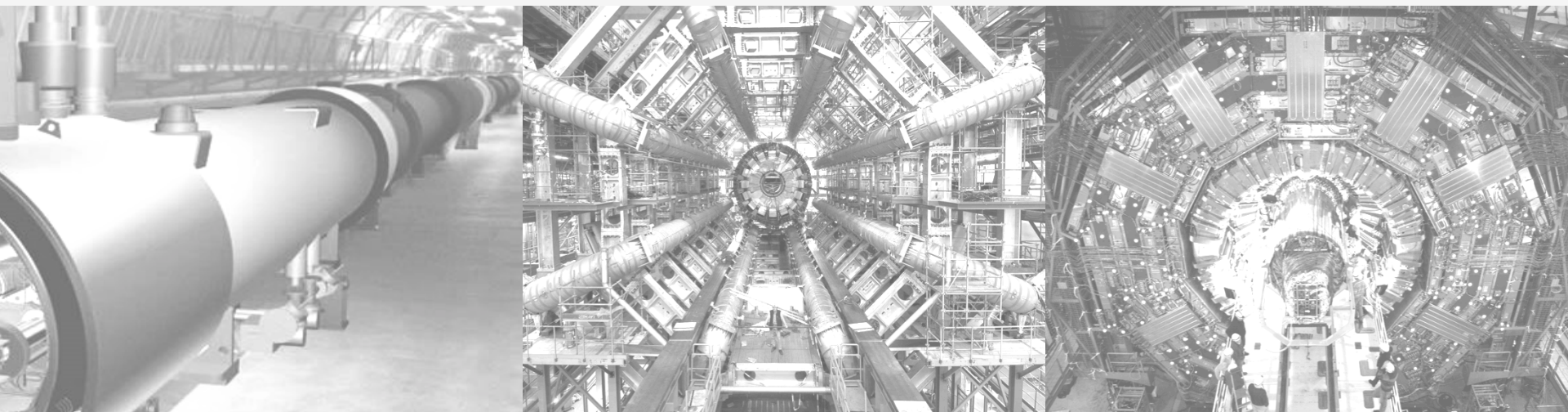


The Higgs Boson

Quest for the last of the particles ?

Andreas Hoecker (CERN, ATLAS Collaboration)

Colloquium, 5 March 2011, Stanford, CA



The LHC proton-proton Physics Programme

1. Mass

- Search for the Higgs Boson, measurement of its properties

2. Hierarchy in the TeV domain

- Search for new phenomena moderating the hierarchy problem

3. Electroweak unification and strong interactions

- Precision measurements (M_W , m_{top}) and tests of the Standard Model
- Tests of perturbative QCD at the high-energy frontier

4. Flavour

- B mixing, rare decays and CP violation as tests of the Standard Model

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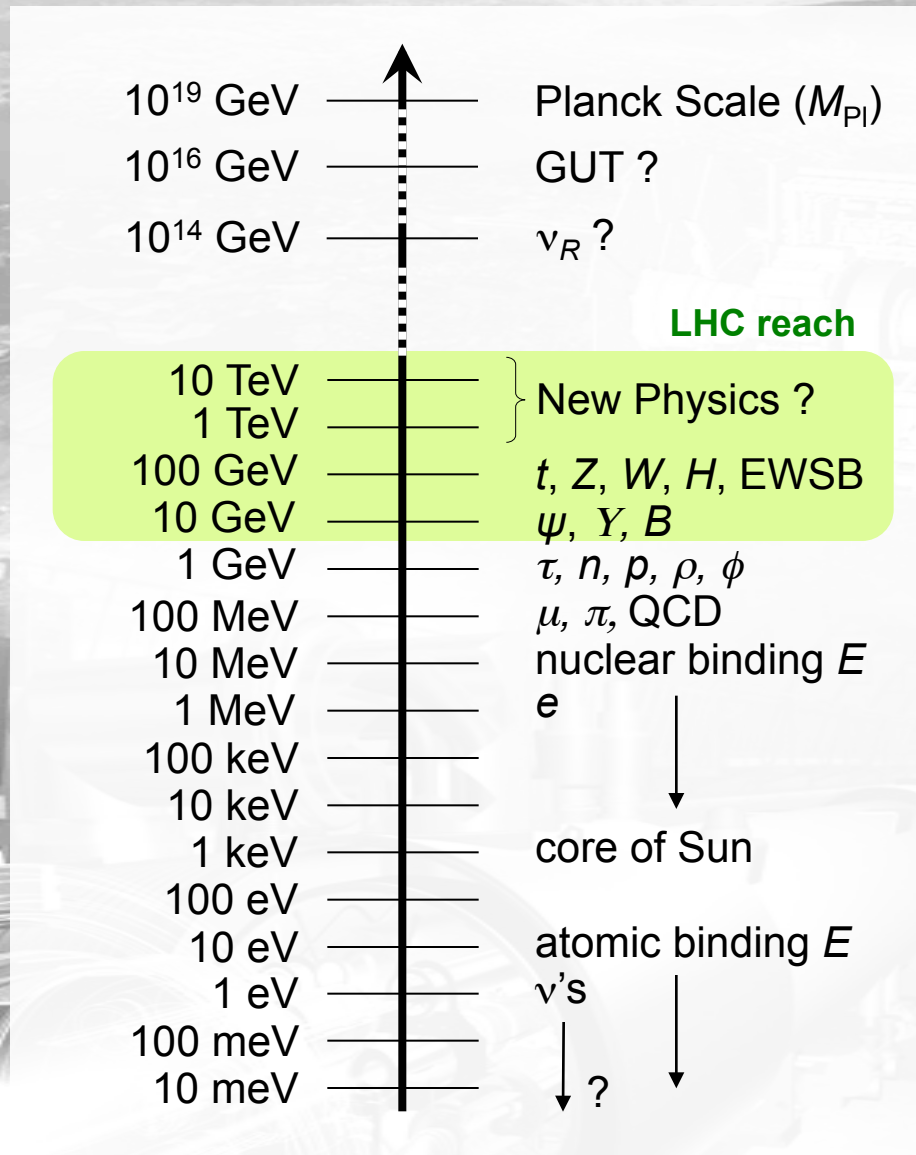
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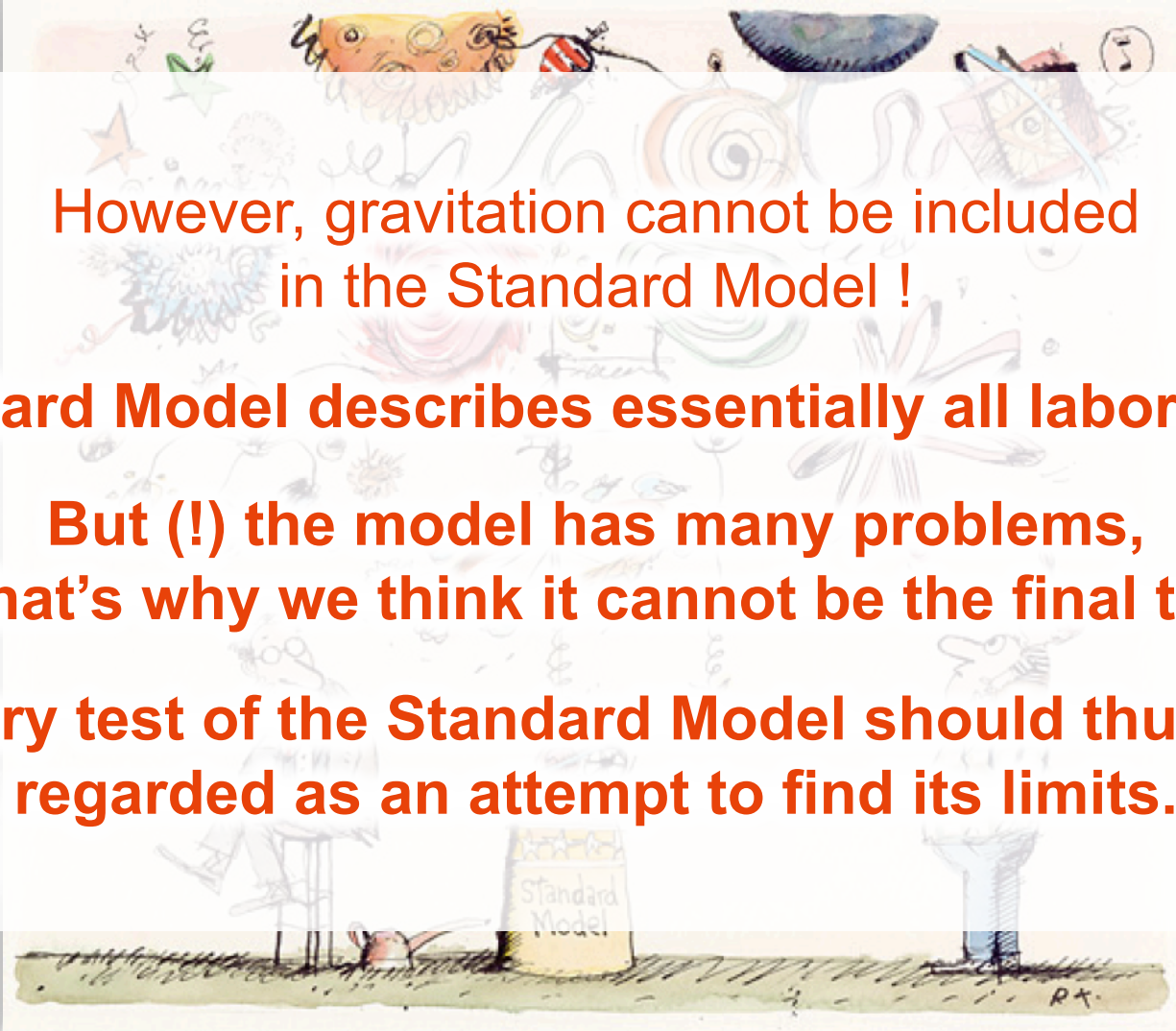
4. Flavour

- B mixing, rare decays and CP violation as tests of the Standard Model

Particle Physics Scales



Everyday life (and particle physics) are described by the Standard Model



However, gravitation cannot be included
in the Standard Model !

The Standard Model describes essentially all laboratory data.

**But (!) the model has many problems,
and that's why we think it cannot be the final theory.**

**Every test of the Standard Model should thus be
regarded as an attempt to find its limits.**

The Standard Model

The Standard Model consists of **24 elementary particles and 3 forces**

Fermions

Matter particles

Organised in 3 families

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

6 Leptons

$$\ell$$

6 Quarks

$$q$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Bosons

Force quanta

Distinguishing 3 forces

Photon

$$\gamma$$

Electro-magnetic force

3 weak bosons

Weak force

$$W^\pm$$

$$Z^0$$

8 Gluons

Strong force

$$g$$

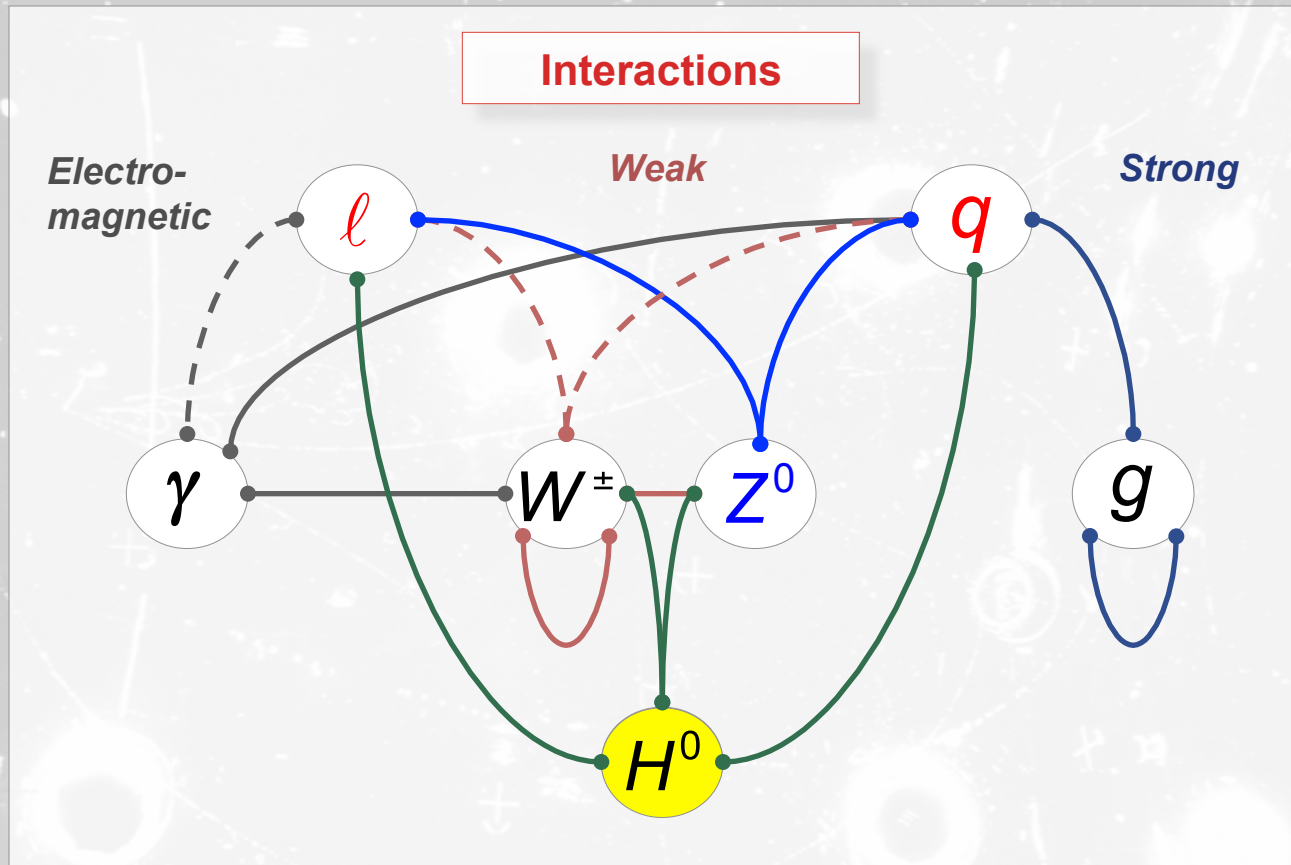
Higgs boson

$$H^0$$

**Breaks electroweak symmetry
Generates fermion and boson masses**

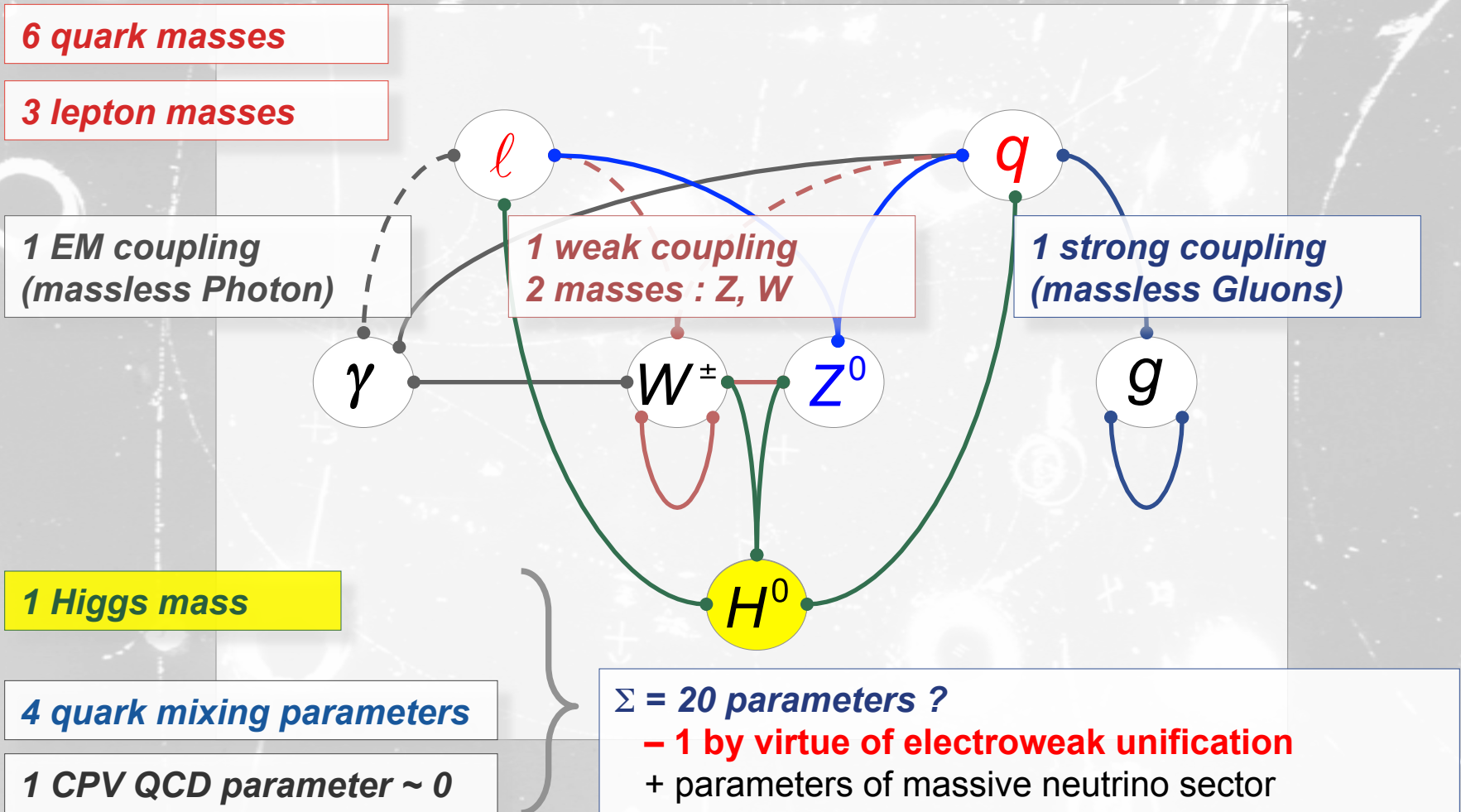
The Standard Model

The Standard Model consists of **24 elementary particles** and **3 forces**



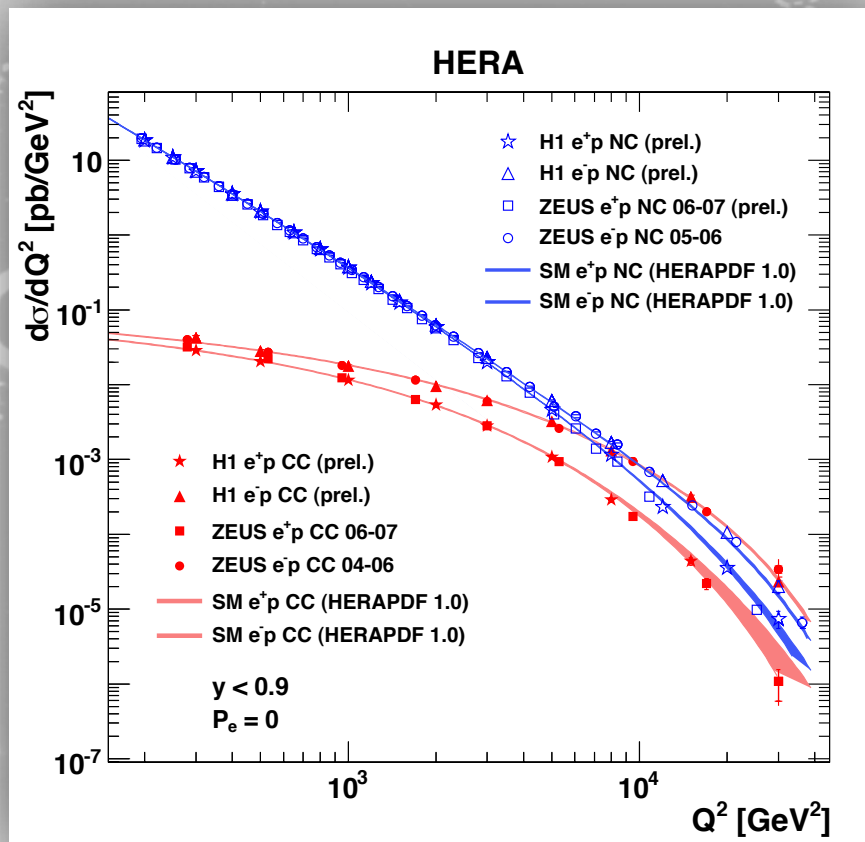
The Standard Model

The SM describes all observed phenomena in particle physics by **19 parameters** (?)



The Standard Model

The SM describes all observed phenomena in particle physics by **19 parameters** (?)



- Above ~100 GeV, electromagnetic and weak interactions are unified
- Below 100 GeV, weak interaction is weaker than electromagnetism

HERA data from electron–quark scattering into $e+q$ (NC = γ, Z) or $\nu+q$ (CC = $W^\pm$)

$\Sigma = 20$ parameters ?

– 1 by virtue of electroweak unification

+ parameters of massive neutrino sector

The Standard Model

Elementary particle physics is successfully described by **local gauge theories**

- Take a gauge group G
- The interactions (gauge bosons) are given by the generators of the group
- The fermions are arranged in multiplets on which the gauge bosons act
- The gauge group of the Standard Model is: $SU(3)_C \times SU(2)_L \times U(1)_Y$
 - $SU(3)_C$: strong interactions with coupling α_s
 - $SU(2)_L \times U(1)_Y$: electroweak interactions with couplings g, g'
- In this scheme **all SM particles must be massless** (otherwise: gauge non-invariance)

The “Higgs Mechanism”

F. Englert, R. Brout, PRL 13 (1964) 321; P.W. Higgs, PL 12 (1964) 132; PRL 13 (1964) 508; G. S. Guralnik, C.R. Hagan, T.W.B. Kibble, PRL 13 (1964) 585

How to give mass without breaking gauge invariance?

The answer is the **Higgs mechanism**, which is based on the observation that scalar mass terms are gauge invariant.

This is exploited to give mass to the gauge bosons *through the back door...*

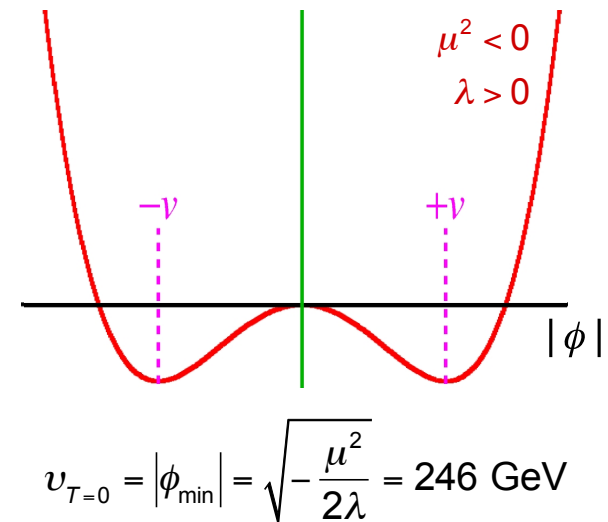
Potential $V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$, ϕ scalar field doublet

For $\mu^2 < 0$, the minimum moves away from $\phi = 0$

The ground state ($T = 0$) acquires a non-zero **vacuum expectation value (vev)** v

Perturbation theory around ground state: $\phi \propto v + H$

H is the **Higgs boson**. The other 3 components of the doublet ϕ are absorbed to give mass to $W^\pm$ and Z



v precisely known from muon decay

The Higgs Mechanism

Let's imagine all particles have zero mass $\rightarrow$ gauge symmetry is respected

A Higgs field fills all space time (but w/o orientation as spin=0)

The particles interact with the Higgs field thus reducing their velocity,
which is equivalent to acquiring a mass

The action of the Higgs field creates a *vacuum viscosity*

Weak interaction becomes short-ranged

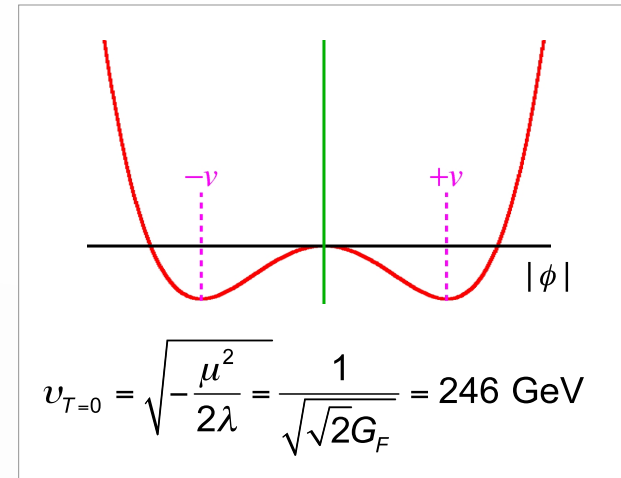
During the history of the big bang, the Higgs field must have appeared during a phase transition (the fermions and bosons were massless in the early unbroken phase of the universe)

“Viscosity” of the Higgs Condensate

$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4, \quad \mu^2 < 0$$

$$\langle 0 | \phi | 0 \rangle_{T=0} = v_{T=0} / \sqrt{2}$$

At $T < T_{EW}$, the massless fermion fields interact with the non-vanishing Higgs “condensates”:



$$\text{fermion line} = \text{propagator: } 1/q + \frac{(g_f v_T / \sqrt{2})}{1/q \text{ --- } \text{Higgs} \text{ --- } 1/q} + \frac{(g_f v_T / \sqrt{2})^2}{1/q \text{ --- } \text{Higgs} \text{ --- } 1/q \text{ --- } \text{Higgs} \text{ --- } 1/q} + \dots$$

Geometric series yields massive propagator creating effective fermion mass

$$\frac{1}{q} + \frac{1}{q} \left(\frac{g_f v_T}{\sqrt{2}} \right) \frac{1}{q} + \frac{1}{q} \left(\frac{g_f v_T}{\sqrt{2}} \right) \frac{1}{q} \left(\frac{g_f v_T}{\sqrt{2}} \right) \frac{1}{q} + \dots = \frac{1}{q} \sum_{n=0}^{\infty} \left(\left(\frac{g_f v_T}{\sqrt{2}} \right) \frac{1}{q} \right)^n = \frac{1}{q - m_f}$$

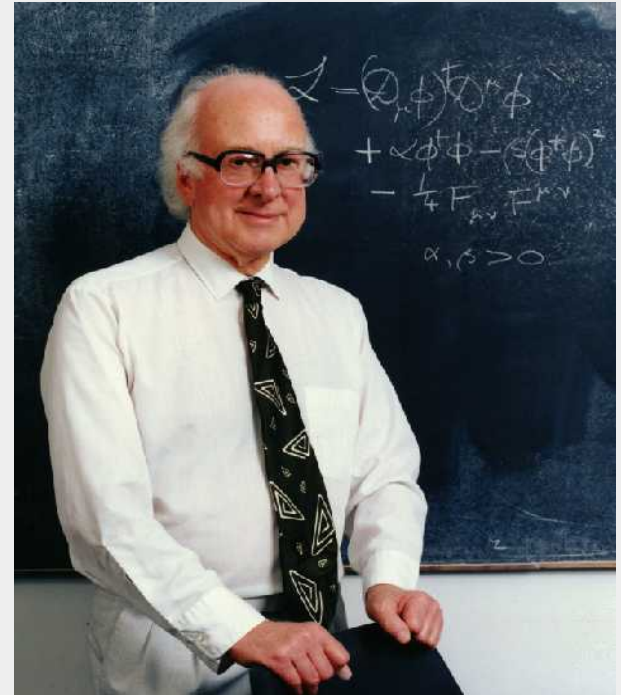
Similar for
gauge
bosons

The Higgs boson is the last elusive elementary particle of the SM

The Higgs boson - last of the particles ?

What is known about the Higgs Boson ?

P.W. Higgs, Phys. Lett. 12 (1964) 132



© CMS

© ATLAS

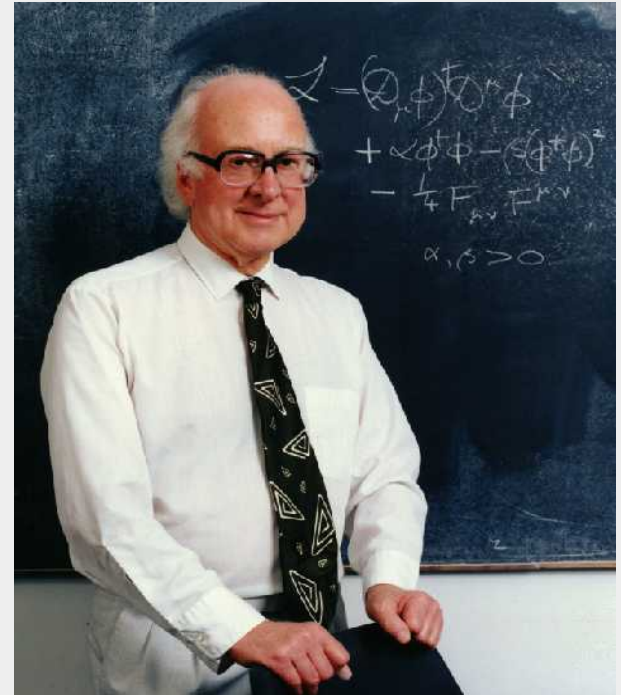
The Higgs boson is the last elusive elementary particle of the SM

Daniel Froidevaux (CERN):

The Higgs has been with us for 4 decades as

- a theoretical concept
- self-interacting scalar fields with non-zero vacuum expectation values
- an incarnation of the “Communist Party since it controls the *Masses*”
[L. Alvarez-Gaumé at CERN summer school in Alushta]
- a painful part of the first chapter in our PhD thesis ...

P.W. Higgs, Phys. Lett. 12 (1964) 132

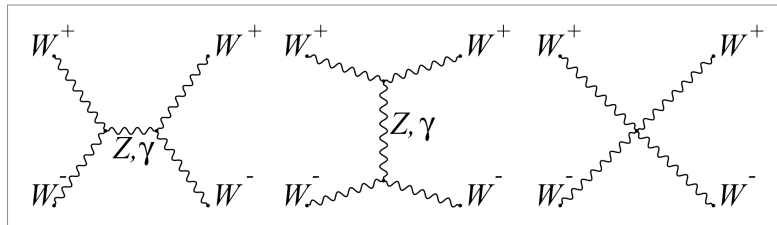


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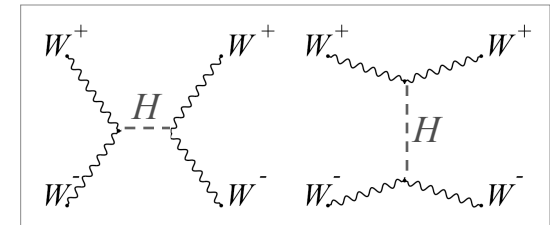
© ATLAS

The Higgs boson should not be too light, and not too heavy...

- Unitarity:** if only Z and γ are exchanged, the amplitude of (longitudinal) W^+W^- scattering diverges with s



Higgs regularises
total amplitude, if
 M_H not too large !



- Perturbativity:** Higgs self-coupling λ is UV divergent (“Landau pole”) $\rightarrow$ non-perturbative regime

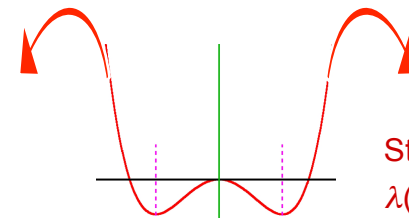
Landau pole decreases with increasing cut-off scale Λ to which the SM is considered to be valid

Since $M_H = v \sqrt{2\lambda} \rightarrow$ upper limit on M_H from limit on $\lambda(\Lambda)$

- Stability:** for a too light Higgs, top quark contributions can decrease λ and make it too small or negative

Critical M_H increases with SM cut-off scale Λ

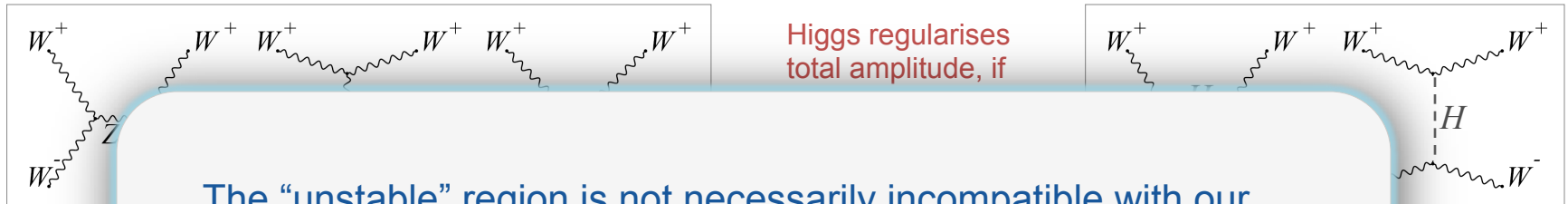
Stability requirement sets lower limit on M_H



Stability criterion:
 $\lambda(\mu) > 0, \forall \mu < \Lambda_{\text{cut-off}}$

The Higgs boson should not be too light, and not too heavy...

- **Unitarity:** if only Z and γ are exchanged, the amplitude of (longitudinal) W^+W^- scattering diverges with s



The “unstable” region is not necessarily incompatible with our existence, as long as the electroweak vacuum survives for a time longer than the age of the universe, before quantum tunneling.

- **Perturbative**

Landau

Since $M_H = 125 \text{ GeV}$

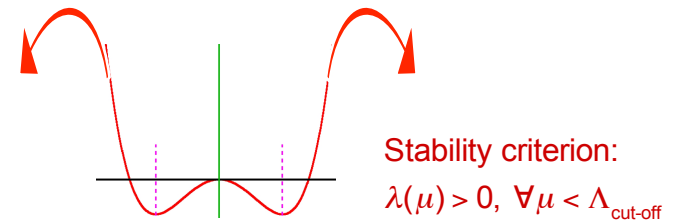
→ Metastability (at zero, or finite temperature)

time
lid

- **Stability:** for a too light Higgs, top quark contributions can decrease λ and make it too small or negative

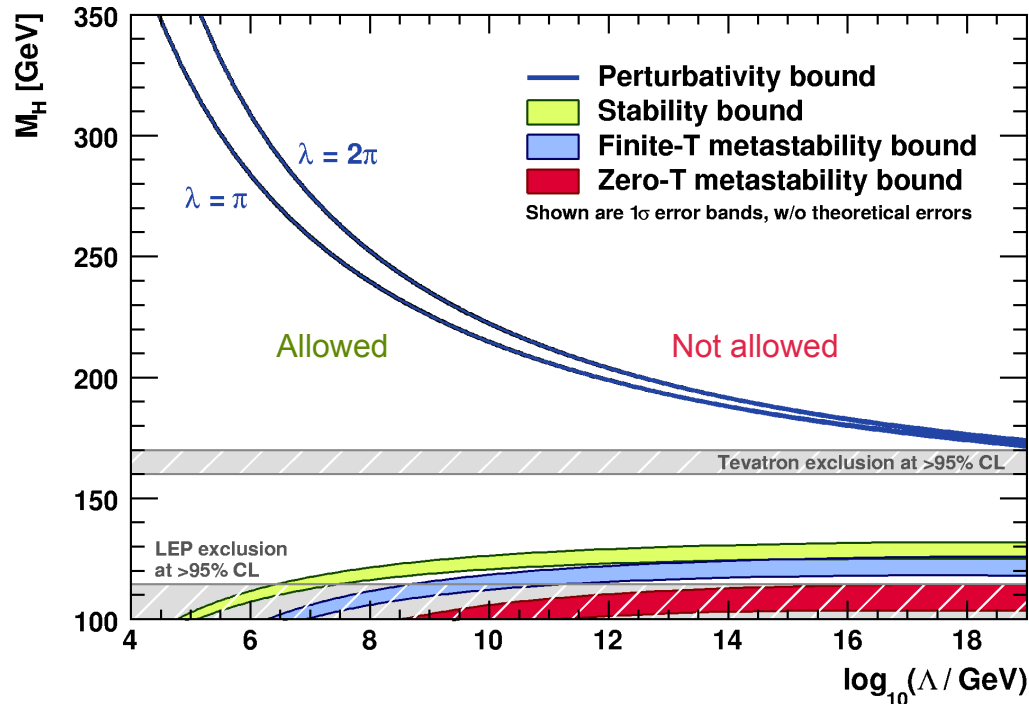
Critical M_H increases with SM cut-off scale Λ

Stability requirement sets lower limit on M_H



Driving the SM to the Planck Scale

Perturbativity and (meta)stability bounds versus the SM cut-off scale Λ

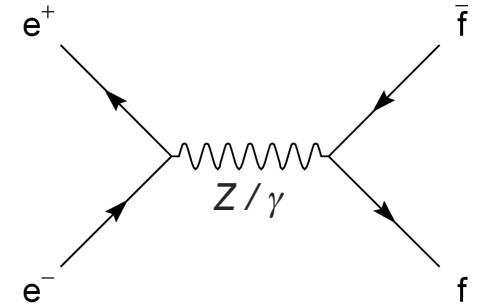
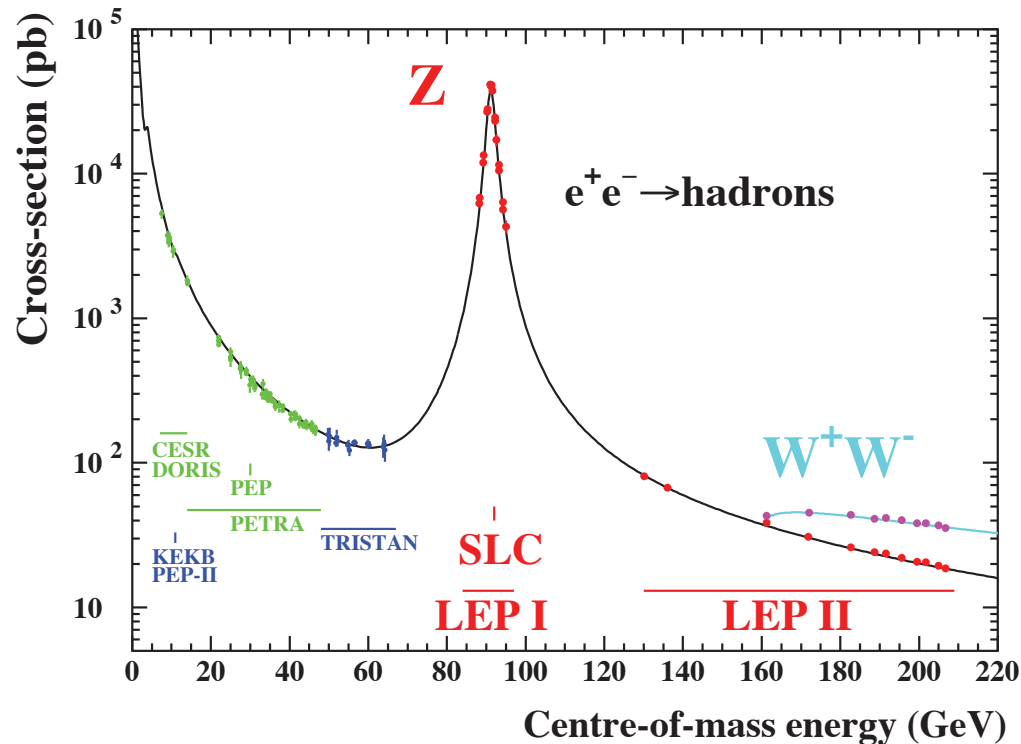


Figures use NLO Higgs potential. The widths of bands account for errors in α_s , m_t and theory.

The SM Higgs must steer a narrow course between two disastrous situations if it is to survive up to the Planck scale $M_P \sim 2 \times 10^{18}$ GeV

Constraints on Higgs mass from electroweak precision data

Electroweak precision observables measured at the Z^0 resonance (LEP, SLC)



Constraints on Higgs mass from electroweak precision data

Significant radiative corrections with virtual Higgs (and top!) exchange

- Modify the couplings and weak mixing at the Z pole:

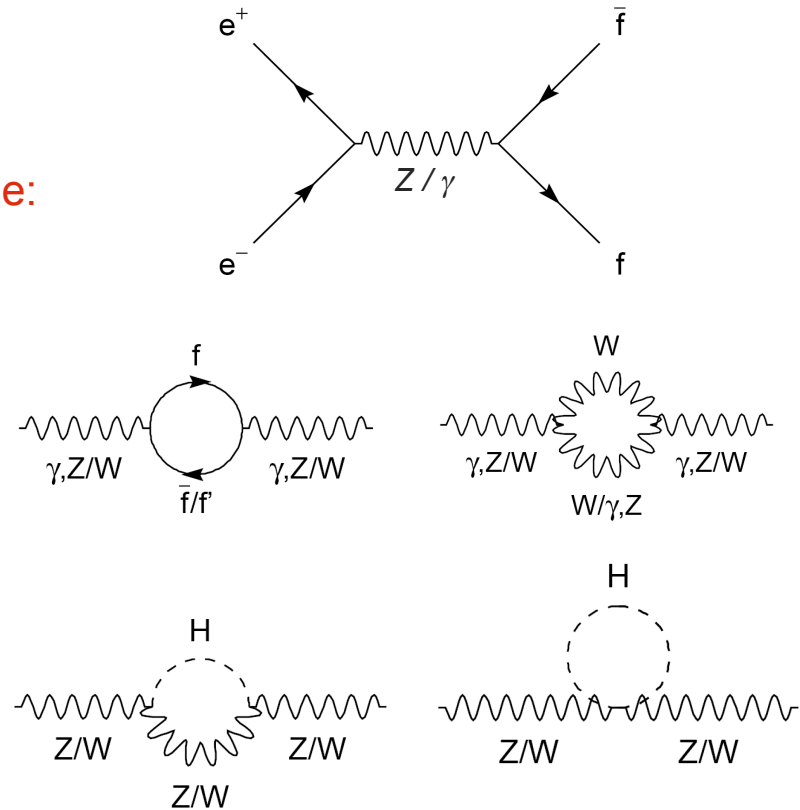
$$g_{V,f} = \sqrt{\rho_Z^f} \left(I_3^f - 2Q^f \sin^2 \theta_{\text{eff}}^f \right)$$

$$g_{A,f} = \sqrt{\rho_Z^f} I_3^f$$

$$\sin^2 \theta_{\text{eff}}^f = \kappa_Z^f \sin^2 \theta_W$$

- Modify the W mass:

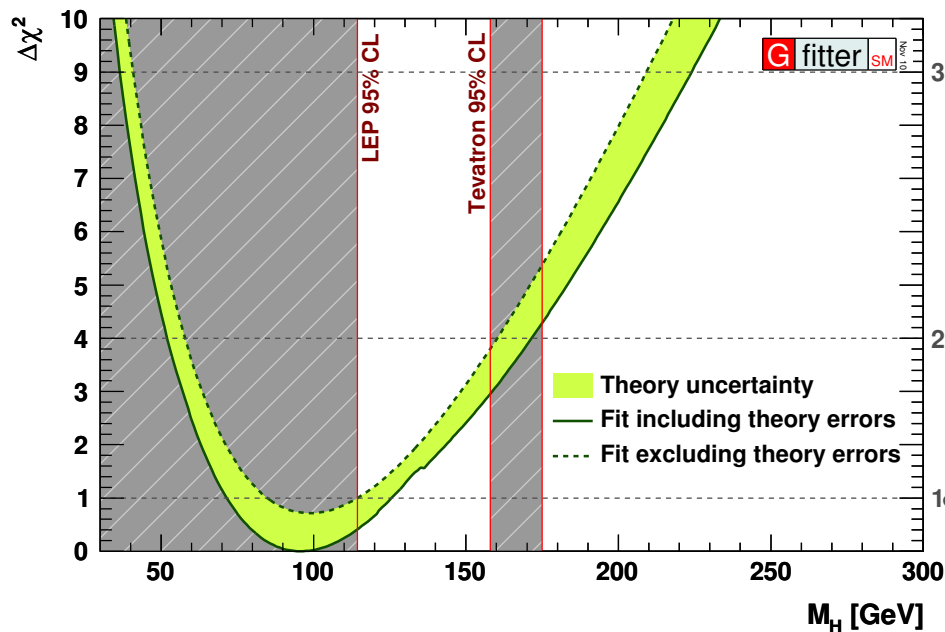
$$M_W^2 = \frac{M_Z^2}{2} \cdot \left(1 + \sqrt{1 - \frac{\sqrt{8\pi\alpha}}{G_F M_Z^2} \cdot (1 - \Delta r)} \right)$$



These couplings are precisely measured around the Z peak (M_W also at Tevatron) via Z decay widths and asymmetry observables sensitive to parity violation $\rightarrow$ fit constrains $\log(M_H)$ and m_t^2

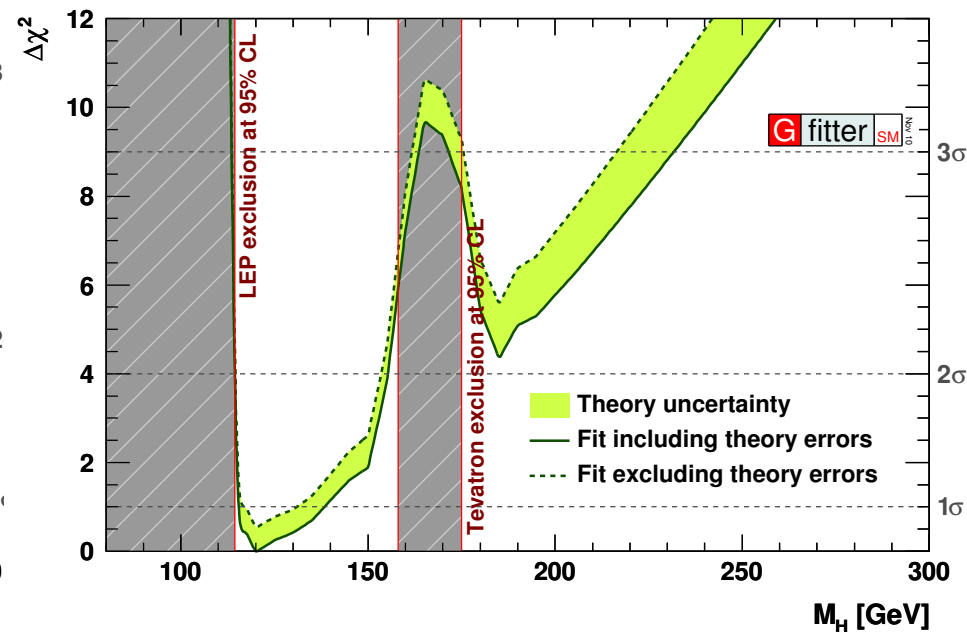
Constraints on Higgs mass from electroweak precision data

Global fit of all EW precision measurements to SM prediction constrains M_H



M_H from Electroweak fit:

- Central value $\pm 1\sigma$: $M_H = 96^{+30}_{-25}$ GeV
- 95% CL upper limit: 170 GeV



M_H from EW fit + Higgs searches

- Central value $\pm 1\sigma$: $M_H = 120^{+18}_{-5}$ GeV
- 95% CL upper limit: 155 GeV

Constraints on Higgs mass from electroweak precision data

In the Standard Model the Higgs must be light (< 155 GeV at 95% CL).

BUT: Beyond the Standard Model the Higgs can be heavy !

→ MUST NOT stop searching for heavy Higgs boson !

[Weak isospin violating new physics contributions may cancel heavy Higgs effects on electroweak precision data !]

M_H from Electroweak fit:

- Central value $\pm 1\sigma$: $M_H = 96^{+30}_{-25}$ GeV
- 95% CL upper limit: 170 GeV

M_H from EW fit + Higgs searches

- Central value $\pm 1\sigma$: $M_H = 120^{+18}_{-5}$ GeV
- 95% CL upper limit: 155 GeV



Once the Higgs boson is discovered
The Standard Model is complete



But ... does it hold tight ?



The Standard Model

During the last 35 years the Standard Model has been tested to great precision



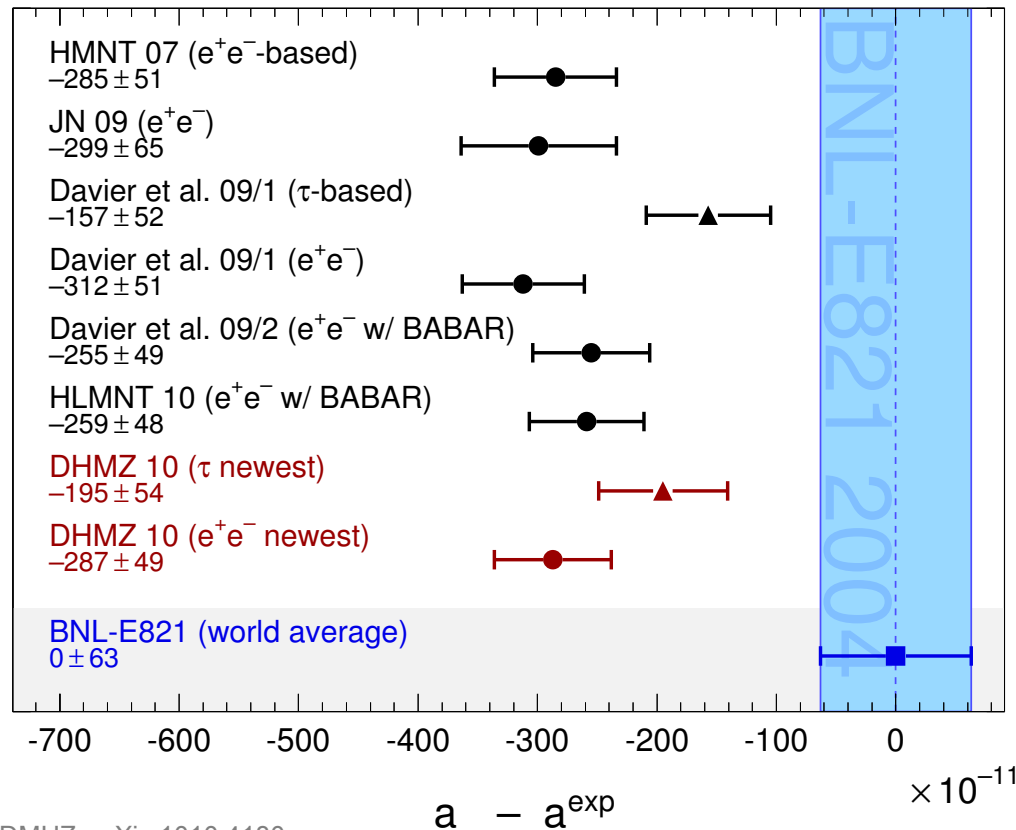
- Excited fundamental bosons or quarks have been excluded up to the TeV scale
- Electroweak unification has been verified at, below and above the Z-boson scale
- Universality of weak interaction has been verified at the per-mil level
- Asymptotic freedom of strong interaction has been verified at the percent level
- All observations of CP violation are described by a single complex parameter in the quark mixing matrix
- The tininess of elementary electric dipole moments has been verified to 10^{-27} ecm
- The electron and muon magnetic moments have been verified at the ppm level...
- *Examples only, there are many more successful tests ...*



The Standard Model

During the last 35 years the Standard Model has been tested to great precision

Muon magnetic moment: comparison between measurement (blue band) and predictions (dots)

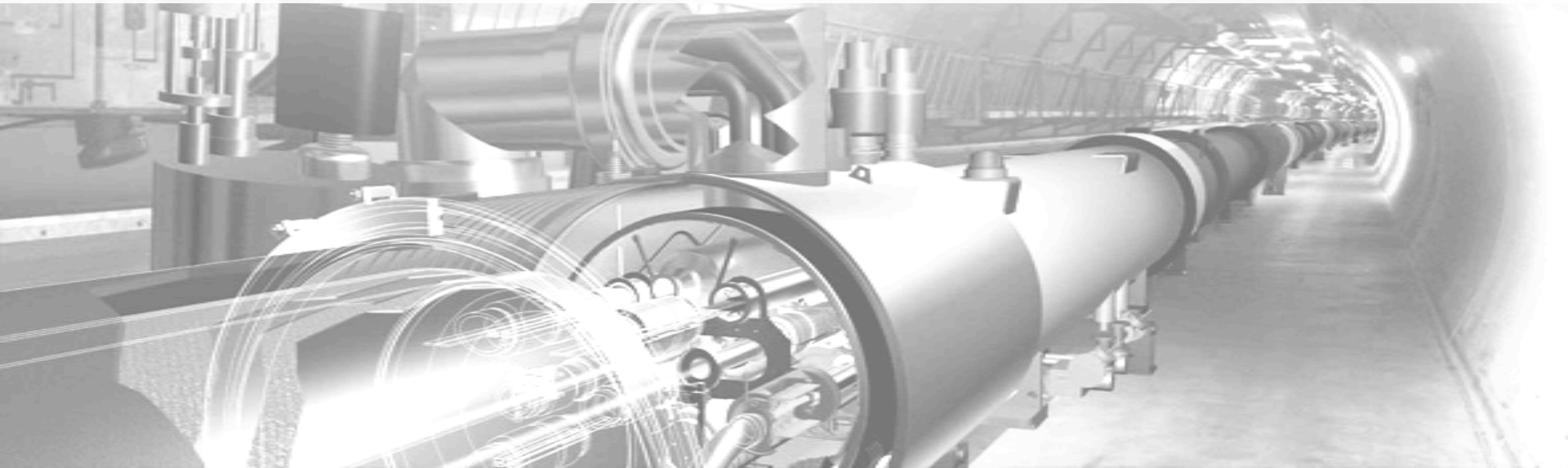


The **magnetic moment of the muon** is predicted to a precision of several 10^{-6} , ...

... but some tension exists ...



Producing the Higgs Boson and Searching for New Physics at the TeV Scale Requires a Huge Machine



Why Colliding Hadrons instead of e^+e^- ?

Advantage of hadron collider

- Can reach higher energies in ring (less synchrotron radiation)

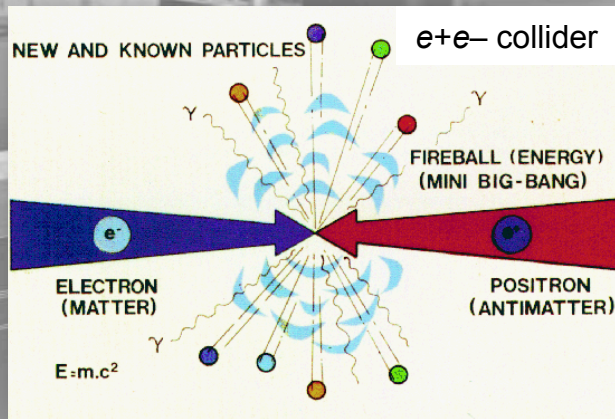
Energy loss per turn:

$$-\Delta E \approx \frac{4\pi\alpha}{3 \cdot R} \left(\frac{E}{m} \right)^4 \approx \begin{cases} 3.5 \text{ GeV for LEP-II at } E_{\text{beam}} = 104.5 \text{ GeV} \\ 6.2 \text{ keV for LHC at } E_{\text{beam}} = 7000 \text{ GeV} \end{cases}$$

High e^+e^- energy
requires linear
collider: *ILC, CLIC*

Disadvantages

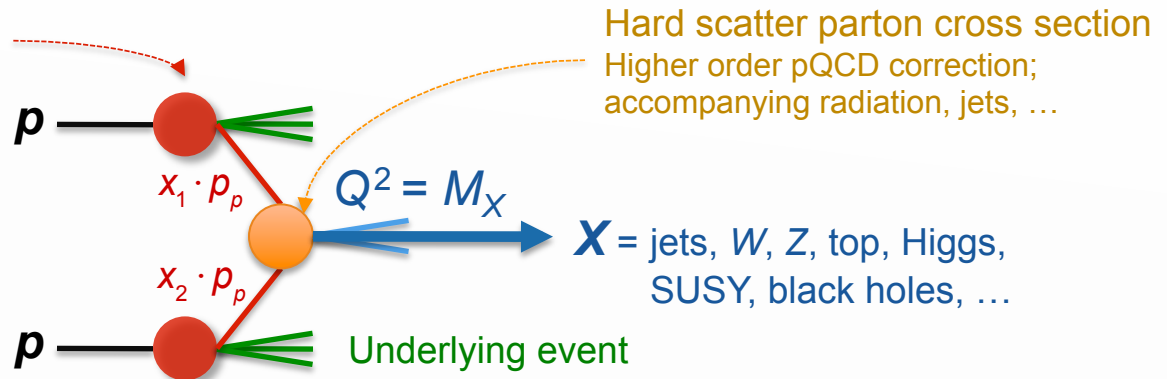
- Hadrons are composites $\rightarrow$ parasitic collisions beyond hard parton scattering
- Energy and type of colliding parton unknown $\rightarrow$ kinematics partially unconstrained



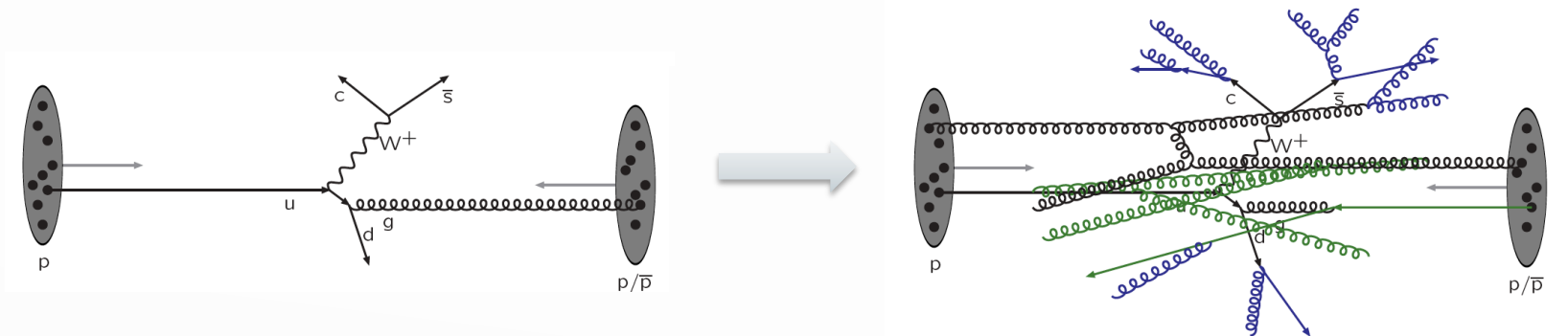
Proton-Proton Collisions

- For proton collisions, cross section is convolution of Parton Density Functions (PDF) with parton scattering Matrix Element

Parton distribution functions
Representing structure of proton

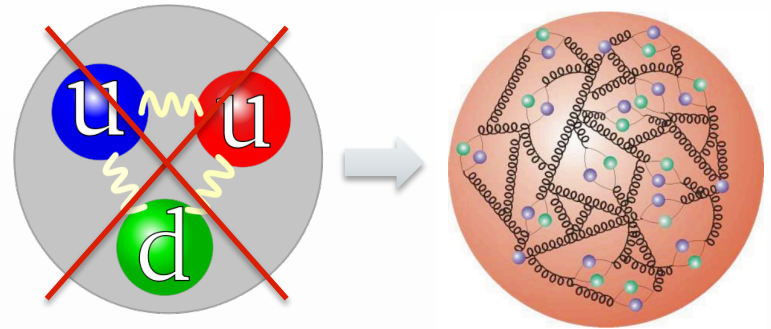


- Proton-proton events are complicated mixture of scattering phenomena



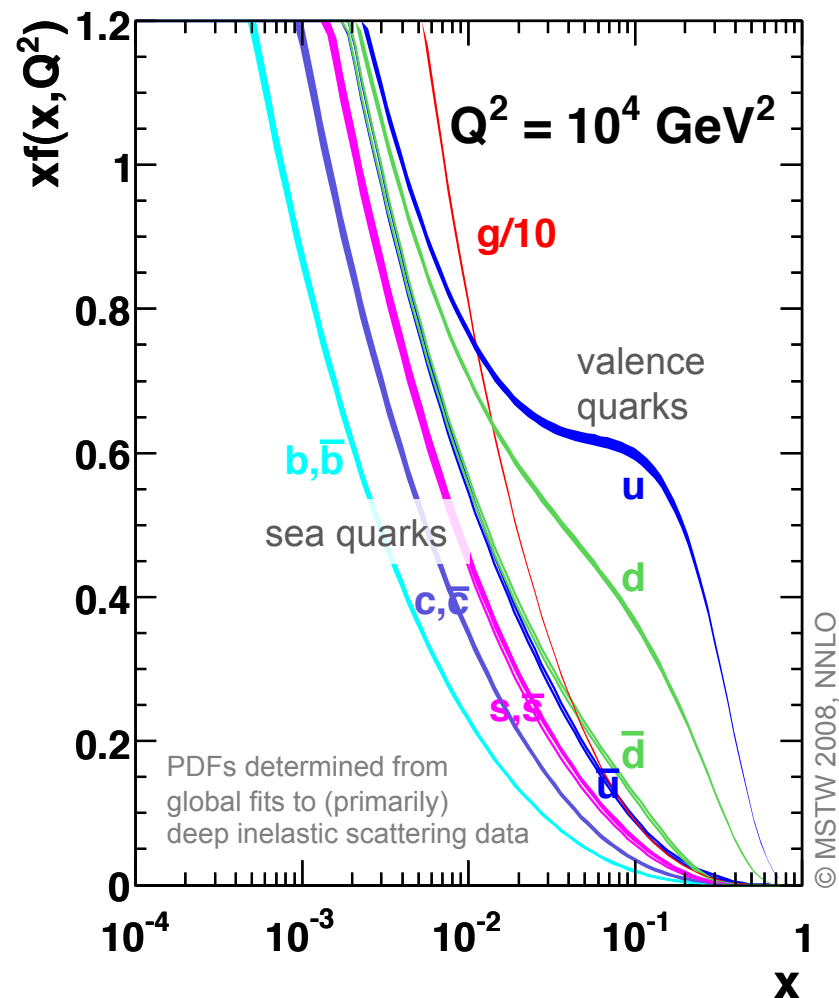
Proton–Proton Collisions

- Proton is complicated composite of valence quarks, gluons and sea quarks
- PDF depends on 2D mixture of
 - Q^2 (evolution in $\ln(Q^2)$ predicted by QCD)
 - Bjorken x momentum fraction
- CM energy of parton collision: $\hat{s} = M_X^2 = x_1 \cdot x_2 \cdot s_{\text{LHC}}$



Proton-Proton Collisions

- Proton is complicated composite of valence quarks, gluons and sea quarks
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 - Q^2 (evolution in $\ln(Q^2)$ predicted by QCD)
 - Bjorken x momentum fraction
- CM energy of parton collision: $\hat{s} = M_X^2 = x_1 \cdot x_2 \cdot s_{\text{LHC}}$
- Typical ' x ' values (assume: $x_1 = x_2$)
 - LHC ($\sqrt{s} = 14 \text{ TeV}$):**
 - $M_X = 100 \text{ GeV (1 TeV)} \rightarrow \langle x \rangle = 0.007 \text{ (0.07)}$
 - Tevatron ($\sqrt{s} = 2 \text{ TeV}$):**
 - $M_X = 100 \text{ GeV (1 TeV)} \rightarrow \langle x \rangle = 0.05 \text{ (0.5)}$
- PDFs rise dramatically towards low x
 - larger cross sections at LHC
 - gluon dominated



CERN, the LHC and ATLAS

Experimental Challenges

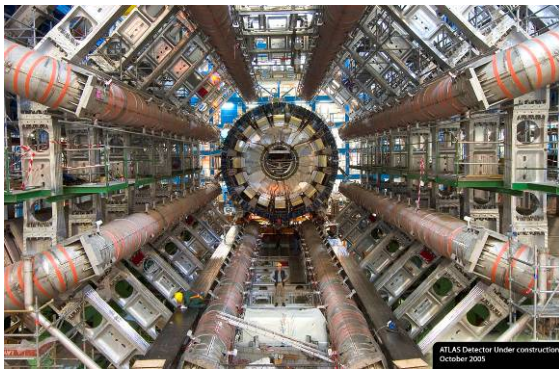


CERN AC/DI/MM 3324-07 07-1998

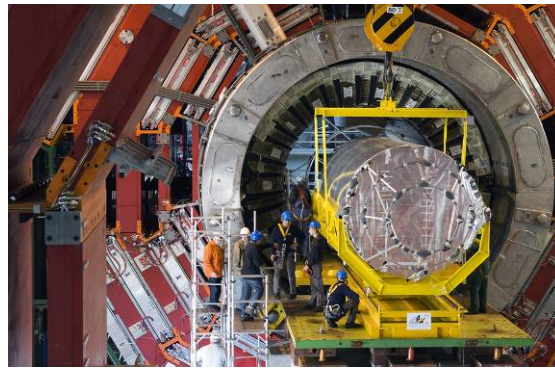
LHC: The Accelerator Challenge

- The search for new phenomena exploits **ever smaller distances** → **ever larger energies**
- Want to produce **rare new particles** → **need high intensity beams**
- **Proton energy is limited by magnets that guide the circular beams**
- $E_{\text{proton}} \sim 0.3 \cdot B \cdot r$: since radius is fixed (4.3 km), use as strong fields as possible (> 8 T), and fill all free LHC sections with dipole magnets ($\sim 2/3$)

ATLAS



CMS



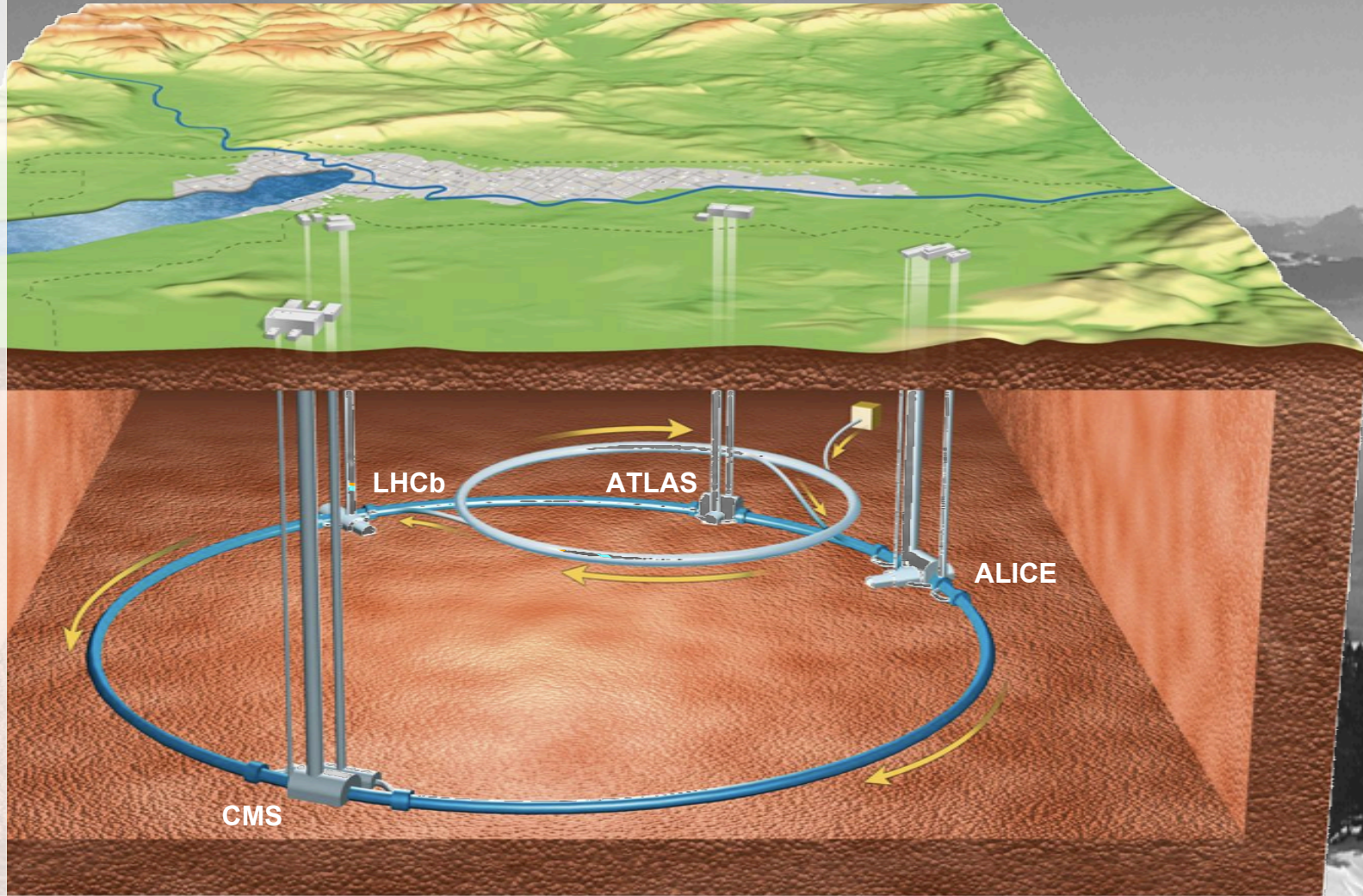
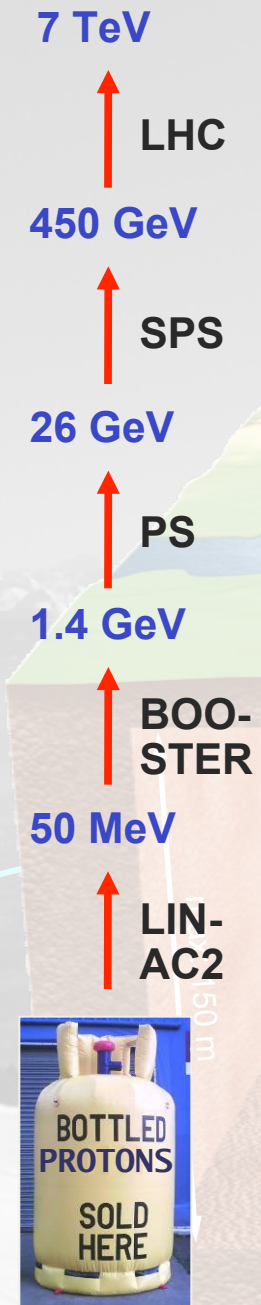
LHCb



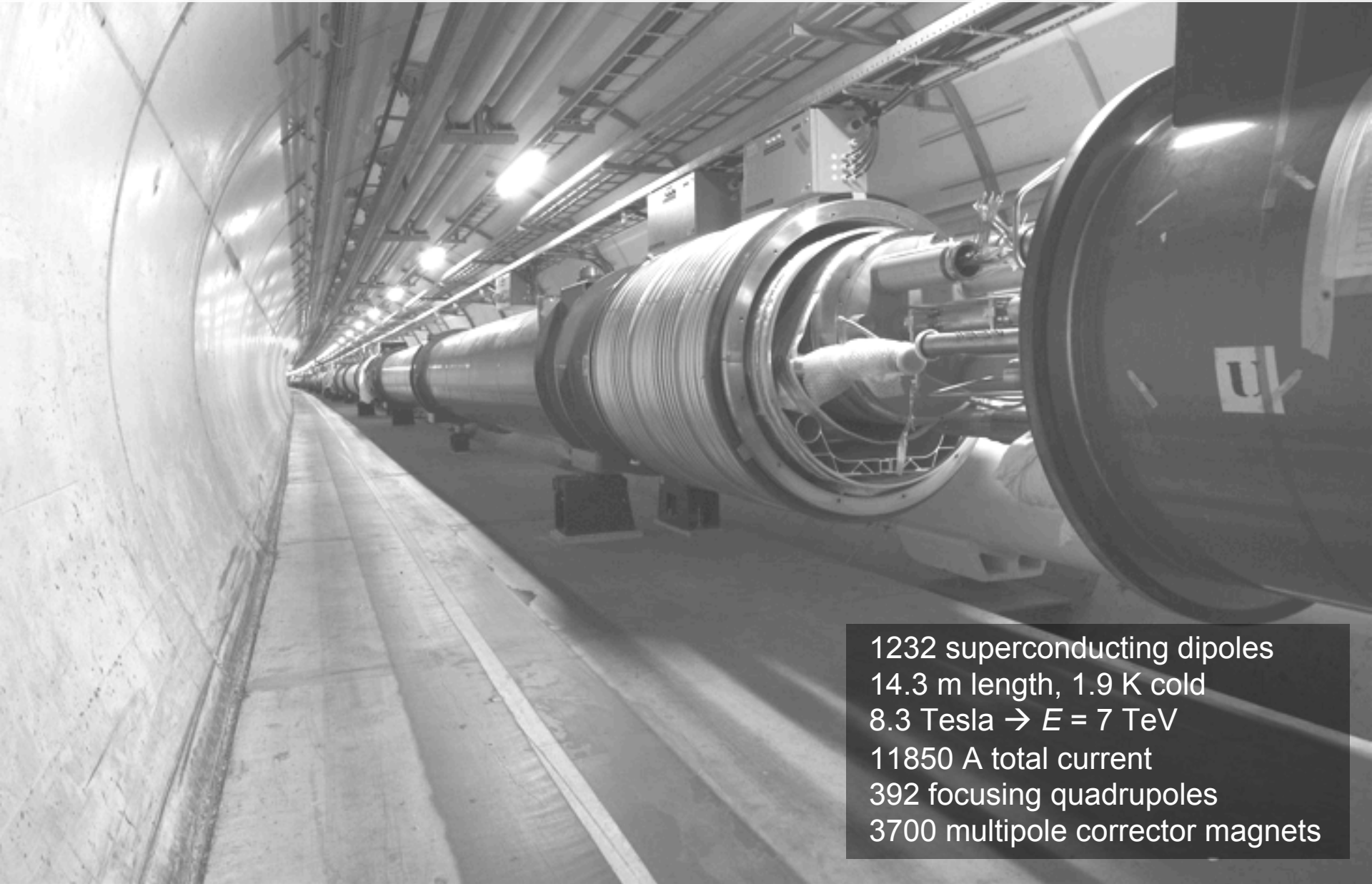
... and also ALICE !

Accelerators for the LHC

LHC has 4 large experiments: ATLAS, CMS, LHCb, ALICE



The LHC Dipole Sections



1232 superconducting dipoles
14.3 m length, 1.9 K cold
8.3 Tesla $\rightarrow E = 7$ TeV
11850 A total current
392 focusing quadrupoles
3700 multipole corrector magnets

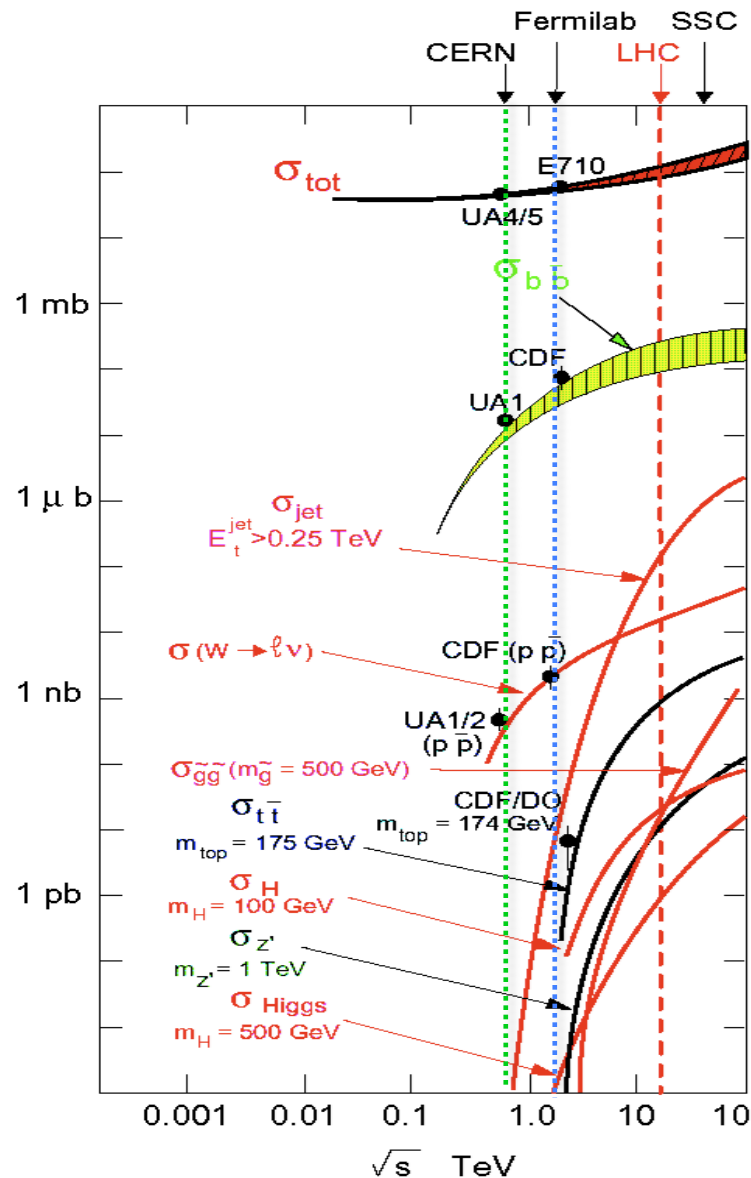
The LHC Dipole Sections



As a consequence of an accident on September 2008, the dipole currents cannot presently be raised to full power. The LHC is thus constrained to run at 7 TeV CM energy in 2010 and 2011, possibly being raised to 8 TeV in 2012. After a repair in 2013 14 TeV CM energy will be targeted in 2014.



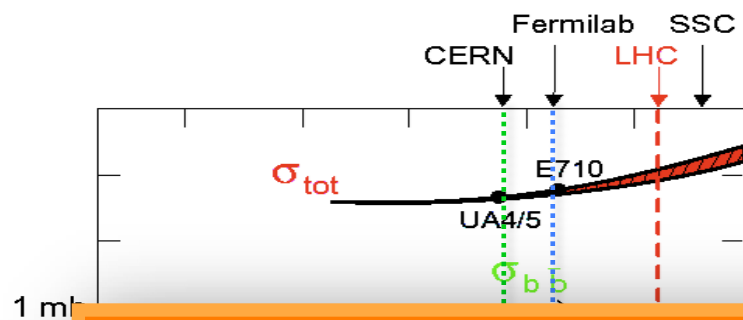
$pp(\bar{p})$ Cross Sections



Process	Cross section (nb) at 14 TeV CM energy	Production rates (Hz) at $L=10^{34} \text{ cm}^{-2}\text{s}^{-2}$
Inelastic	10^8	10^9
$b\bar{b}$	5×10^5	5×10^6
$W \rightarrow \ell \nu$	15	150
$Z \rightarrow \ell \ell$	2	20
$t\bar{t}$	1	10
Z' (1 TeV)	0.05	0.5
$\tilde{g}\tilde{g}$ (1 TeV)	0.05	0.5
H (120 GeV)	0.04	0.4
H (180 GeV)	0.02	0.2

Recall: $1 \text{ pb}^{-1} \triangleq 10^{36} \text{ cm}^{-2}$
 $\Rightarrow 15 \text{ nb} \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} =$
 $15 \text{ nb} \times 10^{-2} \text{ pb}^{-1}\text{s}^{-1} = 150 \text{ Hz}$

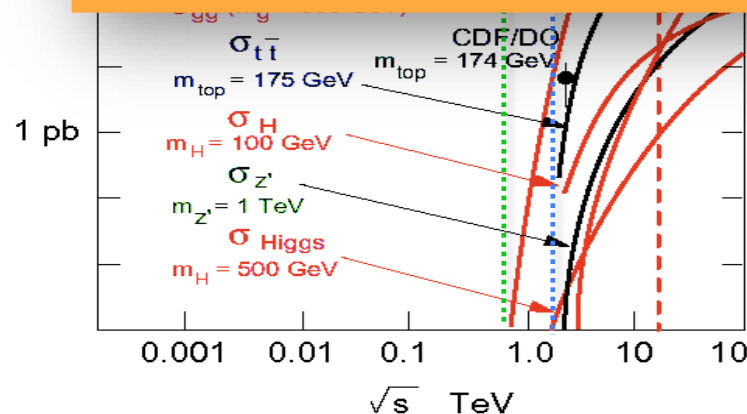
$pp(\text{bar})$ Cross Sections



Process	Cross section (nb) at 14 TeV CM energy	Production rates (Hz) at $L=10^{34} \text{ cm}^{-2}\text{s}^{-2}$
Inelastic	10^8	10^9

Many orders of magnitude between QCD background and primary physics channels (only one in five billion events is Higgs - Tevatron: only every trillionth event!)

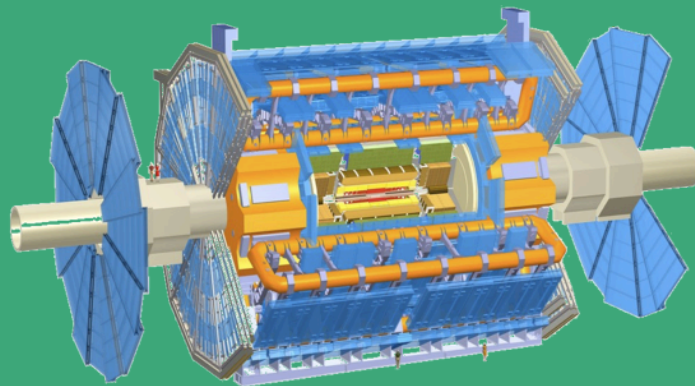
→ This fact drives the detector design



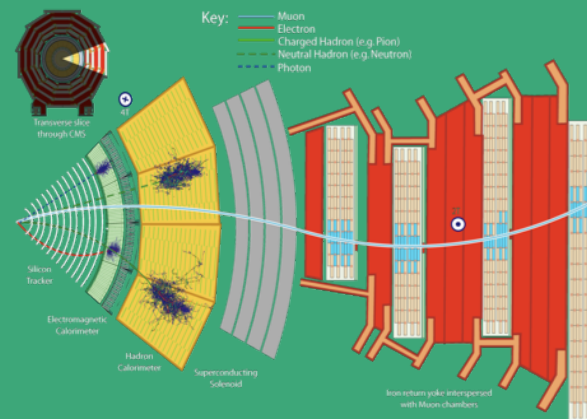
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ATLAS & CMS: Design Choices



ATLAS: emphasis on excellent jet and missing- E_T resolution, particle identification, and standalone muon measurement

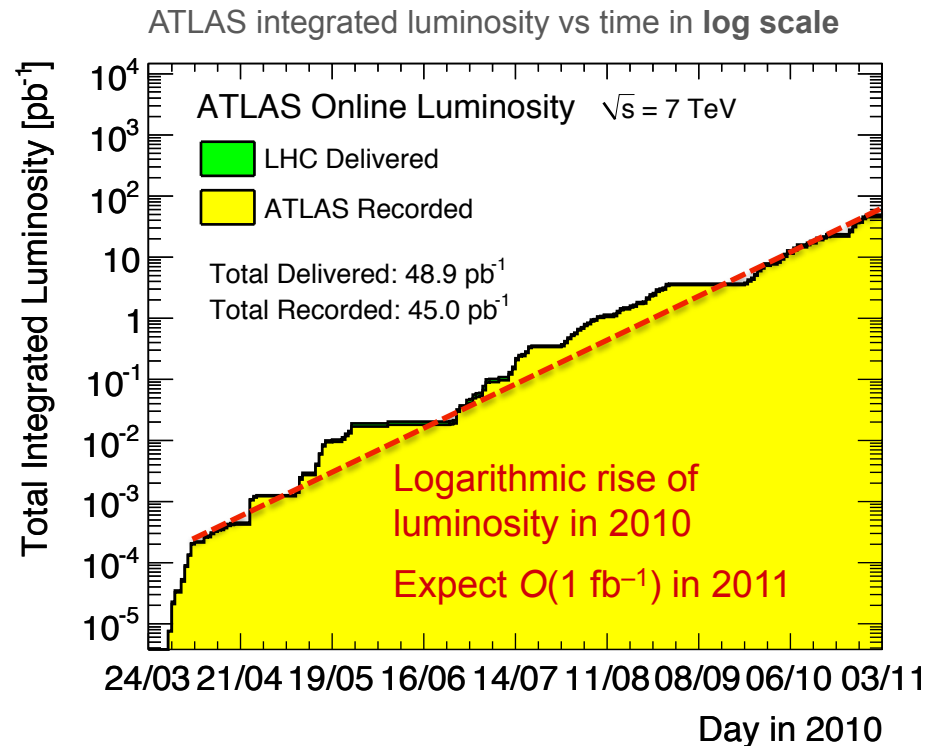
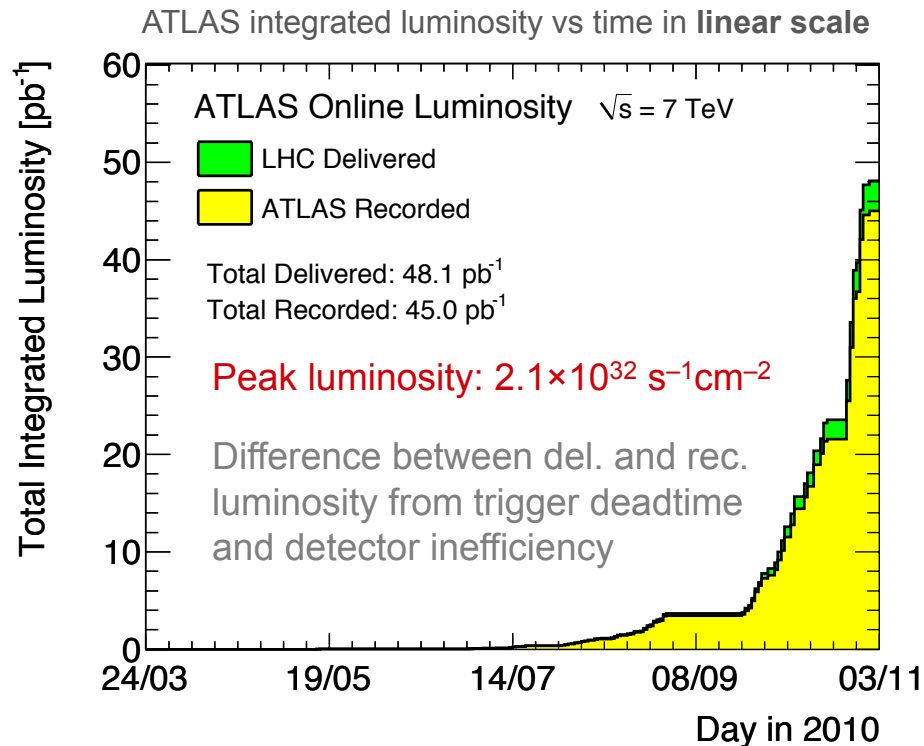


CMS: emphasis on excellent electron/photon and tracking (muon) resolution

Both: excellent hermeticity and forward acceptance – very few “cracks”

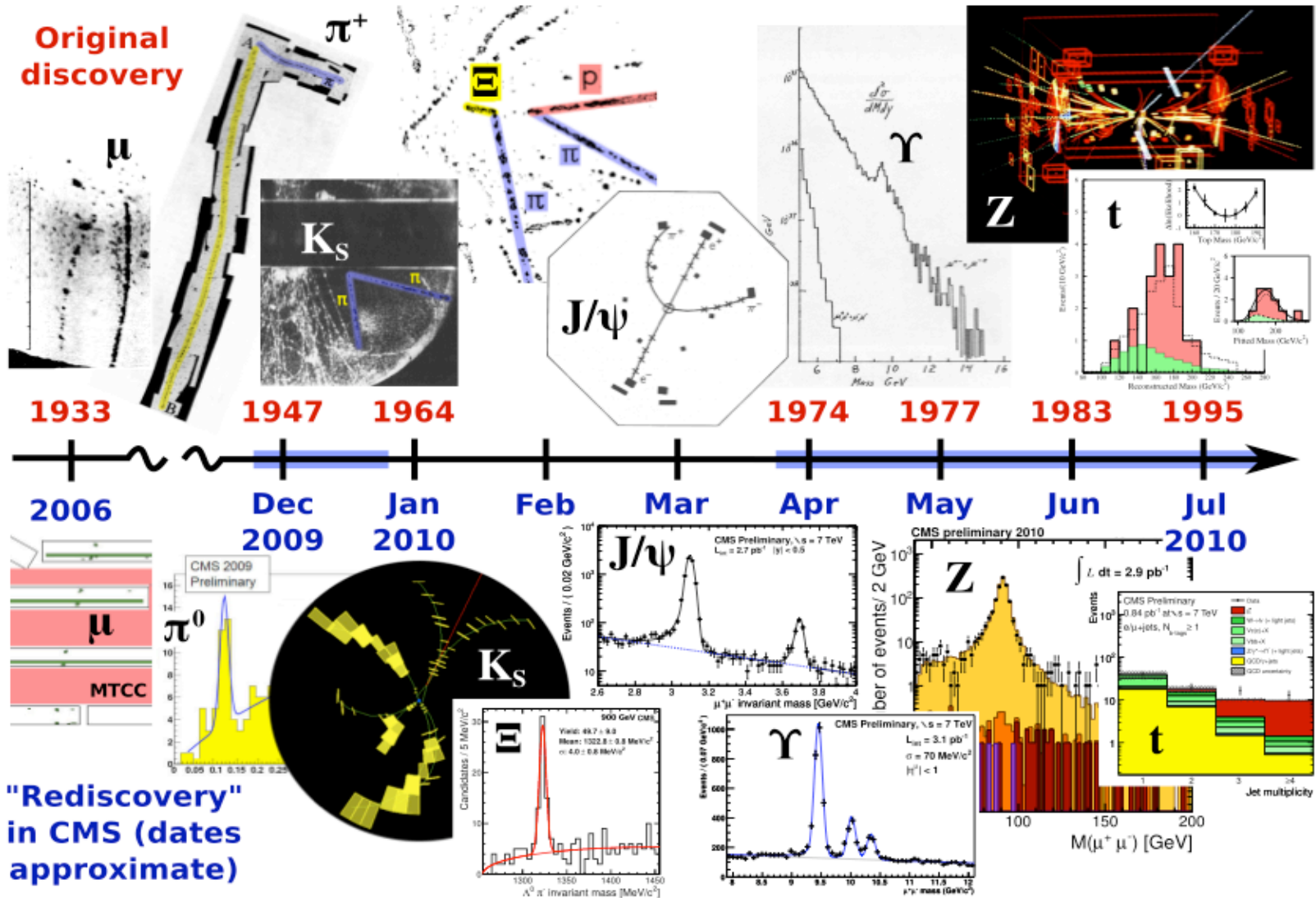
Recorded Luminosity at 7 TeV in 2010

Measured with forward detectors, calibrated with beam separation scans



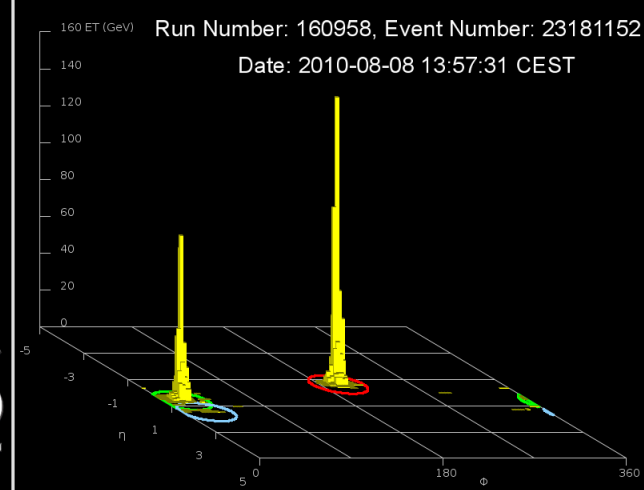
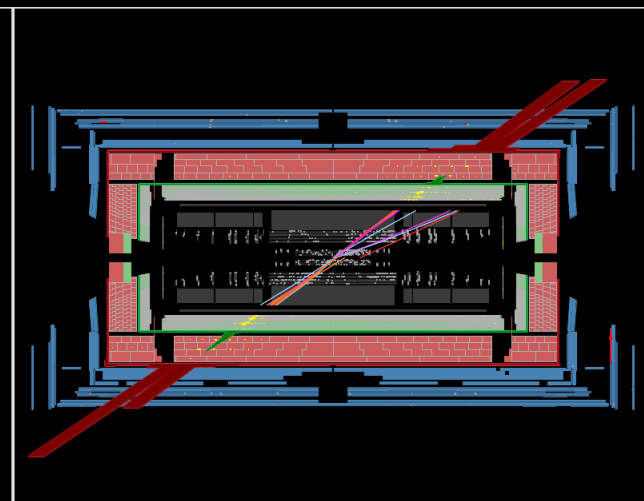
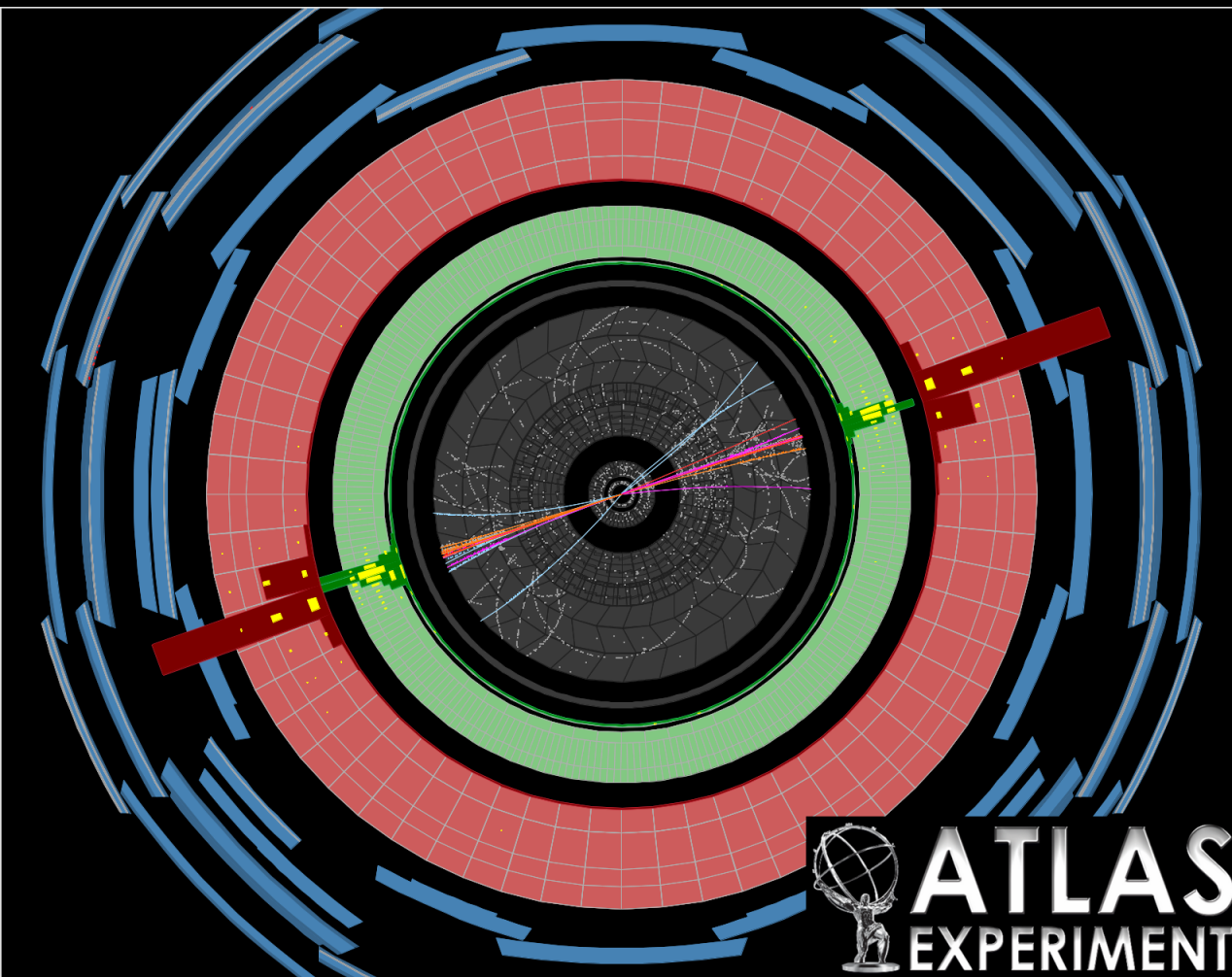
$10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ *instantaneous* luminosity corresponds to an *integrated* luminosity of 0.1 nb⁻¹ per second
→ 180 pb⁻¹ per month (assuming 70% LHC efficiency for physics)

SM particles rediscovered in 2010 (taken from CMS)

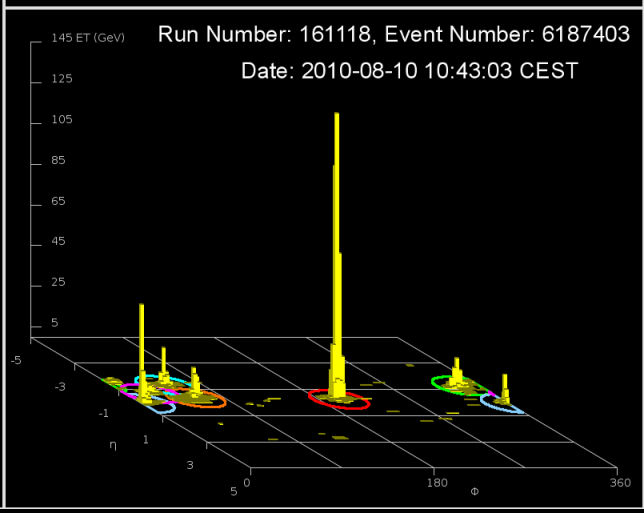
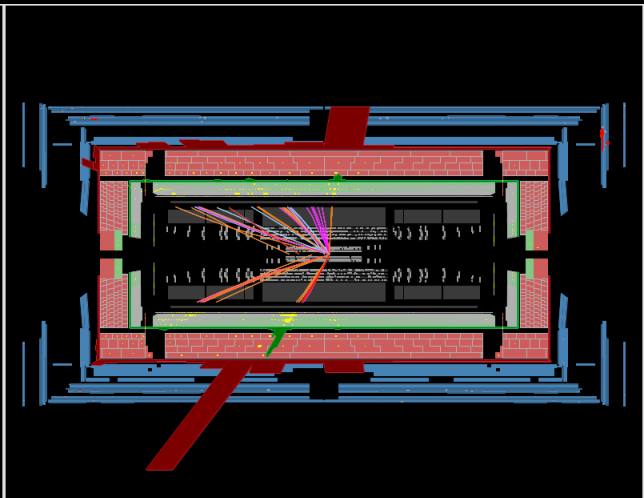
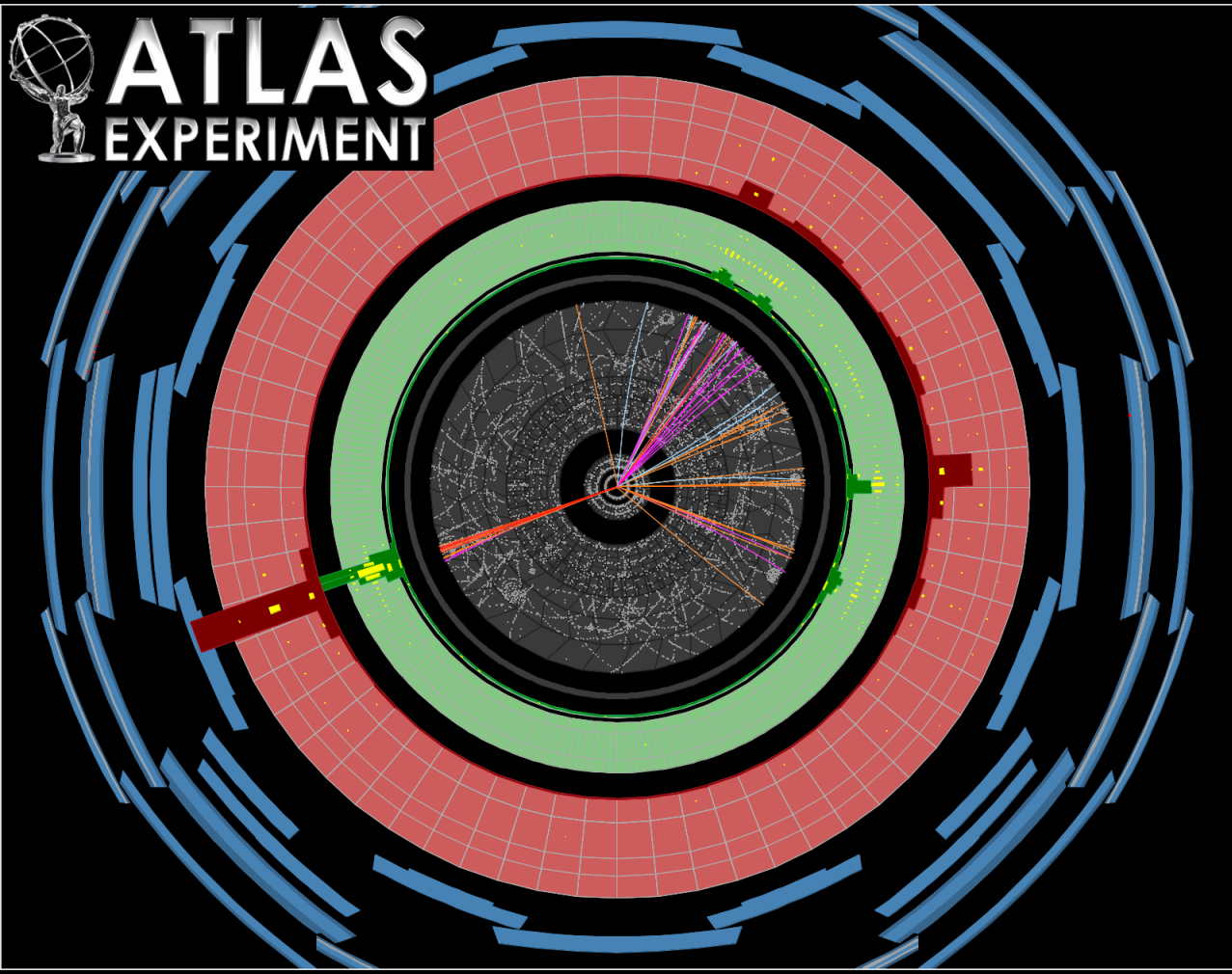


© P. Schieferdecker, Dec 17, 2010 at CERN

A beautiful dijet event from ATLAS: $m(\text{jet-jet}) = 1.9 \text{ TeV}$, $p_T : 0.9 \text{ TeV}, 0.8 \text{ TeV}$



Multijet event seen by ATLAS: 4 jets with $p_T > 200$ GeV, and 6 jets with $p_T > 100$ GeV



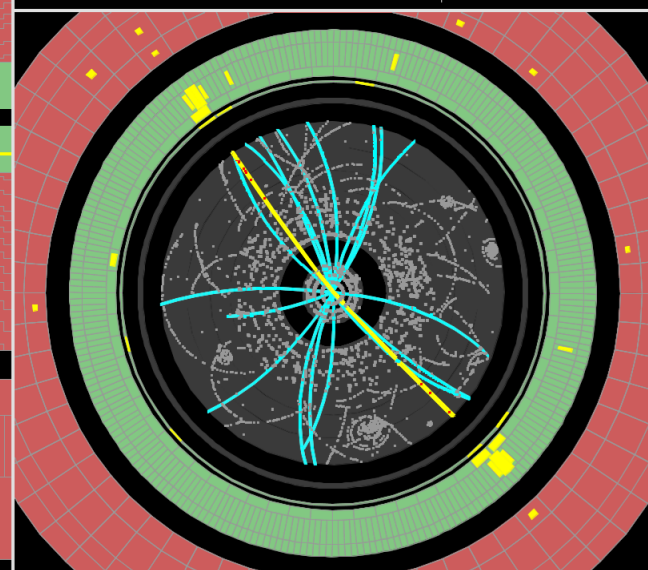
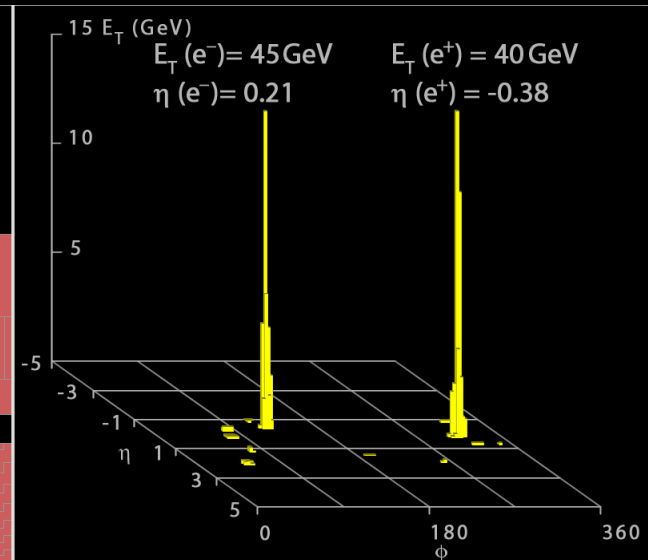
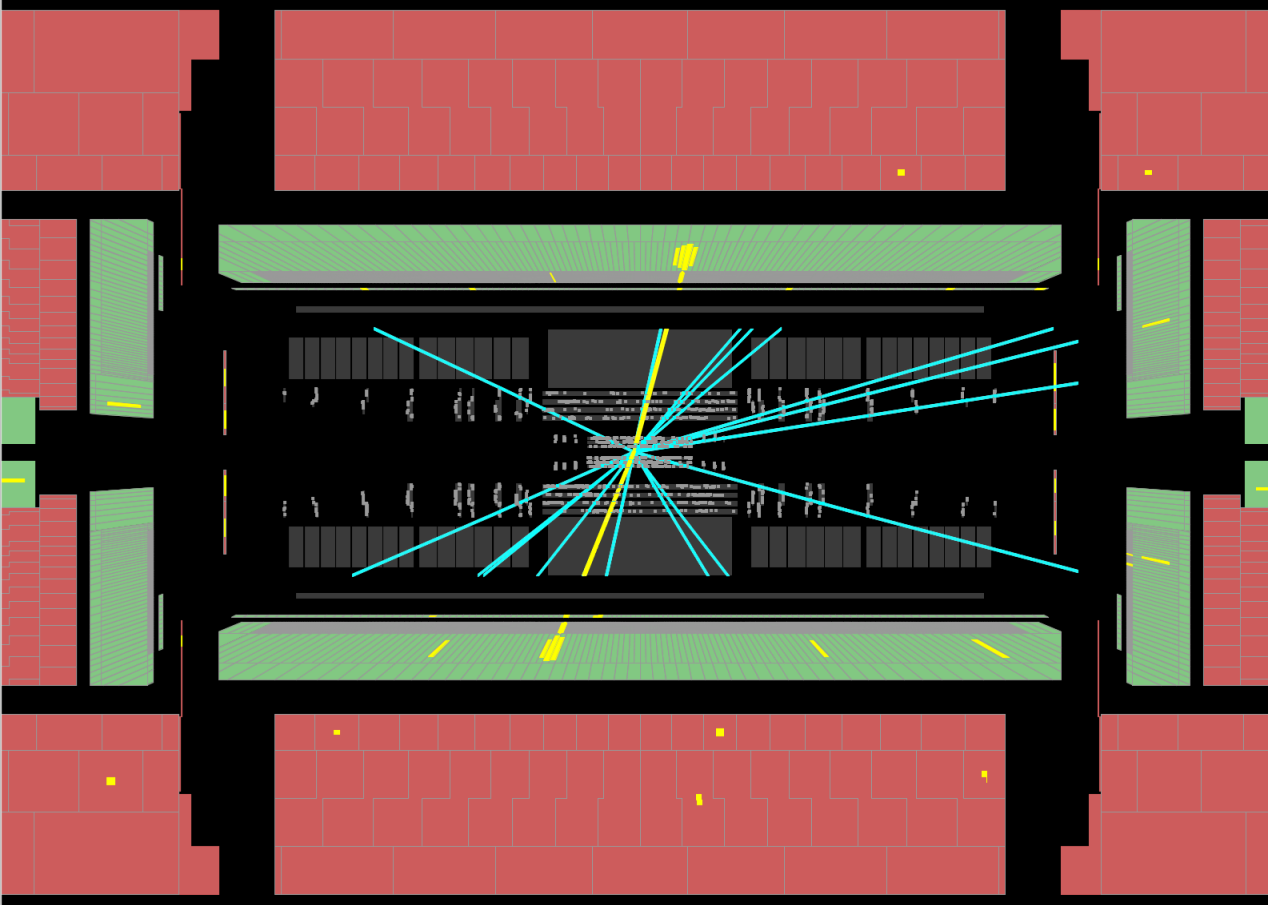
... by now found event with 3.1 TeV (4.0 TeV) di-jet mass for central (forward) jets
...and a highest- p_T di-jet event with 1.5 TeV

Run Number: 154817, Event Number: 968871

Date: 2010-05-09 09:41:40 CEST

$M_{ee} = 89 \text{ GeV}$

$Z \rightarrow ee$ candidate in 7 TeV collisions



$$\begin{aligned}
 p_T(\mu) &= 18 \text{ GeV} \\
 p_T^{\text{vis}}(\tau_h) &= 26 \text{ GeV} \\
 m_{\text{vis}}(\mu, \tau_h) &= 47 \text{ GeV} \\
 m_T(\mu, E_T^{\text{miss}}) &= 8 \text{ GeV} \\
 E_T^{\text{miss}} &= 7 \text{ GeV}
 \end{aligned}$$

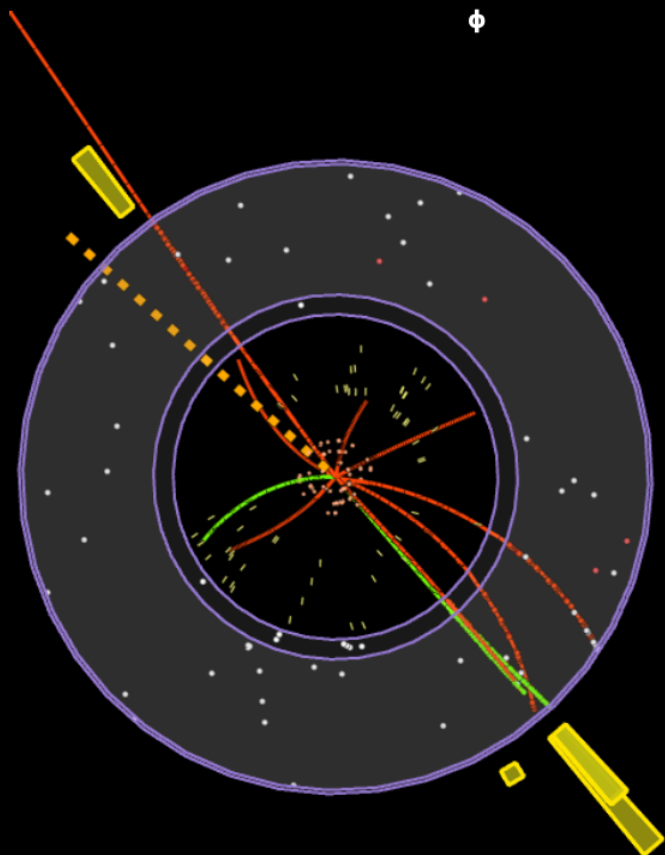
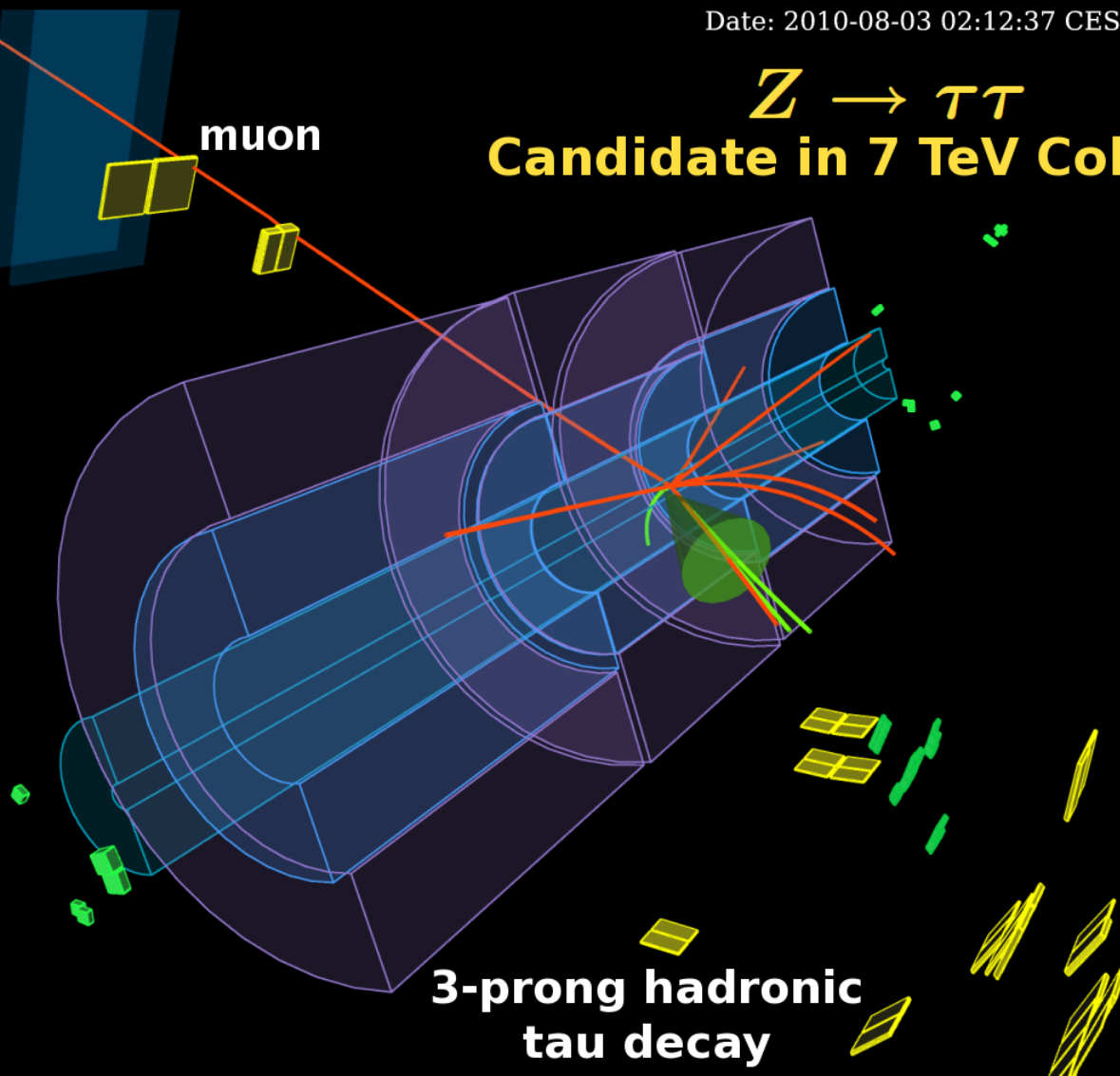
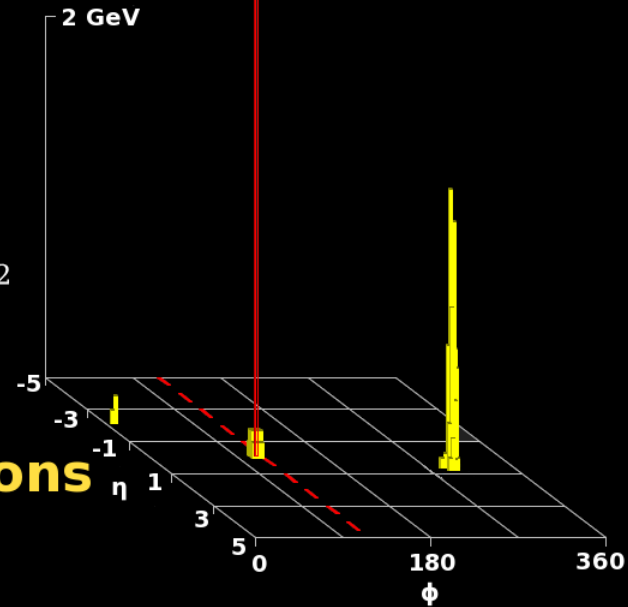


ATLAS EXPERIMENT

Run Number: 160613, Event Number: 9209492

Date: 2010-08-03 02:12:37 CEST

$Z \rightarrow \tau\tau$ Candidate in 7 TeV Collisions

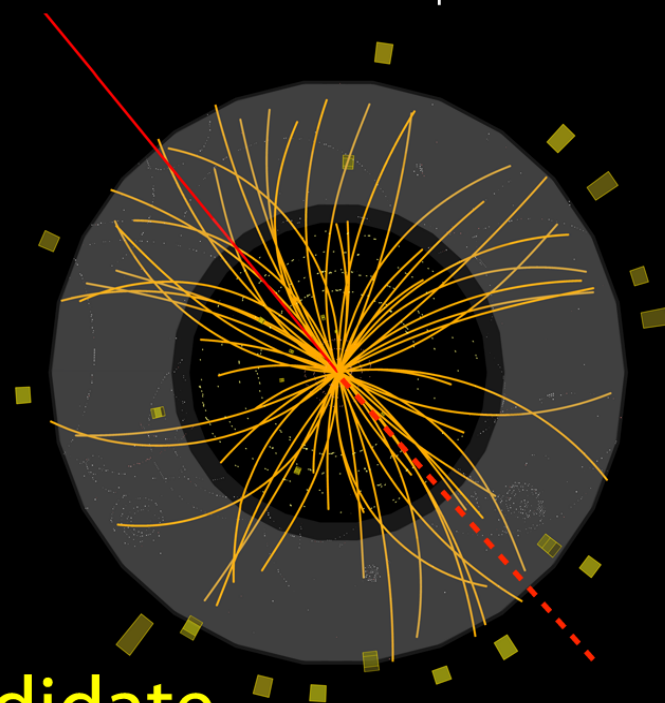
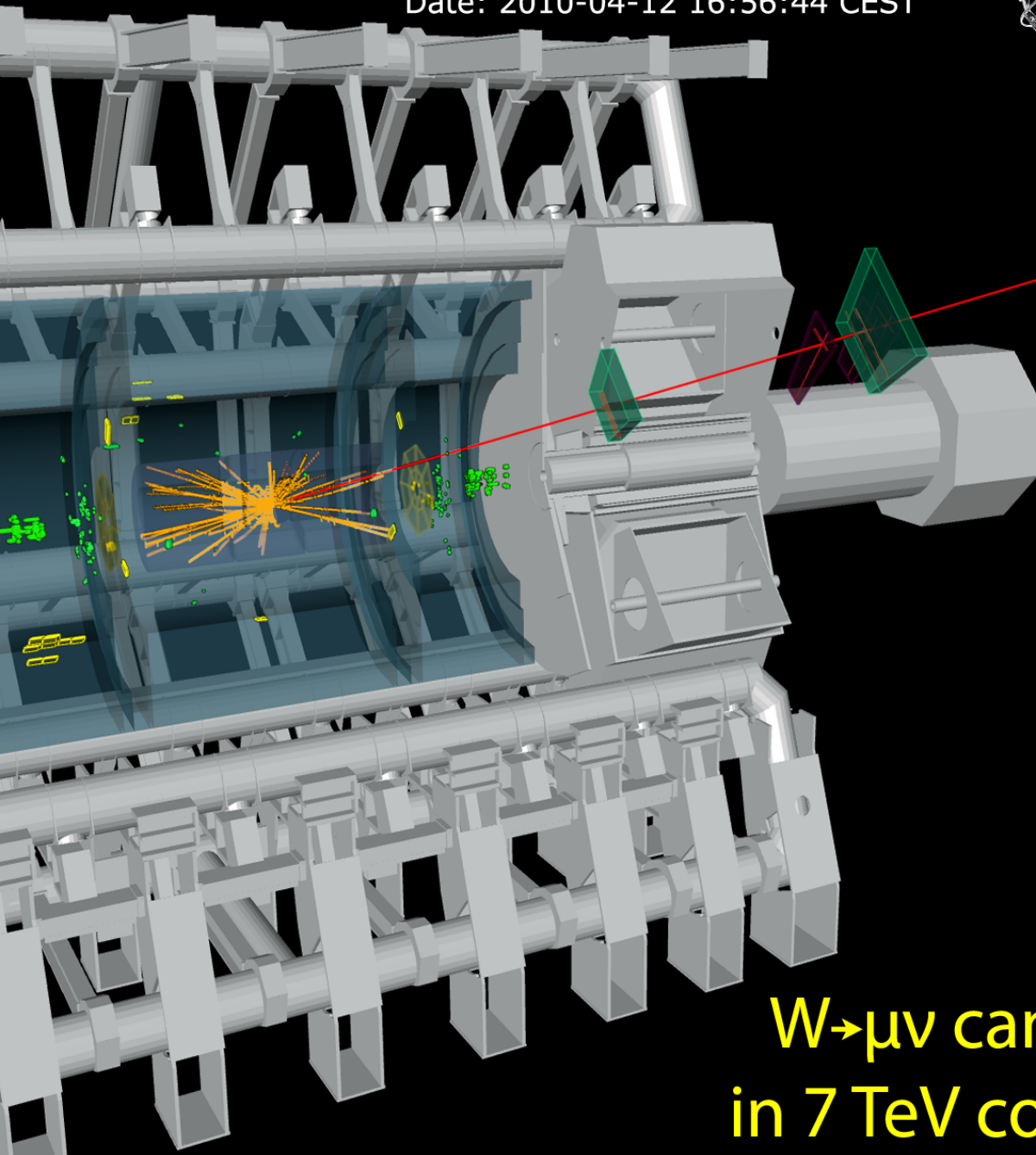


Run: 152845, Event: 3338173
Date: 2010-04-12 16:56:44 CEST



ATLAS EXPERIMENT

$p_T(\mu^-) = 40 \text{ GeV}$
 $\eta(\mu^-) = 2.0$
 $E_T^{\text{miss}} = 41 \text{ GeV}$
 $M_T = 83 \text{ GeV}$



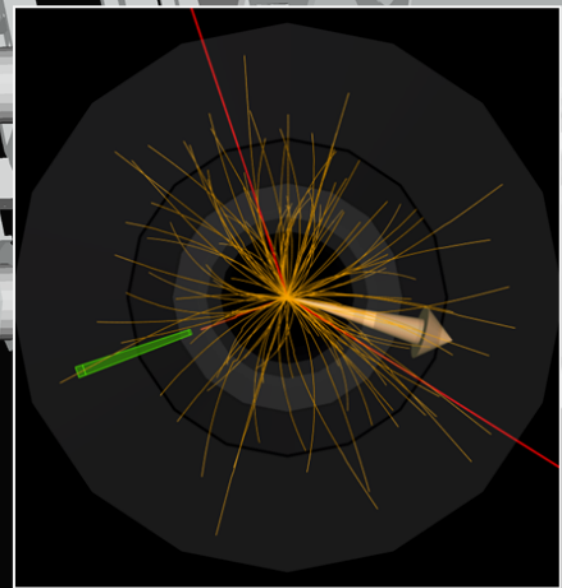
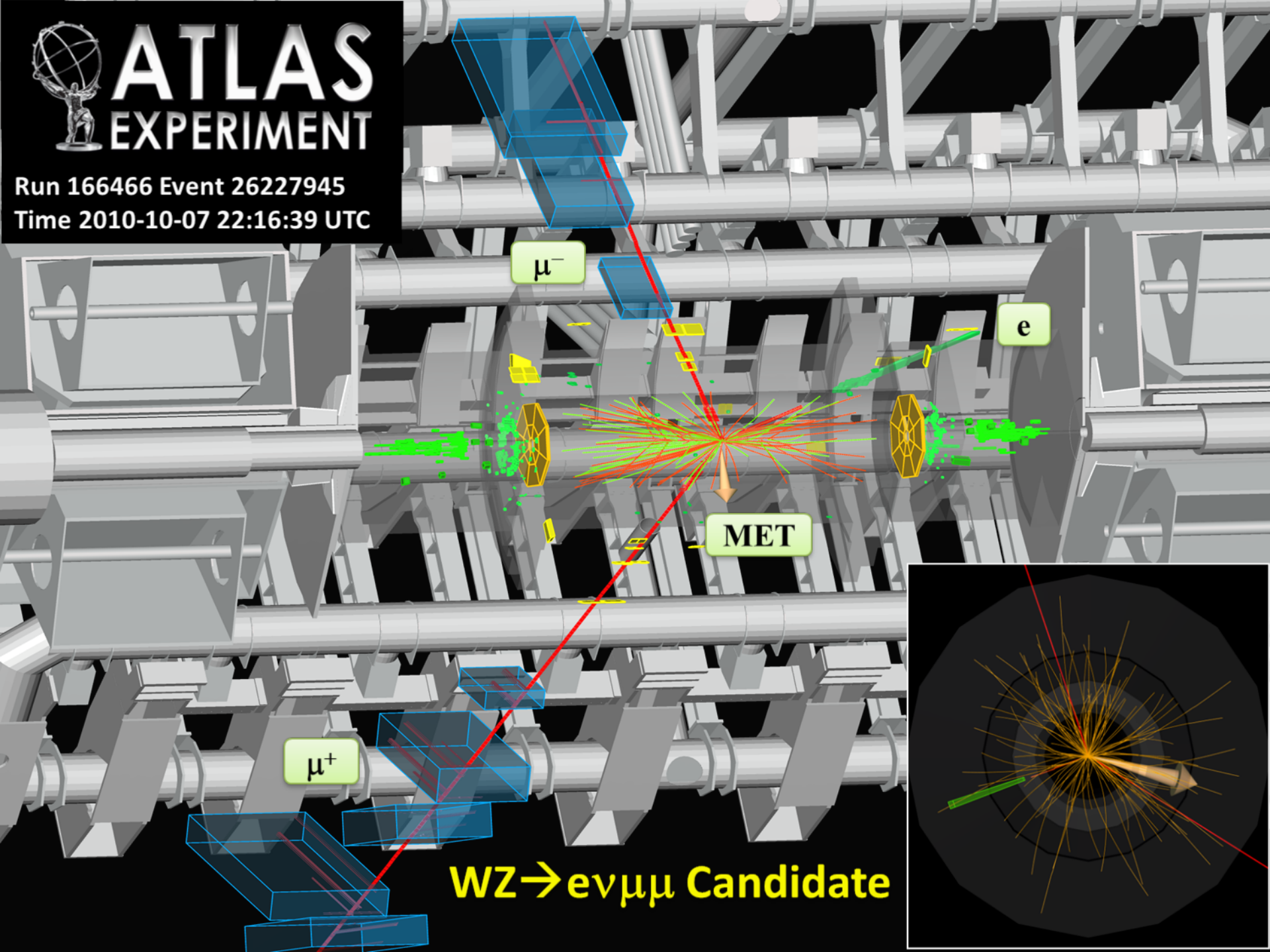
$W \rightarrow \mu \nu$ candidate
in 7 TeV collisions



ATLAS EXPERIMENT

Run 166466 Event 26227945

Time 2010-10-07 22:16:39 UTC

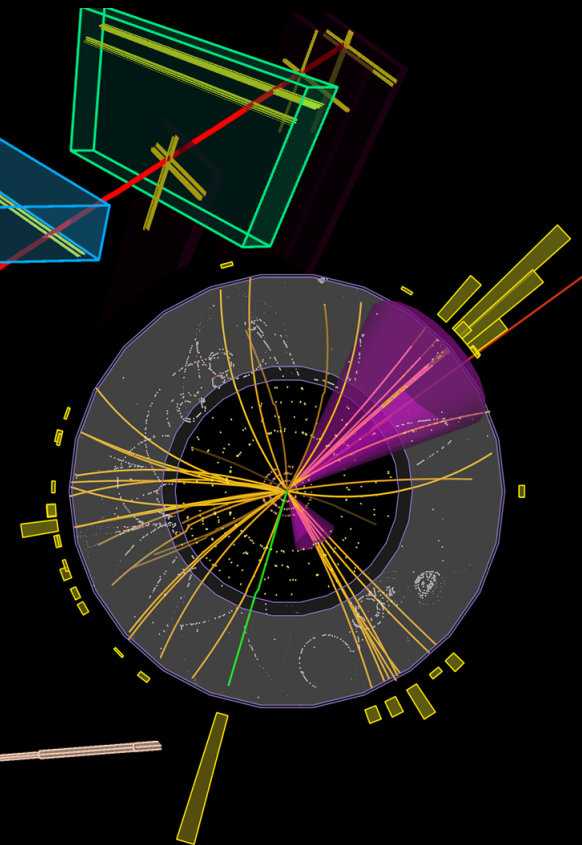
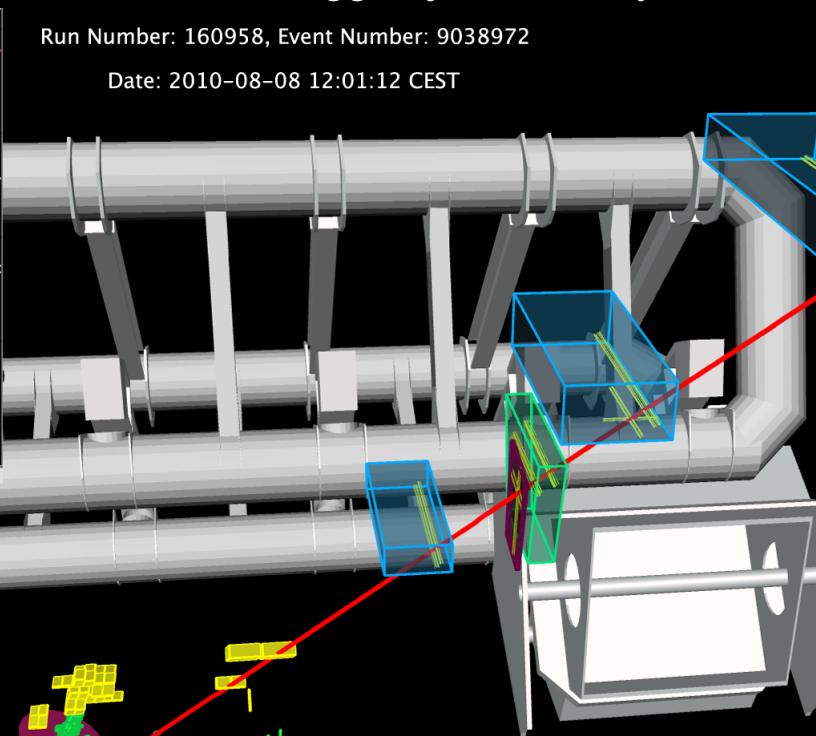
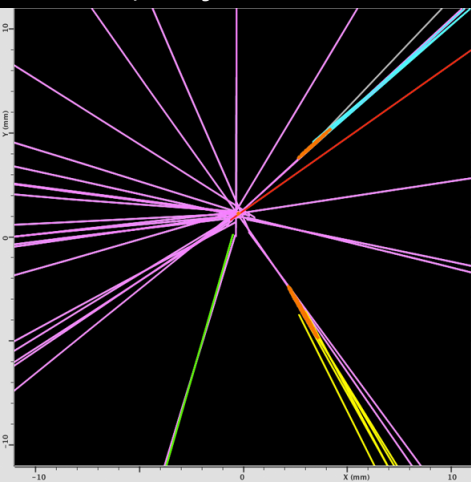


$WZ \rightarrow e\nu\mu$ Candidate

$t\bar{t} \rightarrow e\mu + \text{jets}$ candidate event with 2 b -tagged jets seen by ATLAS

Run Number: 160958, Event Number: 9038972

Date: 2010-08-08 12:01:12 CEST



 **ATLAS**
EXPERIMENT

ATLAS and CMS have Unambiguously Seen top Events

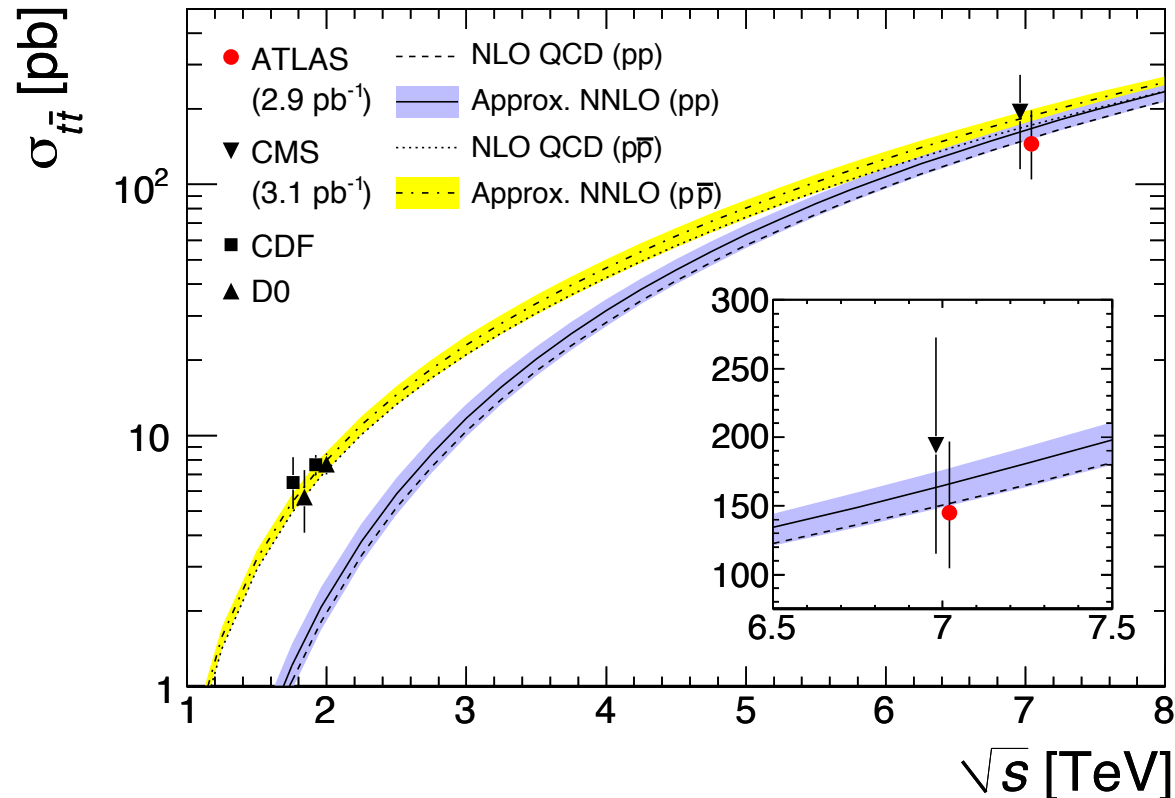
Both experiments published cross section results on ~9% of full statistics

Inclusive $t\bar{t}$ cross section as measured by ATLAS and CMS compared to theory.

Errors (ATLAS):

- 21% statistical
- 21% systematic
- 11% luminosity

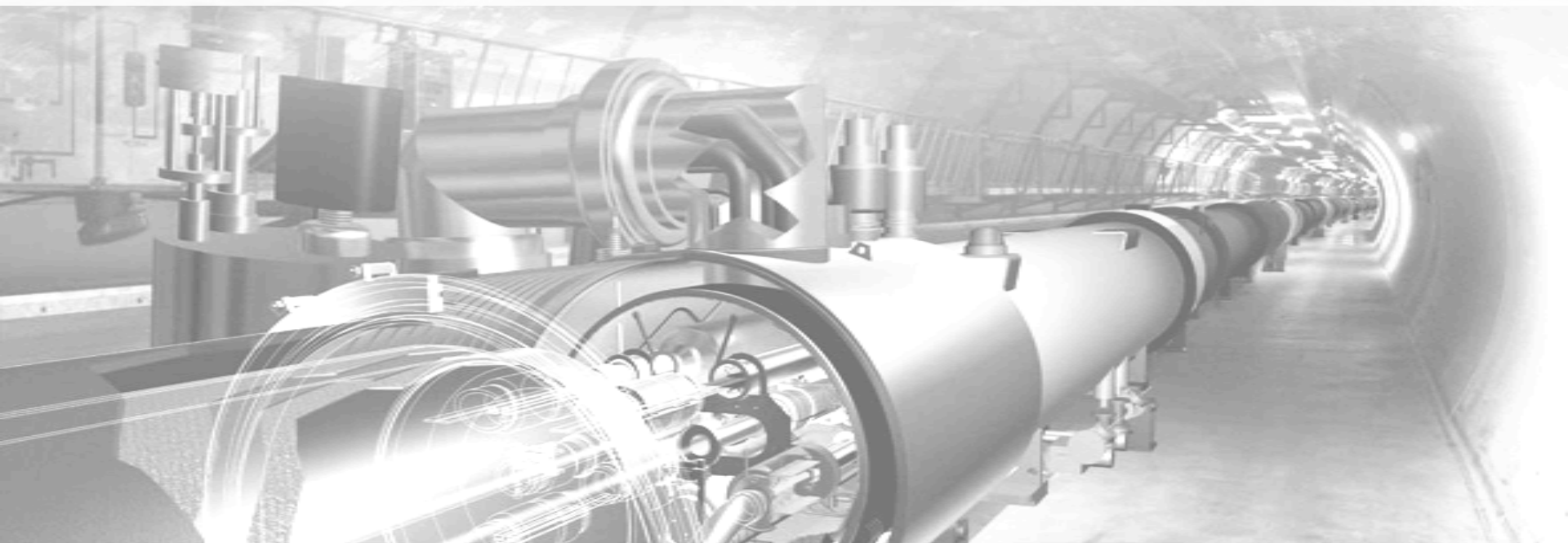
Theory error: ~8%



Many more top results forthcoming including cross section with full statistics & mass

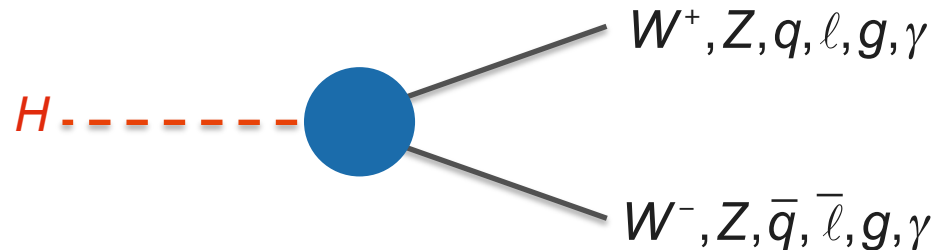


Searching for the Higgs Boson



Higgs Boson Decays

The Higgs decay branching fractions are predicted by the SM ...



...as a function of the Higgs mass

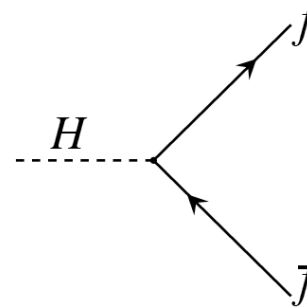
Because of the coupling to the mass of the decay particles:

- ... the Higgs will decay with preference to the heaviest particles allowed by phase space.
- ... the Higgs does not couple directly to photons and gluons, but only via triangular loops involving heavy intermediate states (e.g., top, W)

Higgs Boson Decays

Higgs decay width into **fermion pair**:

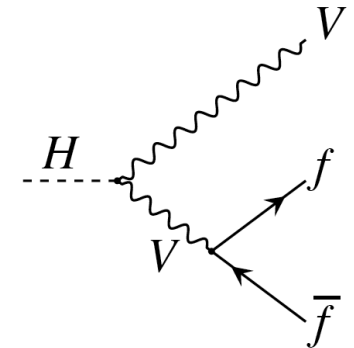
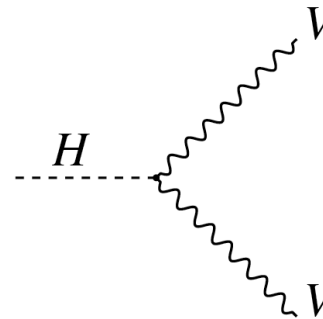
$$\Gamma_{\text{LO}}(H \rightarrow f\bar{f}) \propto N_C \cdot M_H \cdot m_f^2$$



Some leading order diagrams shown only

Higgs decay into **W or Z pairs** (real or virtual)

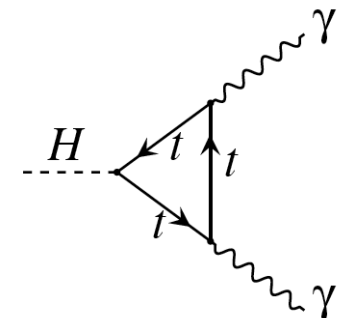
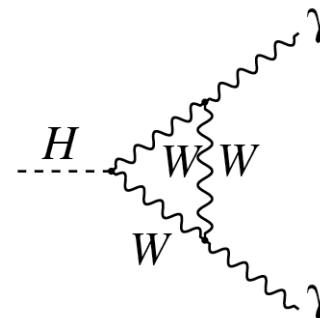
$$\Gamma(H \rightarrow VV) \propto M_H^3 \cdot \begin{cases} 1 & \text{for } V = Z \\ 2 & \text{for } V = W \end{cases}$$



Higgs decay into **photon pair**

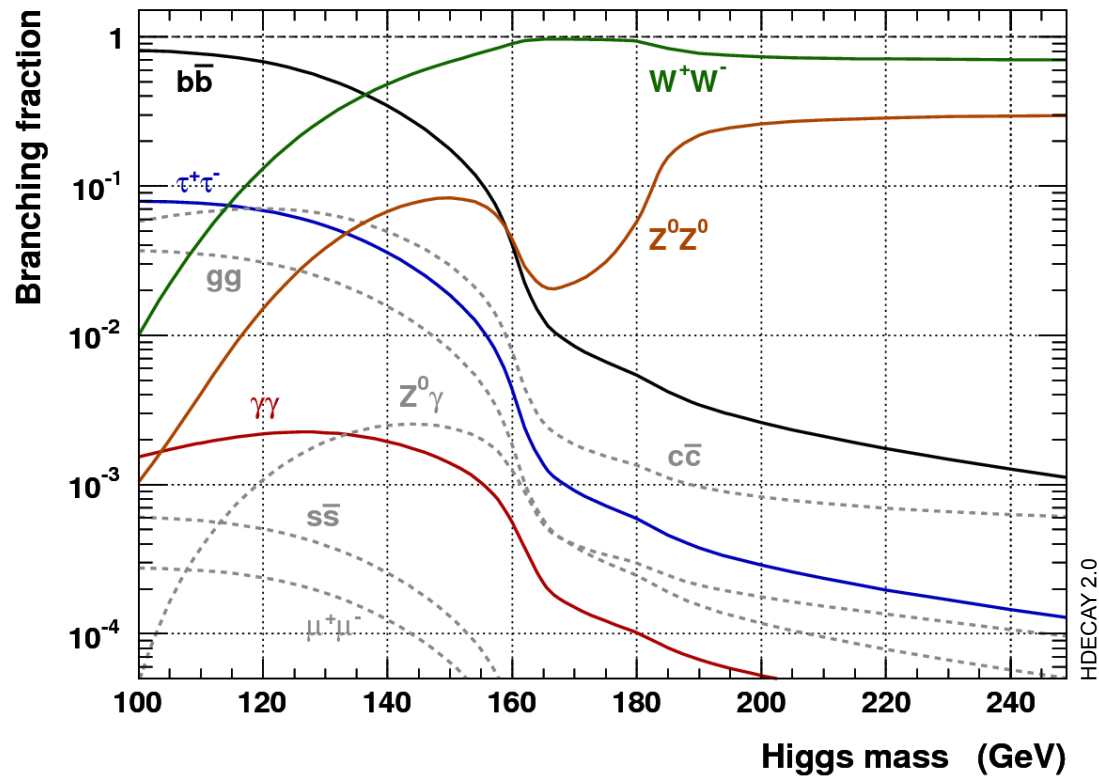
$$\Gamma(H \rightarrow \gamma\gamma) \propto \alpha^2 \cdot M_H^3 \cdot \left| N_C Q_t^2 A_t^H + A_W^H \right|^2$$

Dominated by W loop



Summary of Higgs Boson Decays

Higgs branching fractions and full width as function of Higgs boson mass

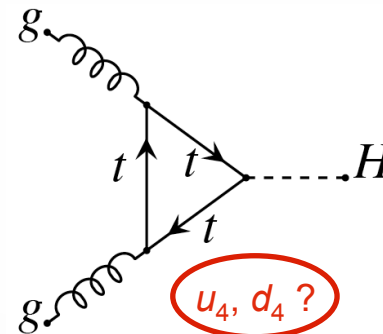


Higgs Boson Production

All QCD (EW)
terms known to
NNLO (NLO)

Gluon fusion

As for $H \rightarrow \gamma\gamma$ loop-induced coupling only
Dominant production mode due to large
gluon density in proton at small x



Due to large α_S ,
 K factors of
NLO/LO ~ 2 ,
NNLO/LO ~ 3
at Tevatron, and
 $\sim 1.7, \sim 2$ at LHC

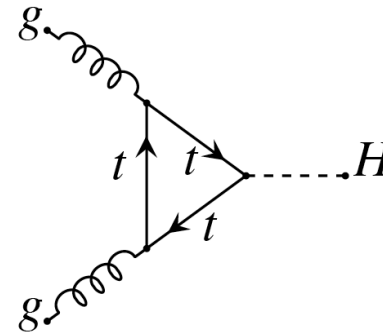
$4^{\text{th}} \text{ generation ?}$
 $K\text{-factor of } \sim 3^2 = 9$
using sequential model

Higgs Boson Production

All QCD (EW)
terms known to
NNLO (NLO)

Gluon fusion

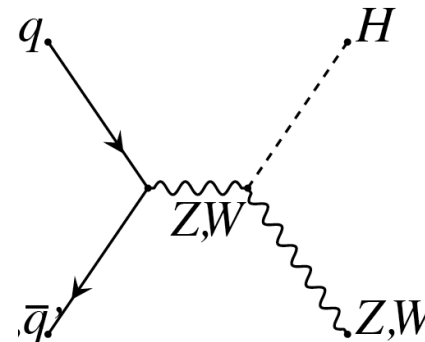
As for $H \rightarrow \gamma\gamma$ loop-induced coupling only
Dominant production mode due to large
gluon density in proton at small x



Due to large α_S ,
 K factors of
NLO/LO ~ 2 ,
NNLO/LO ~ 3
at Tevatron, and
 ~ 1.7 , ~ 2 at LHC

W or Z association (*Higgs-strahlung*)

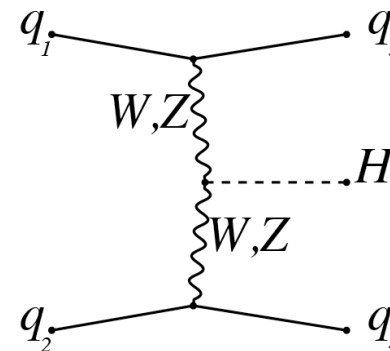
Relatively more important at Tevatron owing
to larger quark density in proton at larger x



More moderate
 K factors for
Higgs-strahlung
and WBF

Weak boson fusion

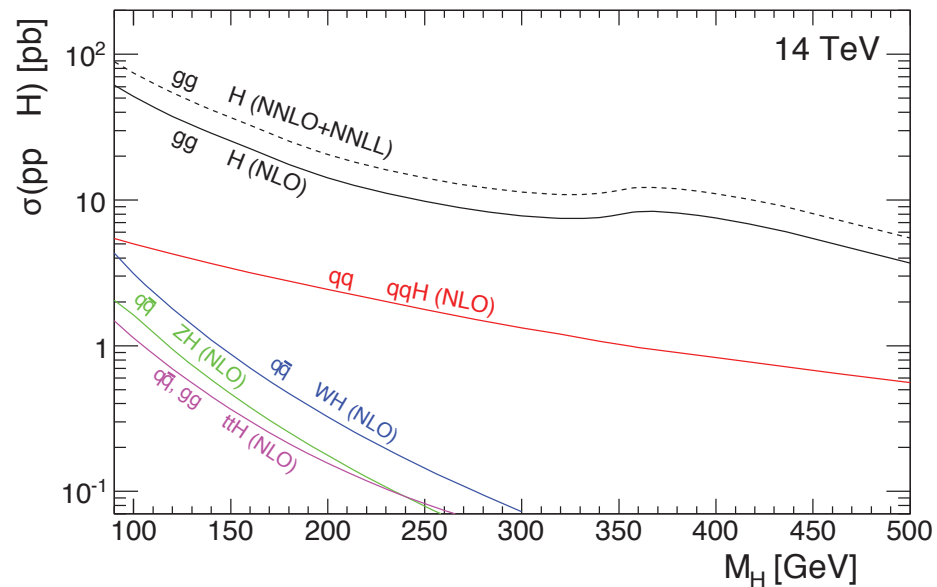
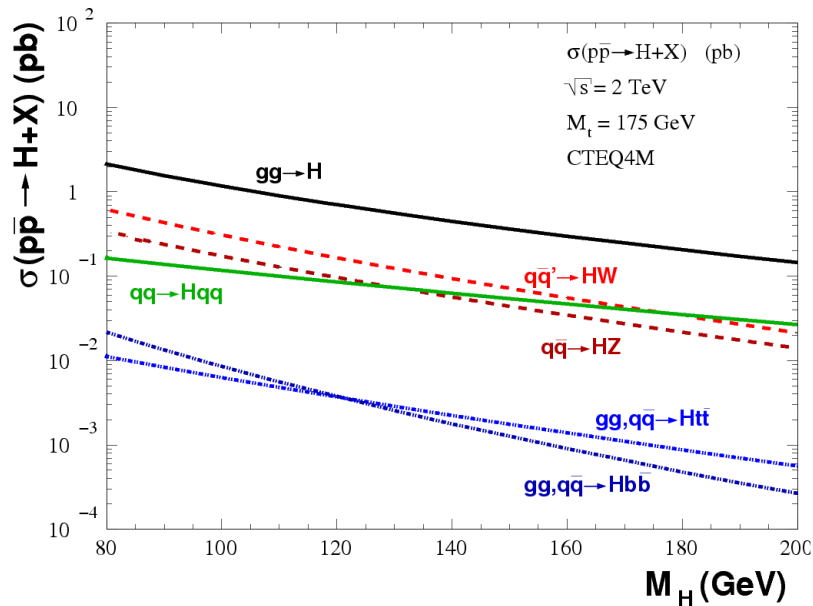
Striking event signature: small q^2 between
quarks and virtual W/Z 's ($M_H/2$ each q)
 $\rightarrow$ large $\Delta\eta$ between jets! Central jet veto.



Large rapidity
gap because no
colour flow
between initial
and final state

Cross Sections at Tevatron & LHC (14 TeV)

Higgs production cross sections versus M_H at the Tevatron and the LHC

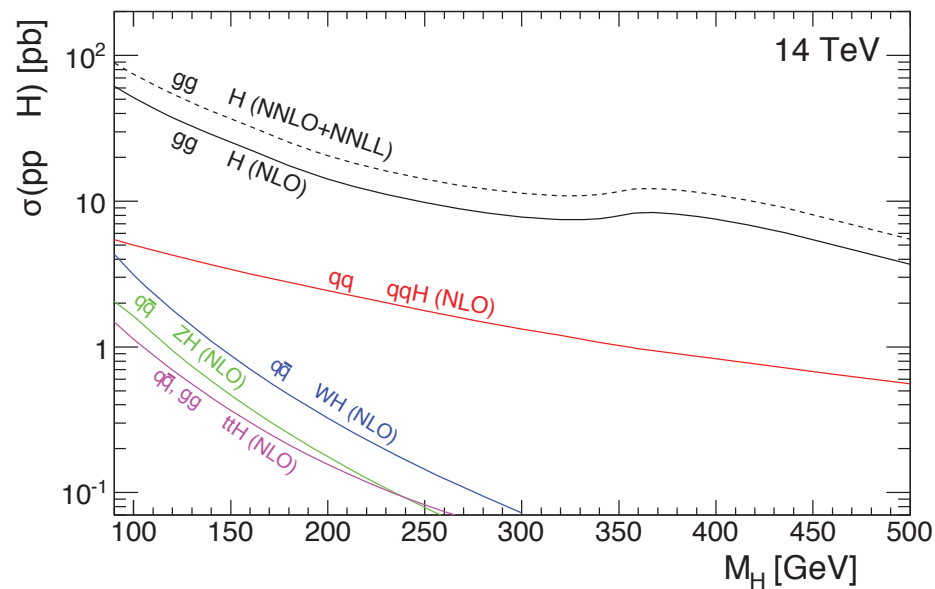
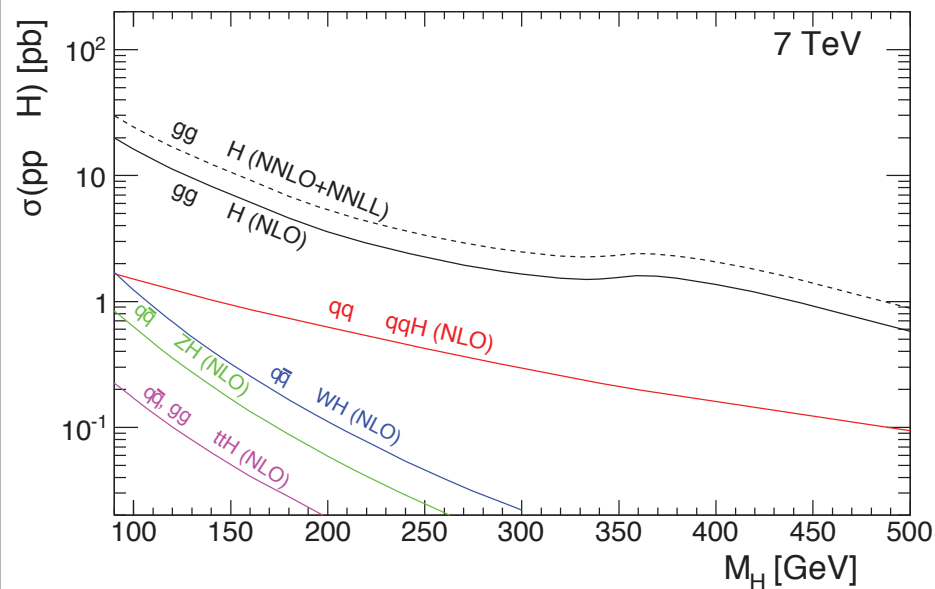


$qq \rightarrow W/Z + H$ cross sections $\sim 10 \times$ larger at the LHC
 $gg \rightarrow H$ $\sim 40\text{--}50 \times$ larger at the LHC

Ongoing debate on $gg \rightarrow H$ cross section errors: Baglio-Djouadi (arXiv:1001.5027) versus CDF/D0 (answers: [link-1](#), [2](#))

LHC 14 TeV vs 7 TeV

Unfortunately, the LHC runs only at 7 TeV CM energy in 2010 and 2011

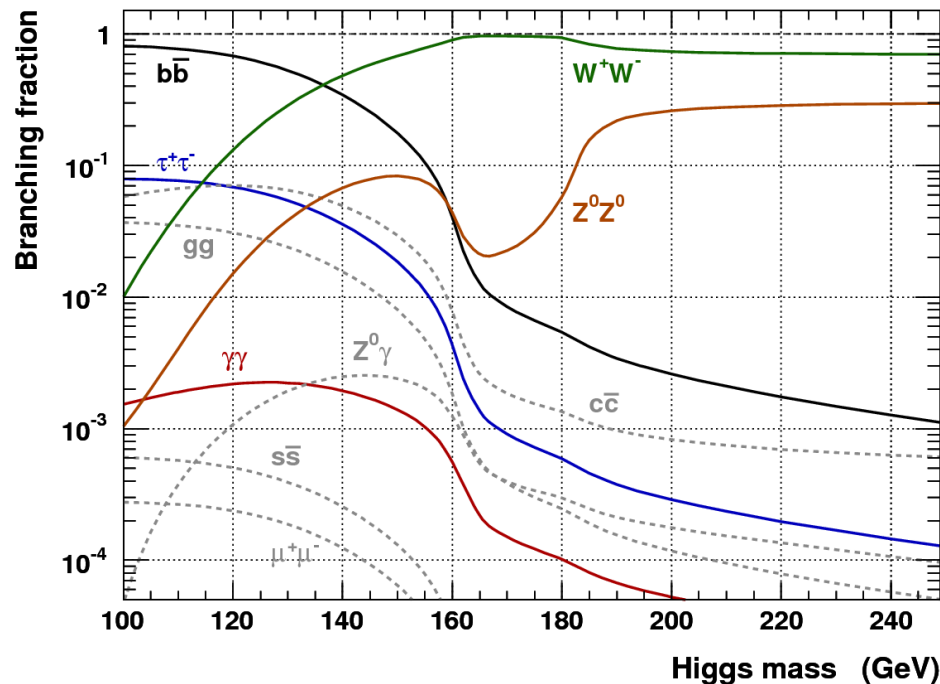


For $M_H = 160$ GeV, reduction by factor of

- ~ 3.6 for $gg \rightarrow H$
- ~ 2.8 for $qq \rightarrow W/Z + H$
- ~ 3.7 for $qq \rightarrow qqH$

Higgs Searches at Hadron Colliders

The dependence of the branching fractions on M_H drives search strategy



For **heavy Higgs**:

- Lepton final states via $WW^{(*)}$, $ZZ^{(*)}$

For **light Higgs**:

- Lepton final states via WW^* , ZZ^*
- Di-photon final state
- Di-tau final state

The dominant $H \rightarrow b\bar{b}$ mode is only exploitable in association with W/Z or $t\bar{t}$, also with strong Higgs boost

(Associated leptons provide trigger signal as they help to reduce huge QCD background, $\sigma(b\bar{b}) \sim 100 \mu\text{b}$)

Briefly: Higgs Searches at Tevatron and LEP



Tevatron

2 general-purpose detectors

CDF & D0

Centre-of-mass energy:

1.96 TeV

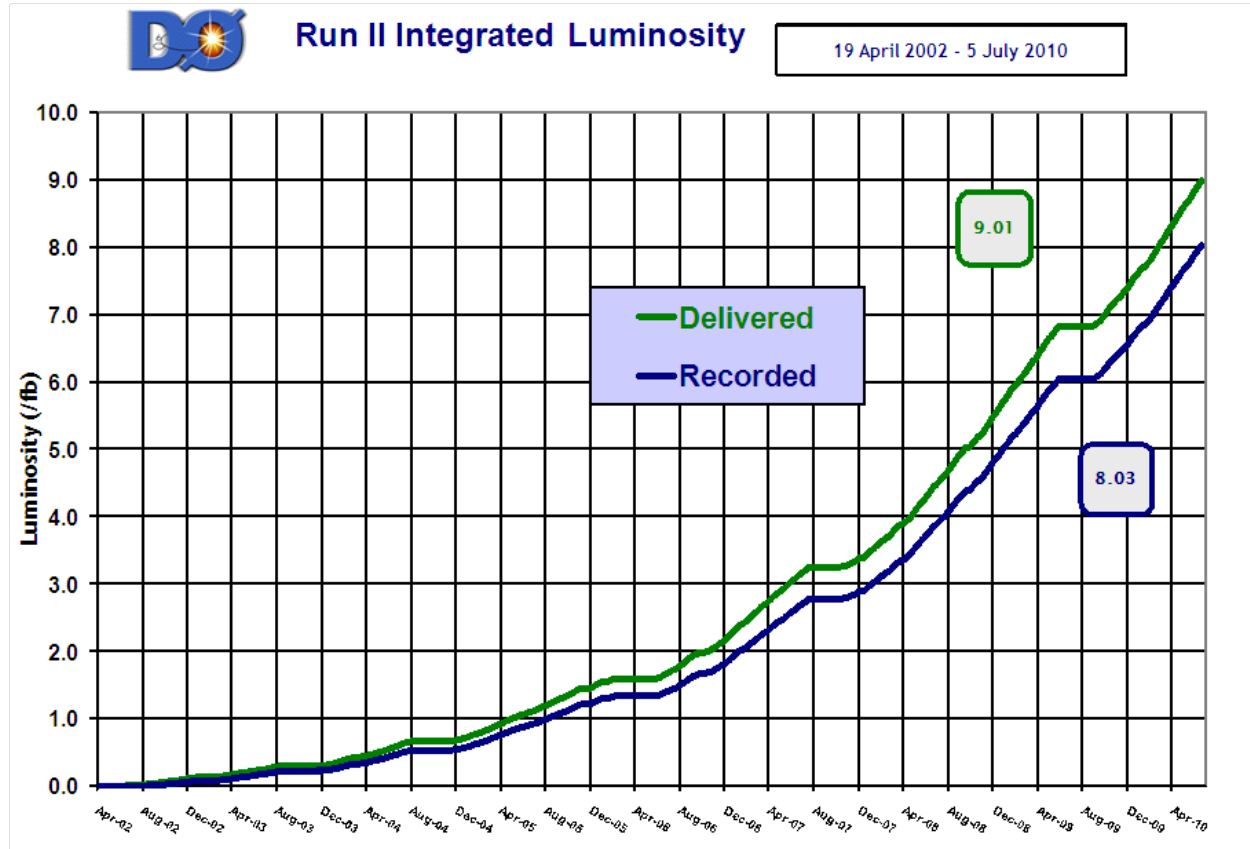
Peak luminosity:

$4.0 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$

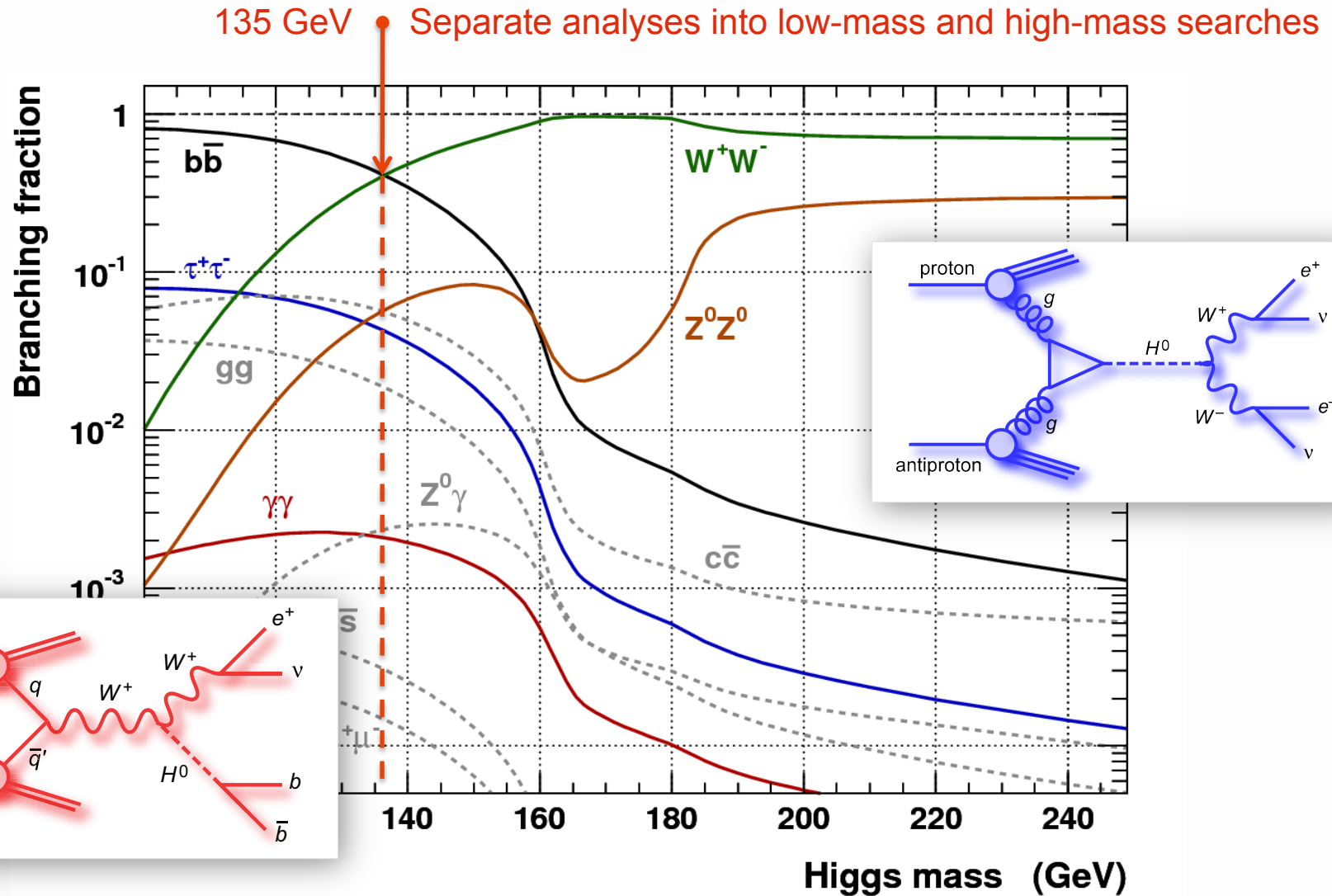
Integrated luminosity:

$\sim 10 \text{ fb}^{-1}$

Anticipate 12–13 fb^{-1}
by fall 2011 (shutdown)



Higgs Search Strategy at the Tevatron



Higgs Search Strategy at the Tevatron

135 GeV • Separate analyses into low-mass and high-mass searches

Higgs search at Tevatron exploits all low and high-mass channels

Significant analysis improvements achieved, e.g.:

- relaxed cuts
- more efficient (looser) lepton identification
- add final states with taus, fully hadronic modes, diphotons
- improved b -tagging (also: b vs. c and b vs. bb (merged) discrimination)
- improved dijet mass resolution in $llbb$ channel from kinematic fit
- improved dijet mass resolution by using tracker information
- improved multivariate methods, e.g., matrix elements as input to boosted decision trees, separate training against different backgrounds, multi-class training
- reduce top background using tight b -jet veto for high-mass search

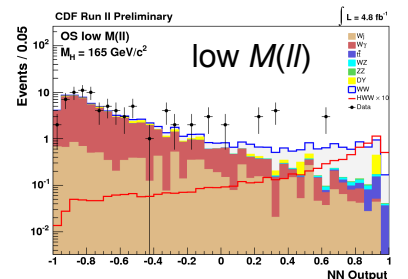
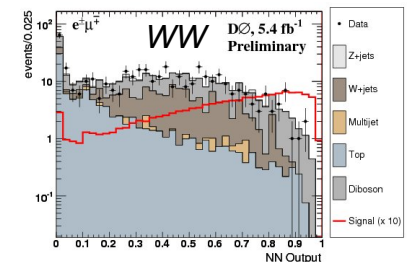
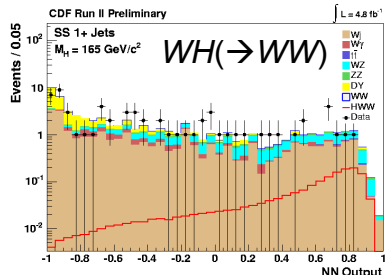
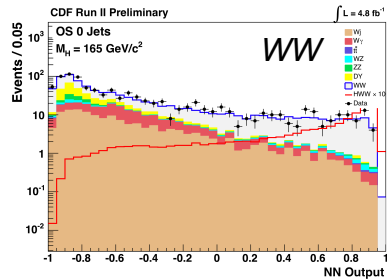
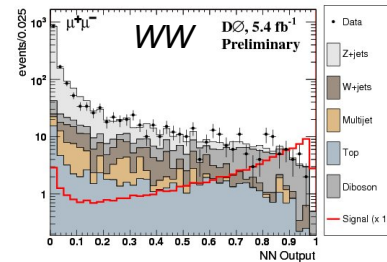
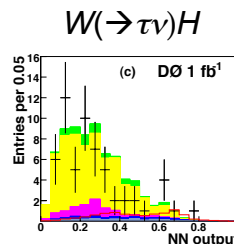
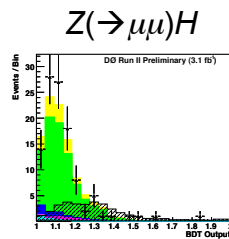
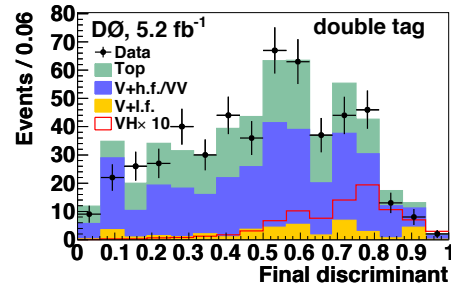
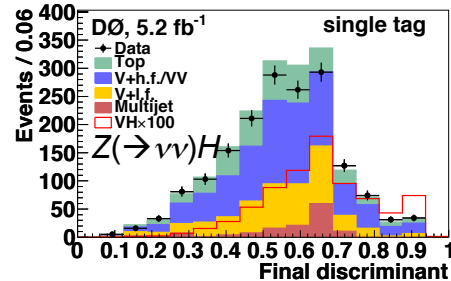
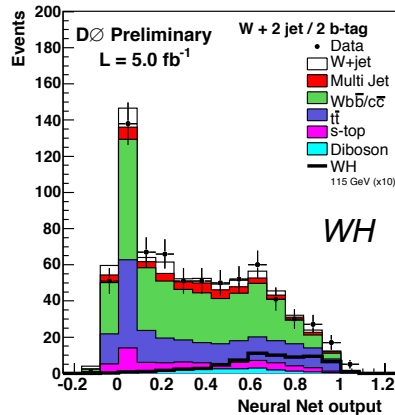
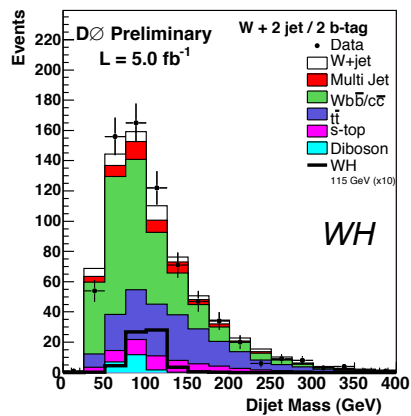
LHC analyses yet miles away from such degree of sophistication !

100 120 140 160 180 200 220 240
Higgs mass (GeV)

Combination of all Higgs Searches

Exclusion of any M_H is not possible by a single Tevatron channel / experiment

Use most powerful statistical discriminators and combine all direct searches



90 mutually
exclusive modes !

Systematic Uncertainties

The analyses are affected by significant systematic uncertainties, such as:

- Background normalisation (7 ~ 20%) and shape modelling (2 ~ 20%)
- Jet modelling (up to 20%) and Jet energy scale (~3%)
- b -tagging (0 ~ 9%)
- Luminosity (4 ~ 6%) and signal cross section (up to 11%), many more effects ...

Systematic uncertainties for background rates are generally several times larger than the signal expectation itself

To minimize the degrading effect of systematic uncertainties on the search sensitivity, the individual background contributions are fitted to the data observation by maximising a likelihood function

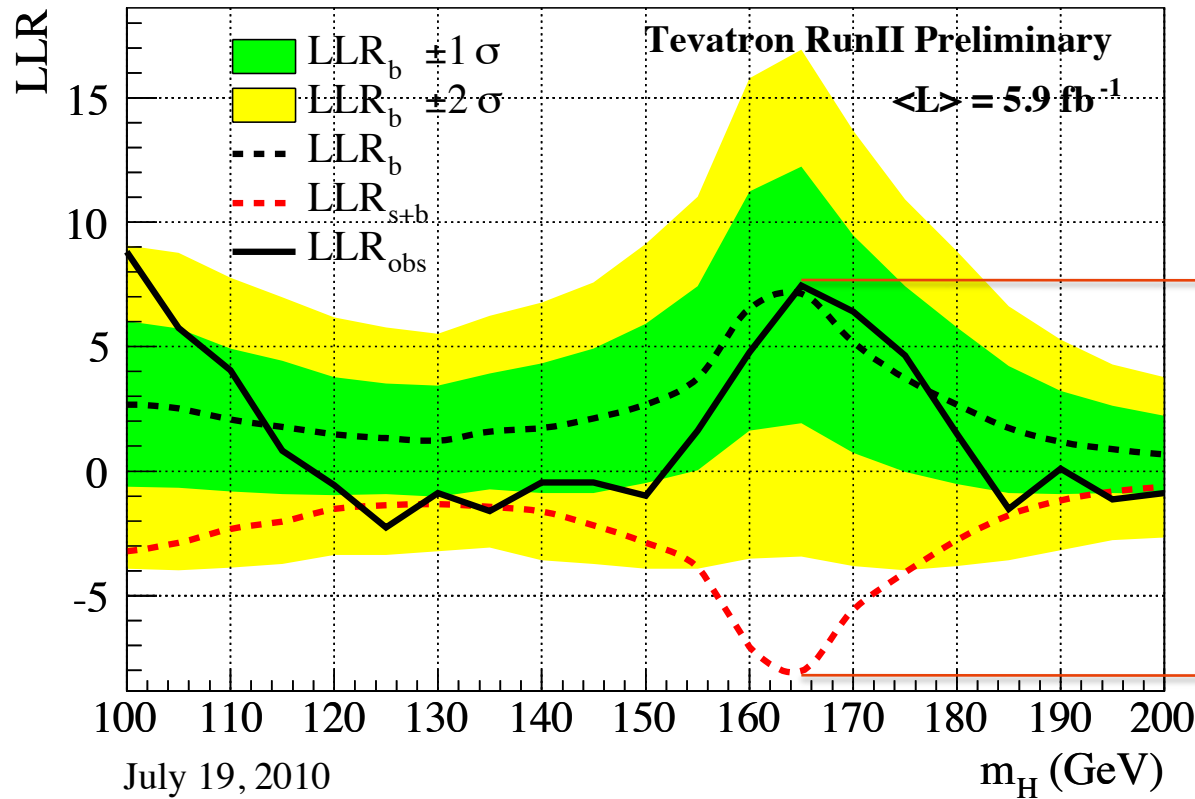
Nuisance parameters allow for variations within errors

Each systematic error (incl. the error on the signal cross section) is folded into the signal and background expectation via Gaussian likelihood

Correlations between nuisance parameters (due to common origin) are identified and preserved

Results of Tevatron Combination

CDF and D0, arXiv:1007.4587

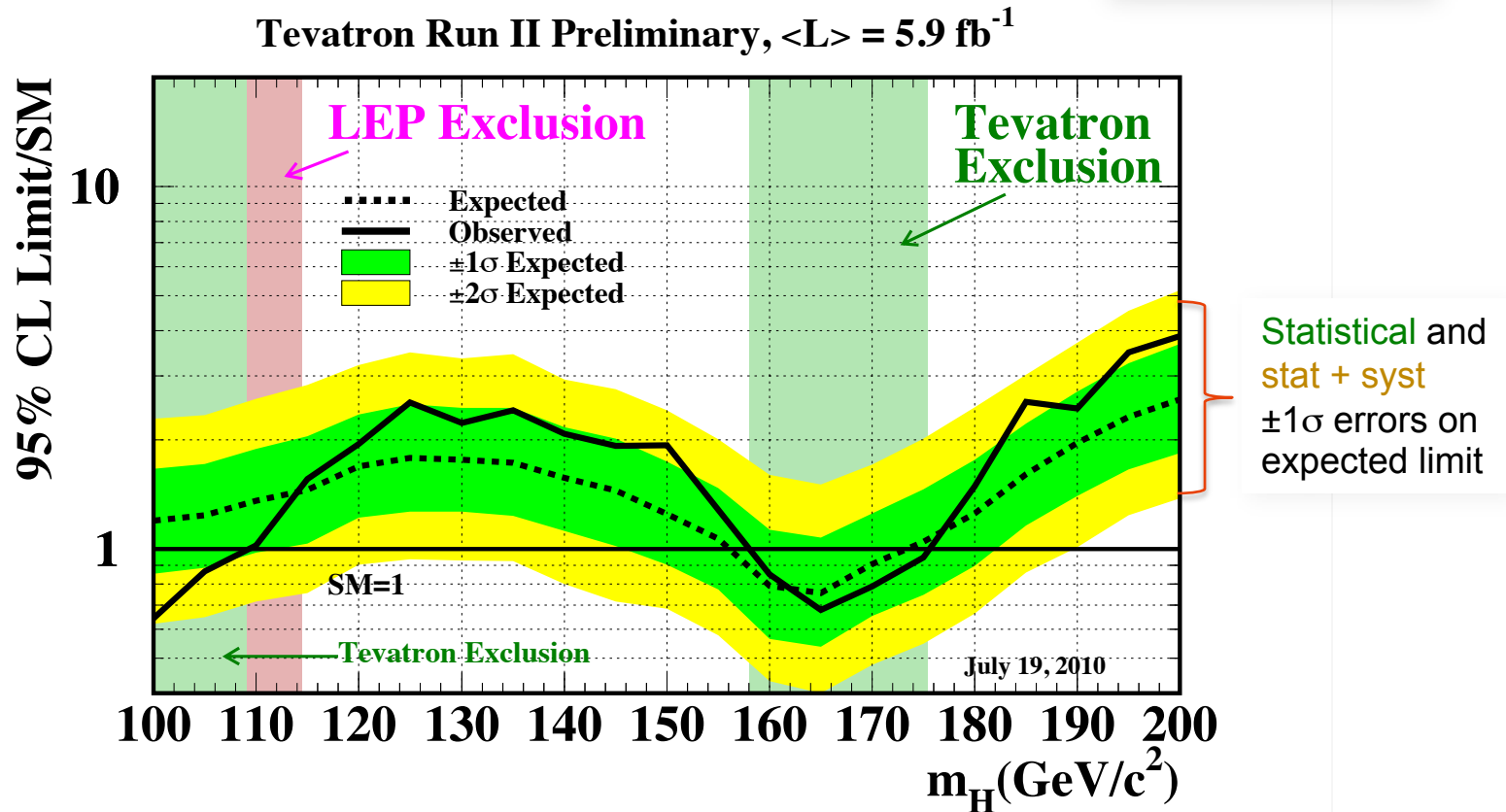


Sensitivity is largest around 165 GeV

Observed $\text{LLR} = -2 \ln Q$, where $Q = L_{S+B} / L_B$, is consistent with background hypothesis, although at low mass, S+B is slightly favoured

Results of Tevatron Combination

CDF and D0, arXiv:1007.4587



Tevatron experiments set a 95% CL exclusion of a SM Higgs boson in the mass region 158 – 175 GeV (first direct exclusion since LEP)



ALEPH

DALI_F1

ECM=206.7

Pch=83.0

Efl=194.

Ewi=124.

Eha=35.9

r01979_2

Nch=28

EV1=0

EV2=0

EV3=0

ThT=0

61-4 -

2:32

Run=54698

Evt=4881

Detb= E3FFFF

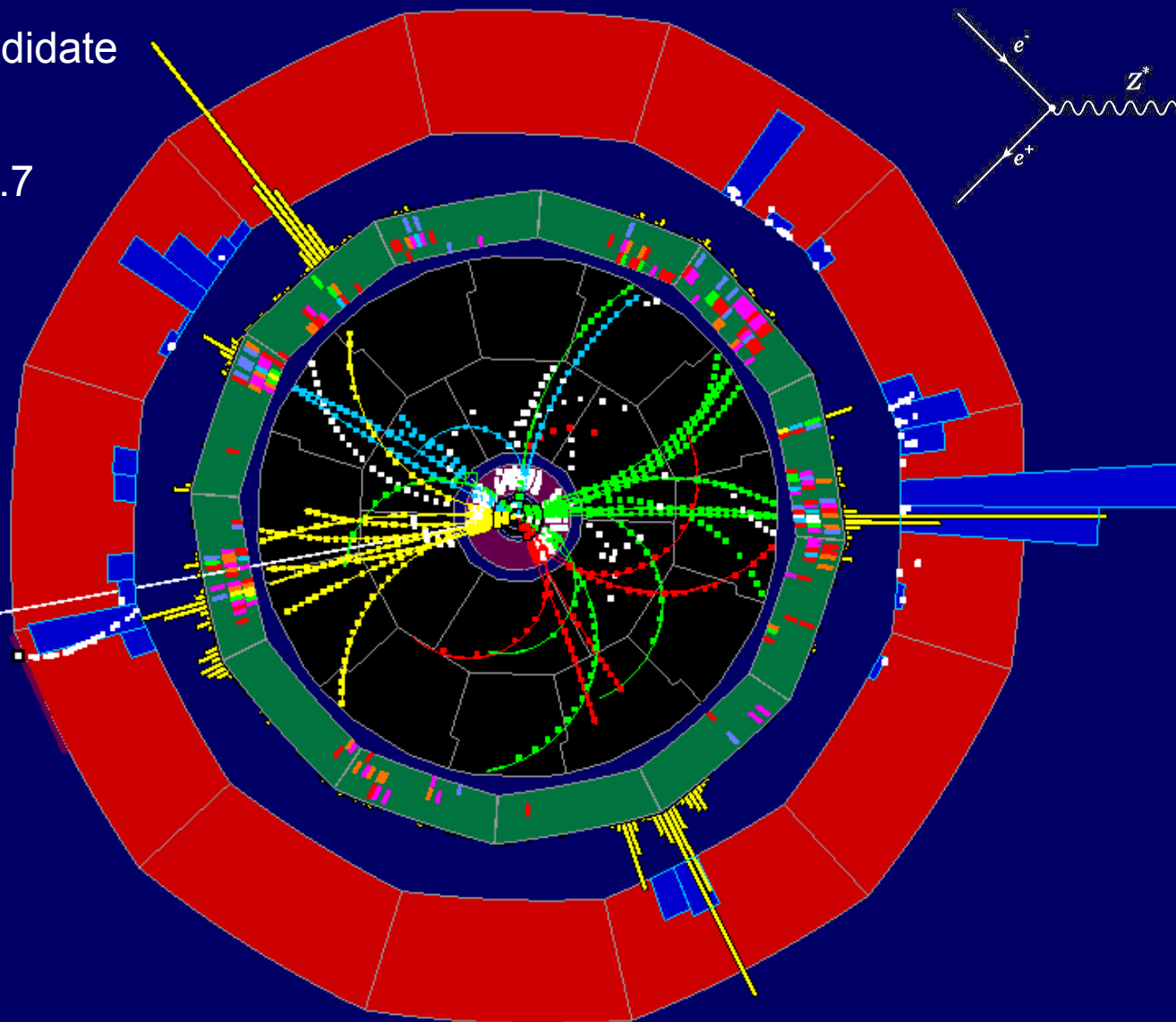
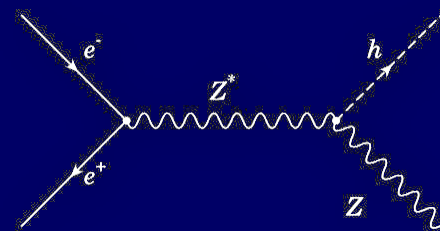
3 GeV EC
1.5 GeV HC

ALEPH

$HZ \rightarrow bb\ qq$ candidate

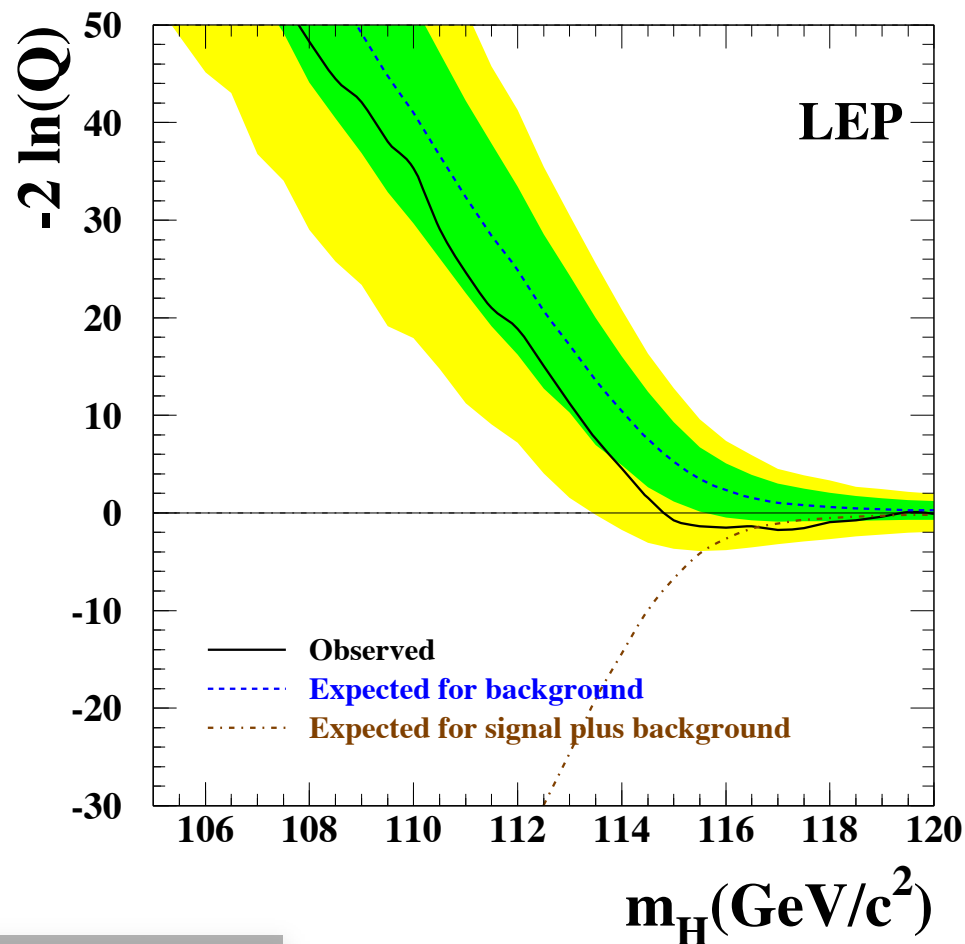
$M_{bb} = 114 \text{ GeV}$

$s/b|_{MH=115 \text{ GeV}} = 4.7$





ALEPH

 $HZ \rightarrow bb \, qq$ candidate $M_{bb} = 114 \text{ GeV}$ $s/b|_{MH=115 \text{ GeV}} = 4.7$ 

ADLO, PL B 565, 61 (2003)

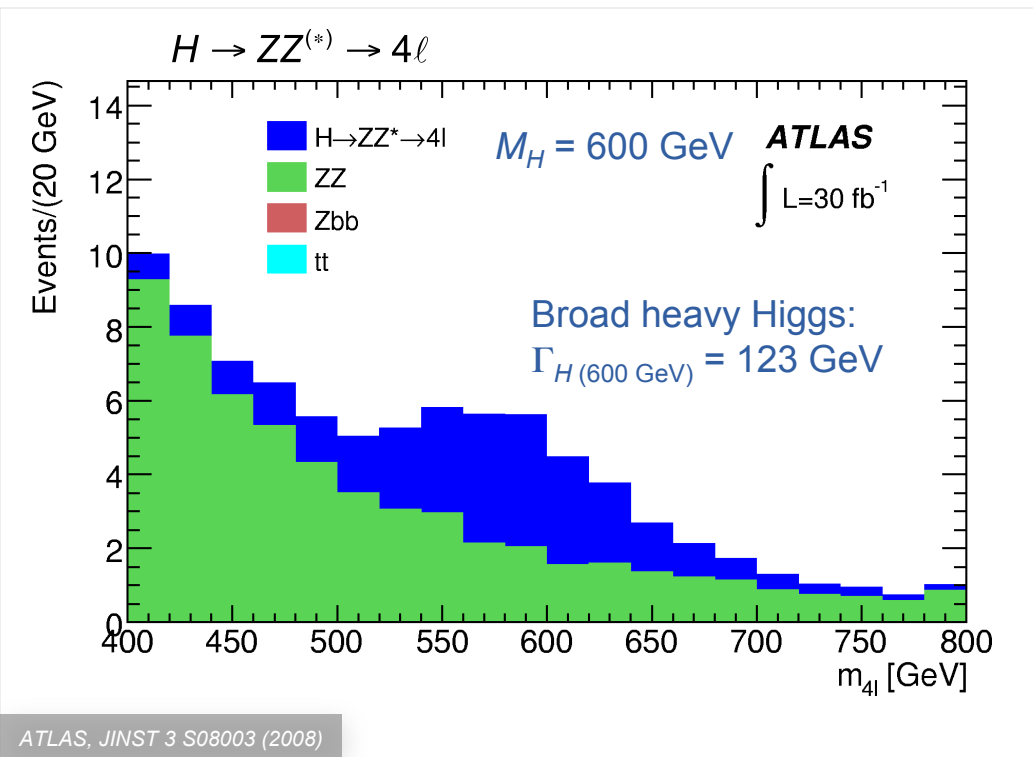
A stylized, high-contrast black and white image of a particle detector event. A central point of interaction is surrounded by a dense, chaotic web of lines. Several distinct, bright, and somewhat diffuse tracks radiate outwards from the center, resembling particle showers or jets. The background is dark, with a lighter, circular gradient centered on the interaction point. A horizontal white line passes through the center of the image, serving as a background for the title text.

Higgs Searches at the LHC

$H \rightarrow ZZ^{(*)} \rightarrow 4 \text{ leptons } (e, \mu)$

Golden discovery channel : $\sigma \times \text{BR} (140 / 200 \text{ GeV} \mid \sqrt{s}=7 \text{ TeV}) \approx 4 / 7 \text{ fb}$

Signal selection: $p_T(1,2/3,4) > 20/7 \text{ GeV}$, $|\eta| < 2.5$, isolated leptons, $M(i,j) \sim M_Z$, $M(n,m) \sim < M_Z$



Backgrounds:

Top production

$$t\bar{t} \rightarrow WbWb \rightarrow \ell\nu \text{ } c\ell\nu \text{ } \ell\nu \text{ } c\ell\nu$$

Also: associated Zbb production

$$Zbb \rightarrow \ell\ell \text{ } c\ell\nu \text{ } c\ell\nu$$

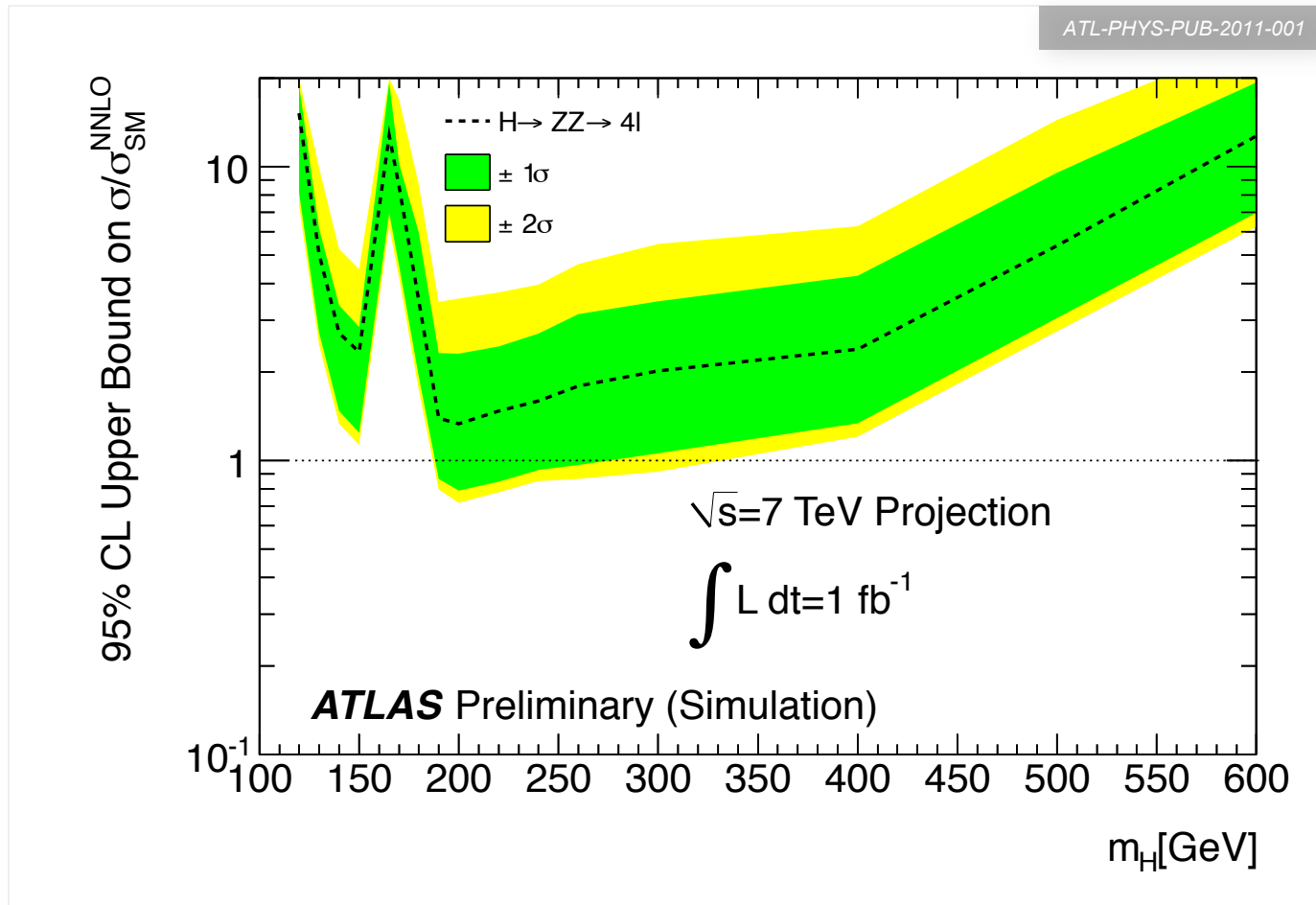
Reject by requiring leptons to be isolated and to match primary vertex

Dominant background after isolation cuts: $ZZ^{(*)}$ continuum

Depending on m_H , between 2 and 10 times smaller than signal

$H \rightarrow ZZ^{(*)} \rightarrow 4 \text{ leptons}$

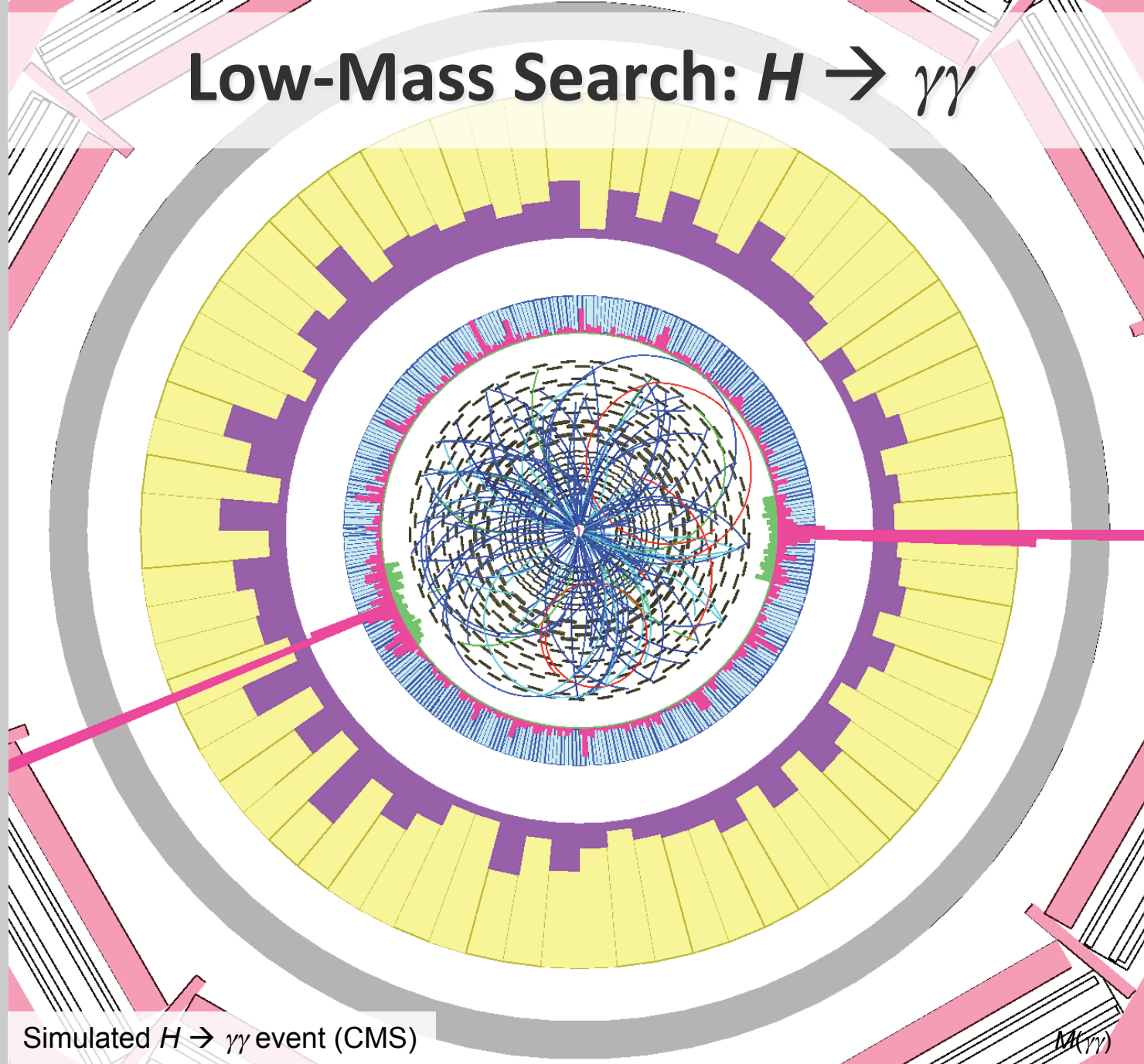
Extrapolated SM Higgs Exclusion potential with 1 fb^{-1}



For $M_H > 270 \text{ GeV}$,
 $H \rightarrow ZZ \rightarrow ll\nu\nu$
more powerful due
to $6 \times \text{BR}$ and large
missing E_T

→ see later

Low-Mass Search: $H \rightarrow \gamma\gamma$



$$H \rightarrow \gamma\gamma$$

Clean discovery channel for light Higgs: $\sigma \times \text{BR}$ (115 / 140 GeV | $\sqrt{s}=7$ TeV) $\approx 48 / 28$ fb

Discovery primarily driven by photon energy resolution... but not only !

“Stochastic term”

Number of shower particles

$$\frac{\sigma(E)}{E} = \frac{S}{\sqrt{E \text{ (GeV)}}} \oplus C \oplus \frac{N}{E \text{ (GeV)}}$$

“Noise term”

Electronics noise
(pile-up also contributes)

“Constant term”

Non-uniformities in
calorimeter response
due to inhomogeneities,
non-linearities

Current C (ATLAS):
1.1% (1.8%) for
barrel (endcap)
from $Z \rightarrow ee$ inter-
calibration

Constant	ATLAS	CMS ^(*)
S	10–12 %	3–5.5 %
C	< 0.4 %	< 0.5 %
N	250 MeV	200–600 MeV

(*) Test beam numbers, w/o ID

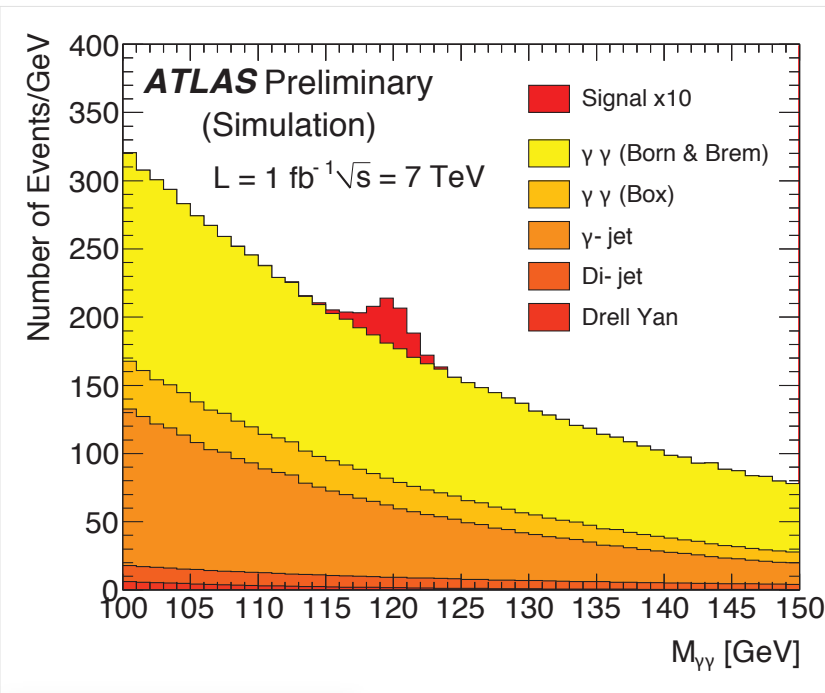
$$\text{Back-on-the-envelope for } H \rightarrow \gamma\gamma : \sigma_{M_{\gamma\gamma}}(E_{\gamma}) \Big|_{p_H=0} \propto \frac{M_H}{\sqrt{2}} \frac{\sigma_{E_{\gamma}}}{E_{\gamma}} \Big|_{M_H=120 \text{ GeV}} \approx \begin{cases} 1.4 \text{ GeV (ATLAS)} \\ 0.8 \text{ GeV (CMS)} \end{cases}$$

But: must include error on opening angle ($\theta_{\gamma\gamma}$), $\gamma \rightarrow ee$ conversions ($\sim 55\%$), jet background

$$H \rightarrow \gamma\gamma$$

Clean discovery channel for light Higgs: $\sigma \times \text{BR}$ (115 / 140 GeV | $\sqrt{s}=7$ TeV) $\approx 48 / 28$ fb

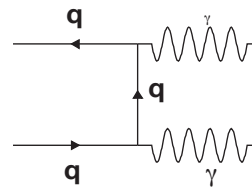
Signal selection: need excellent E_γ resolution, and efficient & pure photon ID; use MVA: $M_{\gamma\gamma}$, $\cos\theta^*$, $p_{T,\gamma\gamma}$



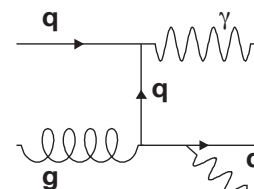
ATLAS, JINST 3 S08003 (2008)

Backgrounds:

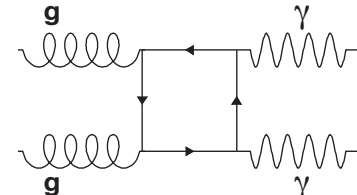
$\gamma + \gamma$ ("irreducible" – not quite)



Quark annihilation
(dominant: $O(\alpha^2)$)

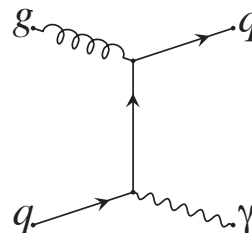


Bremsstrahlung, $O(\alpha^2\alpha_s)$
and quark fragmentation



Box diagram
 $O(\alpha^2\alpha_s^2)$, $\approx$ q-ann.

$\gamma + \text{jet}$ and $\text{jet} + \text{jet}$ (reducible, but $\sim 10^6 \times$ larger than $\gamma\gamma$)

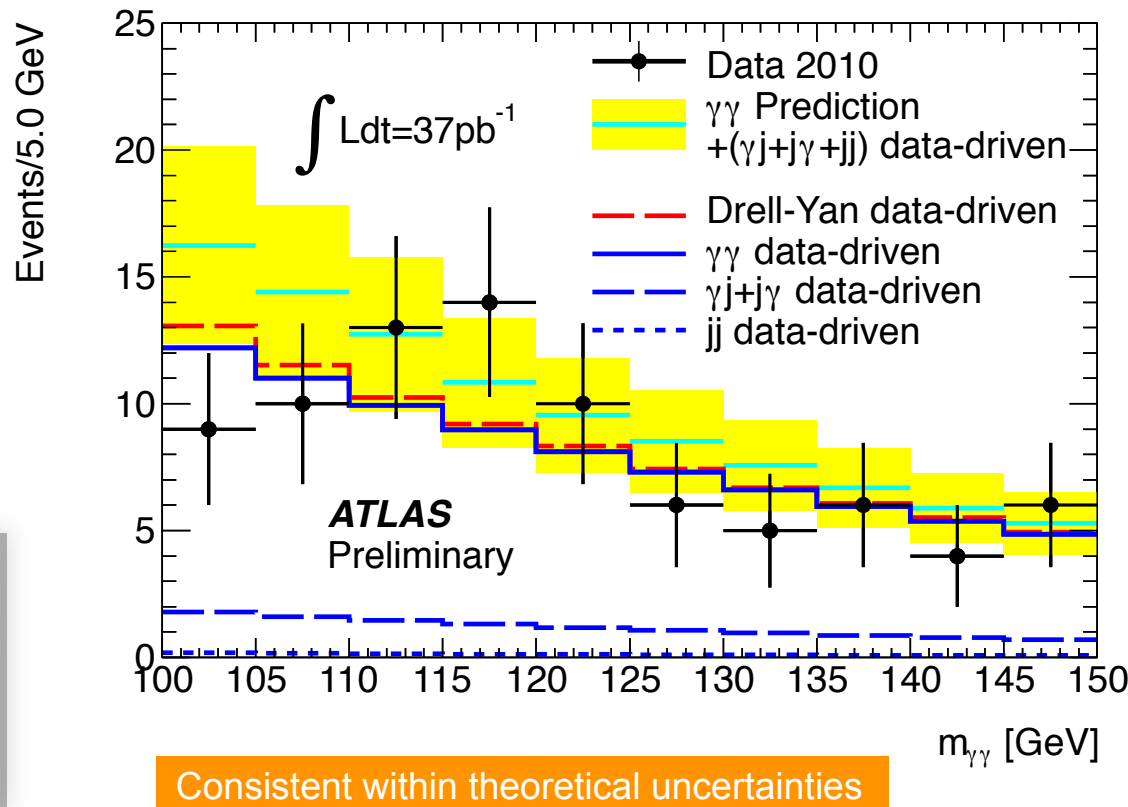


Requires
excellent
calorimeter
based γ -jet
separation

$$H \rightarrow \gamma\gamma$$

Clean discovery channel for light Higgs: $\sigma \times \text{BR}$ (115 / 140 GeV | $\sqrt{s}=7$ TeV) $\approx$ 48 / 28 fb

Signal selection: need excellent E_γ resolution, and efficient & pure photon ID; use MVA: $M_{\gamma\gamma}$, $\cos\theta^*$, $p_{T,\gamma\gamma}$



ATLAS data

Data-driven background fit from sidebands in identification and isolation variables
(“double sideband method”)

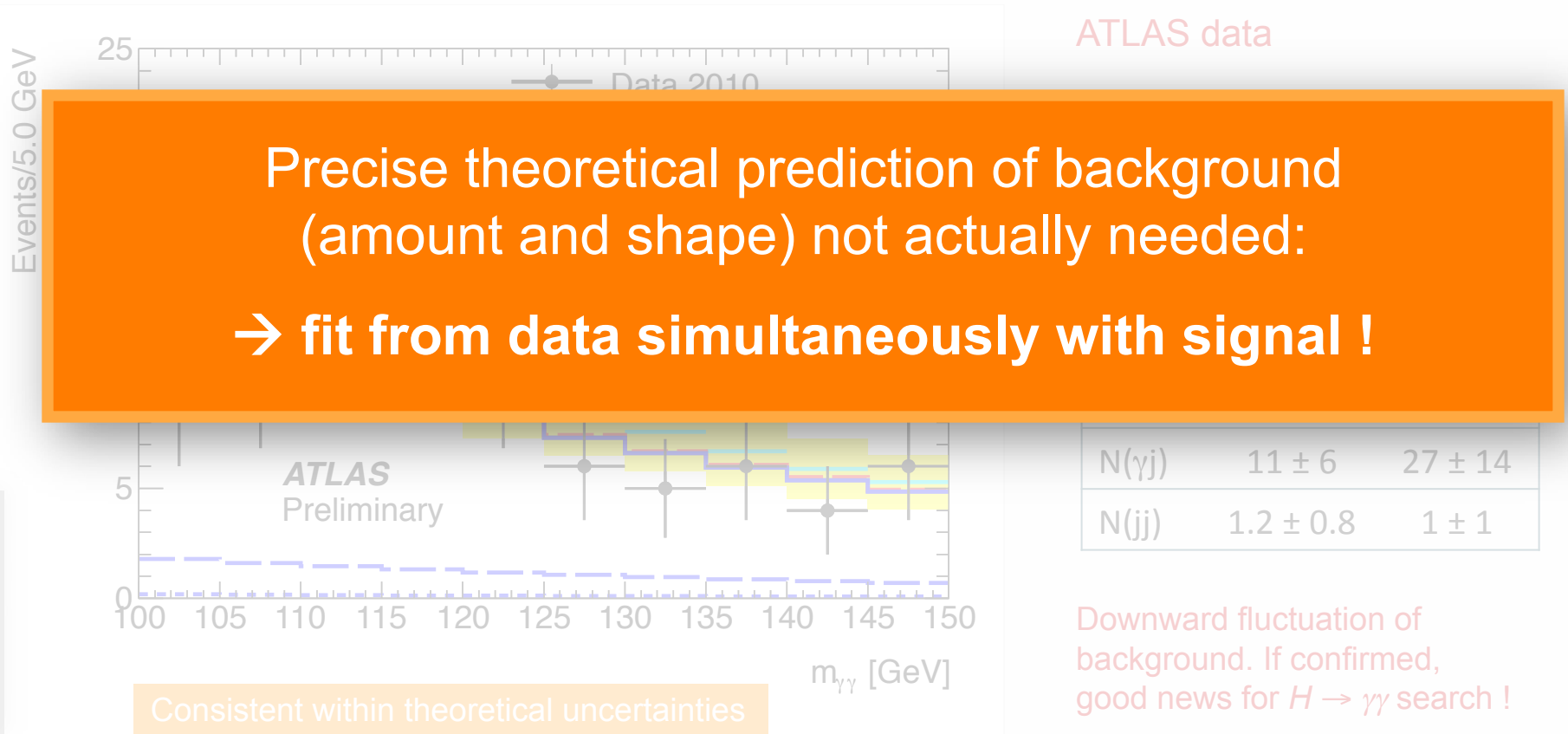
	Data	MC
$N(\gamma\gamma)$	69 ± 12	86 ± 23
$N(\gamma j)$	11 ± 6	27 ± 14
$N(jj)$	1.2 ± 0.8	1 ± 1

Downward fluctuation of background. If confirmed, good news for $H \rightarrow \gamma\gamma$ search !

$$H \rightarrow \gamma\gamma$$

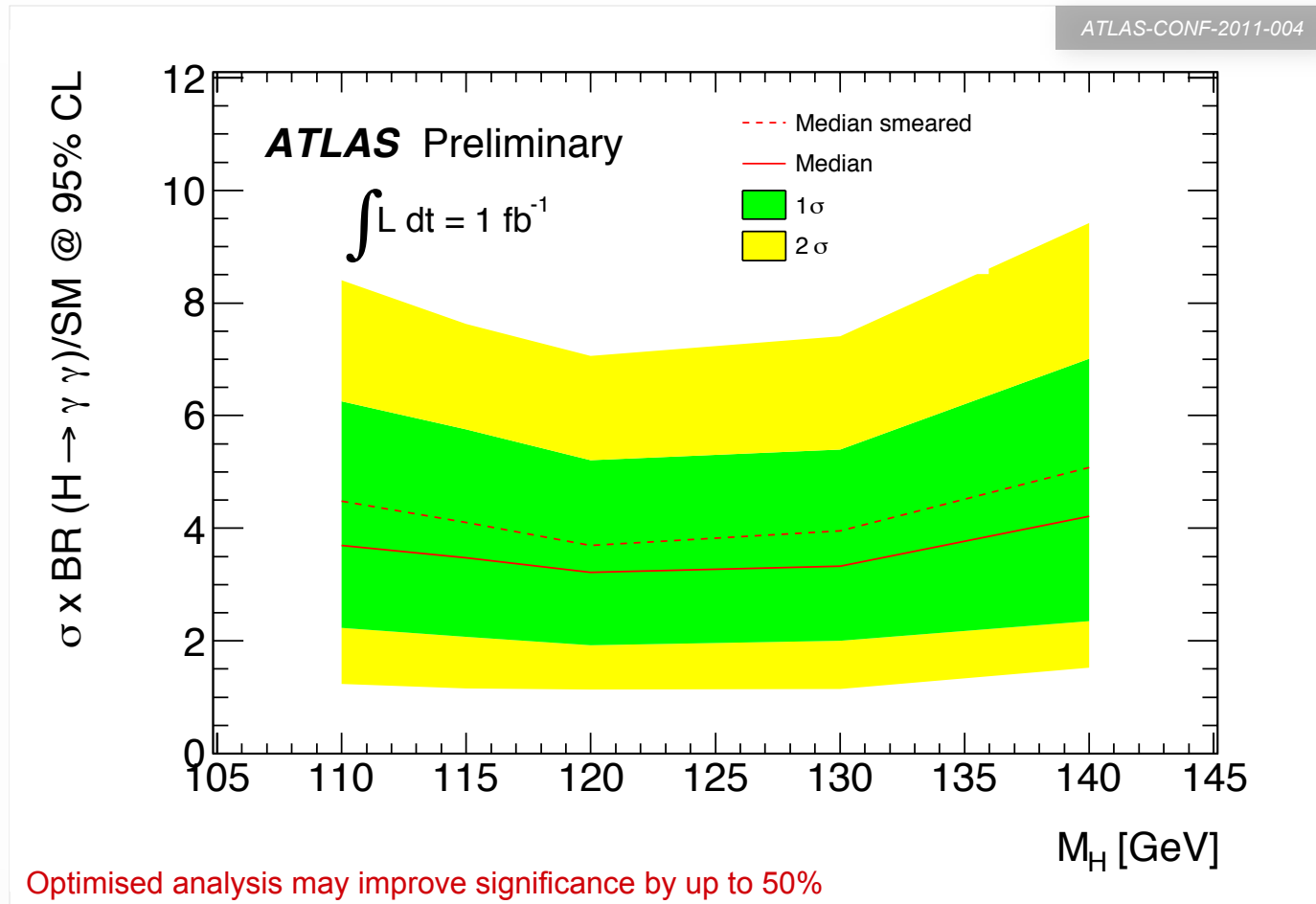
Clean discovery channel for light Higgs: $\sigma \times \text{BR} (115 \text{ GeV}) \approx 100 \text{ fb}$

Signal selection: need excellent E_γ resolution, and efficient & pure photon ID; use MVA: $M_{\gamma\gamma}$, $\cos\theta^*$, $p_{T,\gamma\gamma}$

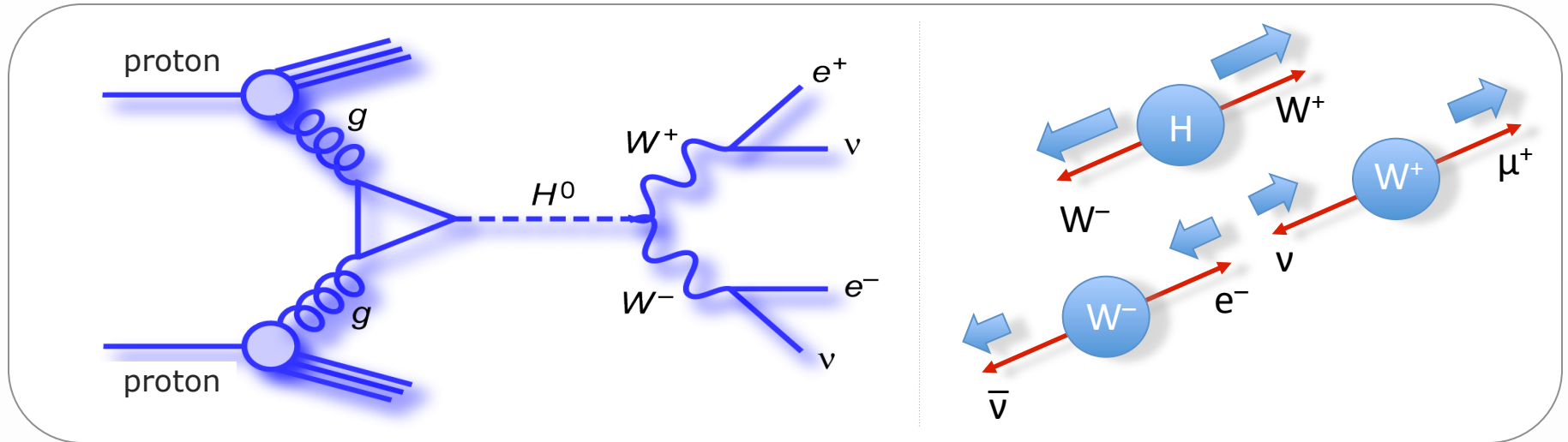


$H \rightarrow \gamma\gamma$ – Exclusion potential

Based on these results, extrapolated SM Higgs Exclusion potential with 1 fb^{-1}



High-Mass Search: $H \rightarrow WW$



W polarisation: correlated lepton emission.
Di-lepton opening angle is strongest discriminant

$$p\bar{p} \rightarrow H + X \rightarrow W^+W^- + X \rightarrow \ell^+ \nu \ell^- \bar{\nu} + X: \text{leptons} + E_T^{\text{miss}} + W_{\text{polarised}}$$

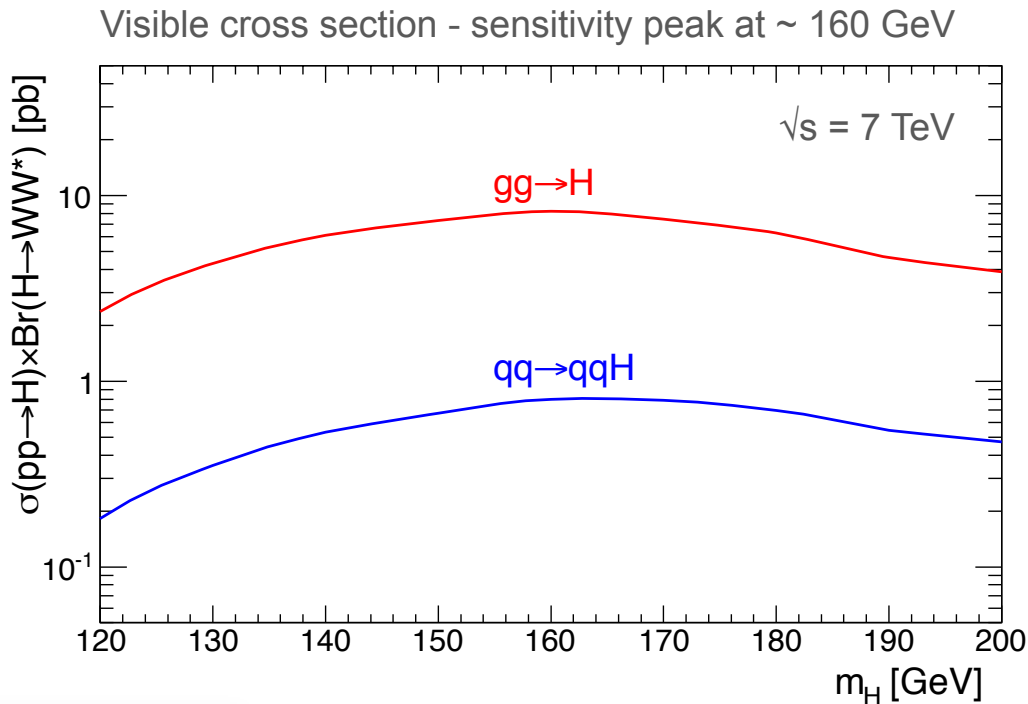
Dominant cross section > 135 GeV, most sensitive channel

$H \rightarrow WW \rightarrow 2 \text{ leptons } (e, \mu) + 2\nu$

No clean channel but large: $\sigma \times \text{BR}$ (120 / 165 / 200 GeV | $\sqrt{s}=7 \text{ TeV}$) $\approx 120 / 400 / 200 \text{ fb}$

Signal selection: large transverse mass, $M_T^2 = (E_{T,\parallel} + E_{T,\text{miss}})^2 - (\mathbf{p}_{T,\parallel} + \mathbf{p}_{T,\text{miss}})^2$, and exploit W polarisation

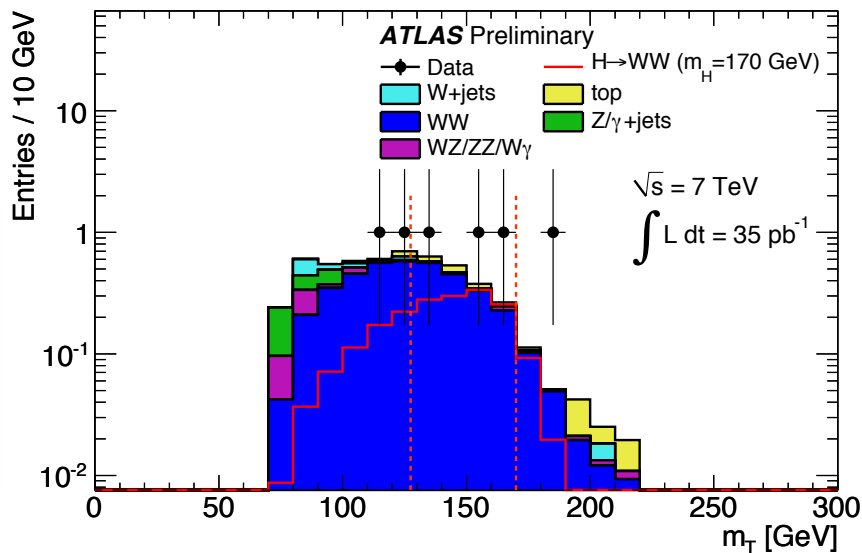
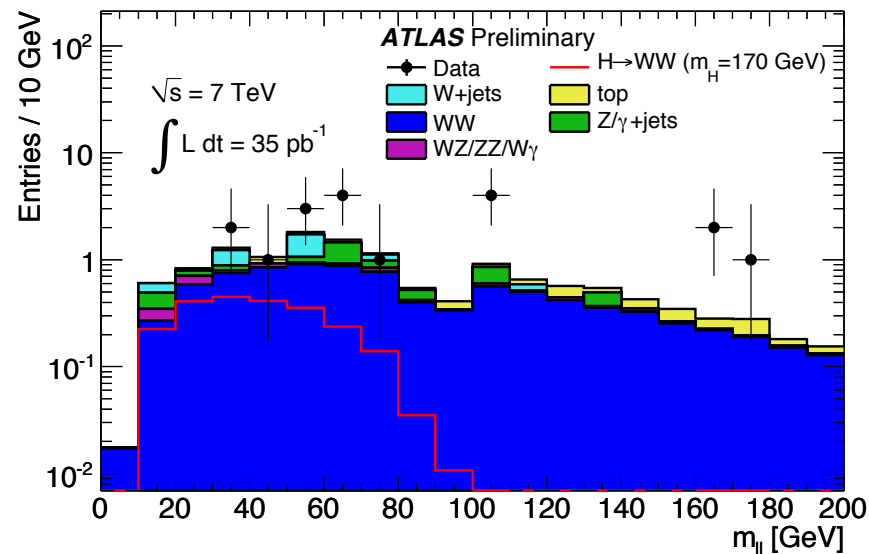
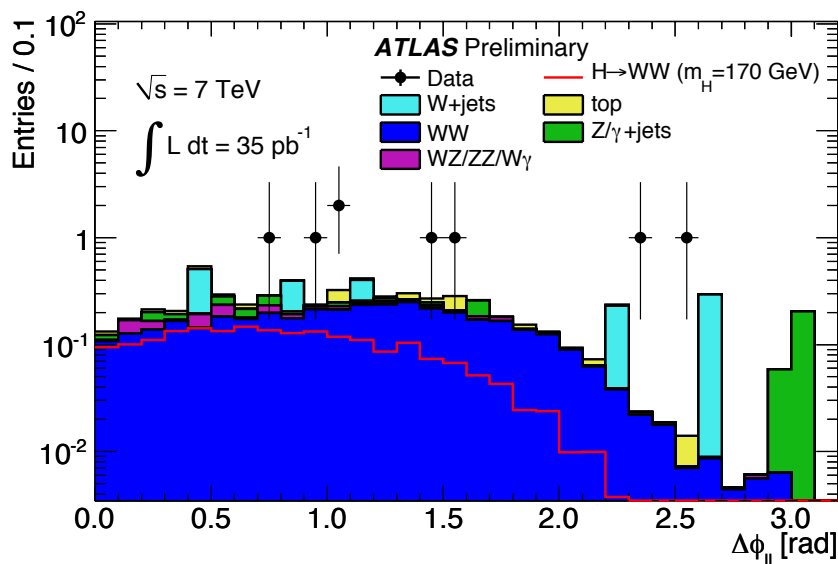
Separate analysis in $H + 0, 1 \text{ jet}$ (gluon fusion), and $H + 2 \text{ jets}$ (weak boson fusion)



Dominant backgrounds from WW continuum, $W + \text{jets}$, top...

ATLAS-CONF-2011-005

- Data-driven background determination using background-enhanced control regions (*anti-cuts*)
- 0-jet channel: $S/B \sim 0.7$ at $M_H = 170$ GeV, after cuts on $\Delta\phi_{ll}$, m_{ll} , m_T , $E_{T,miss}$



Higgs detection depends on good understanding of WW background

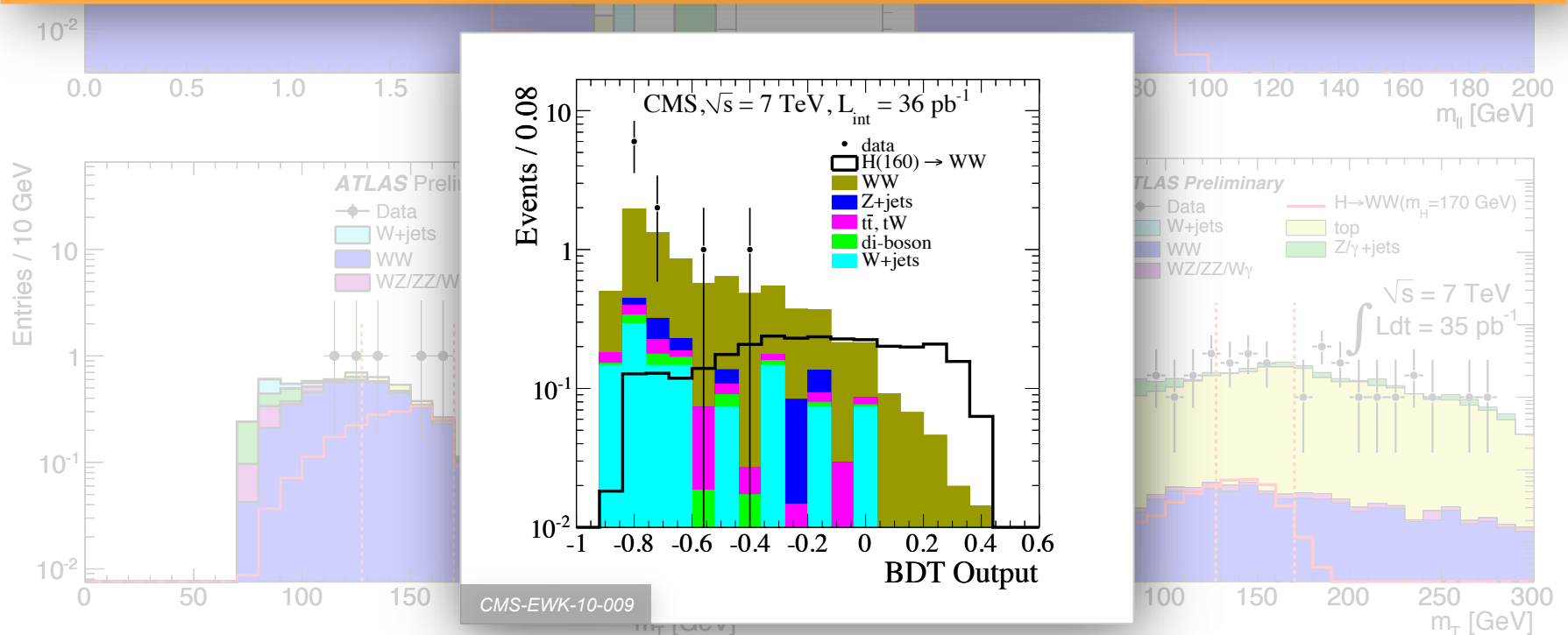
Recent measurement by CMS finds:

$\sigma(pp \rightarrow W^+W^-) = (41.1 \pm 15.3 \pm 7.3) \text{ pb}$
compared to $(43.0 \pm 2.0) \text{ pb}$ in NLO SM

CMS-EWK-10-009

- Data-driven background determination using background-enhanced control regions (*anti-cuts*)
- 0-jet channel: $S/B \sim 0.7$ at $M_H = 170$ GeV, after cuts on $\Delta\phi_{ll}$, m_{ll} , m_T , $E_{T,miss}$

Thanks to the already excellent understanding of the LHC detectors, the experiments also embark into using powerful multivariate methods for background discrimination



$H \rightarrow WW \rightarrow 2 \text{ leptons} + 2\nu$

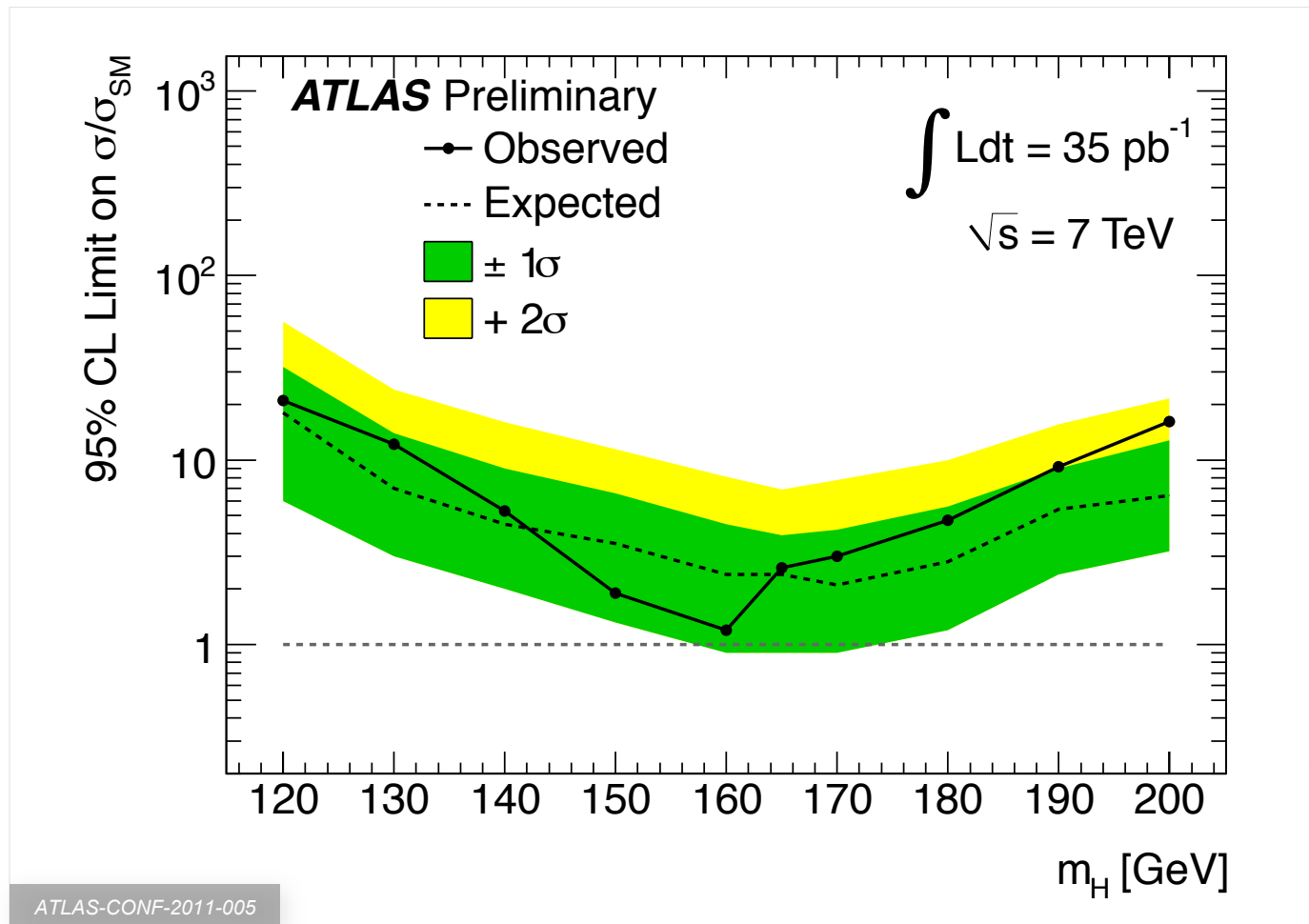
Number of events found by ATLAS and predicted for $M_H = 170$ GeV hypothesis

Channel	Signal	top	WW	WZ/ZZ/W γ	Z+jets	W+jets	Total Bkg.	Observed
$H + 0j$								
$e\mu$	$0.62 \pm 0.01 \pm 0.18$	0.09	0.71	0.02	0.00	0.01	$0.83 \pm 0.07 \pm 0.13$	1
ee	$0.20 \pm 0.01 \pm 0.07$	0.03	0.20	0.00	0.00	0.02	$0.25 \pm 0.08 \pm 0.04$	1
$\mu\mu$	$0.44 \pm 0.01 \pm 0.12$	0.08	0.53	0.01	0.00	0.00	$0.62 \pm 0.05 \pm 0.10$	1
$H + 1j$								
$e\mu$	$0.31 \pm 0.01 \pm 0.09$	0.26	0.18	0.01	0.00	0.02	$0.47 \pm 0.08 \pm 0.16$	0
ee	$0.08 \pm 0.01 \pm 0.03$	0.10	0.05	0.00	0.05	0.03	$0.23 \pm 0.04 \pm 0.06$	0
$\mu\mu$	$0.21 \pm 0.01 \pm 0.06$	0.15	0.16	0.00	0.25	0.00	$0.56 \pm 0.09 \pm 0.14$	1
$H + 2j$								
$e\mu$	$0.03 \pm 0.01 \pm 0.01$	0.01	0.00	0.00	0.00	0.00	$0.01 \pm 0.01 \pm 0.01$	0
ee	$0.01 \pm 0.01 \pm 0.01$	0.00	0.00	0.00	0.00	0.00	0.00	0
$\mu\mu$	$0.02 \pm 0.01 \pm 0.01$	0.00	0.01	0.00	0.00	0.00	$0.01 \pm 0.01 \pm 0.01$	0

Observed events compatible with B and $S + B$ expectations $\rightarrow$ no exclusion yet

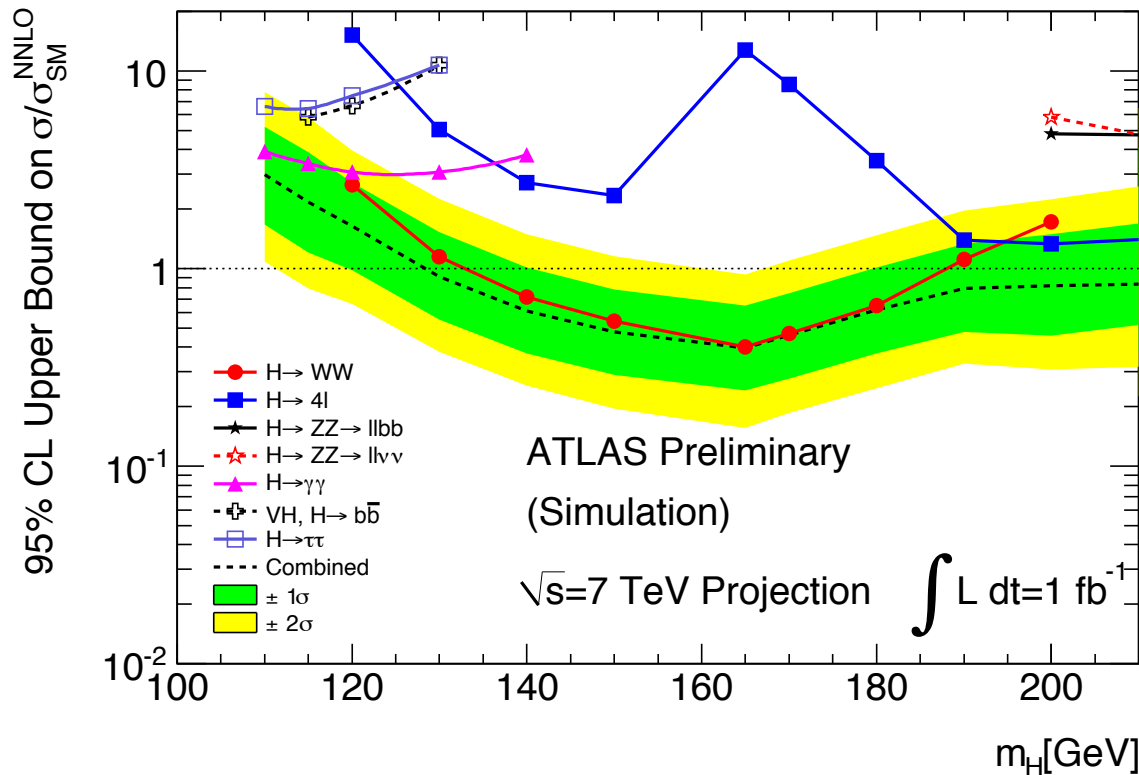
$H \rightarrow WW \rightarrow 2 \text{ leptons} + 2\nu$

ATLAS Standard Model Higgs Exclusion with 35 fb⁻¹



Exclusion Potential – Combination

ATLAS combination of all considered channels at 7 TeV with 1 fb⁻¹ luminosity



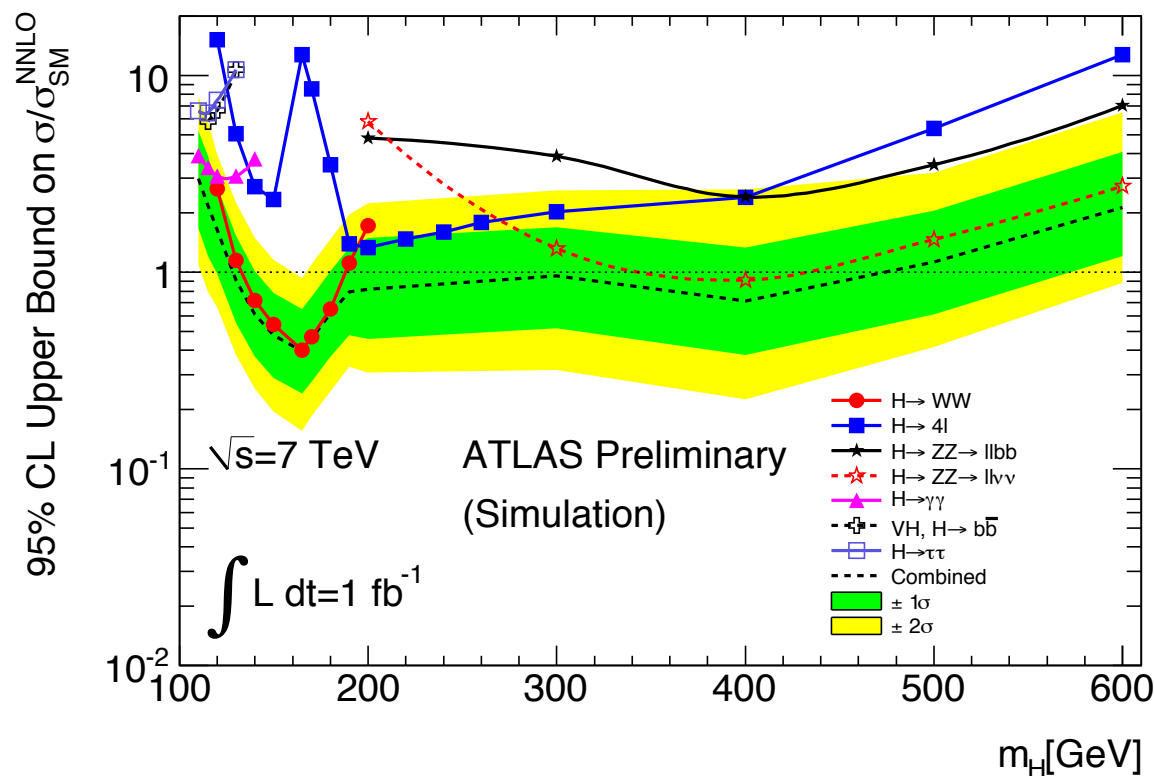
Further improvement
from combination of
ATLAS and CMS

At $M_H = 200$ GeV,
 WW still competitive with $\gamma\gamma$

With some luck, mass range between 129 and ~ 460 GeV can be excluded by one experiment

Exclusion Potential – Combination

ATLAS combination of all considered channels at 7 TeV with 1 fb^{-1} luminosity



Further improvement
from combination of
ATLAS and CMS

Towards higher masses
reduced WW sensitivity due
to (mainly) reduced $gg \rightarrow H$
cross section (PDF), but
entering of $H \rightarrow ZZ \rightarrow ll\nu\nu$

With some luck, mass range between 129 and $\sim 460 \text{ GeV}$ can be excluded by one experiment

A black and white image of a particle collision event, likely from a detector like ATLAS or CMS. It shows a central point of interaction with numerous tracks radiating outwards, forming a complex, star-like pattern. The tracks are more prominent in the upper and lower quadrants, with a dense cluster in the center. The background is dark, and the tracks are light gray/white.

Is it *a* and *the* Higgs Boson ?

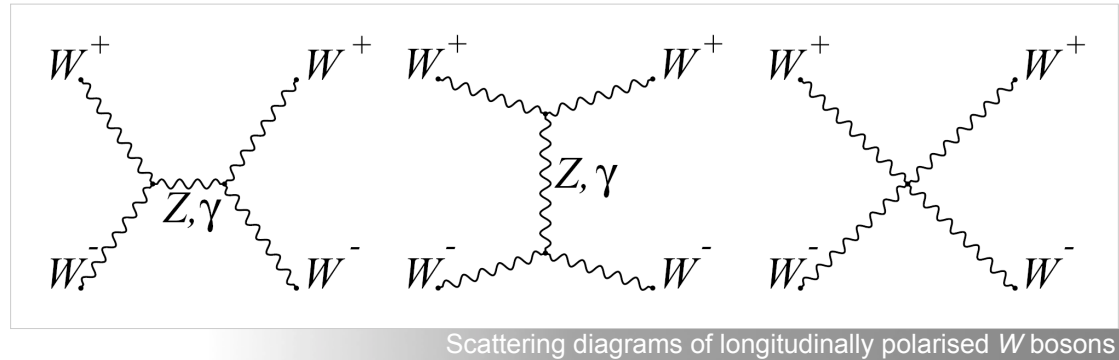
After a Higgs-like discovery, one needs to measure the properties of the new particle to consolidate whether it is indeed the wanted SM Higgs → Measure:

- **Mass** ($< 1\%$ precision with $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{(*)}$)
- **Spin and CP** (angular correlations in $H \rightarrow WW^{(*)}$ (spin only) $H \rightarrow ZZ^{(*)}$ (also CP), spin=0,2 if $H \rightarrow \gamma\gamma$)
- **Couplings to fermions and bosons**
 - model-independent ratios of couplings to Z/W , γ/W , τ/W to 20–30% precision (depends on M_H)
 - Higgs self coupling requires sLHC and more (ILC)

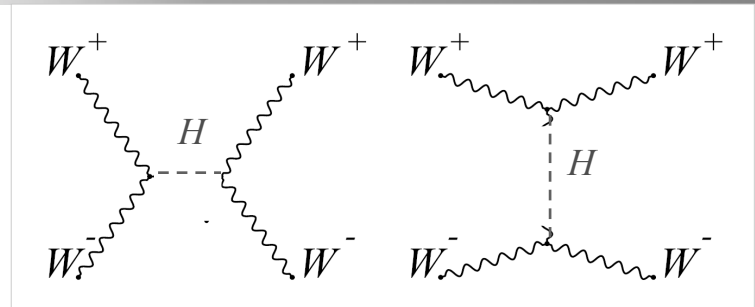
Unitarity – the Higgs Boson as UV Regulator

Unitarity problem: the amplitude of (longitudinal – since the W 's are massive) W^+W^- scattering diverges if only Z bosons and photons are exchanged:

$$\mathcal{M}_{Z,\gamma}(W_L^+W_L^- \rightarrow W_L^+W_L^-) \propto \sqrt{2}G_F \cdot (s+t)$$



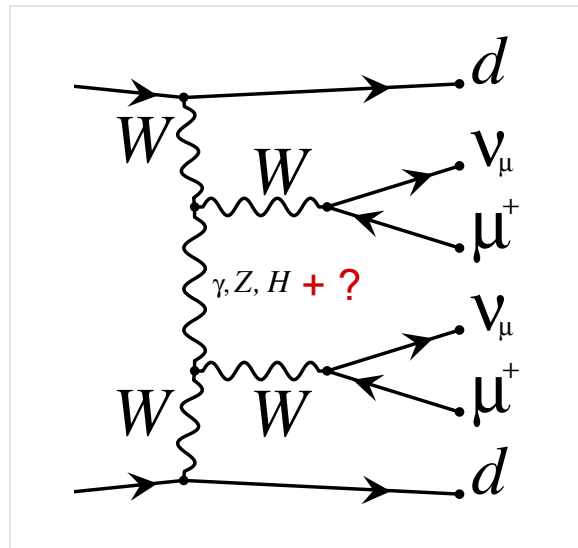
$$\mathcal{M}_{Z,\gamma,H}(W_L^+W_L^- \rightarrow W_L^+W_L^-) \propto -\sqrt{2}G_F \cdot M_H^2 \cdot \left(\frac{s}{s-M_H^2} + \frac{t}{t-M_H^2} \right)$$



- Higgs exchange regularises matrix element (if $M_H \leq 1/\sqrt{G_F} \sim 300$ GeV, while when doing a proper partial wave analysis of the scattering amplitude, the limit weakens)
- Higgs is a “UV Moderator”

Strong WW Scattering ?

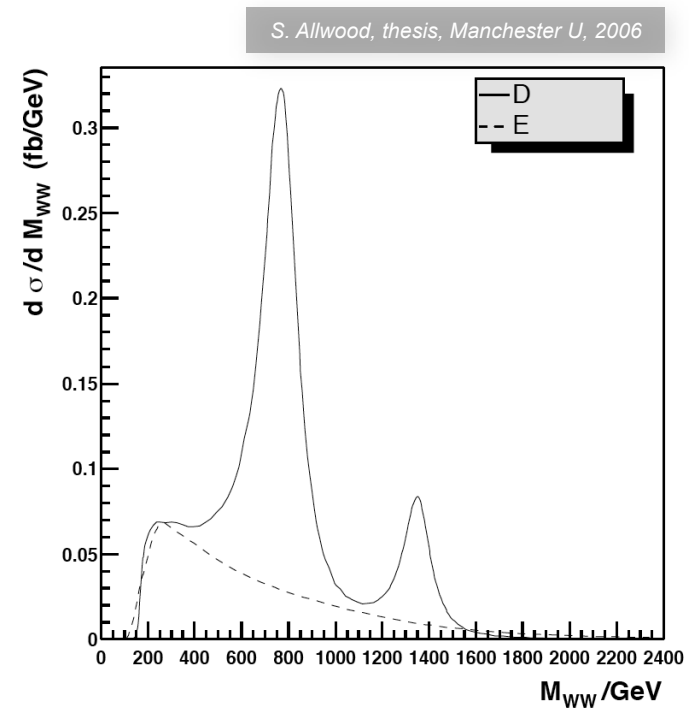
If the Higgs is very heavy, or if EW symmetry is broken by something else than a Higgs condensate (e.g., by strong interactions), W bosons would become **strongly interacting particles at TeV scale**.



Fusion of longitudinally polarised W at the LHC

Growth of scattering amplitude cancelled at $O(\text{TeV})$ by exchange of new fields

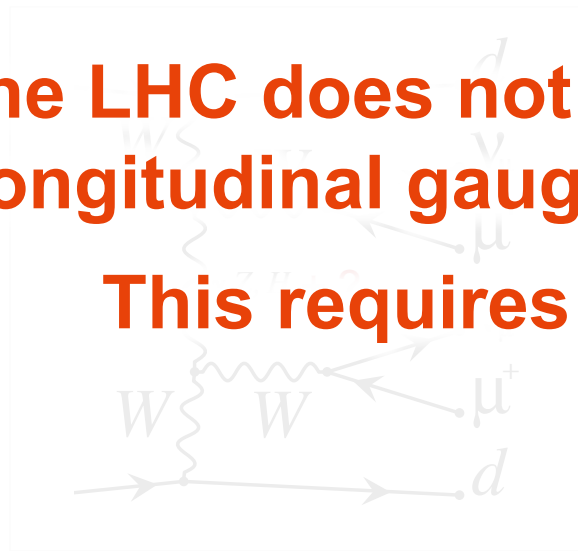
The experimental signature could be strong **WW resonances**



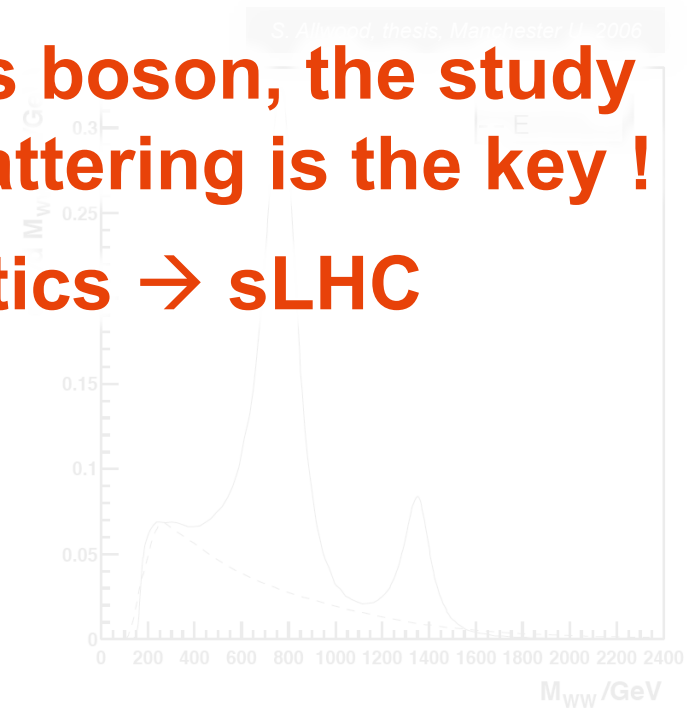
Strong WW Scattering ?

If the Higgs is very heavy, or if EW symmetry is broken by something else than a Higgs condensate (e.g., by strong interactions), W bosons would become **strongly interacting particles at TeV scale**.

If the LHC does not find a Higgs boson, the study of longitudinal gauge boson scattering is the key !
This requires large statistics $\rightarrow$ sLHC



Growth of scattering amplitude cancelled at $O(\text{TeV})$ by exchange of new fields



The experimental signature could be strong WW resonances



Conclusions

Conclusions

Many constraints on the SM Higgs boson have been collected already

- Stability up to M_{Pl} would require $M_H > 129 \text{ GeV}$ (perturbativity sets upper limit)
- Electroweak precision data give: $M_H = 96^{+30}_{-25} \text{ GeV}$
- Direct accelerator searches exclude $M_H < 114 \text{ GeV}$ and $158 < M_H < 175 \text{ GeV}$

The superb performance of the LHC in 2010 stimulates our imagination

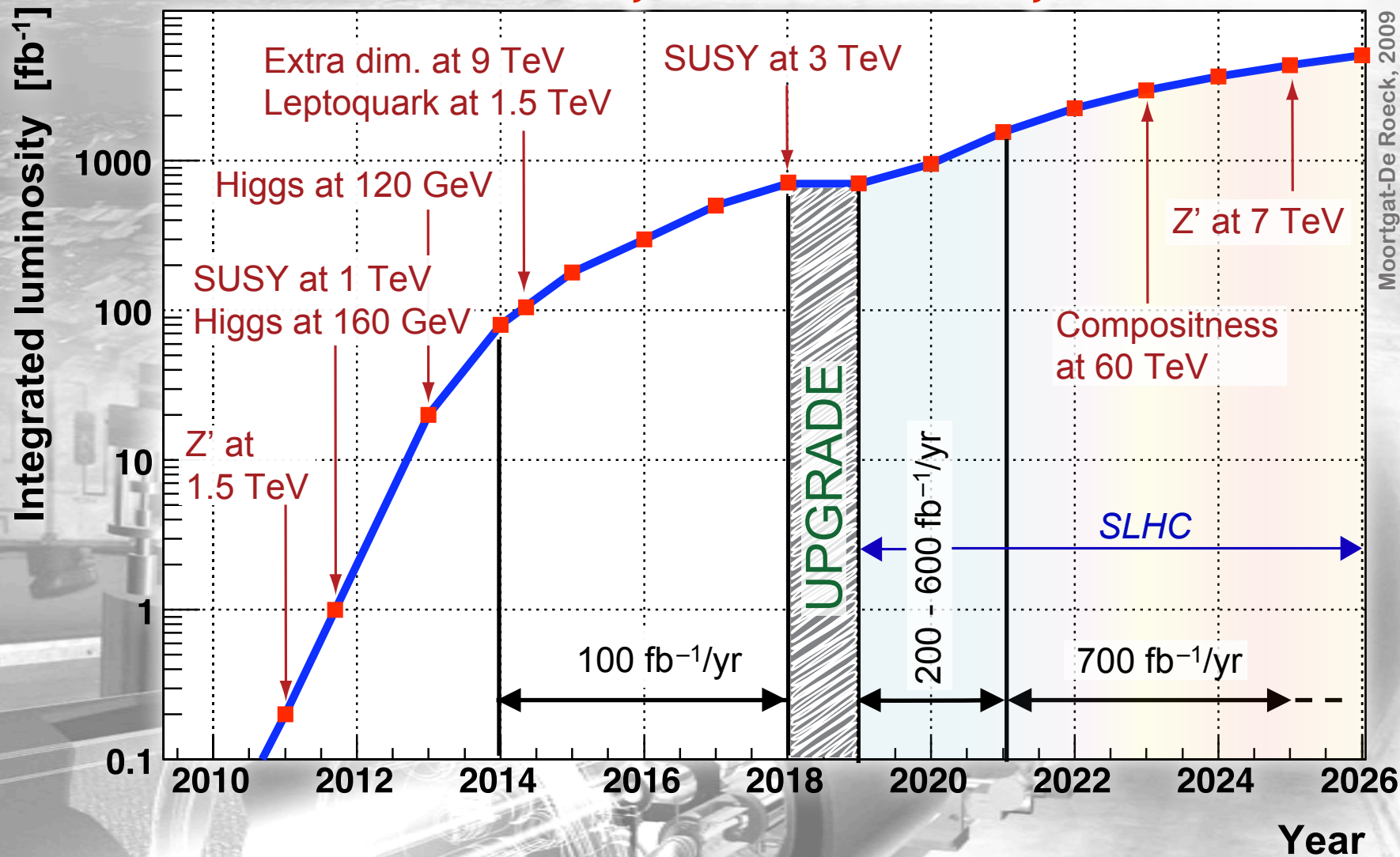
- ATLAS alone expects to exclude $129 < M_H < 460 \text{ GeV}$ with 1 fb^{-1}
- Possible 3σ evidence with ATLAS+CMS combined for $131 < M_H < 430 \text{ GeV}$ with 1 fb^{-1}
- Low mass Higgs is hardest, but $H \rightarrow \gamma\gamma$ channel promising
- Must not stop searching for heavy Higgs as EW constraints easily fooled

Many SM and BSM Higgs results from ATLAS in preparation for Moriond 2011

Expected for 2011: $L_{\text{peak}} \approx 1.3\text{--}2.0 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, $L_{\text{int}} \approx 2.7\text{--}3.7 \text{ fb}^{-1}$

The LHC Programme in a Nutshell

Only look at the luminosity - not the dates !!



A few references for additional reading

Taking a closer look at the LHC: <http://www.lhc-closer.es>
Facts around the LHC and Physics (students level)

ATLAS Physics Book: <http://arXiv.org/abs/arXiv:0901.0512>

CMS Physics TDRs: <http://cmsdoc.cern.ch/cms/cpt/tdr>

LHCb Key Measurements: <http://arXiv.org/abs/arXiv:0912.4179>

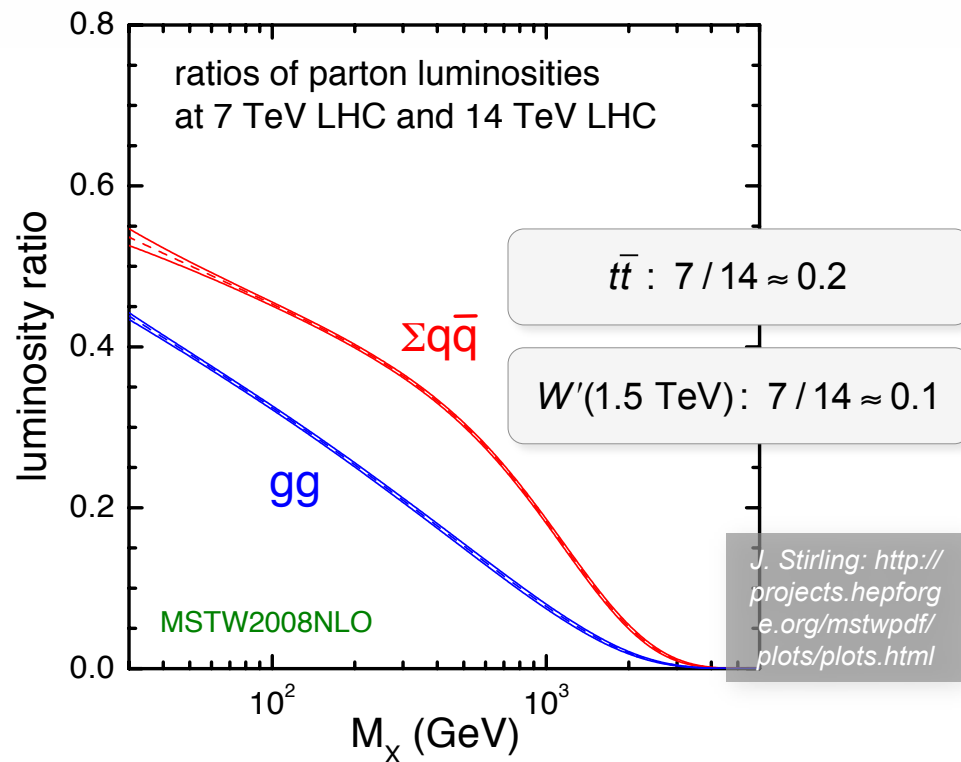
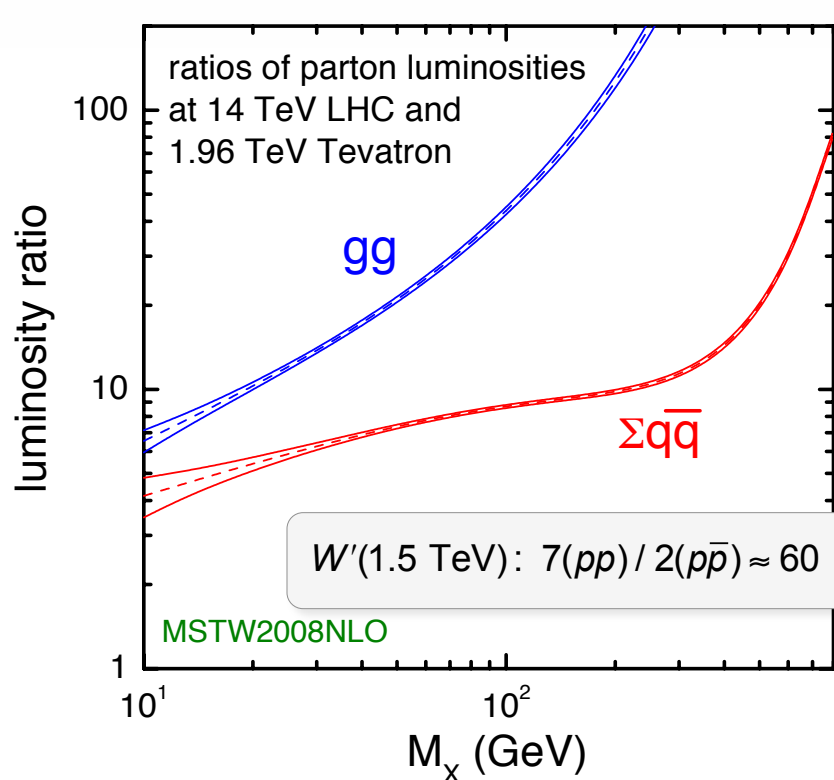
LHC Physics Centre CERN (LPCC): <http://lpcc.web.cern.ch>
Announcements, list of all publications from LHC experiments

CERN Academic Training Lectures: <http://indico.cern.ch/categoryDisplay.py?categId=72>
Large database of lectures around particle physics and beyond

extra slides

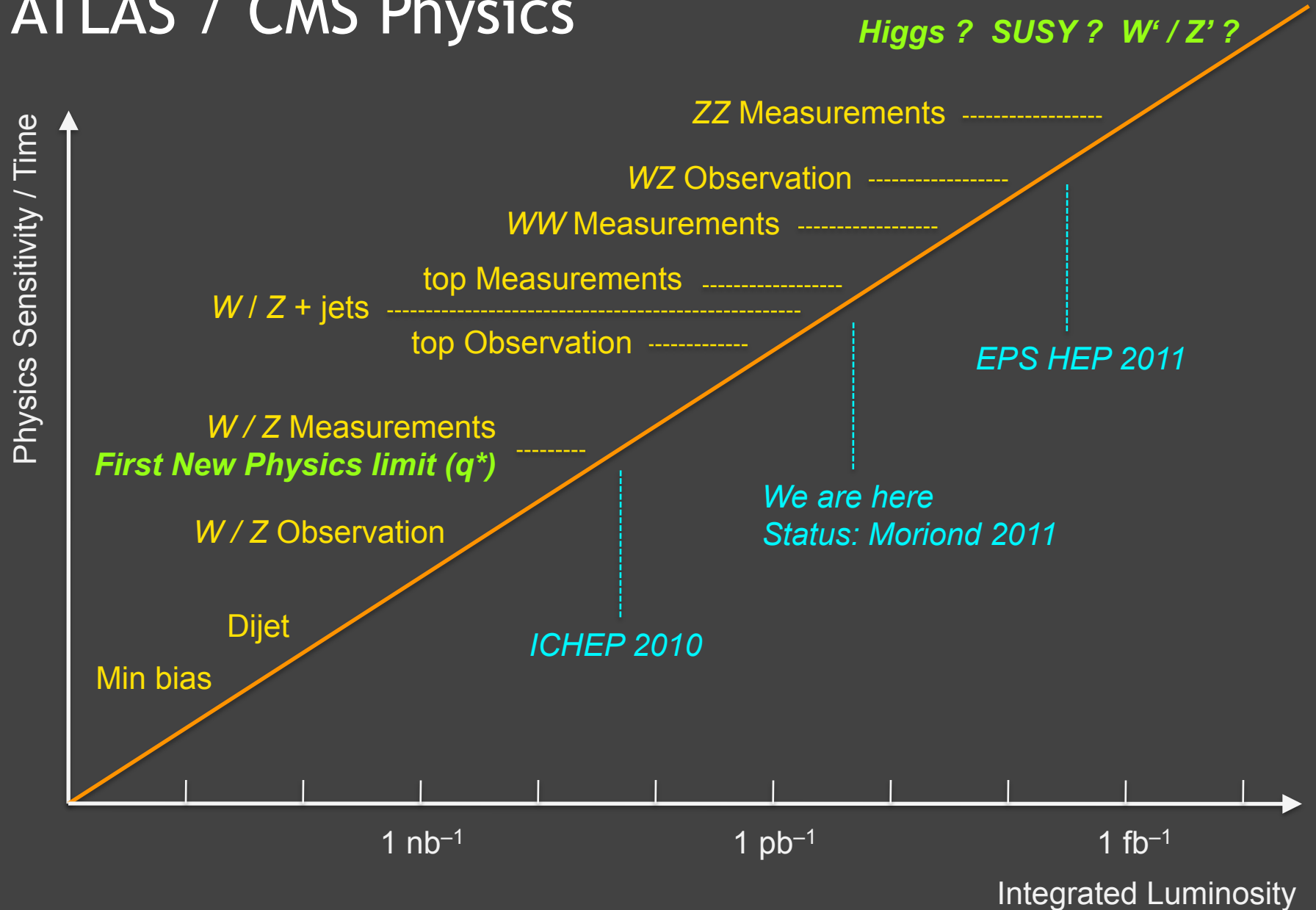
Parton Luminosities at LHC and Tevatron

Ratio of “parton luminosities” of LHC-to-Tevatron and LHC 7 TeV-to-14 TeV



- High M_X production through gluon fusion requires large CM energy
- Less so for quark-antiquark scattering which has slow rise for $M_X < 300 \text{ GeV}$

ATLAS / CMS Physics



Higgs Production at the LHC – Summary

Huge theoretical effort to compute the signal processes, but also the background, at (N)NLO level

New generators and tools used and *validated* (with data) by experimentalists

1. New (N)NLO Monte Carlos (also for backgrounds):

- MCFM Monte Carlo, J. Campbell and K. Ellis, [Web](#)
- MC@NLO Monte Carlo, S. Frixione and B. Webber, [Web](#)
- T. Figy, C. Oleari and D. Zeppenfeld, Phys. Rev. D68, 073005 (2003)
- E.L. Berger and J. Campbell, Phys. Rev. D70, 073011 (2004)
- FEHIP, C. Anastasiou, K. Melnikov and F. Petriello, hep-ph/0409088 and hep-ph/0501130 (differential cross sections through NNLO)
- HNNLO, S. Catani and M. Grazzini (2007, 2008)

2. New approaches to match parton showers and matrix elements (based on algorithm developed by Catani, Krauss, Kuhn and Webber (CKKW)*)

- ALPGEN Monte Carlo + MLM matching, M. Mangano et al.
- PYTHIA, adapted by S. Mrenna
- SHERPA Monte Carlo, F. Krauss et al., [Web](#)

Hypothesis Testing

The observed data are subjected to a likelihood-ratio test of 2 hypotheses:

- **Background scenario** (no Higgs signal assumed)
- **Signal + Background scenario** (Higgs signal with assumed mass added)

Statistical analysis of *hypothesis* M_H is based on likelihood ratio:

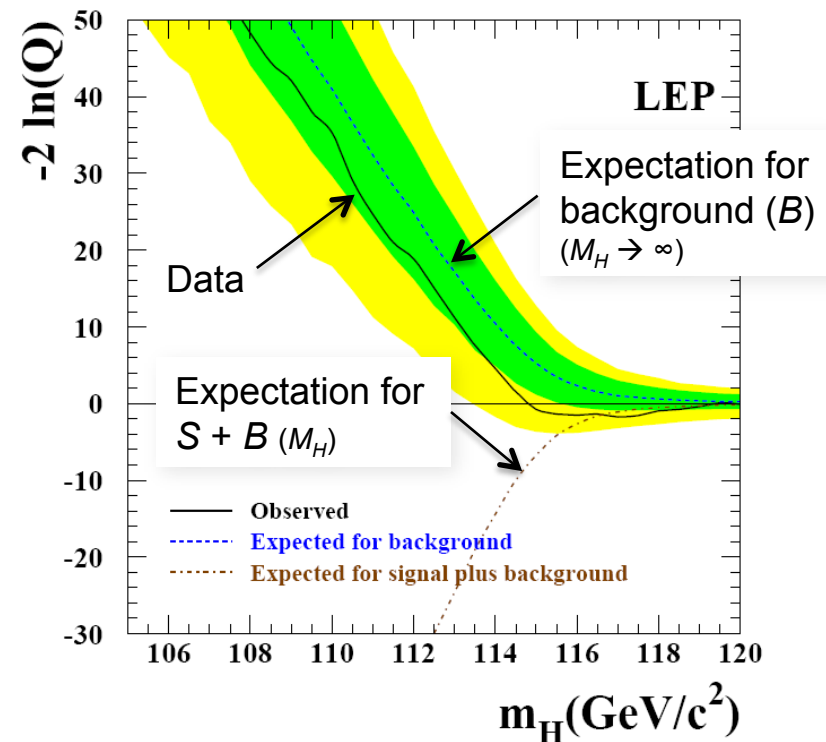
$$Q(M_H) \equiv \frac{L_{s+b}(M_H)}{L_b(M_H)}$$

Use the log-likelihood ratio

$$\text{LLR}(M_H) \equiv -\ln Q(M_H)$$

as *test statistics*

The expected distribution (PDF) of $\text{LLR}(M_H)$ is obtained from MC and compared to data



Hypothesis Testing

Quantify the level of agreement of the data

- with the “*b* only” hypothesis by estimating

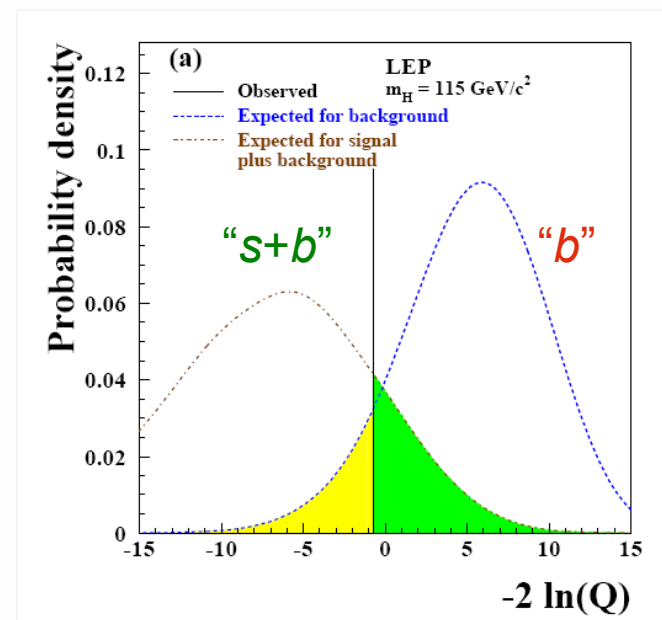
$$CL_b = 1 - P(LLR < LLR_{Data} | B)$$

using pseudo (“toy”) MC experiments

- with the “*s+b*” hypothesis by estimating

$$CL_{s+b} = P(LLR > LLR_{Data} | S+B)$$

using pseudo MC experiments



A frequentist exclusion limit is usually computed using CL_{s+b}

The “*s+b*” hypothesis is excluded at 95% CL if $CL_{s+b} < 0.05$

However, if the data undershoot the background, then CL_{s+b} small even if no sensitivity to signal !

As a protection, collaborations use

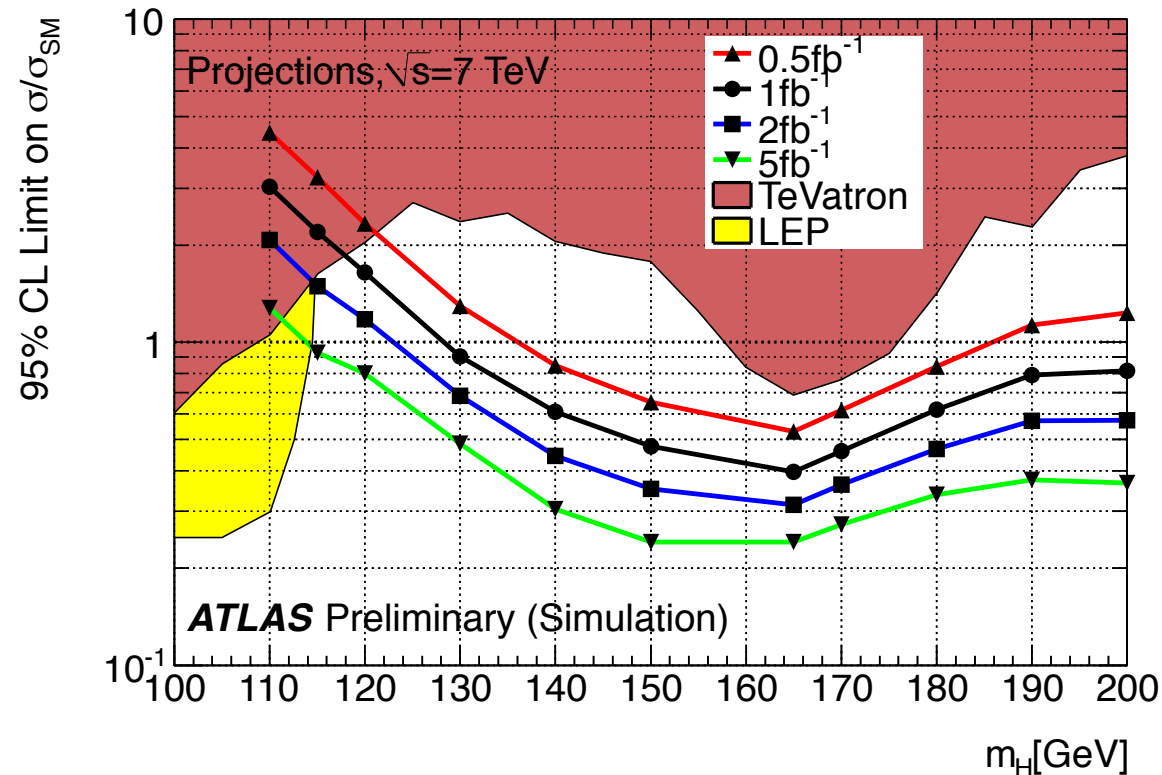
$$CL_s = CL_{s+b} / CL_b$$

for exclusion limits

- Modified frequentist approach* (conservative, as: $CL_s > CL_{s+b}$)
- If $CL_s < 0.05$: “hypothesis excluded at 95% CL”

Exclusion Potential vs. Luminosity

ATLAS combination of all considered channels at 7 TeV with 1, 2, 5 fb⁻¹ luminosity

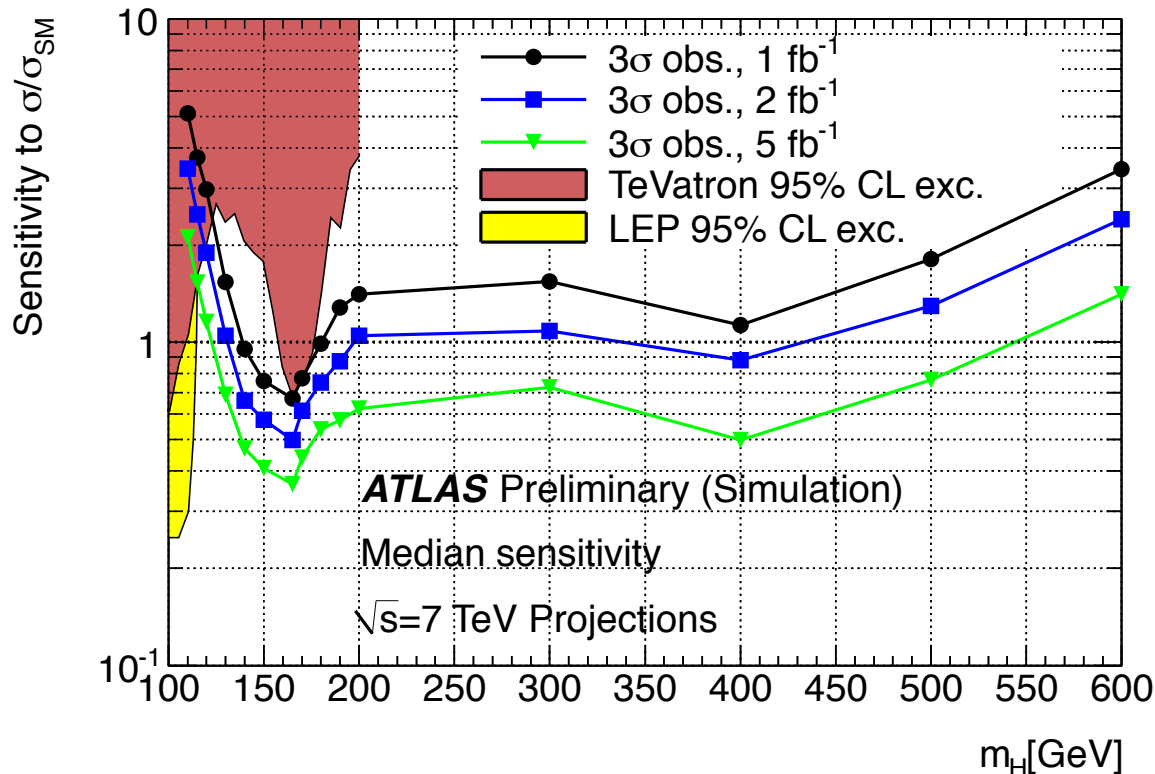


Further improvement
from combination of
ATLAS and CMS

Each doubling of luminosity can reduce lower limit by ~ 7 GeV

3σ Evidence Potential vs. Luminosity

ATLAS combination of all considered channels at 7 TeV with 1, 2, 5 fb^{-1} luminosity



Further improvement
from combination of
ATLAS and CMS

For 1 fb^{-1} , 3σ evidence possible for 139–180 GeV, for ATLAS & CMS → down to 131 GeV

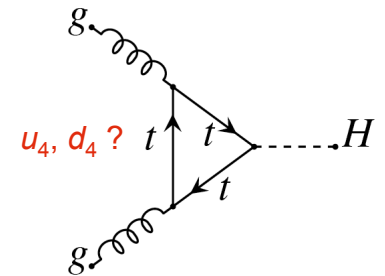
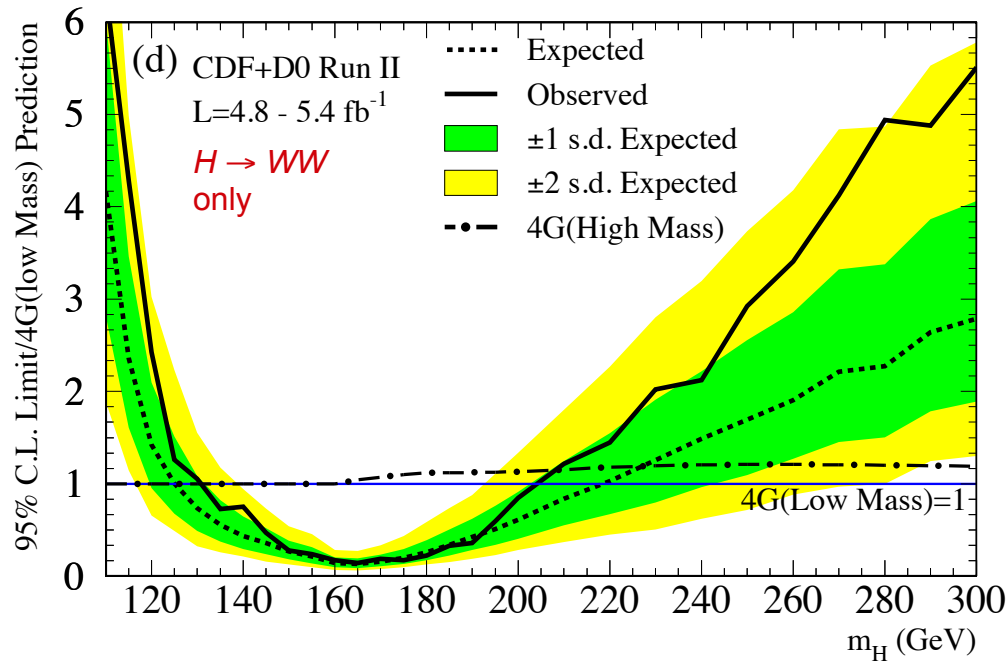
A 4th Generation?

Gluon fusion is very sensitive to additional heavy quarks, which do not decouple in the high-mass limit, and thus contribute $\sim$ as the top quark to the triangular anomaly

Exclusion found for a particular 4th generation model.

Tevatron data already exclude M_H between 131 and 204 GeV for 4th generation.

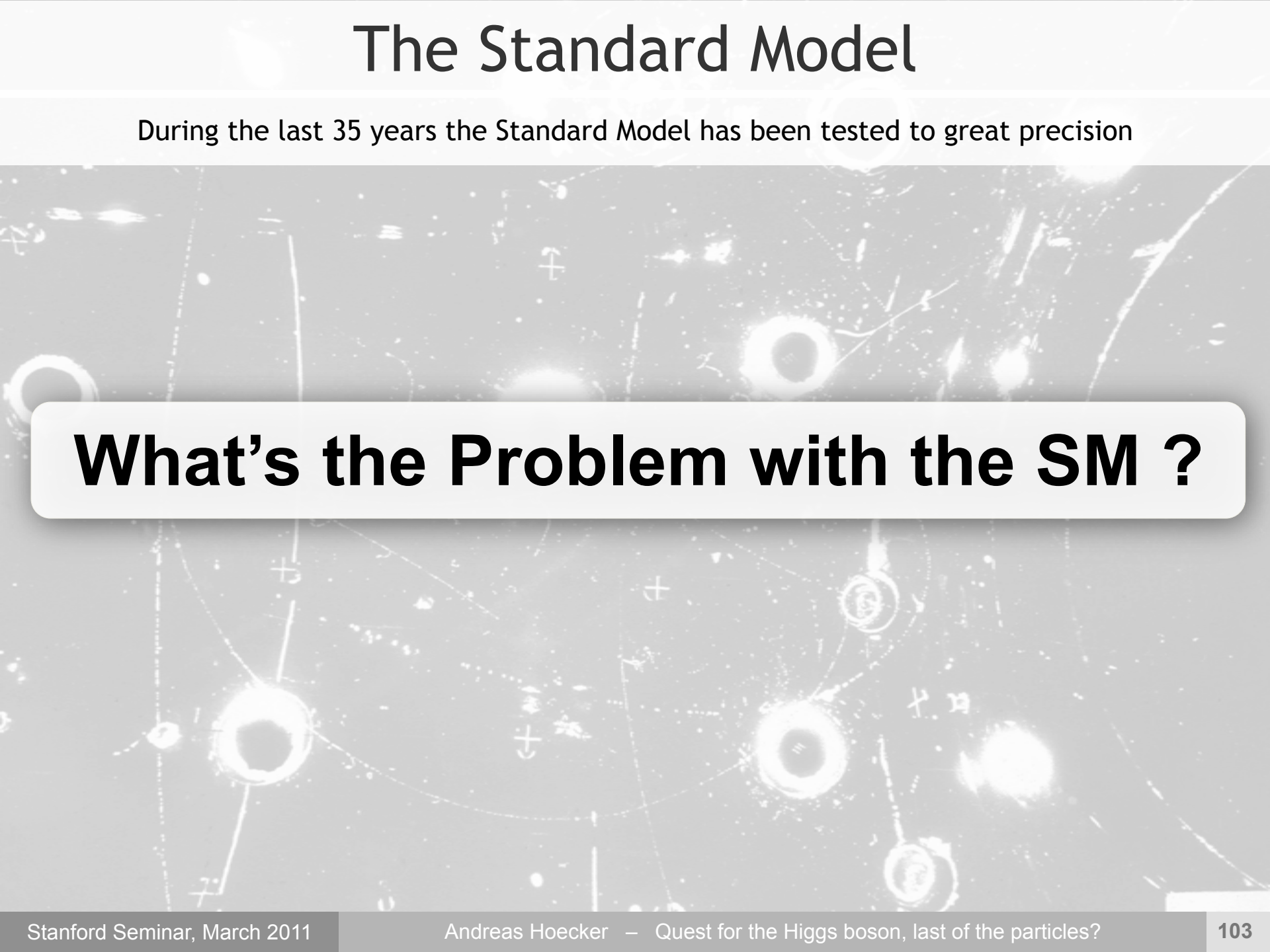
CDF & D0, arXiv: 1005.3216



4th generation:
K-factor of $\sim 3^2 = 9$
using sequential model

The Standard Model

During the last 35 years the Standard Model has been tested to great precision

A background image showing particle tracks, likely from a bubble chamber or cloud chamber, with various circular and linear patterns and small crosshair markers.

What's the Problem with the SM ?

The Problem is...

- The Higgs is not yet discovered !
- The Higgs is the only fundamental scalar
- What is the origin of the huge mass hierarchy between matter particles ?

... and:

- Dark matter and dark energy
- Baryogenesis and Leptogenesis (matter-antimatter asymmetry)
- Grand Unification of the forces (related to baryon decay)
- **The gauge hierarchy Problem...**
- The strong *CP* Problem (why is $\theta \sim 0$?)
- Neutrino masses
- Gravitation

The Mass of the Scalar is Unprotected

- If a Higgs boson with mass < 1 TeV is discovered, the Standard Model is complete !
- However, when computing radiative corrections to the bare Higgs mass a problem occurs:



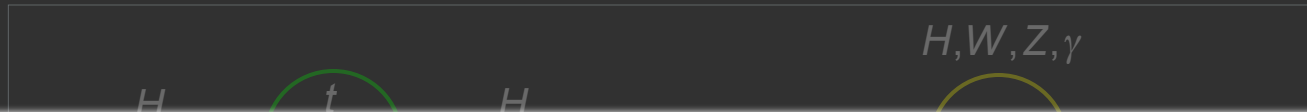
$$\Rightarrow m_H^2 = m_0^2 + \delta m_H^2 \quad \text{where:} \quad \delta m_H^2 \propto \underbrace{\int_0^\infty d^4k \frac{k^2 + m_f^2}{(k^2 + m_f^2)^2}}_{\text{Integral quadratically divergent}} + \dots$$

- The cut-off sets the scale where new particles and physical laws must come in
- Above the EW scale we only know of two scales: GUT ($\sim 10^{16}$ GeV) and Planck ($\sim 10^{19}$ GeV)
- Such a cut-off would require an incredible amount of finetuning to keep m_H light and stable

$$m_H^2 \stackrel{?}{=} (120 \text{ GeV})^2 = m_0^2 + C \cdot \Lambda_{\text{cut-off}}^2$$

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Missing protection of scalar Higgs mass is related to **absence of a symmetry principle**. Setting $m_H = 0$ in SM Lagrangian, **does not restore any symmetry in the model**.

New physics models should address this. In **Supersymmetry** for example fermionic and bosonic d.o.f. conspire to cancel loop divergences, when symmetry is exact

Other models, like the **Little Higgs**, interpret the Higgs as Goldstone boson of some approximate symmetry.

M_H becomes deviation from some exact symmetry, and is thus **intrinsically small** !

$$m_H^2 = (120 \text{ GeV})^2 = m_0^2 + C \cdot \Lambda_{\text{cut-off}}^2$$