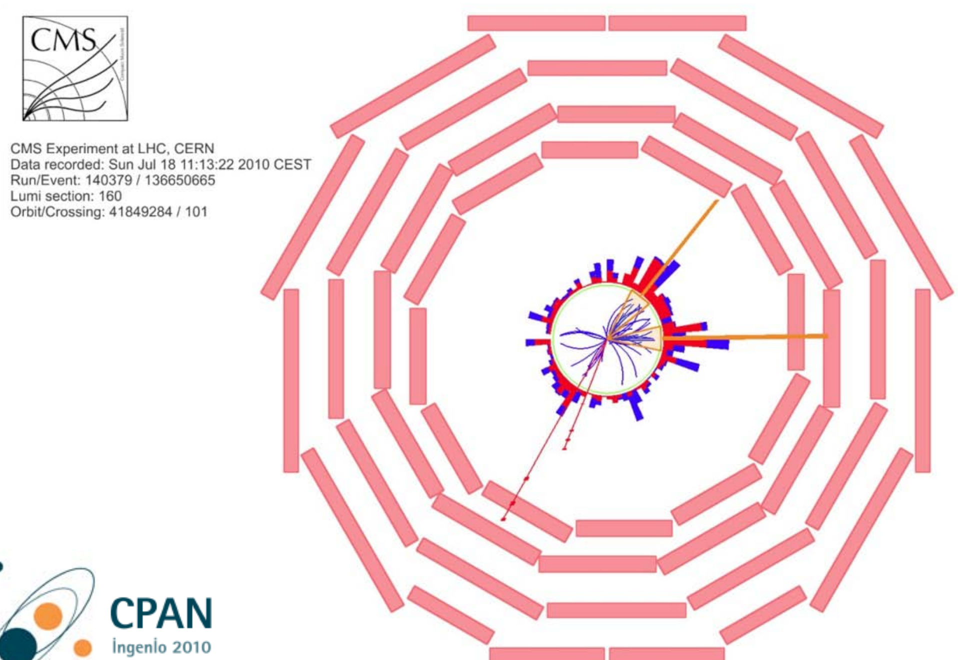
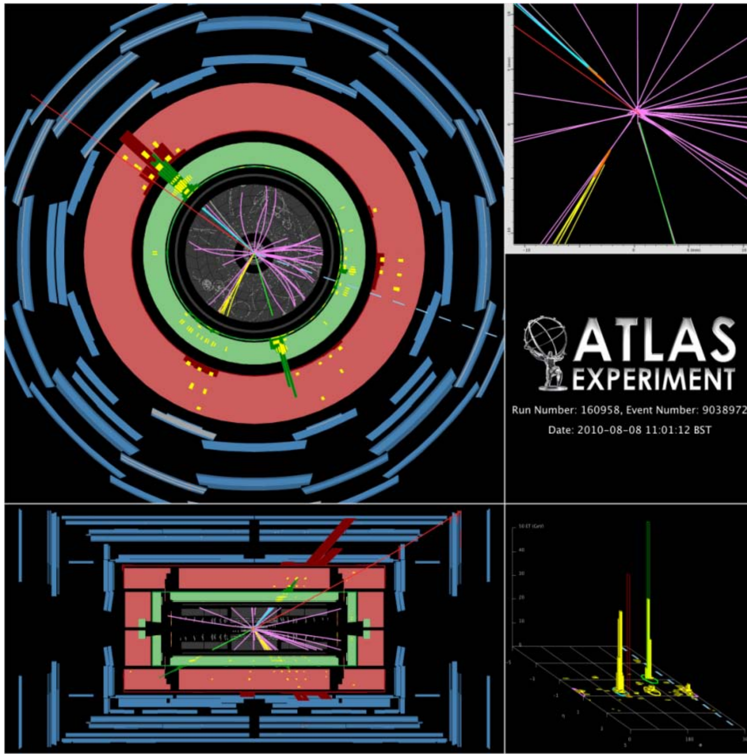
EW Symmetry Breaking: Higgs & Top

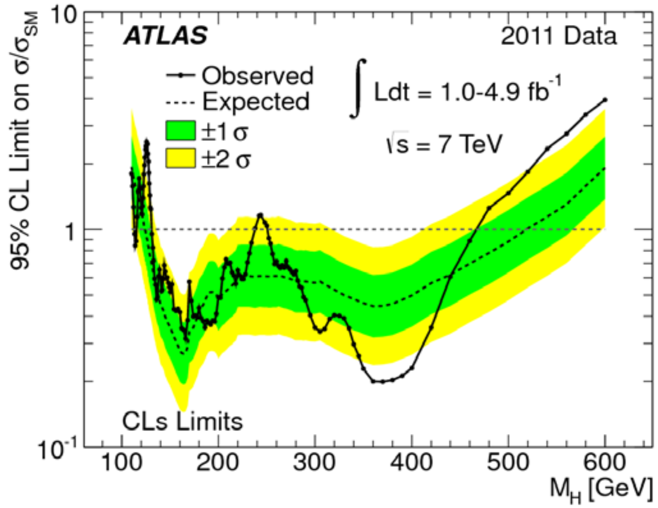
A. Pich
IFIC, Valencia

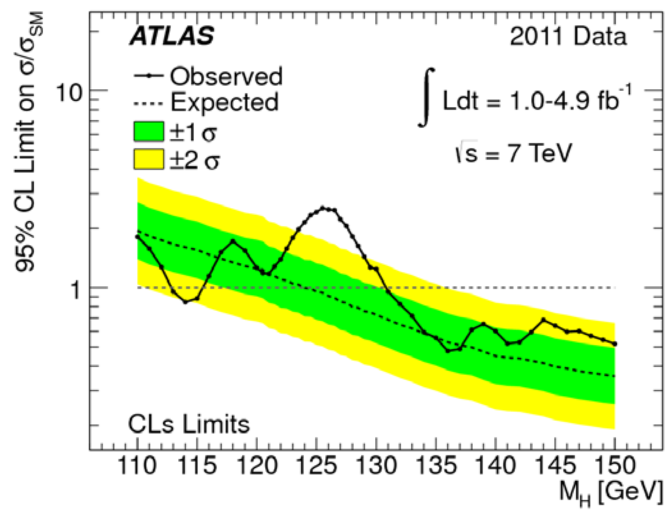


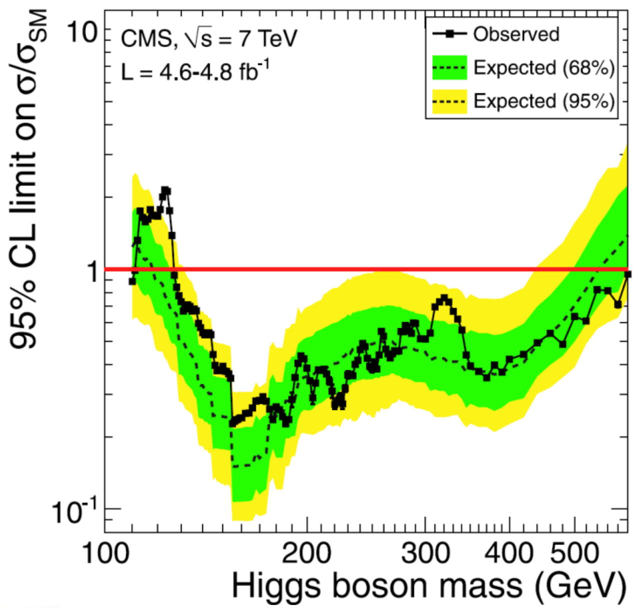


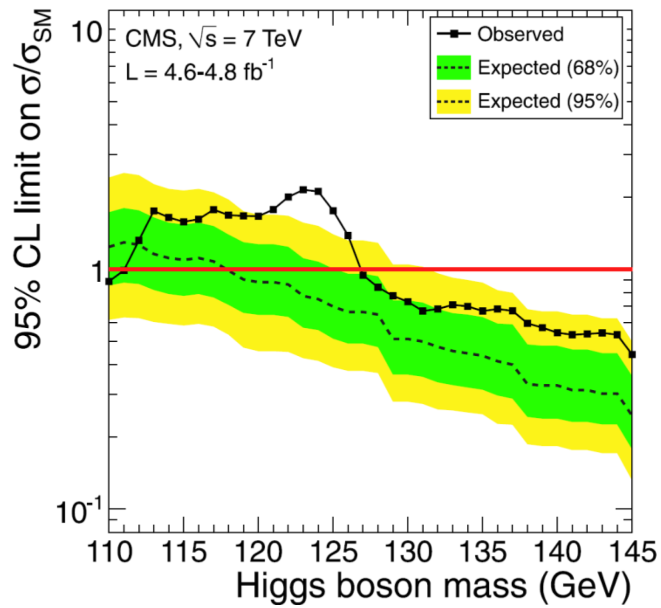
CPAN
Ingenio 2010

Higgs Hunting









Excluded Region

(GeV, 95 % CL)

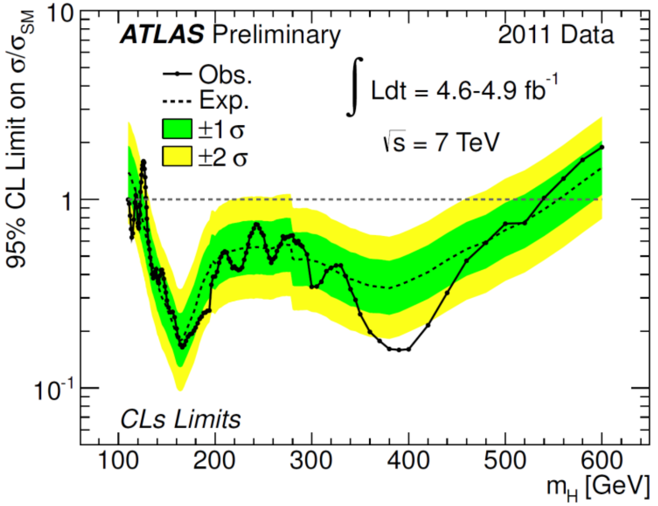
$M_H < 115.5$

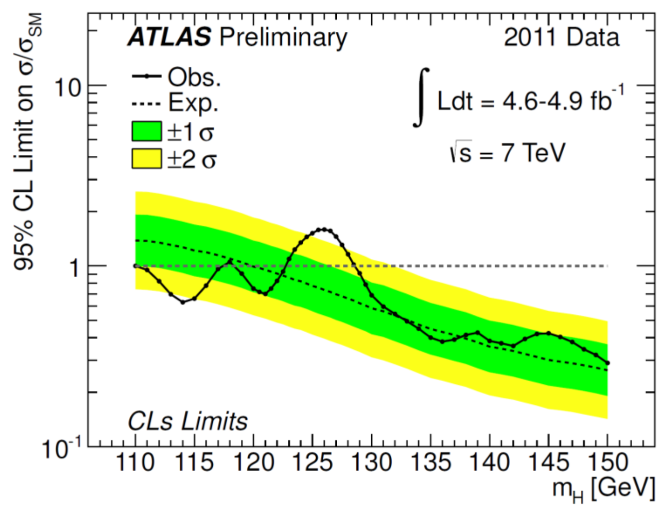
$127 < M_H < 600$

SM

$M_H \in [115.5, 127]$ GeV

Higgs Hunting (2012 preliminary)





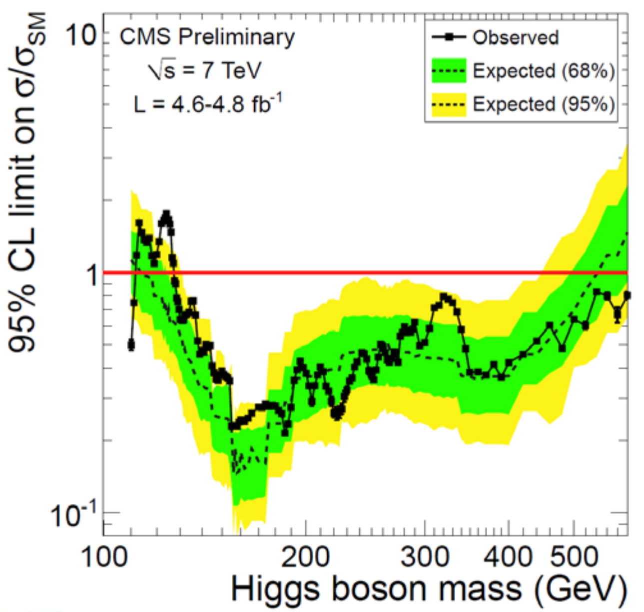
Excluded Region

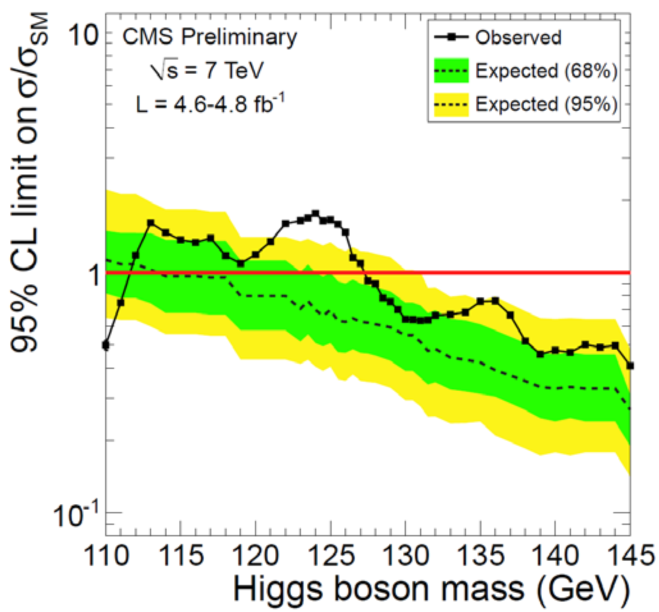
(GeV, 95 % CL)

$M_H < 117.5$

$118.5 < M_H < 122.5$

$127.5 < M_H < 600$





SM

M_H (GeV)

$\in$

[117.5,118.5]

$\cup$

[122.5,127.5]

Possible Scenarios

1. **Light SM Higgs.**

   Favoured by EW precision tests

2. **Alternative perturbative EWSB.**

   Scalar Doublets and singlets (ρ)

3. **Heavy Higgs.**

   Non-perturbative EWSB

4. **No Higgs.**

   Dynamical EWSB

Electroweak Symmetry Breaking

Massless $W^{\pm}\,,\ Z$

3 x 2 polarizations = 6

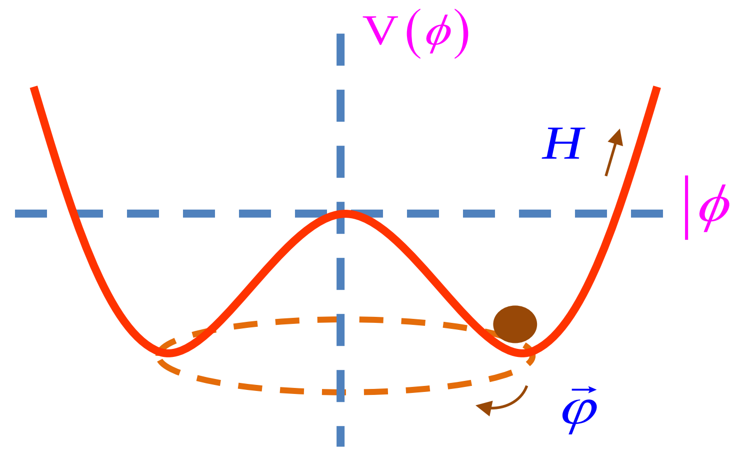
+

3 Goldstones $\vec{\varphi}$

↓

Massive $W^{\pm}\,,\ Z$

3 x 3 polarizations = 9

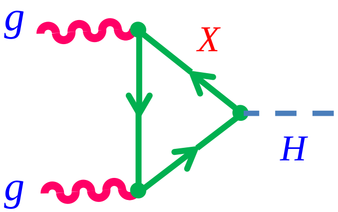


Bosonic Degrees of Freedom

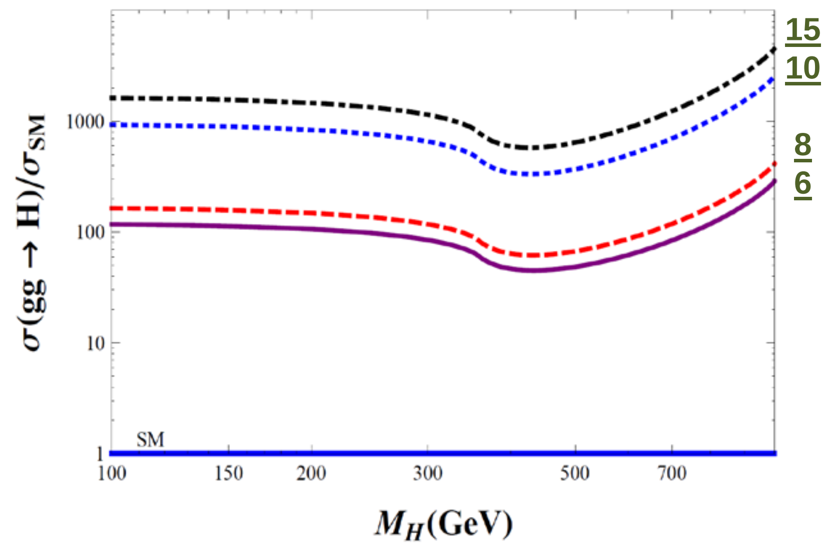
QCD Exotics

(V. Ilisie – A. Pich)

X ∈ SU(3)$_C$ representation R

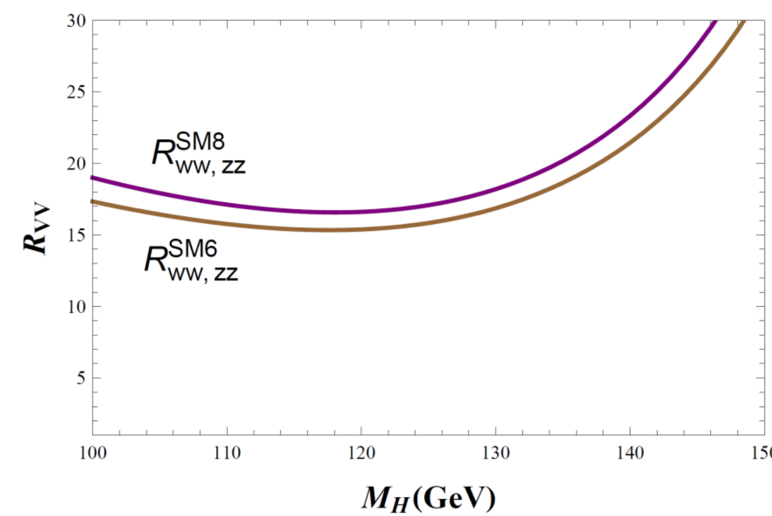


$$\propto \sum_{a=1}^{d_A} \mathrm{Tr}[t_R^a t_R^a] = T_R\, d_A = C_R\, d_R$$



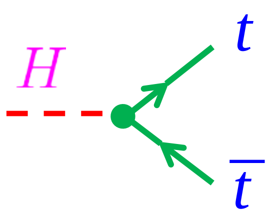
Non decoupling: $\mathcal{L} = -\frac{M_X}{v}\,(\bar{X}X)\,H$

$$R_{VV} \equiv \frac{\sigma(pp \to H)\,\mathrm{Br}(H \to VV)}{\sigma(pp \to H)_{\mathrm{SM}}\,\mathrm{Br}(H \to VV)_{\mathrm{SM}}}$$



Exotic fermions in higher-colour representations could only exist provided their masses are not generated by the SM Higgs mechanism

The Heaviest Mass Scale



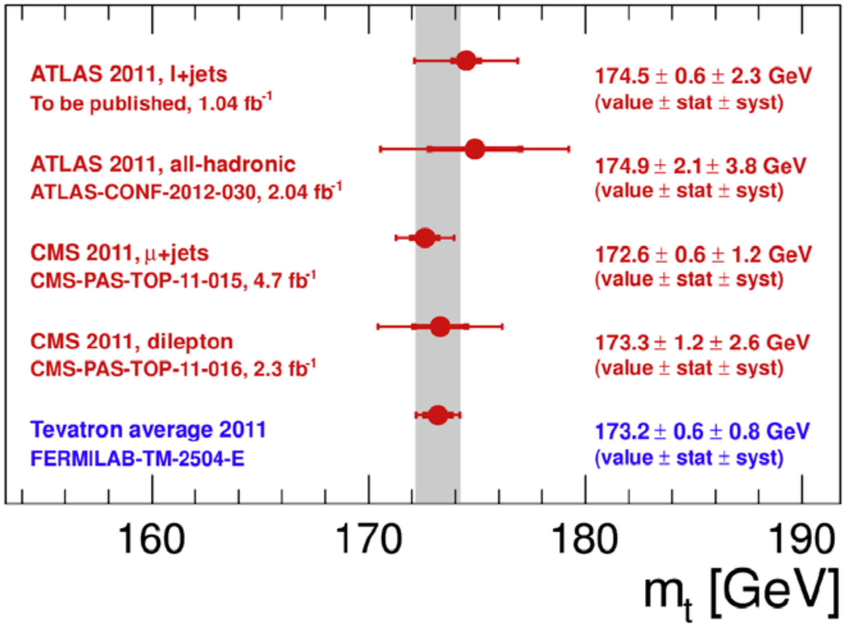
$$y_t = \frac{\sqrt{2}}{v}\, m_t = 2^{3/4}\, G_F^{1/2}\, m_t = 1 \qquad (0.995)$$

The top quark:

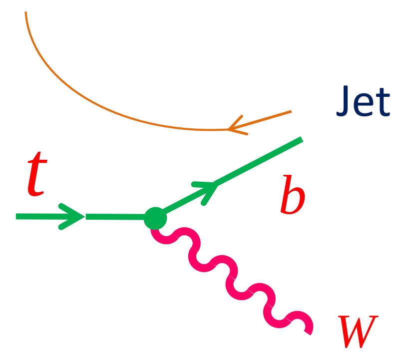
- **Sensitive probe of Electroweak Symmetry Breaking**
- **Non-perturbative (strong) dynamics**
- **Very different from other quarks** $\quad y_b = 0.025\,,\; y_c = 0.007\,\ldots$
- **Is it really a SM quark?**

So far, we only know the decay $t \to b\, W^+$

TOP MASS



Which mass definition ?

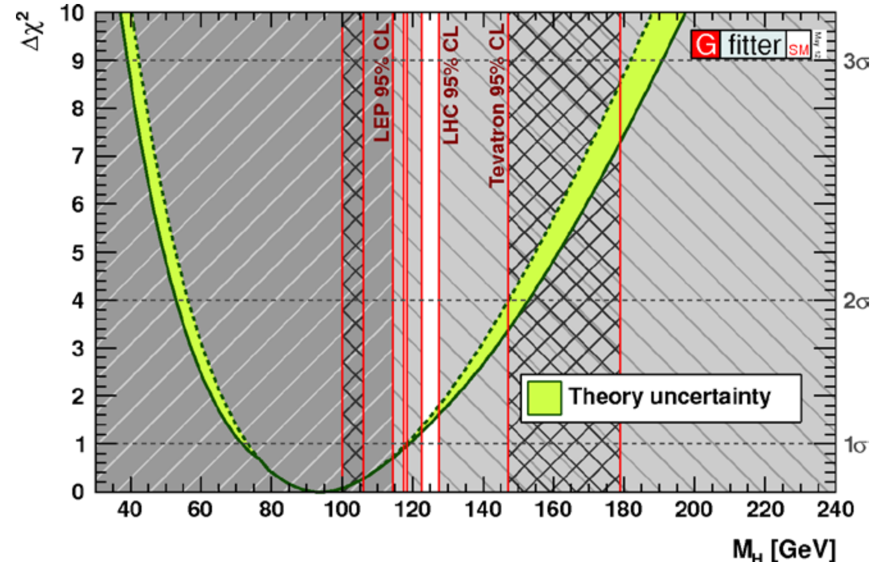


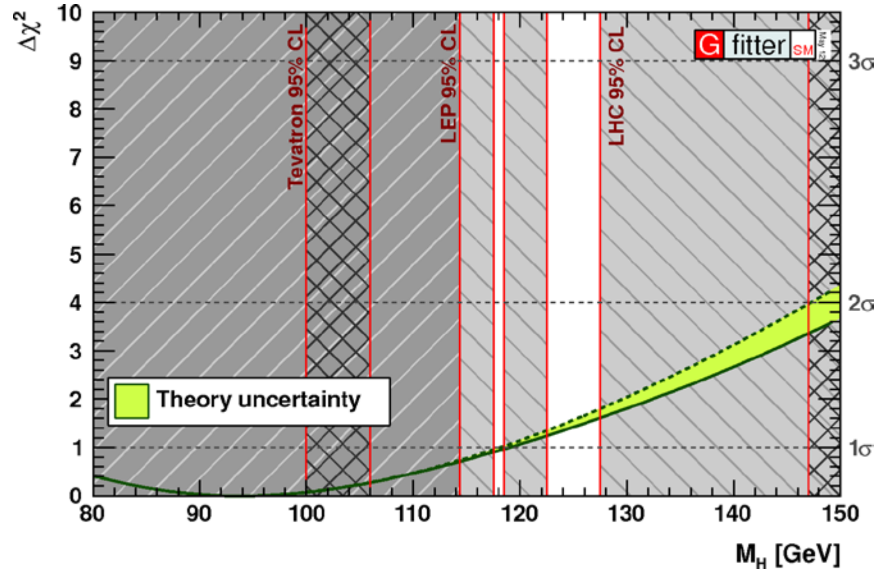
Kinematic mass (Jets) → Colour Singlet → It cannot be (only) the top mass!

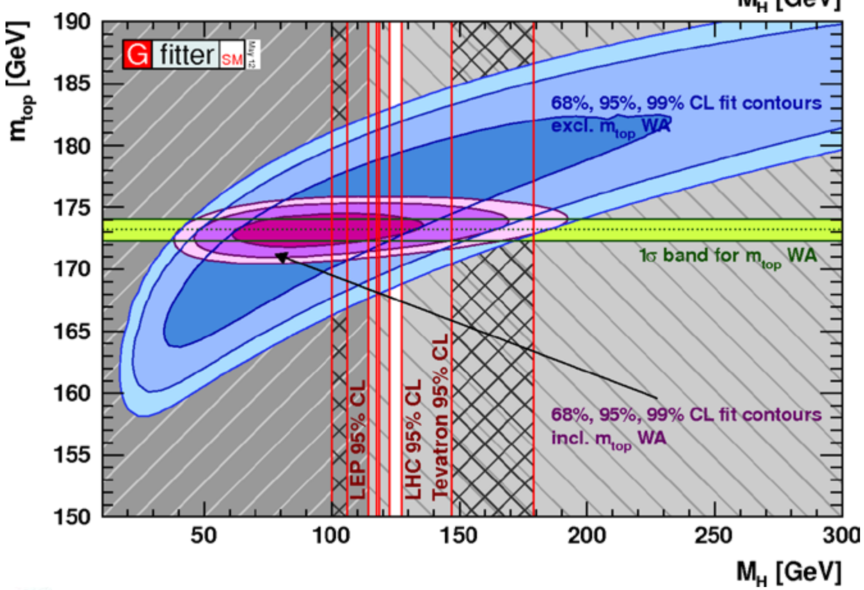
$$M_t^{\mathrm{MC}} = M_t^{\mathrm{pole}} \; \{1 \pm \Delta\} \qquad\qquad \Delta \in \left[\frac{\Lambda_{\mathrm{QCD}}}{M_t} \sim 0.3\% \;,\; \frac{\alpha_S}{\pi} \sim 5\%\right]$$

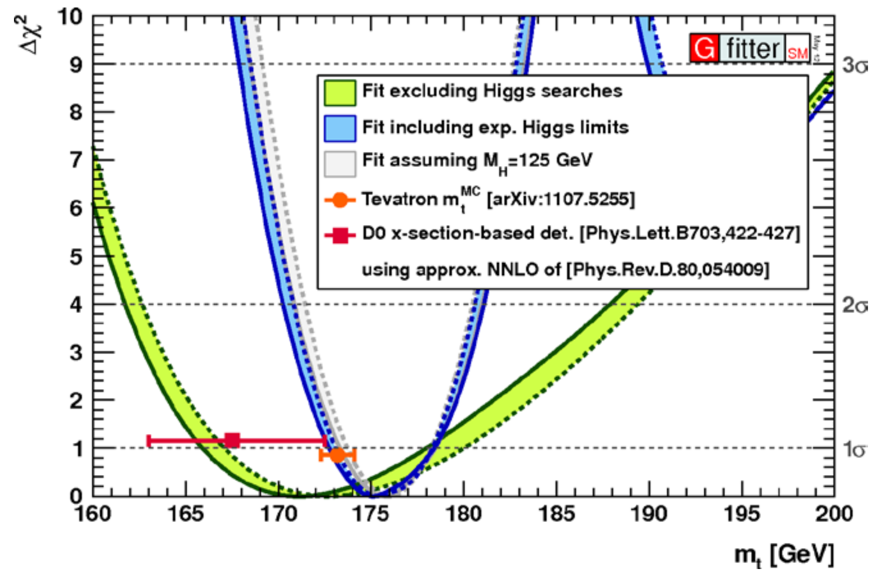
Implications for M_H from electroweak tests

Global Electroweak Fit









Top Mass Definition : $\quad \overline{m}_t(\overline{m}_t) \simeq M_t^{\rm pole} - 7\ {\rm GeV}$

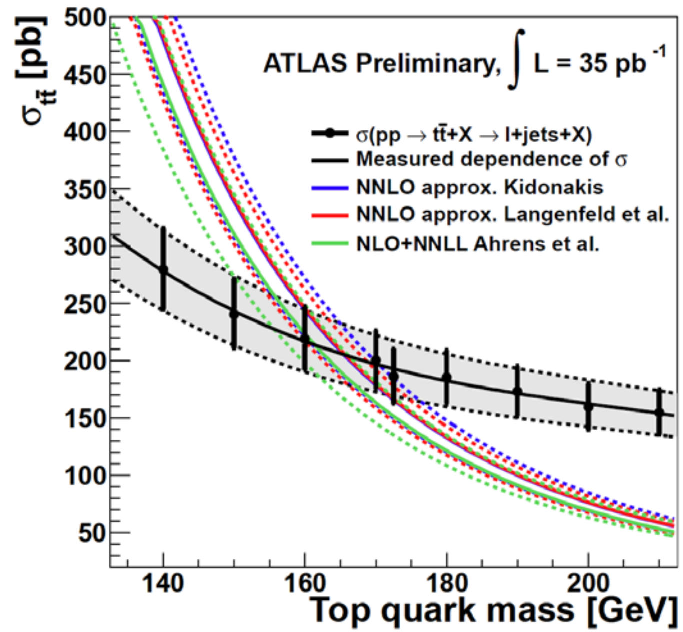
- **Pole Mass** $M_q^{\rm pole}$: Pole of perturbative propagator

  Not well defined. Problematic renormalon contributions

- $\overline{\mathbf{MS}}$ **Mass** $\overline{m}_q(\mu)$:
$$\overline{m}_q(\overline{m}_q) = M_q^{\rm pole}\left\{1-\frac{4}{3}\frac{\alpha_s}{\pi}+\cdots\right\}$$

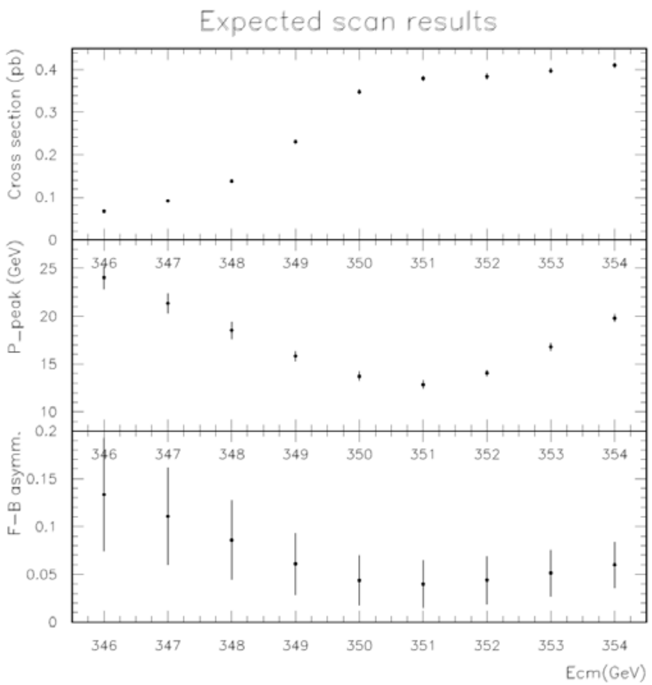
The top mass can be obtained from $\sigma_{t\bar{t}}$:

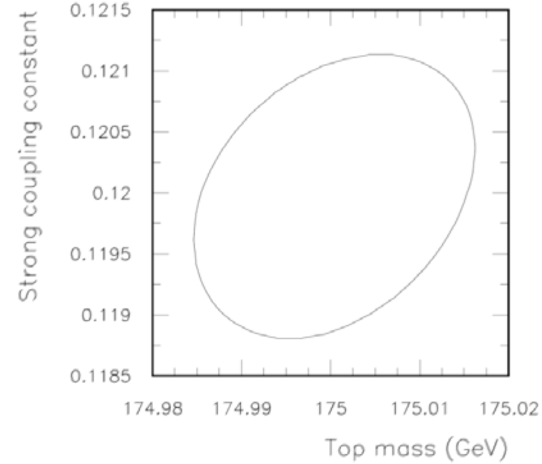
$$M_t^{\rm pole}\ ({\rm GeV}) = \begin{cases} 166.4\,^{+7.8}_{-7.3} & \text{ATLAS} \\ 170.3\,^{+7.3}_{-6.7} & \text{CMS} \\ 167.5\,^{+5.2}_{-4.7} & \text{D0} \end{cases}$$



Threshold Scan

(M. Martínez – R. Miquel '03)





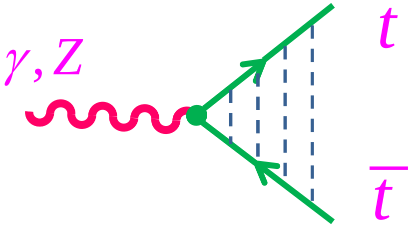
Multi-parameter fit

300 fb^{-1}, TESLA conditions, $\Delta\sigma_{sys} = 3\%$

The simulation assumes: $m_t(1S) = 175$ GeV , $\alpha_s(M_Z) = 0.120$, $M_H = 120$ GeV , $\Delta\sigma_{th} = 3\%$

$\Delta m_t = 20$ MeV , $\Delta\Gamma_t = 30$ MeV , $\Delta\alpha_s(M_Z) = 0.0012$, $\Delta y_t = 35\%$

Assumed theory uncertainties not very relevant

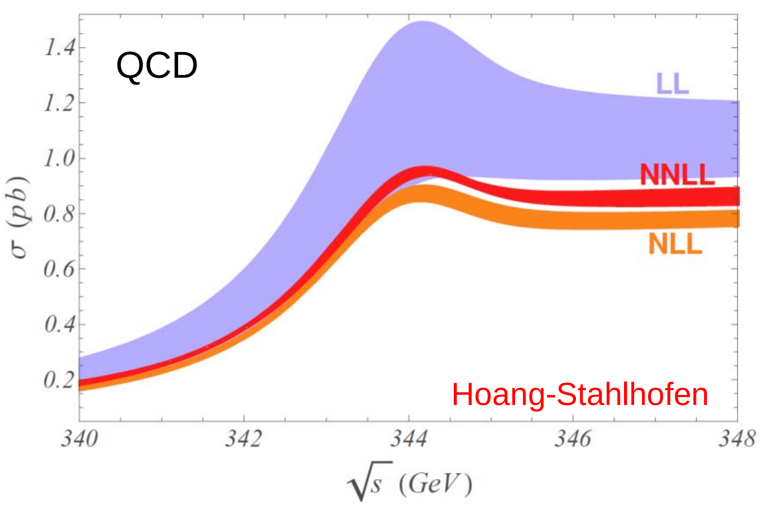


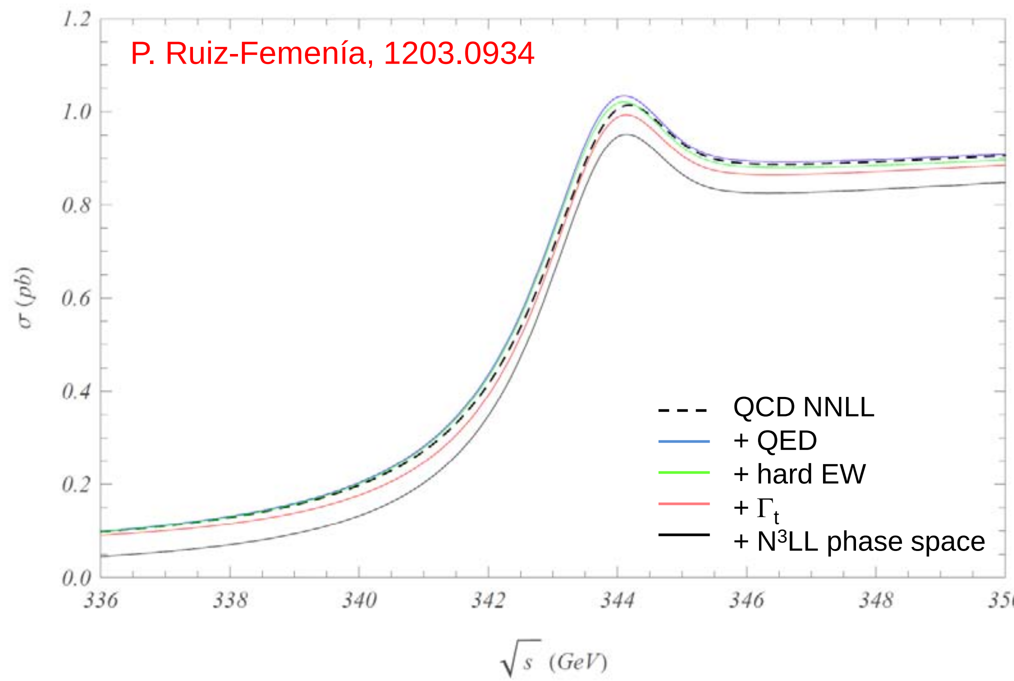
$\sigma(e^+e^- \to t\,\bar{t})_{\rm threshold}$

Coulomb enhancement: $v \equiv \sqrt{1 - 4m_t^2/s} \sim \alpha_s$

NRQCD:
$$\sigma \sim v \sum_k \left(\frac{\alpha_s}{v}\right)^k \sum_i (\alpha_s \log v)^i \times \Big[\underbrace{1}_{\rm LL} \;;\; \underbrace{v, \alpha_s}_{\rm NLL} \;;\; \underbrace{v^2, v\alpha_s, \alpha_s^2}_{\rm NNLL} \;;\; \ldots\Big]$$

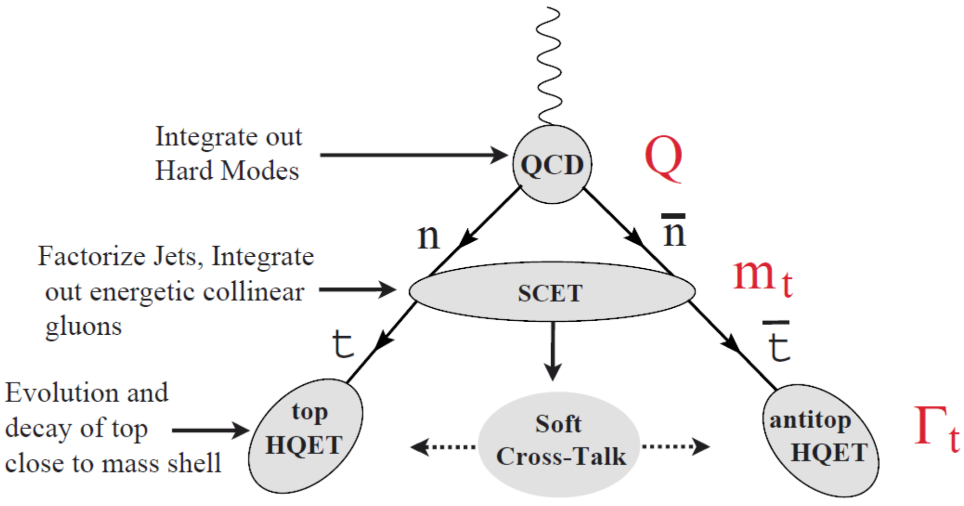
Well-defined top mass: $m_t(1S)$





Jet-Mass Scheme (Fleming et al '08)

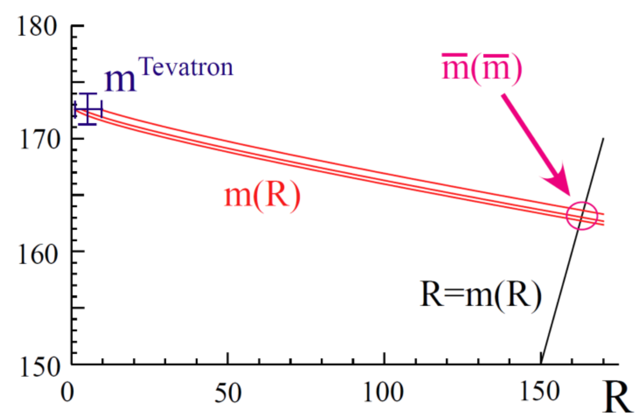
The measured mass depends on the way in which soft radiation is treated



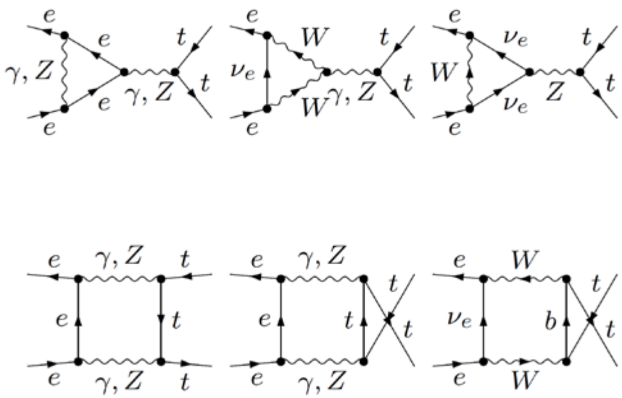
$$Q \gg m_t \gg \Gamma_t > \Lambda_{QCD}$$

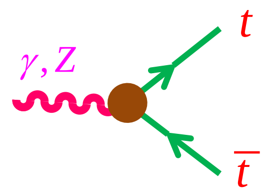
Use EFT techniques to sum large logarithms

Ongoing effort to relate "Jet" and "short-distance" masses



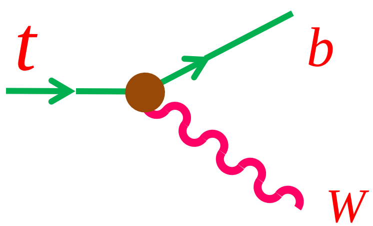
Effective Vertices





$$X_\mu \;=\; A_\mu\,,\; Z_\mu$$

$$X_\mu\,\bar{t}\left[\gamma^\mu\left(g_L^X(s)\,P_L + g_R^X(s)\,P_R\right) + \frac{d^X(s)}{m_t}\,(p-p')^\mu\right] t$$



$$-\frac{g}{\sqrt{2}}\,V_{tb}\,\bar{t}\,\Big\{\gamma^\mu\left[f_1^L(q^2)P_L + f_1^R(q^2)P_R\right]$$

$$-i\,\frac{\sigma^{\mu\nu}}{M_W}\,(p_t-p_b)_\nu\;\left[f_2^L(q^2)P_L + f_2^R(q^2)P_R\right]\Big\}\;b\,W_\mu^\dagger$$

$$+\ \text{h.c.}$$

F.F. related to Effective Operators:

$$\mathcal{L} \;=\; \mathcal{L}_{\rm SM} \;+\; \sum_i \frac{c_i}{\Lambda^{d_i-4}}\,O_i \;+\; \text{h.c.}$$

➡ **Sensitivity to New-Physics**

(Aguilar-Saavedra)

Bounds on Effective Operators

Zhang-Greiner-Willenbrock '2012 (TeV^{-2} units)

Coefficients	Electroweak data	W helicity	$\bar{B} \to X_s\gamma$	$B_{d,s} - \bar{B}_{d,s}$ mixing
$\left(C_{\phi q}^{(3)} + C_{\phi q}^{(1)}\right)/\Lambda^2$	0.016 ± 0.021			
$\left(C_{\phi q}^{(3)} - C_{\phi q}^{(1)}\right)/\Lambda^2$	2.0 ± 2.7		-1.6 ± 1.3	
$C_{\phi t}/\Lambda^2$	1.8 ± 1.9			
$C_{\phi b}/\Lambda^2$	-0.16 ± 0.10			
$C_{\phi\phi}/\Lambda^2$			0.030 ± 0.026	
C_{tW}/Λ^2	-0.4 ± 1.2	0.03 ± 0.94		-0.06 ± 0.79
C_{bW}/Λ^2	11 ± 13			
C_{tB}/Λ^2	4.8 ± 5.3			
C_{bB}/Λ^2	8 ± 19			

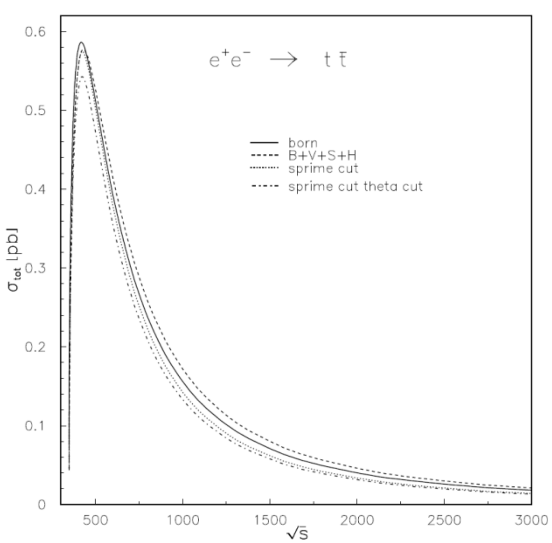
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^{d_i-4}} O_i + \text{h.c.}$$

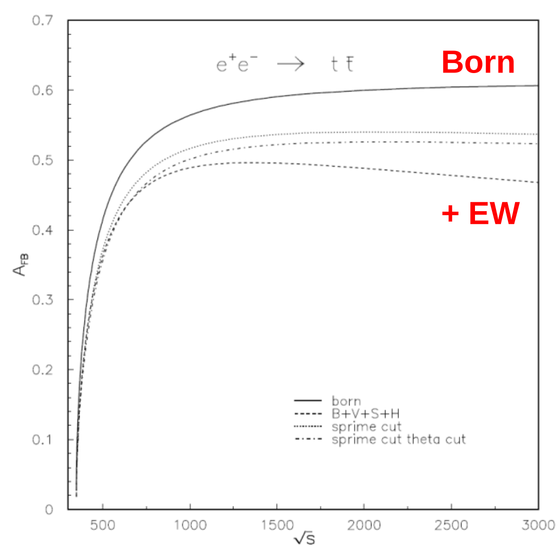
$$\begin{aligned}
O_{\phi q}^{(3)} &= i(\phi^\dagger \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q), \\
O_{\phi q}^{(1)} &= i(\phi^\dagger D_\mu \phi)(\bar{q}\gamma^\mu q), \\
O_{\phi t} &= i(\phi^\dagger D_\mu \phi)(\bar{t}\gamma^\mu t), \\
O_{\phi b} &= i(\phi^\dagger D_\mu \phi)(\bar{b}\gamma^\mu b), \\
O_{\phi\phi} &= i(\tilde{\phi}^\dagger D_\mu \phi)(\bar{t}\gamma^\mu b), \\
O_{tW} &= (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W_{\mu\nu}^I, \\
O_{bW} &= (\bar{q}\sigma^{\mu\nu}\tau^I b)\phi W_{\mu\nu}^I, \\
O_{tB} &= (\bar{q}\sigma^{\mu\nu} t)\tilde{\phi} B_{\mu\nu}, \\
O_{bB} &= (\bar{q}\sigma^{\mu\nu} b)\phi B_{\mu\nu},
\end{aligned}$$

Observables

- Cross section
- Forward-backward asymmetry (either in top production or in top decay)
- Polarized beams
- Final polarization (top decay distribution)
- Spin correlations (similar to τ physics)
- W polarization: spin density matrix (Aguilar-Saavedra–Bernabèu)
- T-odd asymmetries

$$\frac{d\Gamma}{\Gamma\, d\cos\theta} = \frac{1}{2}\left(1 + |\vec{P}|\,\kappa_p \cos\theta\right)$$





Sizeable EW corrections

ISR photons

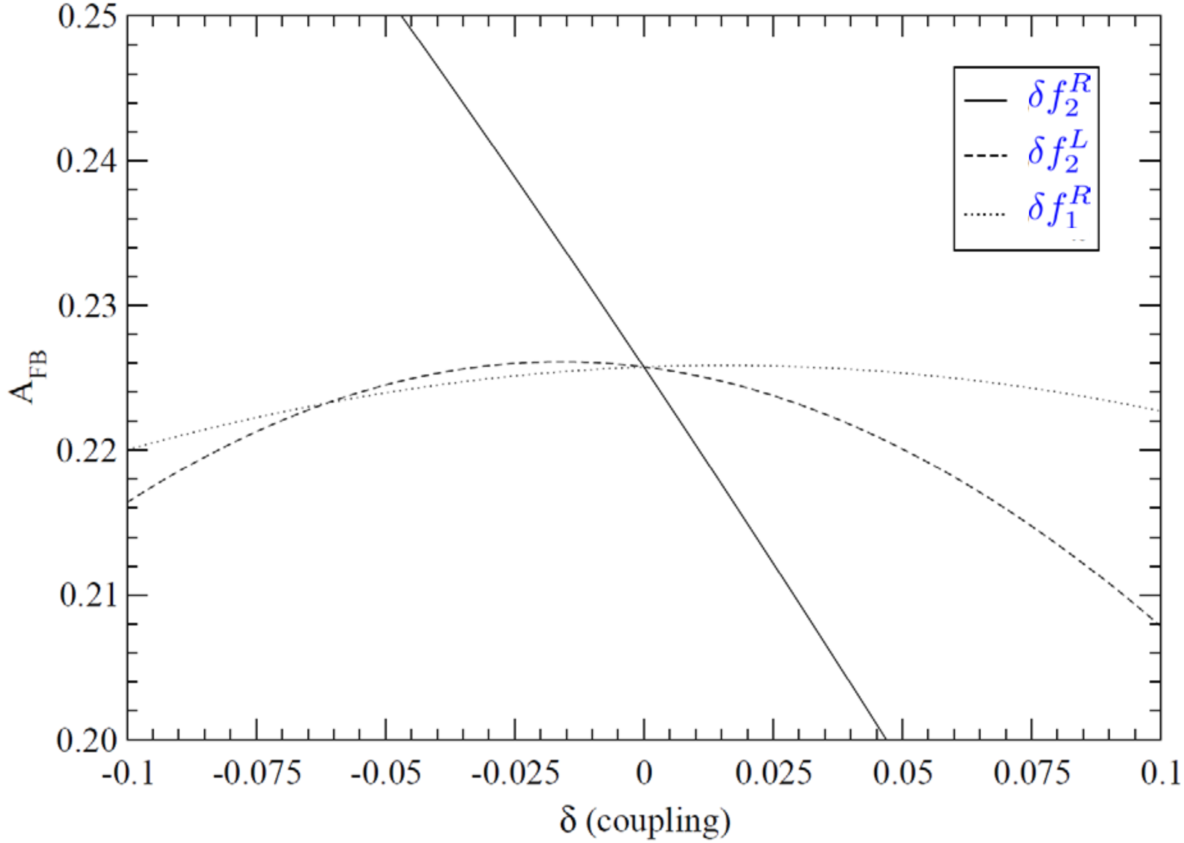
(UV) EW log(E/M_W)

$$\delta\kappa_p^{\mathrm{QCD}} \in [-7.2\%,\, 1.4\%]$$

Glover et al, hep-ph/0410110

Sensitivity to New Physics

$$A_{FB}^{\rm decay} \equiv \frac{N(x_{bl} > 0) - N(x_{bl} < 0)}{N(x_{bl} > 0) - N(x_{bl} < 0)}$$



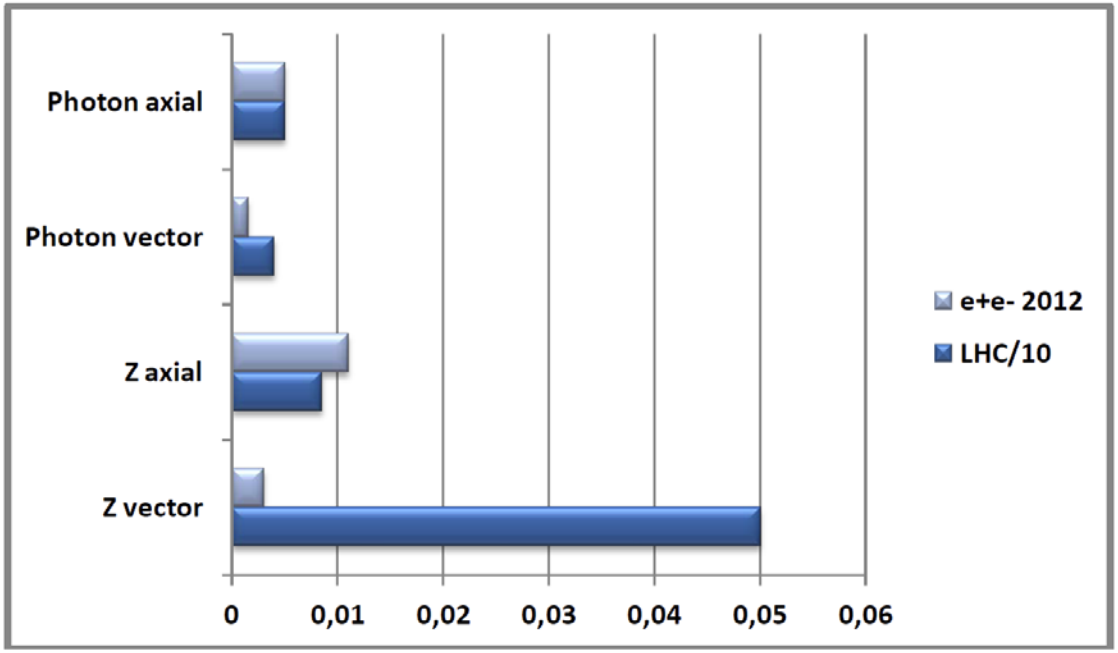
$t \to W^+ b \to l^+ \nu_l b$

$x_{bl} \equiv \cos\theta_{bl}$

Glover et al, hep-ph/0410110

Preliminary ILC Study

(F. Richard et al)



$\delta\sigma_{t\bar{t}} \sim 0.3\,\%$

$\delta A_{LR} \sim 1.24\,\%$ (stat)

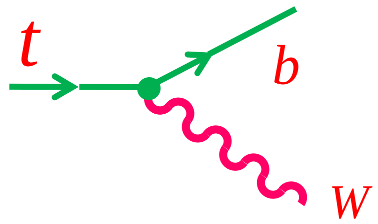
$\delta A_{FB,R} \sim 1.2\,\%$

$\delta A_{FB,L} \sim 1.4\,\%$

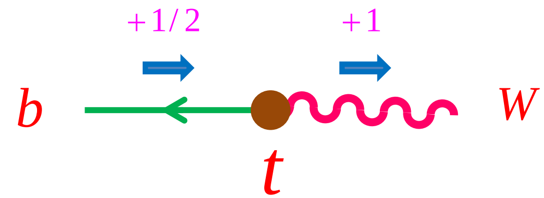
Coupling	SM Value	LHC 300 fb-1	e+e- US Study	e+e- this study
ΔF^{γ}_{1V}	-0.66	+0.043 -0.041	+0.047 200 fb-1 -0.047 P=0.8	±0.0015 500 fb-1 P=0.8,0.3
ΔF^{γ}_{1A}	0	+0.051 -0.048	+0.011 100 fb-1 -0.011 P=0.8	±0.005 id
ΔF^{Z}_{1V}	0.23	+0.34 -0.72	+0.012 200 fb-1 -0.013 P=0.8	±0.003 id
ΔF^{Z}_{1A}	0.59	+.079 -0.091	+.052 200 fb-1 -0.052 P=0.8	±0.011 id

Statistical errors only

Top Decay

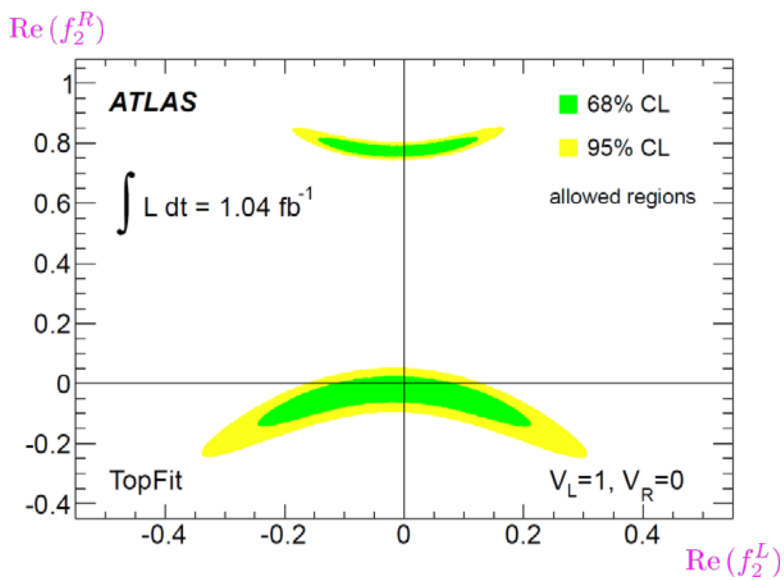


W_R **forbidden** (m_b=0):



$$\mathrm{Br}(t \to bW_0) \approx \frac{m_t^2}{m_t^2 + 2M_W^2} \approx 0.70$$

Polarization Fractions	NNLO QCD Czarnecki et al	ATLAS	Tevatron
F_0	0.687 (5)	0.67 (7)	0.72 (8)
F_L	0.311 (5)	0.32 (4)	$1-F_0-F_R$
F_R	0.0017 (1)	0.01 (5)	-0.03 (5)

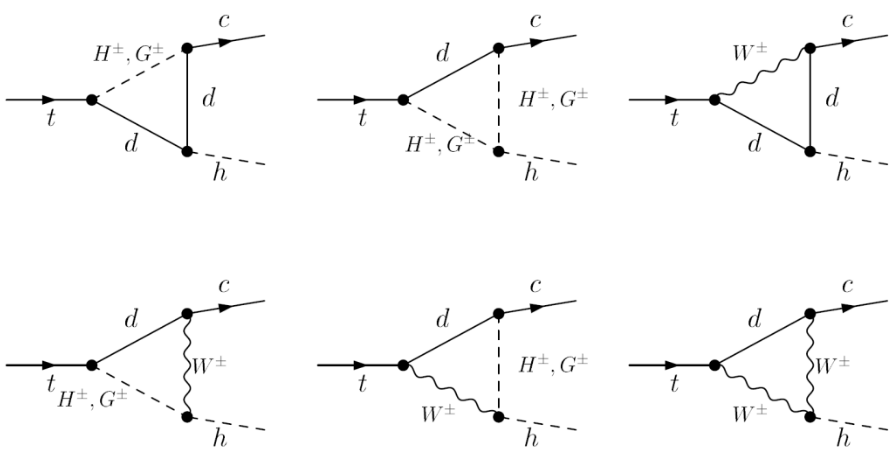


D0: $|f_2^L|^2 < 0.05\,,\quad |f_2^R|^2 < 0.12\,,\quad |f_1^R|^2 < 0.30 \quad (95\%\ \mathrm{CL})$

FCNCs

Strongly suppressed in the SM (GIM): $t \to c\,\gamma$, $t \to c\,Z$, $t \to c\,g$, $t \to c\,h$

FCNCs present in multi-Higgs models **(suppression mechanisms needed)**



Good sensitivity to new physics

Glover et al, hep-ph/0410110	LHC	ILC	ILC+
$\mathrm{Br}(t \to Zc)\ (\gamma_\mu)$	3.6×10^{-5}	1.9×10^{-4}	1.9×10^{-4}
$\mathrm{Br}(t \to Zc)\ (\sigma_{\mu\nu})$	3.6×10^{-5}	1.8×10^{-5}	7.2×10^{-6}
$\mathrm{Br}(t \to \gamma c)$	1.2×10^{-5}	1.0×10^{-5}	3.8×10^{-6}

Custodial Symmetry

$$\boldsymbol{\Sigma} \equiv \left(\phi_C, \phi\right) = \begin{pmatrix} \phi^{(0)*} & \phi^{(+)} \\ -\phi^{(-)} & \phi^{(0)} \end{pmatrix} = \frac{1}{\sqrt{2}}\left[\mathrm{v} + H(x)\right] \, \mathbf{U}(\varphi) \qquad , \qquad \mathbf{U}(\varphi) = \exp\left\{\frac{i}{\mathrm{v}}\vec{\sigma}\,\vec{\varphi}\right\}$$

$$\begin{aligned} \mathcal{L}(\phi) &= (\mathbf{D}_\mu \phi)^\dagger \, \mathbf{D}^\mu \phi - \mu^2 \, \phi^\dagger \phi - h \, (\phi^\dagger \phi)^2 \\ &= \frac{1}{2}\,\mathrm{Tr}\left[\left(\mathbf{D}^\mu \boldsymbol{\Sigma}\right)^\dagger \mathbf{D}^\mu \boldsymbol{\Sigma}\right] - \frac{h}{16}\left(\mathrm{Tr}\left[\boldsymbol{\Sigma}^\dagger \boldsymbol{\Sigma}\right] - \mathrm{v}^2\right)^2 + \frac{h}{2}\,\mathrm{v}^4 \\ &= \frac{\mathrm{v}^2}{4}\,\mathrm{Tr}\left[\left(\mathbf{D}^\mu \mathbf{U}\right)^\dagger \mathbf{D}^\mu \mathbf{U}\right] + O\left(H/\mathrm{v}\right) \end{aligned}$$

- **Invariant under global** $SU(2)_L \otimes SU(2)_R \supset SU(2)_L \otimes U(1)_Y$

$$\boldsymbol{\Sigma} \to g_L \cdot \boldsymbol{\Sigma} \cdot g_R^\dagger \qquad , \qquad g_X \in SU(2)_X$$

- **Same Lagrangian than QCD pions:** $f_\pi \to \mathrm{v} \quad , \quad \pi^\pm, \pi^0 \to \varphi^\pm, \varphi^0 \to W_L^\pm, W_L^0$

Chiral Goldstone Bosons: $SU(2)_L \otimes SU(2)_R \to SU(2)_C$

Higgsless Theories of EWSB

- **Dynamical Symmetry Breaking:** $SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_C$
- **Goldstone Dynamics** ➡ **Effective Chiral Lagrangian**
- **Strong Electroweak Dynamics** ➡ **Heavy Resonances**
- **Many possibilities:** **Technicolour, Walking Technicolour, Conformal Technicolour …**
- **Light scalar resonances** ➡ **Composite Higgs** (Grojean)
- **$W^{\pm}$ and Z self-energies are sensitive to Vector and Axial states**

Can be studied with known QCD techniques **(RχT)**

Electroweak Chiral Effective Theory

Gauge Boson Self-Energies

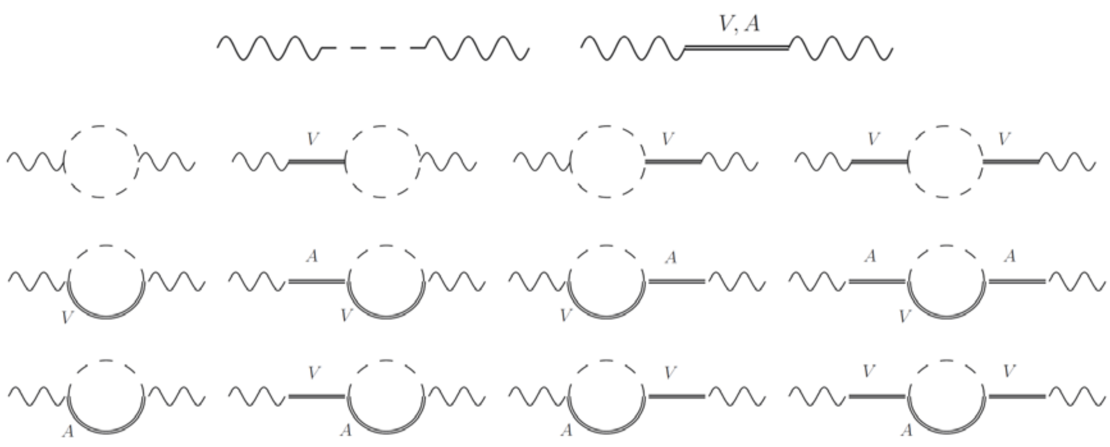
$$\mathcal{L}_{\rm v.p.} \doteq -\frac{1}{2} W^3_\mu\, \Pi^{\mu\nu}_{33}(q^2) W^3_\nu - \frac{1}{2} B_\mu\, \Pi^{\mu\nu}_{00}(q^2) B_\nu - W^3_\mu\, \Pi^{\mu\nu}_{30}(q^2) B_\nu - W^+_\mu\, \Pi^{\mu\nu}_{WW}(q^2) W^-_\nu$$

$$\Pi^{\mu\nu}_{ij}(q^2) = \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) \Pi_{ij}(q^2)$$ (Landau gauge)

$$S \equiv \frac{16}{g^2 \tan\theta_W\, q^2} \left[\Pi_{30}(q^2) - \Pi_{30}(q^2)_{\rm SM}\right] = 0.04 \pm 0.10$$ $(M_H = 120\,\text{GeV})$

LO

NLO



$$S_{\rm LO} = 4\pi \left(\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2}\right) = \frac{4\pi v^2}{M_V^2} \left(1 + \frac{M_V^2}{M_A^2}\right)$$ Peskin-Takeuchi

S Constraints on Higgsless Theories

Rosell, Pich, Sanz-Cillero

LO

$M_V > 1.5$ (2) TeV

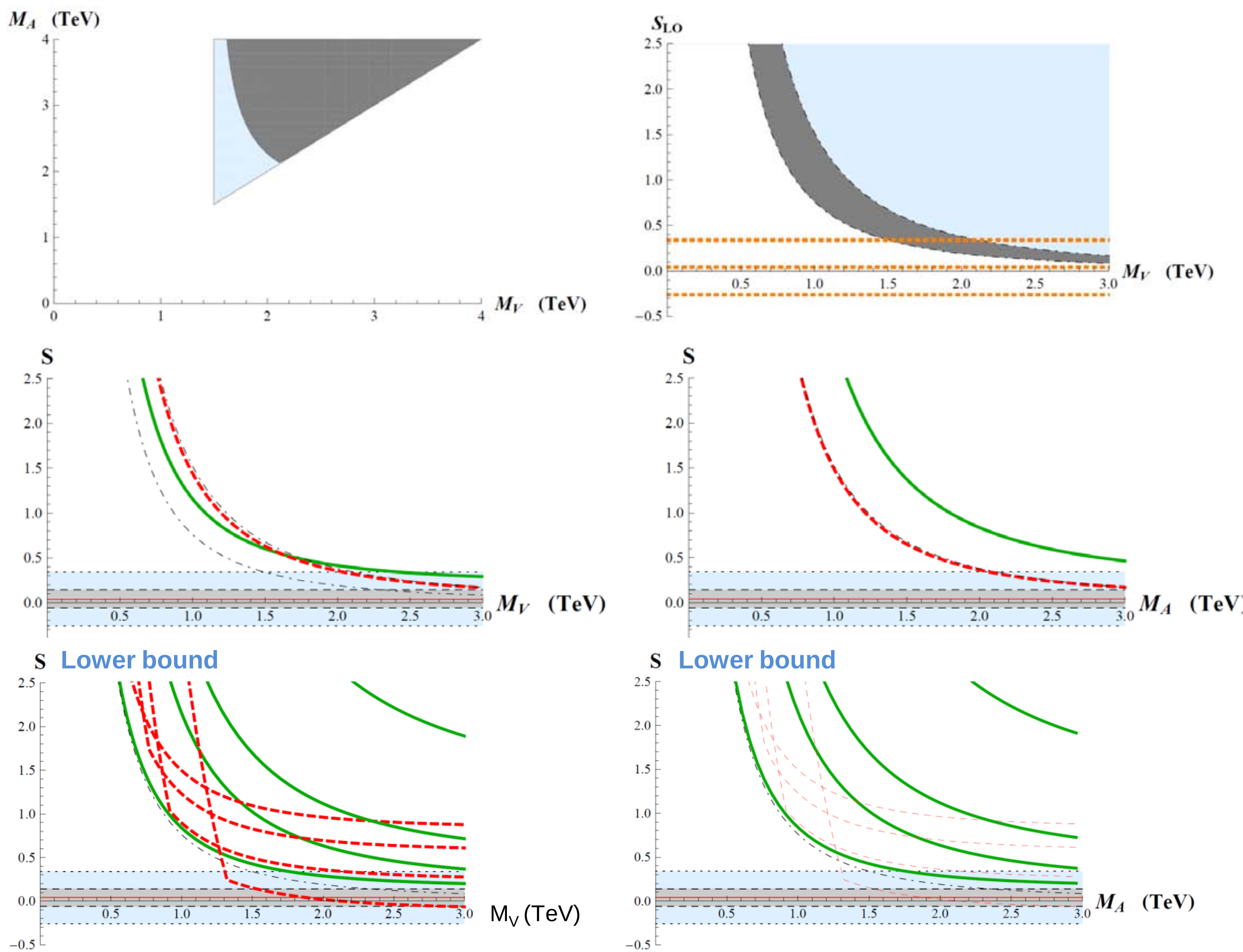
@ 3 (1) σ

NLO
Asymptot.-Free Theories

$M_V > 2.4$ (6) TeV
$M_A > 4$ (10) TeV

NLO
General Fram.

$M_V > 1.8$ (5) TeV



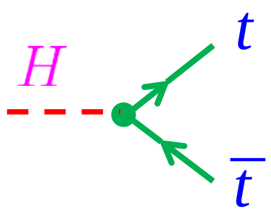
SUMMARY

The Big Question: Nature of EWSB

- **Higgs Boson:** Just one possibility

  Does it exist? (wait for new LHC data)

- **Top Quark:**

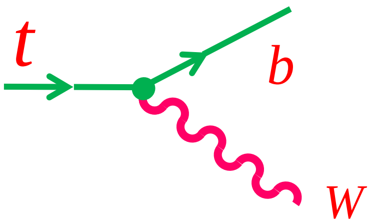


  - **Sensitive probe of EWSB**
  - **Non-perturbative (strong) dynamics**
  - **Is it really a SM quark?**

$$\mathbf{y_t = \frac{\sqrt{2}}{v}\, m_t \approx 1}$$

High Precision data needed

Single-top production: V_{tb}



	$\|V_{tb}\|$	
ATLAS '12	1.13 ± 0.14	> 0.75 (95% CL)
ATLAS '12	1.03 ± 0.19	
CMS '12	$1.14 \pm 0.22 \pm 0.02_{th}$	> 0.68 (95% CL)
CDF '12	$0.96 \pm 0.09 \pm 0.05_{th}$	> 0.78 (95% CL)
D0 '12	1.02 ± 0.11	> 0.79 (95% CL)
Tevatron '09	0.88 ± 0.07	> 0.77 (95% CL)