Top-Asymmetries and Correlations

MSU, August 2012

Keith Ellis, Fermilab

"Top quark processes at NLO in production and decay", arXiv: 1204.1513 [hep-ph]
"ttbarW production and decay at NLO", arXiv:1204.5678 [hep-ph]
Campbell and R.K.Ellis
"MCFMv6.3", Campbell, R.K.Ellis and Williams
"MCFM-POWHEG", Campbell, R.K.Ellis and Nason (in preparation)

Why top now?

- Top is unstudied
  - Tevatron studies of the top quark have limited statistical precision.
- Top is special
  - $1/m_t$ < $1/\Gamma_t$ < $1/\Lambda$ < m_t/Λ^2
    Production time < Lifetime < Hadronization time < Spin decorrelation time
  - Top quark has largish coupling to Higgs, and may play a special role in Electroweak symmetry breaking and other BSM physics.
- Top is ubiquitous.
  - Top cross section is large at LHC because of large gluon flux
  - Top-related processes are significant backgrounds for new physics.

LHC is the new elephant in the room

Process	$\sqrt{s}$ [GeV]	Cross section [pb]	Cumulative luminosity [fb^{-1}]	$\sigma_{Q\bar{Q}}/\sigma_{tot}$
$e^+e^- \to b\bar{b}$	10.48	$\sim$ 1000 pb	530, (1998-2002)	25%
$pp \to t\bar{t}$	14000	$\sim$ 1000 pb	$\sim$ 3000, (2010-2030)	10^{-8}

- LHC accumulated luminosity will in ~10 years surpass the B-factories
- Cross sections are roughly the same for bbar and ttbar respectively.
- A low mass Higgs ensures that physics at the scale of 100-200 GeV will not be dropped from the trigger menu.
- Production dynamics of top will be studied in exquisite detail.
- Need simulation tools adequate for the task.

MCFM

* MCFM is a unified approach to NLO corrections, both to cross sections and differential distributions: http://mcfm.fnal.gov (v6.3, August 2012)
* Publically available code, J. M. Campbell, R. K. Ellis, C. Williams (main authors) R. Frederix, H. Hartanto, F. Maltoni, F. Tramontano, S. Willenbrock, G. Zanderighi....
* Standard Model processes for di-boson pairs, vector boson+jets, heavy quarks, Higgs, photon processes,... (~160 different processes included at NLO).
* Decays of unstable particles are included, maintaining spin correlations.
* Amplitudes (especially the one-loop contributions), calculated *ab initio* or taken from the literature.

New features in v6.2 (April 2012)

- A complete update of top-pair production, t-channel single-top production, s-channel single-top production.
- Top quark is produced on shell but with complete spin correlations through NLO. (For the case of top pair production inclusion of the one-loop analytic amplitudes of Badger, Sattler and Yundin, (arXiv:1101.5947) leading to a factor of 3 improvement in the speed of the code).
  - Inclusion of radiation in decay.
  - Inclusion of off-shell W effects.
  - Full dependence on the mass of the b-quark in top production and decay, (a necessity for four flavor t-channel single top production, a luxury elsewhere).
  - Our treatment builds on our earlier work Campbell, Ellis, Tramontano (hep-ph/0408158) and Melnikov and Schulze, (arXiv:0907.3090, arXiv:1004.3284)

Commonly used programs such as MC@NLO do not currently have a *full* NLO implementation of the top pole approximation.

New features in v6.3 (August 2012)

- New processes
  - t-tbar-$W^{\pm}$ production in the full top-pole approximation, (same-sign lepton events + missing energy+b-quarks!)
  - Upgrade of continuum W^+W^- production and $H\to W^+W^-$ production to give radiation in hadronic decay of the W.
  - $Z\gamma\gamma$ and $Z\gamma$+jet production.
  - Inclusion of the loop-level Higgs boson decay $H \to Z(\to e^+e^-)+\gamma$, and $H \to Z(\to \nu\nu)+\gamma$

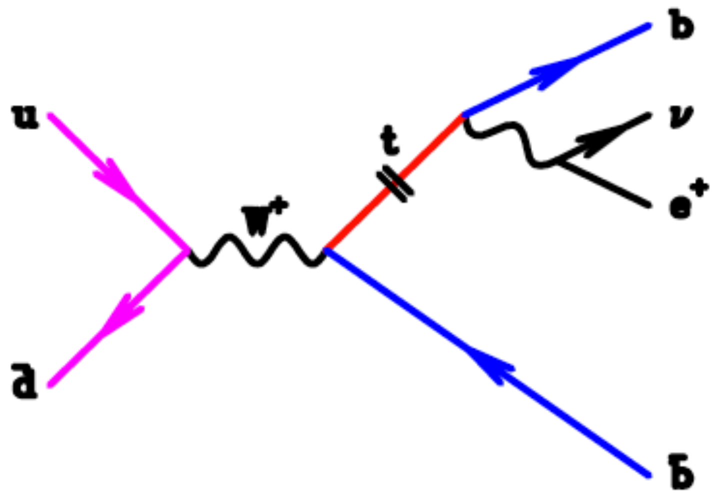
Available for download now at mcfm.fnal.gov

(Double) Resonance Approximation

* In leading order (LO) we can treat top quark production exactly including off-resonance contributions and top quark decays.

* In MCFM at NLO we treat top production in the pole approximation.

Example for s-channel single top at LO



  * Top quarks are produced on shell and then decay giving access to the kinematics of the decay products.

  * All spin correlations are kept.

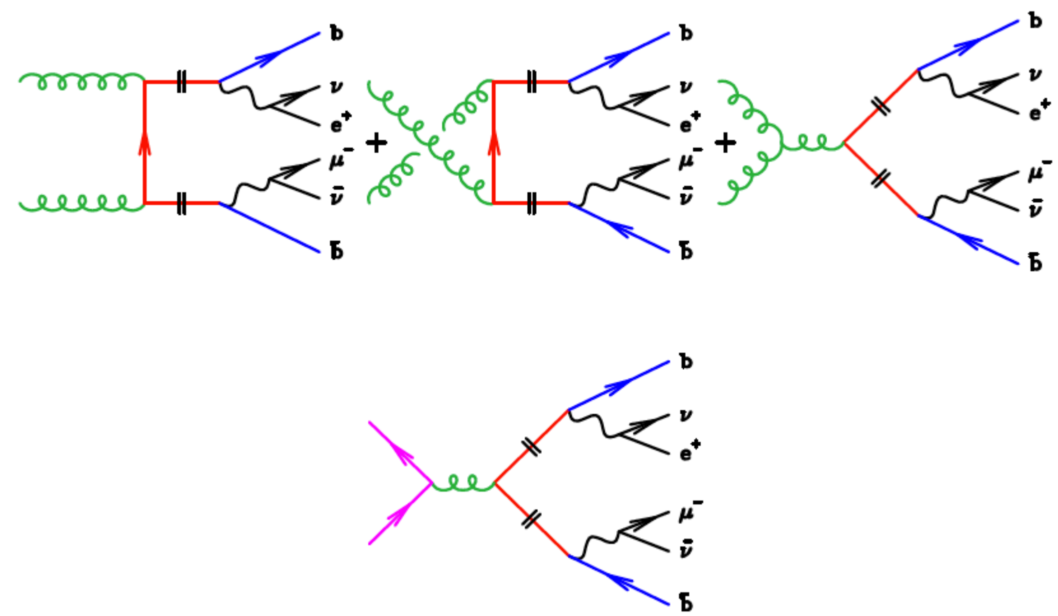
  * A systematic approximation extensible to NLO, NNLO,..

  * Production and decay are separately gauge invariant.

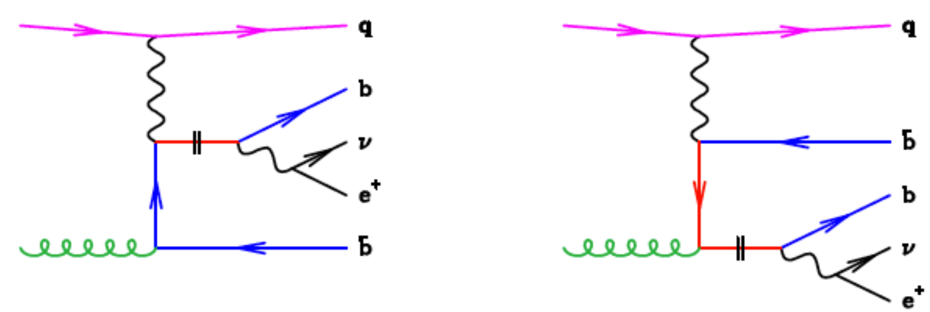
* For a NLO treatment that transcends to double pole approximation, see Denner et al, arXiv 1207.5016. Finite top-width effects are found to be at the percent level whenever top quark resonances dominate.

Lowest order diagrams for currently included processes

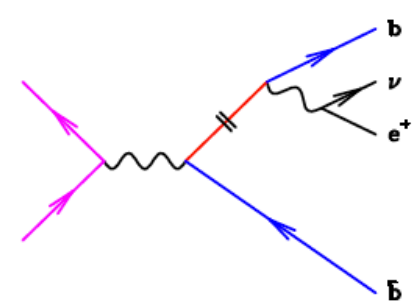
* top-pair production



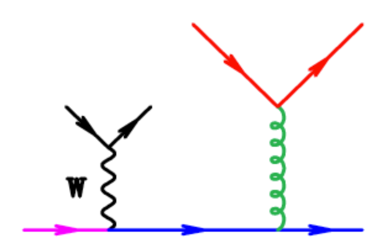
* t-channel single top



* s-channel single top



* Wttbar production



+ ...
(with top decays -not drawn)

Inclusion of spin correlations with on-shell top

* Since characteristic time for production of the top quark is $1/m_t$ whereas characteristic time for decay is $1/\Gamma_t$, interference between production and decay is of order $\alpha_s \Gamma_t / m_t$ and can be neglected.

* Factorization of the calculation into amplitude for production and amplitudes for decay.

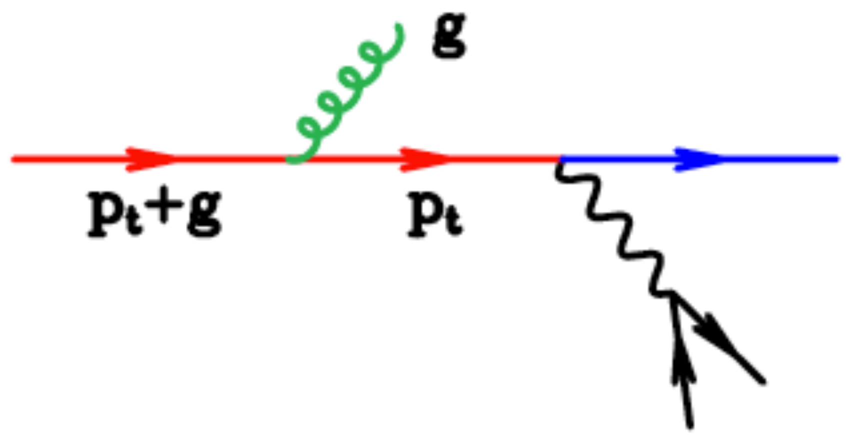
$$\frac{\not{p}_t + m_t}{p_t^2 - m_t^2 + i m_t \Gamma_t} \rightarrow \frac{\sum_\lambda u_\lambda(p_t) \bar{u}_\lambda(p_t)}{i m_t \Gamma_t}$$

* Massive spinors written as combinations of massless spinors

$$u_-(p_t) = (\not{p}_t + m_t)|\eta_t\rangle \frac{1}{\langle t \eta_t \rangle}, \quad u_+(p_t) = (\not{p}_t + m_t)|\eta_t] \frac{1}{[t \eta_t]}$$

* such that $p_t = t^\mu + \alpha \eta, \ \ t.t = \eta.\eta = 0$ and $\sum_{\lambda=\pm} u_\lambda(p_t) \bar{u}_\lambda(p_t) = \not{p}_t + m_t$

Separation of radiation in production and decay



$$\frac{1}{[(p_t+g)^2-m_t^2+im_t\Gamma_t)]\,[p_t^2-m_t^2+im_t\Gamma_t)]} = \frac{1}{2p_t\cdot g}\left\{\frac{1}{[p_t^2-m_t^2+im_t\Gamma_t)]}-\frac{1}{[(p_t+g)^2-m_t^2+im_t\Gamma_t)]}\right\}$$

Radiation in production on this pole

Radiation in decay on this pole

- Artificial separation by partial fractioning makes it clear that radiation in production and decay belong together.

Width of the top quark

- Since we treat the top quark as being on shell, the width of the top quark is an overall scale parameter.
- NLO corrections to the width are relevant to ensure that we only keep terms of order $O(\alpha_s)$.
- We have (re-)performed the NLO calculation of the width including finite mass effects and off-shell corrections for the W.

Czarnecki, Jezabek and Kuhn

- The correction gives $\frac{\alpha_S \Gamma_1}{\Gamma_0} \approx -0.8\alpha_S$ lowering the leading order result by about 10%.

	$m_W = 80.398$ GeV, $m_b = 4.7$ GeV	$m_W = 80.398$ GeV, $m_b = 0$
Γ_0^{BW} [GeV]	1.453518	1.457412
$\Gamma_1^{BW}/\Gamma_0^{BW}$	-0.7878491	-0.7972087
Γ_0^{NW} [GeV]	1.476596	1.480522
$\Gamma_1^{NW}/\Gamma_0^{NW}$	-0.7878090	-0.7971276

Consistent treatment of top decay

- Full cross section integrated over the decay products of the top is given by production cross section X branching fraction to appropriate channel.
- eg. for single top production

$$\sigma^{NLO}(pp \to t(\to \nu e^+ b) + X) = (\sigma_0 + \alpha_S \sigma_1) \times \frac{d\Gamma_0^{(l)} + \alpha_S d\Gamma_1^{(l)}}{\Gamma_0 + \alpha_S \Gamma_1}$$

- Removing superfluous $O(\alpha_s^2)$ corrections we have that

$$\sigma^{NLO} = (\sigma_0 + \alpha_S \sigma_1) \times Br(W \to \nu e^+) + \alpha_S \sigma_0 Br(W \to \nu e^+) \left[\frac{\Gamma_1^{(l)}}{\Gamma_0^{(l)}} - \frac{\Gamma_1}{\Gamma_0} \right]$$

$$\equiv (\sigma_0 + \alpha_S \sigma_1) \times Br(W \to \nu e^+)$$

Melnikov and Schulze, arXiv:0907.3090

- Thus integrating over all decay products, radiation in leptonic top decay does not change total cross section; but in the presence of cuts it can change cross sections.

Application to s-channel single top at the Tevatron

* s-channel single top without cuts

Treatment of W-boson and b-quark	σ_{LO} [fb]	σ_{NLO} (prod.) [fb]	σ_{NLO} (prod.+decay) [fb]
Narrow width, $m_b = 0$	30.98(2)	48.84(3)	48.82(3)
Narrow width, $m_b = 4.7$ GeV	30.78(2)	48.61(3)	48.60(3)
Breit-Wigner, $m_b = 4.7$ GeV	30.77(2)	48.61(3)	48.59(3)

  * Note agreement between columns 2&3 and small b-mass effect.

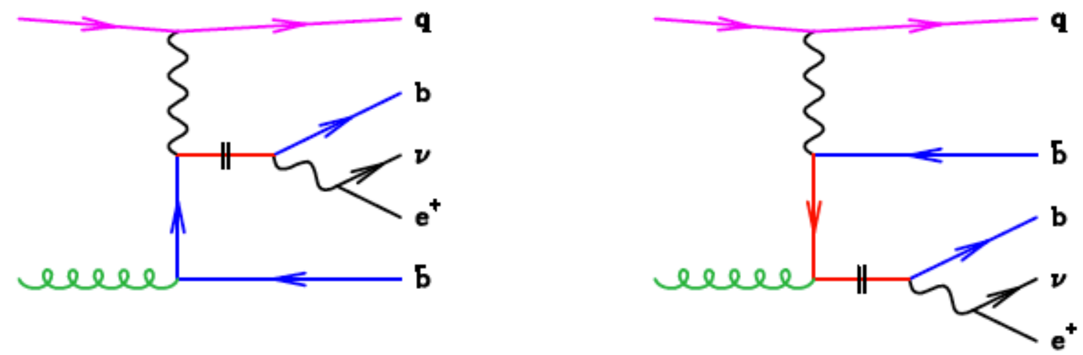
* s-channel single top with Higgs style cuts.

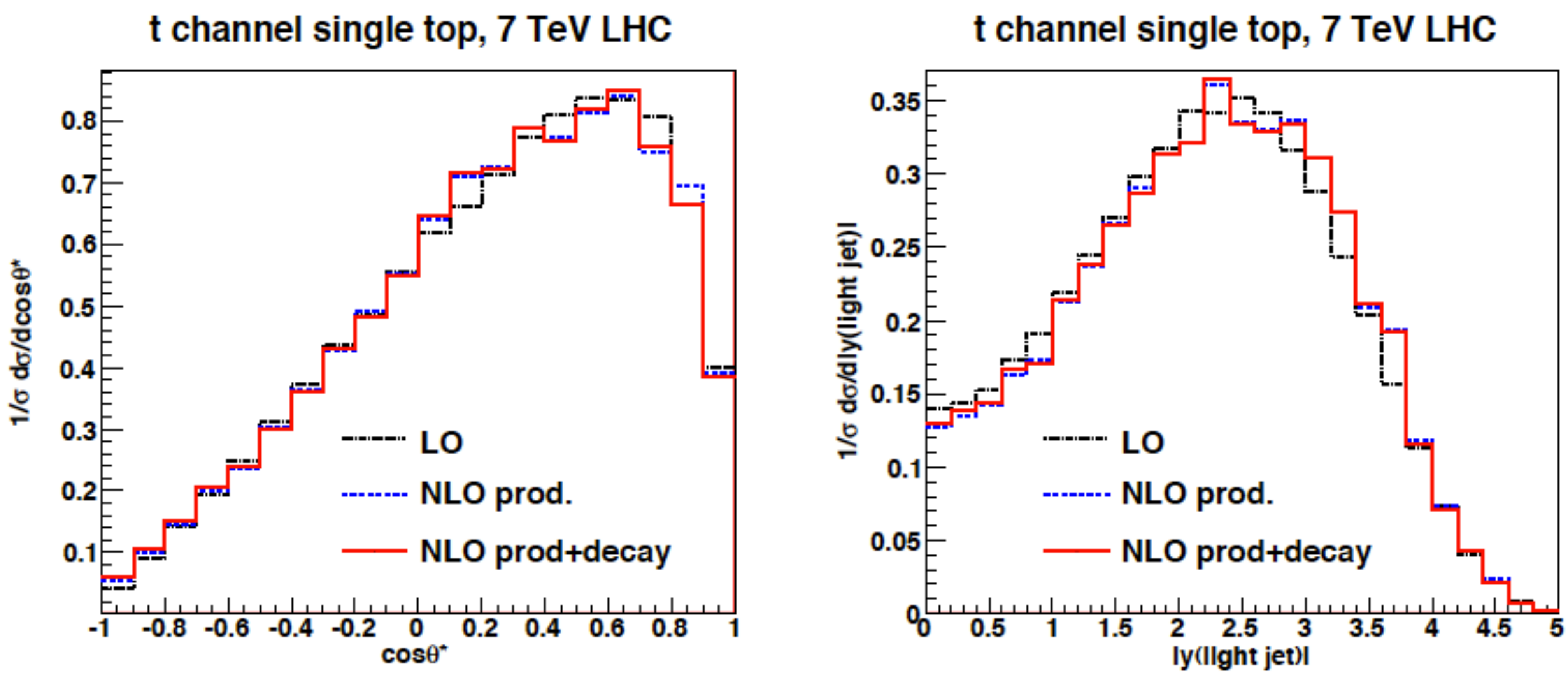
Treatment of W-boson and b-quark	σ_{LO} [fb]	σ_{NLO} (prod.) [fb]	σ_{NLO} (prod.+decay) [fb]
Narrow width, $m_b = 0$	12.14(2)	19.96(2)	20.03(2)
Narrow width, $m_b = 4.7$ GeV	12.12(2)	19.96(2)	20.01(2)
Breit-Wigner, $m_b = 4.7$ GeV	12.08(2)	19.88(2)	19.95(2)

  * Note small difference between columns 2&3 and negligible b-mass effect.

t-channel single top at LHC7

- Important variables are:-
  - rapidity of light jet and
  - angle between lepton and light jet in rest frame of reconstructed top quark

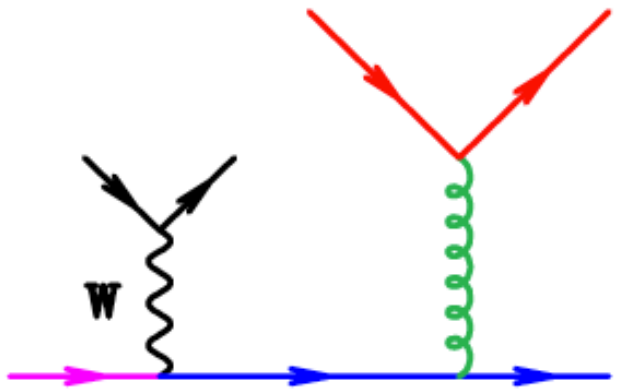




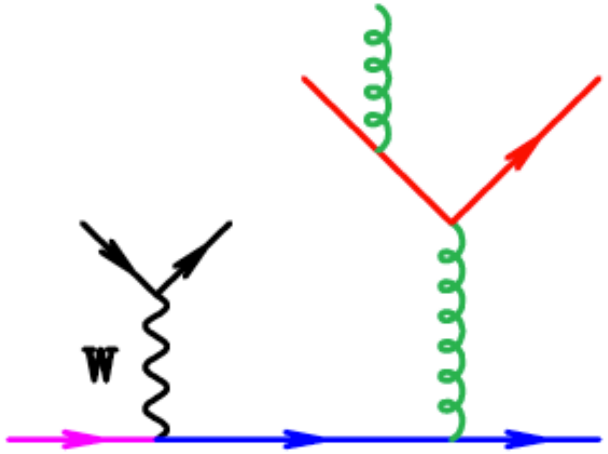
- NLO - slight change in shape, additional corrections due to radiation in decay small.

NLO calculation of ttW±

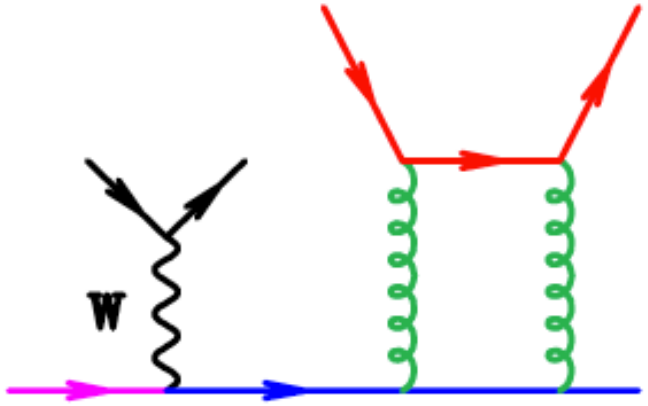
- As usual NLO calculation requires the LO amplitude.



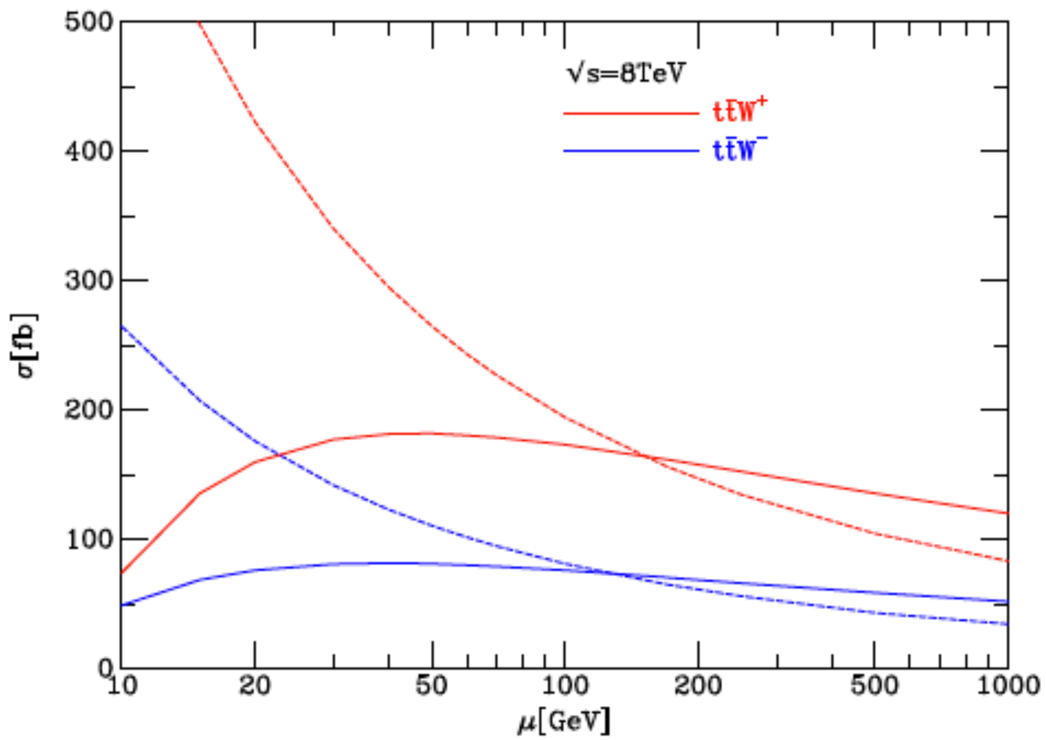
- the amplitude for real emission.

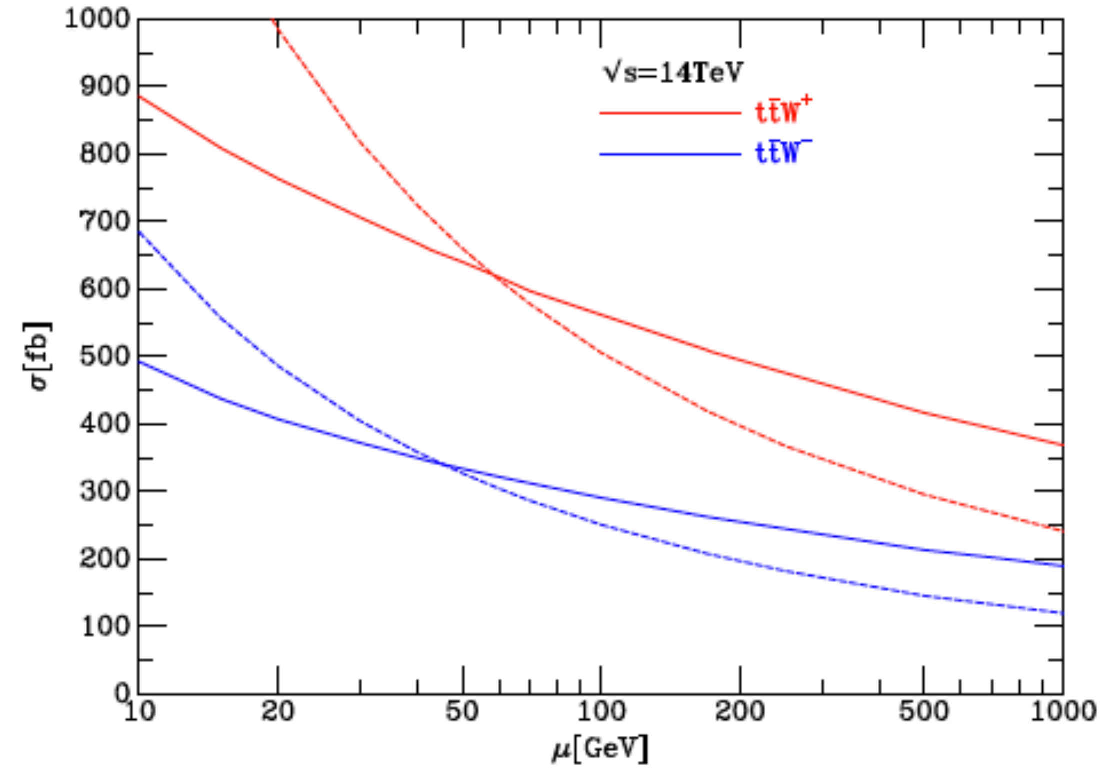


- the one-loop amplitude with masses for heavy quarks,
    - recycled from Wbb~ calculation, Badger et al, arXiv:1011.6647, in turn recycled, in part from Bern et al, hep-ph/9708239).



Theoretical error for ttW±





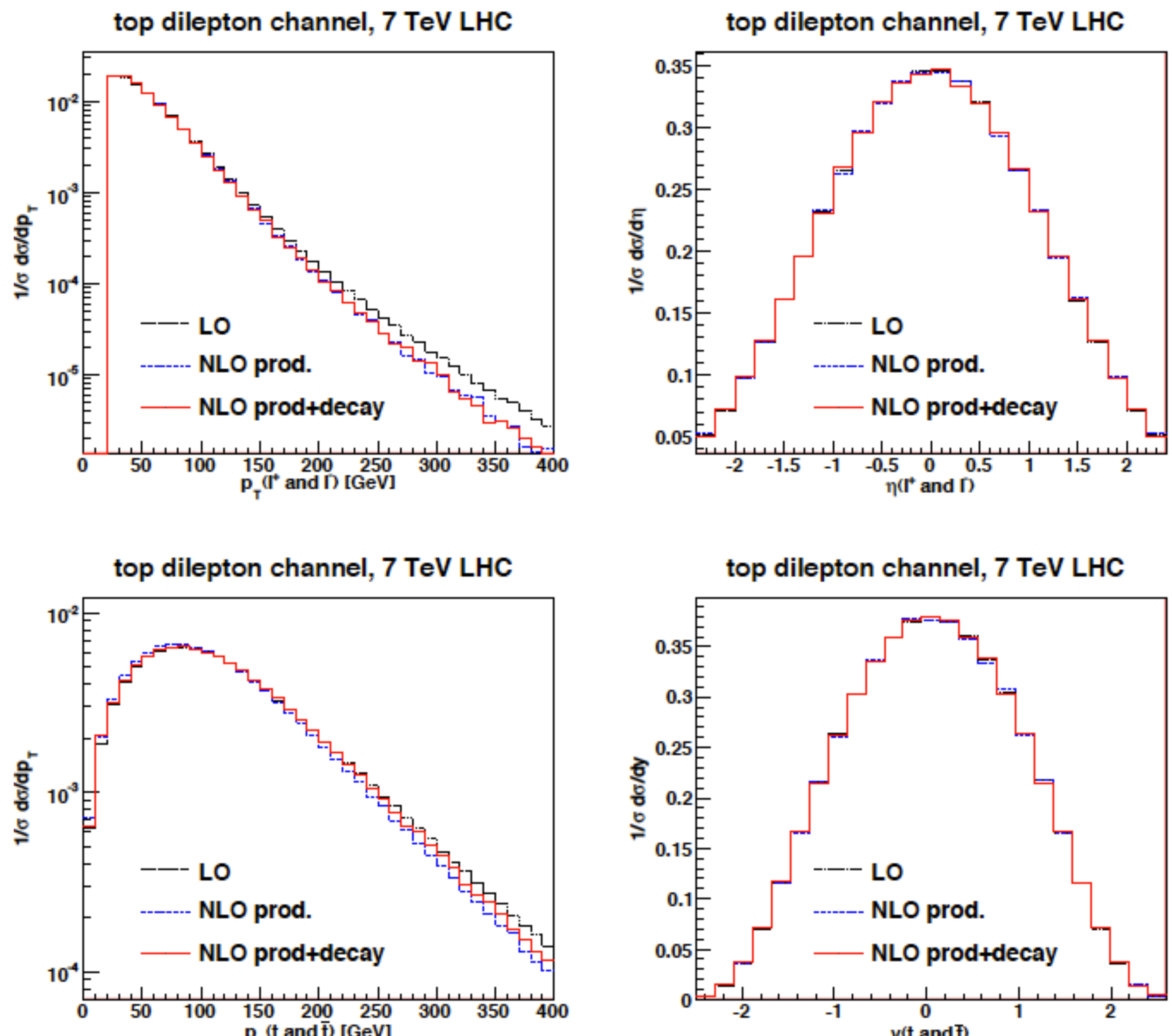
- Scale dependence is better behaved at 7~8TeV. NLO errors above 30%

Best predictions

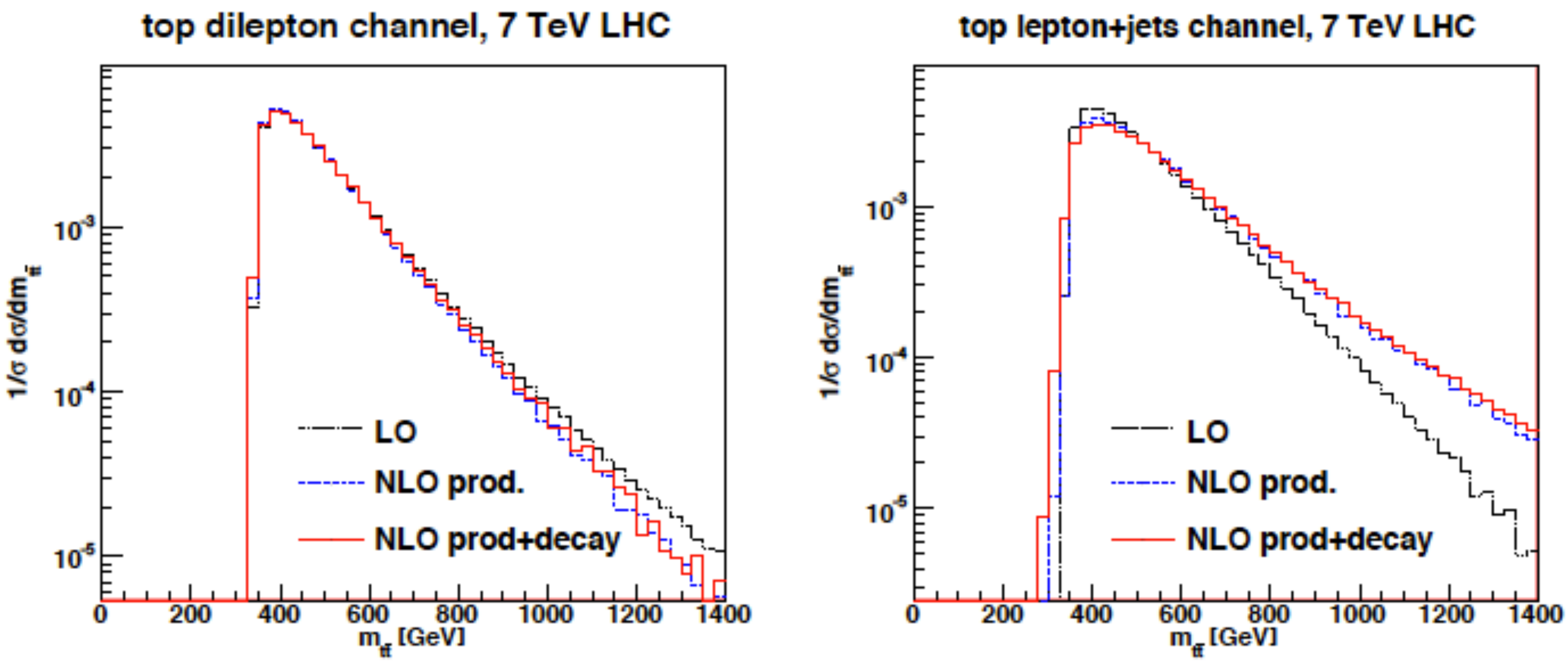
$t\bar{t}W^+$	$\sqrt{s}=7$ TeV	$\sqrt{s}=8$ TeV	$\sqrt{s}=14$ TeV
LO	$118^{+87\%}_{-40\%}(\text{scale})^{+6\%}_{-6\%}(\text{pdf})$	$156^{+83\%}_{-39\%}(\text{scale})^{+6\%}_{-5\%}(\text{pdf})$	$416^{+68\%}_{-36\%}(\text{scale})^{+4\%}_{-4\%}(\text{pdf})$
NLO	$119^{+8\%}_{-20\%}(\text{scale})^{+7\%}_{-8\%}(\text{pdf}+\alpha_s)$	$161^{+12\%}_{-20\%}(\text{scale})^{+7\%}_{-8\%}(\text{pdf}+\alpha_s)$	$507^{+29\%}_{-22\%}(\text{scale})^{+7\%}_{-8\%}(\text{pdf}+\alpha_s)$
$t\bar{t}W^-$	$\sqrt{s}=7$ TeV	$\sqrt{s}=8$ TeV	$\sqrt{s}=14$ TeV
LO	$47^{+87\%}_{-41\%}(\text{scale})^{+6\%}_{-6\%}(\text{pdf})$	$65^{+84\%}_{-40\%}(\text{scale})^{+5\%}_{-6\%}(\text{pdf})$	$206^{+68\%}_{-36\%}(\text{scale})^{+4\%}_{-5\%}(\text{pdf})$
NLO	$50^{+12\%}_{-21\%}(\text{scale})^{+6\%}_{-8\%}(\text{pdf}+\alpha_s)$	$71^{+16\%}_{-21\%}(\text{scale})^{+6\%}_{-8\%}(\text{pdf}+\alpha_s)$	$262^{+31\%}_{-23\%}(\text{scale})^{+7\%}_{-8\%}(\text{pdf}+\alpha_s)$

Top pair production: semileptonic decays

- Our reconstruction of top sample differs in a substantial way from the experimental one.
- Assume leptonically decaying W is perfectly reconstructed; assign remaining light jets with mass closest to W, W +tagged jet with mass closest to top gives top, etc.
- At large P_T there are significant corrections with the NLO prod +decay curve lying between LO and NLO prod.

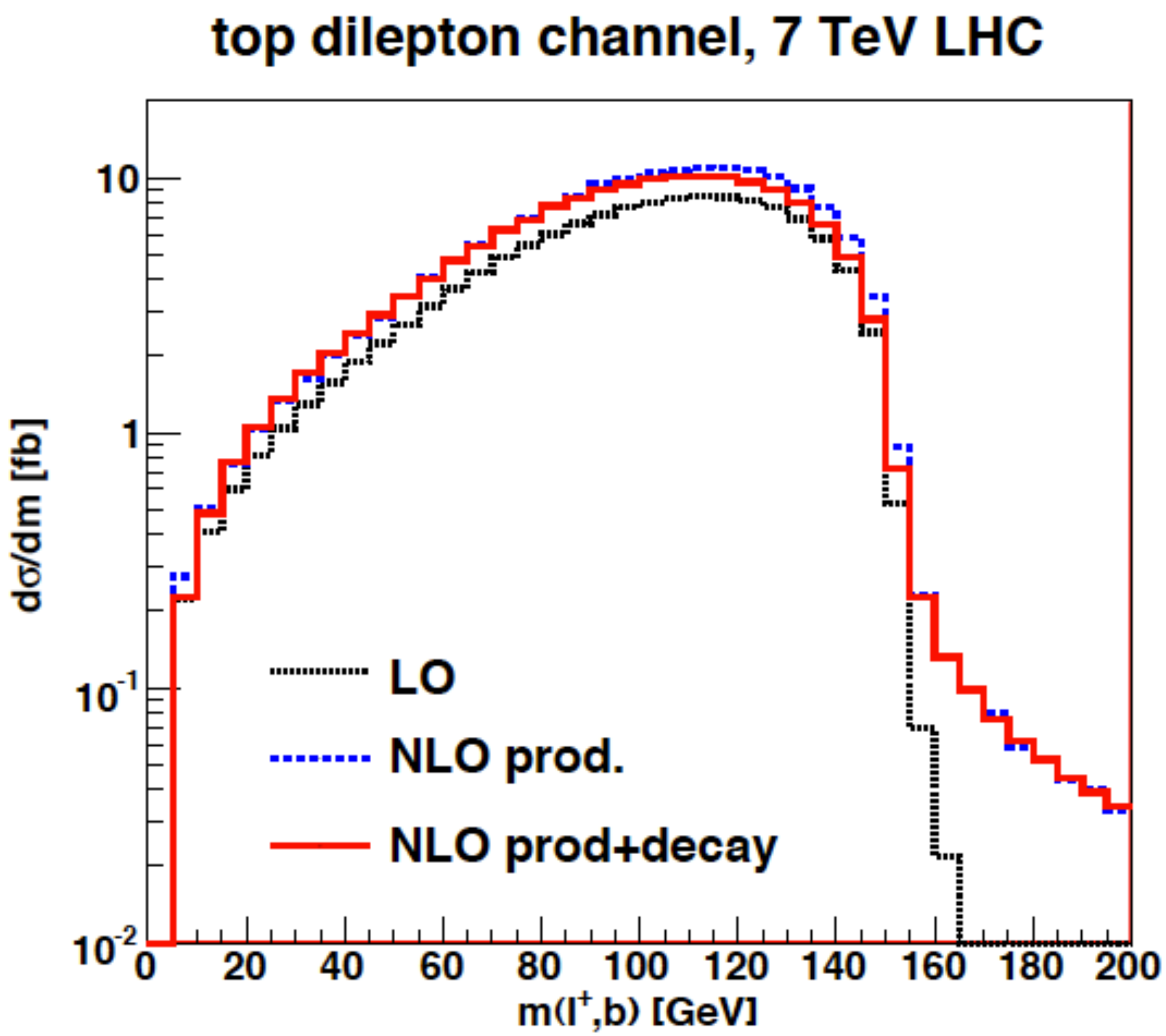


Top pair production: ttbar pair mass



* NLO effects can change the shape of the Mtt distribution, but this is due to radiative effects in production not in decay. Large difference between LO and NLO is due to the choice of scale $\mu=m_t$.
* No evidence of big change due to radiation in decay.

Top pair production: Invariant mass of lepton+b



- Significant effect of radiation in decay as first noted by Melnikov and Schulze
- Could have some influence of extraction of tbW couplings, since the lepton helicity angle is $\cos\theta_e \sim \frac{4 p_b . p_e}{m_t^2 - M_W^2}$

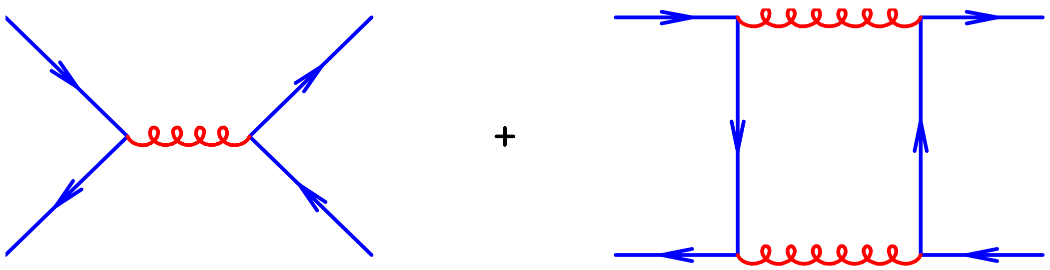
Forward-backward asymmetry at the Tevatron

- Vanishing asymmetry in LO
- Non zero asymmetry appears in NLO in QCD

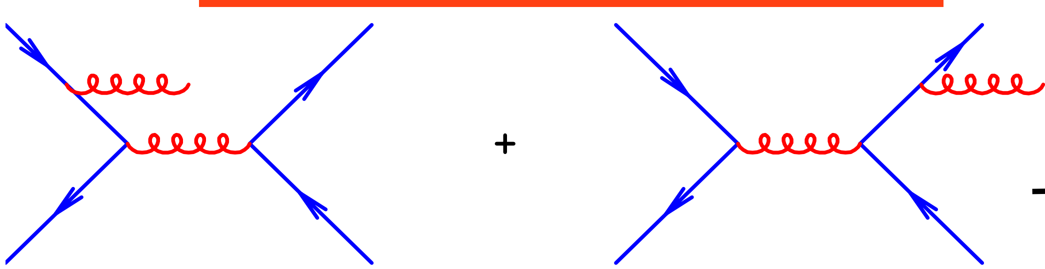
The inclusive cross sections for the production of an antiquark $\overline{\mathrm{Q}}$ differ from those for the production of a quark Q at a given y and p_T. This effect, which first arises in $O(\alpha_S^3)$, is small [20]. Using eq. (2) we calculate the distributions in rapidity and

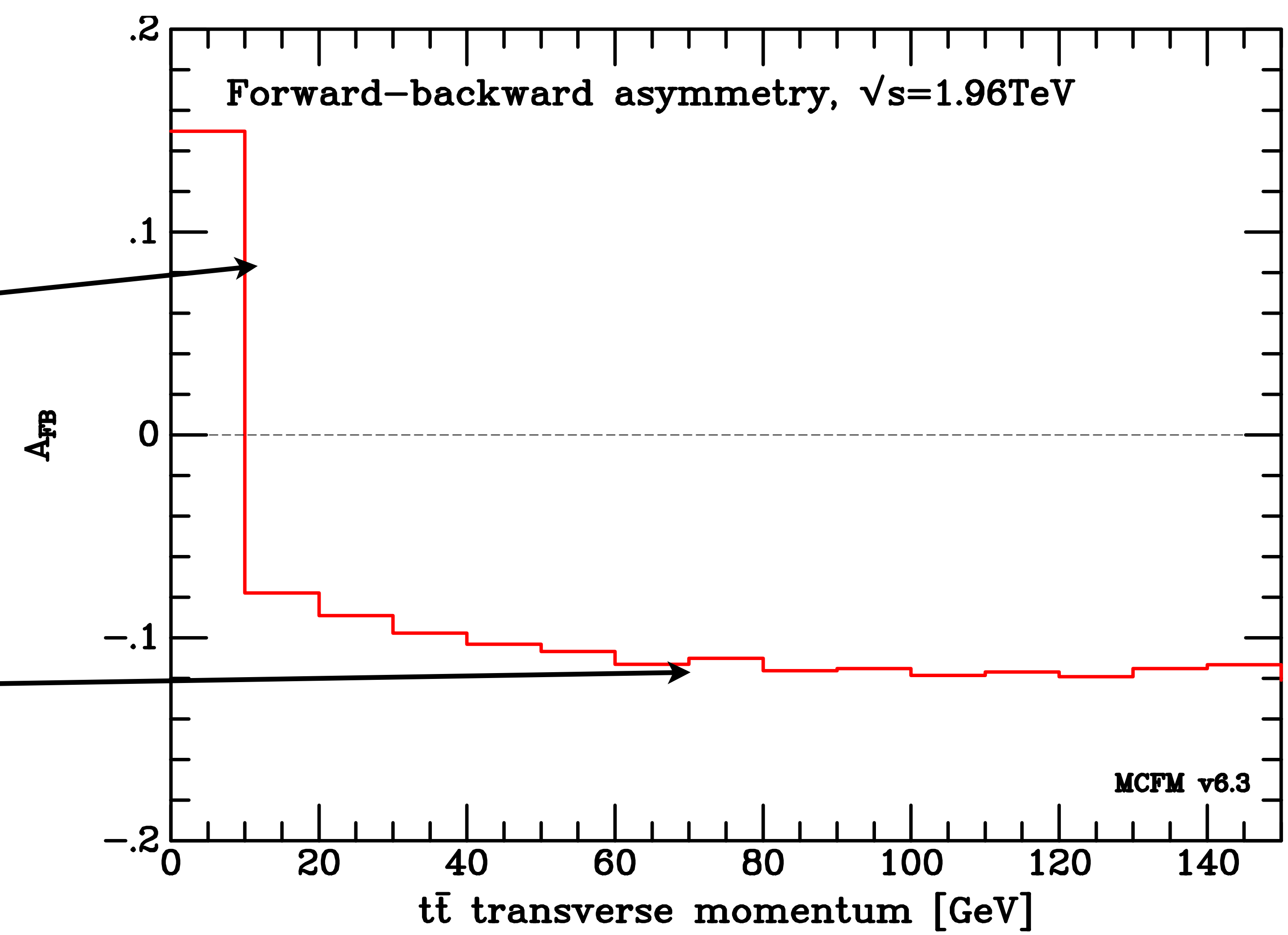
NDE (1988) referring to Halzen, Hoyer and Kim (1987)

Virtual radiation p_{tt}=0



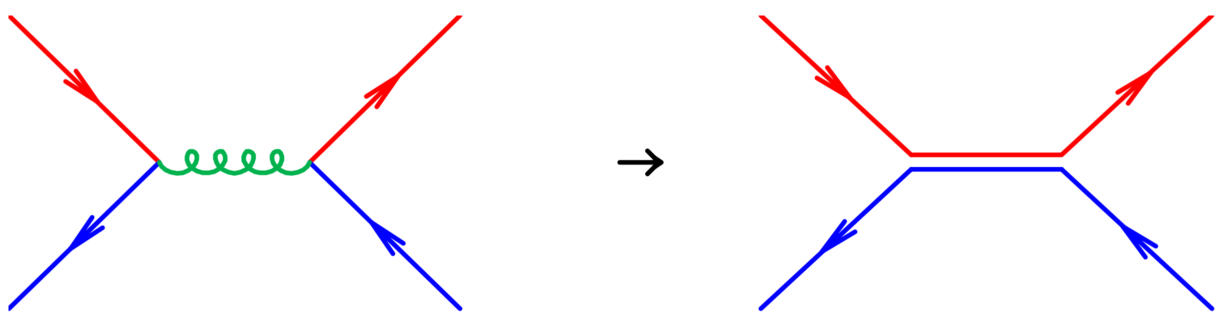
real radiation p_{tt}>0



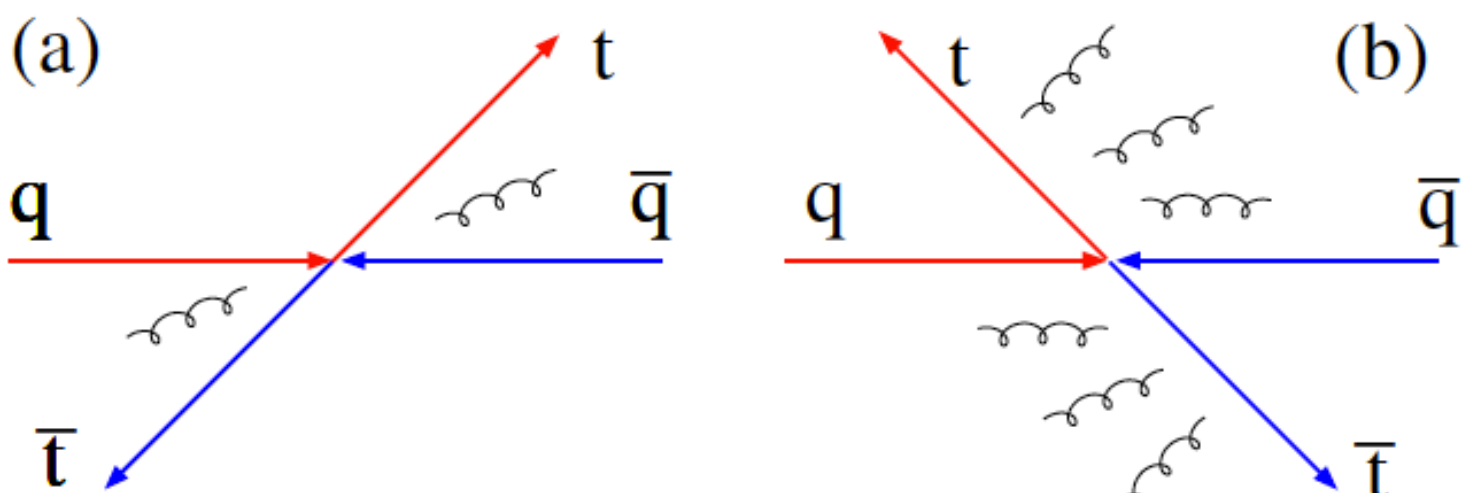


Forward backward asymmetry in parton showers

- Although forward-backward asymmetry is a NLO effect, LO parton showers show a qualitatively similar effect as a result of coherence. (Skands et al, arXiv:1205.1466)



- qqbar scattering simplifies in leading N. More radiation when color connected lines are in the backward direction than the forward.



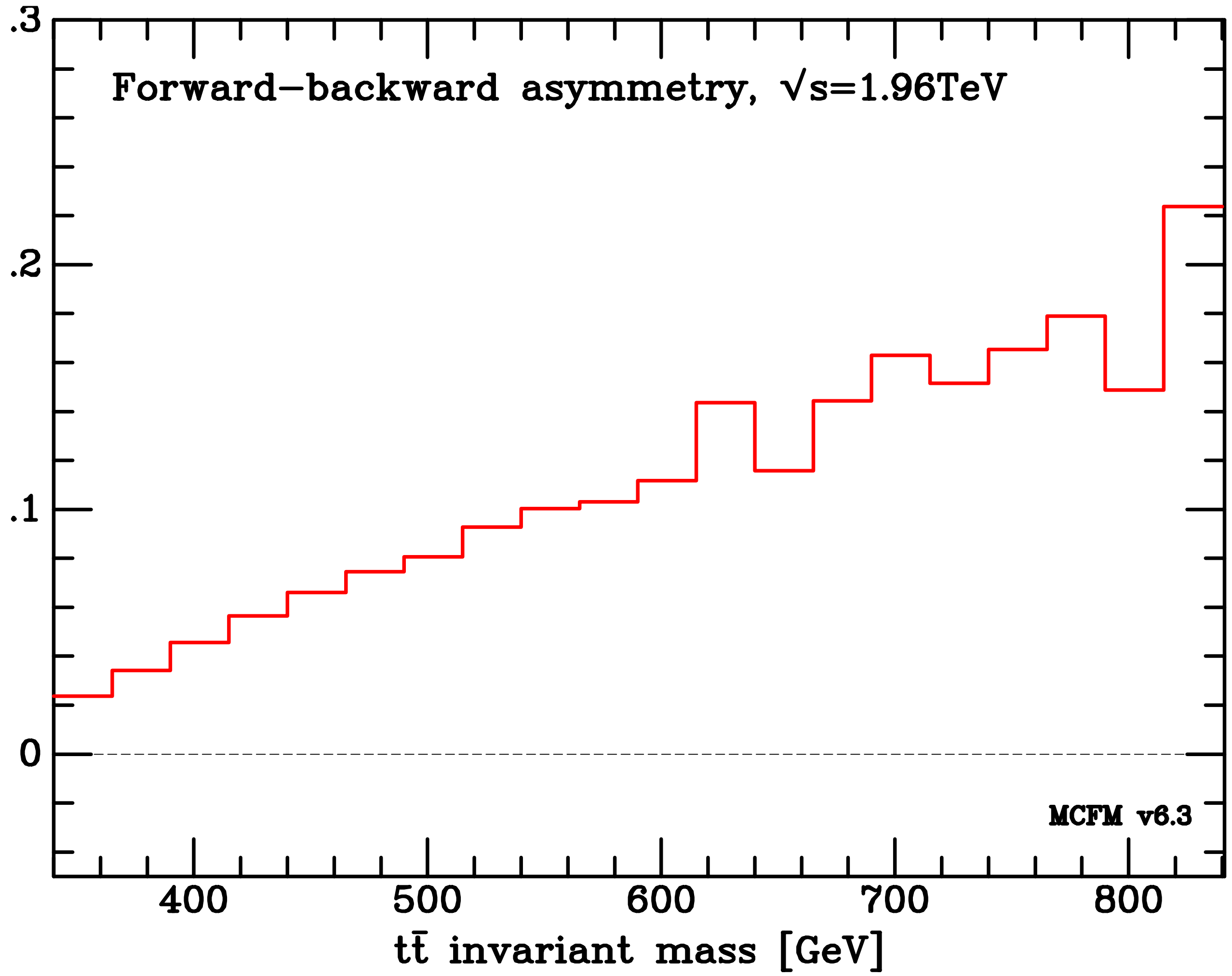
Forward backward asymmetry in parton showers

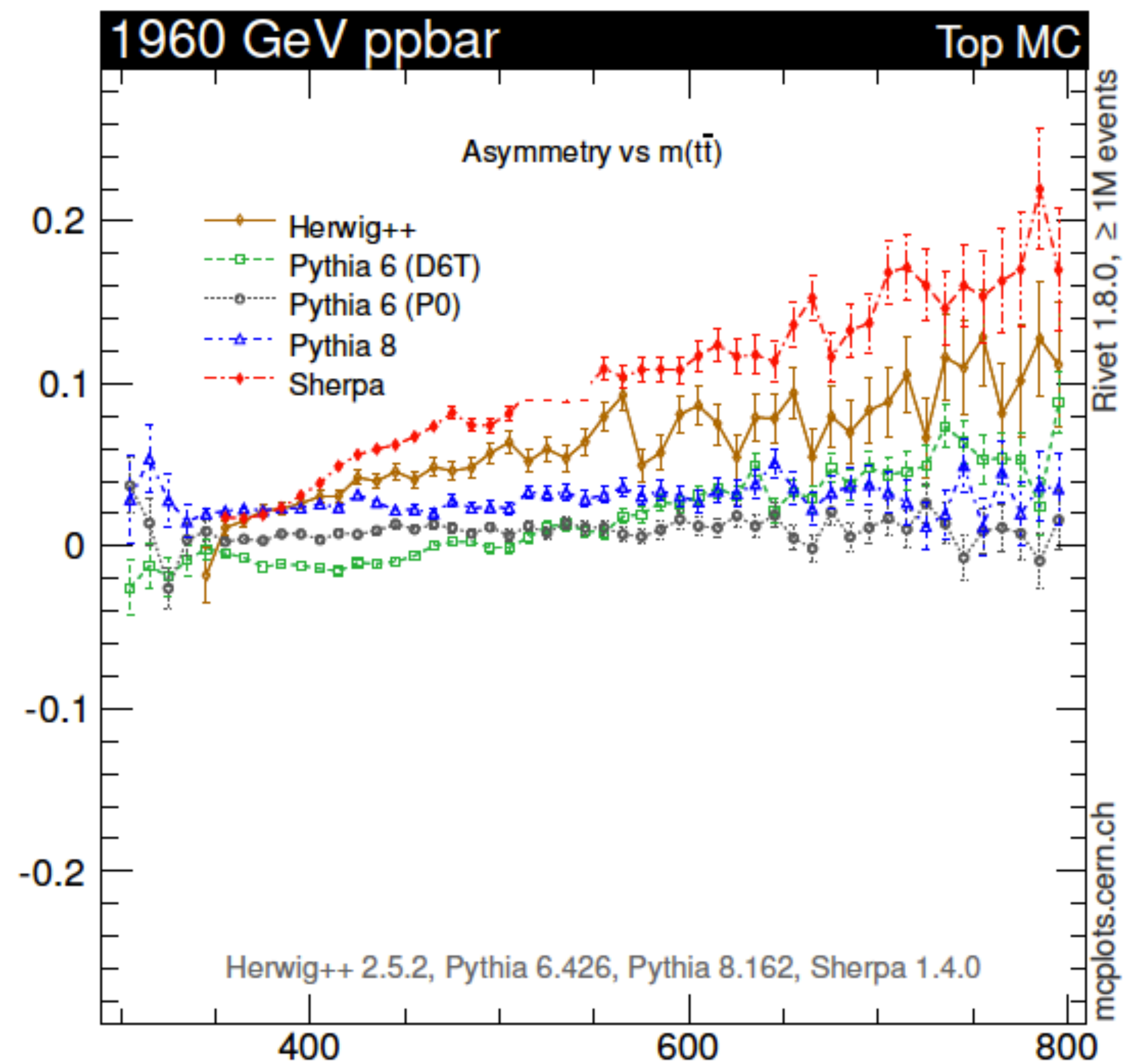
- Looking at the difference between $q(p_1) + \bar{q}(p_2) \to Q(p_3) + \bar{Q}(p_4) + g(k)$ and $q(p_1) + \bar{q}(p_2) \to \bar{Q}(p_3) + Q(p_4) + g(k)$
- In the soft limit we have

$$\mathcal{M}_A = g^6 \frac{(N^2-1)(N^2-4)}{N^3} \left(\frac{\bar{t}^2 + \bar{u}^2}{\bar{s}^2} + \frac{2\,m^2}{\bar{s}} \right) \times \left(W_{13} + W_{24} - W_{14} - W_{23} \right) .$$

- W_{ij} is the eikonal factor $W_{ij} = -\left(\frac{p_i}{p_i \cdot k} - \frac{p_j}{p_j \cdot k} \right)^2$
- Asymmetry vanishes for N=2
- Coherence effect over-estimated in parton showers $(N_c^2-4)/N_c \to (N_c^2-1)/N_c$ in Monte Carlo (~60% over-estimate)

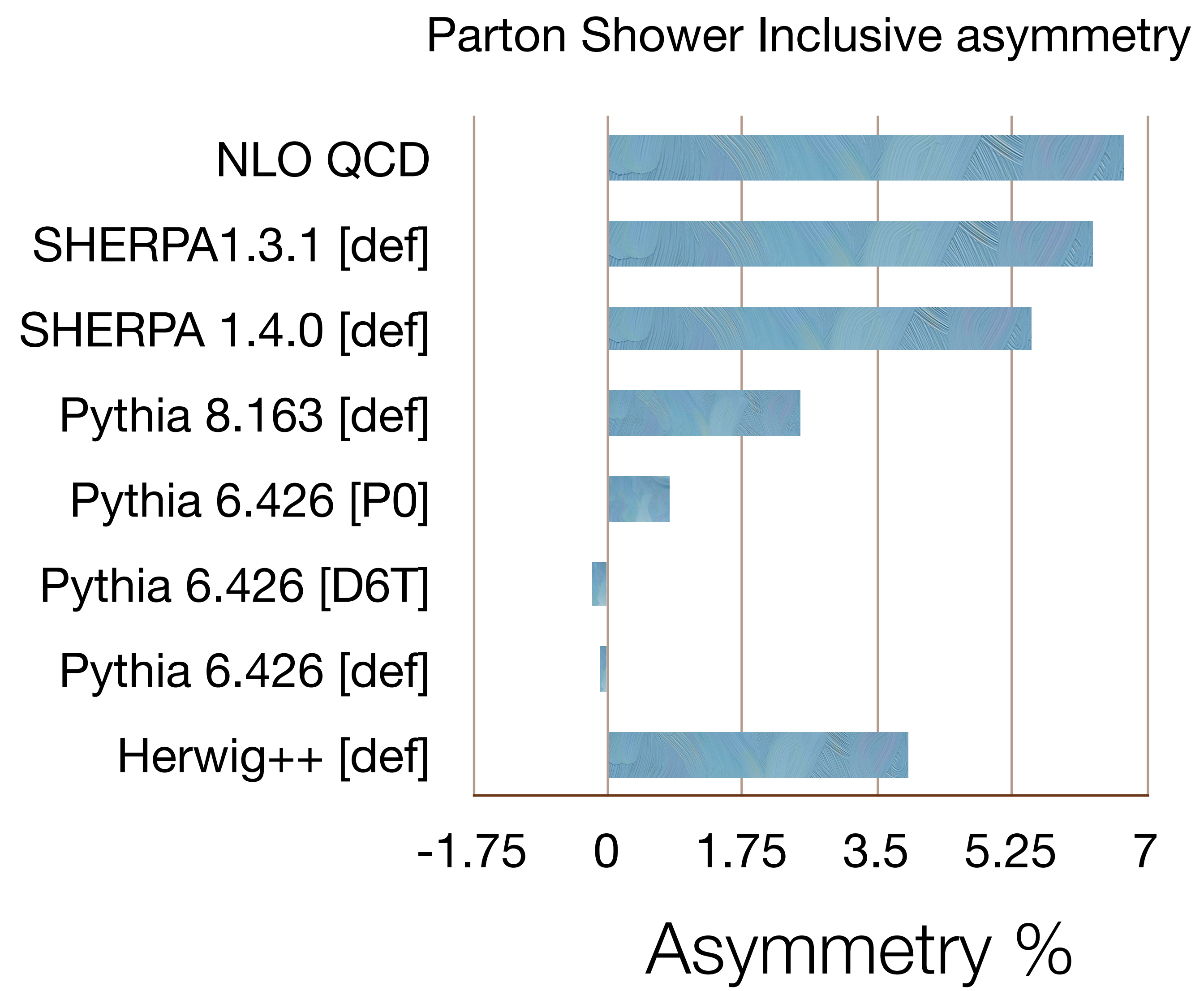
Parton shower asymmetry





Asymmetry in parton showers

- In addition to coherence, in order to generate an asymmetry, the parton shower must contain the possibility of reordering of the top and anti-top rapidity in the branching process.
- Wide range of asymmetries generated by the parton showers, depending on whether the parton branching strategies permit longitudinal re-ordering of the top.

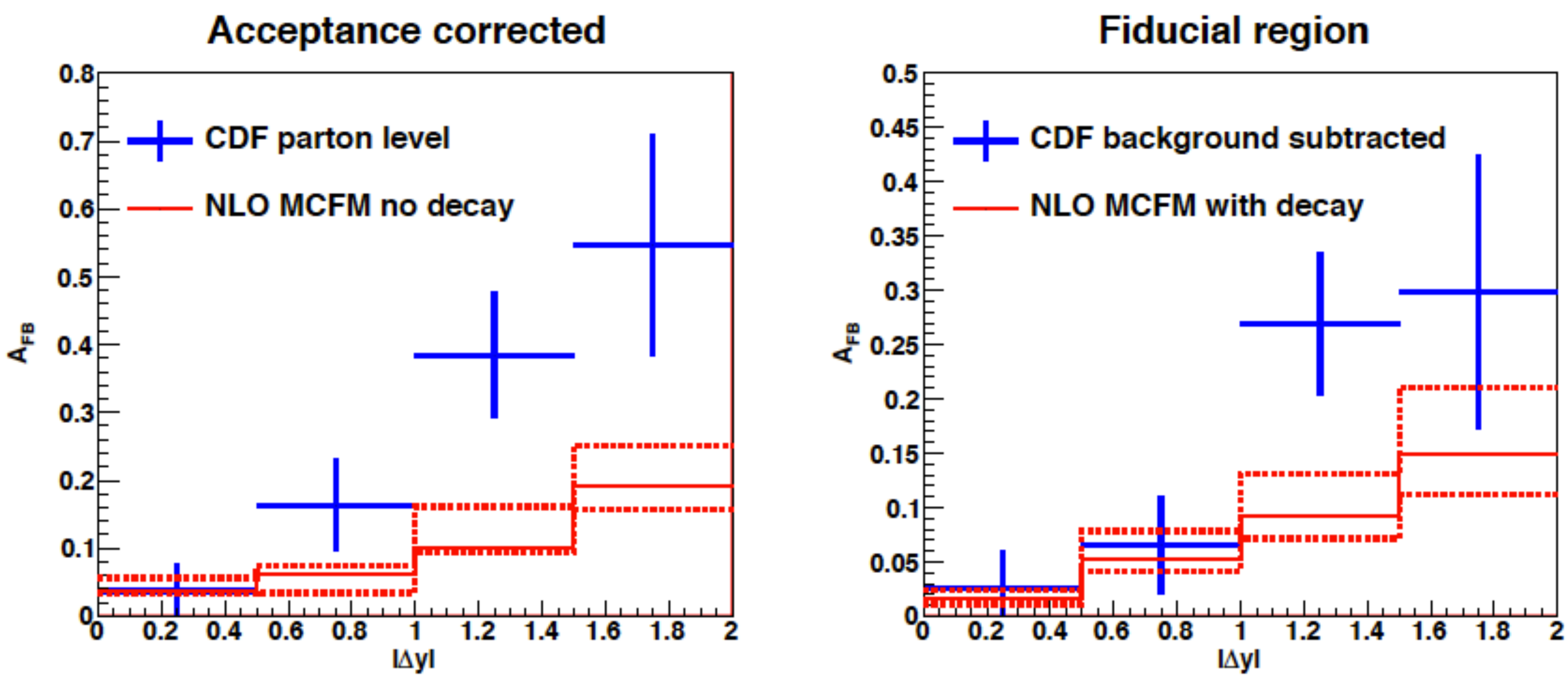


Conclusions on parton showers

Skands et al, arXiv:1205.1466

* Need to be aware of the asymmetry in parton shower programs when performing the analysis.
* Any bias against extra jets in the analysis could increase the measured asymmetry
* This subtle effect can provide a tool to tune recoil strategies in the parton shower programs.

Top pair production: Forward-backward asymmetry



- Left hand plot shows the asymmetry for the reconstructed quarks a la NDE.
- Right hand plot includes radiation in both production and decay and is the result in the fiducial region.
- Dashed lines in both plots show the considerable uncertainties in the theoretical predictions.

Top spin correlations

* Useful tool to probe the dynamics of top production

* Are a large effect, calculable in perturbation theory.

* Pattern of spin correlations different at Tevatron (~qqbar) and LHC (~gg).

Spin correlations

- Net polarization of top quark pairs is small
- Angular distribution of top quark decay products correlated with the top spin axis

$$\frac{1}{\Gamma_T}\frac{d\Gamma}{d\cos\theta_i} = (1+\alpha_i\cos\theta_i)/2 \quad \alpha_i = \begin{cases} +1.0 & l^+ \text{ or } \bar{d}\text{-quark} \\ -0.31 & \bar{\nu} \text{ or } u\text{-quark} \\ -0.41 & b\text{-quark} \end{cases}$$

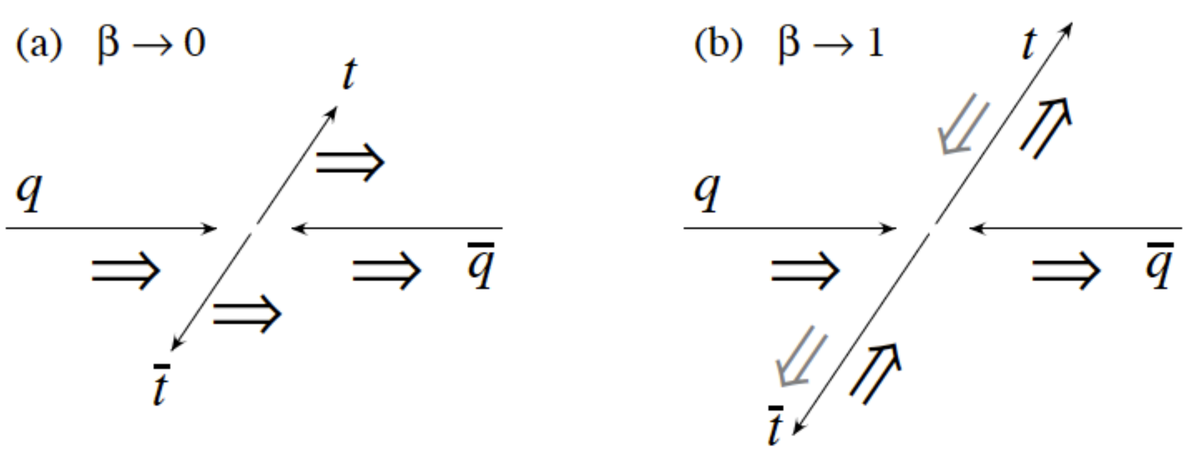
- (θ_i is the angle between decay product and top quark spin in top rest frame).
- Charged lepton has the most analyzing power.

$$\frac{1}{\sigma_T}\frac{d^2\sigma}{d\cos\theta_i d\cos\bar{\theta}_{\bar{i}}} = \frac{1}{4}(1 + C_{t\bar{t}}\ \alpha_i\ \bar{\alpha}_{\bar{i}}\ \cos\theta_i\cos\bar{\theta}_{\bar{i}}).$$

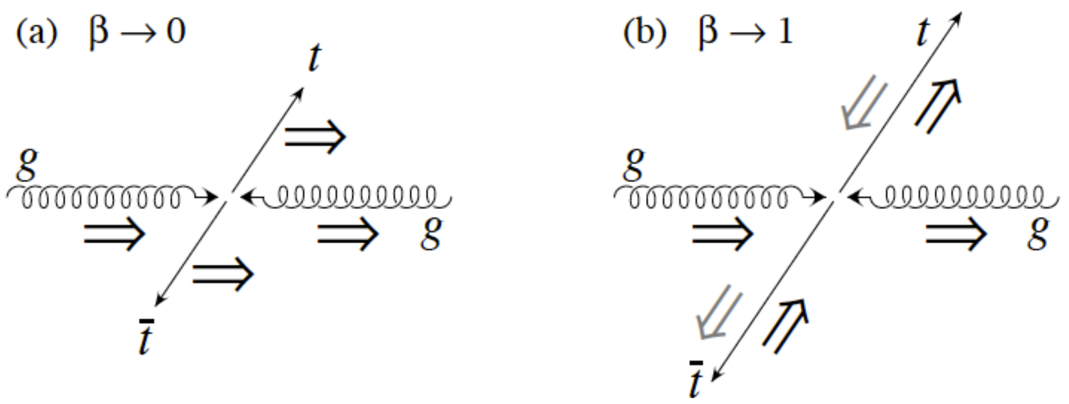
$$C_{t\bar{t}} \equiv \frac{\sigma_{\uparrow\uparrow}+\sigma_{\downarrow\downarrow}-\sigma_{\uparrow\downarrow}-\sigma_{\downarrow\uparrow}}{\sigma_{\uparrow\uparrow}+\sigma_{\downarrow\downarrow}+\sigma_{\uparrow\downarrow}+\sigma_{\downarrow\uparrow}}.$$

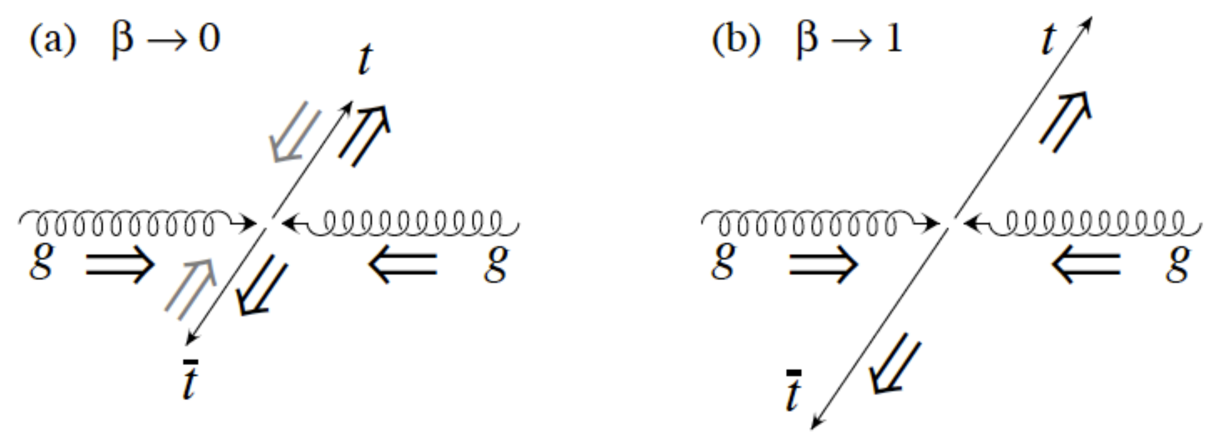
Choice of spin quantization axis

- By judicious choice of the spin quantization axis we can maximize the correlations between the top and the anti-top.
- Best choice of the quantization axis, depends on whether the process is dominated by qq (Tevatron) or gg (LHC)
- qqbar at threshold are in a $^3S_0$ state; quantization in the off-diagonal basis that interpolates between beamline basis $\beta=0$ and helicity basis $\beta=1$.



Spin configurations in gg -> ttbar





Unlike helicity gluons best described in a basis that interpolates between beam direction (β=0) and helicity basis (β=1),cf quarks

Like helicity gluons best described in the helicity basis for all **β**. Like helicity gluons dominate at low invariant mass.

In the ultra-relativistic regime, 100% correlation of the tt spins in the helicity basis for all helicities.

⇨Use helicity basis at LHC

Results for the spin correlation at $\sqrt{s}$=8 TeV

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1\,d\cos\theta_2} = \frac{1}{4}\Big(1 - C\cos\theta_1\ \cos\theta_2\Big)$$

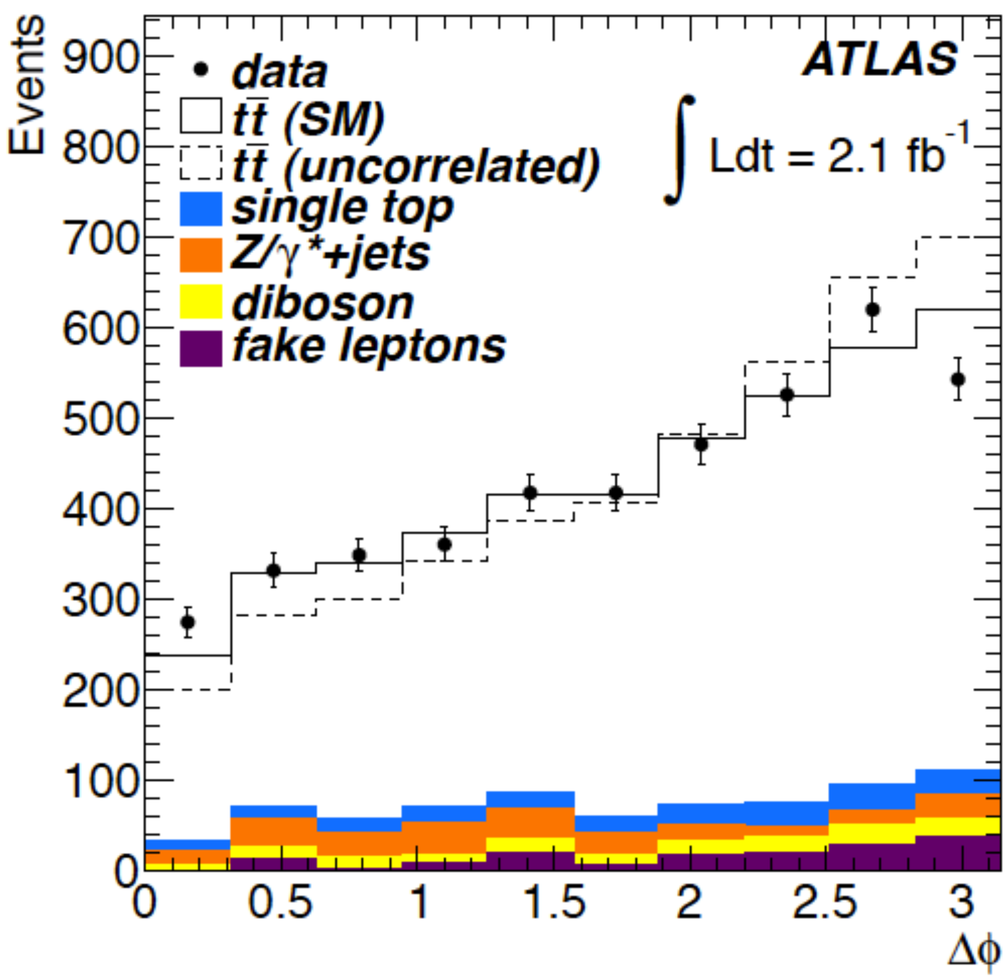
- Results from MCFM for the parameter C at $\sqrt{s}$=8 TeV (Campbell, Ellis, Nason, preliminary), integration errors in brackets

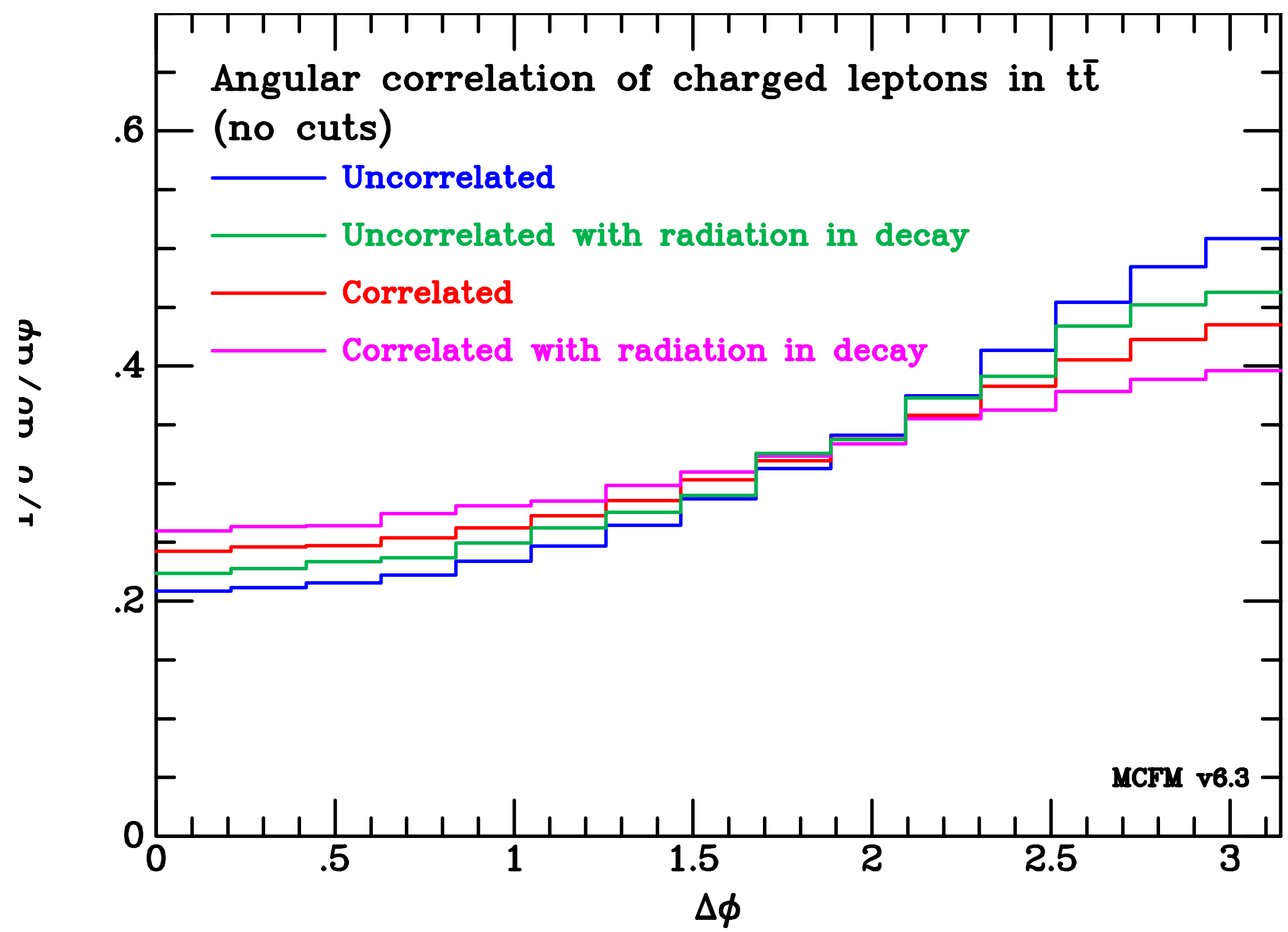
μ	LO	NLO
$m_t/2$	0.271(1)	0.310(3)
m_t	0.263(1)	0.3063(18)
$2m_t$	0.253(1)	0.293(4)
$\frac{1}{2}\sqrt{(m_t^2+p_t^2)}$	0.293(1)	n/a
$\sqrt{(m_t^2+p_t^2)}$	0.281(1)	0.3106(17)
$2\sqrt{(m_t^2+p_t^2)}$	0.291(1)	n/a

- Electroweak effects not included (for a discussion see Bernreuther, arXiv:1003.3926)

Azimuthal separation of leptons in top decay

- Method of looking for spin correlations that does not require top reconstruction (Mahlon and Parke arXiv:1001.3422)
- Measured by Atlas (PRL 108.212001), $C_{hel}=0.4\pm0.04(\text{stat})^{+0.08}_{-0.07}$ (syst)
- Theory curve shows the importance of including radiation on decay.





Conclusions

* Top pole approximation is a consistent approximation scheme to describe processes involving top quarks.
* MCFM now includes ttbar, t-channel single top, s-channel single top, ttW, with decay and radiation in the decay. It provides the most sophisticated possible NLO treatment of these processes within the context of the top pole approximation.
* At the LHC we will have the possibility of studying top production in exquisite detail.
* Asymmetries and spin correlations give a window into top production dynamics, and are calculable in perturbation theory.

Why NLO?

- Less sensitivity to unphysical input scales, (eg. renormalization and factorization scales) at least formally.
- LO uncertainty becomes larger for multijet production, where Born approximation starts at high power of α_s^n
- NLO first approximation in QCD which gives an idea of suitable choice for μ.
- NLO has more physics, parton merging to give structure in jets, initial state radiation, more species of incoming partons enter at NLO.
- A necessary prerequisite for more sophisticated techniques which match NLO with parton showering.