Top physics: theoretical aspects

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Physics at the LHC 2011, Perugia, June 5-11

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11:15 **Top physics: theoretical aspects (25' +5')** *30'*
Speaker: Eric Laenen (Fermi National Accelerator Laboratory (FNAL))

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Top physics: theoretical aspects

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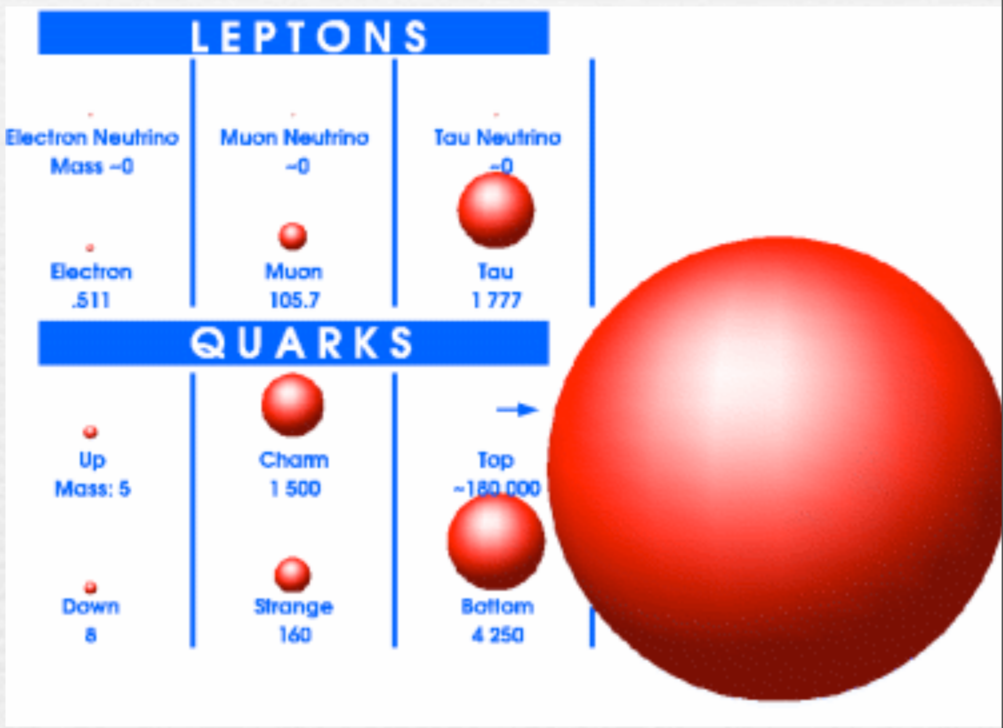
Outline

- Introduction
- Top pair cross section
- Mass
- Single top
- Charge asymmetry
- Tools
- Correlations, angular distributions
- Conclusions

Investing in Top

- 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, measureable
    - Interacts strongly with all forces (gauge +Higgs) in SM



There is upside potential to future developments in Top's value !!

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 — $g_s \left[T_a^{SU(3)} \right]^{ji} \bar{t}_j \gamma_\mu t_i A_\mu^a$ — √
- to Higgs: Yukawa type
  - y_t ~ 1 — $y_t \, h\bar{t}t$ — ?

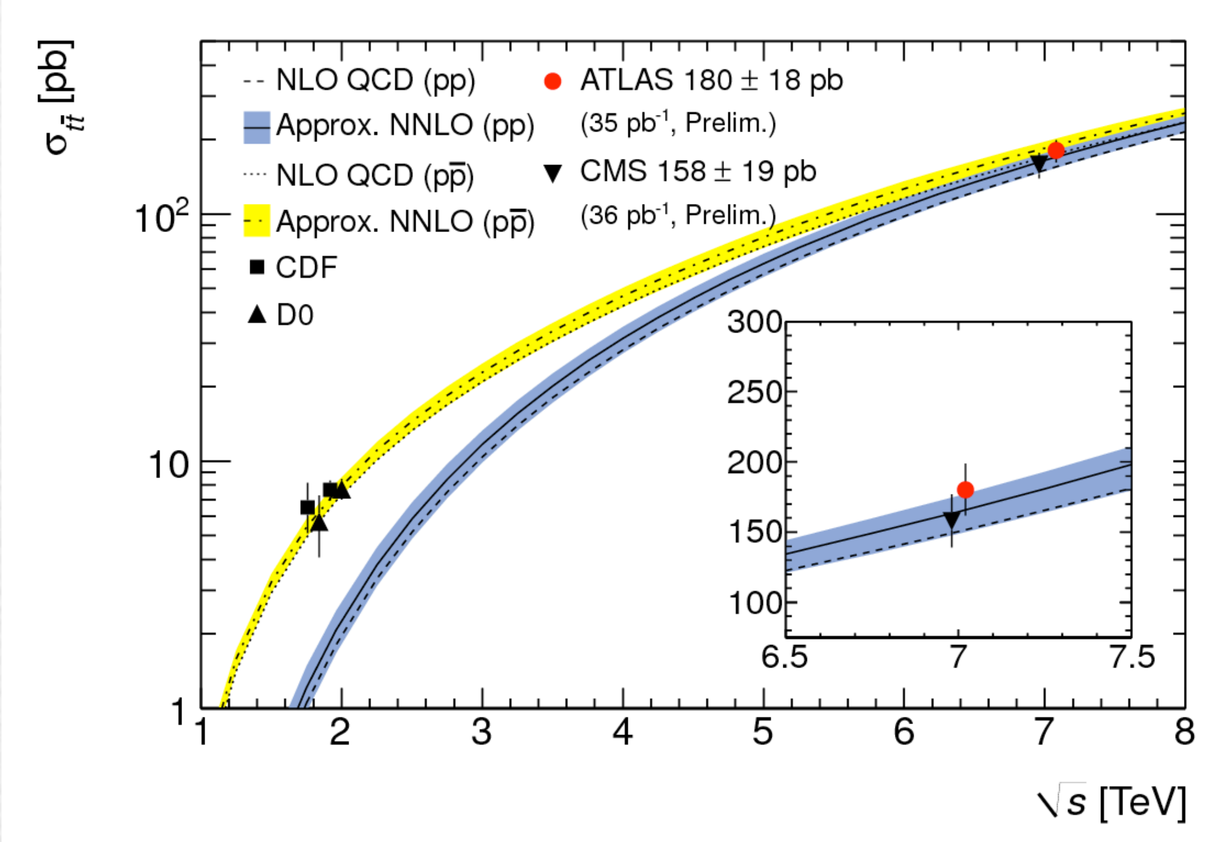
Check structure and strength of all these couplings

Top physics

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

Pair production cross section

- First measurements agree very well
  - ☺ New collider, much higher energy:
    - we really do understand how tops are produced
  - ☹ Makes hunt for BSM that much harder
- Good confidence in Top QCD coupling
- Useable for PDF (gluon) determination

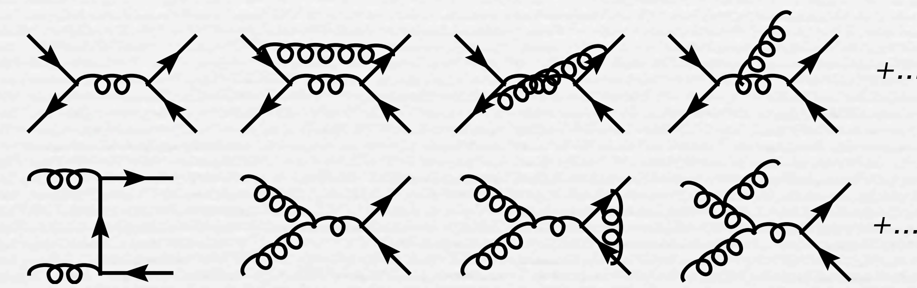


ATLAS, 35/pb: 180 ± 9(stat) ± 5 (sys) ± 6(lum) pb

CMS, 36/pb: 168 ± 18(stat) ± 14(sys) ± 7(lum) pb

Pair production cross section: theory

- NLO since late 80's
  - single particle inclusive and fully differential. Codes (MNR) still available
- Currently, NLO plus PS: MC@NLO, POWHEG
- Resummed-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, $\mathrm{NNLO}_{\mathrm{approx}}$
    - Best one can do, instructive, already less scale uncertainty



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

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

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

Resummation rules of thumb

- Near edge of phase space: Sudakov suppression $\exp(-aL^2)$
- But hadronic cross sections *increase* due to QCD resummation

$$\sigma_{partonic,resum}(N) = \frac{\sigma_{hadronic}(N)}{\phi^2(N)} = \frac{\exp(-\ln^2 N)}{\left(\exp(-\ln^2 N)\right)^2} = \exp(+\ln^2 N)$$

- Factorization scale uncertainty smaller in resummation than in fixed order

$$\phi_{q/P}(N, \mu_F) \simeq e^{\alpha(A \ln N + B)\ln \mu_F + \ldots}$$

Sterman, Vogelsang

$$\sigma_{partonic,resum} = e^{\alpha \ln^2 N - \alpha(A \ln N + B)\ln \mu_F + \ldots}$$

$$\sigma_{partonic,NLO} = 1 + \alpha\left[\ln^2 N - (A \ln N + B)\ln \mu_F\right]$$

Pair production cross section: theory

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

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

- Until recently the status was NLL

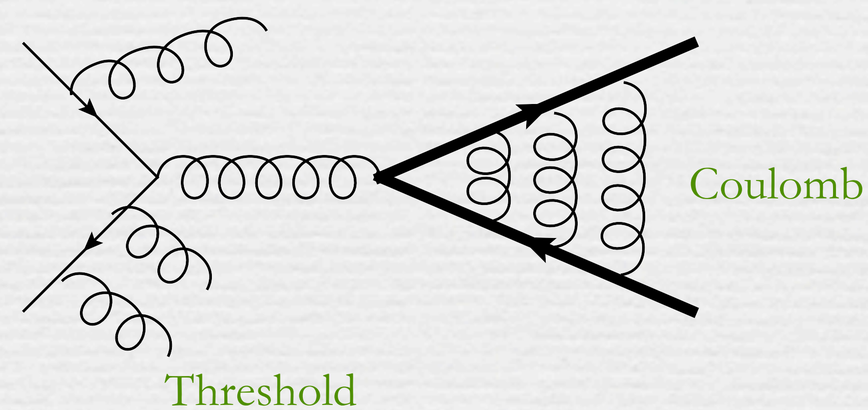
Kidonakis, Oderda, Sterman; Cacciari, Frixione, Mangano, Nason, Ridolfi

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

Moch, Vermaseren, Vogt; Mitov, Sterman, Sung

Beneke, Falgari, Schwinn

  - Also available: Coulomb exchange



- Caveat: different thresholds are used
  - e.g.

$$\sigma(s) = \int dp_T dy \frac{d^2\sigma}{dp_T dy}$$

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

  - Source of uncertainty, as long as NNLO not known exactly

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

σ_{tt}(NNLO) : approx & exact

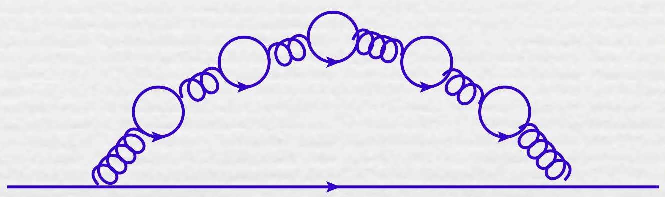
1. $\sum_n \alpha_s^n \ln^{2n}(s - 4m^2)$ $[\sigma(s)]$
2. $\sum_n \alpha_s^n \ln^{2n}(s - 4(m^2 + p_T^2))$ $[d\sigma(s)/dp_T]$
3. $\sum_n \alpha_s^n \ln^{2n}(s - 4(m^2 + p_T^2)\cosh y)$ $[d^2\sigma(s)/dp_T dy]$

- 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 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 under way — Czakon
- 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

Top mass

- Electron mass definition"easy": defined by pole in full propagator
    - If particle momentum satisfies pole, can propagate to ∞
        - $\Rightarrow$ there is no real ambiguity what electron "pole" mass is
- But: quarks are confined, physical on-shell quarks do not exist
    - Leads to non-perturbative ambiguity of few hundred MeV
        - (also revealed by all-order pQCD!)



- LHC: accuracy of 1 GeV possible, similar to Tevatron.
    - But for what mass?
    - What accuracy do we need?

Heavy quark mass definitions

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

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

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 sort of coupling $m_0 = m(\mu)\Big(1 + \frac{\alpha_s}{\pi}\Big[\frac{1}{\epsilon}\Big]\Big)$

One can translate between them $m = m(\mu)\Big(1 + \alpha_s(\mu) d^1 + \alpha_s^2(\mu) d^2 + \ldots\Big)$

What top mass is measured?

Tevatron, 5.6/fb: m =173.3 ± 1.1 GeV/c^2
CMS, 36/pb: m =175.5 ± 4.6(stat) ± 4.6(sys) GeV/c^2
ATLAS, 35/pb: m =169.3 ± 4.0(stat) ± 4.9(sys) GeV/c^2

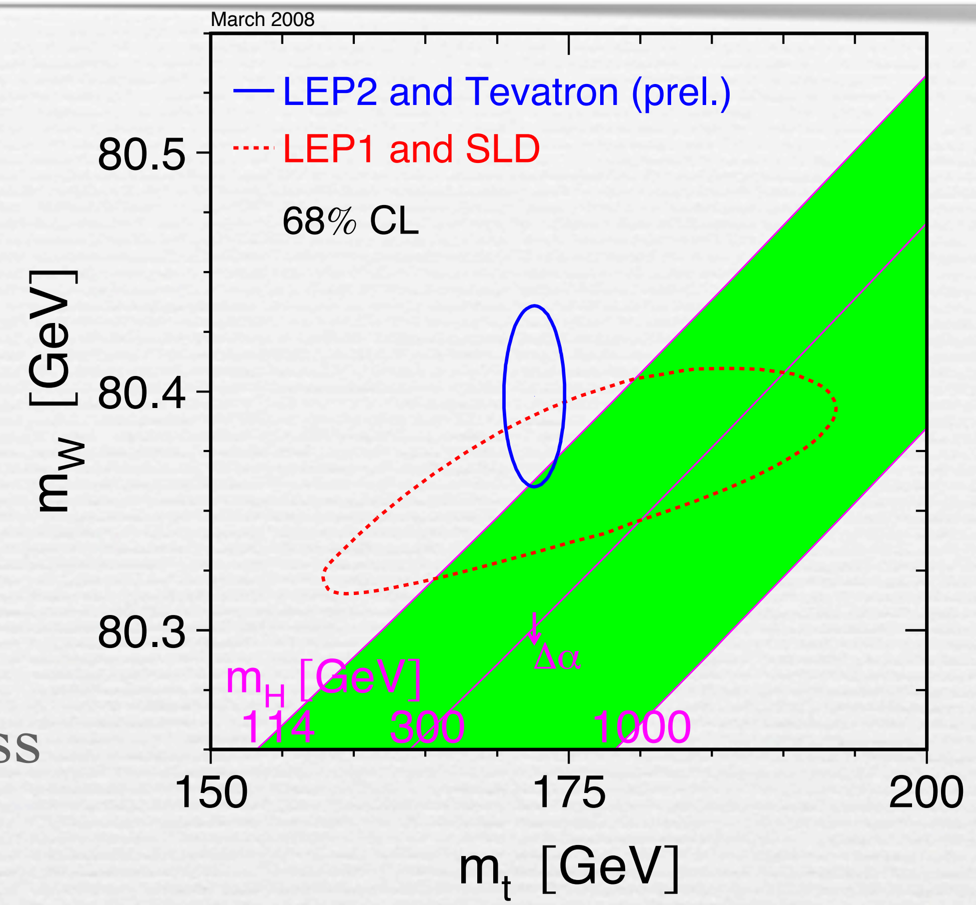
Coincidence? $\frac{m_{top}}{\sigma_{tt}} \sim 1$

- What mass do hadron colliders determine?
  - Pole mass? Pythia mass?
  - Many discussions, no generally accepted conclusion.
    - Map from data to theory parameter via Pythia, templates, cuts, not so clear. Interpreted as pole mass.
- Can infer MSbar mass:
  - compute cross section with pole mass $\sigma_{tt}(m, \alpha_s)$
  - replace pole mass by MSbar mass $m = m(\mu)\Big(1 + \alpha_s(\mu)d^1 + \alpha_s^2(\mu)d^2 + \ldots\Big)$
  - Fit MSbar mass

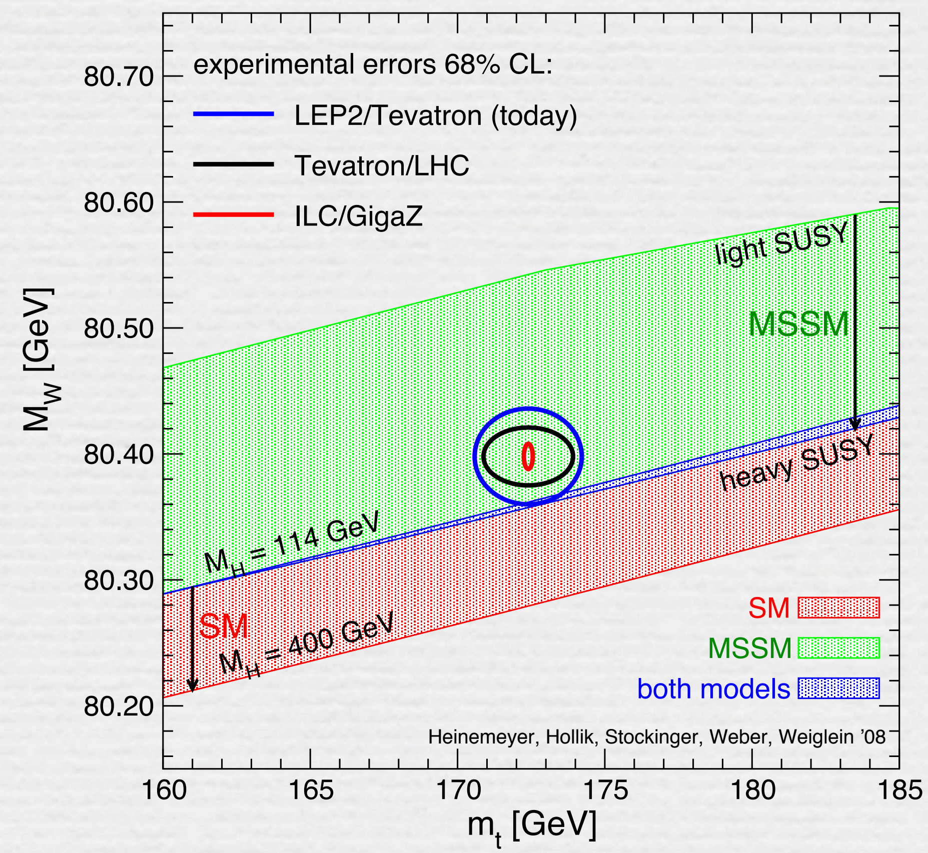
$$\overline{m}(\overline{m}) = 160.0 \pm 3.3 \text{ GeV/c}^2$$

Langenfeld, Moch, Uwer

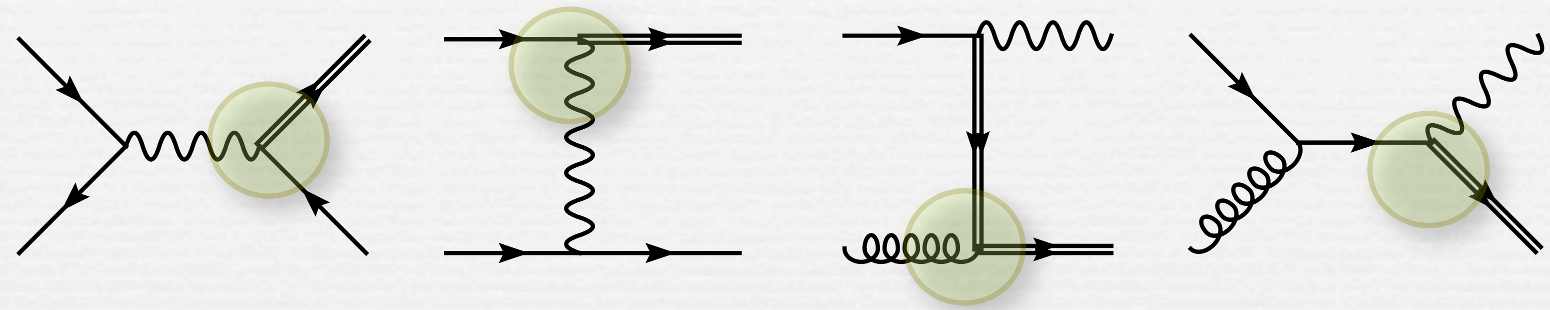
Top mass: how well *should* we know it?



- But 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
- Do need it to constrain BSM theories, if found



Single top



(1) (2) (3)

s-channel:
timelike W

t-channel:
spacelike W

Wt channel: real W

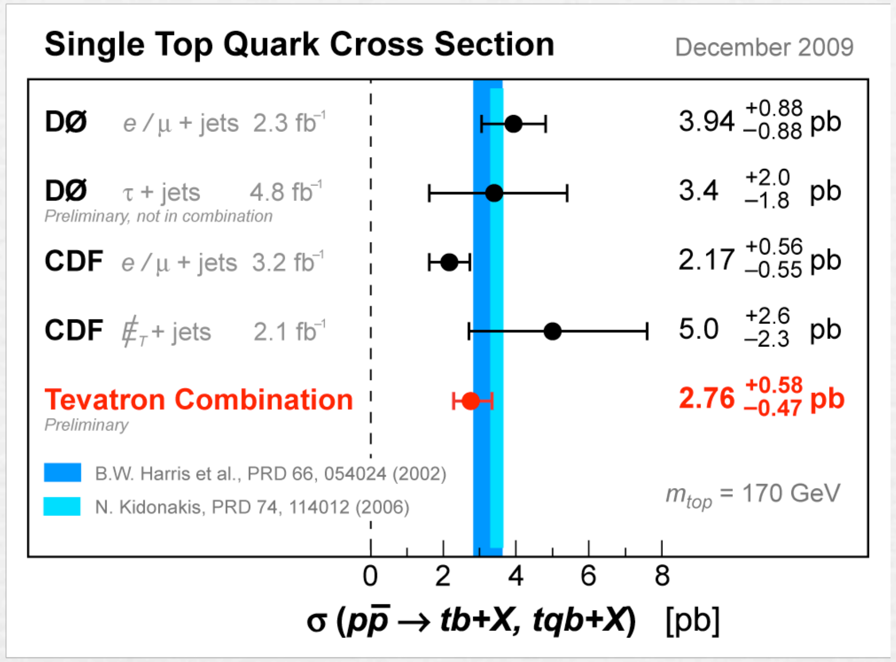
4 pb @ LHC7

62 pb @ LHC7

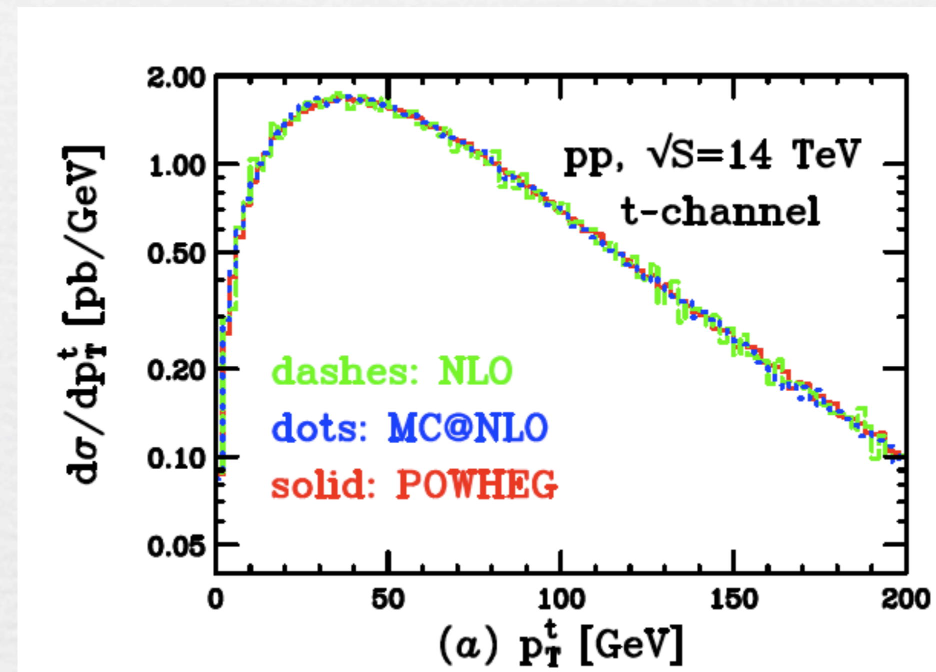
10 pb @ LHC7

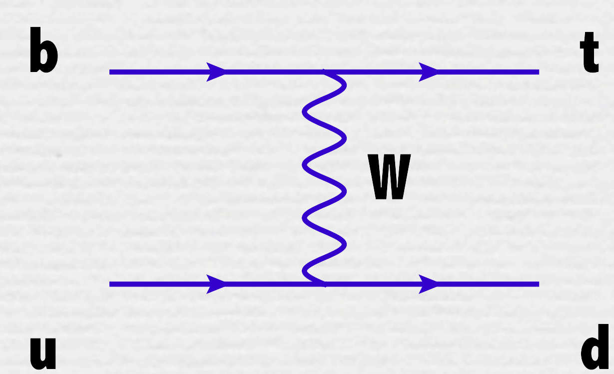
- Test electroweak production of top, through left-handed coupling
- Allows measurement of V_{tb} per channel. Check of structure of Wtb vertex
- Sensitive to different New Physics/channel (FCNC (t-channel), W' resonance (s-channel), non-4 fermion operators (Wt-channel))
- Challenging measurement at Tevatron, now first evidence at LHC (cut & count),

Single top production, theory



- Start of the art: NLO + parton showers
  - NLO inclusive (agrees well with Tevatron measurement)
  - MC@NLO (Frixione, EL, Motylinski, Webber) POWHEG (Aioli, Nason, Oleari, Re); agreement very good
  - All three modes (s,t,Wt) included, including decays with spin correlations
    - t-channel: useful for measuring b-density (5-flavor scheme)
    - in 4-flavor scheme, extra jet for (anti-)tagging

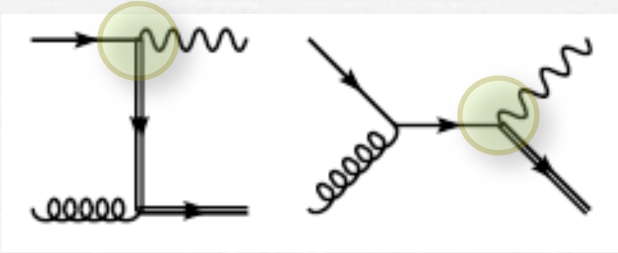




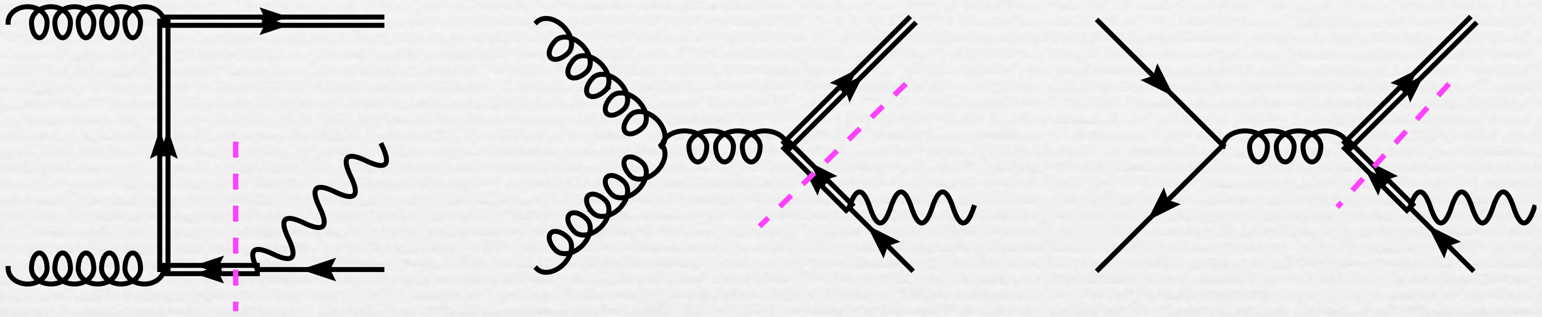
Campbell, Frederix, Maltoni, Tramontano

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

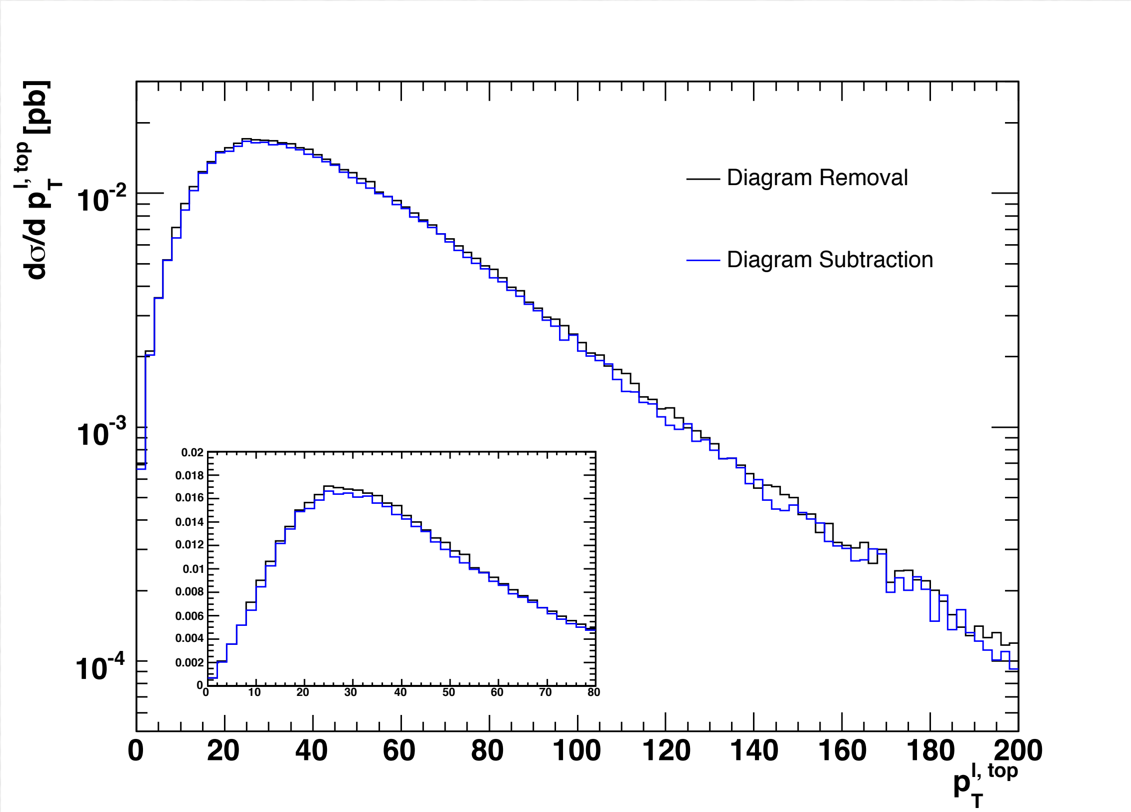
Momentum reshufling

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

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

Compare

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



Can/should we isolate Wt?

White, Frixione, EL, Maltoni

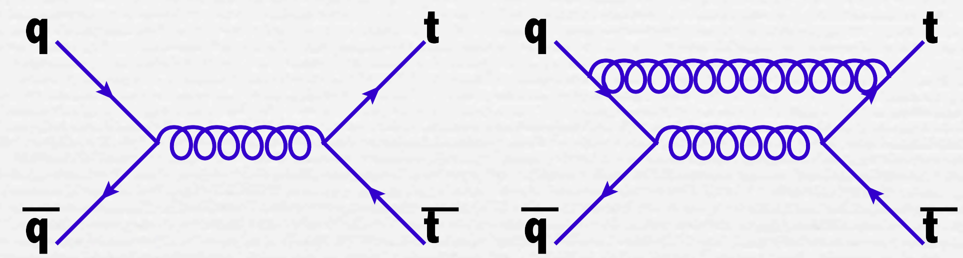
- Answer subject to cuts. Some choices:
  - Cuts to isolate Wt
  - Cuts to suppress Wt and tt as background to H->WW
- Conclusion:
  - Yes, can consider separate NLO corrections for tt (70%) and for Wt (40%)

e_b	r_{lj}	σ_{Wt}^{DR}/pb	σ_{Wt}^{DS}/pb	$\sigma_{t\bar{t}}$/pb
1.0	10^4	$1.206^{+0.039}_{-0.017}$	$1.189^{+0.021}_{-0.010}$	$5.61^{+0.74}_{-0.54}$
0.6	30	$0.717^{+0.020}_{-0.014}$	$0.696^{+0.020}_{-0.005}$	$4.29^{+0.45}_{-0.46}$
0.6	200	$0.748^{+0.014}_{-0.011}$	$0.726^{+0.014}_{-0.007}$	$4.36^{+0.56}_{-0.42}$
0.4	300	$0.505^{+0.026}_{-0.009}$	$0.494^{+0.008}_{-0.008}$	$3.31^{+0.40}_{-0.37}$
0.4	2000	$0.512^{+0.011}_{-0.010}$	$0.503^{+0.001}_{-0.007}$	$3.35^{+0.37}_{-0.38}$

Process	σ_{NLO}/fb
$H \to WW$	81.8 $\pm$0.4
$t\bar{t}$	12.25 $\pm$ 0.3
Wt (DR)	6.91 $\pm$ 0.06
Wt (DS)	6.89 $\pm$ 0.07

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 than σ

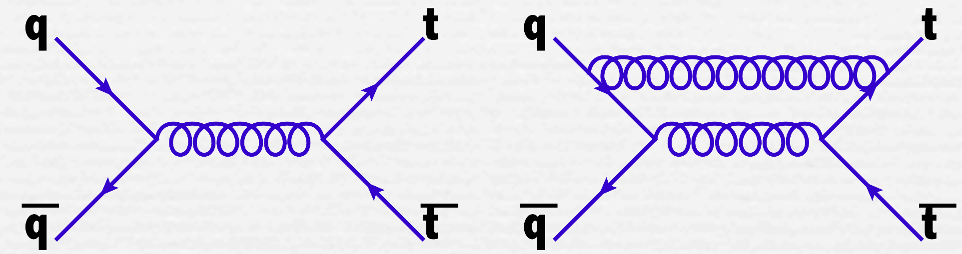
Berends, Gaemers, Gastmans

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

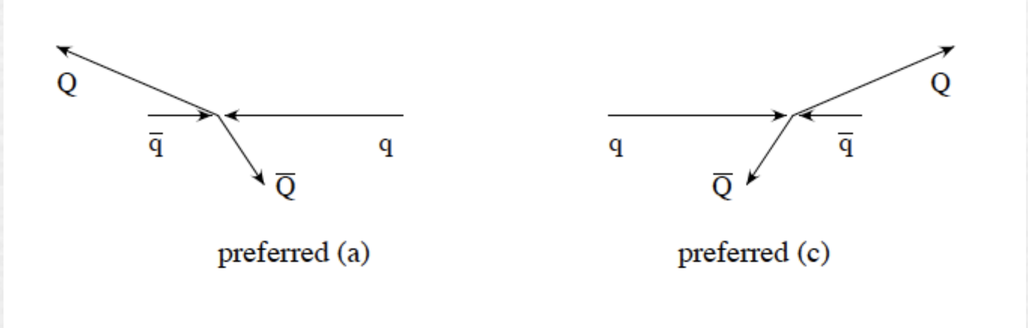
T. Himel, B. Richter, G. S. Abrams, M. S. Alam, A. M. Boyarski, M. Breidenb
W. Chinowsky, G. J. Feldman, G. Goldhaber, G. Hanson, J. A. Jaros,
R. R. Larsen, D. Lüke, V. Lüth, R. Schindler, R. F. Schwitters,
J. L. Siegrist, and G. H. Trilling

$A_{FB} = 0.013 \pm 0.010$

Some intuition about A_{FB}



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

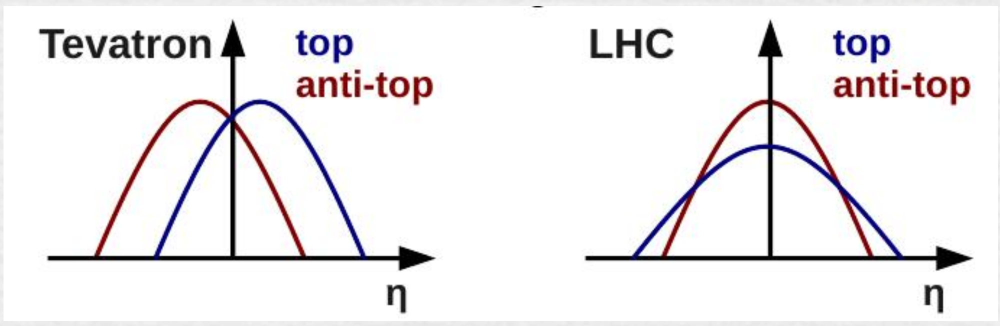


$$\propto \frac{t^2+u^2}{s^2} + \frac{2m^2}{s} \quad = A + B\cos^2\theta$$

Chierici

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

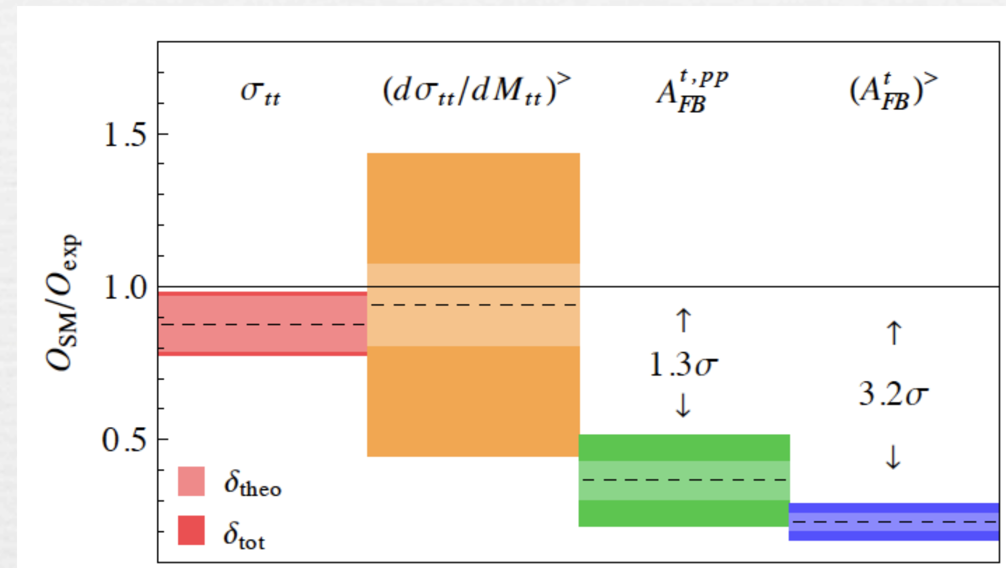
Sterman



A_{FB} in experiment

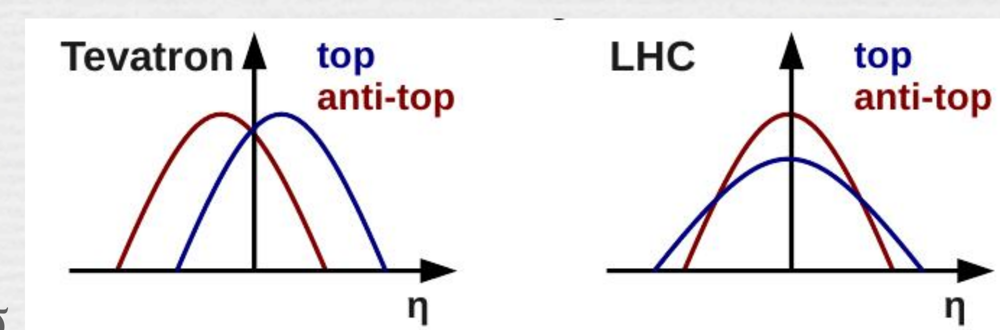
A plethora of asymmetries....

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
  - DO (2010): definition differential in y, includes acceptance (8 ± 4 ± 1) %.
  - Also suggested: lepton-from-top asymmetries: A^l, A^{ll}
- LHC
  - Suggested: asymmetry from events with (anti-)top above a minimum rapidity
- Not easy for NP models to change A_{FB} with changing σ

Chierici



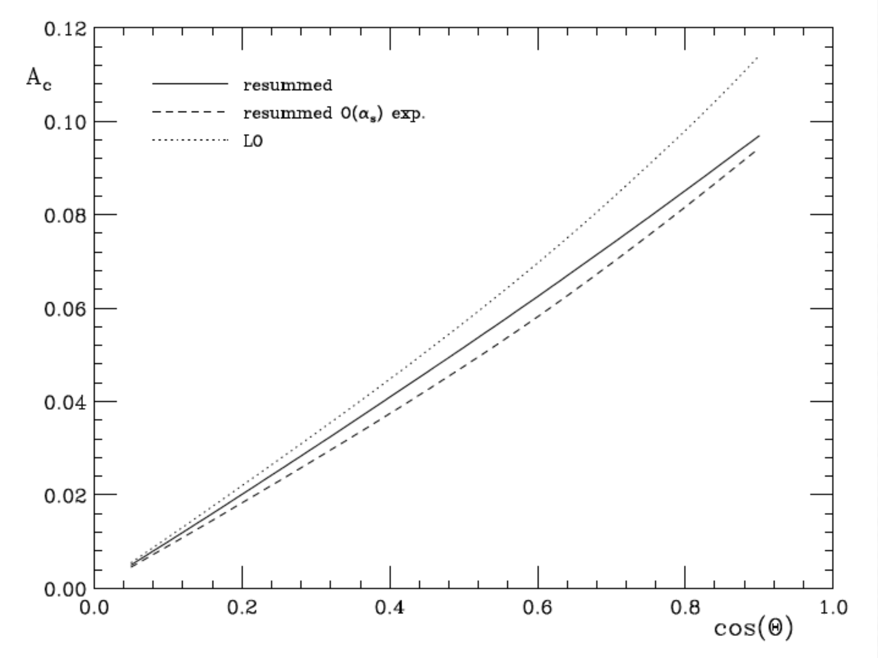
Higher orders in AFB

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

Kidonakis, EL, Moch, Vogt

- AFB is zero at LO, hence the NLO cross section contributes at LO to AFB
- Higher order contributions to AFB from threshold resummation
  - Leading logs charge symmetric, cancel in numerator, but subleading ones remain
  - Find: AFB stable under higher orders
  - Similar conclusion at NNLL

Ahrens, Ferroglia, Neubert, Pecjak, Yang; Kidonakis



Almeida, Sterman, Vogelsang

- AFB already at LO in tt+jet, but NLO corrections reduce this significantly

Dittmaier, Uwer, Weinzierl; Melnikov, Schulze

Asymmetry at LHC

- Can define forward charge asymmetry
  - Find: best for y_0 = 1.5

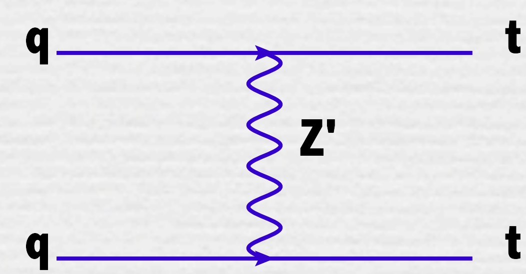
Hewett, Shelton, Spannowsky, Tait, Takeuchi

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

- 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)

Degrande, Gerard, Grojean, Maltoni, Servant

- Other (kinematic) possibility: same-sign tops
  - Encoded not via form factors, but EFT approach (dimension 6 4-fermion operators). Only 5 operators
- Cross section order pb if new physics at 2 TeV



T-factory

- These were some of the core observables, @ Tevatron and LHC
- Lots of tops coming $\Rightarrow$ study asymmetries, angular distributions, exclusive decays, spin-entanglement, ..
  - Top is the new bottom..
- Theoretical tools are ready, and improving:

Top simulation tools

Tree-level, high multiplicity matrix elements, matched to parton showers

- Alpgen: tt + ≤ 6 jets (uses ALPHA algorithm, MLM matching, with spin)
- MadEvent: tt + ≤ 3 jets (uses helicity amps, various matchings)
- CompHep: tt + ≤ 1 jets (squared matrix elements, with spin)

Next-leading order (includes virtual corrections), matched to parton showers

- MC@NLO: tt + ≤ 1 jet (spin correlations included)
- POWHEG: tt + ≤ 1 jet (spin correlations included)

And of course HERWIG, PYTHIA, SHERPA

(Associated) top production at higher order

see also talk by Giulia Zanderighi

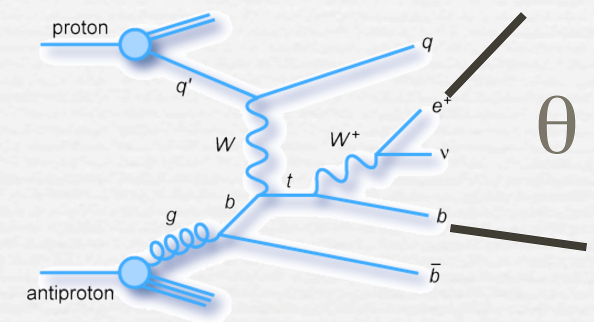
Impressive recent progress

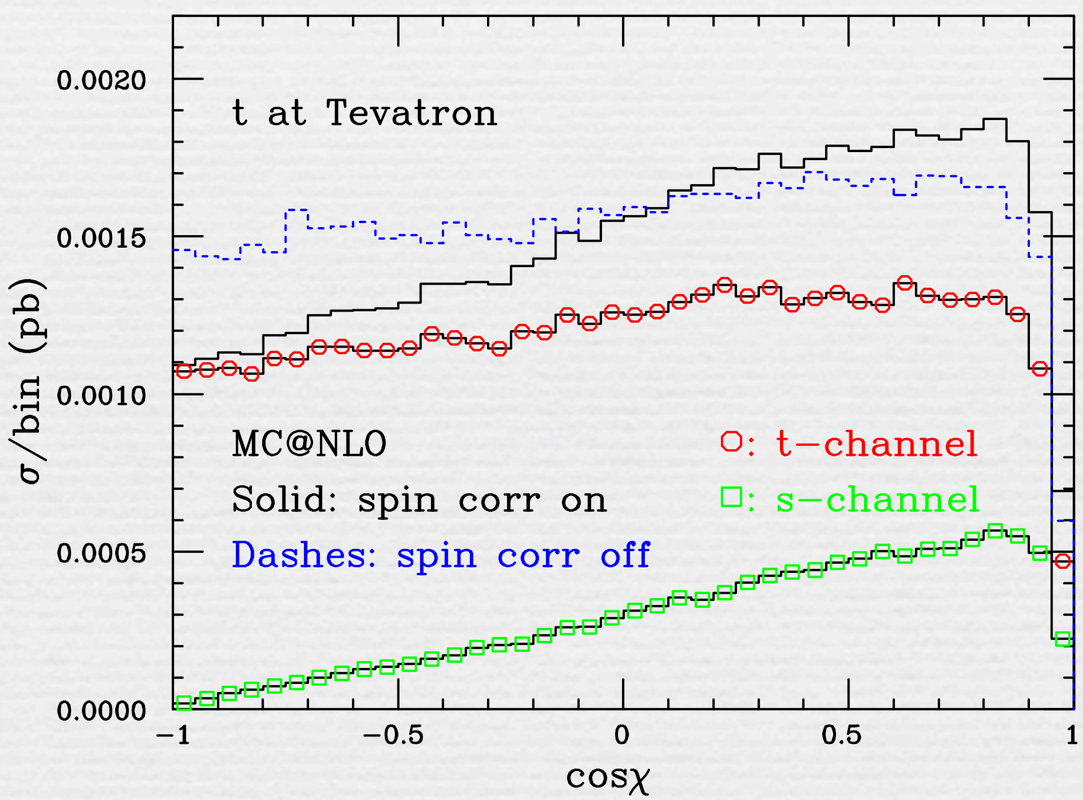
- Electroweak corrections — Bernreuther, Brandenburg, Si, Uwer; Kuhn, Scharf, Uwer; Maina, Moretti, Nolten, Ross
- Associated production at NLO (3+ particles in final state at LO)
  - tt + jet — Dittmaier, Uwer, Weinzierl
  - tt + Higgs — Beenakker, Dittmaier, Krämer, Plumper, Spira, Zerwas; Dawson, Jackson, Orr, Reina, Wackeroth
  - tt + bb — Bredenstein, Denner, Dittmaier,Pozzorini; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek
  - tt + jj — Bevilacqua, Czakon, Papadopoulos, Worek
- Calculations with off-shell top-decay
  - single top: — Falgari, Giannuzzi, Mellor, Signer
  - tt — Bevilacqua, Czakon, Papadopoulos, Worek

Spin correlations for single top in MC@NLO

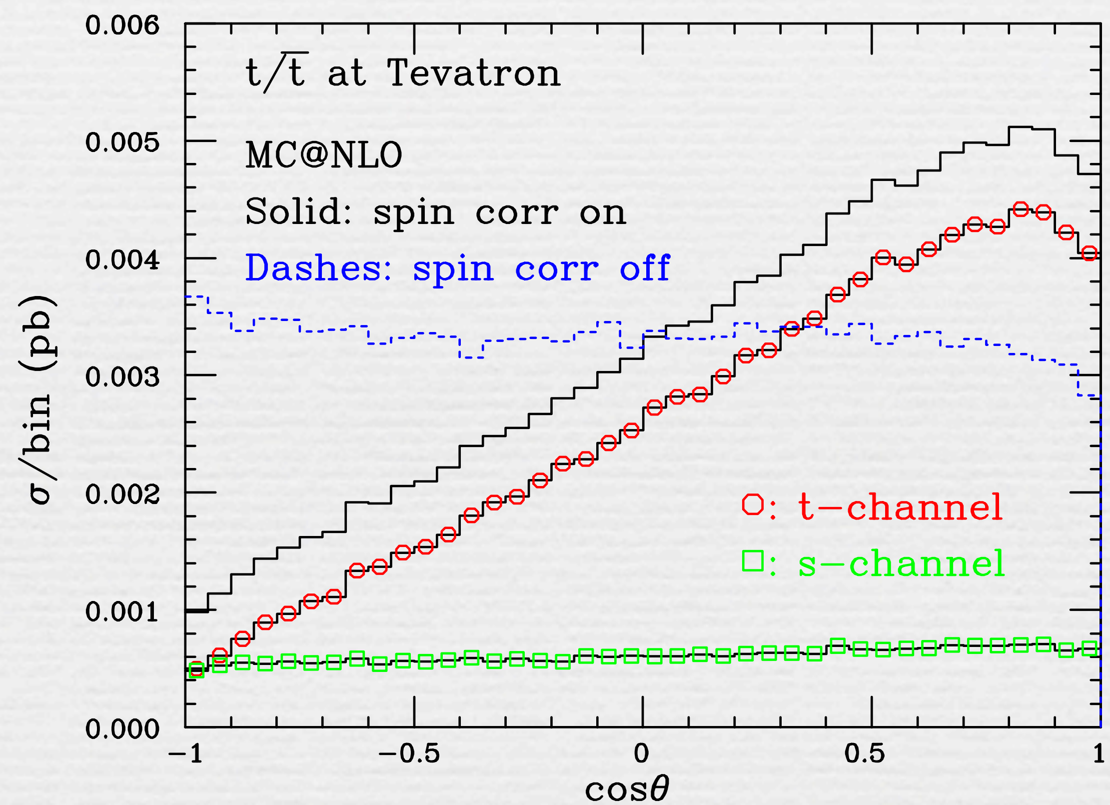
Frixione, EL, Motylinski, Webber

- Top is produced polarized by EW interaction
- Angle of lepton with appropiate axis different per channel
- Included "a posteriori". Also used in POWHEG Aioli, Nason, Oleari, Re





Beam direction



Hardest, non-b jet

Robust correlation, also in event generation

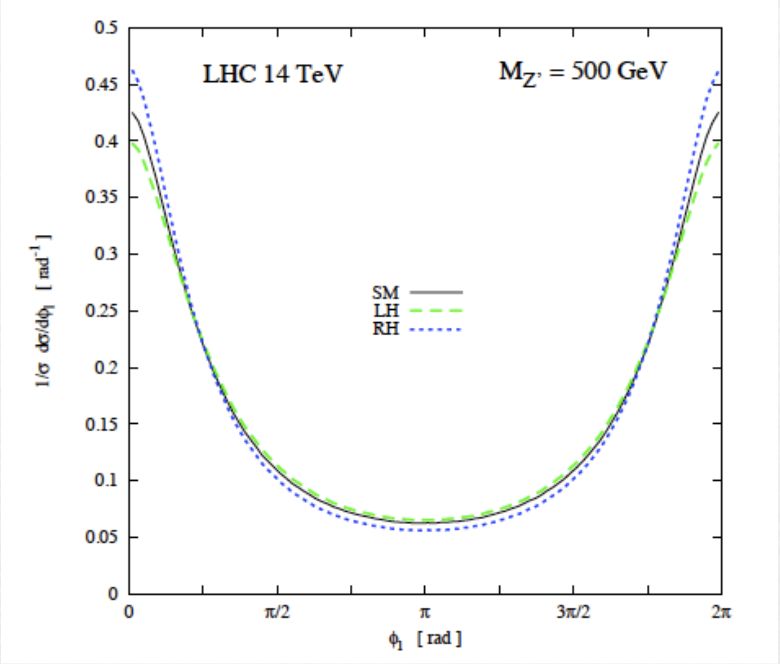
Angular distributions and BSM tests

- Angular distributions can be selective probes of new physics
  - Rely on nearly 100% correlation of decay- lepton with top spin
  - E.g. if Z' polarizes the tops, use distribution in azimuthal angle of lepton
    - Enhance sensitivity by judicious cuts on pT of top
- Construct asymmetry

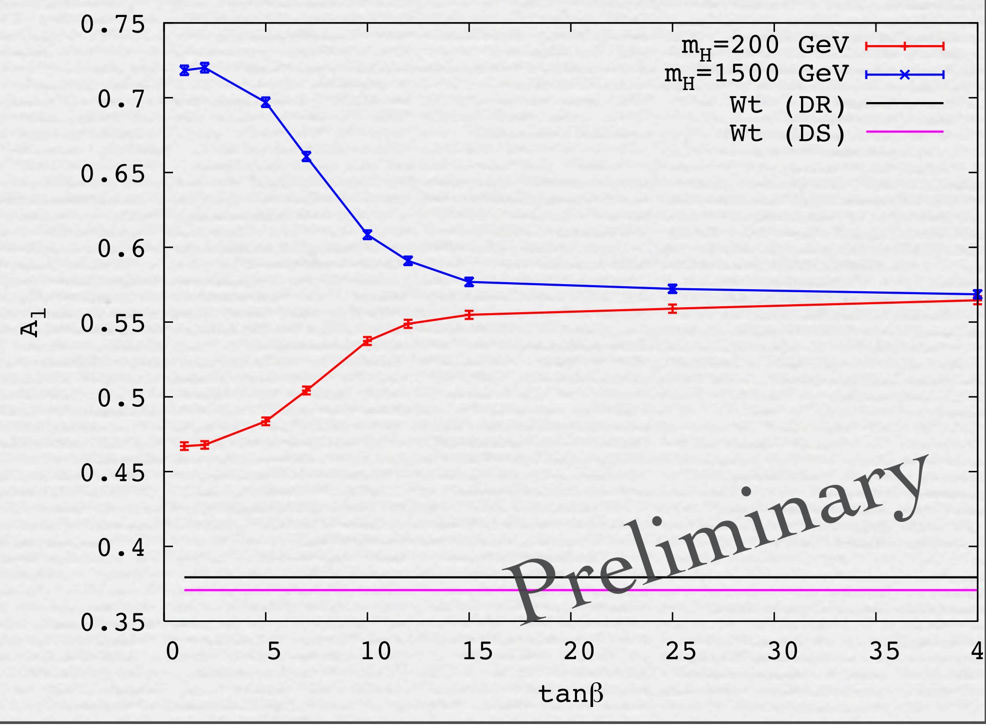
$$A = \frac{\sigma(\cos\phi_l) > 0) - \sigma(\cos\phi_l) < 0)}{\sigma(\cos\phi_l) > 0) + \sigma(\cos\phi_l) < 0)}$$

- Use MC@NLO
    - Discriminates Ht and Wt, and sensitive to parameters
    - Robust under HO corrections

Godbole, Rao, Rindani, Singh

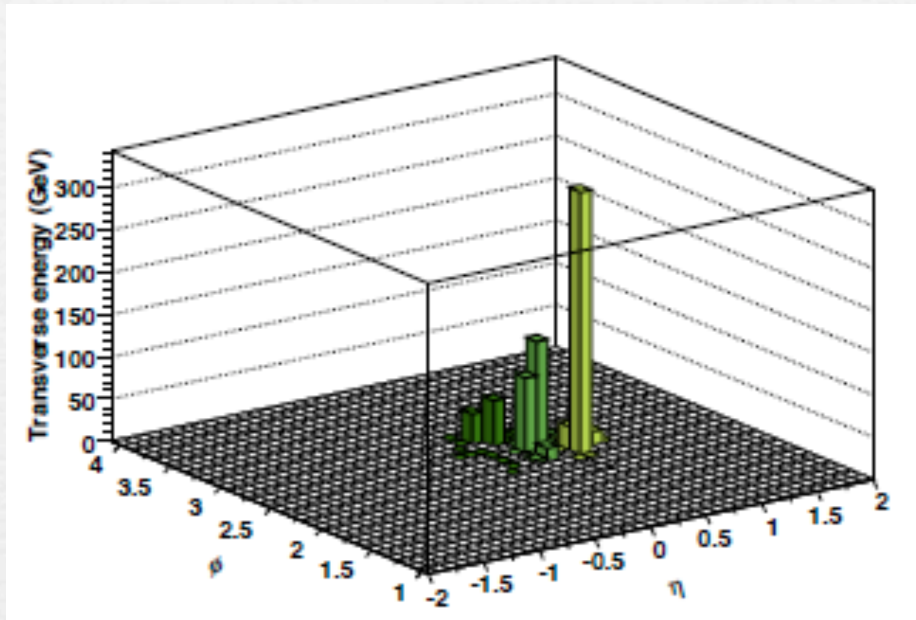


Godbole, Hartgring, Niessen, White



Boosted Tops

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



Butterworth et al

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

- Following ideas to tag Higgs bosons, can one efficiently tag high pt top jets?
  - "Reverse engineer clustered fat top jet", find 3 subjects.
  - Depending on method
    - Can reduce di-jet backgrounds to ttbar resonances by factor order 10K!
    - Is there IR sensitivity?

Conclusions

- LHC poised to "take over" on many "basic" top observables
  - but not all (A_{FB}, studies that need qq initial state,..)
- Analyses requiring large top samples should be starting: LHC as T-factory
  - correlations, angular distributions, other complex final states
- SM theoretical understanding is very good, many excellent tools exist (use right one for right job)
- A new era in top physics has arrived!