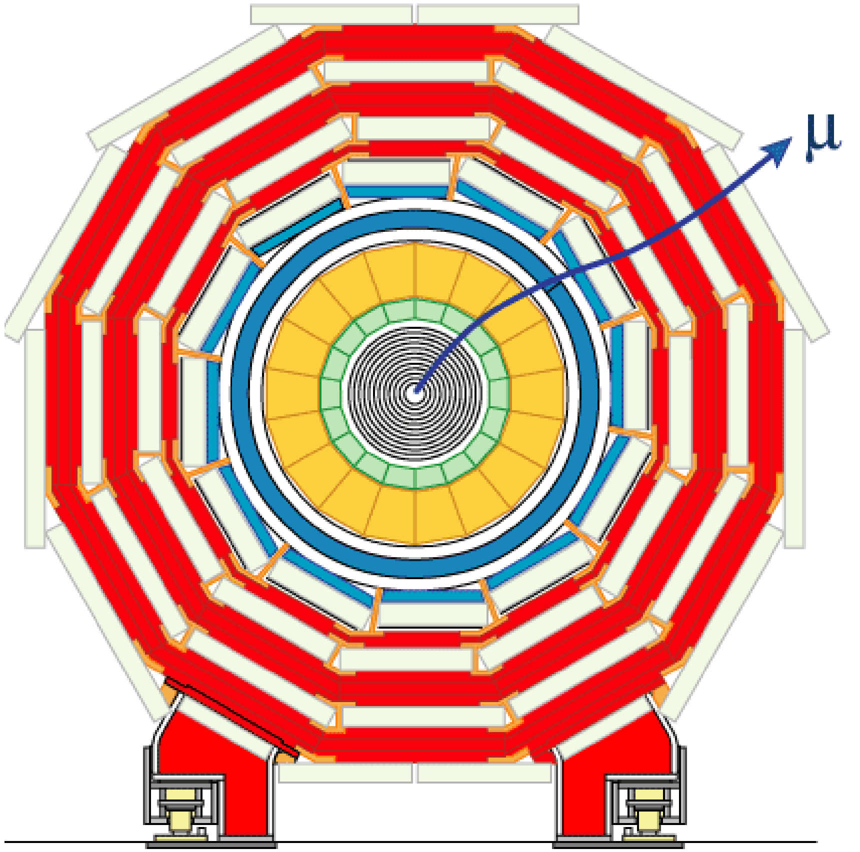


The LHC Detectors

The CMS Muon Detector

Polytechnique





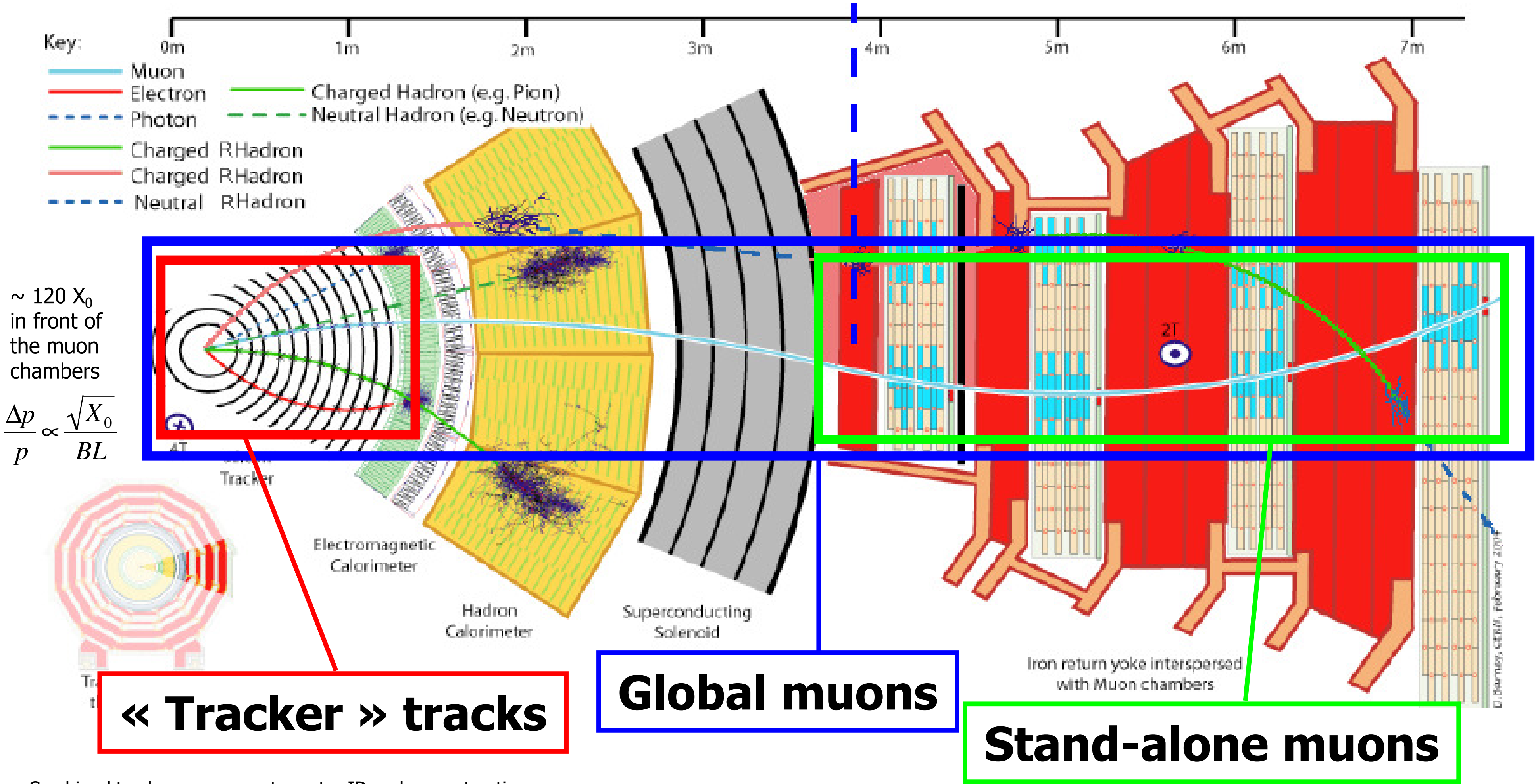
Hits with 100-200 μm resolution

DT: drift tubes

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

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

The CMS Muon Detector



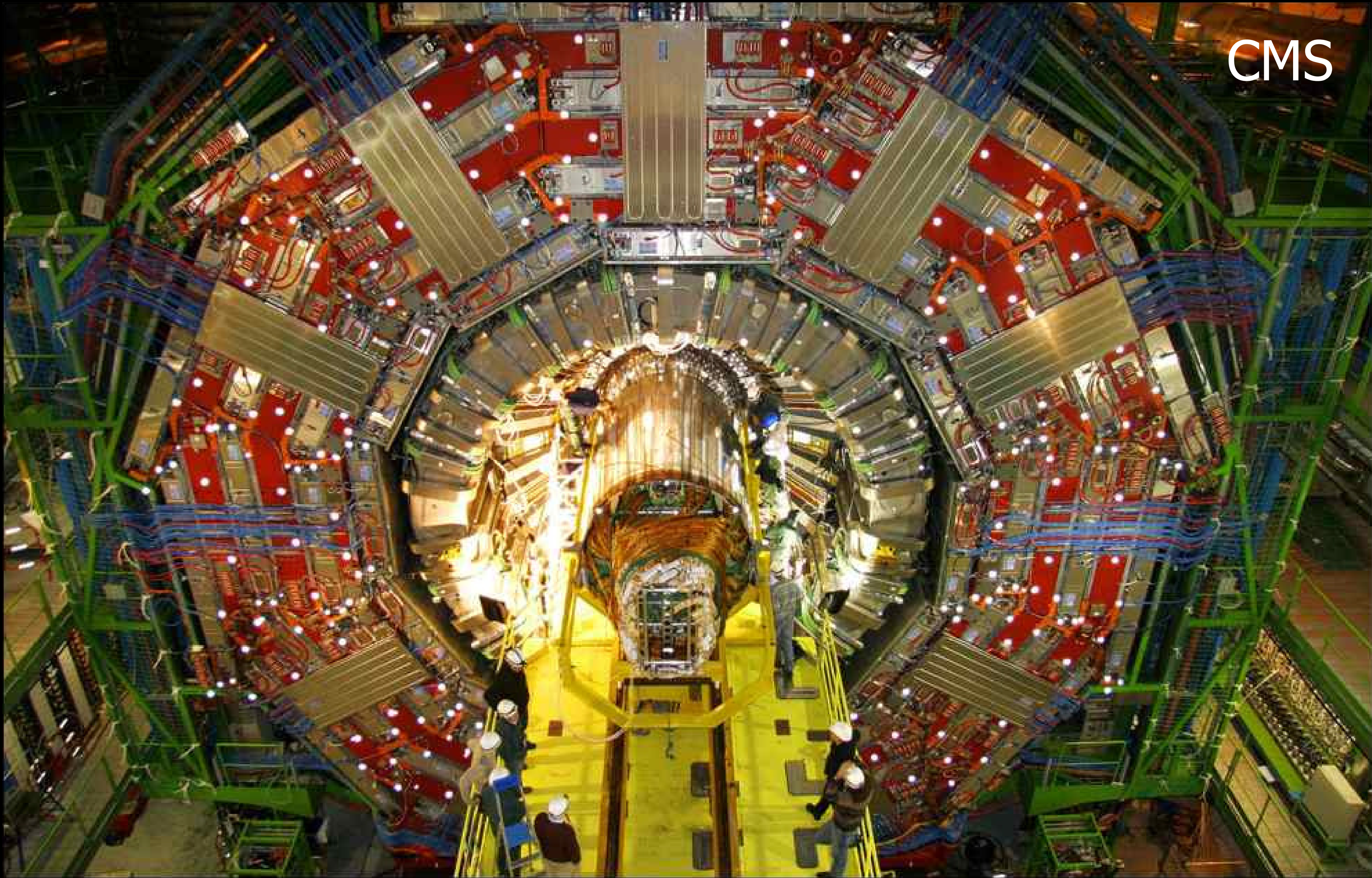
Combined tracker-muon spectrometer ID and reconstruction:

Two Approaches combined for analysis:

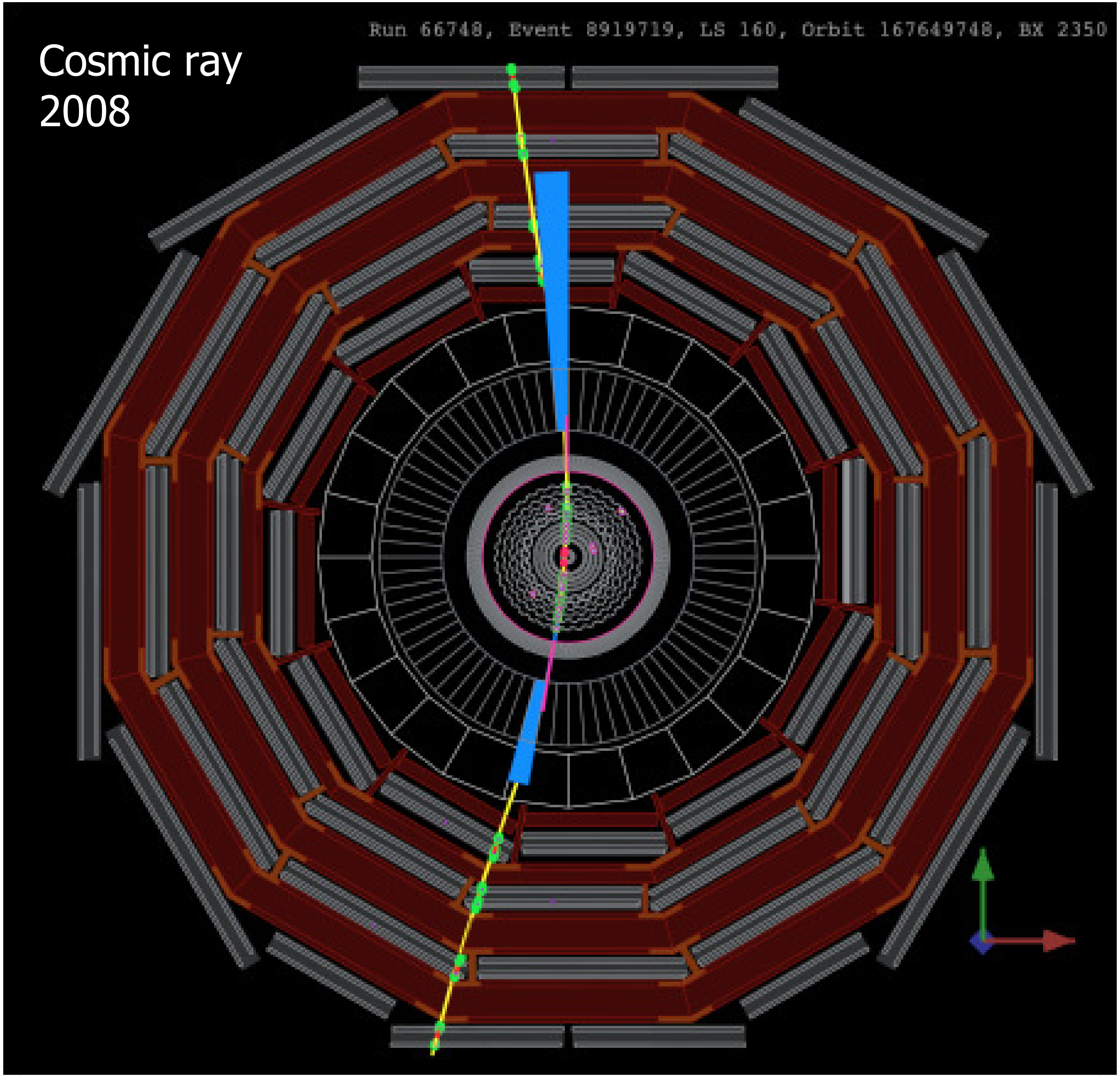
« outside-in »: fit muon hits and search for combatible tracker-track = Global Muon

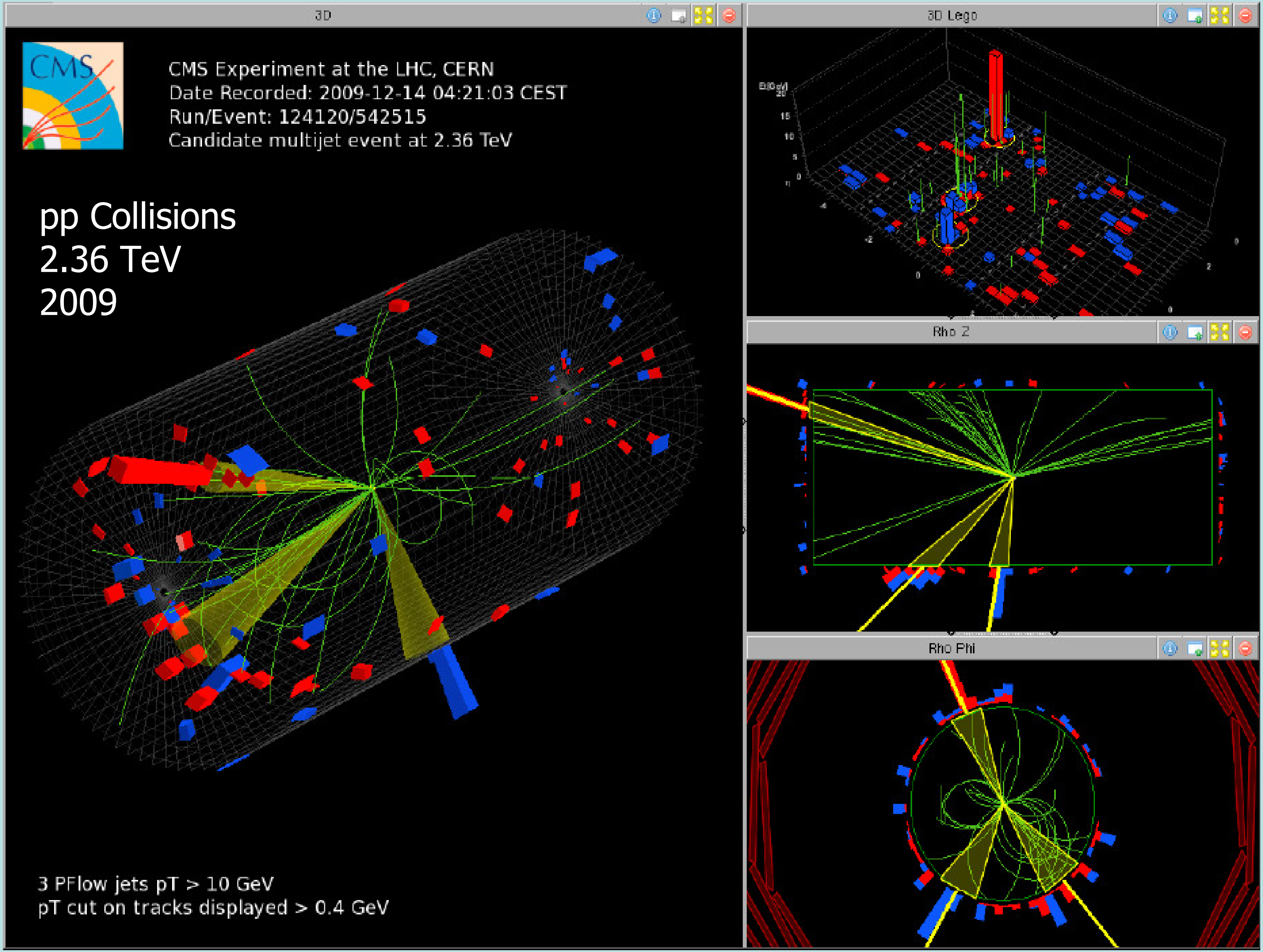
« inside-out »: match tracker tracks with mu segments = Muon Track

From dream to reality:



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

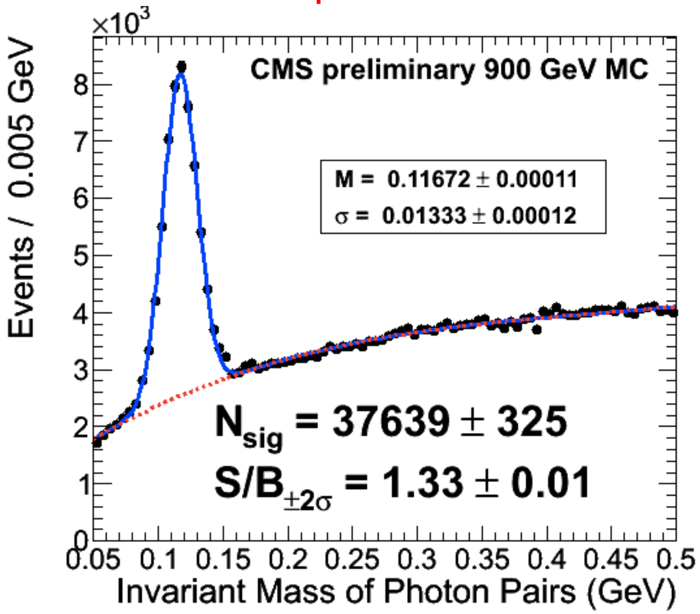

Run 66748, Event 8919719, LS 160, Orbit 167649748, BX 2350
Cosmic ray
2008



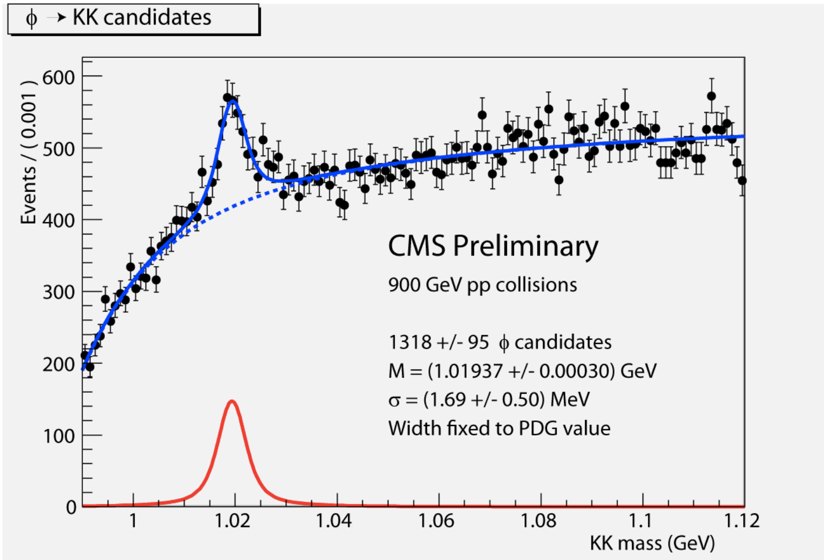
3D
CMS Experiment at the LHC, CERN
Date Recorded: 2009-12-14 04:21:03 CEST
Run/Event: 124120/542515
Candidate multijet event at 2.36 TeV
pp Collisions
2.36 TeV
2009
3 PFlow jets pT > 10 GeV
pT cut on tracks displayed > 0.4 GeV
3D Lego
Rho Z
Rho Phi

From Commissioning to Physics

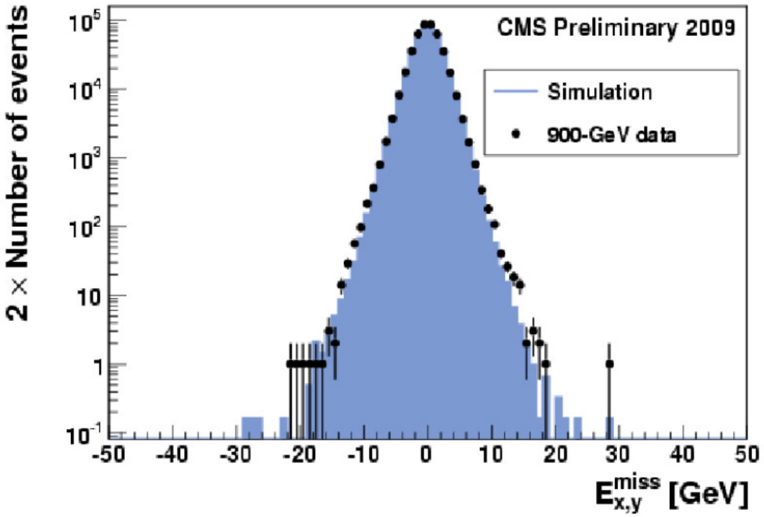
ECAL π^0 with a priori MC corrections:



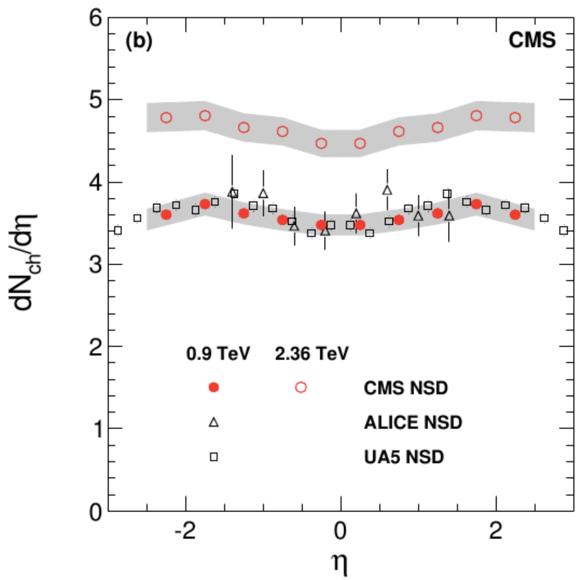
$\Phi \rightarrow K+K-$ using dE/dX selection:



Missing ET components from Pflow objects:



First publication with collision data dN/dη:



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


New York
9/11 2001
Microsoft Windows 95
Adam Malysz
World
Champion
OK COMPUTER
RADIOHEAD
1997
IN / RAINBOWS
2004
Tian'anmen
1989
The
END
USSR 1991
O HEAD
2008
Google
TV On The Radio
DEAR SCIENCE
DOLLY
1996
Tsunami
2004
FRANCE
World Champion
1998
Europe 2004
Lech Walesa
Berlin 1989
... the clone
John Paul II
1991
Irak 2003

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

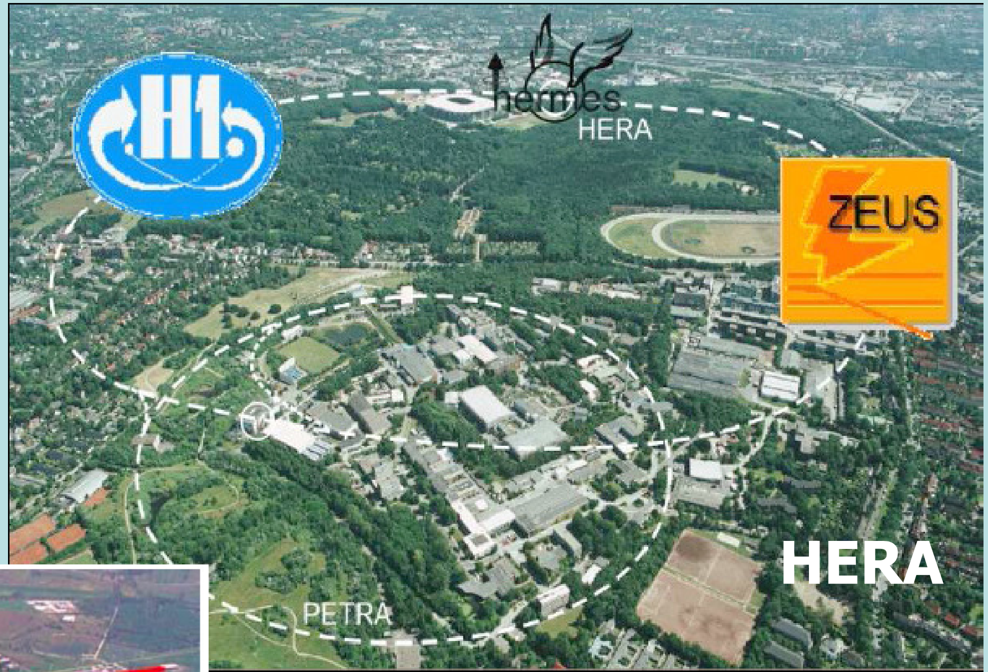
The Physics World

… at the LHC Start-up

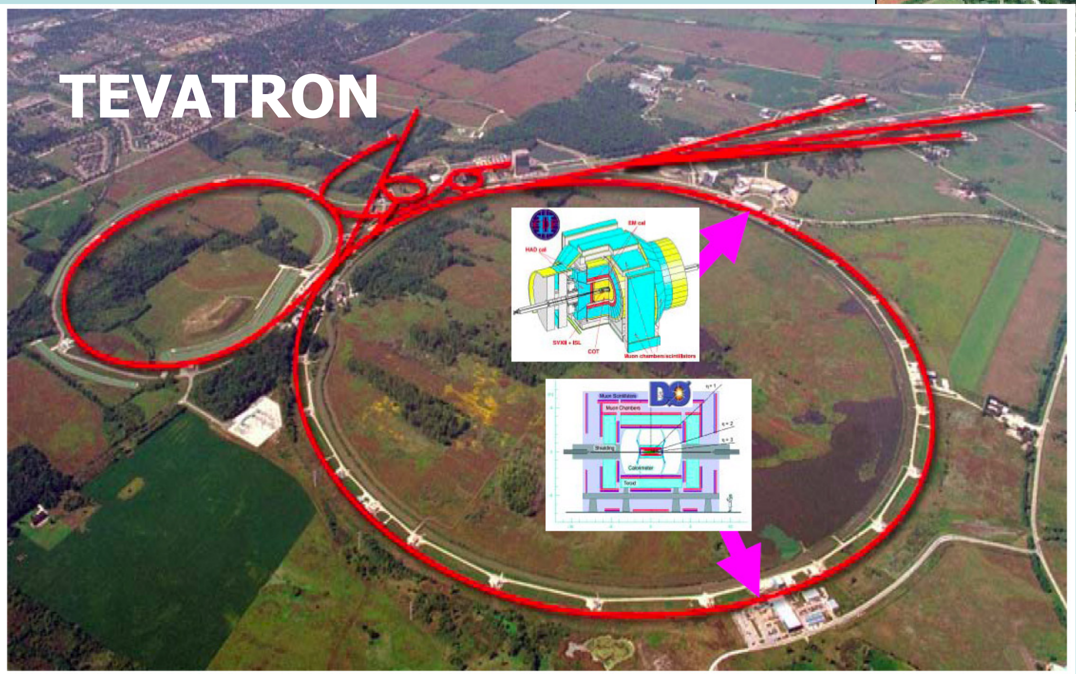
20 years later

Electroweak & QCD Physics

1989-2000



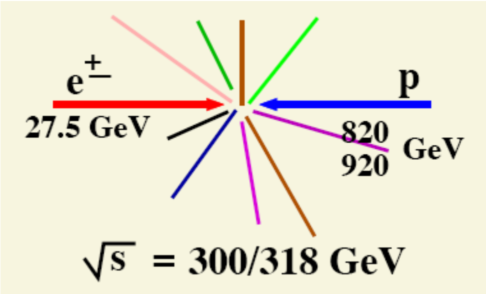
1992-2007



1989-2011

QCD and the Proton Structure at HERA

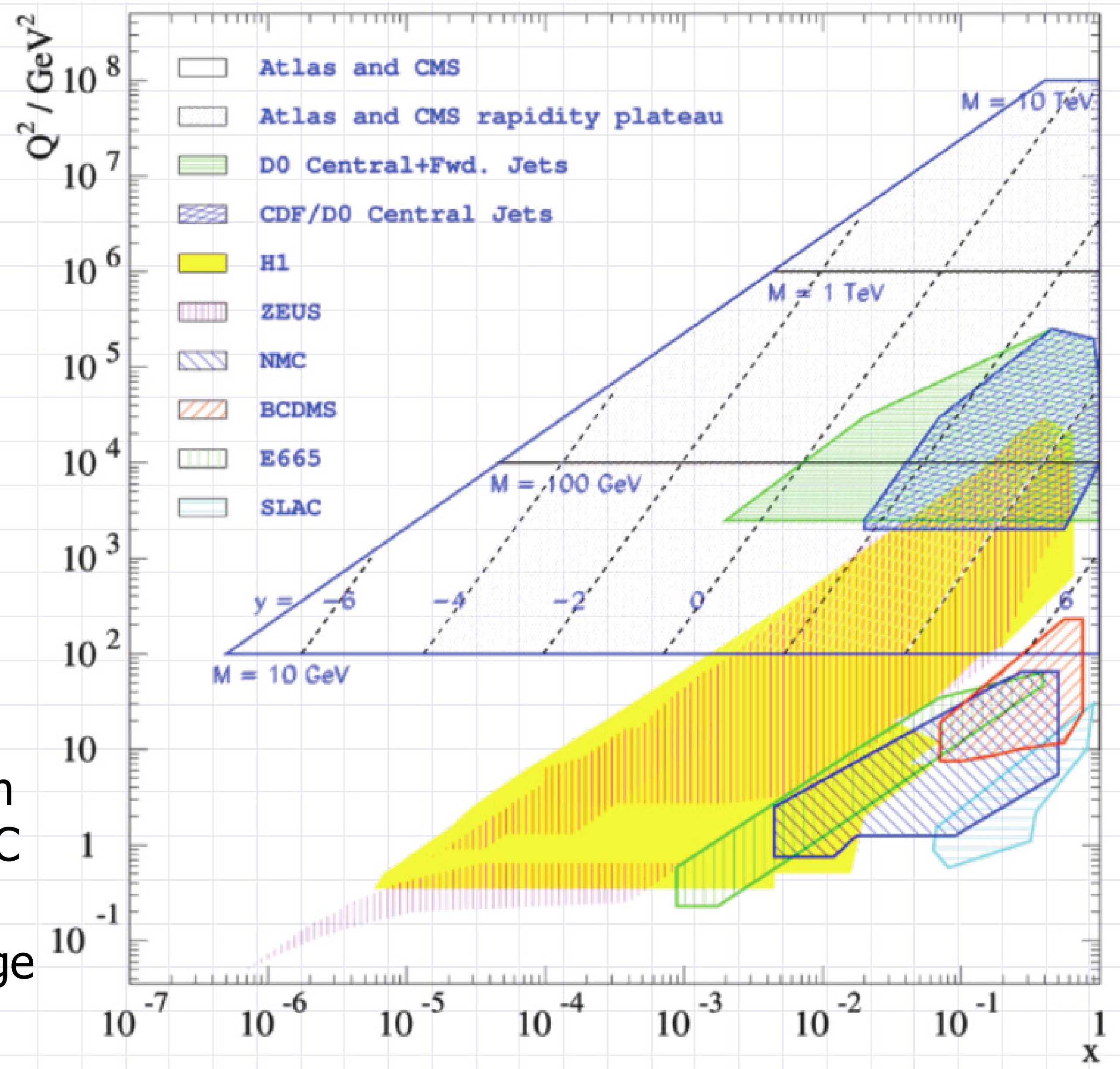
HERA ep Collider



H1 and ZEUS experiments

~ 0.5 fb^{-1} / exp. balanced between e$^+$p and e$^-$p

- Considerable extension of the explored phase space in x and Q^2
- Pdf's constraints in a domain relevant for TeVatron and LHC Colliders
- The rms radius of the charge in the quark found < 10^{-3} fm

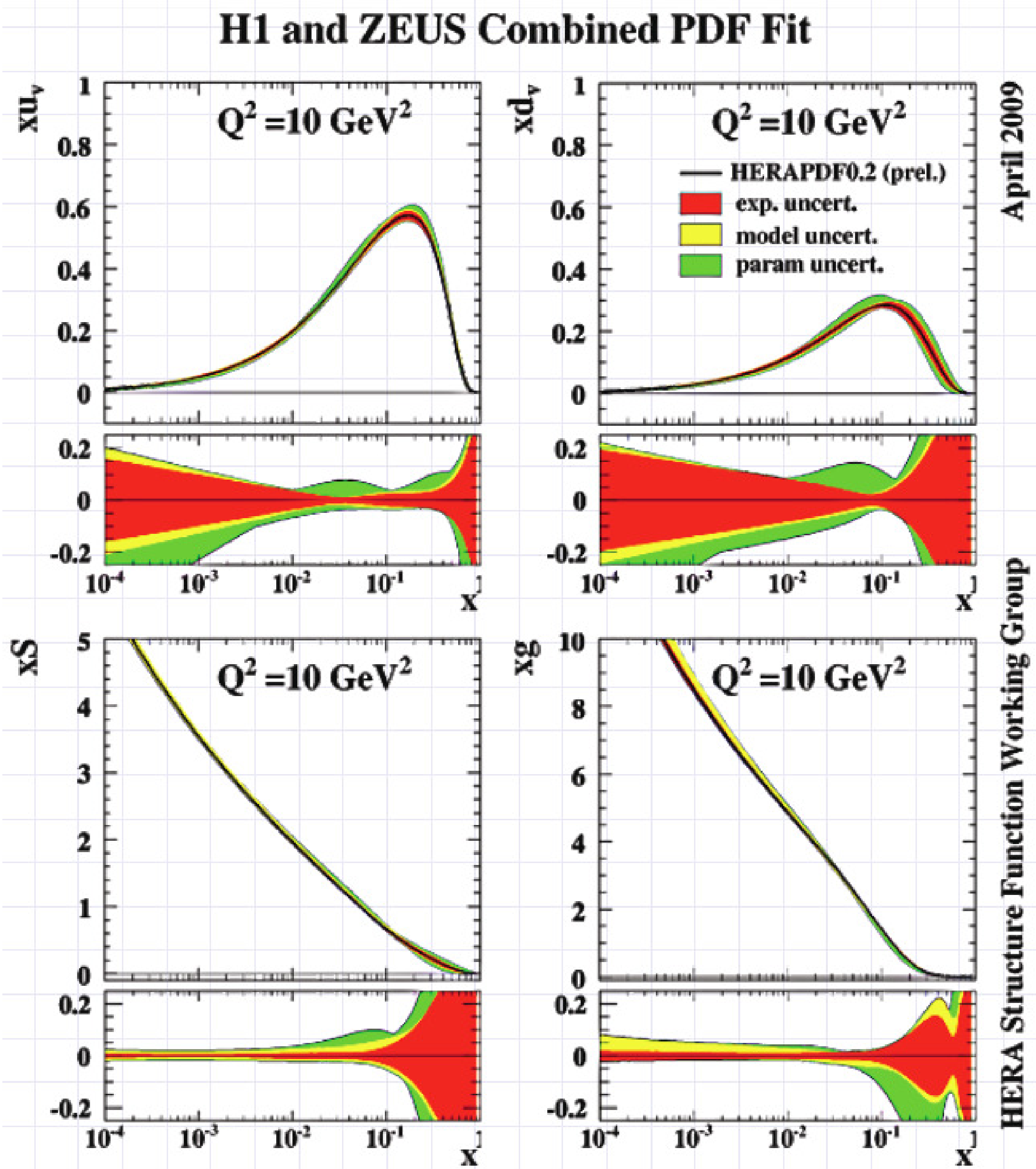


Structure Functions at HERA

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

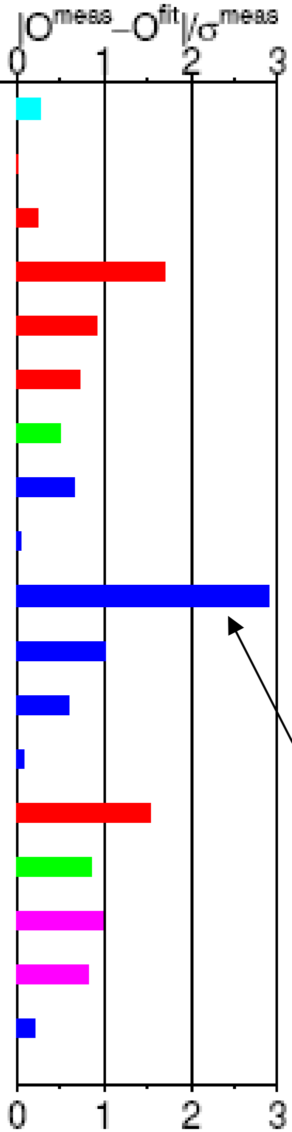
Fully consistent account of experimental, modeling and parametrization errors !

- 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]



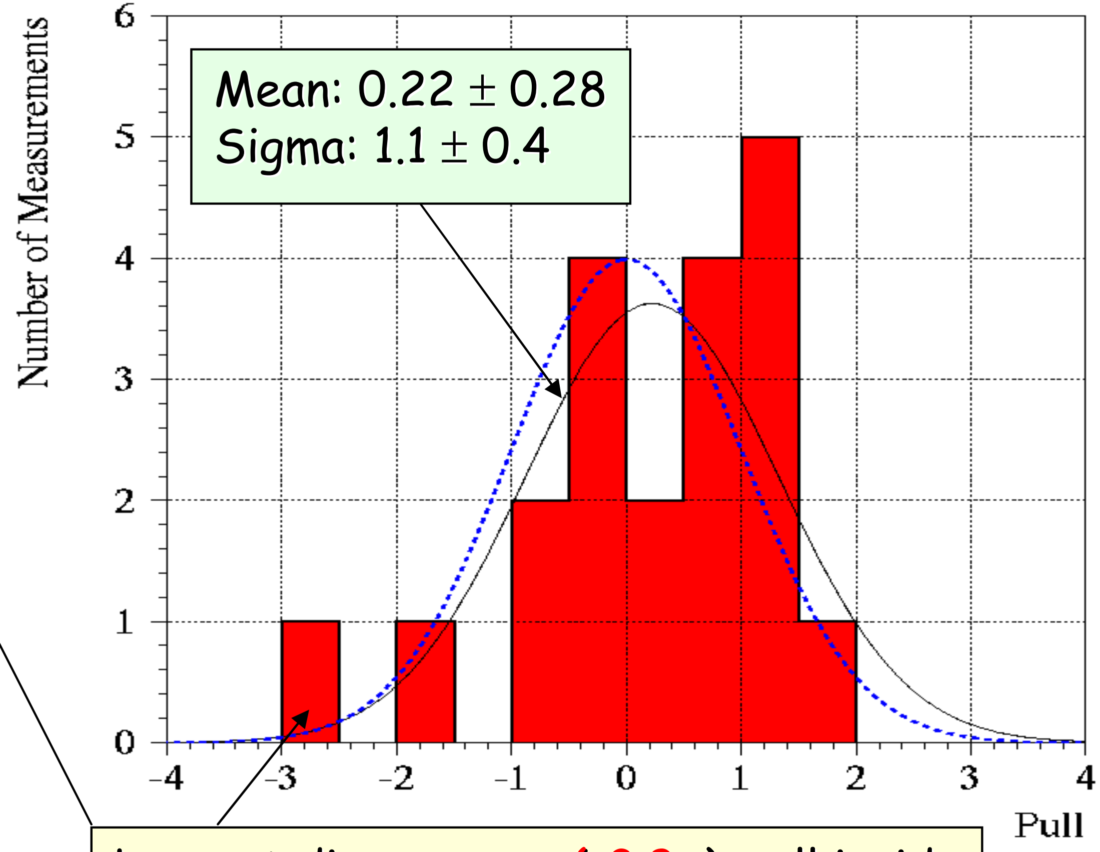
Precision Electroweak Physics at LEP

	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 ?

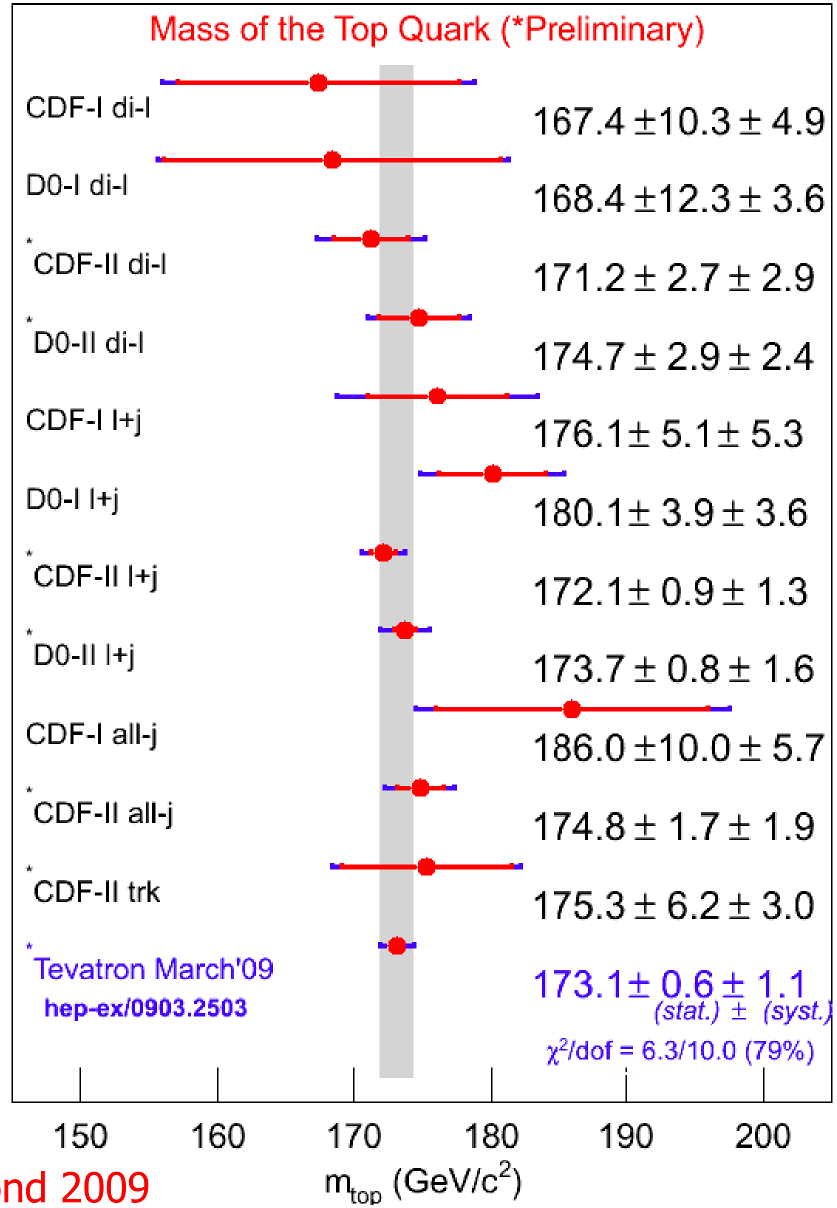
Pull distribution = Normal Gaussian ?



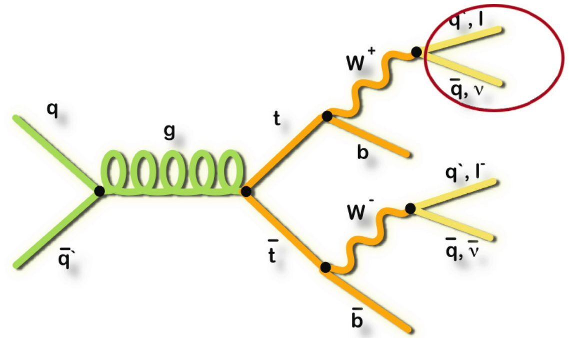
Largest discrepancy (-2.9σ) well inside statistical expectation;

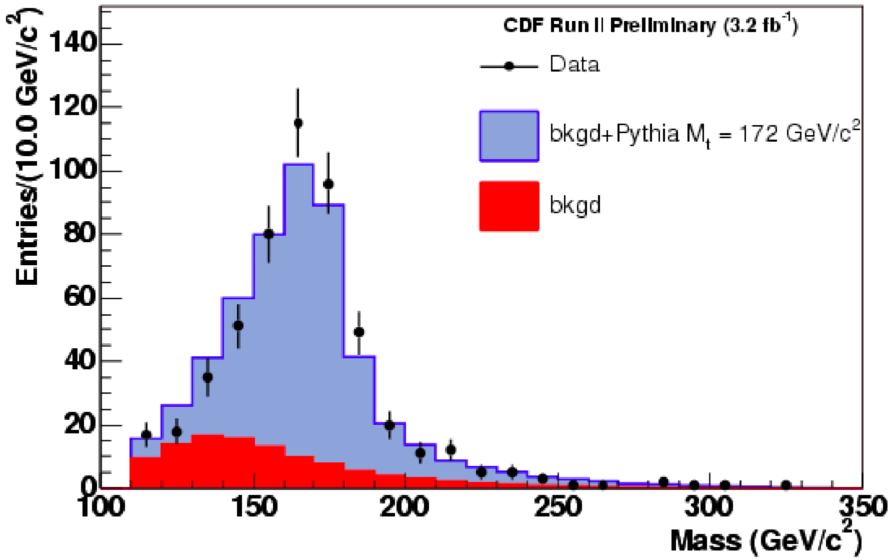
χ^2 probability = 8%. Just fine.

Top Mass Measurement at Tevatron



Moriond 2009





Tevatron Average:

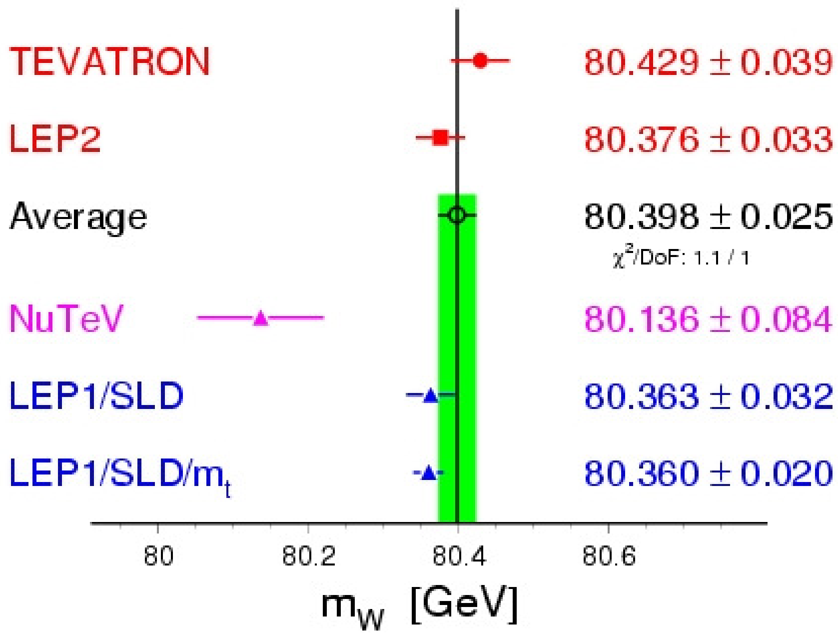
M_{top} = 173.1 ± 1.3 GeV

1.3 = 0.6 (stat.) ⊗ 1.1 (syst.)

$\Delta M/M < 1\%$!!! $\Delta M \propto 1/\sqrt{L}$!!!

W Mass Measurements

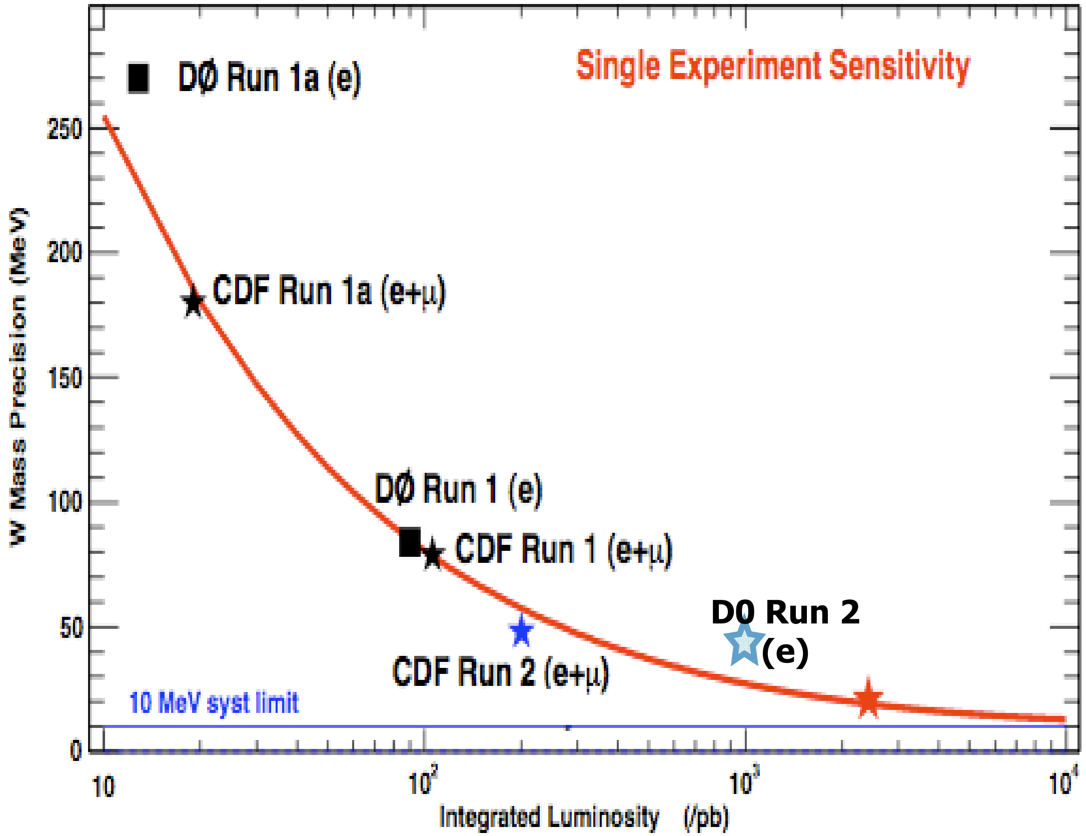
LEP



$m_W(\mathrm{LEP}) = 80.376 \pm 0.033$

Systematics: Beam energy, FSI

Tevatron



m_W (Tevatron)= 80.420 ± 0.031

- Good consistency between colliders
- Will be difficult to beat

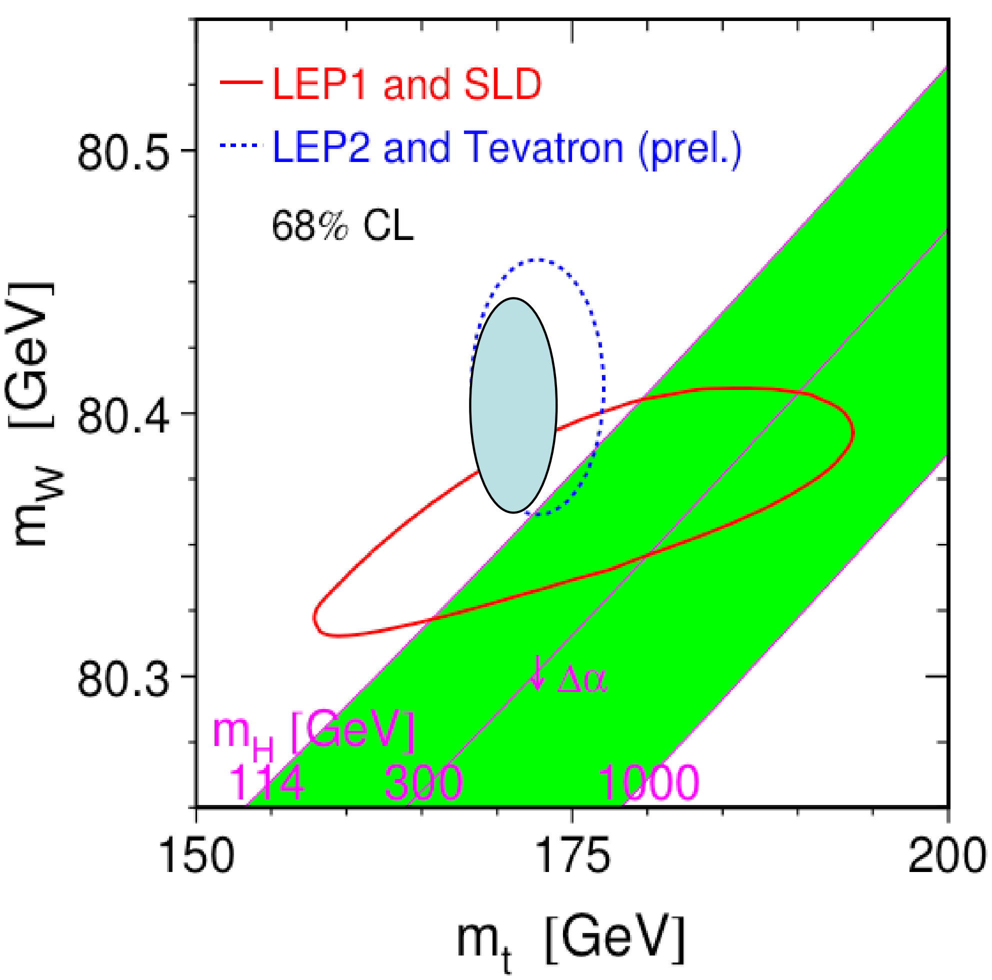
World Average:

$M_W = 80.399 \pm 0.023$ GeV

Precision Measurements … and M_H

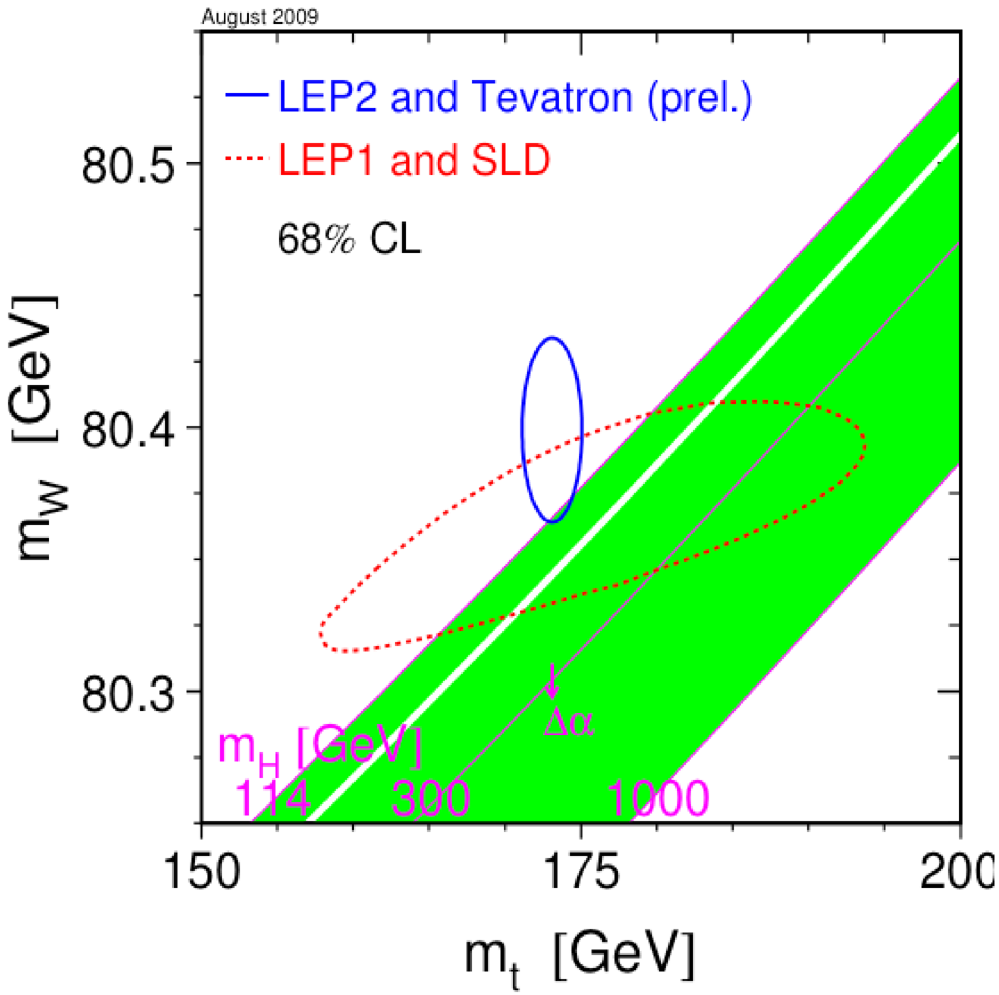
DG1 Talk: Massimo Casarsa

EPS HEP 2007



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

LP 2009



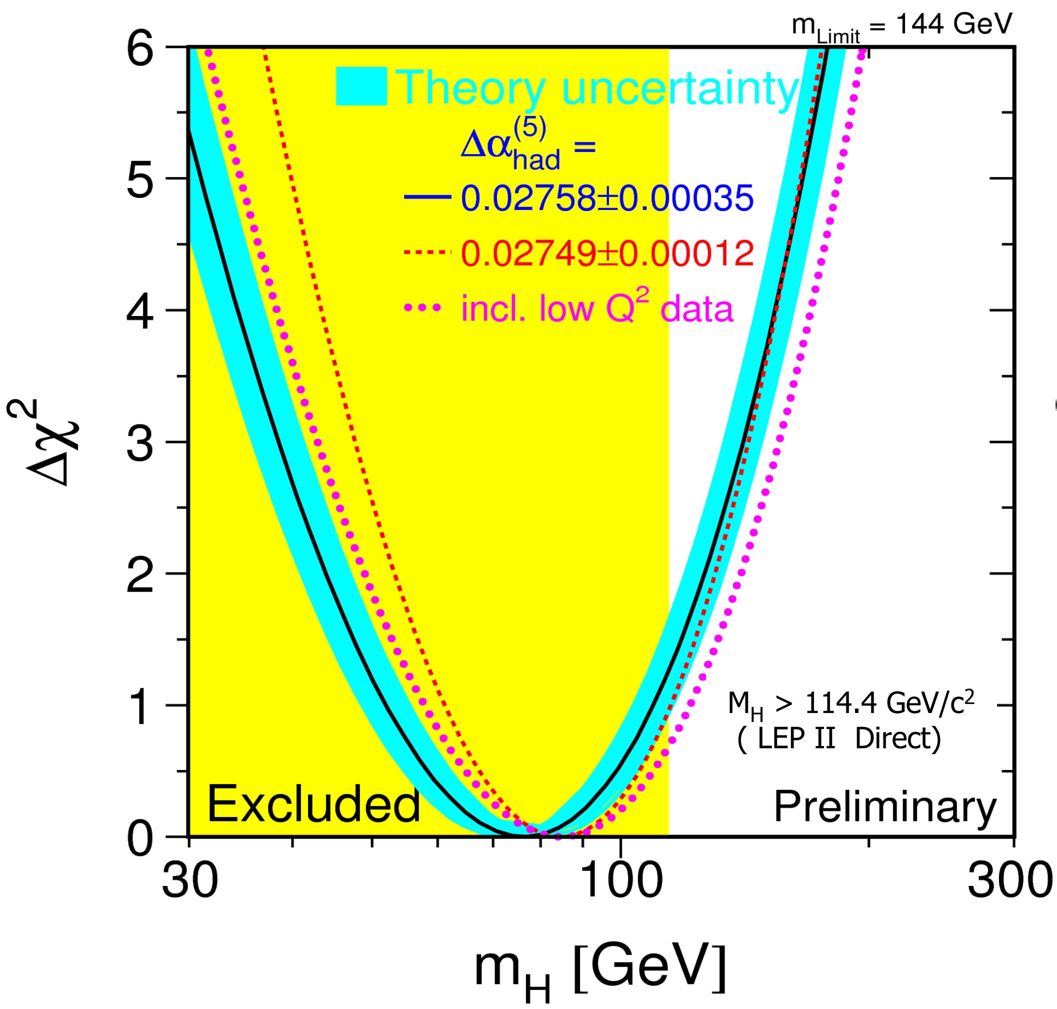
Too light ! .. Physics beyond SM ?

$\Rightarrow$ priority = precision on M_W

Precision Measurements ... and M_H

Polytechnique

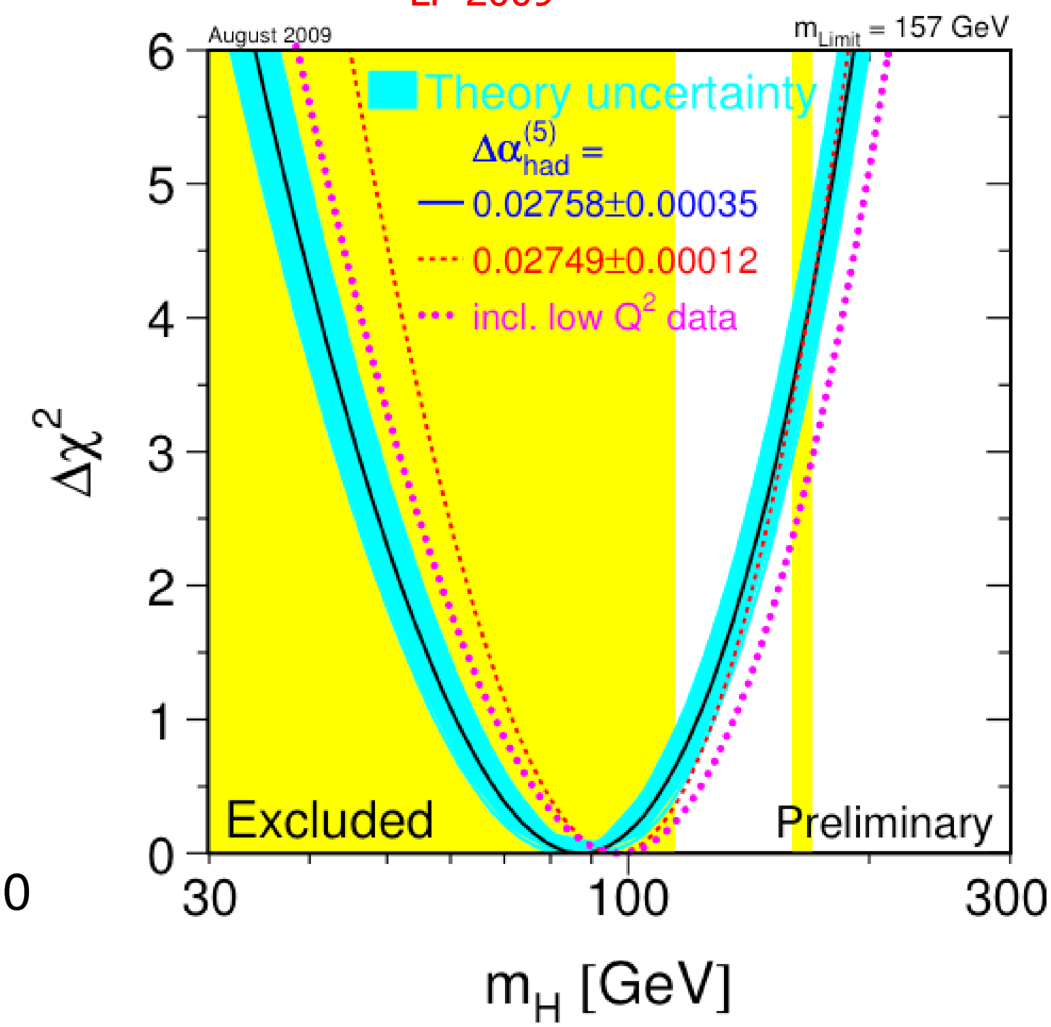
EPS HEP 2007



M_H < 182 GeV/c² at 95% CL

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

LP 2009

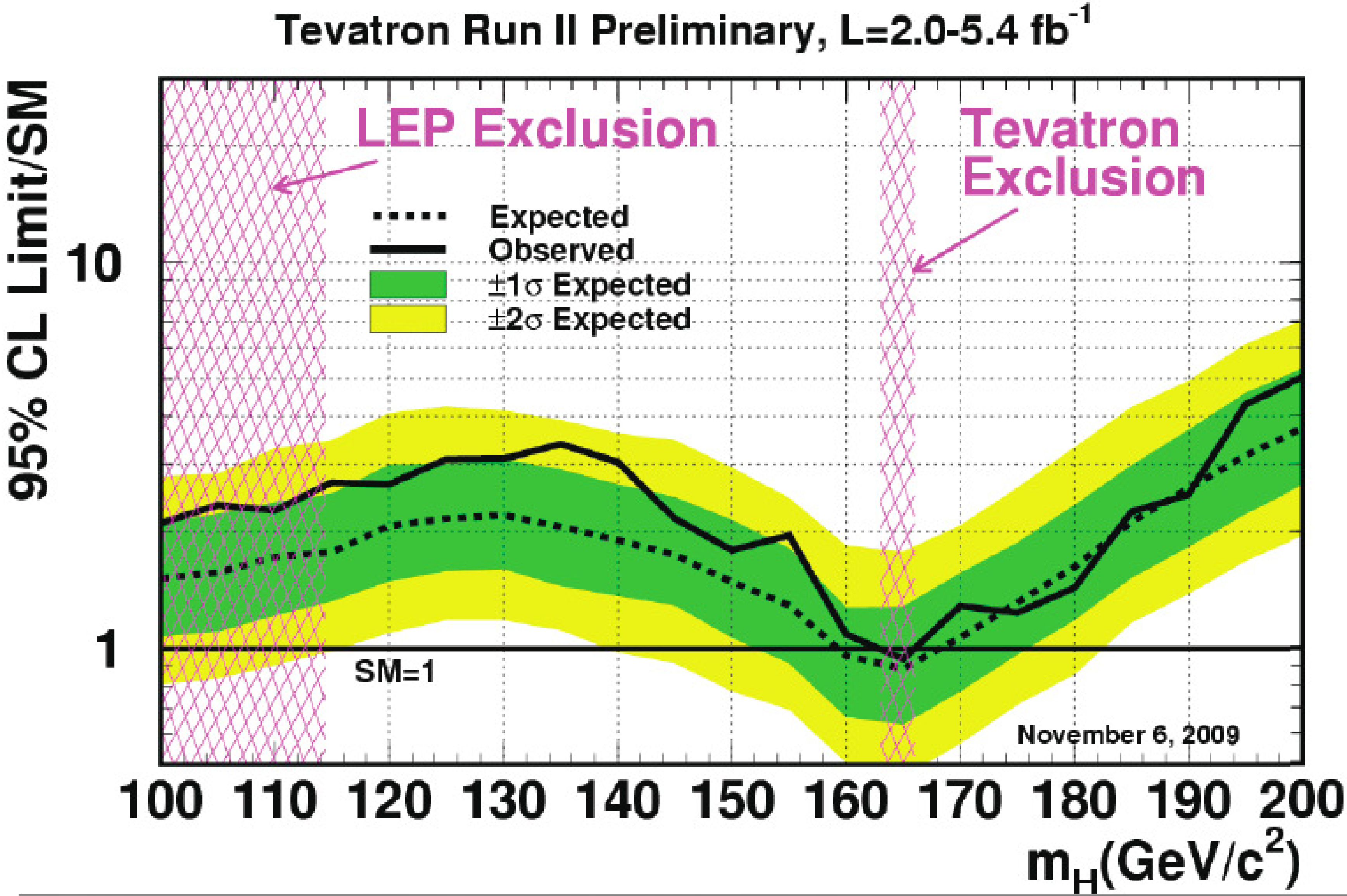


M_H < 186 GeV/c² at 95% CL

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

SM Higgs Search at the TeVatron

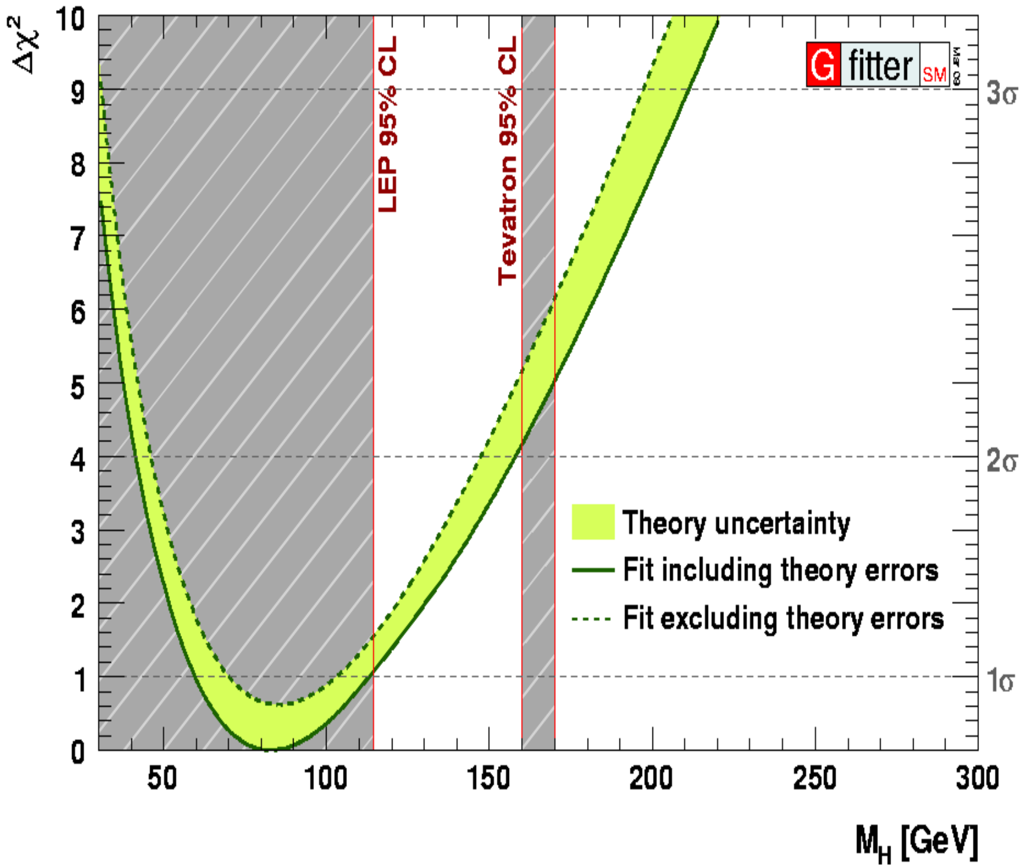
New update (last week at HCP2009)



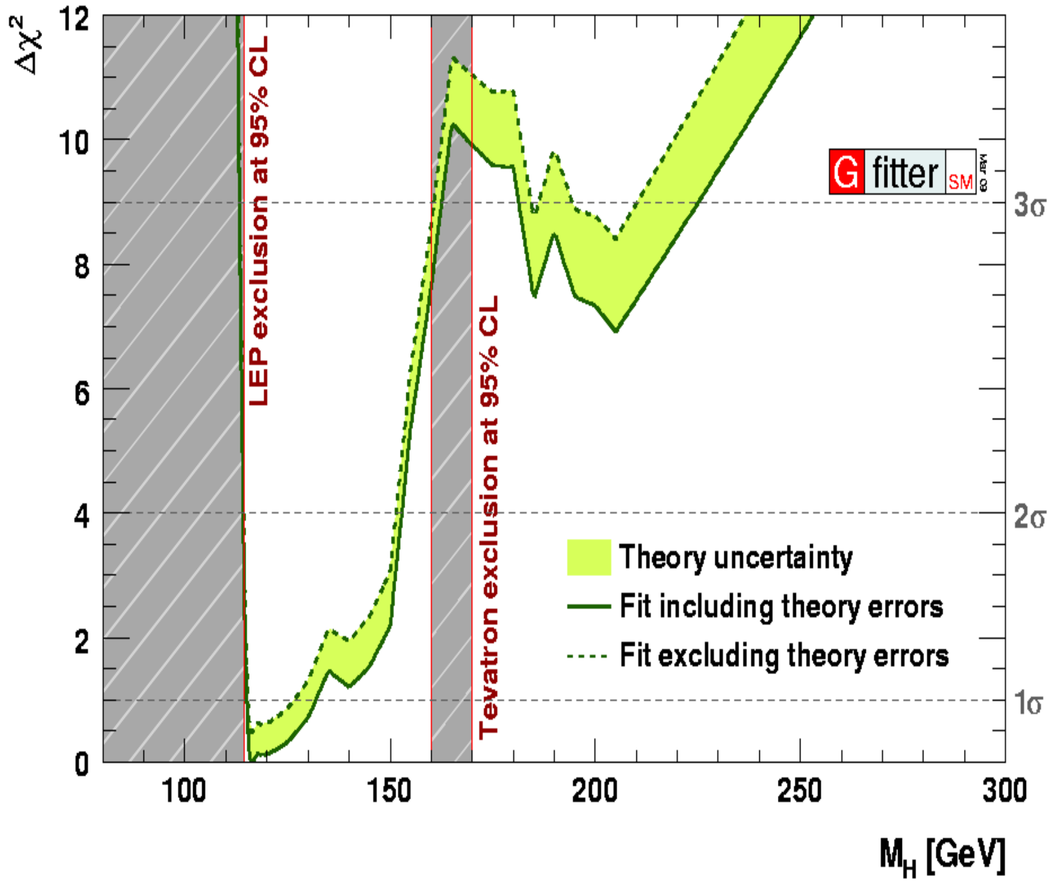
Excluded
163-166 GeV
Expected
159-168 GeV

(95% CL)

SM Higgs Fit - GFitter



Standard fit
(Indirect constraints only)



Complete fit
(Indirect and direct constraints)

SM Higgs Excluded at ~ $2M_W$ … is it ?

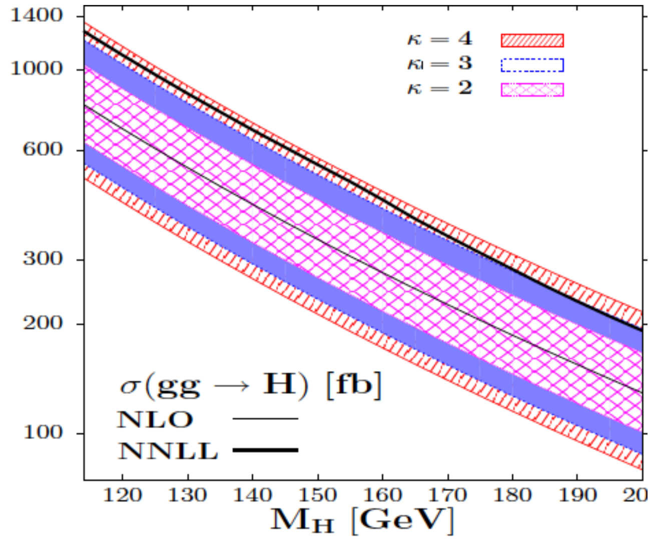
Polytechnique

Provocative talk by Abdelak Djouadi, Moriond 2010

- The K factors are extraordinarily large:

$\sigma_{LO} \approx \sigma_{NLO} \approx \sigma_{NNLO}$ "perturbation theory almost jeopardized !"

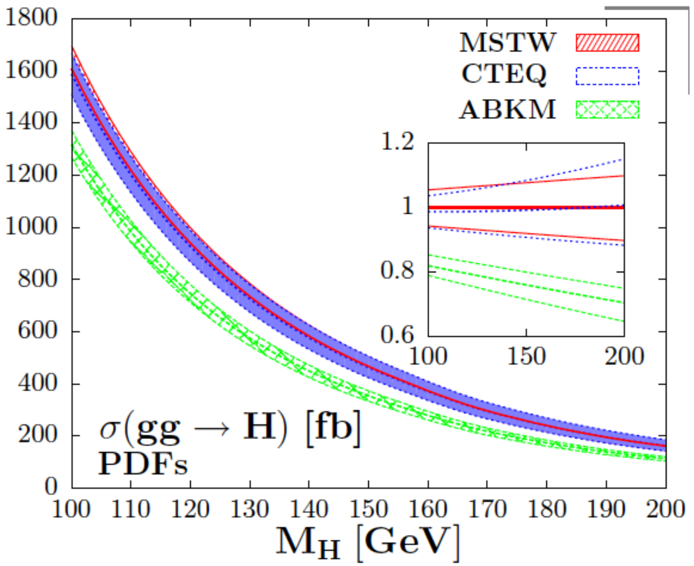
Need K=4 for σ_{NLO} band to catch σ_{NNLL}



- σ_{CUTS} at NNLO differs from σ_{TOT} at NNLO by ~25%

"Tevatron experiments use NNLL … they should rather stick to NNLO"

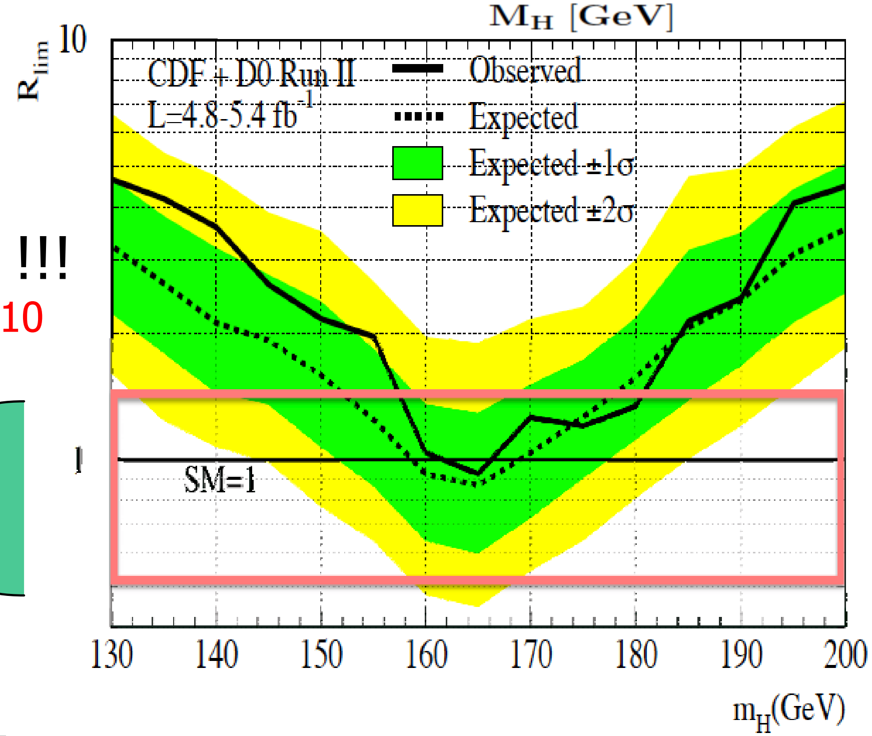
- A ~25% difference in pdf's central value due to …$\Delta\alpha_s$ (exp)



~ 40% SM uncertainty !!!

A.D. Moriond 2010

scale & pdf's+σ



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 ?

Polytechnique

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

Symmetry

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

M_H

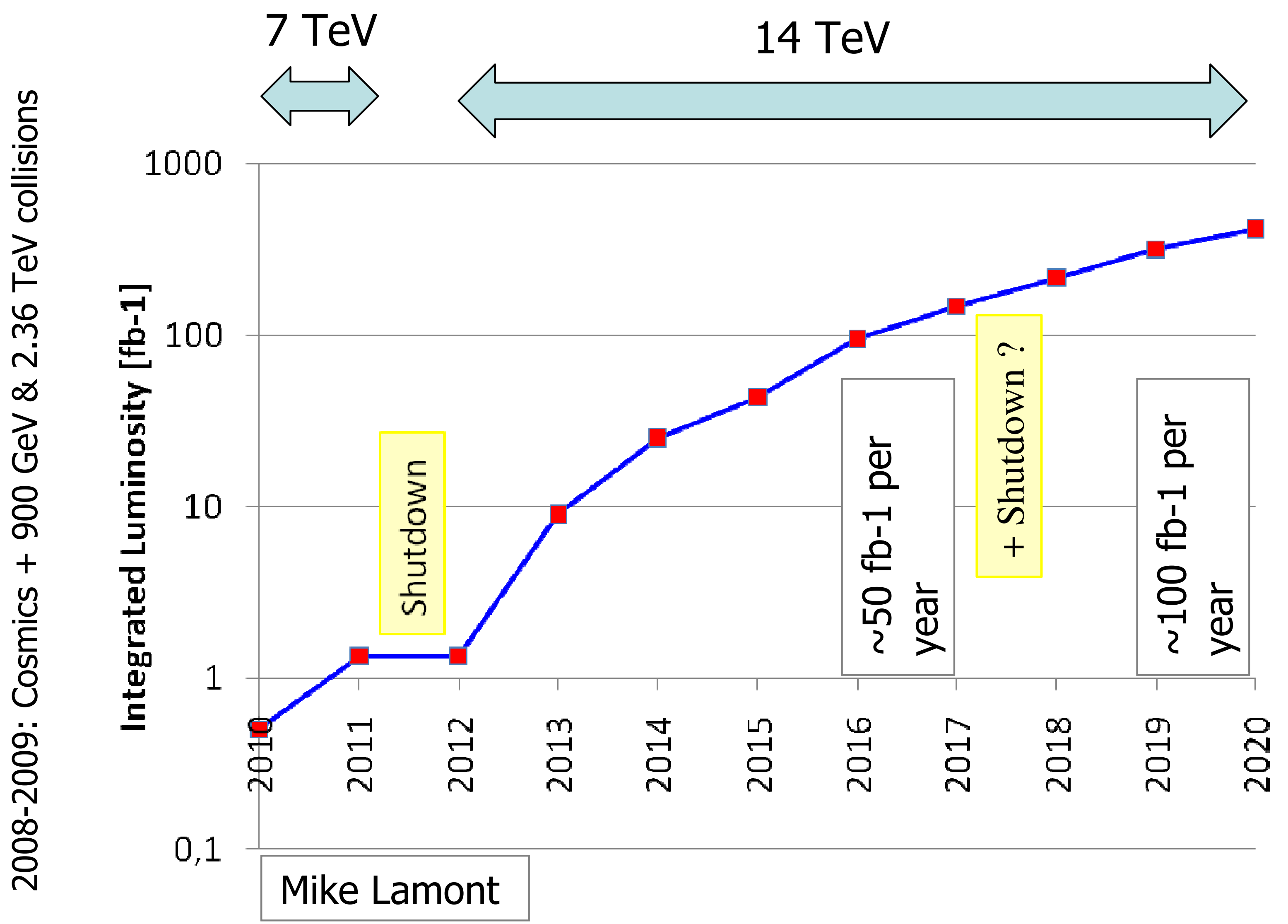
TECHNICOLOR | **HIGGSLESS** | **EXTRA DIMENSIONS**

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

Dynamics

LHC Expectations

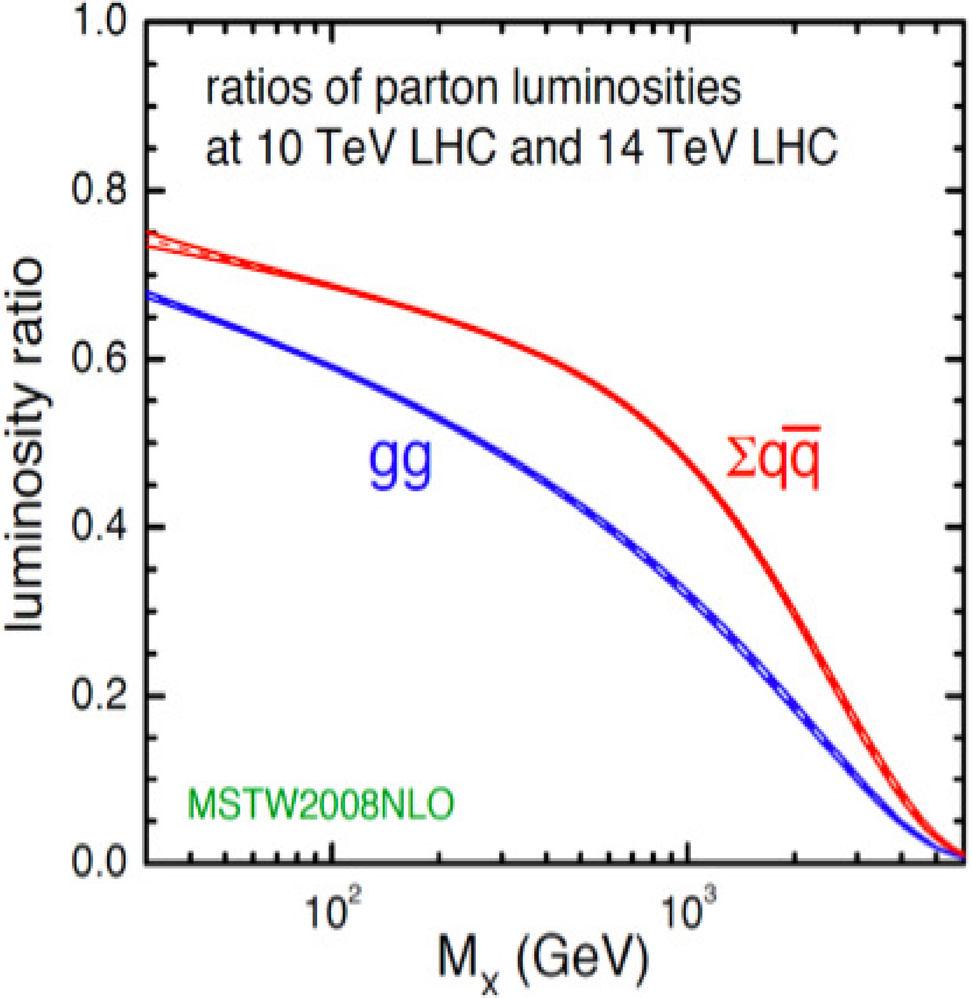
P. Jenni, Moriond 2010



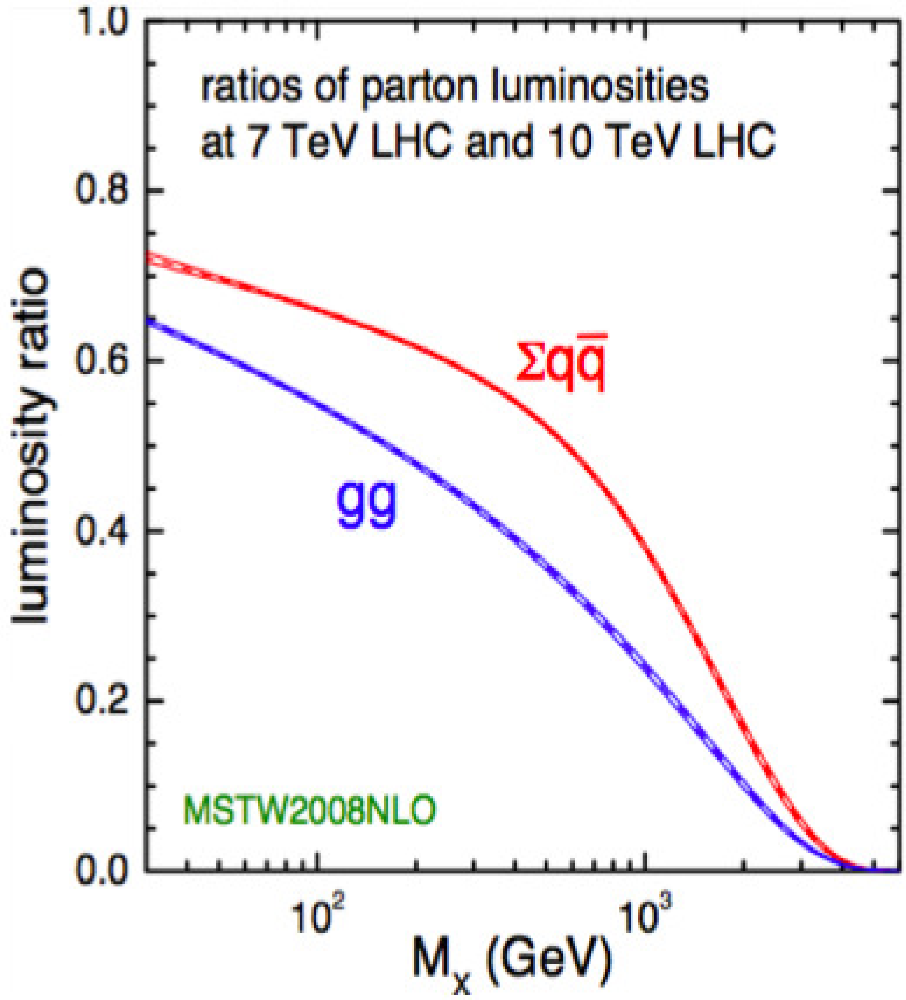
Ultimate sLHC exploitation at 1000 fb-1/year by 2030 ?

CMS PTDR Prospective (30 fb-1/14 TeV) relevant in ~2015

LHC vs LHC

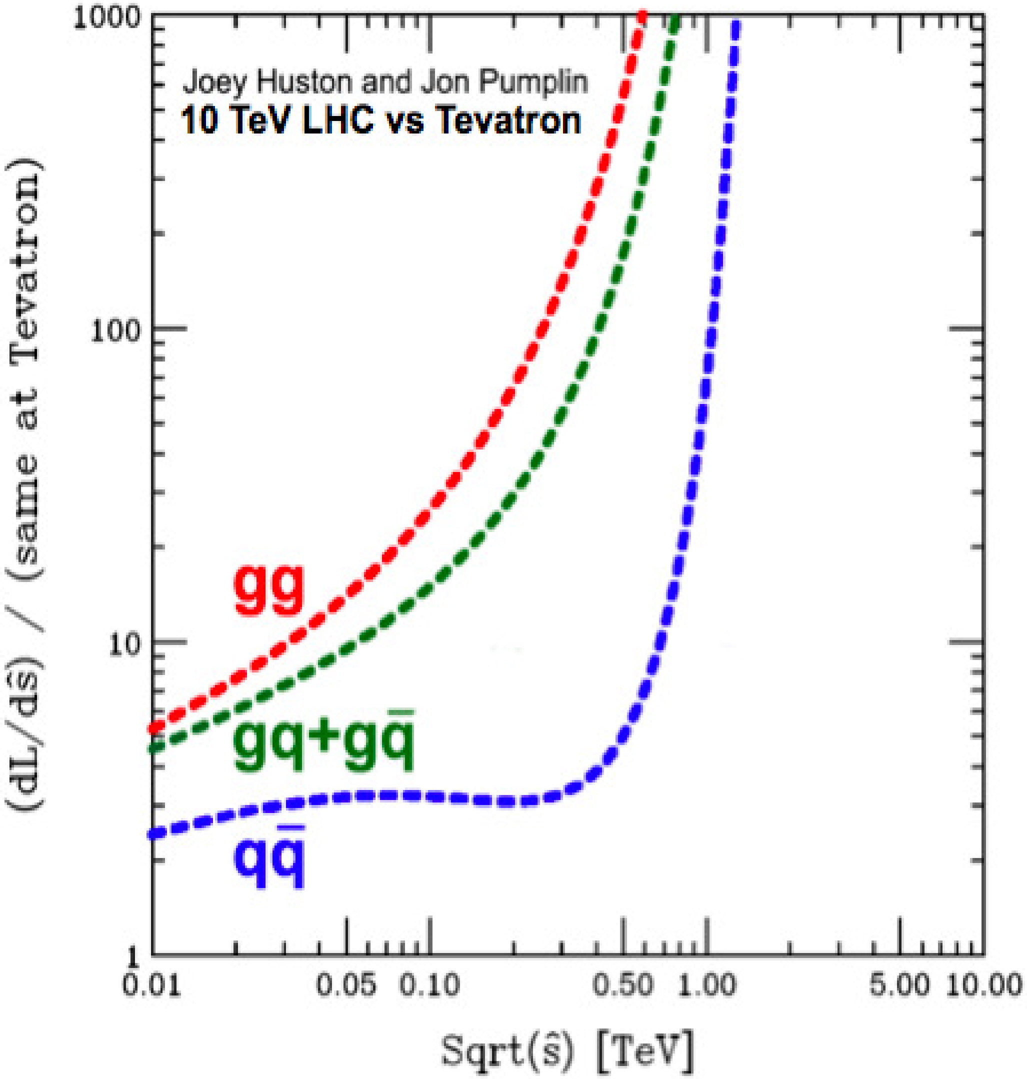


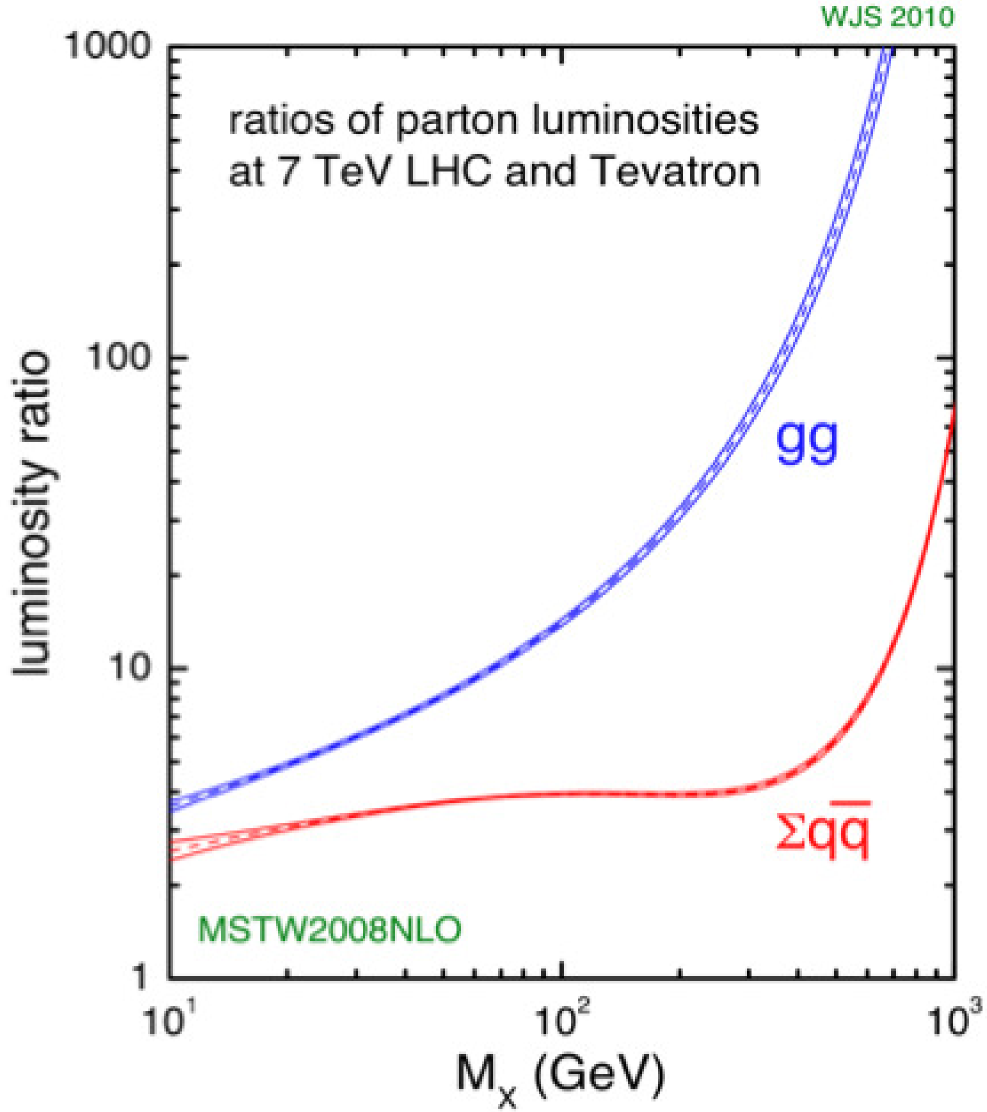
ratios of parton luminosities
at 10 TeV LHC and 14 TeV LHC
luminosity ratio
gg
$\Sigma q\bar{q}$
MSTW2008NLO
M_X (GeV)



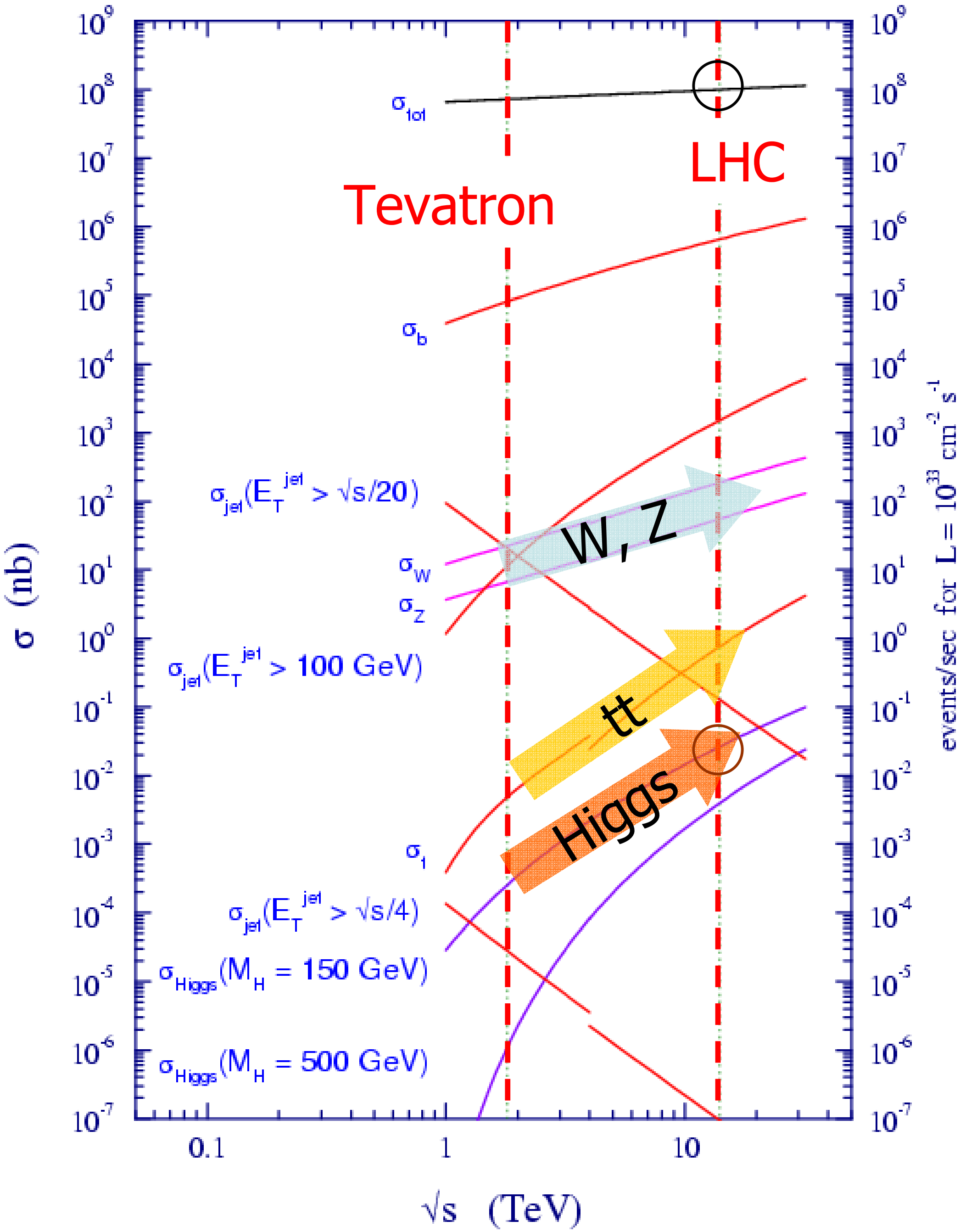
ratios of parton luminosities
at 7 TeV LHC and 10 TeV LHC
luminosity ratio
gg
$\Sigma q\bar{q}$
MSTW2008NLO
M_X (GeV)

LHC vs Tevatron





Evolution of the Cross-Sections



e.g. SM $gg \rightarrow H$ avec $H \rightarrow ZZ^*, WW^*$

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

Ratio of Higgs to EW cross-sections favorable !

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

Relative increase of the tt background

e.g. $H \rightarrow ZZ^* \rightarrow 4l \quad l=e,\mu$

$M_H = 150$ GeV/c^2

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

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

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

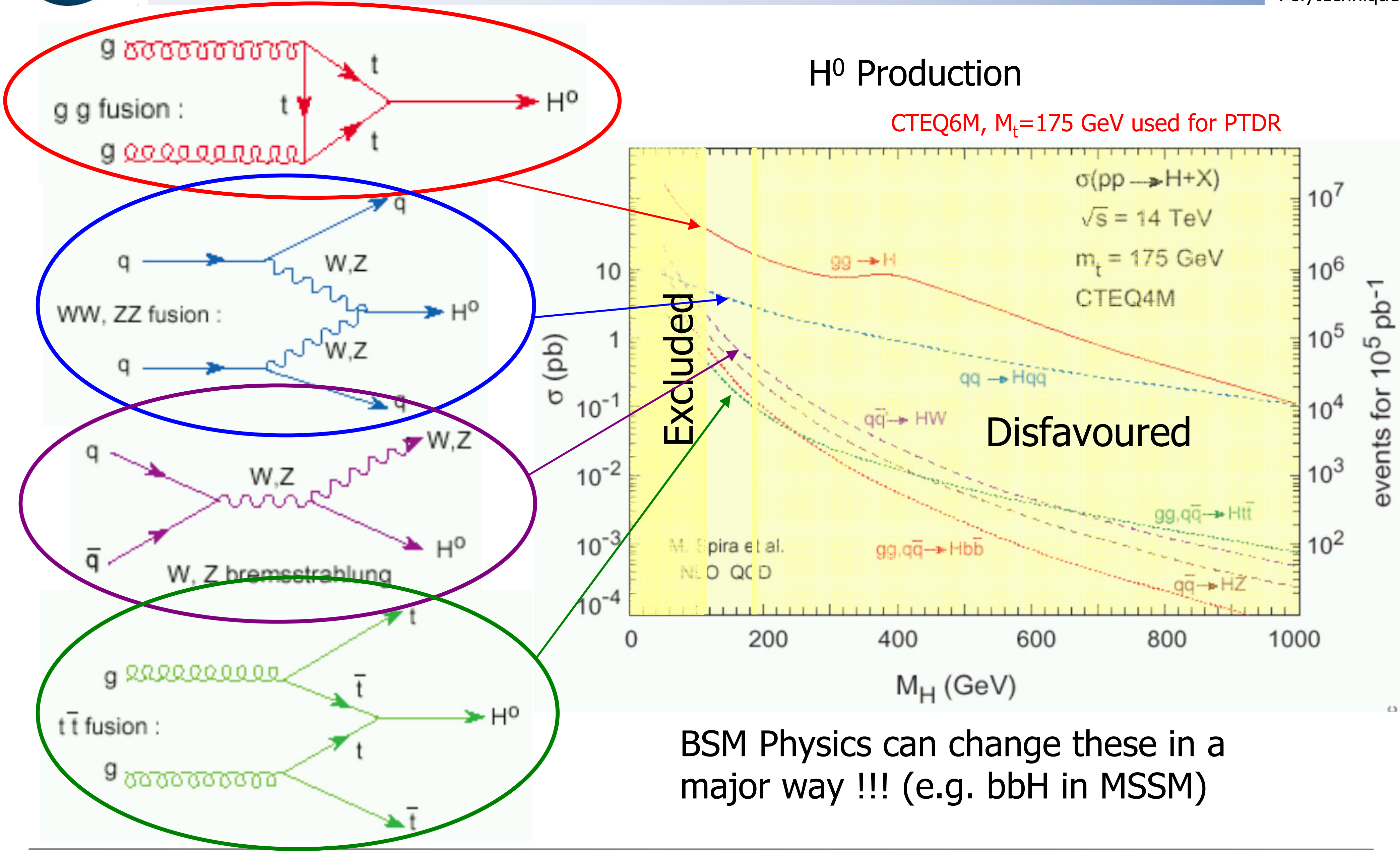
Higgs @ LHC $\Rightarrow$ state of the art of "hadron collider" and "rare decay techniques"

Higgs boson(s) Searches

… from the l-LHC to the s-LHC

A New Decade

Production Modes and Cross-sections



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

Observability

M_H < 140-150 GeV

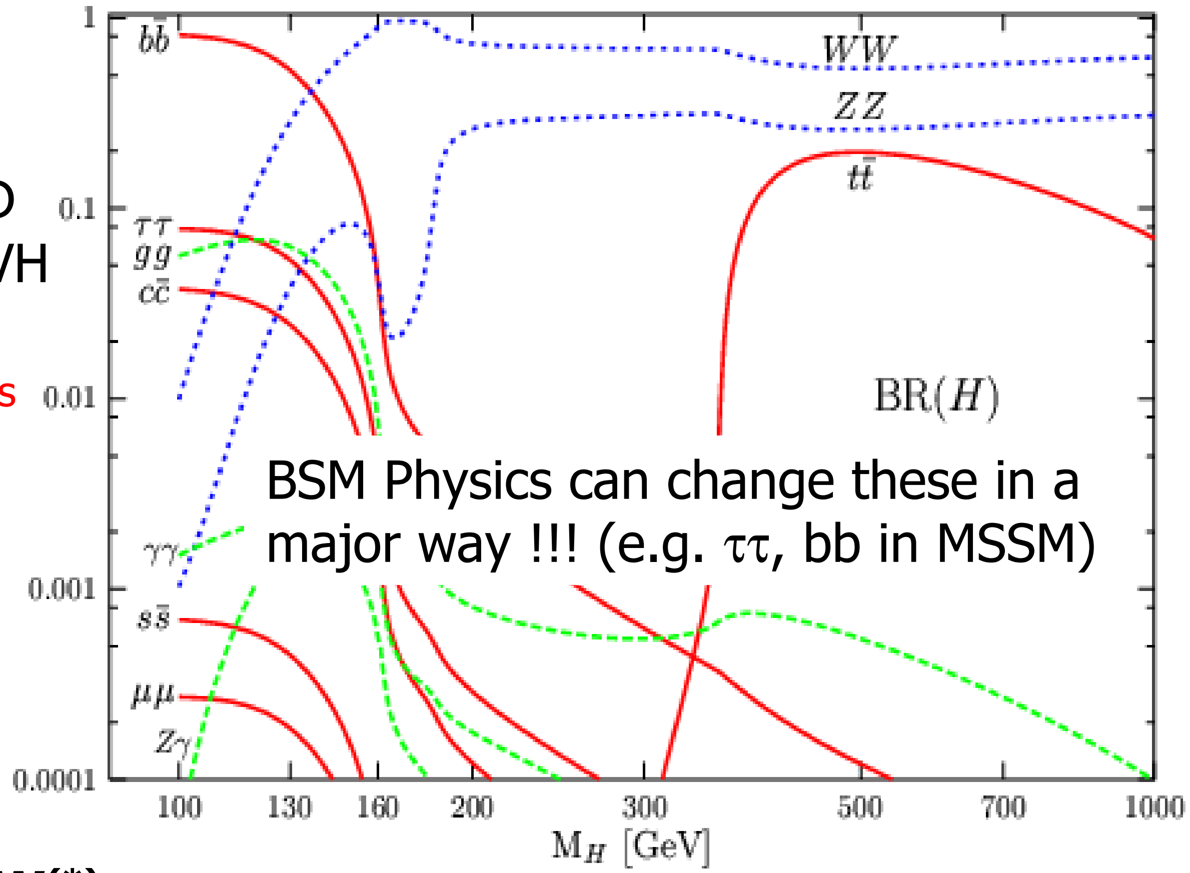
H → bb
Dominant mode … but crippling QCD background … exploitable in ttH or VH associated modes ?

e.g. G. Salam et al. boosted H, "fat" jets

H → $\tau^+\tau^-$
Exploitable at low M_H in The VBF production mode

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

A. Djouadi, hep-ph/0503172



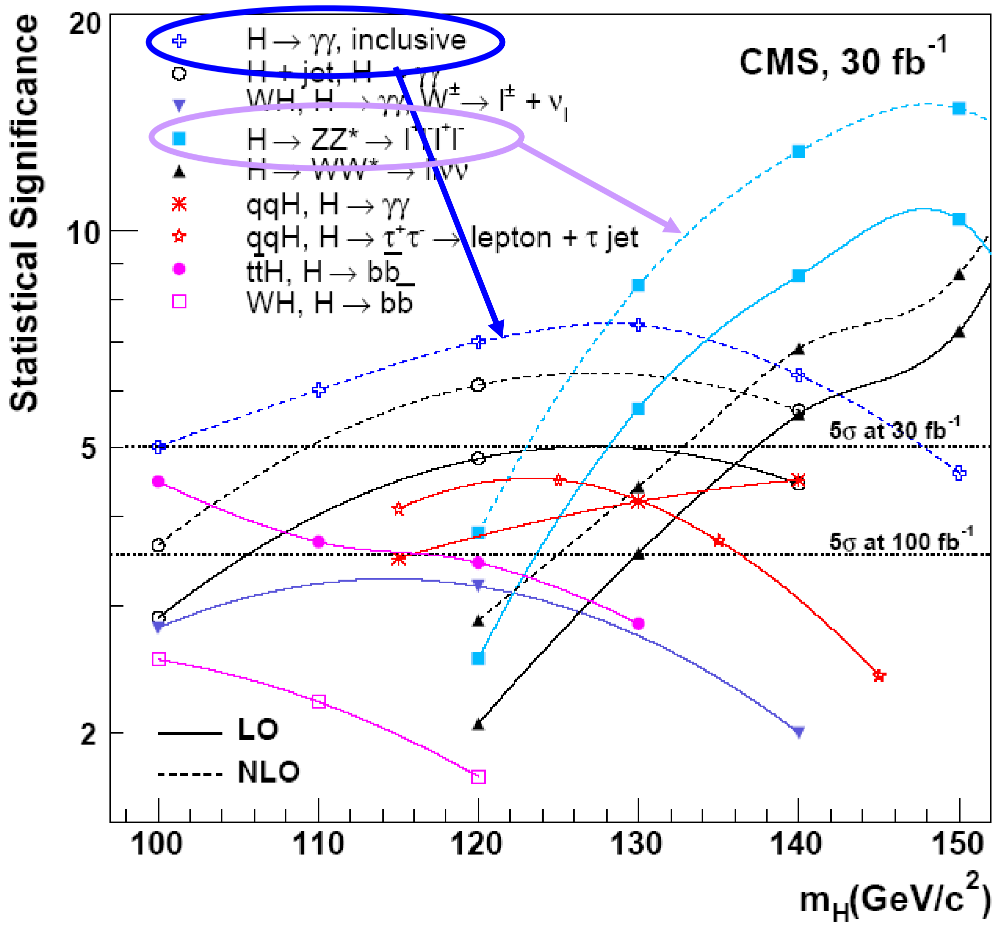
M_H > 125-130 GeV

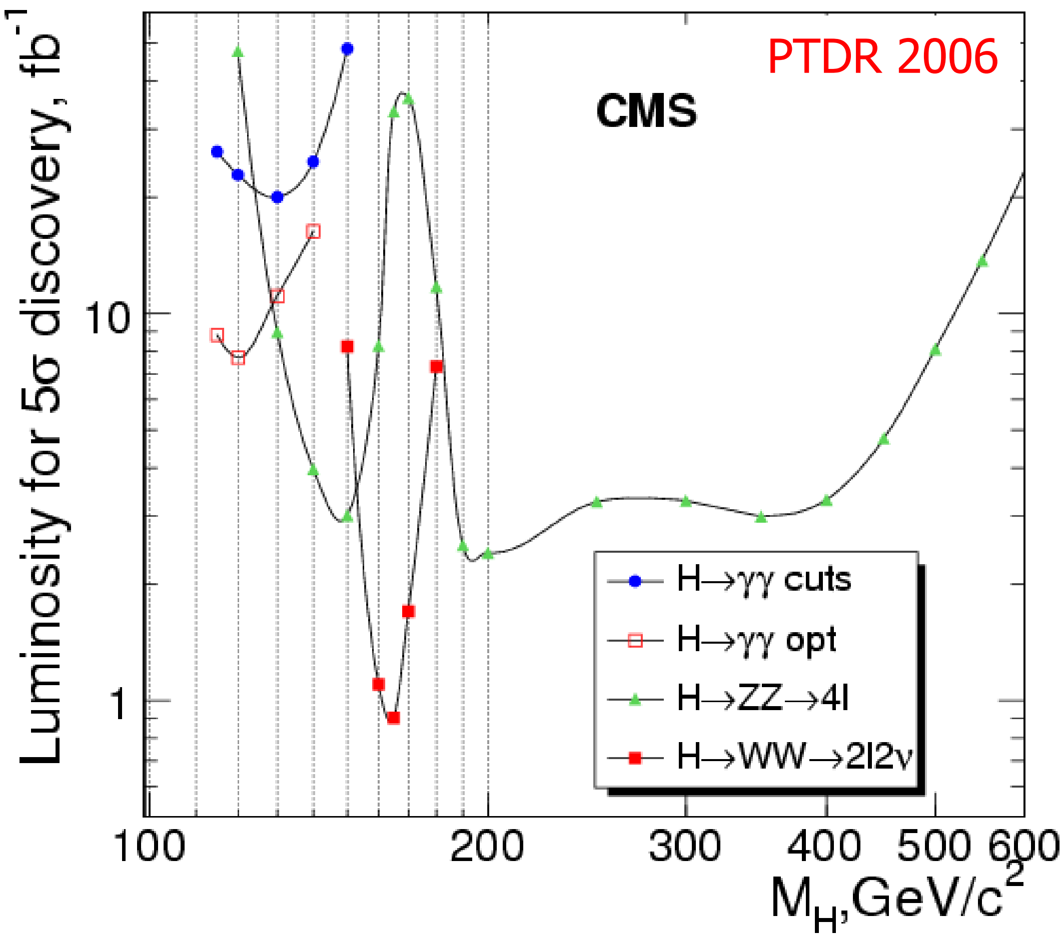
H → WW$^{(*)}$
Dominant mode, $l^+\nu l^-\nu$ channel optimal for M_H = 2 M_W ; $l\nu qq'$ channel exploitable at large MH or through VBF

H → ZZ$^{(*)}$
Small *BR* but "golden mode" for a discovery $l^+l^-\ l^+l^-$

e.g. Discovery Reach (Overview)

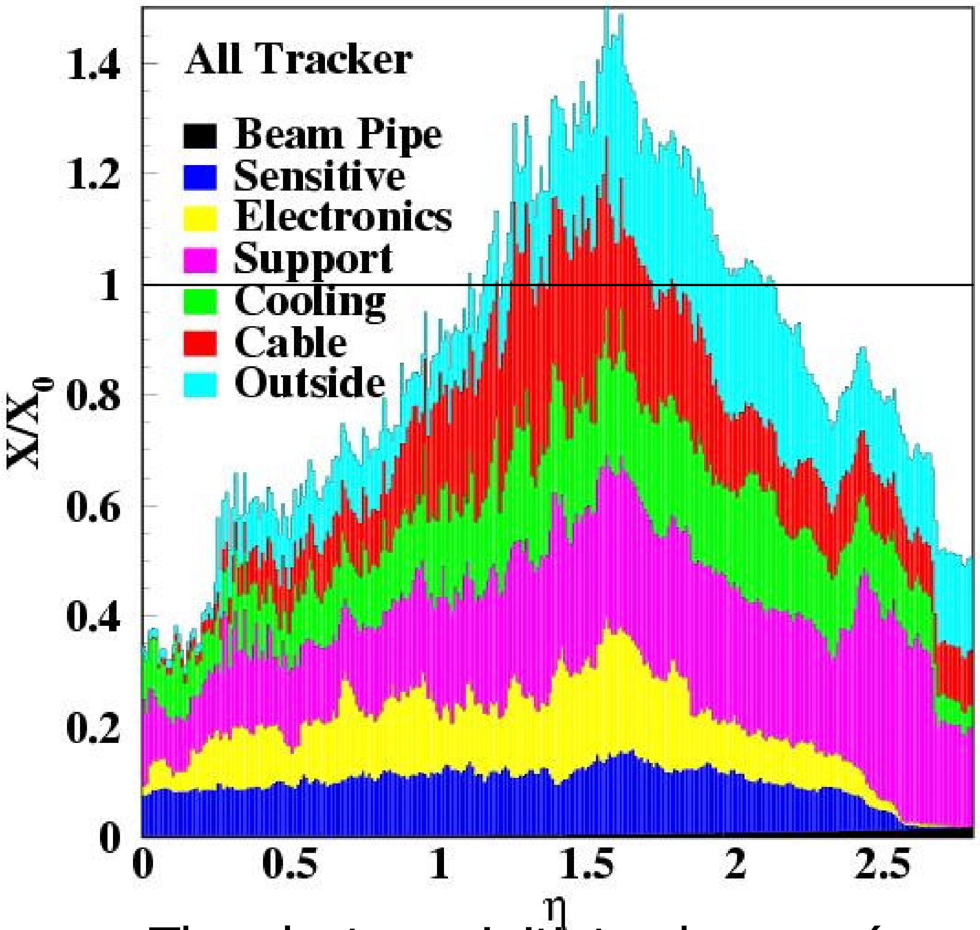
Inclusive Channels:



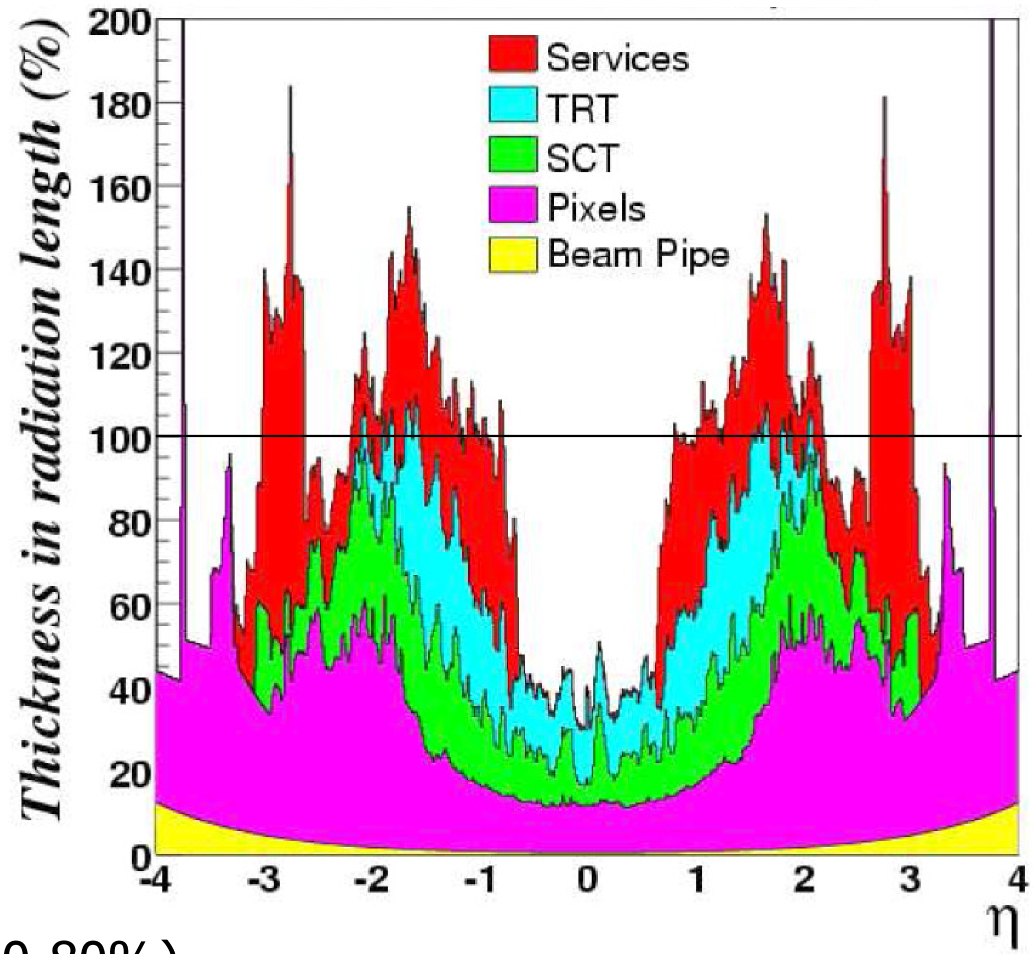


Not so … transparent !

CMS



ATLAS



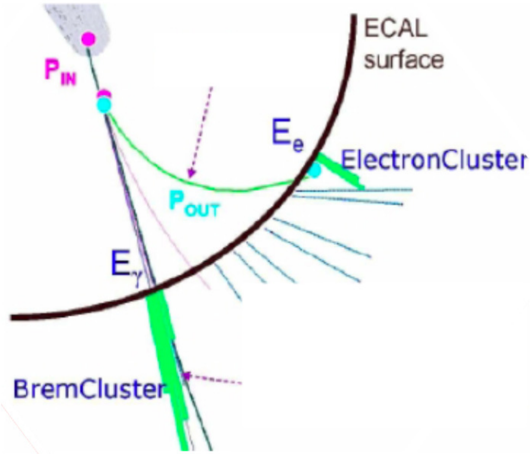
The electrons initiate showers (e.g. 40-80%)

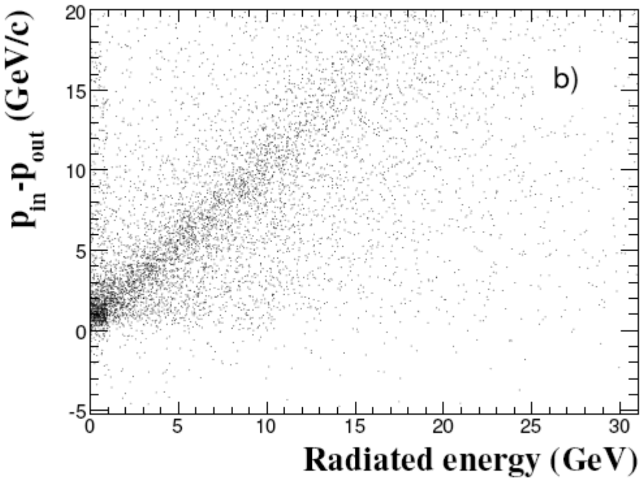
$\Rightarrow$ Identification and efficiency problems, charge mis-identification

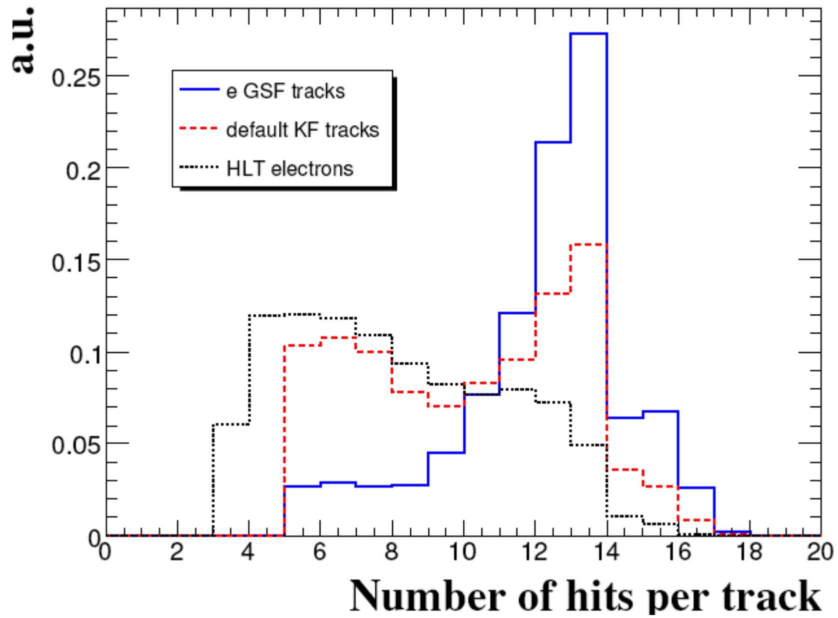
The photons convert (e.g. 20-40%) in e+e– pairs before reaching the ECAL

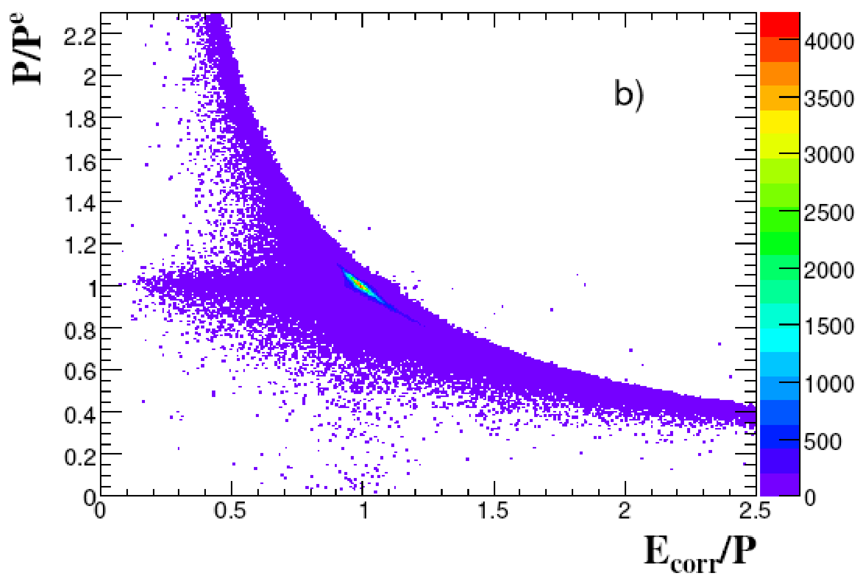
The LHC Detectors

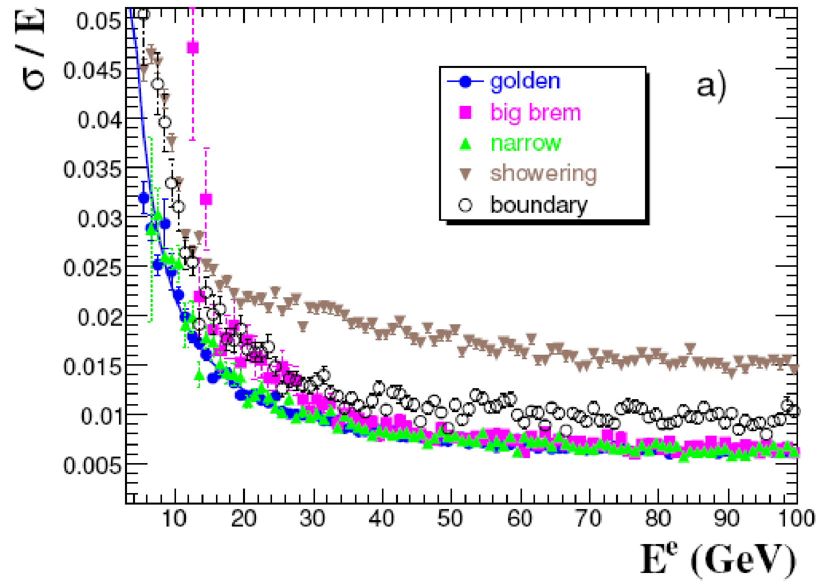
The CMS Electrpmagnetic Calorimeter



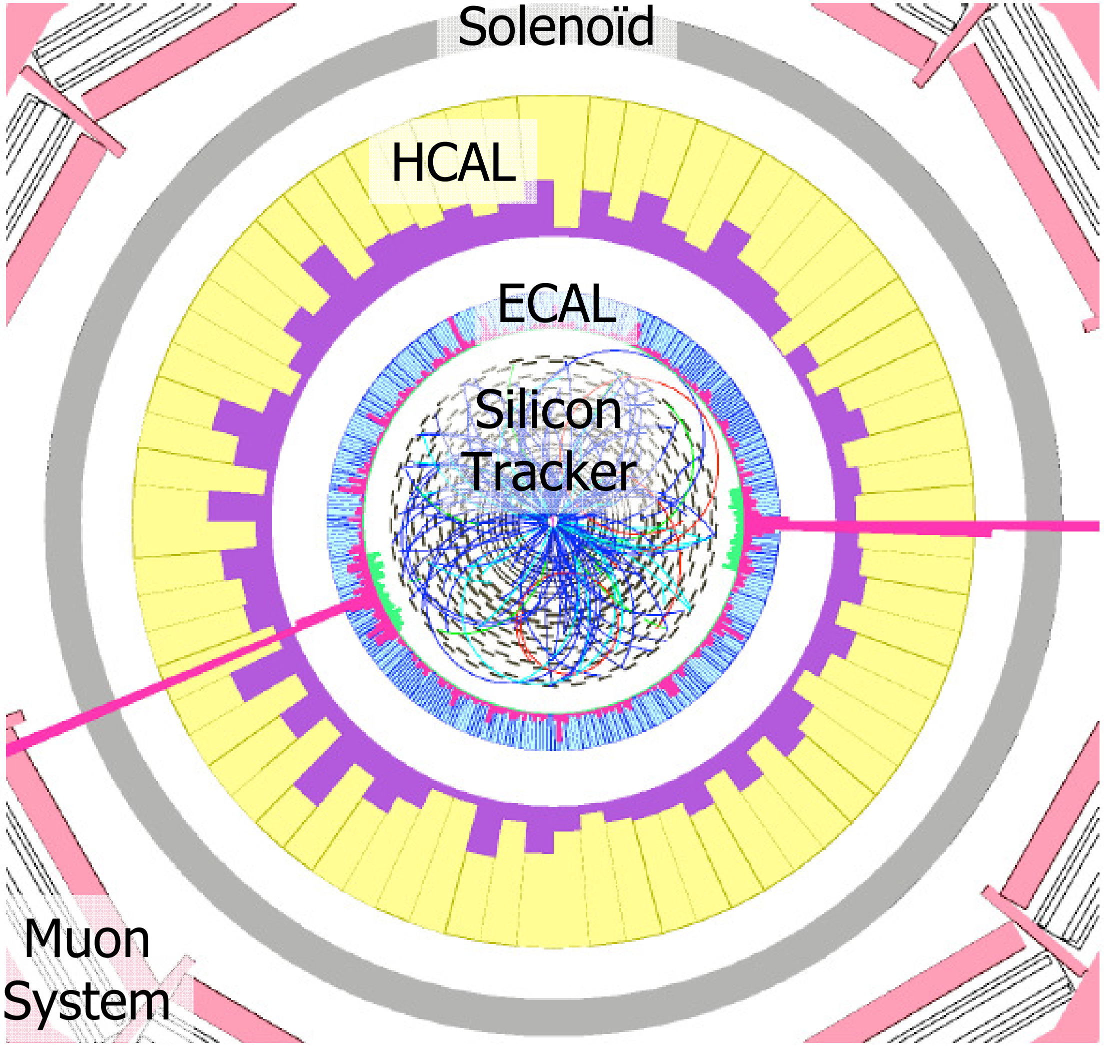








$H \to \gamma\gamma$



CMS-Note 2006/112

Signal:

Rare mode: $Br \sim 2 \times 10^{-3}$

Look for narrow peak on a (locally) ~ flat background

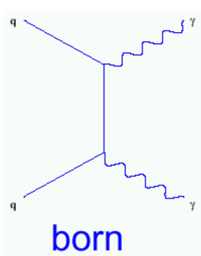
Important for low masses

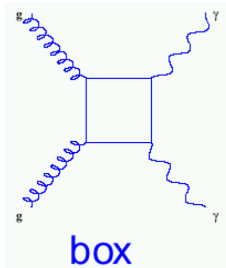
$\sigma \times BR \approx$ 99 $\to$ 65 fb

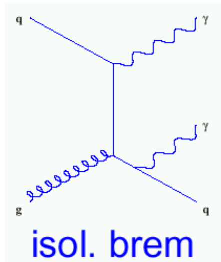
MH = 115 $\to$ 140 GeV/c^2

QCD-induced background:

Irreducible: 2 real γ
(Born + box diagrams)







Reducible: 1 real γ

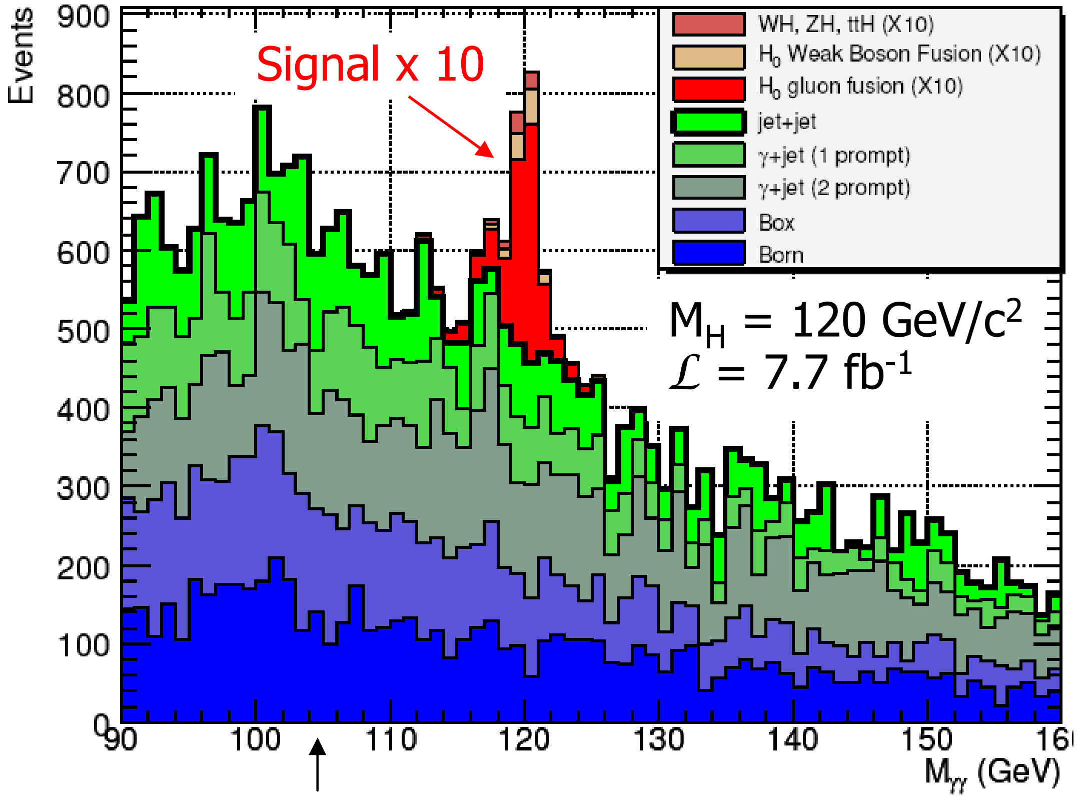
QCD di-jets + γ + jet(s)

$H \rightarrow \gamma\gamma$

Inclusive Modes

Polytechnique

CMS-Note 2006/112



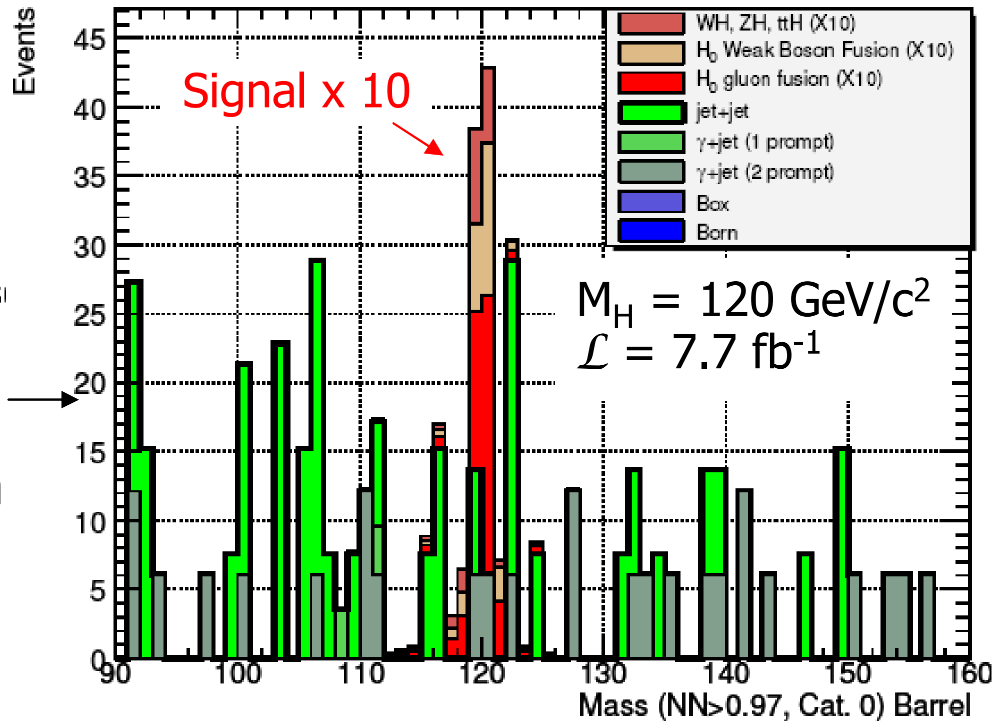
Relaxed NN cut

Background suppression

$\Rightarrow \gamma$ ID et γ Isolation

Background properties measured in "side-bands"

Stringent NN cut



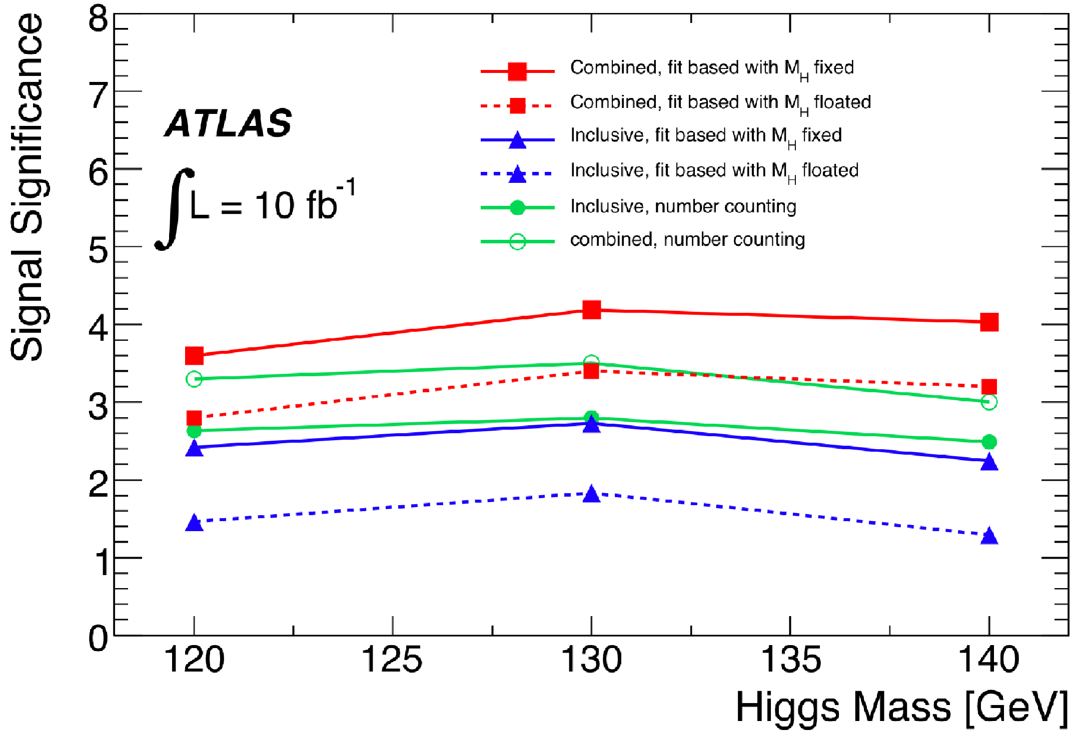
Neural Net exploiting photon classification (S/B per event) + specific properties of teh signal (implicit $P^T_{\gamma\gamma}$, $\Delta\phi_{\gamma\gamma}$, VBF/gg, …)

$H \rightarrow \gamma\gamma$

$\mathcal{L}$ required for a 5 σ discovery:

At LHC experiments:
Low systematic error on the background ("side-bands")

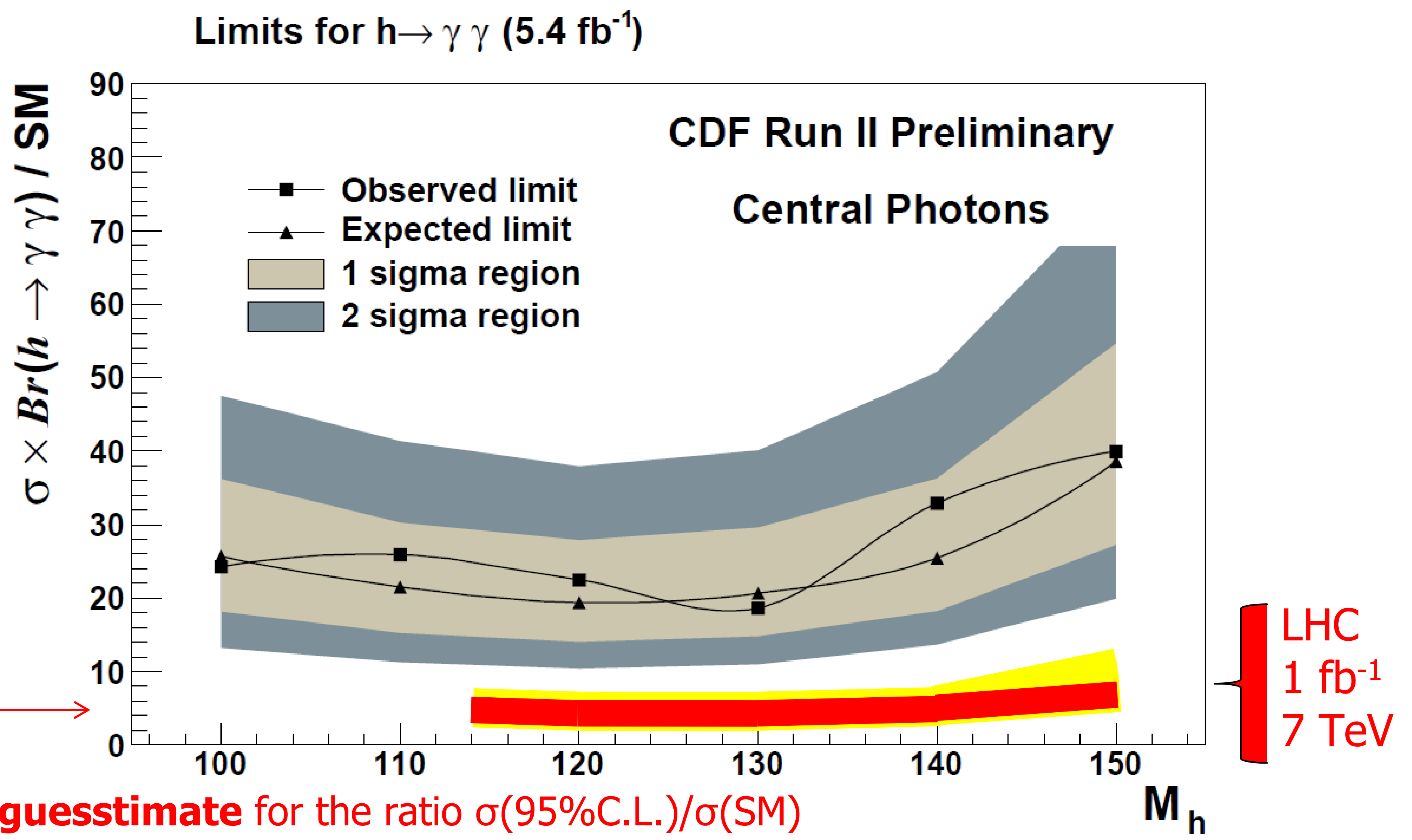
Awaiting for the LHC:
Uncertainties of ~ 20% on the signal



Significance for a SM Higgs SM at M_H=130 GeV for 30 fb^{-1}:

CMS ECAL TDR	CMS PTDR		ATLAS		
ECAL TDR NLO (count.)	NLO cut based	NLO optimized*	TDR (LO)	New, NLO Cut based	New, NLO likelihood
~ 7.5	6.0	8.2	3.9	6.3	8.7

$H \rightarrow \gamma\gamma$: Expectations for 2010-2011



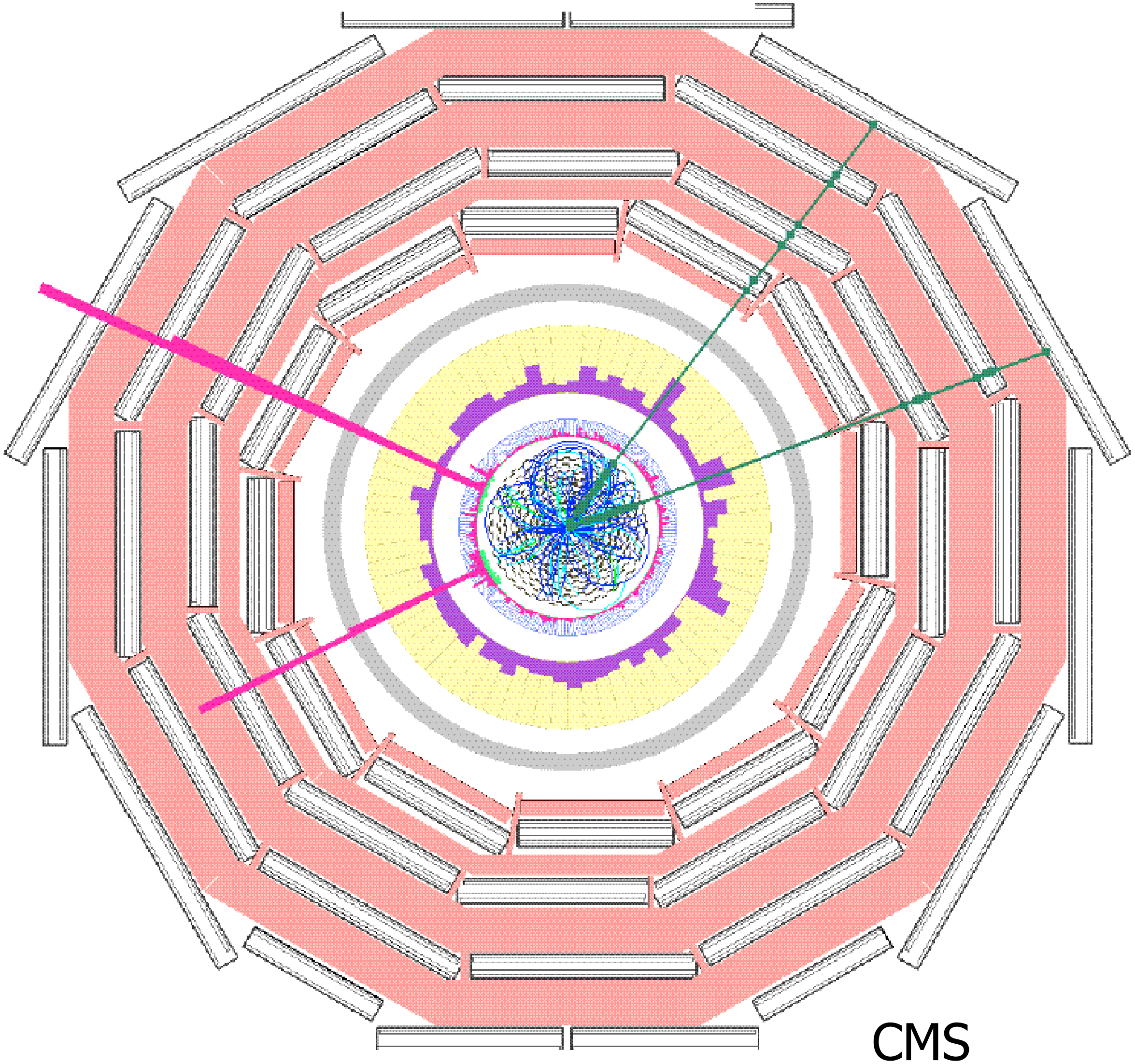
My guesstimate for the ratio σ(95%C.L.)/σ(SM) extrapolated from CMS published prospective

Possible chance for Fermiophobic Higgs ? σ↓ Br(γγ)↑

La Voie Royale: $H \to 4l$

Inclusive Modes

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



Signal:

$4e$, 4μ, $2e2\mu$ (2x)

Narrow resonance,
low background

4 isolated leptons emerging from a common primary vertex

Generally at least one Z on its mass shell

Background:

Irreducible: continuum $ZZ^{(*)}$

Reductible: tt , Zbb

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

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

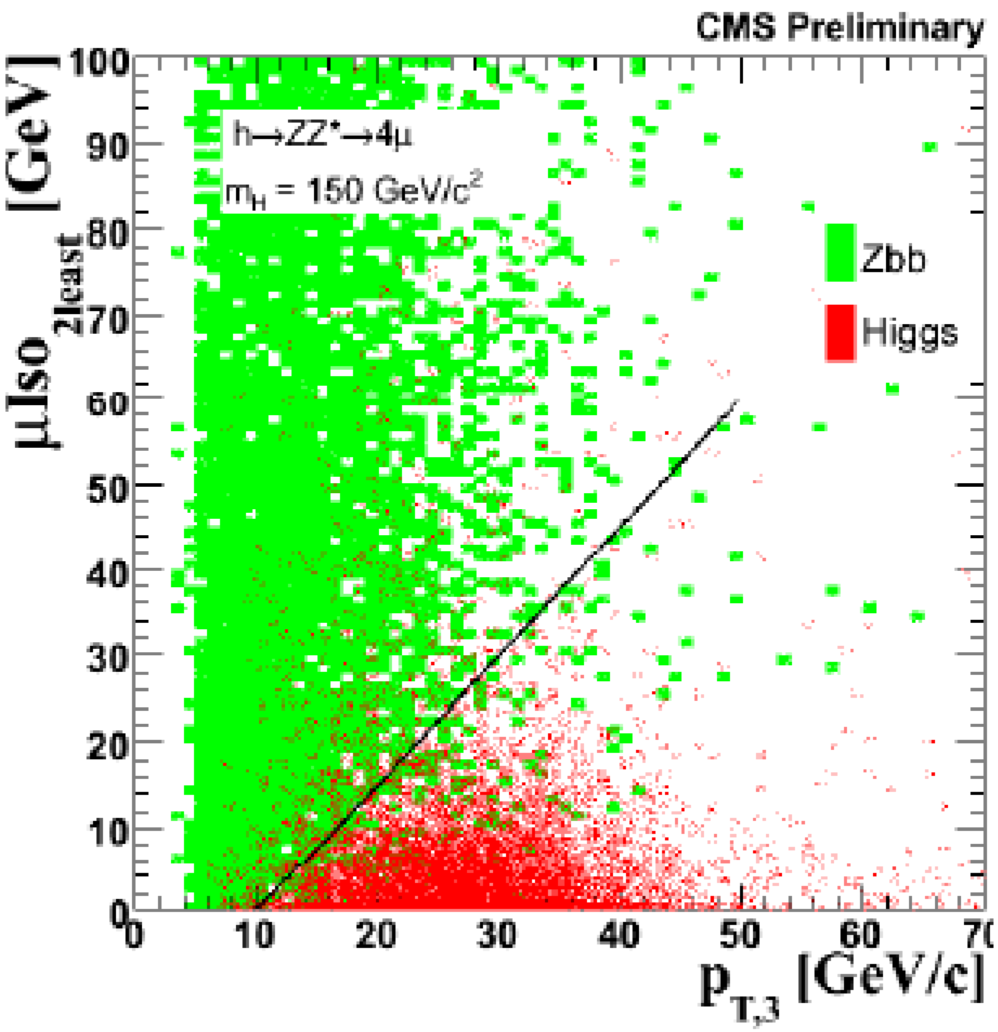
Main experimental challenge:
Preserve highest possible signal detection efficiency (given very low $\sigma \times \beta$)
$\Leftrightarrow$ High efficiency for isolated and identified low PT leptons ($\propto \varepsilon^4$!)

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

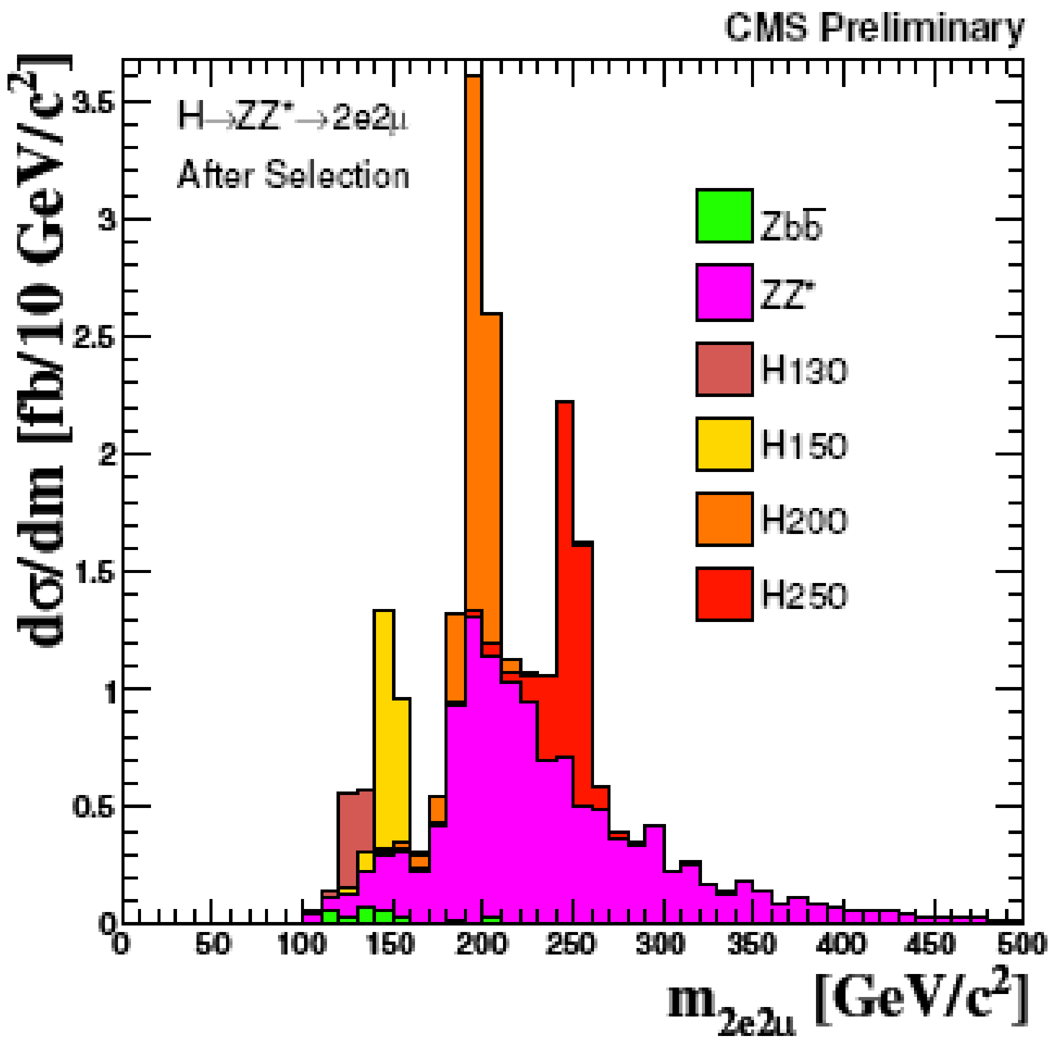
Background sources:	Experimental tools:
QCD multijets / Z + jets	Multileptons, loose ID and Iso. matching pairs (flavour and signs)
Zbb, tt (WbWb)	Tigher iso. and vertex requirements on « b » legs (sources of fake primary leptons);
$ZZ^{(*)}$ continuum	ZZ observation and measurement of $d\sigma/dM_{4l}$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

$$R = (\sigma_{ZZ\to 4e} * \varepsilon_{4e} * \int Ldt) / (\sigma_{Z\to 2e} * \varepsilon_{2e} * \int Ldt)$$

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



CMS Preliminary
h→ZZ*→4μ
m_H = 150 GeV/c²
Zbb
Higgs
μIso_2least [GeV]
p_T,3 [GeV/c]

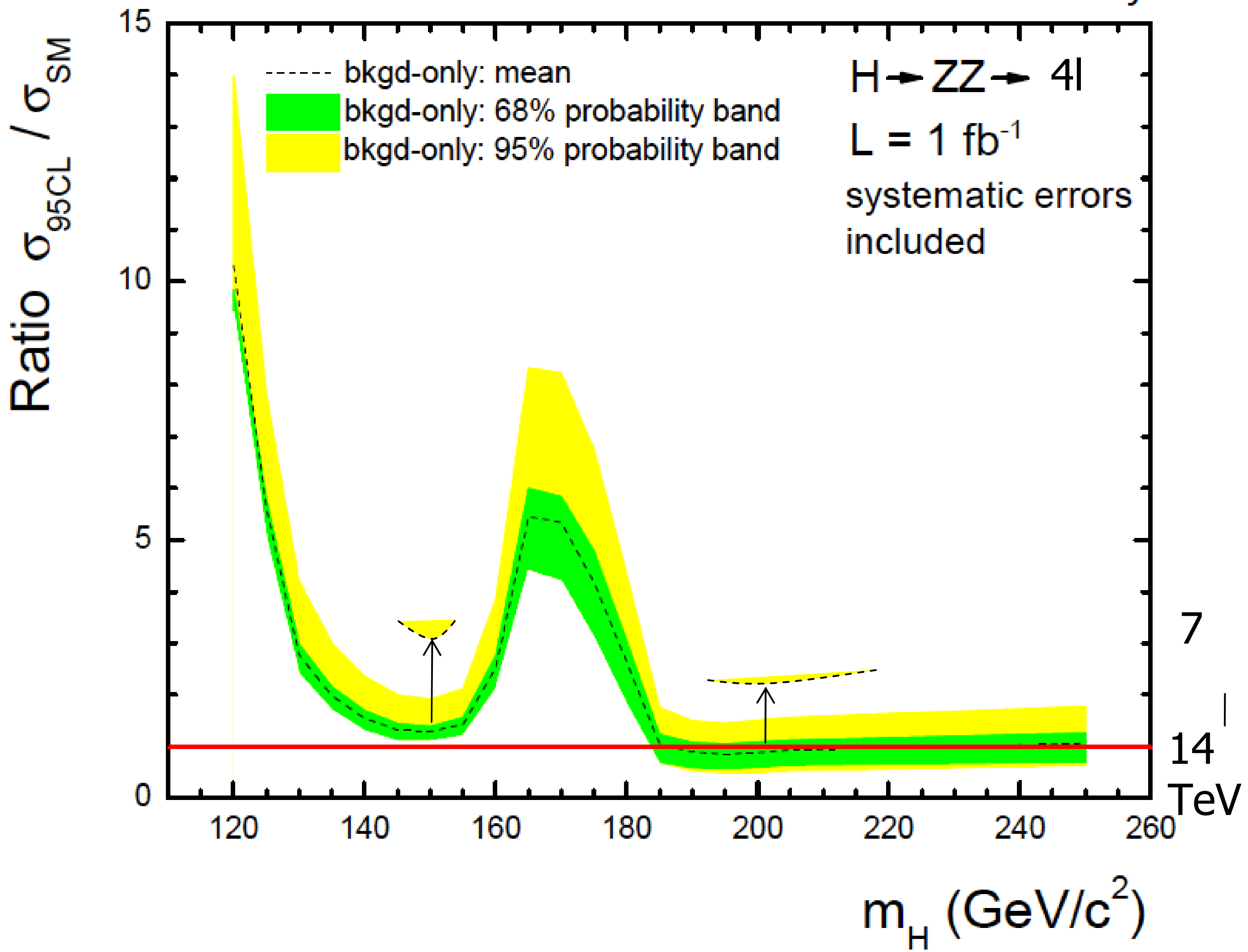


CMS Preliminary
H→ZZ*→2e2μ
After Selection
Zbb̄
ZZ*
H130
H150
H200
H250
dσ/dm [fb/10 GeV/c²]
m_2e2μ [GeV/c²]

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

Results

CMS Preliminary



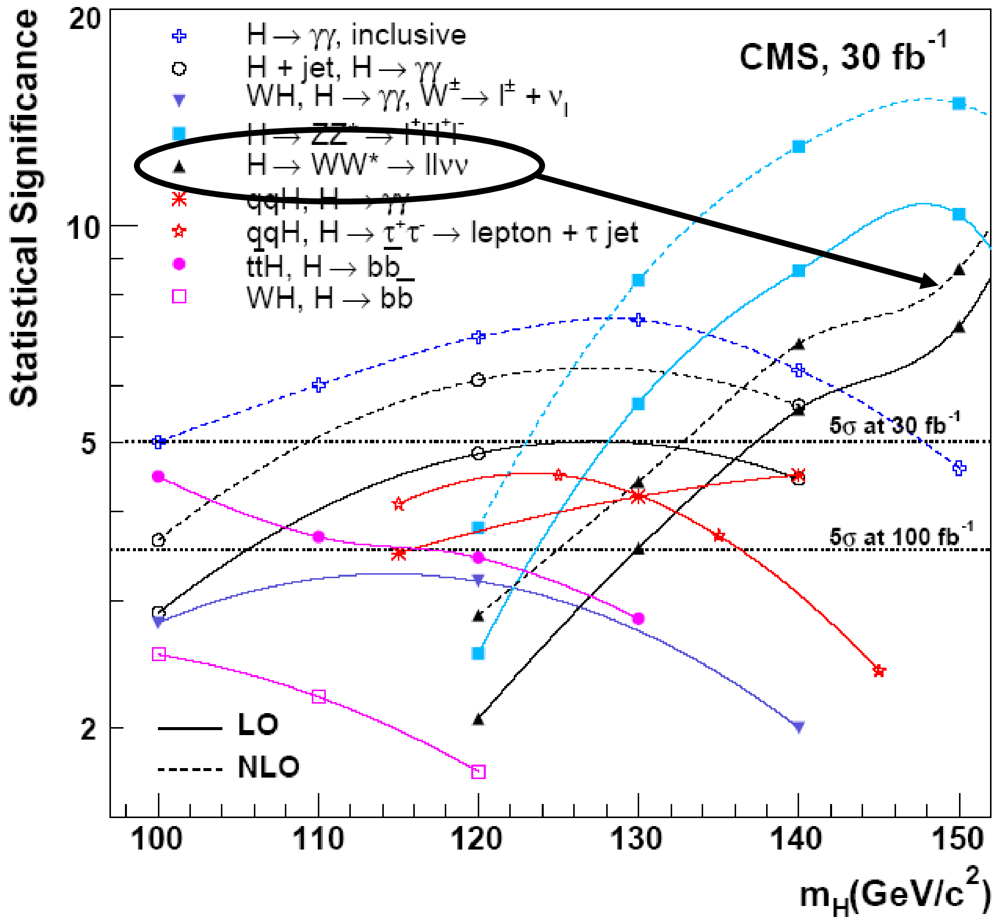
Possible chance for
h ➔ Z′Z′ ➔ 4l
with exotic h′, Z′ from
hidden sector ?

J.D.Wells et al. PRD 2008

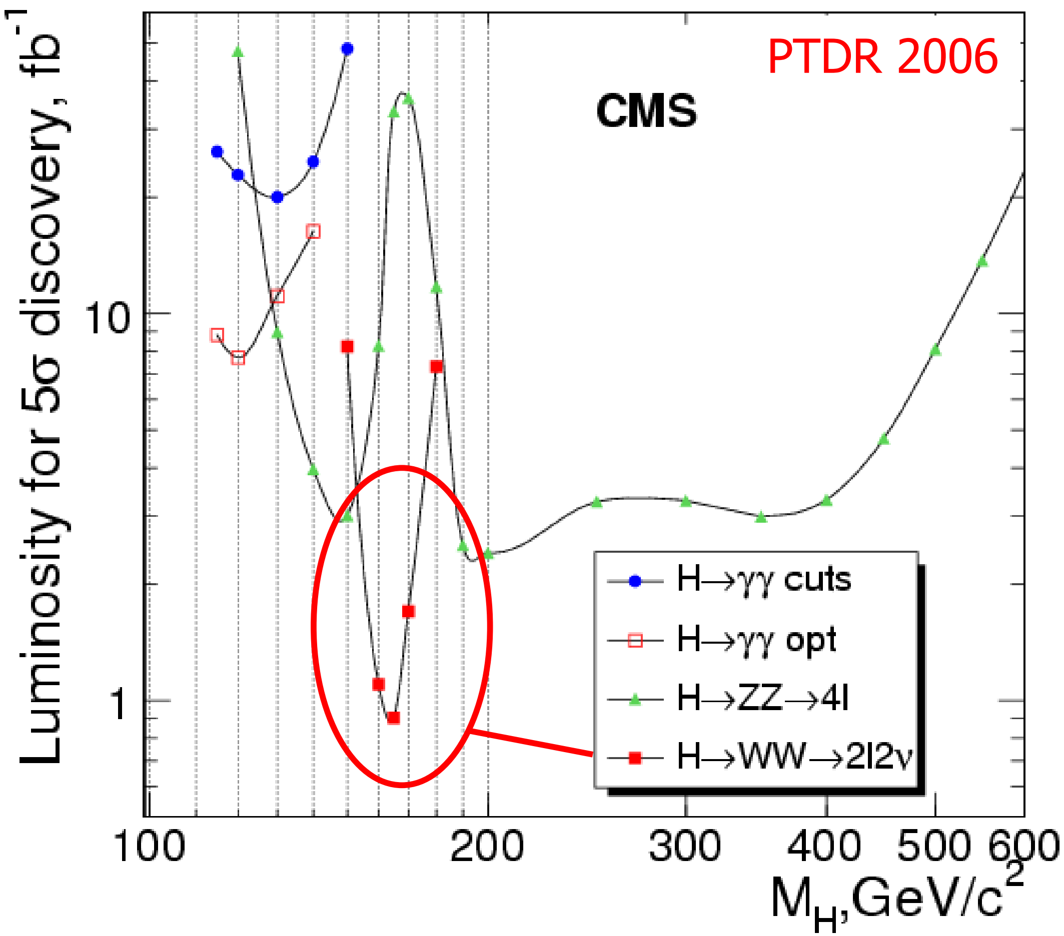
Ounce observed:
Powerful SCP
discrimination
by exploiting the
Cabibbo-Maksymowicz
angles

A. De Rujula et al.
hep-ph March 2010

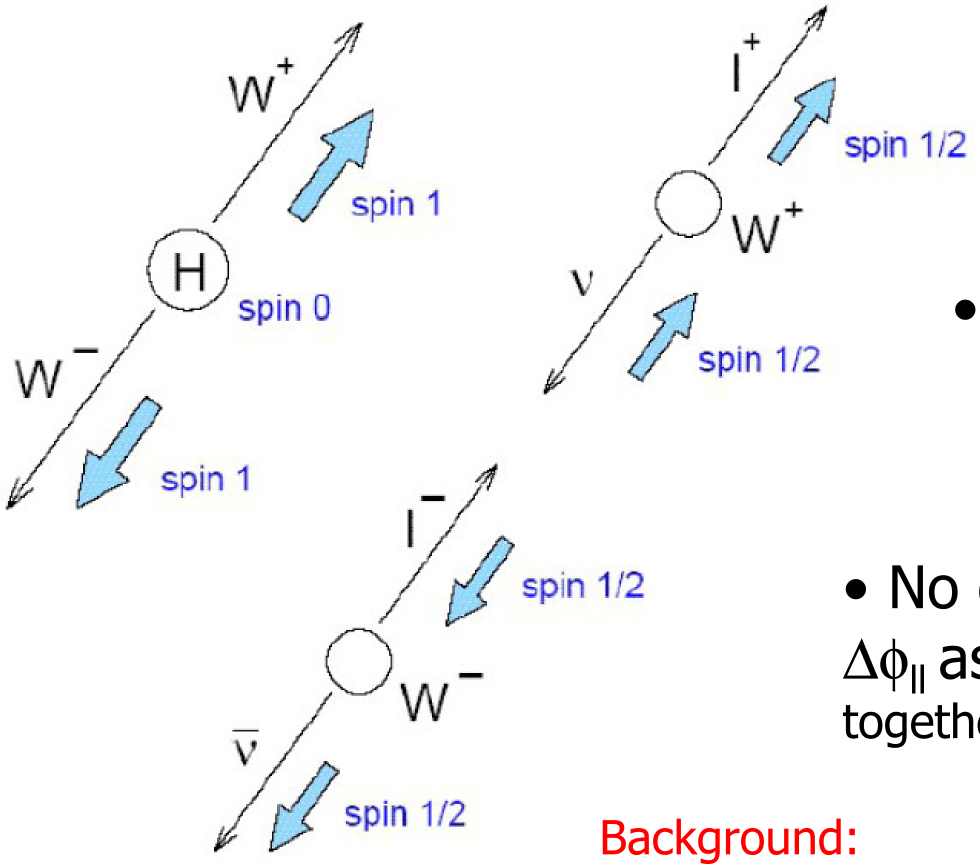
e.g. Discovery Reach (Overview)



Inclusive Channels:



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



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

- Best channel for early discovery at $M_H \sim 2M_W$

  [$M_H \sim 165$ GeV excluded at Tevatron 95% CL]

- No observable resonance peak

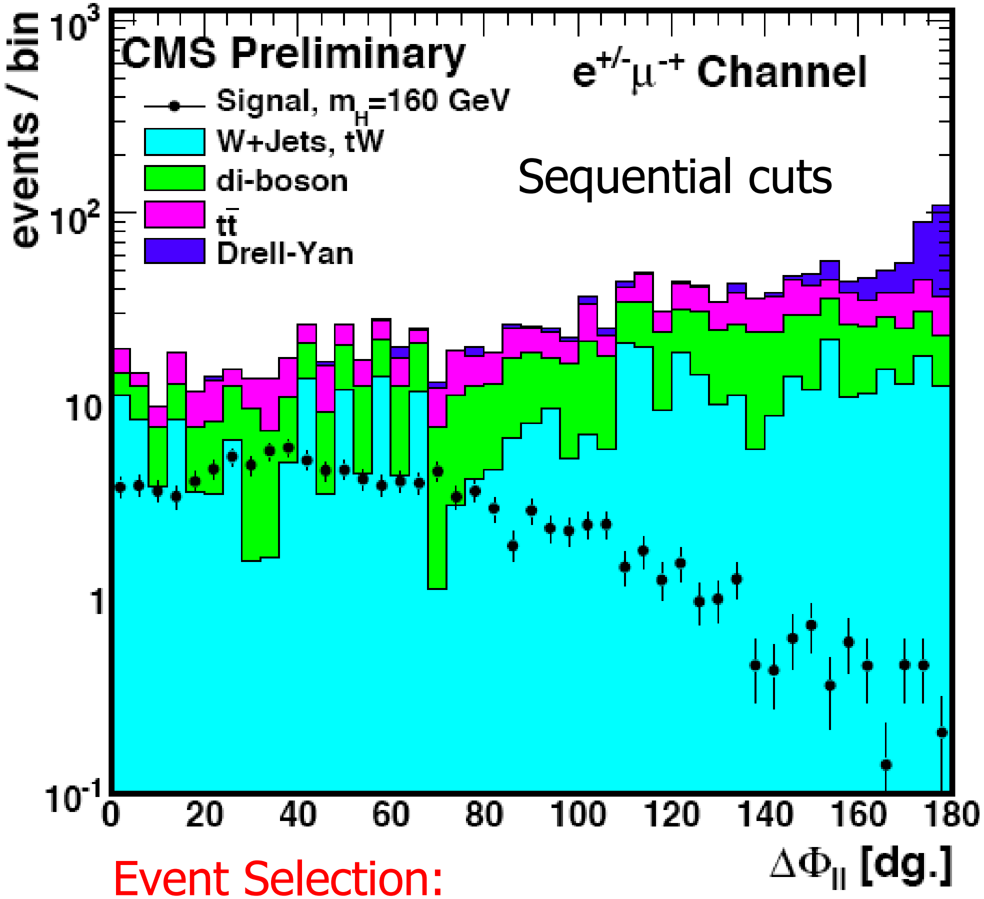
  $\Delta\phi_{ll}$ as most significant observable together with $M_\perp^{ll}$

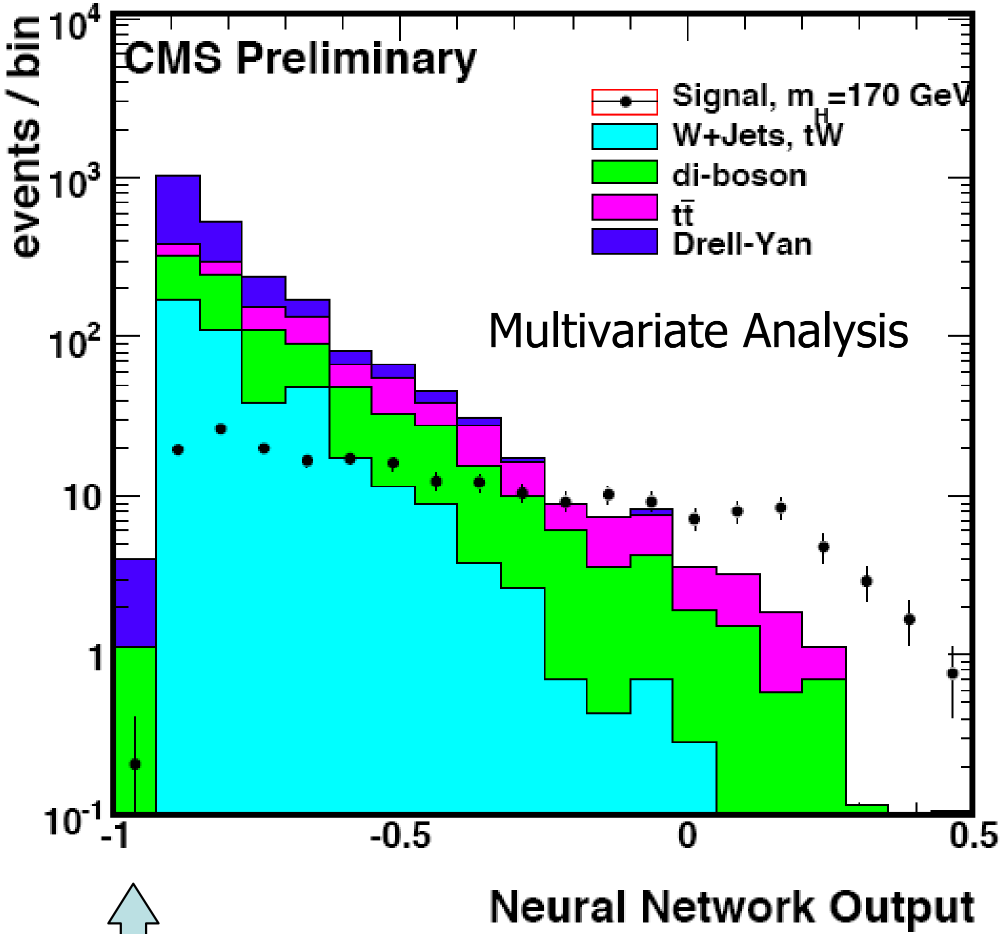
Background:		M_H=160	WW* Cont.	tt
	σ_{NLO}	2.3 pb	114 pb	840 pb

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

Main challenge: data-driven control of background systematics

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





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. $\Delta\phi_{ll} < 45°$)

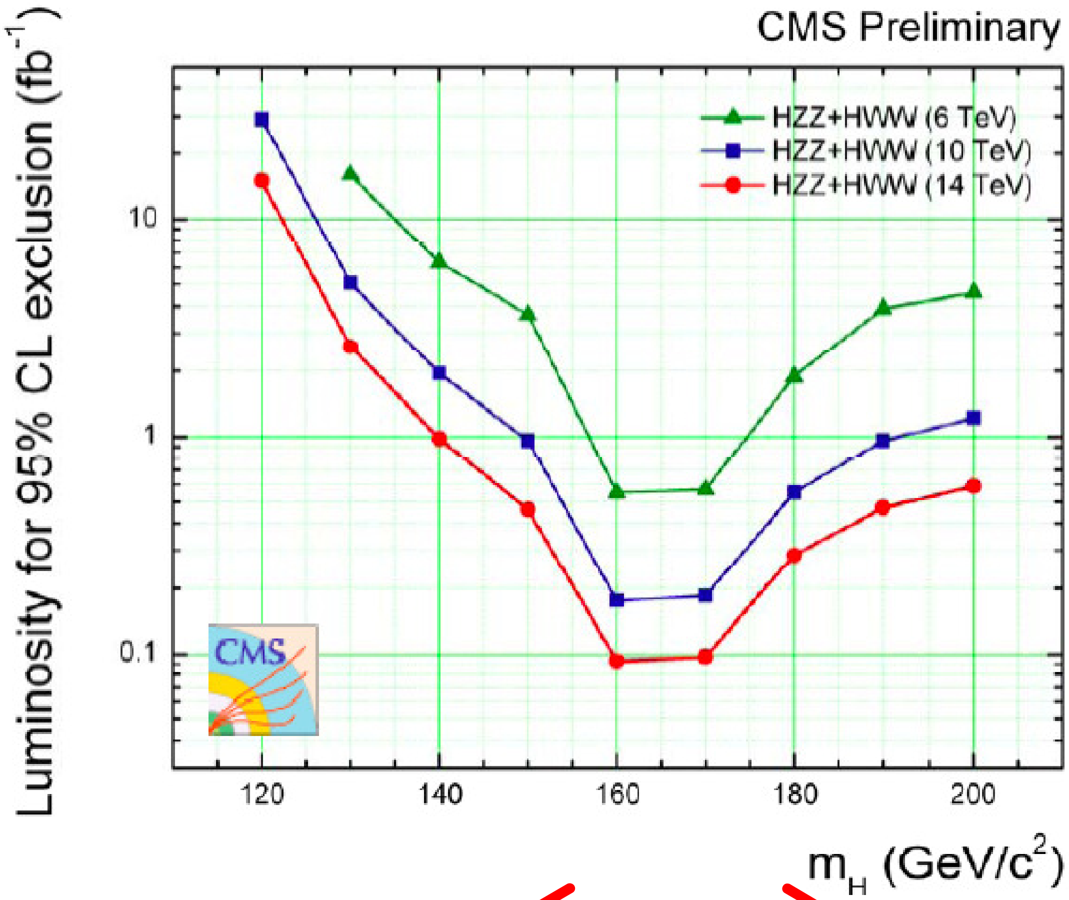
Better exploit correlations and multi-dimensional space of discriminating observables

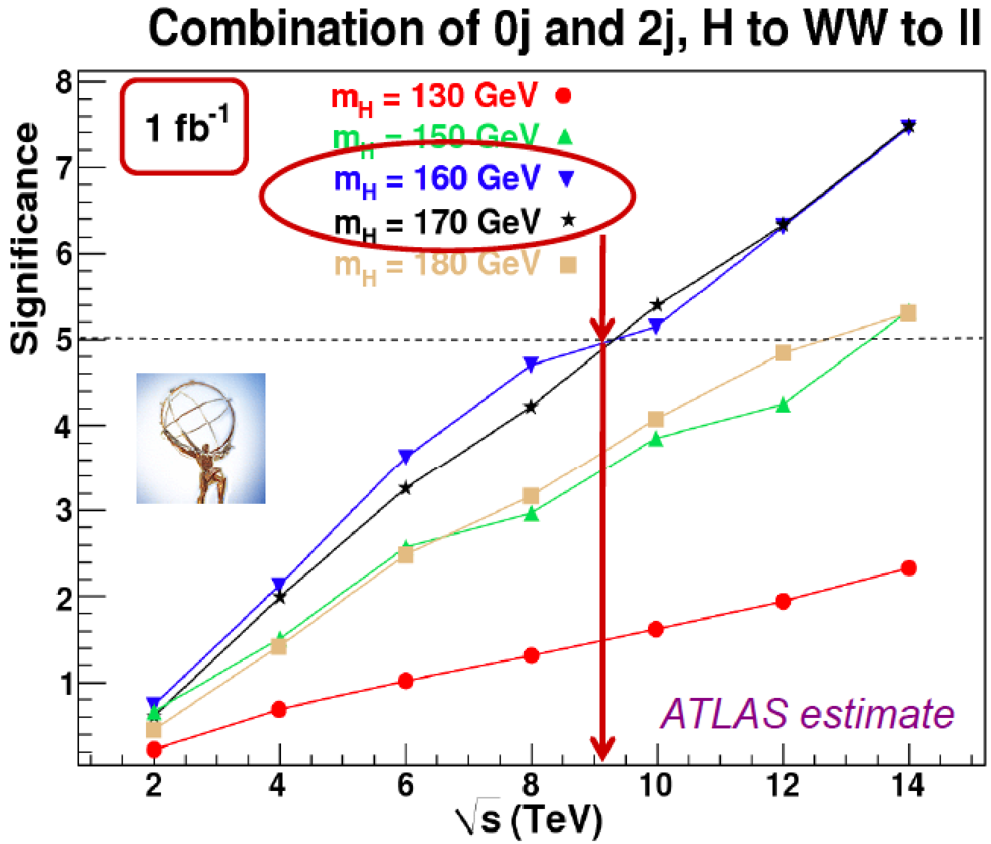
Sensitivity vs √s

Chamonix 2009

For Exclusion

For Discovery



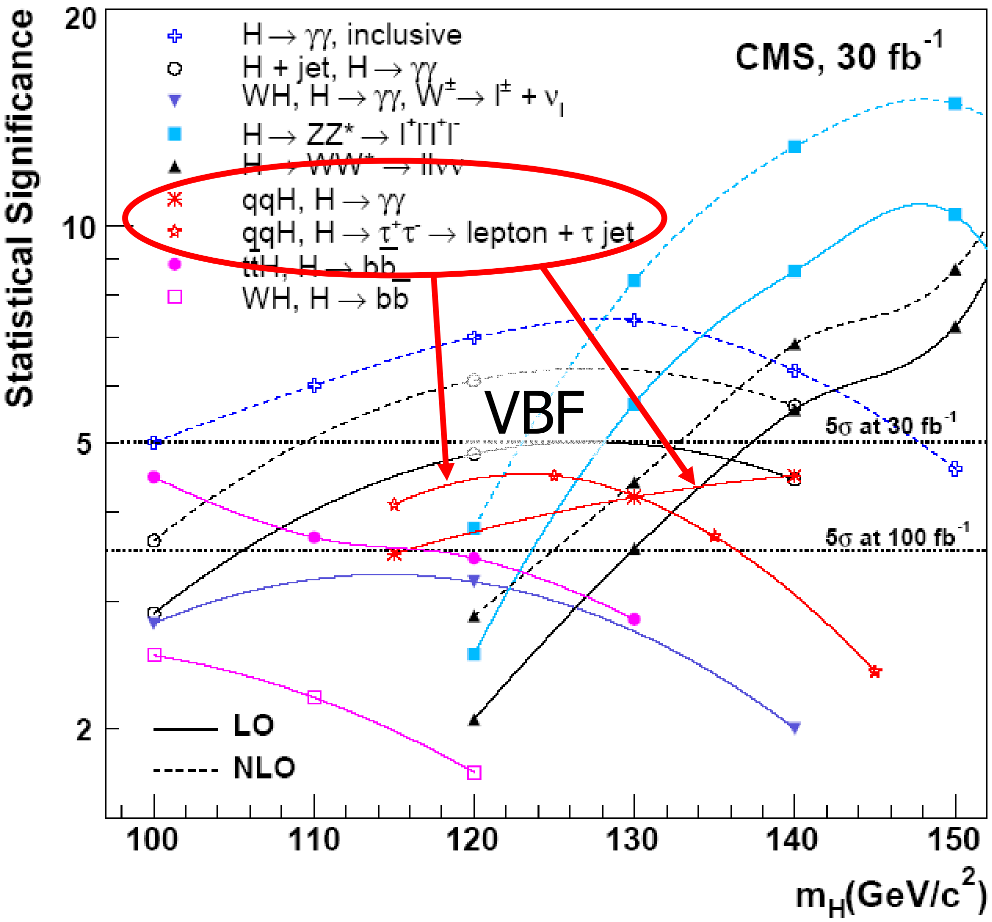


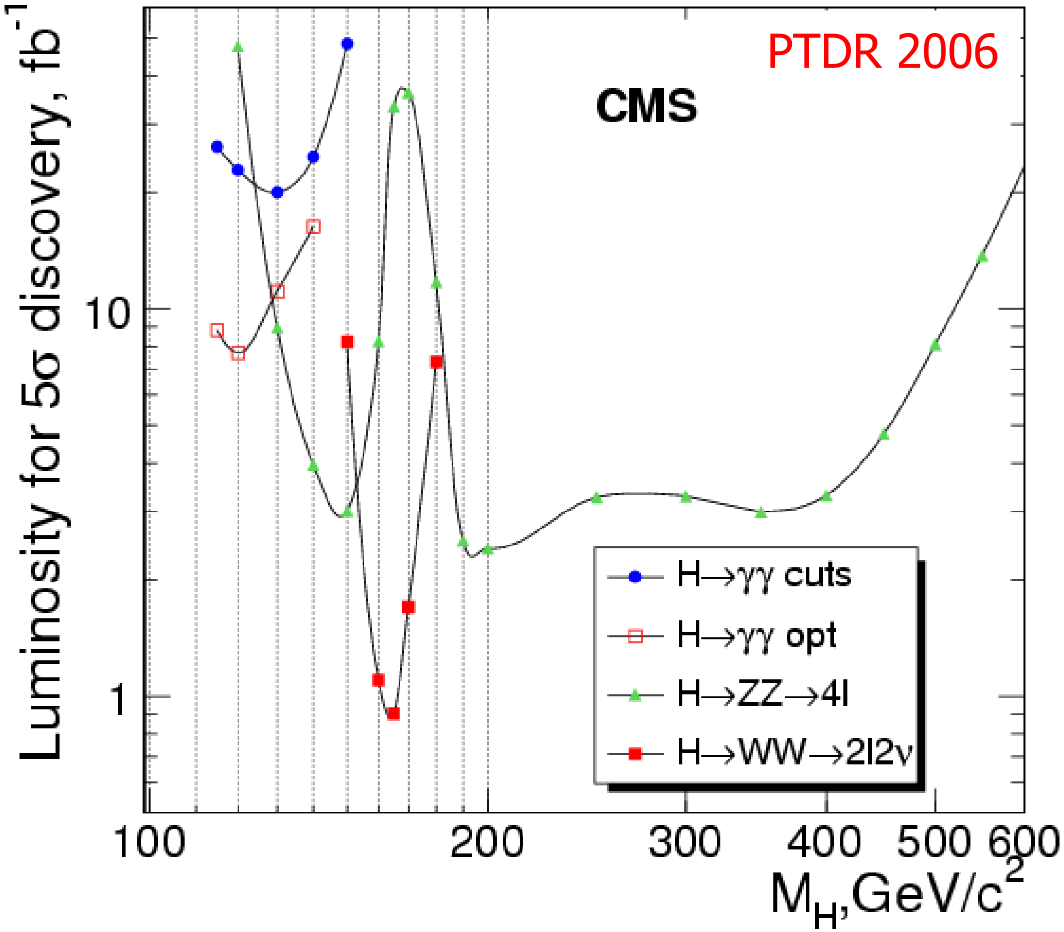
~ 150 to 185 GeV excluded for 1 fb^{-1} at 7 TeV

>~ 3σobservation in that range combining inclusive channels

e.g. Discovery Reach (Overview)

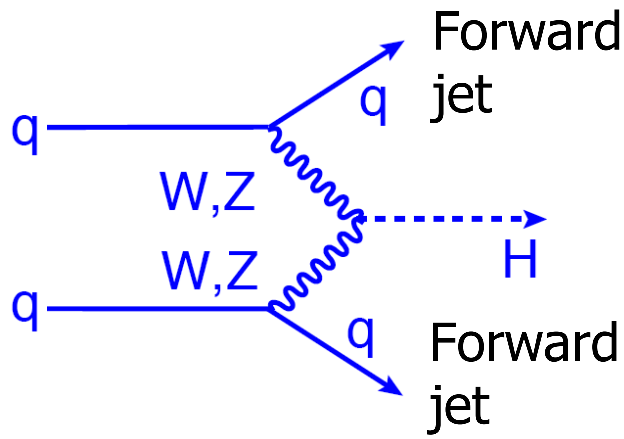
Inclusive Channels:

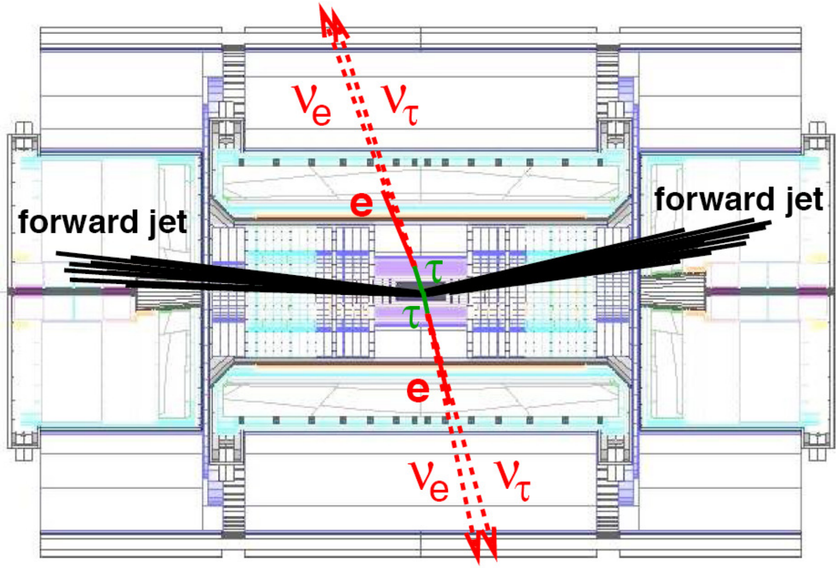




Vector Boson Fusion (VBF)

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 $\Rightarrow$ τ's generally not back-to-back

Modes studied

qq (V V*) $\rightarrow$ qq'H;

H $\rightarrow \tau^+\tau^- \rightarrow$ ($l^+\nu\nu$) ($l^-\nu\nu$)

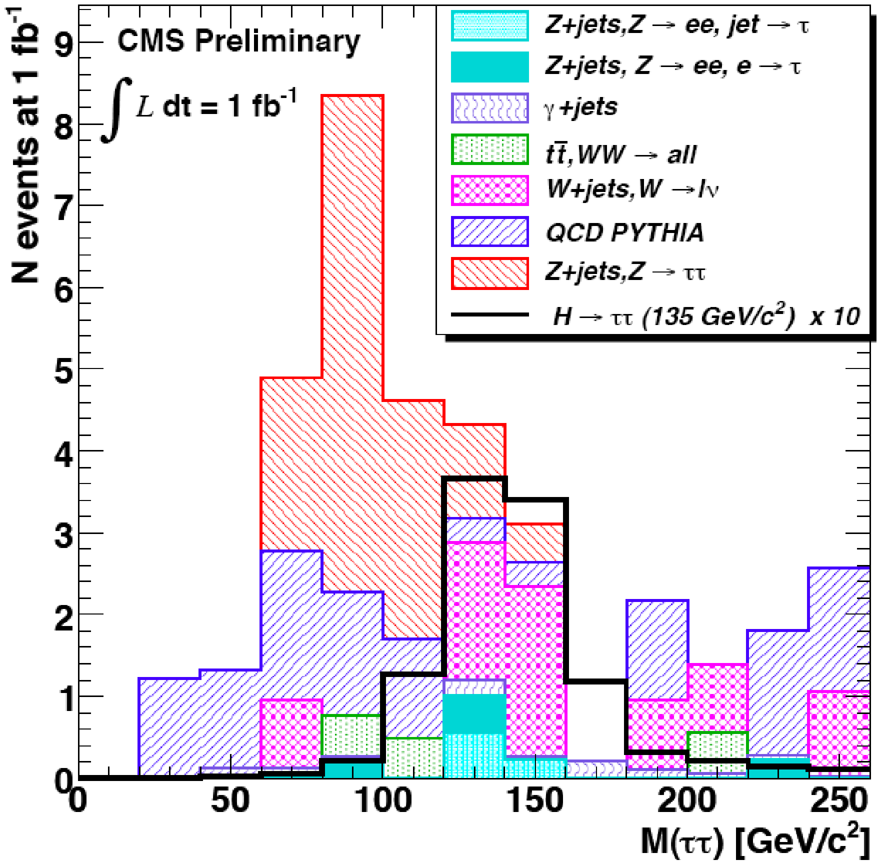
$\rightarrow$ ($l^+\nu\nu$) (jet ν)

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

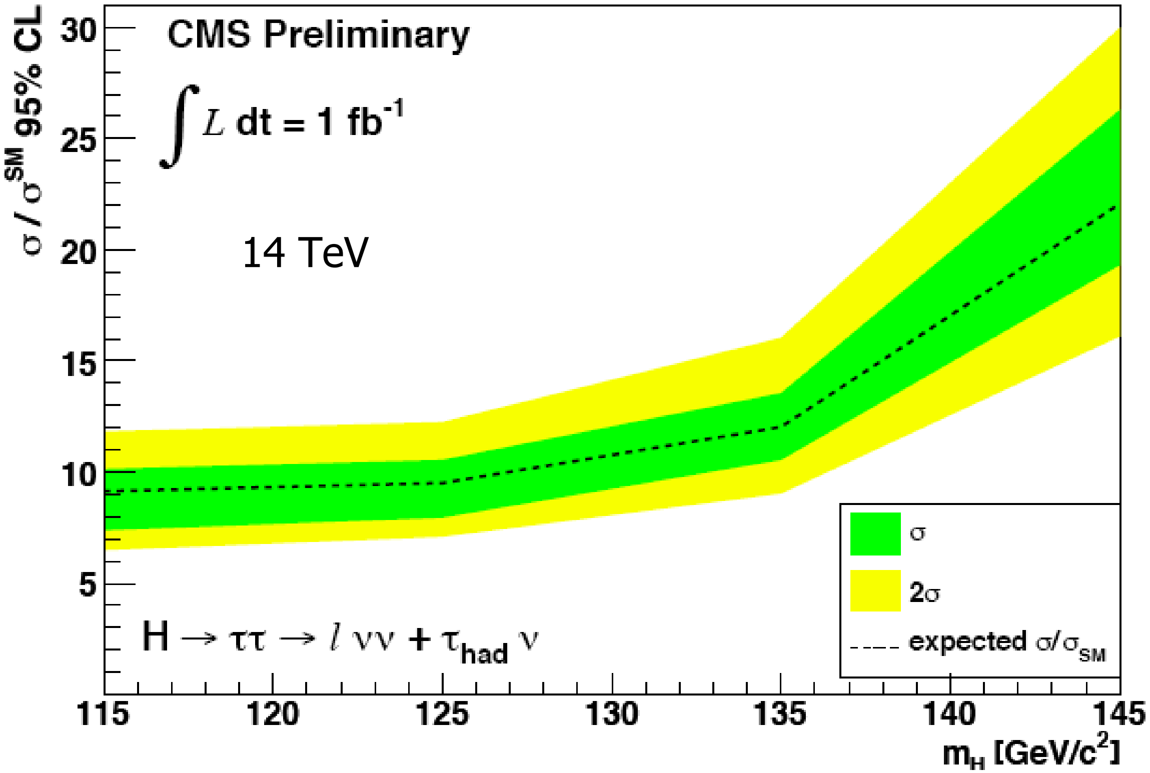
$M_{\tau\tau}$ resolution depends on E_T^{miss}

Best with particle flow techniques

VBF H → 2tau



Exclusion Limits

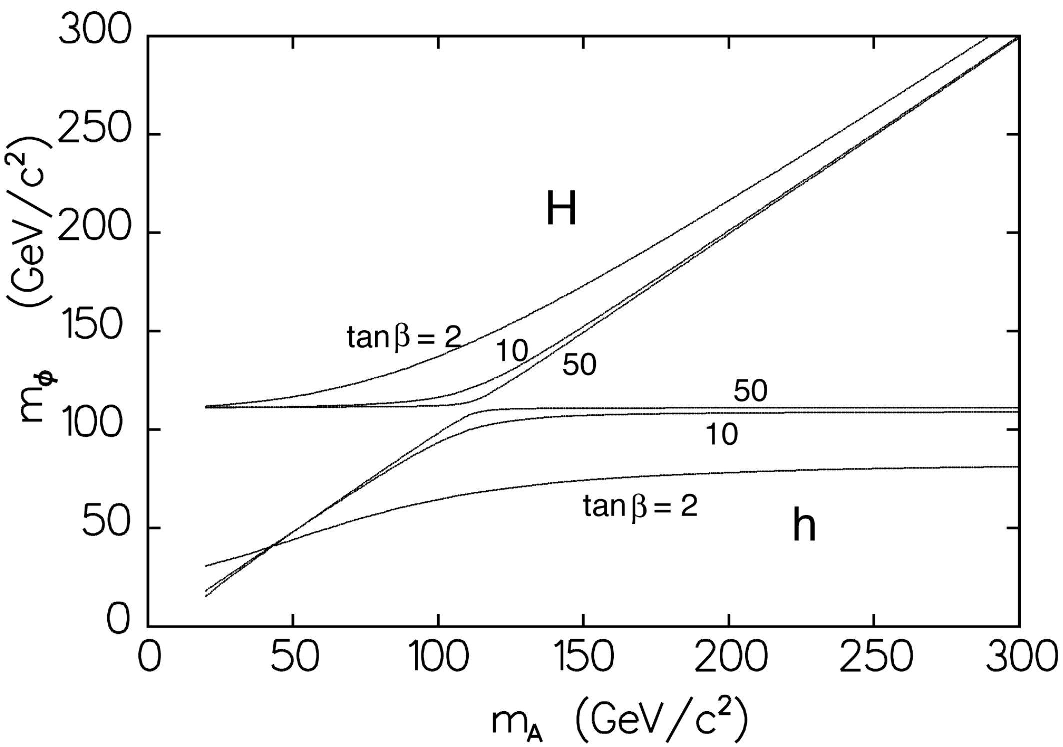


Considerable improvement expected with Particle Flow techniques
e.g. $\sigma(m_{\tau\tau})/\ m_{\tau\tau}$ resolution brought below ~10% and
inefficiency for C.A. reduce by ~ factor 2 !!!

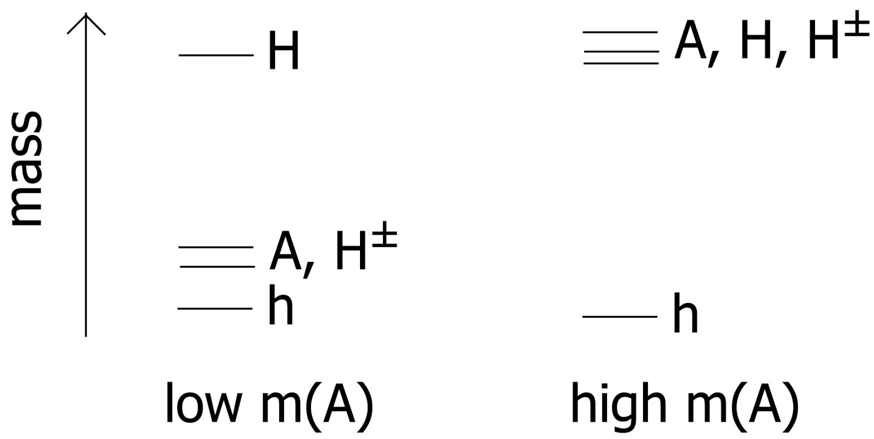
Extended Scalar Sector in Minimal SUSY Models

Minimal SUSY: Mass Spectrum

MSSM Type II Two-Higgs doublet models



- Five physical Higgs Bosons
- Masses governed by m_A, $\tan\beta$
- Couplings governed by α,β



- There must be a light scalar: h
- A,H,$H^\pm$ are nearly mass degenerate at large m_A
- For large m_A it may be difficult to distinguish the the MSSM CP-even Higgs from a SM Higgs boson

Born: $m_{h^0} < m_Z|\cos(2\beta)|$

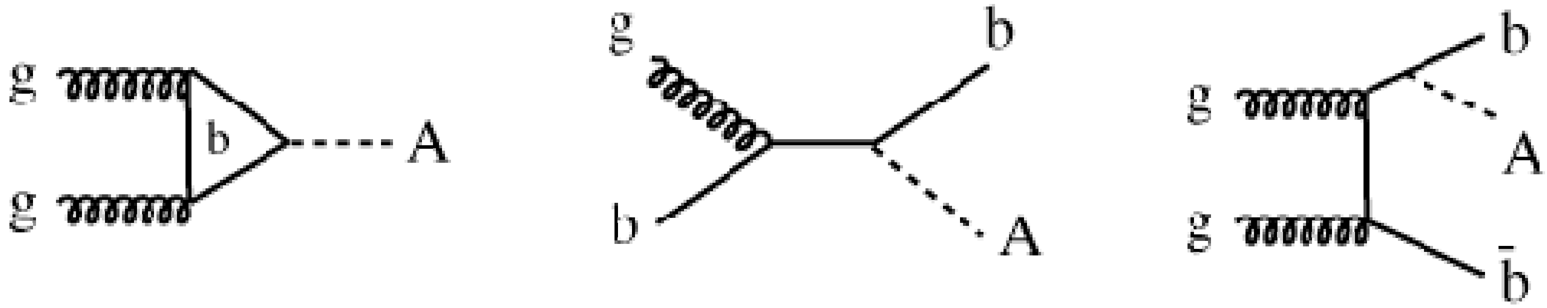
Loop*: $\boxed{m_{h^0} \lesssim 135\ \mathrm{GeV}}$

*top, stop etc.

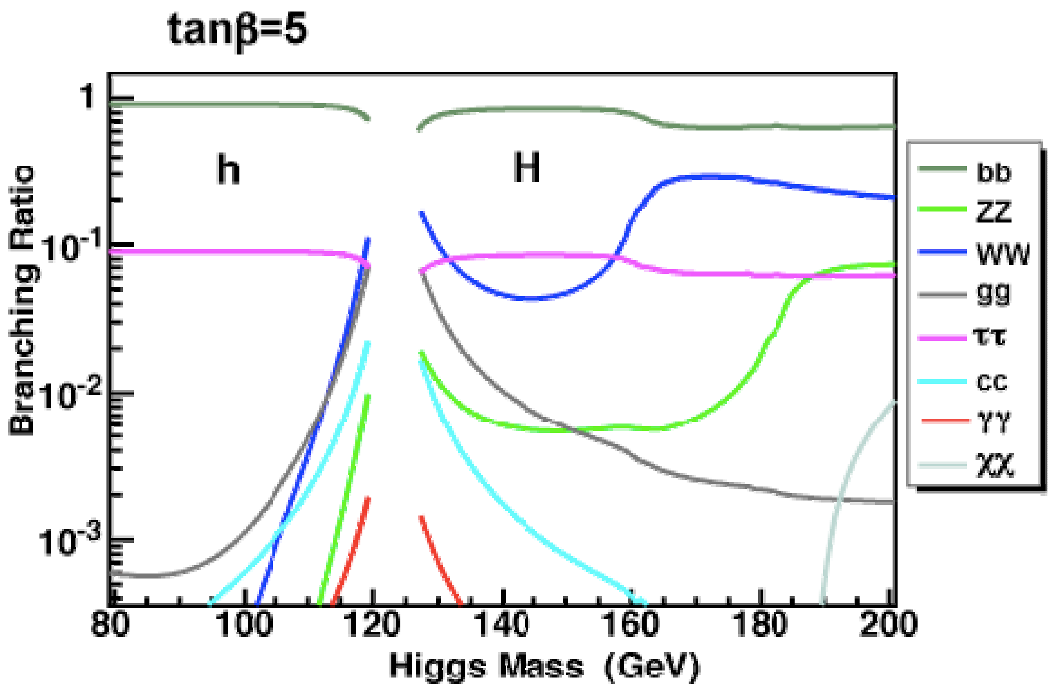
Minimal SUSY: Production and Decay

Large tanβ: enhanced bb A/H couplings suppression of VVH couplings !

e.g.



production cross-sections ➔proportional to $\tan^2\beta$

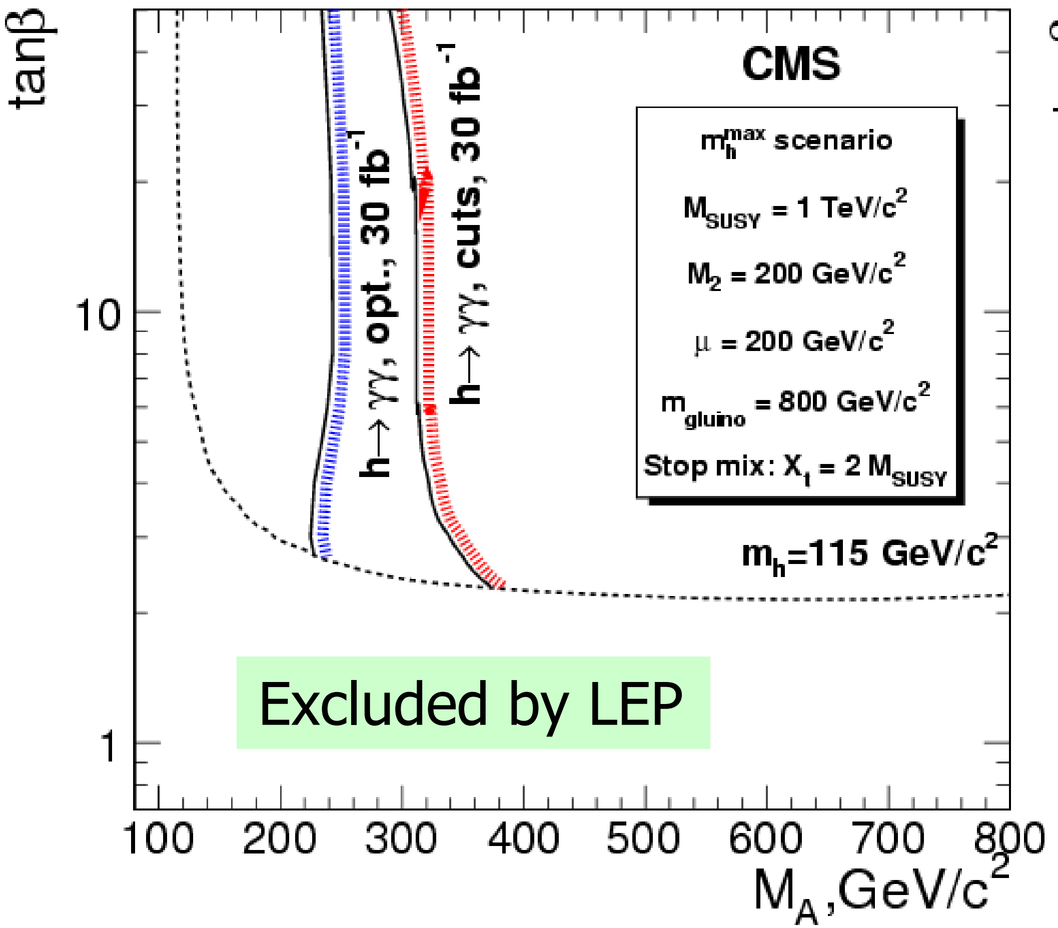


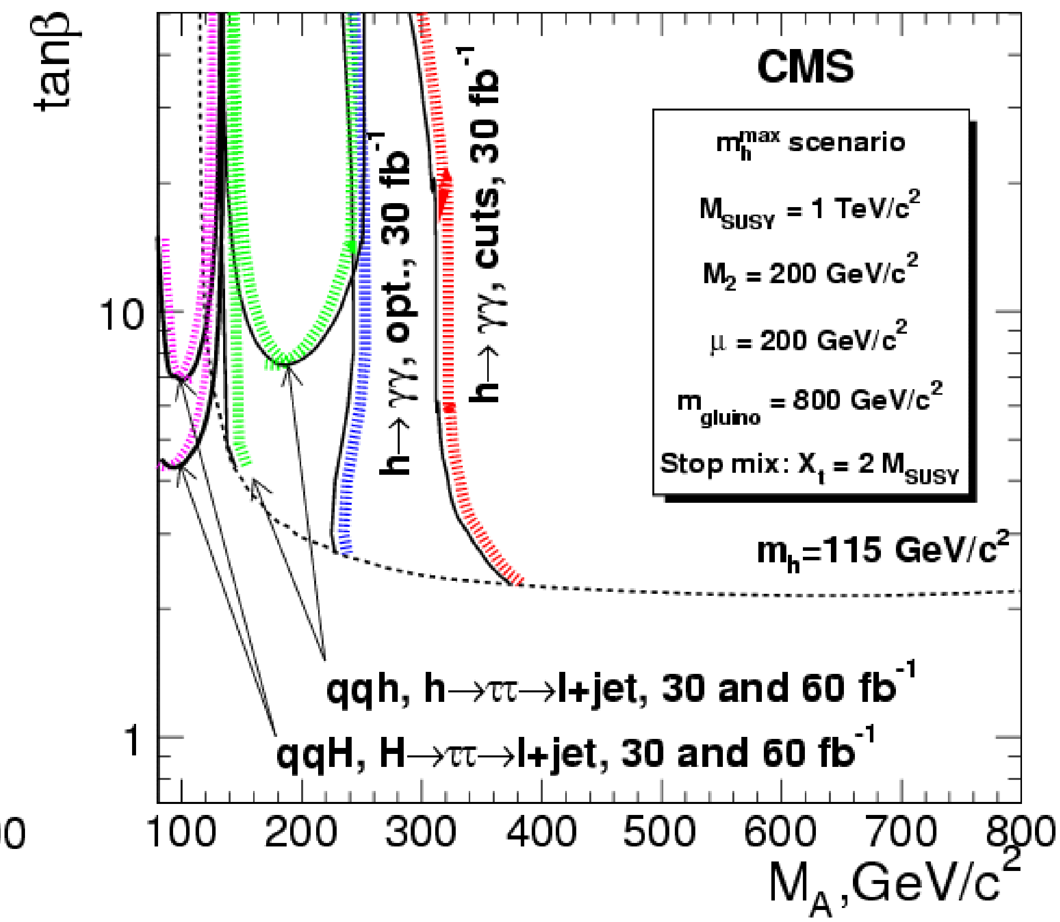
- The CP-odd A does not couple to Z and W (A➔ττ at large tanβ)
- For h,H the ττ decay mode is the most sensitive
- $H^{\pm}$ couples strongly to tb et $\tau\nu$
- ∀ Higgs are narrow (Γ<10 GeV)

$H \to \gamma\gamma$ & VBF $H \to 2\tau$

SM-like Modes

Polytechnique



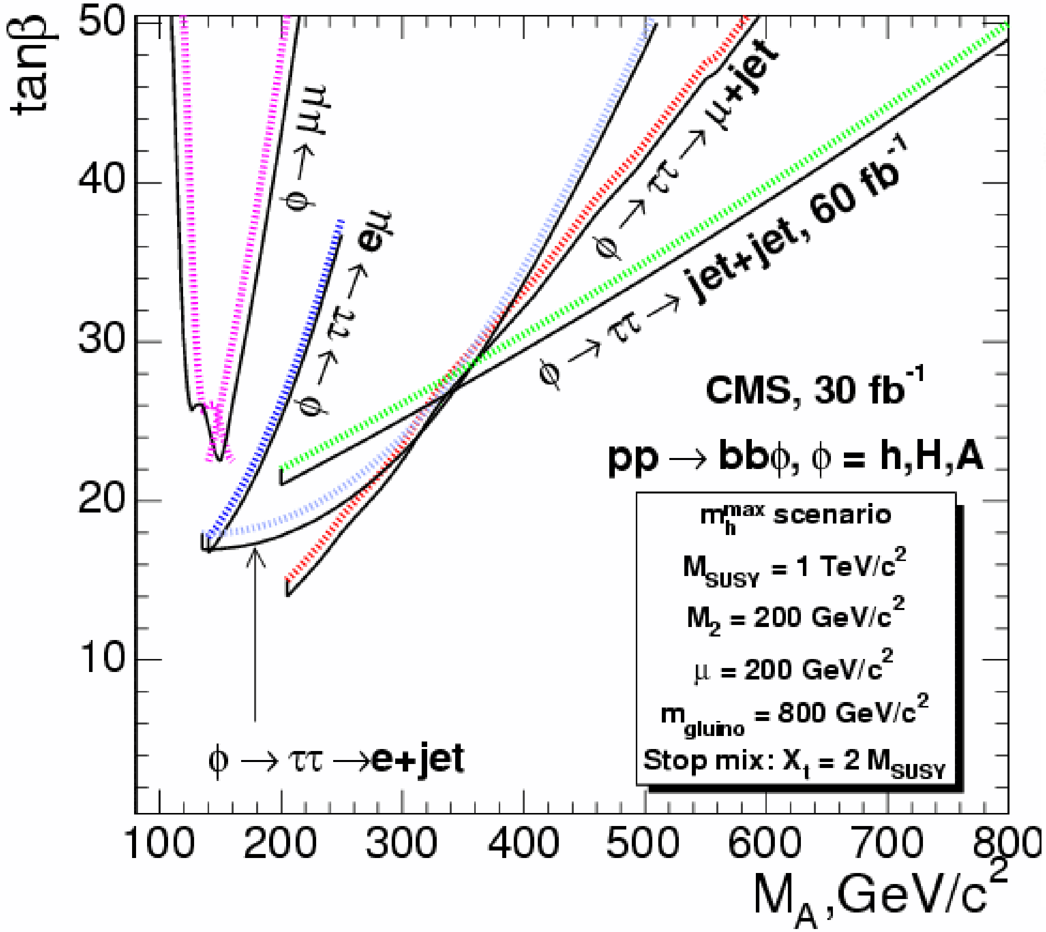


SUSY Higgs

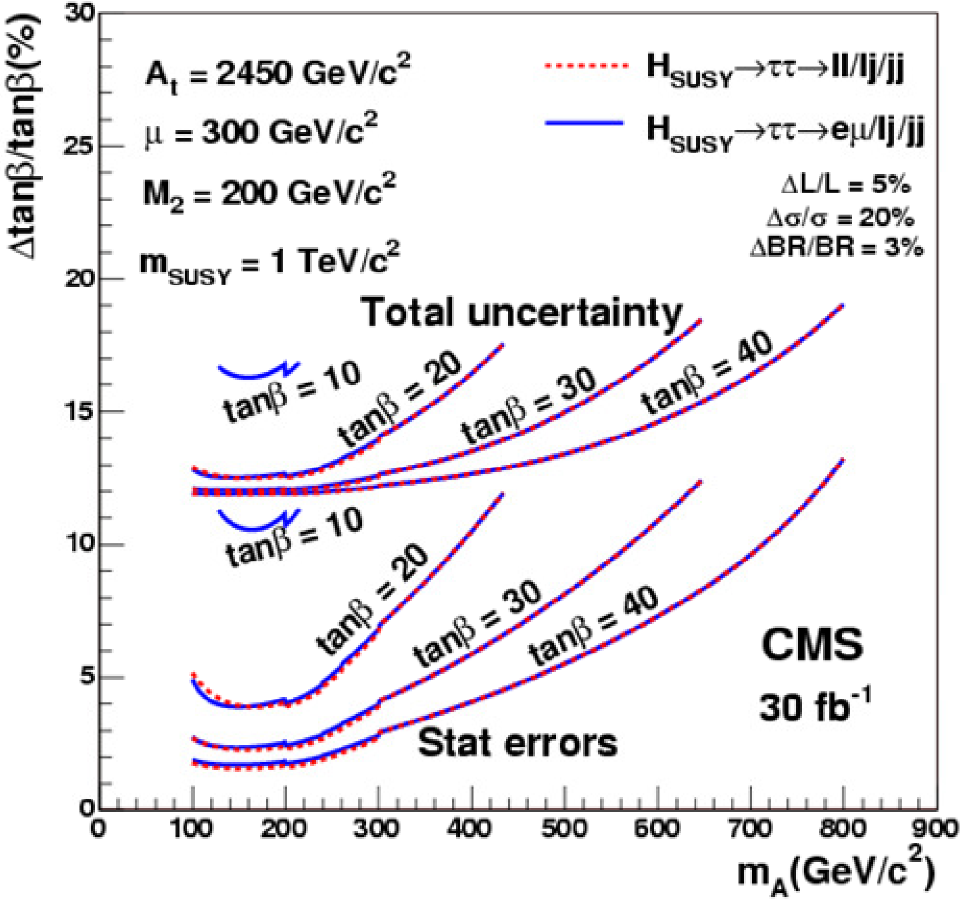
bb ϕ ; $\phi \rightarrow \tau\tau$

Polytechnique

Discovery Reach (14 TeV):



Constraint on tan β using $\sigma(A \rightarrow \tau\tau)$



Note:
use Z ➔ ττ as benchmark for H ➔ ττ
use bbZ as benchmark for bbH

Sensitivity beyond the Tevatron at large M_A – tanβalready for 1fb^{-1} at 7 TeV

Charged Higgs @ LHC

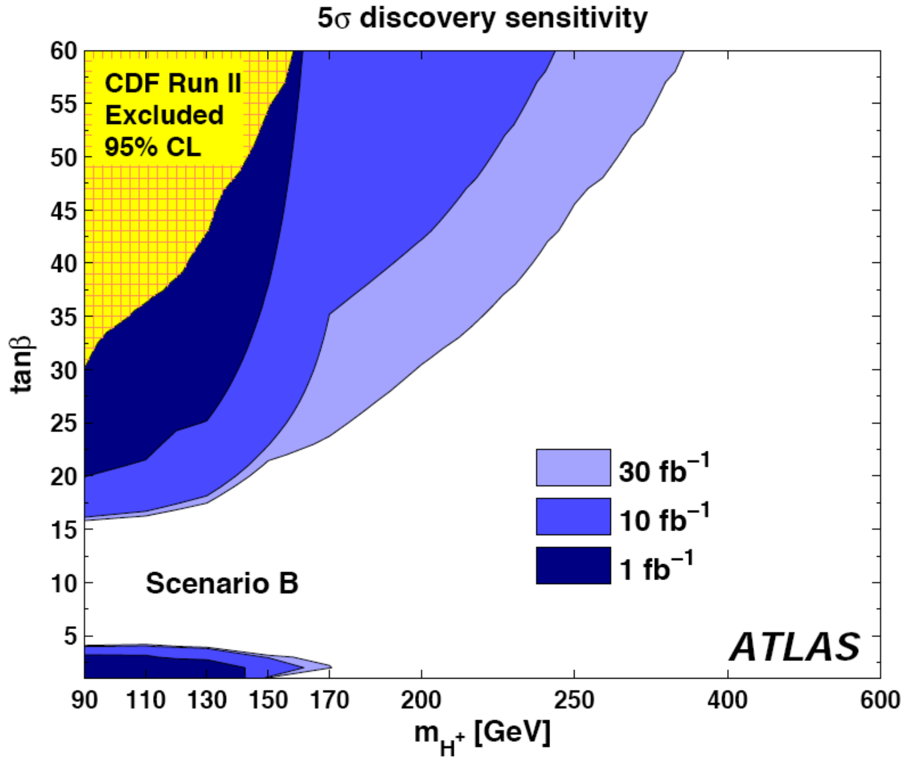
- Low Mass Case $m_{H^+} < m_t$
  - production via $t \to H^+ b$
  - decay via $H^+ \to \tau\nu$
  - small tan β: $H^+ \to cs$ (ATLAS analysis in preparation)
- High Mass Case $m_{H^+} > m_t$
  - production via $gg \to tbH^+$ and $gb \to tH^+$
  - decay via $H^+ \to tb$

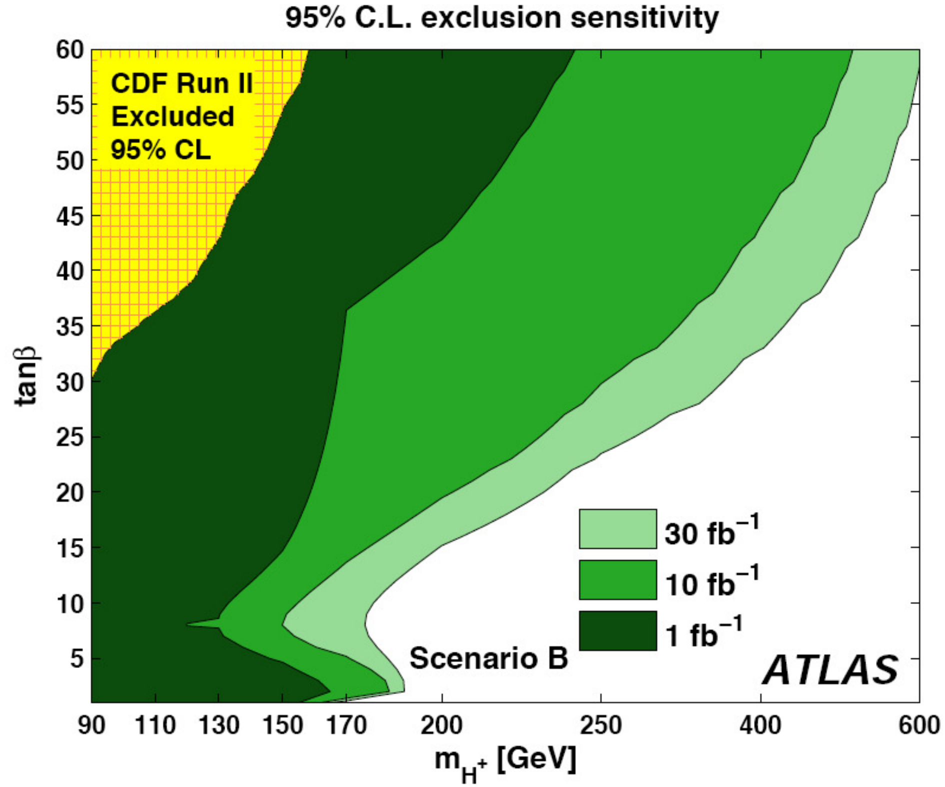
Light Charged Higgs Boson $m_{H^+} < m_t$

- mostly covered at LHC

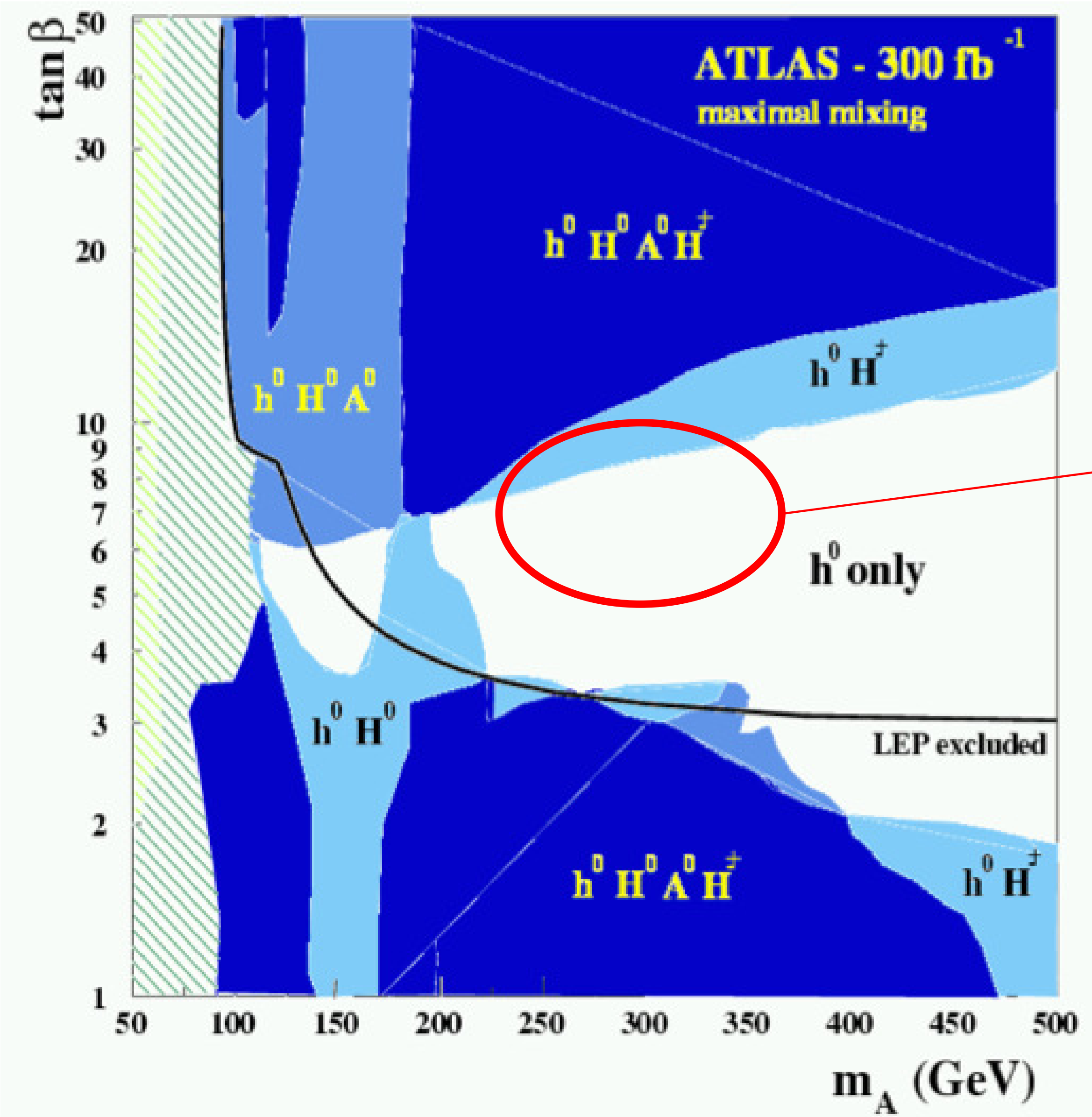
Heavy Charged Higgs Boson $m_{H^+} > m_t$

- difficult except for the highest tan β





Global View (very long term)

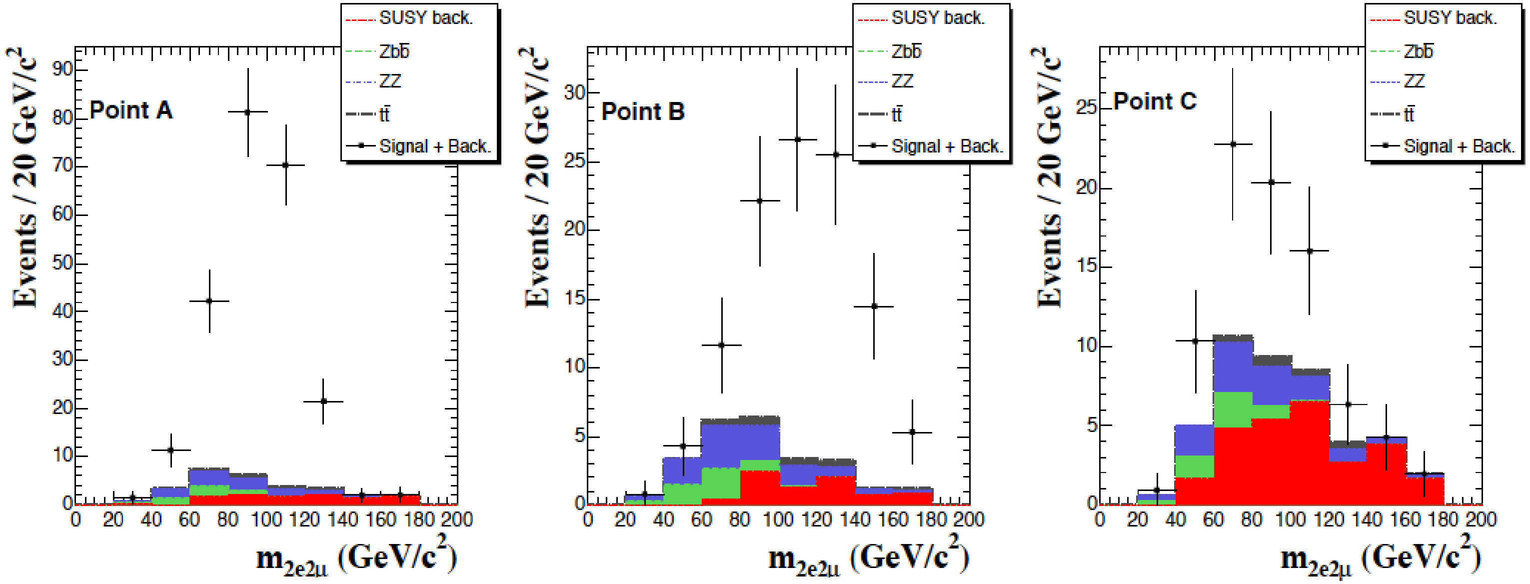


$A^0/H^0 \rightarrow \chi^0_2\chi^0_2$
$\rightarrow$ 4l + missing ET

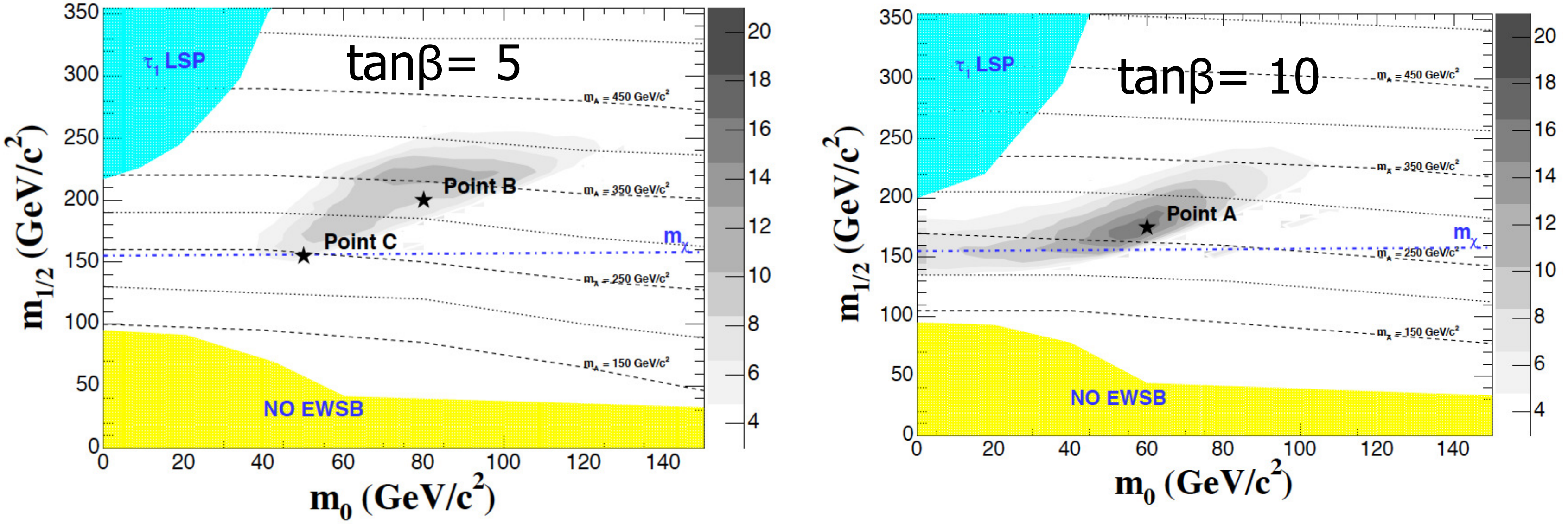
Intermediate Tan β - M_A

R. Salerno, C. Charlot, Y.S.
J.Phys.G. 2007

$A^0/H^0 \rightarrow \chi^0_2\chi^0_2 \rightarrow 4l$ + missing ET



14 TeV
30 fb^{-1}



Conclusions

- 20 years later … the beam is now circulating in the LHC ! we have seen first collisions at $\sqrt{s}$ = 900 GeV (and 2.36 TeV) in 2009 !
  … and are preparing for $\sqrt{s}$ = 7 TeV and 1 fb^{-1} in 2010-2011 !

  [Major media event on the 30/03 at CERN !]

- The experiments are ready and partly commisionned using cosmics collision 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 will partly takeover and extend the searches for the Higgs(es) and new physics beyond the reach of the TeVatron already in 2010-2011