Top physics at the ILC and hadron colliders

LC09
Perugia, Sept. 21-24

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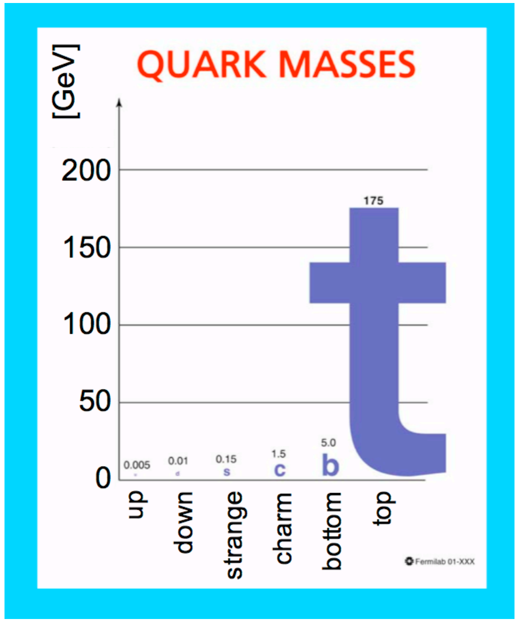
Heavy quark history

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



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..

- This talk: selection of top physics issues at ILC and LHC/Tevatron *)

*) by a non-linear expert

Top in Standard Model: gauge sector

- Fields in representations of fundamental local symmetries

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

- Spacetime derivatives are actually covariant ones

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

Generators of symmetry groups

- Source of interactions with gauge fields

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

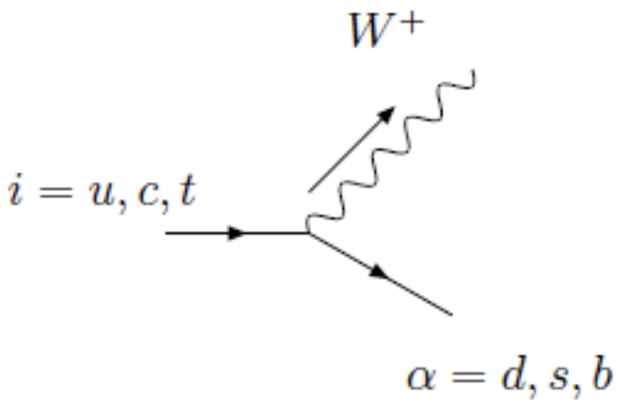
- Left / righthanded top quark charges
  - ✓ Hypercharge 1/6 / 2/3
  - ✓ Weak isospin 1/2 / 0
  - ✓ Both color triplets

Top in Standard Model: 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

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



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*

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

Same couplings that determine masses determine interactions

Standard Model top

- coupling to W bosons mixes flavors, is left-handed $\frac{g}{\sqrt{2}} V_{tq} \left(\bar{t}_L \gamma^\mu q_L\right) W_\mu^+$
- coupling to gluons vectorlike $g_s \left[T_a^{SU(3)}\right]^{ji} \bar{t}_j \gamma_\mu t_i A_\mu^a$
- 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

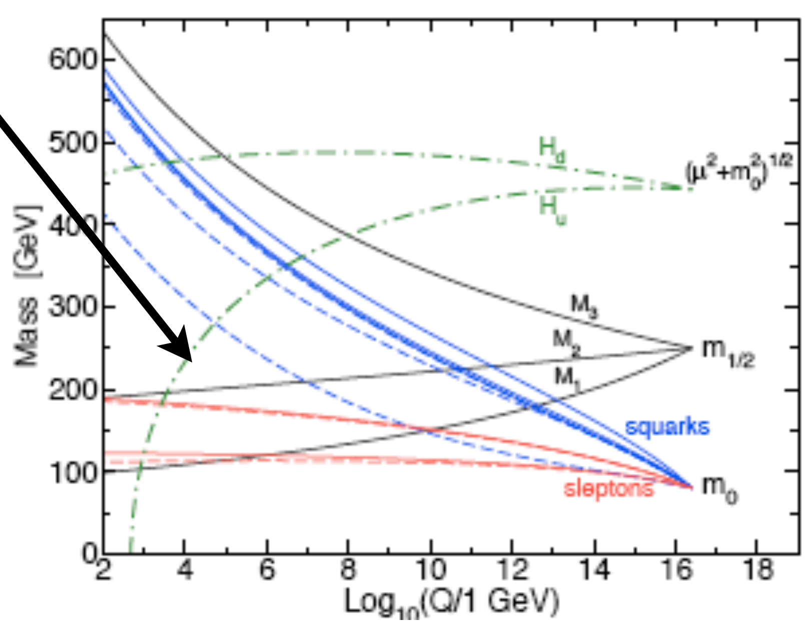
- Verify or falsify these, at the very least
- Requires many tools, and good data analyses
- LHC can do good, ILC can do fantastic job

Top is special because

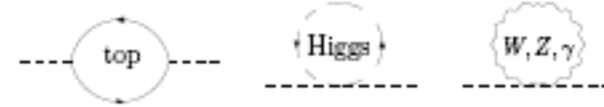
- it has lots of quantum numbers, couples to pretty much everything..
- ..through chiral, vector, scalar structures (SM)
- it has huge mass
  - strong coupling to EWSB mechanism
  - good for pQCD, no hadronization ($m_t > m_W + m_b$)
  - spin information preserved due to rapid decay
- it is trouble maker for SM (quadratic divergences...), enabler for MSSM, Little Higgs...

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

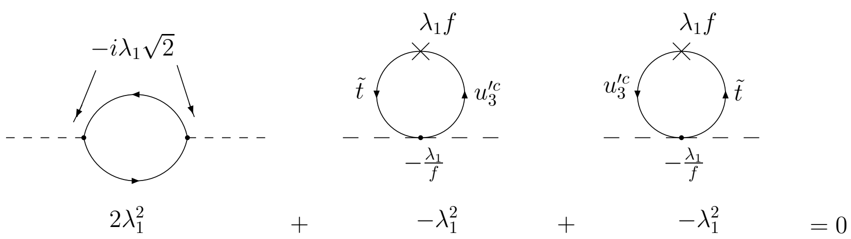


Top and Little Higgs



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.)

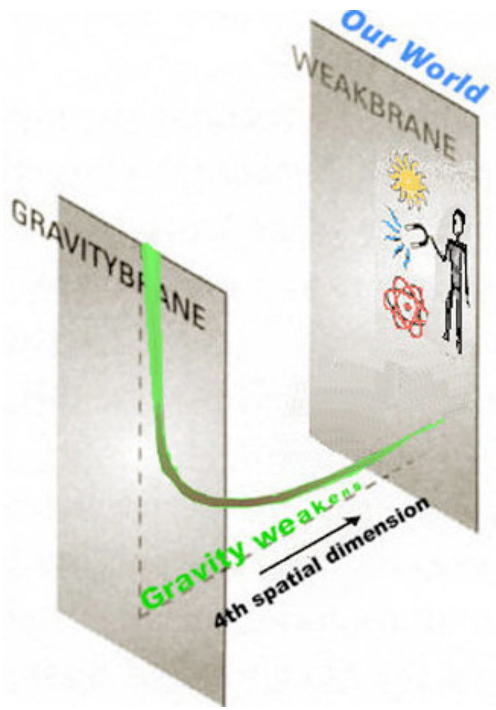


Han, Logan, Wang

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

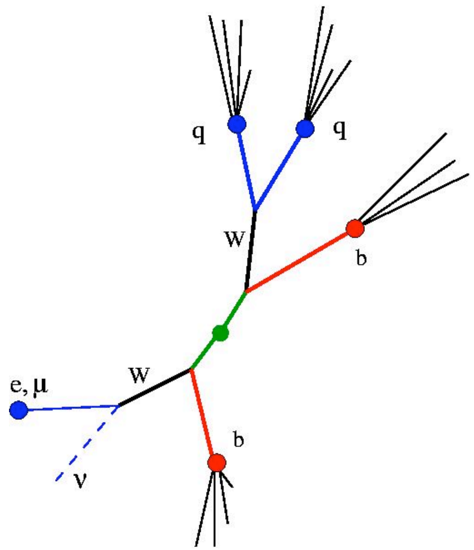
Top and extra dimensions

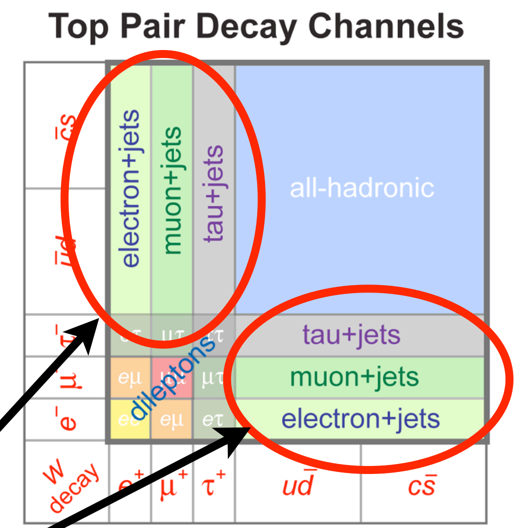


New particles, Kaluza Klein modes

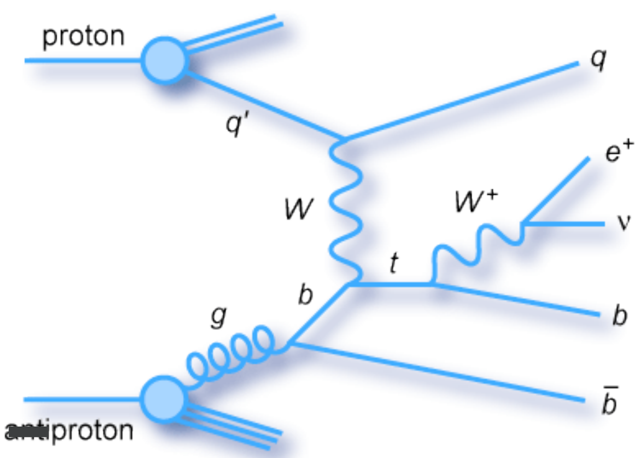
- Gluon KK modes show up as resonances in reaction gg →tt
- Angular distributions of top decay leptons can distinguish scenarios

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

ILC

- With 0.6 pb cross section, about 60K pairs after 100 fb^-1
- Decays as for LHC, but in much cleaner environment
- Precise characteristics
  - ✓ Vary beam energy just around tt threshold
  - ✓ Select phase space regions to capture "all of the top" (no underlying event etc)

Top couplings

- The LHC can determine some of the SM top couplings to some accuracy, but ILC can often do much better

Yukawa

Gay; Juste

- LHC: from ttH, but early optimism (PYTHIA) was misplaced, background more pesky than thought
- ILC: sensitive via virtual (vertex) and real (ttH) Best: combination with LHC
- 6-10% after much data

ttγ, ttZ

Grzadkowski, Hioki; Rindani

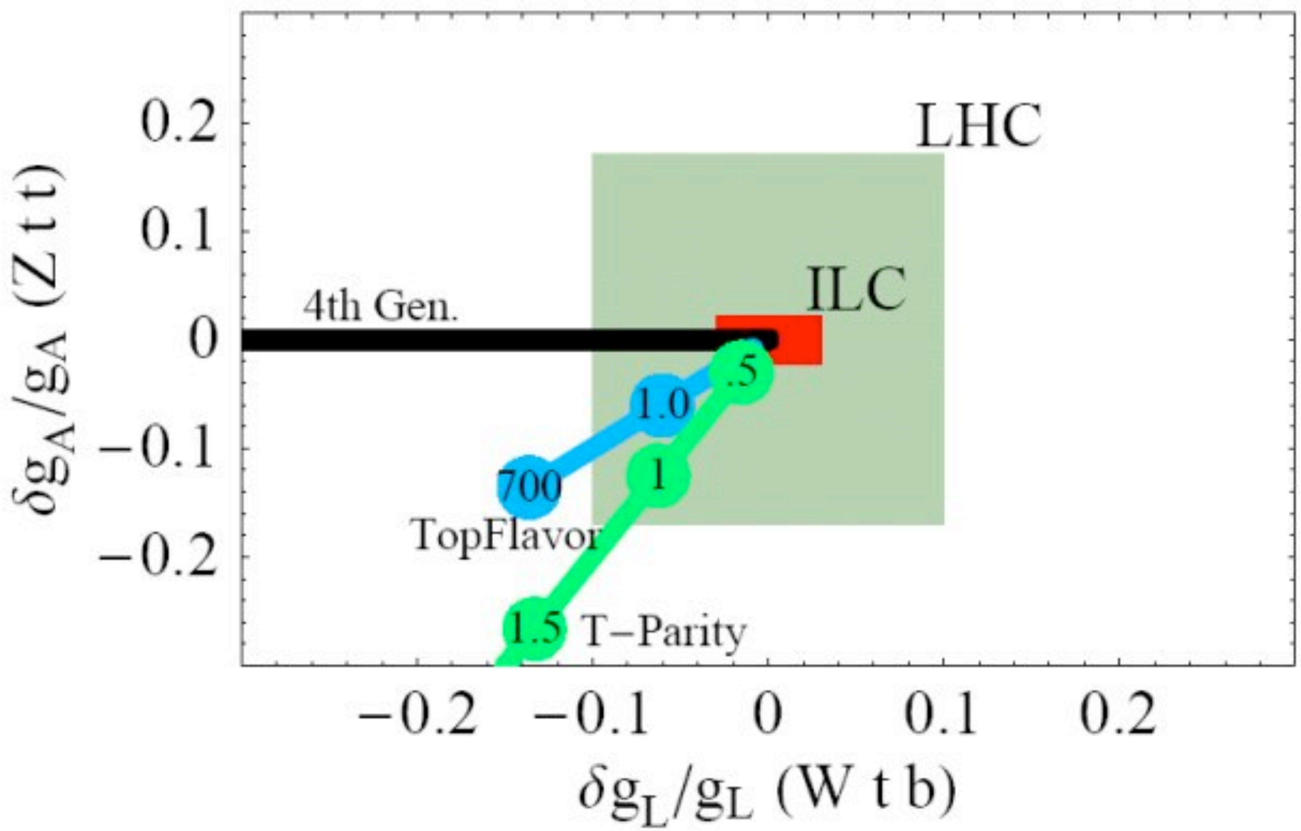
- LHC: not easy,
- ILC; from tt to l+jets. E.g. charge = 0.67 +- 0.05
- ILC: polarizing beam will be useful

Wtb

- LHC/Tevatron: from single top production. Expect about 5% Vtb
- ILC: from below threshold tt production, extract width and g(Wtb) independently
- ILC: Vtb to 4%, or much better

Top couplings, cont'd

Batra, Tait



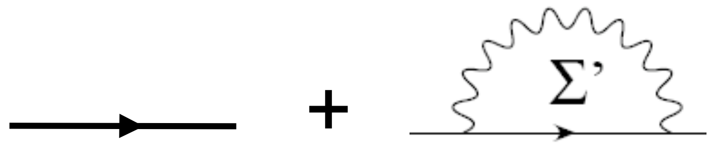
Expected bounds on axial $\bar{t}tZ$ and left–handed tbW couplings from direct LHC (olive) and ILC (red) measurements; superimposed are predicted deviations from representative models

Top mass

Fleming, Hoang, Mantry, Stewart; Beneke, Signer; Hoang

- Electron mass "easy": defined by pole in full propagator
  - ✓ Scattering by external, physical electrons and photons, on-shell
  - ✓ No real ambiguity what electron mass is
- Quarks are confined, physical on-shell quark does not exist
  - ✓ Even perturbation theory "knows": pole mass has factorial growth (renormalon)
  - ✓ Leads to intrinsic non-perturbative ambiguity of few hundred MeV
- LHC: accuracy of 1 GeV possible (like Tevatron). Claim ILC: 100 MeV accuracy
  - ✓ using short-distance masses, without ambiguity

Top threshold mass



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

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

Quark-antiquark potential

Energy of tt pair (for Schrodinger eq)

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

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

Beneke

Various similar definitions exist

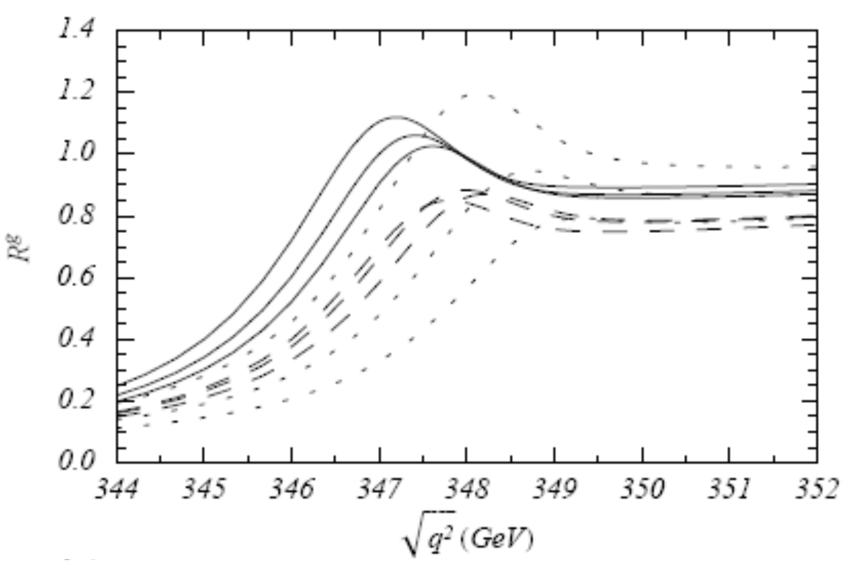
Hoang, Teubner; Bigi et a;

Top threshold mass

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

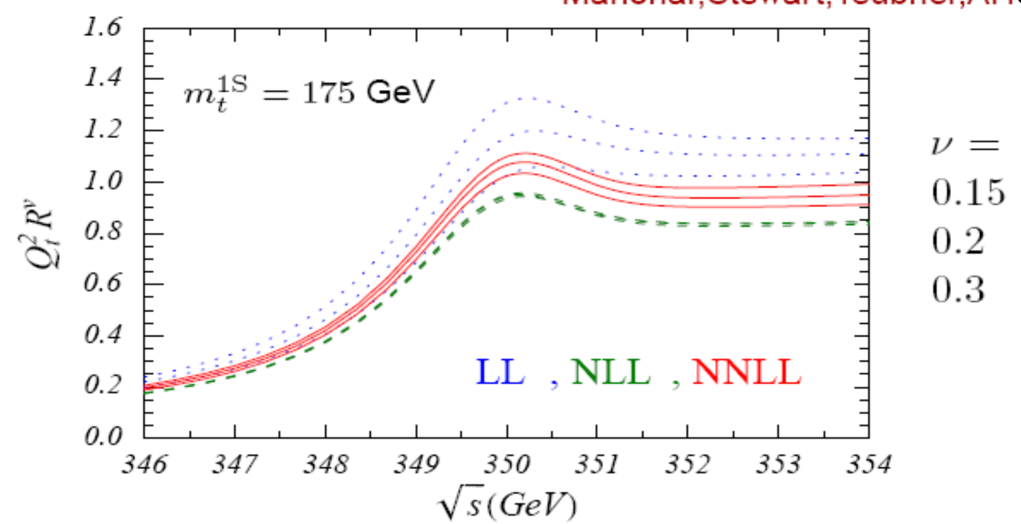
$$R = \frac{\sigma_{t\bar{t}}}{\sigma_{\mu^+\mu^-}} = v \sum_k \left(\frac{\alpha_s}{v}\right)^k \sum_i (\alpha_s \ln v)^i \times \left\{1\,(\mathrm{LL}); \alpha_s, v\,(\mathrm{NLL}); \alpha_s^2, \alpha_s v, v^2\,(\mathrm{NNLL})\right\}$$

Pole mass, bad



Threshold mass, good

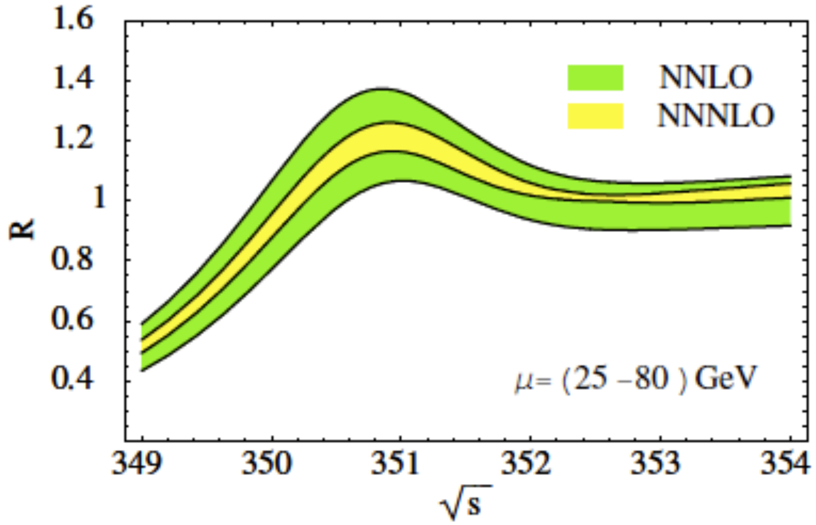
Manohar,Stewart,Teubner,AHoang



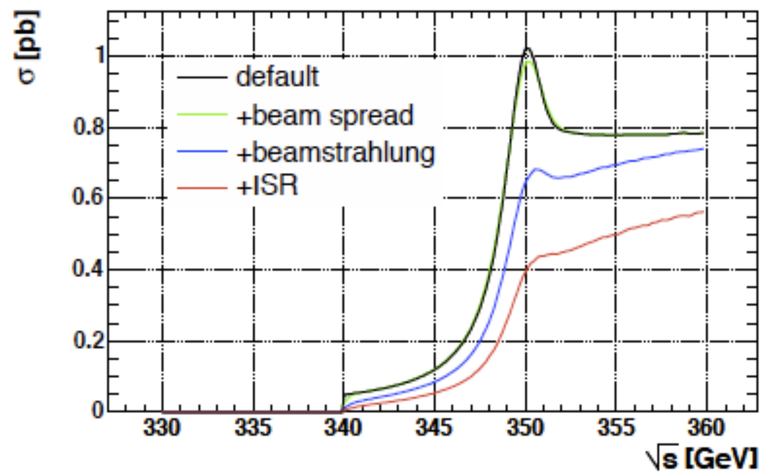
Top threshold mass

- NNNLO necessary, since NNLO gave large corrections

Beneke, Kiyo, Fuller



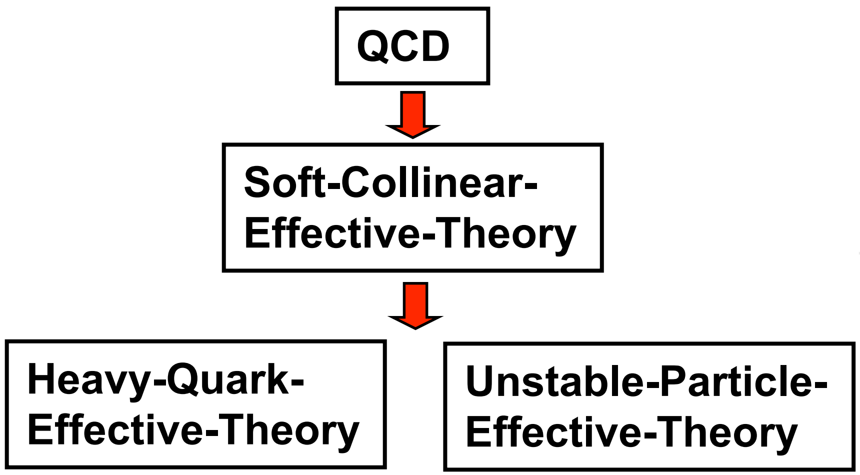
- But other effects must be brought under control..

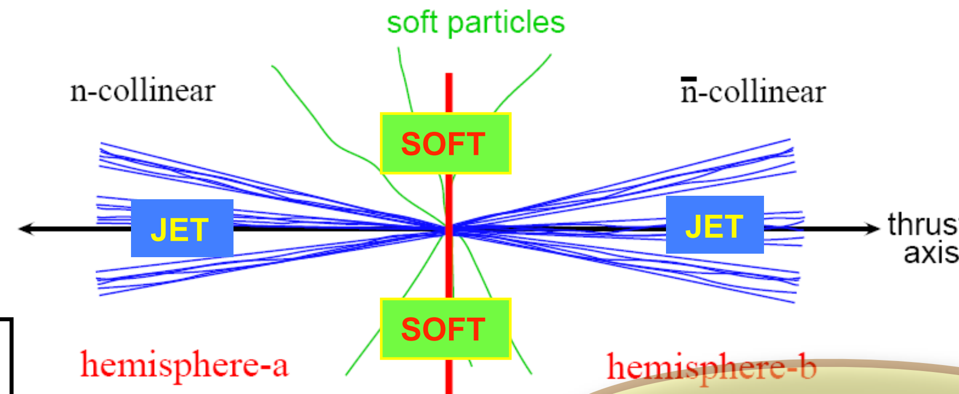


Top jet mass, from factorization

$$Q \gg m_t \gg \Gamma_t > \Lambda_{\rm QCD}$$

Fleming, Hoang, Mantry, Stewart;





Extract from jet event shapes

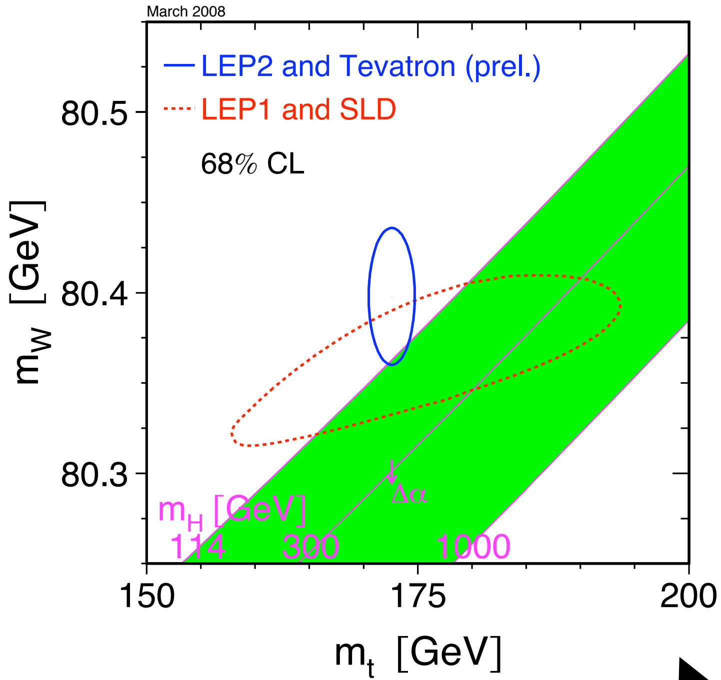
$$\left(\frac{d^2\sigma}{dM_t^2\,dM_{\bar t}^2}\right)_{\rm hemi} = \sigma_0\, H_Q(Q,\mu_m)\, H_m\!\left(m,\frac{Q}{m},\mu_m,\mu\right) \times \int_{-\infty}^{\infty} d\ell^+ d\ell^-\, B_+\!\left(\hat s_t - \frac{Q\ell^+}{m},\Gamma,\mu\right) B_-\!\left(\hat s_{\bar t} - \frac{Q\ell^-}{m},\Gamma,\mu\right) S_{\rm hemi}(\ell^+,\ell^-,\mu)$$

$$\hat s = \frac{M_t^2 - m_J^2}{m_J}$$

JET JET SOFT

Accurate top jet mass determination possible

Top mass

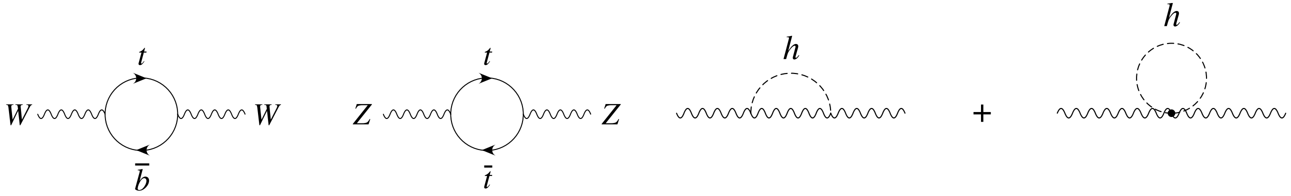


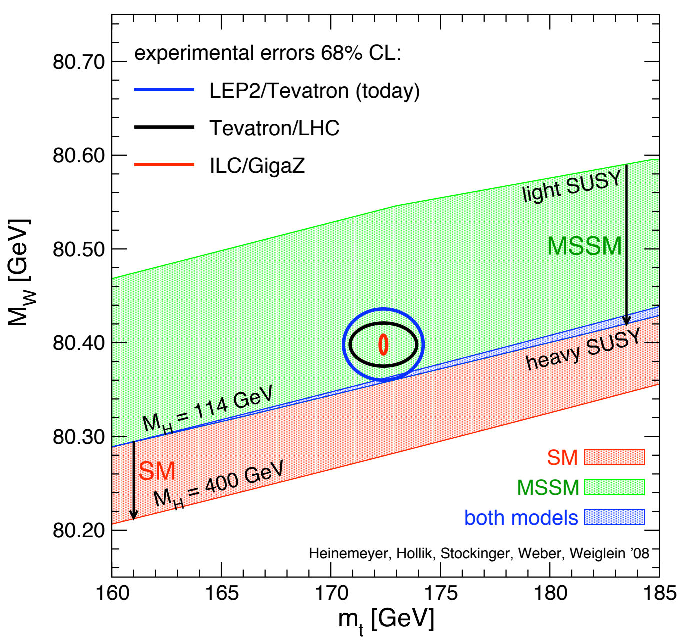
Heinemeyer, Weiglein

now: 173.1 ± 1.3 GeV (Tevatron)

<1% !!

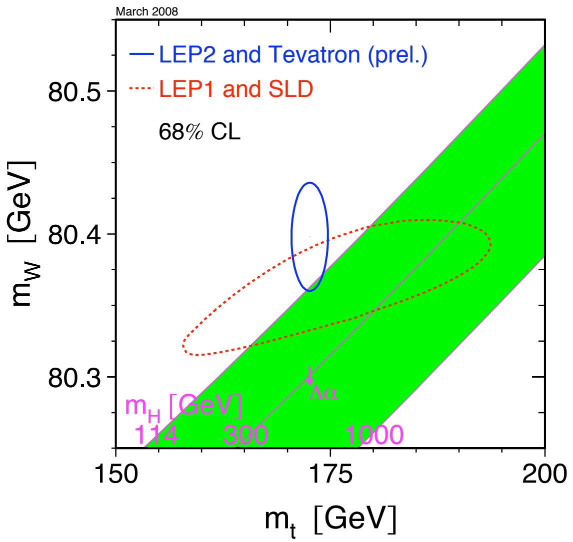
$$M_W^2 = \frac{\pi\alpha}{\sqrt{2} G_F \sin^2\theta_w} \frac{1}{1 - \Delta r(m_t, m_H)}$$





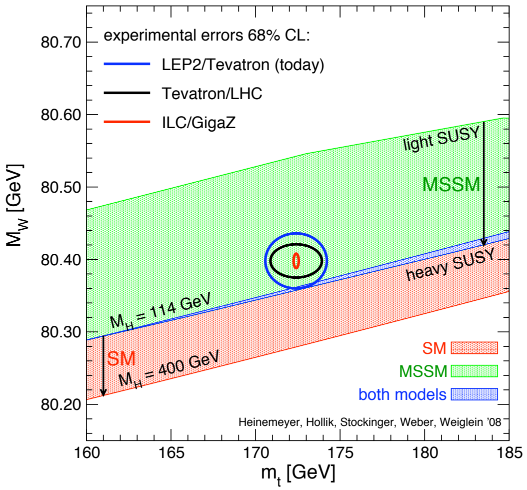
- Measure via reconstruction of final state, or via cross section
- Relate m_W, m_t, m_H to constrain SM, MSSM

Top width measurement only possible at linear collider



Top mass use

- 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
- But do need it to constrain BSM theories.



NLO cross sections at hadron colliders

Multi-differential hadronic NLO cross section

NLO PDF's

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

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

Multi-differential partonlevel NLO cross section

Power corrections.

Renormalization and Factorization scale

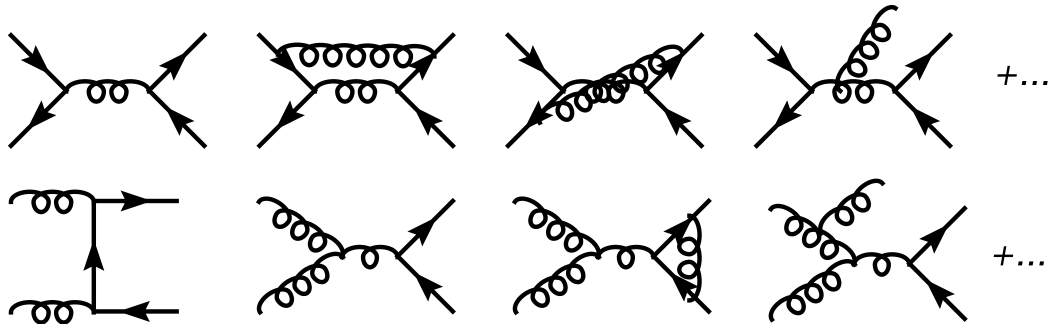
For NNLO, add "N" in all the right places..

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



Czakon, Mitov, Moch; Dittmaier, Uwer, Weinzierl

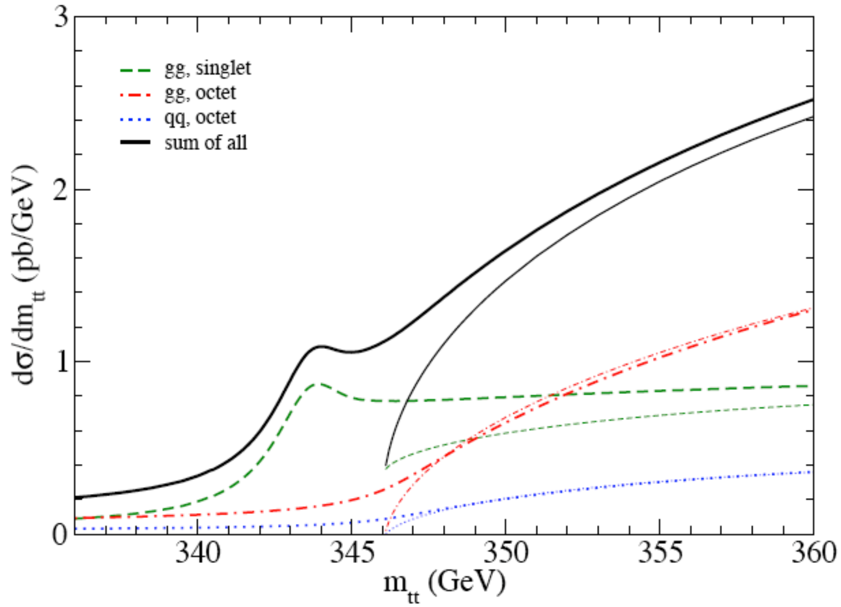
- NNLO is making remarkable progress
- Real done. Virtual via Mellin-Barnes techniques

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

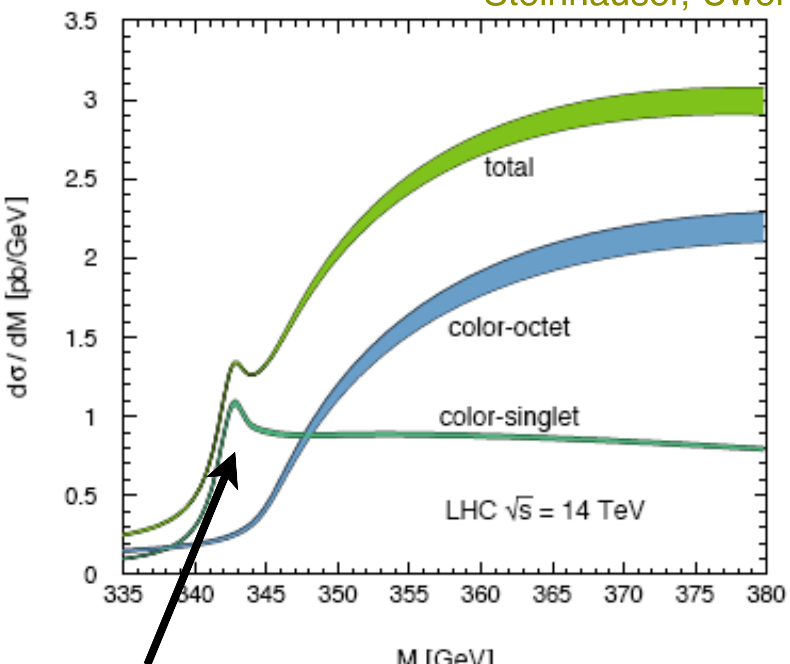
Kuehn, Mirkes; Petrelli, Cacciari, Greco, Maltoni, Mangano

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

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

$$\hat{O} = 1 + \alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \ldots$$
$$= \exp\left(\underbrace{\underbrace{Lg_1(\alpha_s L)}_{LL} + g_2(\alpha_s L)}_{NLL} + \alpha_s g_3(\alpha_s L) + \ldots\right)\underbrace{C(\alpha_s)}_{\text{constants}}$$
$$+ \text{ suppressed terms}$$

- ✓ Algebraic proof: "eikonal" perturbation theory is exponent of "web" diagrams

- ✓ For Higgs/Drell-Yan inclusive cross section:

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

- ✓ 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, Bozzi, Grazzini, de Florian, Forte, Ridolfi, Vogelsang, Kidonakis, Kulesza, EL, Magnea, Moch, Vogt,Vogt, Eynck, Ravindran, Becher, Neubert, Ji, Idilbi,...

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

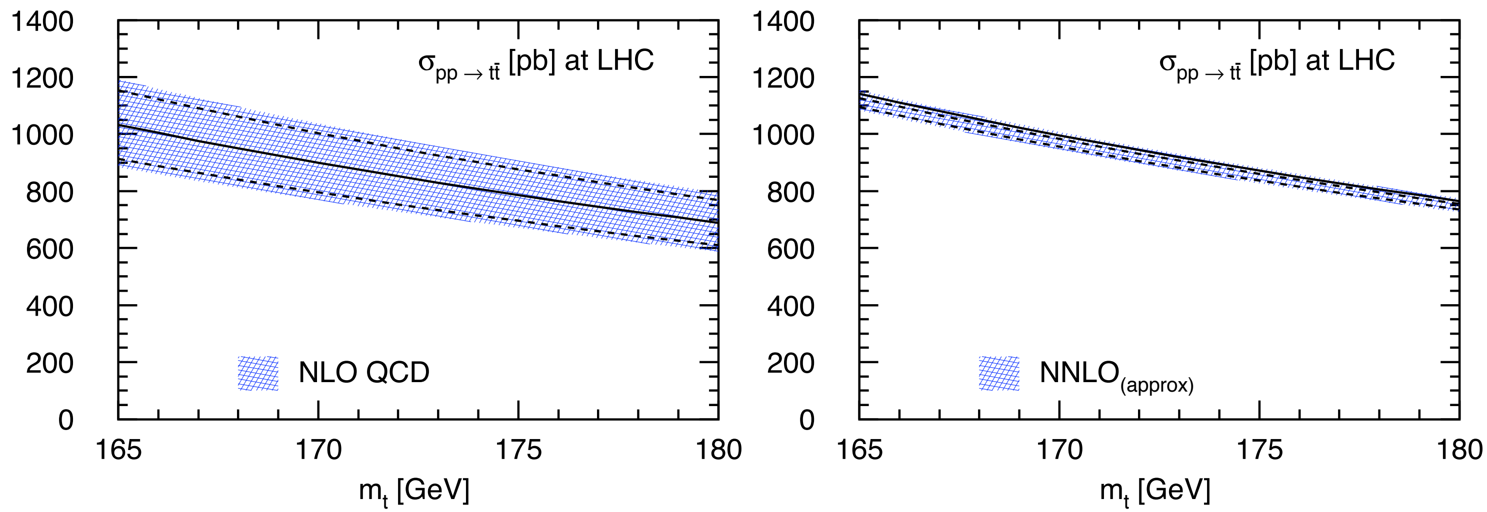
Remarkable: Known to 3 loops | Known to 2 loops

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?

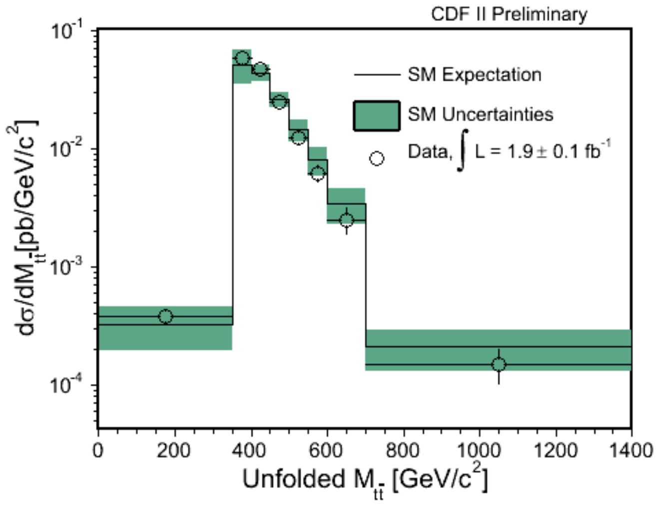
Moch, Uwer



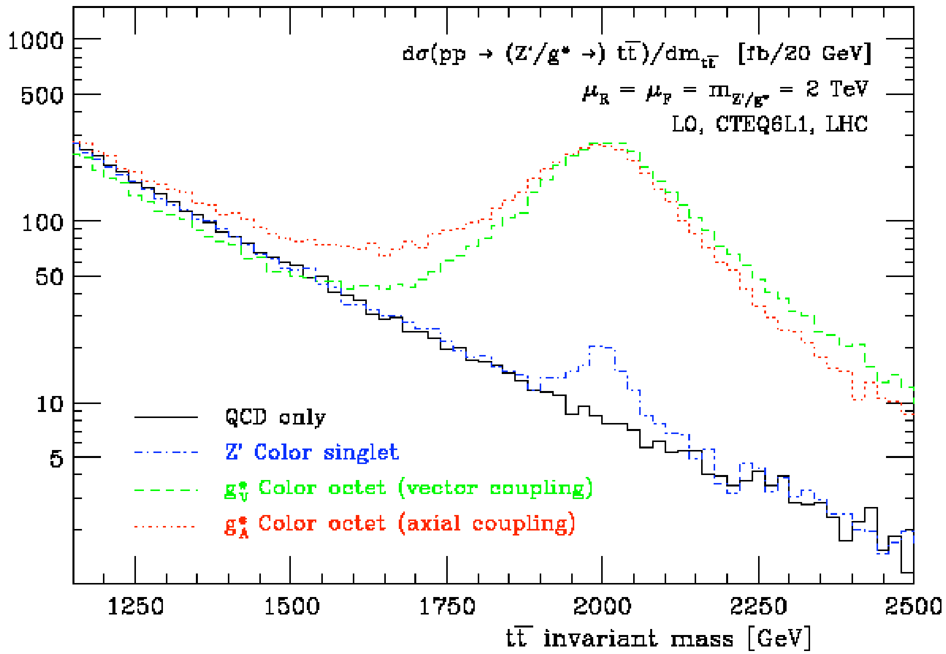
Perhaps too small?

Pair-invariant mass distribution

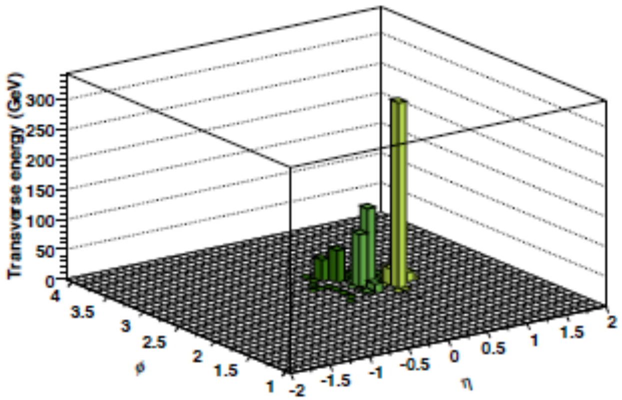
Frederix, Maltoni



- 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.



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 factor 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

Higher order associated top production

Much 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
- Monte Carlo descriptions, both parton-shower and matrix-element based

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:

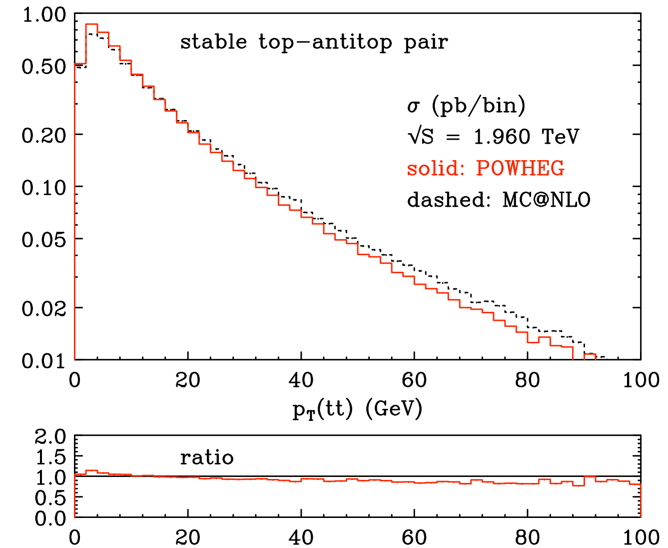
- emission from NLO and PS should be counted once
- virtual part of NLO and Sudakov form factor should not overlap
- some freedom in this:

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

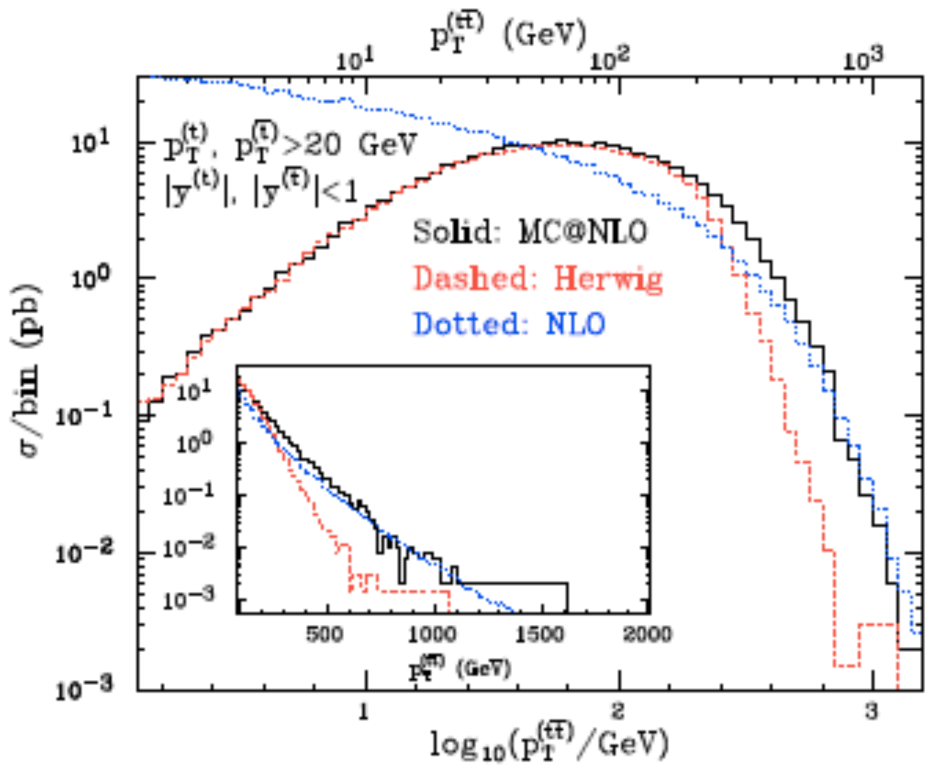
✓ MC@NLO has more processes built in for now. But it should be easier to do that for POWHEG.



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

Frixione, Nason, Webber

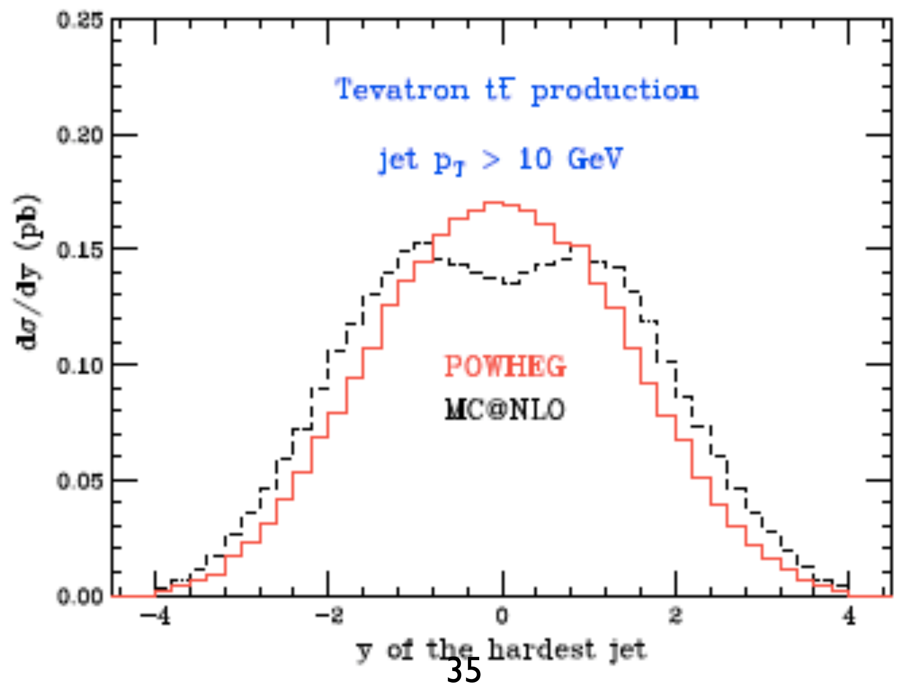
- First process in MC@NLO with final state colored partons, multiple color flows
- Interpolates well between NLO and parton showers



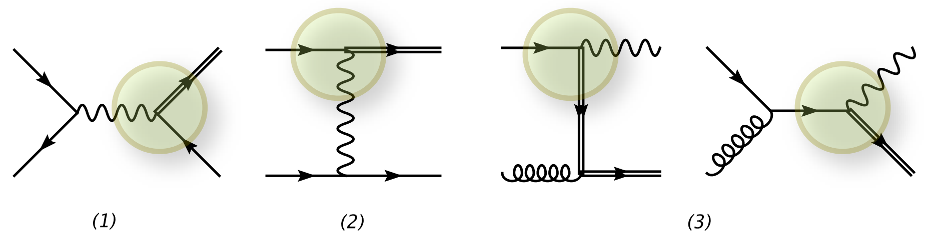
Top MC comparisons

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 soft radiation in HERWIG



Single top at NLO



s-channel:
timelike W

t-channel:
spacelike W

Wt channel: real W

- Allows measurement of V_{tb} per channel
- Infer the b-density Campbell, Frederix, Maltoni, Tramontano
- Sensitive to FCNC's (t-channel), or W' resonances (s-channel)

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

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

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
- Directly measurable, 3 times, through single top production

Alwall et al [Louvain]

- In practice: not so easy.
  - CDF/D0: > 0.71/0.78 at 95% CL
  - ILC expectation: < 4 % Batra, Tait

Single top in MC@NLO

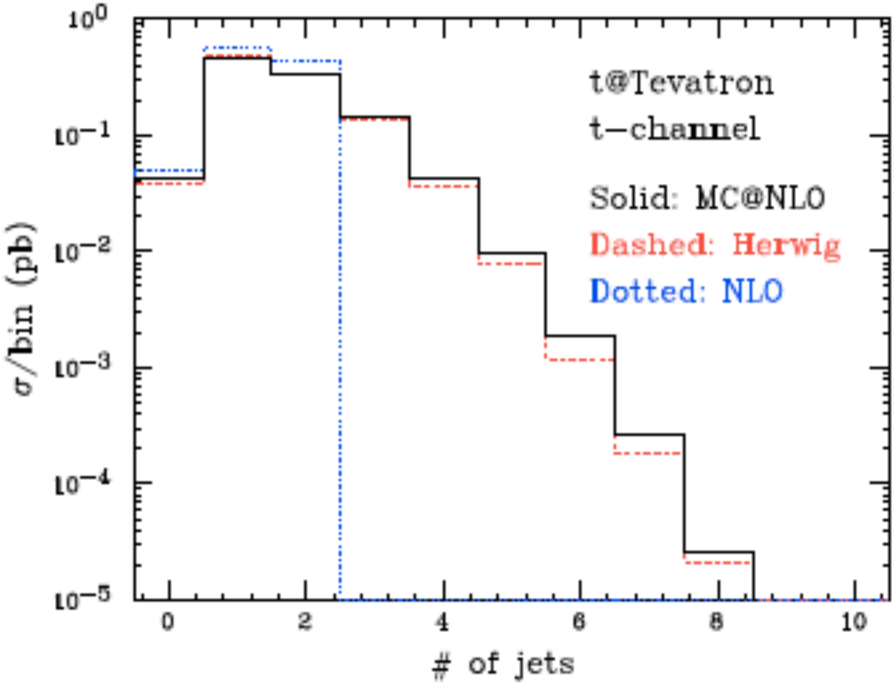
Frixione, EL, Motylinski, Webber

Single top in POWHEG:
Aioli, Nason, Oleari, Re

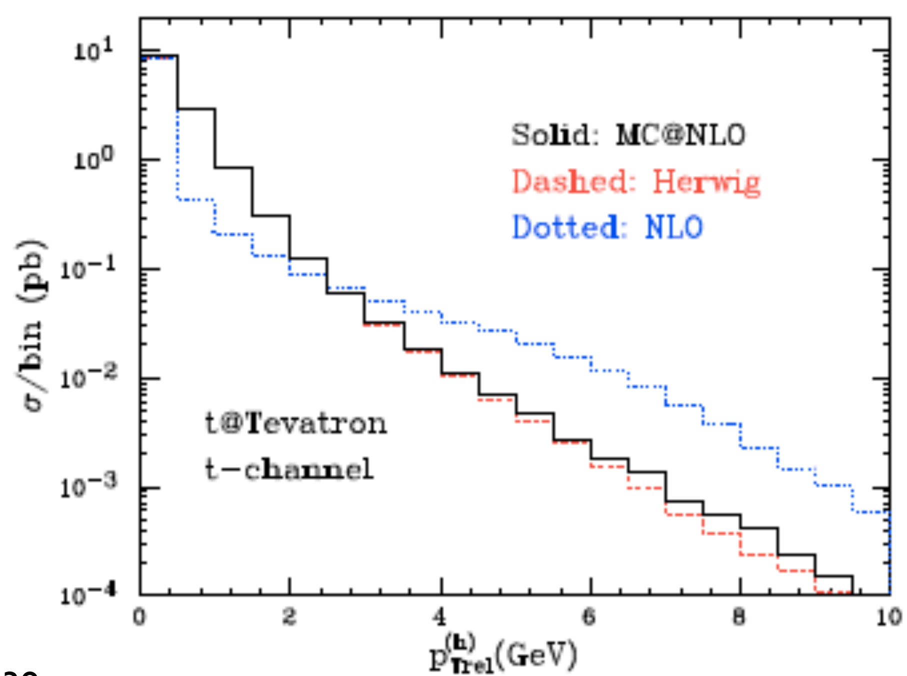
Adds MC@NLO benefits to this process, but also

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

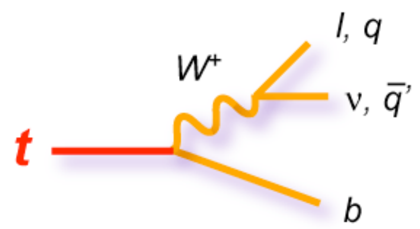
Number of jets



pT relative to jet axis in hardest light jet

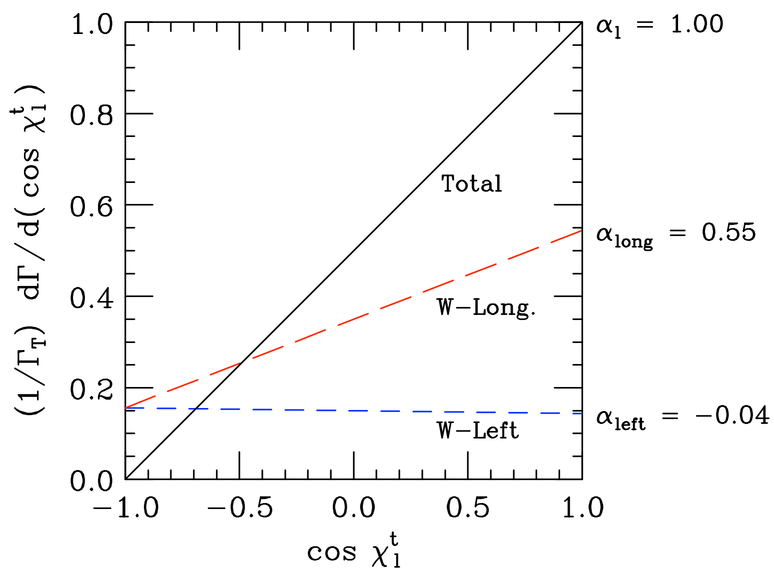


Top decay: spin



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

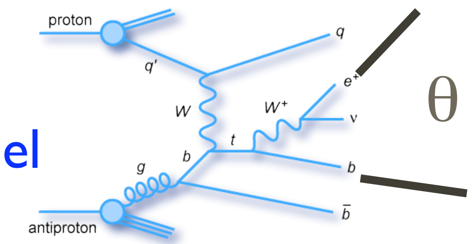
- Top self-analizes its spin: 100% correlation ($\alpha_f = 1$) of t-spin with l^+-direction
- QCD corrections to α_f very small
- Worthy of verification (e.g. charged Higgs decay would lower α_f)
- Powerful probe of spin quantum numbers of top, and any process that produced it (single top, resonance,..)

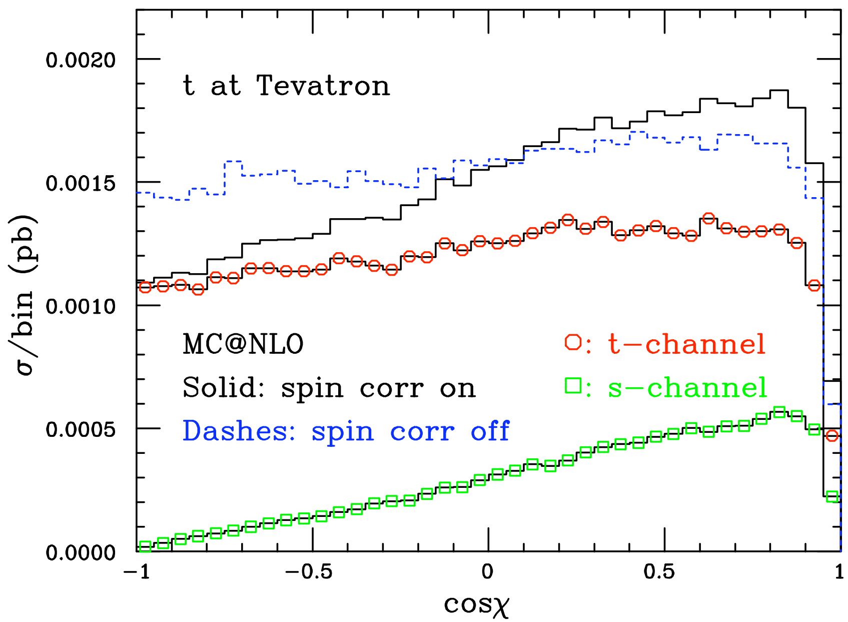


Spin correlations for single top in MC@NLO

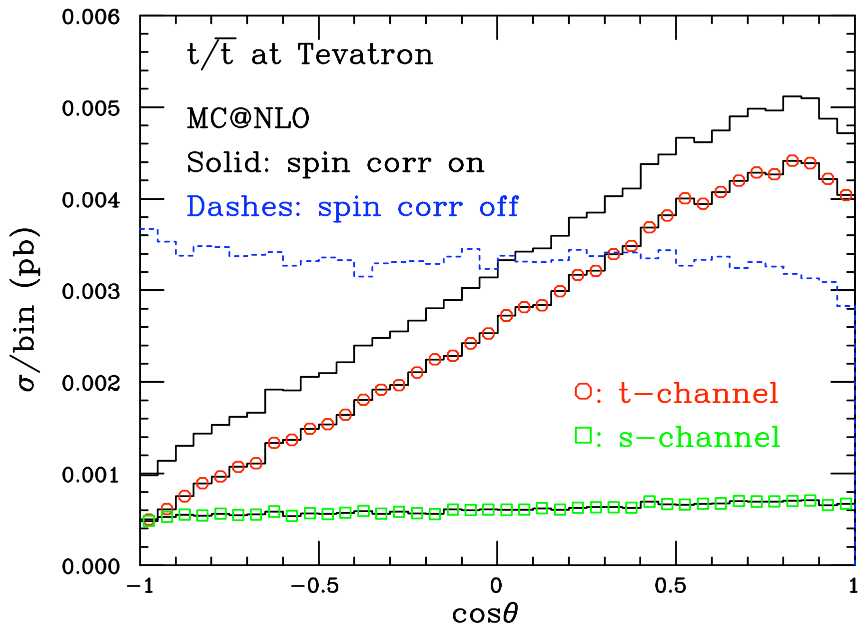
Frixione, EL, Motylinski, Webber

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





Beam direction

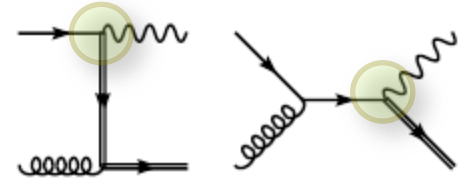


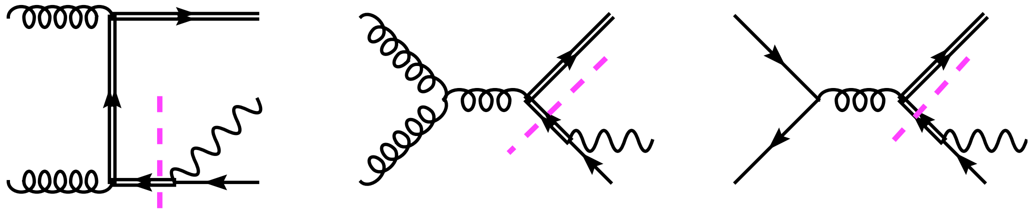
Hardest, non-b jet

Robust correlation, even in event generation

Frixione, EL, Motylinski, Webber, White

Wt meets tt..





+ non-resonant diagrams

Serious interference with pair production (15 times bigger)

- 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;
- What can one do in event generation?
- Can one actually define Wt separately from tt?

Can we define Wt 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

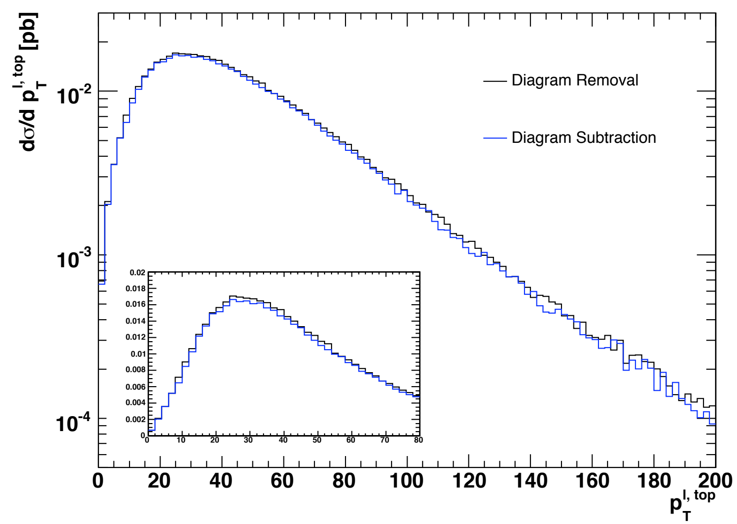
Momentum reshufling

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

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

Compare

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



White, Frixione, EL, Maltoni

Can/should we isolate Wt?

- Answer subject to cuts
  - ✓ Cuts to isolate Wt
  - ✓ Cuts to isolate to suppress Wt and tt as background to H->WW
- Yes! Separation allows important NLO corrections for tt and for Wt

e_b	r_{lj}	$\sigma_{Wt}^{DR}/\text{pb}$	$\sigma_{Wt}^{DS}/\text{pb}$	$\sigma_{t\bar{t}}/\text{pb}$
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 ± 0.4
$t\bar{t}$	12.25 ± 0.3
Wt (DR)	6.91 ± 0.06
Wt (DS)	6.89 ± 0.07

Conclusions

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- For LHC and ILC, top is the new bottom, useful everywhere at once, plays a role in almost every activity at the Terascale
- Theory tools good, and keep remarkable pace of innovation
- Top will be central to collider physics programs in the next decades