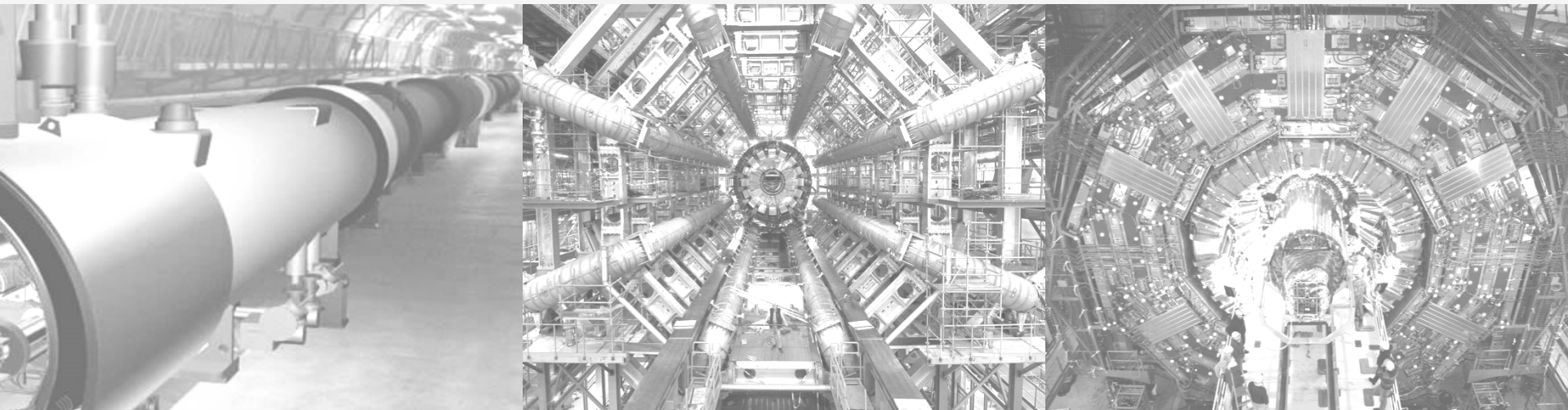


Quest for the Higgs Boson

Last Round LHC ?

Andreas Hoecker (CERN, ATLAS Collaboration)

Seminar, 5 March 2011, Stanford, CA



Seminar Themes

- 
- I. Higgs Mechanism
 - II. Indirect constraints on the Higgs boson mass
 - III. ATLAS and the LHC
 - IV. Higgs boson searches at the LEP, Tevatron and the LHC

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'
 - $SU(2)_L [W^+, W^0, W^-]$ couples to left-handed fermion doublets only
 - $U(1)_Y [B]$ couples to left and right-handed fermions
- 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...*

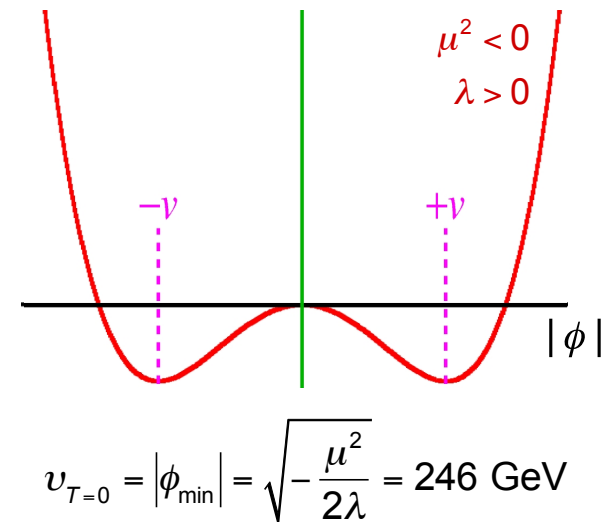
Potential $V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$, ϕ scalar field doublet

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 $\text{spin}=0$)

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

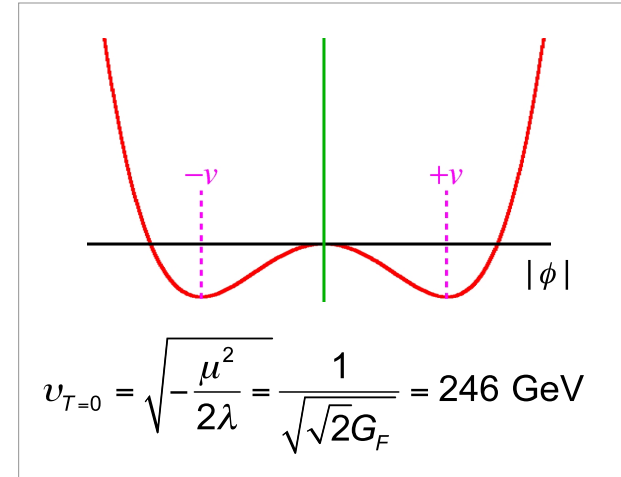
During the history of the big bang, the Higgs field must have appeared during a phase transition (the fermions and bosons were massless in the early unbroken phase of the universe)

“Viscosity” of the Vacuum

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

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

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

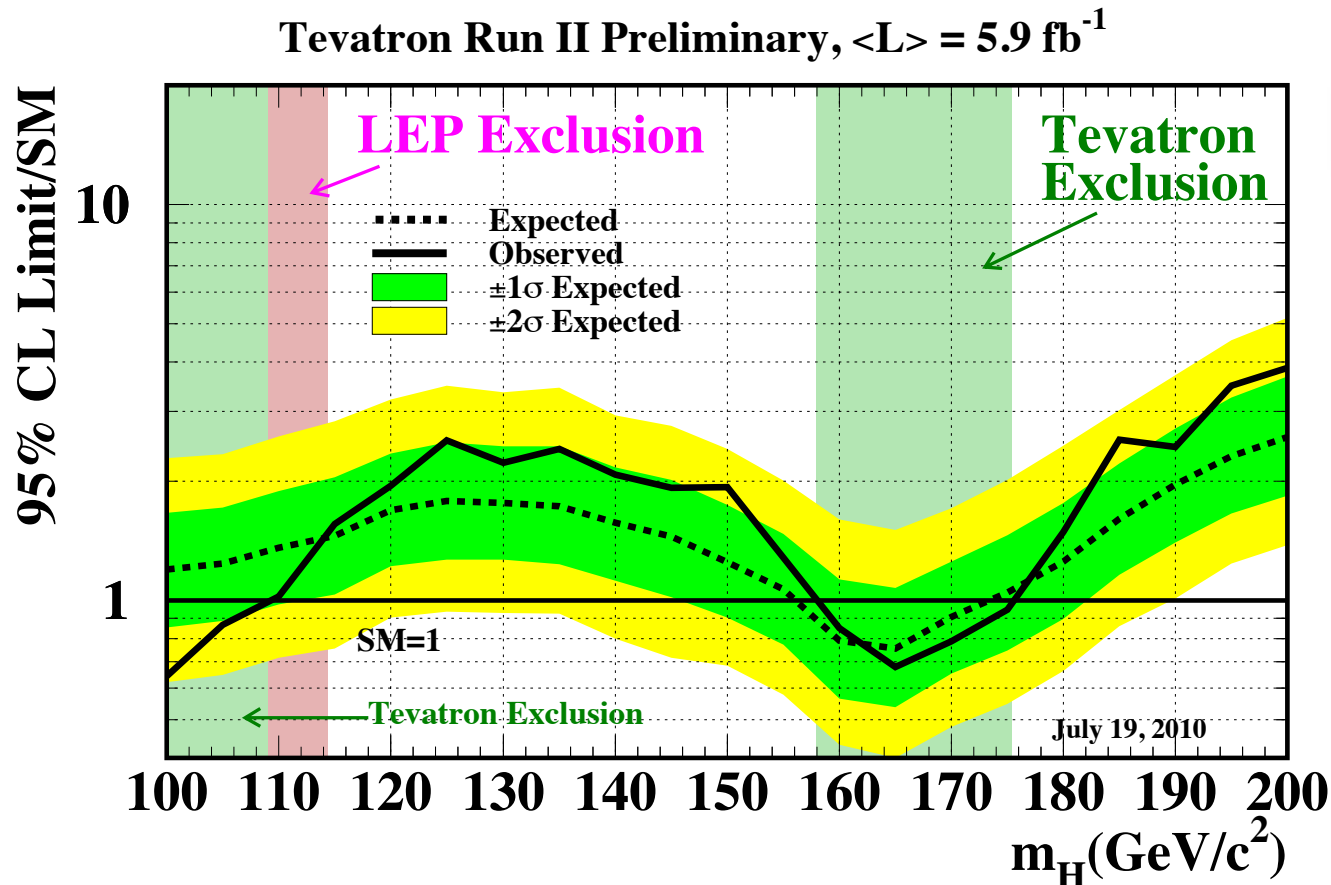
The Higgs boson is the last elusive elementary particle of the SM

The Higgs boson - last of the particles ?

What is known about the Higgs Boson ?

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

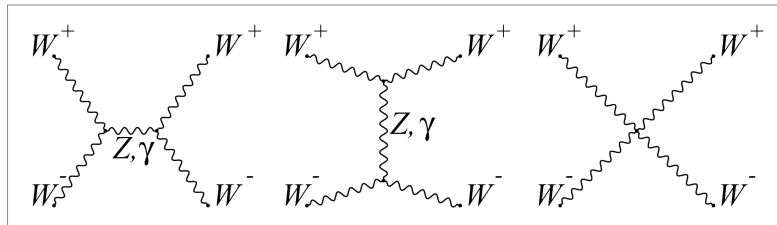
Direct Higgs searches at LEP and Tevatron have been unfruitful so far...



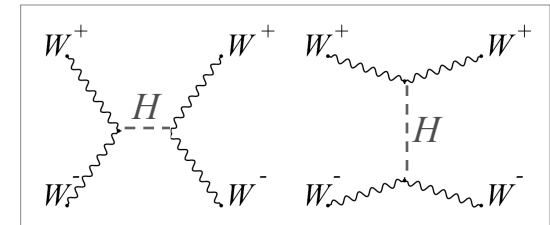
CDF & D0:
arXiv: 1007.4587

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

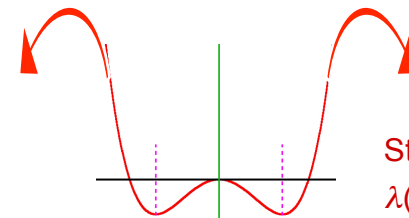
Landau pole decreases with increasing cut-off scale Λ to which the SM is considered to be valid

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

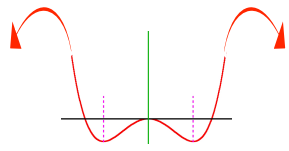
- Stability:** for a too light Higgs, top quark contributions can decrease λ and make it too small or negative

Critical M_H increases with SM cut-off scale Λ

Stability requirement sets lower limit on M_H



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



Vacuum Stability

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

- Requiring that the SM cannot develop a minimum deeper than the electroweak vacuum up to the Planck scale (i.e., $\lambda(\mu) > 0$, for all $\mu < \Lambda$) gives the **stability bound**:

$$M_H > 128.6 \text{ GeV} + 2.6 \text{ GeV} \cdot \left(\frac{m_t - 173.1 \text{ GeV}}{1.3 \text{ GeV}} \right) - 2.2 \text{ GeV} \cdot \left(\frac{\alpha_s(M_Z) - 0.1193}{0.0028} \right) \pm 1 \text{ GeV}$$

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.

→ Metastability (at zero, or finite temperature)

age of the universe, **stability bound**:

$$\left(\frac{\alpha_s(M_Z) - 0.1193}{0.0028} \right) \pm 3 \text{ GeV}$$

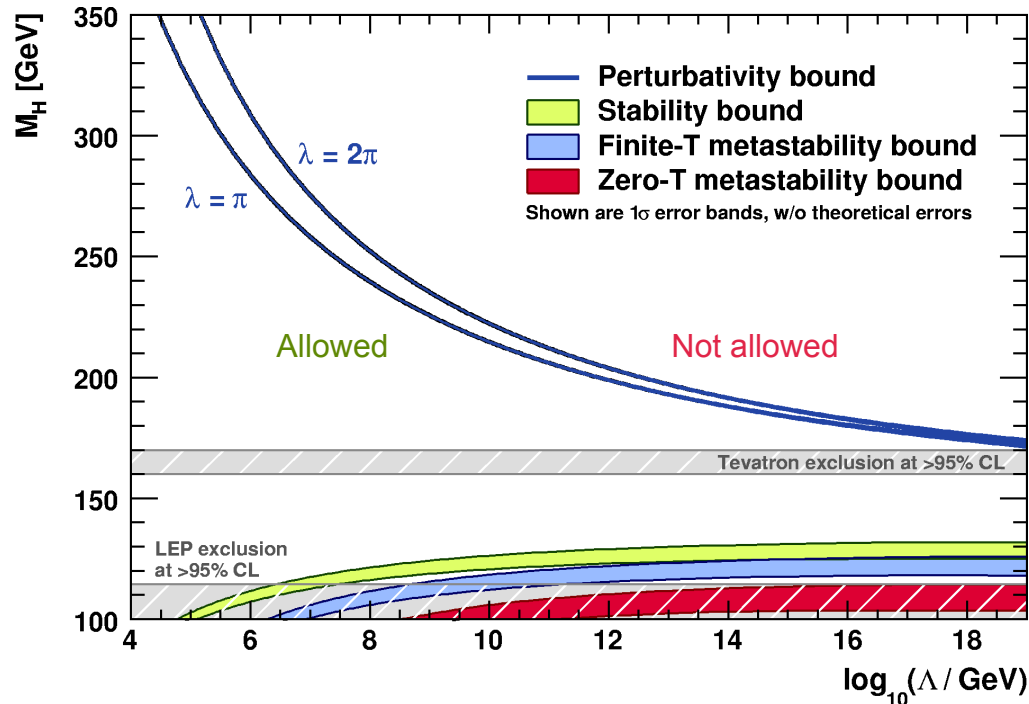
- Requiring the local SM minimum to be stable against thermal fluctuations up to temperatures as large as the Planck scale translates into **finite- T metastability bound**:

$$M_H > 122.0 \text{ GeV} + 3.0 \text{ GeV} \cdot \left(\frac{m_t - 173.1 \text{ GeV}}{1.3 \text{ GeV}} \right) - 2.3 \text{ GeV} \cdot \left(\frac{\alpha_s(M_Z) - 0.1193}{0.0028} \right) \pm 3 \text{ GeV}$$

Calculations based on NLO Higgs potential: J. Ellis et al., arXiv:0906.0954

Driving the SM to the Planck Scale

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

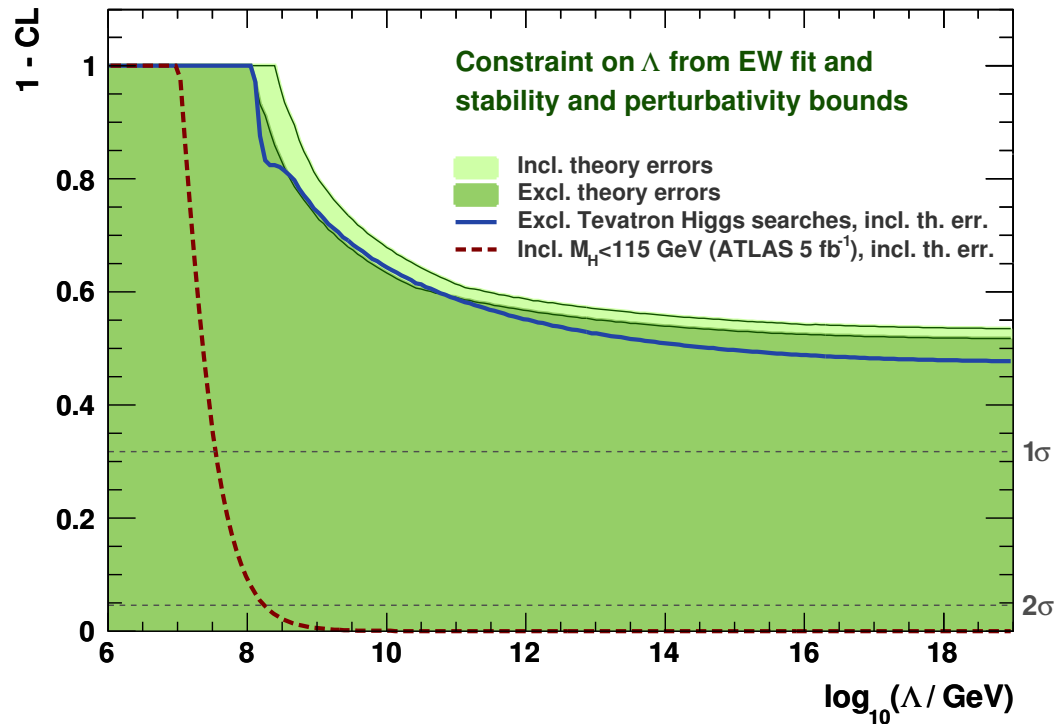


Figures use NLO Higgs potential. The widths of bands account for errors in α_s , m_t and theory.

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

Driving the SM to the Planck Scale

Limits on cut-off scale Λ when requiring absolute vacuum stability

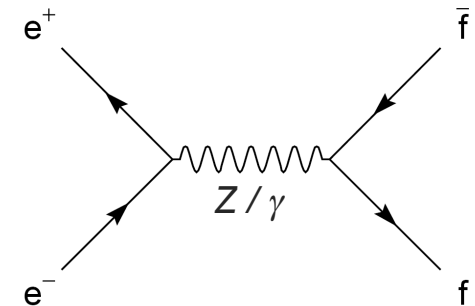
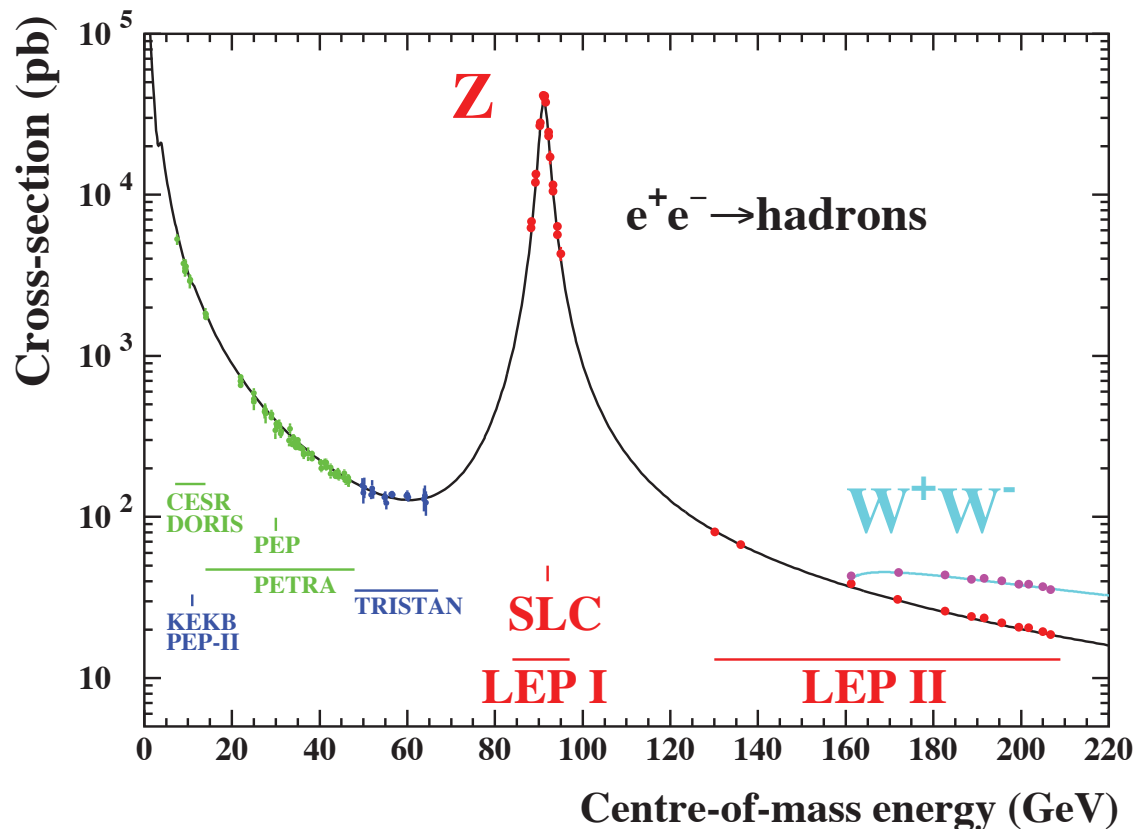


Figures use NLO Higgs potential. Theoretical errors from α_s , m_t uncertainties included.

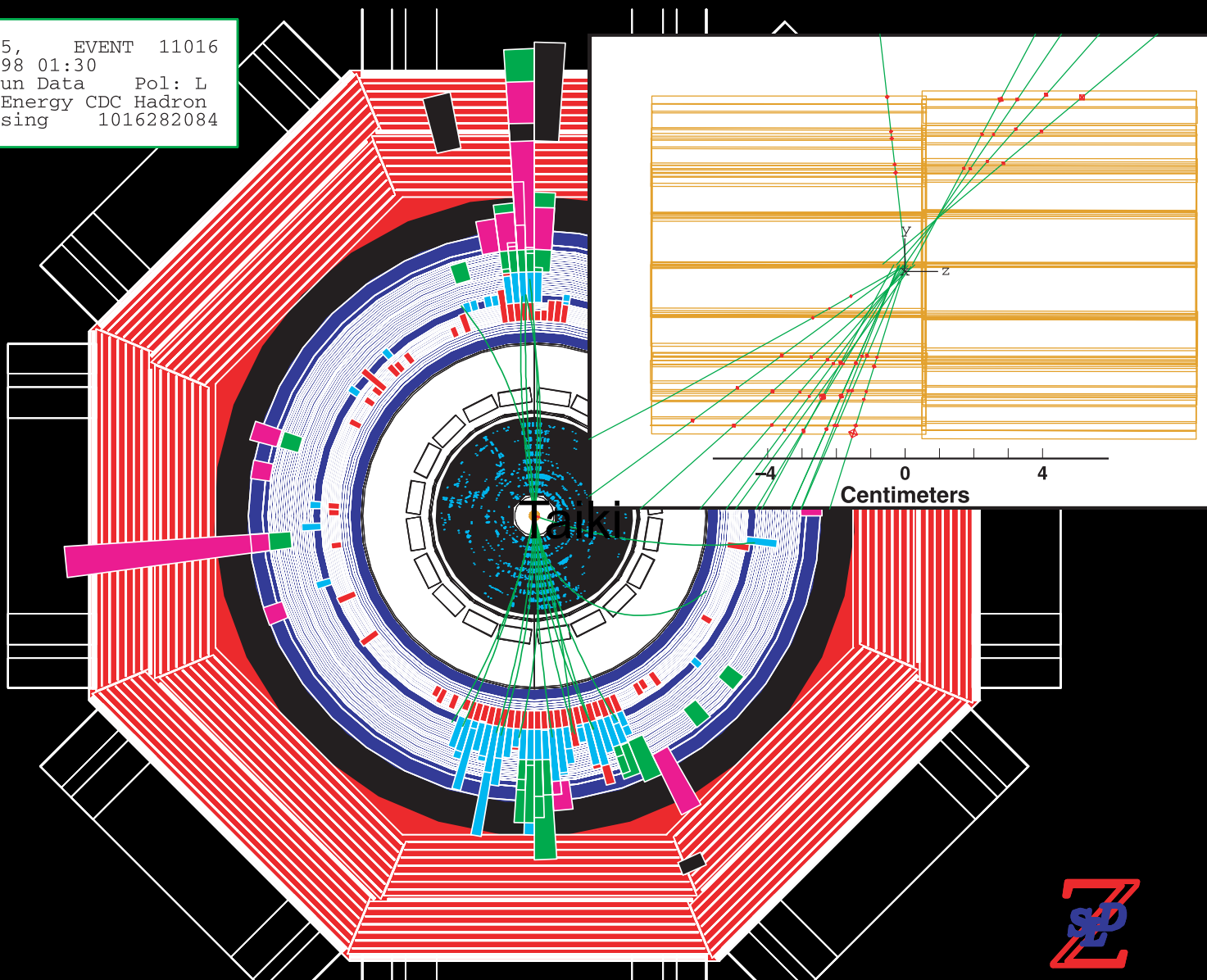
If an SM Higgs of 115 GeV is found, there must be new physics at around 10^9 GeV or the electroweak vacuum would be metastable

Constraints from EW Precision Data

Electroweak precision observables measured at the Z^0 resonance (LEP, SLC) and at the Tevatron can be used to constrain the Higgs boson mass



Run 42725, EVENT 11016
9-APR-1998 01:30
Source: Run Data Pol: L
Trigger: Energy CDC Hadron
Beam Crossing 1016282084



A $Z \rightarrow b\bar{b}$ event with displaced vertices seen in SLD

Electroweak Physics at the Z Pole

Radiative corrections – modifying propagators and vertices

Significance of radiative corrections
can be illustrated by verifying tree level
relation:

$$\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

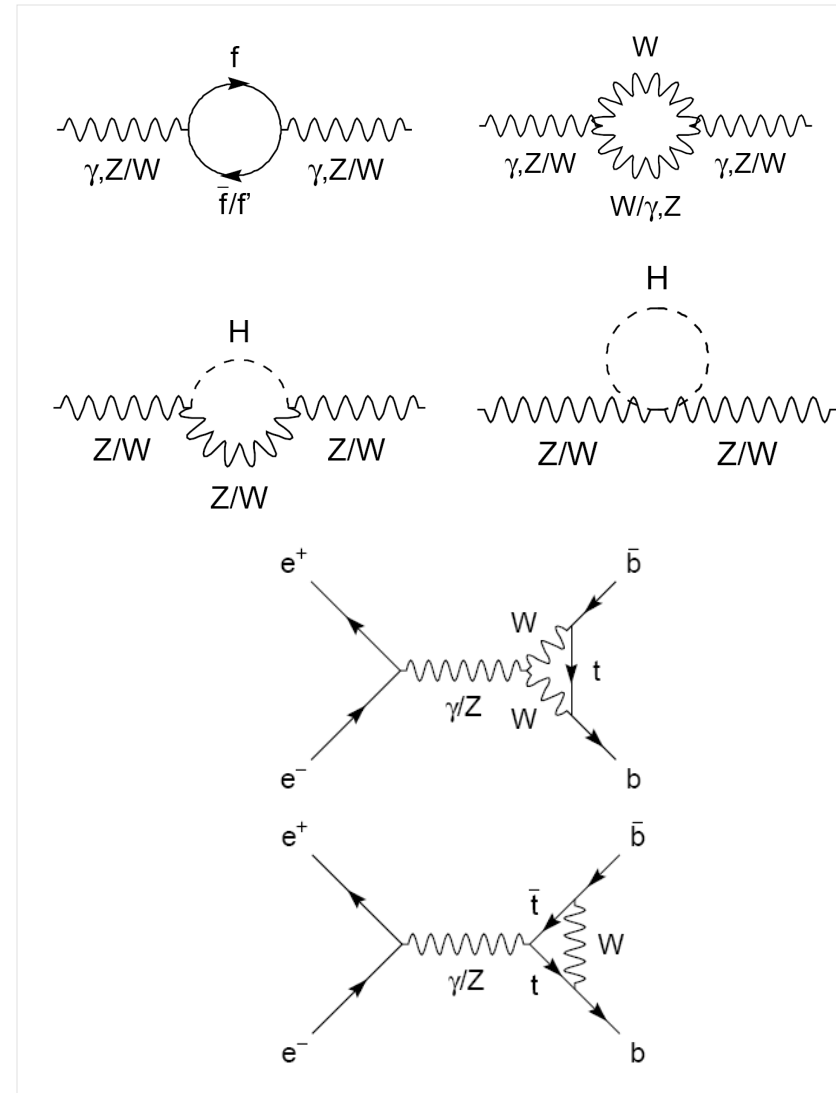
- Using the measurements:

$$M_W = (80.399 \pm 0.023) \text{ GeV}$$

$$M_Z = (91.1875 \pm 0.0021) \text{ GeV}$$

one predicts: $\sin^2 \theta_W = 0.22284 \pm 0.00045$

which is 18σ away from the experimental
value obtained by combining all asymmetry
measurements: $\sin^2 \theta_W = 0.23153 \pm 0.00016$



Electroweak Physics at the Z Pole

Radiative corrections – modifying propagators and vertices

Parametrisation of radiative corrections:
“electroweak form-factors”: ρ , κ , Δr

- Modified (“effective”) couplings at the Z pole:

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

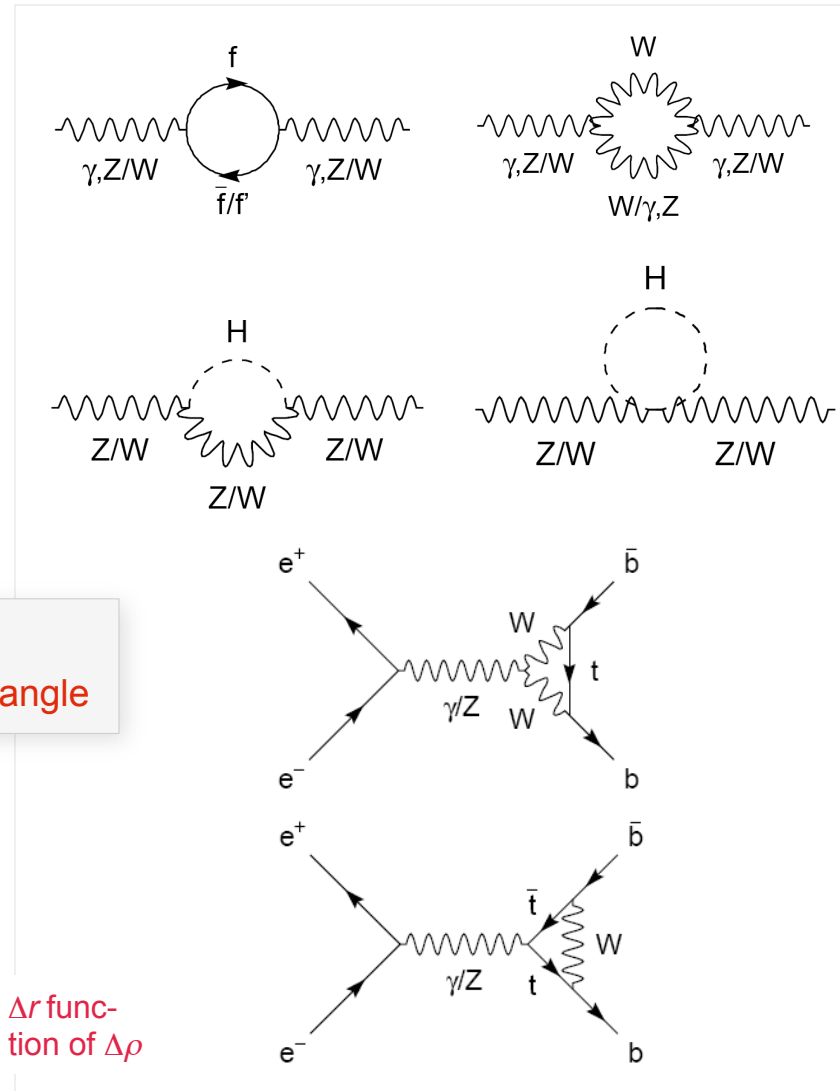
$$g_{A,f} = \sqrt{\rho_Z^f} I_3^f$$

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

ρ : overall scale
 κ : on-shell mixing angle

- Modified W mass:

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



Electroweak Physics at the Z Pole

Radiative corrections – modifying propagators and vertices

Leading order terms ($M_W \ll M_H$)

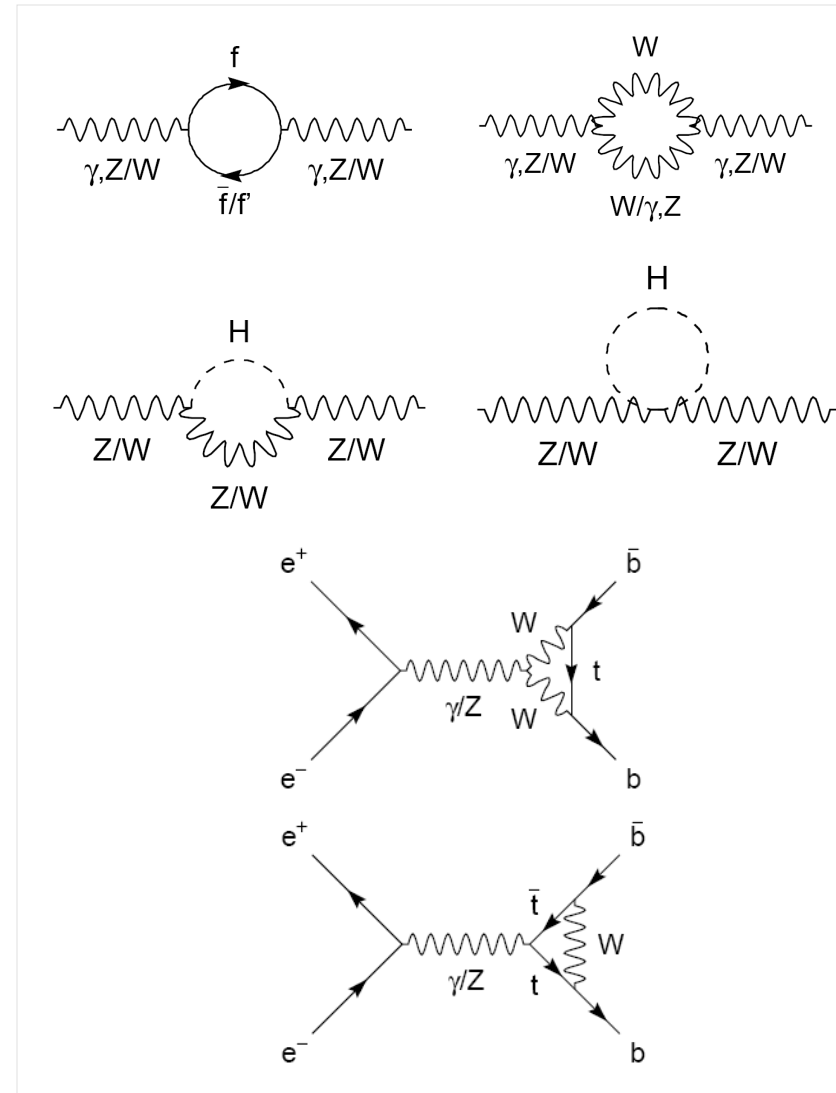
- ρ_Z and κ_Z can be split into sum of universal contributions from propagator self-energies:

$$\Delta\rho_Z = \frac{3G_F M_W^2}{8\sqrt{2}\pi^2} \left[\frac{m_t^2}{M_W^2} - \tan^2 \theta_W \left(\ln \frac{M_H^2}{M_W^2} - \frac{5}{6} \right) + \dots \right]$$

$$\Delta\kappa_Z = \frac{3G_F M_W^2}{8\sqrt{2}\pi^2} \left[\frac{m_t^2}{M_W^2} \cot^2 \theta_W - \frac{10}{9} \left(\ln \frac{M_H^2}{M_W^2} - \frac{5}{6} \right) + \dots \right]$$

- and flavour-specific vertex corrections, which are very small, except for top quarks, owing to large mass and $|V_{tb}|$ CKM element

$$\Delta\rho^f = -2\Delta\kappa^f = -\frac{G_F m_t^2}{2\sqrt{2}\pi^2} + \dots$$



Electroweak Physics at the Z Pole

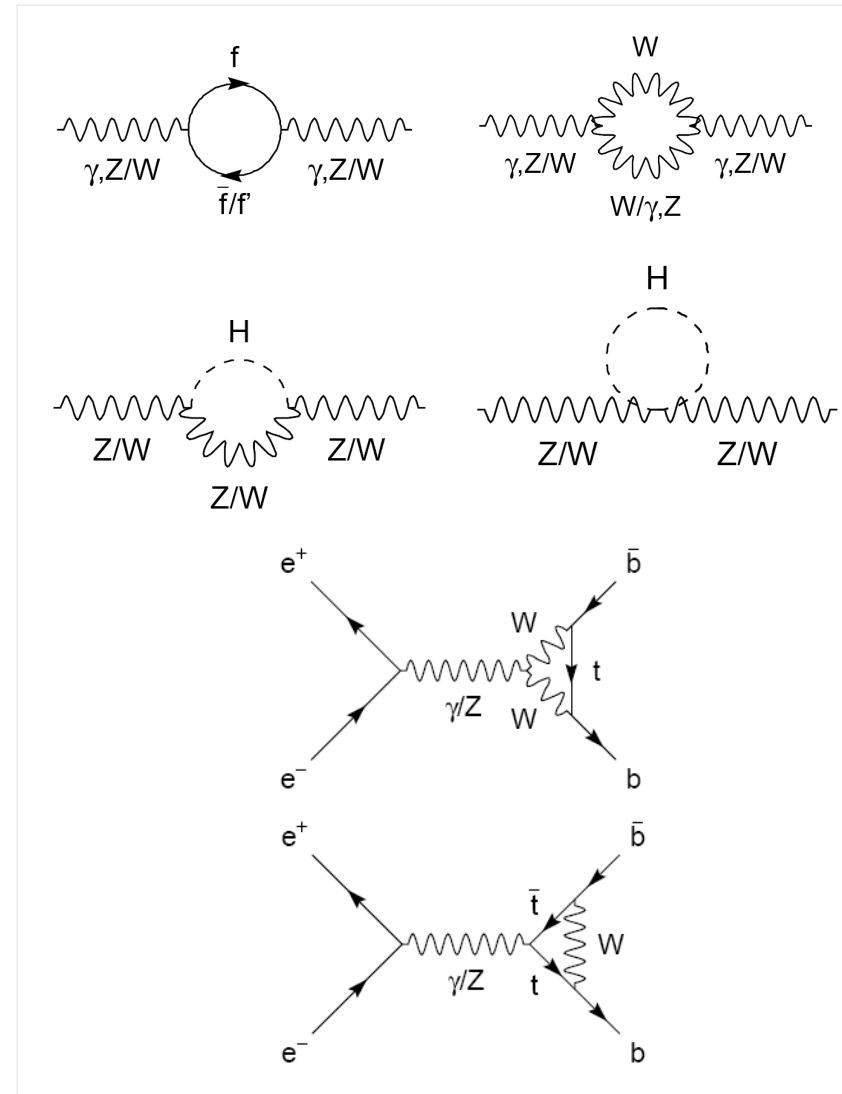
Radiative corrections – modifying propagators and vertices

Leading order terms ($M_H \ll M_W$)

Radiative corrections
allow us to test the SM
and to constrain unknown
SM parameters

- ρ_Z and κ_Z can be split into sum of universal contributions from propagator self-energies:
- and flavour-specific vertex corrections, which are very small, except for top quarks, due to large $|V_{tb}|$ CKM element

$$\Delta\rho^f = -2\Delta\kappa^f = -\frac{G_F m_t^2}{2\sqrt{2}\pi^2} + \dots$$



Observables in the Global Fit

Experimental results:

- **Z-pole observables:** LEP/SLD results (corrected for ISR/FSR QED effects)
[ADLO & SLD, Phys. Rept. 427, 257 (2006)]
 - **Total and partial cross sections** around Z: M_Z , Γ_Z , σ_{had}^0 , R_l^0 , R_c^0 , R_b^0
Sensitive to the total coupling strength of the Z to fermions
 - **Asymmetries** on the Z pole: $A_{\text{FB}}^{0,l}$, $A_{\text{FB}}^{0,b}$, $A_{\text{FB}}^{0,c}$, A_l , A_c , A_b , $\sin^2\theta_{\text{eff}}^l(Q_{\text{FB}})$
Sensitive to the ratio of the Z vector to axial-vector couplings (i.e. $\sin^2\theta_{\text{eff}} \rightarrow$ parity violation)
- M_W and Γ_W : LEP + Tevatron average
[ADLO, hep-ex/0612034] [CDF, Phys. Lett. 100, 071801 (2008)]
[CDF & D0, Phys. Rev. D 70, 092008 (2004)] [CDF & D0, arXiv:0908.1374v1]
- m_t : latest Tevatron average [CDF & D0, new combination for ICHEP 2010, arXiv:1007.3178]
- $\bar{m}_c$, $\bar{m}_b$: world averages [PDG, Phys. Lett. B667, 1 (2008) and 2009 partial update for the 2010 edition]
- $\Delta\alpha_{\text{had}}(M_Z)$: [DHMZ arXiv:1010.4180 (2010)] + rescaling mechanism to account for α_s dependency
- **Direct Higgs searches** at LEP and Tevatron (ICHEP 2010 average)
[ADLO: Phys. Lett. B565, 61 (2003)] [CDF & D0: arXiv:1007.4587 (2010)]

The Global Electroweak Fit

Theory predictions – state-of-the art calculations, in particular:

- M_W and $\sin^2\theta_{\text{eff}}^f$: full two-loop + leading beyond-two-loop form factor corrections
[M. Awramik et al., Phys. Rev D69, 053006 (2004) and ref.] [M. Awramik et al., JHEP 11, 048 (2006) and refs.]
- **Radiator functions**: 3NLO prediction of the massless QCD cross section
[P.A. Baikov et al., Phys. Rev. Lett. 101 (2008) 012022]
- **Theoretical uncertainties**: M_W ($\delta_{\text{theo}}(M_H) = 4\text{--}6 \text{ MeV}$), $\sin^2\theta_{\text{eff}}^l$ ($\delta_{\text{theo}} = 4.7 \cdot 10^{-5}$)

Fit parameters

- In principle, **all parameters used in theory predictions are varying freely in fit**
- Masses of leptons and light quarks fixed to world-averages from PDG
- Free are running charm, bottom and top masses $\rightarrow m_t$ strongest impact on fit !



List of freely varying parameters in the SM fit:

$$\Delta\alpha_{\text{had}}^{(5)}(M_Z), \alpha_S(M_Z), M_Z, M_H, \bar{m}_c, \bar{m}_b, m_t$$

Parameter	Input value	Free in fit	Results from global EW fits:		<i>Complete fit w/o exp. input in line</i>
			<i>Standard fit</i>	<i>Complete fit</i>	
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1874 ± 0.0021	91.1877 ± 0.0021	$91.1942^{+0.0168}_{-0.0114}$
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4960 ± 0.0015	$2.4956^{+0.0015}_{-0.0014}$	$2.4952^{+0.0014}_{-0.0016}$
σ_{had}^0 [nb]	41.540 ± 0.037	–	41.478 ± 0.014	41.478 ± 0.014	41.469 ± 0.015
R_ℓ^0	20.767 ± 0.025	–	20.742 ± 0.018	$20.741^{+0.018}_{-0.017}$	20.718 ± 0.026
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010	–	0.01641 ± 0.0002	$0.01625^{+0.0002}_{-0.0001}$	$0.01624^{+0.0002}_{-0.0001}$
$A_\ell^{(*)}$	0.1499 ± 0.0018	–	0.1479 ± 0.0010	$0.1472^{+0.0010}_{-0.0006}$	–
A_c	0.670 ± 0.027	–	$0.6683^{+0.00044}_{-0.00043}$	$0.6680^{+0.00042}_{-0.00027}$	$0.6679^{+0.00039}_{-0.00022}$
A_b	0.923 ± 0.020	–	0.93469 ± 0.00009	$0.93466^{+0.00005}_{-0.00008}$	$0.93466^{+0.00005}_{-0.00009}$
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035	–	0.0741 ± 0.0005	$0.0738^{+0.0005}_{-0.0003}$	0.0739 ± 0.0004
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016	–	0.1037 ± 0.0007	$0.1032^{+0.0007}_{-0.0004}$	$0.1036^{+0.0005}_{-0.0004}$
R_c^0	0.1721 ± 0.0030	–	0.17225 ± 0.00006	0.17225 ± 0.00006	0.17225 ± 0.00006
R_b^0	0.21629 ± 0.00066	–	$0.21578^{+0.00005}_{-0.00008}$	$0.21576^{+0.00007}_{-0.00008}$	$0.21577^{+0.00005}_{-0.00008}$
$\sin^2\theta_{\text{eff}}^\ell(Q_{\text{FB}})$	0.2324 ± 0.0012	–	0.23141 ± 0.00012	$0.23150^{+0.00007}_{-0.00013}$	$0.23149^{+0.00008}_{-0.00011}$
M_H [GeV] ^(o)	Confidence levels	yes	$95.7^{+30.6[+75.8]}_{-24.2[-43.7]}$	$120.2^{+18.1[+35.1]}_{-4.7[-5.8]}$	$95.7^{+30.6[+75.8]}_{-24.2[-43.7]}$
M_W [GeV]	80.399 ± 0.023	–	$80.382^{+0.014}_{-0.015}$	80.370 ± 0.008	$80.360^{+0.016}_{-0.018}$
Γ_W [GeV]	2.085 ± 0.042	–	2.092 ± 0.001	2.092 ± 0.001	2.092 ± 0.001
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.16}_{-0.07}$	$4.20^{+0.16}_{-0.07}$	–
m_t [GeV]	173.3 ± 1.1	yes	173.4 ± 1.1	173.7 ± 1.0	$177.4^{+11.8}_{-3.5}$
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)^{(\dagger\Delta)}$	2749 ± 10	yes	2750 ± 10	2748 ± 10	2729^{+39}_{-55}
$\alpha_s(M_Z^2)$	–	yes	$0.1192^{+0.0028}_{-0.0027}$	$0.1193^{+0.0028}_{-0.0027}$	$0.1193^{+0.0028}_{-0.0027}$
$\delta_{\text{th}} M_W$ [MeV]	$[-4, 4]_{\text{theo}}$	yes	4	4	–
$\delta_{\text{th}} \sin^2\theta_{\text{eff}}^\ell^{(\dagger)}$	$[-4.7, 4.7]_{\text{theo}}$	yes	4.7	4.7	–
$\delta_{\text{th}} \rho_Z^f^{(\dagger)}$	$[-2, 2]_{\text{theo}}$	yes	2	2	–
$\delta_{\text{th}} \kappa_Z^f^{(\dagger)}$	$[-2, 2]_{\text{theo}}$	yes	2	2	–

Higgs Mass Constraints

M_H from *Standard fit*:

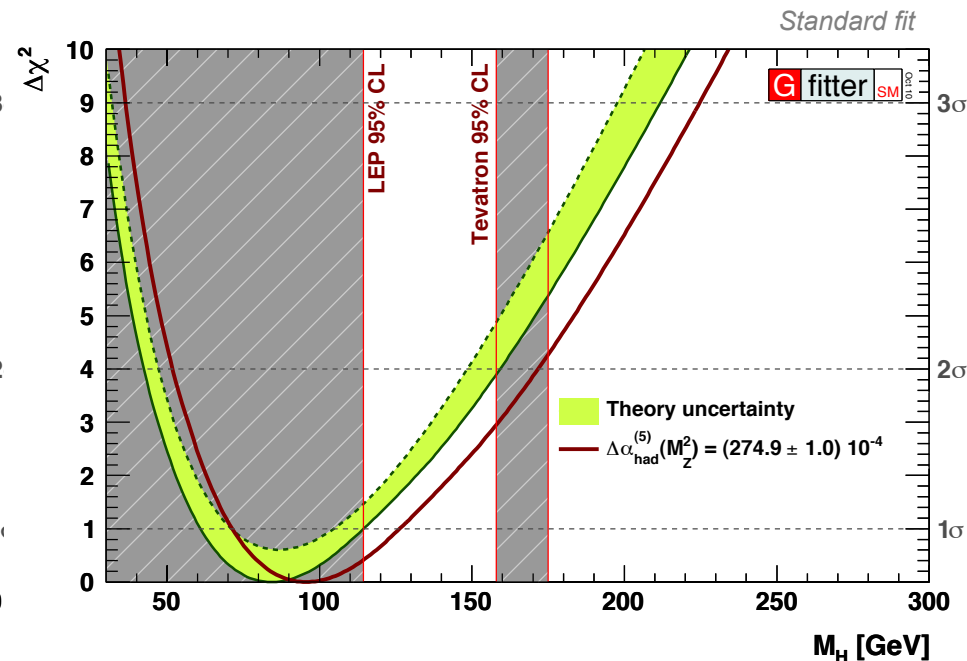
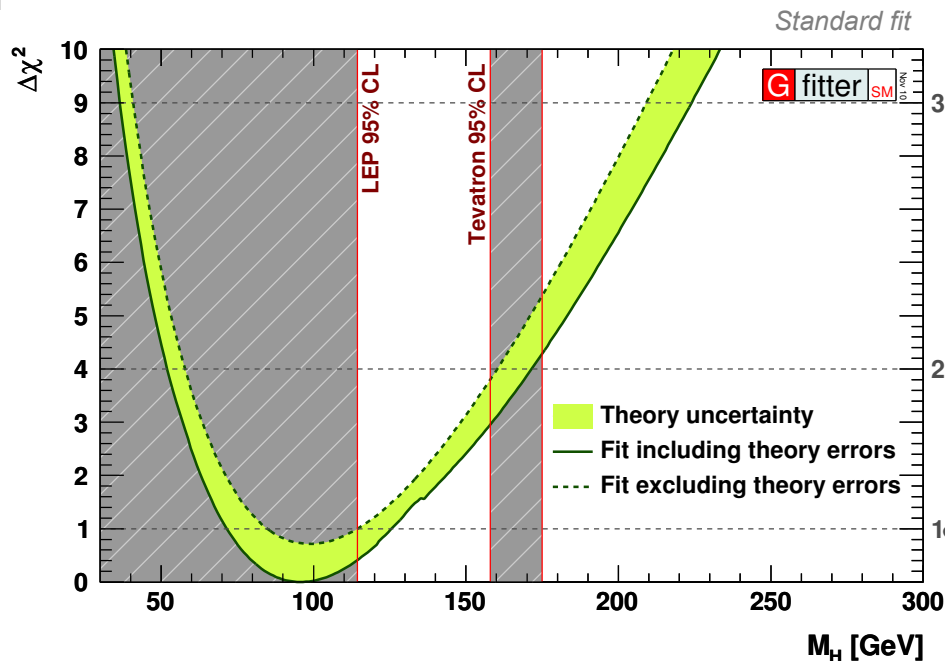
- Central value $\pm 1\sigma$: $M_H = 96^{+30}_{-25}$ GeV
- 95% CL upper limit: 170 GeV

Green band due to *Rfit* treatment of theory errors, fixed errors lead to larger $\chi^2_{\min}$

M_H from *old Standard fit*:

- Central value $\pm 1\sigma$: $M_H = 90^{+30}_{-24}$ GeV
- 95% CL upper limit: 164 GeV

Illustrate effect from new $\Delta\alpha_{\text{had}}$ precision determination (reduced EM coupling !)



Oblique Corrections

At low energies, BSM physics appears dominantly through vacuum polarisation

- Aka, *oblique corrections*

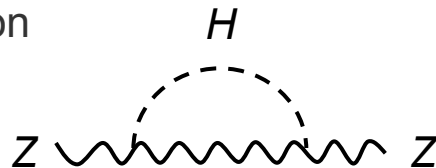
$$\begin{array}{c} \mu \\ \text{---} \end{array} \text{---} \text{---} \begin{array}{c} \nu \\ \text{---} \end{array} = i\Pi_{AB=\{W,Z,\gamma\}}^{\mu\nu}(q)$$

- Direct corrections (vertex, box, bremsstrahlung) generally suppressed by m_f / Λ

Oblique corrections reabsorbed into electroweak parameters $\Delta\rho$, $\Delta\kappa$, Δr

Electroweak fit sensitive to BSM physics through oblique corrections

- In direct competition with Higgs loop corrections



- Oblique corrections from New Physics described through **STU parameters**

[Peskin-Takeuchi, Phys. Rev. D46, 381 (1992)]

$$O_{\text{meas}} = O_{\text{SM,ref}}(M_H, m_t) + c_S \mathbf{S} + c_T \mathbf{T} + c_U \mathbf{U}$$

- S**: (**S+U**) New Physics contributions to **neutral (charged) currents**
- T**: Difference between neutral and charged current processes – sensitive to **weak isospin violation**
- U**: Constrained by M_W and Γ_W . Usually very small in NP models (often: $U=0$)

The Oblique Parameters in the Standard Model

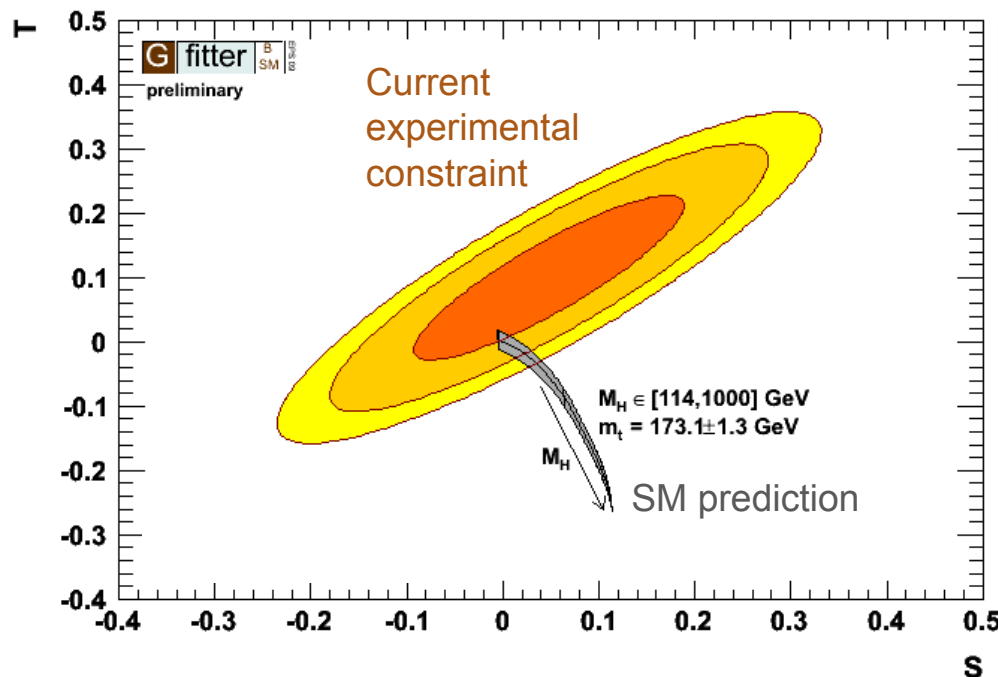
STU references in SM obtained from fit to EW observables

- SM_{ref} chosen at:
 $M_H = 120 \text{ GeV}$ and $m_t = 173.1 \text{ GeV}$
- This defines $(S, T, U) = (0, 0, 0)$



Results from S, T, U fit to all the EW observables:

$S = 0.02 \pm 0.11$		S	T	U
$T = 0.05 \pm 0.12$	S	1	0.88	-0.47
$U = 0.07 \pm 0.12$	T		1	-0.72
	U			1



S, T depend logarithmically on M_H

Preference for low M_H values

Accommodate large M_H values by shifting T (S) positive (negative)

Fourth (sequential) Fermion Generation

Introduce new lepton and quark states

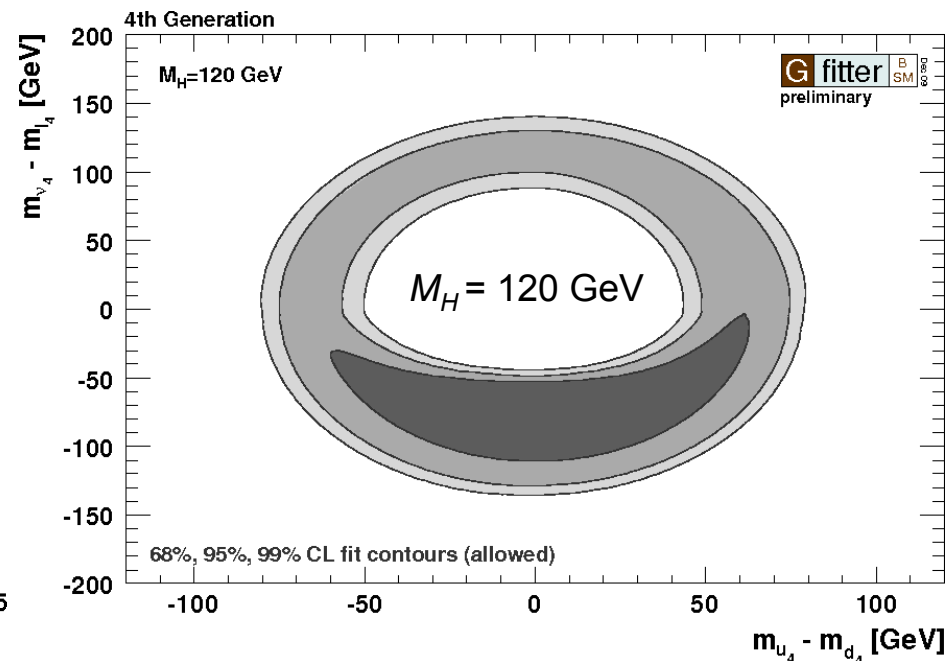
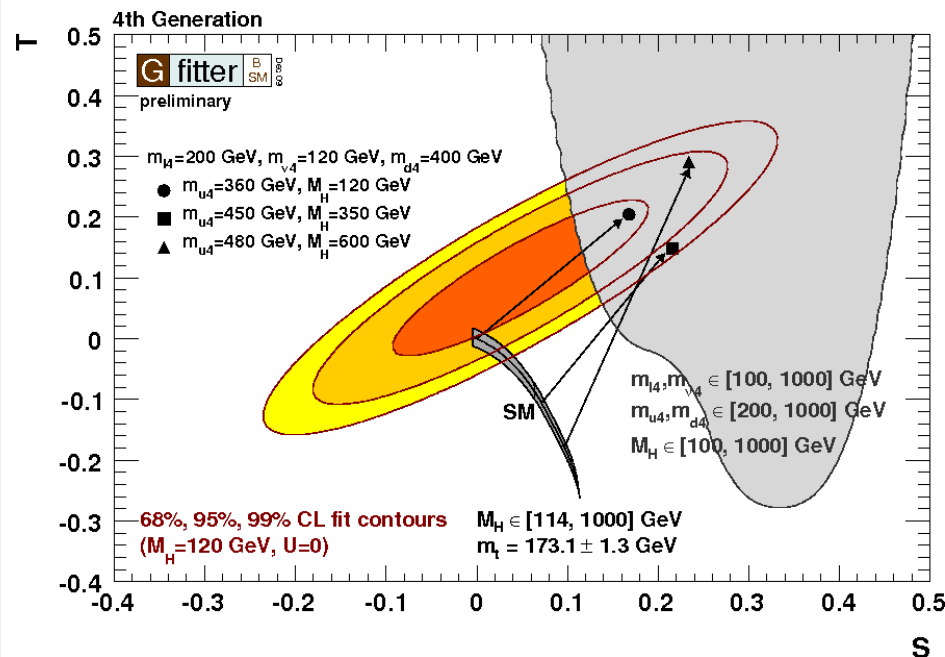
Free parameters: m_{u_4} , m_{d_4} , m_{e_4} , m_{ν_4}

– Assume: no mixing of extra fermions

- Shift $\Delta S \approx 0.21$ from heavy generation
- Sensitive to mass difference between up- and down-type fields (not to absolute mass scale)

Results:

- With appropriate mass differences: fourth fermion model consistent with EW data
 - In particular a large M_H is allowed
- 5+ generations disfavored



Fourth (sequential) Fermion Generation

Introduce new lepton and quark states

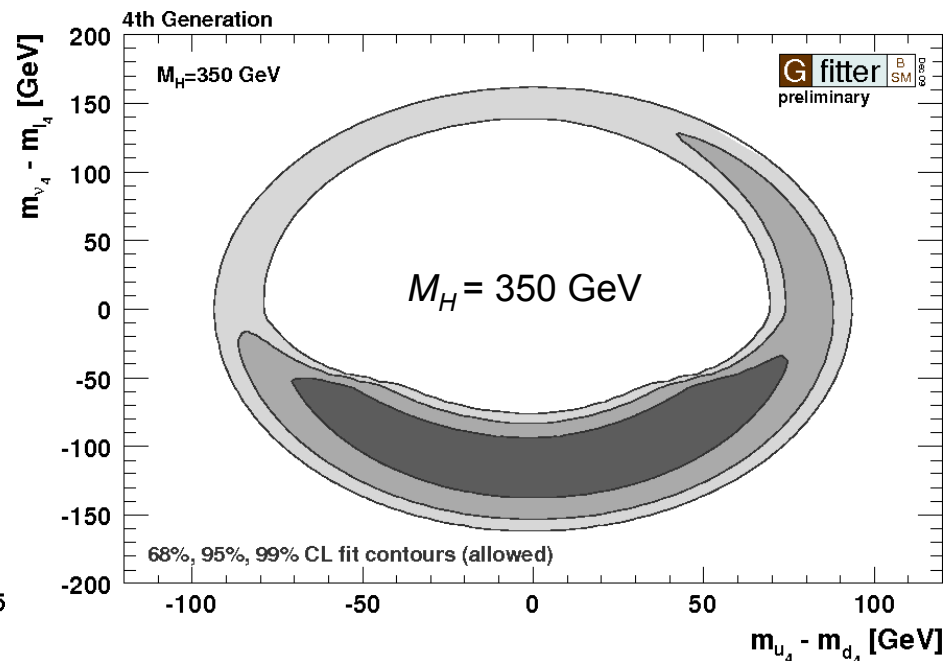
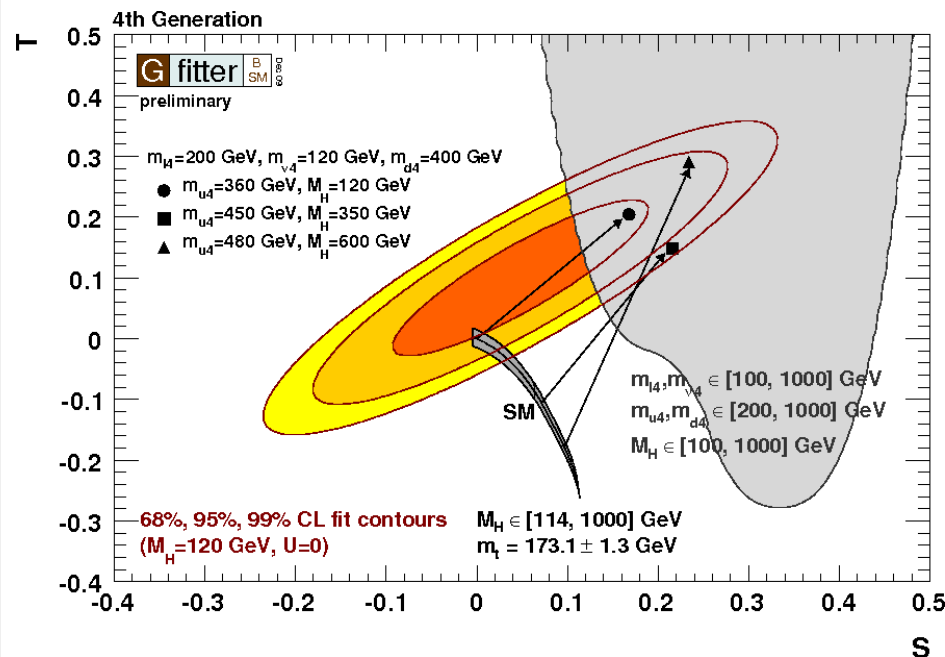
Free parameters: m_{u_4} , m_{d_4} , m_{e_4} , m_{ν_4}

– Assume: no mixing of extra fermions

- Shift $\Delta S \approx 0.21$ from heavy generation
- Sensitive to mass difference between up- and down-type fields (not to absolute mass scale)

Results:

- With appropriate mass differences: fourth fermion model consistent with EW data
 - In particular a large M_H is allowed
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Fourth (sequential) Fermion Generation

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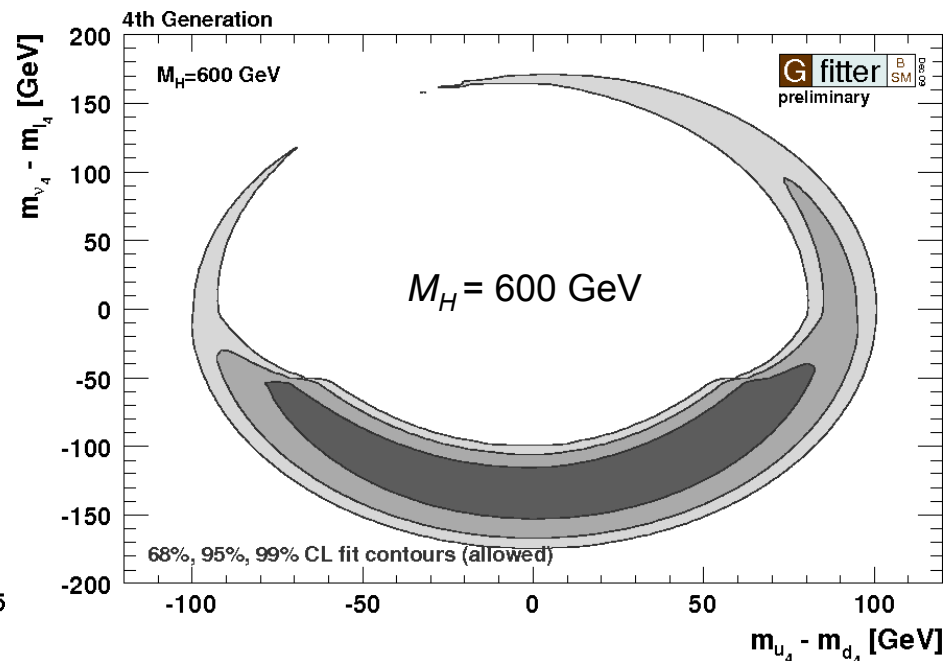
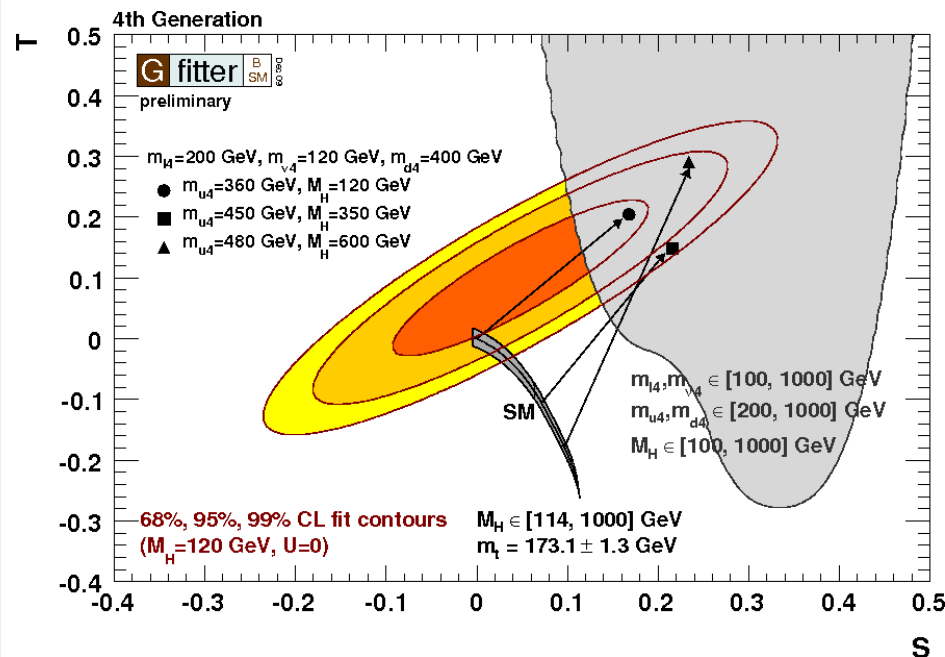
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Fourth (sequential) Fermion Generation

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Results:

- With appropriate mass differences: fourth fermion model consistent with EW data
 - In particular a large M_H is allowed
- 5+ generations disfavored

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

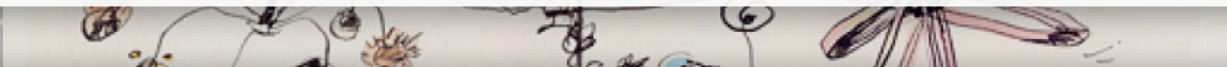
BUT: Beyond the Standard Model the Higgs can be heavy !

→ MUST NOT stop searching for heavy Higgs boson !

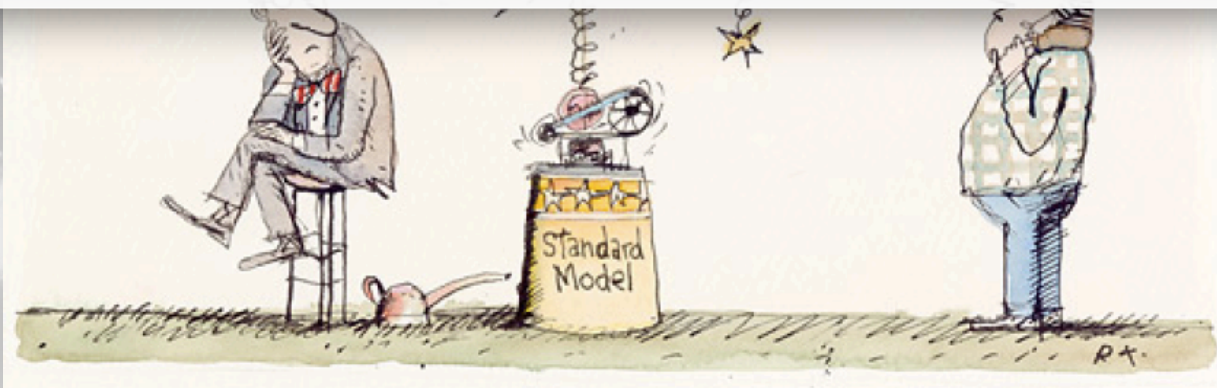
[Weak isospin violating new physics contributions may cancel heavy Higgs effects on electroweak precision data !]



Once the Higgs boson is discovered
The Standard Model is complete



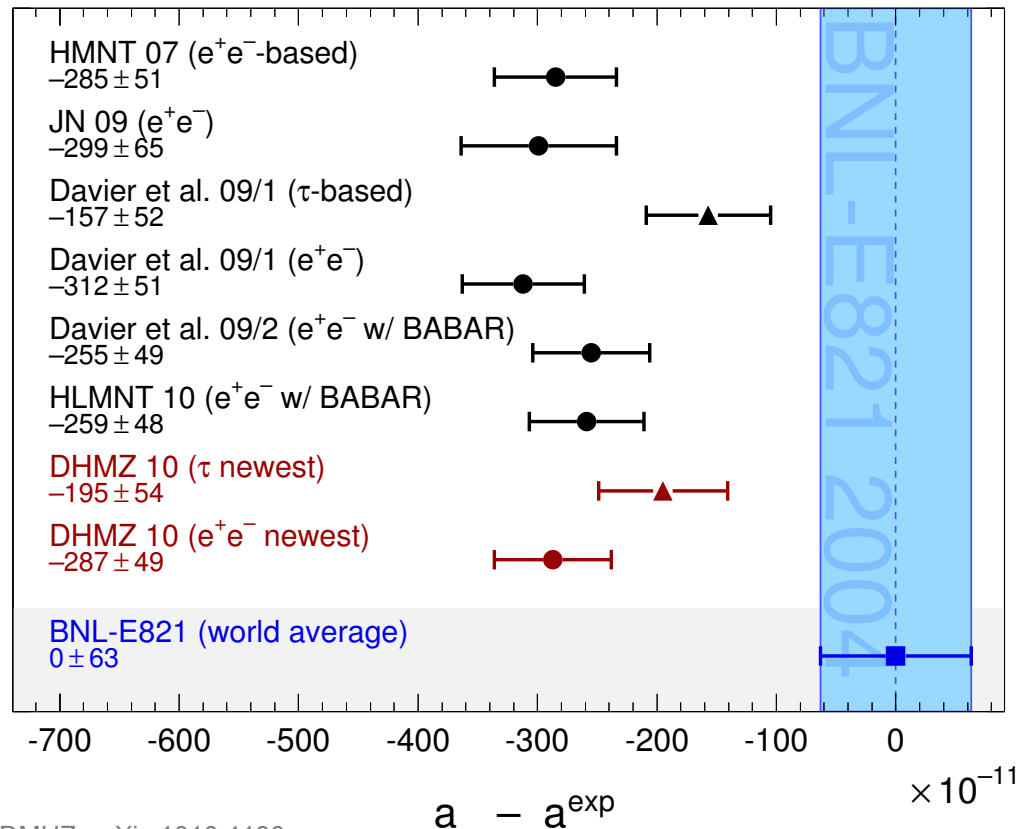
But ... does it hold tight ?



It does !

- 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 (*all ?*)
- 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 ...*

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



DMHZ, arXiv:1010.4180

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

... but some tension exists ...

A black and white photograph of a particle detector, likely a bubble chamber, showing various tracks and interaction points. Several bright, circular spots are visible, some with concentric rings, indicating particle collisions or decays. Faint lines and dots trace paths across the image, representing the movement of ionizing particles. The overall image has a grainy, high-contrast appearance typical of older scientific photography.

Let's find that Higgs boson !

CERN, the LHC and ATLAS

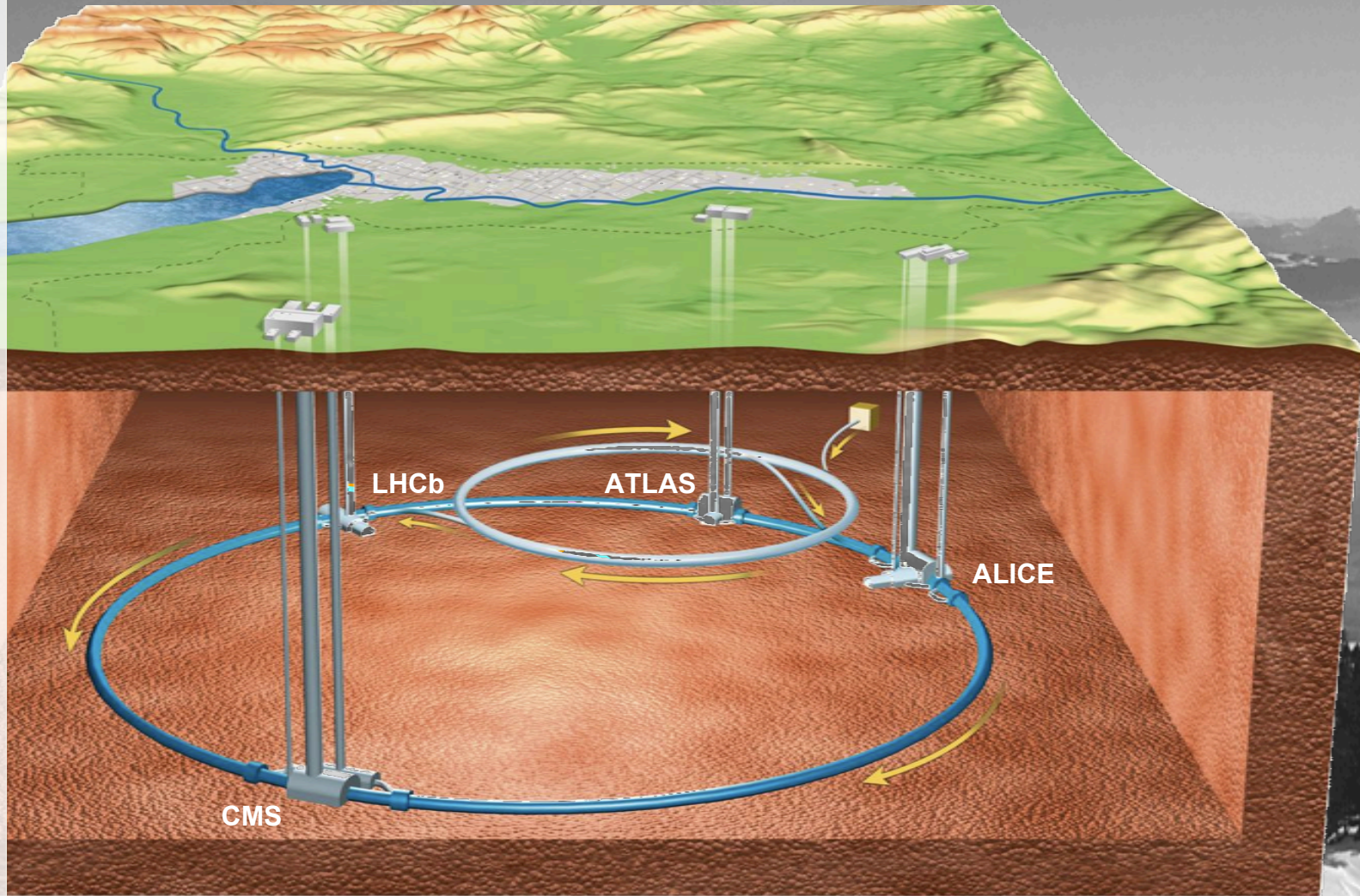
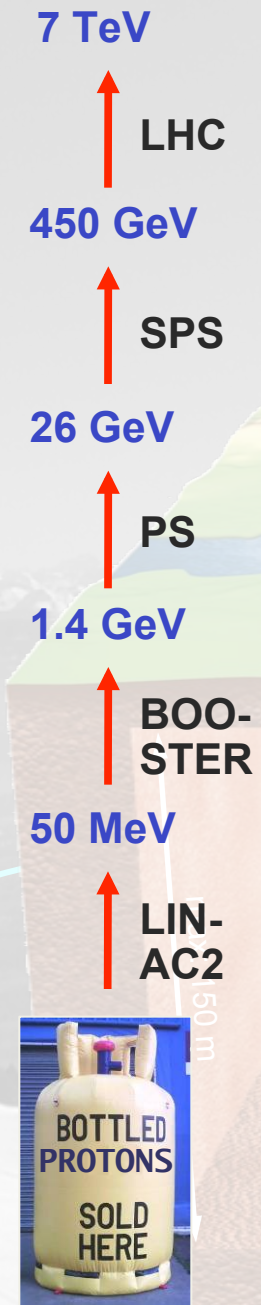
Experimental Challenges



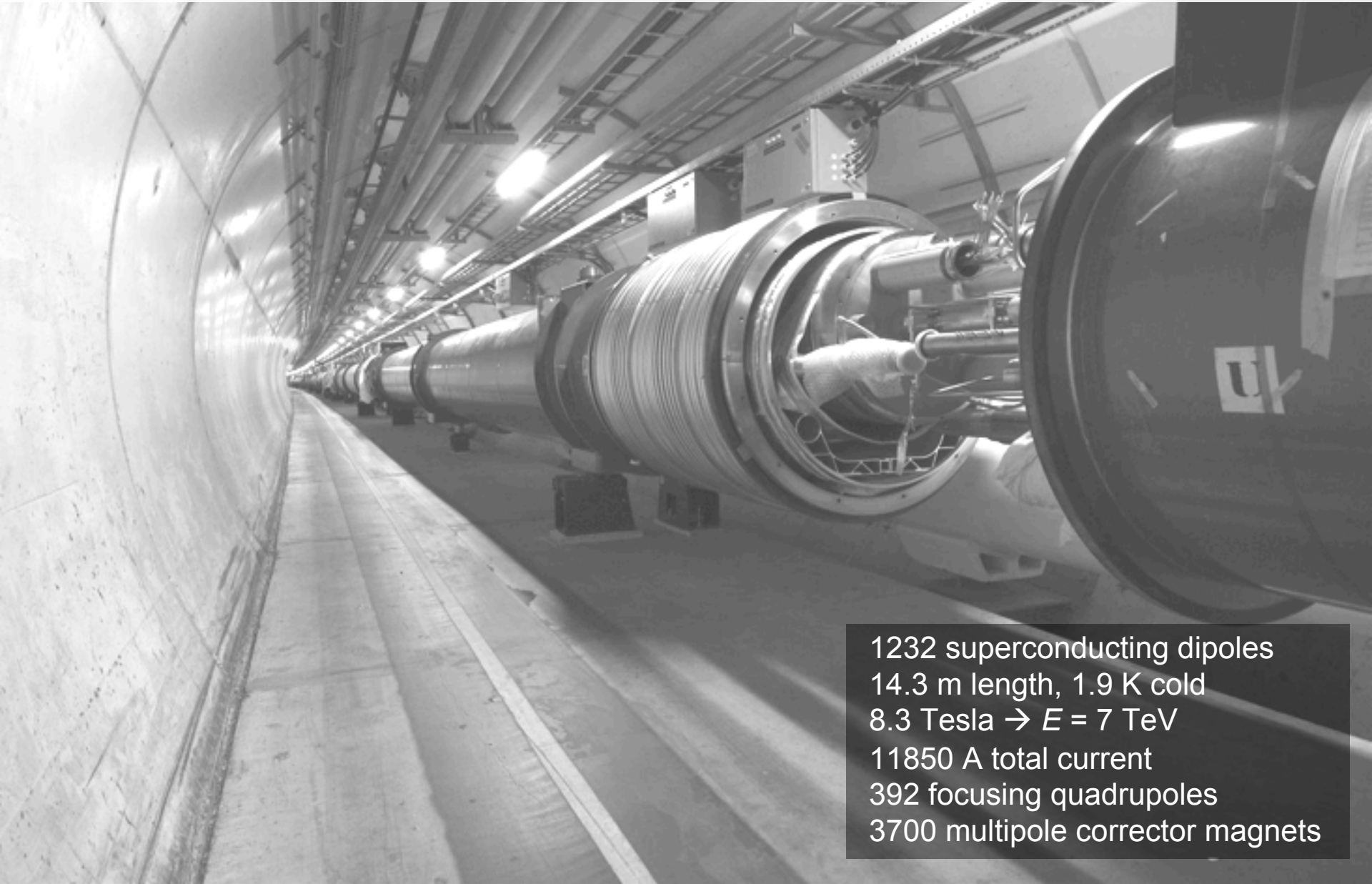
CERN AC/DI/MM 3324-07 07-1998

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.





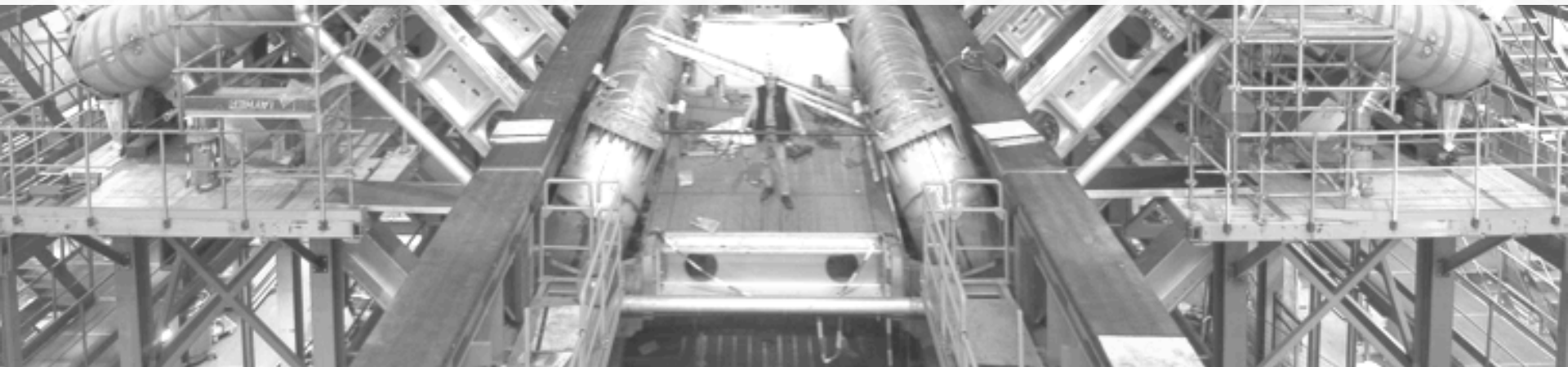
The High- p_T LHC Detectors



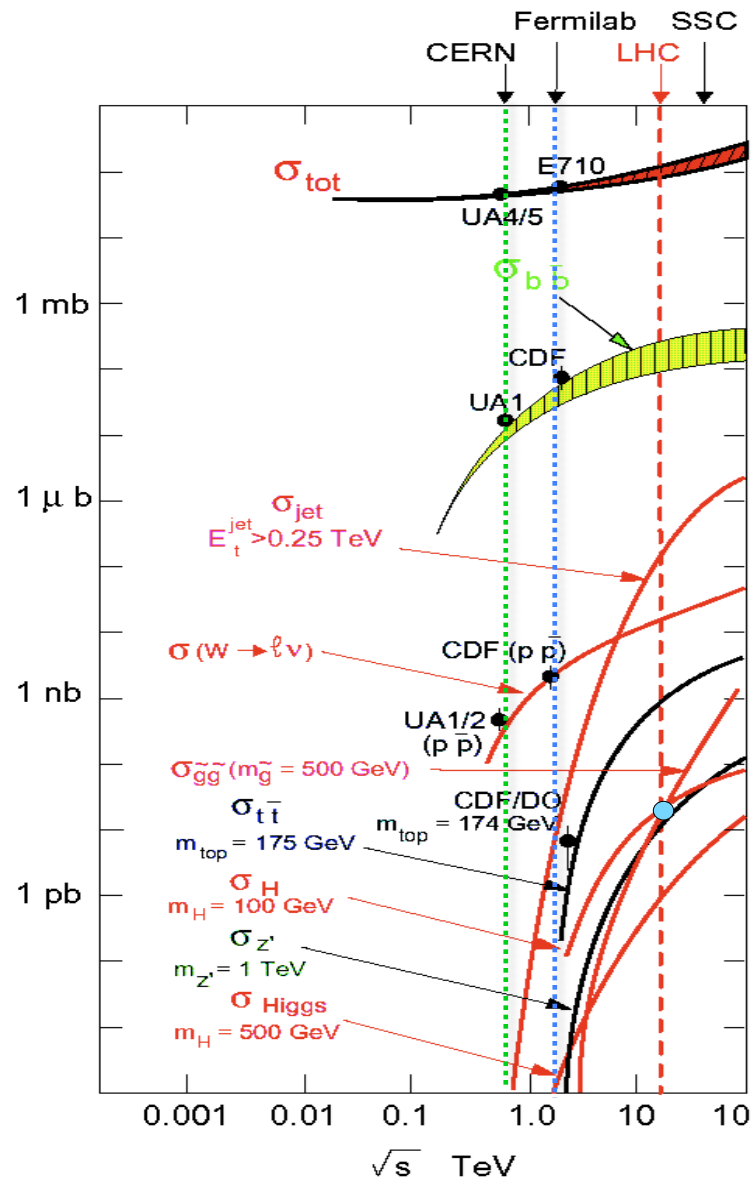
ATLAS and CMS are “general purpose detectors”, capable of adequately covering the entire physics programme reachable with high-luminosity 14 TeV pp collisions

From charm and beauty physics at lowest transverse momenta (~ 3 GeV) ...

... to new physics searches up to the highest reachable scales (several TeV)



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



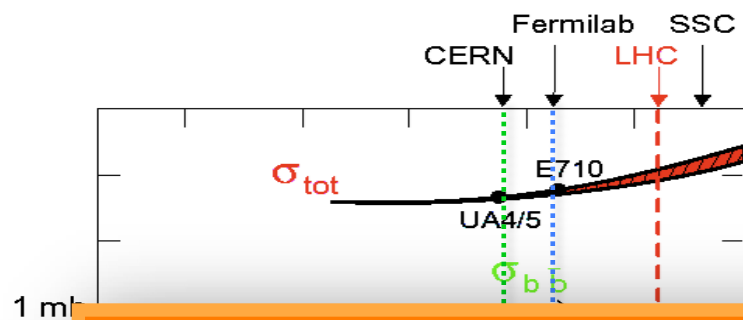
Process	Cross section (nb) at 14 TeV CM energy	Production rates (Hz) at $L=10^{34} \text{ cm}^{-2}\text{s}^{-2}$
Inelastic	10^8	10^9
$b\bar{b}$	5×10^5	5×10^6
$W \rightarrow \ell \nu$	15	150
$Z \rightarrow \ell \ell$	2	20
$t\bar{t}$	1	10
$Z' (1 \text{ TeV})$	0.05	0.5
$\tilde{g}\tilde{g} (1 \text{ TeV})$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

Recall: $1 \text{ pb}^{-1} \triangleq 10^{36} \text{ cm}^{-2}$

$\Rightarrow 40 \text{ pb} \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} =$

$40 \text{ pb} \times 10^{-2} \text{ pb}^{-1}\text{s}^{-1} = 0.4 \text{ Hz}$

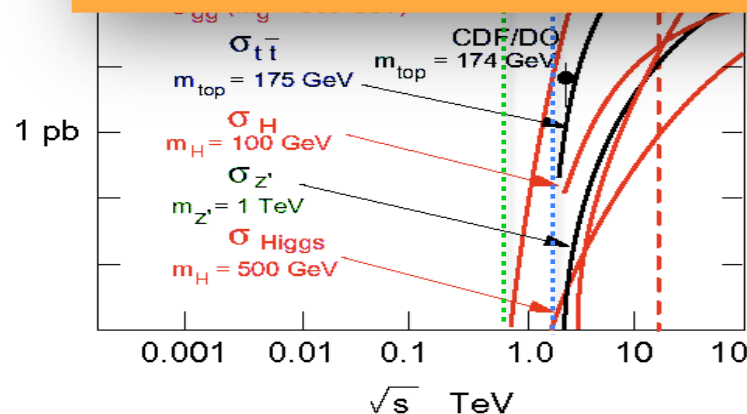
$pp(\text{bar})$ Cross Sections



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!)

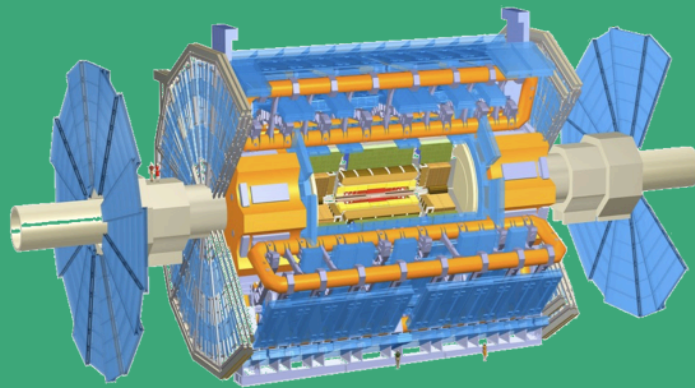
→ This fact drives the detector design



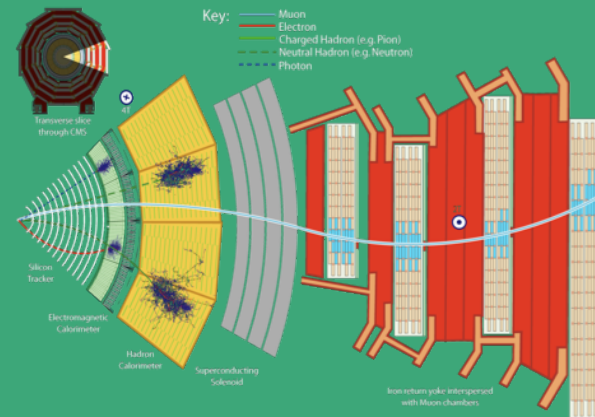
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ATLAS & CMS: Design Choices



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

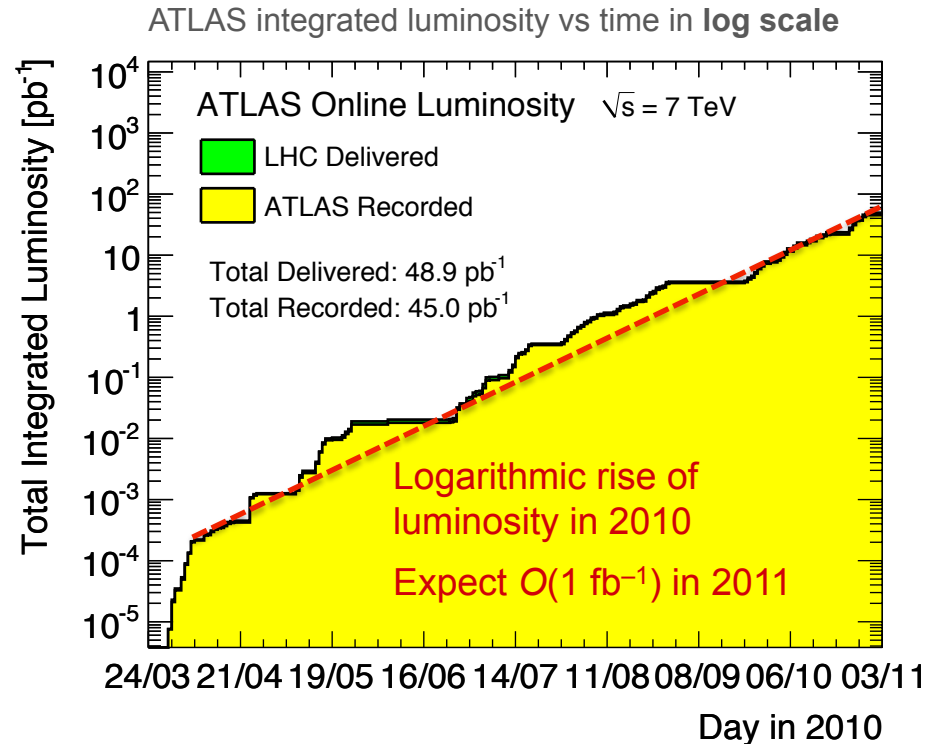
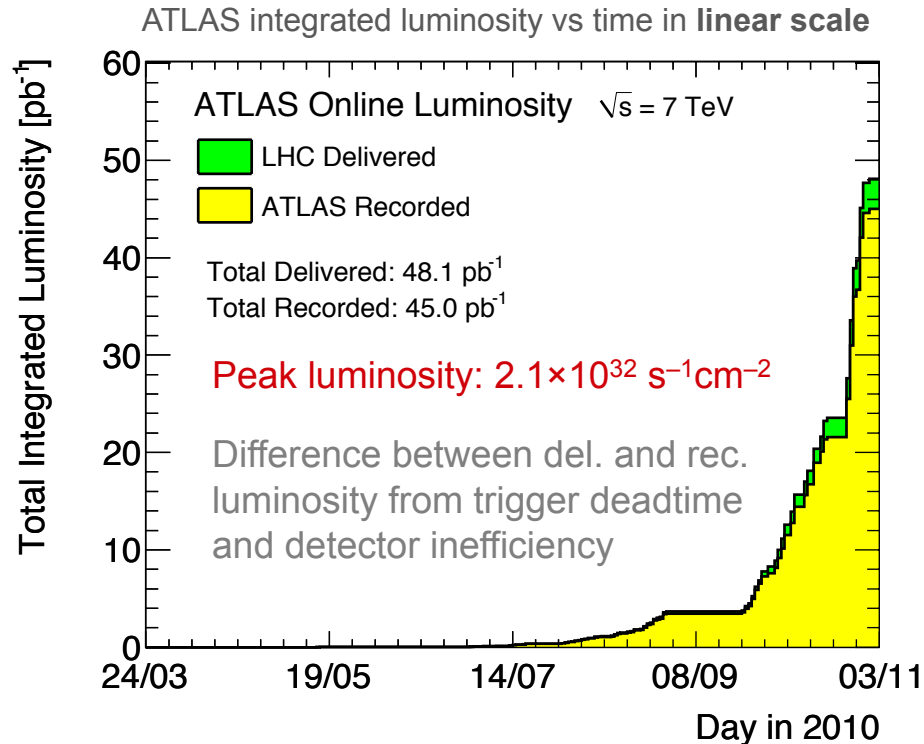


CMS: emphasis on excellent electron/photon and tracking (muon) resolution

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

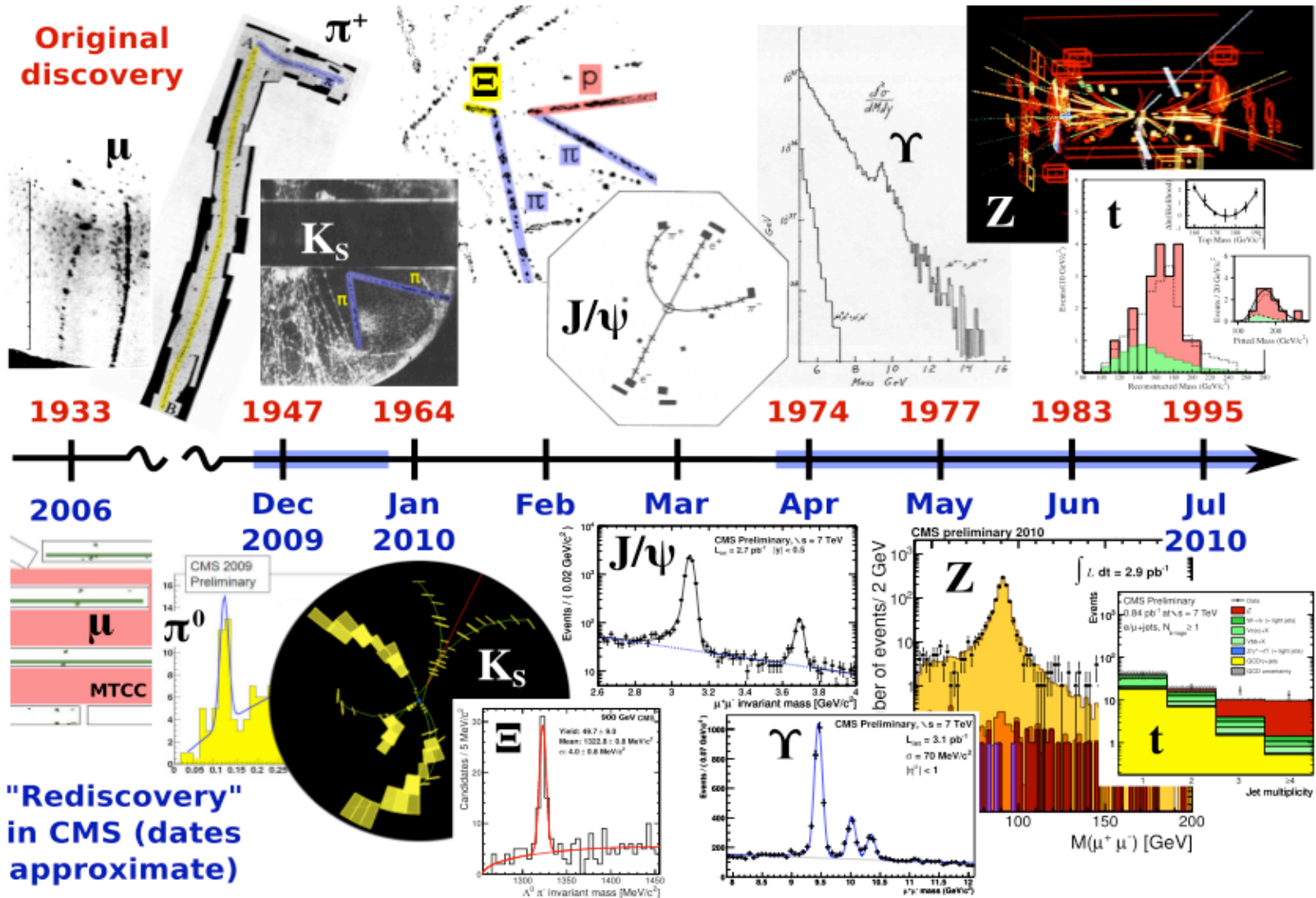
Recorded Luminosity at 7 TeV in 2010

Measured with forward detectors, calibrated with beam separation scans



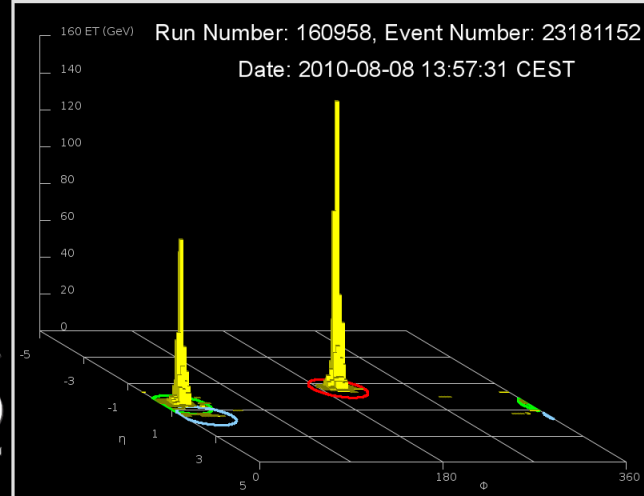
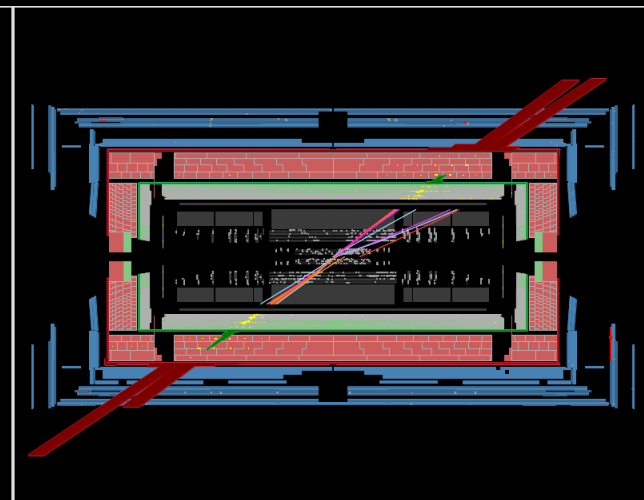
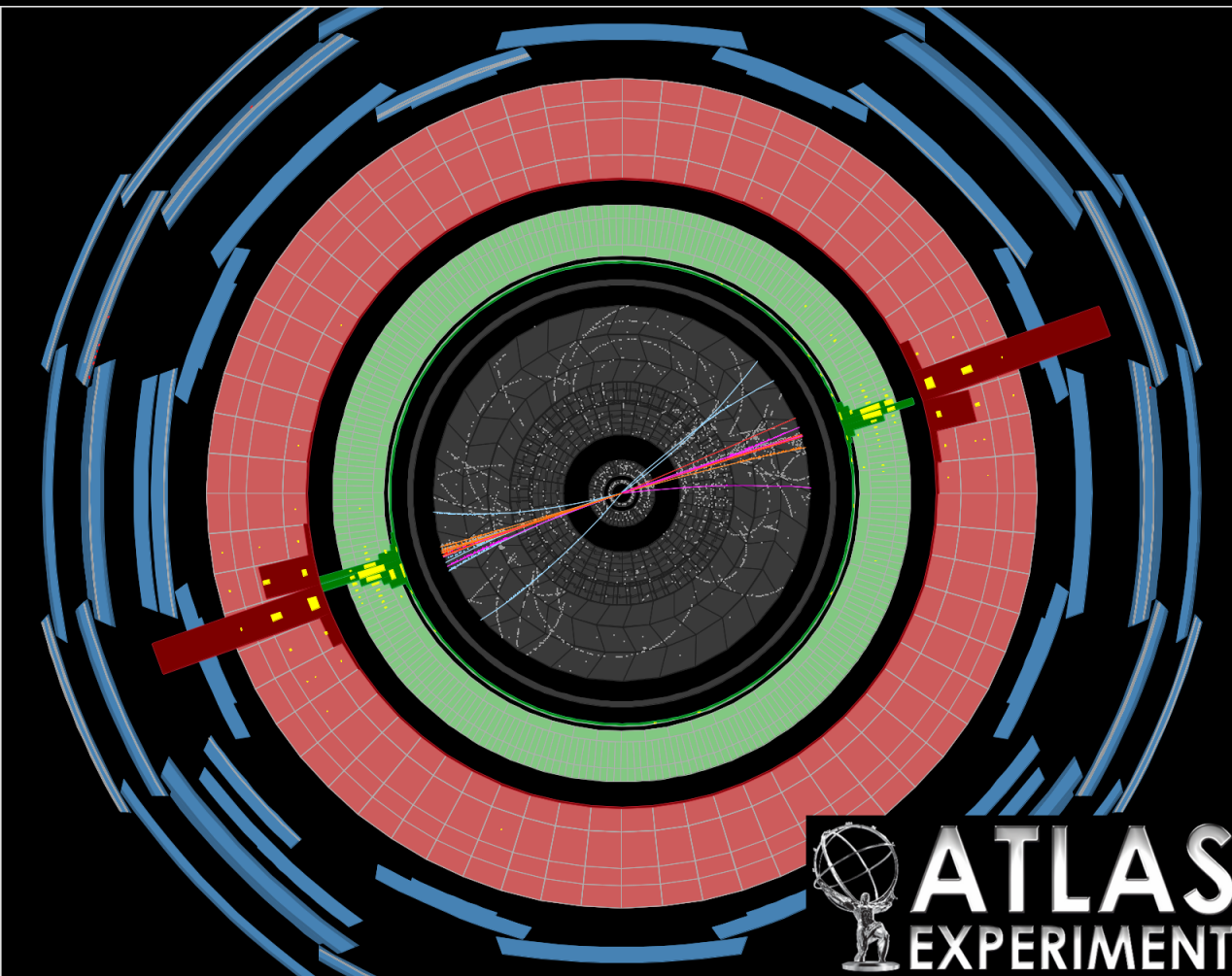
$10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ *instantaneous* luminosity corresponds to an *integrated* luminosity of 0.1 nb⁻¹ per second
→ 180 pb⁻¹ per month (assuming 70% LHC efficiency for physics)

SM particles rediscovered in 2010 (taken from CMS)



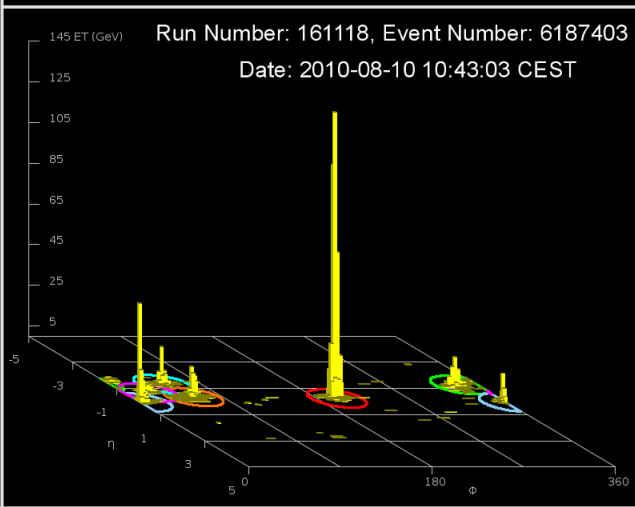
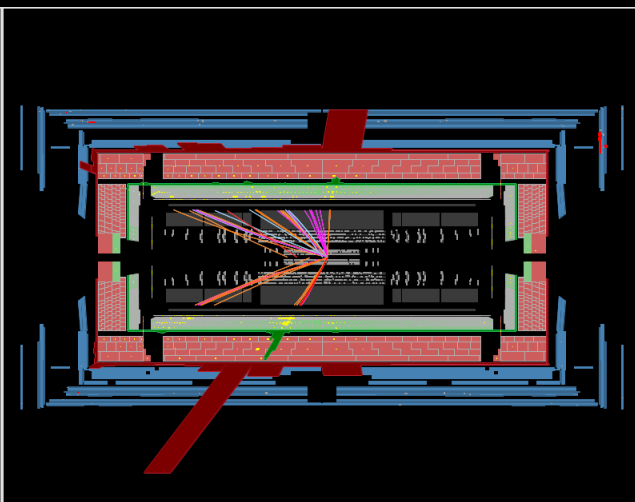
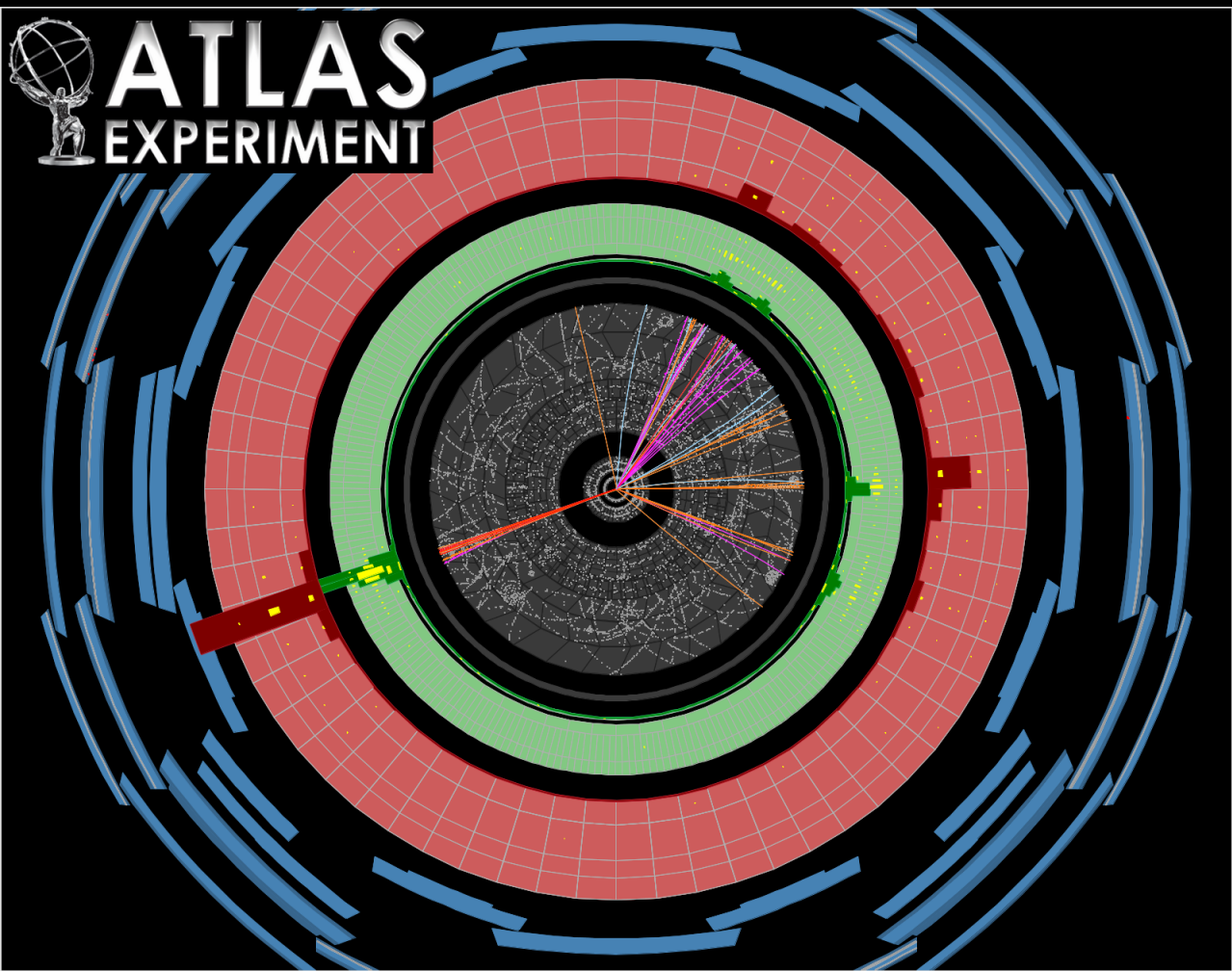
© P. Schieferdecker, Dec 17, 2010 at CERN

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

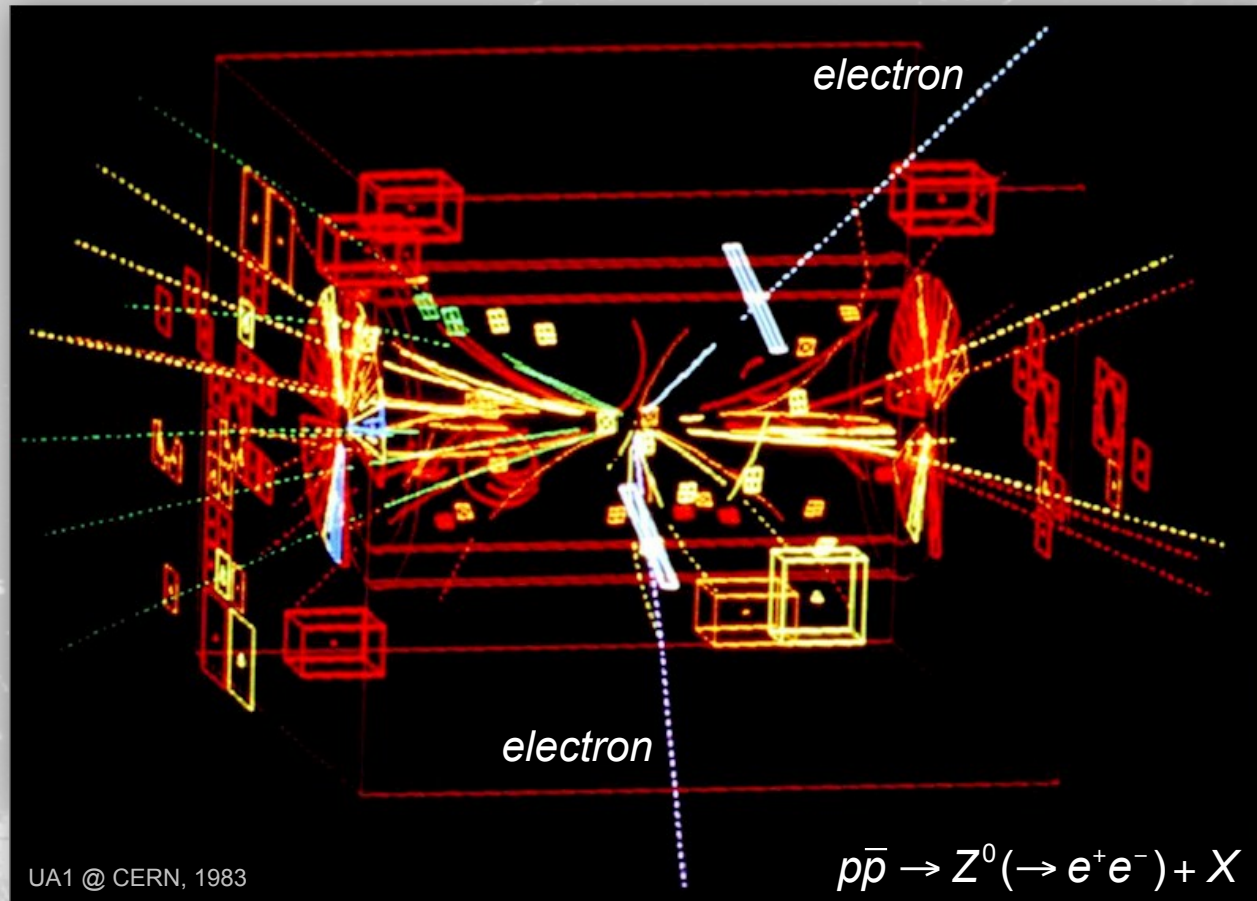


... by now found event with 3.1 TeV (4.0 TeV) di-jet mass for central (forward) jets
...and a highest- p_T di-jet event with 1.5 TeV

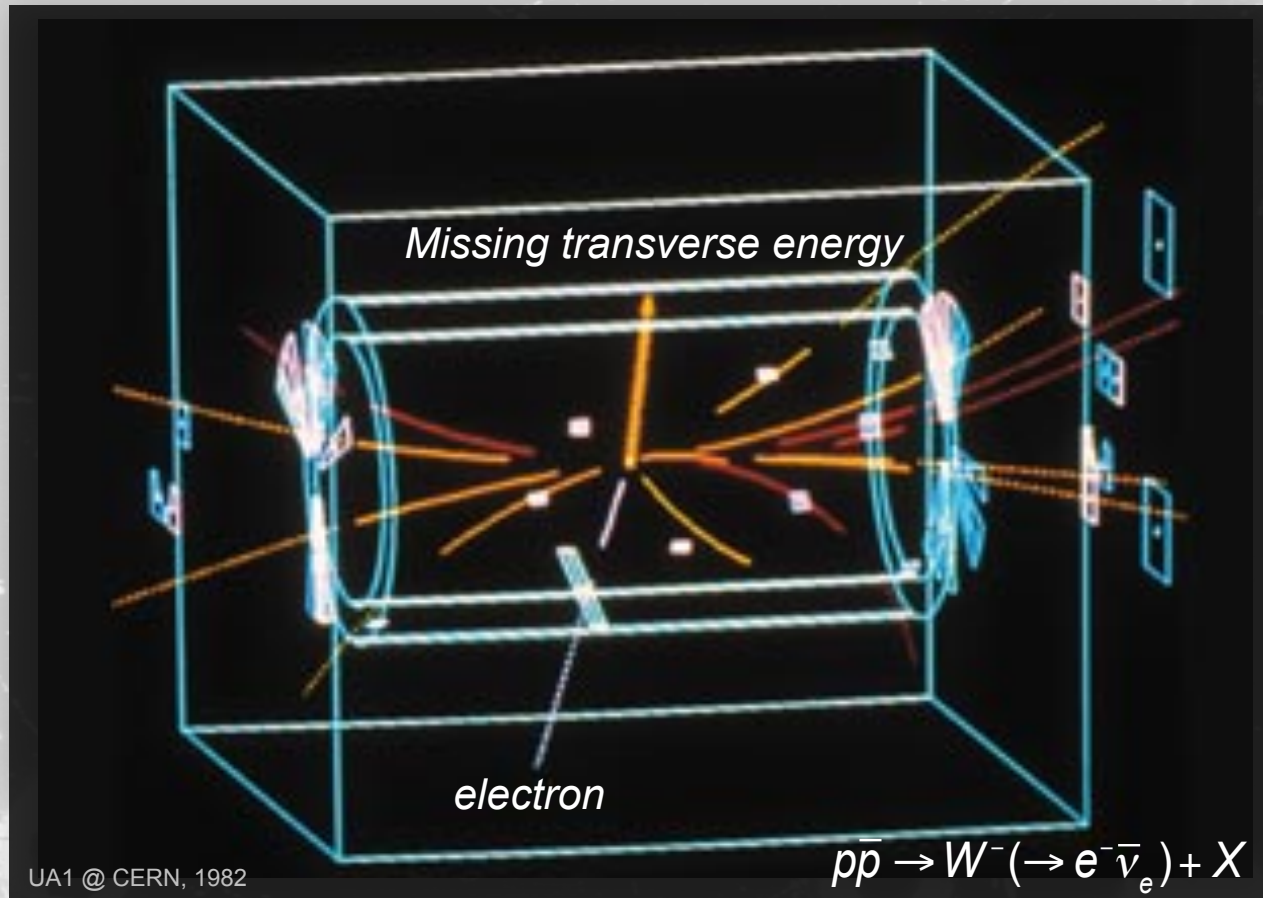
Multijet event seen by ATLAS: 4 jets with $p_T > 200$ GeV, and 6 jets with $p_T > 100$ GeV



Z boson production on the mass shell, seen in April 1983 by UA1



W boson production on the mass shell, seen in Jan. 1983 by UA1



W boson production on the mass shell, seen in Jan. 1983 by UA1

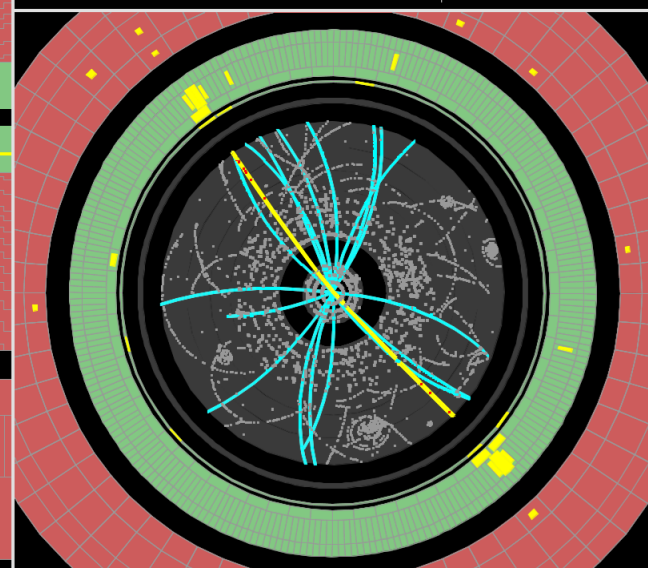
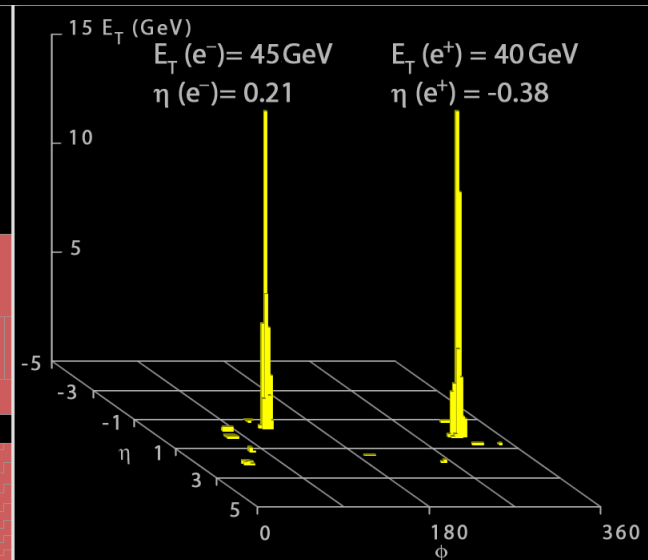
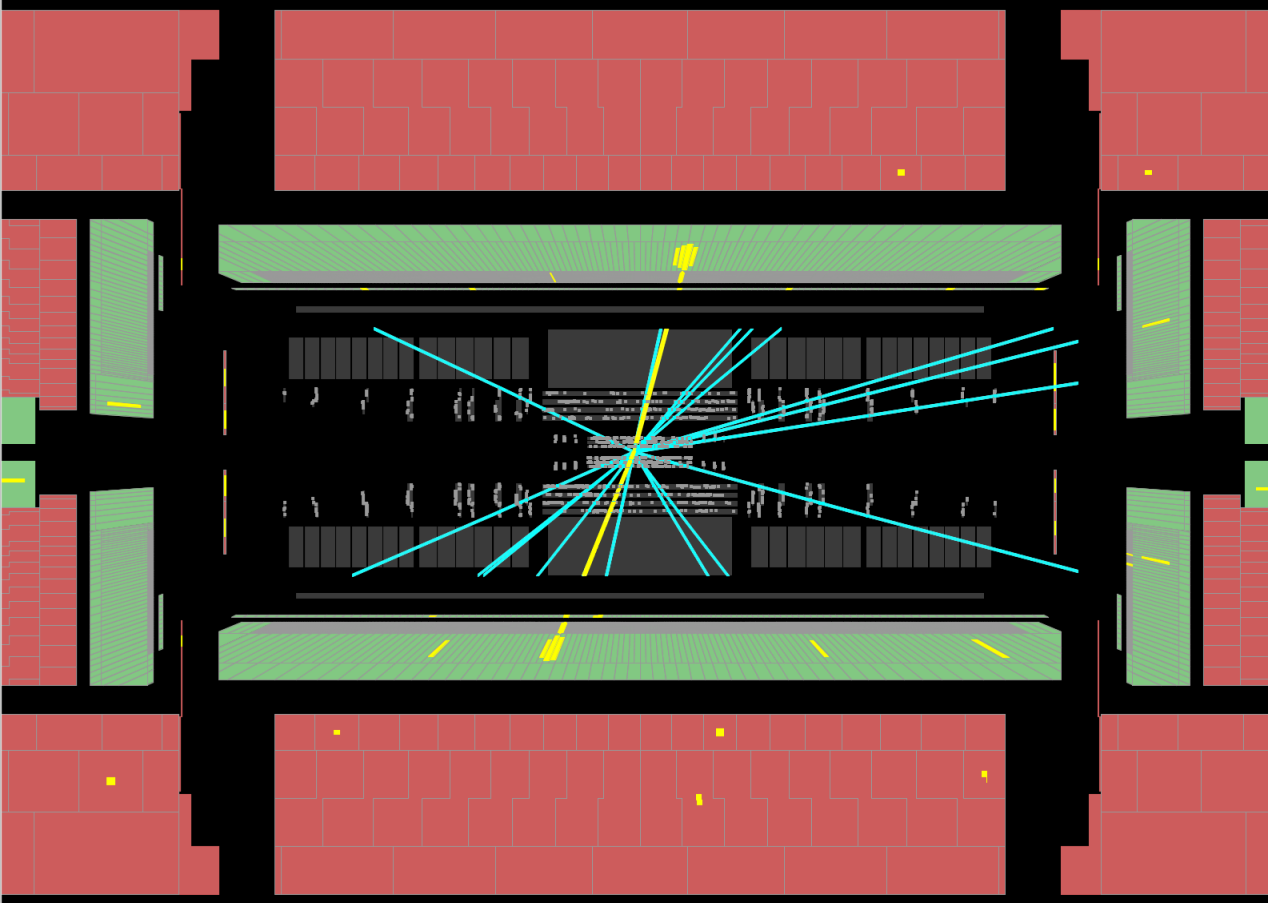


Run Number: 154817, Event Number: 968871

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

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

$Z \rightarrow ee$ candidate in 7 TeV collisions



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

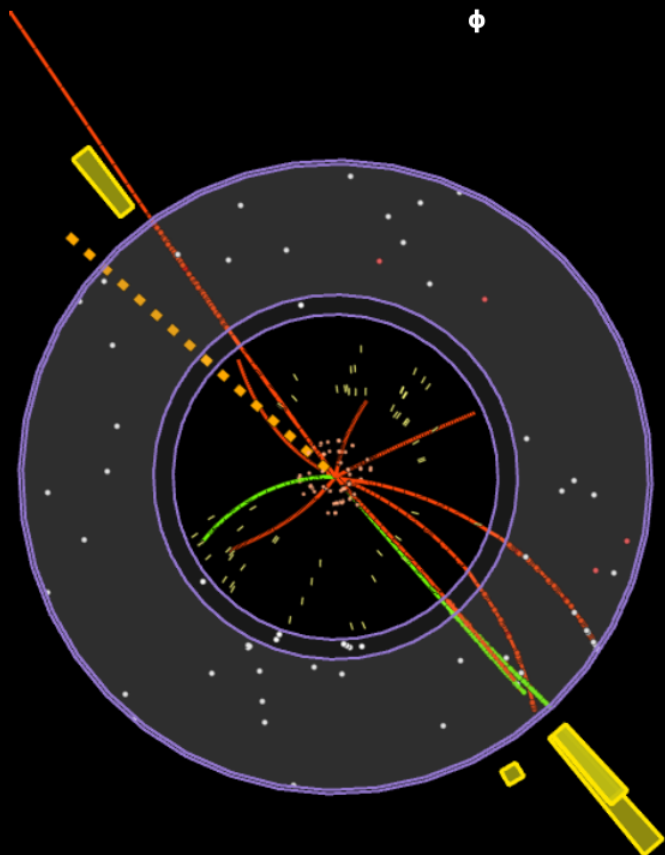
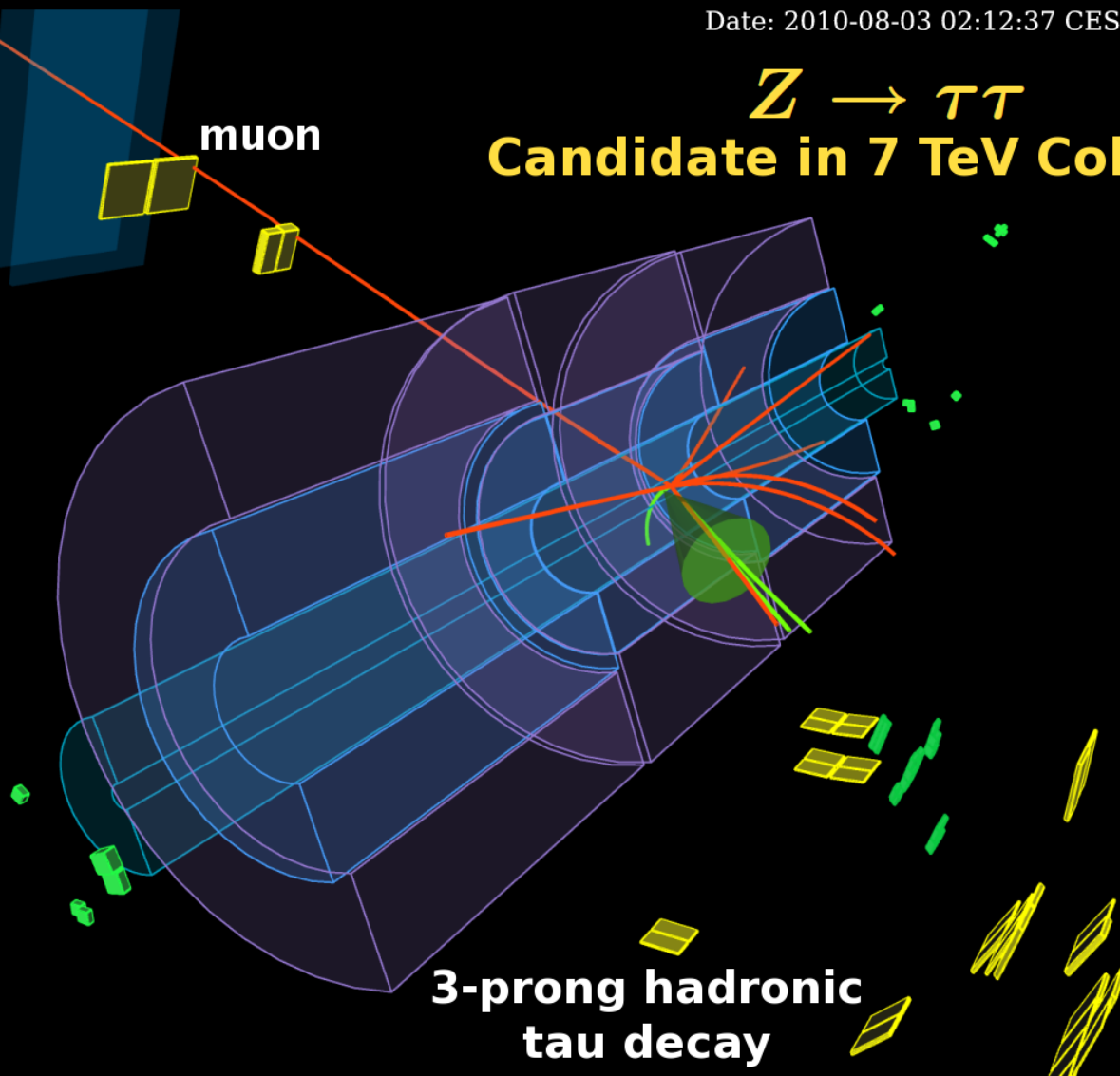
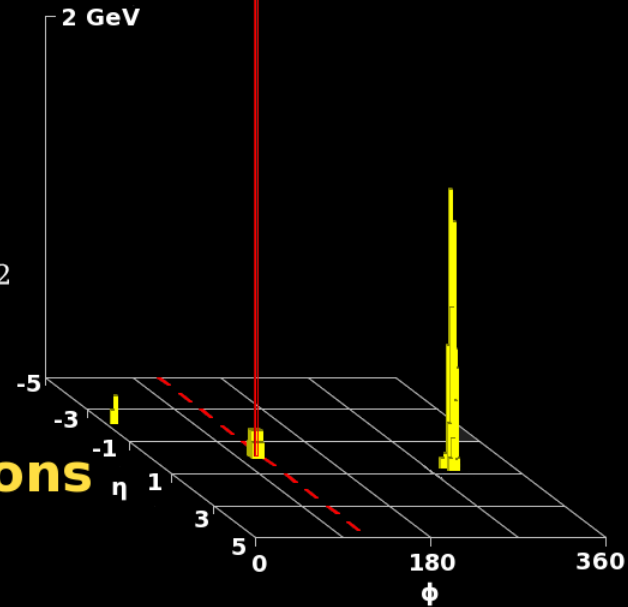


ATLAS EXPERIMENT

Run Number: 160613, Event Number: 9209492

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

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



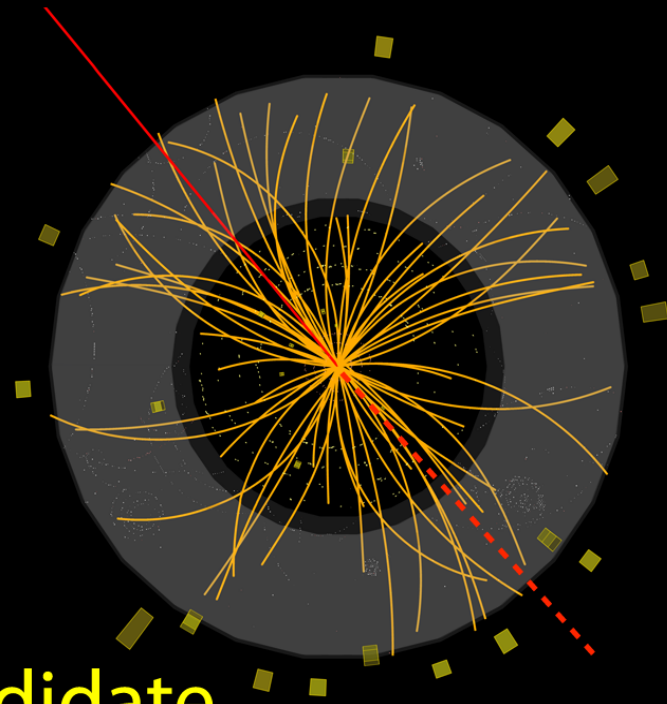
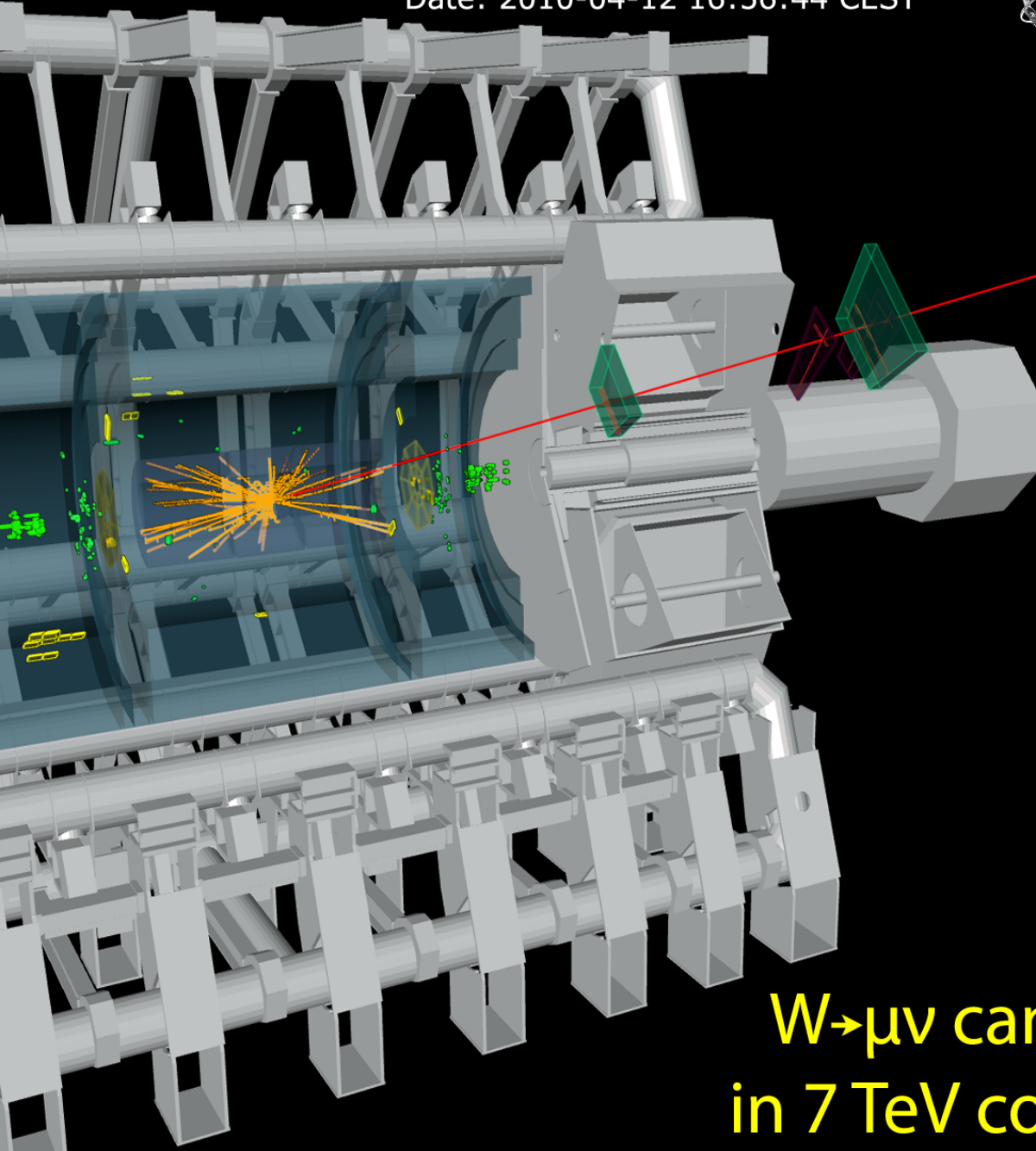
3-prong hadronic
tau decay

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



ATLAS EXPERIMENT

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



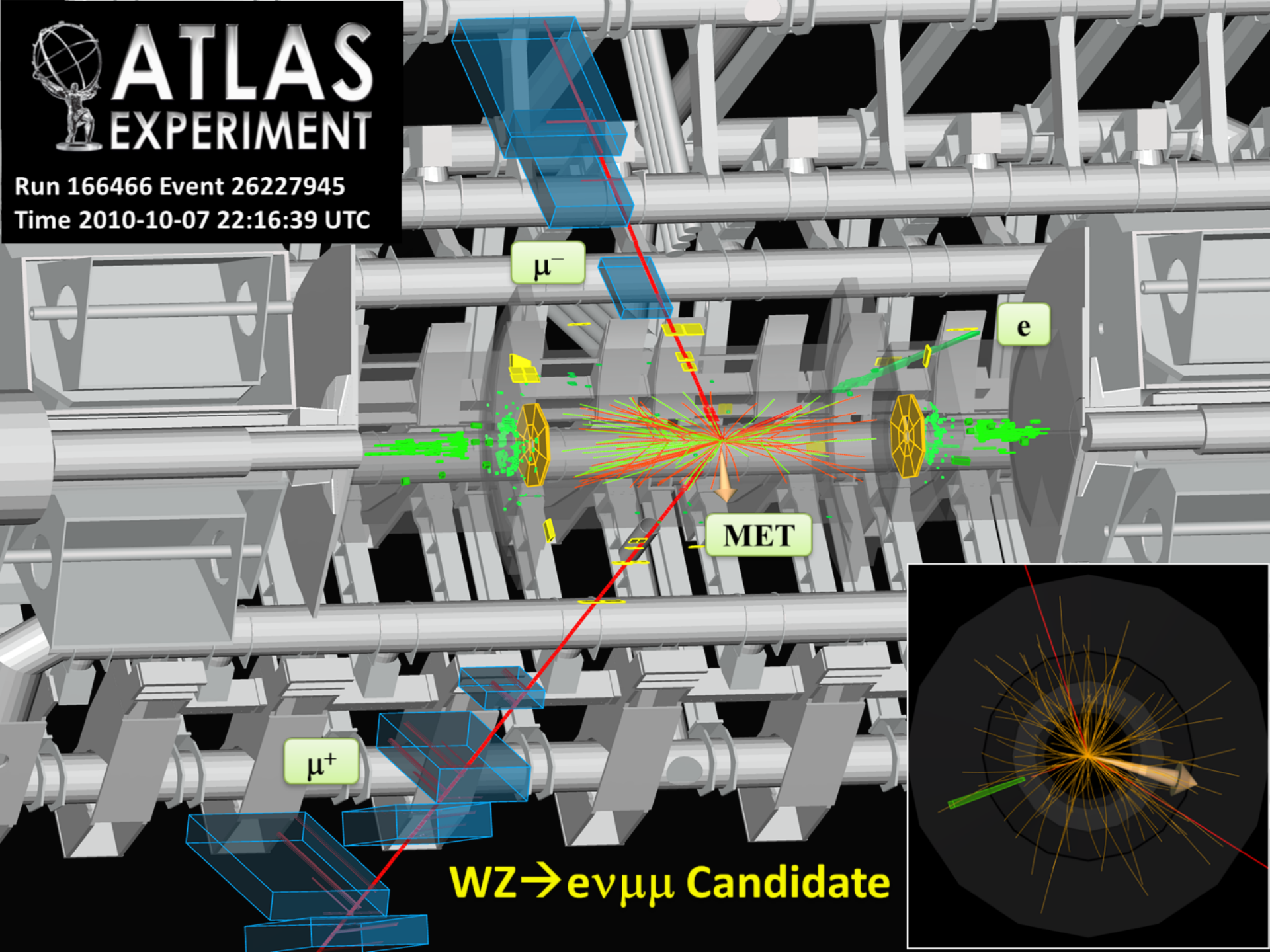
$W \rightarrow \mu \nu$ candidate
in 7 TeV collisions



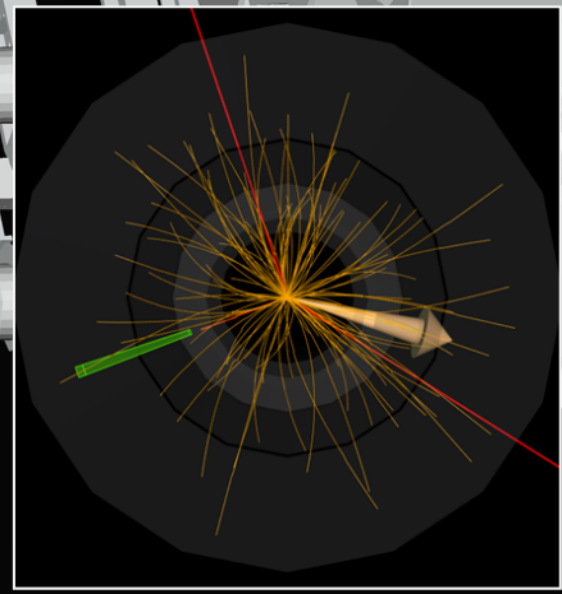
ATLAS EXPERIMENT

Run 166466 Event 26227945

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



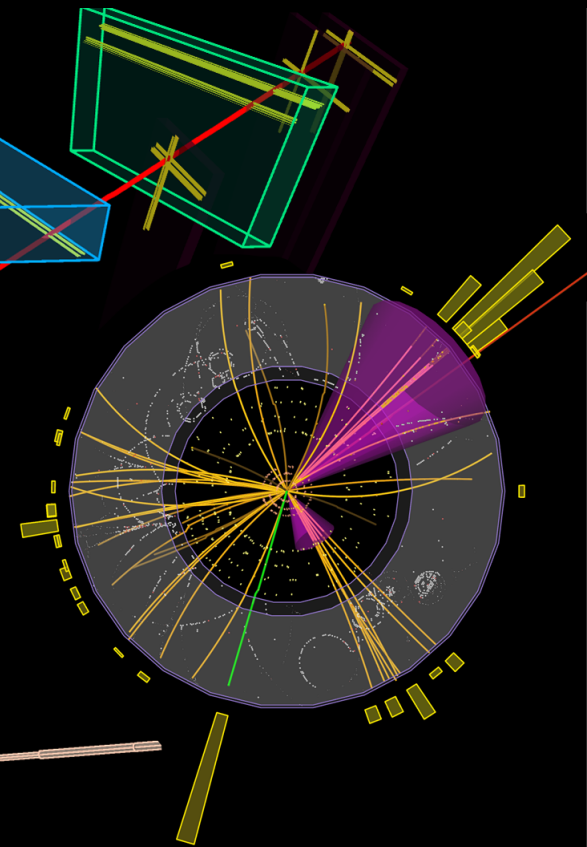
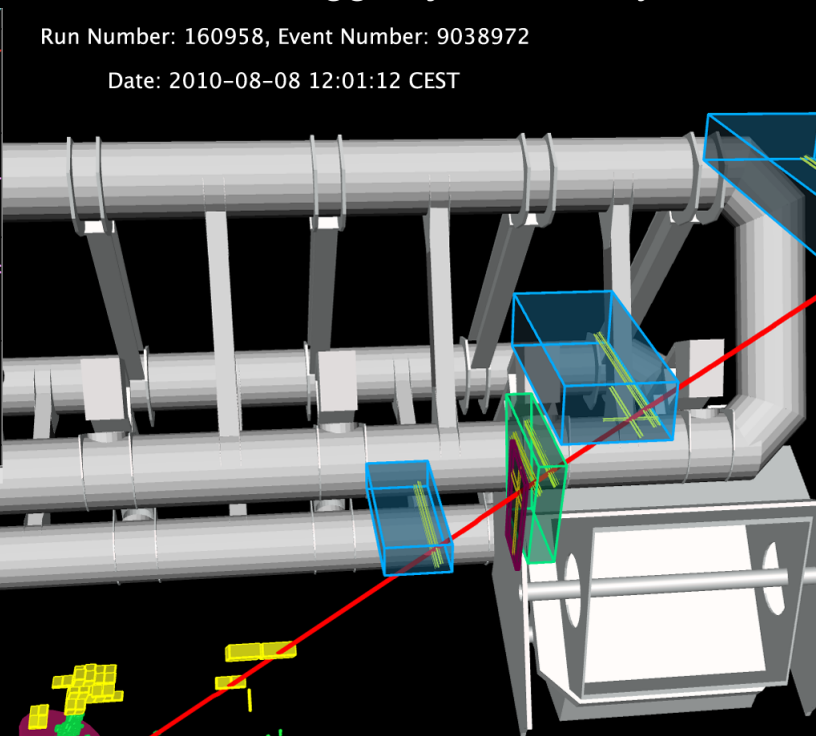
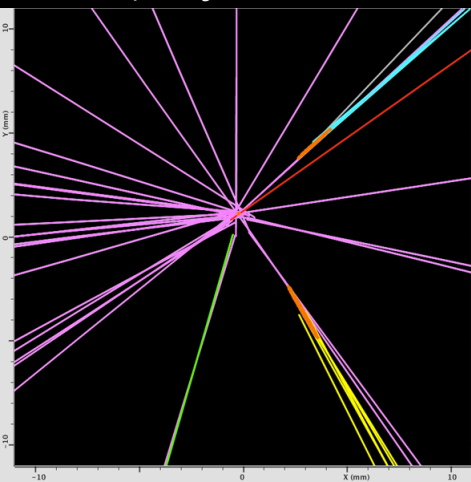
$WZ \rightarrow e\nu\mu$ Candidate



$t\bar{t} \rightarrow e\mu + \text{jets}$ 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

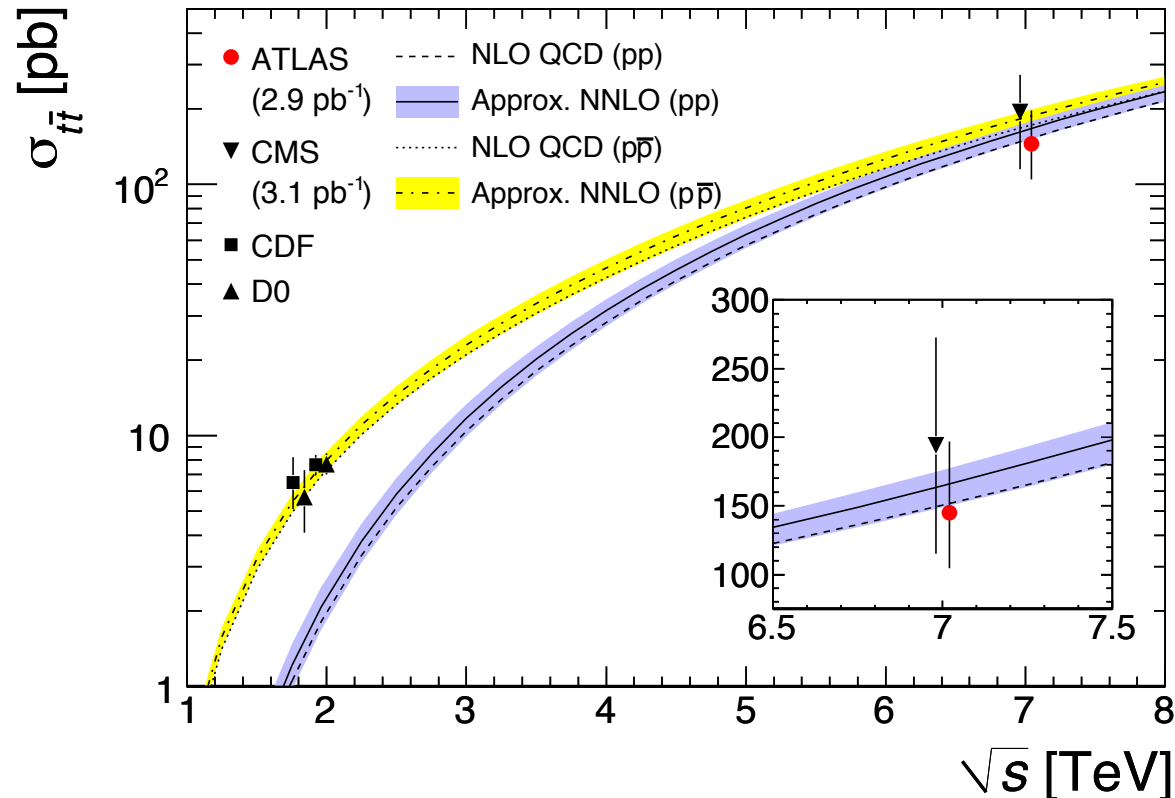
Both experiments published cross section results on ~9% of full statistics

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

Errors (ATLAS):

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

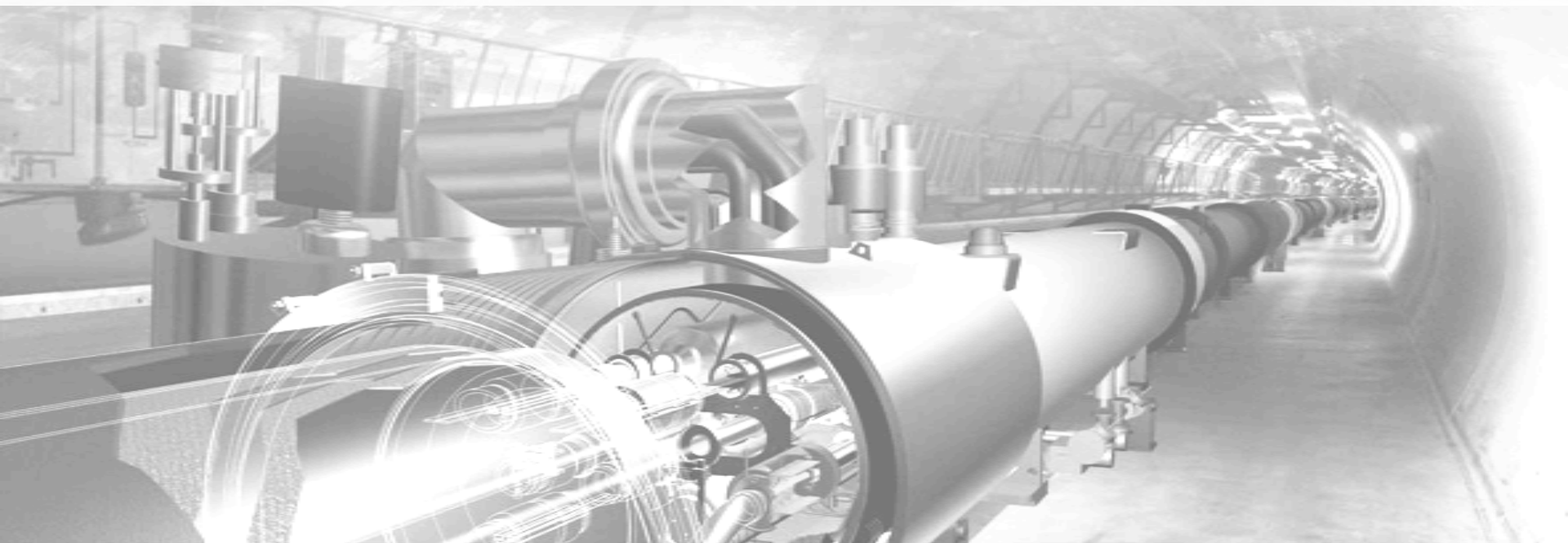
Theory error: ~8%



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



Searching for the Higgs Boson



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:

$$\hat{s} = M_X^2 = x_1 \cdot x_2 \cdot s_{\text{LHC}}$$

- Typical ' x ' values (assume: $x_1 = x_2$)

LHC ($\sqrt{s} = 14 \text{ TeV}$):

- $M_X = 100 \text{ GeV (1 TeV)} \rightarrow \langle x \rangle = 0.007 \text{ (0.07)}$

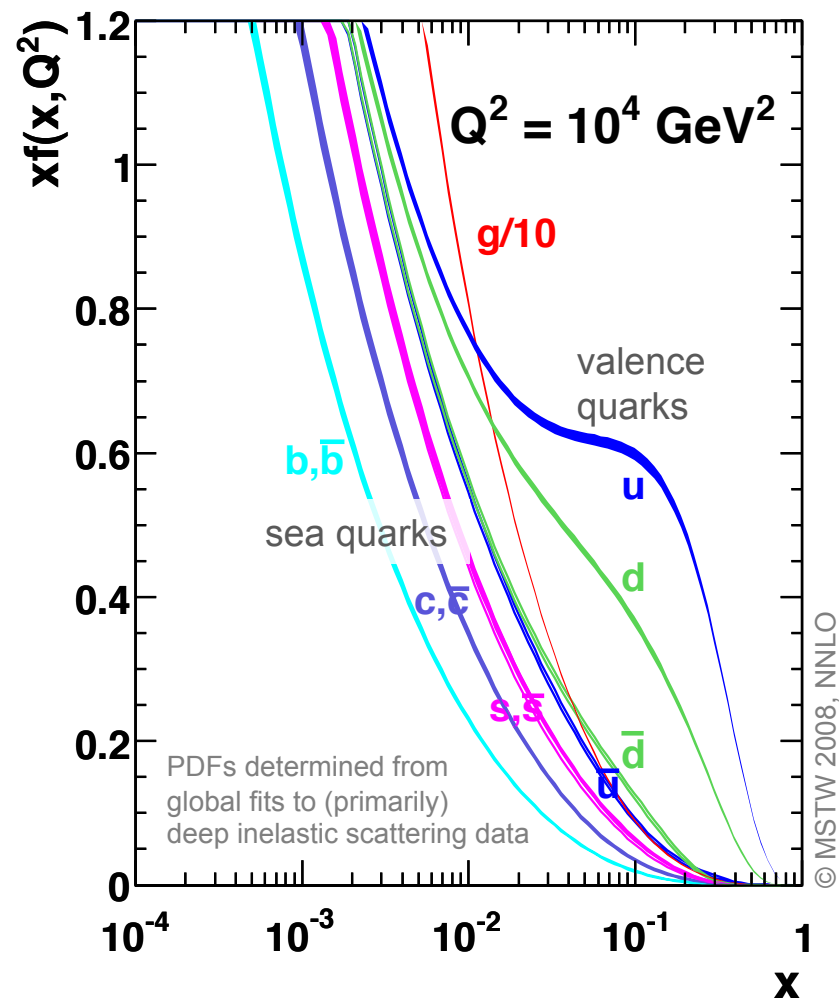
Tevatron ($\sqrt{s} = 2 \text{ TeV}$):

- $M_X = 100 \text{ GeV (1 TeV)} \rightarrow \langle x \rangle = 0.05 \text{ (0.5)}$

- PDFs rise dramatically towards low x

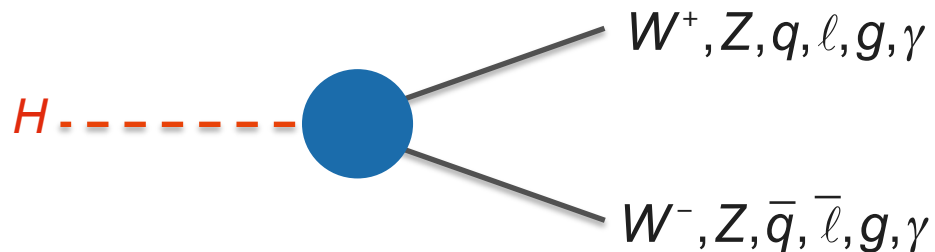
→ larger cross sections at LHC

→ gluon dominated



Higgs Boson Decays

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



...as a function of the Higgs mass

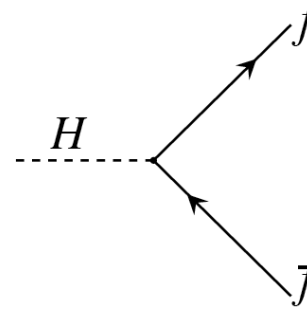
Because of the coupling to the mass of the decay particles:

- ... 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**:

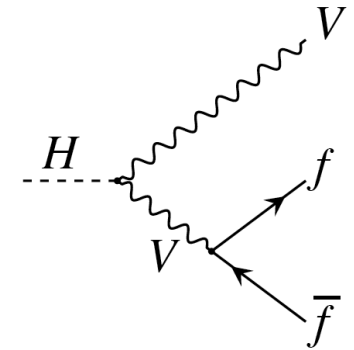
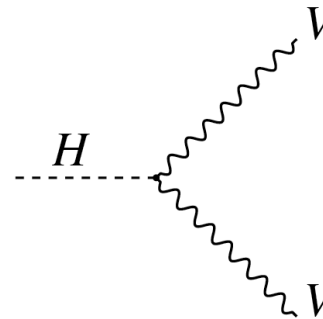
$$\Gamma_{\text{LO}}(H \rightarrow f\bar{f}) \propto N_C \cdot M_H \cdot m_f^2$$



Some leading order diagrams shown only

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

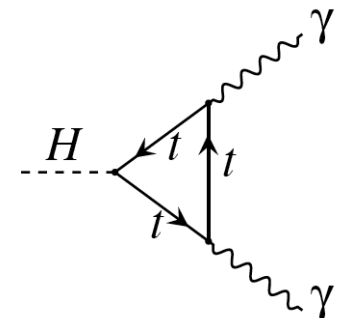
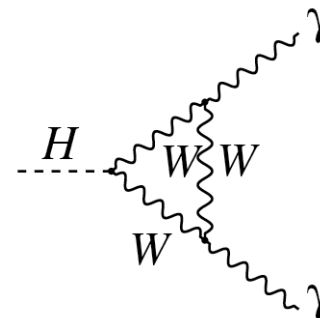
$$\Gamma(H \rightarrow VV) \propto M_H^3 \cdot \begin{cases} 1 & \text{for } V = Z \\ 2 & \text{for } V = W \end{cases}$$



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

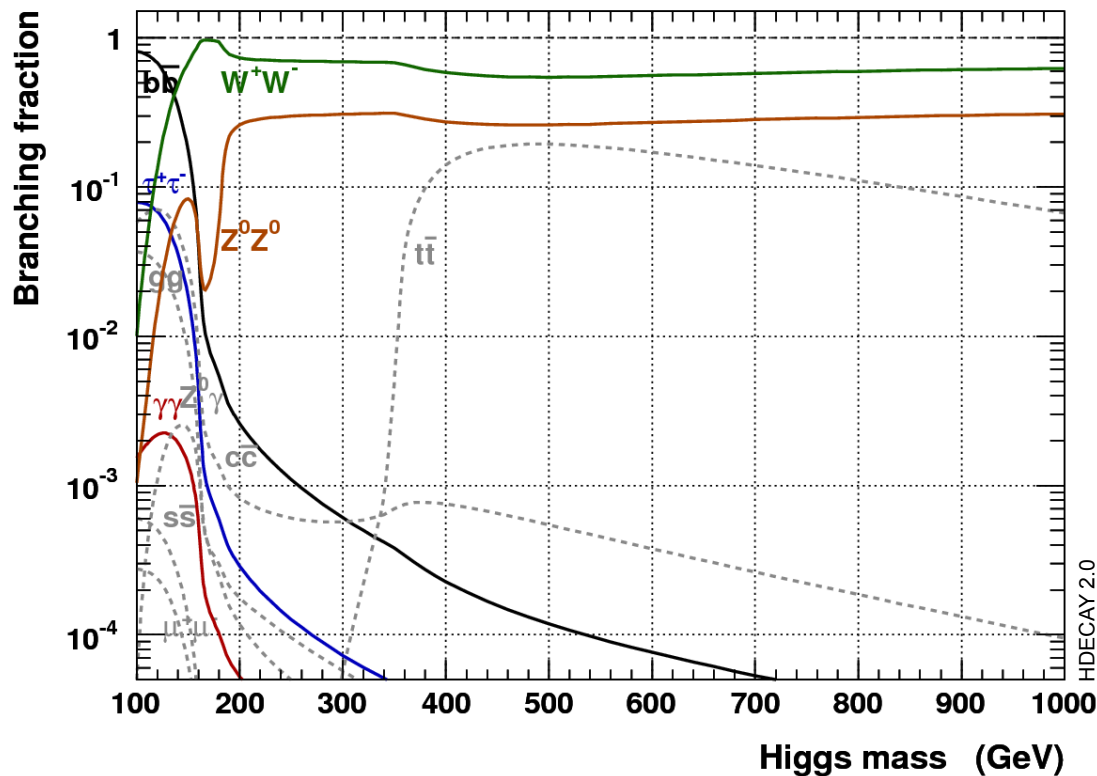


Higgs branching fractions and full width as function of Higgs boson mass



Summary of Higgs Boson Decays

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

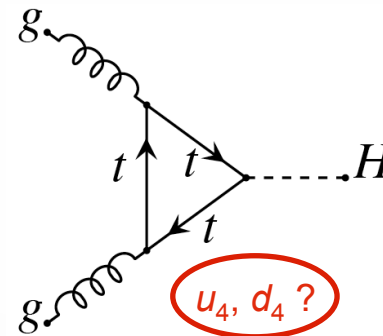


Higgs Boson Production

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
 ~ 1.7 , ~ 2 at LHC

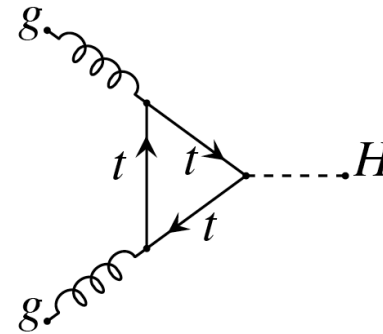
4^{th} generation ?
 K -factor of $\sim 3^2 = 9$
using sequential model

Higgs Boson Production

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

Gluon fusion

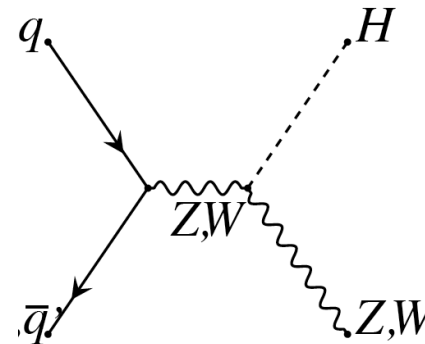
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gluon density in proton at small x



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*)

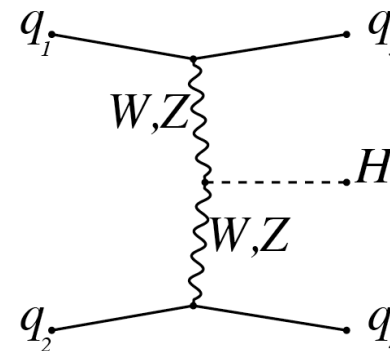
Relatively more important at Tevatron owing
to larger quark density in proton at larger x



More moderate
 K factors for
Higgs-strahlung
and WBF

Weak boson fusion

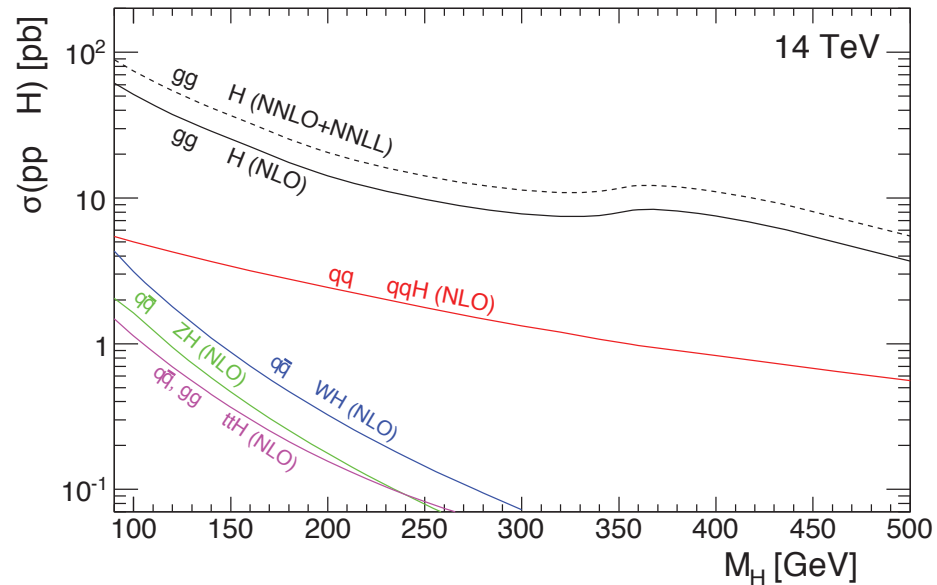
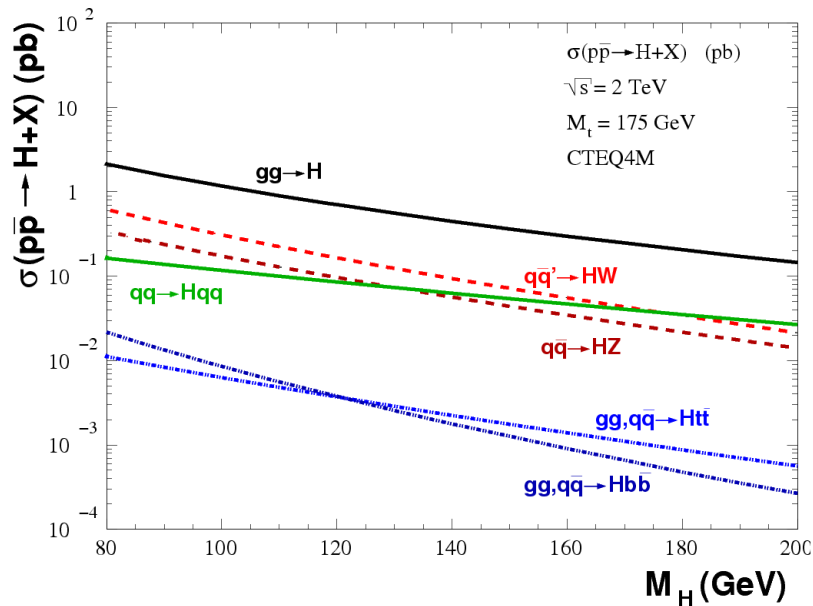
Striking event signature: small q^2 between
quarks and virtual W/Z 's ($M_H/2$ each q)
 $\rightarrow$ large $\Delta\eta$ between jets! Central jet veto.



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

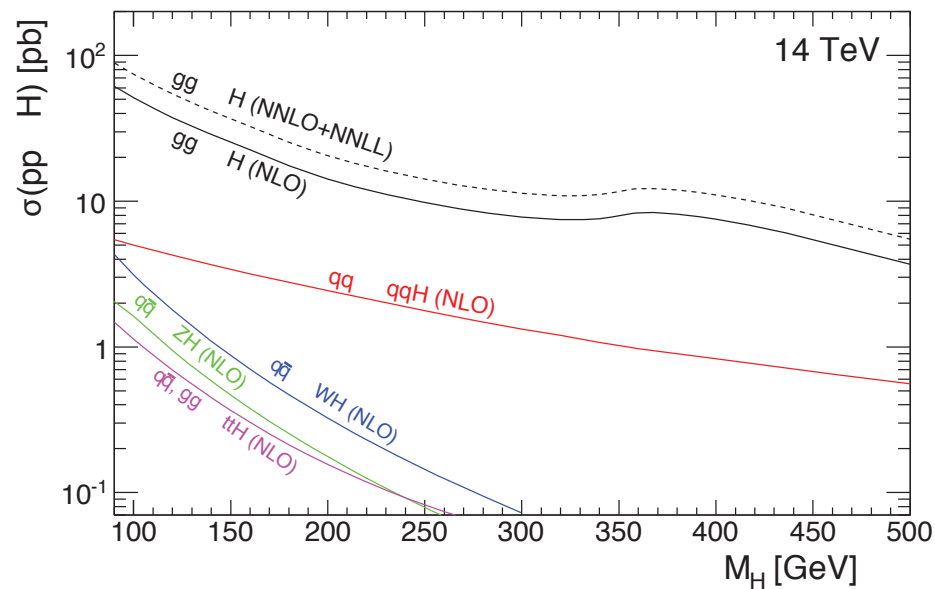
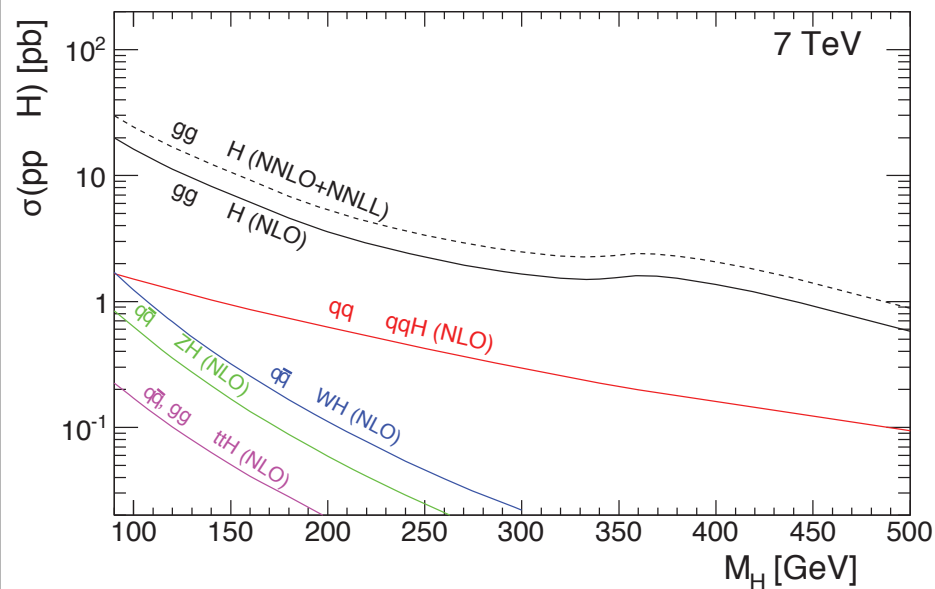


$qq \rightarrow W/Z + H$ cross sections $\sim 10 \times$ larger at the LHC
 $gg \rightarrow H$ $\sim 40\text{--}50 \times$ larger at the LHC

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

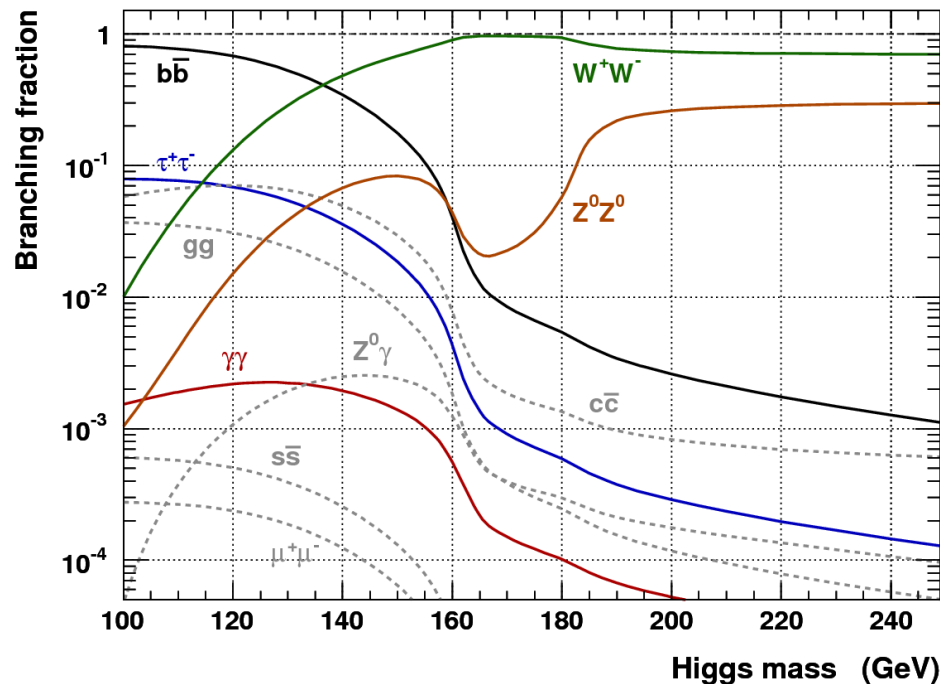


For $M_H = 160$ GeV, reduction by factor of

- ~ 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

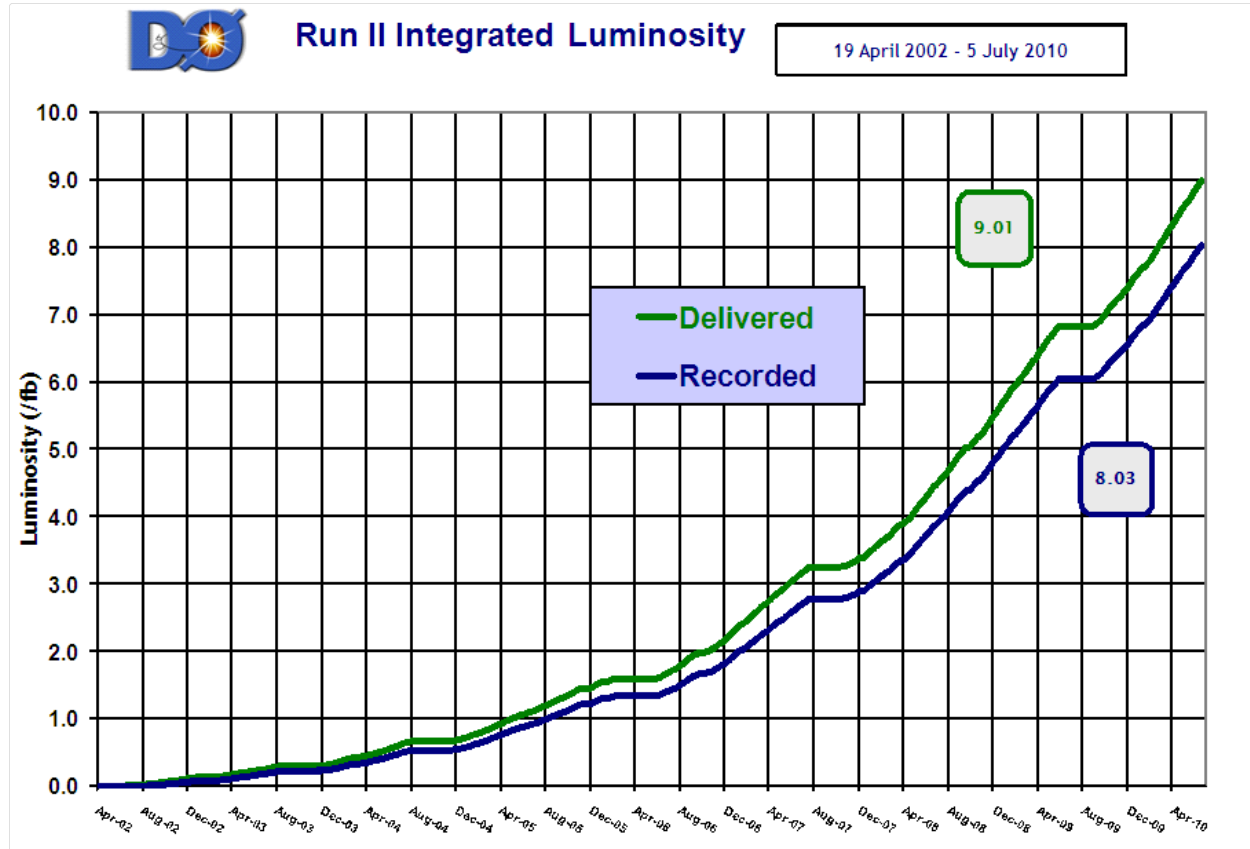
Peak luminosity:

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

Integrated luminosity:

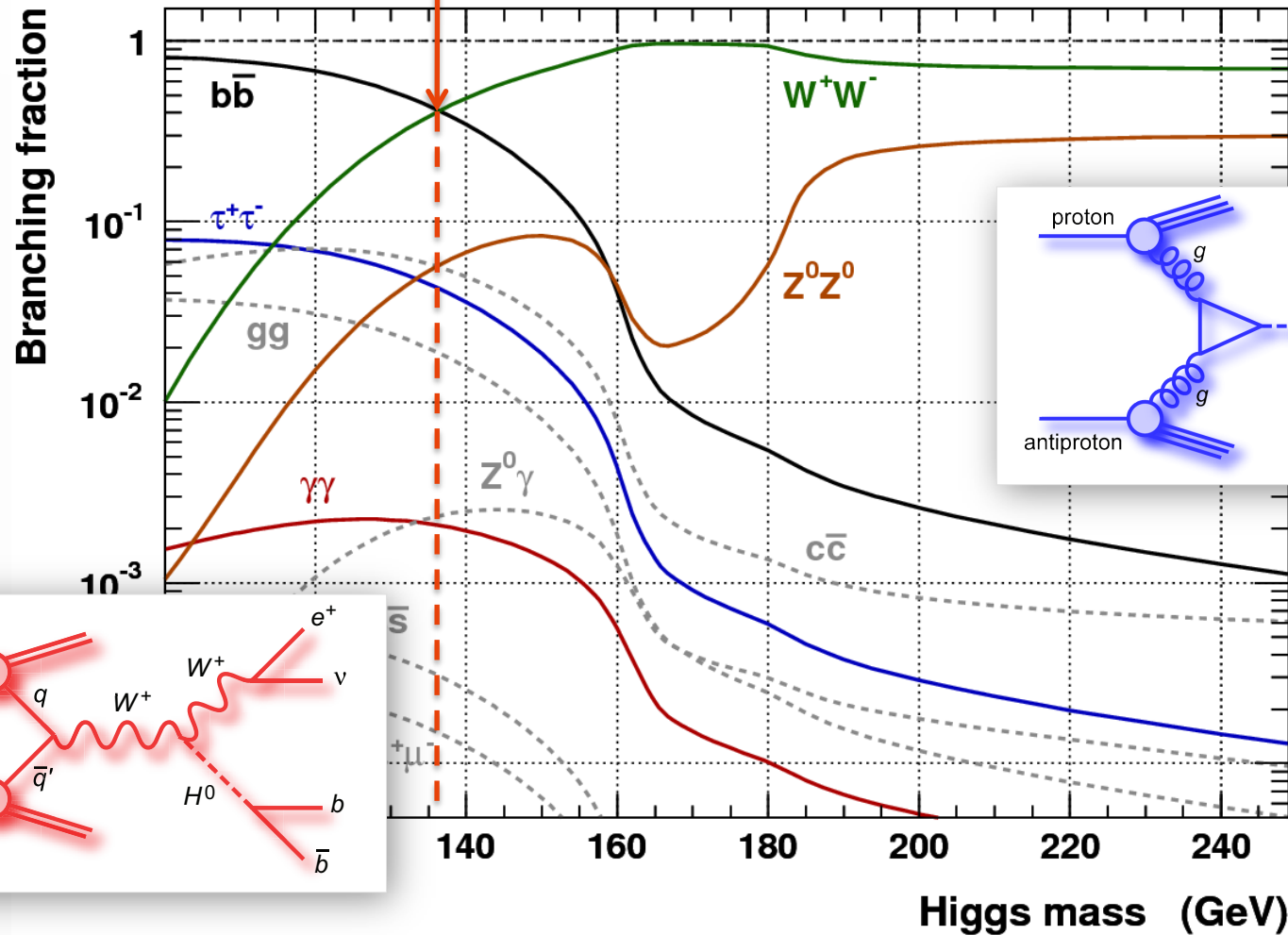
$\sim 10 \text{ fb}^{-1}$

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



Higgs Search Strategy at the Tevatron

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



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

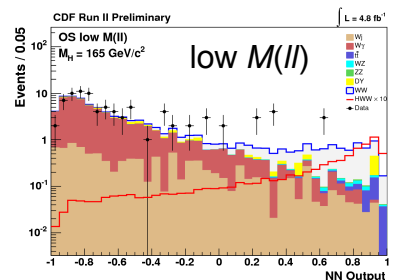
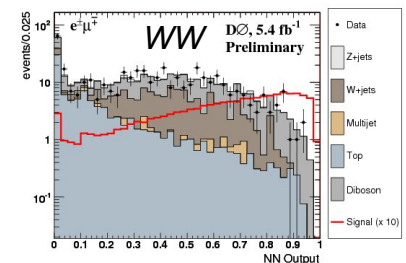
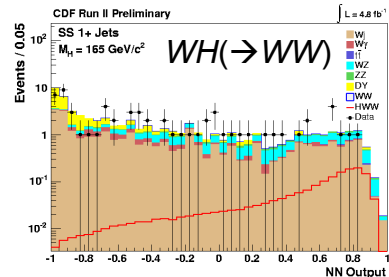
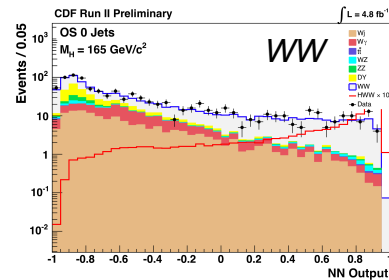
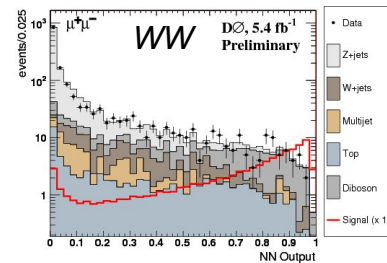
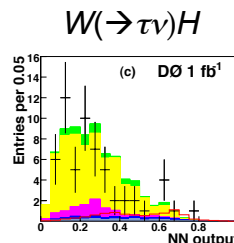
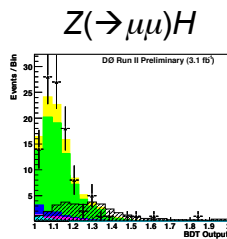
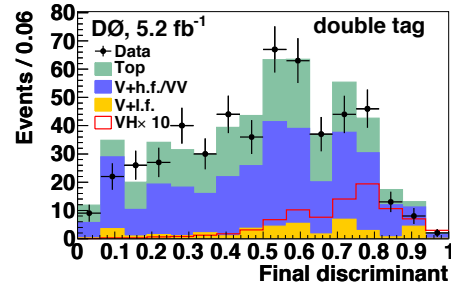
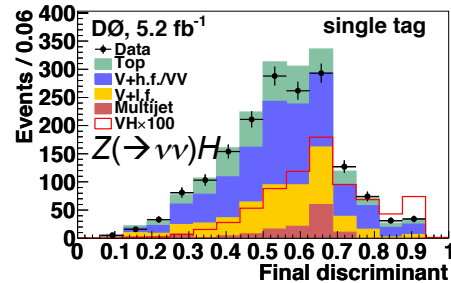
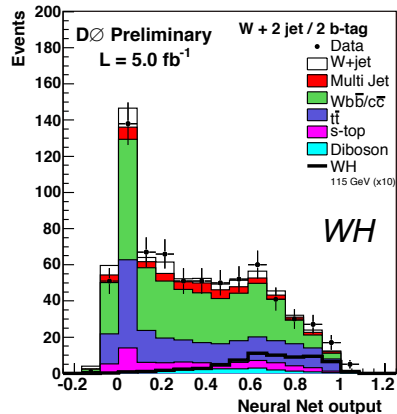
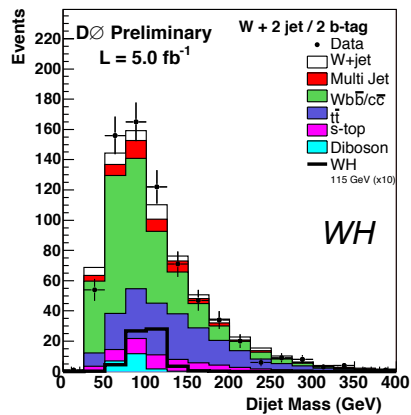
LHC analyses yet miles away from such degree of sophistication !

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

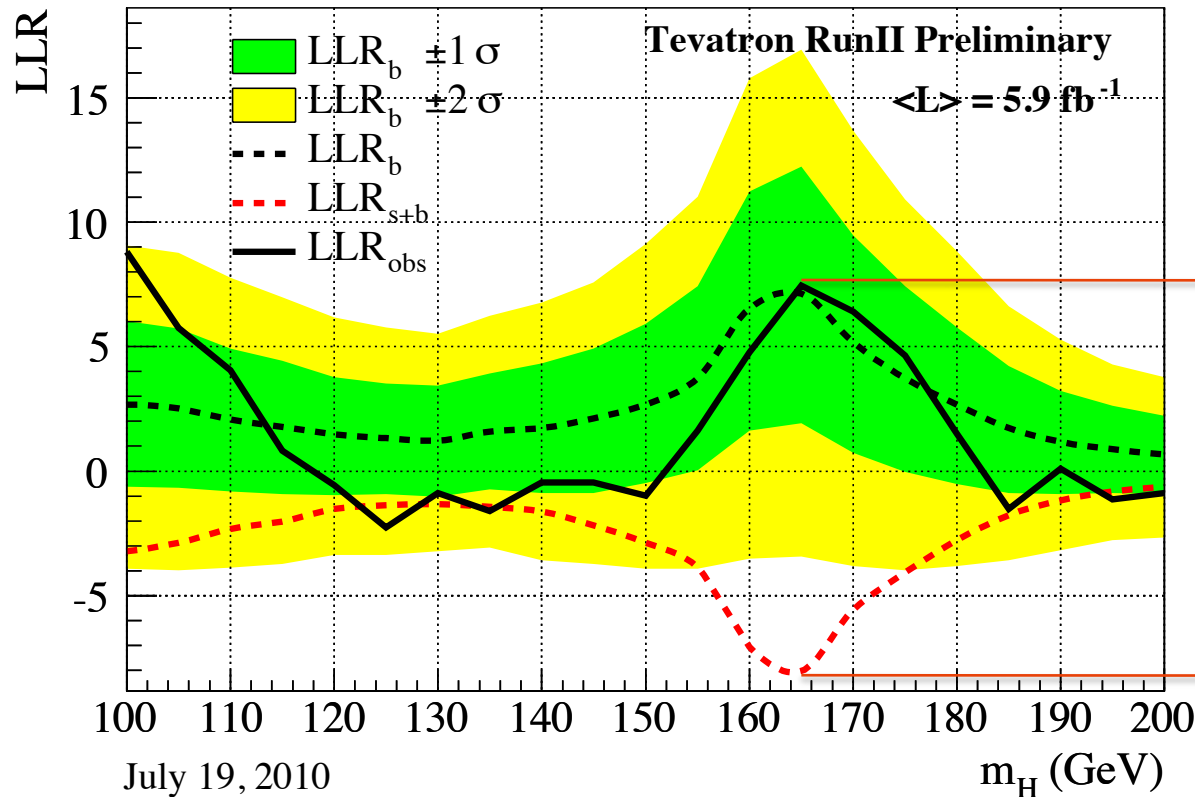
Nuisance parameters allow for variations within errors

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

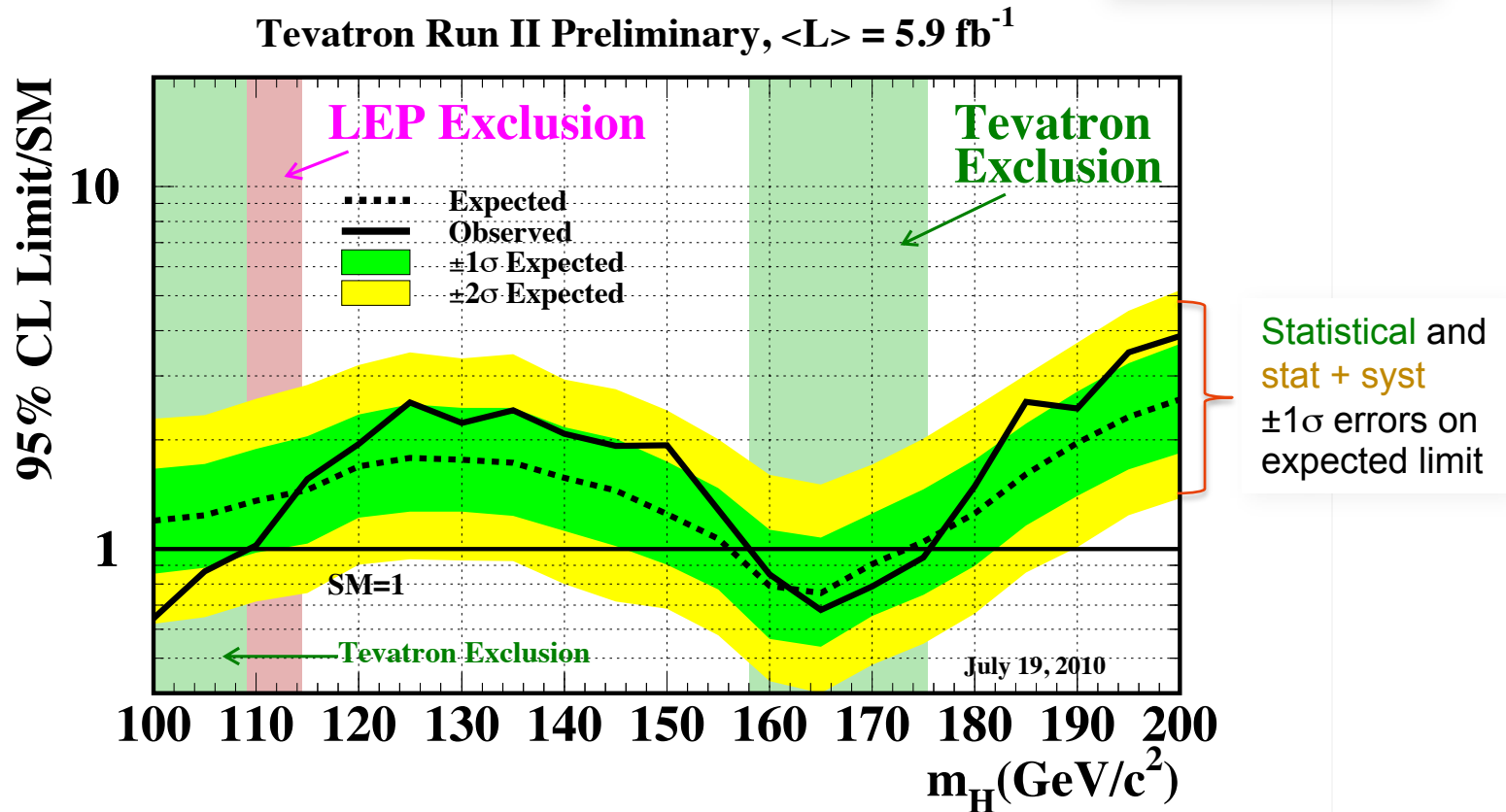


Sensitivity is largest around 165 GeV

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

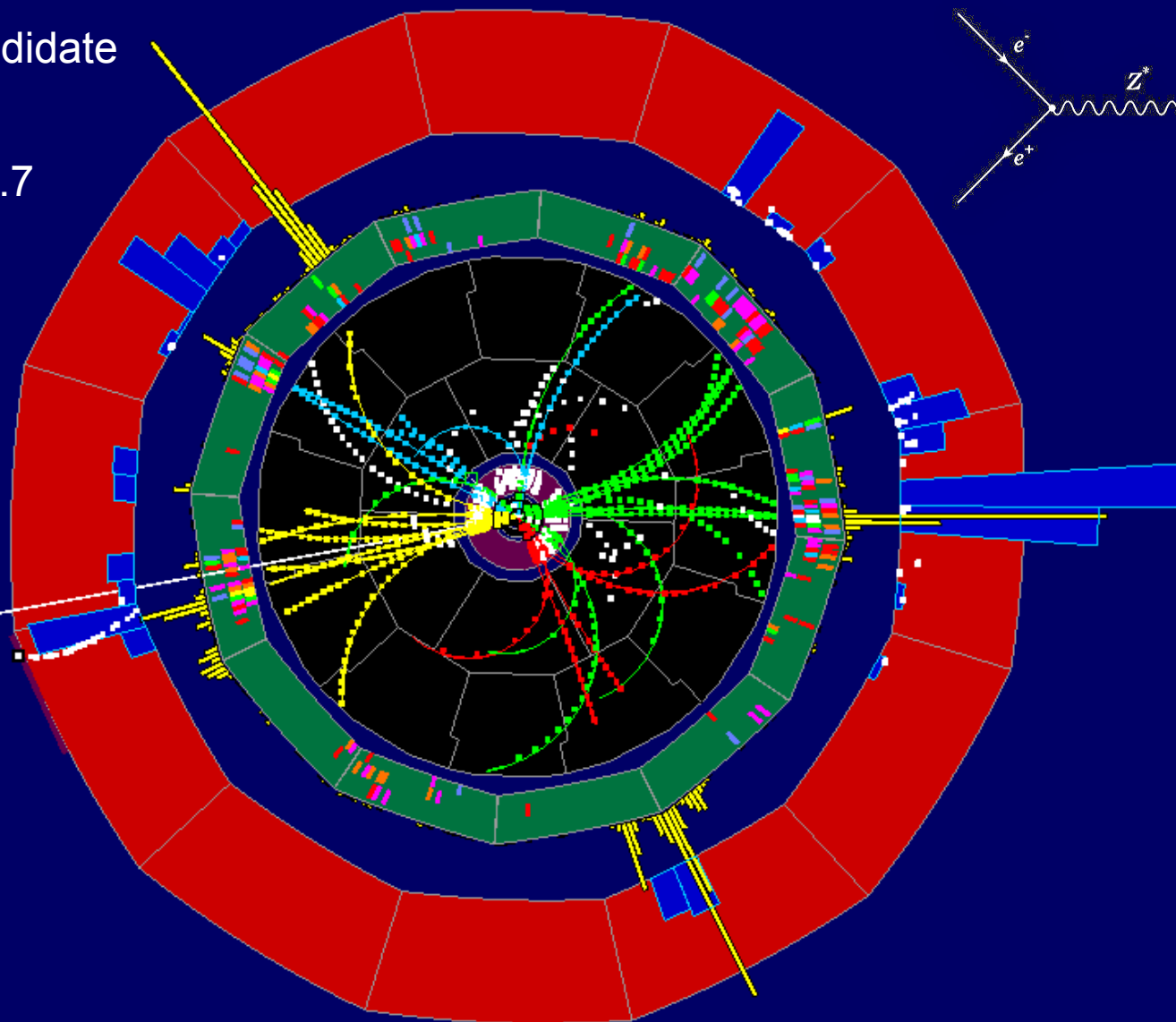
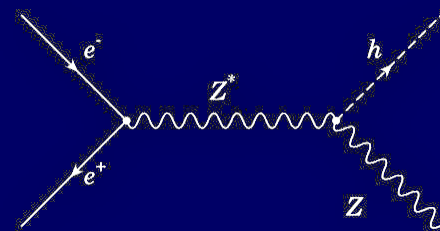
61-4 -

2:32

Run=54698

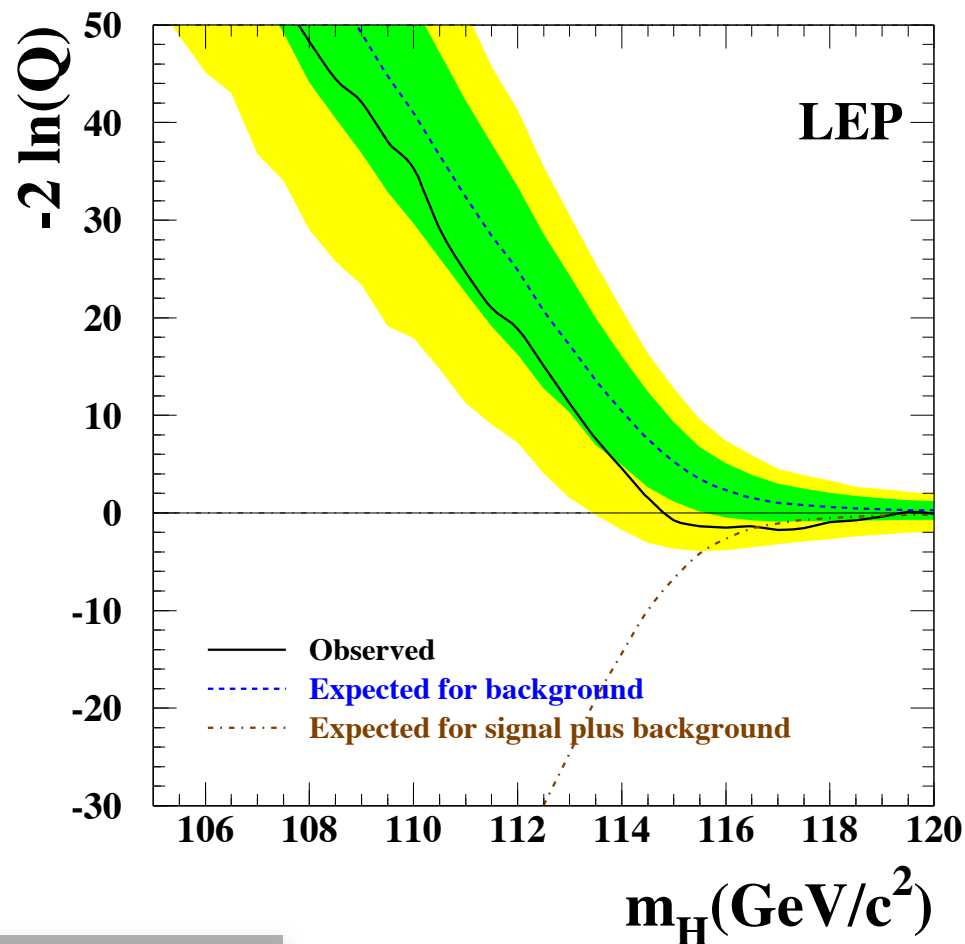
Evt=4881

Detb= E3FFFF

 3 GeV EC
 1.5 GeV HC
ALEPH*HZ* → *bb qq* candidate $M_{bb} = 114 \text{ GeV}$ $s/b|_{MH=115 \text{ GeV}} = 4.7$ 



ALEPH

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

ADLO, PL B 565, 61 (2003)

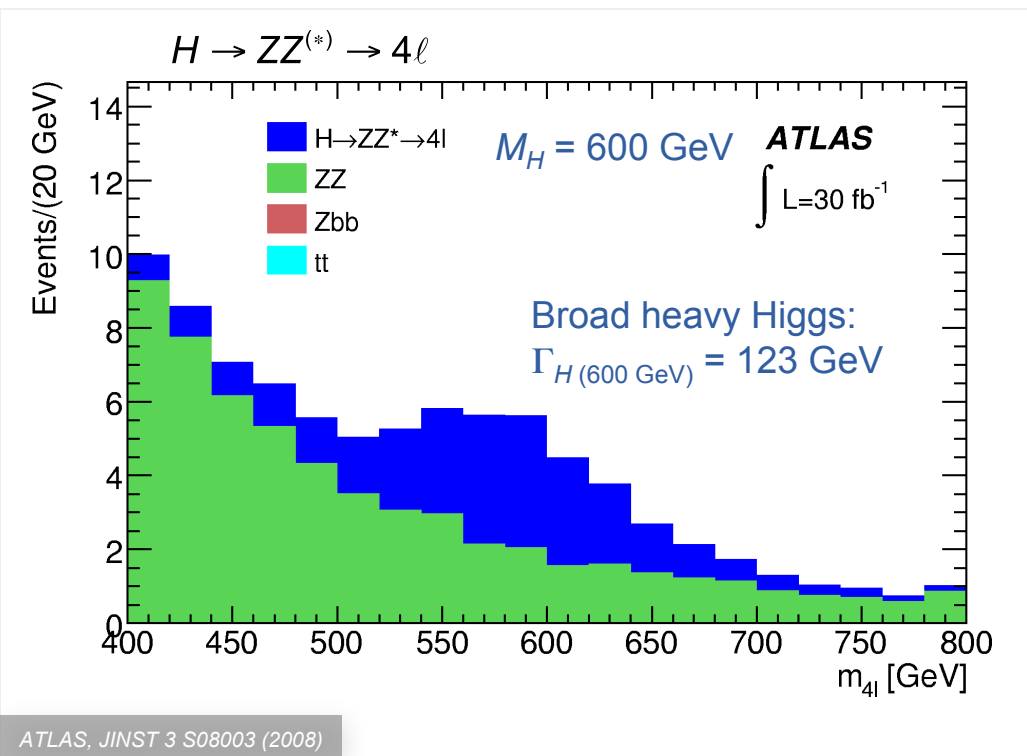
A black and white visualization of a particle collision event, likely from the LHC. It shows a central point of interaction with numerous tracks radiating outwards, some forming dense clusters. A horizontal band across the center contains the title text.

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

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

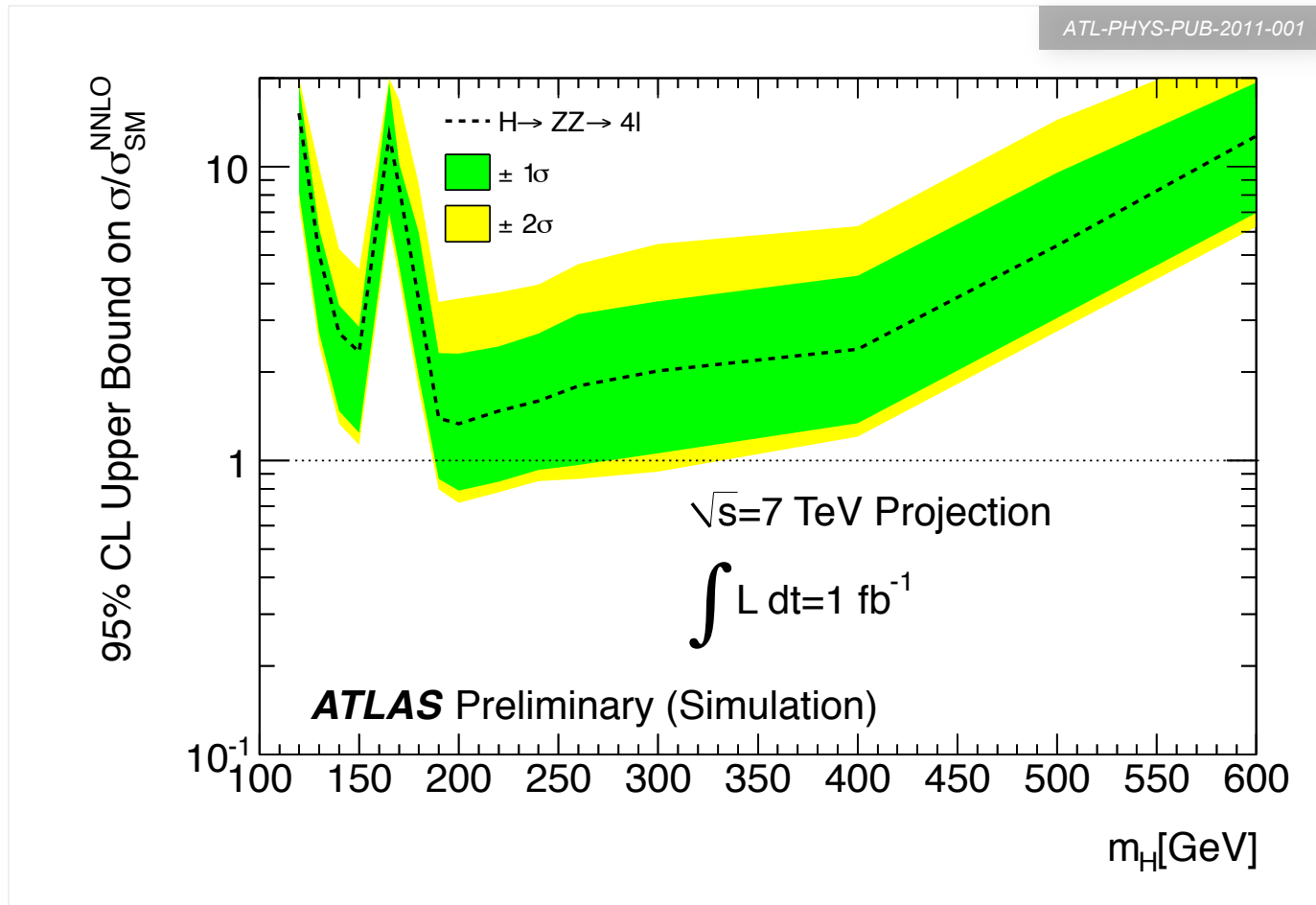
Reject by requiring leptons to be isolated and to match primary vertex

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

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

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

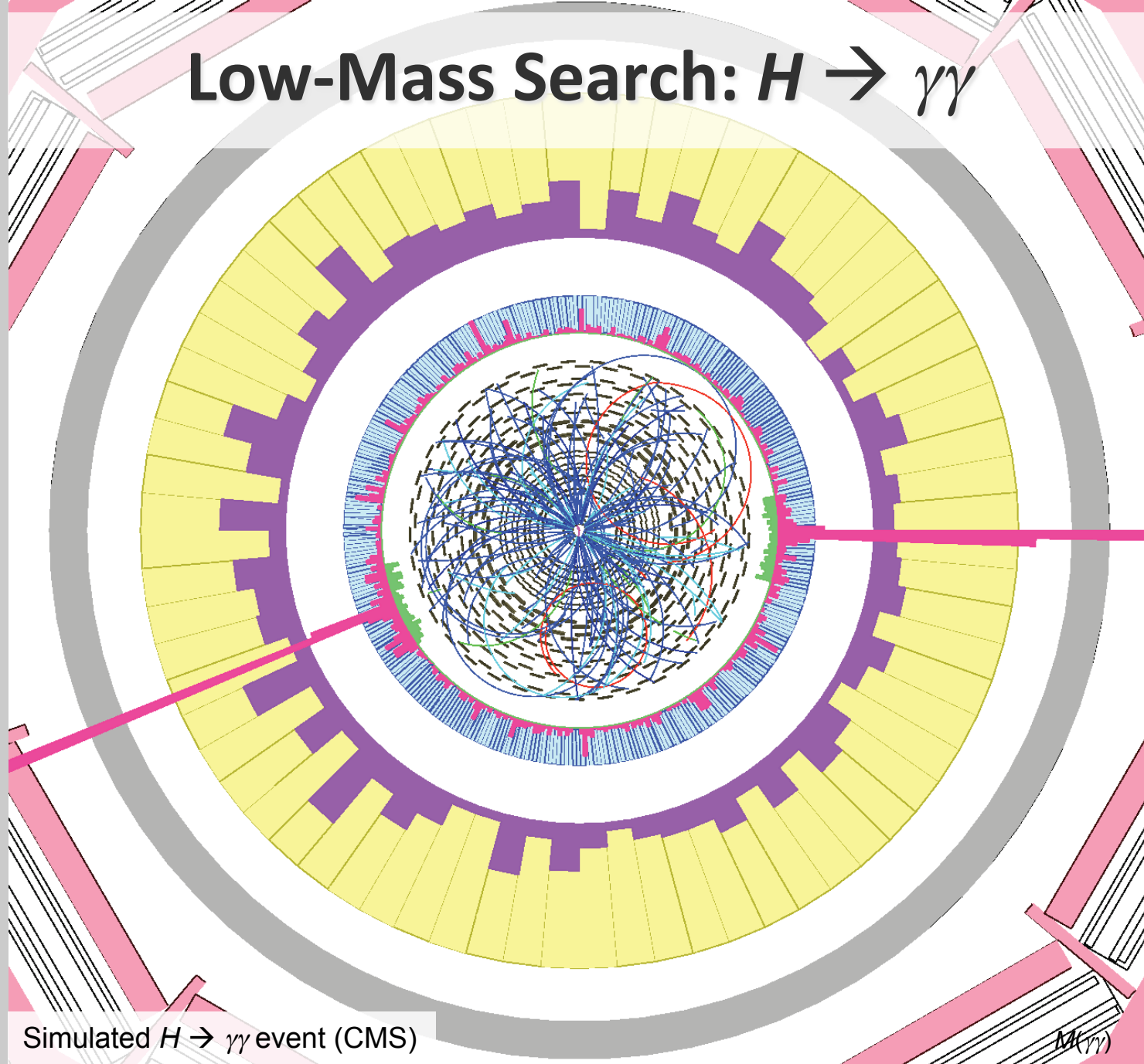
Extrapolated SM Higgs Exclusion potential with 1 fb^{-1}



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: $H \rightarrow \gamma\gamma$



Simulated $H \rightarrow \gamma\gamma$ event (CMS)

$M(\gamma\gamma)$

$$H \rightarrow \gamma\gamma$$

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

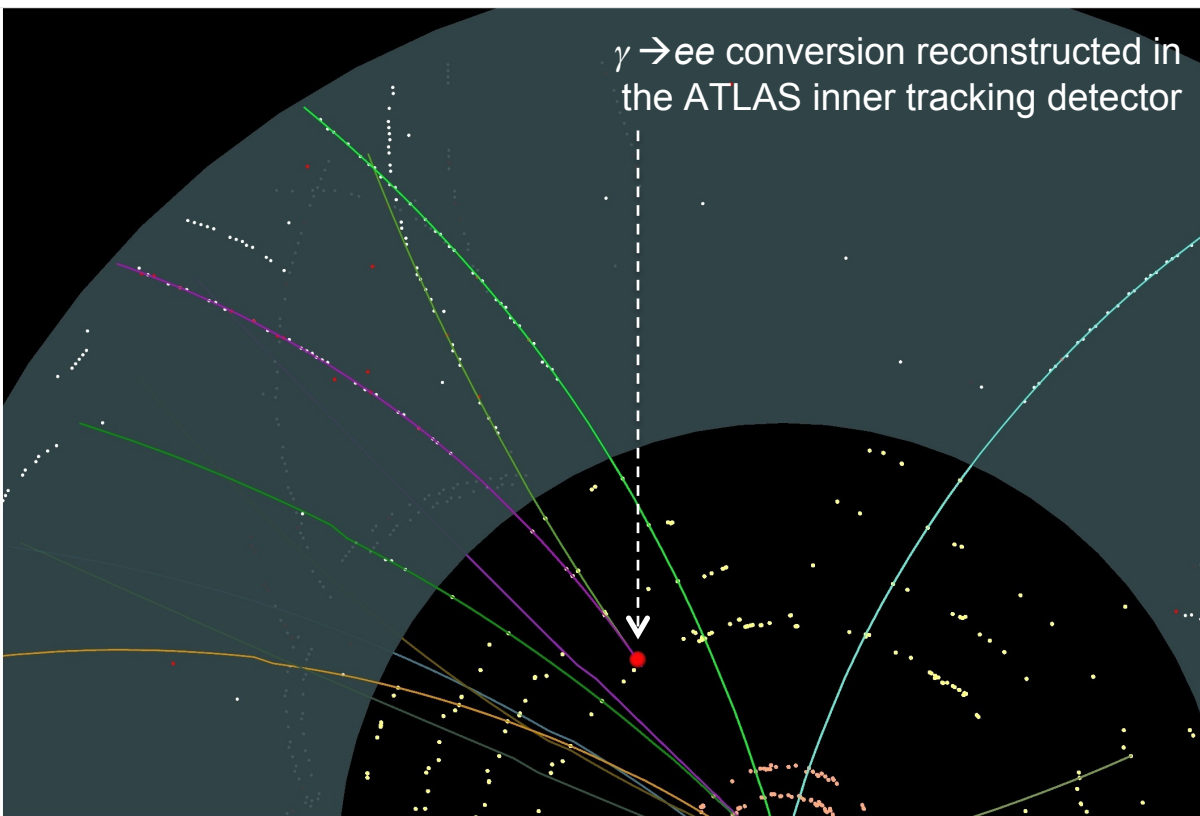
(*) Test beam numbers, w/o ID

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

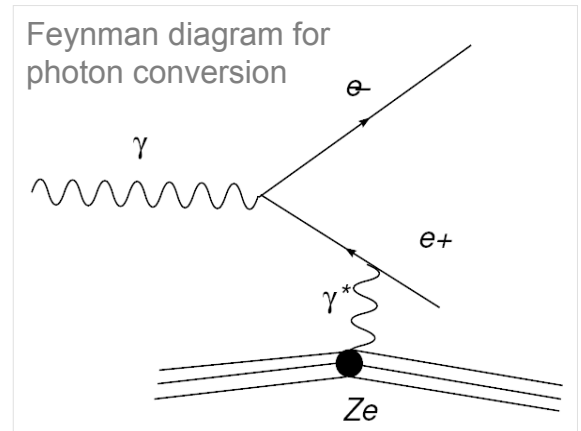
But: full picture must include error on opening angle ($\theta_{\gamma\gamma}$), $\gamma \rightarrow ee$ conversions, jet backgr.

$$H \rightarrow \gamma\gamma$$

Significant amount of material in the ATLAS and CMS inner tracking systems ($X/X_0 \sim 0.4 - 1.4$) requires to include and efficiently reconstruct $\gamma \rightarrow ee$ conversions



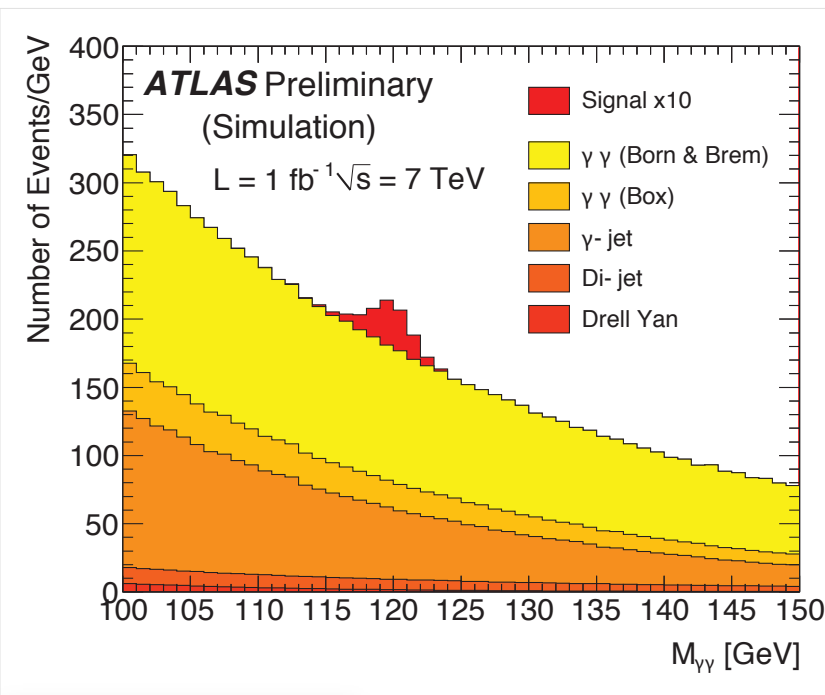
Fractions of converted photons $\sim 55\%$, strong angular dependence



$$H \rightarrow \gamma\gamma$$

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

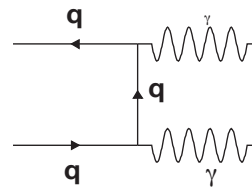
Signal selection: need excellent E_γ resolution, and efficient & pure photon ID; use MVA: $M_{\gamma\gamma}$, $\cos\theta^*$, $p_{T,\gamma\gamma}$



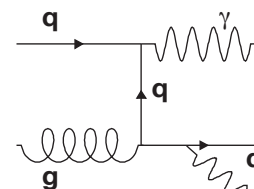
ATLAS, JINST 3 S08003 (2008)

Backgrounds:

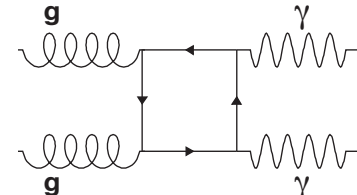
$\gamma + \gamma$ ("irreducible" – not quite)



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

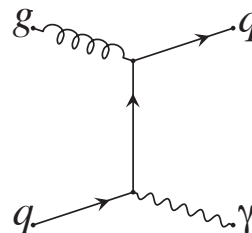


Bremsstrahlung, $O(\alpha^2\alpha_s)$
and quark fragmentation



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 $\gamma\gamma$)

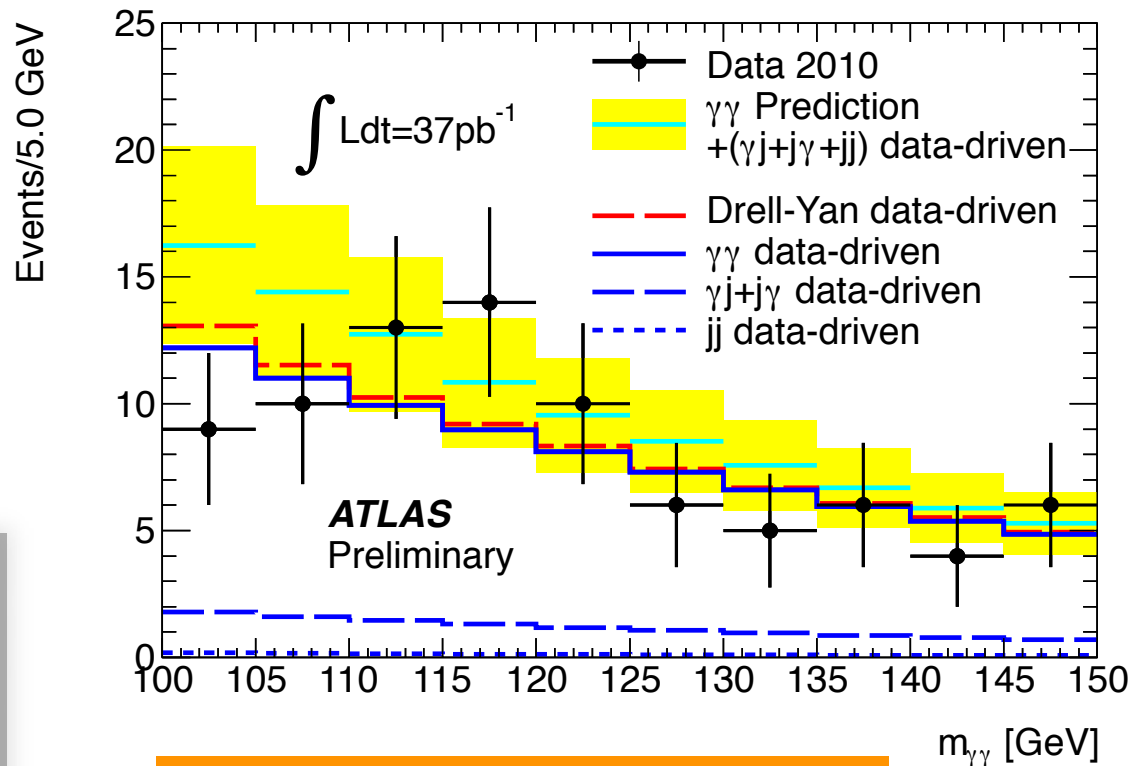


Requires
excellent
calorimeter
based γ -jet
separation

$$H \rightarrow \gamma\gamma$$

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”)

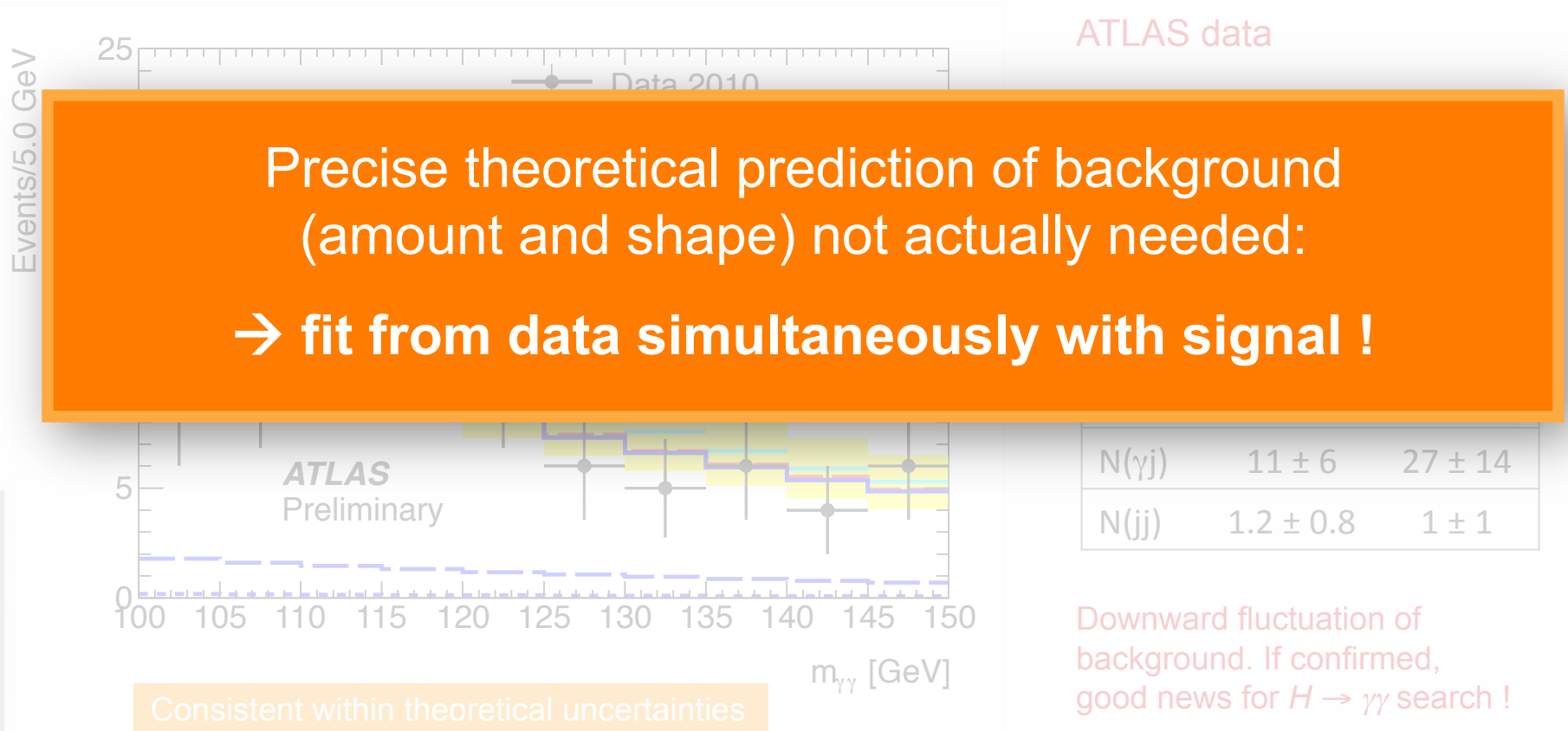
	Data	MC
$N(\gamma\gamma)$	69 ± 12	86 ± 23
$N(\gamma j)$	11 ± 6	27 ± 14
$N(jj)$	1.2 ± 0.8	1 ± 1

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

$$H \rightarrow \gamma\gamma$$

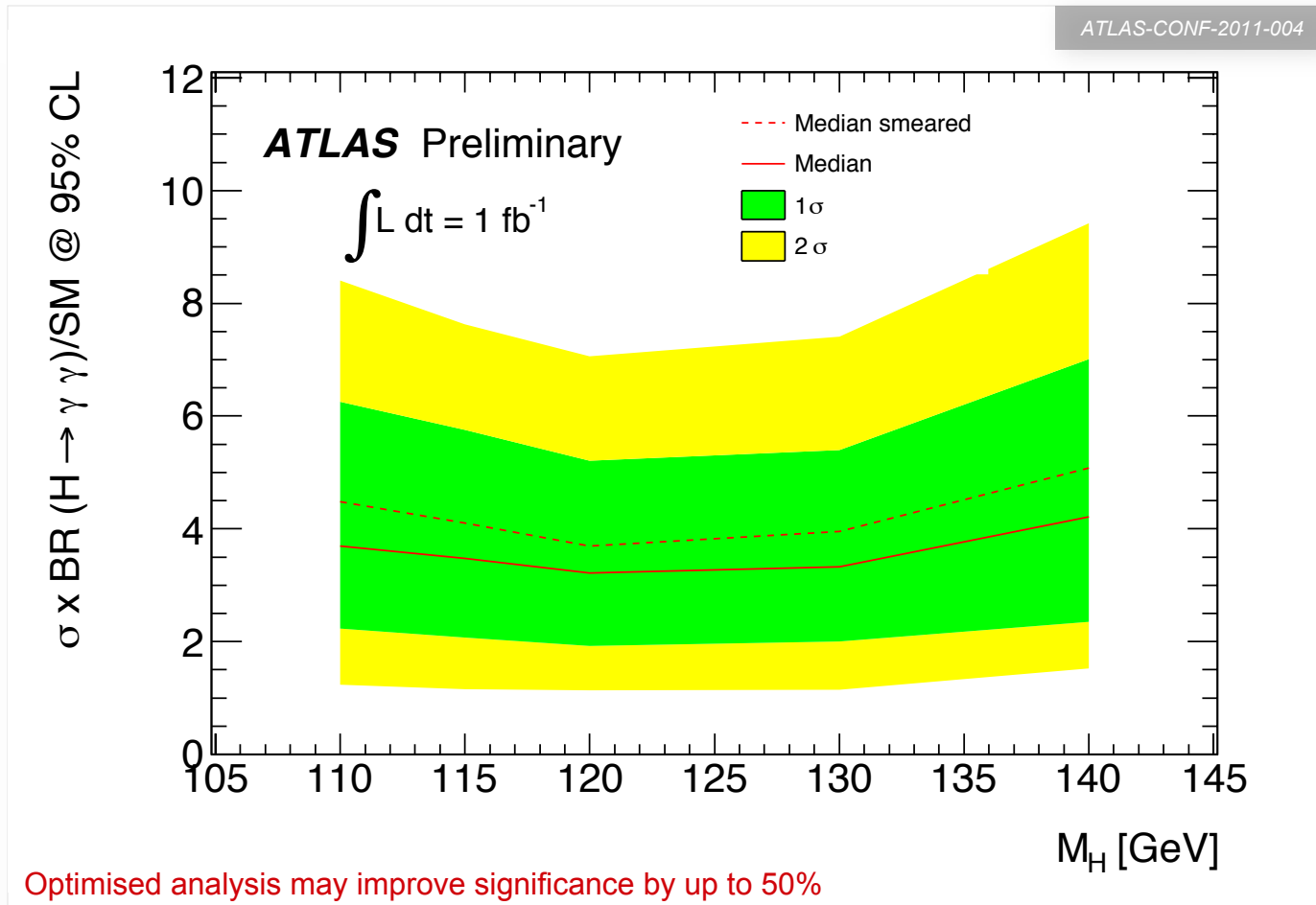
Clean discovery channel for light Higgs: $\sigma \times \text{BR} (115 \text{ GeV}) \approx 100 \text{ fb}$

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

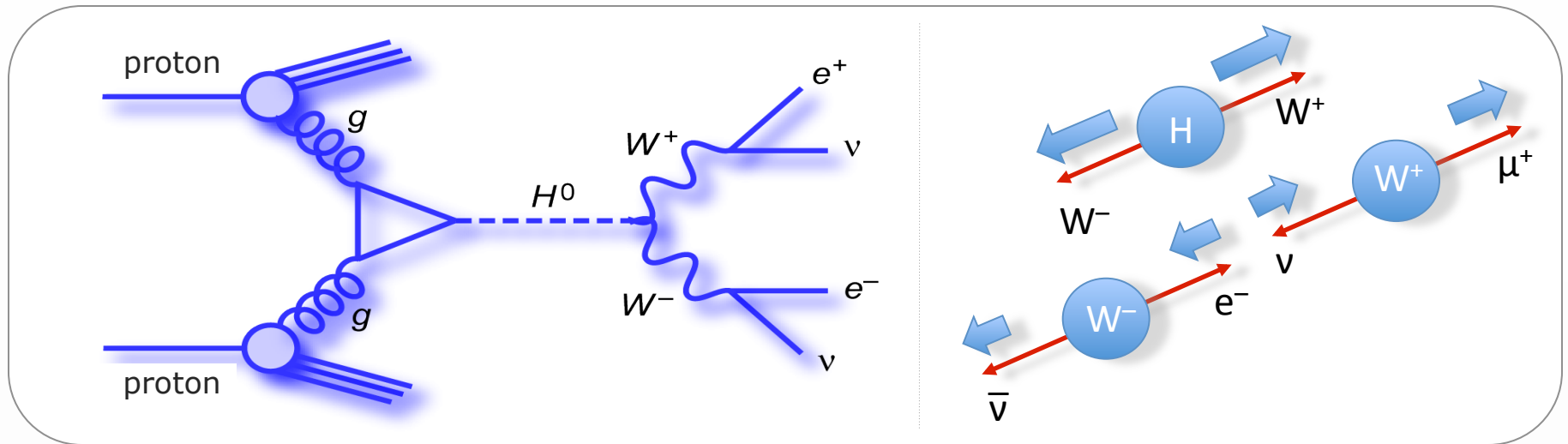


$H \rightarrow \gamma\gamma$ – Exclusion potential

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

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

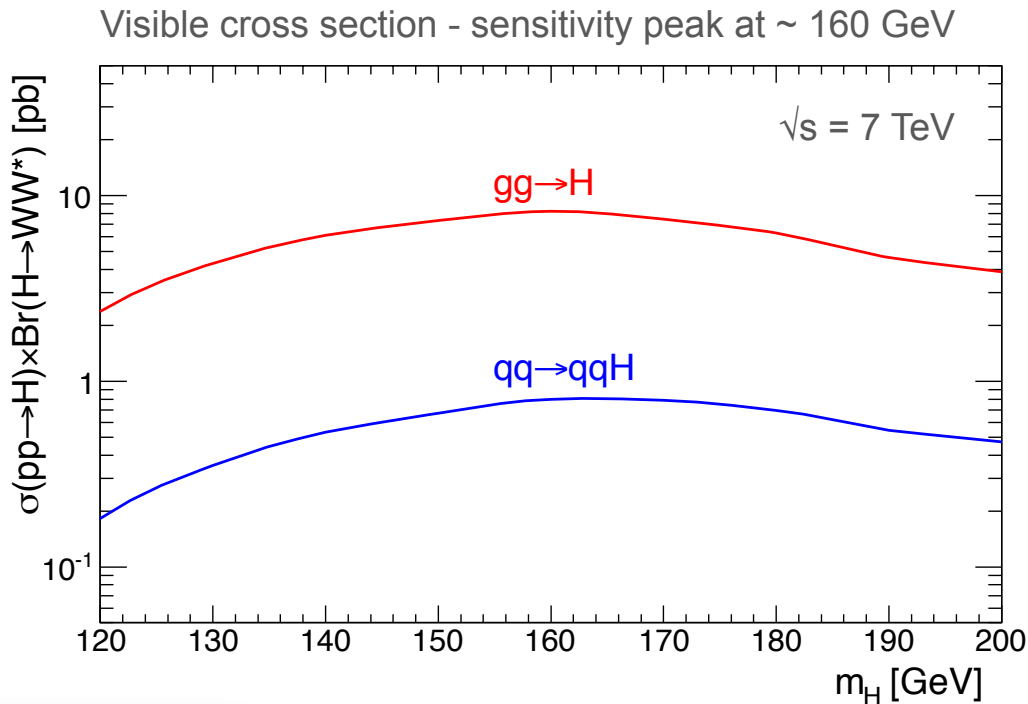
Dominant cross section > 135 GeV, most sensitive channel

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

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

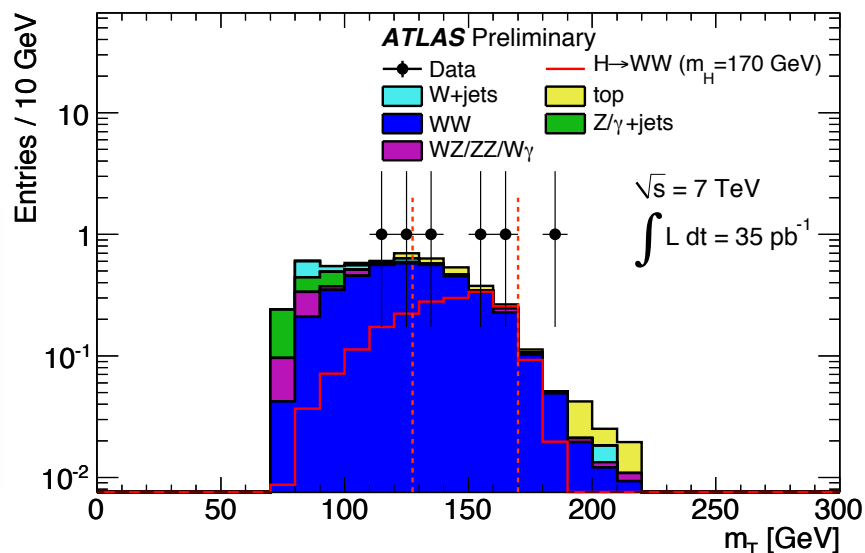
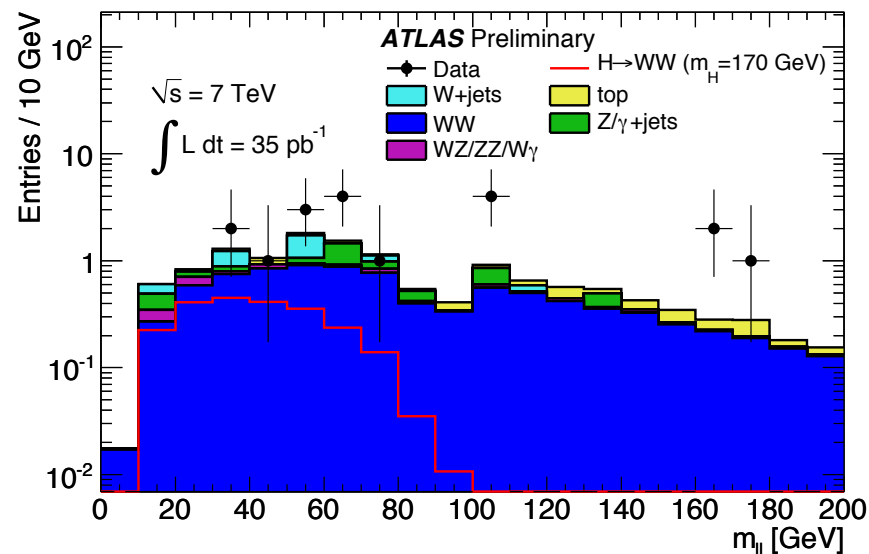
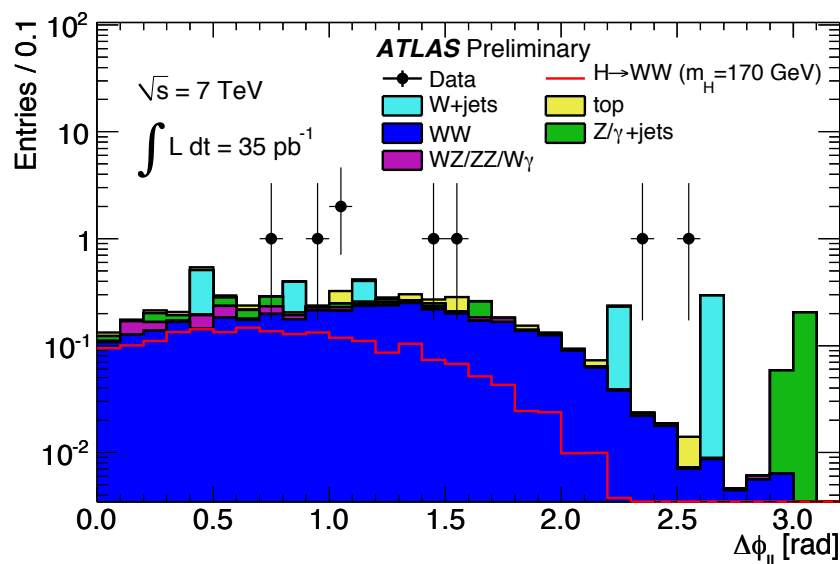
Separate analysis in $H + 0, 1 \text{ jet}$ (gluon fusion), and $H + 2 \text{ jets}$ (weak boson fusion)



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 , $E_{T,miss}$



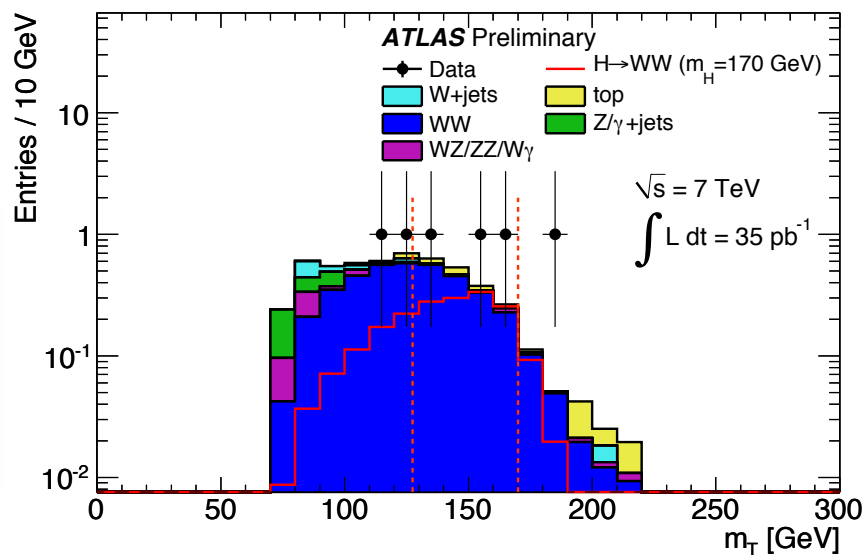
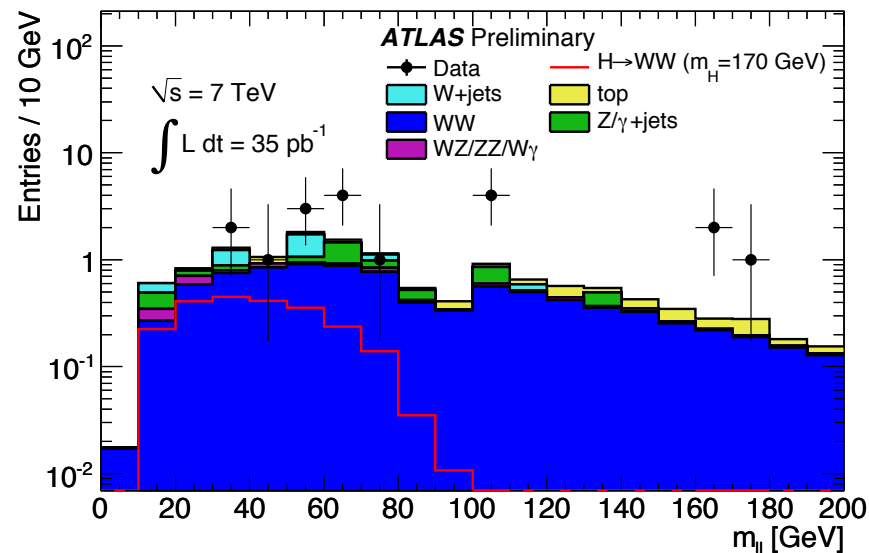
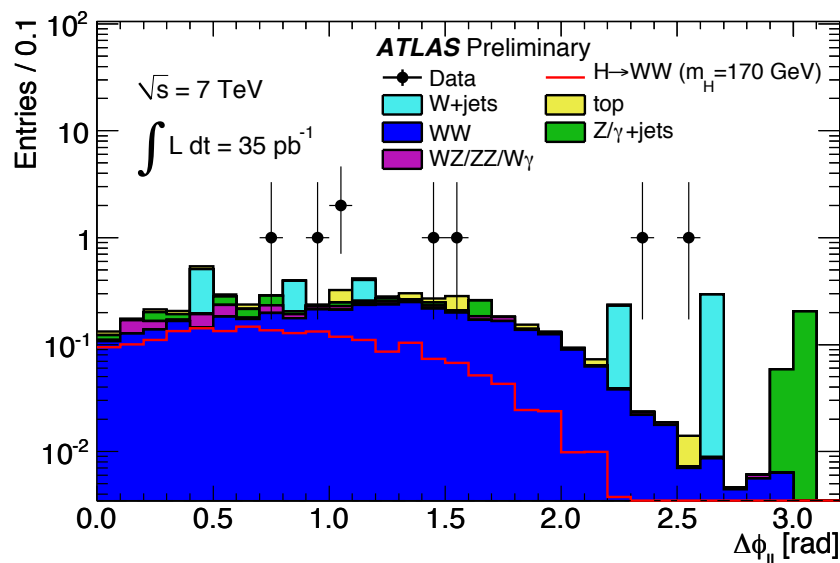
Higgs detection depends on good understanding of WW background

Recent measurement by CMS finds:

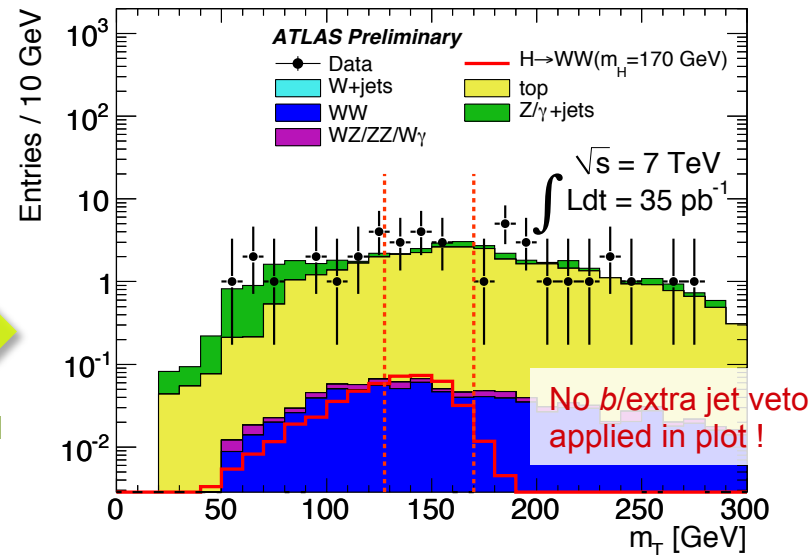
$\sigma(pp \rightarrow W^+W^-) = (41.1 \pm 15.3 \pm 7.3) \text{ pb}$
compared to $(43.0 \pm 2.0) \text{ pb}$ in NLO SM

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 , $E_{T,\text{miss}}$

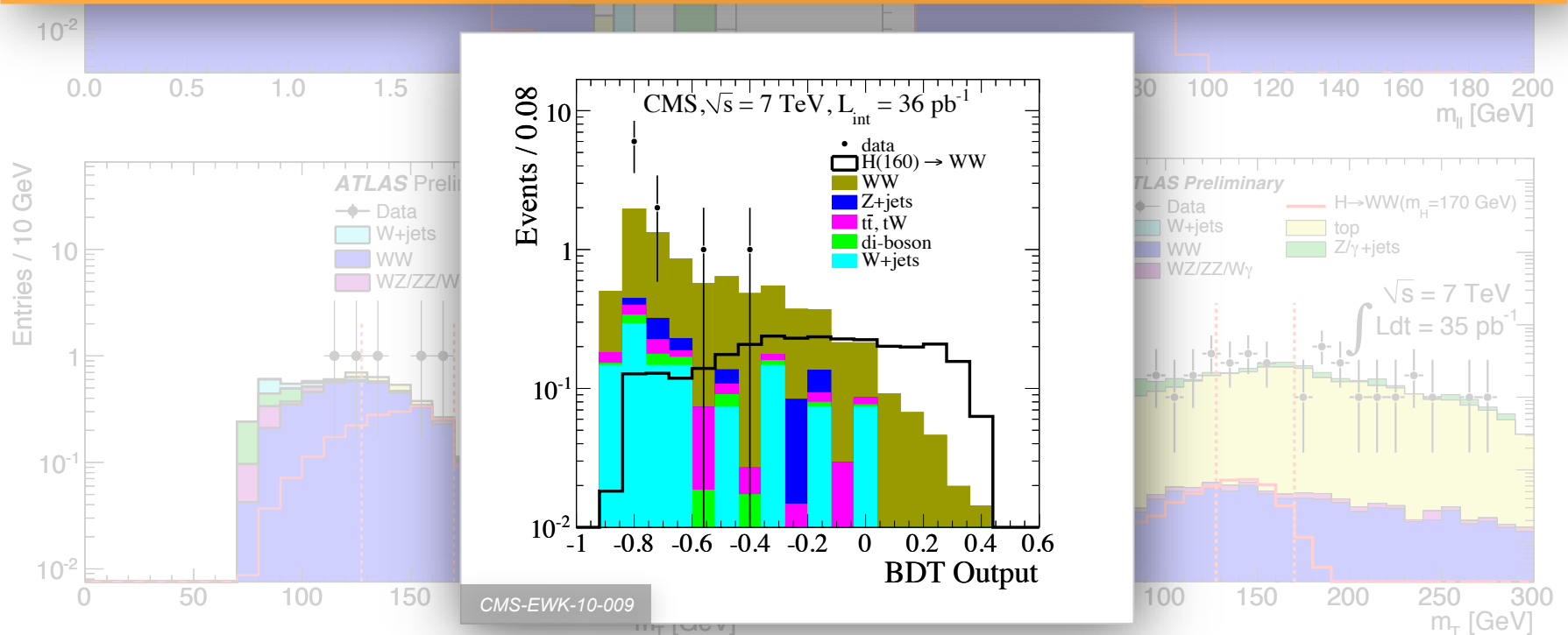


2-jet channel



- 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



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

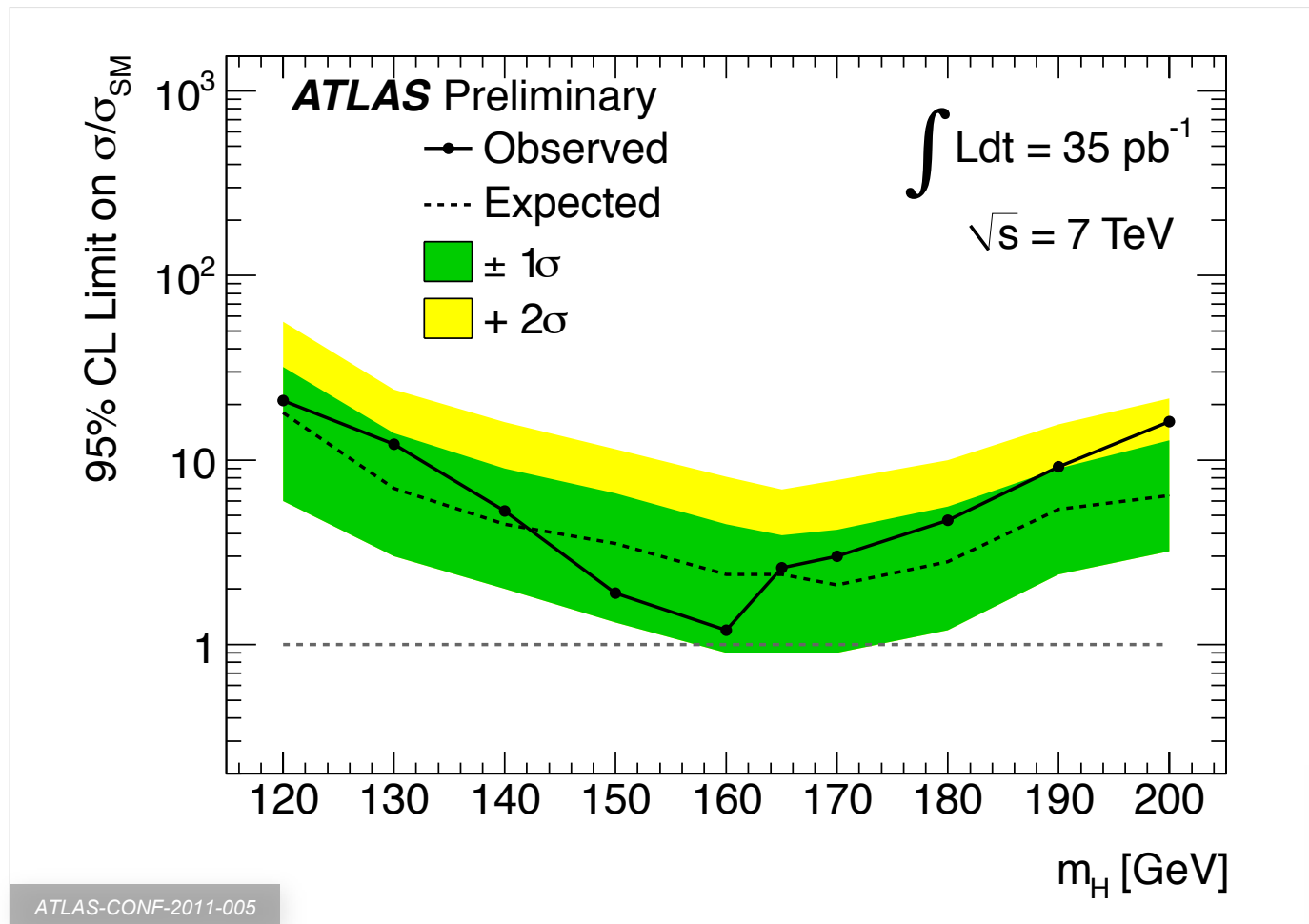
Number of events found by ATLAS and predicted for $M_H = 170$ GeV hypothesis

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

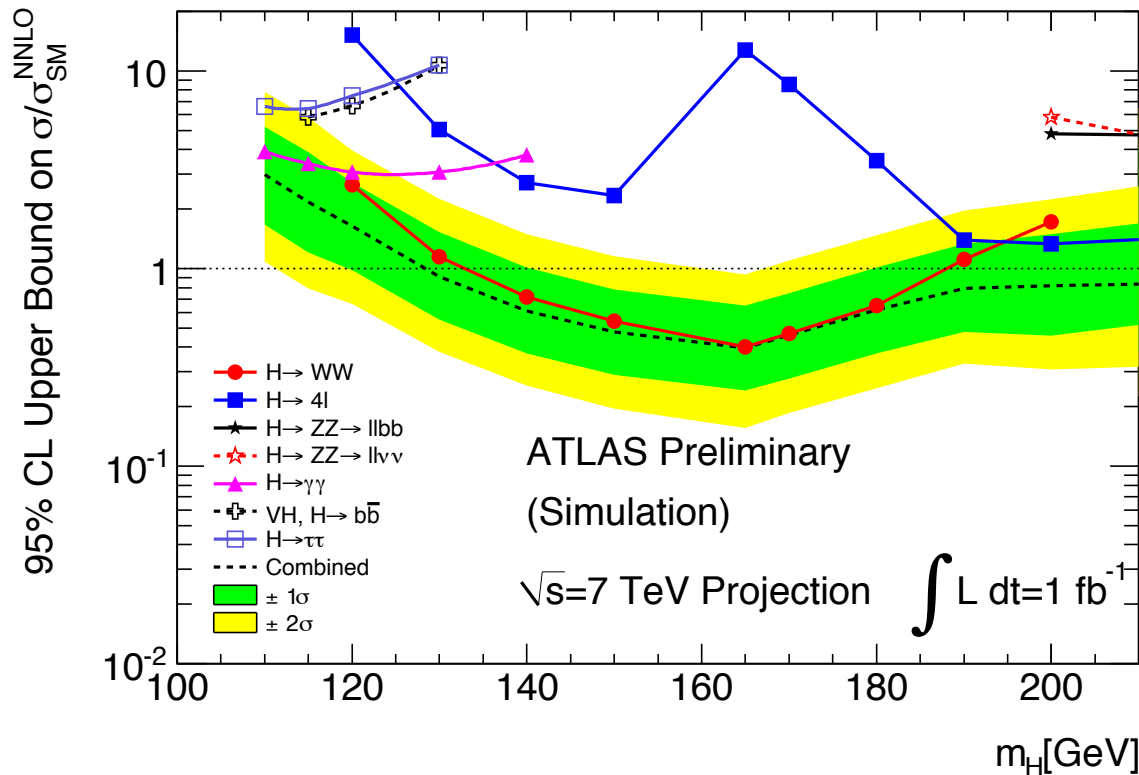
$H \rightarrow WW \rightarrow 2 \text{ leptons} + 2\nu$

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



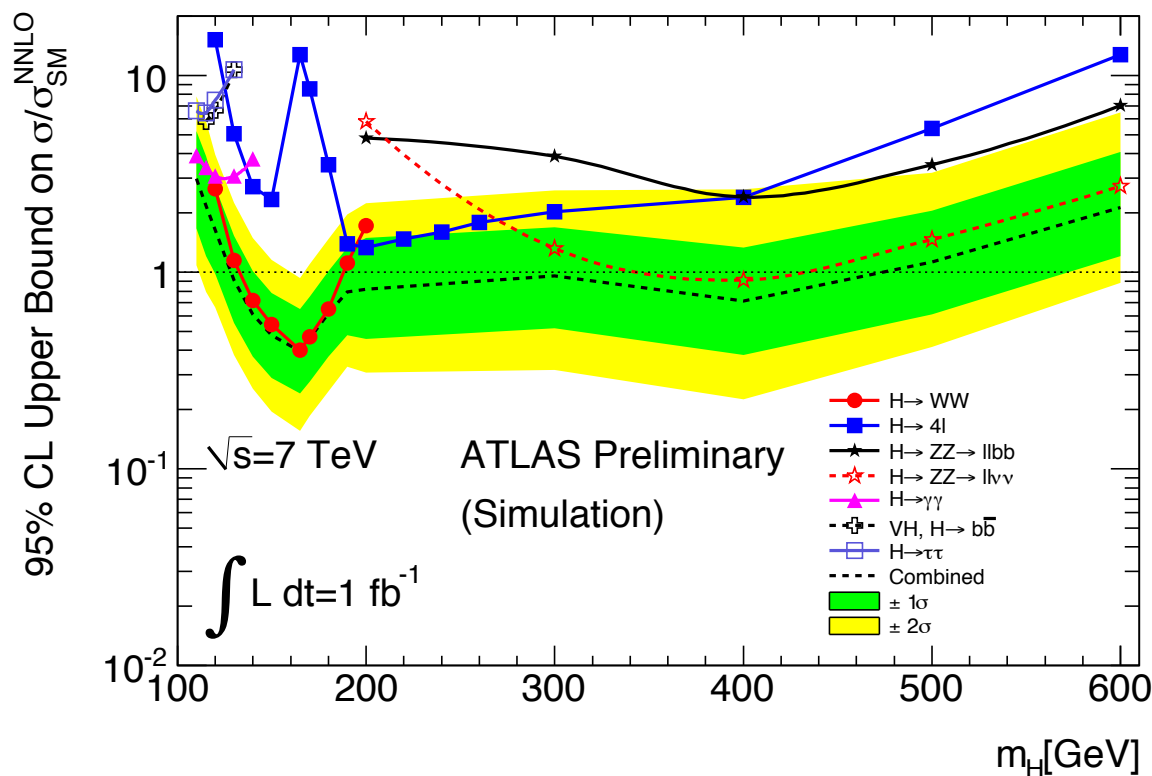
Further improvement
from combination of
ATLAS and CMS

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 ~ 460 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 vertex from which many tracks radiate outwards, forming two main jets of particles. The background is dark with some horizontal bands.

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

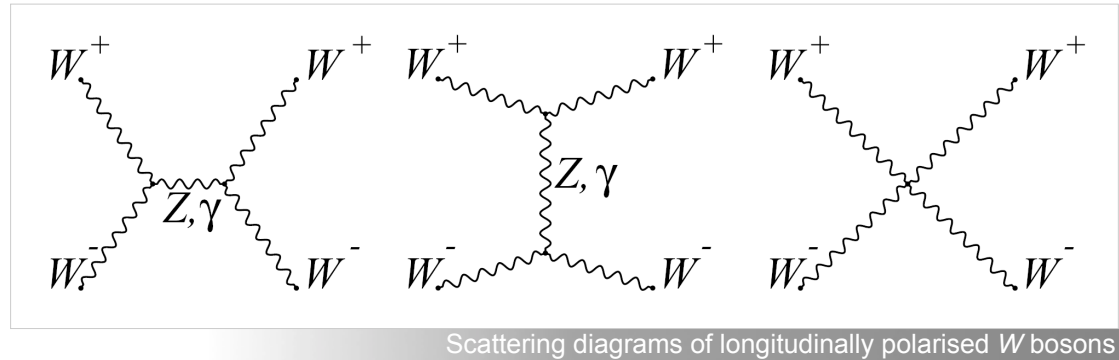
After a Higgs-like discovery, one needs to measure the properties of the new particle to consolidate whether it is indeed the wanted SM Higgs → Measure:

- **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)

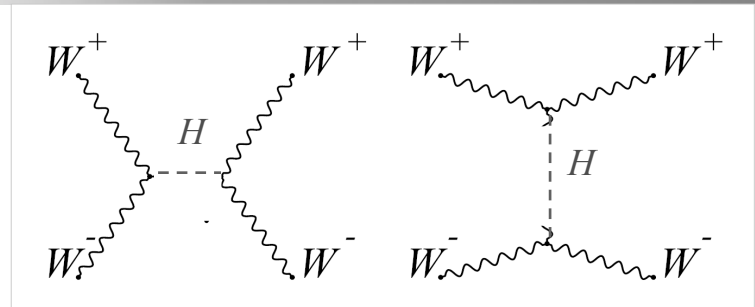
Unitarity – the Higgs Boson as UV Regulator

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

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



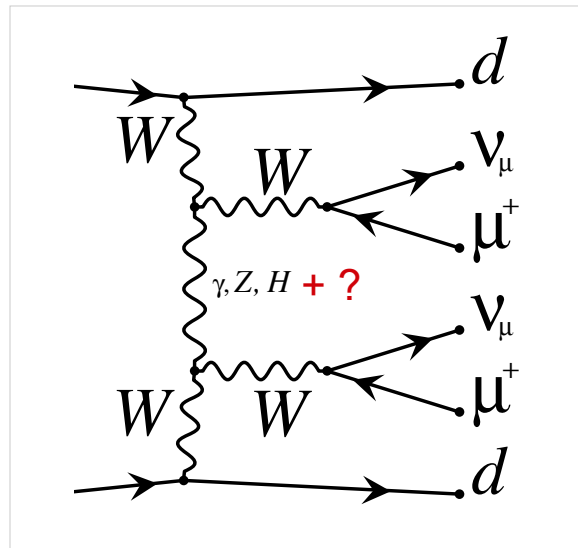
$$\mathcal{M}_{Z,\gamma,H}(W_L^+W_L^- \rightarrow W_L^+W_L^-) \propto -\sqrt{2}G_F \cdot M_H^2 \cdot \left(\frac{s}{s-M_H^2} + \frac{t}{t-M_H^2} \right)$$



- 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 ?

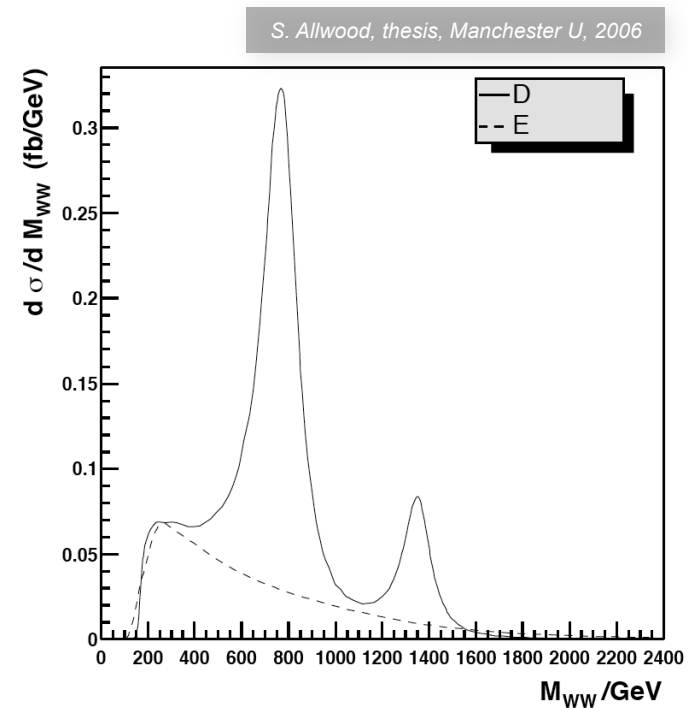
If the Higgs is very heavy, or if EW symmetry is broken by something else than a Higgs condensate (e.g., by strong interactions), W bosons would become **strongly interacting particles at TeV scale**.



Fusion of longitudinally polarised W at the LHC

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

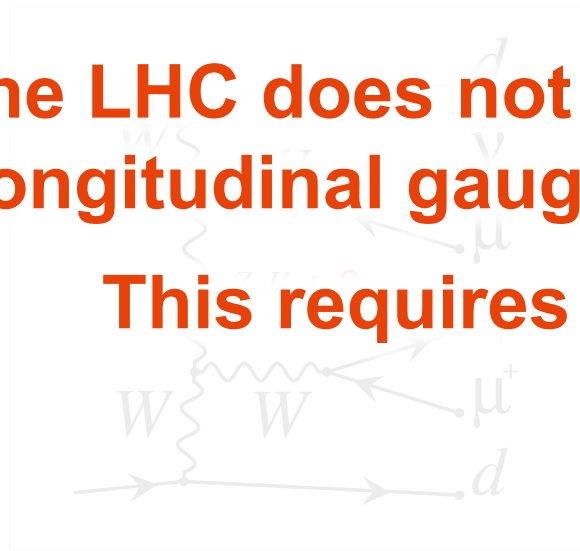
The experimental signature could be strong **WW** resonances



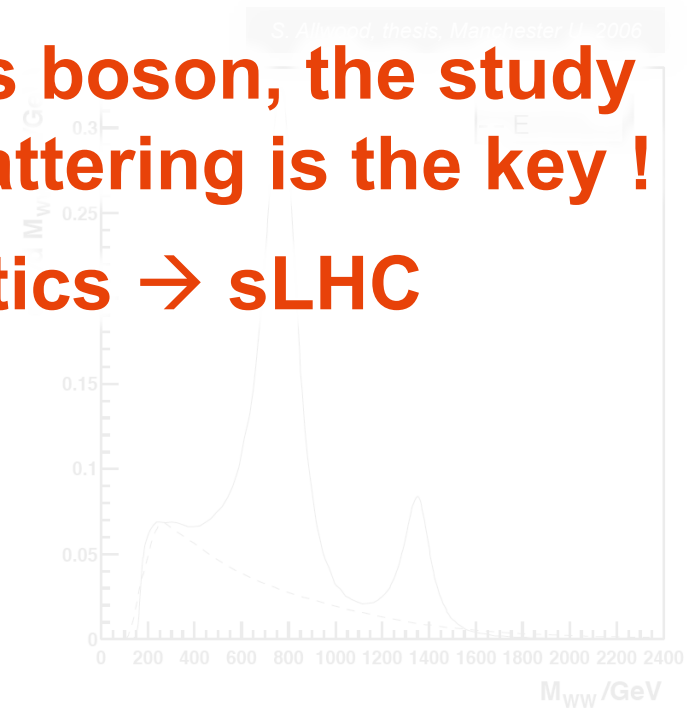
Strong WW Scattering ?

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 $M_H > 129$ GeV (perturbativity sets upper limit)
- Electroweak precision data give: $M_H = 96^{+30}_{-25}$ GeV
- Direct accelerator searches exclude $M_H < 114$ GeV and $158 < M_H < 175$ GeV

The superb performance of the LHC in 2010 stimulates our imagination

- ATLAS alone expects to exclude $129 < M_H < 460$ GeV with 1 fb^{-1}
- Possible 3σ evidence with ATLAS+CMS combined for $131 < M_H < 430$ 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

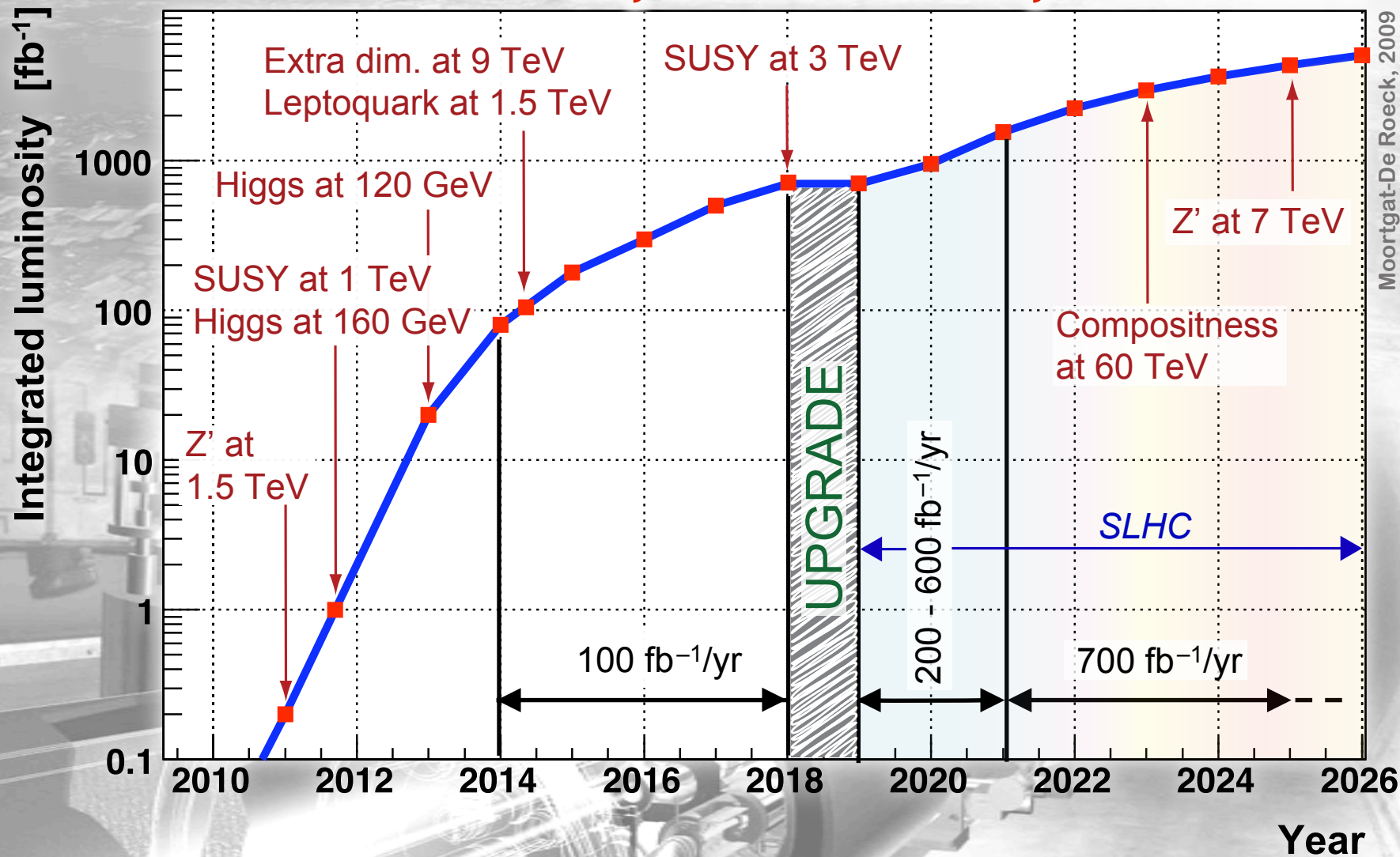
Many SM and BSM Higgs results from ATLAS in preparation for Moriond 2011

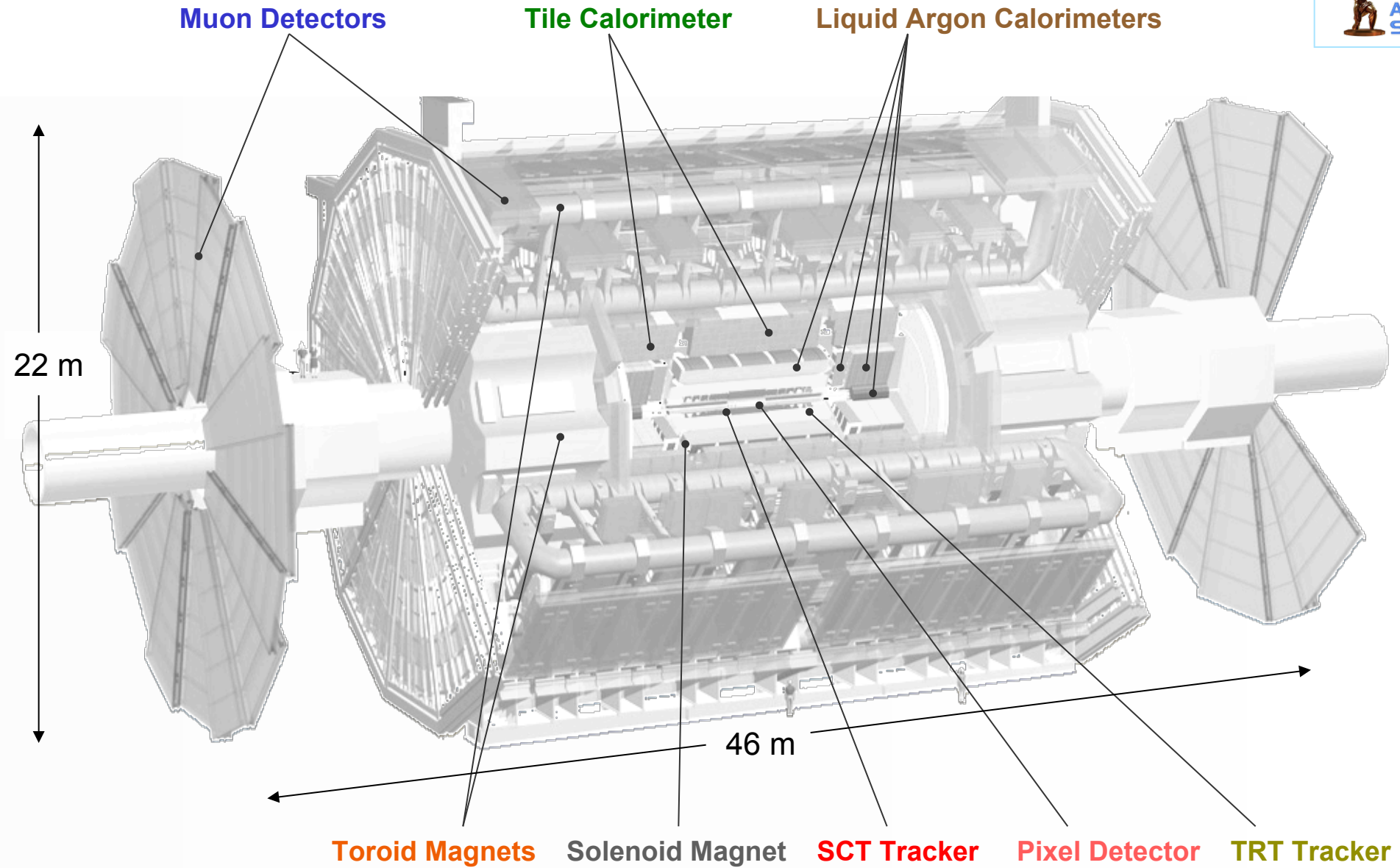
Expected for 2011: $L_{\text{peak}} \approx 1.3\text{--}2.0 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, $L_{\text{int}} \approx 2.7\text{--}3.7 \text{ fb}^{-1}$

extra slides

The LHC Programme in a Nutshell

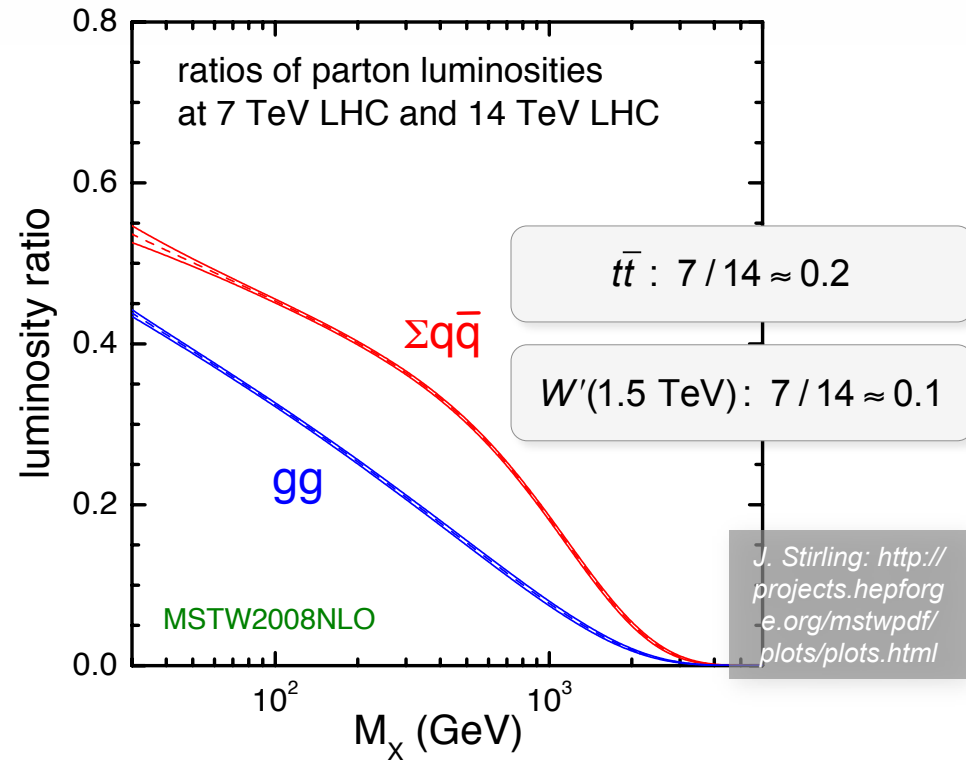
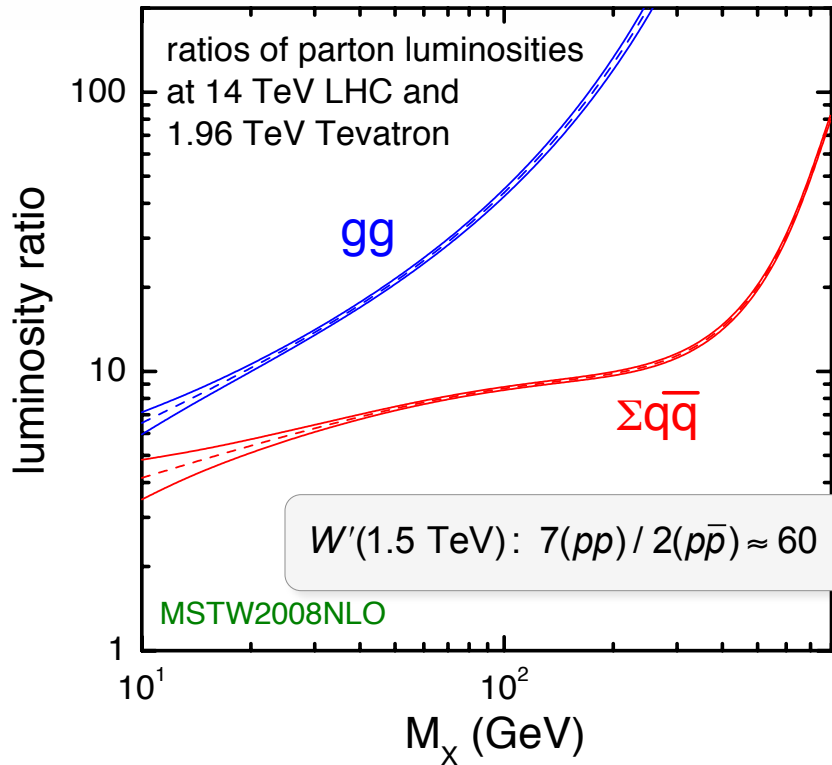
Only look at the luminosity - not the dates !!





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 $M_X < 300 \text{ GeV}$

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:

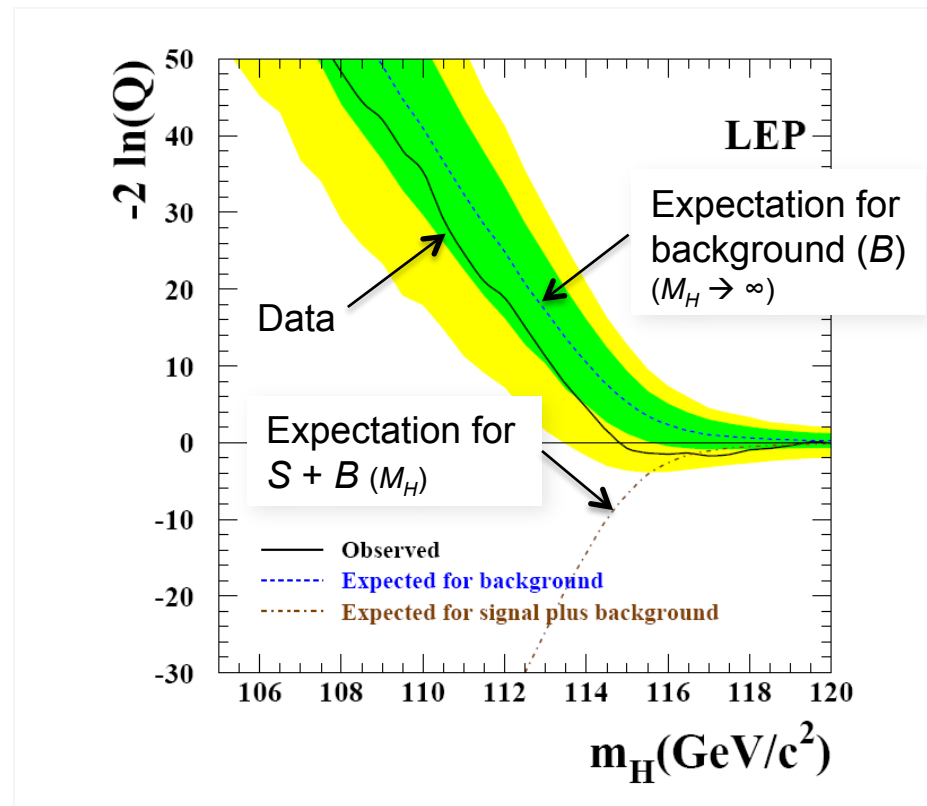
$$Q(M_H) \equiv \frac{L_{s+b}(M_H)}{L_b(M_H)}$$

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

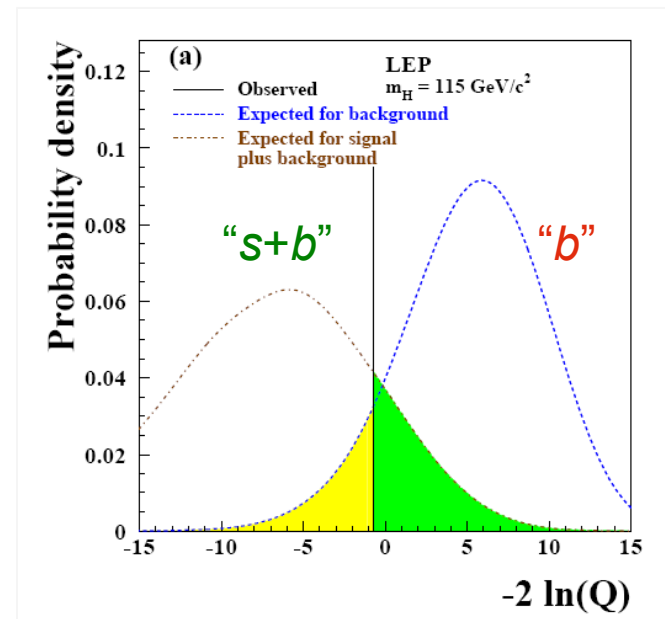
$$CL_b = 1 - P(LLR < LLR_{Data} | B)$$

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

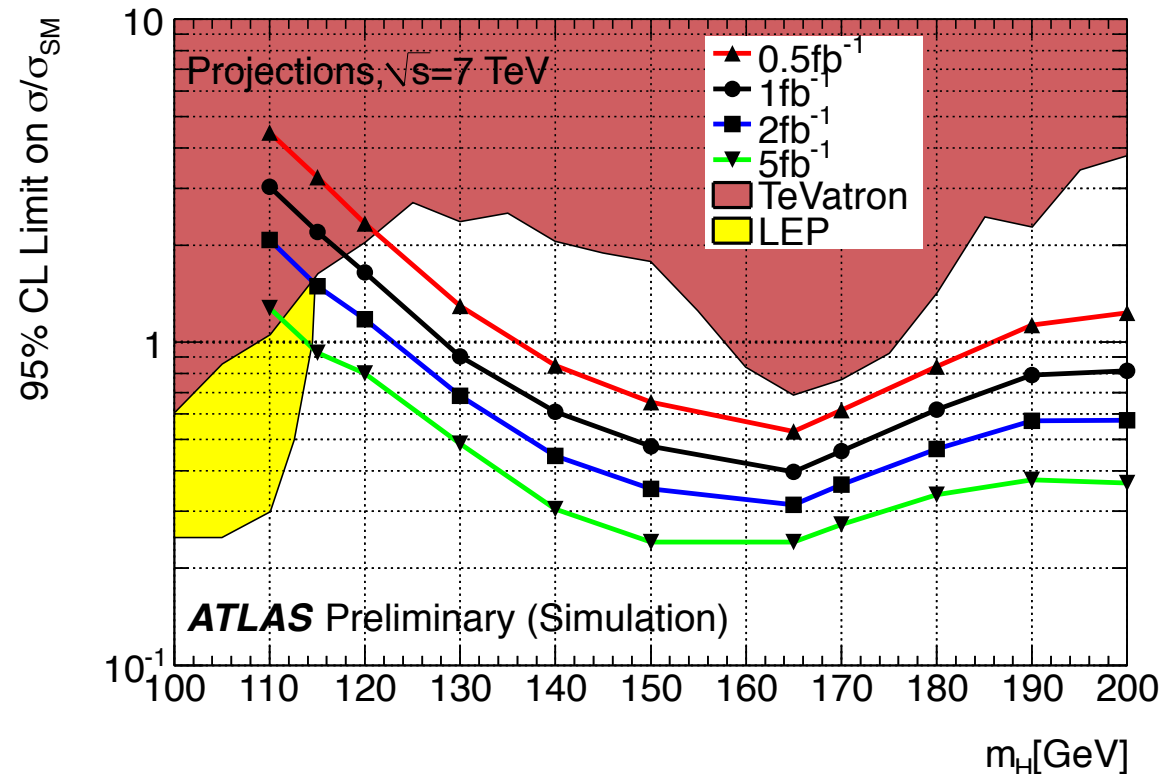
$$CL_s = CL_{s+b} / CL_b$$

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

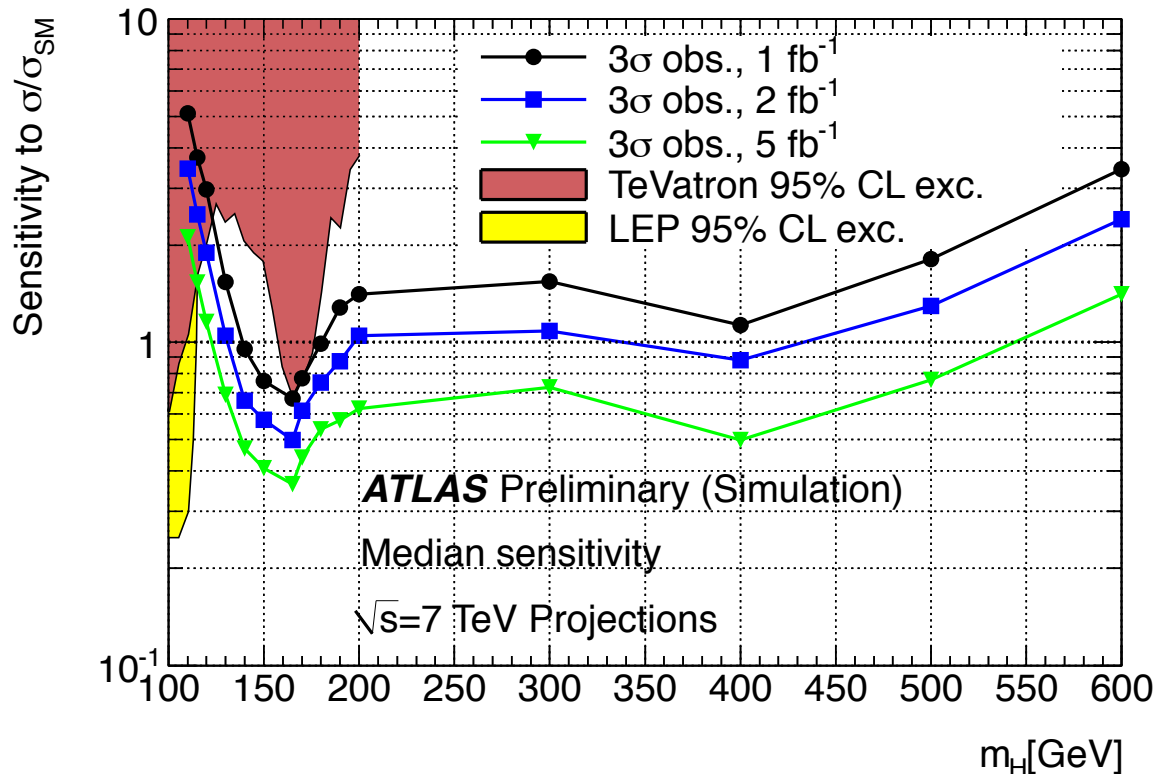


Further improvement
from combination of
ATLAS and CMS

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

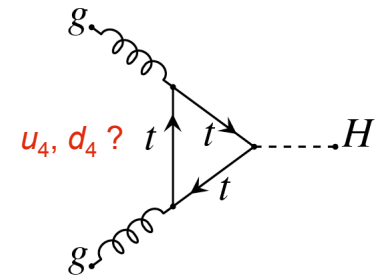
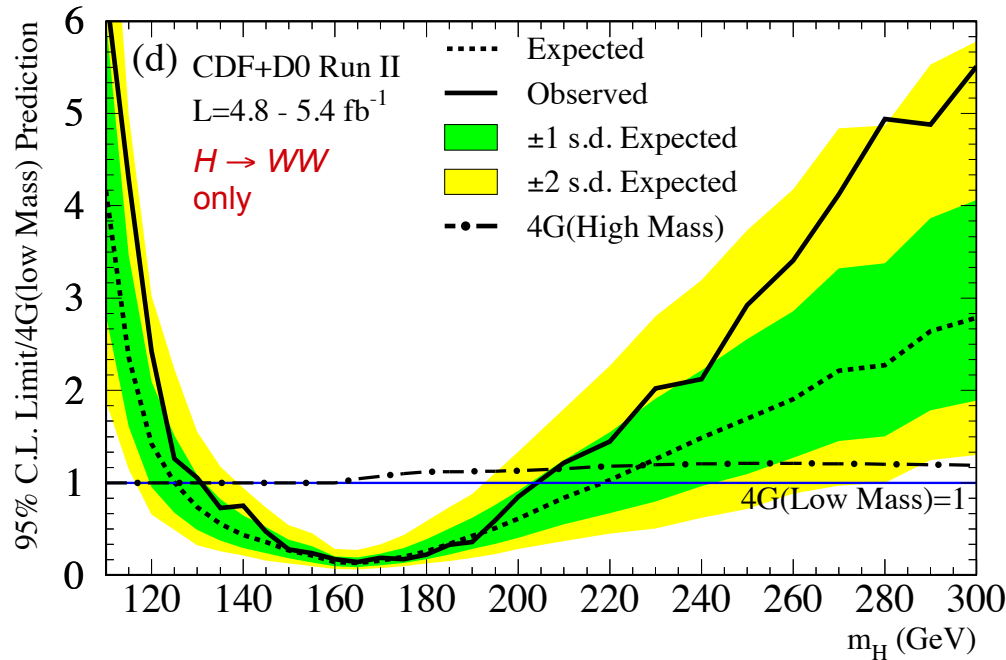
A 4th Generation?

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