The Ubiquitous Top

Top Quark Institute
Cern, May 18-June 5

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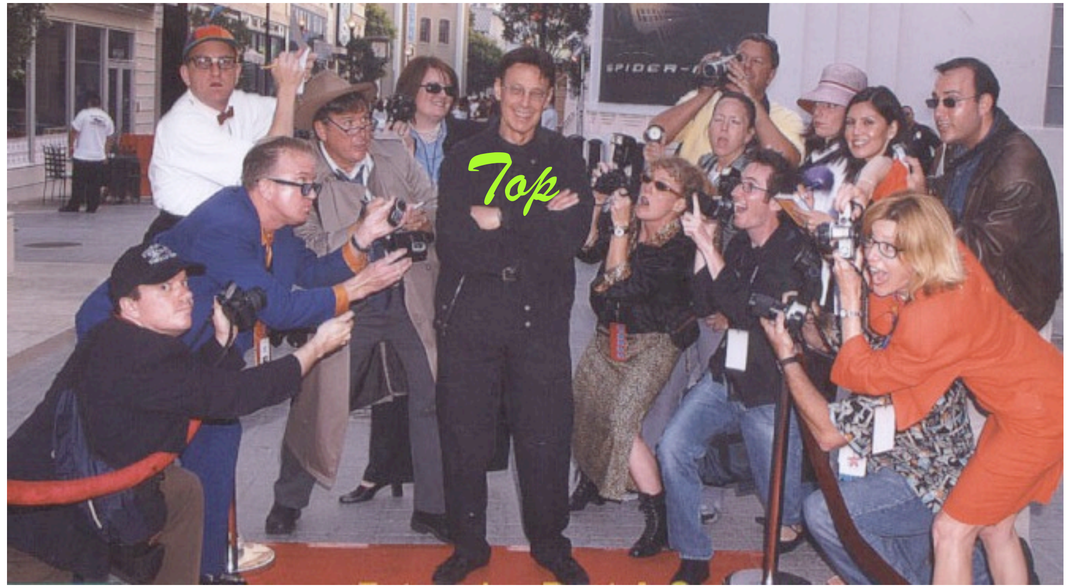
Top

- Discovered by CDF and D0 in 1995.
  - ✓ Bizarrely heavy
  - ✓ Completes the 3rd generation
- Charm (1974) made SM consistent, cemented belief in QCD
- Bottom (1977), 3rd family, allowed for CKM mechanism
- What will top's contribution be?

Top: Star of the Hadron Colliders



- most expensive, most glamorous
- interacts with everybody that matters
- has been, and will be center of attention while..
- ... until a new star comes along..

Top @ 14

- We know much about it already from CDF and D0 at Tevatron
  - ✓ that it exists!
  - ✓ mass, spin, QCD coupling, EW coupling, constraints on its mixing, helicity in decays
  - ✓ pair production cross section
  - ✓ early distributions
- Very recently: single top!

Top is everywhere...

- Tell-tale for new physics signals
  - as its direct decay product
  - indirect influence on its couplings
- Background to many signals, even to itself (tt for t)
- Calibration of detectors..

  - We have much to learn from top..
  - ..which is why we're here

- In talk I recall some reasons why top, though ubiquitous, is special..
  - .. and visit some interesting issues (with advance apologies)

Standard Model gauge sector

- Fields in representations of fundamental local symmetries

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

- Spacetime derivatives are actually covariant ones

$$D_\mu = \partial_\mu + i g_s G_\mu^a T_a + i g' B_\mu Y + i g W_\mu^i T_i$$

- Source of interactions with gauge fields

Generators of symmetry groups

$$\overline{t_L} \not{D} t_L + \overline{t_R} \not{D} t_R$$

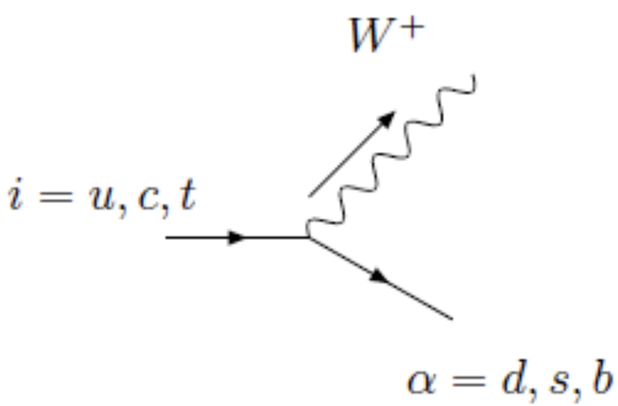
- Left / righthanded top quark charges
  - ✓ Hypercharge 1/6 / 2/3
  - ✓ Weak isospin 1/2 / 0
  - ✓ Both color triplets

Yukawa sector

$$\mathcal{L}_{Yukawa} = y_u^{ij}\ \overline{Q_L^i}\sigma_2\Phi^* u_R^j + y_d^{ij}\ \overline{Q_L^i}\Phi d_R^j + \ldots$$

- Diagonalizing quark mass matrix causes flavor mixing
  - ✓ Top can lose its personality

$$\mathcal{L}|_{W\pm-\text{quark}}(x) = g_w W_\mu^-(x)\, V_{tb}\ (\bar{t_L}(x)\gamma^\mu b_L(x))$$
$$+g_w W_\mu^-(x)\, V_{ts}\ (\bar{t_L}(x)\gamma^\mu s_L(x)) + g_w W_\mu^-(x)\, V_{td}\ (\bar{t_L}(x)\gamma^\mu d_L(x)) + c.c.$$



Quark mixing $\propto V_{\alpha i}$

Top mass and Yukawa coupling

Expand Higgs doublet around the true groundstate

$$\Phi(x) = e^{i\xi^i(x)\sigma_i} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

Absorbed by $W^{\pm}$,Z boson — *Higgs boson field*

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

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

Same couplings that determine masses determine interactions

Standard Model top couplings

- coupling to W bosons mixes flavors, is left-handed $\frac{g}{\sqrt{2}} V_{tq} \, (\bar{t}_L \gamma^\mu q_L) W^+_\mu$
- coupling to gluons vectorlike $g_s \left[T_a^{SU(3)} \right]^{ji} \bar{t}_j \gamma_\mu t_i A^a_\mu$
- coupling to Z parity violating $\frac{g}{4\cos\theta_w} \, \bar{t} \left((1 - \frac{8}{3} \sin^2\theta_w) \gamma^\mu - \gamma^\mu \gamma^5 \right) t \, Z_\mu$
- coupling to Higgs of Yukawa type, strength 1 $y_t \, h \bar{t} t$

Top physics

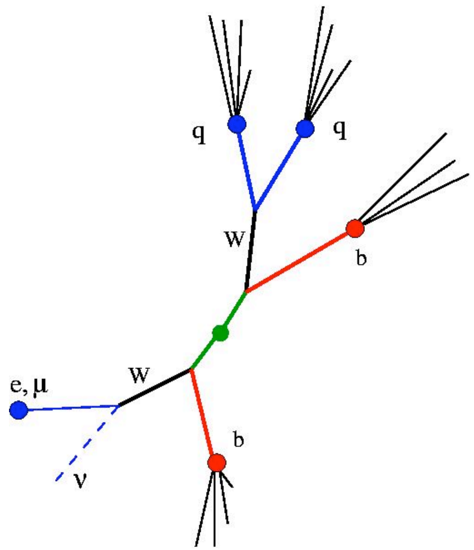
- Verify or falsify these, at the very least
- Requires many tools, and good data analyses

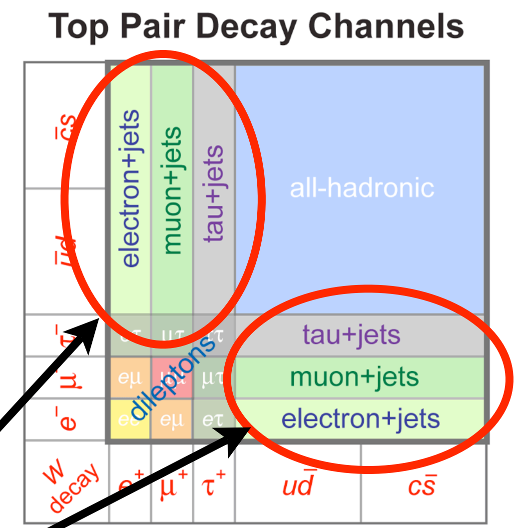
Why is top special?

- It has lots of quantum numbers, couples to pretty much everything..
- ..through chiral, vector, scalar structures (SM)
- Large mass
  - strong coupling to EWSB mechanism
  - good for pQCD, no hadronization ($m_t > m_W + m_b$)
  - spin information preserved due to rapid decay
- Top is trouble maker for SM (quadratic divergences...), enabler for MSSM, Little Higgs...
- Tevatron made the first precious few, now many more. LHC a top factory

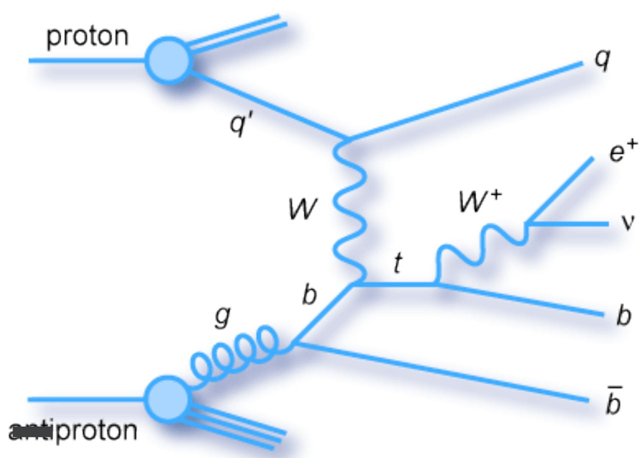
Recent excellent reviews by Han, and Bernreuther

LHC: T-factory





- Pairs: 8 MEvents/year (x 10)
- after 10 fb^{-1}: 70K lepton + jet events



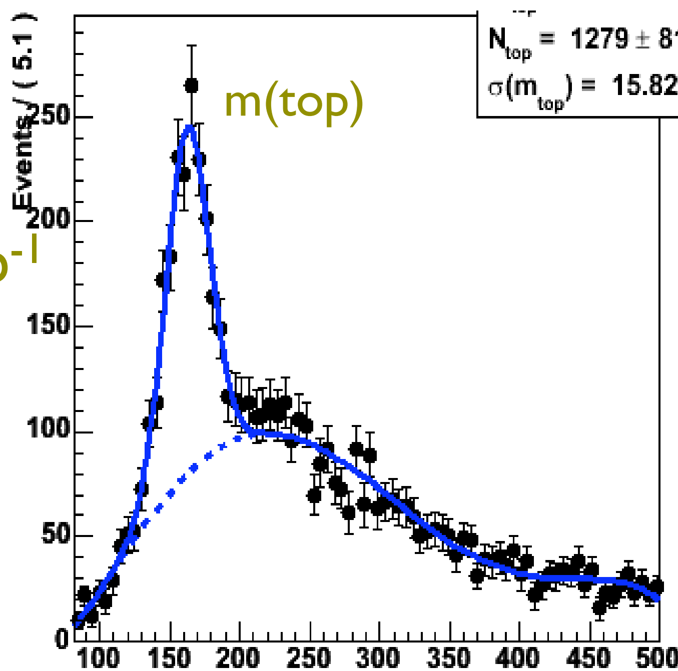
- Single: 2 MEvents/year (x 10)
- after 10 fb^{-1}: 5K events

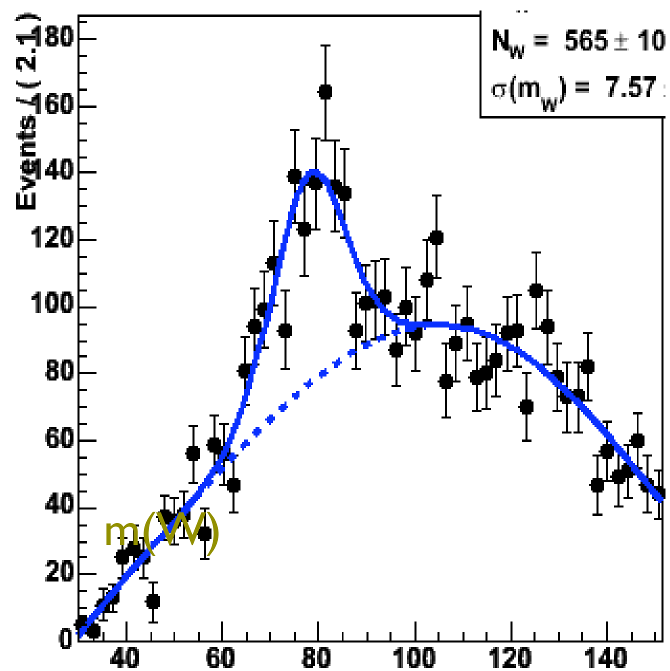
Top will immediately be used for calibration

Top calibration

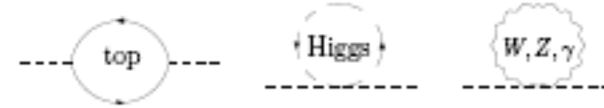
- Lepton + jets channel easy to trigger, high purity possible after b-tags
- At low luminosity, about 50 events/day
- Reconstruct first W (light jets), then add b-jet (top)
- Can find top without b-tagging, then use sample to study b-tagging

L = 300 pb^{-1}



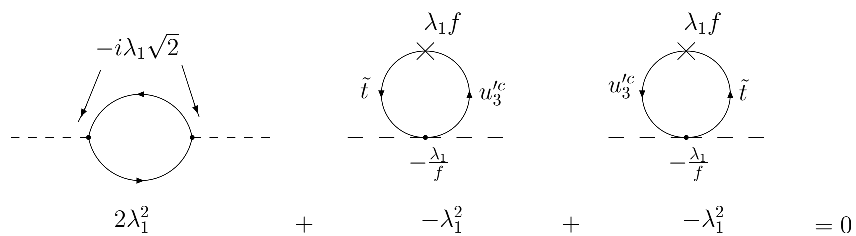


Top and Little Higgs



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

- Symmetries forbid one-loop Higgs mass term: solves little hierarchy problem
- ..which was caused, anyway, mostly by top loop corrections
- Little Higgs models cancel (top) quadratic divergences with similar particles of same spin (vectorlike top T e.g.)



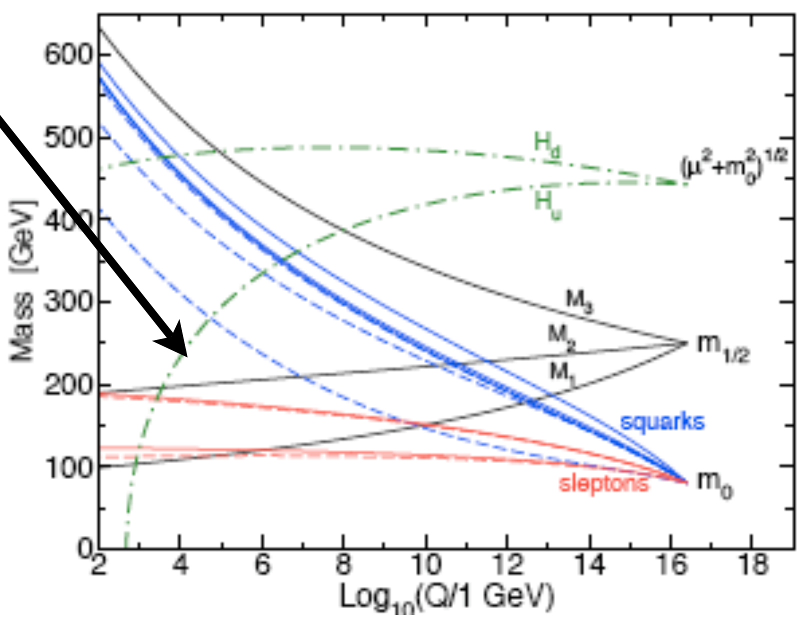
Han, Logan, Wang

Good number of models (gauge groups, T-parity), can be unraveled

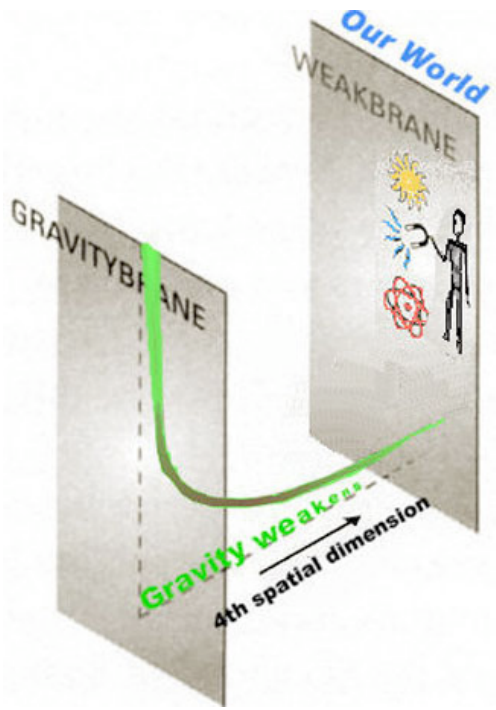
- measuring couplings in the top, T sector, and m_T (cross section 0.01-100 fb)
- test vector character of T

Top and SUSY

- Keeps MSSM alive via (top, stop) corrections on lightest Higgs mass
- Radiative EW symmetry breaking
- Many LHC SUSY signals involve top, or top mimics them
- Heavy Higgses may decay to top, can determine their CP properties



Top and extra dimensions

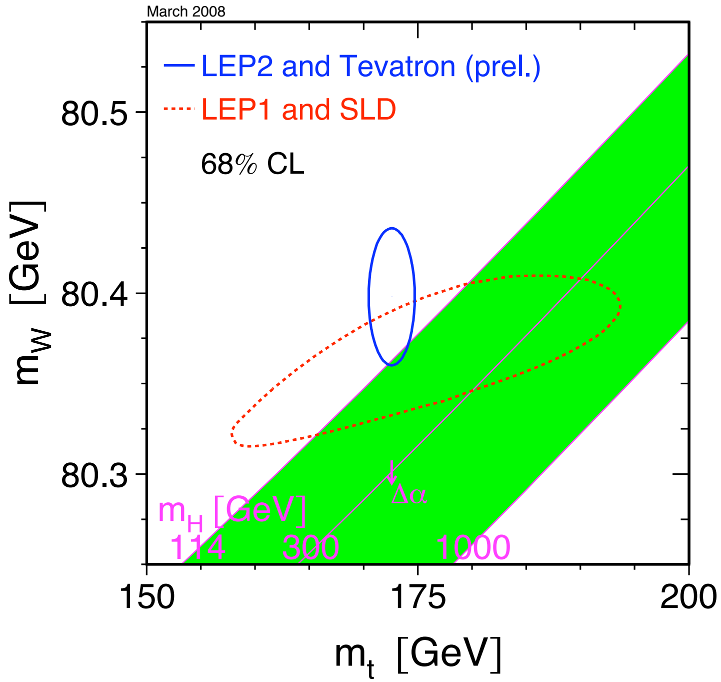


New particles, Kaluza Klein modes

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

Top mass

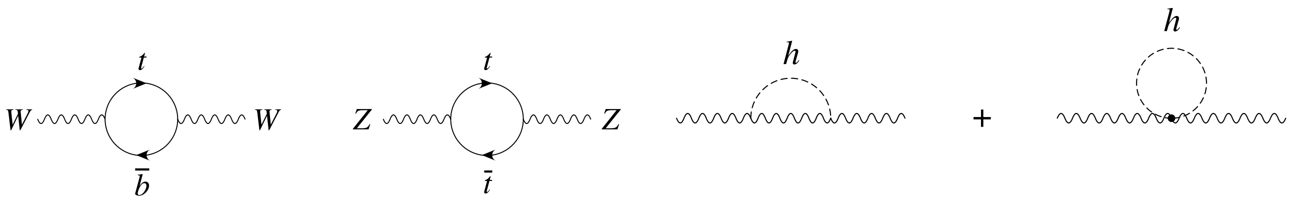
$\Gamma_t \cong 1.28$ GeV



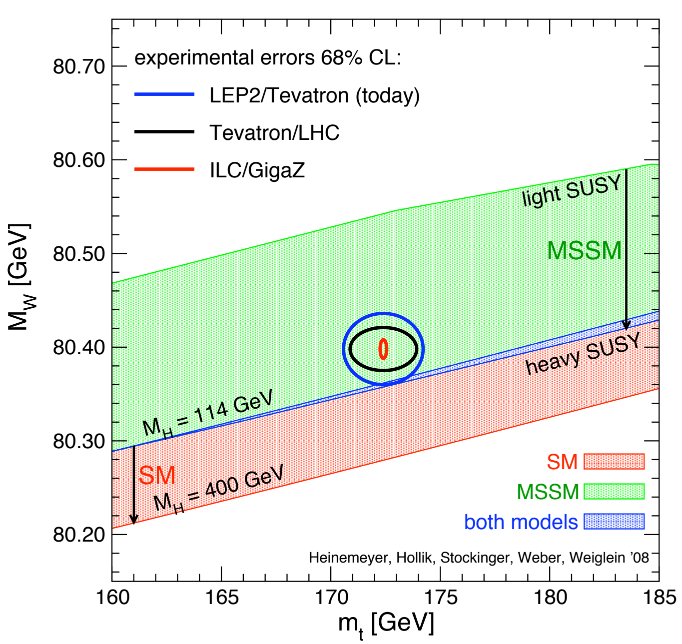
now: 173.1 ± 1.3 GeV (Tevatron)

<1% !!

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



Heinemeyer, Weiglein



- Measure via reconstruction of final state, or via cross section
- Relate m_W, m_t, m_H to constrain SM, MSSM

Top mass

- LHC: accuracy of 1 GeV possible→ 6 MeV accuracy of m_W at fixed m_H
- Experiments and theorists assume one reconstructs essentially the pole mass in hadron colliders
  - ✓ Hoang, Stewart: actually, a short-distance mass can be extracted
  - ✓ ..based on similarity of parton shower and e+e- factorization Fleming, Hoang, Mantry, Stewart; Beneke, Signer; Hoang
- Other mass definition perhaps through t→ b(→ J/ψ) + lν at LHC Karchilava, certainly (I)LC should allow precise short-distance mass extraction

NLO cross sections

Multi-differential hadronic NLO cross section

NLO PDF's

$$\frac{d\sigma^{pp\to X}}{d^3p_1\ldots d^3p_n} = \sum_{a,b}\int dx_1 dx_2 f_a(x_1,\mu_F) f_b(x_2,\mu_F)$$

$$\times\ \hat{\sigma}_{ab}(p_a+p_b\to p_X, \alpha_s(\mu_R), \mu_R, \mu_F) + \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right)$$

Multi-differential partonlevel NLO cross section

Power corrections.

Renormalization and Factorization scale

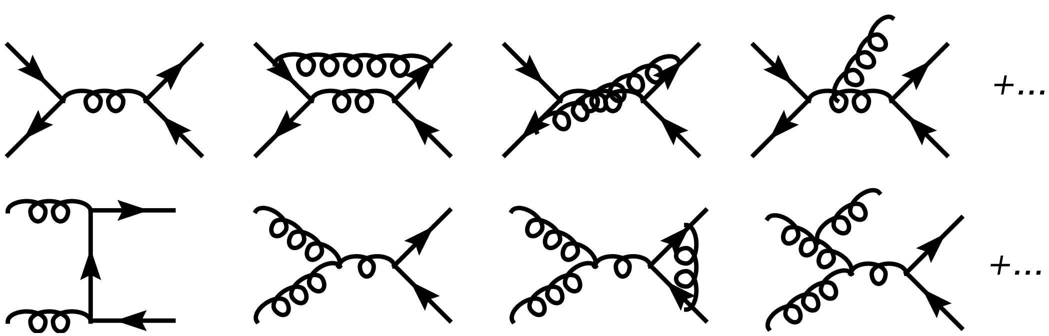
For NNLO, add "N" in all the right places..

Top pair production at NLO

Beenakker, Kuijf, Smith, van Neerven, Meng, Schuler; Nason, Dawson, Ellis — (Single particle) inclusive

Mangano, Nason, Ridolfi — Fully differential: HVQMNR

- It was for many years the most difficult NLO calculation done
- Many techniques and results (integrals) useful for other calculations



$\bar{t}t$ + electroweak corrections

Bernreuther, Brandenburg, Si, Uwer
Kuhn, Scharf, Uwer
Maina, Moretti, Nolten, Ross

- Order α_w corrections known
- Small effects on total rate at LHC
- Large (10%) effect at large p_T and M_{tt} (weak Sudakovs)

Exact top production at NLO

Czakon, Mitov

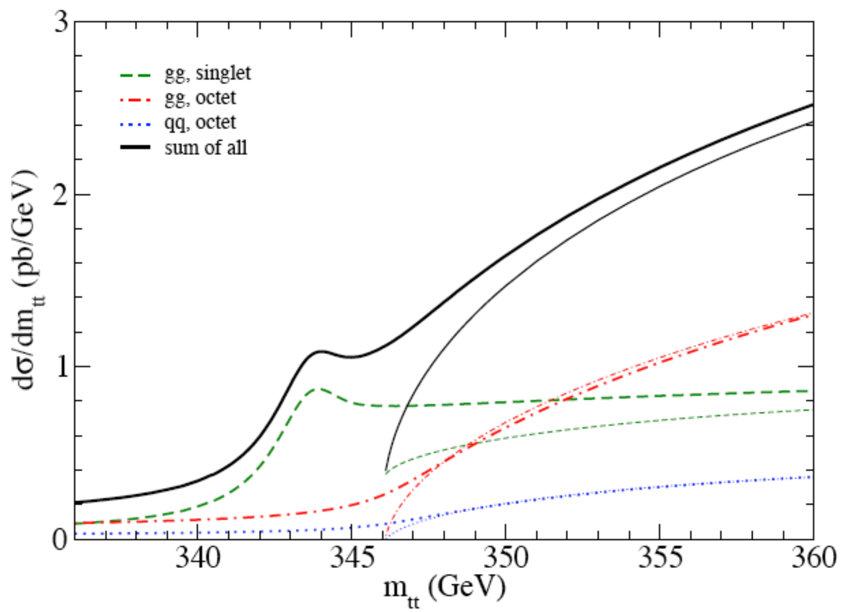
- Inclusive NLO cross section now computed fully analytically in terms of harmonic polylogs.
- Array of techniques (integration by parts, Mellin-Barnes..), test case
- Important ingredient for going to NNLO

NLO bound state effects

- In analogy to Linear Collider treatment, include threshold effects for M_{tt} distribution
- Consider production of tt pair in particular color state
- Two recent studies, including results from

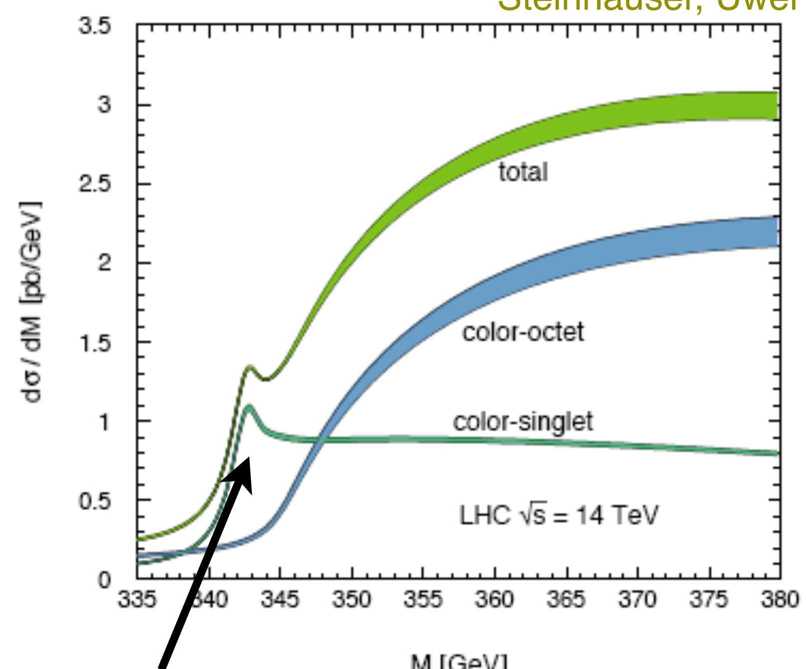
Kuehn, Mirkes; Petrelli, Cacciari, Greco, Maltoni, Mangano

Hagiwara, Sumino, Yokoya



Possibly significant and interesting aspect. Esp. LHC

Kiyo, Kuehn, Moch, Steinhauser, Uwer



Would allow a conceptually different top quark mass measurement

A bit of threshold resummation

All order sum of large logs

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

- "Threshold" depends on observable.
  - *But note*: for total cross section, one *could* use all three.
- For ease, first take moments of $(s\text{-}4m^2)$ etc

$$\sum_n \alpha_s^n \ln^{2n} N$$

- Then resum. Then, undo moments

A bit of threshold resummation

- ✓ Logs L from soft/collinear gluons, can be summed to all orders

$$\hat{O} = 1 + {}_s(L^2 + L + 1) + {}^2_s(L^4 + L^3 + L^2 + L + 1) + \ldots$$
$$= \exp\left(\underbrace{\underbrace{L g_1({}_sL)}_{LL} + g_2({}_sL)}_{NLL} + {}_s g_3({}_sL) + \ldots\right) \underbrace{C({}_s)}_{\text{constants}}$$
$$+ \text{ suppressed terms}$$

- ✓ Many ways to derive exponential form
- ✓ Algebraic proof: "eikonal" perturbation theory is exponent of "web" diagrams
- ✓ For Higgs/Drell-Yan inclusive cross section:

$$\hat{\sigma}_i(N) = C(\alpha_s) \times \exp\left[\int_0^1 dz \frac{z^{N-1} - 1}{1 - z}\left\{2\int_{\mu_F^2}^{(1-z)^2Q^2} \frac{d\mu^2}{\mu^2} A_i(\alpha_s(\mu^2)) + D_i(\alpha_s(1-z)Q^2)\right\}\right]$$

- ✓ A: Cusp anomalous dimension. D: known to 3rd order
- ✓ Similar for top, but D is a *matrix in color space*

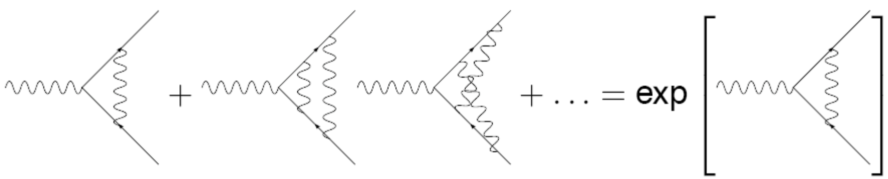
Sterman; Catani, Trentadue, Gatheral, Frenkel, Taylor, Grazzini, de Florian, Forte, Ridolfi, Vogelsang, Kidonakis, Kulesza, EL, Magnea, Moch, Vogt,Vogt, Eynck, Ravindran, Becher, Neubert, Ji, Idilbi,...

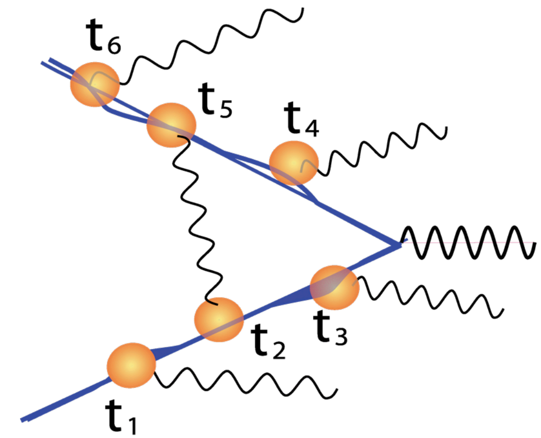
Aside: a path integral approach to exponentiation

EL, Stavenga, White

Scattering amplitude as particle path integral

$$\int \mathcal{D}x^{\mu}(t)\ \exp[i\int dt(\frac{1}{2}\dot{x}^2 - \frac{1}{2}x^2 - \dot{x}\cdot A(x))]$$





- Eikonal vertices as gauge field source terms
- Exponentiation is just usual exponentation of all diagrams in terms of connected ones..
- Generalized to non-abelian case using "replica trick" of stat. mech.
- Next-to-eikonal terms as path fluctuations

Theoretical top cross sections

- ✓ NLL resummed, with exact NLO
- ✓ Tevatron top near threshold, LHC not so much
- ✓ Since 2003 better PDF's, new results in resummation
- ✓ CTEQ6.5, MRST2006-NNLO
- ✓ Time to update the inclusive top cross section, and its errors

Cacciari, Frixione, Mangano, Nason, Ridolfi

- ✓ Vary μ_R, μ_F independently, conservatively
- ✓ No error combinations
- ✓ At LHC: scale uncertainty >> PDF uncertainty
- ✓ Tevatron: 10% LHC: 10 % (NLO-NLL)

Moch, Uwer

- ✓ Vary $\mu_R = \mu_F$
- ✓ Linear error combinations
- ✓ Tevatron: 7% LHC: 5% (NNLO-approx)

Nadolsky, Lai, Cao, Huston, Pumplin, Stump, Tung, Yuan

- ✓ Vary $\mu_R = \mu_F$
- ✓ CTEQ6.6
- ✓ Use cross section as gluon probe, standard candle

Approximate NNLO cross section

Moch, Uwer

Resummed cross section
$$\frac{\hat{\sigma}^N_{ij,I}(m_t{}^2,\mu_f^2,\mu_r^2)}{\hat{\sigma}^{(0),N}_{ij,I}(m_t{}^2,\mu_f^2,\mu_r^2)} = g^0_{ij,I}(m_t{}^2,\mu_f^2,\mu_r^2)\cdot\exp\left(G^{N+1}_{ij,I}(m_t{}^2,\mu_f^2,\mu_r^2)\right)$$

Improved

Czakon, Mitov

Exponent:
$$G^N_{q\bar{q}/gg,I} = G^N_{\mathrm{DY/Higgs}} - \delta_{I,8} G^N_{Q\bar{Q}},$$

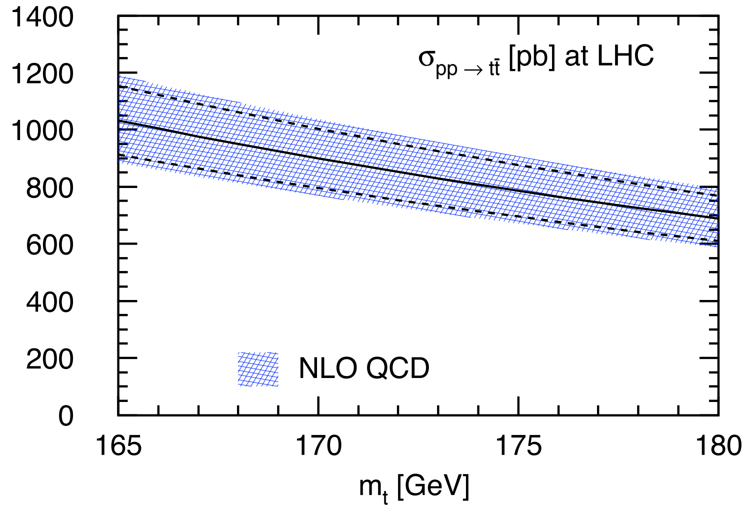
Remarkable: Known to 3 loops; Known to 2 loops

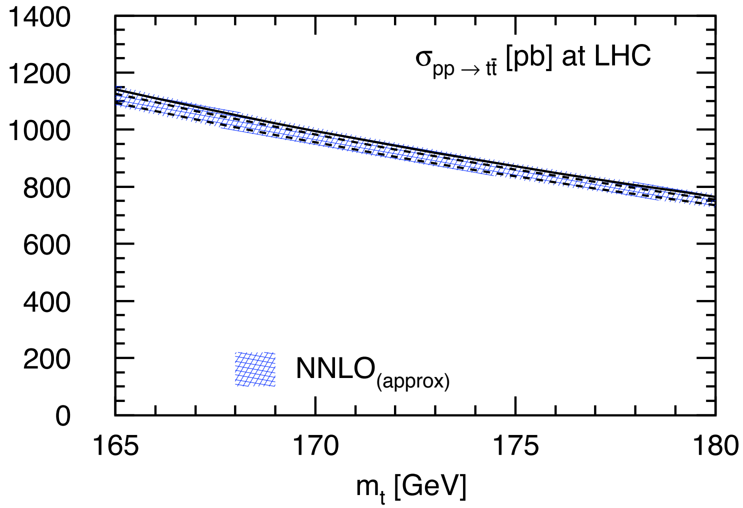
Aybat, Dixon, Sterman
Mitov, Sterman, Sung

Result:
$$\alpha_s^2 \sum_{n=0}^{4} c_n \ln^n\beta + \text{Coulomb}, \qquad \beta = \sqrt{1-\frac{4m^2}{s}}$$

Other thresholds?

Moch, Uwer





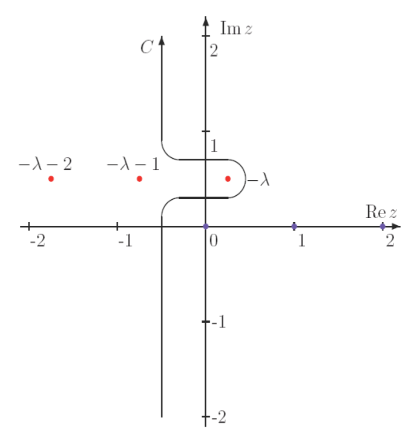
Perhaps too small?

Exact NNLO top cross section?

Czakon, Mitov, Moch

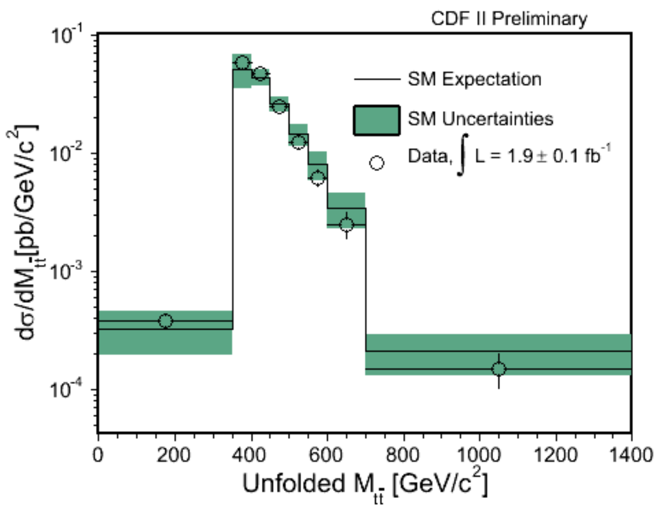
- Full exact NNLO 2 →2 does not yet exist for massless partons
- Part of real corrections (1 virtual + 1 emission) known (Dittmaier, Uwer, Weinzierl)
- Virtual corrections now computed for $m_t^2 << s,t,u$
  - $\log(m_t)$ from Factorization + 2-loop massless results (Mitov, Moch)
  - Direct calculation via Mellin-Barnes (Czakon) methods
- Now also large m_t virtual results

$$\frac{1}{(A+B)^{\nu}} = \frac{1}{\Gamma(\nu)}\frac{1}{2\pi i}\int_C dz\, \frac{A^z}{B^{\nu+z}}\Gamma(-z)\Gamma(\nu+z)$$

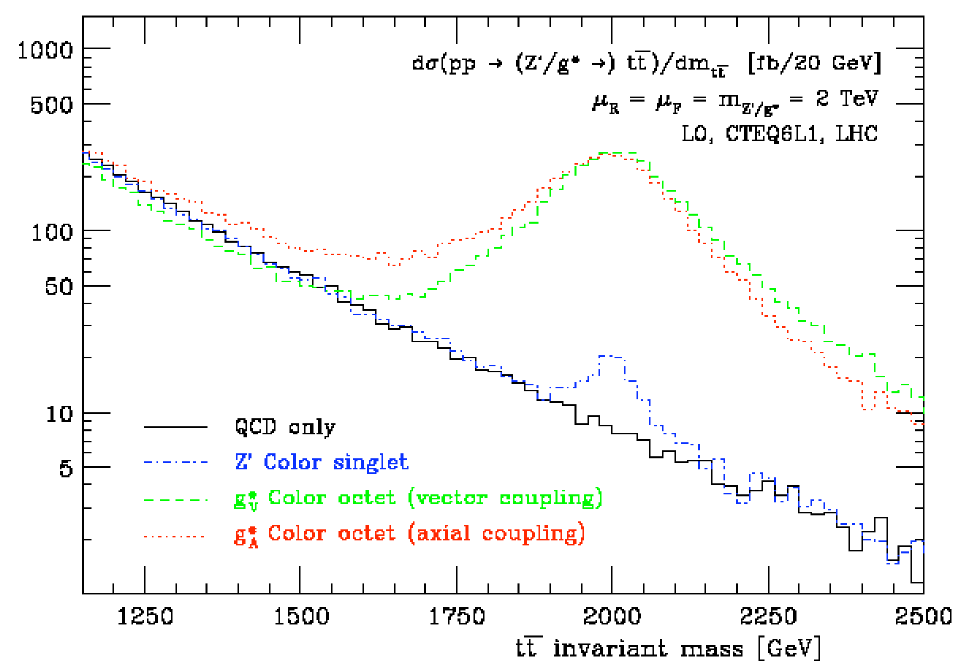


Pair-invariant mass distribution

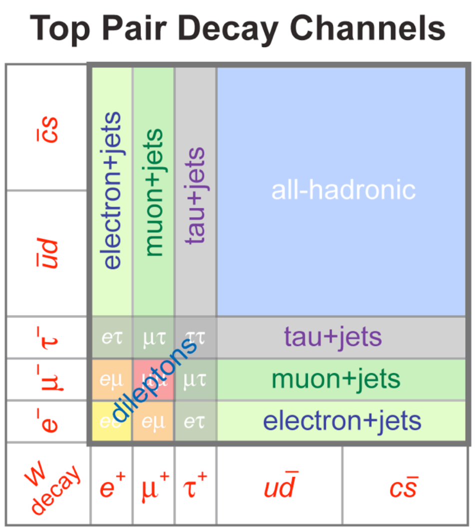
Frederix, Maltoni



- Sensitive to many SM extensions decaying to top pairs
- Bottom-up approach, don't assume full model
- Use MadEvent/Madgraph
- Study of (pseudo) scalar, vector, spin-2 resonances. Gives masses, widths, parity, spin. Interference matters.

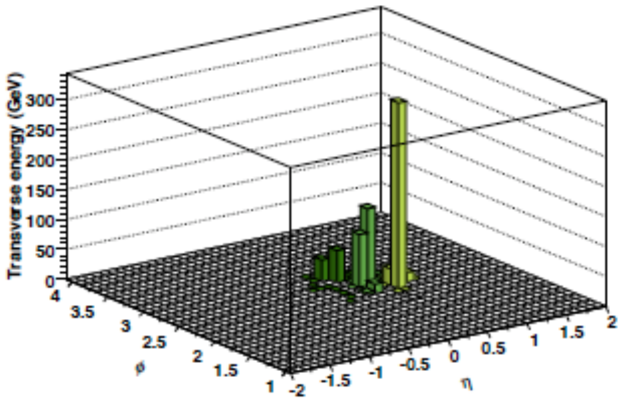


Top decay and detection



- Standard Model: almost 100% to W+b
  - ✓ "Easiest": for ttbar lepton + missing E_T + 4 jets, with b-tags
  - ✓ For single top multi variate methods were needed
- Rare decays monitored

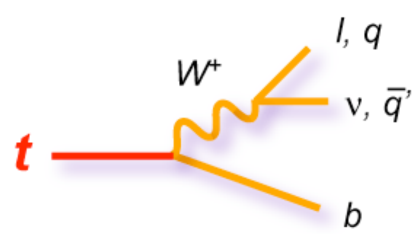
Boosted Tops



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

Butterworth et al

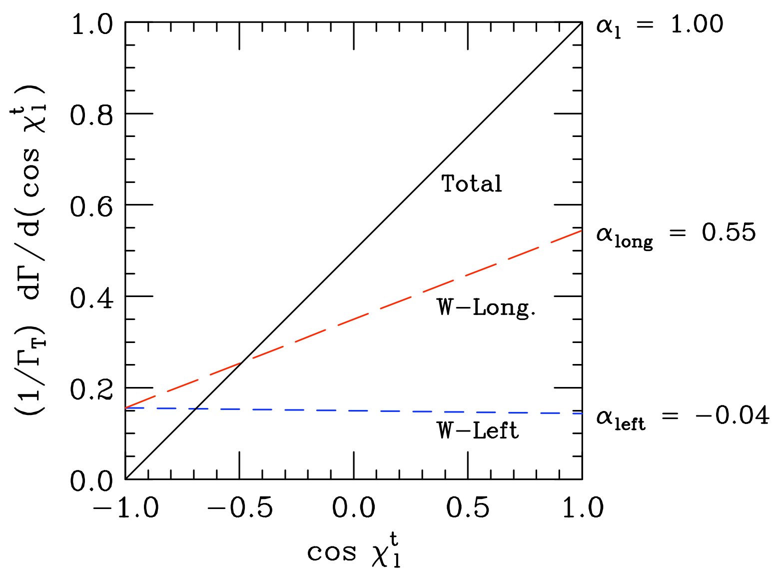
- Following ideas to tag Higgs and other Jets, can one efficiently tag high pt top jets?
  - "Reverse engineer clustered fat jet", find 3 subjects.
    - ✓ Reduce dijet backgrounds to ttbar resonances by 10K
  - For two-body decay, use "z" asymmetry. Challenging.
    - ✓ For three-body decay, use special event shape instead of subclusters, or W constraint
  - Use jet mass cuts, plus jet shapes



Top decay: spin

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

- Top self-analizes its spin: 100% correlation (α_f = 1) of t-spin with l^+-direction
- QCD corrections to α_f very small
- Worthy of verification (e.g. charged Higgs decay would lower α_f)
- Powerful probe of spin quantum numbers of top, and any process that produced it (single top, resonance,..)



Higher order associated top production

Much recent progress

- Associated production at NLO (3+ particles in final state at LO)
- Monte Carlo descriptions, both parton-shower and matrix-element based
- Top spin included

$t\bar{t}$ + Higgs to NLO

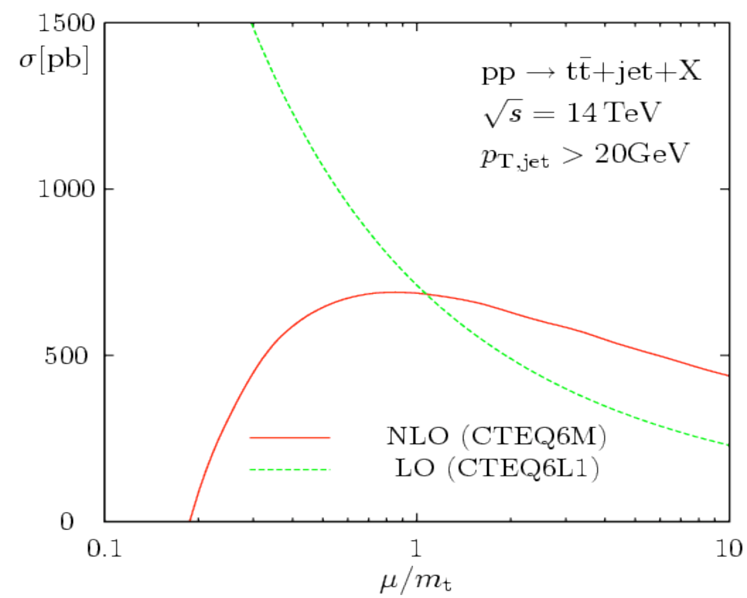
Beenakker, Dittmaier, Krämer, Plumper, Spira, Zerwas;
Dawson, Jackson, Orr, Reina, Wackeroth

- Helps measure top yukawa coupling
- Early studies: excellent for discovering light Higgs (→ bb)
- Recent studies [ATLAS,CMS]: backgrounds probably too hard for Higgs discovery
- NLO 2 →3 process with different masses feasible, both for phase space slicing and subtraction methods
- Spin-off: bb → Higgs (for MSSM) (Harlander, Kilgore; Maltoni, Sullivan, Willenbrock)
- Recent: first results for ttbb production at NLO (Bredenstein, Denner, Dittmaier, Pozzorini)

Dittmaier, Uwer, Weinzierl

$t\bar{t}$ + jet to NLO

- Helps unravel top pair production, sensitive to new physics
- Important background to many BSM signals
- Possibly measure top charge asymmetry in pp
- Theoretical testing ground: 2 →3 full QCD at NLO, with mass, and complicated color structure
- Many advanced techniques used (novel reductions, dipole method, Berends-Giele recursion). Two fully independent calculations
- Computer algebra crucial

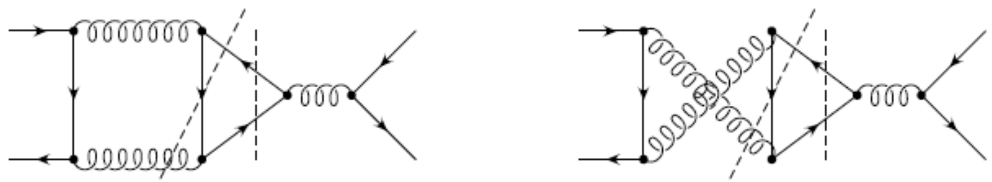


Charge asymmetry

aka forward-backward asymmetry

CDF: 24 ± 13 ± 4 %

D0: 12 ± 8 ± 1 %



- Rate difference of top vs. anti-top at fixed angle (or rapidity)
- At LO from Electroweak, or BSM mechanisms
- Shows up in QCD first at $O(\alpha_s^3)$ through (a) interference Born-Virtual, or (b) radiative. Nason, Dawson, Ellis
  Beenakker, Kuijf, van Neerven, Meng, Schuler, Smith
- Interference of C-odd and C-even amplitudes. Proportional to SU(3) d_{abc} Rodrigo, Kuhn
- NLL threshold resummation [Almeida, Sterman, Vogelsang] for charge asymmetry from that for
  $$\frac{d\sigma^{t\bar{t}}}{dM_{t\bar{t}}\, d\cos\theta}$$
  Kidonakis, EL, Moch, Vogt
  Kidonakis, Sterman
- Sizeable enhancement at large M_{tt}, but overall moderate, and more accurate

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

Bernreuther, Brandenburg, Fücker, Si, Uwer
Mahlon, Parke
Godbole, Rindani, Singh

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

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

- C depends on quantization axis, highest in helicity basis in zero momentum frame
  - $C_{hel} = 0.326$ ($C_{beam} = -0.07$)

Top and Monte Carlo

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 included)
- POWHEG: tt + ≤ 1 jet

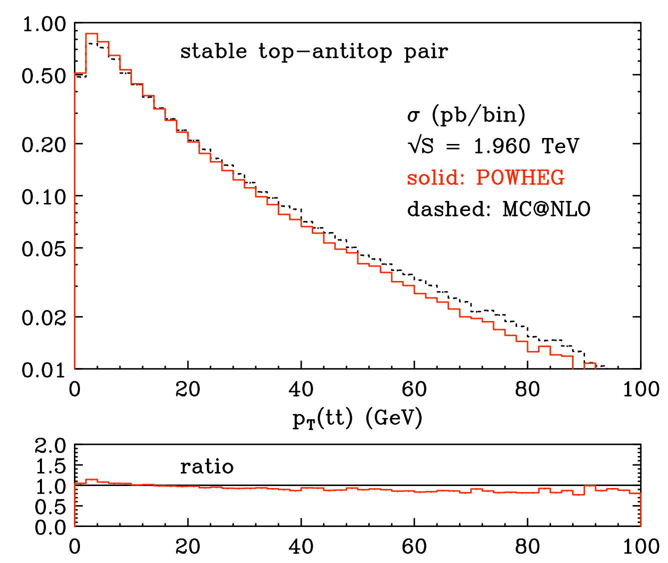
Matching NLO to PS

Double counting dangers:

- emission from NLO and PS should be counted once
- virtual part of NLO and Sudakov form factor should not overlap
- some freedom in this:

Frixione, Webber; Nason

- ✓ MC@NLO matches to HERWIG angular ordered showers. Uses FKS.
- ✓ POWHEG insists on having positive weights, exponentiates complete real matrix element. Can use dipole method or FKS. Nason; Frixione, Oleari
- ✓ MC@NLO has more processes built in for now. But it should be easier to do that for POWHEG.



Frixione, Webber

MC@NLO

Expanded parton shower

$$\frac{d\sigma}{dO} = \int_0^1 dx \Big[I_{MC}(O, x_M(x)) \frac{\alpha(R(x) - B\,Q(x))}{x} + I_{MC}(O,1) \frac{B + \alpha V + \alpha B(Q(x)-1)}{x} \Big]$$

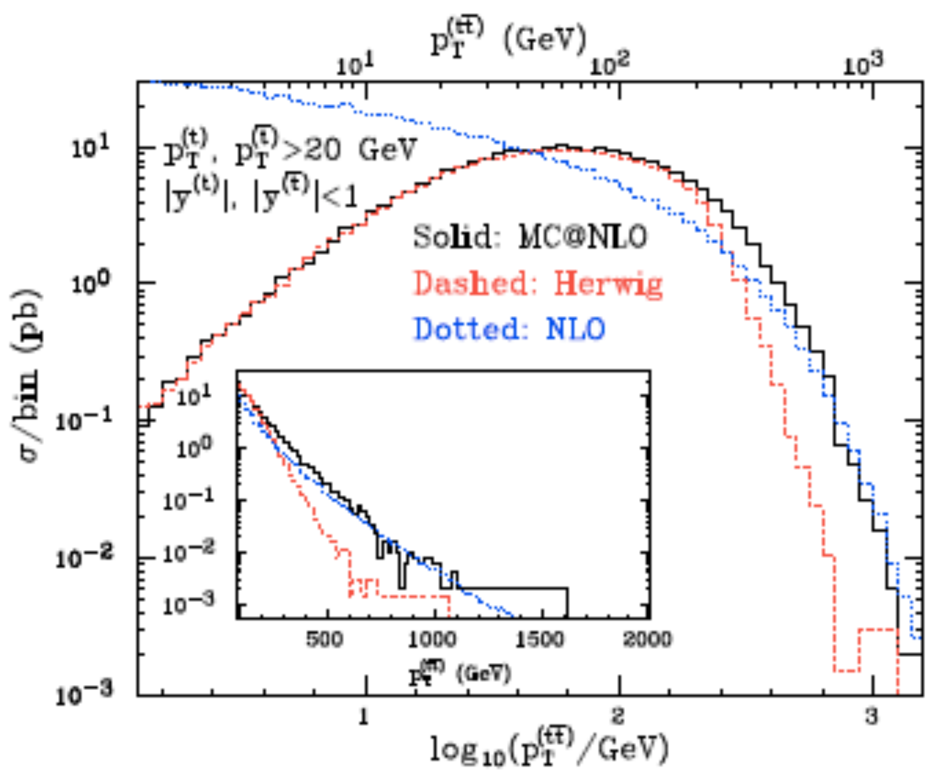
Interface to parton shower

- Events have weight +1 or -1 (< 15%)
- Showers from hard processes of NLO cross section, 2→2 and 2→3
- Inclusive rate is σ(NLO)

MC@NLO and $t\bar{t}$

Frixione, Nason, Webber

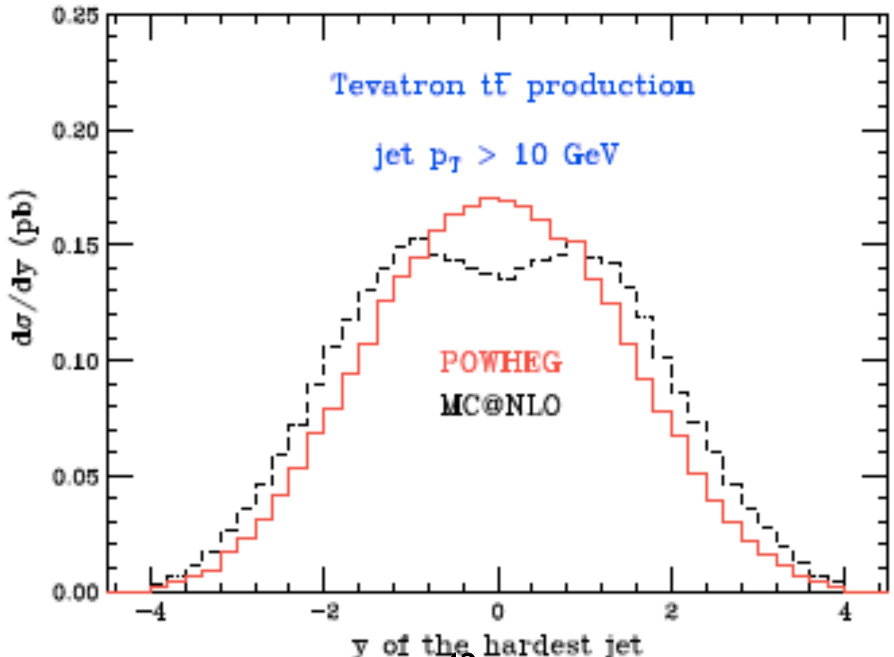
- First process in MC@NLO with final state colored partons, multiple color flows
- Interpolates well between NLO and parton showers



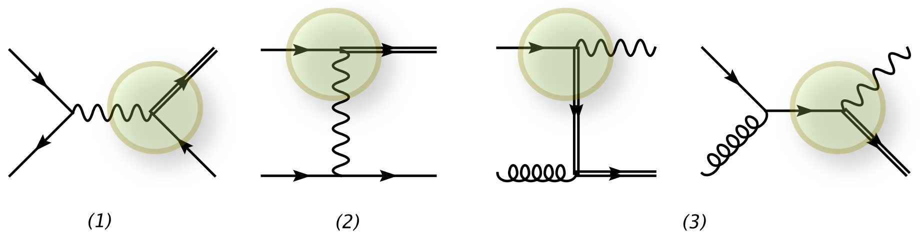
Top MC comparisons

With MC descriptions of top physics so central, it is important to understand differences

- POWHEG (Nason; Oleari, Frixione no negative weights, different showering) vs MC@NLO
- MC@NLO vs. ALPGEN for tt+jet
- Dip related to HERWIG



Single top at NLO



s-channel: timelike W

t-channel: spacelike W

Wt channel: real W

- Allows measurement of V_{tb} per channel
- Easier check of chiral structure of Wtb vertex than tt
- Infer the b-density   Campbell, Frederix, Maltoni, Tramontano
- Sensitive to FCNC's (t-channel), or W' resonances (s-channel)

Harris,EL,Phaf,Sullivan, Weinzierl; Cao, Schwienhorst, Yuan; Zhu; Campbell, Ellis, Tramontano

σ(NLO)	s-channel [pb]	t-channel [pb]	Wt-channel [pb]
Tevatron	0.90	2.00	0.00
LHC	10.20	245.00	60.00

Four is the number thou might count..

Alwall, Frederix, Gerard, Giammanco, Herquet, Kalinin, Kou , Lemaitre, Maltoni ;
Chanowitz;   Holdom, Hou, Hurth, Mangano, Sultansoy, Unel

- Recent studies on viability of fourth fermion family
  - ✓ Fourth generation not excluded by EW data, falsifiable at LHC
  - ✓ Baryogenesis viable, narrower Higgs window, dark matter candidate, strong dynamics?
- 3-4 mixing allowed, of Cabibbo-like strength
- obviously relevant for top physics..

V_{tb}

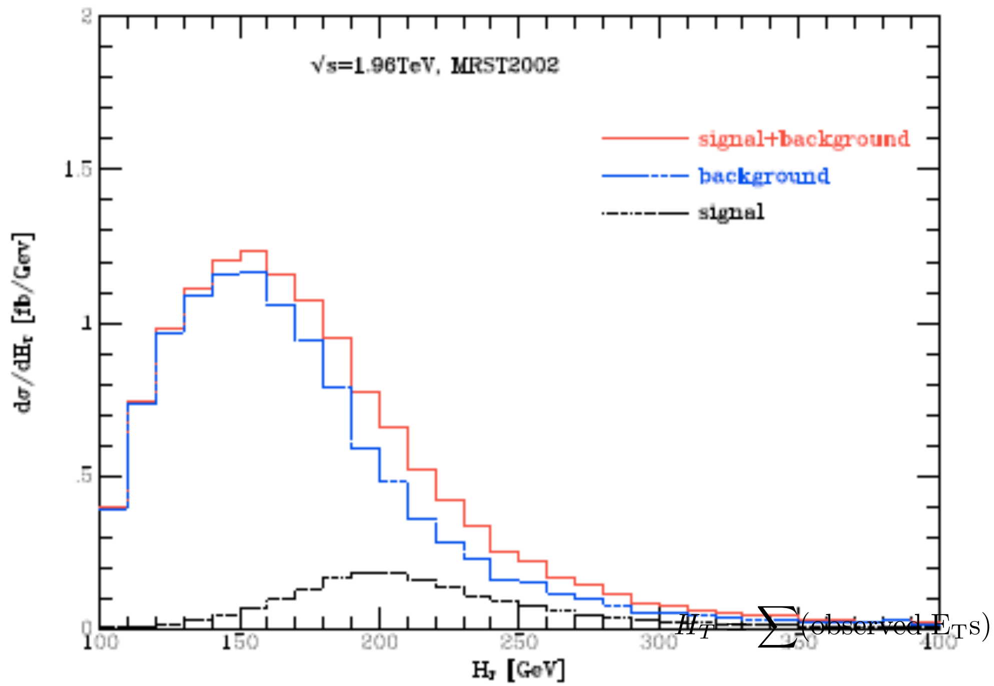
- In SM constrained to be 0.9998 by unitarity
- E.g. if extra vector-like quark, or 4th generation, V_{tb} > 0.8 - 0.9, depending on assumptions Alwall et al [Louvain]
- Directly measurable, 3 times, through single top production
- In practice: not so easy.
  - CDF/D0: > 0.71/0.78 at 95% CL

Single top at NLO, cont'd

Differential distributions at NLO

- Calculated with about all phase space slicing and subtraction mechanisms known to Man
- Top spin, in NWA, included using NLO density matrix

Campbell, Ellis, Tramontano [MCFM]



Signal: lepton, E_T-miss, 2j (1b)
Bkgd: W+ 2j, tt, mistags

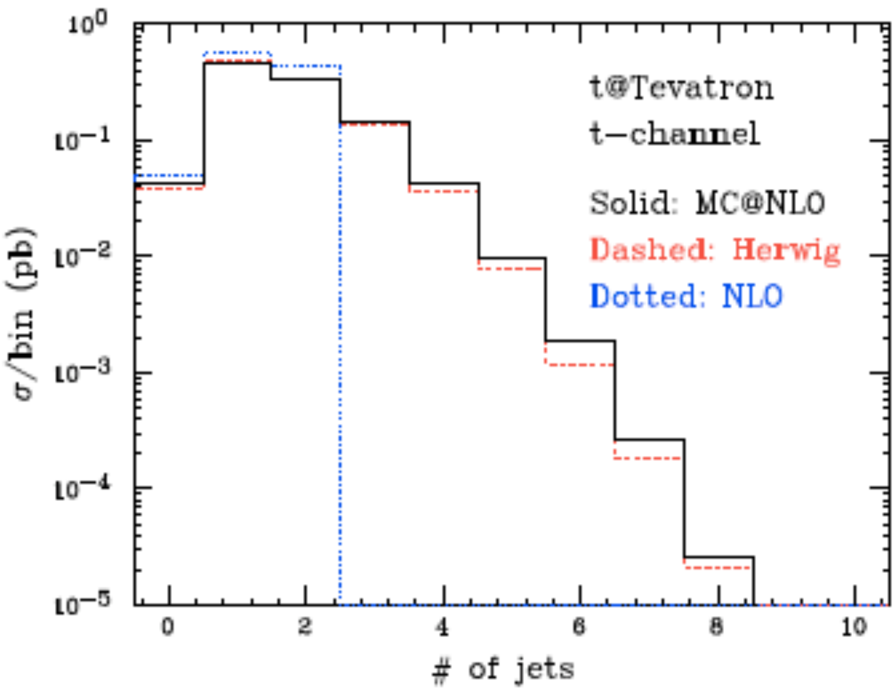
Single top in MC@NLO

Frixione, EL, Motylinski, Webber

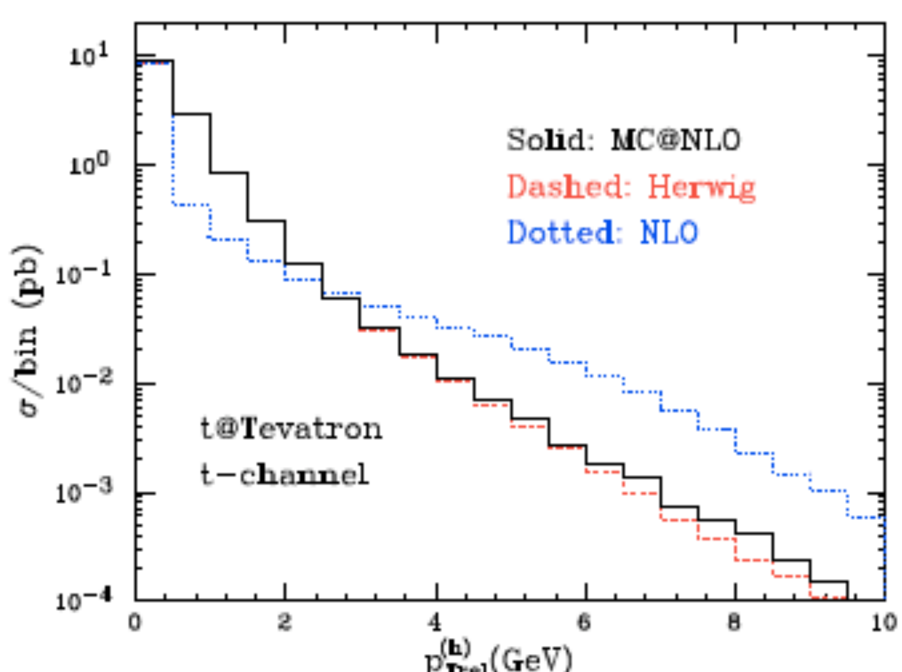
Adds MC@NLO benefits to this process, but also

- required extension of MC@NLO to final state jets
- simplified subtraction method

Number of jets



pT relative to jet axis in hardest light jet



Spin correlations in MC

Frixione, EL, Motylinski, Webber

$$a + b \to (P \to d_1 + \dots d_n) + X$$

Efficient way to include spin correlations $d_i \cdot a,\ d_i \cdot b$ into event generation if one did not have it before.

- Use resonant diagrams, LO density matrix for P-decay (top or W,Z)
- Steps:

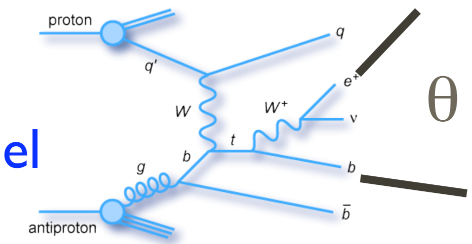
1. integrate NLO result for stable top
2. generate 3 extra momenta for its decay
3. compute tree level full decay matrix element
4. do simple hit-and-miss using maximum of spin-density matrix, and tree-level helicity amplitudes for full process

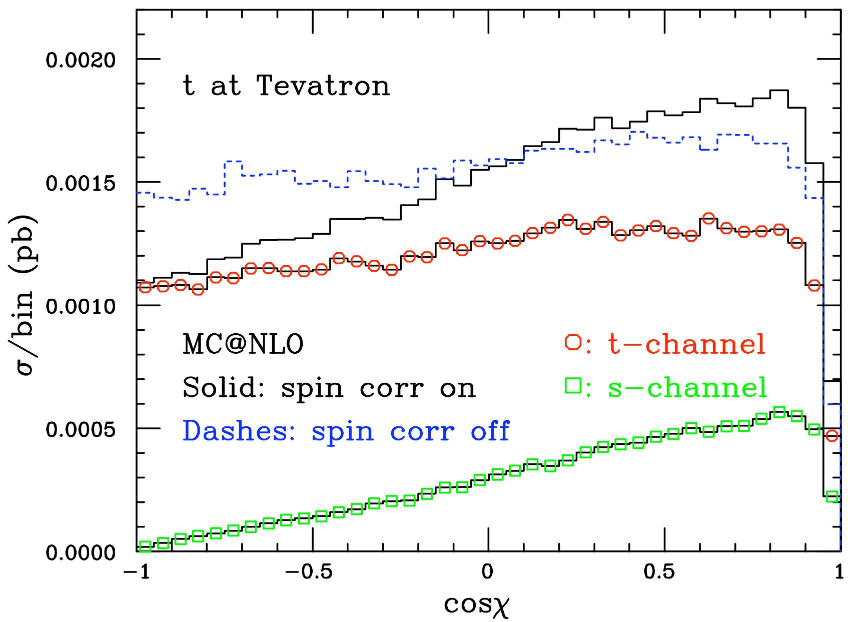
$$d\sigma(e^+\nu_e b) < d\sigma^{\mathrm{NLO}}(t_{s'}) \otimes \rho_{s's}$$

Spin correlations for single top in MC@NLO

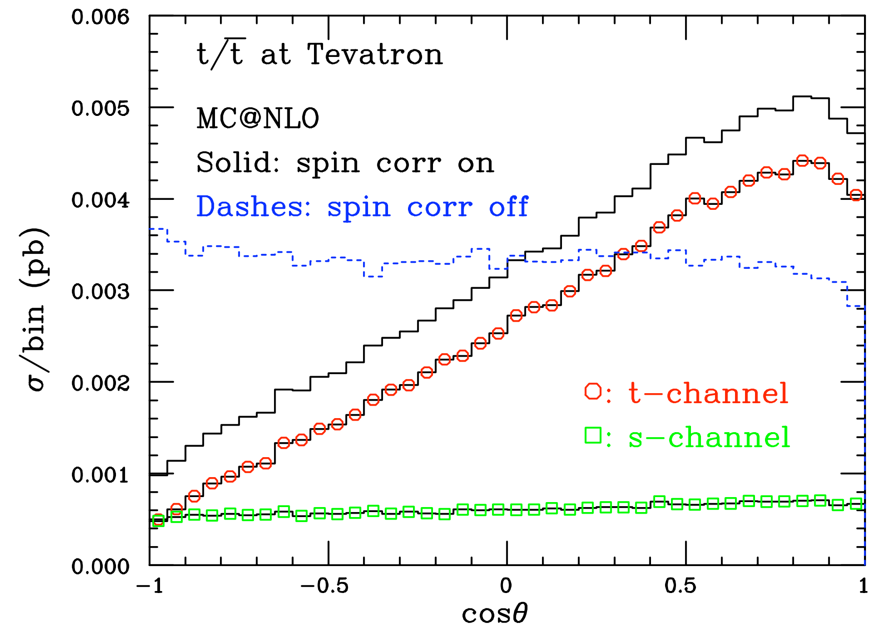
Frixione, EL, Motylinski, Webber

- Top is produced polarized by EW interaction
- Angle of lepton with appropiate axis different per channel





Beam direction

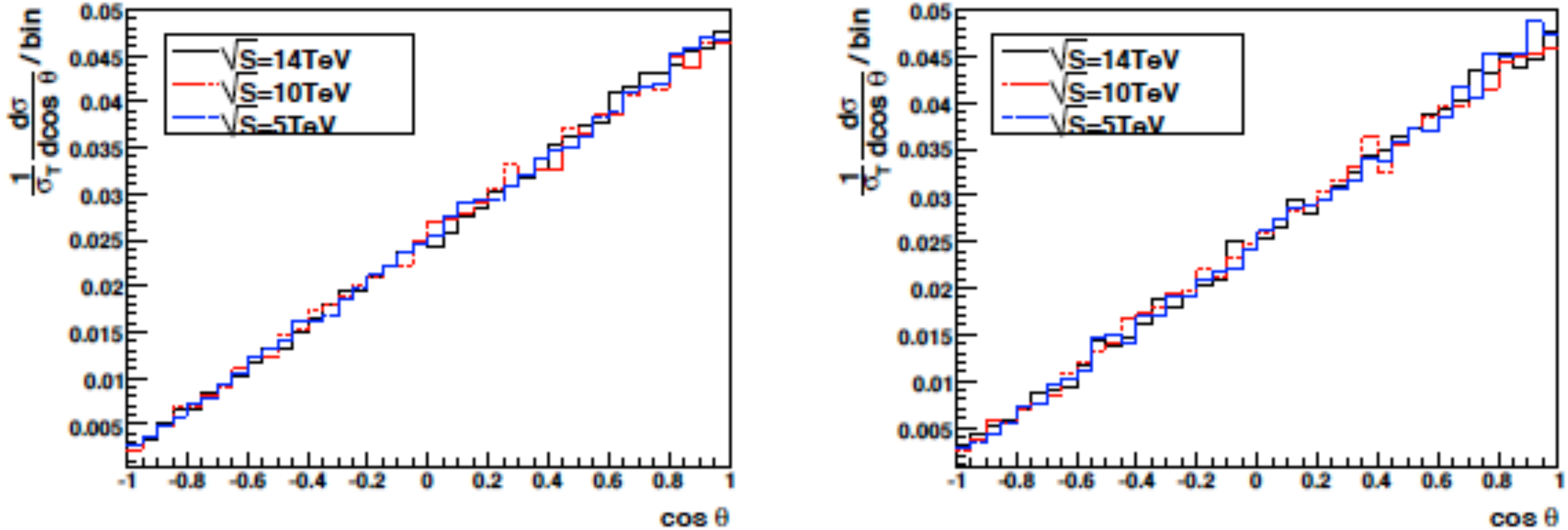


Hardest, non-b jet

Robust correlation, even in event generation

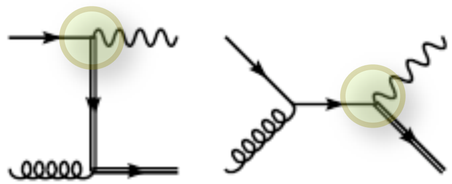
Spin correlations at other LHC energies

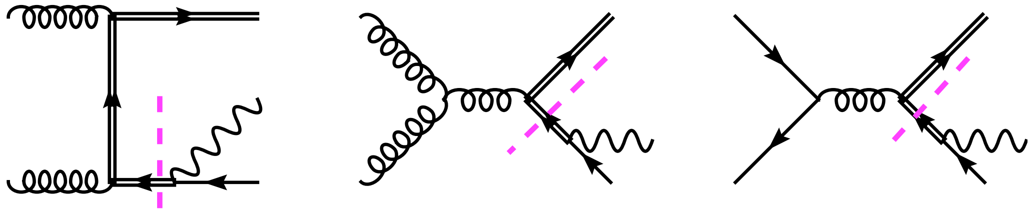
Motylinski



Frixione, EL, Motylinski, Webber, White

Single top in Wt mode meets tt..





+ non-resonant diagrams

Serious interference with pair production (15 times bigger)

- Other solution: compute WWb(b) (Kauer, Zeppenfeld), don't separate. NLO?
- Previous: cut on invariant Wb invariant mass (Belyaev, Boos, Dudko), subtraction of resonant cross section (Tait)
- MCFM (Campbell, Tramontano) Veto if p_T of 2nd hardest b (or B) is too hard; suppress channels through scale choice
- What can one do in event generation?
- Can one actually define this process?

Can we define W+t as a process?

We also include p_T veto. Two approaches

- Remove resonant diagrams (DR) (- not gauge invariant)
- Constructed a gauge invariant, local counterterm. Diagram subtraction (DS)
- DS - DR is measure of interference

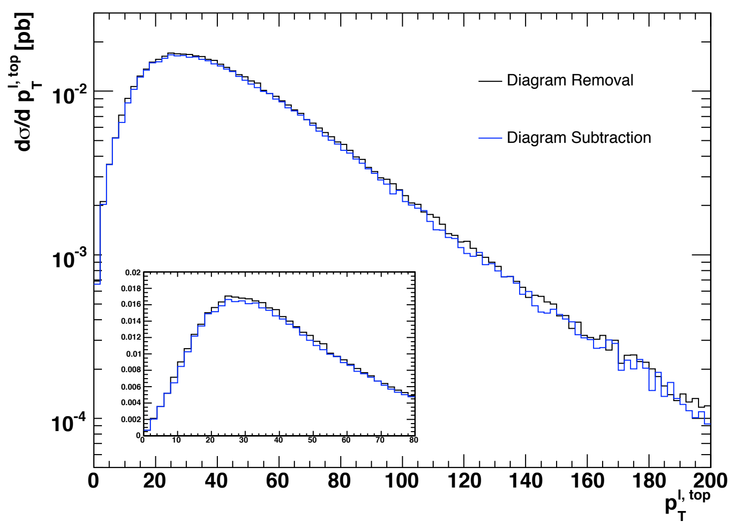
Momentum reshufling

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

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

Compare

- Interference effects quite small
- Gauge variant result always very close to gauge invariant
- Prototype for other, BSM cases (t+H- e.g.)
- Next question: can one isolate Wt?



Conclusions

- Top is the new bottom, useful everywhere at once
- It plays a role in almost every activity at the Terascale
- Theory tools good, and keep remarkable pace of innovation
- Top will remain central to LHC and Tevatron physics program
- We have much to learn from top, and from eachother
- ... so can look forward to an excellent workshop