The ubiquitous top quark

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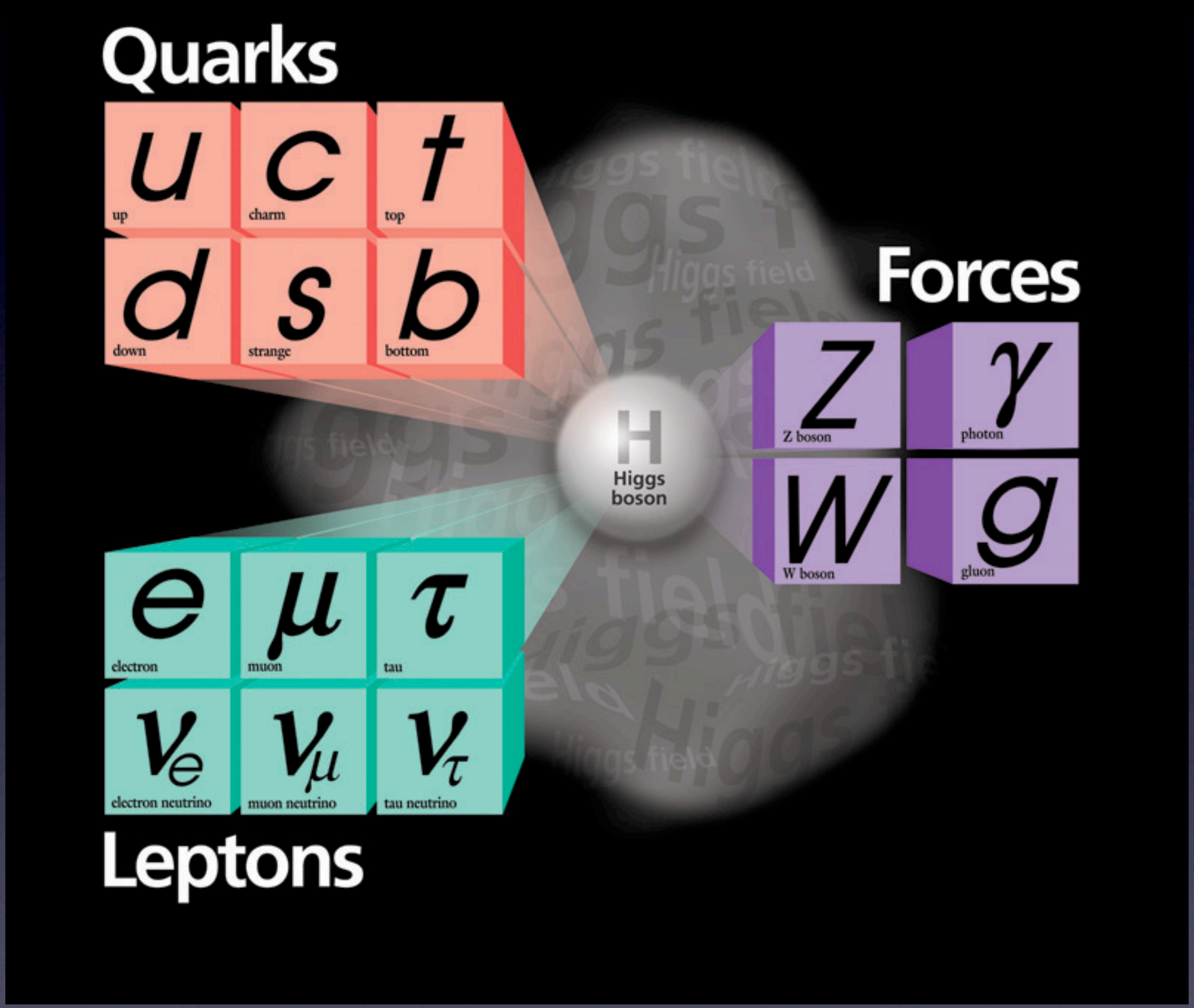
Standard Model particles

masses
u,d: 10 MeV
s: 100 Mev
c: 1.5 GeV
b: 5 GeV
t: 170 GeV



masses
W: 80 GeV
Z: 91 GeV

masses
e: 0.5 MeV
mu: 100 MeV
tau: 1.77 GeV
nu's: non-zero!

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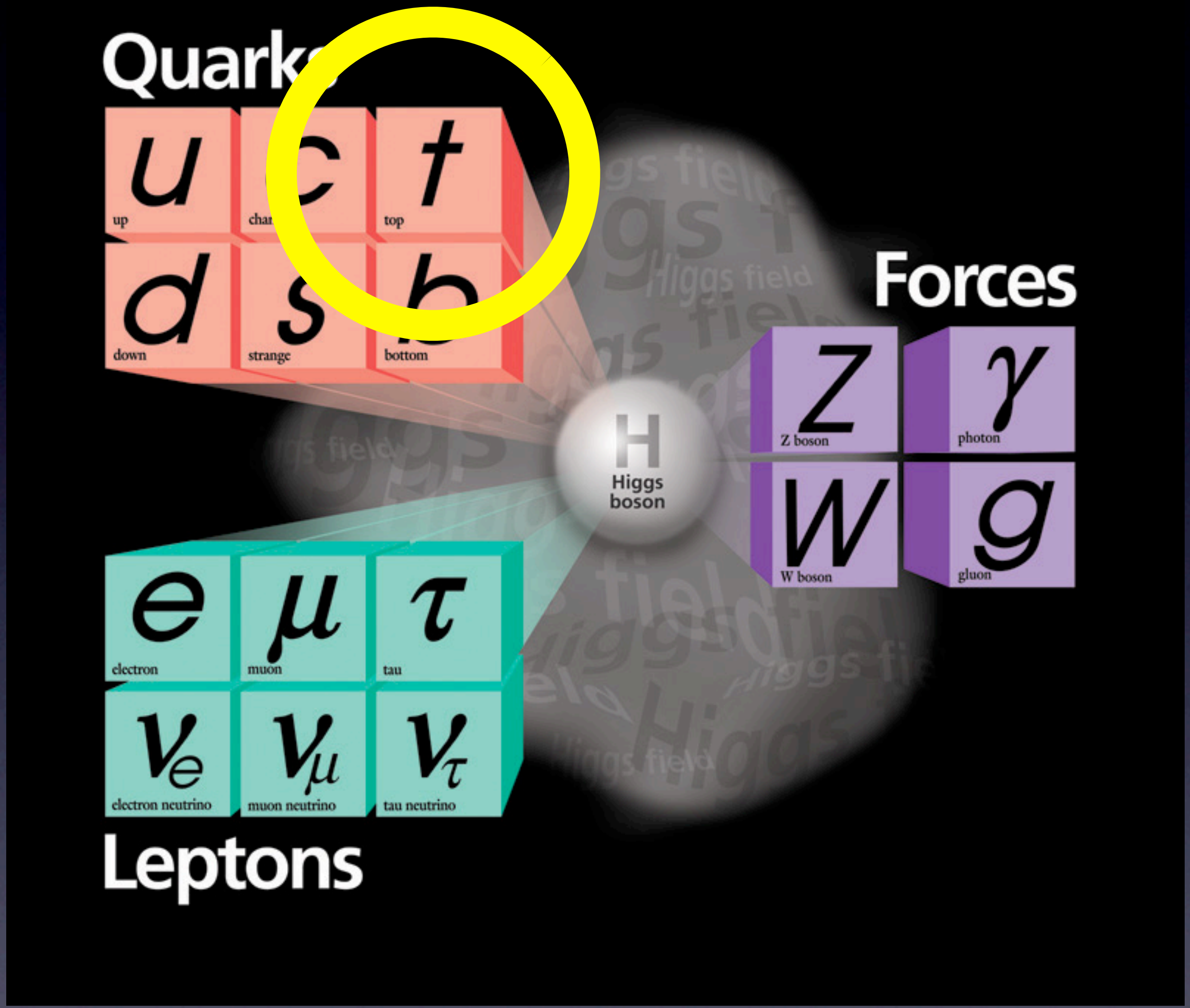

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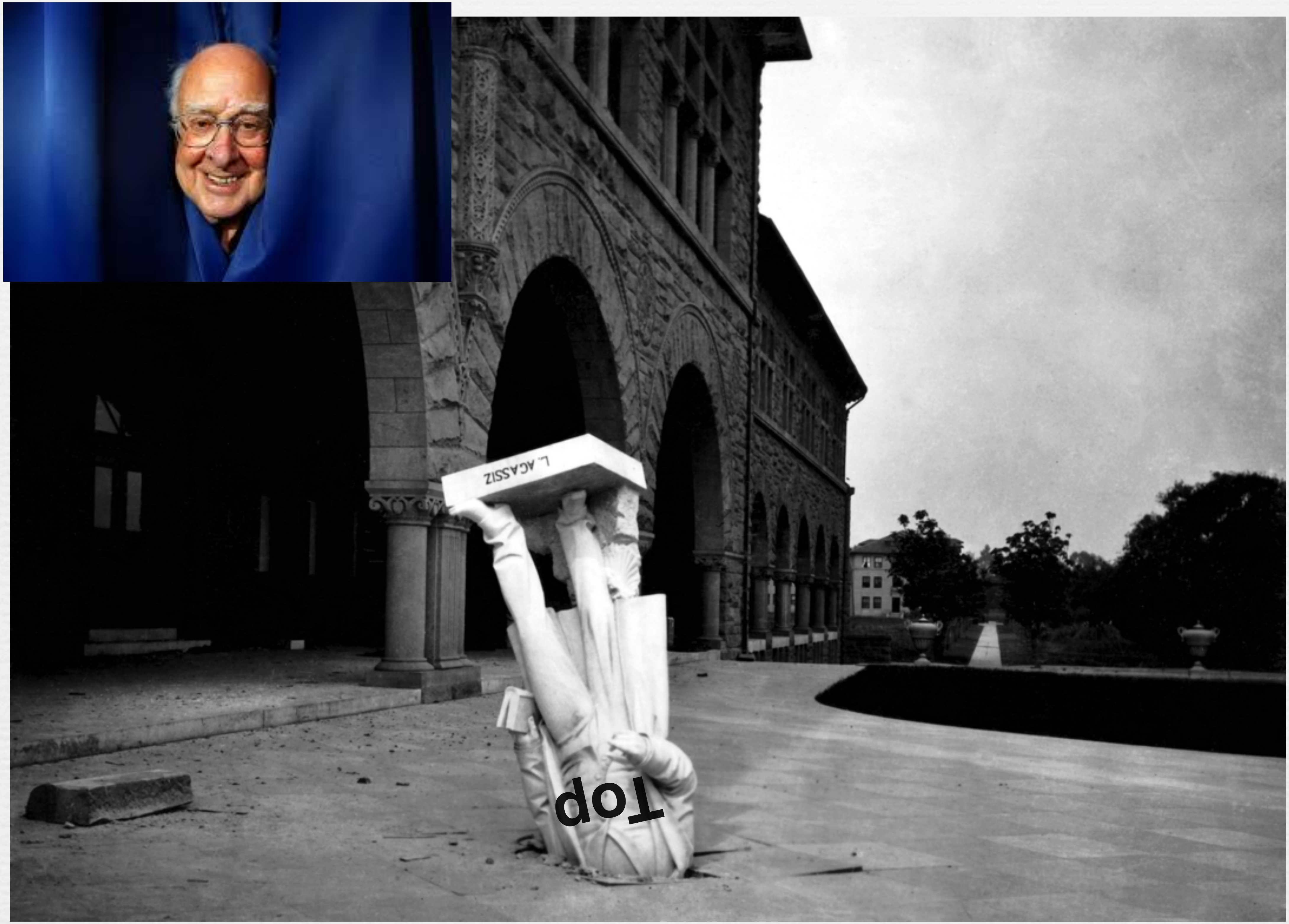
The many roles of top

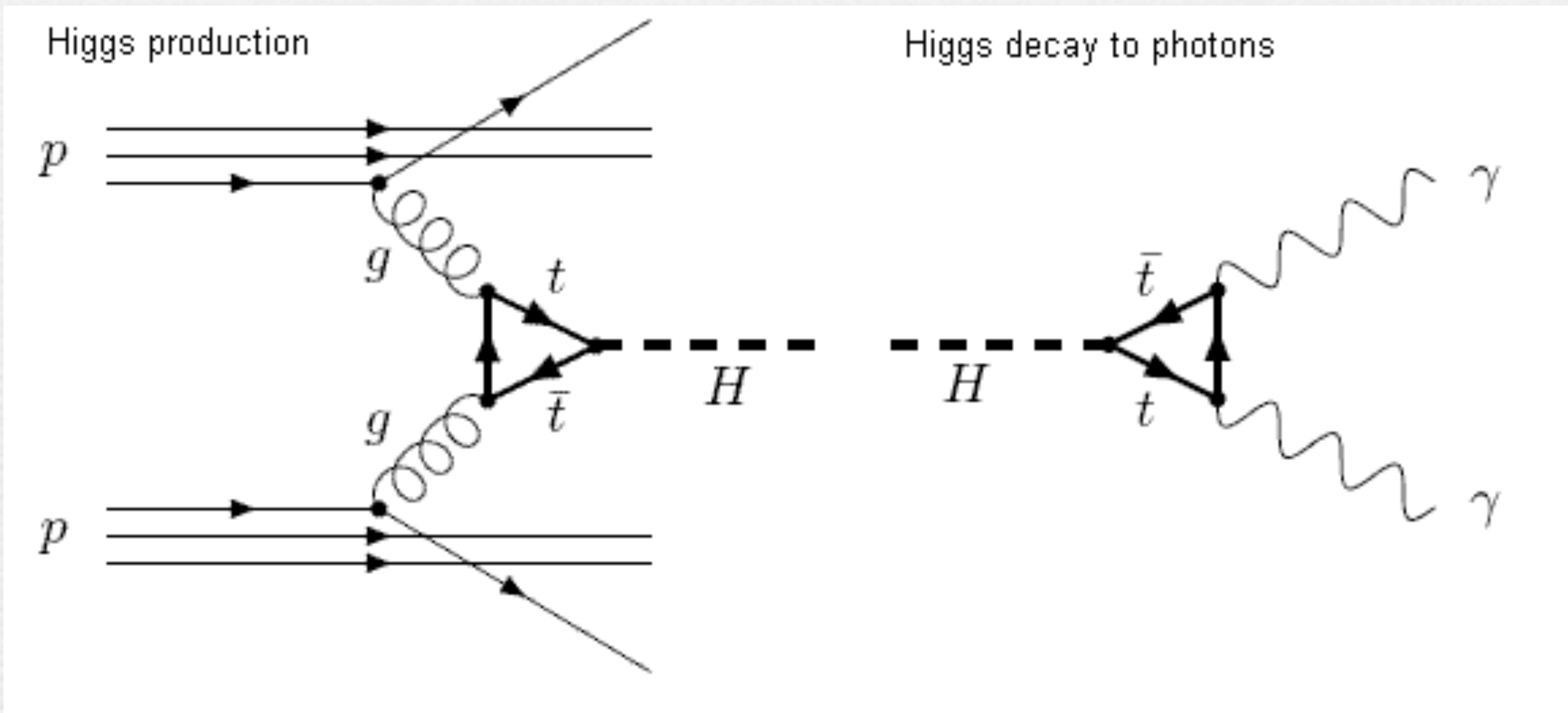
- The heaviest *elementary* particle so far, that's already interesting
- Theoretically, a beautiful, shiny object

  - so imperfections (of the Standard Model) easier to spot
- Gateway to physics above the 100 GeV scale (Higgs boson,..)
- Until recently, top was the most special particle, put on a pedestal

But, things change.

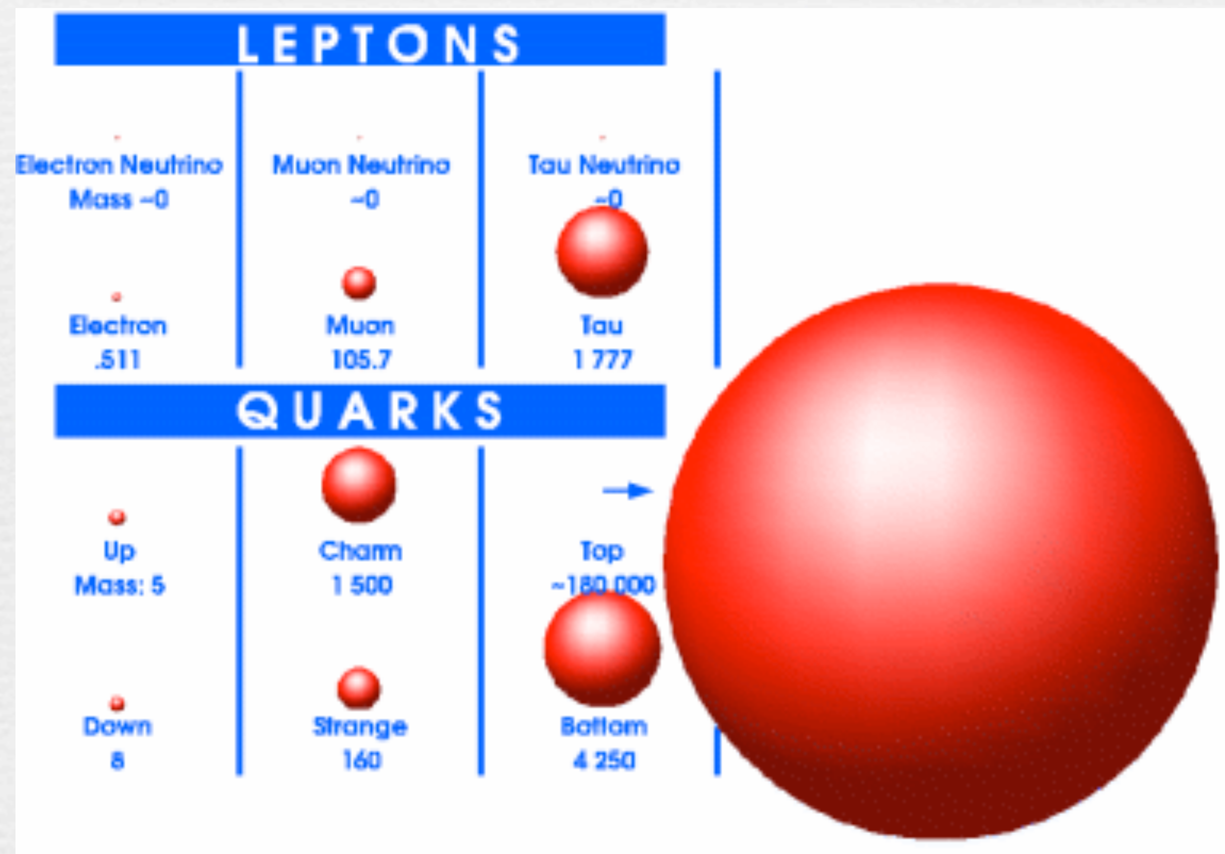


Still, top = matter of life and death for Higgs boson



What heavy quarks taught us

- 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?
  - Its the most expensive quark
    - Interacts strongly with all forces (gauge+Higgs) in SM



Top mass generation in SM

Expanding scalar field doublet around the 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

Other top SM couplings

Exp. tested?

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

Top physics: check structure and strength of all these couplings

Top is special

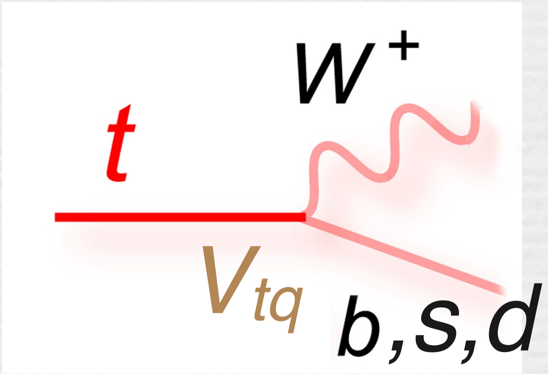
Why is top special? 1. Heavy

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). Perhaps top has a special role in the EWSB mechanism.



Large mass makes for a *really* short lifetime

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

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

Compare to other lifetimes

$$\tau_{bottom} = 10^{-12}\, s \qquad \tau_\pi = 10^{-8}\, s \qquad \tau_\mu = 10^{-6}\, s \qquad \tau_{talk} = 10^3 s$$

Mass implications

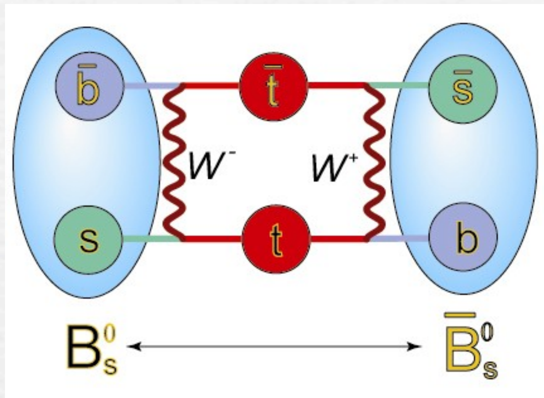
- Top will decay before it hadronizes fully
  - the only “bare”(=undressed by QCD) quark
  - gives us access to its spin
- For QCD interactions of the top, the natural scale to put in the running QCD coupling is m_t.
  - good for perturbative approach

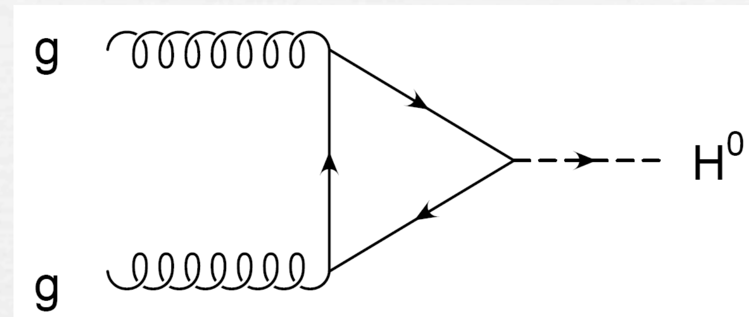
$$\alpha_s(m_t) \simeq 0.1$$

  - (but not always good enough)

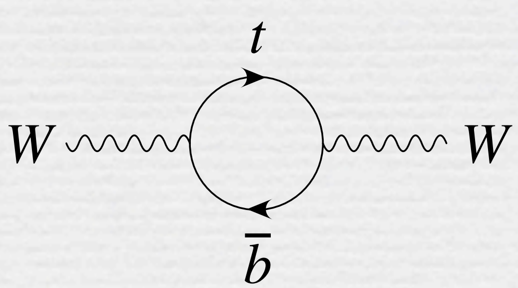
Why is top special? 2. Noisy in loops

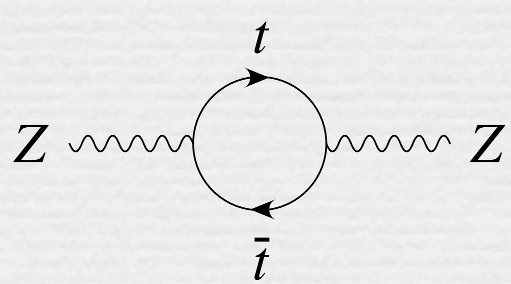
- Even if top is virtual, it makes itself loudly known





  - 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





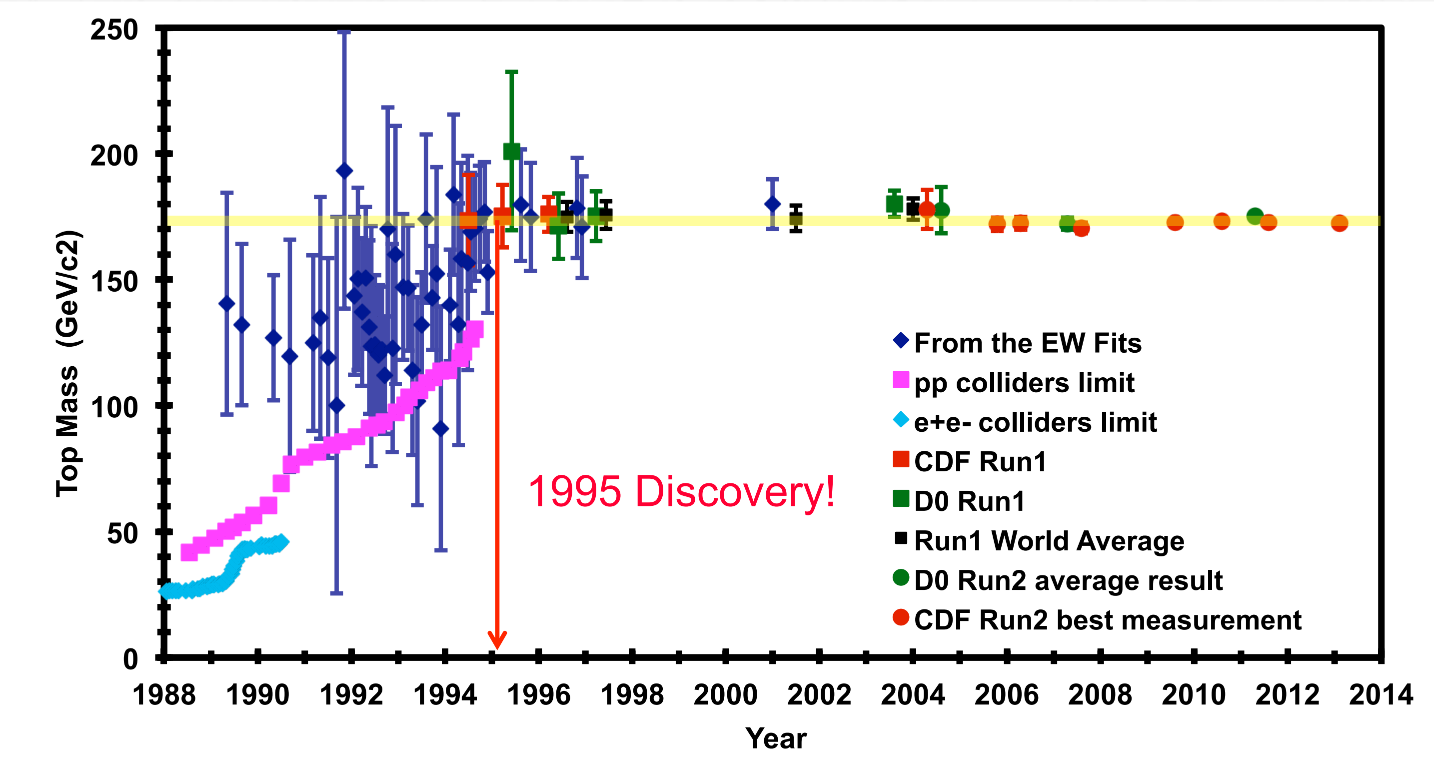
- Express the W mass in terms of 3 fundamental weak parameter, with loop corrections

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

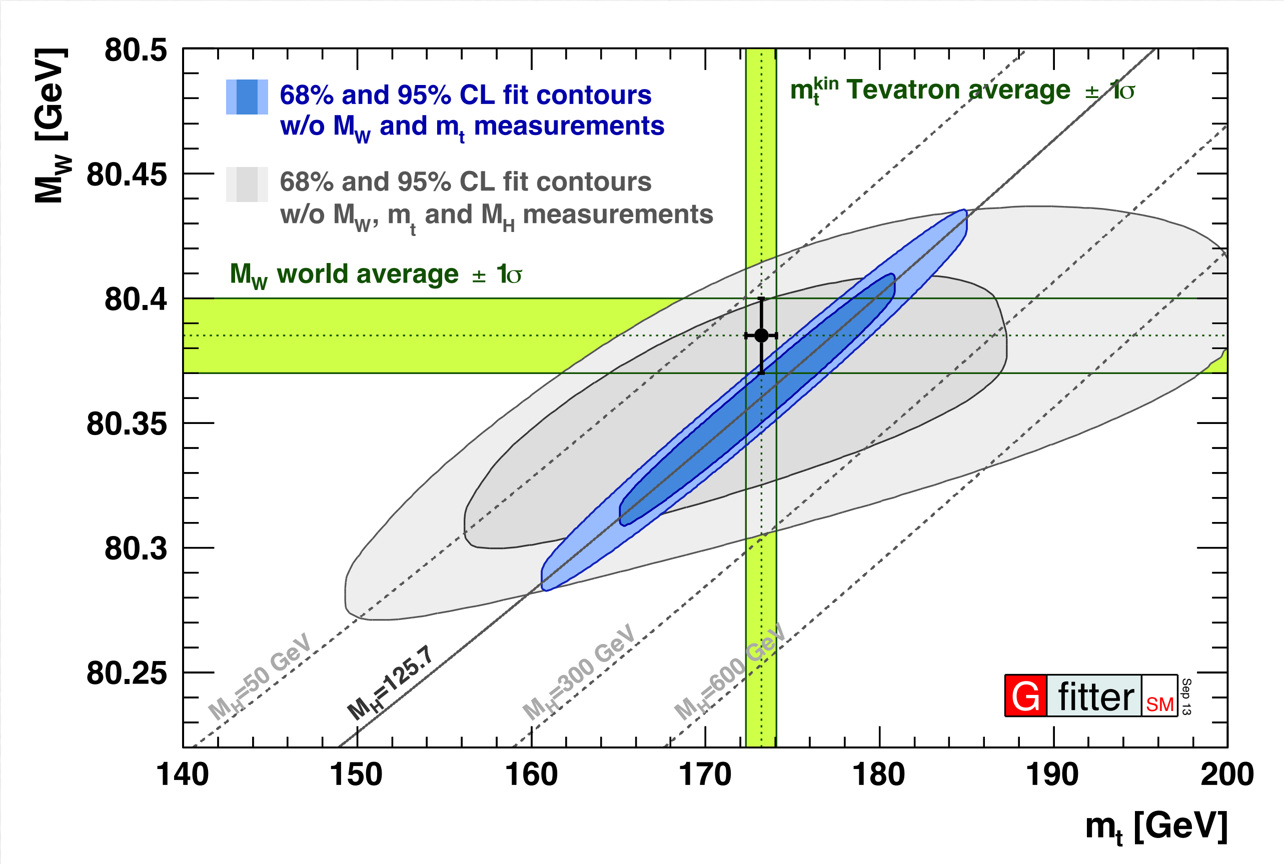
$$\Delta r_{top} = -\frac{3}{8\pi^2}\frac{G_F}{\sqrt{2}\tan^2\theta_w}m_t^2$$

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

Top predicted in advance, as “noise behind wall”



Now impressive consistency between top, Higgs, W mass



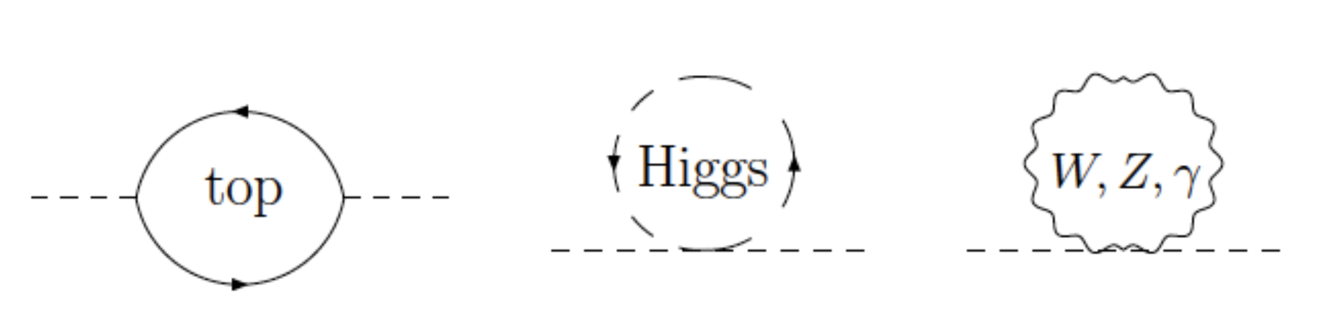
Top loop noise: no morals

- Good:
  - new phenomena may occur
  - more stringent test of Standard Model couplings
  - loop effects sensitive to energy scales well beyond current collider energies
- Evil:
  - new problems and questions may arise
    - but even that is good

Top loop 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 culprit

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 (e.g.) cutoff

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

- m_{tree} must precisely compensate: fine-tuning, awkward

Top and Supersymmetry

- One fix might be supersymmetry, predicting "scalar top" partner
- Top loop quadratic Higgs mass corrections cancelled by "stop" loop corrections, leaving

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

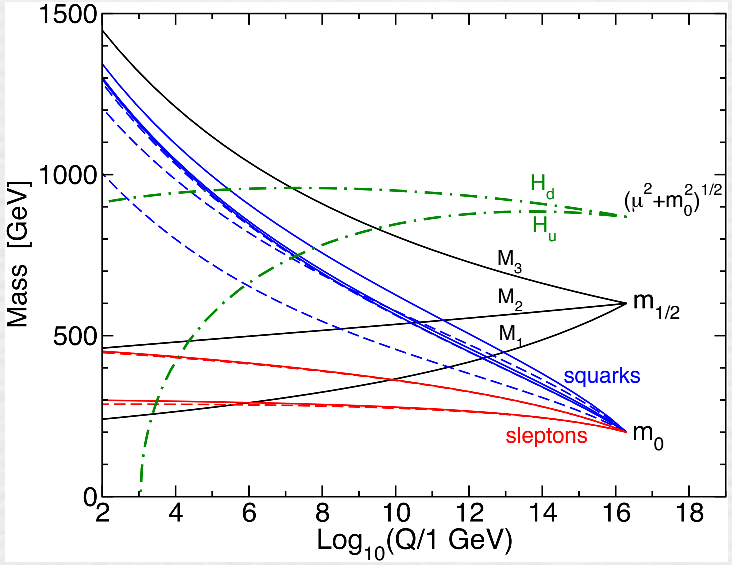
  - fermions in loops always get a minus sign w.r.t. bosons
  - makes dependence on cut-off logarithmic, which is acceptable/ natural

Top and SUSY: troublemaker turns cooperative

- SUSY fixes trouble caused (mostly) by top
- Top also keeps SUSY alive via (top, stop) m_t^4 corrections on lightest Higgs

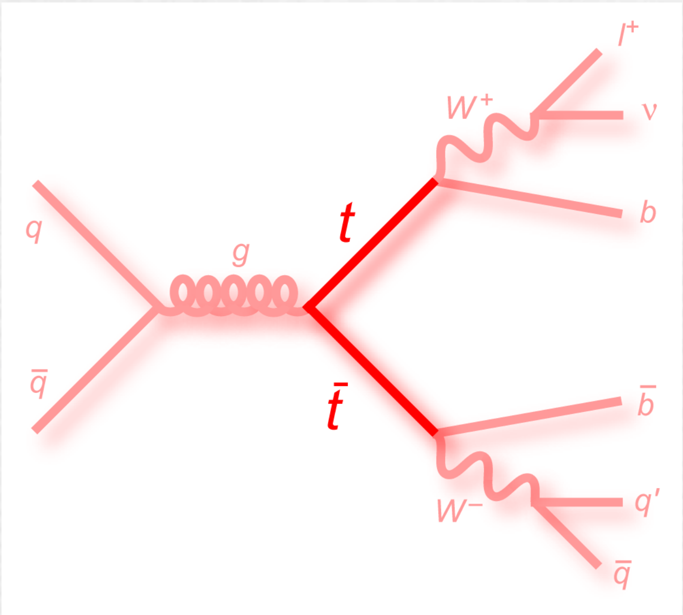
$$\Delta(m_{h^0}^2) = \frac{3}{4\pi^2}\cos^2\alpha\ y_t^2 m_t^2 \ln\left(m_{\tilde{t}_1} m_{\tilde{t}_2}/m_t^2\right)$$

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

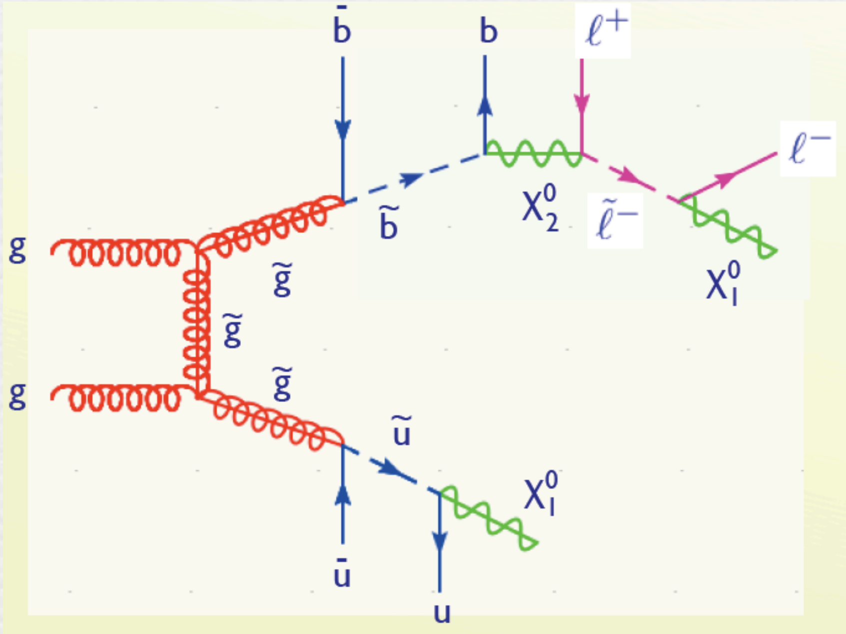


Why is top special? 3. Teaches new methods

- Methods:
  - It was the first particle whose discovery and study has been due to Monte Carlo simulation programs
    - 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 methods

- Top is often a background, e.g. to
  - New Physics
    - $gg \to H$, $qq \to Hqq$ ($H \to WW$), SUSY, Little Higgs
    - ttj and ttjj for ttH
  - Itself
    - tt is background to single top

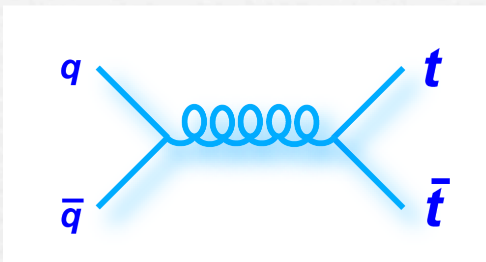
Story so far

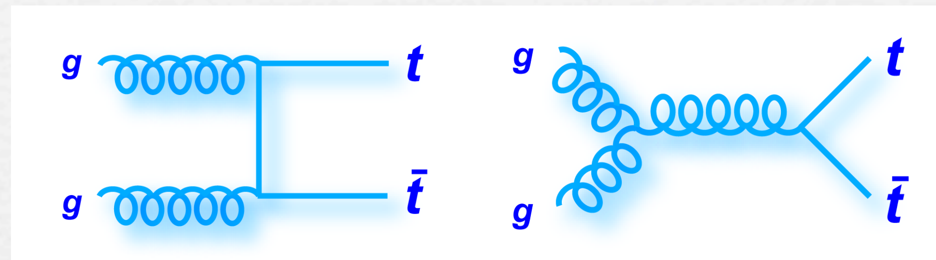
- Top ubiquitous in high-scale particle physics, central in the duels about the status of the Standard Model
- Top should be extra-sensitive to effects of New Physics, real or virtual
- Large mass, short life, easy access
- Next:
  - Visit important observables related to
    - top pairs, single top, mass, spin
  - and provide some background to these

Producing tops

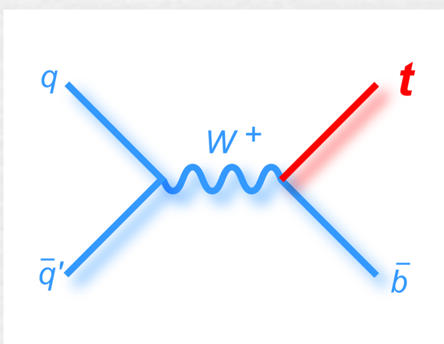
Producing top in hadron colliders

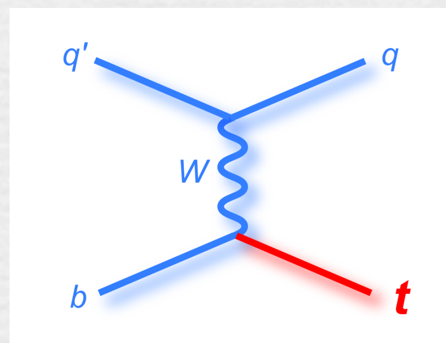
- "Doubles": Can be done via strong interaction, in pairs. These are the LO diagrams

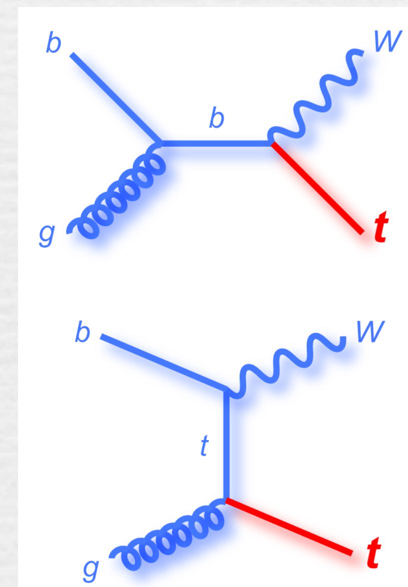




- "Singles": Can be done via the weak interaction, singly.







  - All these modes have now been seen

Top production: Tevatron and LHC

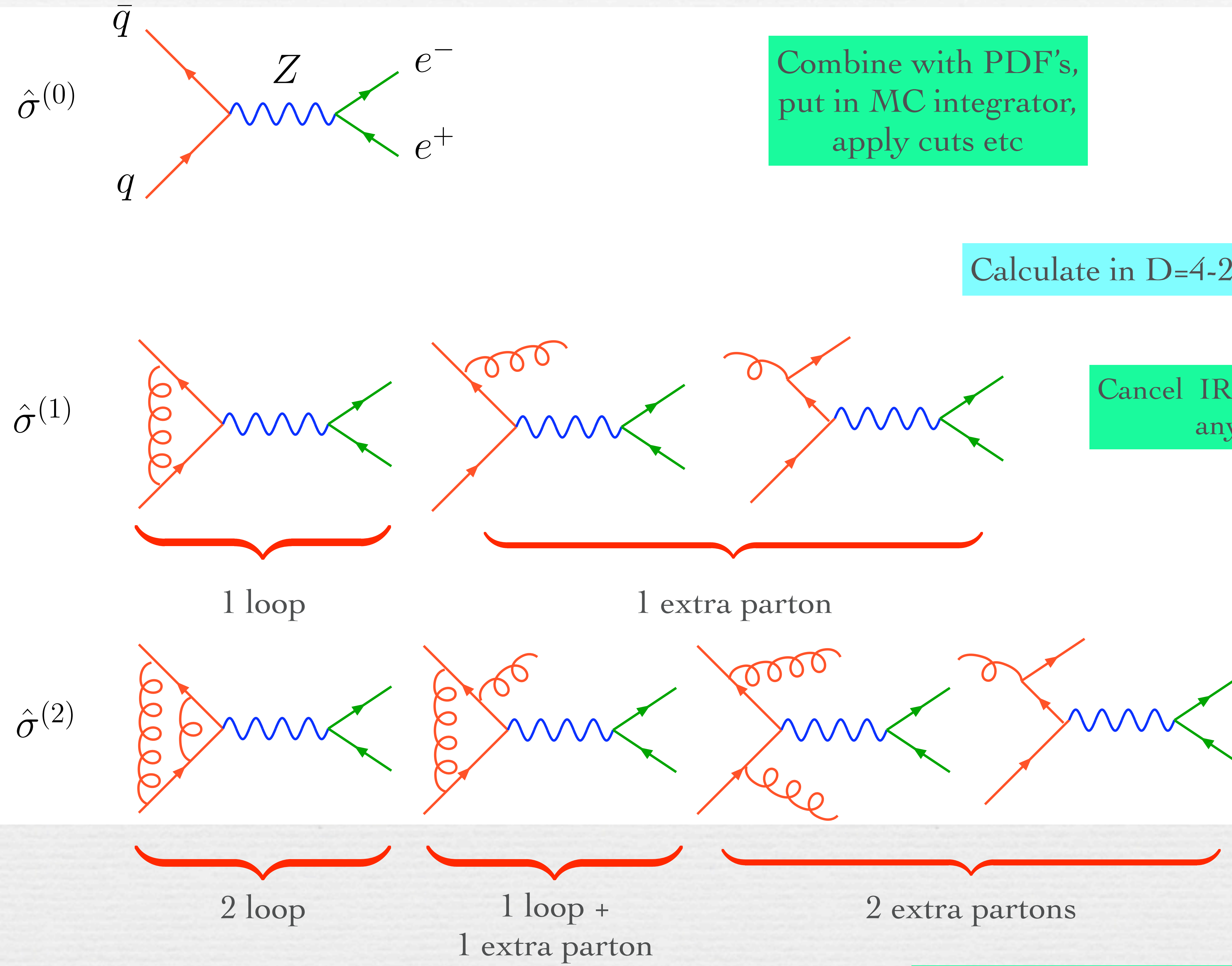
- Tevatron: top foundry
    - about 70K top pairs produced, discovery (1995), first tests of properties
- LHC: top factory
    - So far about 6M top pairs produced
    - Next phase (> 2015) about 90M/year

LO, NLO, etc

LO

NLO

NNLO



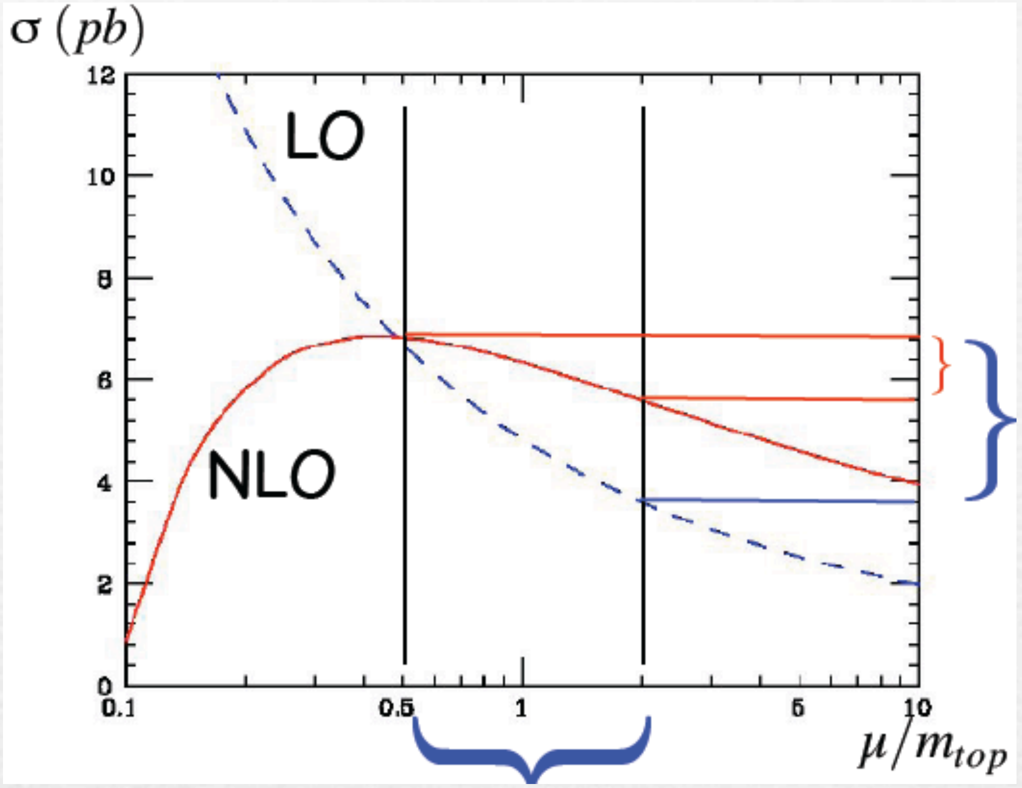
Combine with PDF's, put in MC integrator, apply cuts etc

Calculate in D=4-2ε dimensions

Cancel IR poles $1/\varepsilon^2$ before anything else

Cancel IR poles $1/\varepsilon^4$ etc before anything else; hard!

NLO: smaller scale uncertainty



Uncertainty

Customary scale variation

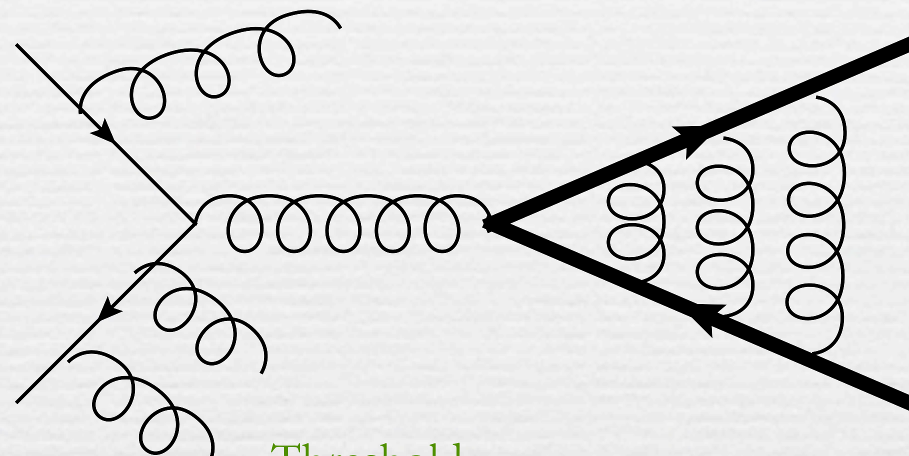
- LO (if proportional to α_s) is essentially unnormalized
- NLO becomes normalized, but its error is LO
- NNLO even better normalized, with NLO error

All orders; soft gluon resummation

$$\sigma^{resum} = \Big\{ \underbrace{\alpha_s^2 C_0}_{\text{LL,NLL}} + \underbrace{\alpha_s^3 C_1}_{\text{NNLL}} \Big\} \times$$

Moch, Vermaseren, Vogt; Mitov, Sterman, Sung
Ahrens Ferroglia, Neubert, Pecjak, Yang

$$\exp\Big[\underbrace{L g_1(\alpha_s L)}_{\text{LL}} + \underbrace{g_2(\alpha_s L)}_{\text{NLL}} + \underbrace{\alpha_s g_3(\alpha_s L)}_{\text{NNLL}} + \ldots \Big]$$



- Present status: NNLL
- L = log(threshold condition)

NNLO top cross section

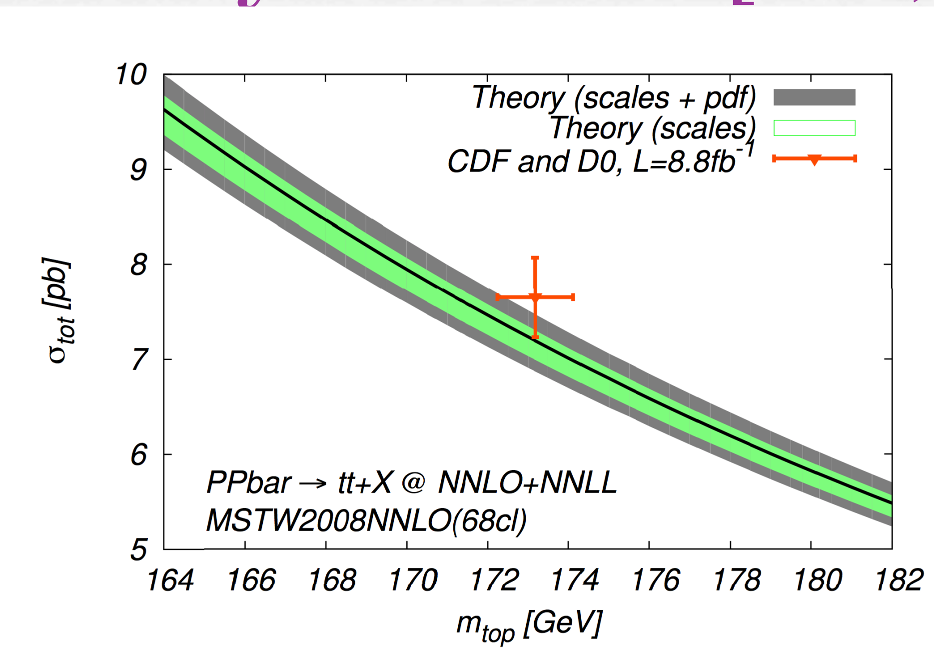
Baernreuther, Fiedler, Mitov, Czakon

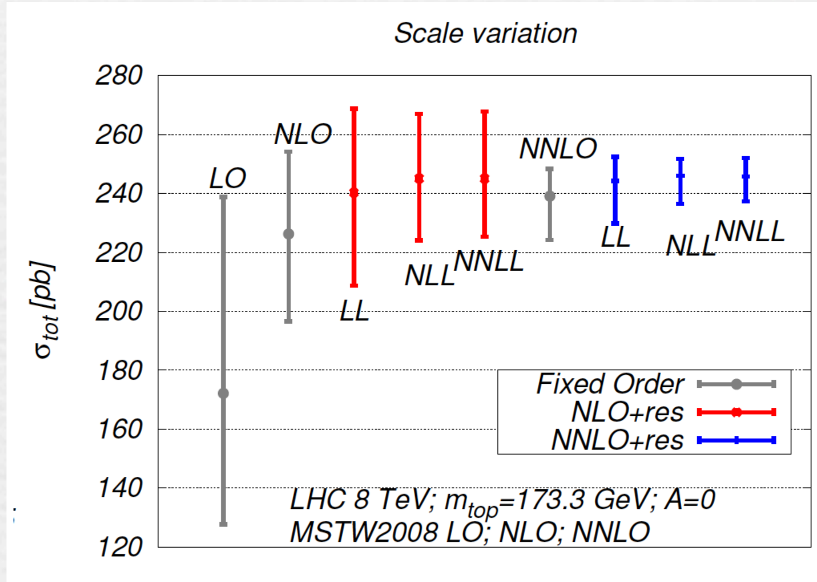
- **First NNLO calculation with initial hadrons and full color structure just completed**
    - One for the (QCD) history books
    - A massive achievement..
- Tools:
    - Highly involved computation and management of Feynman diagrams, Mellin-Barnes methods etc.
- At TOP2013 excitement of experimenters > theorists!!

NNLO top cross section

Baernreuther, Fiedler, Mitov, Czakon

- **Pay-off excellent [fame, fortune, convergence, agreement with data]**



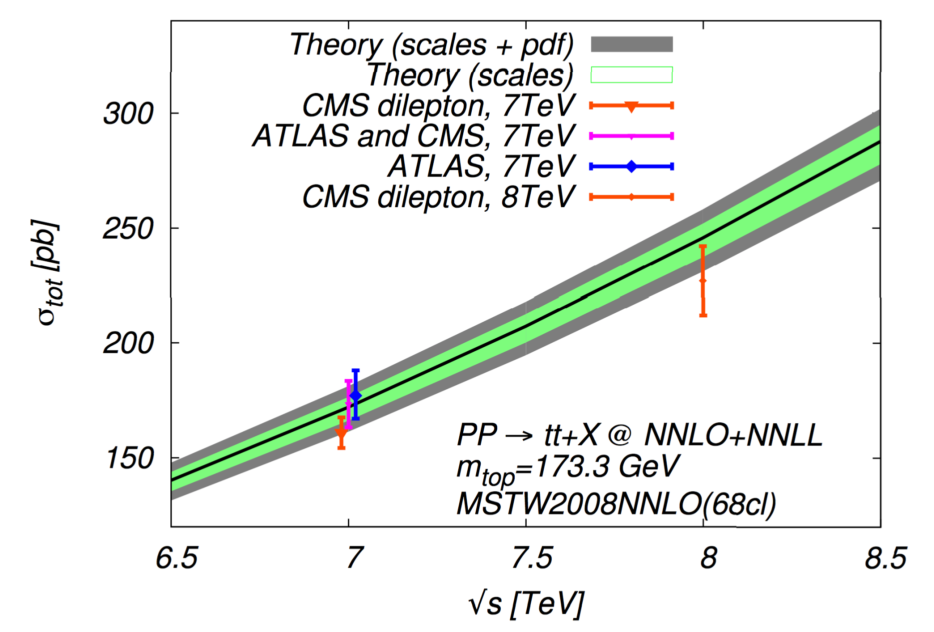


Concurrent uncertainties:

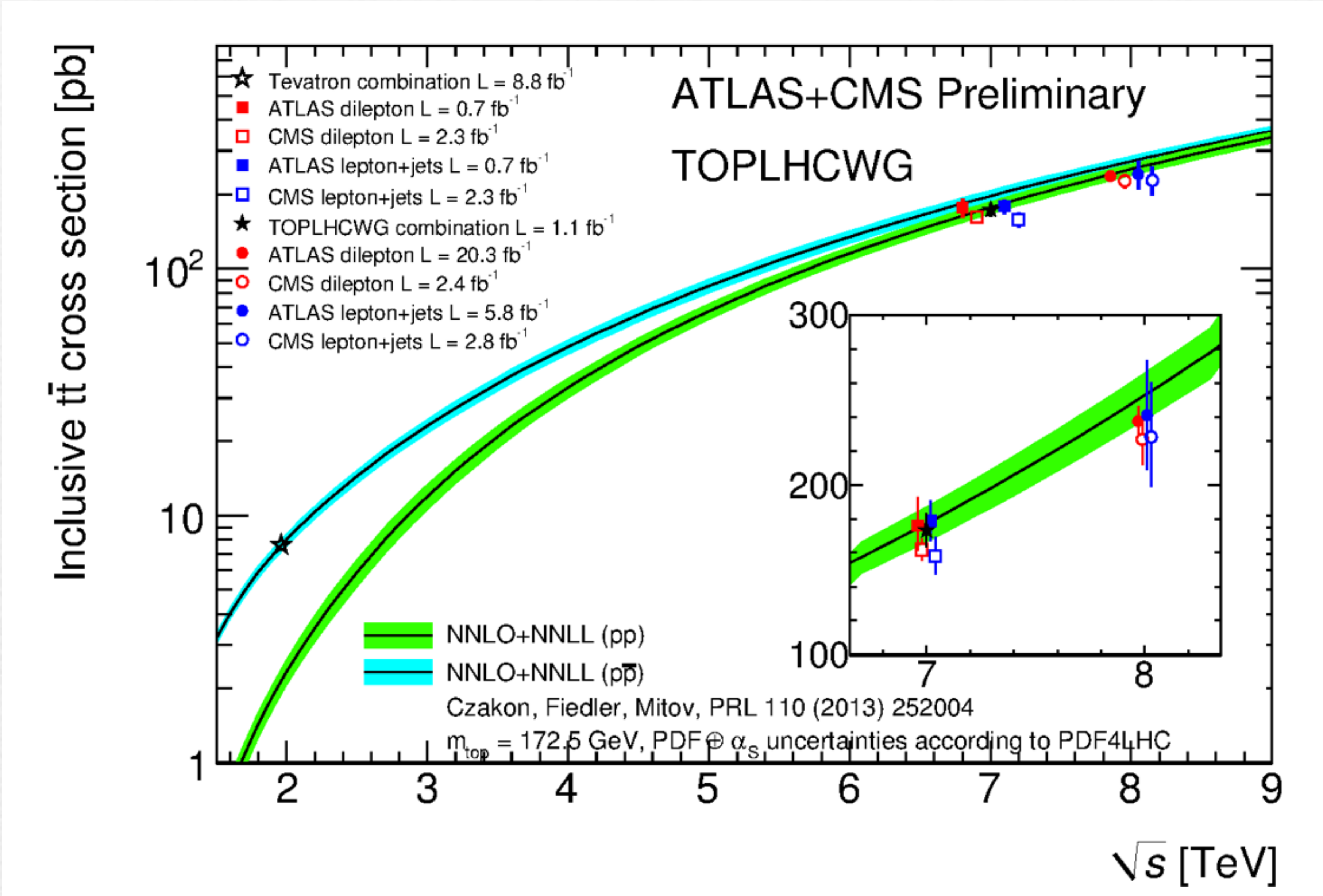
Scales	~ 3%
pdf (at 68%cl)	~ 2-3%
α_S (parametric)	~ 1.5%
m_{top} (parametric)	~ 3%

Soft gluon resummation makes a differenc

5% -> 3%



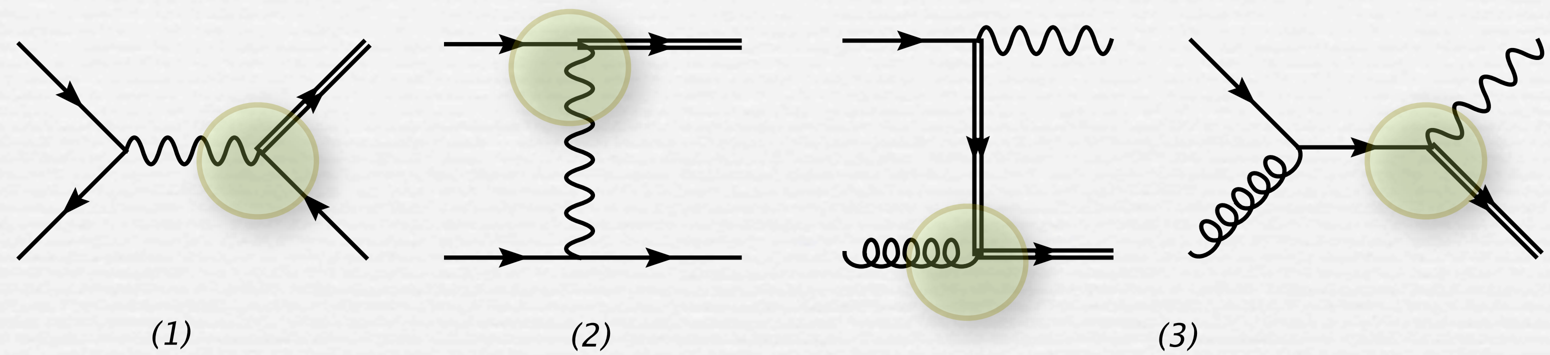
Beautiful agreement at LHC



- More naturalness:
  - σ_{tt}(7 TeV) / m_t = 172.3/173.2 = 0.99
  - σ_{tt}(8 TeV) / $\sqrt{2}$ x m_t = 238/245 = 0.97

Single top

Single top production



s-channel:
timelike W

4 pb @ LHC7

t-channel:
spacelike W

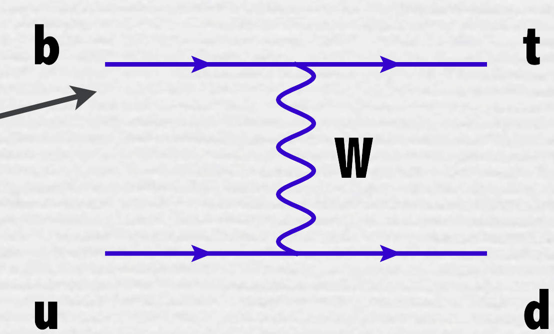
62 pb @ LHC7

Wt channel: real W

10 pb @ LHC7

Things you can do with single top production

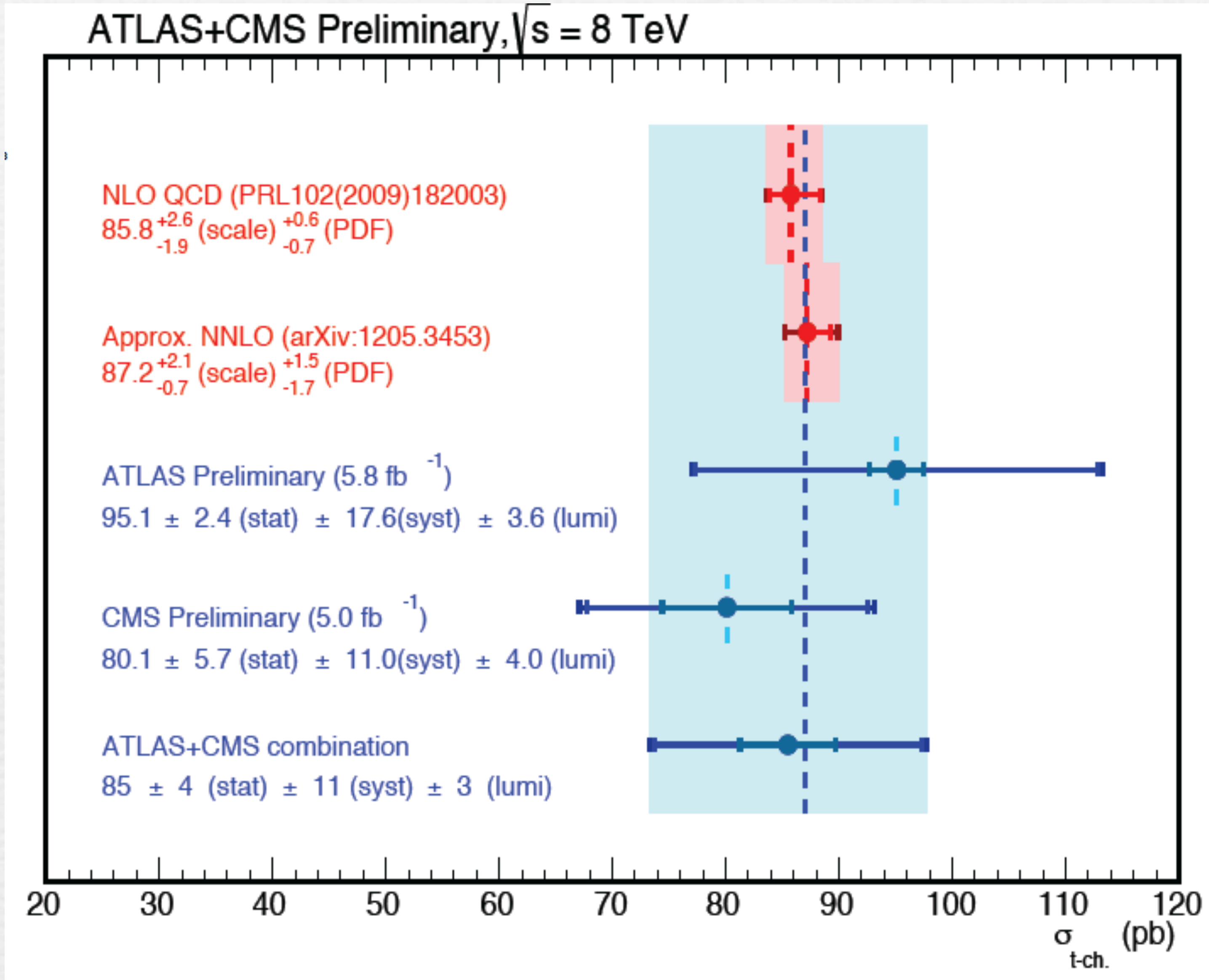
- process is sensitive to different New Physics/channel (FCNC (t-channel), W' resonance (s-channel), non-4 fermion operators (Wt-channel)
- It helpt determine (t-channel) the high-scale b-quark PDF
- It tests electroweak production of top, through left-handed coupling
    - It allows measurement of V_{tb} per channel.



Theory vs expt.

LHC

works well
so far



t-channel

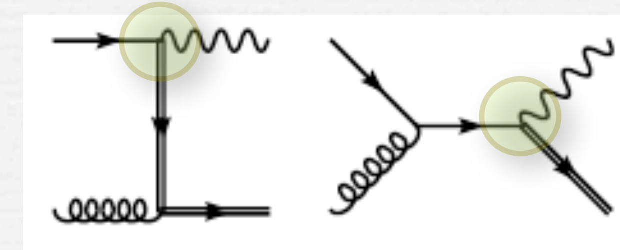
Summer 2013 on Wt channel, seen!

CMS: 6.0 sigma !
ATLAS: 4.2 sigma

works well
so far

Frixione, EL, Motylinski, Webber, White

Single top in Wt mode meets tt..



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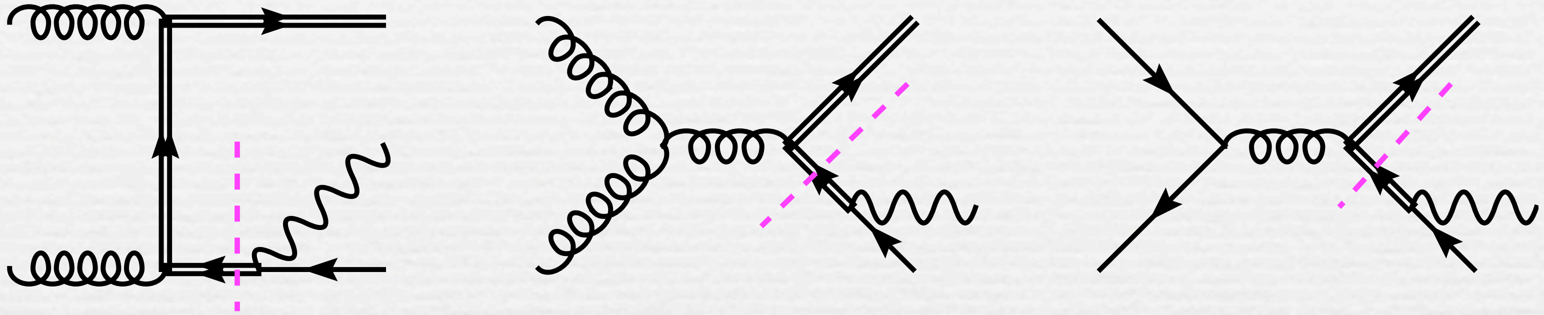


+ non-resonant diagrams

Serious interference with pair production (15 times bigger) (same problem in Ht)

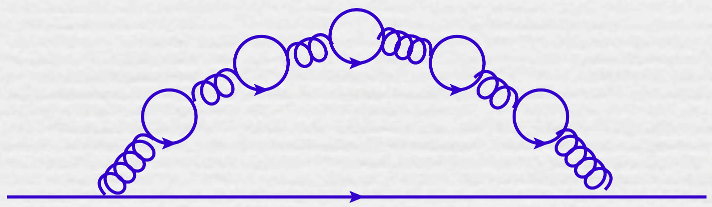
- In earlier calculations, subtract in calculation/cut on invariant mass
- Can one actually define this process?
  - Yes: one can separate the resonant tt background, using cuts, and testing for interference
  - Much recent work on proper description of production + decay

Papanasthasiou,
Cascioli, Kallweit, Maierhoefer, Pozzorini

Top Mass

Top mass

- Electron mass definition is"easy": defined by pole in full propagator
  - If particle momentum satisfies pole condition ($p^2=m^2$), can propagate to ∞
    - $\Rightarrow$ 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?
    - Need good theoretical definition, and good exp. measurement
    - Easier said than done..

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

Mass definitions differ in the choice of z_{finite}

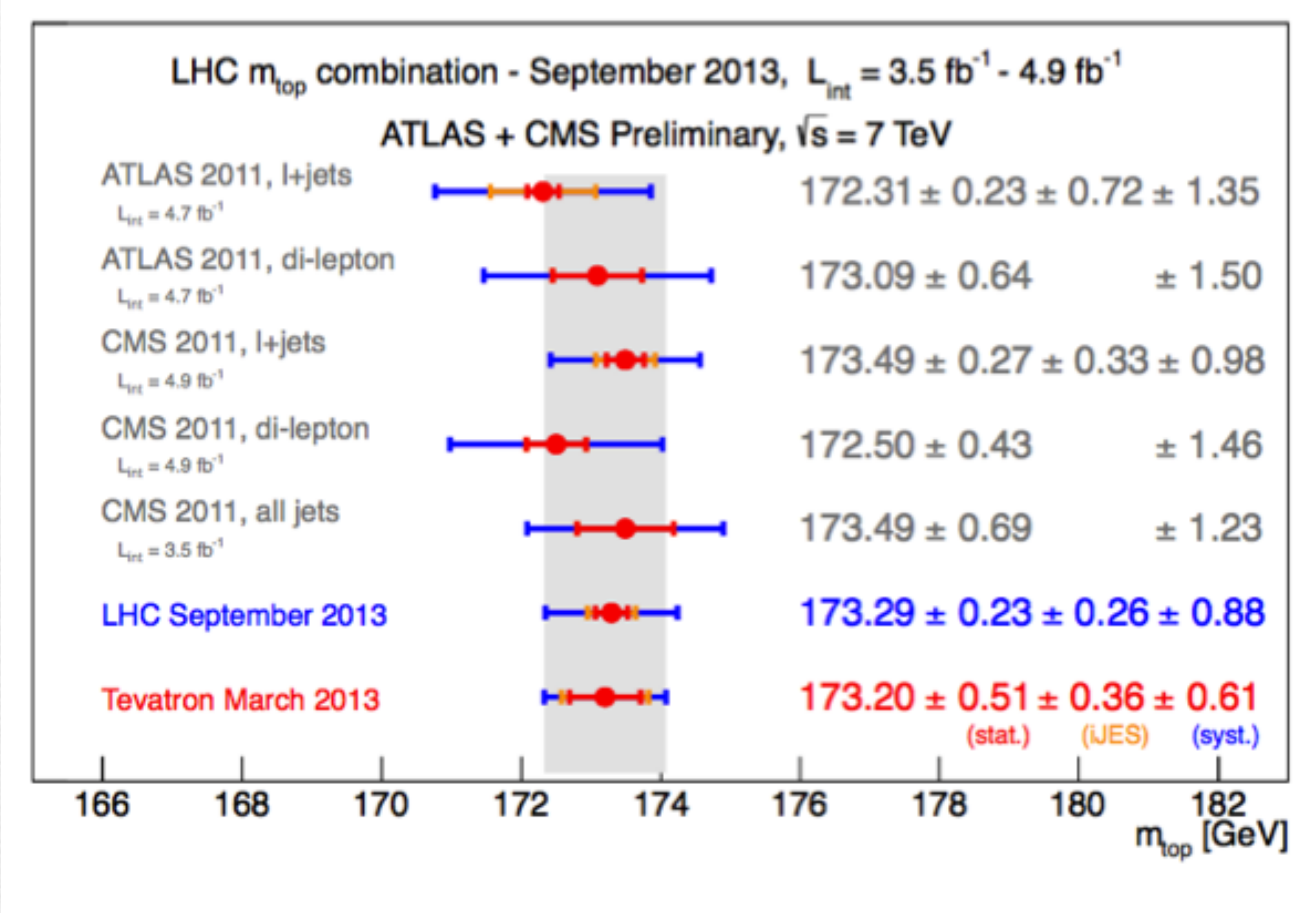
Pole mass: pretend quarks are free and long-lived $\quad \frac{1}{\not p - m_0 - \Sigma(p, m_0)} = \frac{c}{\not p - m}$

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

One can translate between them,
relation is known to 3 loops

$$m = m(\mu) \Big(1 + \alpha_s(\mu) d^1 + \alpha_s^2(\mu) d^2 + \dots \Big)$$

Top mass



Measured to well below 1% uncertainty

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, two definitions can differ by 10-15 GeV
  - It is also relevant for the fate of the universe

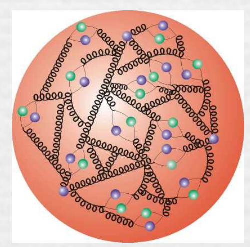
The last of the mass problems?

- We thought we had solved it in the 17th century

I. Newton (1687)

  - (i) resistance force and (ii) gravitational coupling

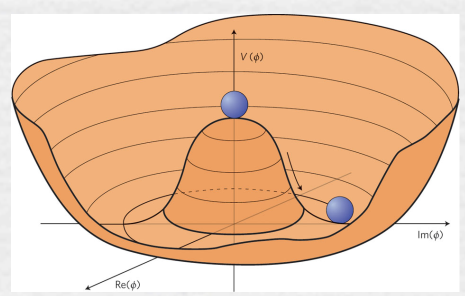

- New insight in 1905: condensed energy
  - Non-trivial for proton



A. Einstein (1905)

K. Wilson; Durr et al (2008)

- Yet newer insight: coupling to condensate



R, Brout, F. Englert, P. Higgs, Kibble, Hagen, Guralnik (1964 -2012)

- Finally
  - Mass of confined particle? Conceptually solved, but practically subtle

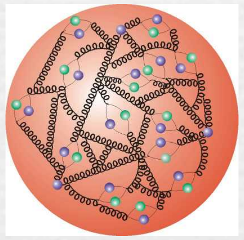
The last of the mass problems?

- We thought we had solved it in the 17th century
  - (i) resistance force and (ii) gravitational coupling

I. Newton (1687)

Gravity holds universe together

- New insight in 1905: condensed energy
  - Non-trivial for proton



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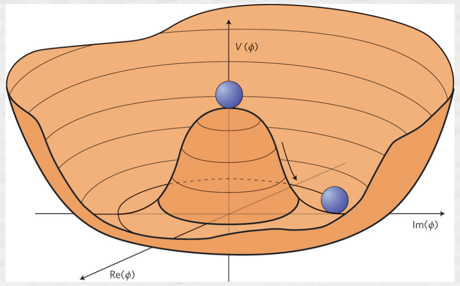

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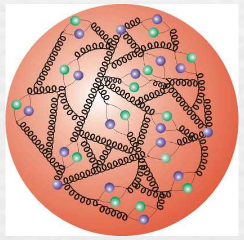

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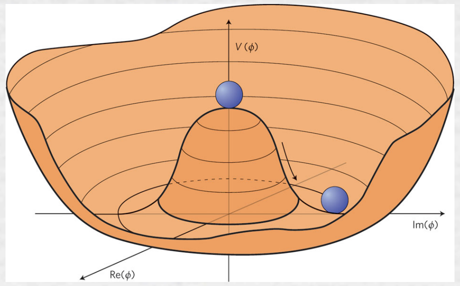

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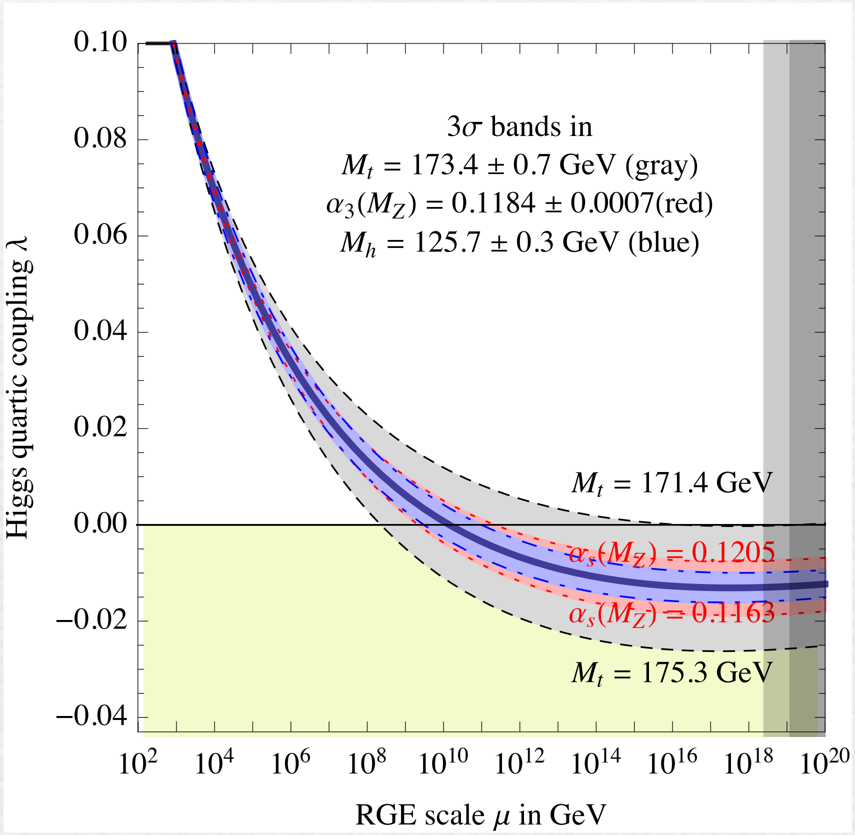
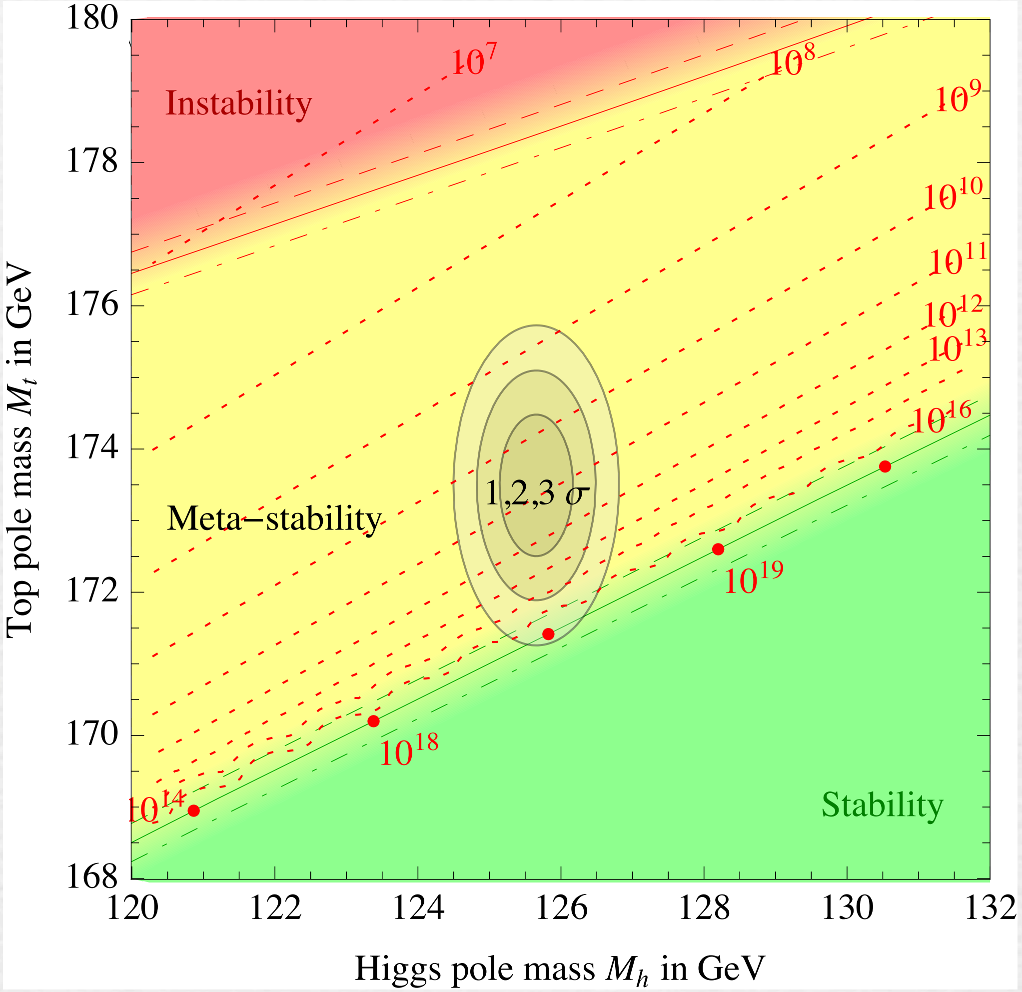
Does top make the universe fall apart?

State of the Vacuum

- Top quark dominant in loop corrections that make the Higgs 4-pt coupling evolve. Full two-loop analysis:

Buttazzo et al (July 2013)





- Depends on precise top quark mass
  - within 300 MeV or so
- No worries about universe

At the edge

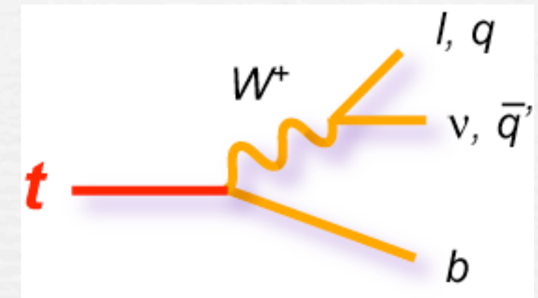
Buttazzo et al (July 2013)

- Universe on the edge, near critical could be attractor point in multiverse
  - Example: sand dunes
  - Slope of sand dunes always near "angle of repose"
  - Competition between gravity collapse and wind build-up

Top spin

Top "self-analyzes" its spin

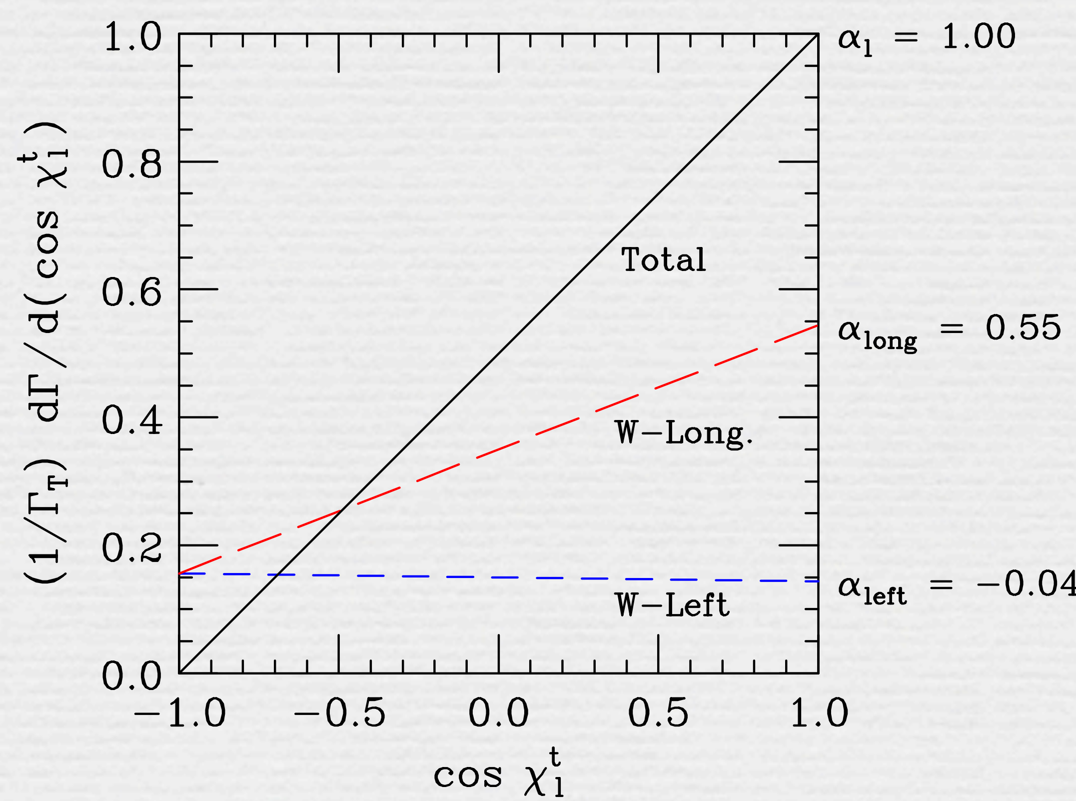
- 100% correlation of charged lepton direction with top spin
  - Top self-analyzes its spin
  - Charged leptons easy to measure



- For spin-up top the polar angle distribution is

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

$$\frac{1}{\Gamma_T}\frac{d\Gamma_{(\uparrow)}}{d(\cos\theta_{e^+})} = \frac{1}{2}(1+\cos\theta_{e^+})$$



- It decays so fast, we only have to measure lepton direction and then know about top quark spin state
  - direct view of structure of interaction!

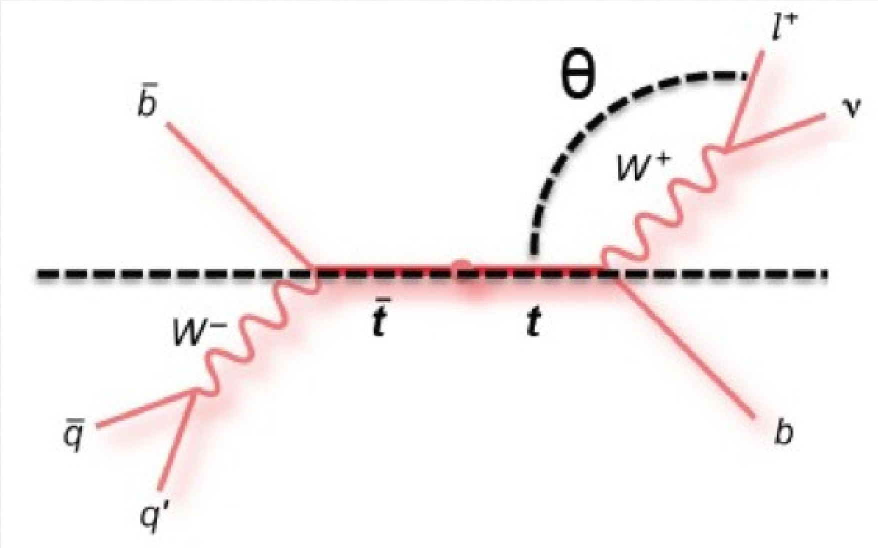
Top entanglement

Bernreuther, Brandenburg, Fücker, Si, Uwer

- At LHC, tops in pair production are produced essentially unpolarized
- But they do have clear mutual spin correlation (entanglement)

$$\frac{d\sigma}{d\cos\theta_a \cos\theta_b} = \frac{\sigma}{4}(1 + B_1 \cos\theta_a + B_2 \cos\theta_b - C \cos\theta_a \cos\theta_b)$$

- C depends on quantization axis, highest in helicity basis in zero momentum frame
  - $C_{hel} = 0.326$ ($C_{beam} = -0.07$) for LHC(14)
- We can check this!

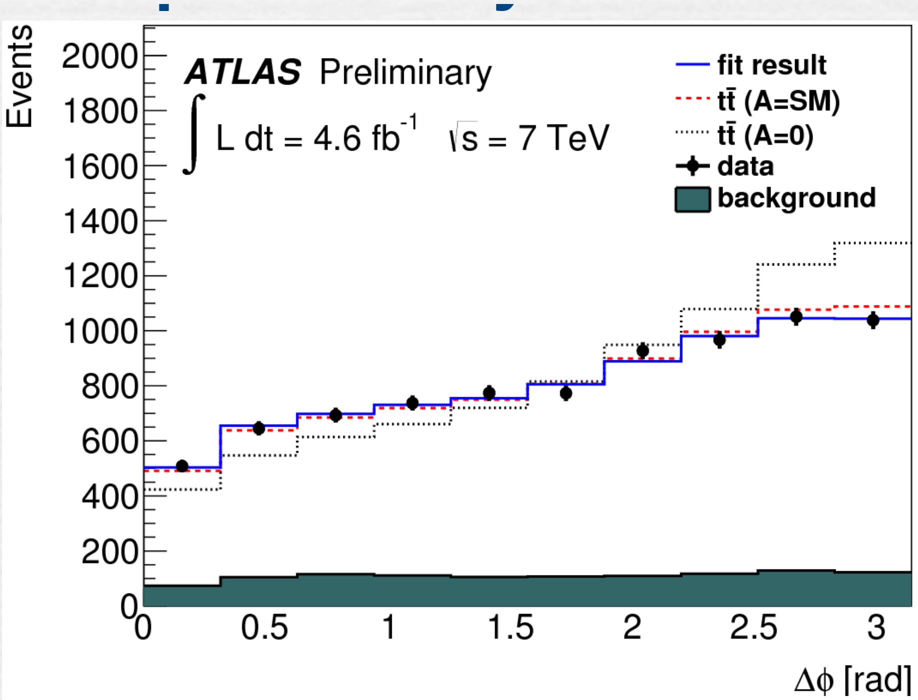


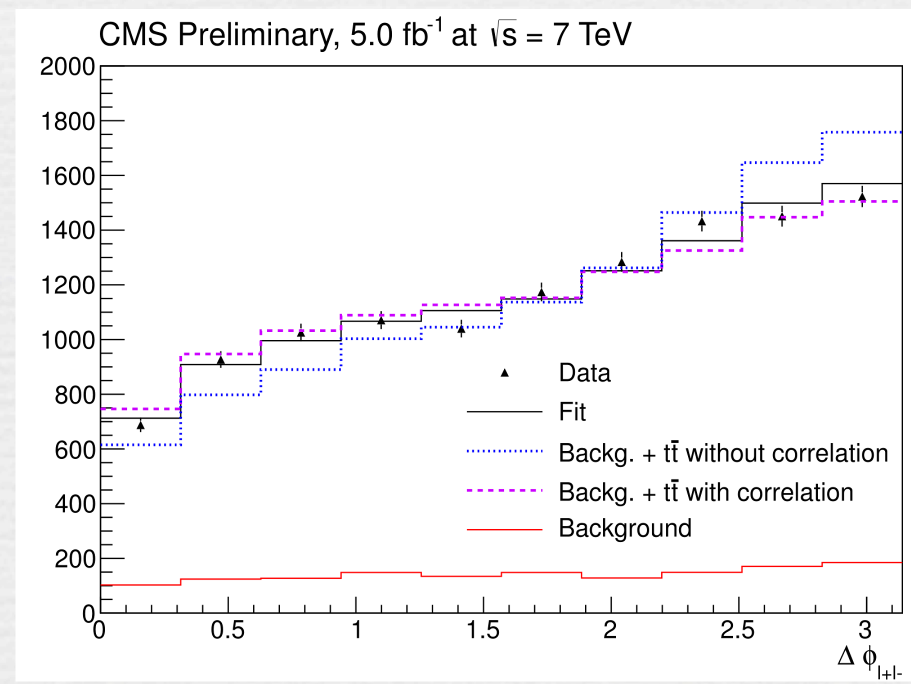
Wednesday, January 8, 14

Entangled tops

- Can test SM spin correlations in tt using invariant mass cut, and dilepton decay channel
  - Visible through azimuthal distribution Δφ of leptons in lab frame

Mahlon Parke



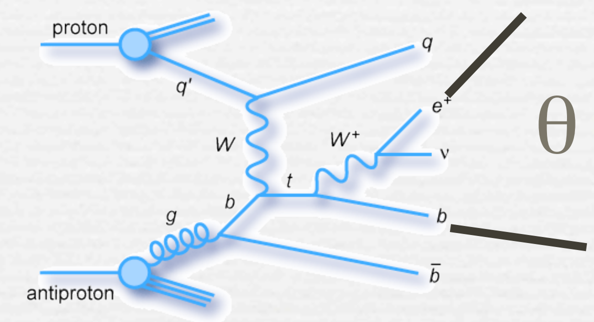


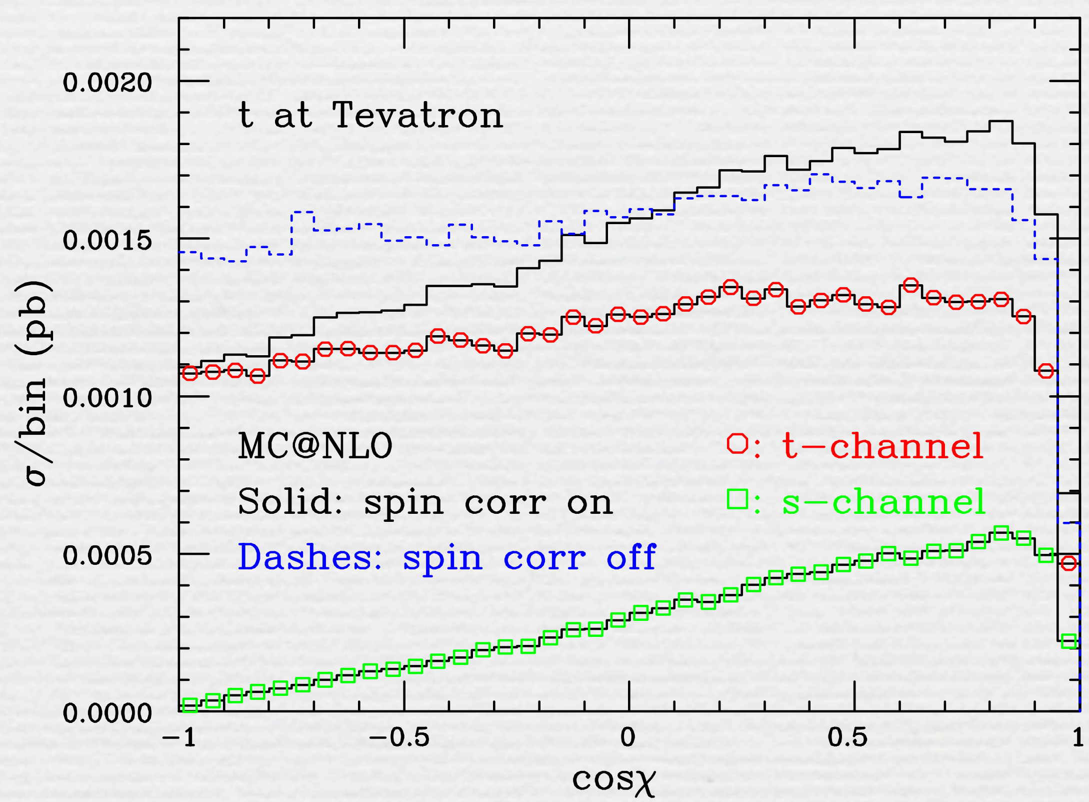
- CMS and ATLAS confirm no no-correlation
- So far in agreemet with SM

Spin correlations for single top in MC@NLO

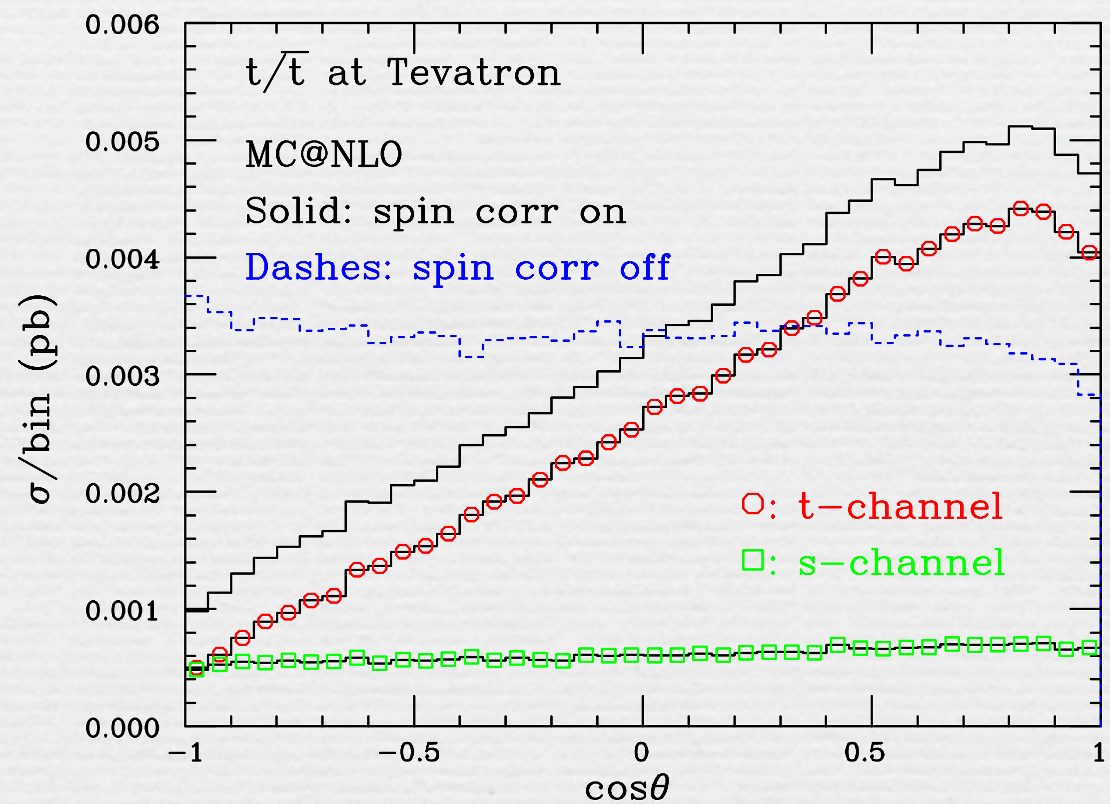
Frixione, EL, Motylinski, Webber

- Top is produced polarized by EW interaction
  - 100% correlation between top spin and charged lepton direction
- Angle of lepton with appropriate axis is different per channel





Beam direction

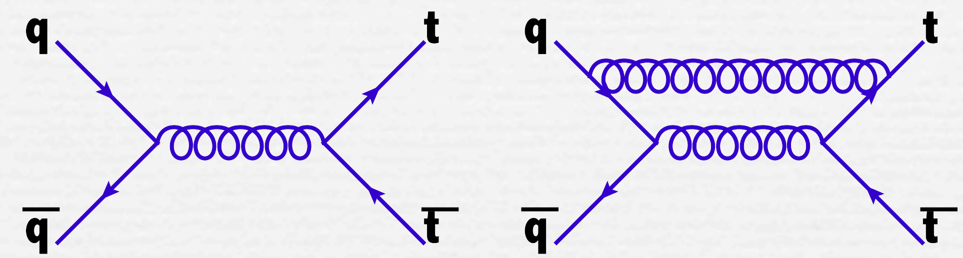


Hardest, non-b jet

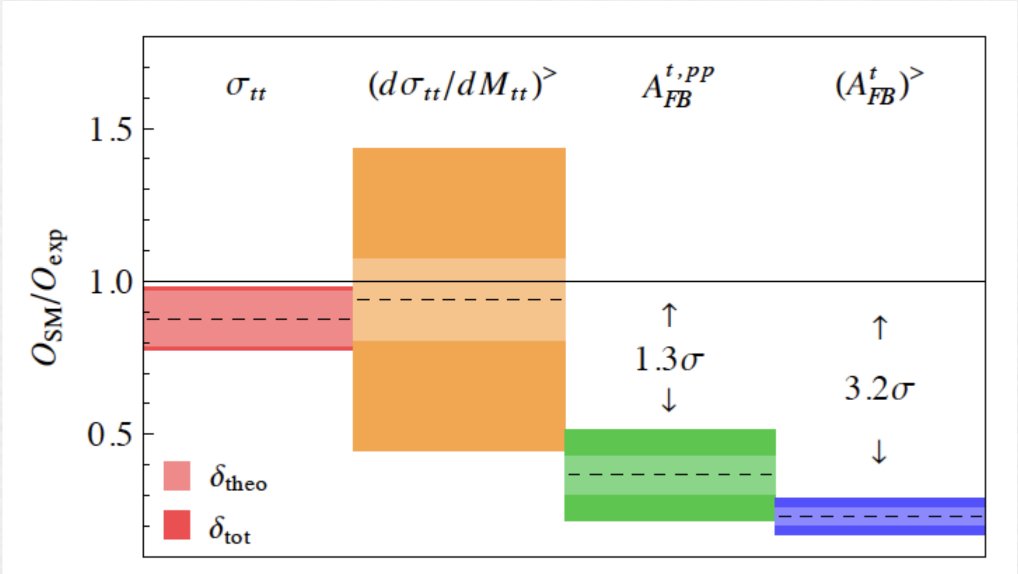
Robust correlation in NLO event generation

Does everything then agree? Not quite..

$$A_t(y) = \frac{N_t(y) - N_{\bar{t}}(y)}{N_t(y) + N_{\bar{t}}(y)}$$



- Study if top quarks and distibuted just as top antiquarks
- A small difference expected from QCD effects,
  - in QCD, proportional to SU(3) d_{abc} symbol
- It is another test of tt production
- Serious discrepancies in some measurements with SM
  - More difficult to test at LHC
  - Meaning? Here to stay? Not yet clear.



Conclusions

- Top quark, even off its pedestal, is right in the middle of many issues in stress-testing the Standard Model
- With top-factory era coming on, expect significant expanded testing
  - spin correlations, other complex final states
  - determination of top Yukawa coupling?
- Theoretical directions
  - precision!
  - Optimal top mass definition
  - Role of top in near-criticality of SM
    - no cause for alarm, but cause for interesting times ahead