The theory of Single Top Production

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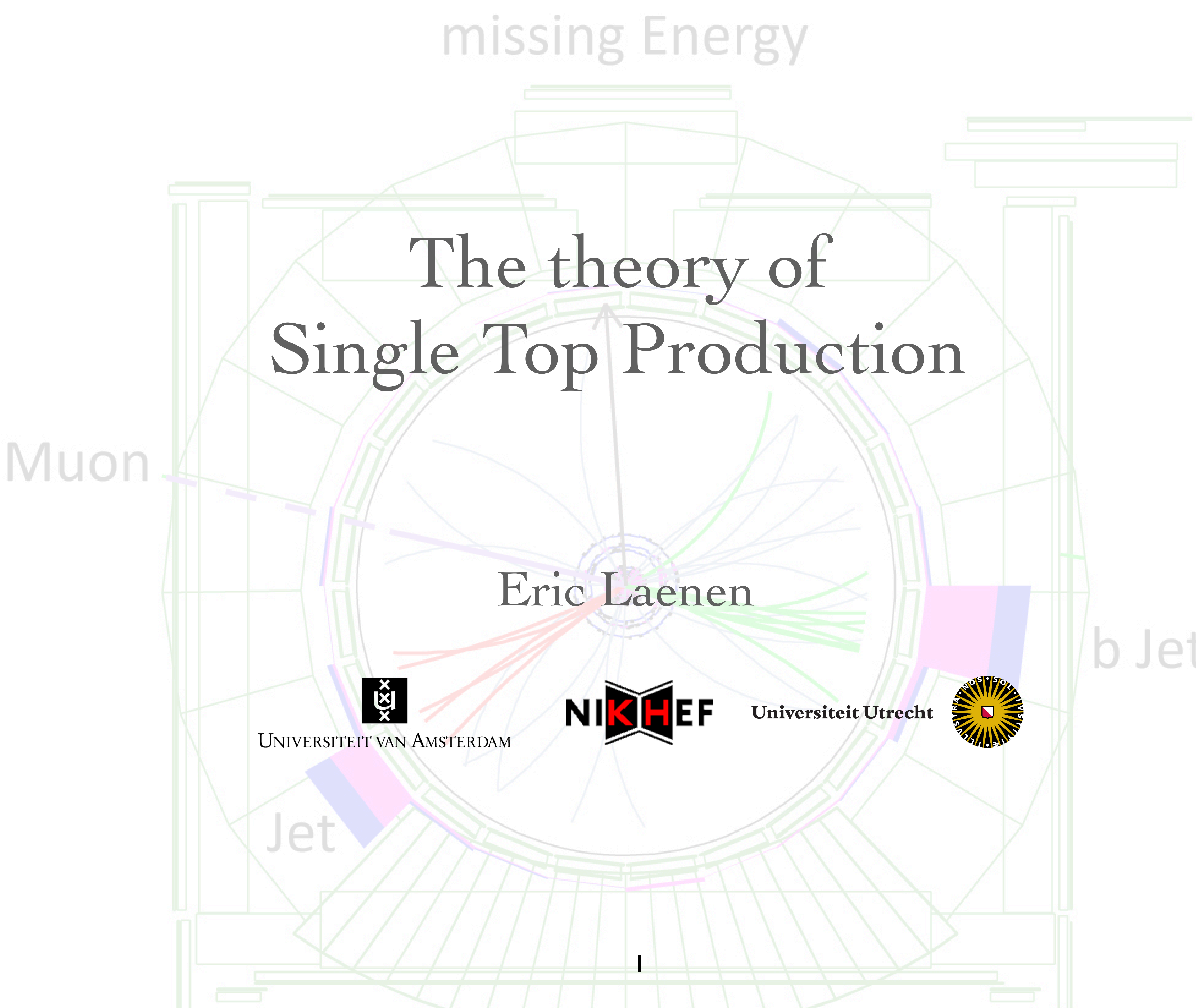
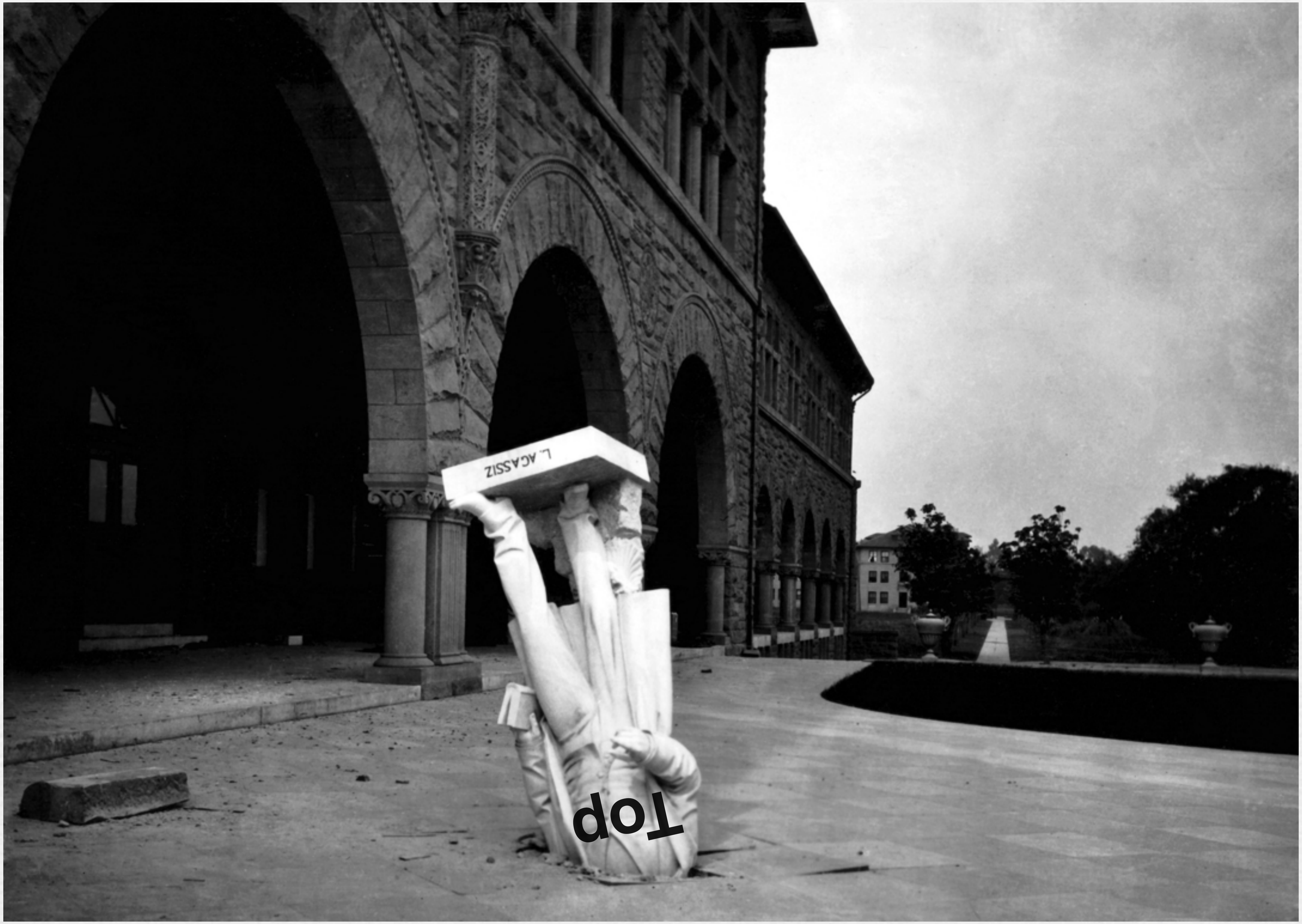


DESY Theory workshop "Lessons from the first phase of the LHC", Sept. 25-28, DESY, Hamburg

A single top quark after July 4

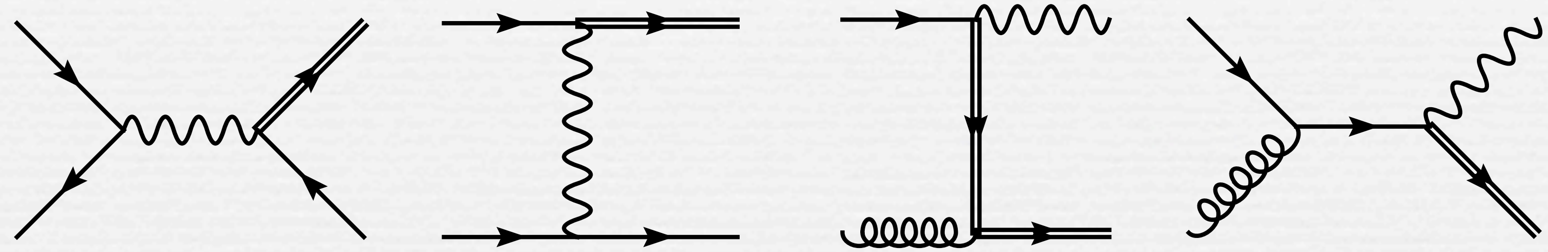


Outline

- The interest of single top quark events
- What can you do with single top?
  - CC vertex, V_{tb}, b-density,...
- Theoretical aspects in production and decay of single top
  - and connections (spin, virtuality,.)

How to make a single top?

"Omne trium perfectum"



(1) (2) (3)

s-channel:
timelike W

4 pb @ LHC7

t-channel:
spacelike W

62 pb @ LHC7

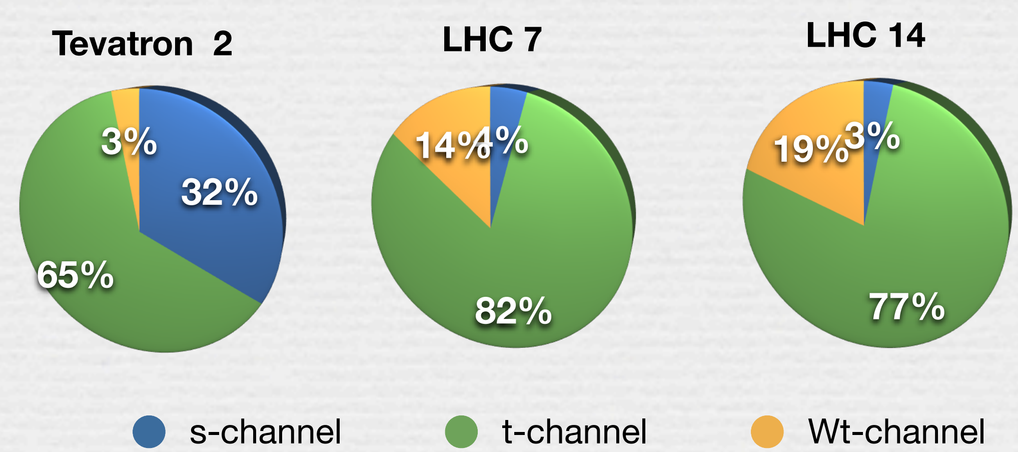
Wt channel: real W

10 pb @ LHC7

- In SM: through charged current interaction

$$\frac{g}{\sqrt{2}} V_{tq}\, (\bar{t}_L \gamma^\mu q_L) W_\mu^+$$

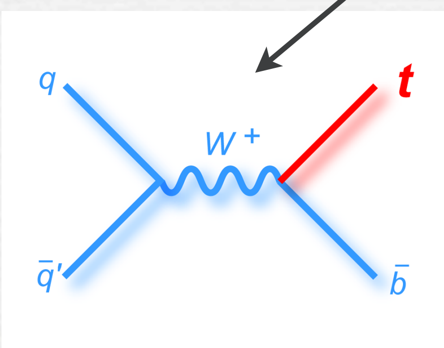
- Interesting because:
  - strength (V_{tb} in particular)
  - left-handedness, i.e. spin
  - Effect of W-virtuality?

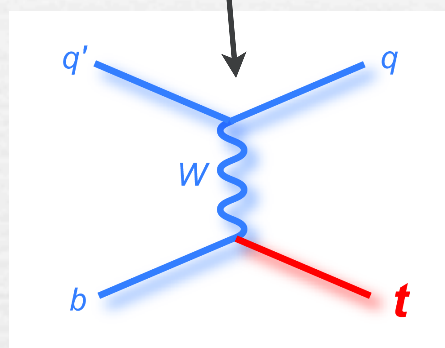


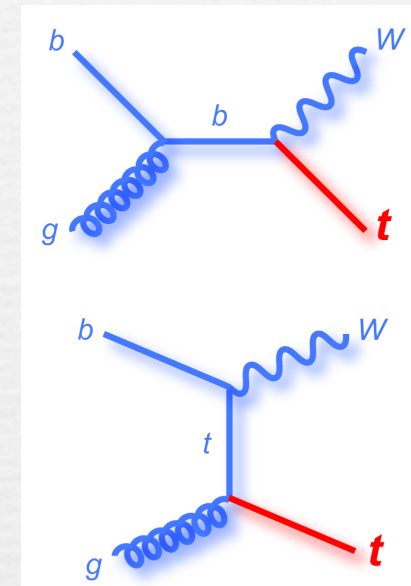
- Note: channels start mixing at sufficiently high order

Single top production in a nut-shell

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
  - At NLO, no box diagrams
- 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.

Discovery, still not long ago

- Even though the cross sections at the Tevatron are not that much smaller than for pair production, discovery of single top production took much longer (2009) than for pair production (1995)

Observation of Single Top-Quark Production

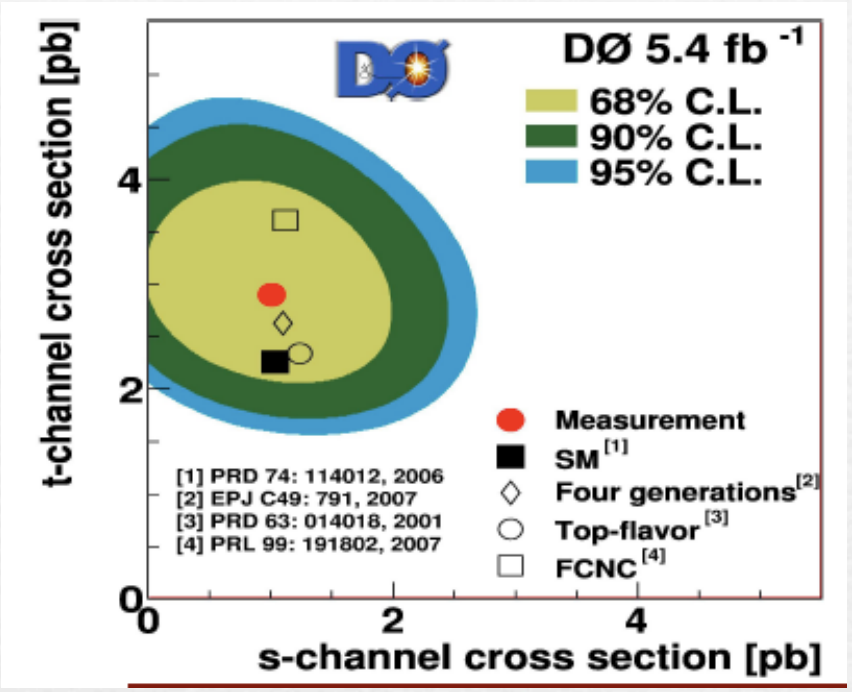
We report observation of the electroweak production of single top quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV based on 2.3 fb^{-1} of data collected by the D0 detector at the Fermilab Tevatron Collider. Using events containing an isolated electron or muon and missing transverse energy, together with jets originating from the fragmentation of b quarks, we measure a cross section of $\sigma(p\bar{p} \to tb + X, tqb + X) = 3.94 \pm 0.88$ pb. The probability to measure a cross section at this value or higher in the absence of signal is 2.5×10^{-7}, corresponding to a 5.0 standard deviation significance for the observation.

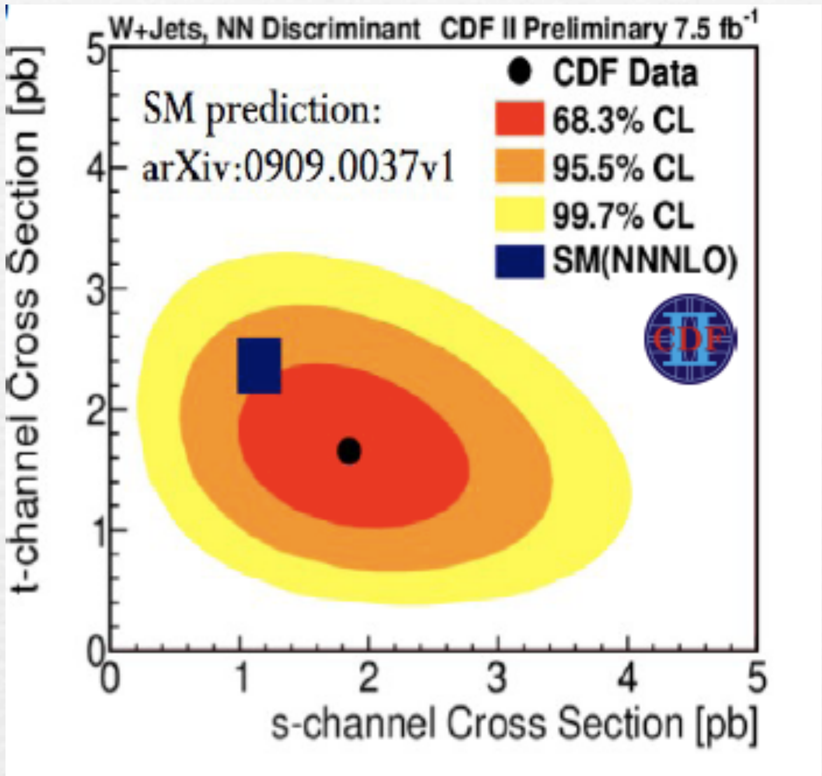
First Observation of Electroweak Single Top Quark Production

We report the first observation of single top quark production using 3.2 fb^{-1} of $p\bar{p}$ collision data with $\sqrt{s} = 1.96$ TeV collected by the Collider Detector at Fermilab. The significance of the observed data is 5.0 standard deviations, and the expected sensitivity for standard model production and decay is in excess of 5.9 standard deviations. Assuming $m_t = 175$ GeV/c^2, we measure a cross section of $2.3^{+0.6}_{-0.5}(\mathrm{stat} + \mathrm{syst})$ pb, extract the CKM matrix element value $|V_{tb}| = 0.91 \pm 0.11(\mathrm{stat} + \mathrm{syst}) \pm 0.07(\mathrm{theory})$, and set the limit $|V_{tb}| > 0.71$ at the 95% C.L.

Experimental status: Tevatron

D0, through Ann Heinson, major supplier of single top Feynman diagrams..

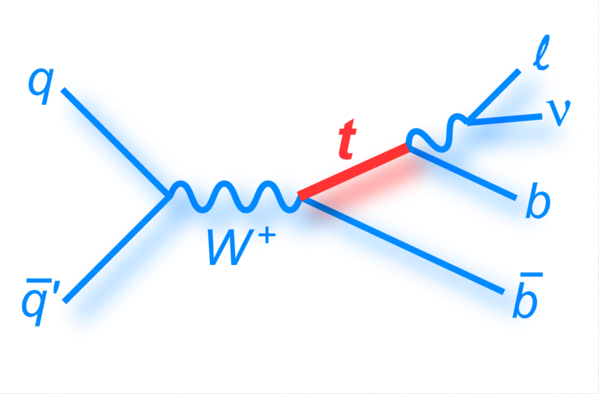


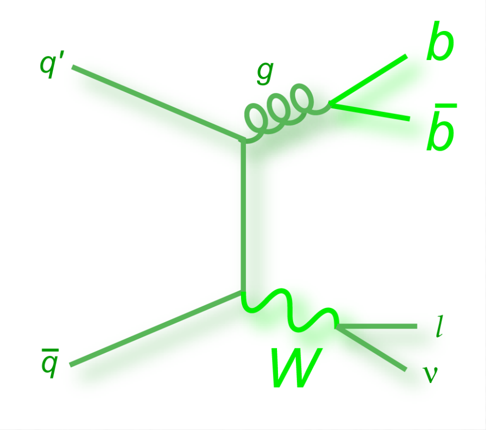


- D0: 5.5σ for t-channel, no separate s-channel discovery
- CDF: t-channel a bit low, s-channel a bit high
  - Background fiendishly difficult
- Full dataset, and D0+CDF combination await

Finding single tops

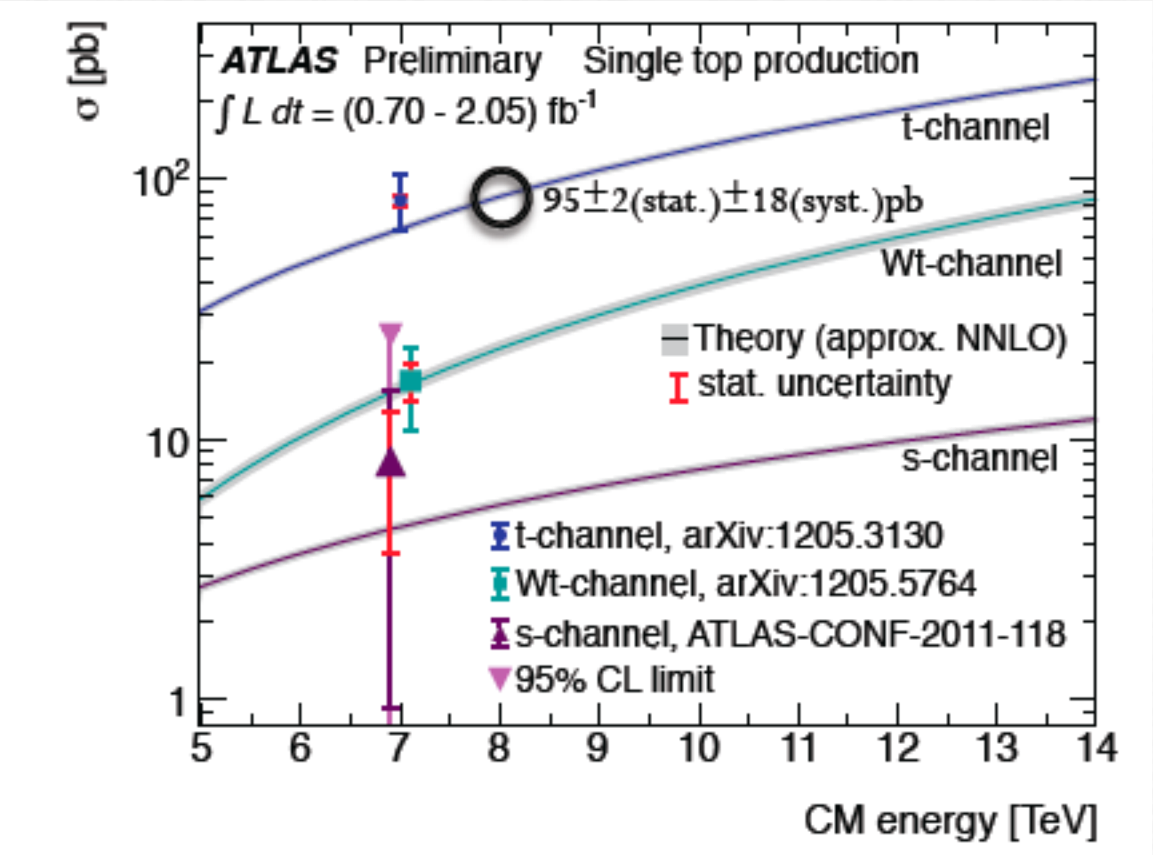
- Why was it so hard to find?
  - Backgrounds large in size and similar in shape compared to signal

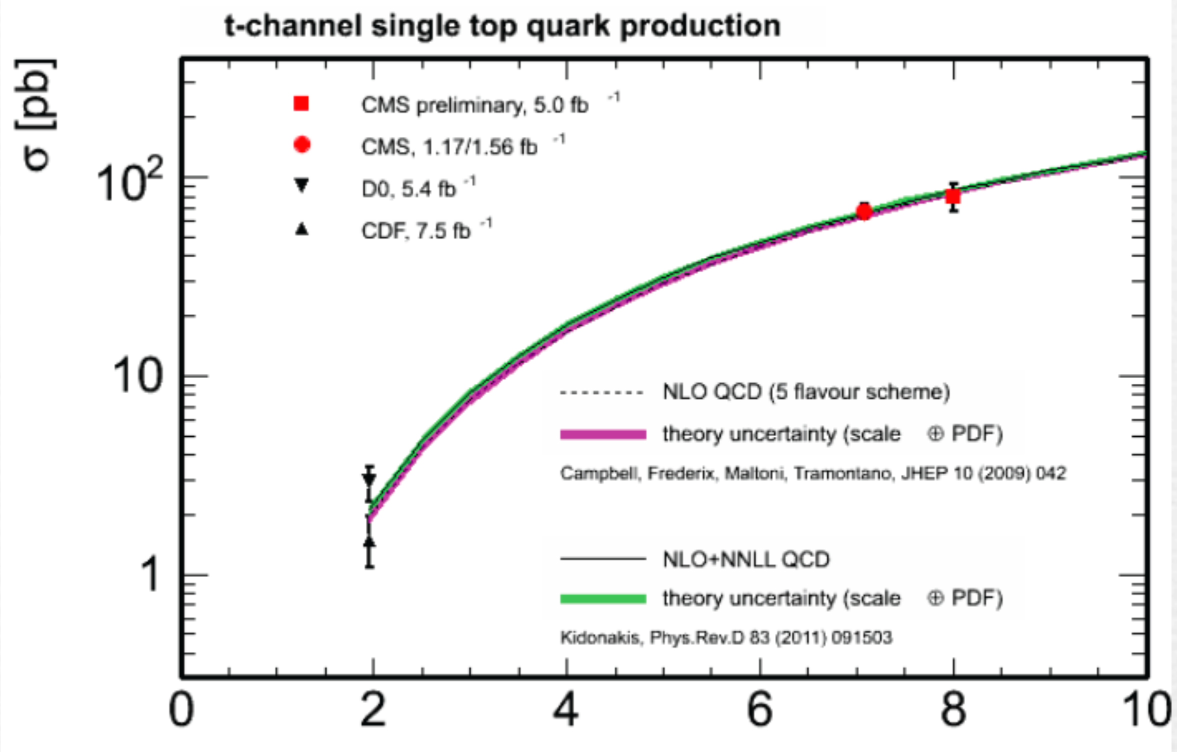




  - especially Wj, tt and multijet backrounds
  - Cut & count did not work at the Tevatron: needed multi-variate techniques
    - With 1 charged lepton, >1 jets, large missing E,   S/B = 1/185
    - After b-tagging, S/B = 1/20, still tough
    - Then enhance signal with multi-variate techniques

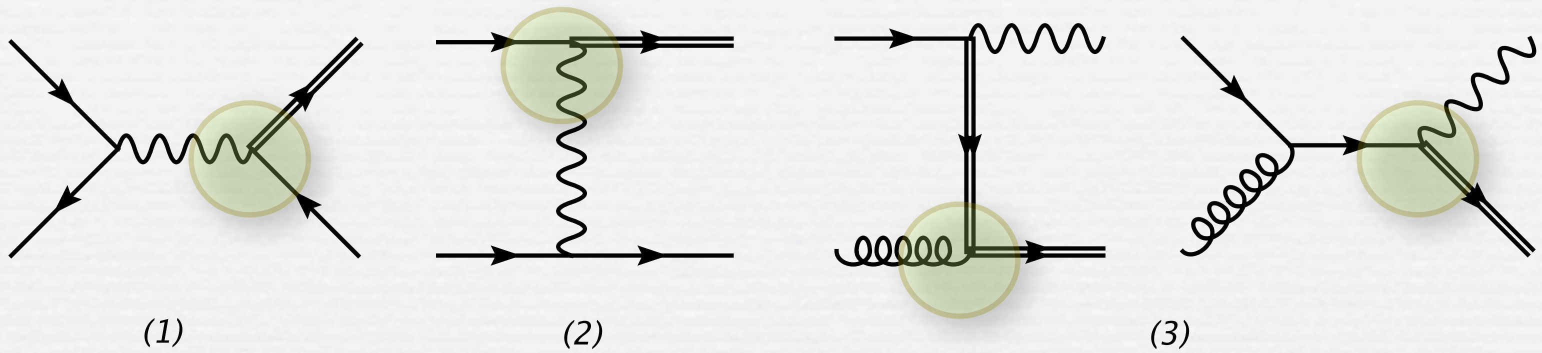
Experimental status: LHC





- Single top process established at LHC
  - Inclusive cross sections in good agreement so far
  - But backgrounds remain tough

Things one can do with single top



s-channel:
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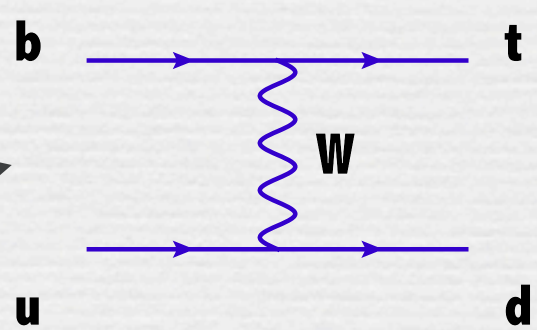
Wt channel: real W

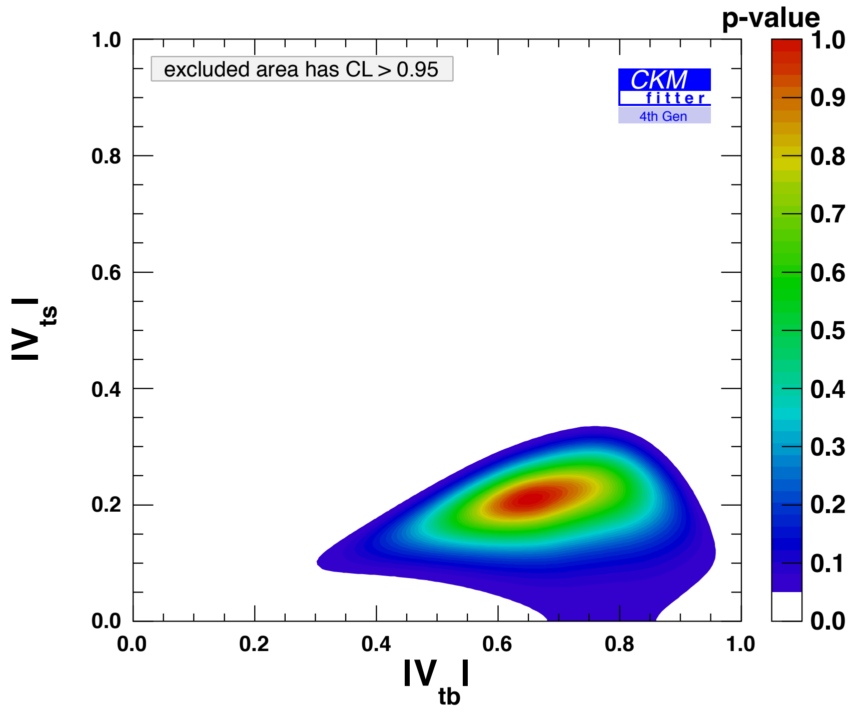
10 pb @ LHC7

- 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 $$R = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$ Alwall et al; Lacker et al
  - 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
    - assume 4x4 CKM matrix (to avoid unitarity), take efficiencies for other flavor (mis)tags into account
  - $V_{tb} = 1$ well outside 95% CL contour



Single top at NLO, on-shell

- NLO corrections known since long. Inclusive
  - t-channel [Bordes, van Eijk; Stelzer, Willenbrock Sullivan]
  - s-channel [Smith, Willenbrock]
  - Wt-channel [Zhu, Cao]
- Fully differential
  - s&t: [Harris, EL, Phaf, Sullivan, Weinzierl]
  - Wt: [Giele, Keller, EL; Frixione, EL, Motylinski, Webber, White; Campbell, Tramontano]
- LO + Parton shower is not like NLO, so this was necessary.

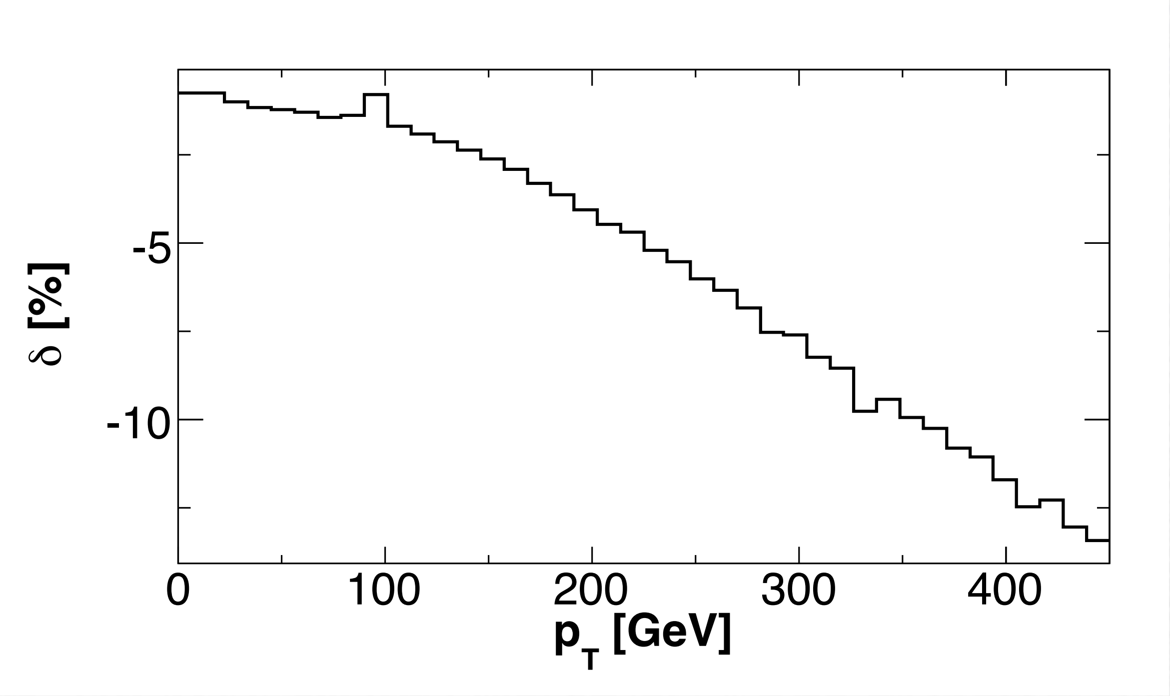
Electroweak & SUSY-QCD corrections

Beccaria, Carloni-Calame, Mirabella, Piccinini, Renard, Verzegnassi / Marcorini, Moretti, Panizzi; Bardin, Bondarenko, Kalinovskaya, Kolesnikov, von Schlippe

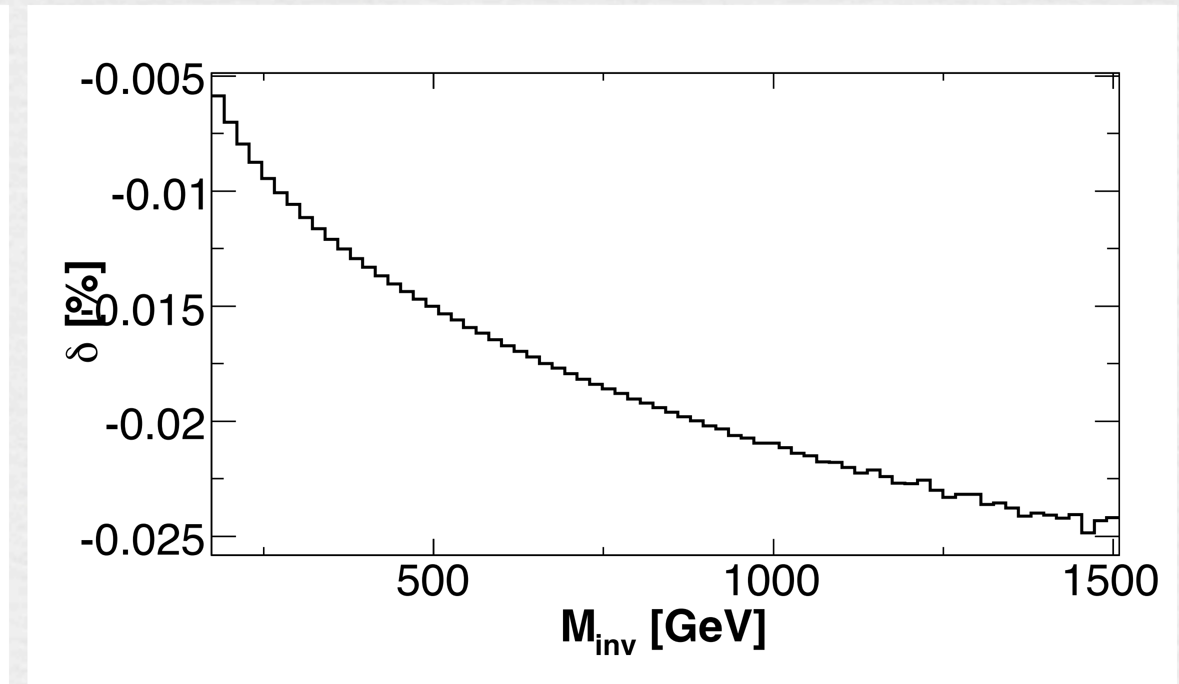
- (Wt,t)-channel / (s,t)-channel
- EW correction not so small (esp. for p_T)
- SUSY-QCD corrections much smaller

t-channel

EW % correction in SM



SUSY % correction in MSSM



Threshold resummation for single top; beyond NLO..

- .. but that is not yet NNLO. For single top, based on all-order resummation

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

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

- There are two varieties of such predictions
  - all order predictions
    - Benefit: all-order, systematic, smaller scale uncertainty, but some ambiguities
  - after expanding resummed to second order, get $\text{NNLO}_{\text{approx}}$
    - Instructive, already less scale uncertainty than NLO, no all-order ambiguities

Resummation rules of thumb

1. Near edge of phase space: Sudakov suppression $\exp(-aL^2)$

2. But hadronic cross sections *increase* due to QCD resummation

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

$N \to \infty$

3. 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

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

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

Threshold resummation

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

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

Kidonakis; Li, Wang, Zhang, Zhu

- Present status is NNLL
- Caveat: different thresholds can be used
  - e.g.

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

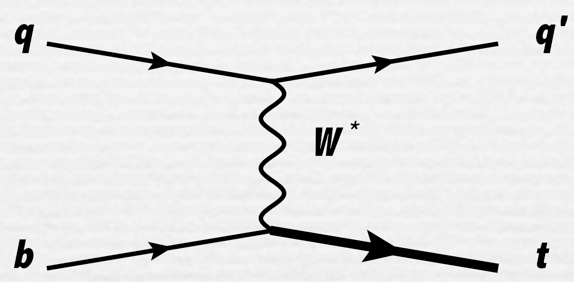
- L = ln(threshold condition). The two calculations use slightly different versions of 3. Small approximate NNLO effects in t-channel.
  - For Wt channel, another 14% on top of NLO

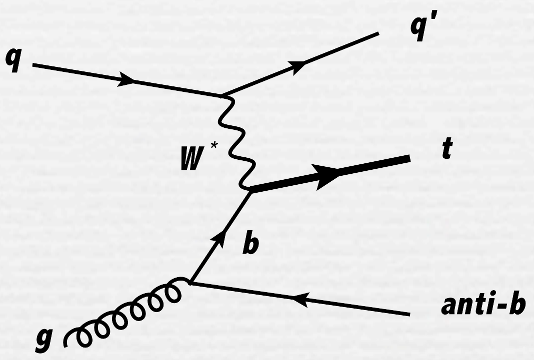
Single top and b-quark density

Campbell, Frederix, Maltoni, Tramontano

- Only if one calculates with 5 dynamical/active partons
  - i.e. contribute to evolution of PDF's in DGLAP equation, and in α_s.

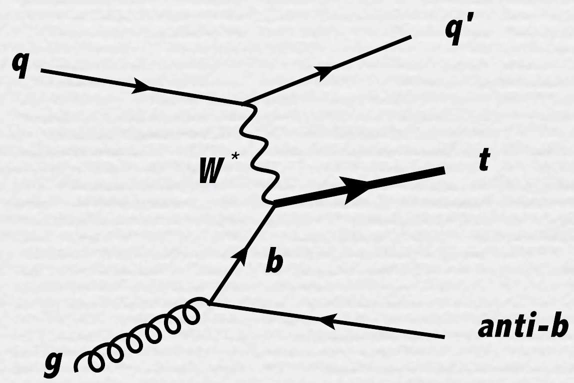
LO





part of NLO

- In 4-flavor scheme, neither top nor bottom are partons



LO

  - NLO corrections to this proess in 4F scheme computed
- Both are legal, equal to sufficiently high order. Obvious differences
  - order in perturbation theory, easier to reach NLO in 5-flavor scheme
  - at LO, predictions for "spectator" anti-b distribution

b-density

- Extracting b-density from single top important for high-scale LHC processes
  - bb -> Higgs tests, high-pT jets, etc
  - must be done at NLO for use in modern applications
- In practice, this would be done by adding it to a global analysis data set

ABKM09, JR09

- There is a more "theoretical way" to determine b-density
- Determine, from global fits, a 4-flavor set of (MSbar) PDF's

$$u^{(4)}, d^{(4)}, s^{(4)}, c^{(4)}, g^{(4)}$$

- Choose a matching scale (e.g. m_b), and use (NNLO) matching conditions

$$b^{(5)}|_{\mu=m_b} = f_b(u^{(4)}, d^{(4)}, \ldots)|_{\mu=m_b}, \text{ etc}$$

Buza, Matouine, Smith, van Neerven

- Then use 5-flavor DGLAP to evolve to scales above m_b
- Comparison will be interesting

Campbell, Frederix, Maltoni, Tramontano

4 vs 5 flavor scheme

$\sigma^{\rm NLO}_{\rm t-ch}(t+\bar{t})$	$2 \to 2$ (pb)	$2 \to 3$ (pb)
Tevatron Run II	$1.96\ {}^{+0.05}_{-0.01}\ {}^{+0.20}_{-0.16}\ {}^{+0.06}_{-0.06}\ {}^{+0.05}_{-0.05}$	$1.87\ {}^{+0.16}_{-0.21}\ {}^{+0.18}_{-0.15}\ {}^{+0.06}_{-0.06}\ {}^{+0.04}_{-0.04}$
LHC (10 TeV)	$130\ {}^{+2}_{-2}\ {}^{+3}_{-3}\ {}^{+2}_{-2}\ {}^{+2}_{-2}$	$124\ {}^{+4}_{-5}\ {}^{+2}_{-3}\ {}^{+2}_{-2}\ {}^{+2}_{-2}$
LHC (14 TeV)	$244\ {}^{+5}_{-4}\ {}^{+5}_{-6}\ {}^{+3}_{-3}\ {}^{+4}_{-4}$	$234\ {}^{+7}_{-9}\ {}^{+5}_{-5}\ {}^{+3}_{-3}\ {}^{+4}_{-4}$

Scale PDF m_t m_b

- At NLO, satisfying agreement, better at high energy
- Careful analysis shows
  - 2-> 3 factorizes into “collinear logarithm” x reduced cross section
  - “collinear logarithm” large at large x, so less important for higher collision energy

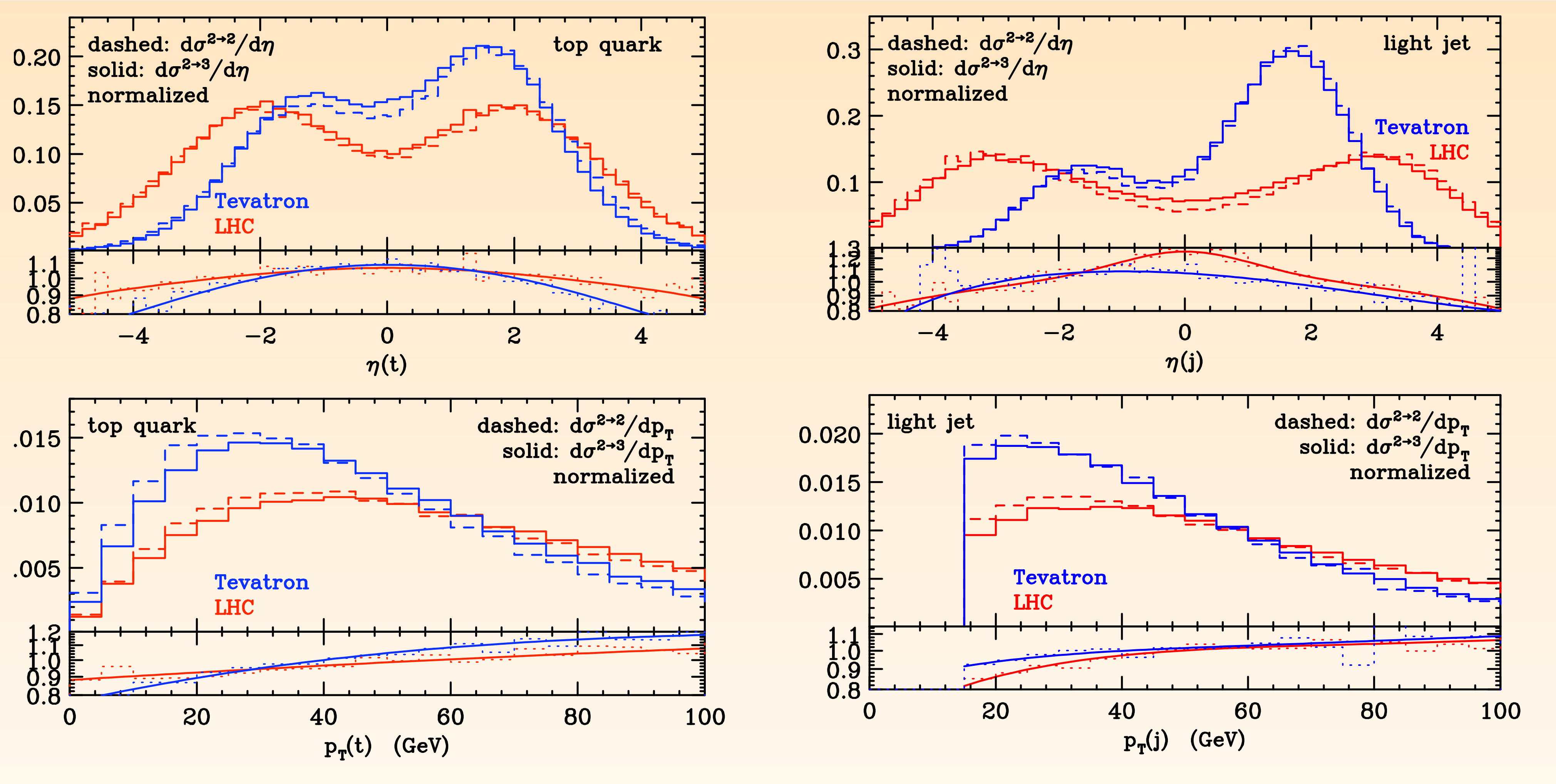
Maltoni, Ridolfi, Ubiali

$$\int_{t_{\rm min}}^{t_{\rm max}} dt \frac{d\hat{\sigma}_2^{\rm 4F}}{dt} = \frac{3\alpha_s g_W^2 C_F}{64(s+Q^2)} \frac{z^2+(1-z)^2}{2} \log \frac{\mathcal{Q}^2(z)}{m_b^2},$$

$$\mathcal{Q}^2(z) = \frac{(M_t^2+Q^2)^2}{M_t^2+(1-z)Q^2} \frac{(1-z)^2}{z}$$

Distributions in t-channel, 4F vs 5F

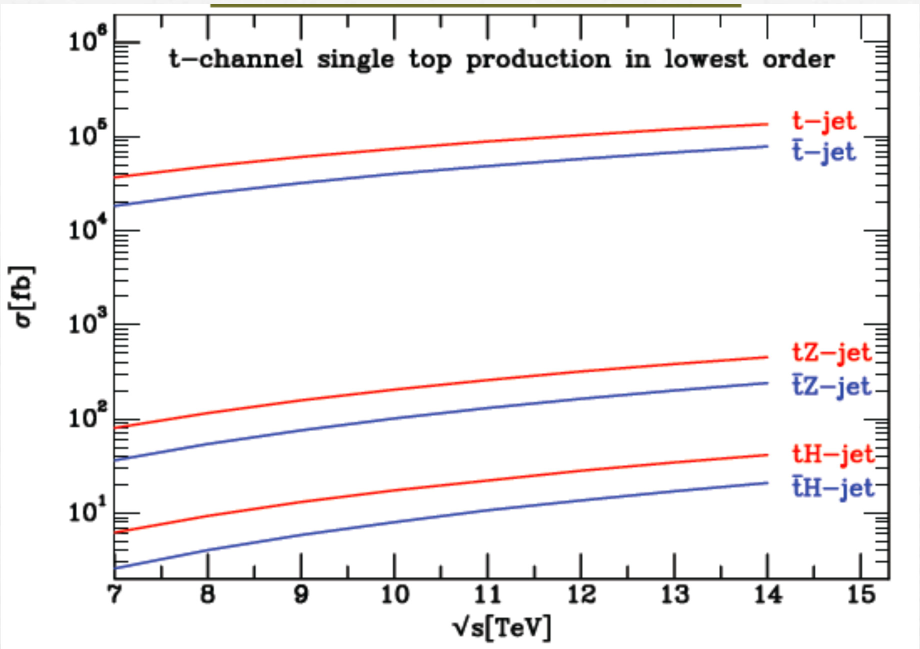
Campbell, Frederix, Maltoni, Tramontano



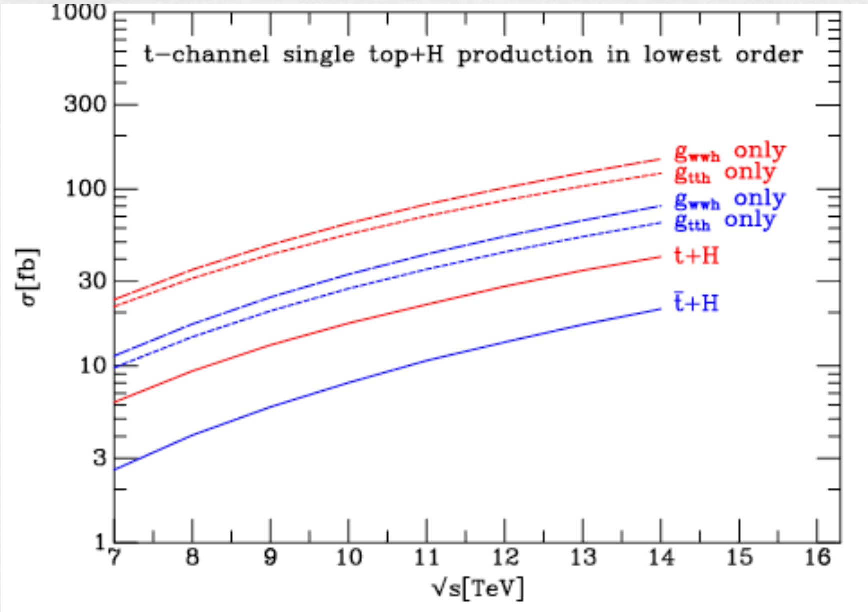
- Also for distributions, good agreement
  - about 10% devilations
- Even for anti-bottom (only at tree-level in 5F NLO) in fairly good agreement (max 20%)

Single top plus bosons: t+Z,h

- t+Z:
  - significant gauge cancellations
  - some sensitivity to t-Z coupling

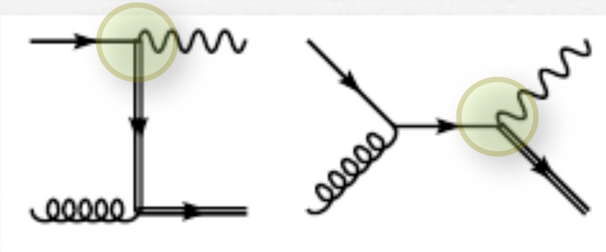


- t+h
  - **very** small cross section (few fb), much destructive interference between radiation off W and off top.

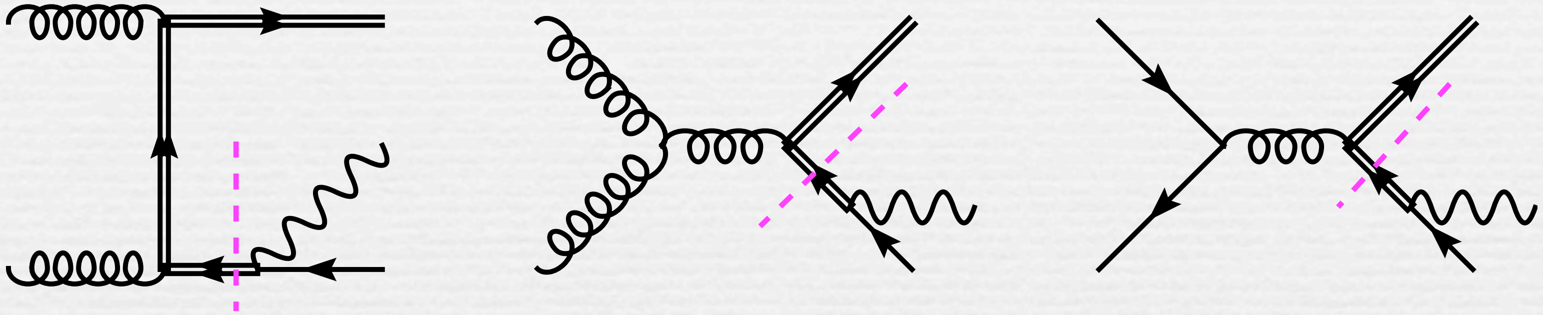


Ellis@Top2012
Barger, McKaskey, Shaughnessy
Maltoni, Stelzer, Willenbrock

Wt-channel at NLO



Among real corrections:



+ non-resonant diagrams

Interference with pair production (15 times bigger at 14 TeV)

- In earlier calculations, subtract in calculation/cut on invariant mass
  - Important cut: veto hard second b-jet suppress tt
  - All NLO processes in MCFM

Campbell, Ellis, Tramontano

Address in context of NLO + parton shower

Frixione, EL, Motylinski, Webber, White

Matching NLO to parton showers

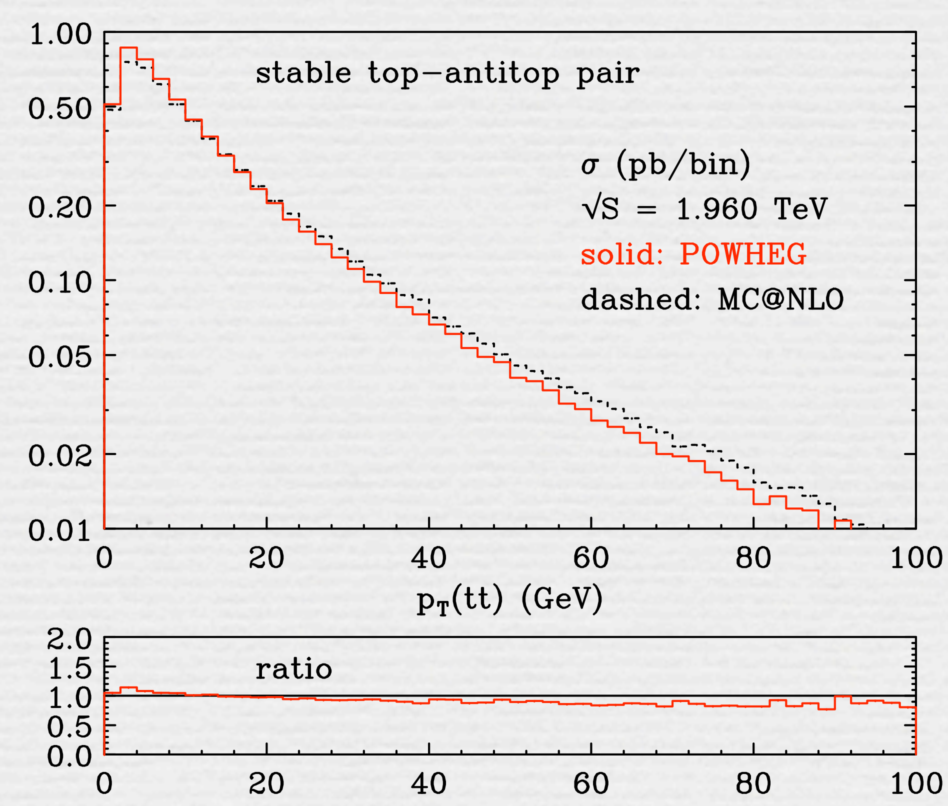
- Issue: double counting
  - emission from NLO and PS, should be counted once
  - virtual part of NLO and Sudakov form factor should not overlap
  - some freedom in this:

    Frixione, Webber; Nason

    - MC@NLO matches to HERWIG(++) angular ordered showers (PYTHIA initial state).

    Nason; Frixione, Oleari

    - POWHEG insists on having positive weights, exponentiates complete real matrix element (PYTHIA or HERWIG)
    - Automatization: POWHEG Box, aMC@NLO

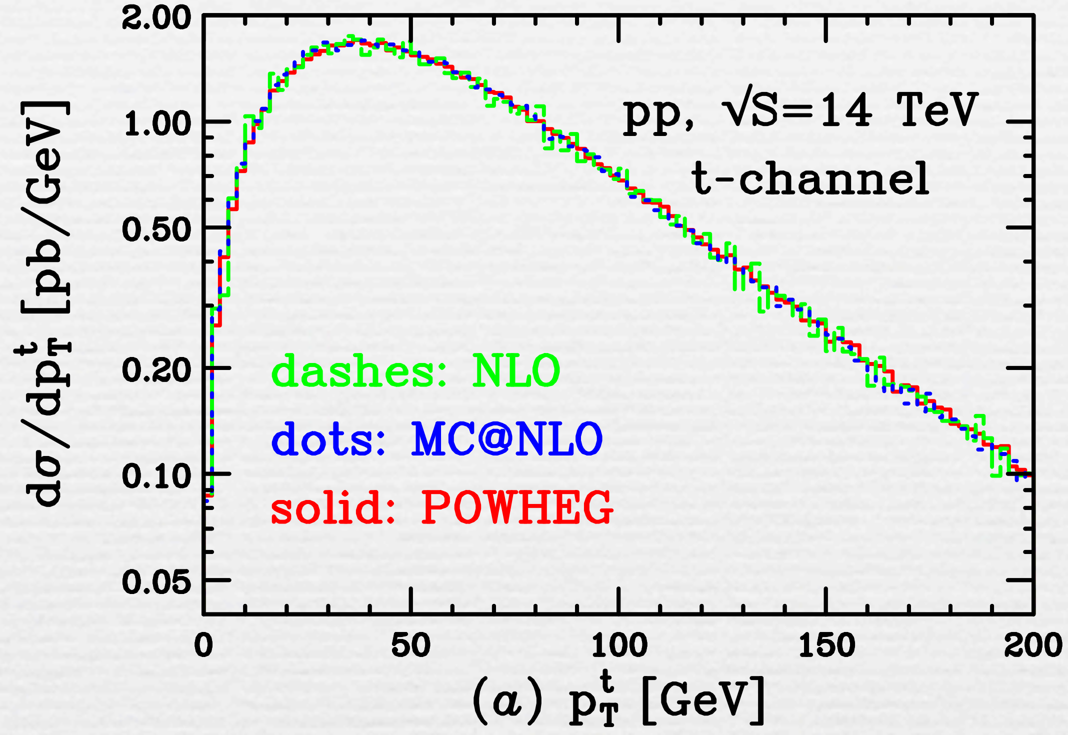


For most observables, good agreement
(more anon..)

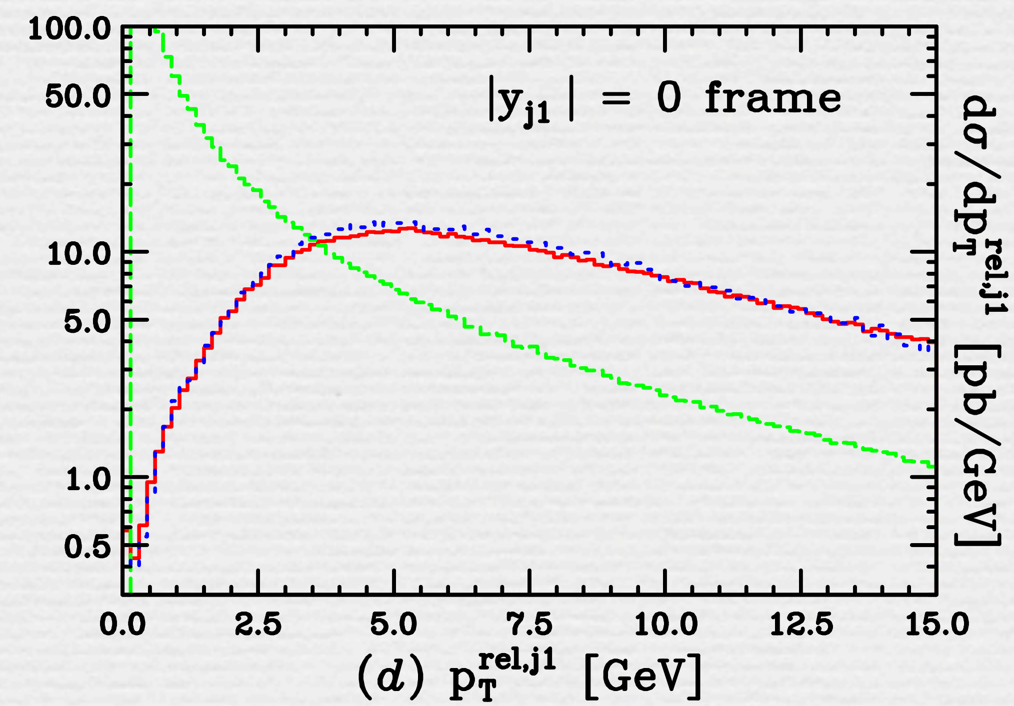
s&t channel in MC@NLO & POWHEG

Frixione, EL, Motylinski, Webber '05
Alioli, Nason, Oleari, Re '09

- Very good agreement
  - pT of top in t-channel

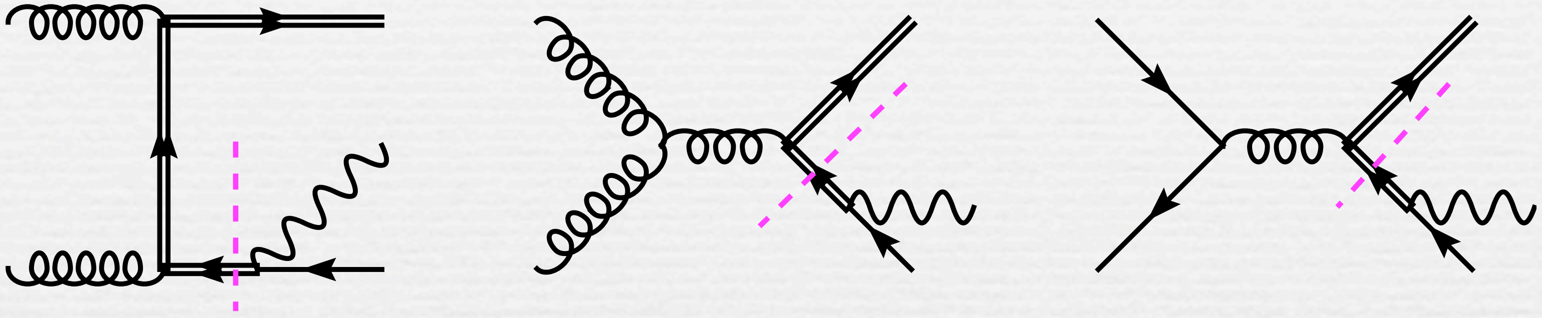


  - summed pT of all partice in hardest jet



Single top in Wt mode meets tt..

Frixione, EL, Motylinski, Webber, White



+ non-resonant diagrams

Serious interference with pair production (same problem in Ht)

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

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

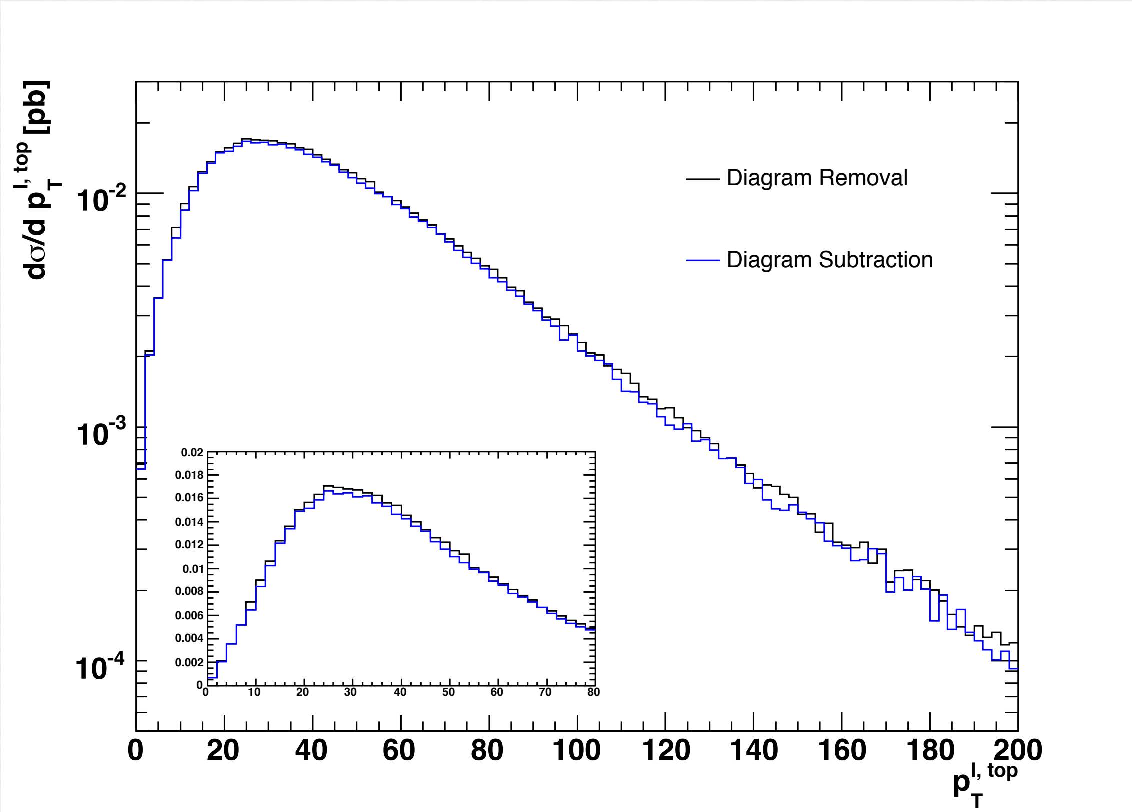
Momentum reshufling

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

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

Compare

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



DR vs DS

MC@NLO					NLO				
$\sigma^{(\mathrm{DR})}$	$\sigma^{(\mathrm{DS})}$	$\sigma^{(\mathrm{LO})}$	$K^{(\mathrm{DR})}$	$K^{(\mathrm{DS})}$	$\sigma^{(\mathrm{DR})}$	$\sigma^{(\mathrm{DS})}$	$\sigma^{(\mathrm{LO})}$	$K^{(\mathrm{DR})}$	$K^{(\mathrm{DS})}$
$p_{\mathrm{T}}^{(veto)} = 10$ GeV									
34.66	33.89	26.60	1.30	1.27	35.05	34.74	34.67	1.01	1.00
$p_{\mathrm{T}}^{(veto)} = 30$ GeV									
41.86	40.74	31.85	1.31	1.28	39.93	39.67	34.67	1.15	1.14
$p_{\mathrm{T}}^{(veto)} = 50$ GeV									
44.61	42.92	33.71	1.32	1.27	42.81	42.00	34.67	1.23	1.21
$p_{\mathrm{T}}^{(veto)} = 70$ GeV									
45.63	43.65	34.31	1.33	1.27	44.41	42.90	34.67	1.28	1.24
$p_{\mathrm{T}}^{(veto)} = \infty$									
46.33	44.12	34.67	1.34	1.27	46.33	44.12	34.67	1.34	1.27

Influence of interference depends on $p_{T}^{(veto)}$ cut

Can/should we isolate Wt?

White, Frixione, EL, Maltoni

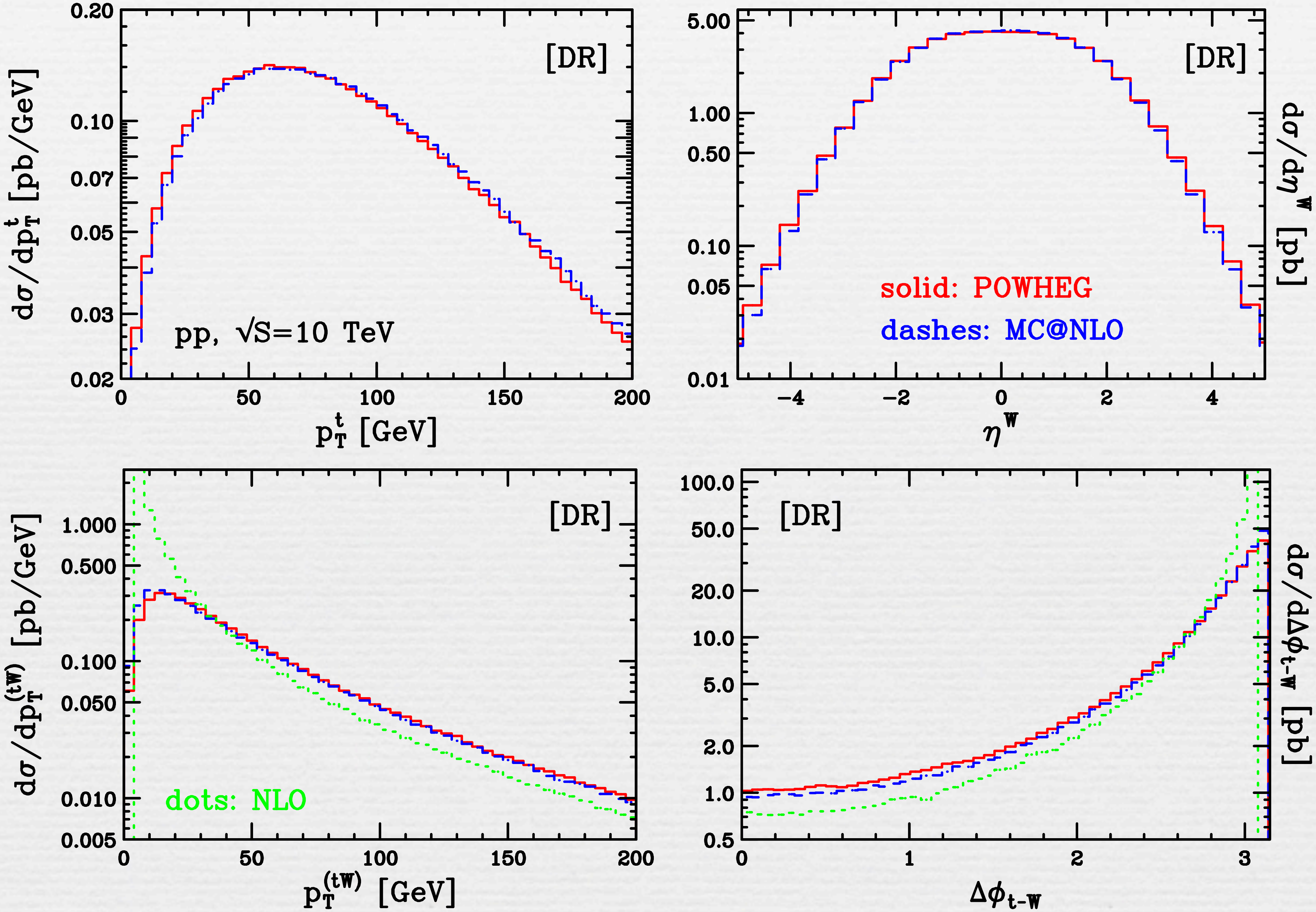
- Answer subject to cuts. Some choices:
  - Cuts to isolate Wt
  - Cuts to suppress Wt and tt as background to H->WW
- Conclusion:
  - Yes, can consider separate NLO corrections for tt (70%) and for Wt (40%)

e_b	r_{lj}	σ^{DR}_{Wt}/pb	σ^{DS}_{Wt}/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

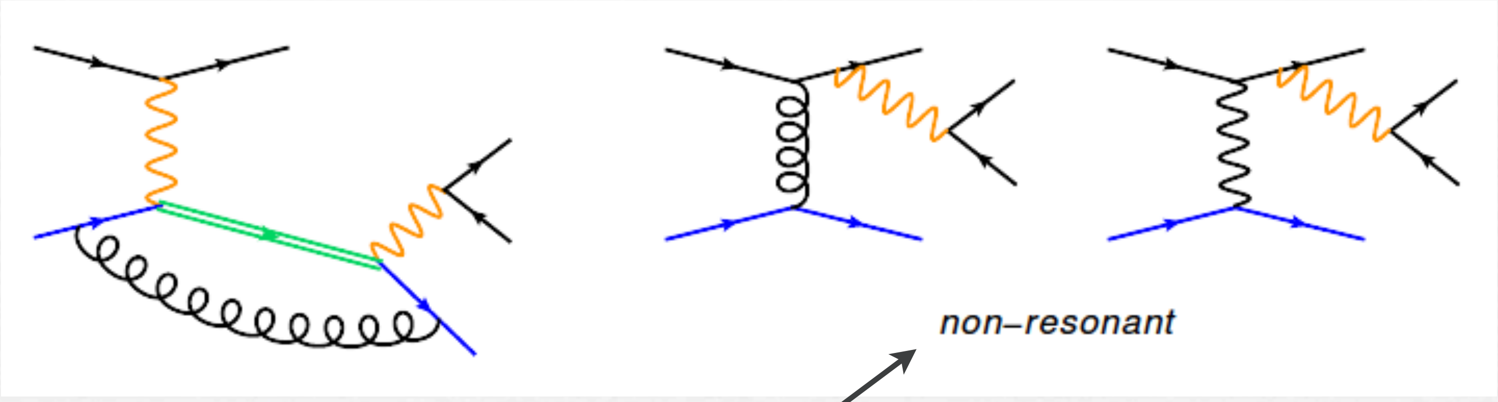
POWHEG and MC@NLO: Wt case

Re



- Very close
- Note difference with NLO due to PS

Production and decay interferences



- Usually separated through the narrow width approximation

$$\frac{1}{(p^2-m^2)+(m\Gamma)^2} \xrightarrow{NWA} \frac{\pi}{m\Gamma}\delta(p^2-m^2)+\mathcal{O}(\Gamma/m)$$

  - neglects non-resonant diagrams
- NWA in single top (except s-channel) pretty good... van der Heide, EL, Phaf, Weinzierl '00

LHC	σ_{tot}	$\lvert m_{\nu\bar{l}b}-m_t\rvert < 20$ GeV	narrow width
Wg	4.6 ± 0.2 pb	4.5 ± 0.4 pb	4.6 ± 0.1 pb
Wb	13.1 ± 0.3 pb	13.0 ± 0.4 pb	13.3 ± 0.1 pb
$q\bar{q}$	685 ± 19 fb	479 ± 16 fb	432 ± 4 fb

- ... for inclusive quantities at tree level.
- Distributions? NLO? Can use effective field theory approach

Falgari, Giannuzzi, Mellor, Signer

Effective FT approach to non-resonance

- Using small parameter

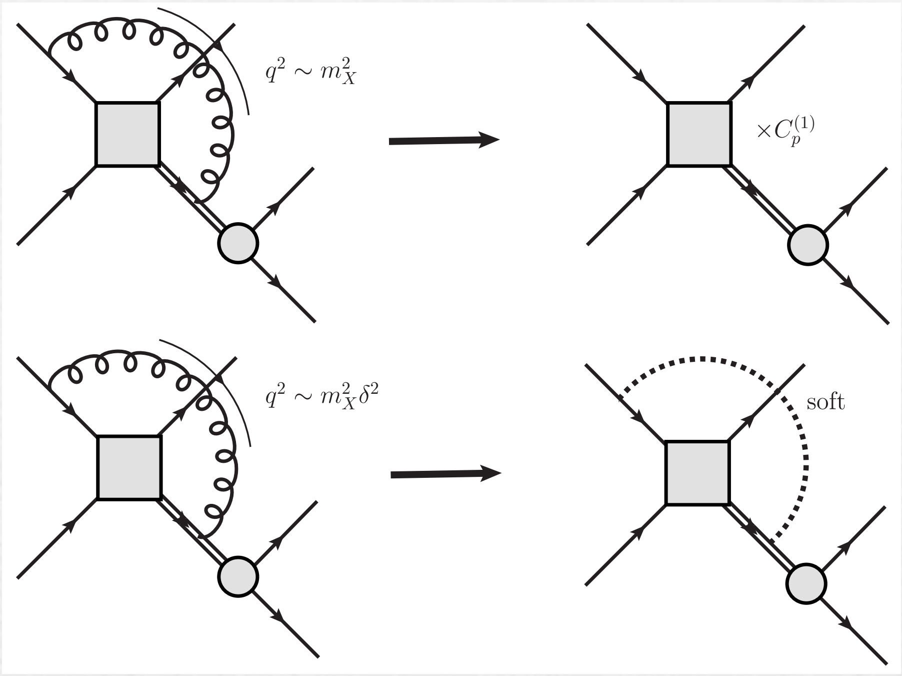
$$\delta = \frac{p^2 - m^2}{m^2}$$

- separate full process into
  - hard: $q^2 \simeq m^2$, factorizable correction
  - soft: $q^2 \simeq m^2\, \delta^2$, non-factorizable, interference
    - using method of regions
- Compute corrections to

$$N_1 N_2 \to J_b J_l e^+ \not{E}_T + X \qquad \text{t-channel}$$
$$N_1 N_2 \to J_b J_{\bar{b}} e^+ \not{E}_T + X \qquad \text{s-channel}$$

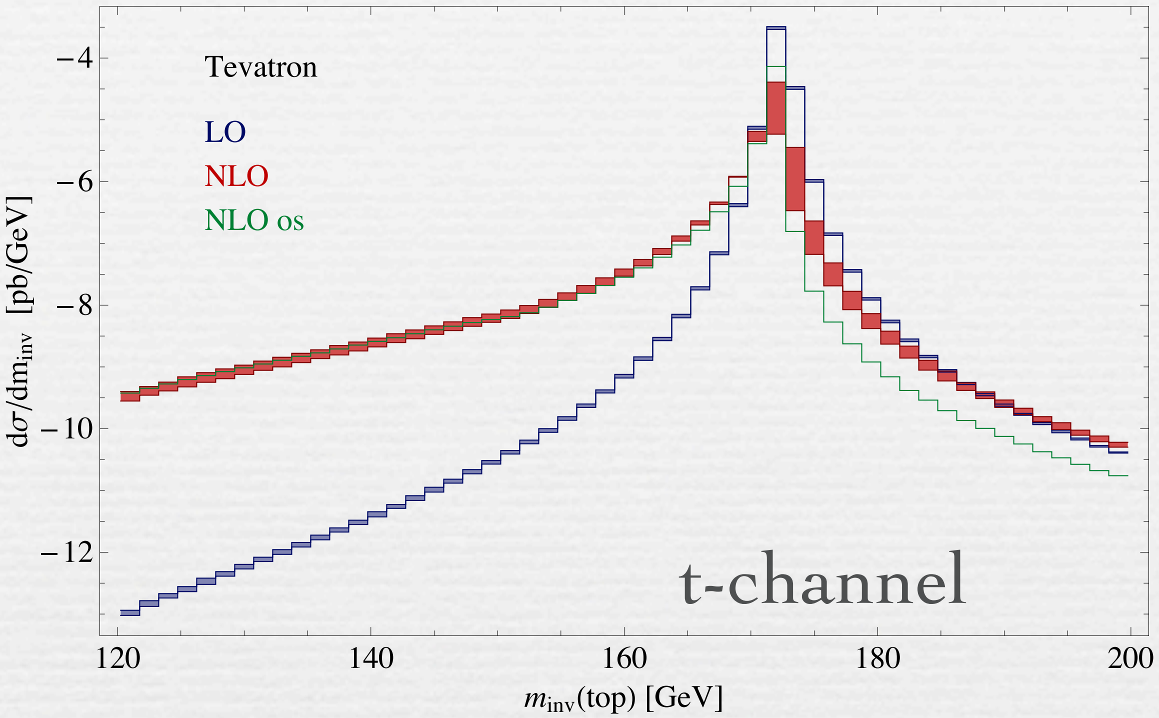
- Gauge invariant method
  - (would be interesting to compare with complex-mass scheme)

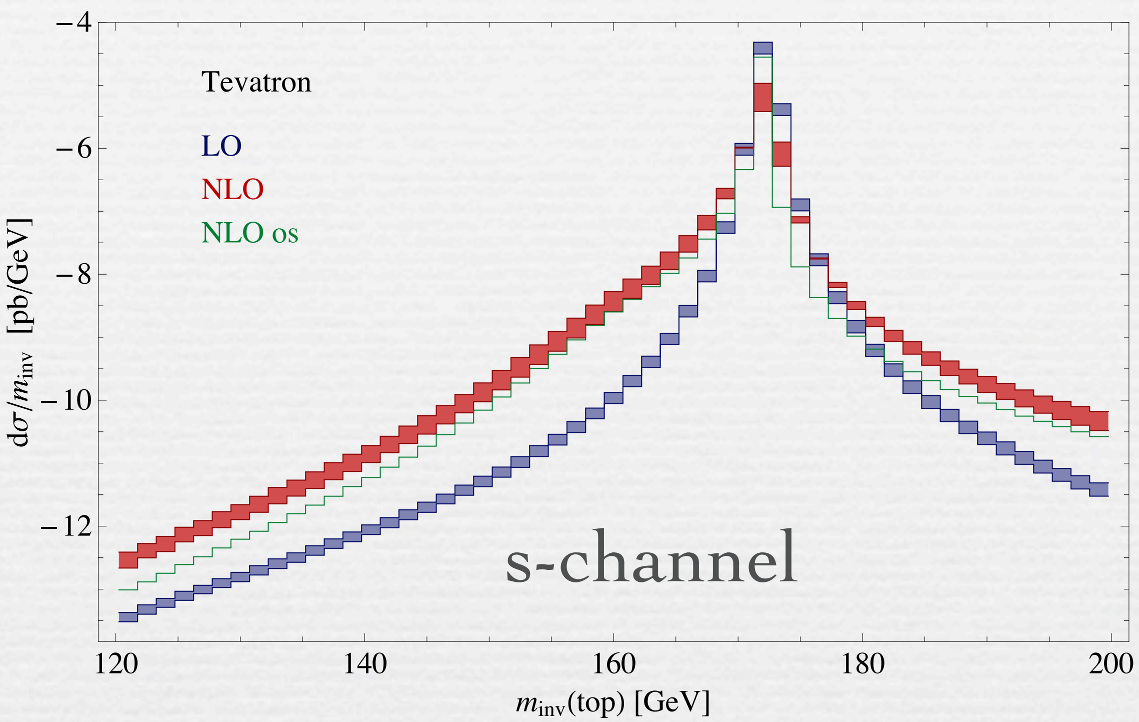
Beneke, Chapovsky, Signer, Zanderighi



Distributions

Invariant mass distribution, LHC 7





- Non-factorizable corrections change sign around peak
- Off-shell effects large close to peak
  - Largely cancels for inclusive cross section, as in tT

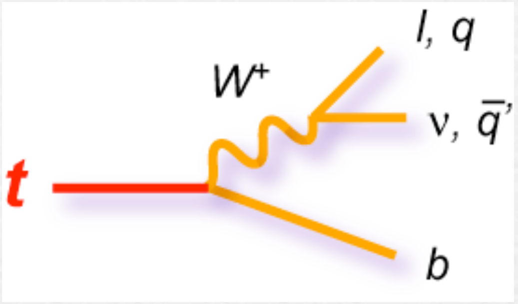
Bevilacqua, Czakon, v. Hameren, Papadopoulos, Worek
Denner, Dittmaier, Kallweit, Pozzorini

$pp \to J_b J_l e^+ \not{E}_T + X$		**ET**	**NWA**
	LO[pb]	$3.460(1)^{+0.278}_{-0.403}$	$3.505(1)$
	NLO[pb]	$1.609(6)^{+0.303}_{-0.240}$	$1.642(1)$
$pp \to J_b J_{\bar{b}} e^+ \not{E}_T + X$		**ET**	**NWA**
	LO[pb]	$0.1654(1)^{+0.0001}_{-0.0010}$	$0.1677(1)$
	NLO[pb]	$0.1618(4)^{+0.0021}_{-0.0005}$	$0.1635(1)$

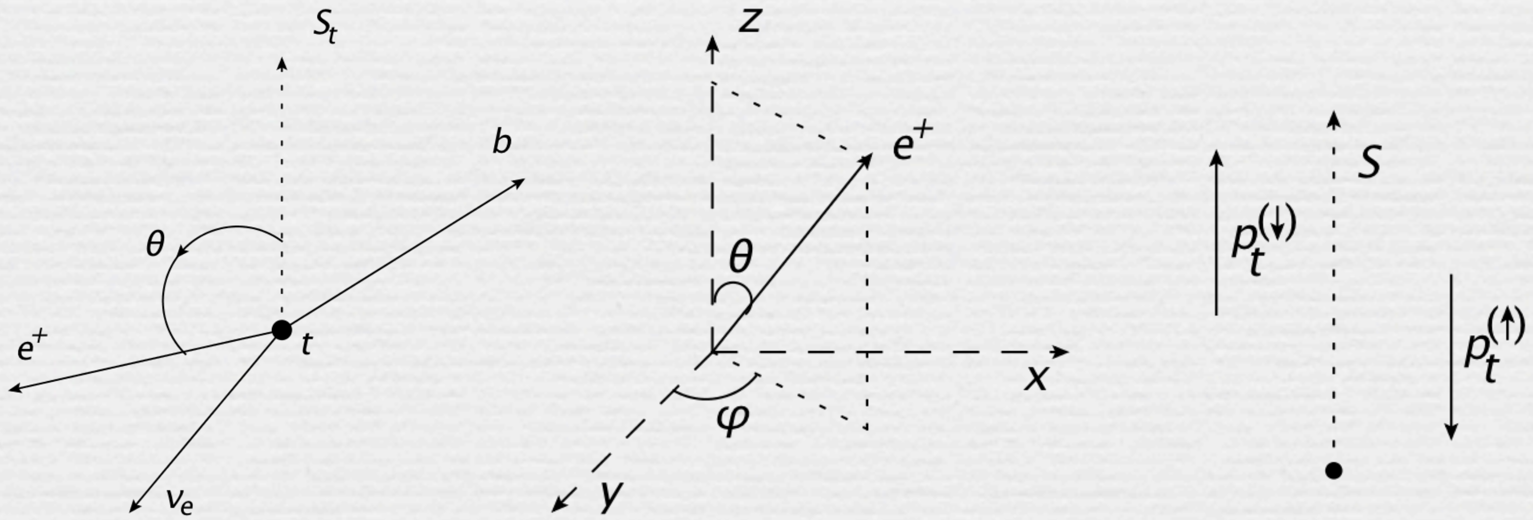
Falgari, Giannuzzi, Mellor, Signer

Top quark spin

- Let us now assume we can somehow polarize the top quark sample. Can we detect the top quark spin?
  - Full decay



  - Take the top spin vector conveniently along the z-axis



(A) Spin axis - products (B) e^+ momentum decomposition (C) Top quark rest frame

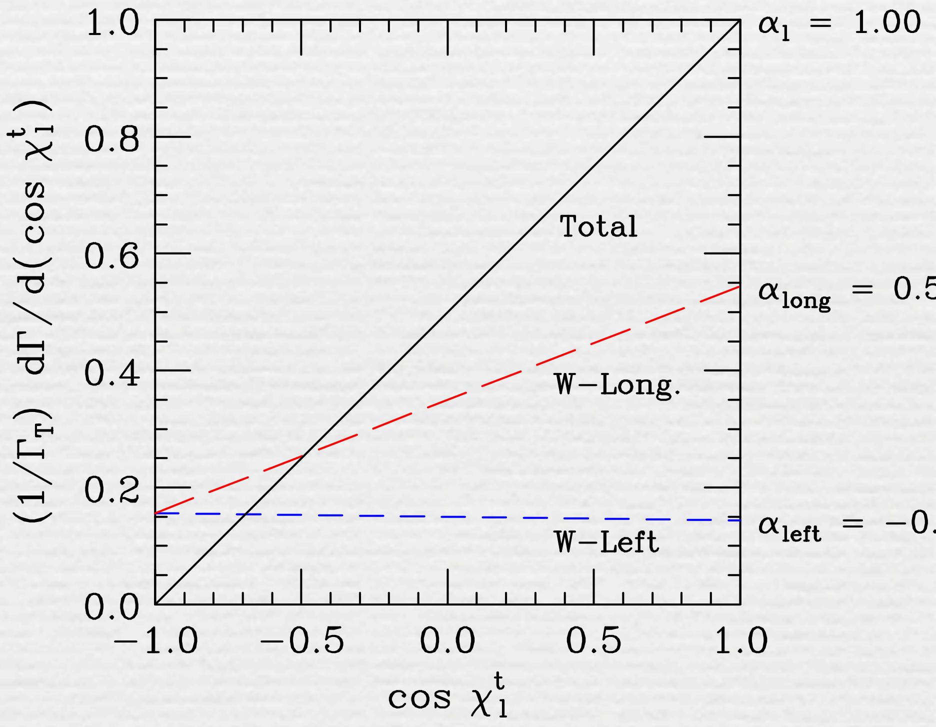
  - Angular distribution of charged lepton for spin-up top

$$\frac{1}{\Gamma_f}\frac{d\Gamma_{f,(\uparrow)}}{d(\cos\theta_f)} = \frac{1}{2}(1 + pc_f\cos\theta_f)$$

Polarized top decay

- For f = charged lepton: c=1 $\Rightarrow$ 100% correlation !
  - Top self-analyzes its spin
  - Charged leptons easy to measure, good handle on top spin
    - if they can be produced in a polarized fashion
    - **single top production does so!**

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



- Note: charged lepton has larger “spin-analyzing power” than its parent W!
  - Reason: for this distribution intermediate λ = 0 and λ = - amplitudes interference.
    - If decay can take place via intermediate charged Higgs, the distribution would change..

Spin correlations

- A process with an intermediate "resonant" particle P (e.g. W, Z, top..) reads

$$a + b \longrightarrow P(\longrightarrow d_1 + \cdots + d_n) + X$$

- has "production" spin/angular correlations if it depends on $d_i.a$, $d_i.b$ or $d_i.X$
- Let P be an intermediate W, which will be nearly on-shell. We can approximate the intermediate W propagator through the Narrow Width approximation

$$\frac{1}{(q^2 - m_V^2)^2 + (m_V \Gamma_V)^2} \longrightarrow \frac{\pi}{m_V \Gamma_V} \delta\left(q^2 - m_V^2\right) .$$

- Resulting expression

$$\sum_{spin} |A|^2 = \frac{\pi}{m_V \Gamma_V} \sum_{\lambda\lambda'} \tilde{M}_\lambda \rho_{\lambda\lambda'} \tilde{M}^*_{\lambda'} \, \delta\left(q^2 - m_V^2\right)$$

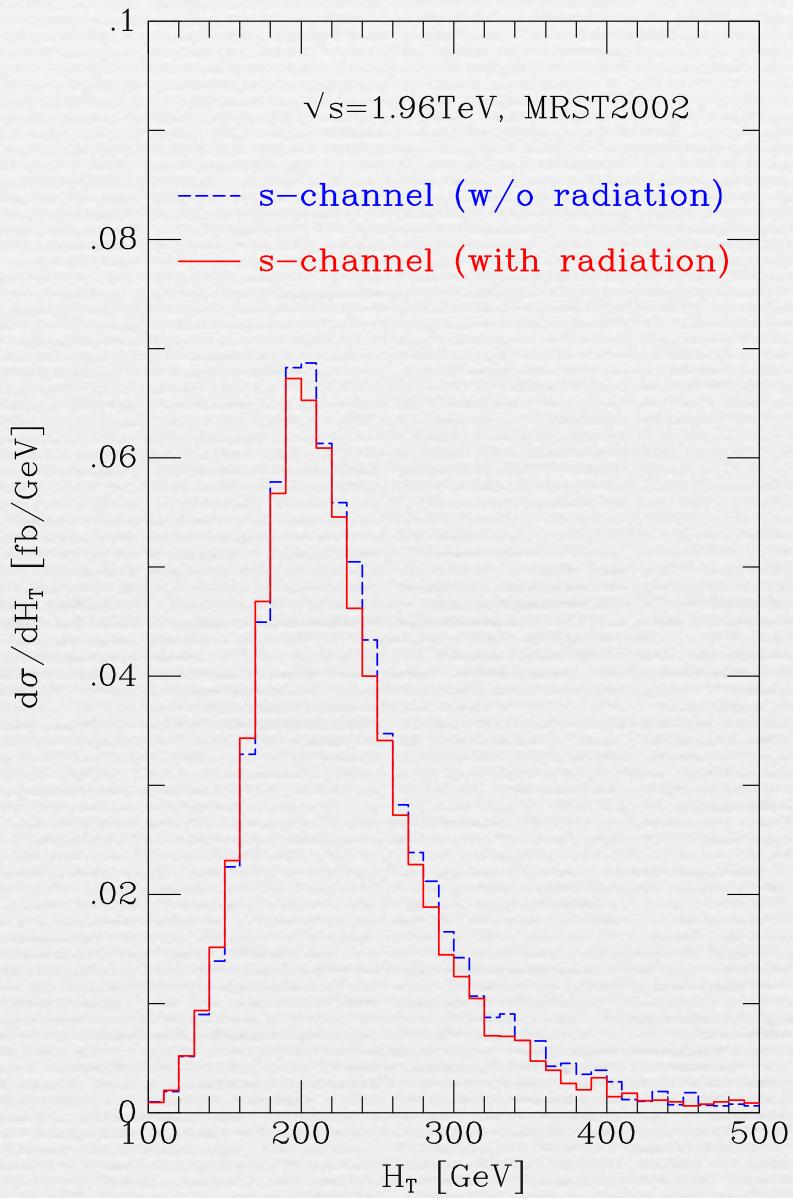
- with $\rho_{\lambda\lambda'}$ the spin-density matrix for W-decay. Can do this also for top decay.
- Can now include QCD corrections to production and decay separately

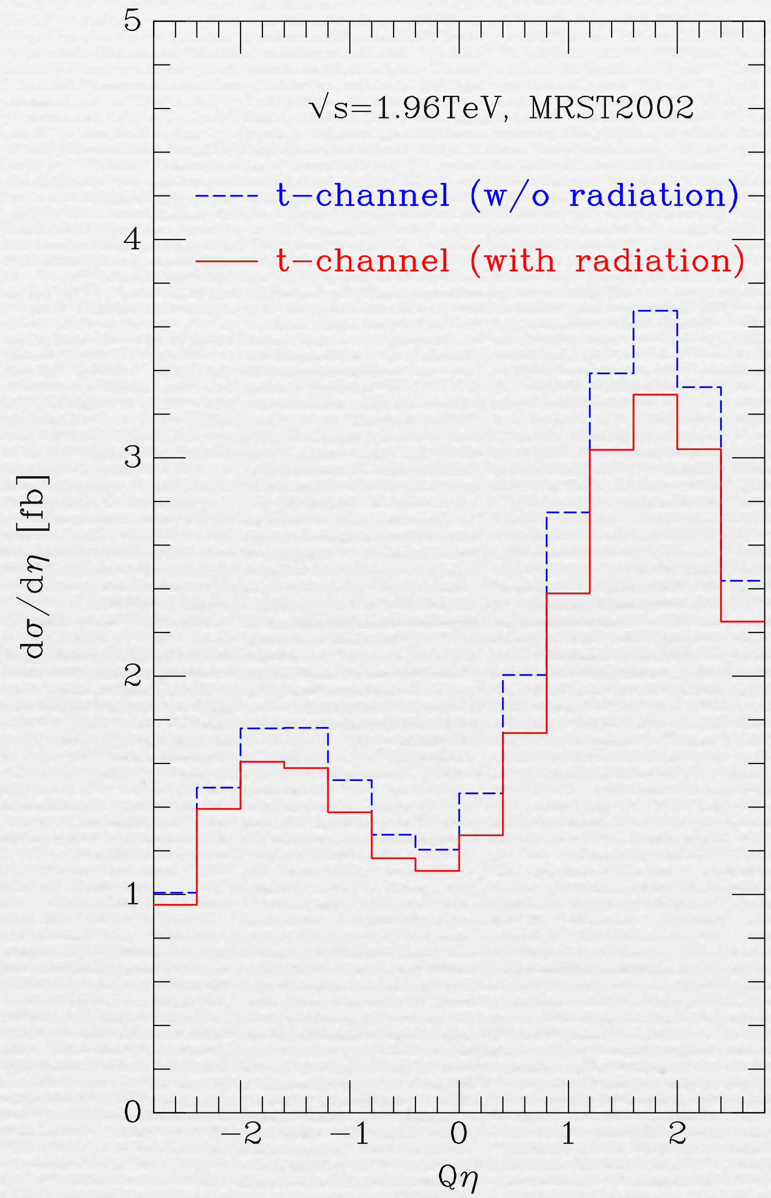
Campbell, Ellis, Tramontano
Schweinhorst, Yuan, Mueller, Cao, Heim

- Can include decay with spin correlations (half-NLO, no loops in decay) a posteriori in MC@NLO, by reweighting according to full tree level

Frixione, EL, Motylinski, Webber

Production and decay at NLO





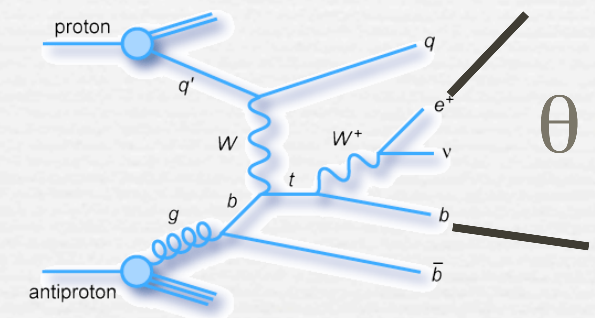
Campbell, Ellis, Tramontano
Schweinhorst, Yuan, Mueller, Cao, Heim

Little effect of radiation on shape, for rate a little more

Spin correlations for single top in MC@NLO

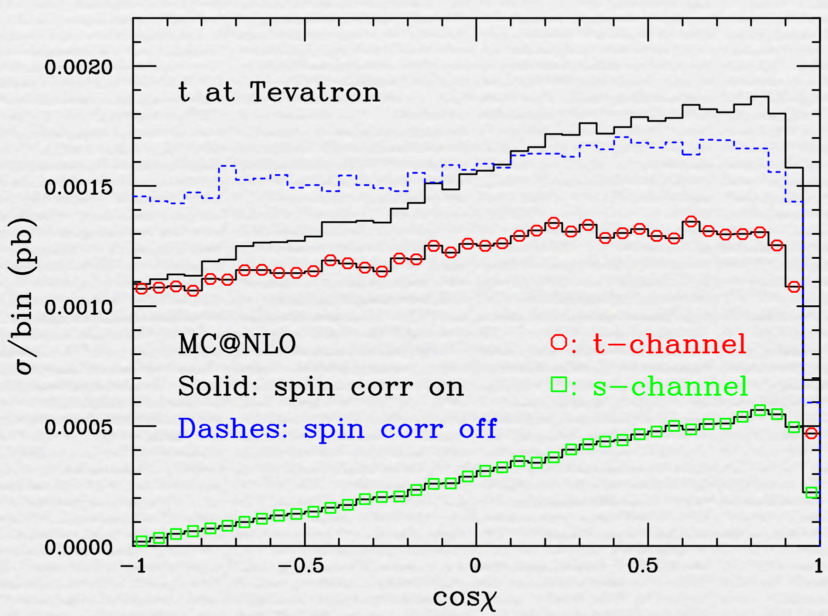
Frixione, EL, Motylinski, Webber

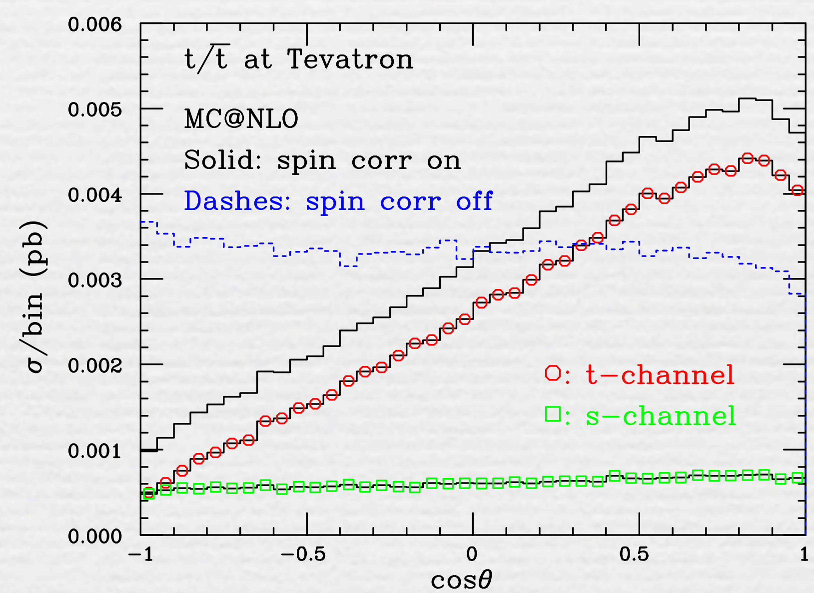
- Top is produced polarized by EW interaction
  - 100% correlation between top spin and charged lepton direction
- Angle of lepton with appropriate axis is different per channel
- Method included "a posteriori". Now also used in POWHEG



Aioli, Nason, Oleari, Re

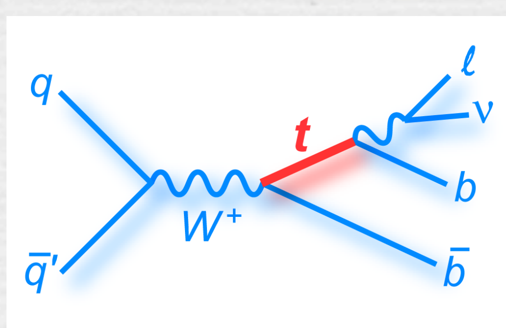
Beam direction





Hardest, non-b jet

Robust correlation in NLO event generation

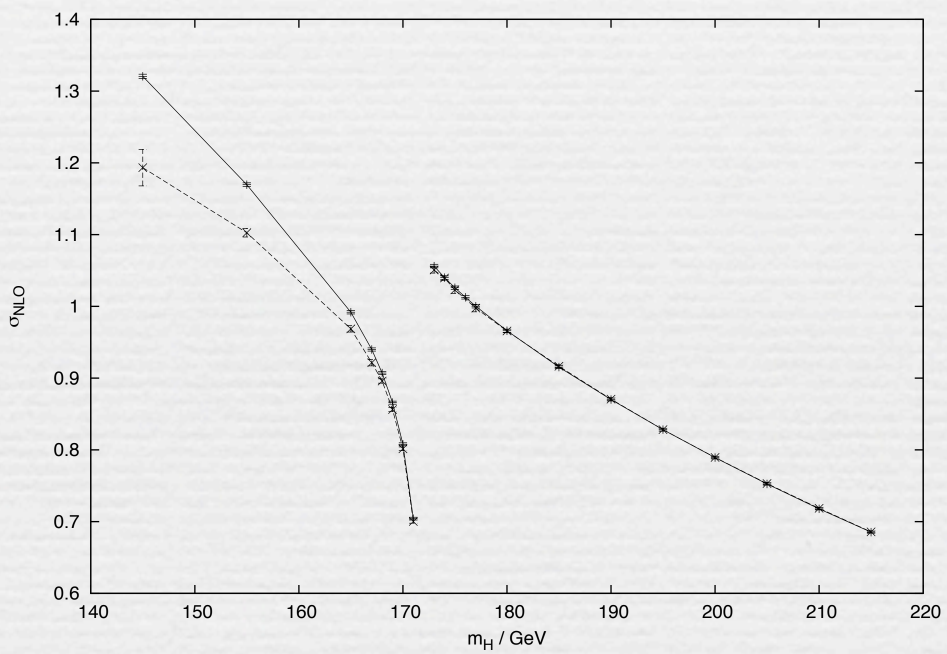


spin-space correlation
works both ways

MC@NLO: Ht

Frixione, Herquet, Klasen, EL, Plehn, Stavenga, Weydert, White

- To calculate, very similar to Wt
  - but tT interference problem only if $m_{H+} < m_t$



Total cross section vs. charged Higgs mass. Solid: DR, dashed: DS

  - also: Yukawa coupling and renormalization

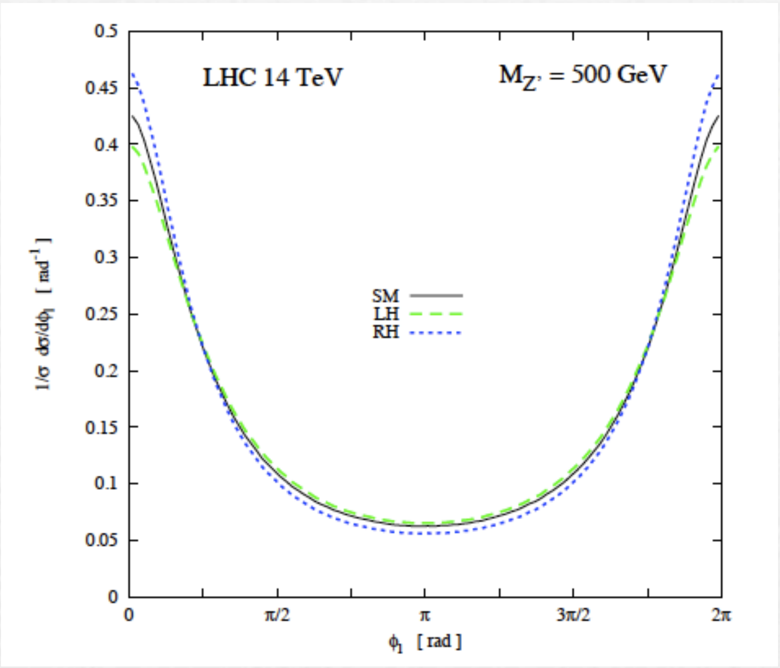
Azimuthal distributions and BSM tests

- 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
  - Construct asymmetry

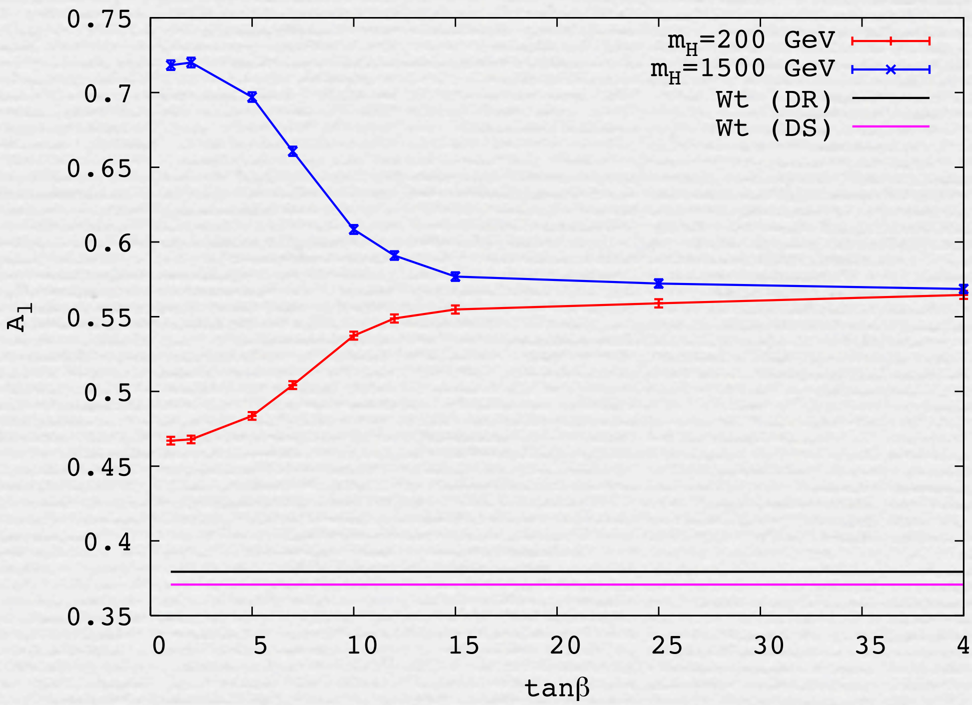
$$A = \frac{\sigma(\cos\phi_l) > 0) - \sigma(\cos\phi_l) < 0)}{\sigma(\cos\phi_l) > 0) + \sigma(\cos\phi_l) < 0)}$$

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

Godbole, Rao, Rindani, Singh



Godbole, Hartgring, Niessen, White



Conclusions

- Single top has it all:
  - top, EW scale, spin, flavor
- Measurements bedeviled by tough background, require multi-variate methods
- Theoretical descriptions and tools good
  - more precise checking of single top behavior imminent