Top quark physics

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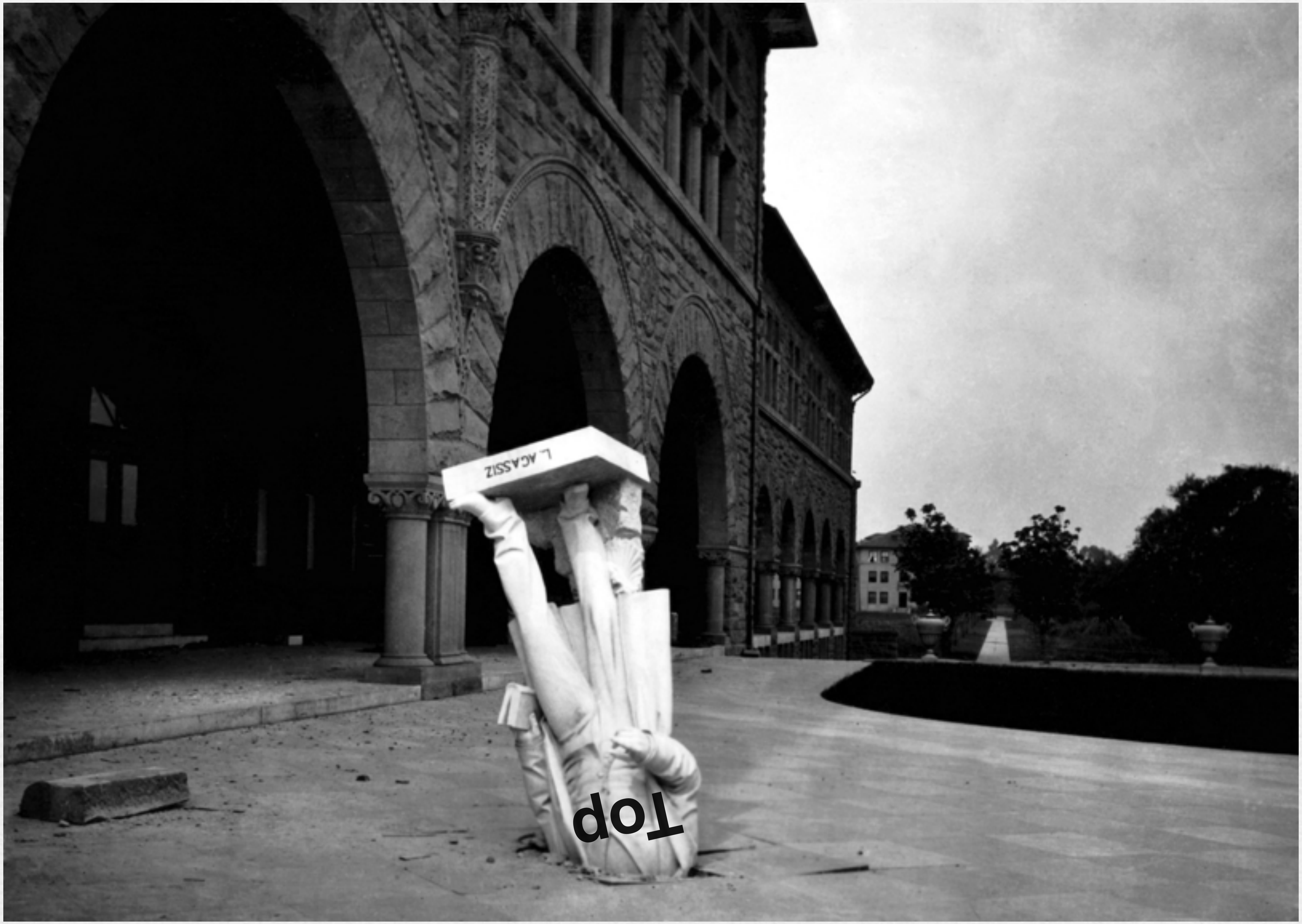
Cargese 2012 Summer School
Across the TeV frontier with the LHC

The manifold uses of top

- The heaviest elementary particle so far, that's already interesting
- A beautiful, shiny object

  - Imperfections (indicating more than SM) easier to spot
- Gateway to physics above the EW scale (Higgs,..)
- Until recently, top was a rare creation, on a pedestal

But, things change.



Top sightings

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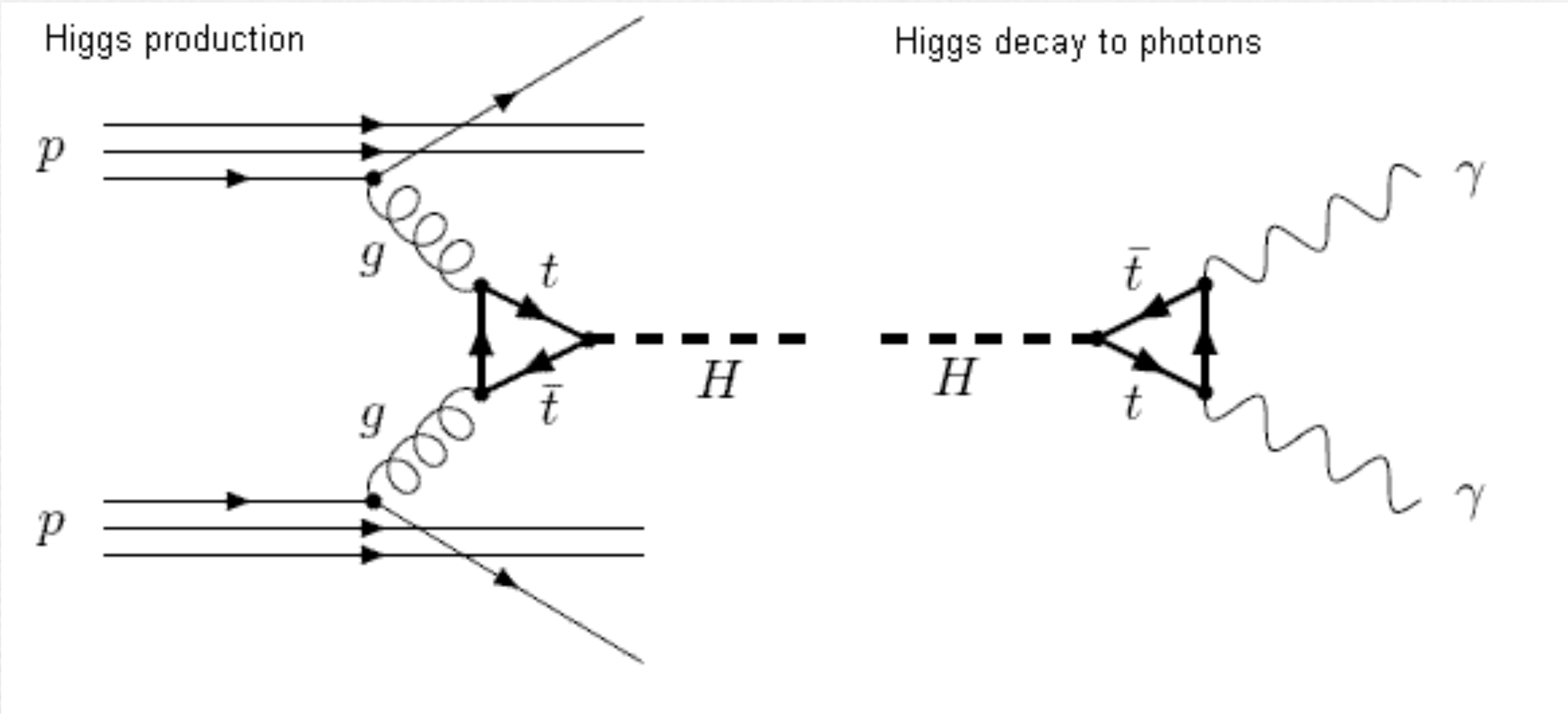
In fact, many many tops produced by now

Still, top = matter of life and death for Higgs



Outline

- Top in the Standard Model
- Top beyond the Standard Model
- Top mass
- Top decay
- Top production
  - Doubles
  - Singles
  - Mixed
- Modern top

Top in the Standard Model

SM fermions

				$SU(3)$	$SU(2)$	$U(1)_Y$
$Q^i_L =$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	3	2	$\frac{1}{6}$
$u^i_R =$	u_R	c_R	t_R	3	1	$\frac{2}{3}$
$d^i_R =$	d_R	s_R	b_R	3	1	$-\frac{1}{3}$
$L^i_L =$	$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	1	2	$-\frac{1}{2}$
$e^i_R =$	e_R	μ_R	τ_R	1	1	-1

Toolkit: how to build the SM

1. Gather fields in representations of fundamental symmetries

$$SU(3)_{\rm color} \otimes SU(2)_{\rm isospin} \otimes U(1)_{\rm hypercharge}$$

3. Combine into invariant combinations obeying also lepton number and baryon number conservation etc

4. Replace all spacetimes derivatives with covariant ones

$$D_\mu = \partial_\mu + i g_s G^a_\mu T_a + i g' B_\mu Y + i g W^i_\mu T_i$$

This brings in interactions with gauge fields

Generators of symmetry groups

5. Add usual kinetic terms for 3 gauge fields

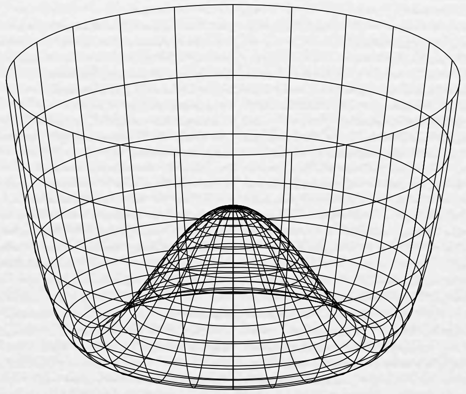
$$\mathcal{L}_{gauge} = -\frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{4} G^{\mu\nu}_a G^a_{\mu\nu} - \frac{1}{4} W^{\mu\nu}_i W^i_{\mu\nu}$$

Electroweak symmetry breaking in SM

Symmetries forbid explicit mass terms of type $m^2\phi^2$ $\quad m\bar{\psi}\psi$ $\quad m^2 Z_\mu Z^\mu$

6. Add scalar field doublet, with potential $V(\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$

For $\mu^2 < 0$ it looks like



Assumption

In minimum $\langle\Phi\rangle_0 = \begin{pmatrix} 0 \\ v \end{pmatrix}, \qquad v = \sqrt{-\mu^2/2\lambda}$

7. Add Yukawa interactions

$$\mathcal{L}_{Yukawa} = y_u \bar{Q}_L \epsilon \Phi^* u_R + y_d \bar{Q}_L \Phi d_R + \ldots + h.c.$$

Mass generation

8.Expanding around the true groundstate $\Phi(x) = e^{i\xi^i(x)\sigma_i} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$

Higgs boson field

Fermion mass term *Higgs-fermion-fermion interaction*

$$y_f[v + h(x)]\bar{\psi}_f\psi_f = m_f\bar{\psi}_f\psi_f + y_f h(x)\bar{\psi}_f\psi_f$$

All SM masses are so generated, and have form: coupling × v

Same couplings that determine masses determine interactions

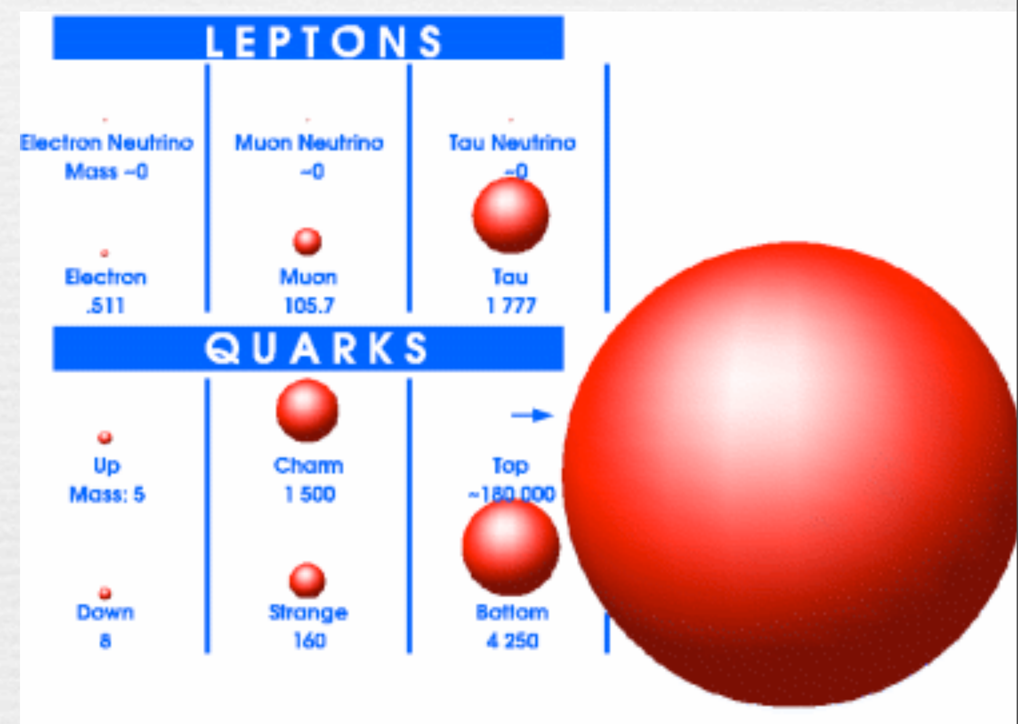
9. Rotate to mass states, with θ_W, V_{CKM}, V_{MNS}

Winner of mass competition

World record: 173 GeV.

Top value

- We learned much from Charm
  - Consistent SM, cemented belief in QCD
- and from Bottom
  - 3rd family, allows for CKM
- What will we learn from Top?
  - It's expensive...
  - Fermionic stepping stone at EW scale
    - Well calculable, measurable
    - Interacts strongly with all forces (gauge +Higgs) in SM



Top couplings

Exp. tested?

- to W boson: flavor mixing, lefthanded
  - $g_W \sim 0.45$ $\quad \frac{g}{\sqrt{2}} V_{tq} \, (\bar{t}_L \gamma^\mu q_L) W^+_\mu$ $\quad \surd ?$
- to Z boson: parity violating
  - $g_Z \sim 0.14$ $\quad \frac{g}{4\cos\theta_w} \, \bar{t} \left((1 - \frac{8}{3} \sin^2\theta_w) \gamma^\mu - \gamma^\mu \gamma^5 \right) t \, Z_\mu$ $\quad ?$
- to photon: vectorlike, bare 2/3 charge
  - $e_t \sim 2/3$ $\quad e_t \, \bar{t} \gamma^\mu t A_\mu$ $\quad \surd ?$
- to gluon: vectorlike, non-trivial in color
  - $g_s \sim 1.12$ $\quad g_s \left[T_a^{SU(3)} \right]^{ji} \bar{t}_j \gamma_\mu t_i A^a_\mu$ $\quad \surd$
- to Higgs: Yukawa type
  - $y_t \sim 1$ $\quad y_t \, h \bar{t} t$ $\quad ?$

Top is special

Why is top special? 1. Heavy

It is natural/unnatural (depending on your point of view)

$$y_t = \frac{\sqrt{2} m_t}{v} = \frac{\sqrt{2} 173}{246} \simeq 0.99$$

If natural, then all other fermions unnatural..

This shows that the top interacts strongly with the Higgs(es). Suggests that top maybe has a special role in the EWSB mechanism.

Large mass makes for a *really* short lifetime

$$\tau_{\text{hadronization}} = \hbar/\Lambda_{QCD} = 2 \times 10^{-24}\, s \qquad \hbar \simeq 6.6 \times 10^{-25} \text{GeV}\, s$$

$$\tau_{top} = \hbar/\Gamma_t = 5 \times 10^{-25}\, s \qquad \Gamma_t \simeq \frac{G_F m_t^3}{8\pi\sqrt{2}} |V_{tb}|^2 \simeq 1.4\, \text{GeV}$$ (more on this later)

Compare to other lifetimes

$$\tau_{bottom} = 10^{-12}\, s \qquad \tau_\pi = 10^{-8}\, s \qquad \tau_\mu = 10^{-6}\, s \qquad \tau_{\text{lecture}} = 10^4\, s$$

Mass implications

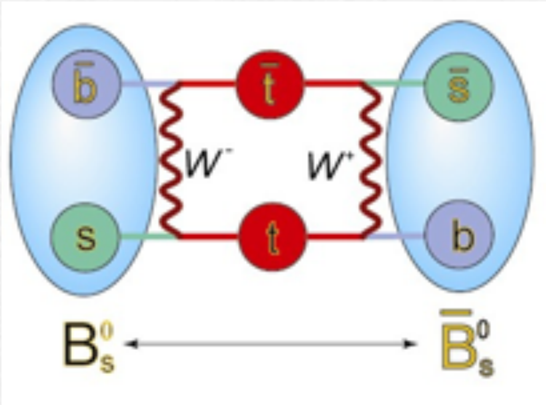
- Top will decay before it hadronizes fully
    - but that does not mean there is no effect of hadronization dynamics
  - the only "bare" quark
  - gives us access to its spin states (more later)
- For QCD interactions with the top, the natural scale to put in the strong coupling is m_t.

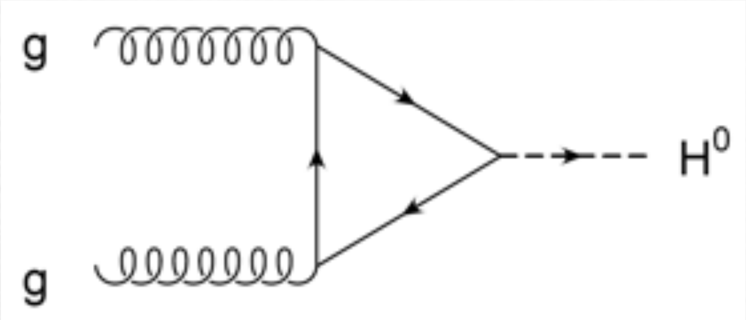
$$\alpha_s(m_t) \simeq 0.1$$

- so good for perturbative QCD. NLO perhaps enough
  - we will see: not always..

Why is top special? 2. Loud in loops

- Even if top is virtual, it makes itself loudly known





  - in a loop integral a fixed mass scale always occurs in the result
  - even more if there is no particle with (roughly) equal mass to compensate

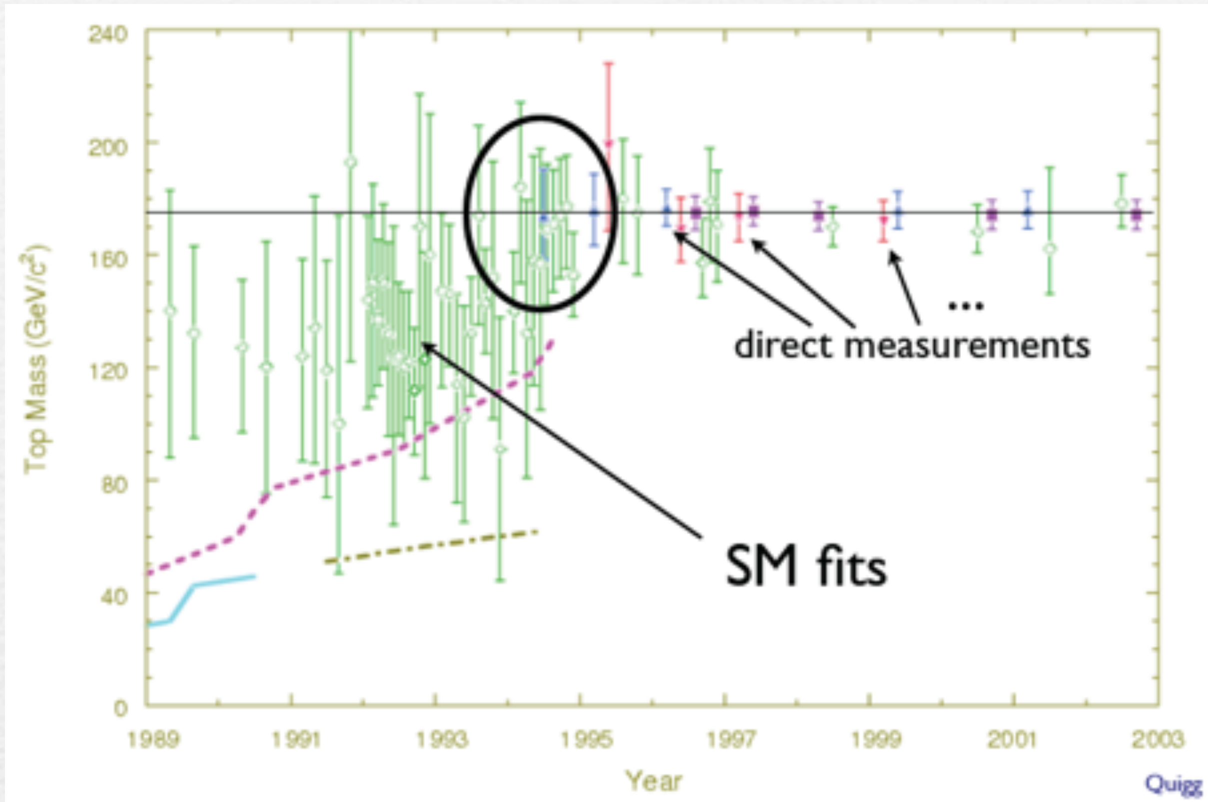
- Express the W mass in terms of 3 fundamental weak parameter, with loop corrections

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2} G_F \sin^2\theta_w} \frac{1}{1 - \Delta r(m_t, m_H)}$$

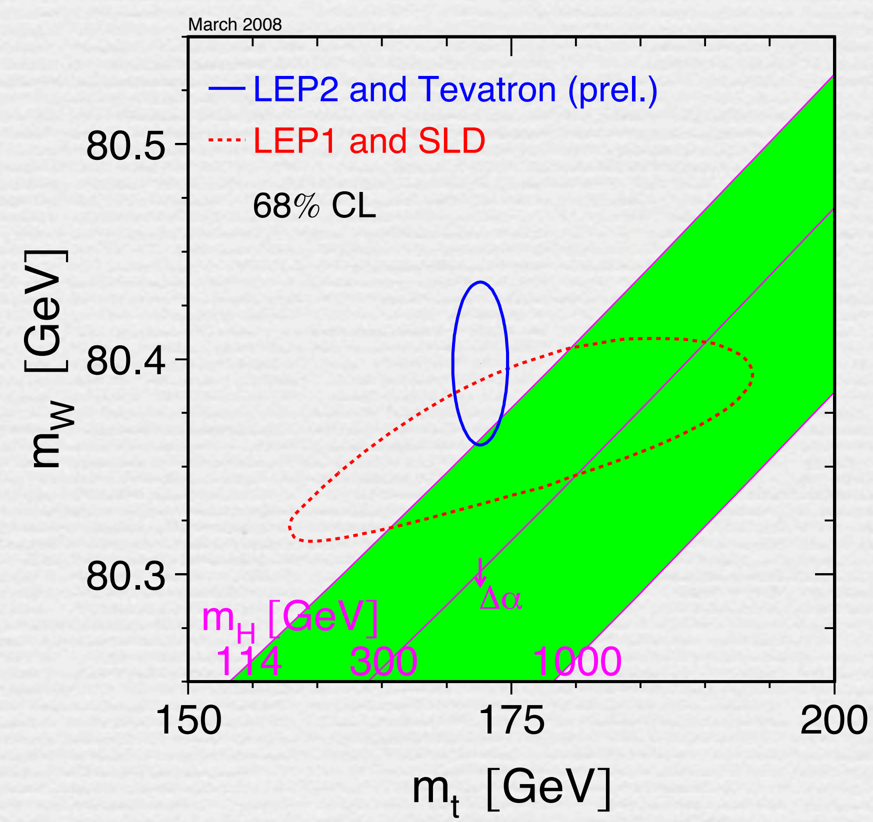
$$\Delta r_{top} = -\frac{3}{8\pi^2} \frac{G_F}{\sqrt{2}\tan^2\theta_w} m_t^2$$

$$\Delta r_{Higgs} = \frac{3}{8\pi^2} \frac{G_F}{\sqrt{2}\tan^2\theta_w} m_W^2 \left(2\ln(m_H/m_Z) - 5/6\right)$$

Top predicted in advance, by noise behind wall



and it looks like it worked again!



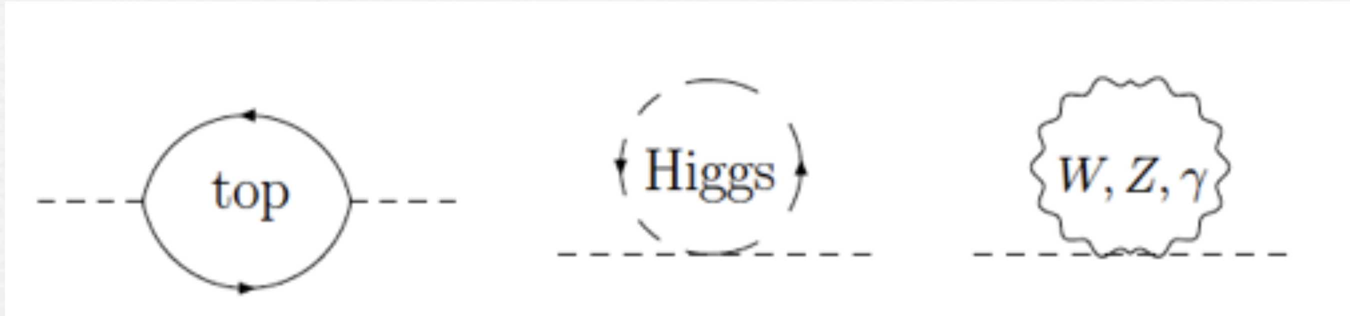
Implications of top loop noise

- Good:
  - new phenomena may occur
  - more stringent test of Standard Model couplings
  - observables can be sensitive to energy scales well beyond current collider re
- Evil:
  - new problems and questions may arise
    - but in todays world that is also fine

Top trouble: naturalness

- Top is a trouble maker for the Standard Model, if one values natural values of parameters.
  - ‘t Hooft: parameter is naturally small if, when it is zero, a new symmetry emerges
    - electron mass = 0: chiral symmetry
    - gauge coupling = 0: gauge fields are free particles, separately conserved
    - but scalar mass = 0, no extra symmetry
- Such symmetries protect the parameters
  - corrections to the electron mass are multiplicative
- But the Higgs mass is unprotected, so corrections can be very large
  - top is the worst bully here

Top and naturalness



$$\delta m_H^2 = -\frac{3}{8\pi^2} y_t^2 \Lambda^2 \text{ [top]} + \frac{1}{16\pi^2} g^2 \Lambda^2 \text{ [gauge]} + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 \text{ [Higgs]}$$

- Then for 10 TeV cutoff

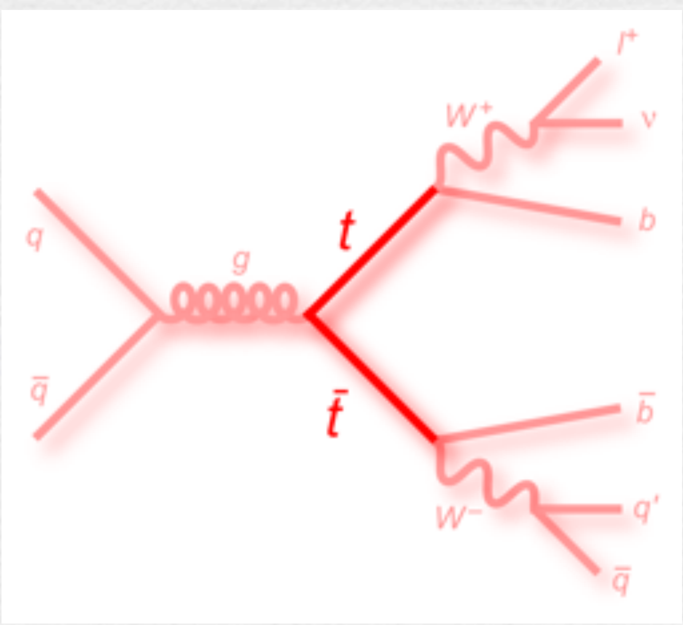
$$m_H^2 = m_{\rm tree}^2 - [100 - 10 - 5](200\ \text{GeV})^2$$

  - even worse for GUT scale cut-off
- $m_{\rm tree}$ must precisely compensate: fine-tuning

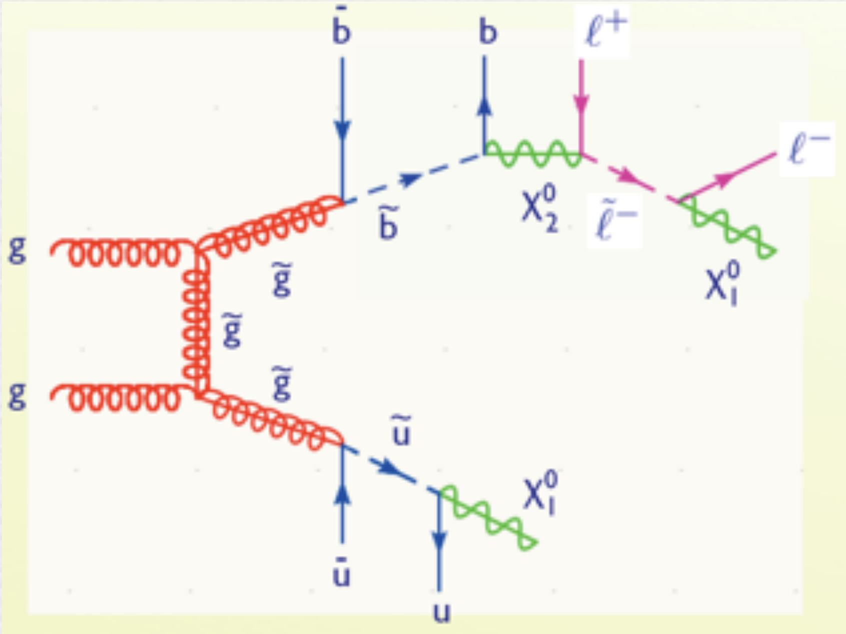
A theoretical aside on naturalness, on blackboard

Why is top special? 3. Teaches new things

- Methods:
  - It was the first particle whose discovery and study has been due to Monte Carlos
    - VECBOS in 1994 - ... - ALPGEN now, many others
  - How to deal with complex final states, with significant missing energy, and taggable particles



Top



Susy

Why is top special? 3. Teaches new things

- Data: top is often a background, to
  - New Physics
    - gg → H, qq → Hqq (H→ WW), SUSY, Little Higgs
    - ttj and ttjj for ttH
  - Itself
    - tt is background to single top (again, more later)

Top beyond the Standard Model

Top and SUSY

- Top loop quadratic cut-off corrections to Higgs mass largely cancelled by "stop" loop corrections

$$\delta m_H^2 \propto (m_t^2 - m_{\tilde{t}}^2) \ln \frac{\Lambda}{m_t}$$

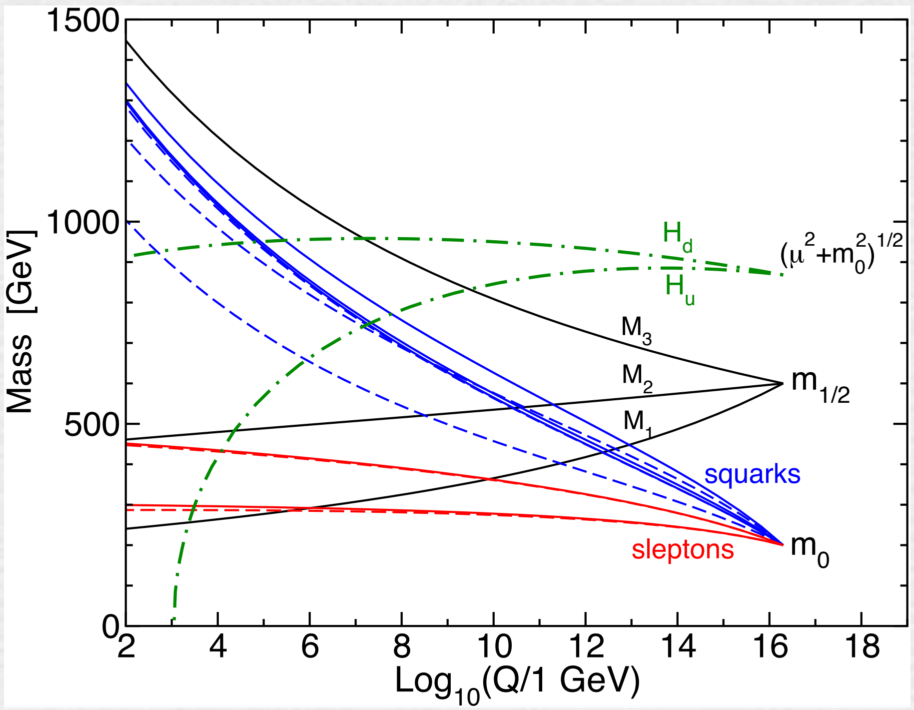
  - minus due to fact that fermions in loop always get a minus sign
  - makes dependence on cut-off logarithmic, which is acceptable/ natural

Top and SUSY

- Top keeps MSSM alive via (top, stop) m_t^4 corrections on lightest Higgs

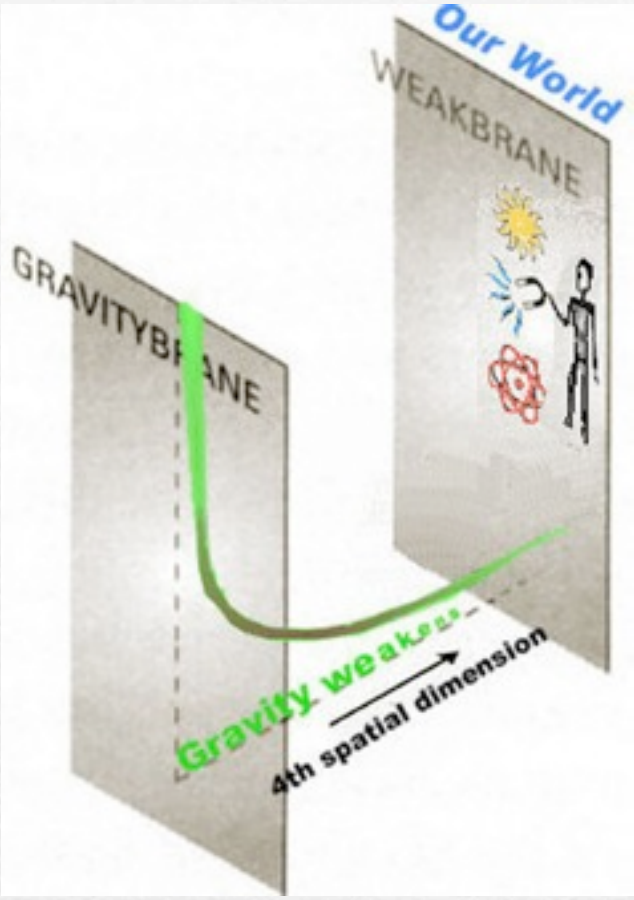
$$\Delta(m_{h^0}^2) = \frac{3}{4\pi^2}\cos^2\alpha \; y_t^2 m_t^2 \ln\left(m_{\tilde{t}_1} m_{\tilde{t}_2}/m_t^2\right)$$

  - otherwise the lightest Higgs could be no heavier than a Z boson
  - giving about 130-140 GeV upper limit
- Top drives radiative EW symmetry breaking in SUSY



- Heavy Higgses may decay to top, can determine their CP properties

Top and extra dimensions



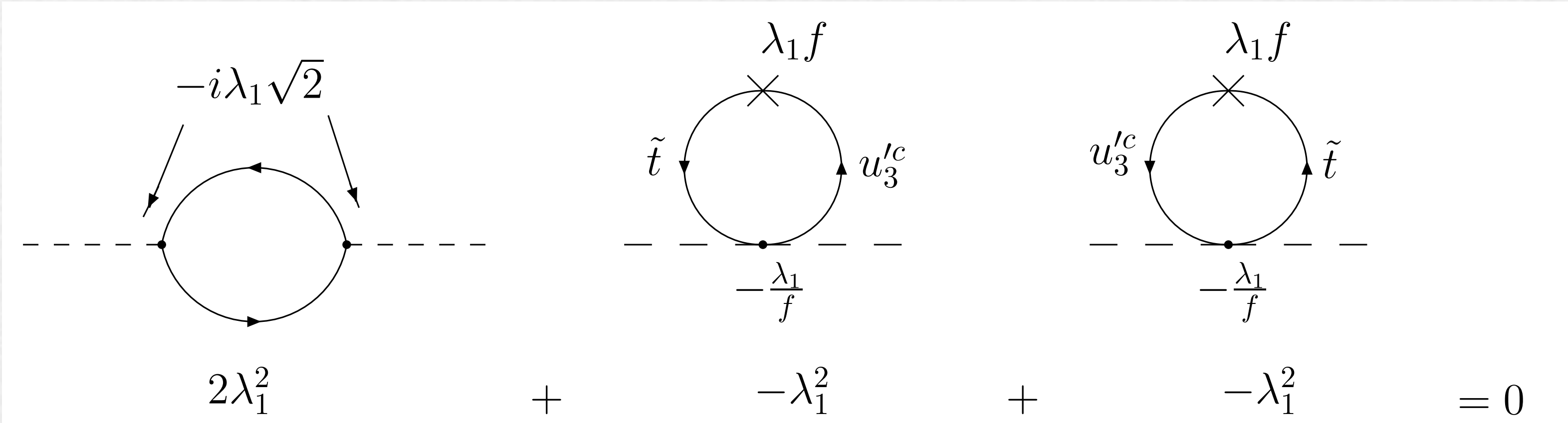
New particles are Kaluza Klein modes

- Gluon KK modes show up as resonances in reaction gg →tt
- Angular distributions of top decay leptons can distinguish scenarios

Top and Little Higgs

Little Higgs: models in which the Higgs is a pseudo-Goldstone boson, therefore light

- Symmetries forbid one-loop Higgs mass term: solves "little hierarchy" problem
- Little Higgs models cancel (top) quadratic divergences with similar particles of same spin (vectorlike top T e.g.)



Han, Logan, Wang

Various models (with various gauge groups, T-parity or not) have been proposed, could be unraveled by

- measuring couplings in the top, T sector, and m_T (cross section 0.01-100 fb)
- testing vector character of T

Top strong dynamics

- TC2: topcolor-assisted technicolor
  - Top mass dynamically generated by topcolor (like gap equation in BCS)
  - Technicolor for EW symmetry breaking
  - (Pseudo)Scalars: Top-Higgs = tt bound states (a la BCS), Top-pions
- Large class of models, already in major trouble/excluded by LHC data
  - diphoton signal ok, for Top-pion of 125 GeV, but then no excess in ZZ-> 4l

Chivukula, Ittisamai, Simmons, Coleppa, Logan, Martin, Ren

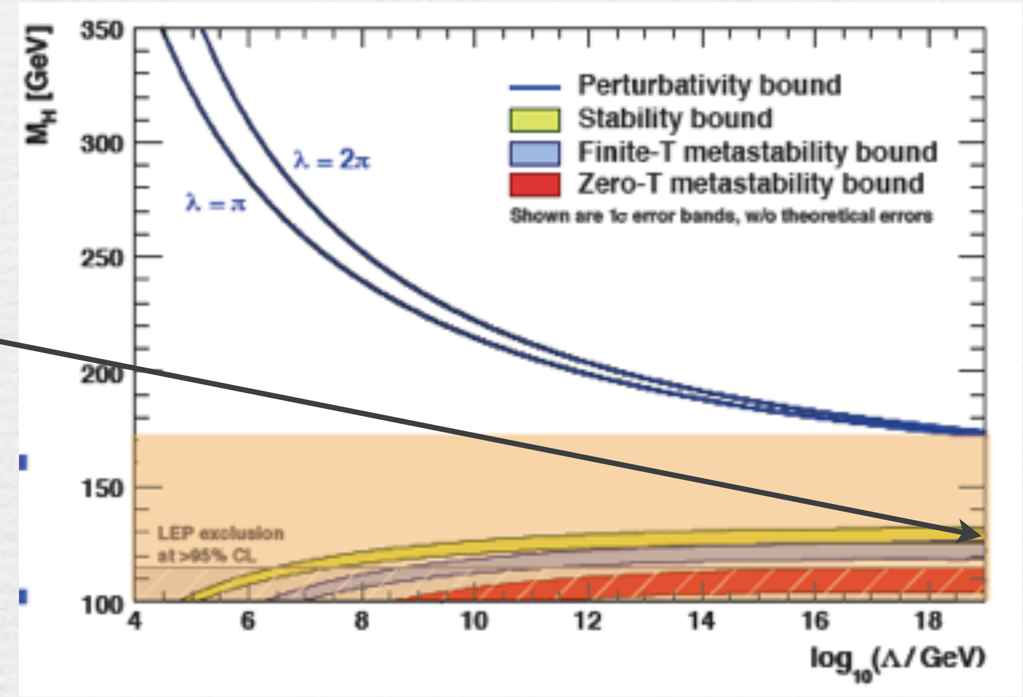
Summary I.

- Top is special indeed
  - Due to large mass
- Good study object in Standard Model
  - To detect deviant behavior
  - To learn about new things
- Gateway to physics beyond the Standard Model
  - Plays intriguing role in Standard Model conflicts and possible resolutions

Top quark mass

Top mass

- Important to measure well, because
  - m_t is a fundamental parameter of the Standard Model
  - it is important for stringent electroweak precision tests
    - is the Higgs mass in the funnel?
    - on the edge

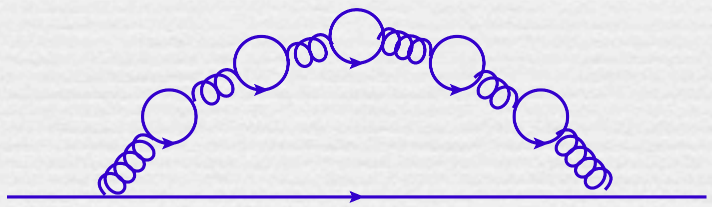


- Remember we are talking about a bare quark, so we must think about what a mass really means
  - we cannot use a quick rule like the following for c and b

$$m_c = \frac{1}{2} m_{J/\psi} \qquad m_b = \frac{1}{2} m_\Upsilon$$

Top mass

- Let us think about the electron mass definition first. It is“easy”: defined by pole in full propagator
  - If particle momentum satisfies pole condition (p^2=m^2), can propagate to ∞
    - ⇒ there is no real ambiguity what electron “pole” mass is
- But: quarks are confined, so physical on-shell quarks cannot exist
  - Leads to non-perturbative ambiguity of few hundred MeV
    - (revealed by all-order pQCD!)



- Relevant questions
  - How can we define the top quark mass best?
  - What accuracy do we need?

Heavy quark mass, definition(s)

$$= \frac{1}{\not{p} - m_0 - \Sigma(p, m_0)}$$

$$m_0 \frac{\alpha_s}{\pi} \left[\frac{1}{\epsilon} + \text{finite stuff} \right]$$

To make finite, substitute $$m_0 = m_R \Big(1 + \frac{\alpha_s}{\pi} \Big[\frac{1}{\epsilon} + z_{finite} \Big] \Big)$$

Mass definitions differ in the choice of z_{finite}

Pole mass: pretend quarks are free and long-lived $$\frac{1}{\not{p} - m_0 - \Sigma(p, m_0)} = \frac{c}{\not{p} - m}$$

MSbar mass: treat mass as a coupling $$m_0 = m(\mu) \Big(1 + \frac{\alpha_s}{\pi} \Big[\frac{1}{\epsilon} \Big] \Big)$$

One can translate between them,
relation is known to 3 loops $$m = m(\mu) \Big(1 + \alpha_s(\mu) d^1 + \alpha_s^2(\mu) d^2 + \dots \Big)$$

What top mass is measured?

- What mass do hadron colliders determine?
  - Pole mass? "Pythia" mass?
    - Typically the path from data to a value for m involves Pythia (or other MC) templates, generated with the Pythia mass parameter
  - Many discussions, no universally accepted conclusion.
    - Map from data to theory parameter via Pythia, templates, cuts, not so clear. Interpreted as pole mass.
  - It matters numerically, as the two differ by about 10-15 GeV

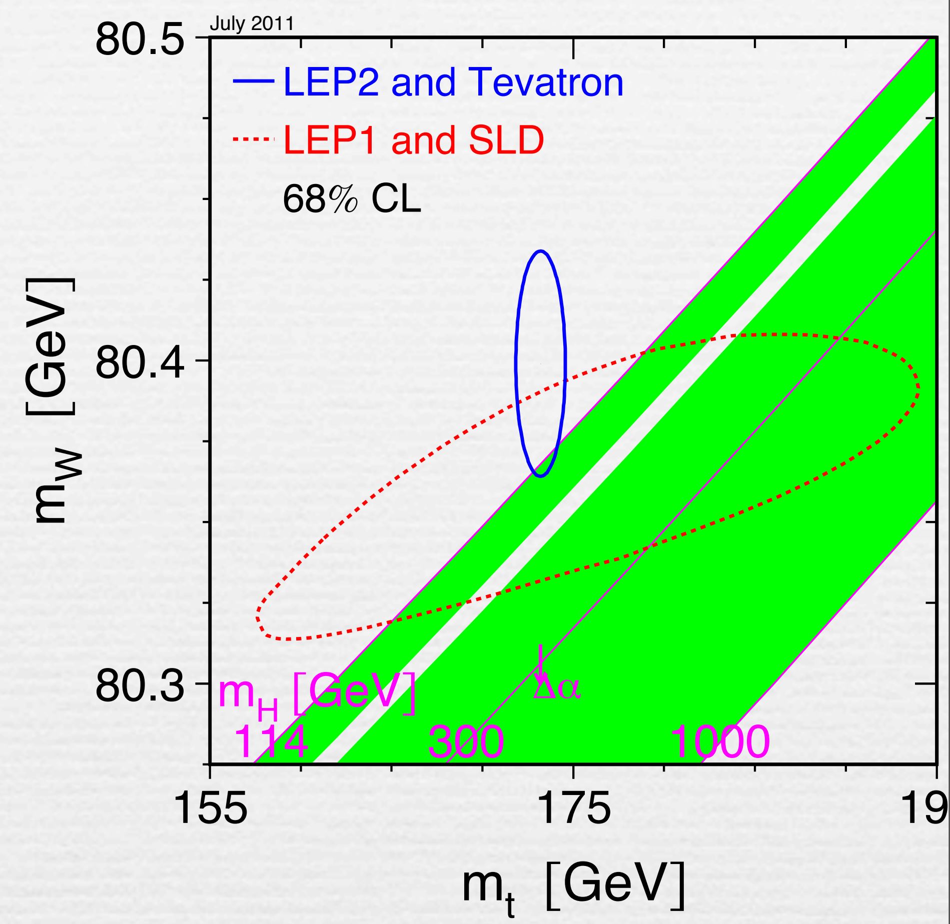
Heavy quark mass uncertainty

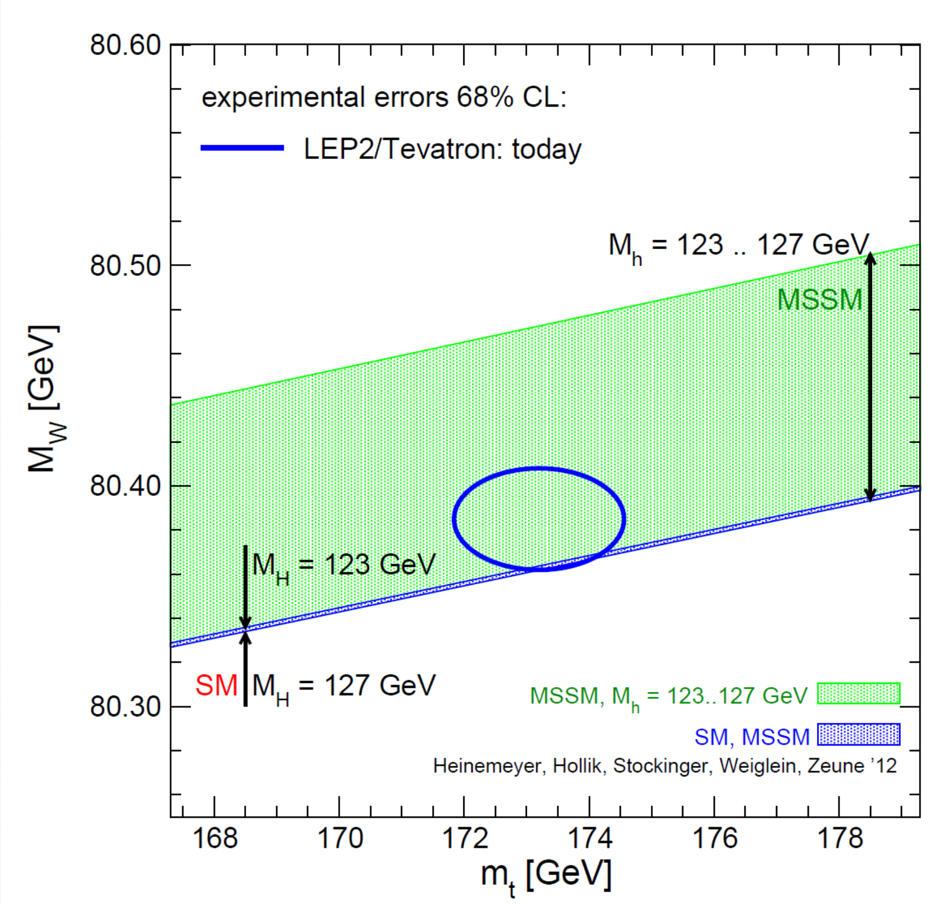
A theoretical aside on renormalons, on blackboard

- Upshot: pole mass has intrinsic uncertainty of order Λ_{QCD}

Top mass: how well *should* we know it?

- With known Higgs mass, and 6 MeV m(W) accuracy, we only need 1 GeV accuracy in top mass
    - For Standard Model, we do not need 100 MeV accuracy
- But would need it to constrain BSM theories, if found





Another mass: top threshold mass

$$= p - m^0 + \Sigma(\not{p}, m^0)$$
$$\sim p - m^{\text{pole}}$$

$$\Sigma(m,m) \sim \sum_n \alpha_s^{n+1}(2\beta_0)^n n! \;=\; -\frac{1}{2}\int \frac{d^3q}{(2\pi)^3}V(\vec{q}^2)$$

Quark-antiquark potential

Energy of tt pair (for Schrodinger eq)

$$E_{\text{static}} = 2m^0 - 2\Sigma(m,m) + V(r)$$
$$= 2m^{\text{PS}}(R) + \left[V(r) - \int_{q<R} \frac{d^3q}{(2\pi)^3}V(\vec{q}^2)\right]$$

Bad behavior cancels
between V and m(pole)
"Potential subtracted mass"

Beneke

Various similar definitions exist

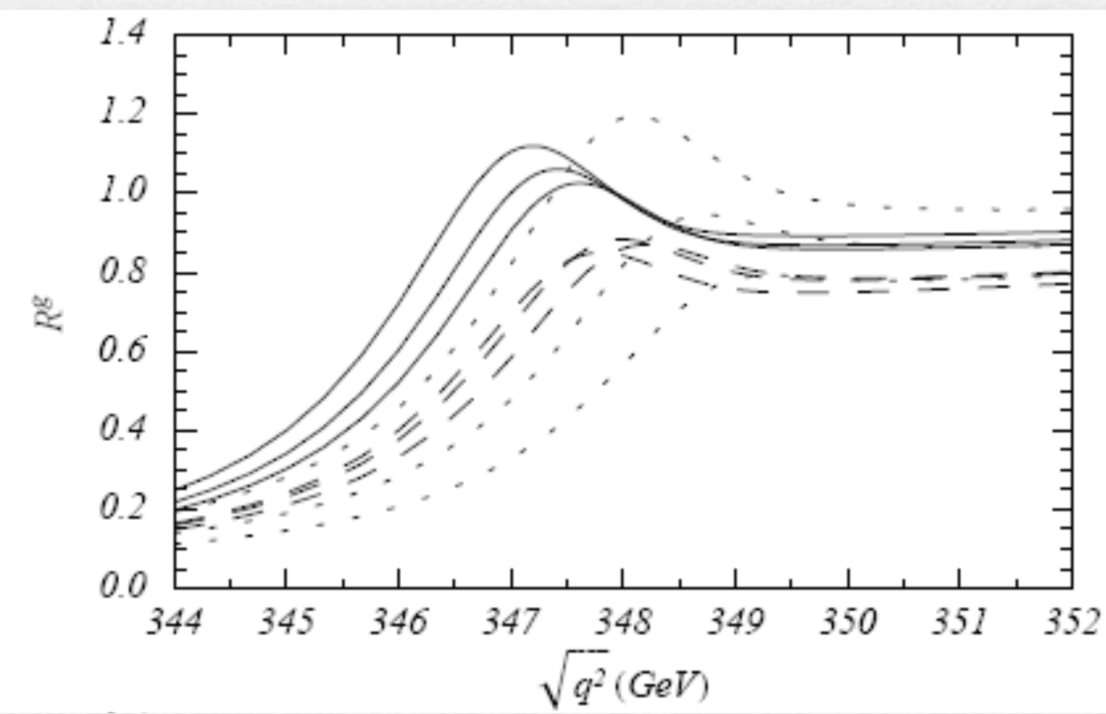
Hoang, Teubner; Bigi et a;

Top threshold mass

- How to make use of that? Scan the ttbar threshold at linear collider by varying beam energy
- Compare measured distribution with calculation using Schrodinger equation and appropiate short-distance mass
- Corrections large, need for NNNLO, using non-relativistic effective field theory

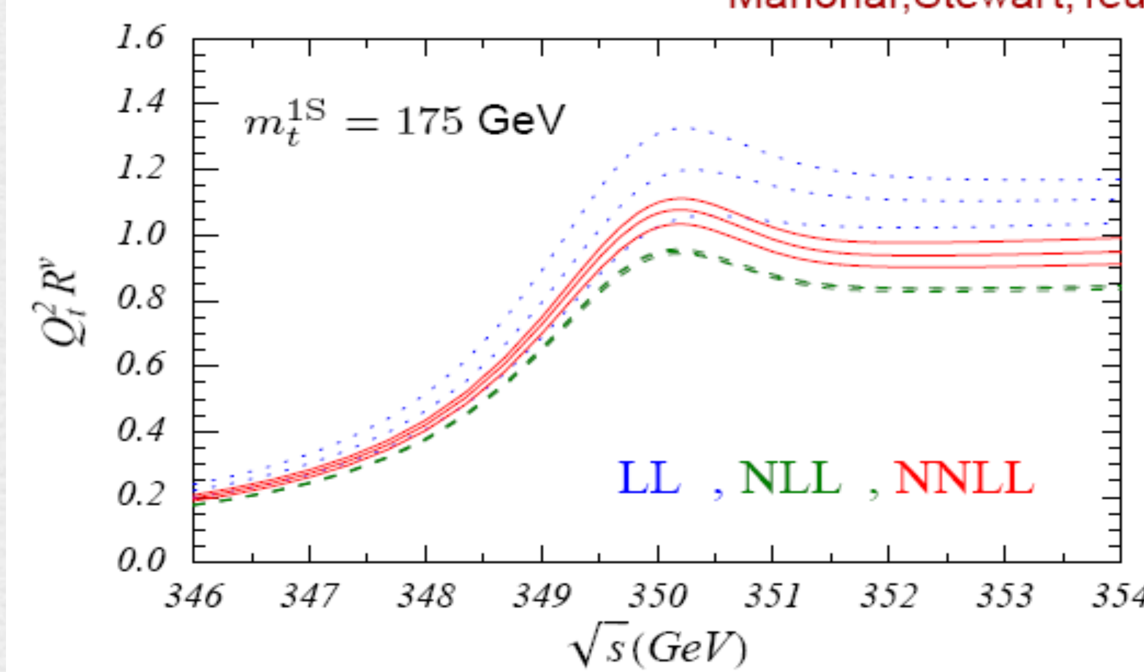
$$R = \frac{\sigma_{t\bar{t}}}{\sigma_{\mu^+\mu^-}} = v \sum_k \left(\frac{\alpha_s}{v}\right)^k \sum_i (\alpha_s \ln v)^i \times \left\{1\,(\mathrm{LL});\alpha_s, v\,(\mathrm{NLL});\alpha_s^2, \alpha_s v, v^2\,(\mathrm{NNLL})\right\}$$

Pole mass, bad



Threshold mass, good

Manohar,Stewart,Teubner,AHoang



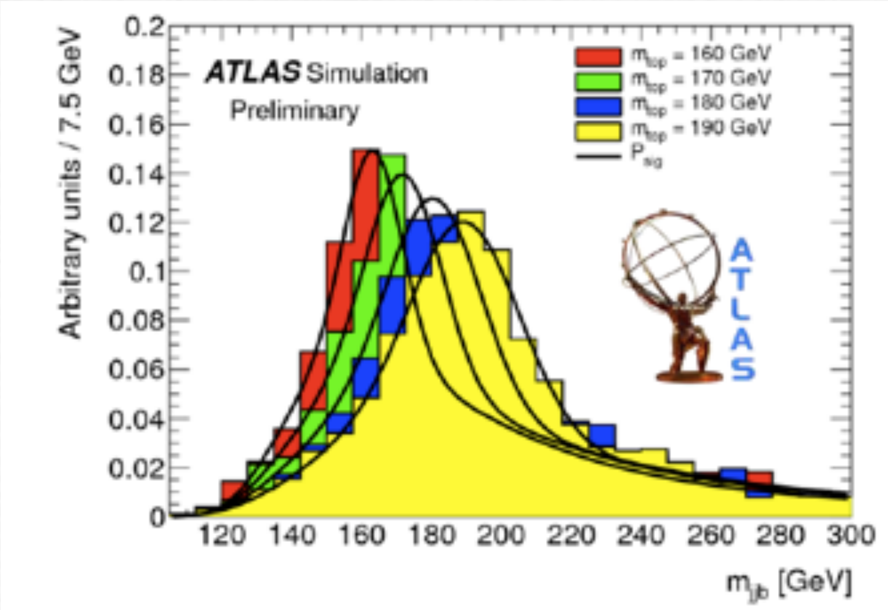
$\nu =$
0.15
0.2
0.3

Experimental mass determinations

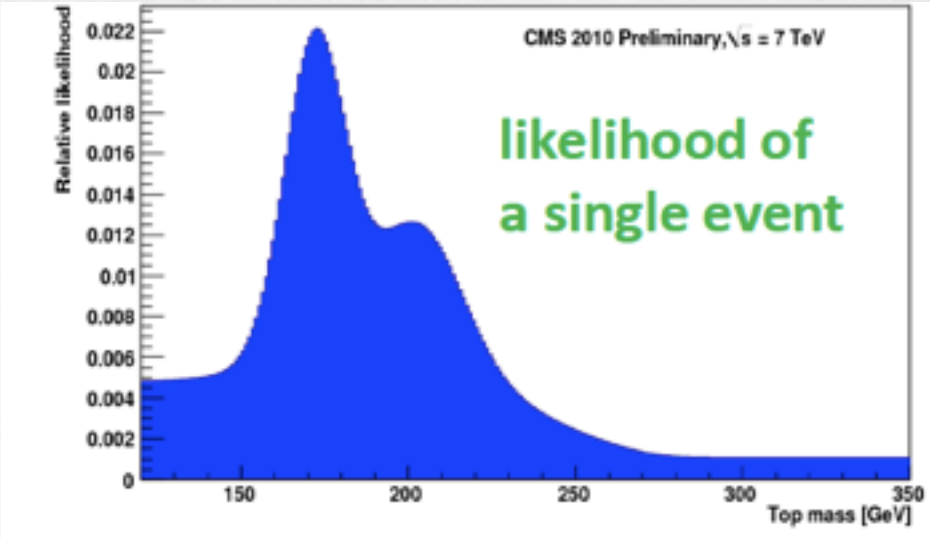
In theory there is no difference between theory and practice; in practice there is

P. Uwer, talk at SM@LHC, quoting Yogi Berra

- What do experiments do?
  - Template method: compare observables in data with MC templates generated with different masses



  - Matrix element method: build event likelihood for full (LO) top quark matrix element, with full kinematics



  - “Ideogram”, and other methods

Matrix element method

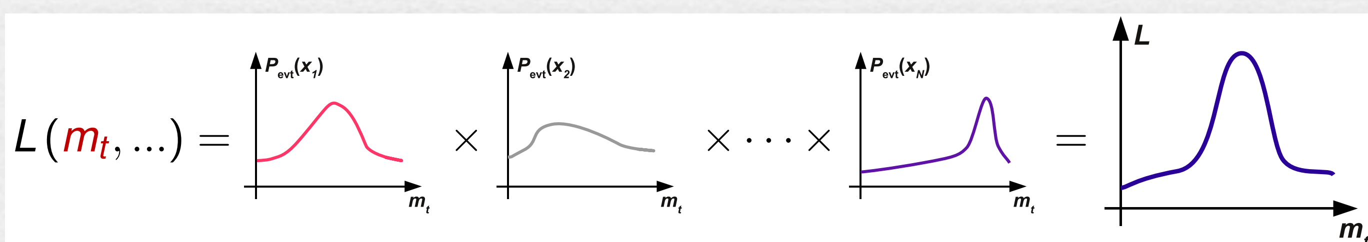
$$P(x, m_t) = \frac{1}{\sigma(m_t)} \int \sum_{\text{flavors}} f(q_1) f(q_2) \sigma(y, m_t) \mathcal{W}(x, y) dy dq_1 dq_2$$

$f(q_i)$	parton distribution functions
$\sigma(y, m_t)$	multi-differential cross section; y=phase space point
$\mathcal{W}(x, y)$	transfer function from ideal y to measured x

Including acceptance and background

$$P_{\text{evt}}(x, m_t, f) \propto A(x) \left[f\, P_{\text{sig}}(x, m_t) + (1 - f)\, P_{\text{bkg}}(x) \right]$$

Combine into 1 big likelihood, infer top mass



$$\Downarrow$$

$$L(\{x_i\}; f, m_t) = \prod_i P_{\text{evt}}(x_i; f, m_t)$$

Matrix element method

Uwer, Talk at SM@LHC

- Nice, but there are issues

Main issues:

- Only leading-order matrix elements are used

→ mass scheme is not fixed, since higher corrections are not taken into account

- Method depends on the quality of the “modeling”

Similar comments hold for template and other methods

Matrix element method

Possible improvements:

→ extension of the matrix element method beyond leading order

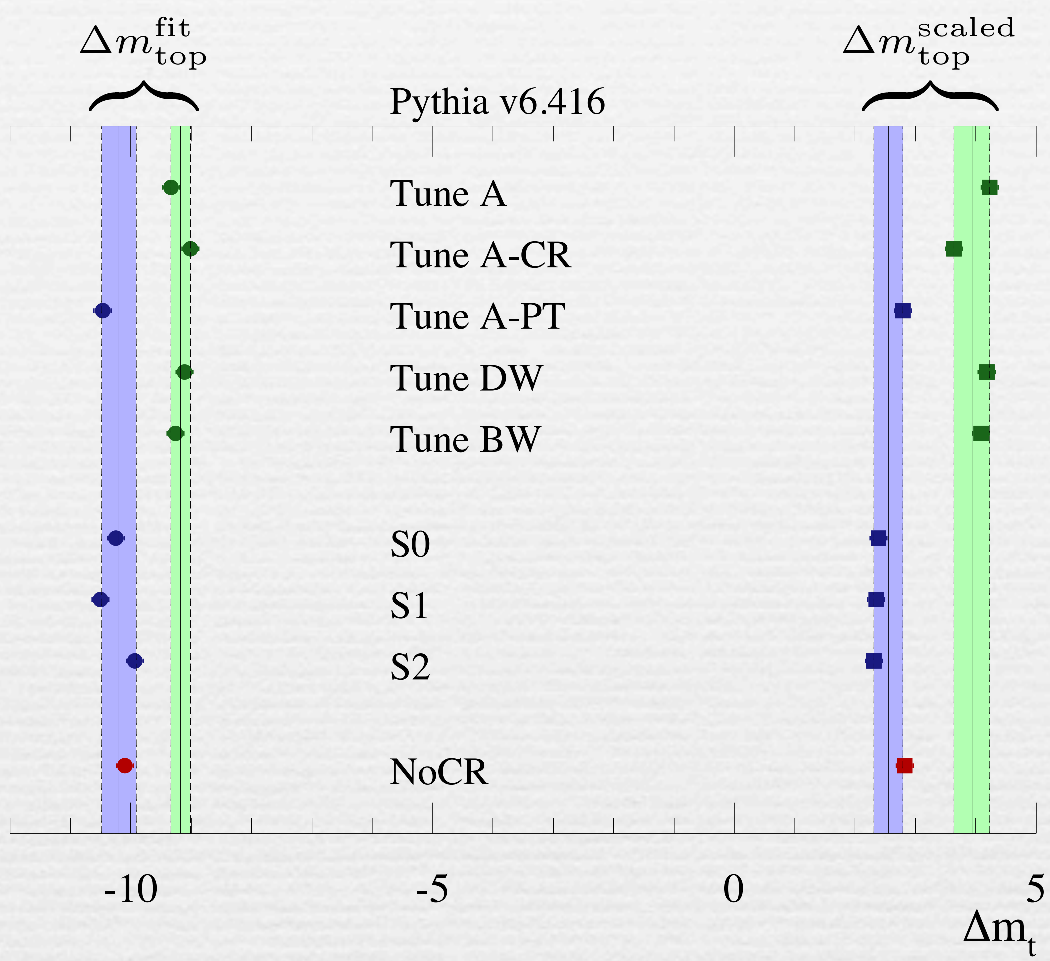
first steps, see C.Williams, J. Campbell and W. Giele

[Moriond QCD 2012]

→ mass scheme could be fixed, higher order effects can be taken into account

- Template method: use NLO Monte Carlo program (MC@NLO, POWHEG, ..)

Color reconnection issue?



[Skands,Wicke '08]

- Different NP models/tunes in Pythia leads to different offsets between reconstructed mass and MC nominal mass
  - Extra uncertainty of order 0.5 GeV

Recent direct measurements

Most precise l+jets measurements per experiment

	lumi (fb^{-1})	comment	method	JES fit?	Mt ±(stat) ±(syst) GeV	%
CDF	8.7	Conf note 10761	Template	Yes	172.85 ± 0.71 ± 0.84	0.6
D0	3.6	PRD 84, 032004 (2011)	Matrix El.	Yes	174.94 ± 1.14 ± 1.04	0.9
ATLAS	1.0	submitted to EPJC	Template	Yes	174.50 ± 0.6 ± 2.3	1.4
CMS	4.7	only μ+jets	Ideogram	Yes	172.64 ± 0.57 ± 1.18	0.8

11/04/2012 Martijn Mulders (CERN) 8

- However, there are other, indirect ways
  - Take any observable O that depends on the top mass

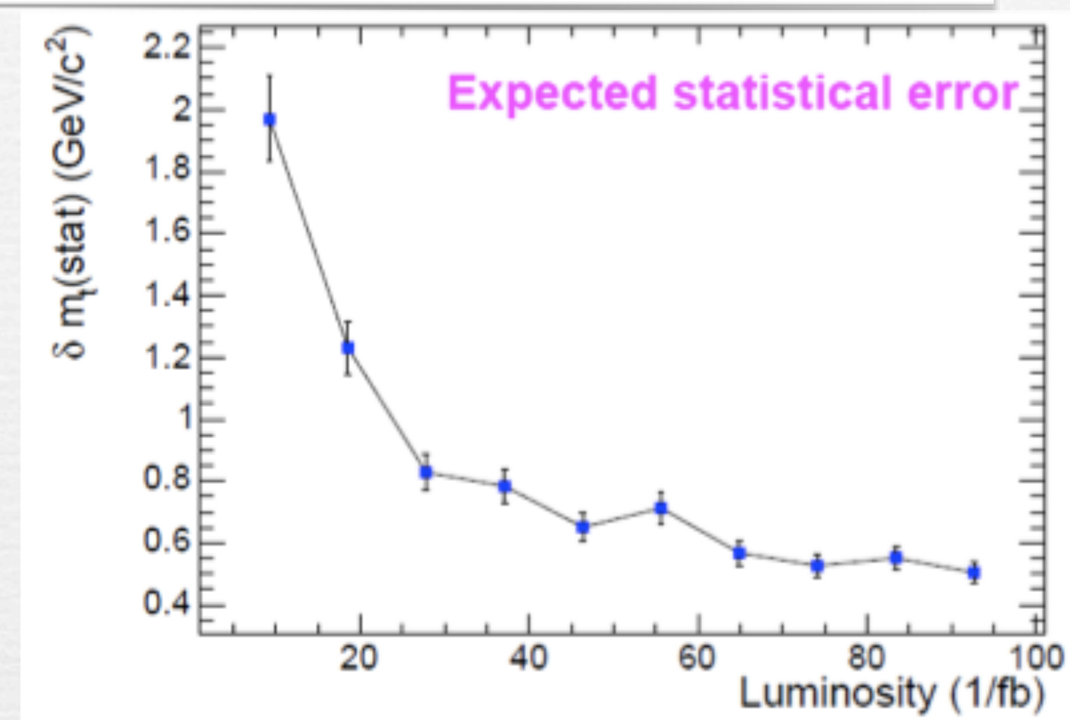
$$\frac{\Delta O}{O} = k\frac{\Delta m}{m}, \quad \text{k preferentially large}$$

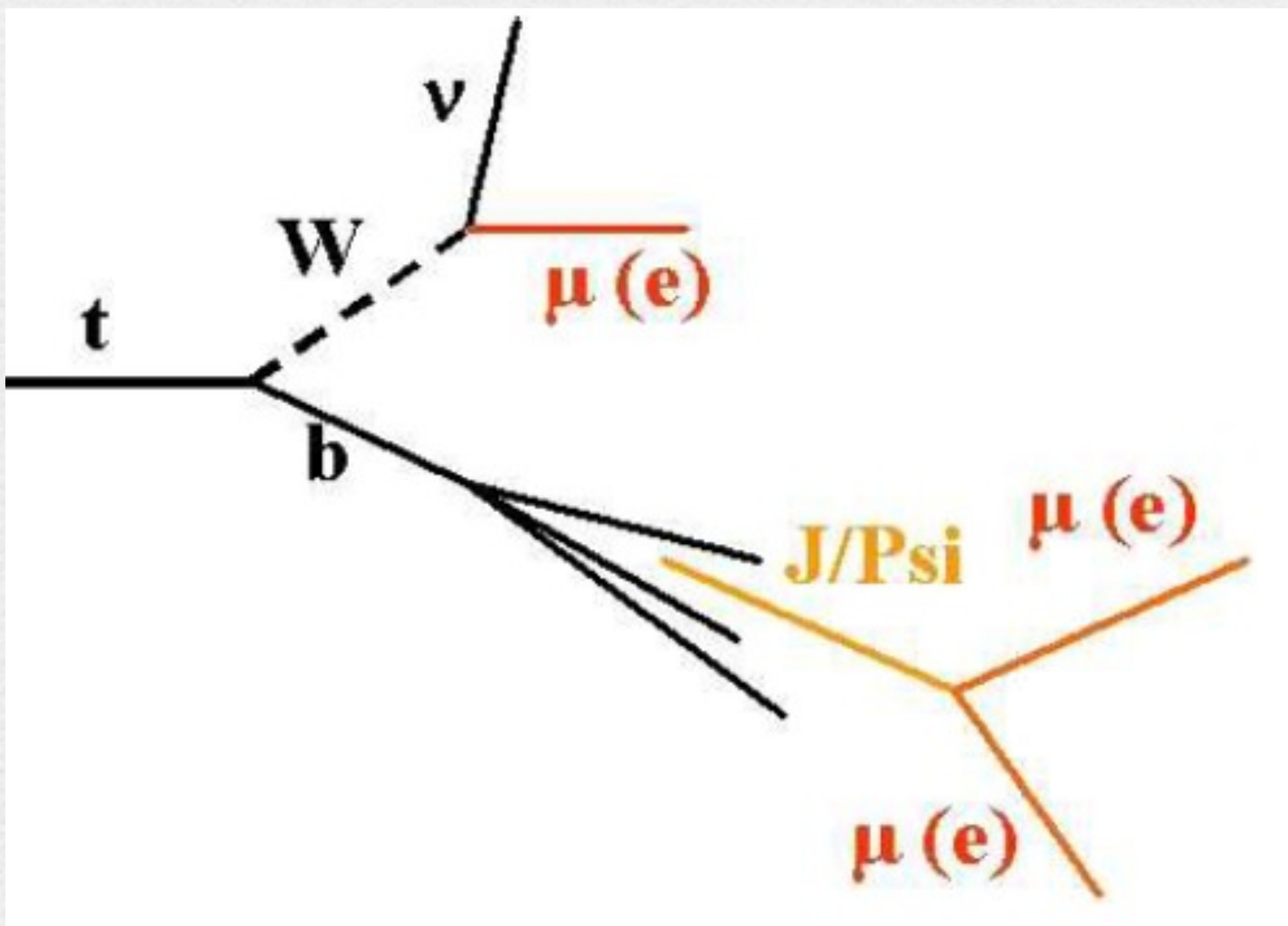
  - Measure O, infer m

M_{lb} in leptonic top-quark decays

[R. Chierici, A. Dierlamm
CMS Note 2006/058], Karchilava

Interesting idea : infer top mass from correlation with e/mu and J/Psi invariant mass





Source	δm_t (GeV/c^2)
Proton PDF	0.28
Scale definition	0.71
Λ_{QCD}	0.31
Q^2	0.56
Light jet fragmentation	0.46
b-quark fragmentation	0.51
Minimum bias/Underlying event	0.64
Total theoretical	1.37
Electron E scale	0.21
Muon p scale	0.38
Electron E resolution	0.19
Muon p resolution	0.12
Jet E scale	0.05
Jet E resolution	0.05
Background knowledge	0.21
Total experimental	0.54
Total systematic	1.47

Measuring the MSbar mass

- How to determine the MSbar mass?
  - Problem: on-shell condition of final state top must be pole mass

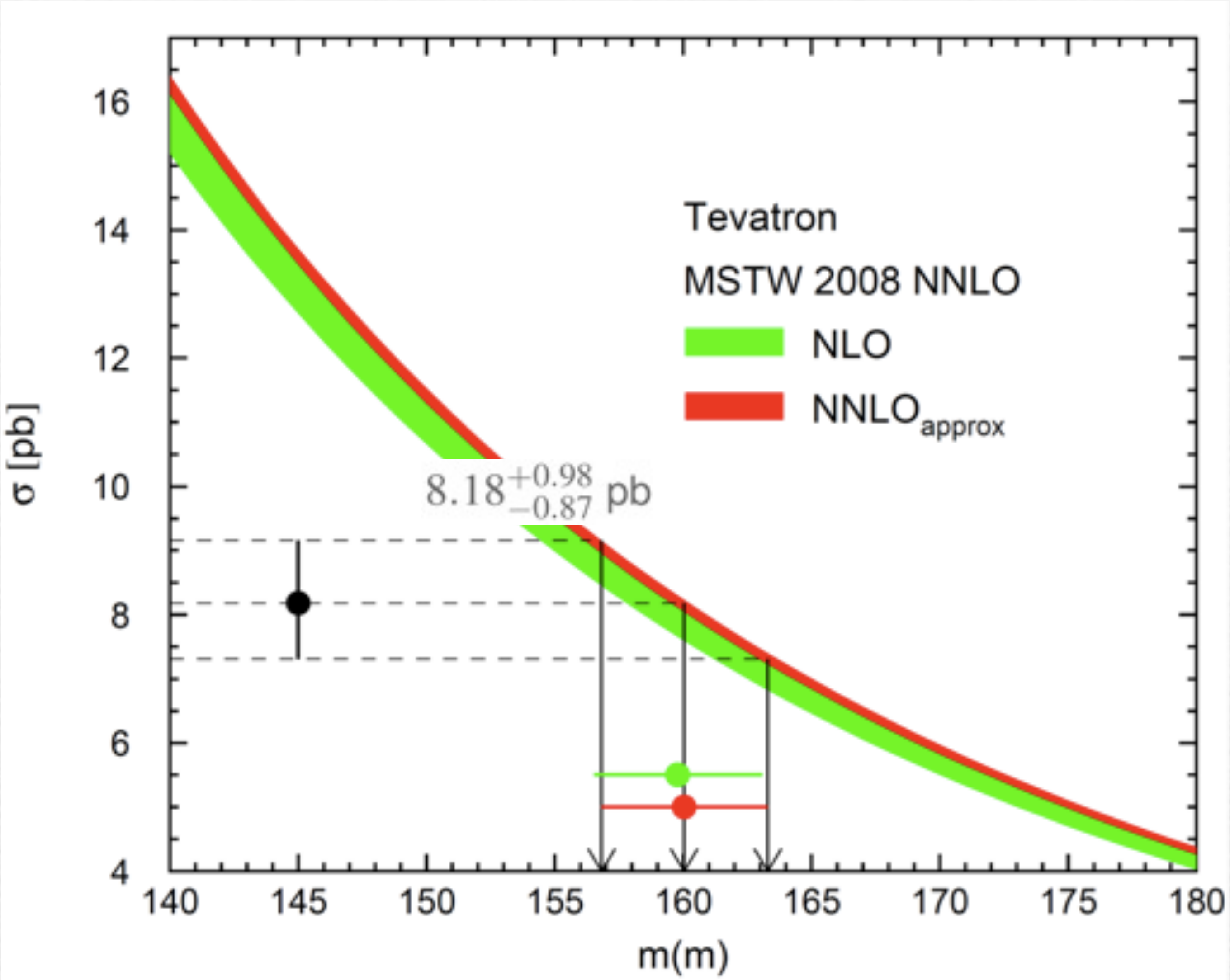
$$\mathrm{Im}\left[\frac{1}{p^2 - m^2 + i\varepsilon}\right] = \delta(p^2 - m^2)$$

- Here's a recipe
  - compute cross section using pole mass $\sigma_{tt}(m, \alpha_s)$
  - replace pole mass by MSbar mass, using $m = \overline{m}(\mu)(1 + \alpha_s(\mu)d^1 + \alpha_s(\mu)^2 d^2 + \ldots$
  - Fit to data, extract MSbar mass

Langenfeld, Moch, Uwer

MSbar mass extraction

Langenfeld, Moch, Uwer



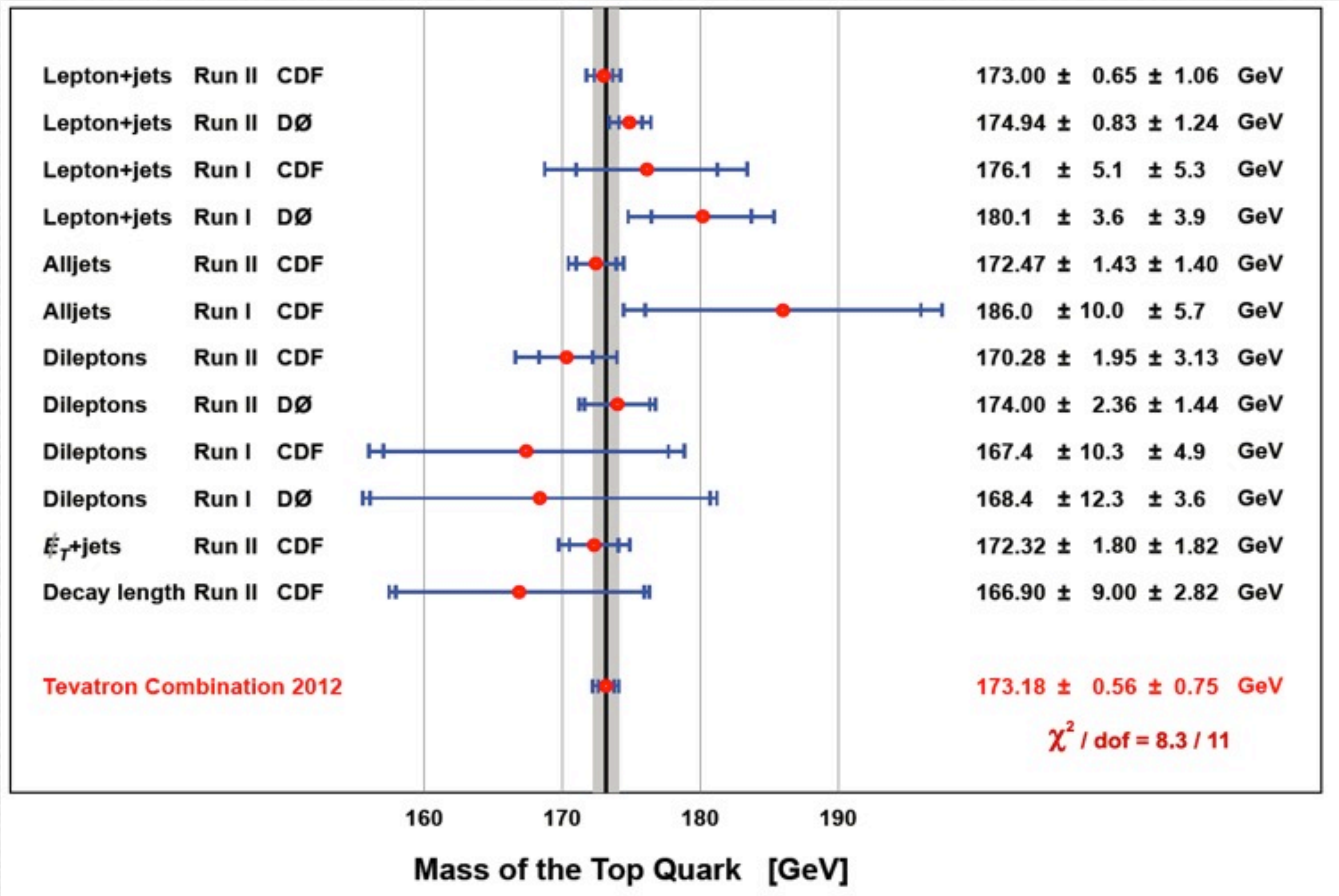
	$\overline{m}$ [GeV]	m_t [GeV]
LO	$159.2^{+3.5}_{-3.4}$	$159.2^{+3.5}_{-3.4}$
NLO	$159.8^{+3.3}_{-3.3}$	$165.8^{+3.5}_{-3.5}$
NNLO	$160.0^{+3.3}_{-3.2}$	$168.2^{+3.6}_{-3.5}$

- Accuracy at this point limited by m_t sensitivity and PDF uncertainties
- Other proposals: (moments of) the invariant mass distribution

Frederix, Maltoni

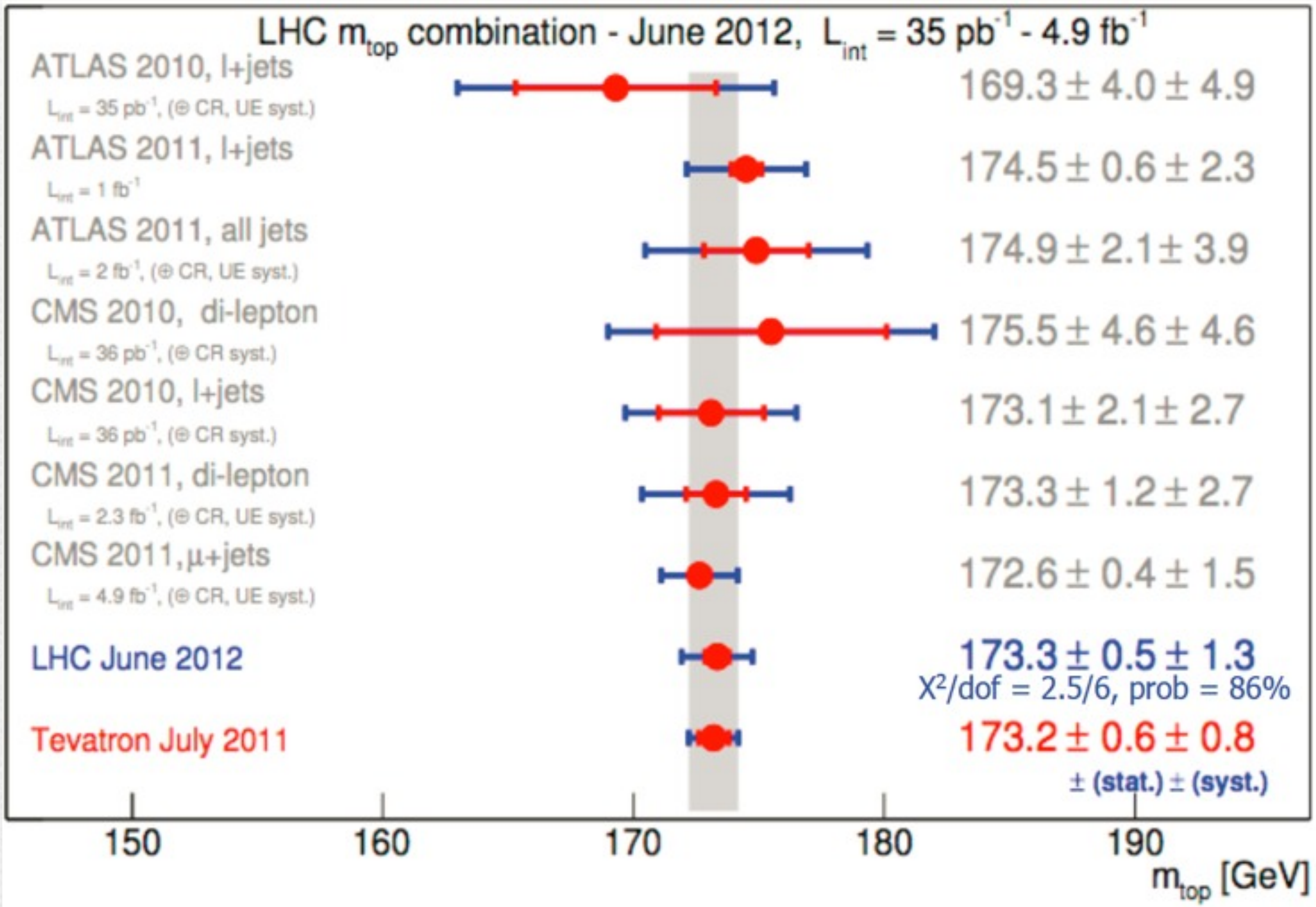
Top “pole” mass at Tevatron

[arXiv:1207.1069]



Top “pole” mass at LHC

[Frédéric Déliot, ICHEP2012]



0.8 %

0.6 %

Top mass is the best known quark mass