Top physics at LHC

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- to use the top to probe the EWSB sector

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- $\begin{pmatrix} t_{2/3} \\ b_{-1/3} \end{pmatrix}_L^{i=1,2,3}$ $\quad t^i_R$

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  $m_t \sim 170\,\mathrm{GeV} \longrightarrow y_t \sim 1$

  strong interaction with the Higgs

  hints of a special role in the EWSB mechanism

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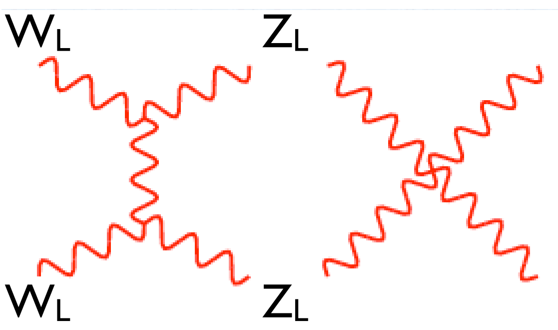
- very short lifetime: it decays before hadronising

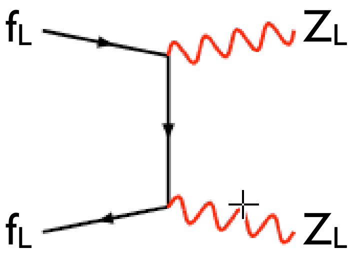
  $\tau_t \sim 10^{-24} s\,, \quad \Gamma^{-1} \sim (1.5\,\mathrm{GeV})^{-1} \ll \Lambda_{\mathrm{QCD}}^{-1} \sim (200\,\mathrm{MeV})^{-1}$

  - no spectroscopy
  - spin transferred to decay products: Wb

Top & unitarity



$$a_0 \sim \frac{s}{v^2}$$



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top, Higgs and EWSB are intertwined

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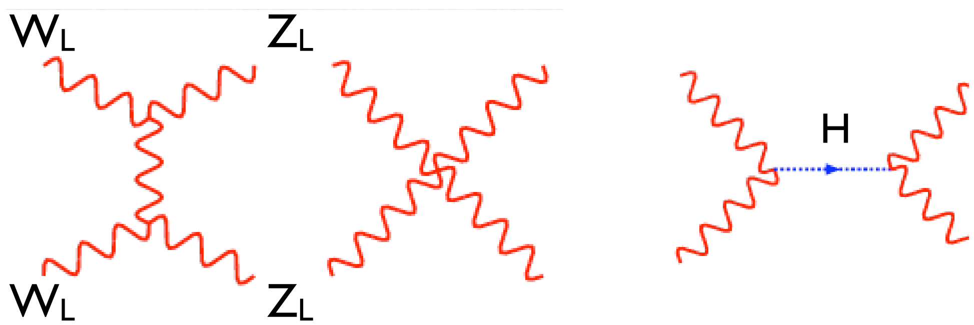

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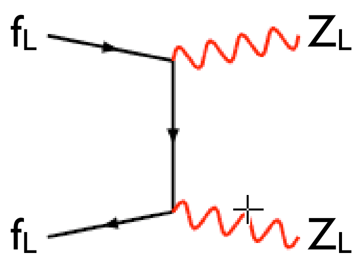

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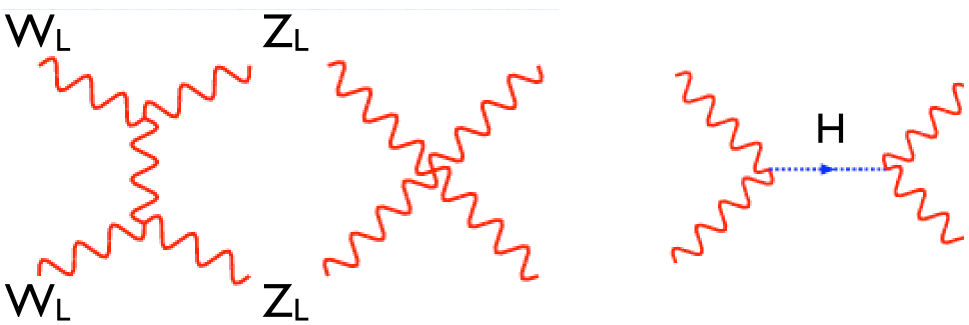

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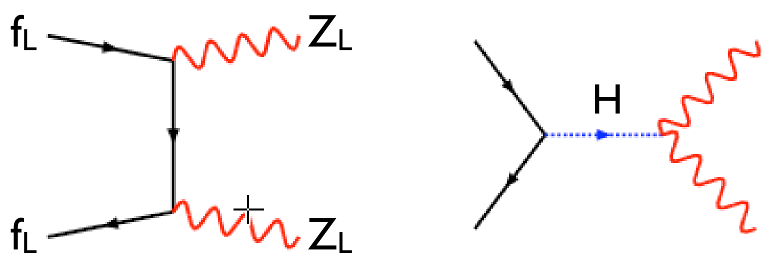

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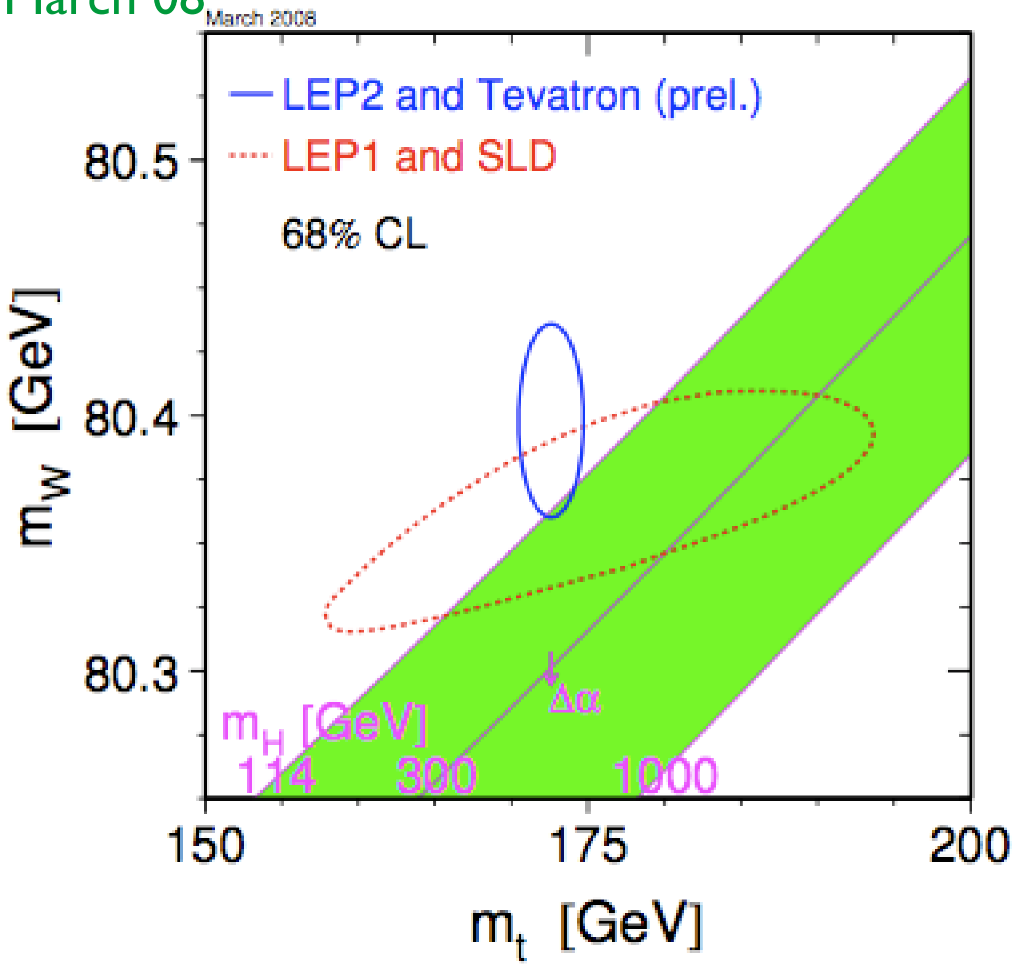
Effects on global EW fits

March 08



tree level $m_W = m_Z \cos\theta_W$

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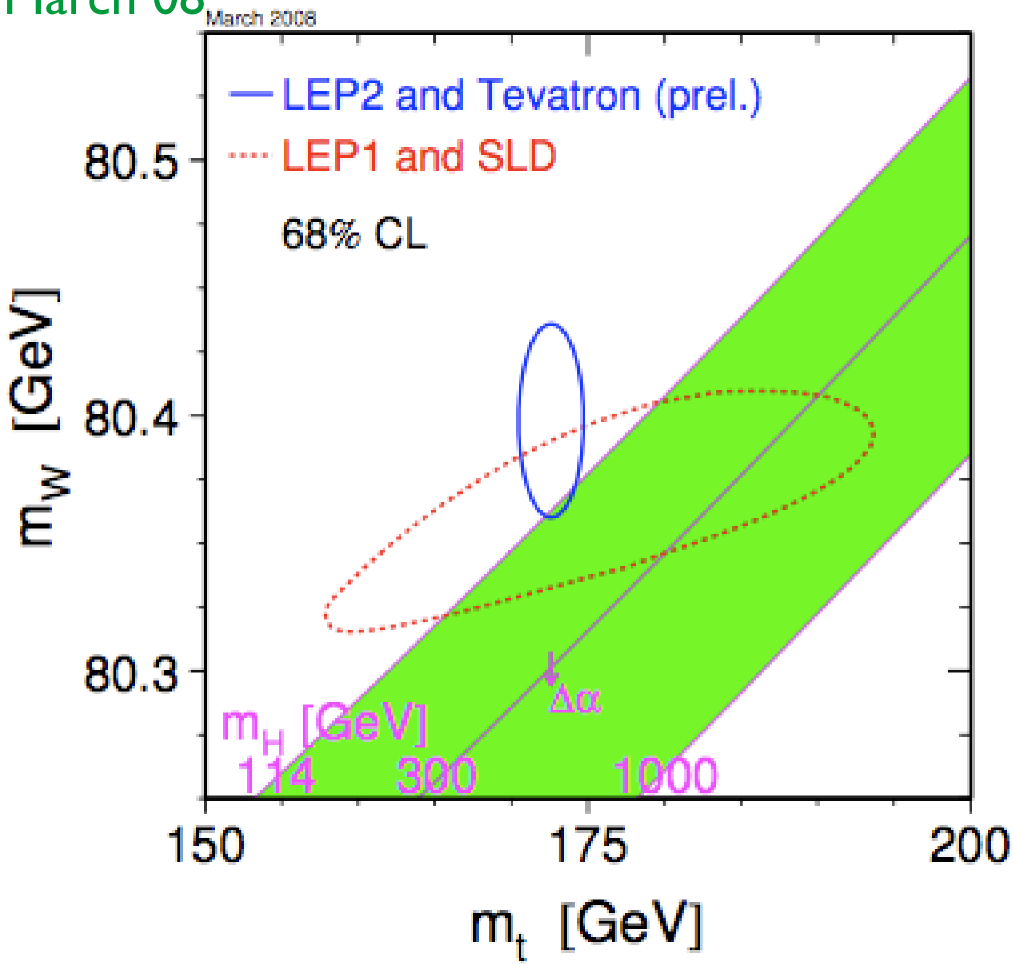

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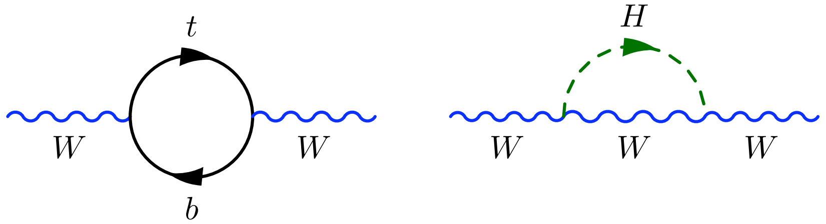
one loop

$$m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$



$$\Delta r_t = -\frac{3\alpha}{16\pi}\frac{\cos^2\theta_W}{\sin^4\theta_W}\frac{m_t^2}{m_W^2}$$

$$\Delta r_H = \frac{11\alpha}{48\pi\sin^2\theta_W}\ln\frac{m_H^2}{m_W^2}$$

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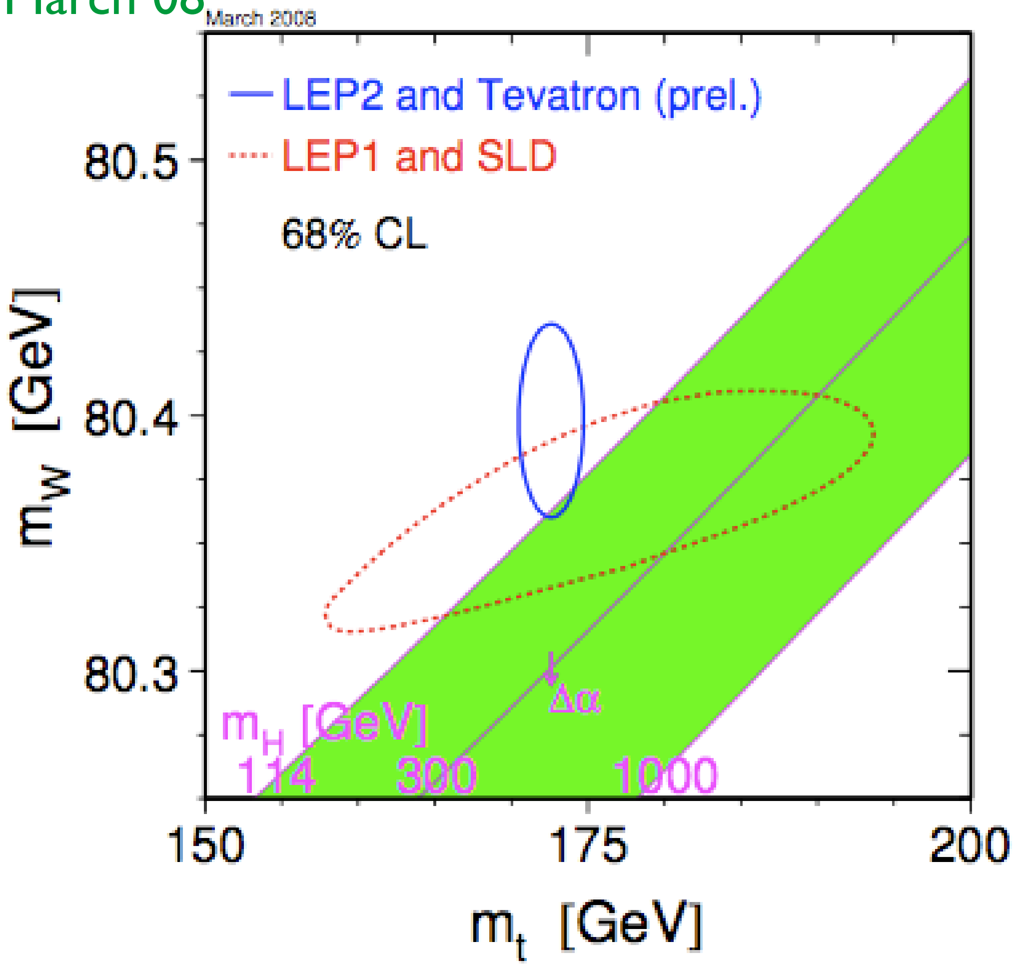

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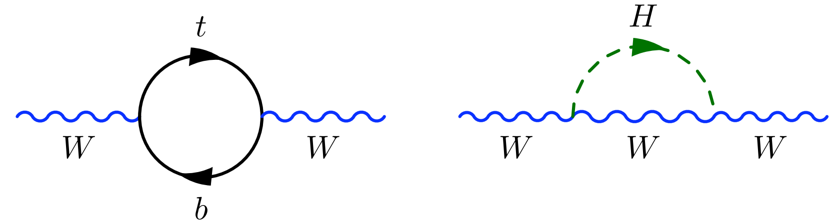

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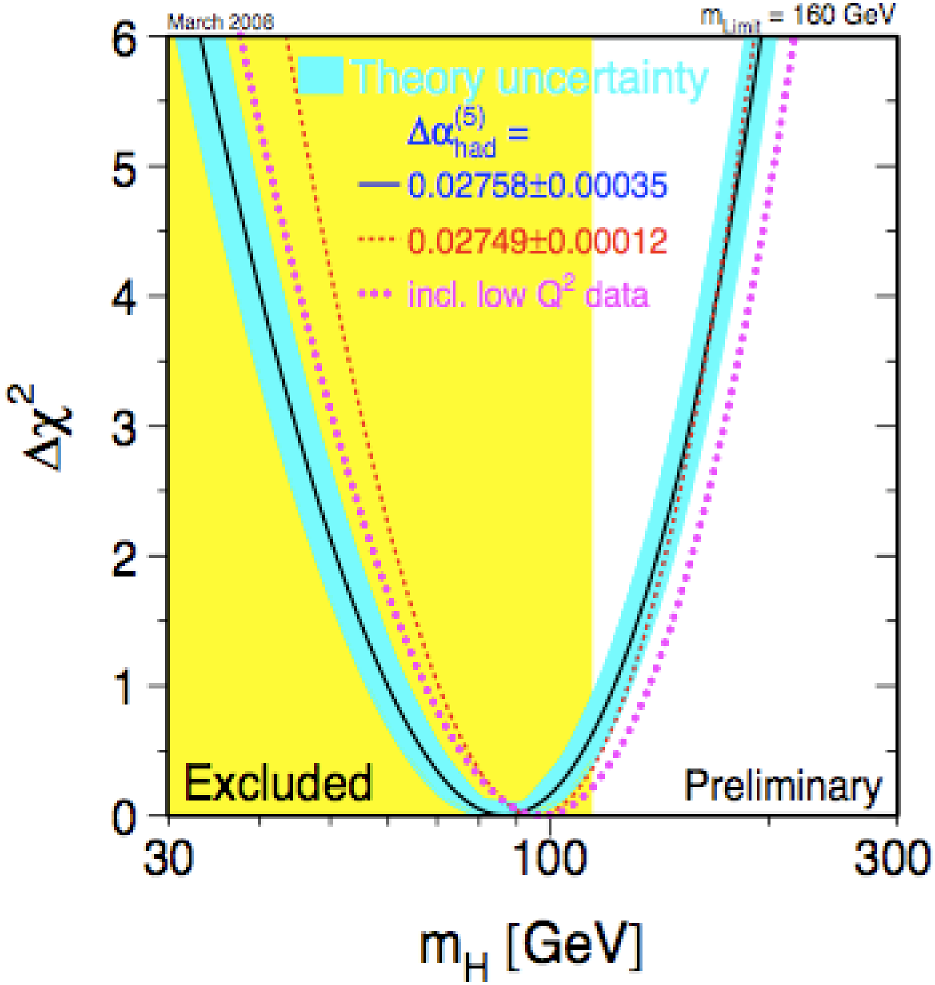
so $\delta m_W \propto m_t^2$ $\delta m_W \propto \ln m_H$

$\delta m_t = 1$ GeV $\Rightarrow \delta m_W(m_t) = 6$ MeV

if $\delta m_W = 10\text{-}15$ MeV
then $\delta m_t = 1\text{-}2$ GeV

Effects on Higgs mass

March 08



m_H > 114.4 GeV
from direct search at LEP

$m_H = 87^{+36}_{-27}$ GeV
from EW fits

At 95% CL
m_H < 160 GeV from EW fits
m_H < 190 GeV combined with direct search at LEP

Effects on Higgs mass

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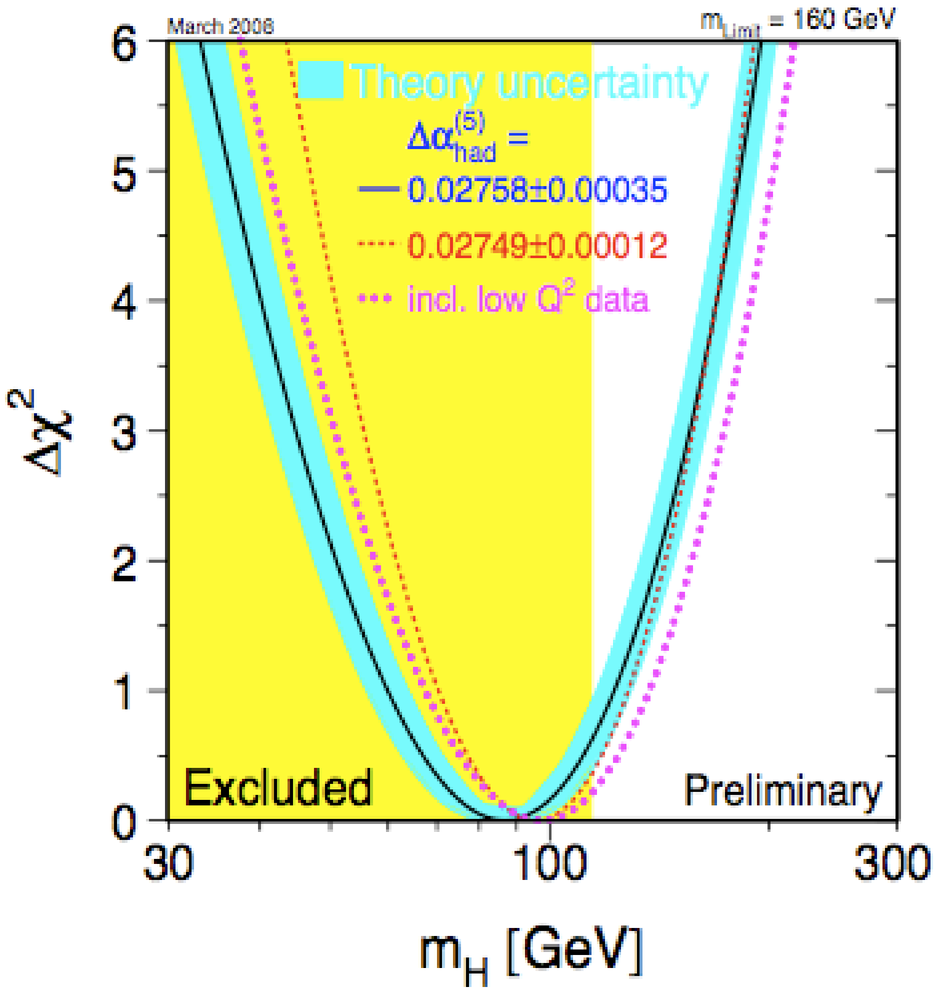

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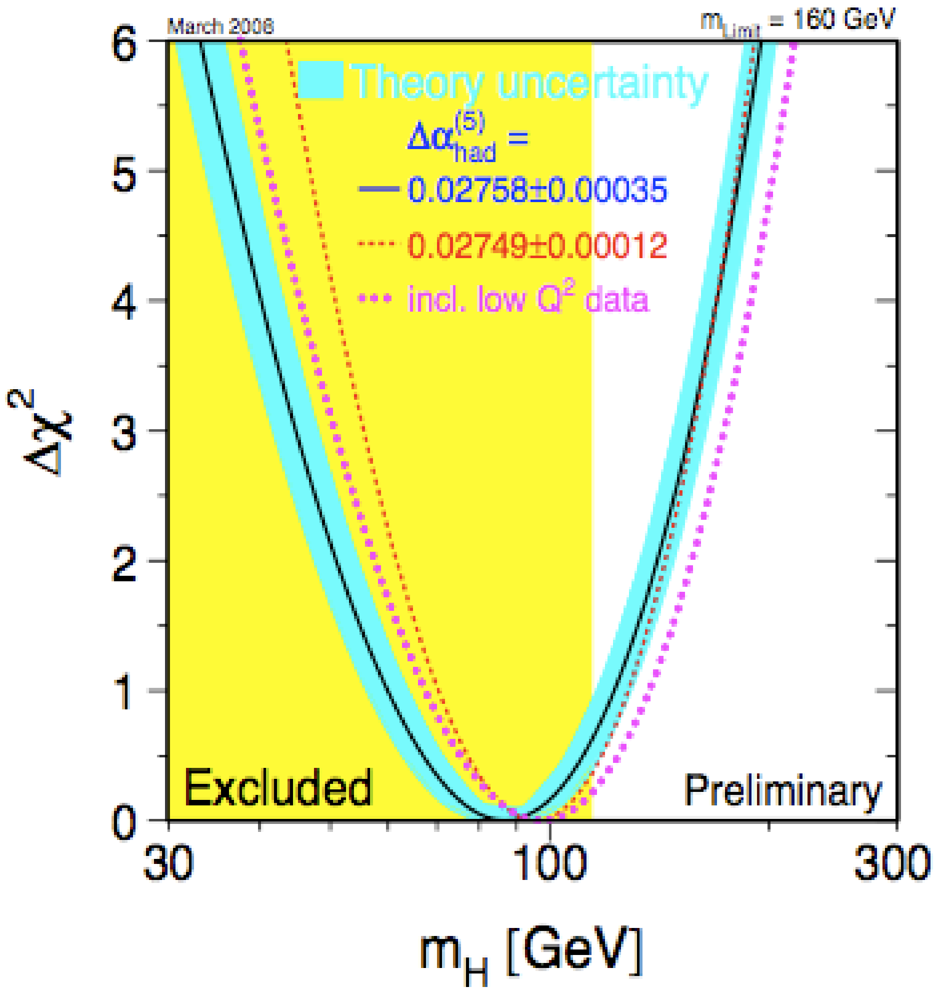

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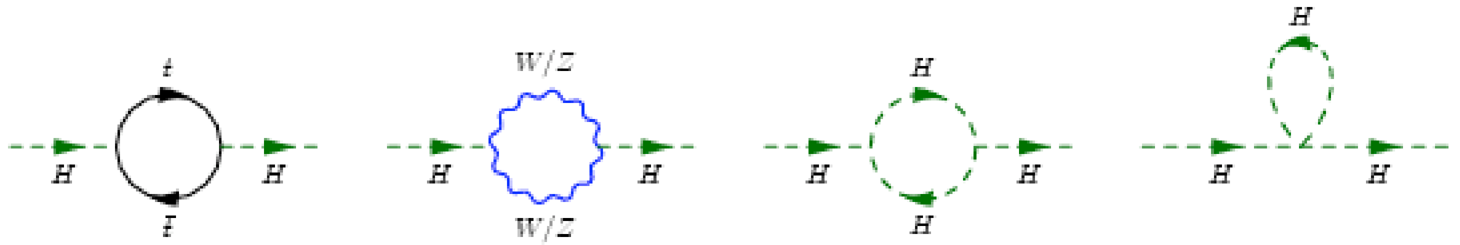
- use m_t to estimate m_H from EW corrections
- as m_t changes, large shifts in m_H

Hierarchy problem in the SM

the top affects sizeably the stability of m_H

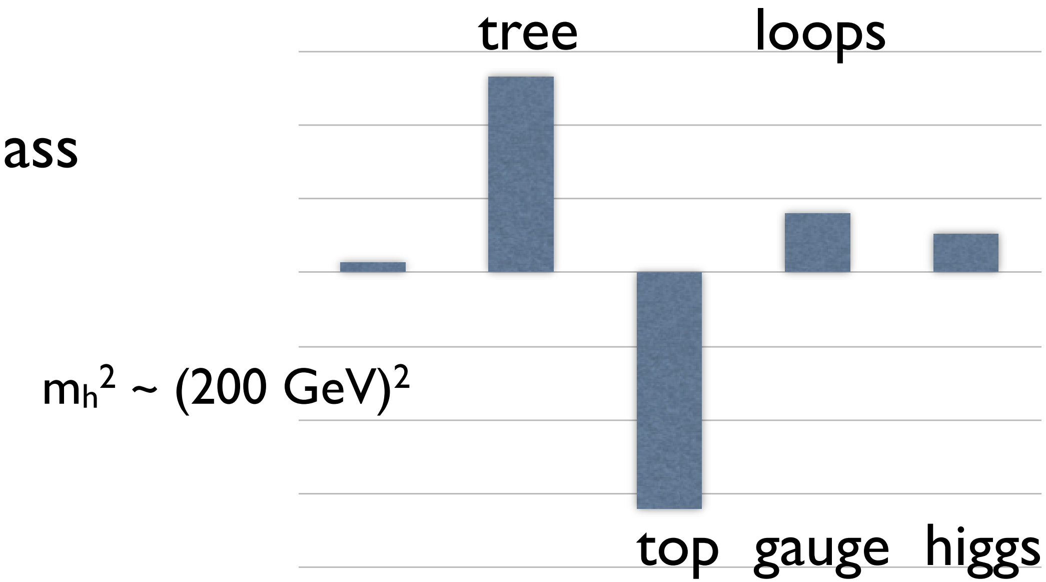


Higgs self-energy

$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\Lambda^2$$

$$(200\,\mathrm{GeV})^2 = m_{H0}^2 + \left[(700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2 - (2\,\mathrm{TeV})^2\right]\left(\frac{\Lambda}{10\,\mathrm{TeV}}\right)^2$$

shift on the Higgs mass



Fine tuning and unnaturalness

Higgs self-energy

$$m_H^2(Q^2) - m_H^2(Q_0^2) = \frac{3G_F}{4\sqrt{2}\pi^2}(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2)(Q^2 - Q_0^2)$$

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implies that

$$m_H^2(Q_0^2) - \frac{3G_F}{4\sqrt{2}\pi^2}(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2)\, Q_0^2 = const. = \mathcal{O}(\mathrm{v}^2)$$

because for $Q_0^2 = \mathcal{O}(\mathrm{v}^2)$ the Higgs mass is in the range of the EW data $m_H^2(Q_0^2) = \mathcal{O}(\mathrm{v}^2)$

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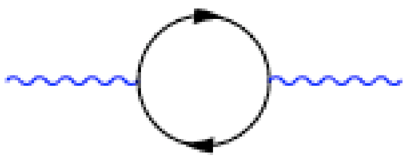
but for $Q_0^2 = \mathcal{O}(M_{Pl}^2)$ one must fine tune $m_H^2(M_{Pl}^2)$ to the level of $\mathrm{v}^2/M_{Pl}^2 \sim 10^{-33}$

for the cancellation to yield a figure of $\mathcal{O}(\mathrm{v}^2)$ ⟹ unnatural

Weakly coupled models at the TeV scale

Symmetry principles protect against power-like divergences



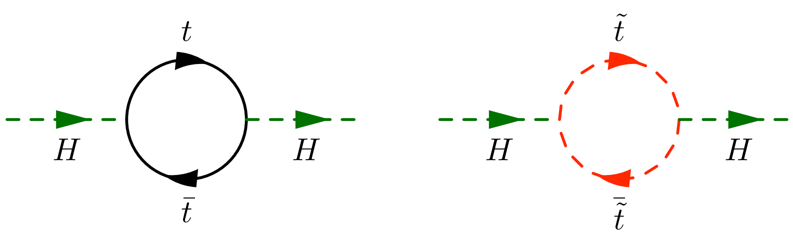
photon self-energy $\delta m_\gamma^2 \propto \cancel{\Lambda^2} + m_\gamma^2 \ln \Lambda$

gauge symmetry protects against quadratic divergence

A *natural* solution to hierarchy: supersymmetry

postulate a new symmetry principle, which yields new particles that cancel the quadratic divergences of the Higgs self-energy, such that

$$\delta m_H^2 \sim \mathcal{O}(m_H^2) \ln \Lambda$$



$$\delta m_H^2 \propto G_F \, m_t^4 \ln(m_t/m_{\tilde{t}})$$

Weakly coupled models at the TeV scale

Another solution to hierarchy: little Higgs models

- embed SM in a larger group

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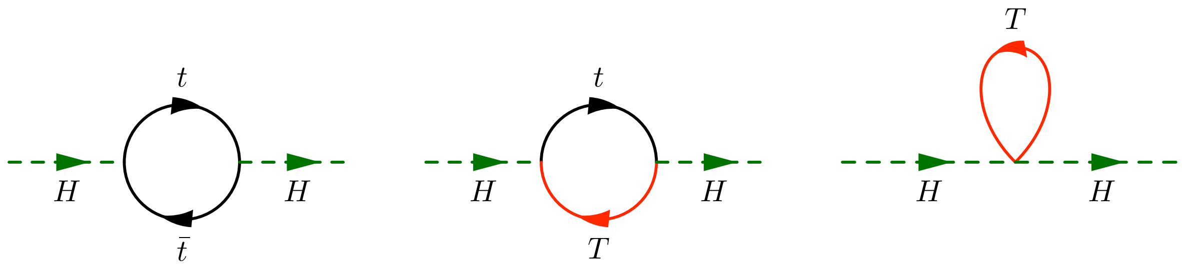

$$\frac{\Lambda}{16\pi^2}\left(+\lambda_t^2 \qquad + \lambda_T^2 \qquad - \frac{\lambda_T m_T}{f}\right) = 0$$

f symmetry-breaking scale of *O*(1 TeV)

shift in Higgs mass $\delta m_H^2 = \frac{6 G_F\, m_t^2}{\sqrt{2}\pi^2}\, m_T^2 \ln \frac{\Lambda}{m_T}$

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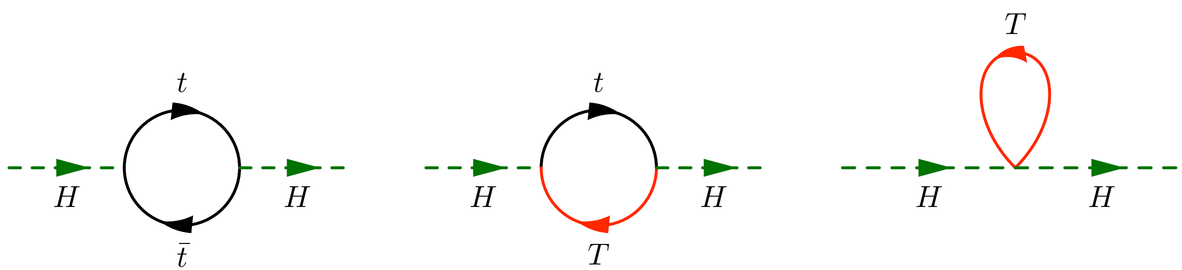

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  LHC can explore m_T up to 2 TeV, but huge statistics are required

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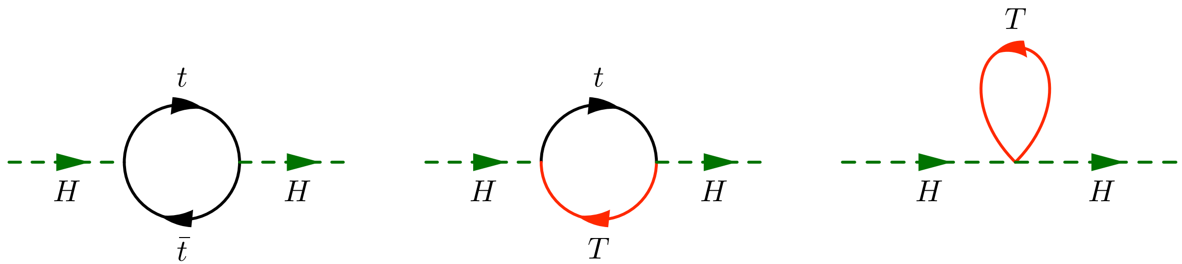

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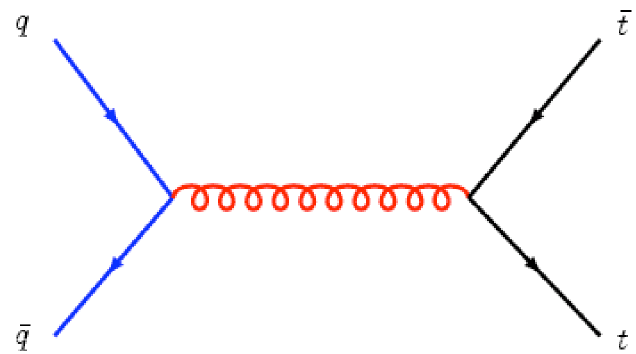
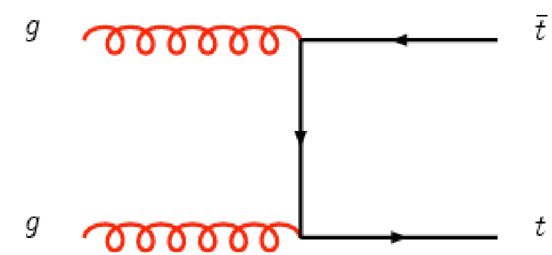
  LHC can explore m_T up to 2 TeV, but huge statistics are required
- T ⇒ tH and tZ decays allowed

t tbar production from Tevatron to LHC





Tevatron	85 %	15 %
LHC	~ 10 %	~ 90 %

Tevatron
- 10 tt pairs/day → ~ 20000 tt produced
- 60 % with p_t (tt) > 15 GeV

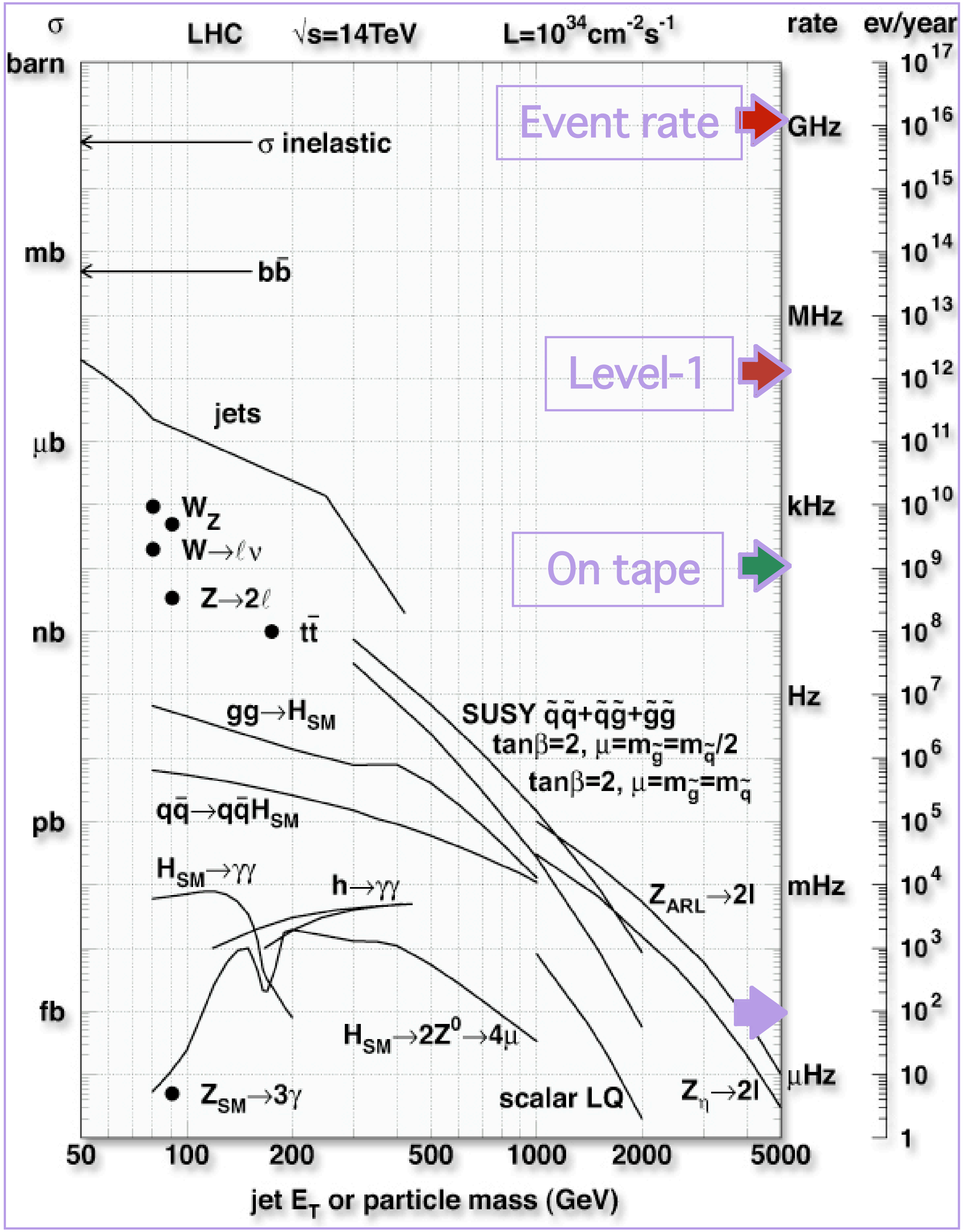
LHC
- 1 tt pairs/sec → at hi lumi ~10^7 tt produced/year
- 70 % with p_t (tt) > 30 GeV

t tbar production from Tevatron to LHC

pb	tt	$W \to e\nu$	$W \to e\nu + 4j$
Tevatron	7	2000	1
LHC	910	18500	220
ratio	130	9	220

$p_{Tj} > 20$ GeV $|\eta_j| < 3$ $\Delta R > 0.7$

- tt cross section increases more than 100 times from Tevatron to LHC (Drell-Yan only 9 times) $\Rightarrow$ top is a major bckgnd to a lot of NP
- however, also a lot of hard radiation from Drell-Yan



LHC is a QCD machine

SM processes are backgrounds to New Physics signals

design luminosity

$L = 10^{34}\ cm^{-2}\ s^{-1} = 10^{-5}\ fb^{-1}\ s^{-1}$

integrated luminosity (per year)

$L \approx 100\ fb^{-1}\ yr^{-1}$

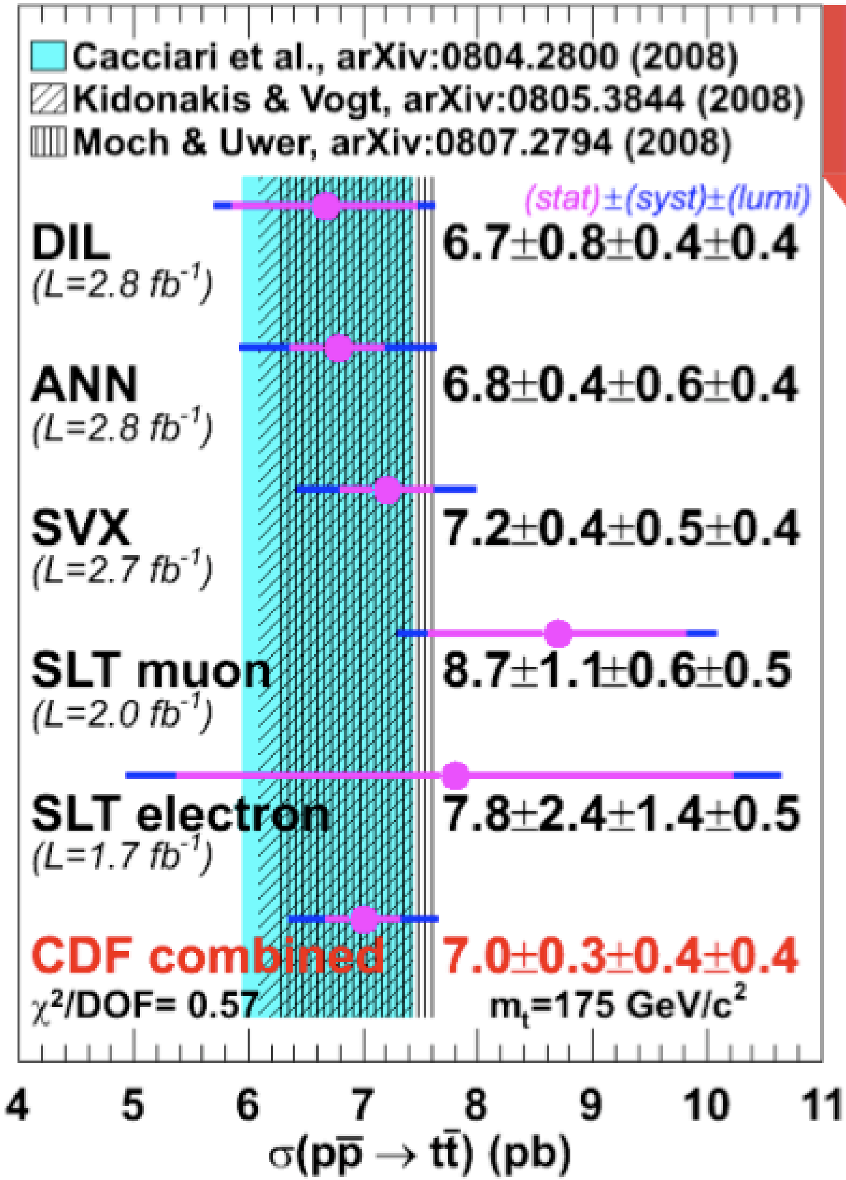
With 1 fb^{-1} we shall get ...

final state	events	overall # of events (2008)
jets (p_T > 100 GeV)	10^9	
jets (p_T > 1 TeV)	10^4	
$W \to e\nu$	$2 \cdot 10^7$	10^7 (Tevatron)
$Z \to e^+e^-$	$2 \cdot 10^6$	10^6 (LEP)
$b\bar{b}$	$5 \cdot 10^{11}$	10^9 (BaBar, Belle)
$t\bar{t}$	$9 \cdot 10^5$	$2 \cdot 10^4$ (Tevatron)

even at very low luminosity, LHC beats all the other accelerators

t tbar x-section at the Tevatron

T. Schwarz, Fermilab wine & cheese, Oct 08



$$\sigma = 6.73^{+0.72}_{-0.63}\ pb$$

$$\sigma = 6.90^{+0.46}_{-0.64}\ pb$$

$$\sigma = 6.73^{+0.71}_{-0.79}\ pb$$

$$\frac{\Delta\sigma}{\sigma} = 8 - 10\%$$

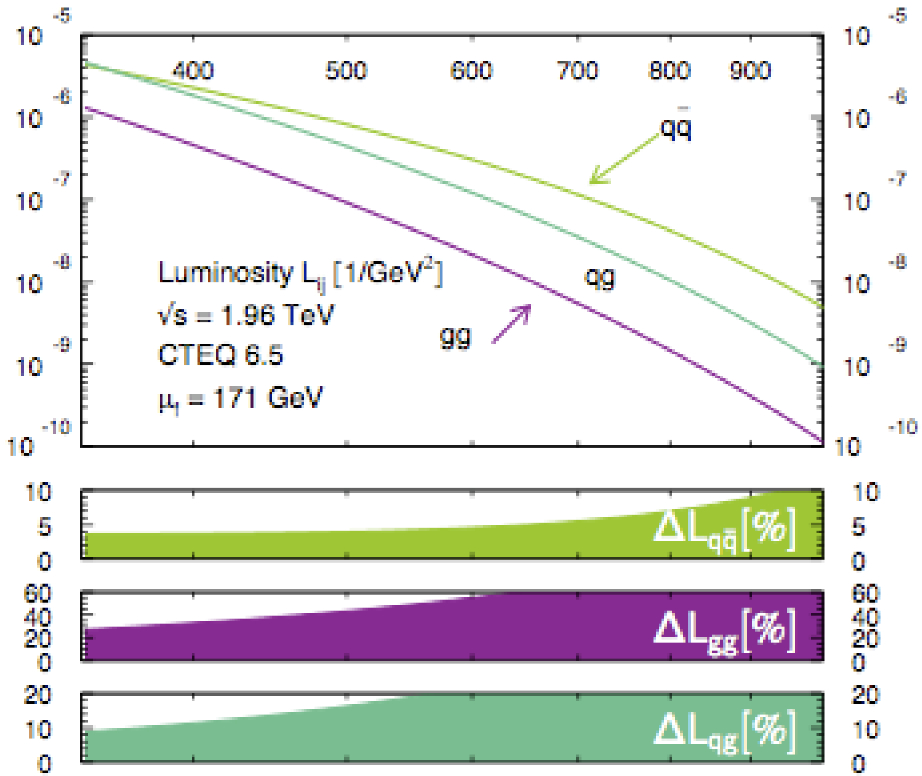
$$\frac{\Delta\sigma}{\sigma} = 9\%$$

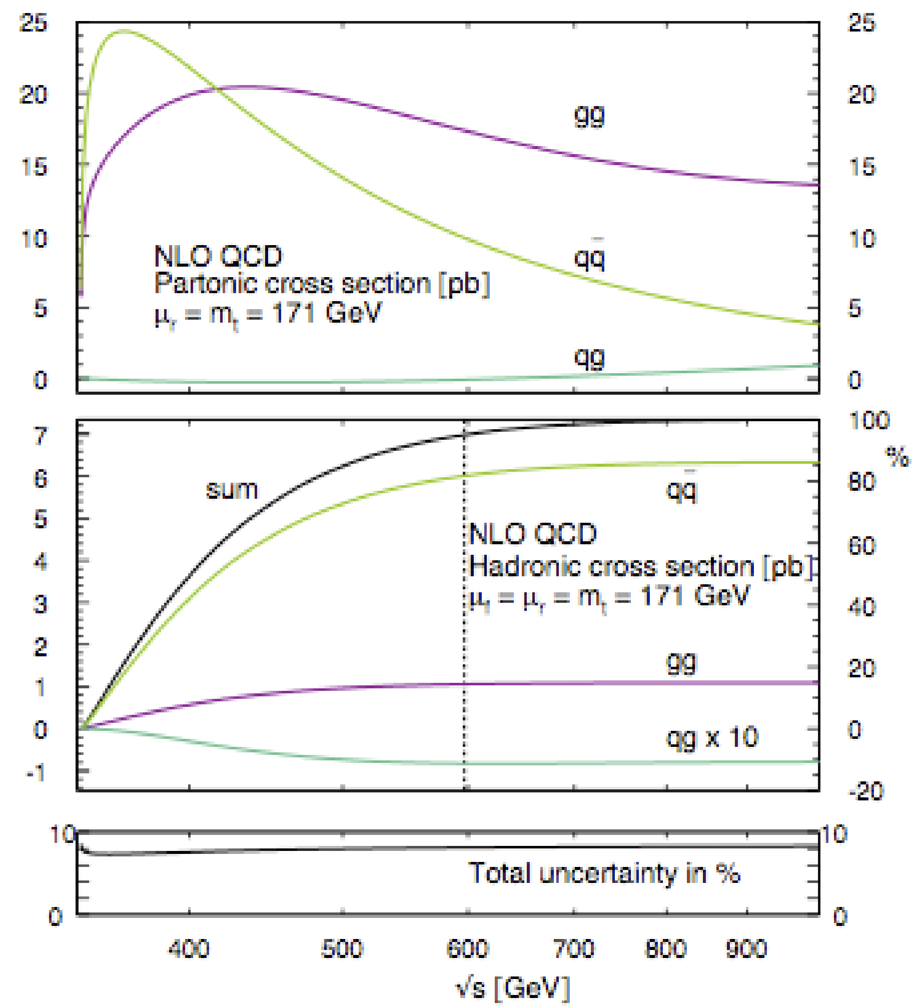
assume $m_t = 175$ GeV

based on $L = 2.8\ fb^{-1}$

t tbar x-section at the Tevatron

Moch, Uwer April 08

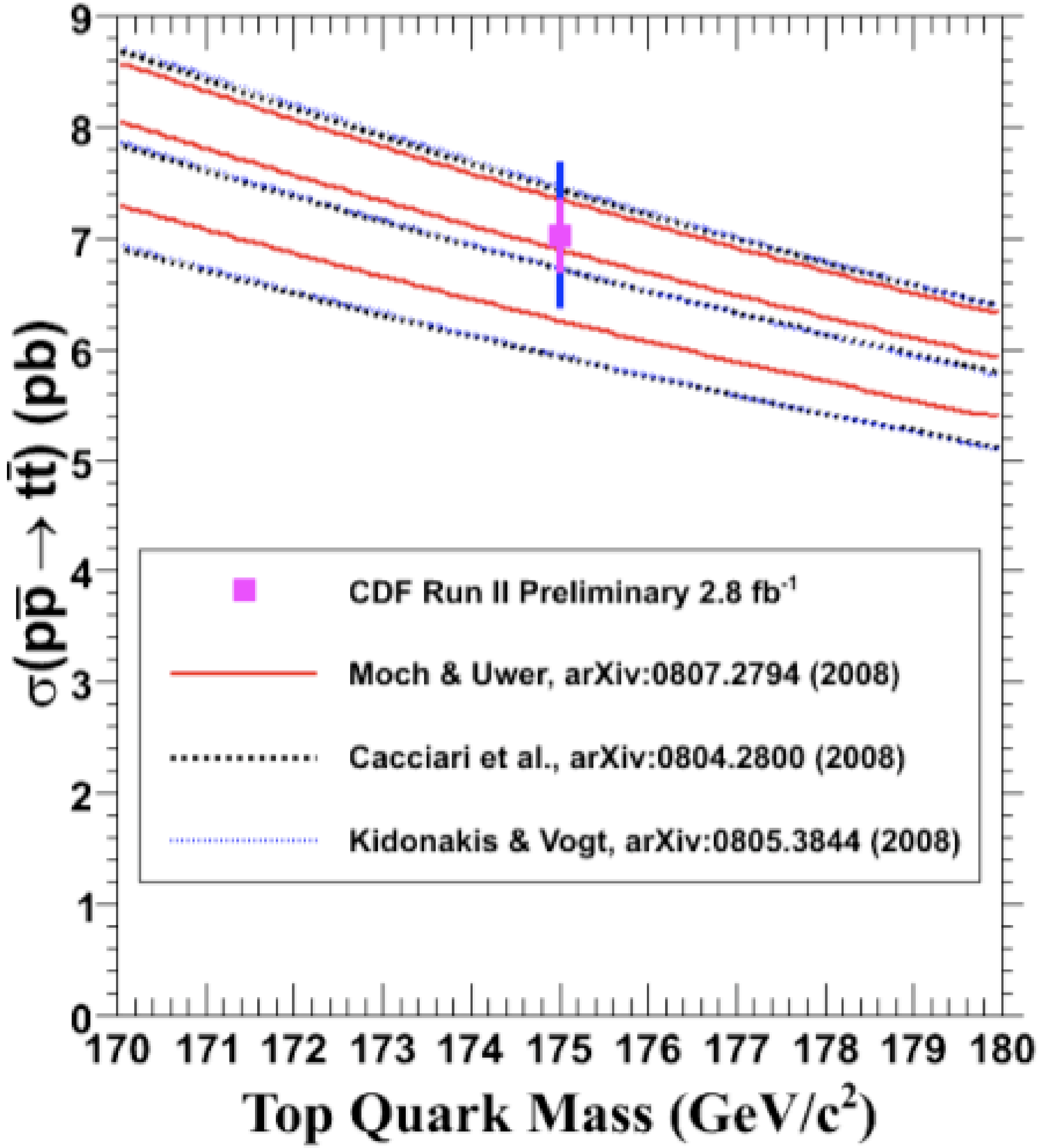




Parton luminosities
PDF uncertainties

Partonic cross section
Hadronic cross section

95% of total cross section for $s < (600\ \text{GeV})^2$
Total uncertainty driven by overall PDF uncertainty, due to sensitivity of the gluon PDF at large *x*



TH & EXP have comparable errors

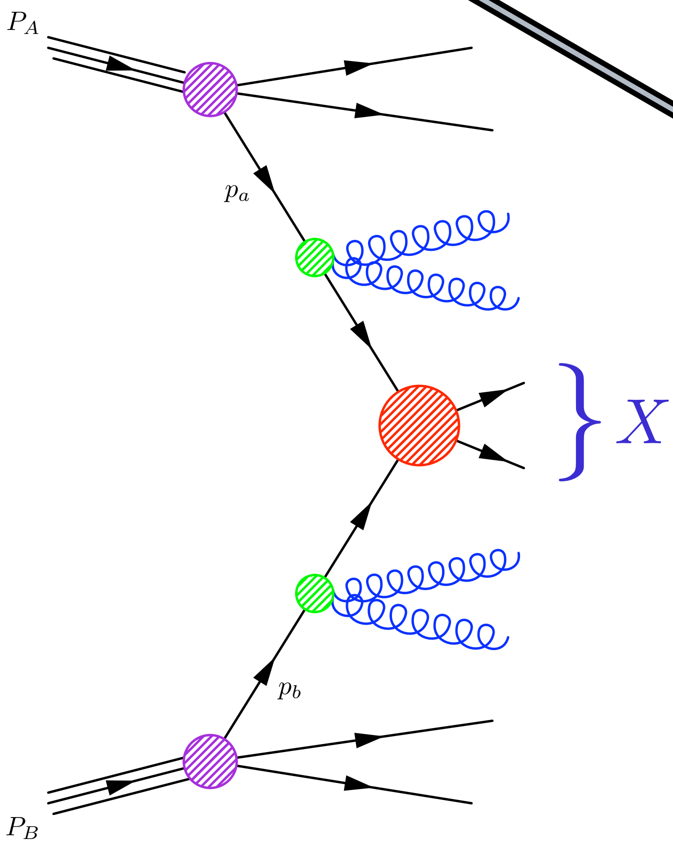
theory is NLO + NLL

Factorisation

extracted from data
evolved through DGLAP

computed in pQCD

is the separation between
the short- and the long-range interactions



$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_{a/A}(x_1, \mu_F^2) \, f_{b/B}(x_2, \mu_F^2)$$
$$\times \; \hat{\sigma}_{ab \to X} \left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_F^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2} \right)$$

$$X = W, Z, H, Q\bar{Q}, \text{high-}E_T\text{jets}, \ldots$$

$\hat{\sigma}$ is known as a fixed-order expansion in α_S

$$\hat{\sigma} = C\alpha_S^n (1 + c_1\alpha_S + c_2\alpha_S^2 + \ldots)$$

$c_1 =$ NLO $\qquad c_2 =$ NNLO

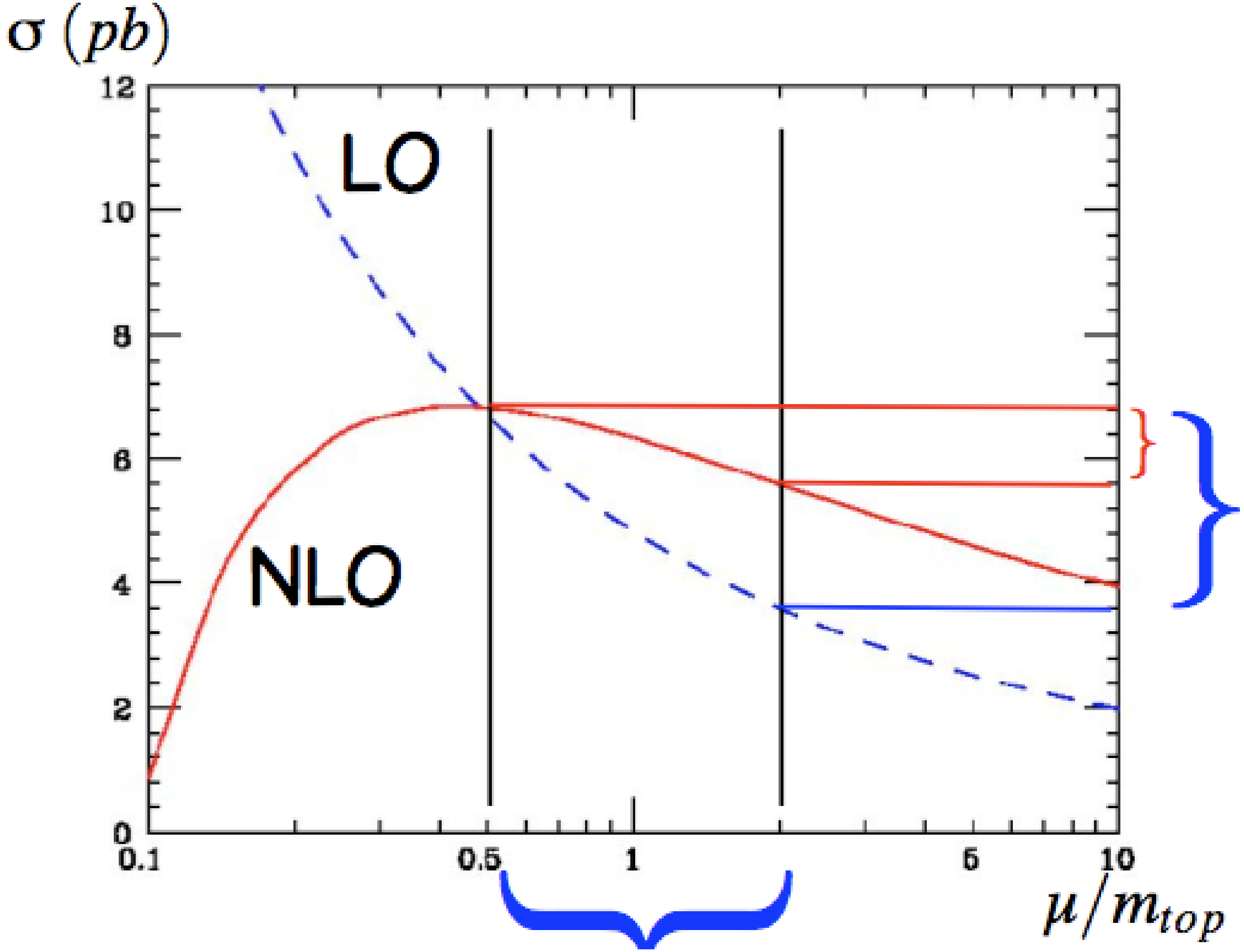
or as an all-order resummation

$$\hat{\sigma} = C\alpha_S^n [1 + (c_{11}L + c_{10})\alpha_S + (c_{22}L^2 + c_{21}L + c_{20})\alpha_S^2 + \ldots]$$

where $L = \ln(M/q_T), \ln(1-x), \ln(1/x), \ln(1-T), \ldots$

$c_{11}, c_{22} =$ LL $\qquad c_{10}, c_{21} =$ NLL $\qquad c_{20} =$ NNLL

Estimate of TH uncertainties

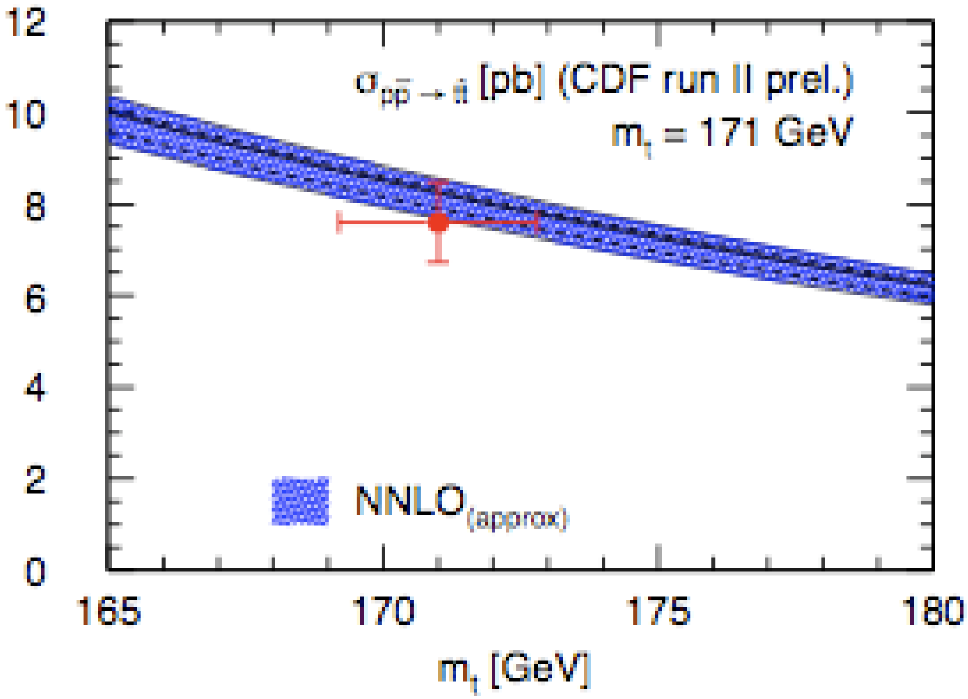


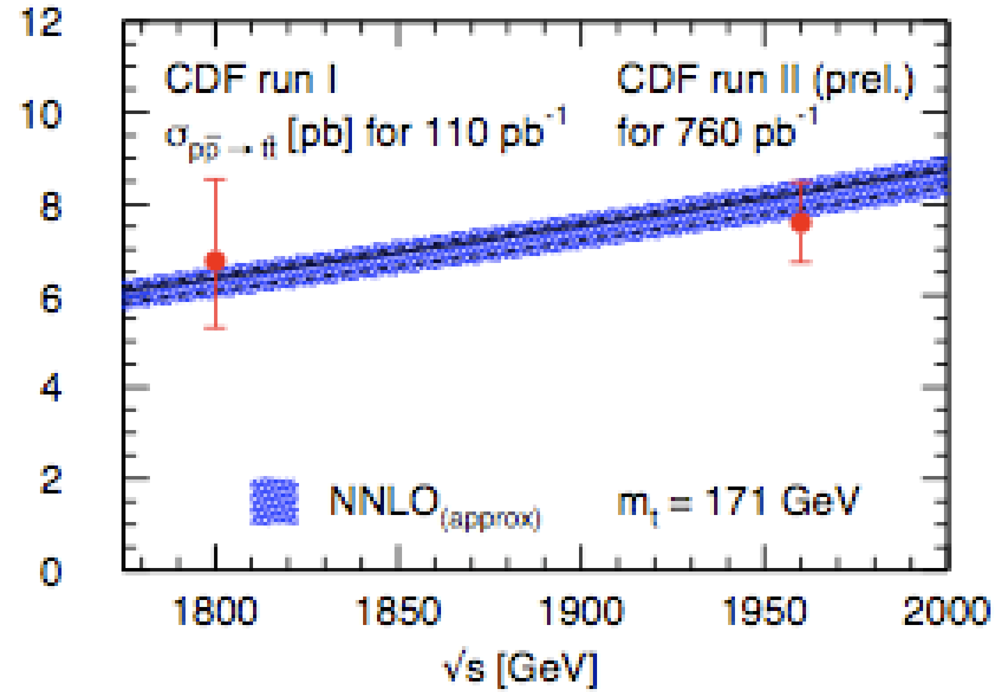
NLO: good estimate of the cross section, first estimate of the uncertainty

NNLO: good estimate of the uncertainty

t tbar x-section at the Tevatron

Approximate NNLO (scale variations) Moch, Uwer April 08





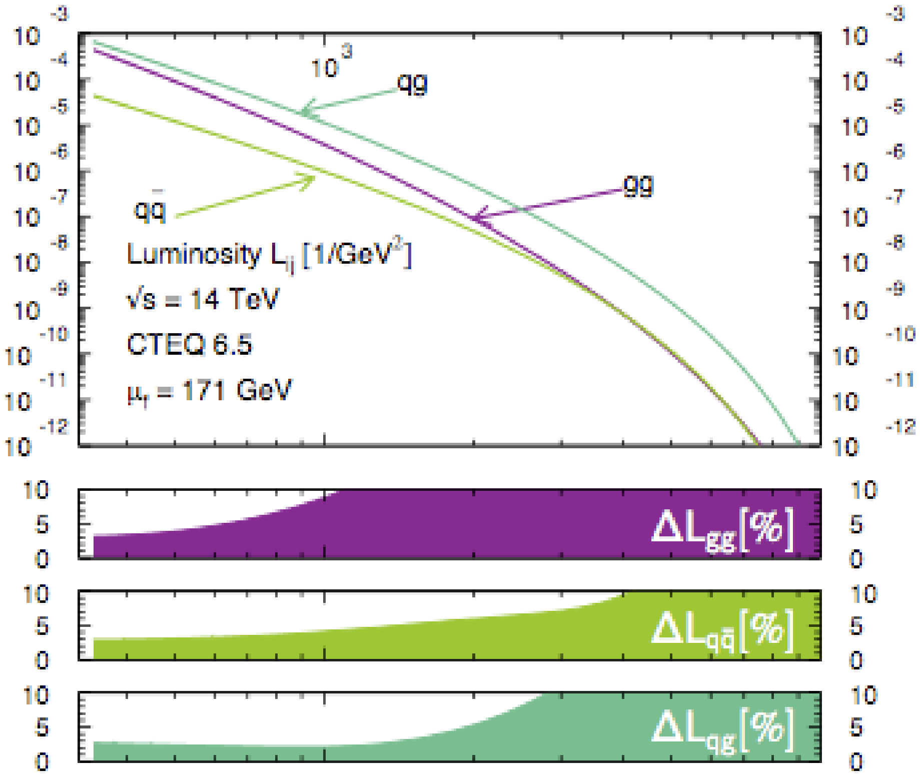
solid line: central value at $\mu = m_t$

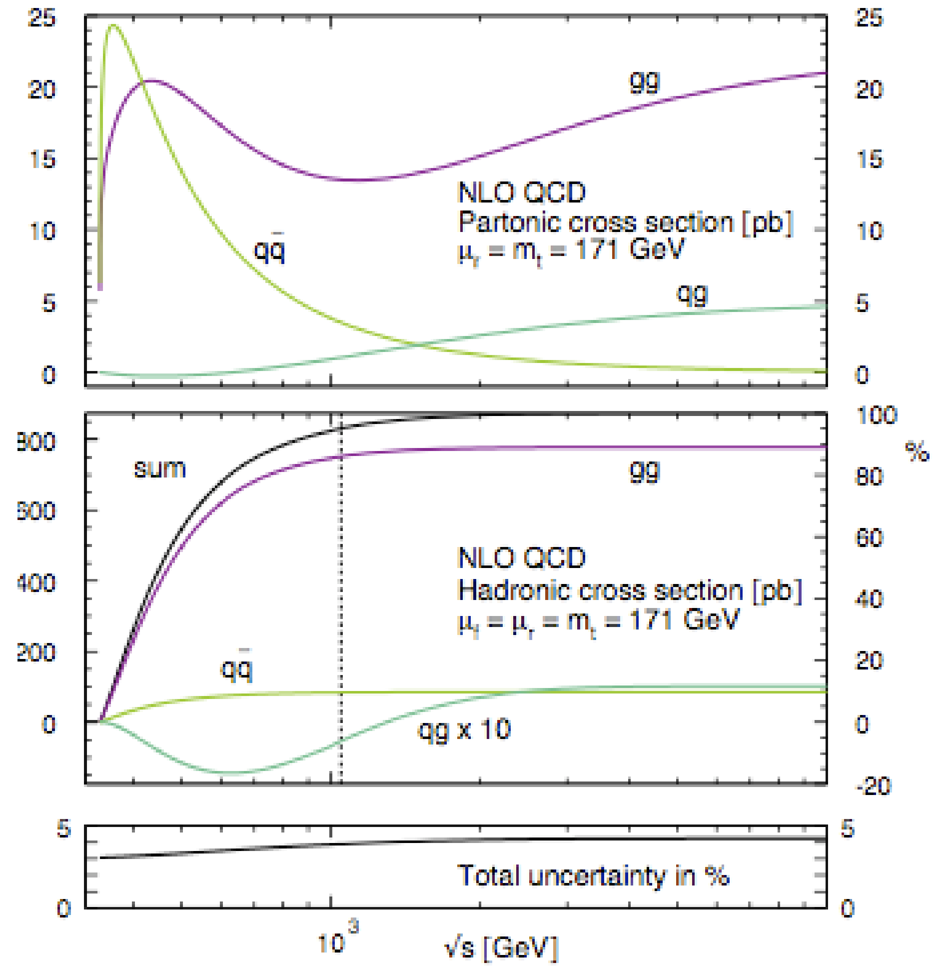
upper (lower) dashed line: value at $\mu = m_t/2$ ($\mu = 2m_t$)

band: scale variation + PDF uncertainties (MRST-2006 NNLO)

t tbar x-section at the LHC

Moch, Uwer April 08





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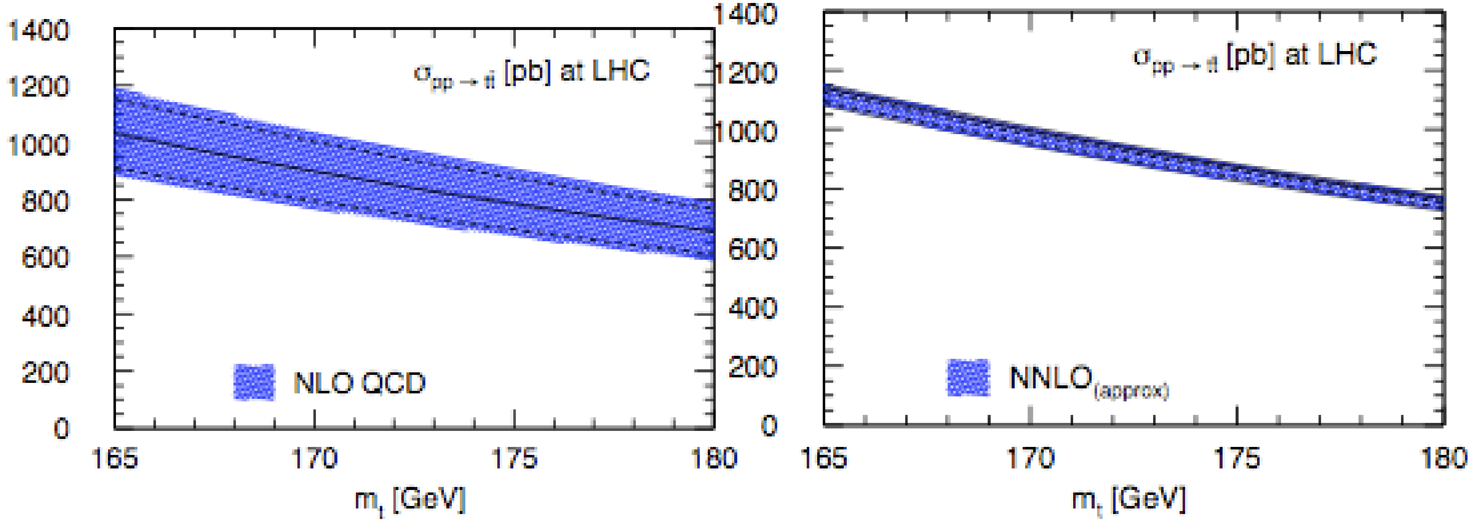
Hadronic cross section

95% of total cross section for $s < (1\ \text{TeV})^2$
Total uncertainty is about half as large as at Tevatron

t tbar x-section at the LHC

At the LHC threshold region less important than at the Tevatron
theory improvement goes through NNLO calculations



Moch, Uwer April 08

solid line: central value at $\mu = m_t$
upper (lower) dashed line: value at $\mu = m_t/2$ ($\mu = 2m_t$)
band: scale variation + PDF uncertainties (MRST-2006 NNLO)

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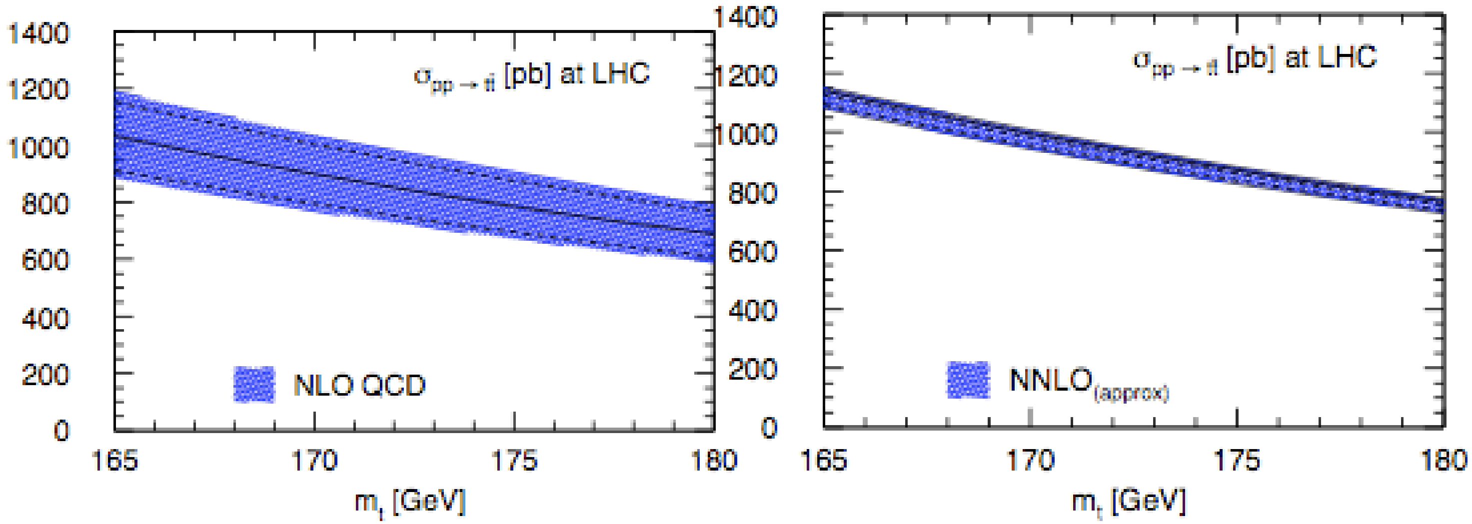

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Caveat

CTEQ6.5 $\sigma = 908\ ^{+82(9.0\%)}_{-85(9.3\%)}\ (\text{scales})\ ^{+30(3.3\%)}_{-29(3.2\%)}\ (\text{PDFs})\ \text{pb}$

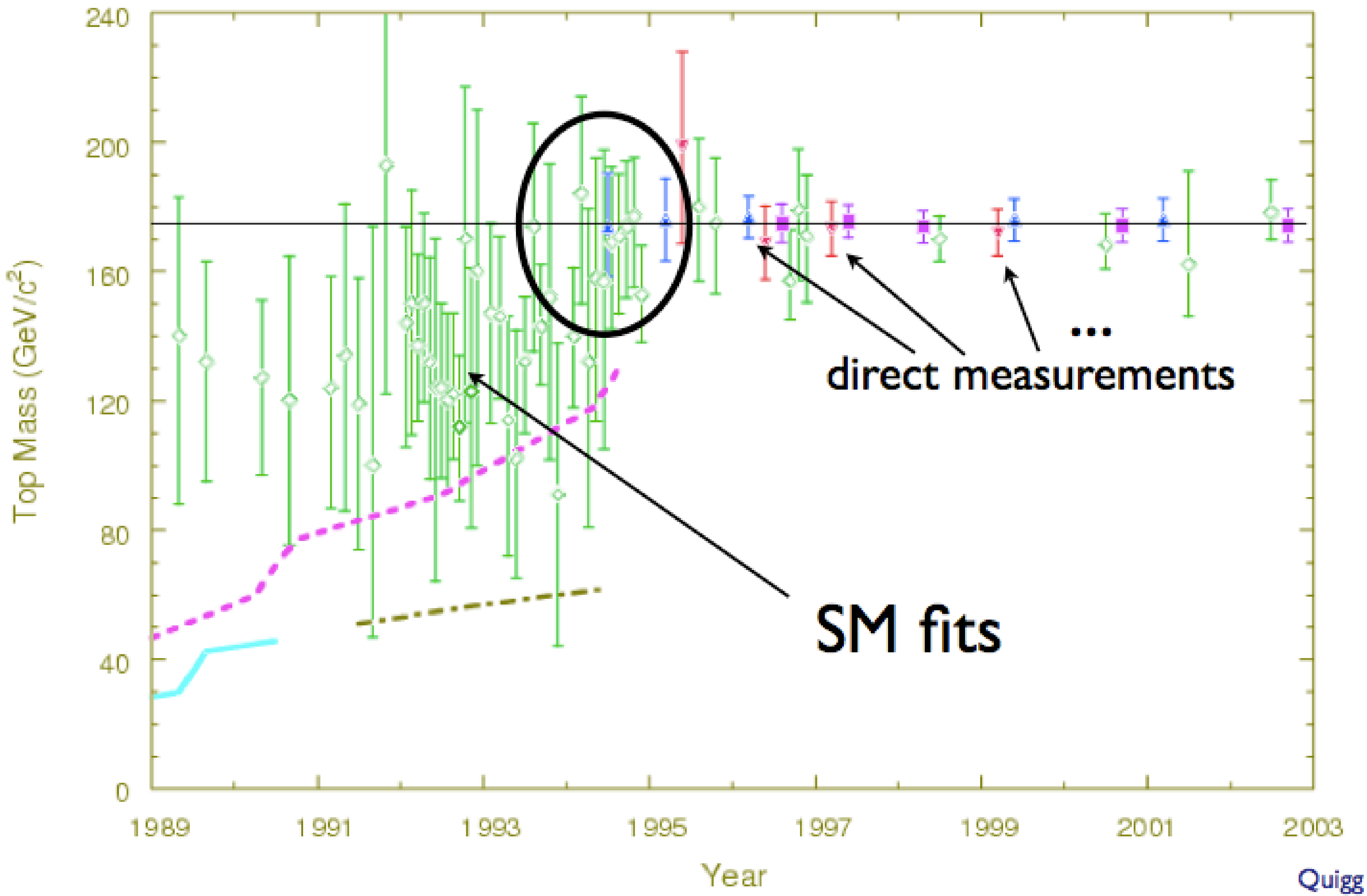
Mangano'08

MRSTW-06 $\sigma = 961\ ^{+89(9.2\%)}_{-91(9.4\%)}\ (\text{scales})\ ^{+11(1.1\%)}_{-12(1.2\%)}\ (\text{PDFs})\ \text{pb}$

MRST–CTEQ = 53 ± 33 pb

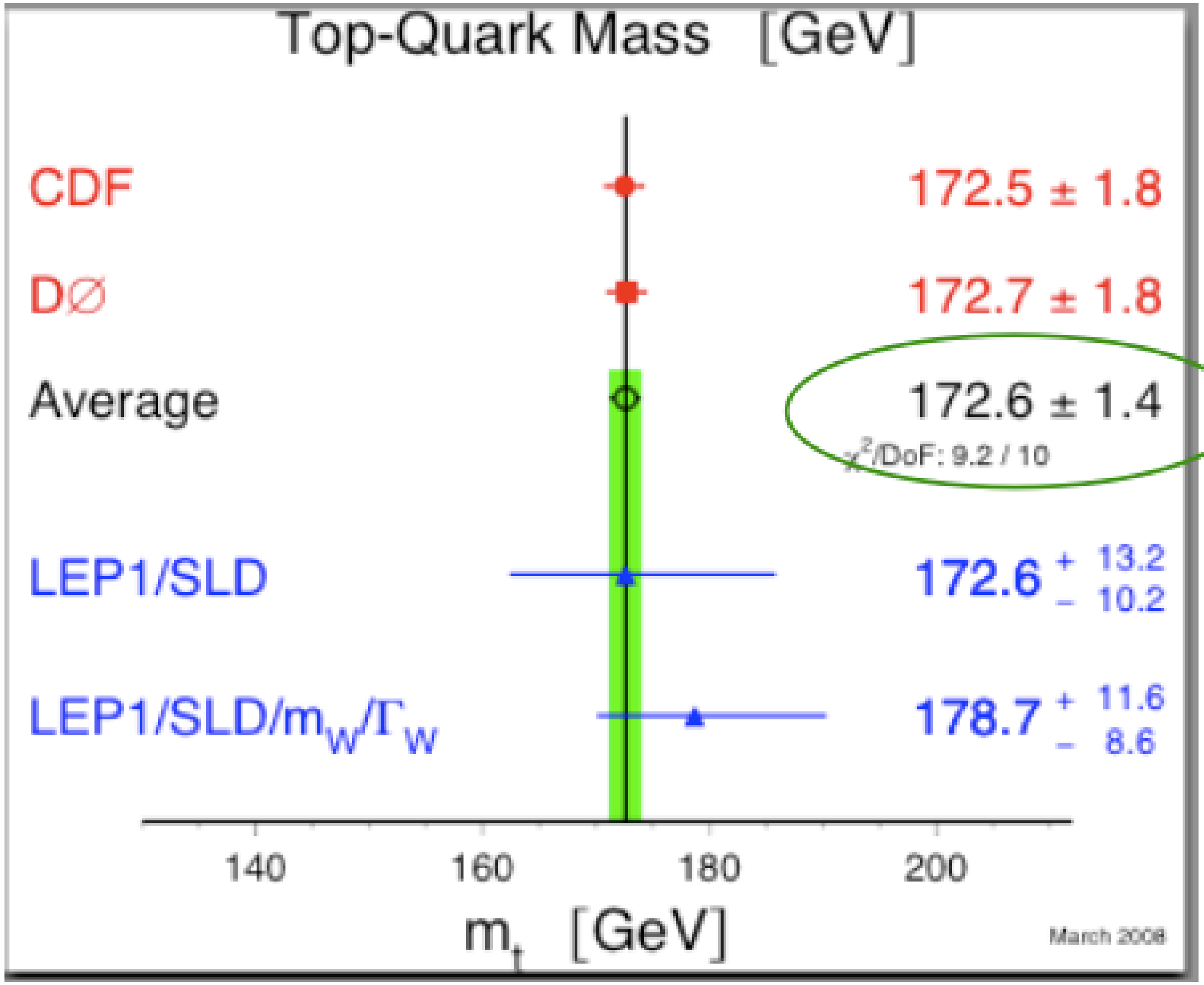
PDF underestimated ?

Top mass history



hint of a large top mass from EW fits

Top mass

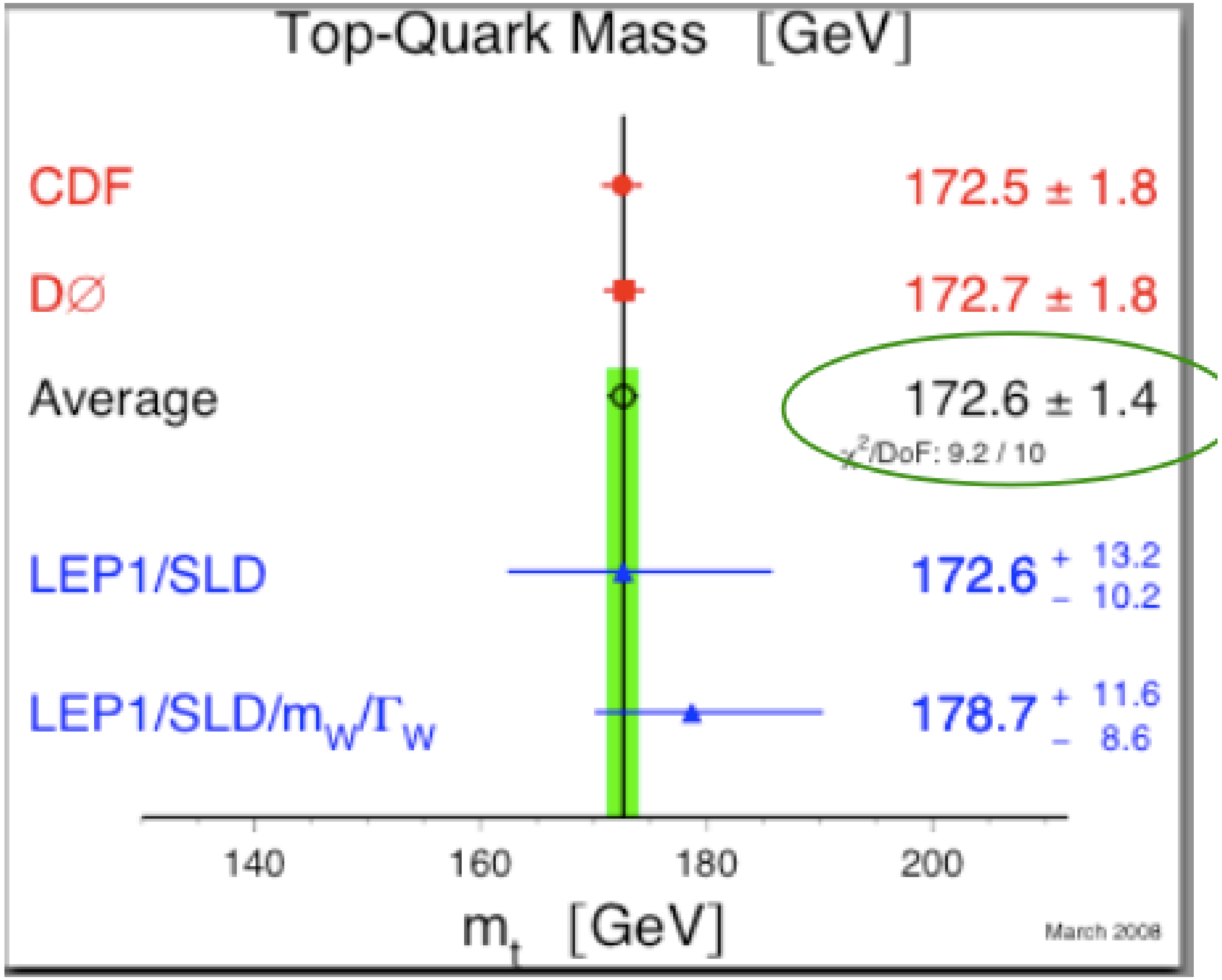


March 08

m_t = 172.6 ± 0.8 ± 1.1 GeV

error is now at % level

Top mass



March 08

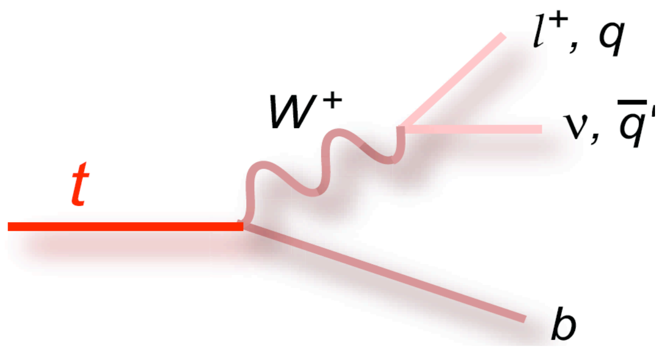
m_t = 172.6 ± 0.8 ± 1.1 GeV

error is now at % level

$\delta m/m = 0.2\ \delta\sigma/\sigma$ TH: $\delta\sigma/\sigma$ = 9% → Δm = 3 GeV

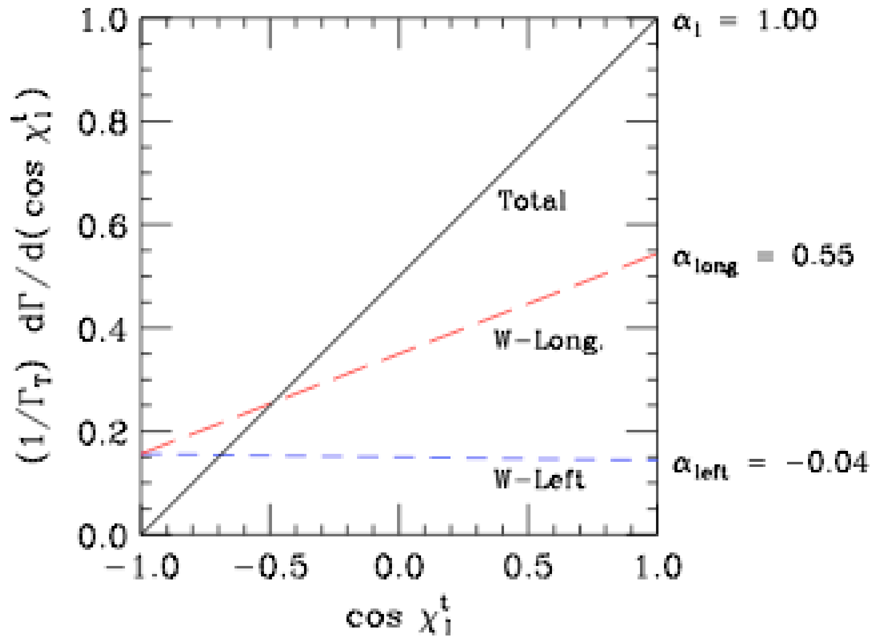
At the LHC the expected EXP error is Δm = 1 GeV
so the TH cross section should be known at 3% level

Top spin



$$\frac{d\ln\Gamma_f}{d\cos\chi_f} = \frac{1+\alpha_f\cos\chi_f}{2}$$

- In top decay, its spin is 100% correlated ($\alpha_f = 1$) with l^+ direction
- QCD corrections are tiny
- probe of BSM (*e.g. H*$^+$ would lower α_f)



t tbar as a background

- tt in $gg \Rightarrow H$ & $qq \Rightarrow qqH$, with $H \Rightarrow WW$
- tt in single top
- *tt jets* in *ttbb* & *ttH*
- *tt jets* & *ttW* in SUSY searches

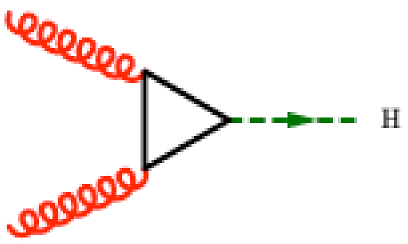
*t*heory tools

- NLO + shower for *tt* production with spin correlations
  MC@NLO, POWHEG
- NLO + shower single-top production with spin correlations
  MC@NLO
- *tt* + *1 jet* at NLO
- *tt jets, ttQQ jets*: ME + shower in ALPGEN, MADEVENT, SHERPA

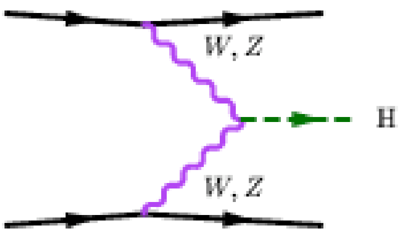
Higgs production modes at the LHC

In proton collisions at 14 TeV, and for $M_H > 100$ GeV the Higgs is produced mostly via

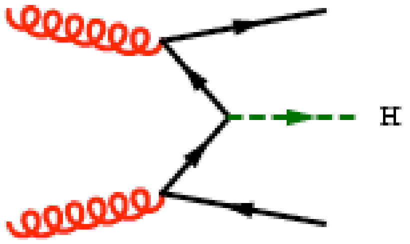
- gluon fusion $gg \to H$
  - largest rate for all M_H
  - proportional to the top Yukawa coupling y_t



- weak-boson fusion (WBF) $qq \to qqH$
  - second largest rate (mostly $u\, d$ initial state)
  - proportional to the WWH coupling



- $t\bar{t}(b\bar{b})H$ associated production
  - fourth largest rate
  - same initial state as in gluon fusion, but higher x range
  - proportional to the heavy-quark Yukawa coupling y_Q
  - possible discovery channel for a light $H \to bb$
  - $bb \to H$ for MSSM



Top & flavour physics

$J_\mu^+ = \bar{u}_L \gamma_\mu d_L$ ⟶ $J_\mu^+ = \bar{U}_L \gamma_\mu V_{CKM} D_L$

weak eigenstates — mass eigenstates

$$|\mathrm{V}_{\mathrm{CKM}}| = \begin{pmatrix} 0.9738 \pm 0.0005 & 0.2200 \pm 0.0026 & (3.67 \pm 0.47) \times 10^{-3} \\ 0.224 \pm 0.012 & 0.996 \pm 0.013 & (41.3 \pm 1.5) \times 10^{-3} \\ ? & ? & ? \end{pmatrix}$$

(assuming 3 generations) unitarity implies

$$|V_{td}| \simeq 0.0048 - 0.014, \quad |V_{ts}| \simeq 0.037 - 0.043, \quad |V_{tb}| \simeq 0.9990 - 0.9992$$

$\mathcal{O}(\lambda^3)$ $\mathcal{O}(\lambda^2)$ $\mathcal{O}(1)$

with $\lambda \cong 0.22$

Top & flavour physics

$$J^+_\mu = \bar{u}_L \gamma_\mu d_L \quad \Longrightarrow \quad J^+_\mu = \bar{U}_L \gamma_\mu V_{CKM} D_L$$

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with $\lambda \cong 0.22$

for example, CDF measurements on B_s mixing

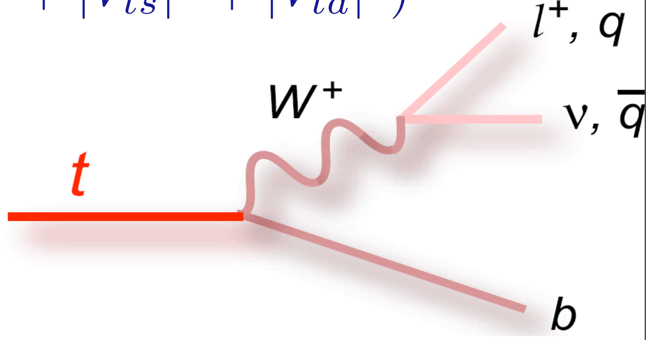
$$\Delta M_s = 17.33^{+0.42}_{-0.21}(\text{stat.}) \pm 0.07(\text{syst.})\text{ps}^{-1}$$

implies (in good agreement with SM predictions)

$$0.20 < |V_{td}/V_{ts}| < 0.22$$

Top & flavour physics at Tevatron

top can decay into a real W $\Gamma_t \sim G_F\, m_t^3\,(|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2)$



but only ratio of widths is measured

$$R = \frac{\Gamma(t \to Wb)}{\Gamma(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

$$1.12^{+0.21}_{-0.19}(\text{stat})^{+0.17}_{-0.13}(\text{syst}),\ \text{CDF}, \quad 1.03^{+0.19}_{-0.17}\ (\text{stat} + \text{syst}),\ \text{DØ}$$

but this only entails that $|V_{ts}|/|V_{tb}|$ and $|V_{td}|/|V_{tb}|$ are small
it has no bearing on size of V_{tb}

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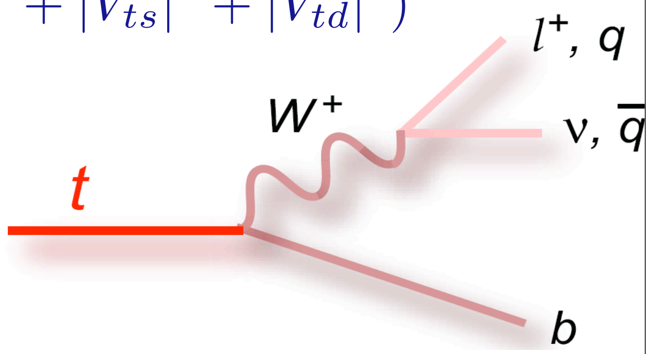

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but this only entails that $|V_{ts}|/|V_{tb}|$ and $|V_{td}|/|V_{tb}|$ are small
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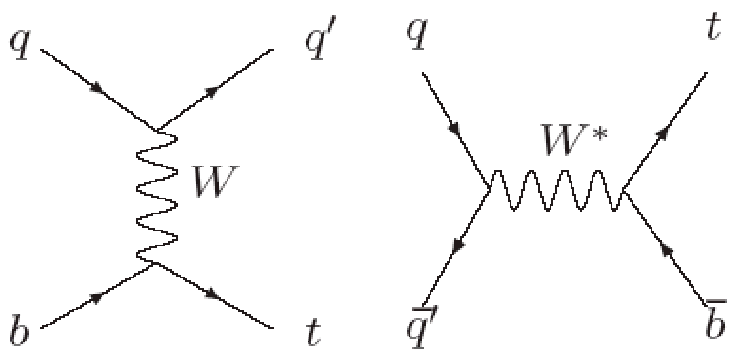
so V_{tb} cannot be measured from top decay
need quantities which are proportional only to $|V_{tb}|^2$

→ single Top

Single Top & flavour physics at Tevatron



t channel: spacelike *W*

$$\sigma(pp \to tX) = |V_{tb}|^2\sigma_b + |V_{ts}|^2\sigma_s + |V_{td}|^2\sigma_d$$

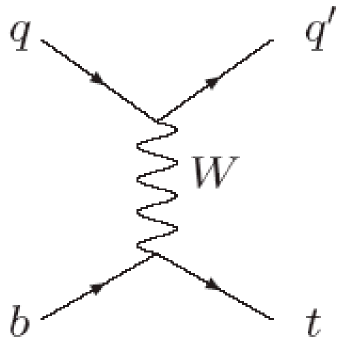
NLO: 2 pb

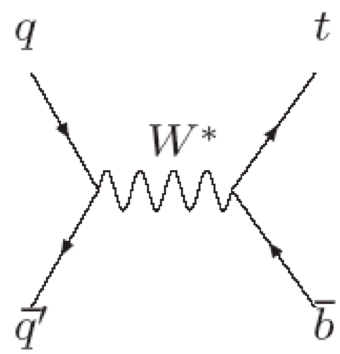
s channel: timelike *W*

$$\sigma(pp \to tX) = (|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2)\sigma^{s-\text{channel}}$$

NLO: 0.9 pb

Single Top & flavour physics at Tevatron





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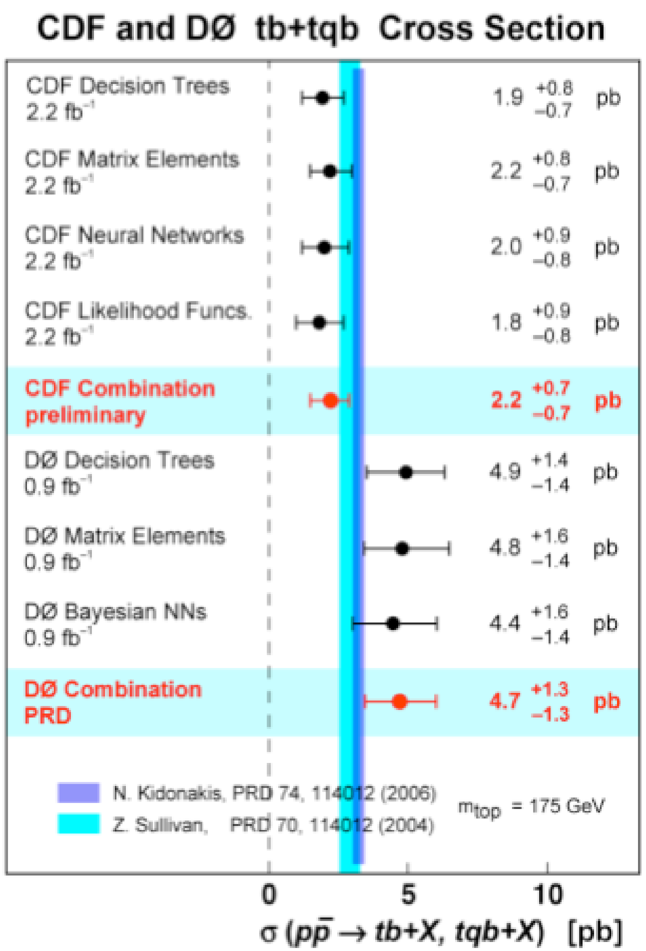

$$\sigma(p\bar{p} \to tb + X, tqb + X) = 2.2 \pm 0.7 \text{ pb}$$

with 2.2 pb^{-1} and 3.7 σ significance

$$\sigma(p\bar{p} \to tb + X, tqb + X) = 4.7 \pm 1.3 \text{ pb}$$

with 0.9 pb^{-1} and 3.4 σ significance

Single Top & flavour physics at LHC

t channel

largest rate at the LHC
final state: forward jet, central top, sometimes extra forward b
main background: Wbb + jet
sensitive to new production modes through FCNC ($qc \to qt$)

s channel

smallest rate at the LHC
Drell-Yan can be used as a normalise it
final state: high-p_T b jet
main background: tt, t + jet, Wbb
sensitive to vector (W') resonances

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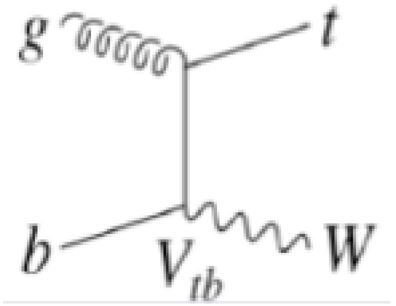
At the LHC there is also the Wt channel: real W

leptonic-decay final state:
2 leptons, 1 b jet, missing E_T



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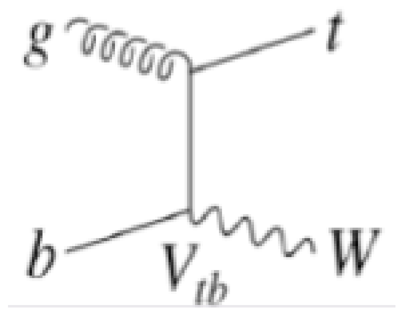

σ (NLO) [pb]	s channel	t channel	Wt channel
Tevatron	0.9	2.0	negligible
LHC	10.2	245.0	60.0

Conclusions

- top is one of best probes of EWSB and fermion masses
- measure top features (mass, spin, couplings) as well as possible to have hints on BSM physics
- common feature of BSM models is to have top partners
- EXP: Tevatron is doing a wonderful job, and lumi keeps growing
  LHC will be blessed by huge statistics
- TH: is steadily improving
  plethora of BSM models with top partners
  sophisticated MC models already available
  more NLO calculations are in progress