Top quark physics

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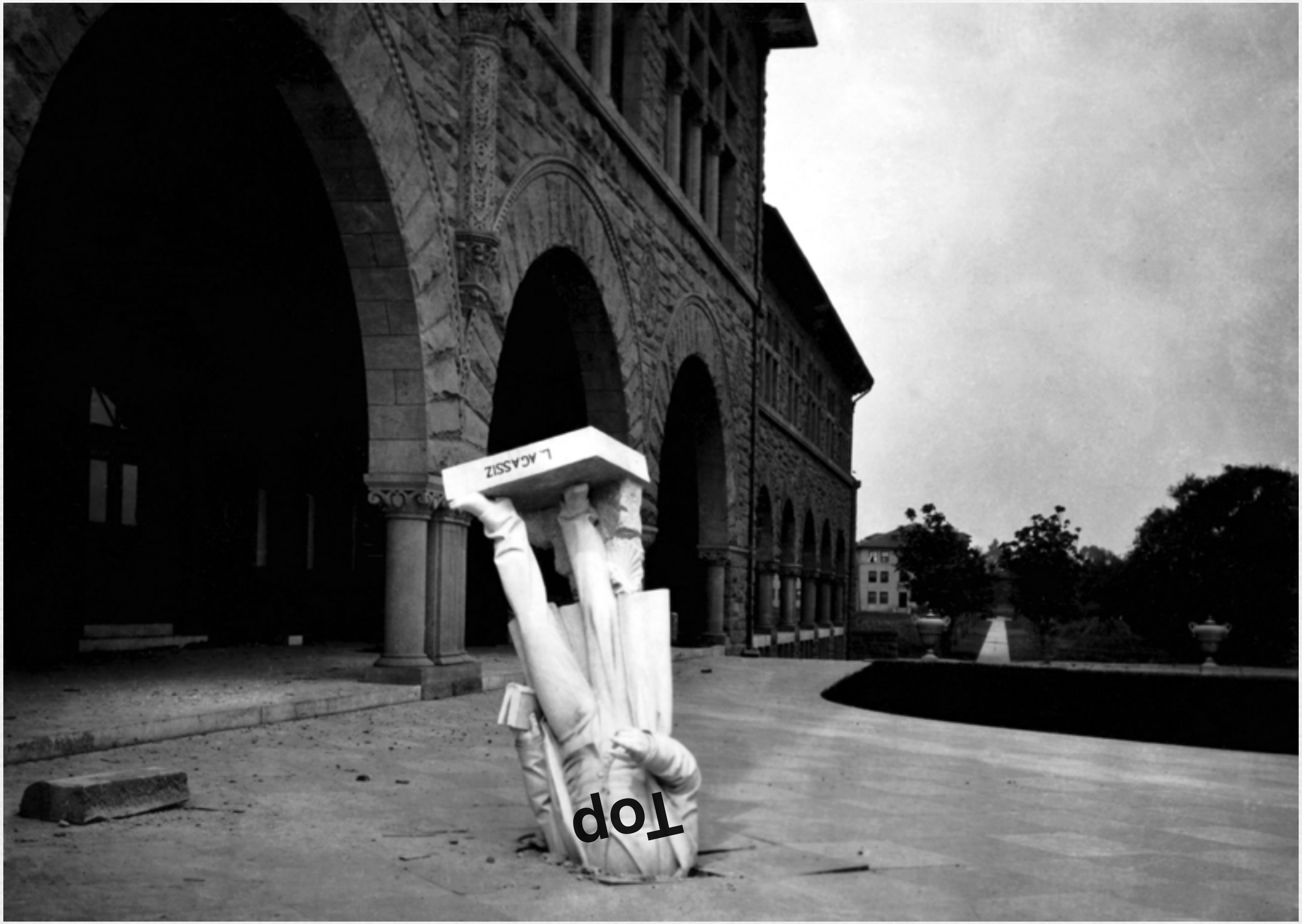
The manifold uses of top

- 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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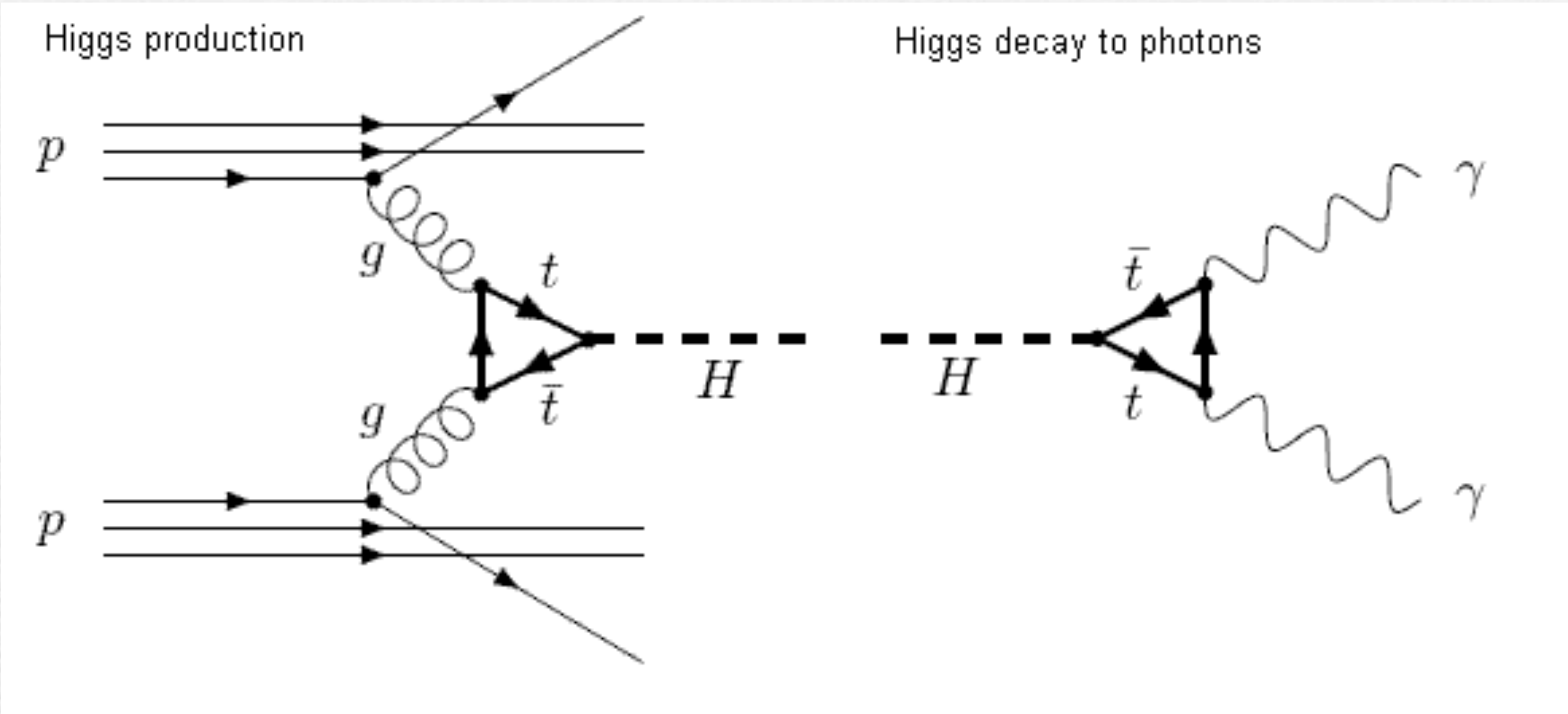
In fact, many many tops produced by now

Still, top = matter of life and death for Higgs



Monday, April 29, 13

Outline

- Top in the Standard Model
- Top beyond the Standard Model
- Various top observables
  - Top pairs
  - Mass
  - Single top
  - Charge asymmetry
- Correlations, angular distributions
- Conclusions

Standard Model Lagrangian

$$\mathcal{L}_{SM} = \sum_f \bar{\psi}_f \not{D} \psi_f + Tr\,[D_\mu, D_\nu][D^\mu, D^\nu] + D_\mu \Phi^\dagger D^\mu \Phi - V(\Phi) + Y(\psi, \Phi)$$

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- Lagrangian made of fields monomials (powers 2,3,4) and couplings
- Fields correspond to (anti)particles
- More quantum numbers than just spin: flavor, color, isospin,...
- Form dictated by symmetries, both global and local
- E.g. left-handed 3rd generation quark (fermionic) field

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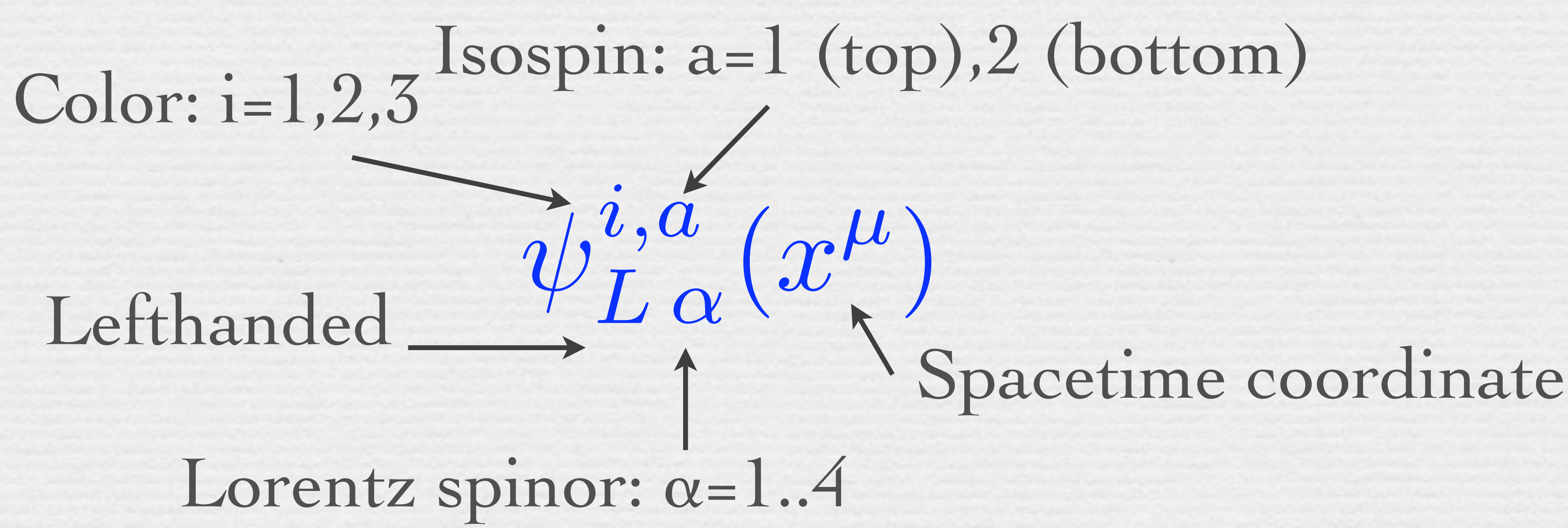


Mass generation in SM

Expanding Higgs 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*

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

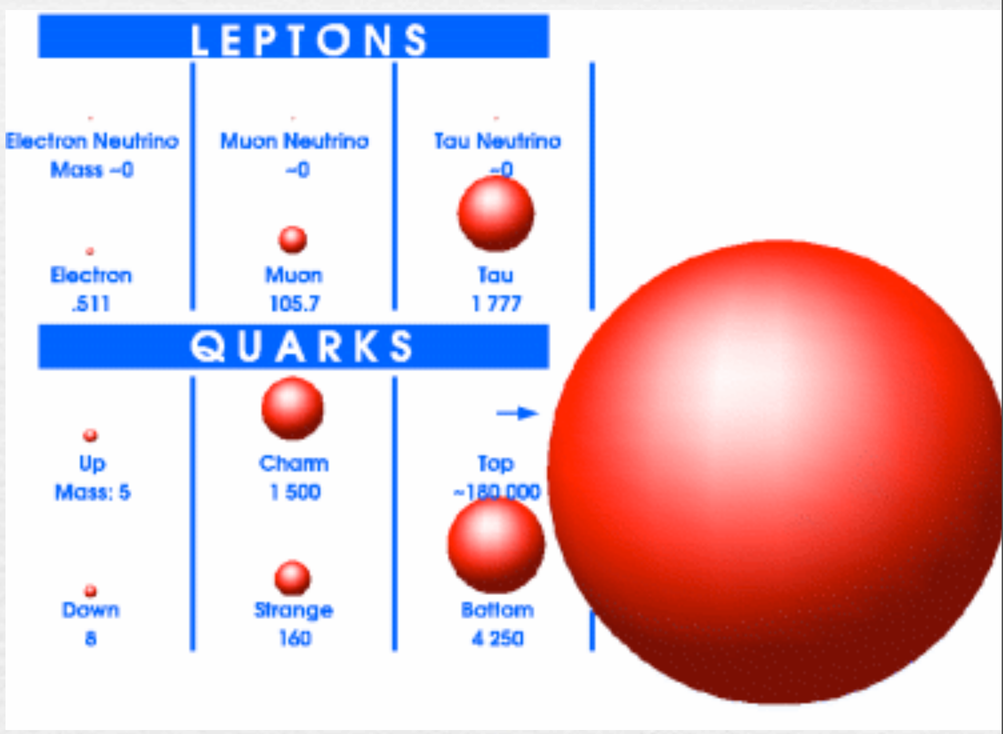
All SM masses are so generated, and have form: coupling × v

Same couplings that determine masses determine interactions

Analogous to Meissner-Ochsenfeld effect in BCS superconductors

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 coupling

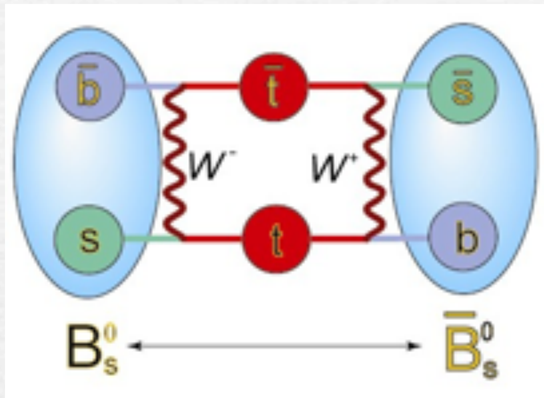
Exp. tested?

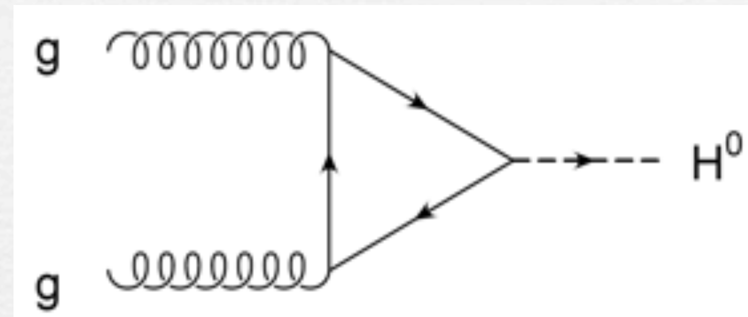
- to W boson: flavor mixing, lefthanded
  - gw ~ 0.45 $\frac{g}{\sqrt{2}} V_{tq} \, (\bar{t}_L \gamma^\mu q_L) W^+_\mu$ √?
- to Z boson: parity violating
  - gz ~ 0.14 $\frac{g}{4\cos\theta_w} \, \bar{t} \left((1 - \frac{8}{3} \sin^2\theta_w) \gamma^\mu - \gamma^\mu \gamma^5 \right) t \, Z_\mu$?
- to photon: vectorlike, bare 2/3 charge
  - 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 $y_t \, h\bar{t}t$ √?

Check structure and strength of all these couplings

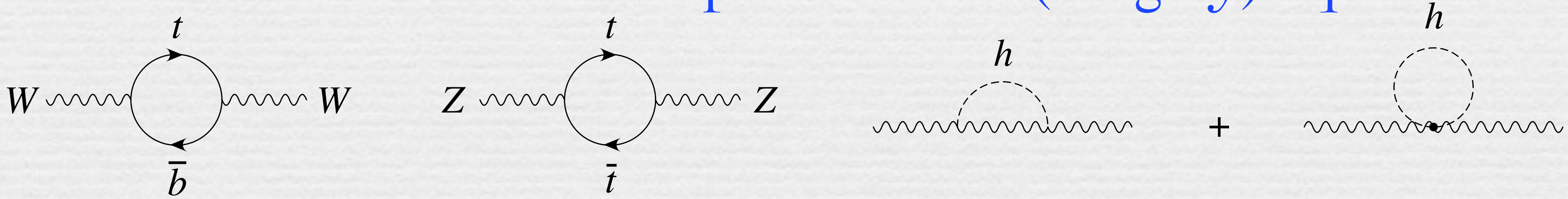
Top in loops

- 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

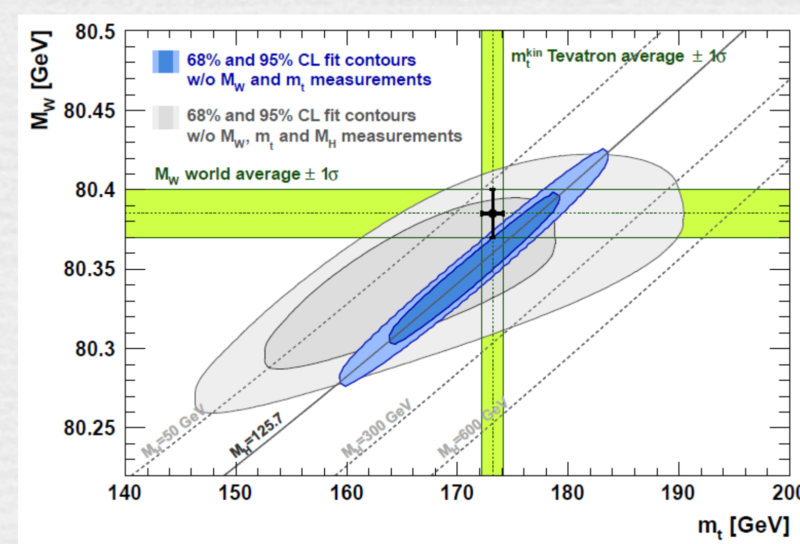


- Express the W mass in terms of 3 fundamental weak parameter, with loop corrections

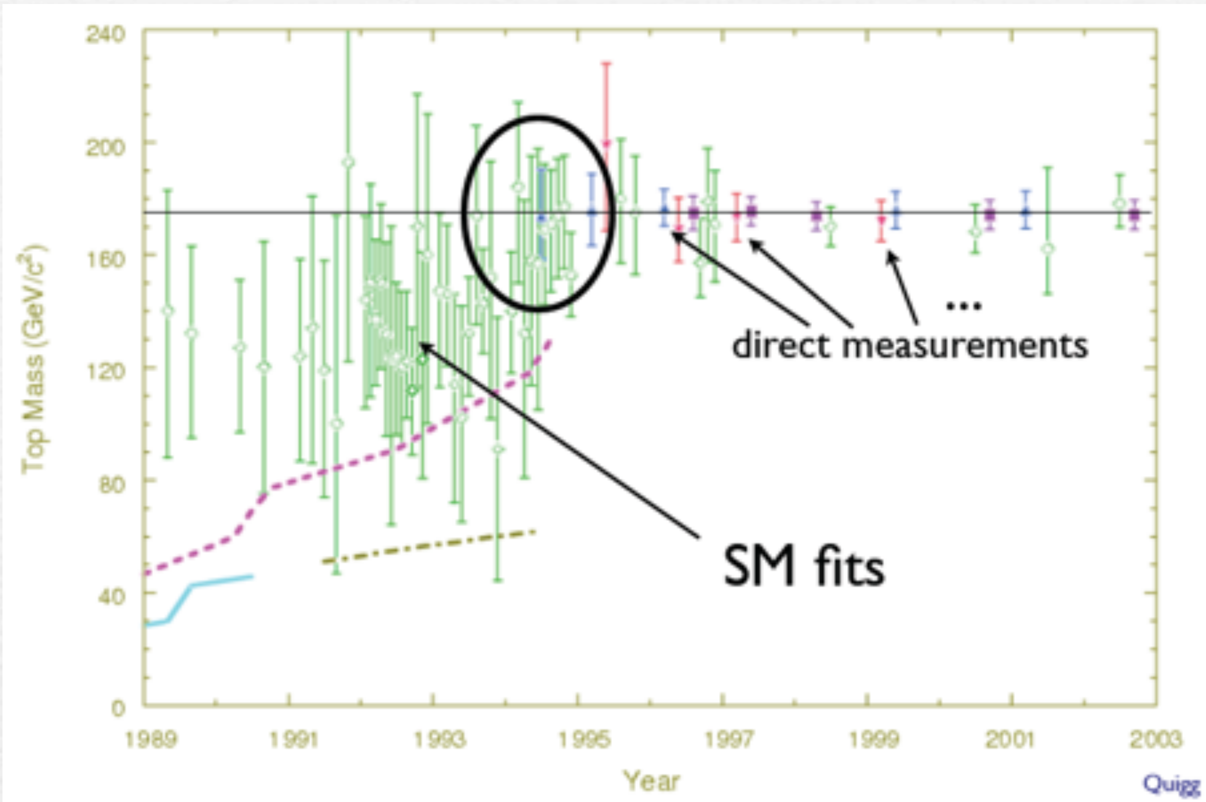
$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F \sin^2\theta_w}\frac{1}{1-\Delta r(m_t, m_H)}$$

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

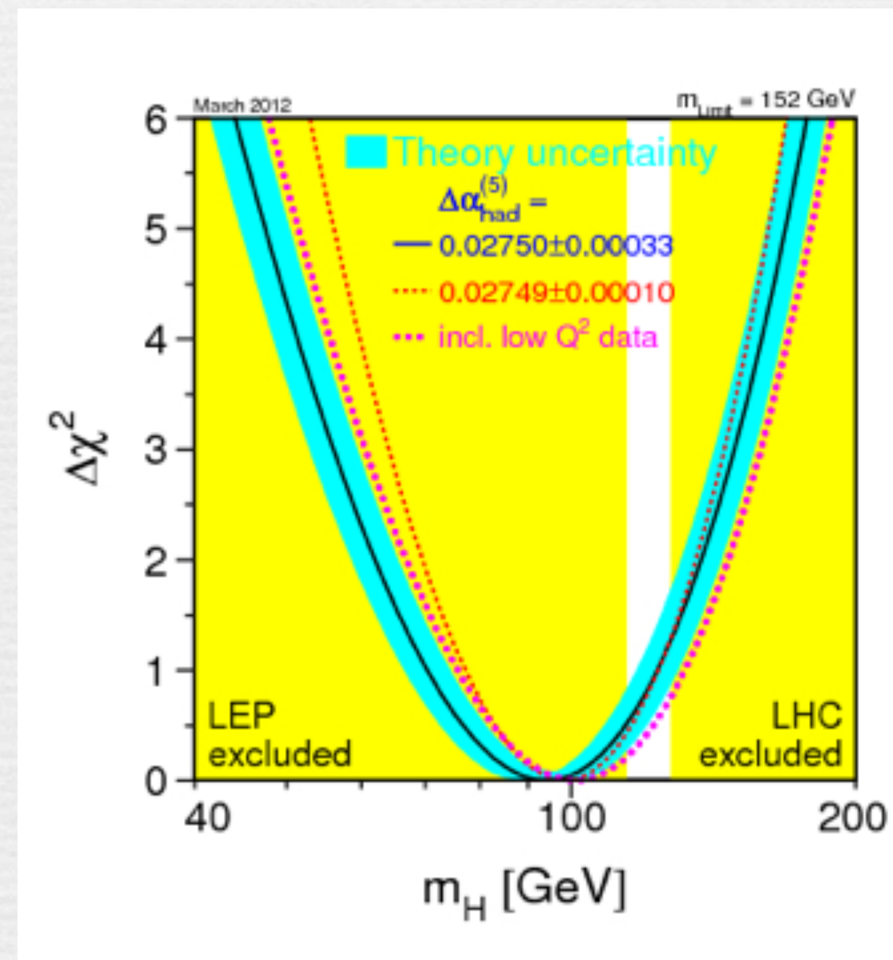
$$\Delta r_{Higgs} = \frac{3}{8\pi^2}\frac{G_F}{\sqrt{2}\tan^2\theta_w}m_W^2\left(2\ln(m_H/m_Z) - 5/6\right)$$



Top predicted in advance, by noise behind wall



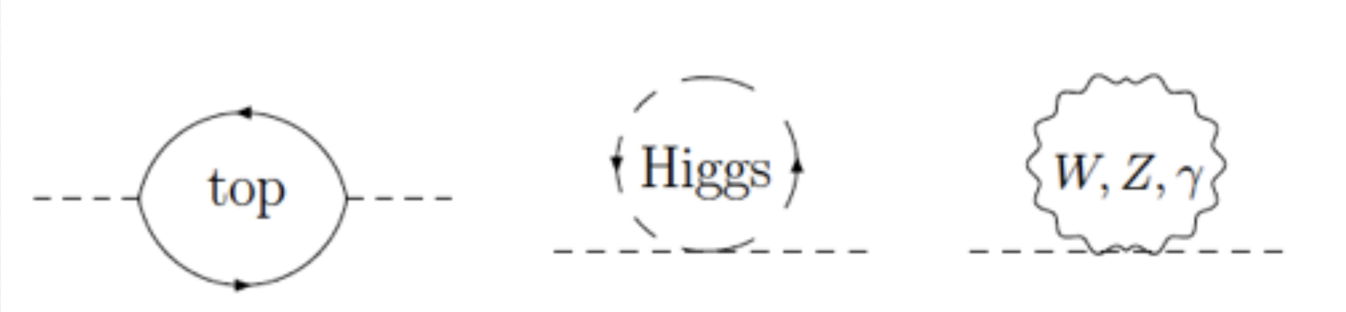
and it looks like it worked again



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 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

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

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

Top and SUSY

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

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

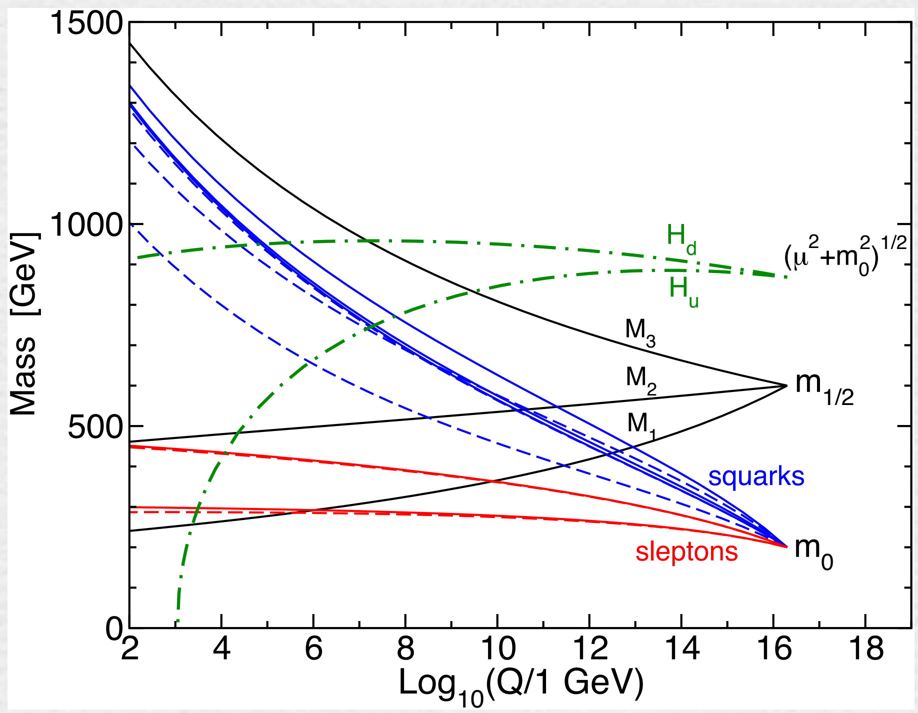
  - minus due to fact that fermions in loop always get a minus sign
  - makes dependence on cut-off logarithmic, which is acceptable/ natural

Top: SUSY saviour

- 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

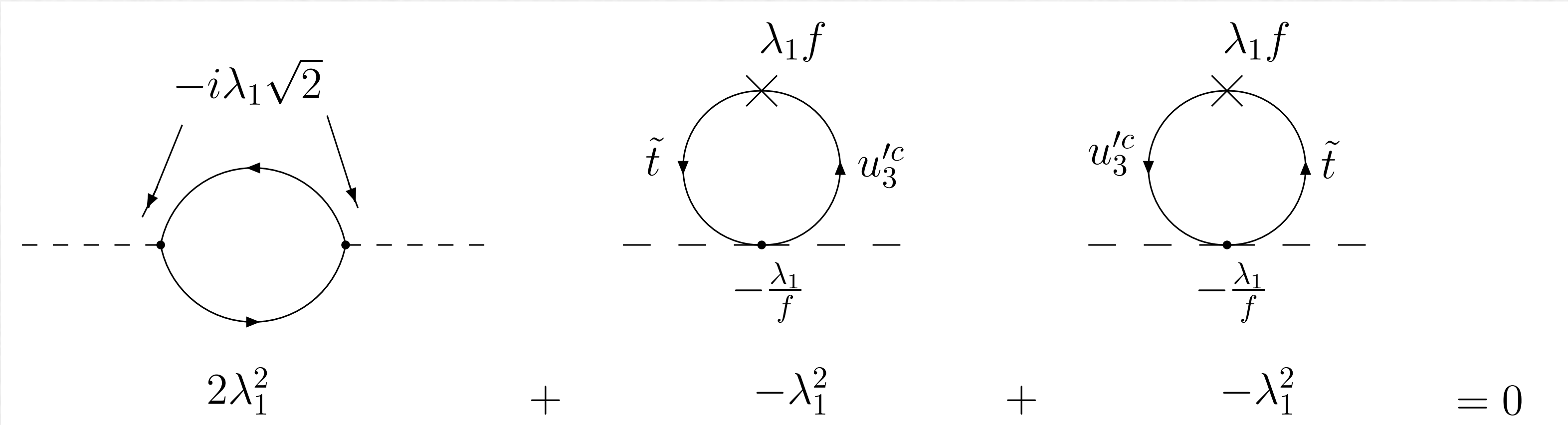


- Heavy Higgses may decay to top, can determine their CP properties

Top and 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

Higgs compositeness/strong dynamics

- Still a viable scenario, with top in leading role
  - Higgs = pseudo Nambu-Goldstone boson (like pion)
  - natural solution to naturalness problem
- E.g.: 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 in trouble/excluded by LHC data
  - but not all

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

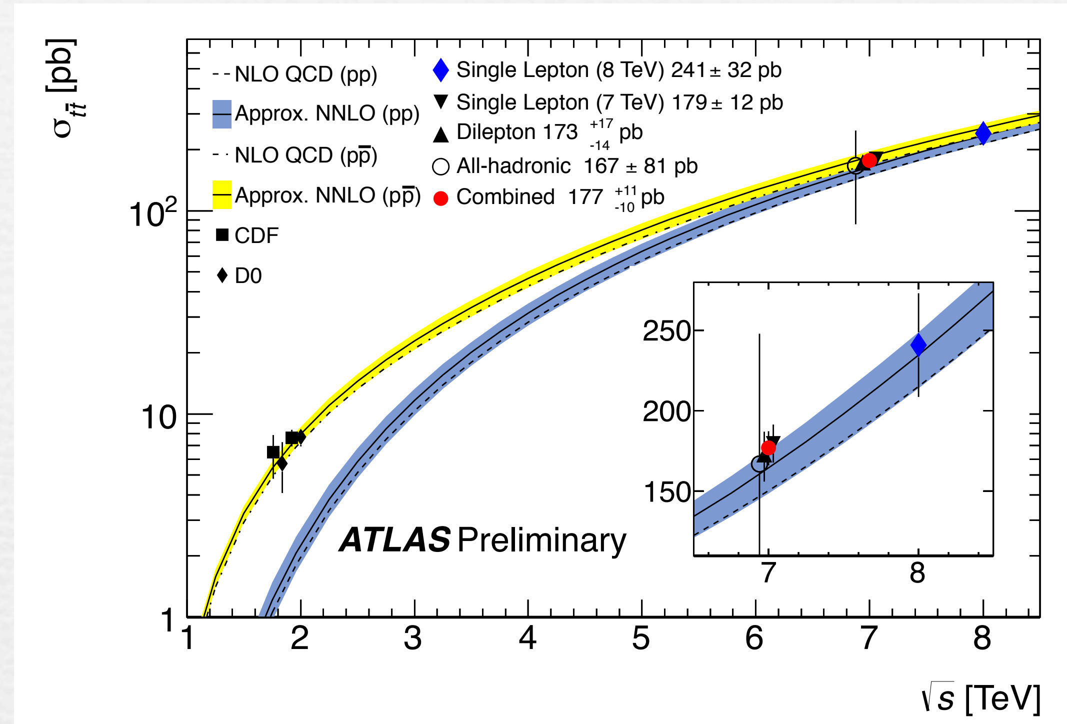
Top object

- Top should be extra-sensitive to BSM effects, real or virtual
- Large mass, short life, easy access
- Goal for this talk:
  - Visit important observables
    - σ, m_t, single top, A_{FB}, angular correlations
      - What is the state-of-the-art description? What do we learn?
  - Provide some background to these
    - Apologies in advance for omissions

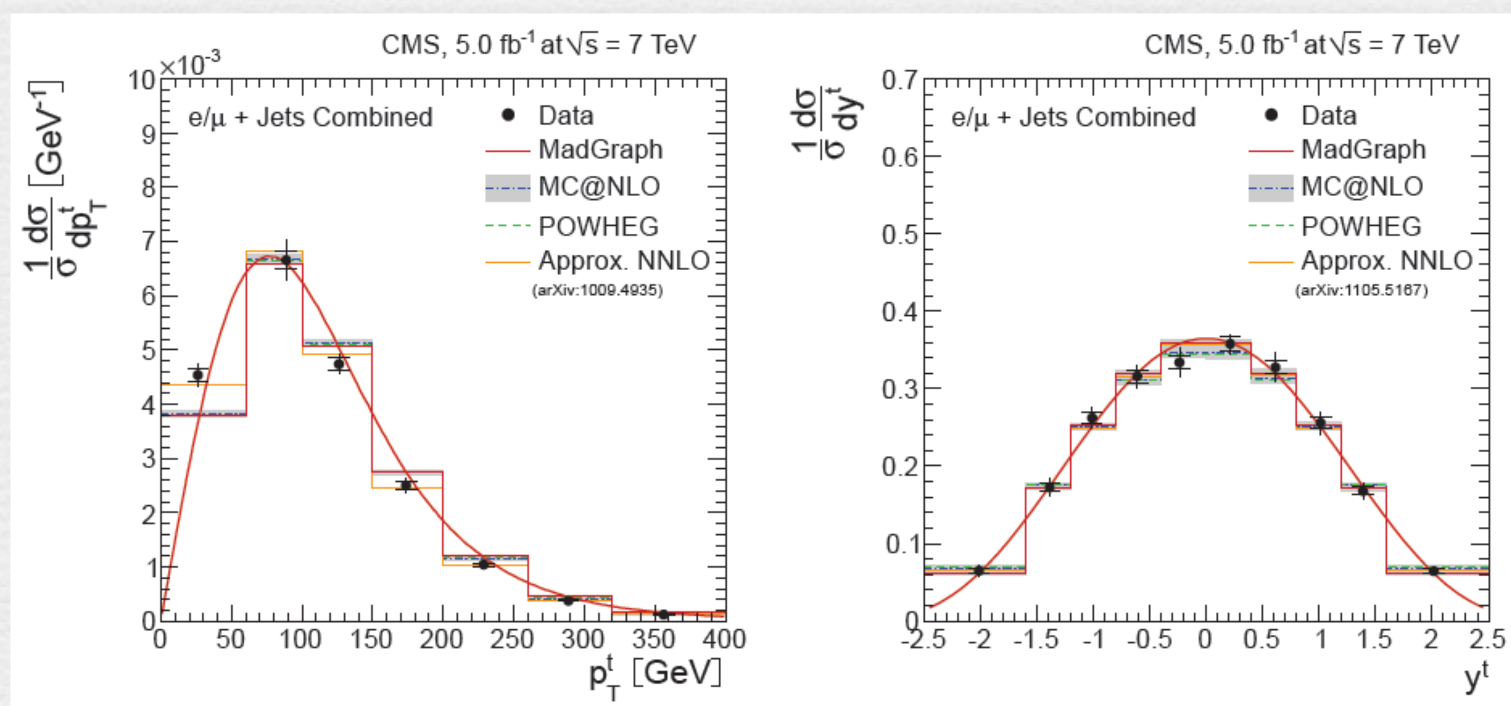
Doubles

Pair production cross section

- Measurements at 7, 8 TeV agree well with theory
  - ☺ New collider, much higher energy:
    - we really do understand how tops are produced
- Good confidence in Top QCD coupling
- Useable for PDF (gluon) determination



Differential distributions ok (ATLAS, CMS, CDF, D0)



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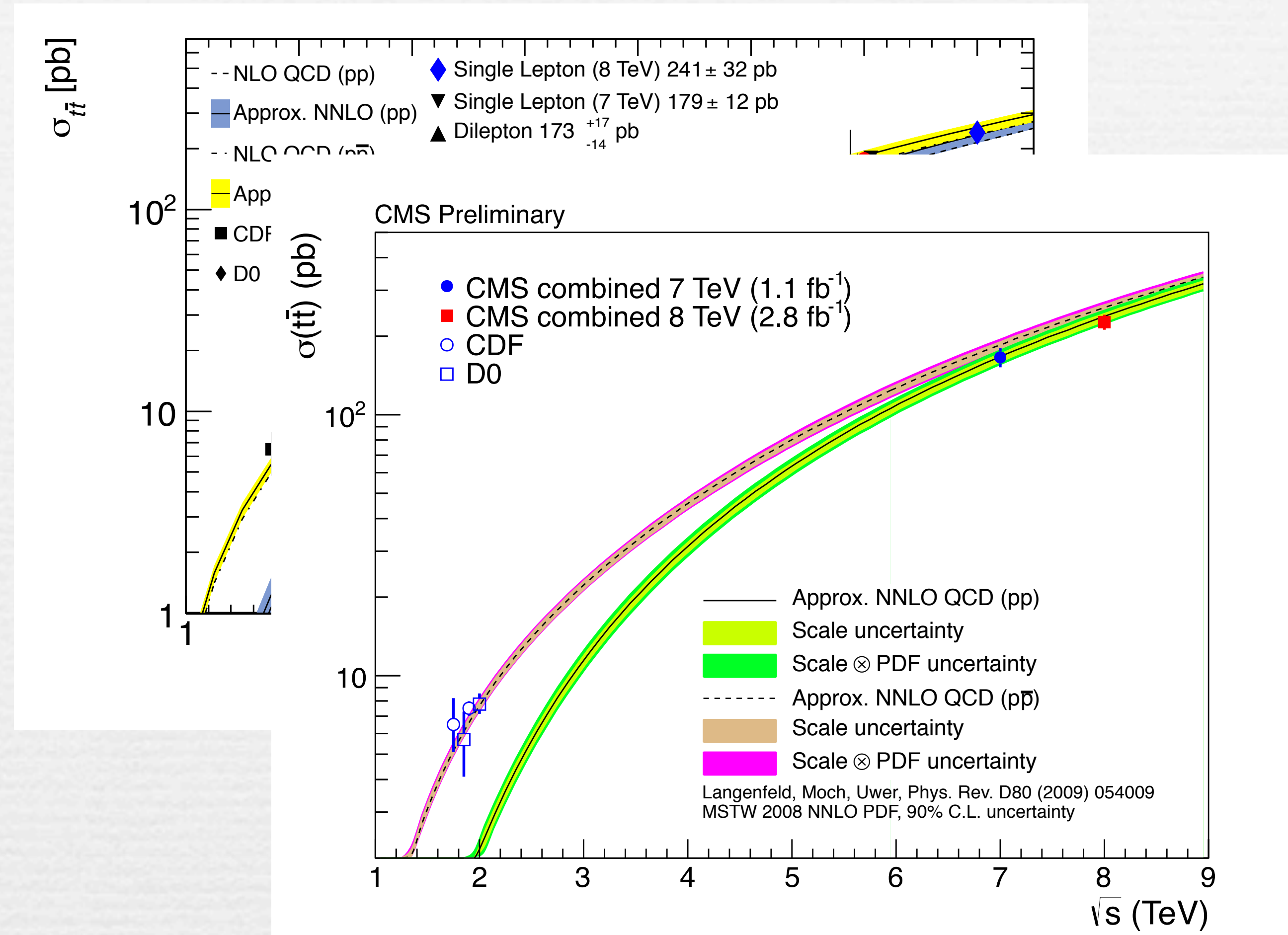

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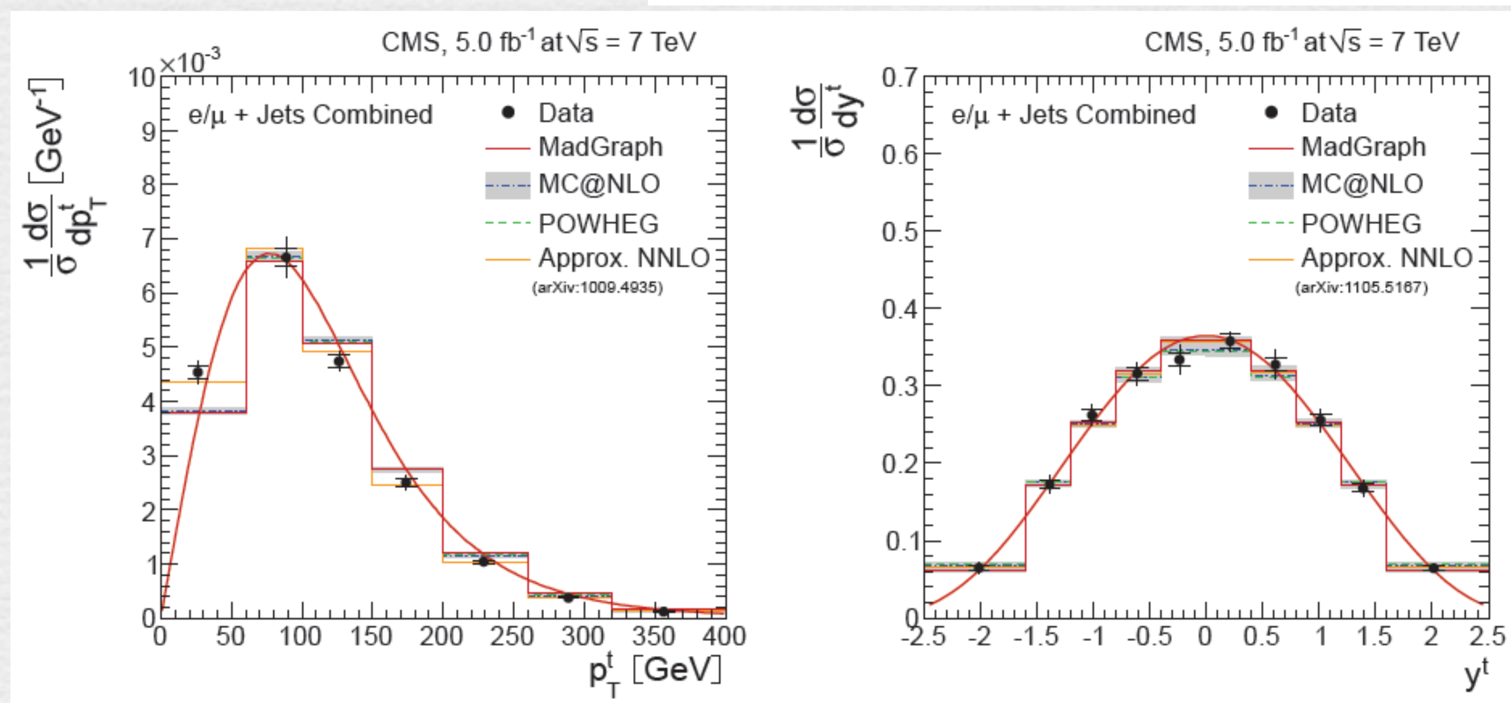

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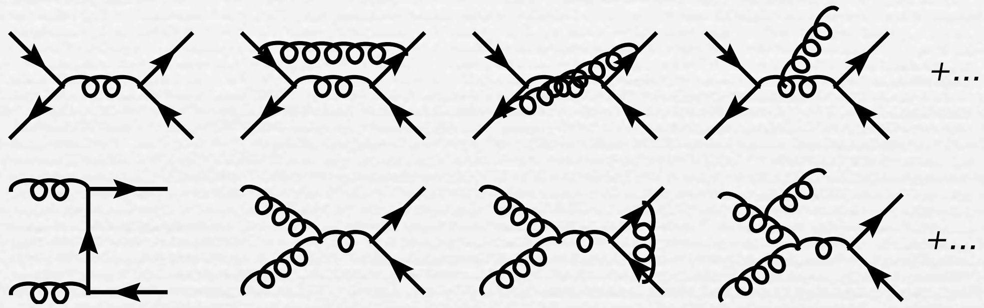
Pair production cross section: theory I



- NLO since late 80's
  - single particle inclusive and fully differential. Codes (MNR) still available

Beenakker, Kuijf, Smith, van Neerven, Meng, Schuler; Nason, Dawson, Ellis; Mangano, Nason, Ridolfi

- Currently, NLO plus PS: MC@NLO, POWHEG

Frixione, Webber; Nason, Oleari

- Resummation-based, two varieties
  - all order predictions, to various accuracies
    - Benefit: all-order, systematic, smaller scale uncertainty
    - (Top has propelled much resummation research over the years)
  - after expanding resummed to second order, get $\text{NNLO}_{\text{approx}}$
    - Instructive, already less scale uncertainty

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

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

Pair production cross section: theory II

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

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

- Until recently the status was NLL

  Kidonakis, Oderda, Sterman; Cacciari, Frixione, Bonciani, Mangano, Nason, Ridolfi

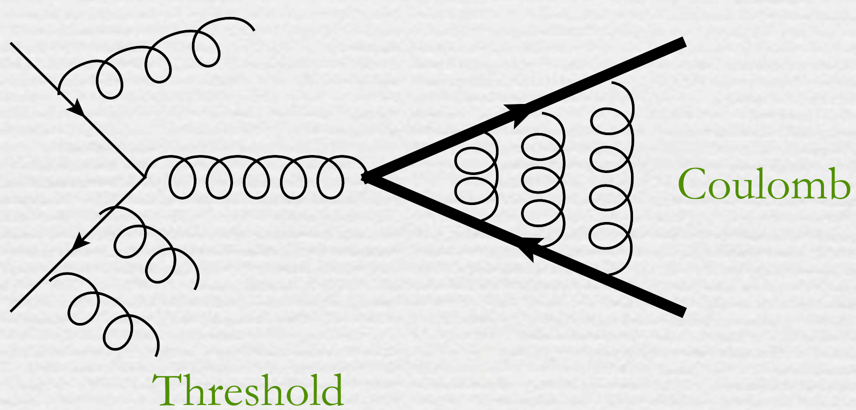
- All ingredients now upgraded
  - Jet function & soft function (g_3), hard part (C_1)

    Moch, Vermaseren, Vogt; Mitov, Sterman, Sung

    Ahrens Ferroglia, Neubert, Pecjak, Yang
  - Also available: Coulomb exchange

    Beneke, Falgari, Schwinn; +Czakon, Mitov
- Caveat: different thresholds are used
  - e.g.

    $$\sigma(s) = \int dp_T dy \frac{d^2\sigma}{dp_T dy}$$
  - Source of uncertainty, as long as NNLO not known exactly



1. $\sum_n \alpha_s^n \ln^{2n}(s - 4m^2)$ $[\sigma(s)]$
2. $\sum_n \alpha_s^n \ln^{2n}(s - 4(m^2 + p_T^2))$ $[d\sigma(s)/dp_T]$
3. $\sum_n \alpha_s^n \ln^{2n}(s - 4(m^2 + p_T^2)\cosh y)$ $[d^2\sigma(s)/dp_T dy]$

Kidonakis, EL, Moch, Vogt; Ahrens Ferroglia, Neubert, Pecjak, Yang

σ_{tt}(NNLO) : approximations

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- NNLO approximate
  - Kidonakis (2008): **3** (PIM, 1PI) 163 ± 11 pb
  - Hathor: **1** Aliev, Lacker, Langenfeld, Moch, Uwer, Wiedermann 164 ± 12 pb
  - Ahrens et al: **3** (PIM, 1PI). Have code. Ahrens Ferroglia, Neubert, Pecjak, Yang 155 ± 8 pb ± 14 pb
- Even though approximate, heavy theoretical machinery necessary. Errors now (at 7 TeV): 8 - 10%
- Calculations with threshold 3 useful for A_{FB}

- NNLO exact,very tough, but approaching:
- 2 real emission; done — Czakon; Abelof, Gehrmann-de-Ridder; Bernreuther, Bogner, Dekkers, Mitov, Fiedler
- 1-loop, 1 real emission; done — Dittmaier, Uwer, Weinzierl; Melnikov, Schulze
- 2 loop; analytical+numerical largely done — Moch, Mitov, Czakon; Bernreuther, Bonciani, Gehrmann, Mastrolia, Heinesch, Leineweber, Remiddi; Bonciani, Ferroglia, Gehrmann, Manteuffel, Studerus

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Here!

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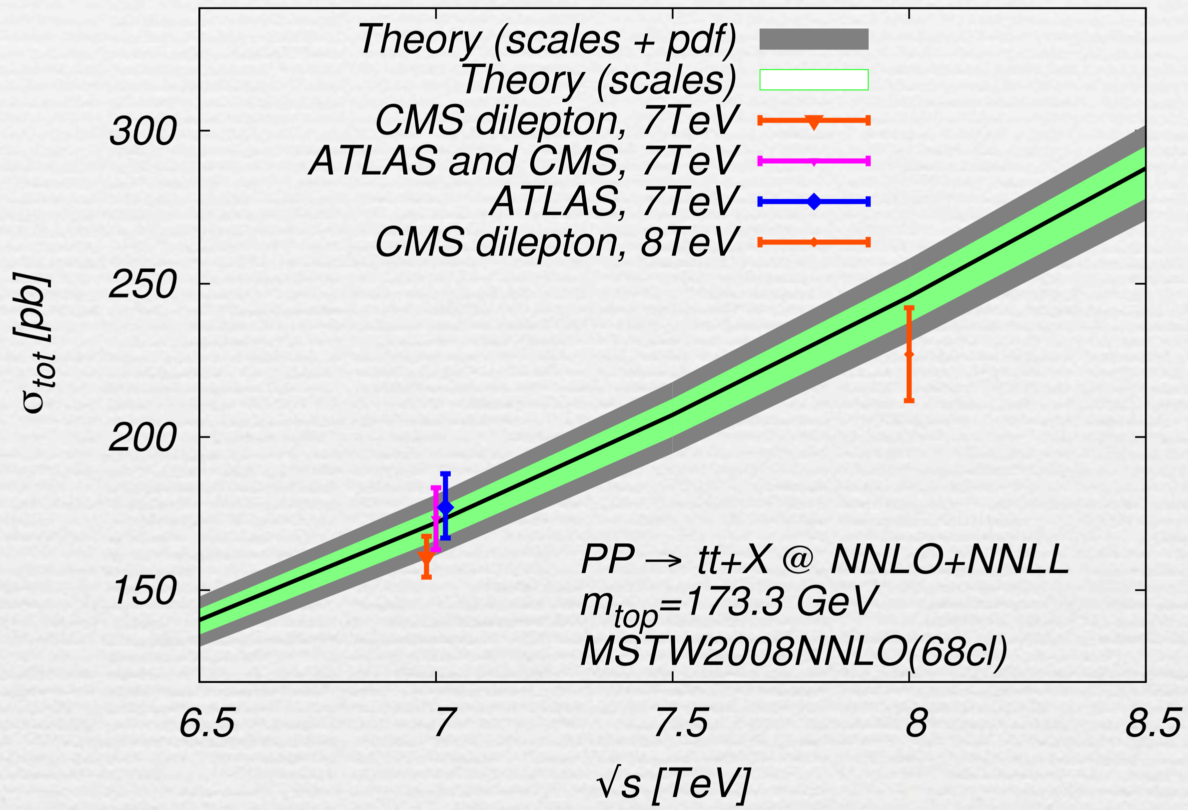
Excitement: NNLO top cross section finally here

LHC

Baernreuther, Fiedler, Mitov, Czakon, '12, '13

Collider	$\sigma_{\rm tot}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.009	$+0.259(3.7\%)$ $-0.374(5.3\%)$	$+0.169(2.4\%)$ $-0.121(1.7\%)$
LHC 7 TeV	167.0	$+6.7(4.0\%)$ $-10.7(6.4\%)$	$+4.6(2.8\%)$ $-4.7(2.8\%)$
LHC 8 TeV	239.1	$+9.2(3.9\%)$ $-14.8(6.2\%)$	$+6.1(2.5\%)$ $-6.2(2.6\%)$
LHC 14 TeV	933.0	$+31.8(3.4\%)$ $-51.0(5.5\%)$	$+16.1(1.7\%)$ $-17.6(1.9\%)$

Pure NNLO



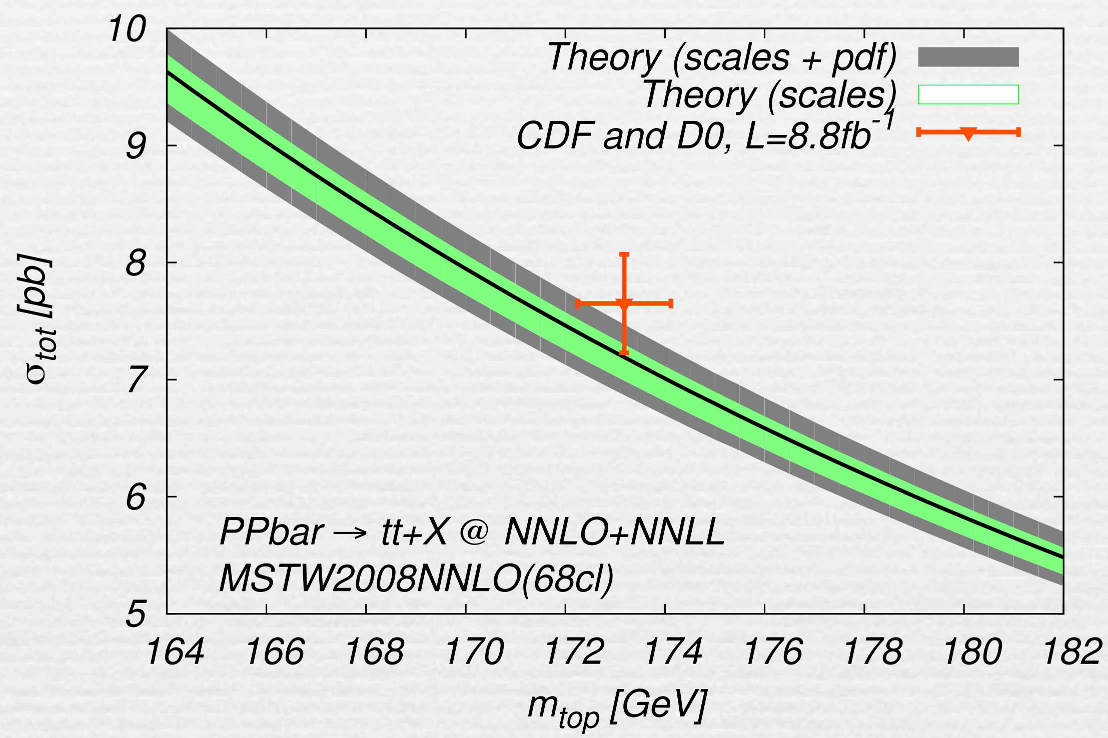
- First full NNLO calculation with initial hadrons and full color structure
- Heroic effort plus innovative subtraction methods
- Uncertainty now only a few % at NNLO + NNLL
  - reduction of factor 3 in scale wrt. NLO+NLL
- Approximations: quality not terrible, but notable differences

NNLO top cross section

Tevatron

Baernreuther, Fiedler, Mitov, Czakon, '12, '13

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$^{+0.110(1.5\%)}_{-0.200(2.8\%)}$	$^{+0.169(2.4\%)}_{-0.122(1.7\%)}$
LHC 7 TeV	172.0	$^{+4.4(2.6\%)}_{-5.8(3.4\%)}$	$^{+4.7(2.7\%)}_{-4.8(2.8\%)}$
LHC 8 TeV	245.8	$^{+6.2(2.5\%)}_{-8.4(3.4\%)}$	$^{+6.2(2.5\%)}_{-6.4(2.6\%)}$
LHC 14 TeV	953.6	$^{+22.7(2.4\%)}_{-33.9(3.6\%)}$	$^{+16.2(1.7\%)}_{-17.8(1.9\%)}$

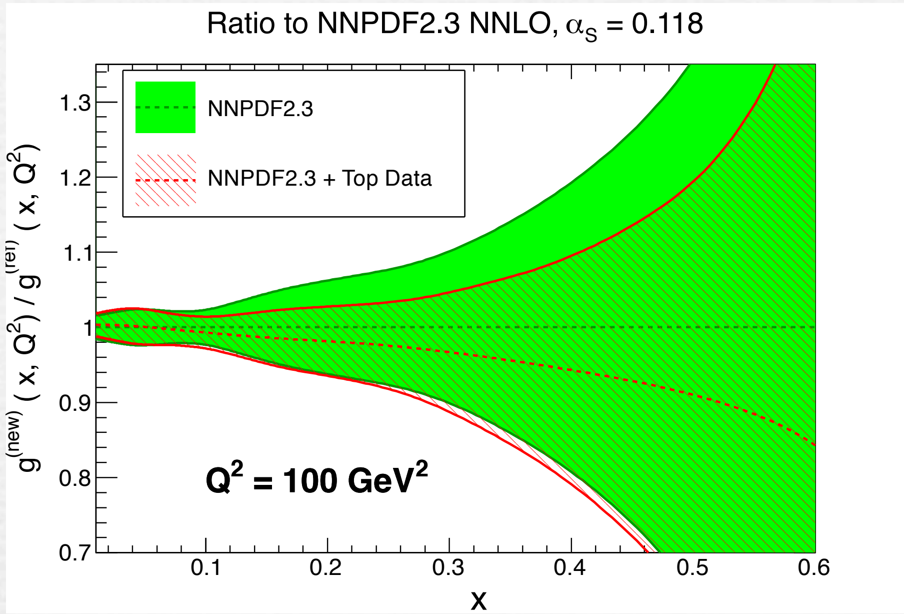


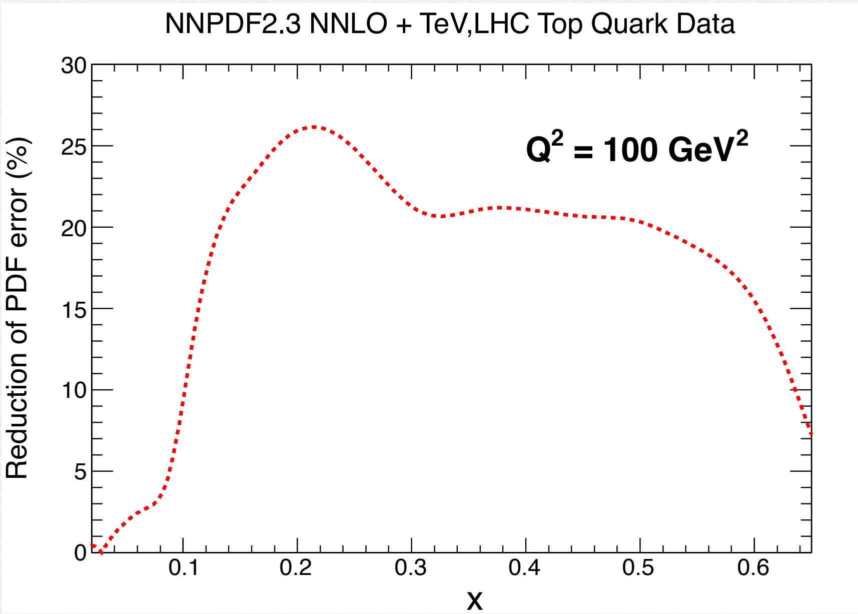
NNLO+NNLL

- Excellent agreement between experiment and NNLO theory
    - Update weakest link: PDF's, especially large-x gluon density

Mangano, Czakon, Mitov, Rojo, '13

Impact on PDF's (esp. large-x gluon)





Mangano, Czakon, Mitov, Rojo, '13

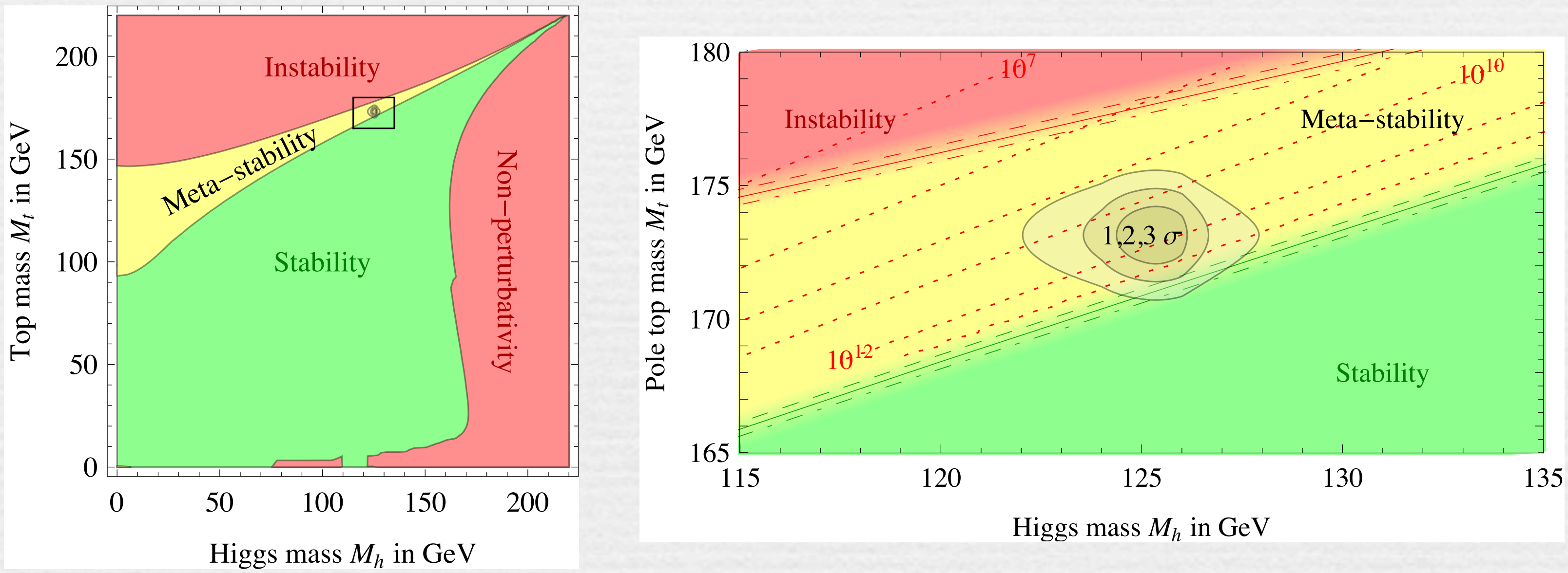
- Excellent probe, no NP contamination
- Less uncertainty in various BSM predictions that rely on large-x gluons

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? Fate of universe depends on it!

Degrassi, di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia

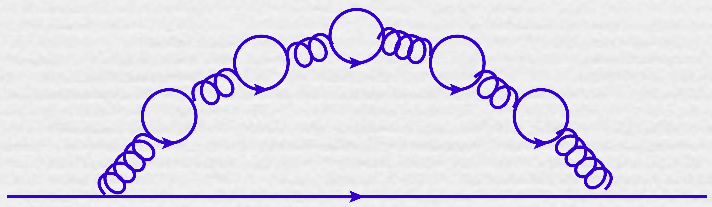


- Remember we are talking about a bare quark, so we must think about what a mass really means
  - we cannot use a quick rule like the following for c and b

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

Top mass

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

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

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

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

Measuring the MSbar mass

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

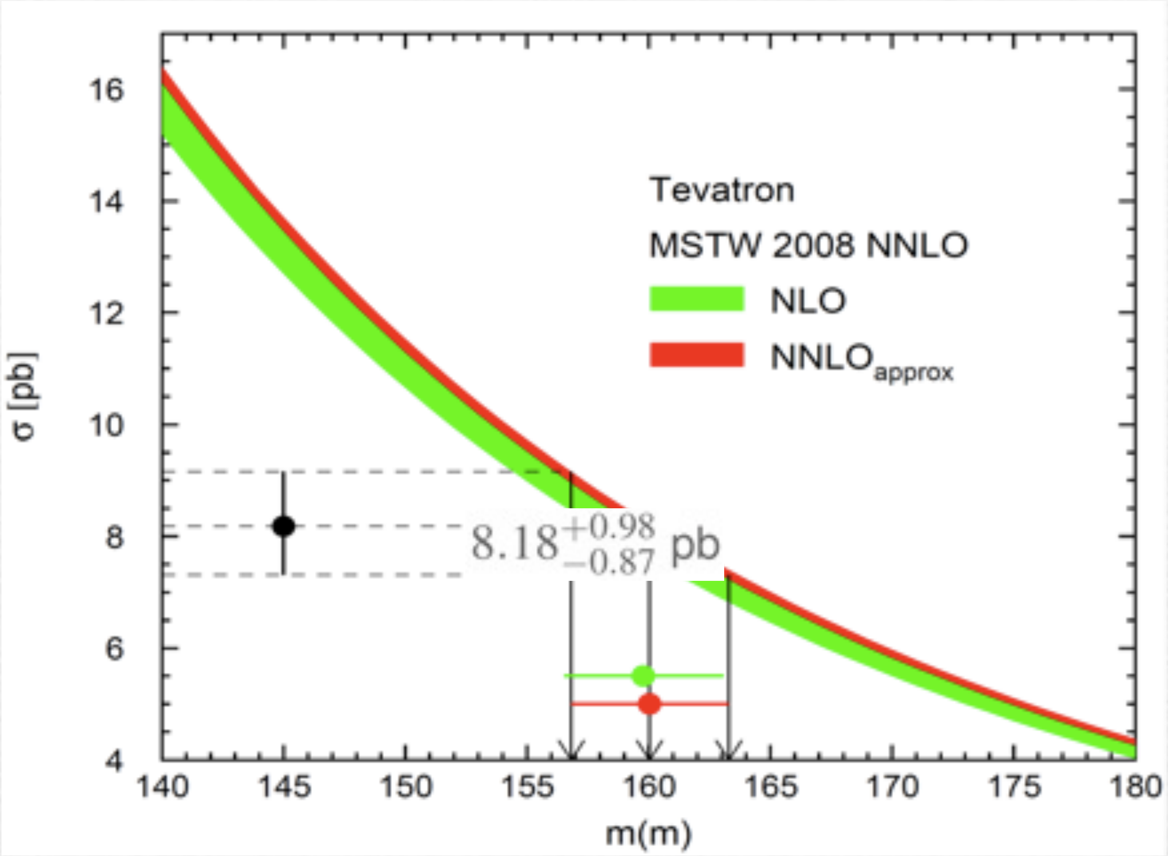
$$\mathrm{Im}\left[\frac{1}{p^2 - m^2 + i\varepsilon}\right] = \delta(p^2 - m^2)$$

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

Langenfeld, Moch, Uwer

MSbar mass extraction

Langenfeld, Moch, Uwer



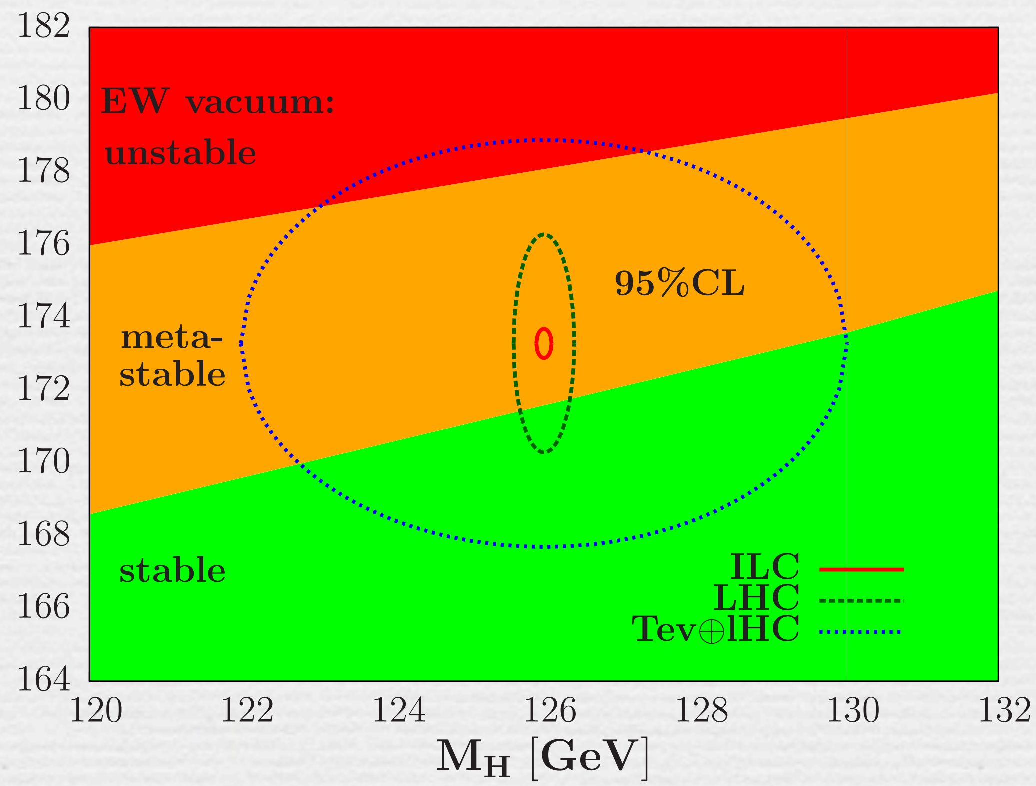
	$\overline{m}$ [GeV]	m_t [GeV]
LO	$159.2^{+3.5}_{-3.4}$	$159.2^{+3.5}_{-3.4}$
NLO	$159.8^{+3.3}_{-3.3}$	$165.8^{+3.5}_{-3.5}$
NNLO	$160.0^{+3.3}_{-3.2}$	$168.2^{+3.6}_{-3.5}$

- Accuracy at this point limited by m_t sensitivity and PDF uncertainties
- Other proposals:
  - (moments of) the invariant mass distribution
  - tt+1 jet, more sensitive than tt cross section — Alioli, Fernandez, Fuster, Irles, Moch, Uwer, Vos
  - other short-distance mass definitions

Frederix, Maltoni

Top mass

- Pole mass from MSbar mass: 173.3 +- 2.8 GeV
  - m_H > 129.4 +- 5.6 GeV
  - Universe's fate still uncertain

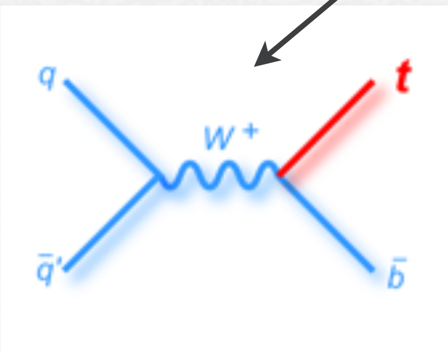


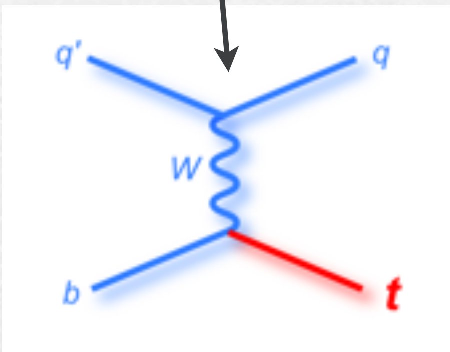
Alekhin, Djouadi, Moch

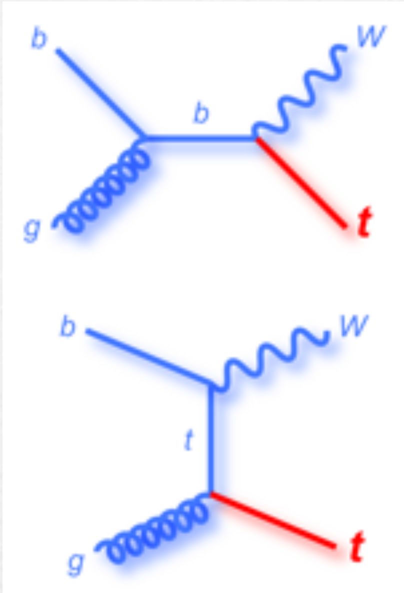
Singles

Basic facts about single top production

LO at α_w^2 for s and t channel, $\alpha_w \alpha_s$ for Wt channel
Cross section:
3 pb at Tevatron
300 pb at LHC14 (60 pb) at LHC7



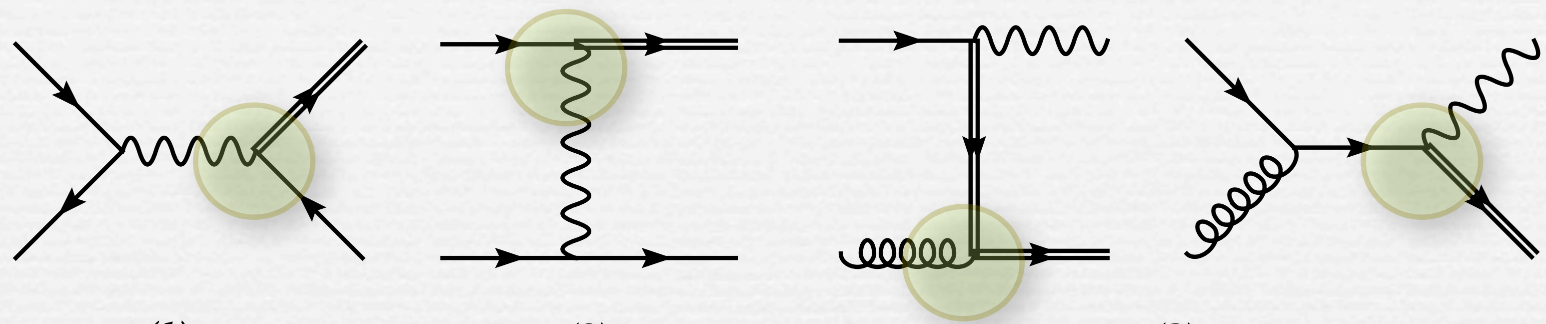




- s channel 1 pb at Tevatron, Wt negligible there
- s-channel like Drell-Yan, t-channel like Deep-Inelastic Scattering
- QCD corrections moderate
- Test different kinds of new physics

- 60pb at LHC14, s-channel negligible there
- NLO QCD corrections about 40%
- Tricky at LHC, hard to distinguish from top pair production. More on this later.

Single top production



(1) (2) (3)

s-channel:
timelike W

4 pb @ LHC7

t-channel:
spacelike W

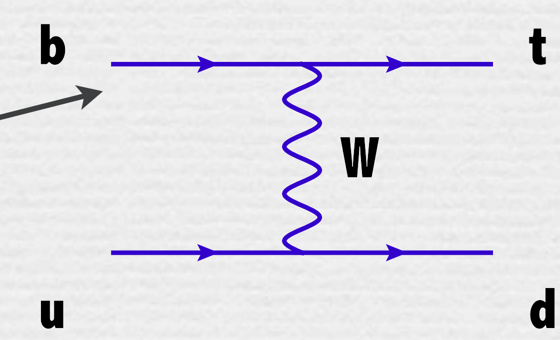
62 pb @ LHC7

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.



s & t fallacy

- One might think: since these cross sections are proportional to $|V_{tb}|^2$, we can just extract this value easily.
  - But since

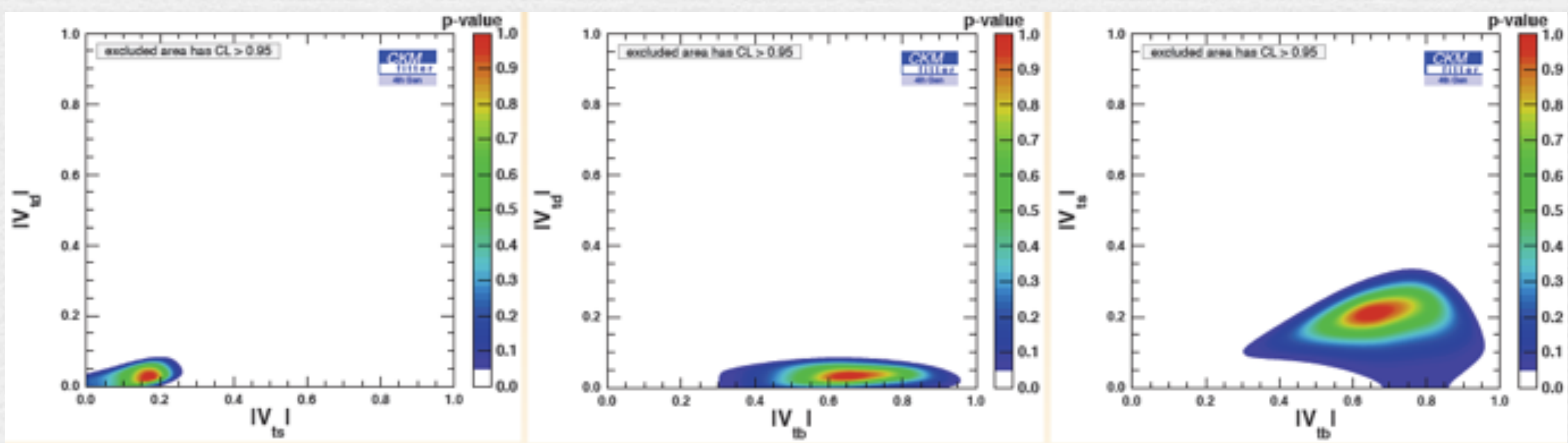
Alwall et al; Lacker et al

$$R = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

  - has recently been measured by D0 to be about 0.9, we cannot use

$$|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$$

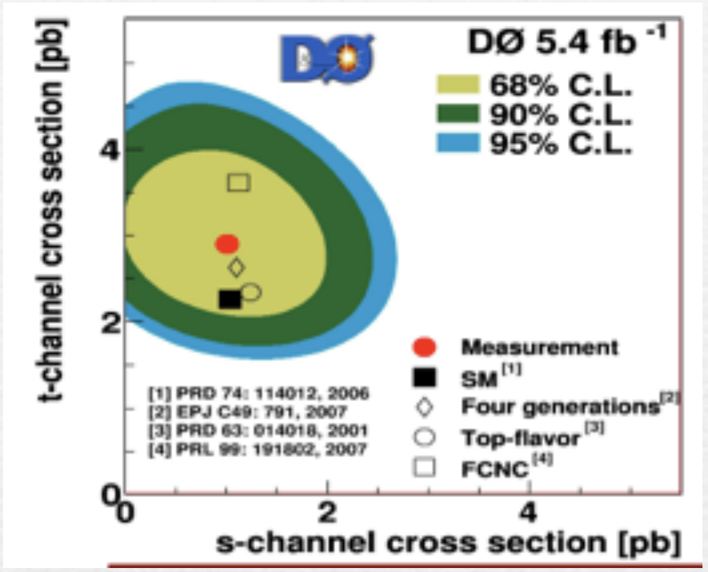
  - so easily. A first attempt at doing it properly:

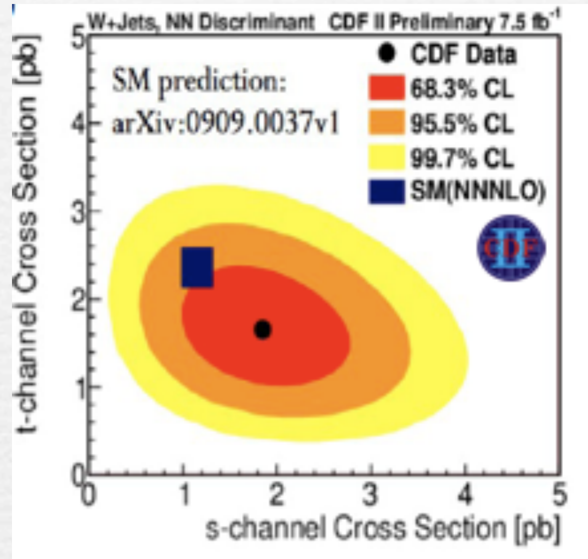


  - Vtb = 1 not quite favored...

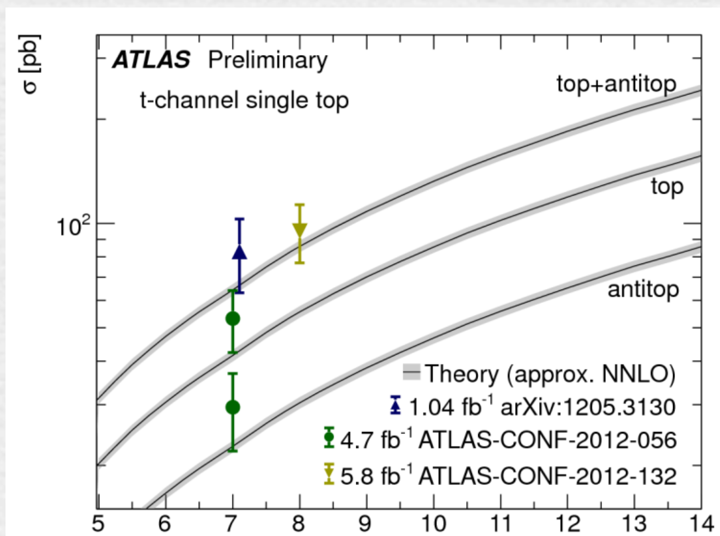
Recent results for s & t channel

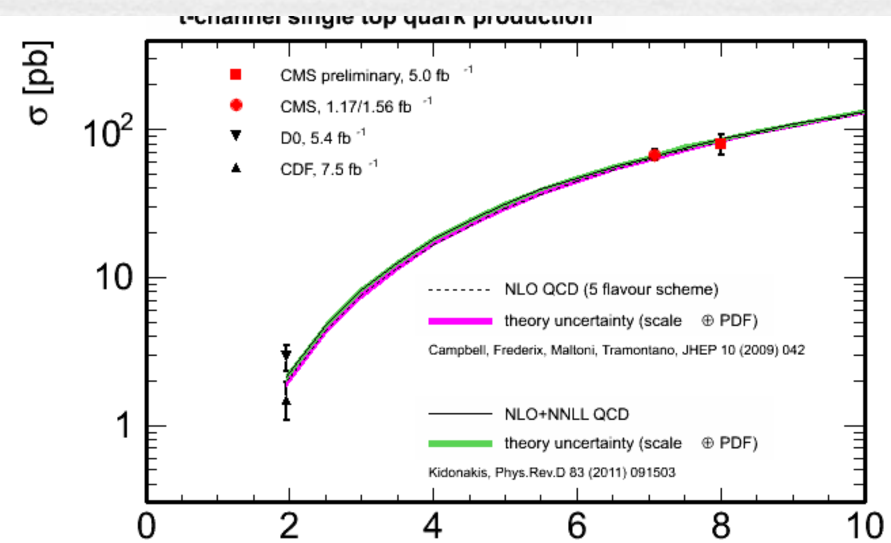
- Clever: measure both channels at the same time, and confront with some NP models





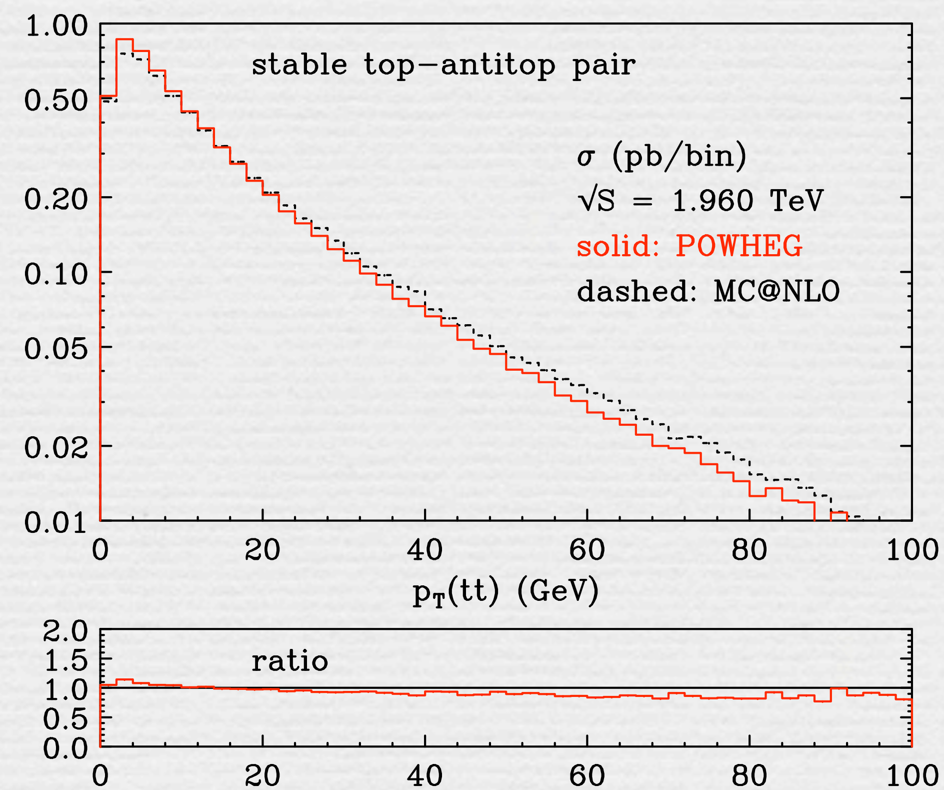
- Also ATLAS and CMS have nice measurements, in general agreement with Standard Model (s-channel hard at LHC). T-channel:





Theory status: NLO to parton showers

- Issue: double counting
  - emission from NLO and PS, should be counted once
  - virtual part of NLO and Sudakov form factor should not overlap
  - some freedom in this:
    - MC@NLO matches to HERWIG(++) angular ordered showers (PYTHIA initial state). — Frixione, Webber; Nason
    - POWHEG insists on having positive weights, exponentiates complete real matrix element (PYTHIA or HERWIG) — Nason; Frixione, Oleari
    - Automatization: POWHEG Box, aMC@NLO

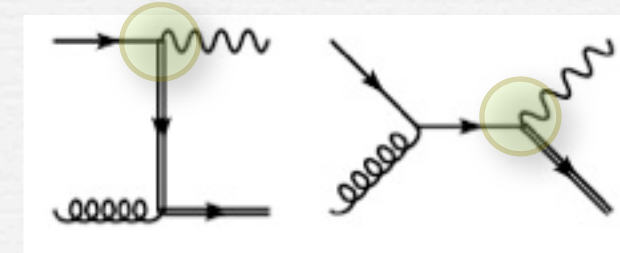


For most observables, good agreement

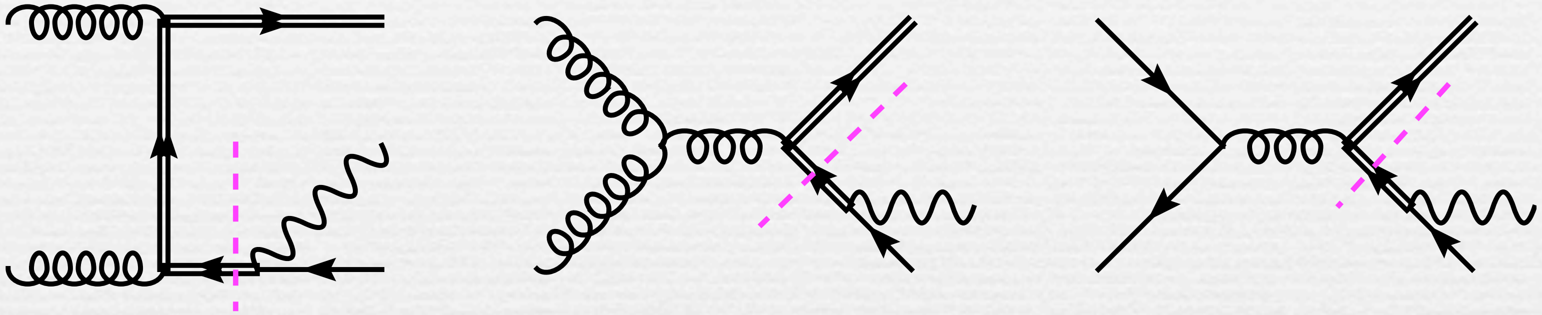
Increasingly important tools for experiment

Frixione, EL, Motylinski, Webber, White

Single top in Wt mode meets tt..



Frixione, EL, Motylinski, Webber, White



+ 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
- What can one do in event generation? Prototypical for future cases.
- Can one actually define this process?
    - Important cut: veto hard second b-jet suppress tt

Campbell, Ellis, Tramontano

Can we define Wt as a process?

Frixione, EL, Motylinski, Webber, White

Two approaches in MC@NLO (now also in POWHEG (Re))

- I. Remove resonant diagrams (DR)
- II. Construct a gauge invariant, local counterterm: diagram subtraction (DS)
- DS - DR is measure of interference

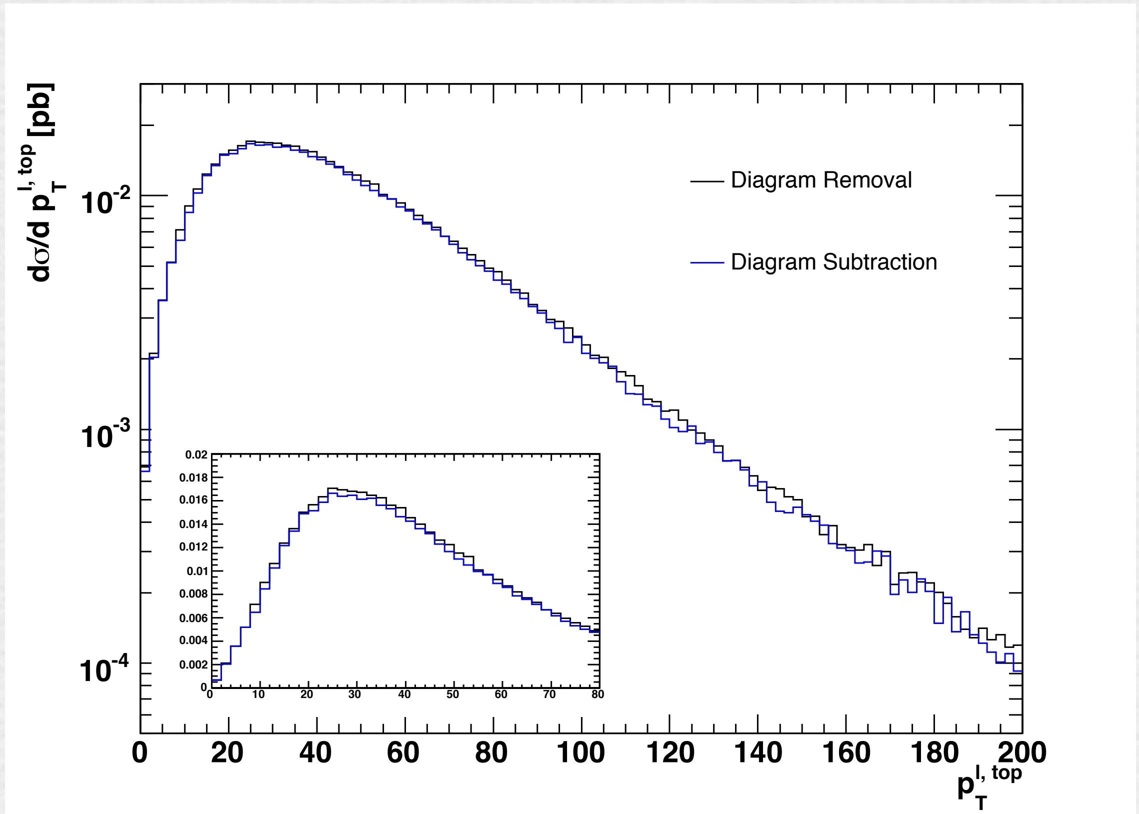
Momentum reshufling

$$\tilde{\mathcal{D}}_{gg} = \frac{BW(M_{\bar{b}W})}{BW(M_t)} |A_{gg}^{t\bar{t}}|^2_{\text{reshuffled}}$$

$$d\sigma^{(2)} + \sum_{\alpha\beta} \int \frac{dx_1 dx_2}{2x_1 x_2 S} \mathcal{L}_{\alpha\beta} \left(\hat{\mathcal{S}}_{\alpha\beta} + \mathcal{I}_{\alpha\beta} + \mathcal{D}_{\alpha\beta} - \widetilde{\mathcal{D}}_{\alpha\beta} \right) d\phi_3$$

Compare

- Interference effects quite small, in general
- Next question: can one isolate Wt?



Isolating Wt

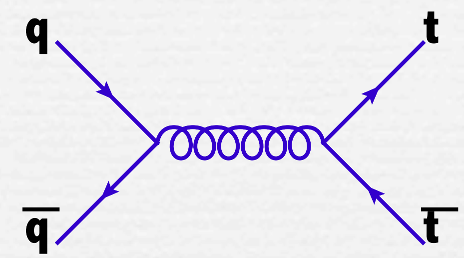
White, Frixione, EL, Maltoni

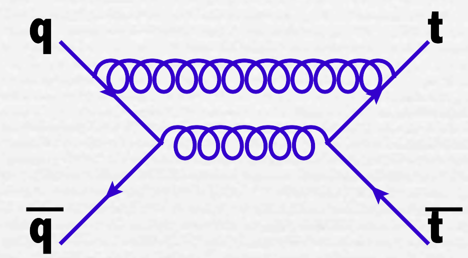
- Can we isolate Wt then? Answer subject to cuts. Some choices:
    - Cuts to isolate Wt
    - Cuts to suppress Wt and tt as background to H->WW
- Find:
    - Yes, can consider separate NLO corrections for tt (70%) and for Wt (40%)
- LHC experiments use boosted decision trees and neural nets, so far only evidence (in rough agreement with SM)

Forward-backward

Charge/forward-backward asymmetry

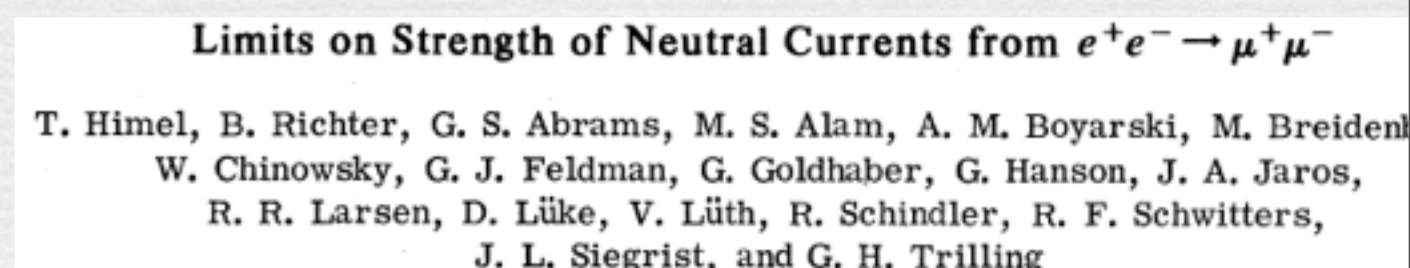
$$A_t(y) = \frac{N_t(y) - N_{\bar{t}}(y)}{N_t(y) + N_{\bar{t}}(y)}$$





- Why not present at LO, like W-charge asymmetry?
  - Incoming quark/antiquarks are already forward-backward asymmetric
    - But the produced gluon has no memory of that ⇒ charge symmetric
- At NLO, interference of tree and box produces a (small) asymmetry.
  - Already present in QED
  - "Measured" (1978)
  - in QCD, proportional to SU(3) d_{abc} symbol
- Charge asymmetry is equivalent to FB asymmetry, since CP is conserved in QCD.
- Other test of tt production mechanism besides σ

SLAC-LBL@SPEAR

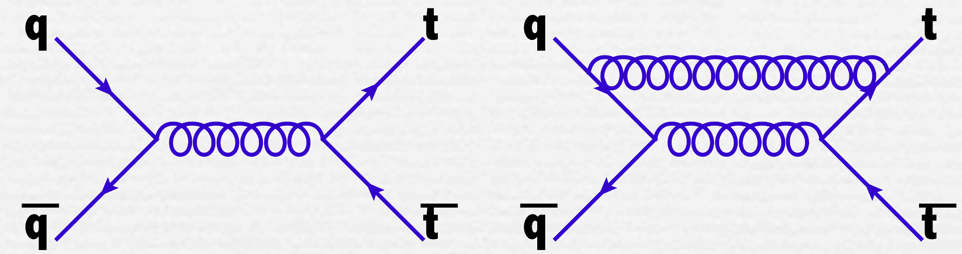


Limits on Strength of Neutral Currents from $e^+e^- \to \mu^+\mu^-$

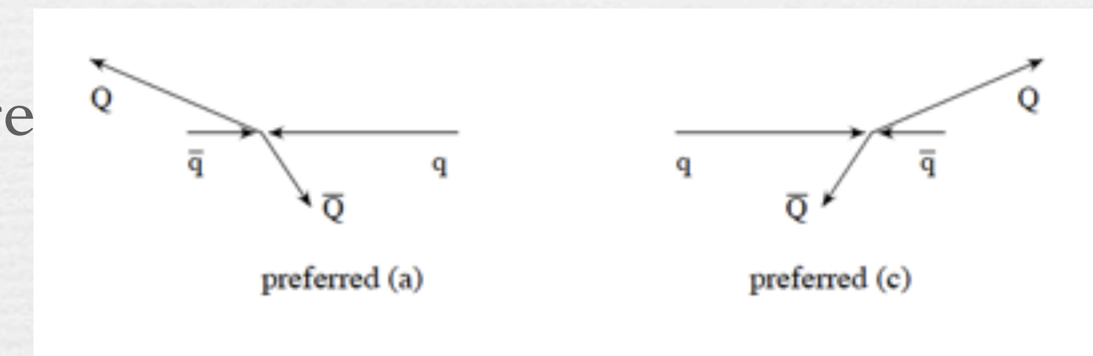
T. Himel, B. Richter, G. S. Abrams, M. S. Alam, A. M. Boyarski, M. Breidenb
W. Chinowsky, G. J. Feldman, G. Goldhaber, G. Hanson, J. A. Jaros,
R. R. Larsen, D. Lüke, V. Lüth, R. Schindler, R. F. Schwitters,
J. L. Siegrist, and G. H. Trilling

$A_{FB} = 0.013 \pm 0.010$

Some intuition about A_{FB}



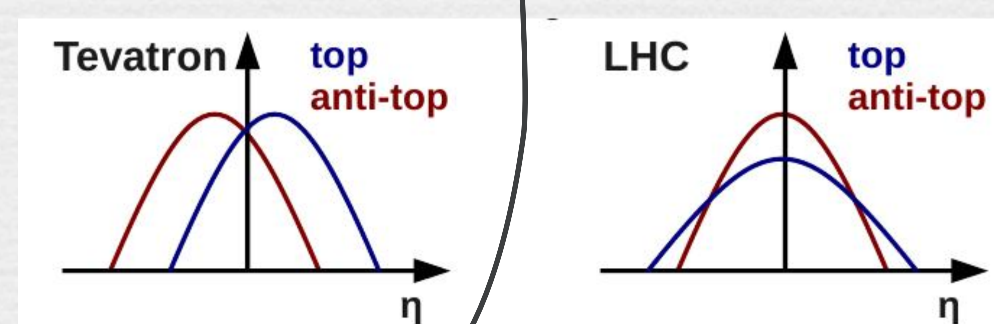
- Compute matrix element as function of t, u
- Charge conjugation equivalent to t, u interchange



$$\propto \frac{t^2+u^2}{s^2} + \frac{2m^2}{s} \quad = A + B\cos^2\theta$$

- In box contribution, find terms that are proportional to t^2-u^2 ⇒ linear in cosθ
- Quark "repels" top via second gluon, leading to "preferred" situations, or plots below Sterman

Chierici

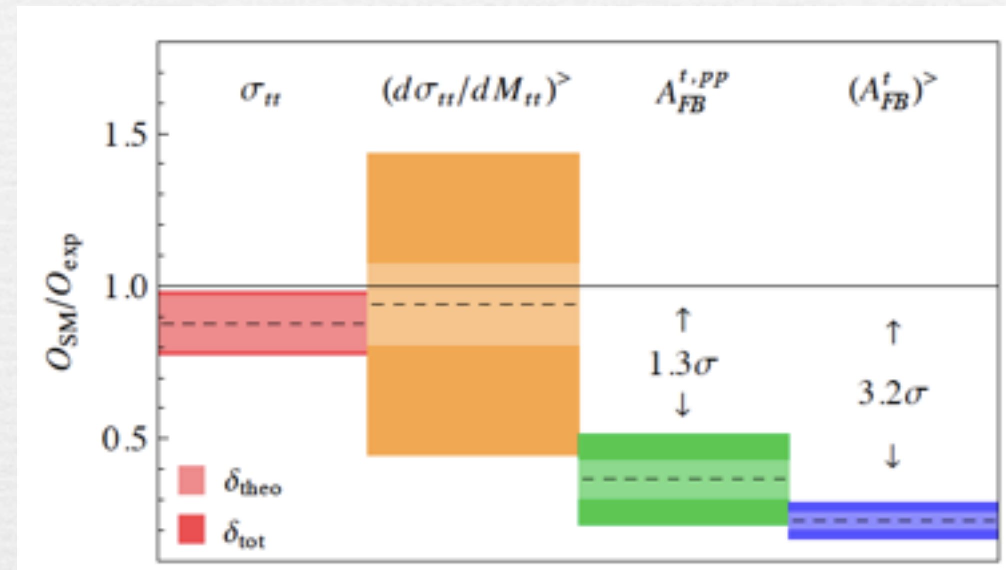


From resummation formulae:
$$\frac{\Delta\sigma}{\sigma} \simeq \exp\left\{\alpha_s L\left[\frac{32}{6}-\frac{27}{6}\right]\ln\frac{u}{t}\right\}$$

A_{FB} in experiment

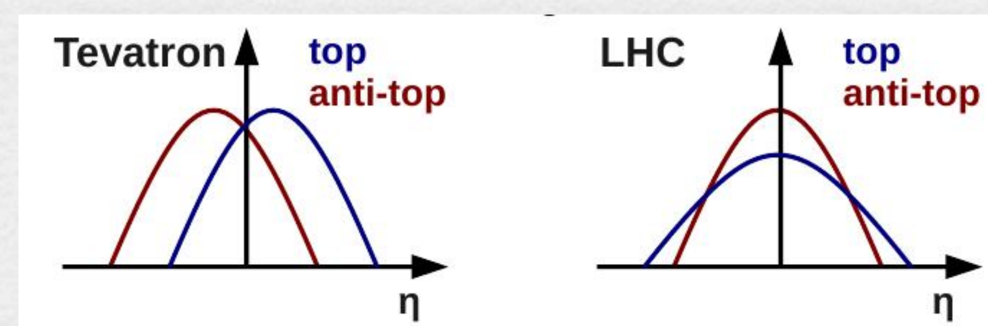
A plethora of asymmetries....

Westhoff



- Tevatron
  - CDF (2010/11): defines 4: 2 in lab frame, 2 in tt frame
    - using (or not) rapidity of leptonic/hadronic top
    - differential (in M_{tt}, and/or rapidity)
    - now also in di-lepton channel
  - CDF (2010, l+jets, 5.3/fb):
  - DO (2011, l+jets, 5.4/fb): 19.6±6.5% [2.4σ], larger for lepton-based asymmetry
    - some trouble with modelling SM pair p_T
- LHC
  - Suggested: asymmetry from events with (anti-)top above a minimum rapidity
- Not easy for NP models to change A_{FB} without changing σ

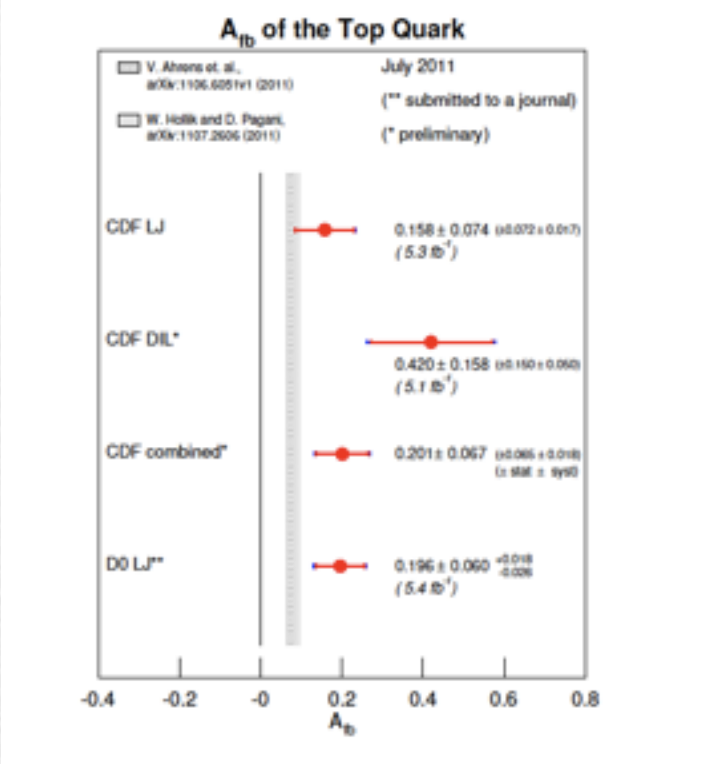
Chierici



Higher orders in A_{FB}

NLL: Kidonakis, EL, Moch, Vogt

$$\frac{d^2\sigma^2}{dM^2 d\cos\theta} = C_4(\theta)\left[\frac{\ln^3(1-M^2/s)}{1-M^2/s}\right]_+ + C_3(\theta)\left[\frac{\ln^2(1-M^2/s)}{1-M^2/s}\right]_+ + \ldots$$



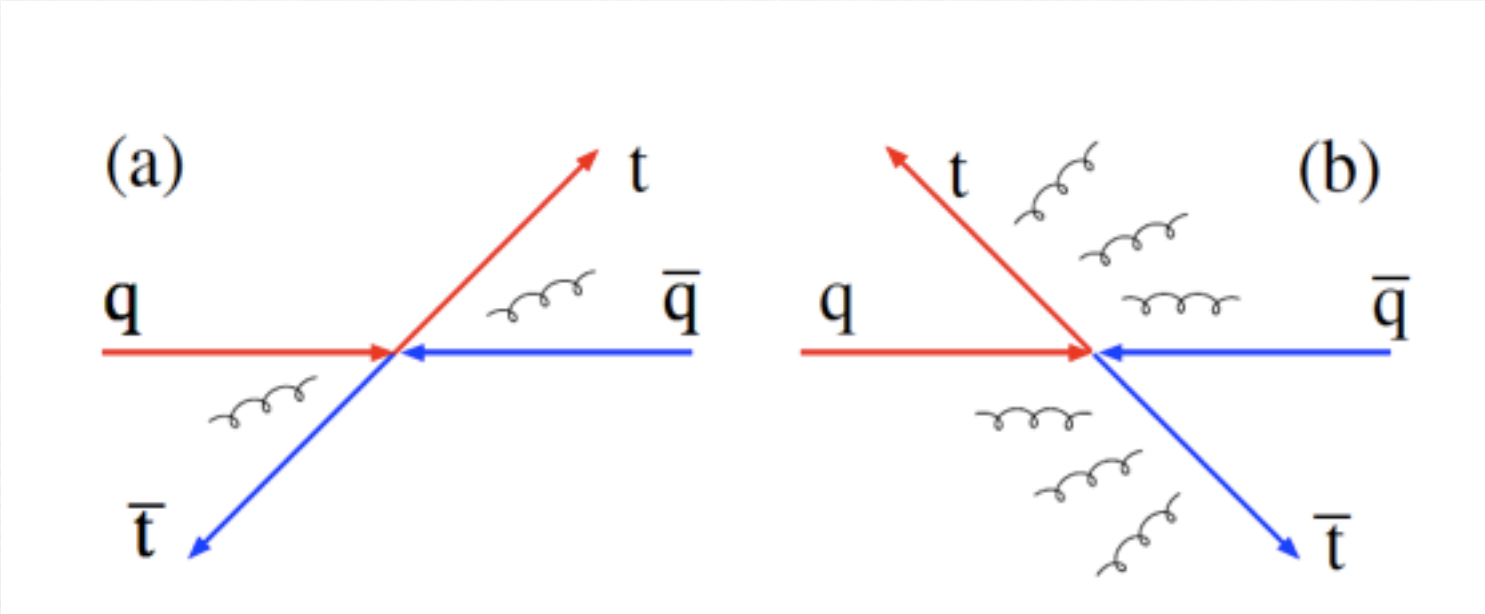
- A_{FB} is zero at LO, hence the NLO cross section contributes at LO to A_{FB}
- Higher order contributions to A_{FB} from threshold resummation
  - Leading logs charge symmetric, cancel in numerator, but subleading ones remain Almeida, Sterman
  - Find: A_{FB} stable under higher orders
  - Similar conclusion at NNLL Ahrens, Ferroglia, Neubert, Pecjak, Yang; Kidonakis
- A_{FB} already at LO in tt+jet, but NLO corrections reduce this significantly Dittmaier, Uwer, Weinzierl; Melnikov, Schulze
  - likely stable under yet higher orders

$$A_{FB}(ttj) = \alpha_s^3 \frac{C}{\ln(m/p_{T,j})} + \alpha_s^4 D_{hard}$$ Melnikov, Schulze

- Also for ttjj NLO term reduces LO A_{FB} Bevilacqua, Czakon, Papadopoulos, Worek
- Including EW effects reduce discrepancy Hollik, Pagani

Color coherence effects and A_{FB}

Skands, Webber, Winter



- Color coherence:
  - backward tops produce more QCD radiation
    → more central pair
  - forward tops “left behind”
- Full impact for prediction, and acceptance, to be studied

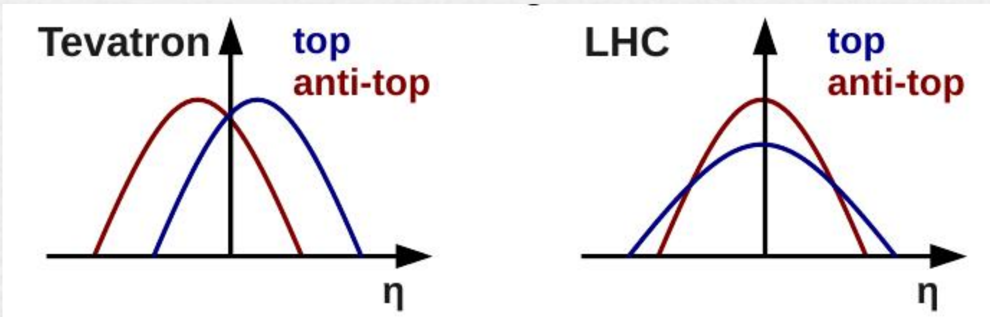
Asymmetry at LHC

- Can define forward charge asymmetry
  - Find: best for y_0 = 1.5
- Not easy for SM, but for new physics, doable:
  - If SM: 5σ after 60/fb
  - If CDF: 5σ after 2/fb (with Z' model, $m_{Z'}$ = 160 GeV)

Hewett, Shelton, Spannowsky, Tait, Takeuchi

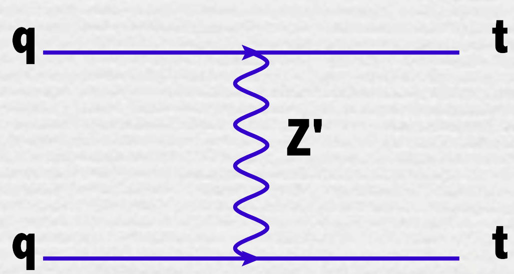
$$A_F(y_0) = \frac{N_t(y_0 < |y|) - N_{\bar{t}}(y_0 < |y|)}{N_t(y_0 < |y|) + N_{\bar{t}}(y_0 < |y|)}$$

Chierici



- Other (kinematic) possibility: same-sign tops
  - Cross section can be O(pb) if new physics at 2 TeV

Degrande, Gerard, Grojean, Maltoni, Servant

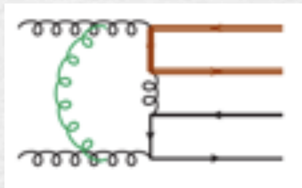


Mixed

(Associated) top production at higher order

Impressive recent progress

- Electroweak corrections — Bernreuther, Brandenburg, Si, Uwer; Kuhn, Scharf, Uwer; Maina, Moretti, Nolten, Ross
- Associated production at NLO (3+ particles in final state at LO)
  - tt + jet — Dittmaier, Uwer, Weinzierl; Melnikov, Schulze, Scharf
  - tt + Higgs — Beenakker, Dittmaier, Krämer, Plumper, Spira, Zerwas; Dawson, Jackson, Orr, Reina, Wackeroth; +PS: Frederix, Frixione, Hirshi, Maltoni, Pittau, Torrieli
  - tt + bb — Bredenstein, Denner, Dittmaier,Pozzorini; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek
  - tt + jj — Bevilacqua, Czakon, Papadopoulos, Worek

10K X 

- Calculations with off-shell top-decay (thus also with spin correlations)
  - single top: — Falgari, Giannuzzi, Mellor, Signer
  - tt (dileptons) — Bevilacqua, Czakon, Papadopoulos, Worek

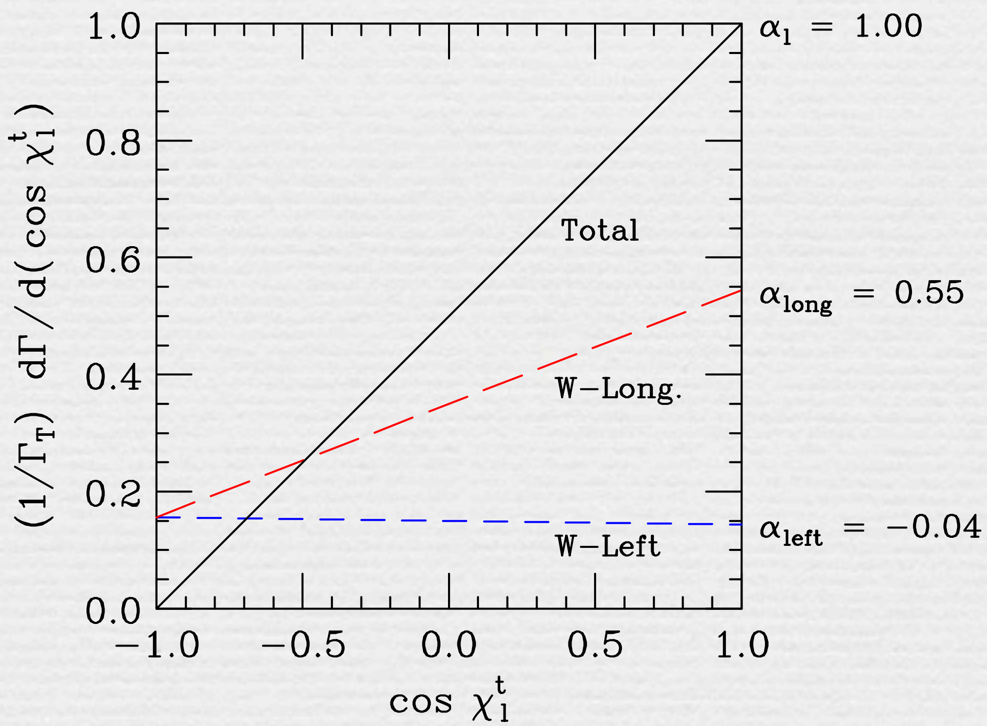
Top self-analyzes its spin

- 100% correlation of charged lepton with top spin
  - Top self-analyzes its spin
  - Charged leptons easy to measure
- For spin-up top the polar angle distribution is

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

- Interesting quantum interference..

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



$t\bar{t}$ spin correlations at NLO

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

Mahlon, Parke

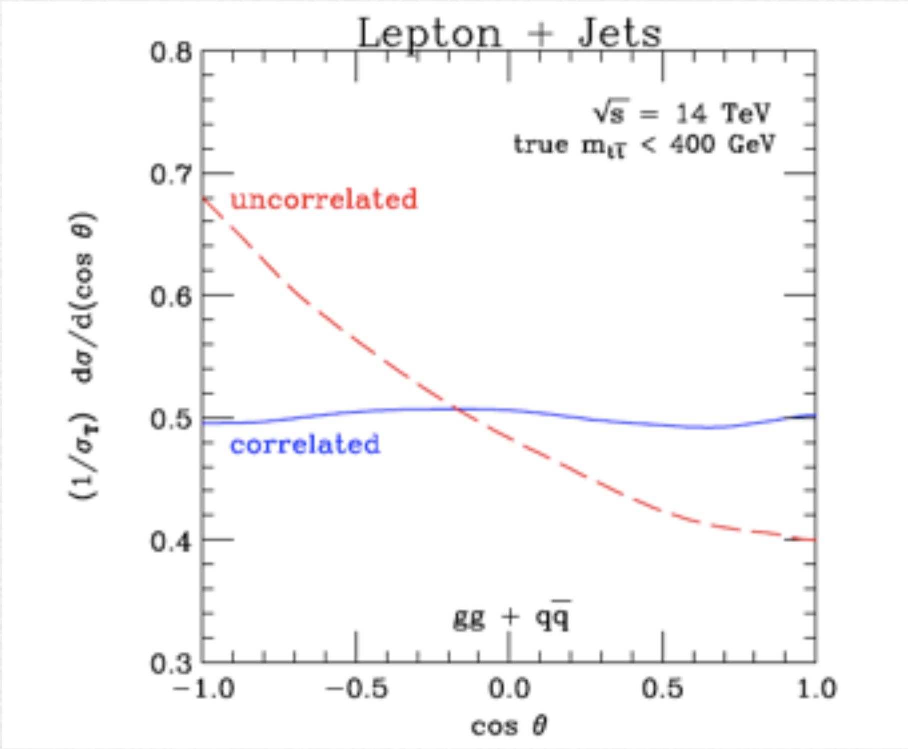
  - C_{hel} = 0.326 (C_{beam} = -0.07) for LHC(14)
  - NLO corrections small (EW corrections tiny)

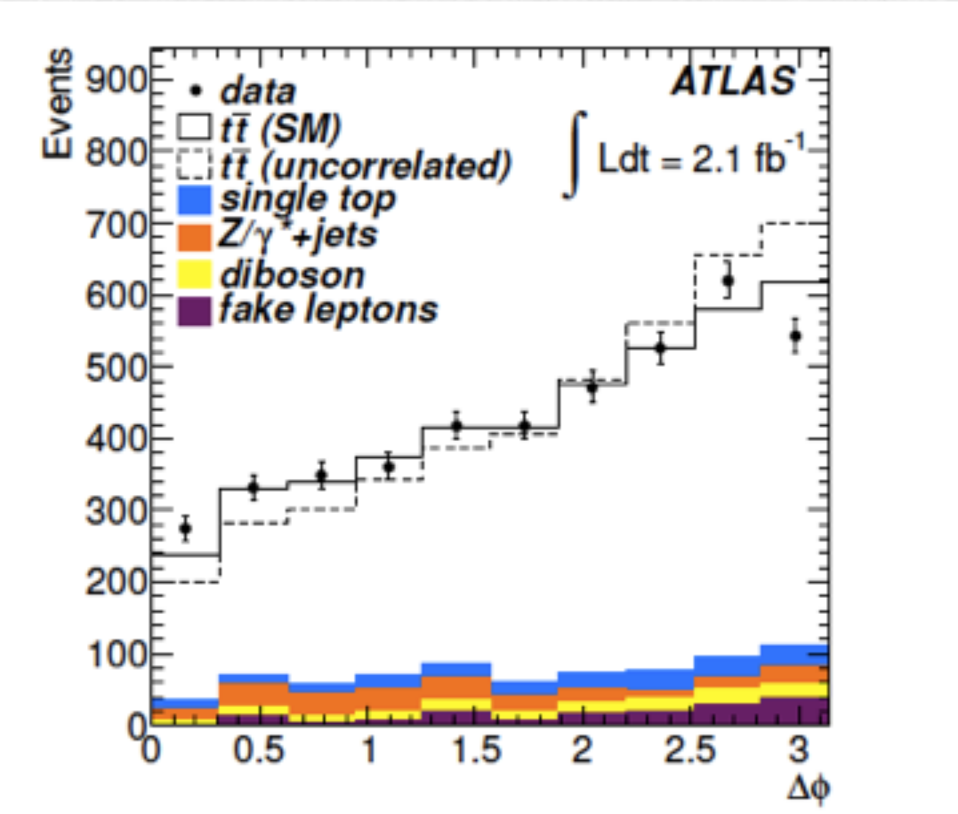
Azimuthal angular distributions

- Can test SM spin correlations in tt using invariant mass cut, and dilepton decay channel
  - Visible through Δφ of leptons in lab frame
    - Even after summing over spurious neutrino momentum solutions
    - Can be upgraded to NLO, and a likelihood-based analysis

Melnikov, Schulze

Mahlon Parke



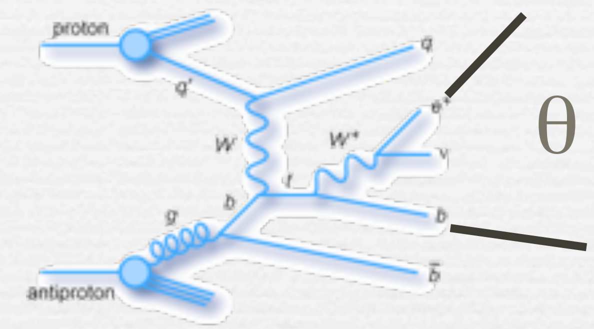


- ATLAS excludes zero correlation at 5.1 σ
- Agrees with SM

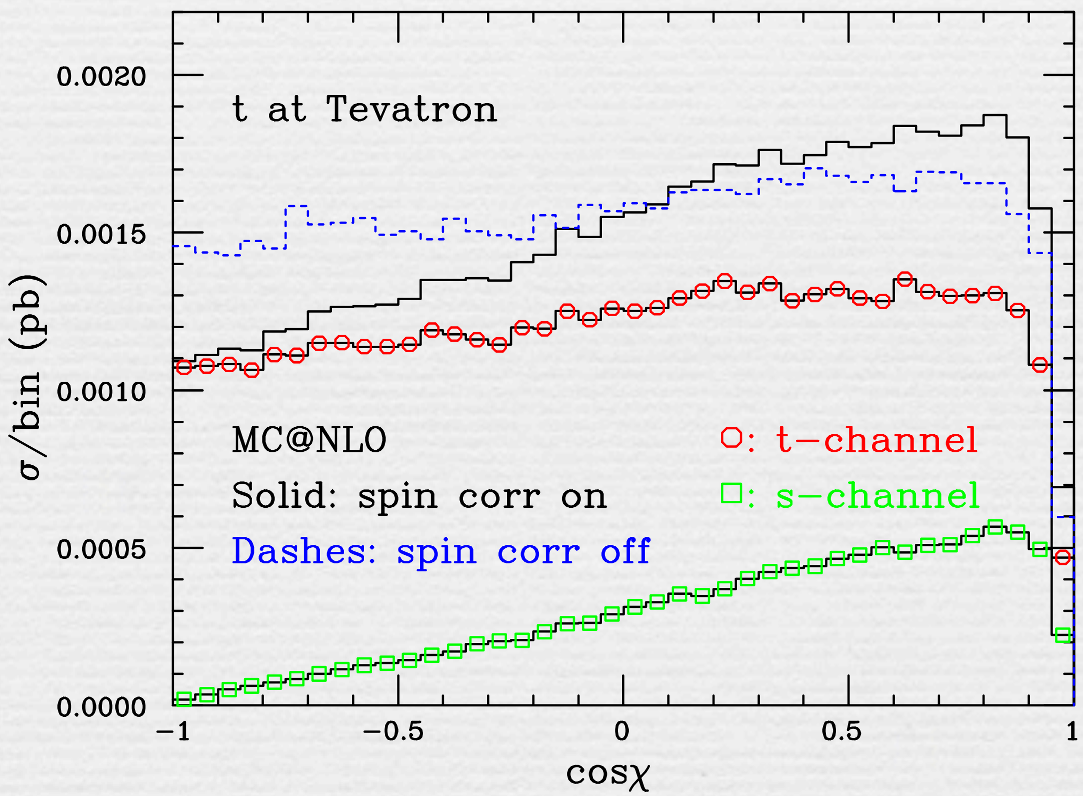
Spin correlations for single top in MC@NLO

Frixione, EL, Motylinski, Webber

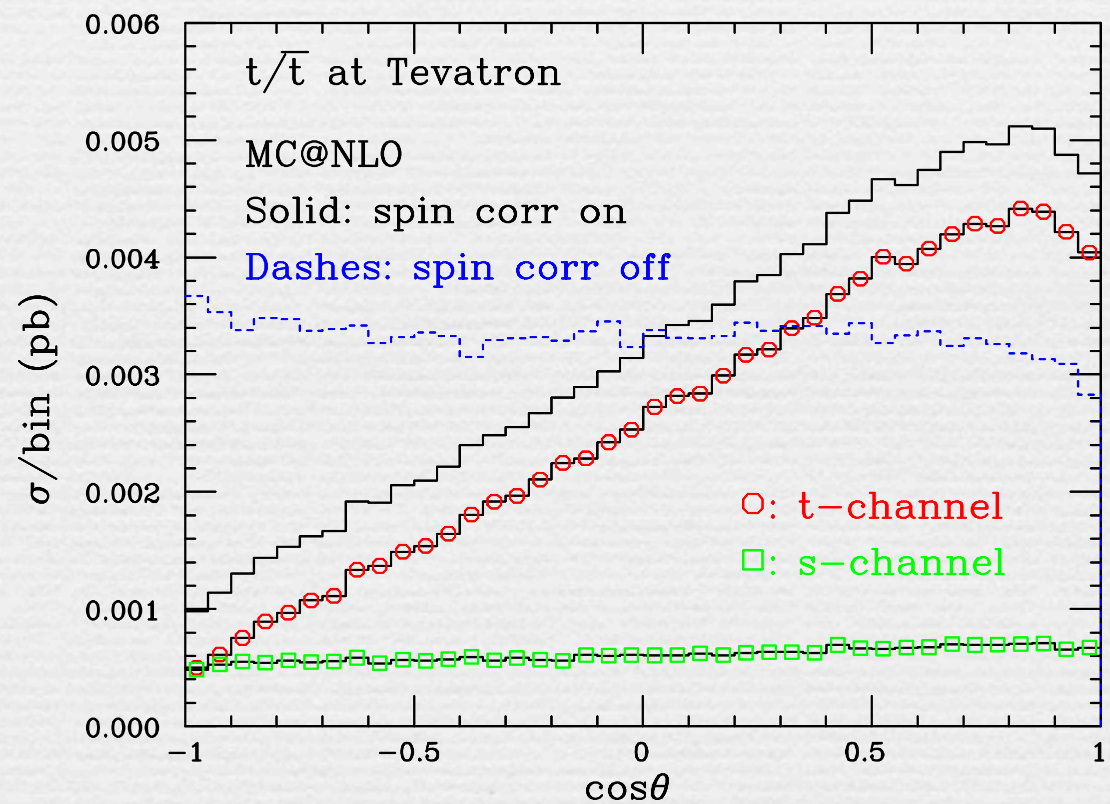
- Top is produced polarized by EW interaction
  - 100% correlation between top spin and charged lepton direction
- Angle of lepton with appropriate axis is different per channel
- Method included "a posteriori". Also used in POWHEG



Aioli, Nason, Oleari, Re



Beam direction

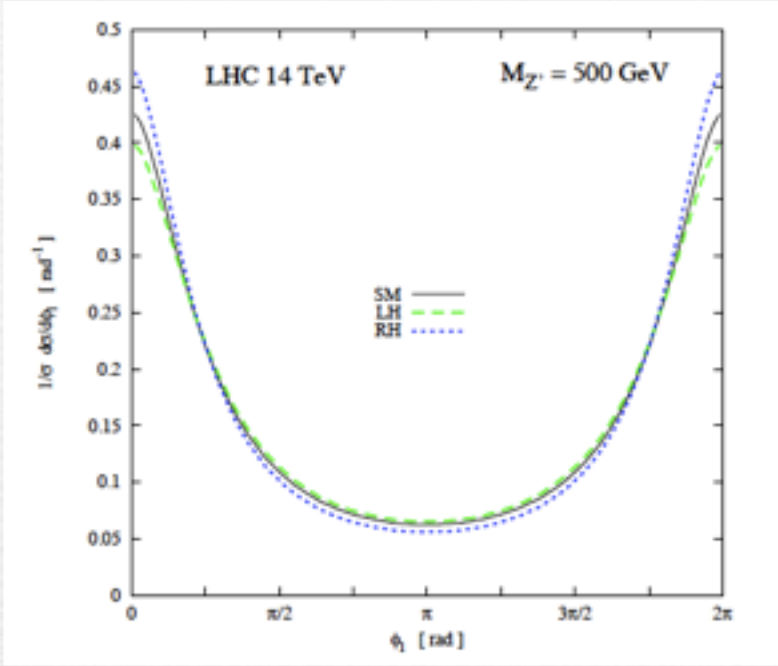


Hardest, non-b jet

Robust correlation in NLO event generation

Azimuthal distributions and BSM tests

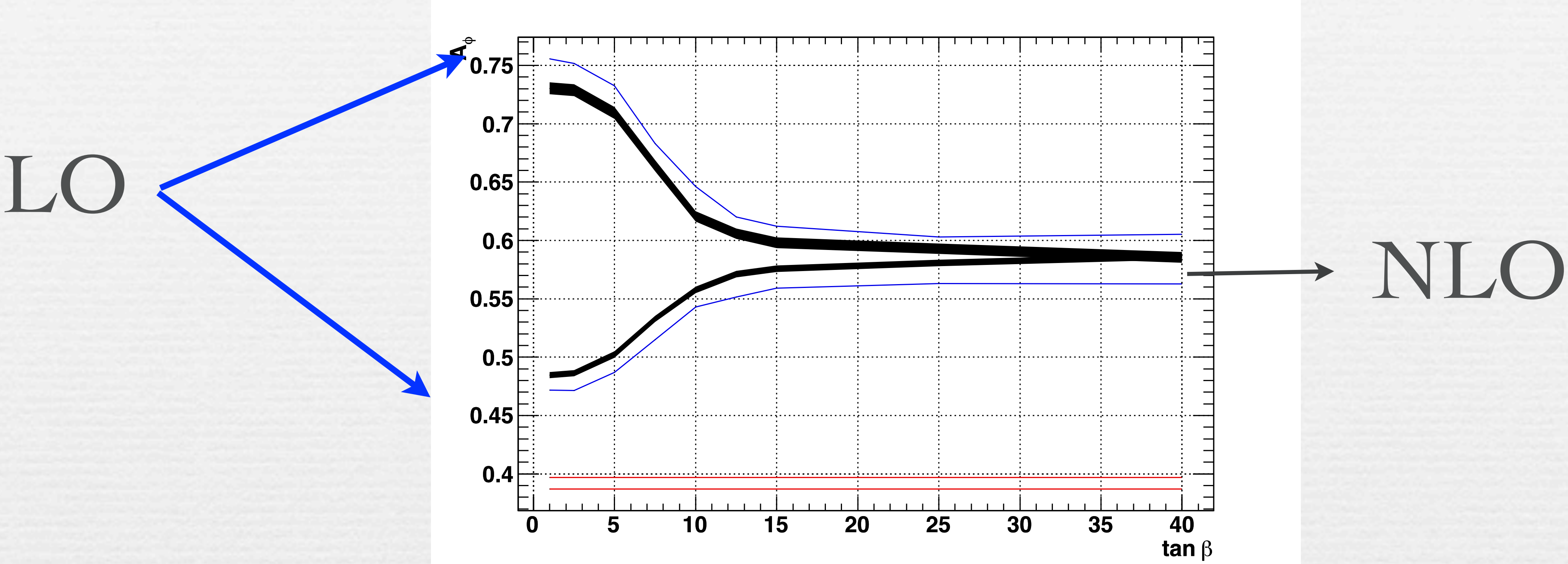
Godbole, Rao, Rindani, Singh



- Angular distributions (and others) can be selective probes of new physics
  - Rely on nearly 100% correlation of decay- lepton with top spin
  - If, e.g., Z' polarizes the tops, can use distribution in azimuthal angle of lepton (wrt. beam-top plane) to study dynamics
    - Enhance sensitivity by judicious cuts on p_T of top

Ht vs. Wt

Godbole, Hartgring, Niessen, White



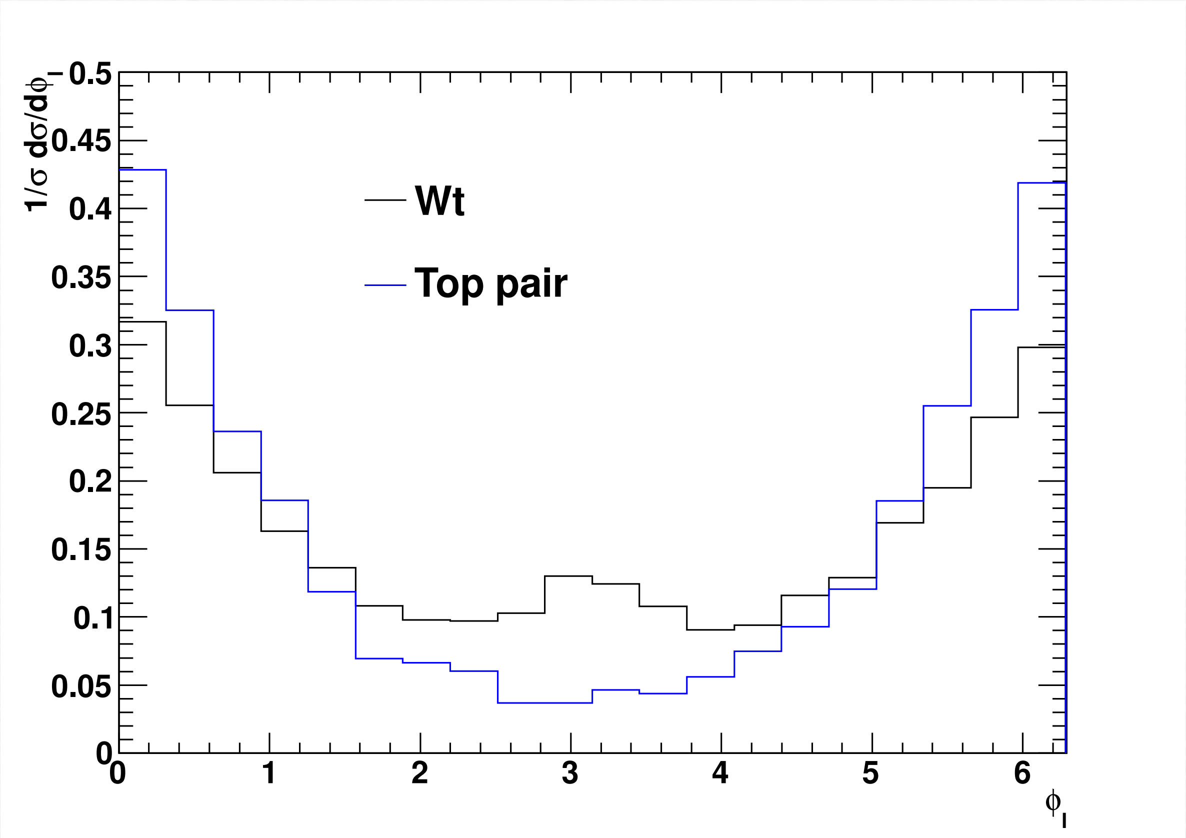
- Construct asymmetry

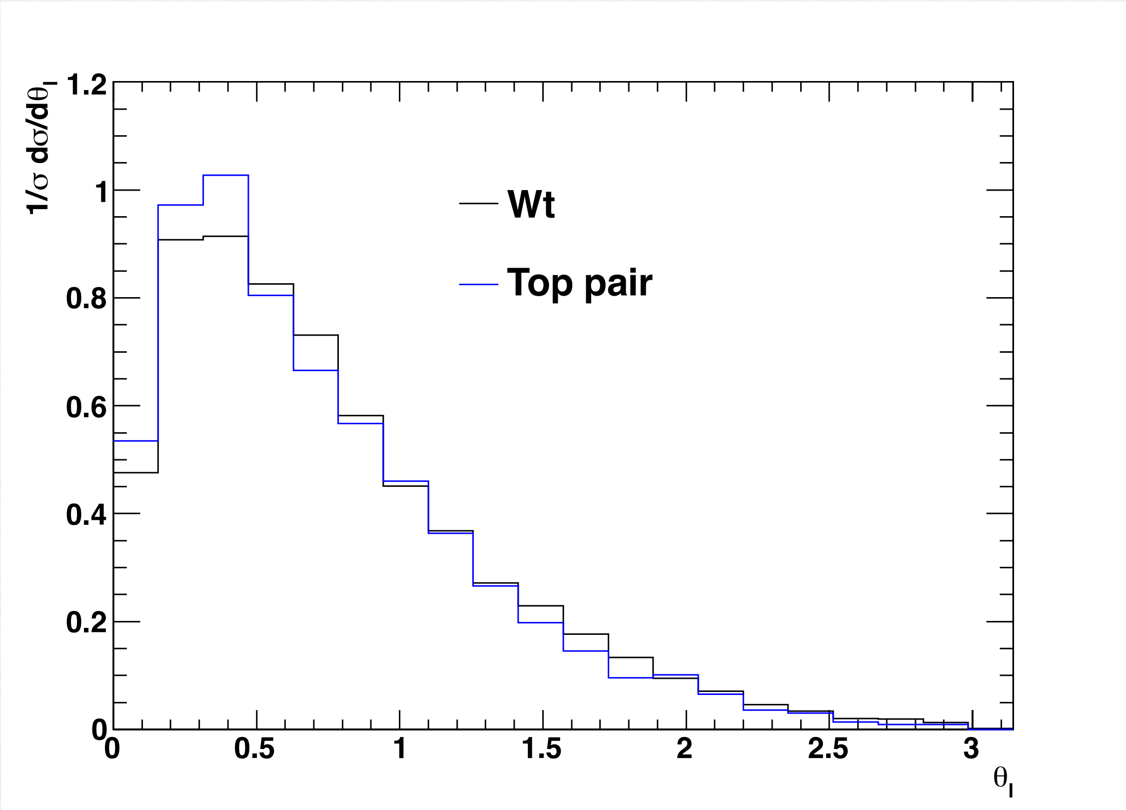
$$A = \frac{\sigma(\cos\phi_l) > 0) - \sigma(\cos\phi_l) < 0)}{\sigma(\cos\phi_l) > 0) + \sigma(\cos\phi_l) < 0)}$$

- Test robustness under HO corrections (via MC@NLO), quite ok

Angular distributions for Wt and ttbar separation

Godbole, Hartgring, Niessen, White





A_ϕ

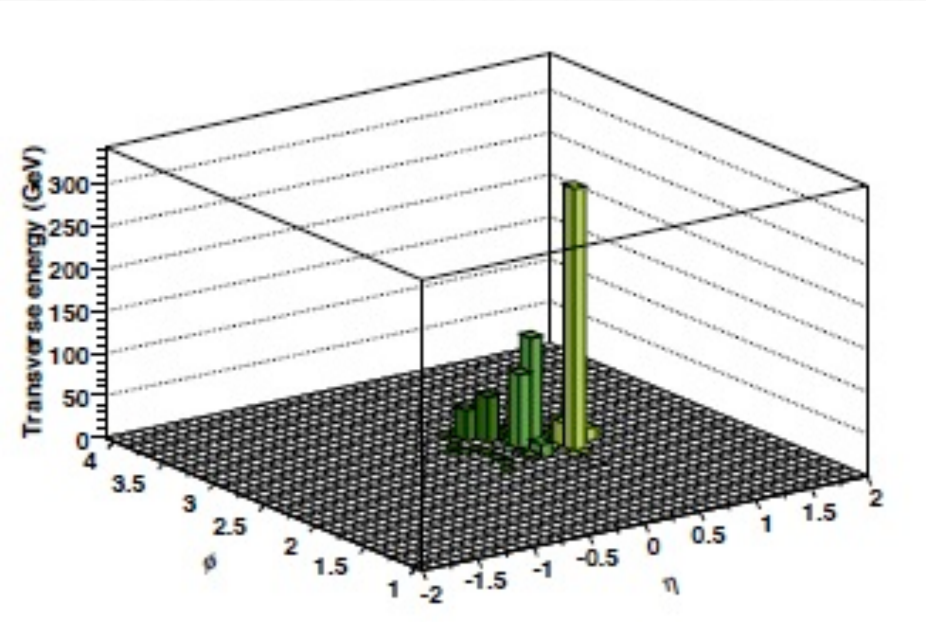
B_{cut}	Wt	Top pair
0	0.33 ± 0.01	0.63 ± 0.02
0.8	0.41 ± 0.02	0.70 ± 0.05
0.9	0.42 ± 0.03	0.70 ± 0.07
0.95	0.44 ± 0.04	0.68 ± 0.08

A_θ

B_{cut}	Wt	Top pair
0	0.02 ± 0.01	0.26 ± 0.02
0.8	0.18 ± 0.02	0.38 ± 0.04
0.9	0.49 ± 0.03	0.75 ± 0.07
0.95	0.70 ± 0.05	0.97 ± 0.10

Boosted Tops

Pruning, Trimming
Grooming



Thaler, Wang
Kaplan, Rehermann, Schwartz, Tweedie
Almeida, Lee, Perez, Sung, Virzi

- Following ideas to tag Higgs bosons, can one efficiently tag high pt top jets? Software: Butterworth, Ellis, Salam, et al
  - "Reverse engineer clustered fat top jet", find 3 subjets.
  - Can reduce di-jet backgrounds to ttbar resonances by factor order 10K!
    - depending on method
- (Semi-)analytical approach Almeida, Lee, Perez, Sterman, Sung, Virzi
  - Enrich boosted top sample by weighting them with IR safe top decay templates

See BOOST2010 report. Karagoz, Spannowsky, Vos (eds)

Conclusions

- LHC has now definitely taken over for most top observables
  - but not all (A_{FB}, studies that need qq initial state,..)
- Analyses requiring large top samples are now here: LHC as T-factory
  - top is the new bottom
  - correlations, angular distributions, other complex final states, so far agreeing with SM
- SM theoretical understanding is very good now
  - can scale up extensive verification/falsification project for top
  - things work all too well..
  - but much remains to be done