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Top quark — theory

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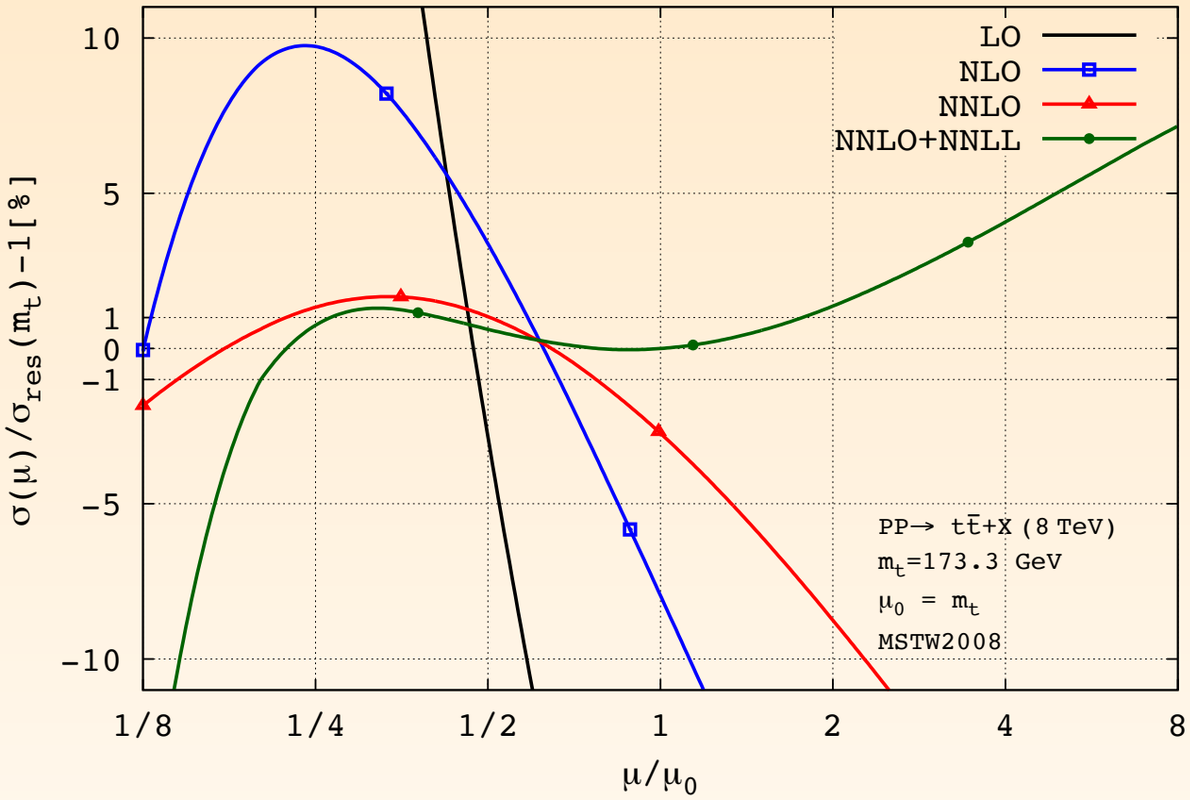
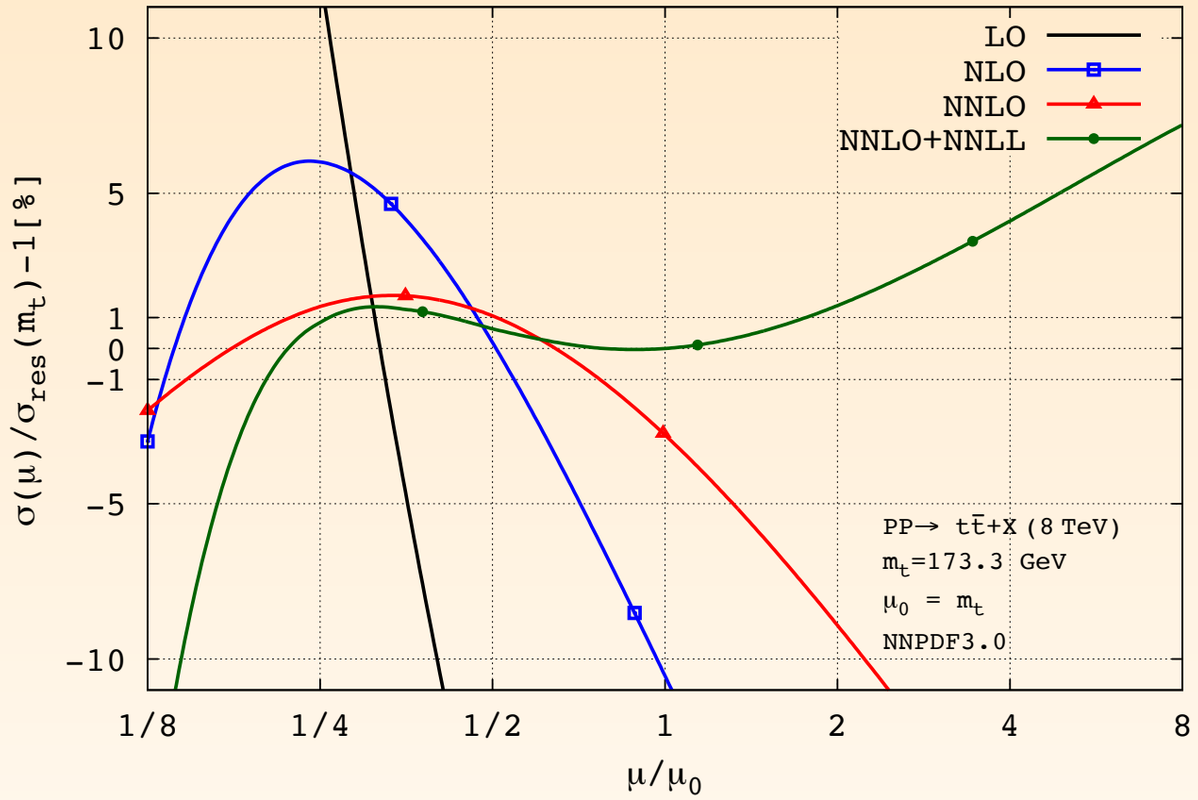
Plan and disclaimer

- LHC is top factory
  - Need precise and accurate predictions
  - Many new results available. Mostly related to off-shell effects, but also NLO ttbar+3jets, and NNLO single-top and decay in NWA
  - And, of course, high-precision differential NNLO results for top pairs
- Other important recent results that I'll not address in this talk are
  - 4-loop relation between MSbar and on-shell mass: the 4-loop term yields a 200 MeV contribution [Marquard, Smirnov, Smirnov, Steinhauser 2015]
  - Studies on top quark mass calibration in MC event generators [Butenschoen et al. 2016]
  - EFT for top pheno (all relevant dim-6 operators) at NLO [Zhang + collaborators 2015, 2016]
  - Resummation…
  - …

TOP PAIR TOTAL CROSS SECTION: SCALE DEPENDENCE - 1

[Czakon, Heymes, Mitov 2016]

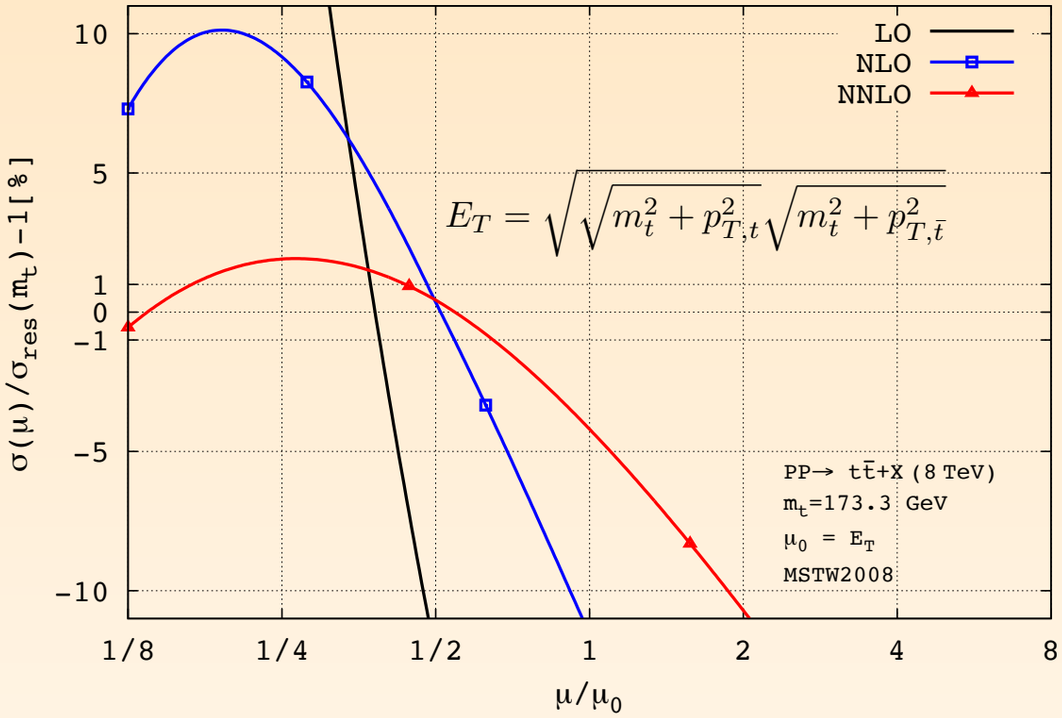


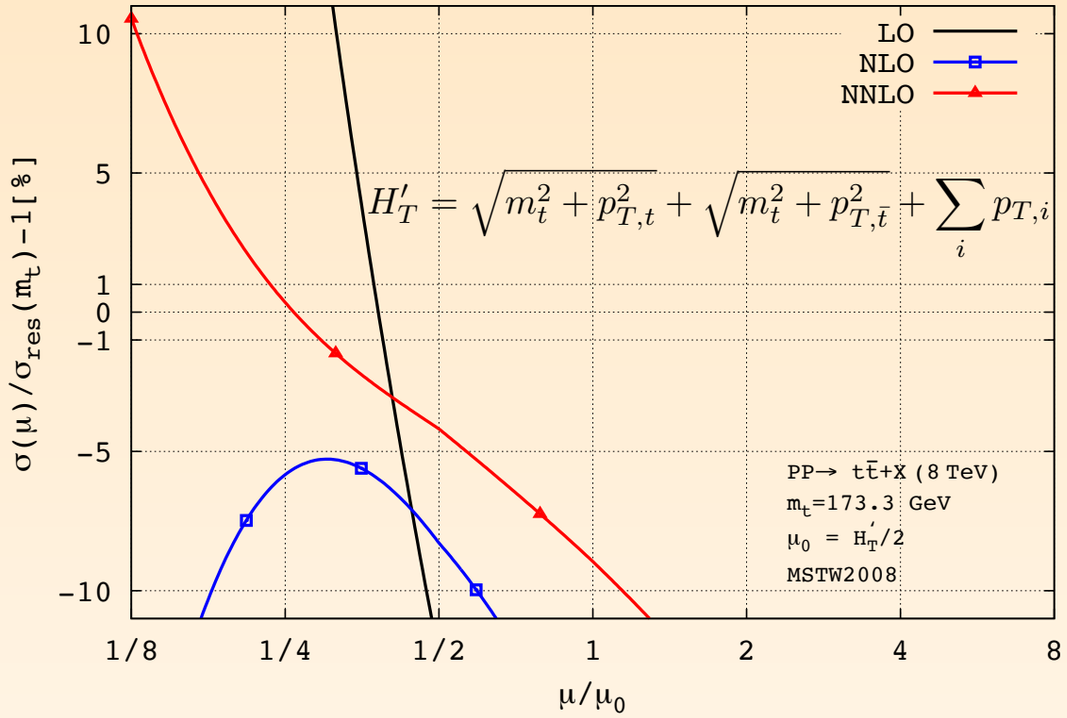


- top pairs: nice convergence of perturbative series in total cross section
- Preferred scale seems to be somewhat closer to $m_{top}/2$ than m_{top}

TOP PAIR TOTAL CROSS SECTION: SCALE DEPENDENCE - 2

[Czakon, Heymes, Mitov 2016]



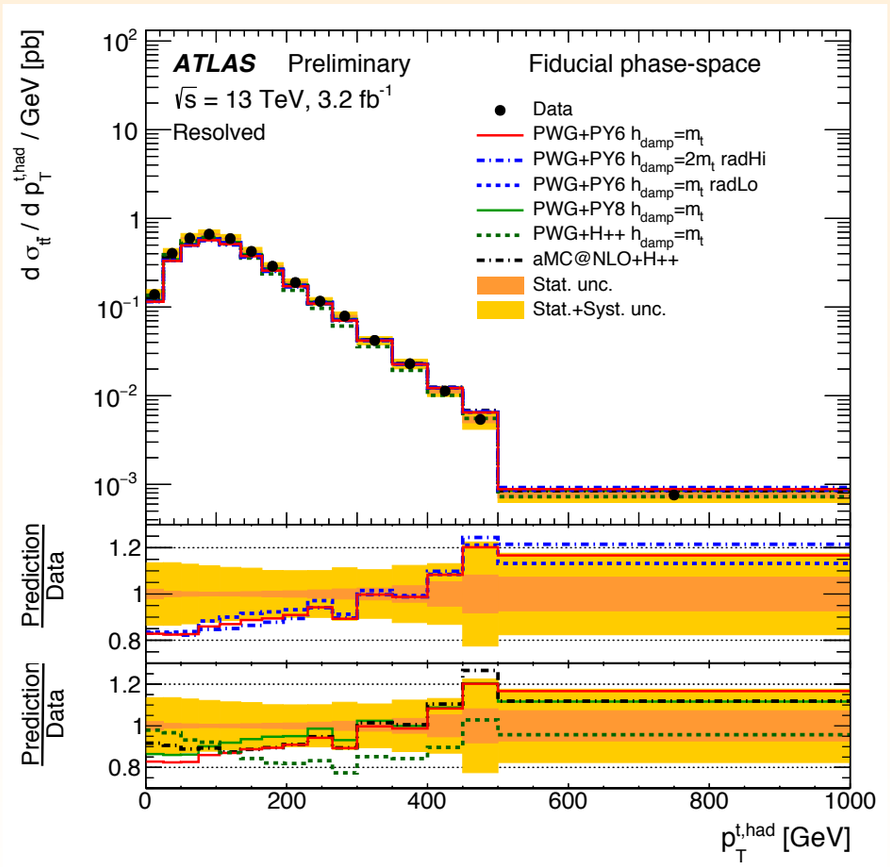


- Surprise: $H_T'/2$ scale does not seem to be reasonable at NNLO
  - Claimed to be a scale very sensitive to singular emissions. But I don't fully understand the reason (it's perfectly IR safe)
  - Worrying because scale definition very common in NLO computations. E.g. default scale in NLO mode of MG5_aMC and used for many BlackHat +Sherpa results for V+jets, and OpenLoops+Sherpa results for ttbar+jets (see later)

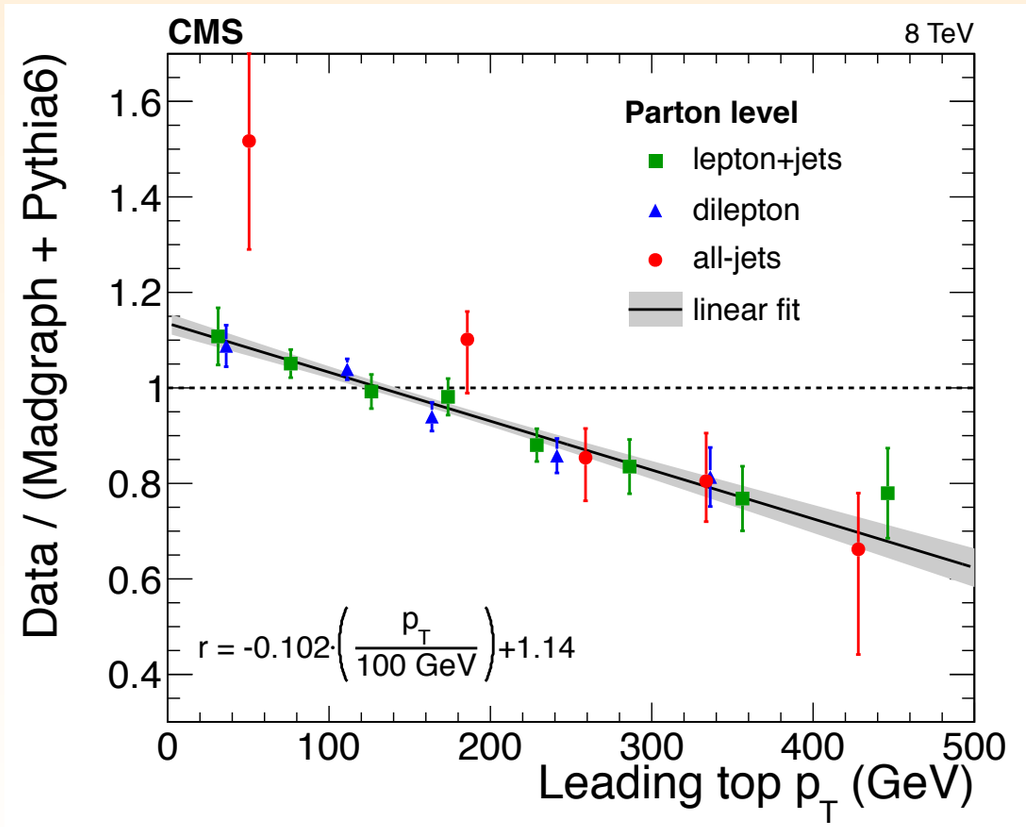
TOP QUARK P_T

- Most striking difference in data—theory comparisons is in the transverse momentum of the top quark
- NLO MonteCarlo generators are softer than the data. Both in Run-I and Run-II data
- Visible in all top decay modes

ATLAS-CONF-2016-40



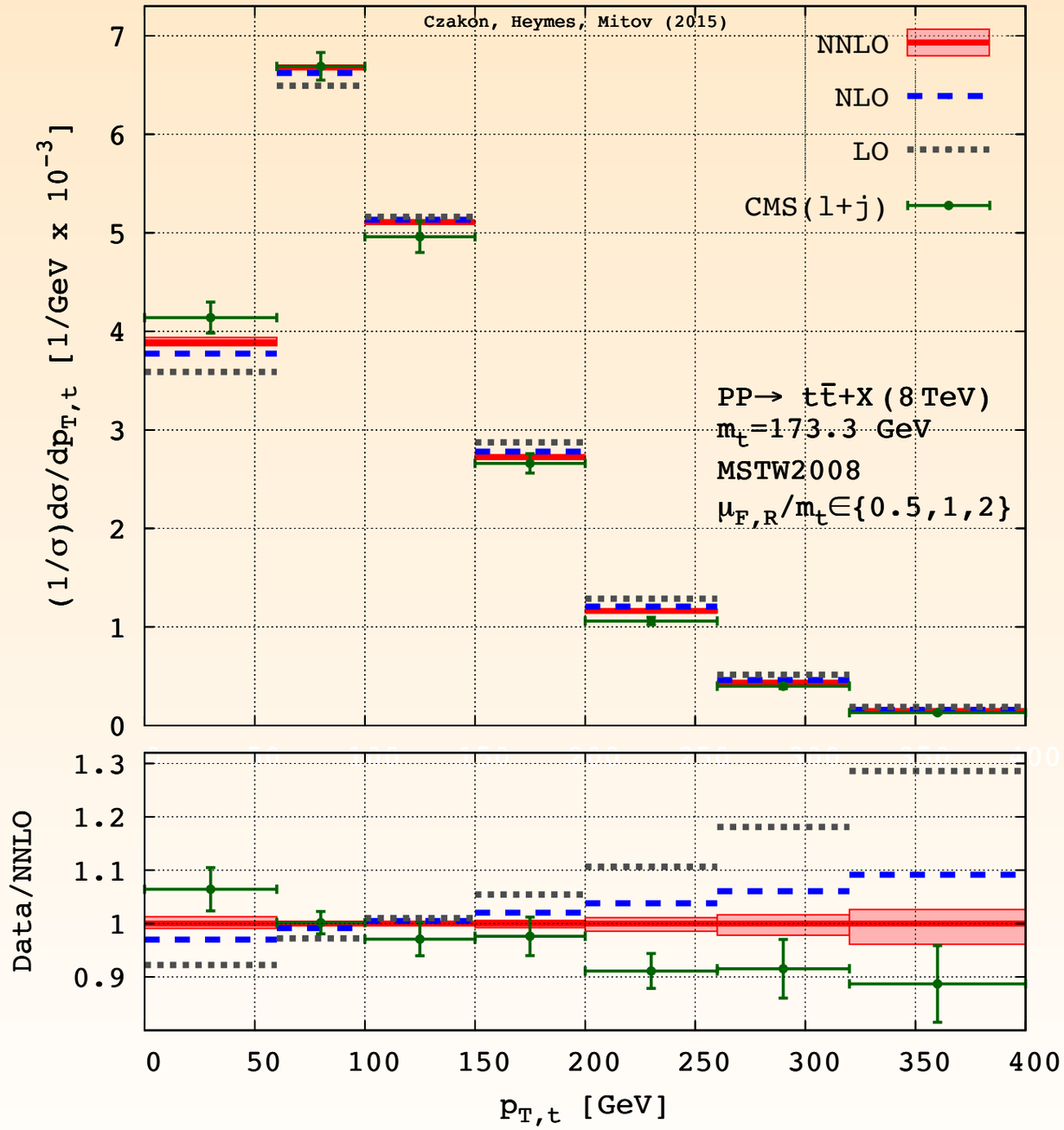
CMS-PAS-TOP-15-011;
Eur. Phys. J. C76, 128



DIFF. NNLO TOP PAIRS

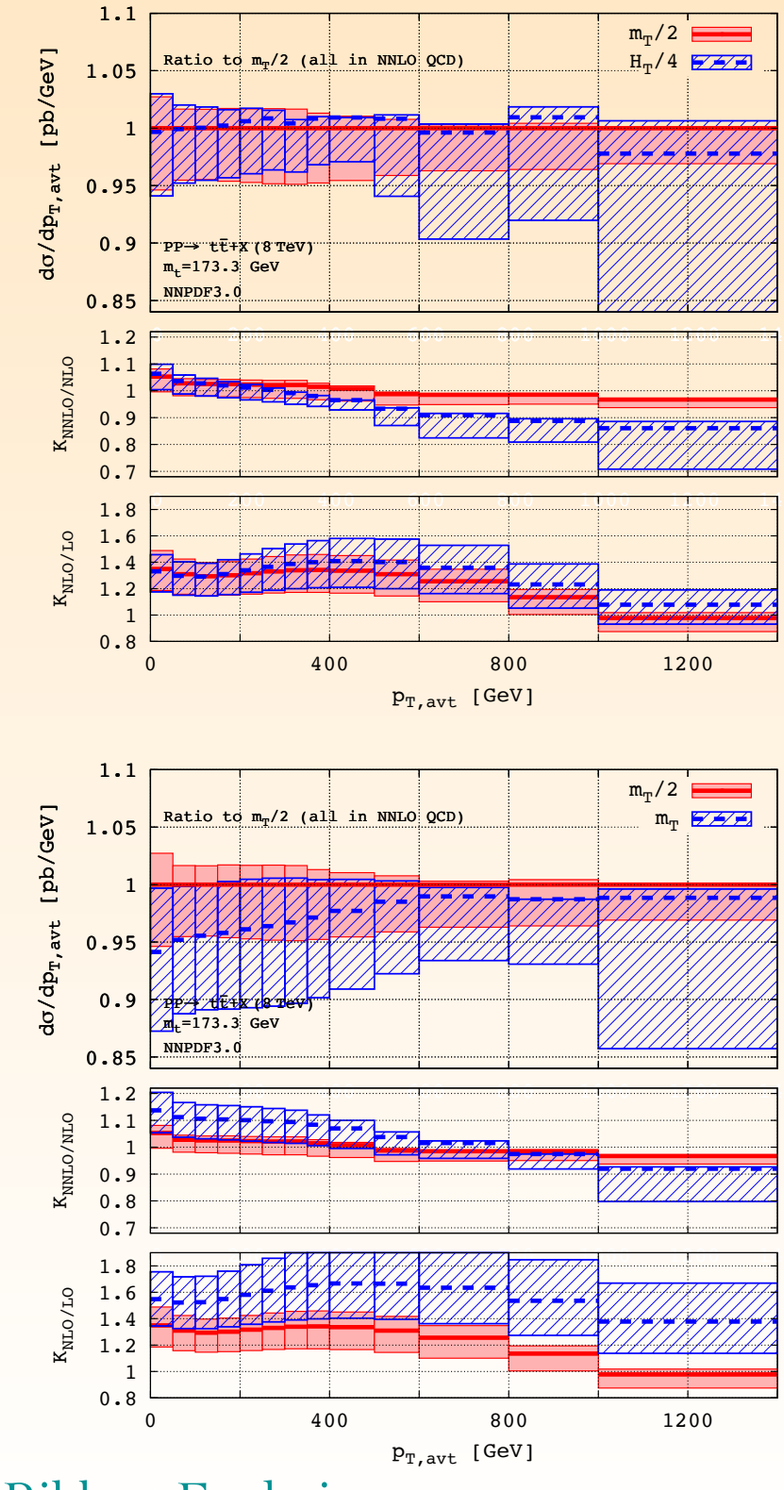
Czakon, Heymes, Mitov 2015

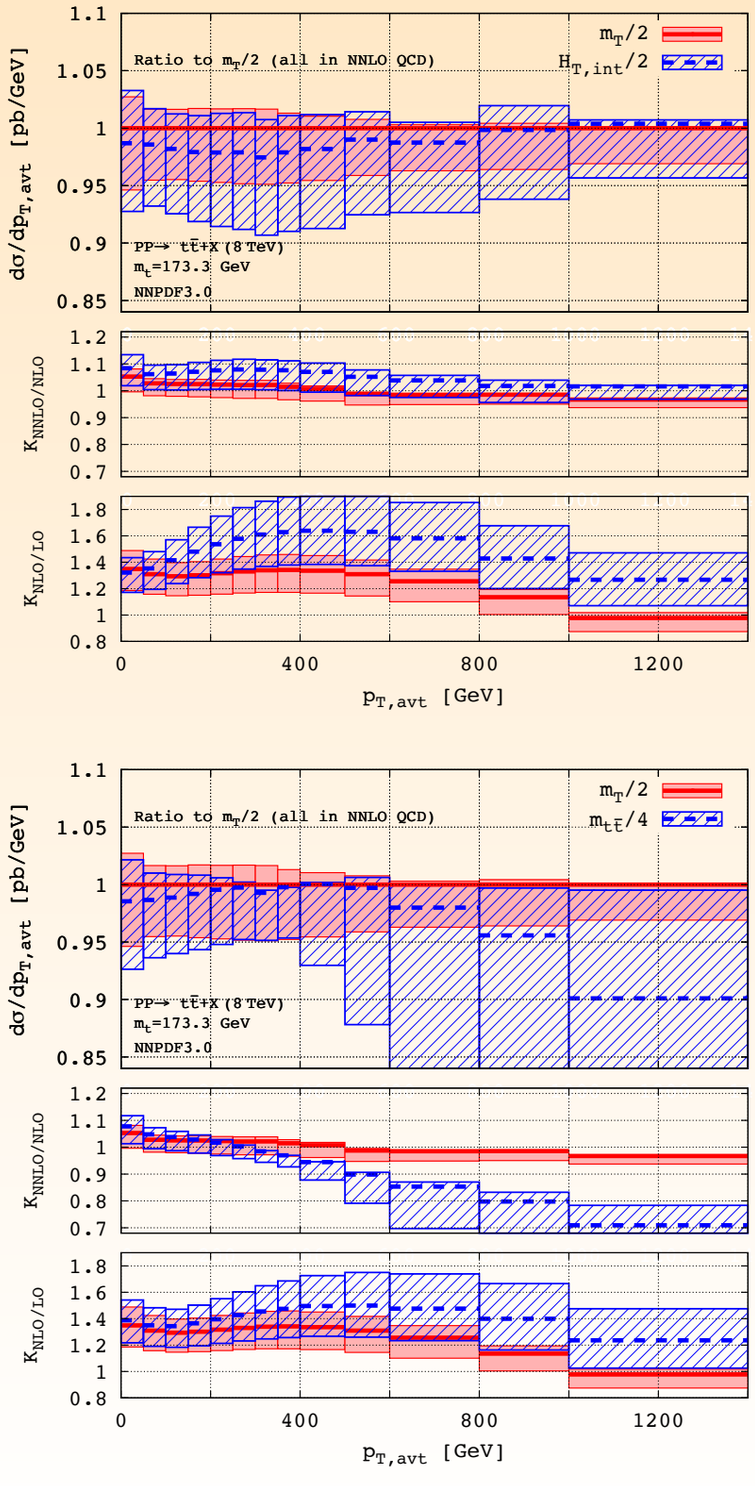
- Diff. NNLO top pair production seems to be in better agreement with data than (N)LO
- However, dependent on scale choice
- In fact, difference between NLO and NNLO with $\mu_R=m_{top}$ is as large as NLO with $\mu_R=m_{top}$ and NLO μ_R=default POWHEG/ MC@NLO scales
- Question: what happens if you use an event-by-event scale at NNLO?



EVENT-BY-EVENT SCALES

Czakon, Heymes, Mitov 2016

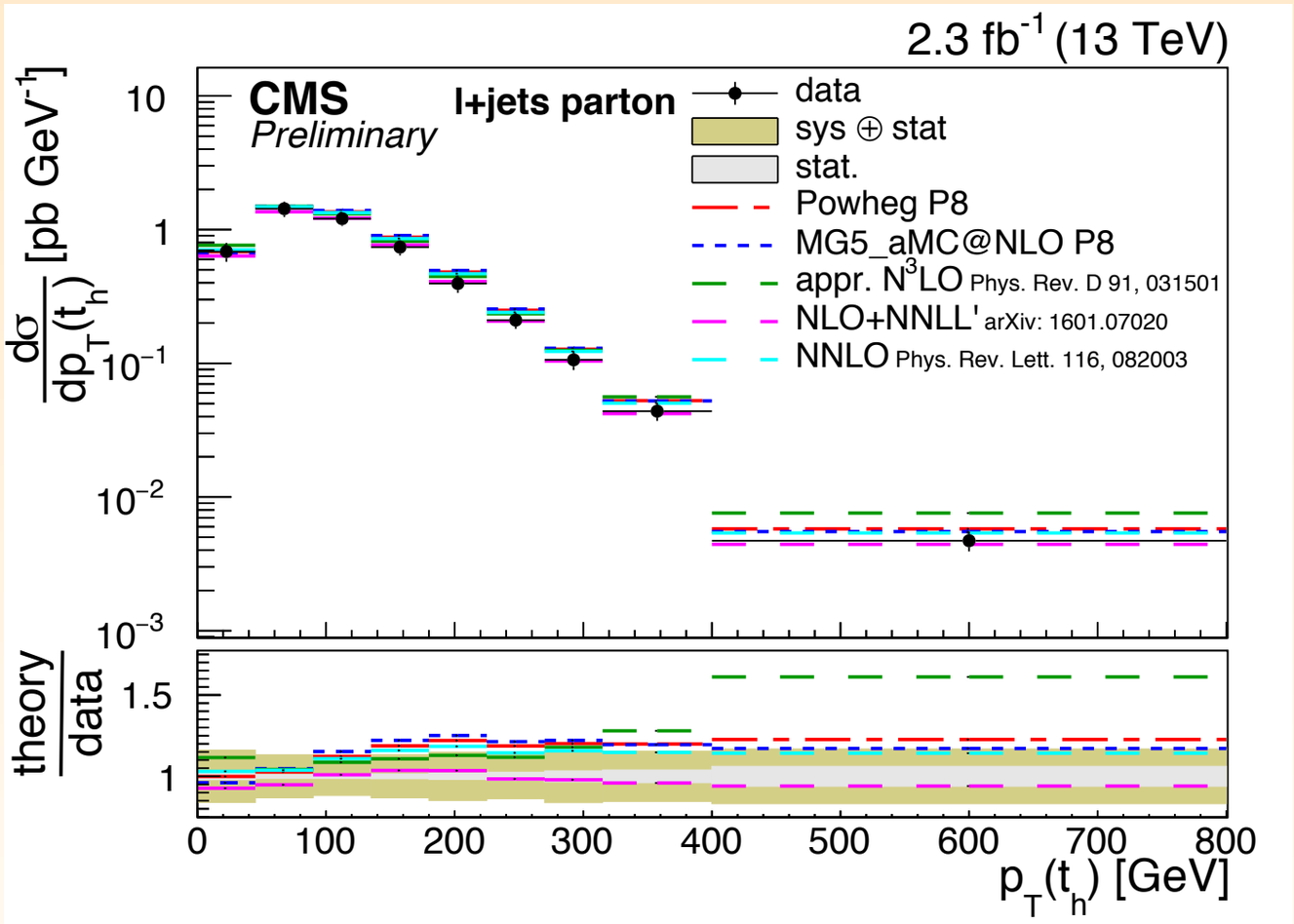




- This year: diff. NNLO with event-by-event scales
- From all the scales presented, $m_T/2$ is closest to what's used in POWHEG and MC@NLO
- In going from NLO to NNLO, hardly any difference in shape! (in particular below ~400 GeV)

CMS 13 TeV top p_T

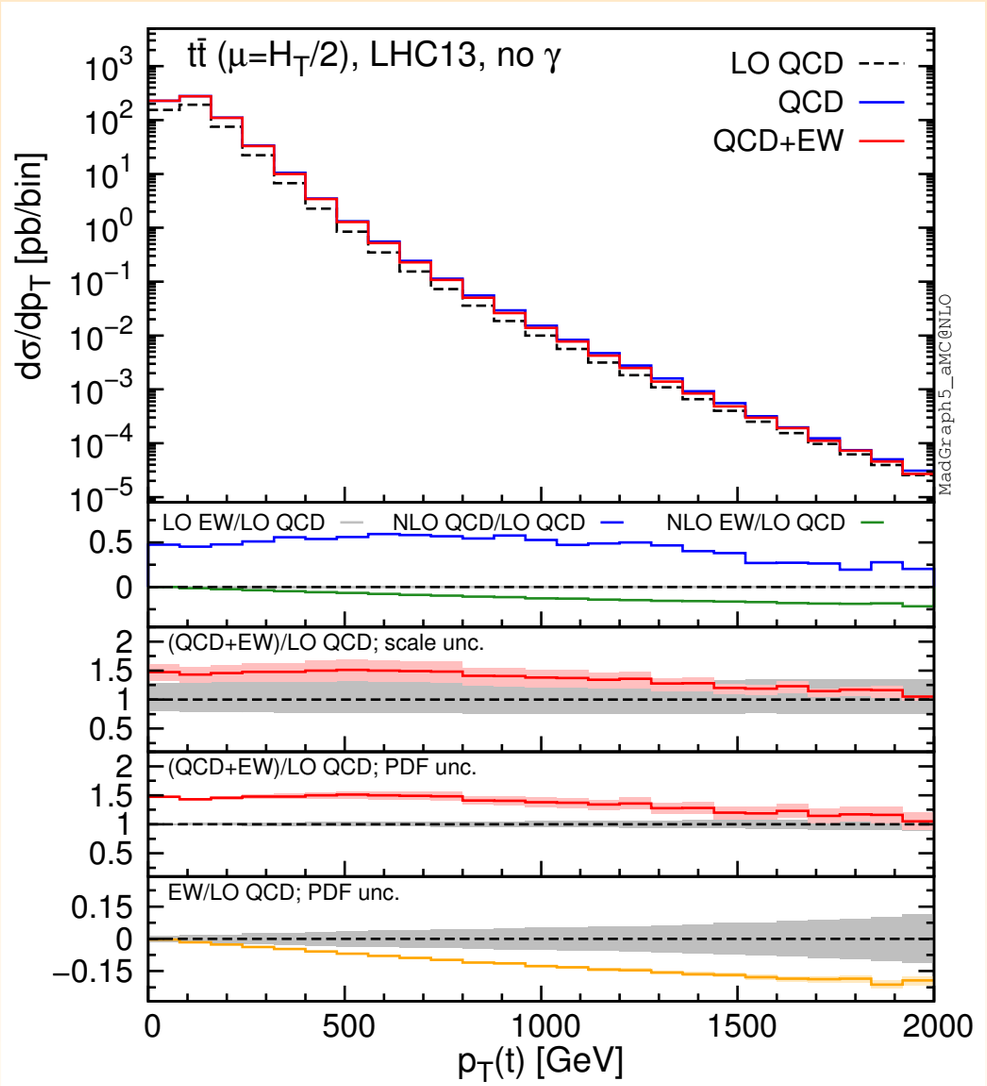
CMS-PAS-TOP-16-008



- Similar to what's seen by 13 TeV CMS results. NNLO does not differ much from POWHEG/MC@NLO
- Still, agreement with data seems to be better than at 8 TeV, and also better than with 13 TeV ATLAS results
- Still something to understand here…

EW corrections in top pair production

- (Electro-)weak corrections can be sizeable at large energies
- For top pair production the corrections are relatively small: same order as NLO uncertainty band
  - Not within NNLO uncertainty band
  - Preliminary results for NNLO QCD + NLO EW
- talk by Pagani



[Pagani, Tsinikos, Zaro 2016]

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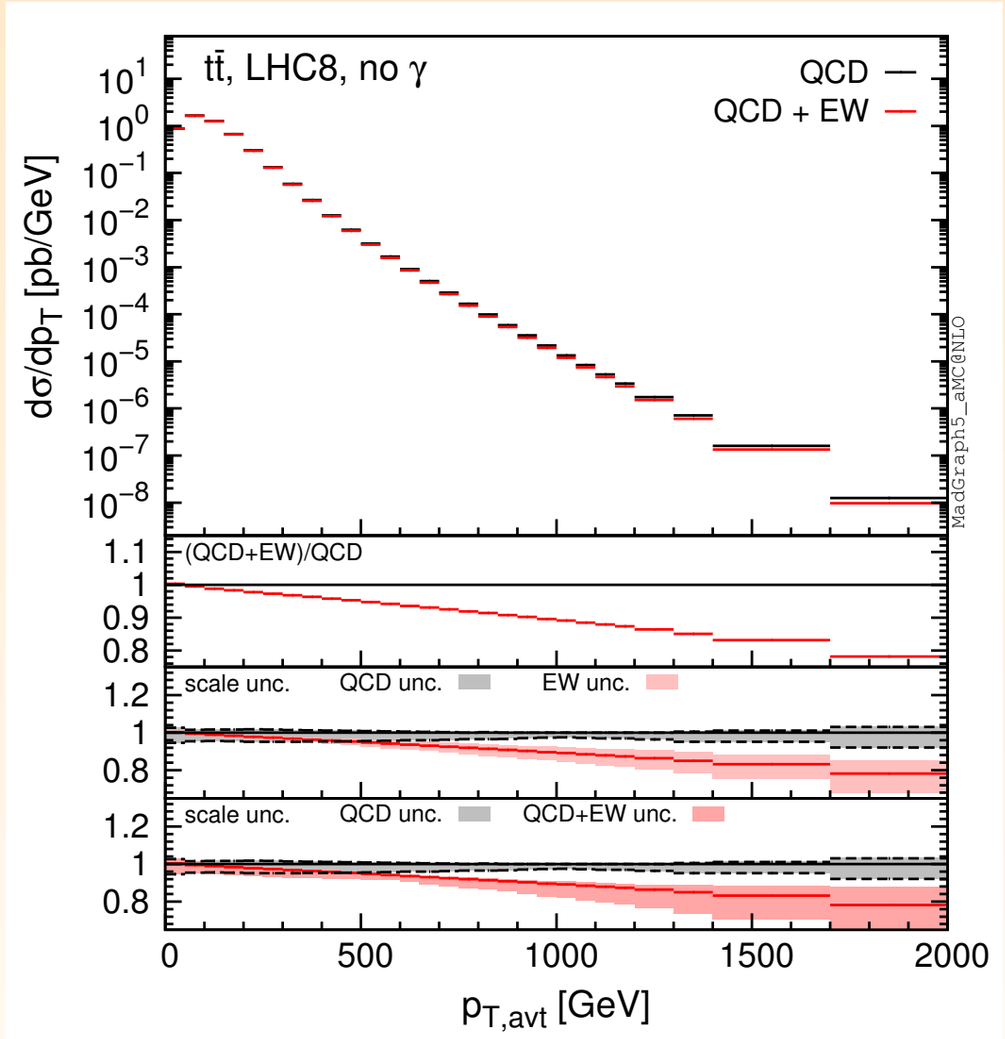


[Czakon, Heymes, Pagani, Tsinikos, Zaro (in prep.)]

Fixed order ttbar+jets

[Höche, Maierhöfer, Moretti, Pozzorini & Siegert 2016]

- About 1 in every 10 ttbar events has 3 additional jets (with p_T>25, |η|<2.5) at 13 TeV LHC
- Top pair production + 3jets @ fixed order NLO
- No top decays
- Very impressive results with many one-loop diagrams
  - Factorial growth of number of diagrams?
  - Pleasantly surprised that this many diagrams can still be tackled by diagram-based methods
  - CS-dipole subtracted real-emission computed with Berends-Giele recursion as implemented in Comix [Gleisberg & Höche 2008]

partonic channel \ N	0	1	2	3
$gg \to t\bar{t} + N\,g$	47	630	9'438	152'070
$u\bar{u} \to t\bar{t} + N\,g$	12	122	1'608	23'835
$u\bar{u} \to t\bar{t}u\bar{u} + (N-2)\,g$	–	–	506	6'642
$u\bar{u} \to t\bar{t}d\bar{d} + (N-2)\,g$	–	–	252	3'321

Number of one-loop diagrams

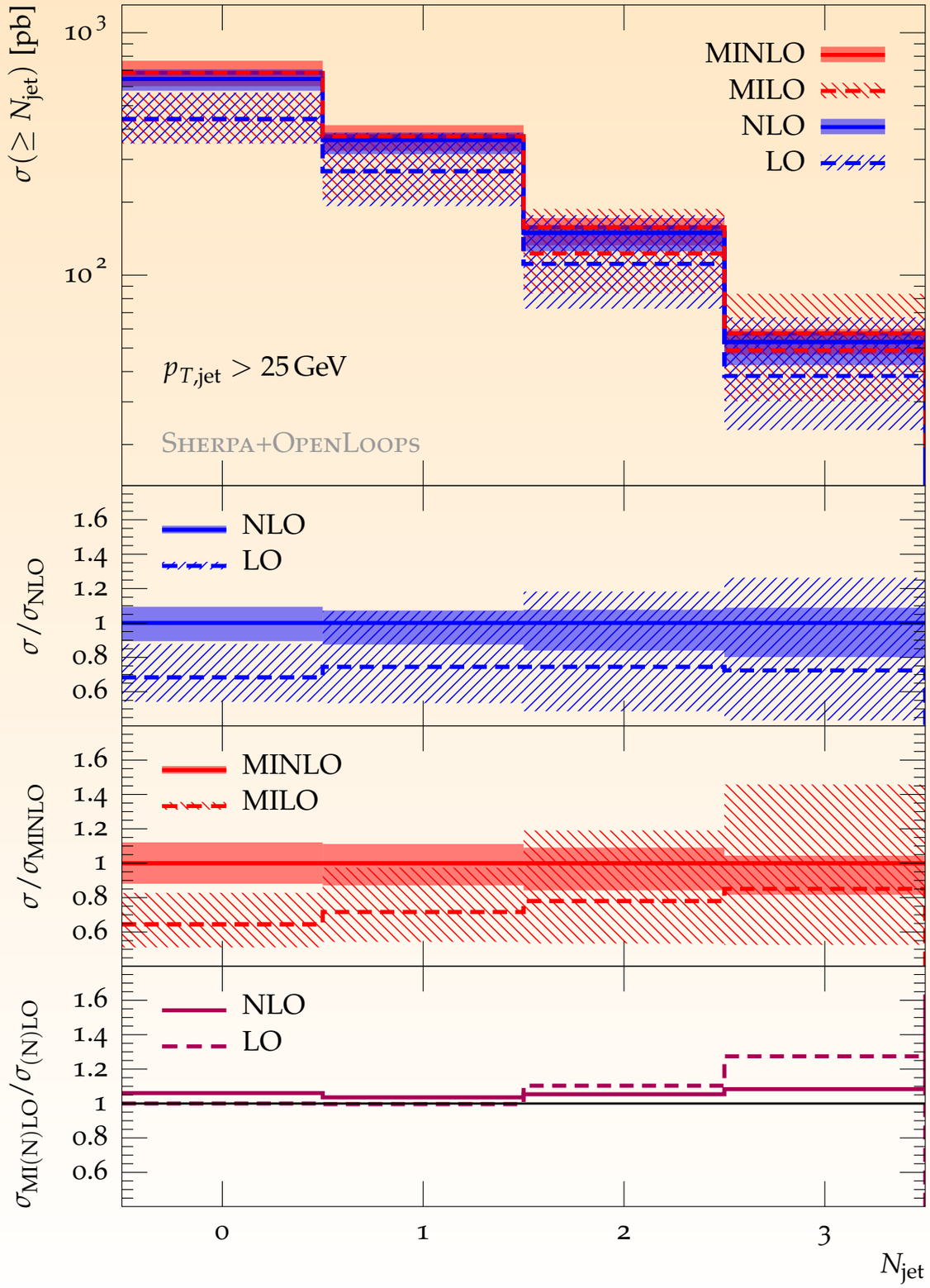
Fixed order ttbar+jets: scale setting

[Höche, Maierhöfer, Moretti, Pozzorini & Siegert 2016]

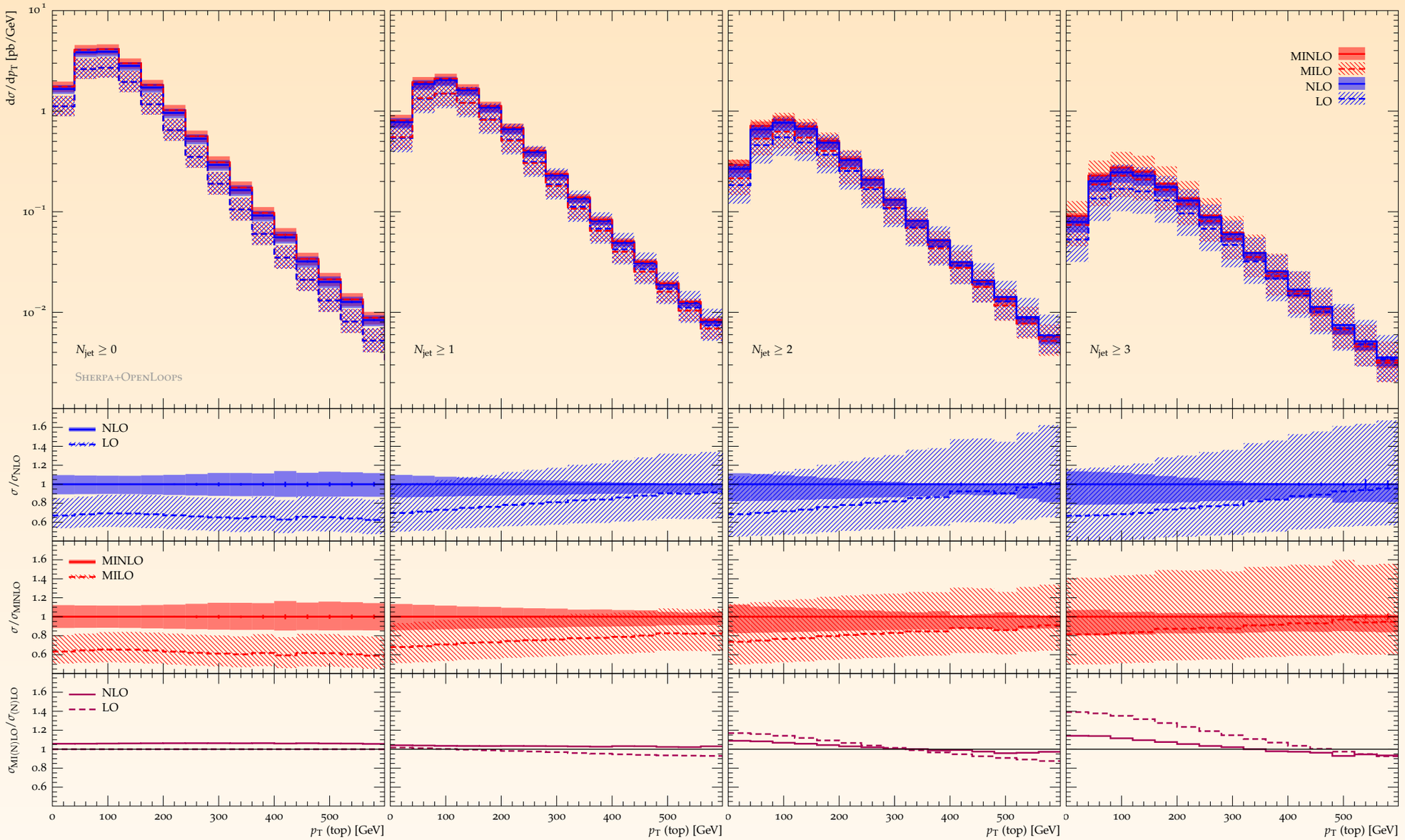
- Renormalisation/Factorisation scale choices
  - $H_T'/2$ (default (N)LO scale)
  - Minlo (labeled 'MI(N)LO' in plots) [Hamilton, Nason, Zanderighi 2013]
    - Designed for processes with multiple scales due to parton emissions
    - Renormalisation scale based on k_T-clustering scale for each (hard) emission
    - Fixed-order augmented with Sudakov Form factors
    - Very similar to CKKW (but with some tweaks needed to keep NLO accuracy)
- Useful for other processes, e.g. W/Z+jets
  - Possible to extend to NNLO, e.g. for H/Z/W+j

Fixed order ttbar+jets: cross sections

- NLO cross sections for ttbar, requiring 0, 1, 2 or 3 additional jets
- LHC 13 TeV
- Jet definition:
  anti-k_T, R=0.4, p_T>25 GeV, $|\eta|$<2.5
- Scale uncertainties under control. Very good perturbative convergence, in particular for large jet multiplicities
- At NLO, the two scale setting procedures are very consistent
  - No sign of irregularities for $H_T'/2$



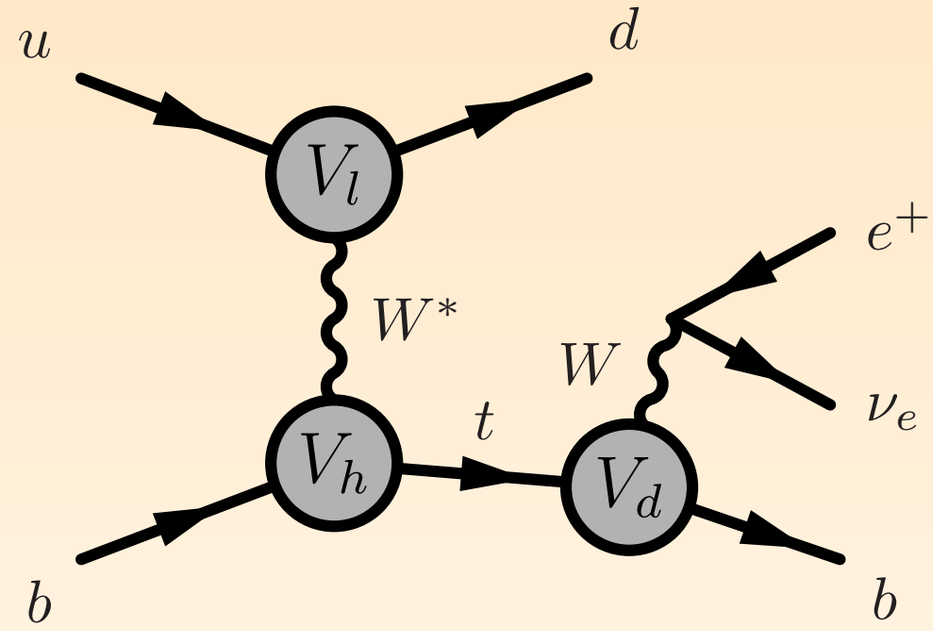
Fixed order ttbar+jets: Diff. distributions



- Transverse momentum of the top quark, requiring at least 0, 1, 2 or 3 jets in the events
- Consistency between scale choices
  - Why is $H_T'/2$ not a good scale at NNLO for inclusive ttbar production?

NNLO SINGLE TOP IN NWA

[Berger, Gao, Yuan, Zhu 2016]



- single-top + decay @ NNLO in the narrow width approximation (NWA)
- Complete factorisation of higher order corrections: separate for light quark line, heavy quark line and decay
  - Justified because
    - corrections between heavy and light lines only enter at NNLO and are colour suppressed
    - corrections between production and decay are suppressed by the top quark width

NNLO single top: Fiducial cross section

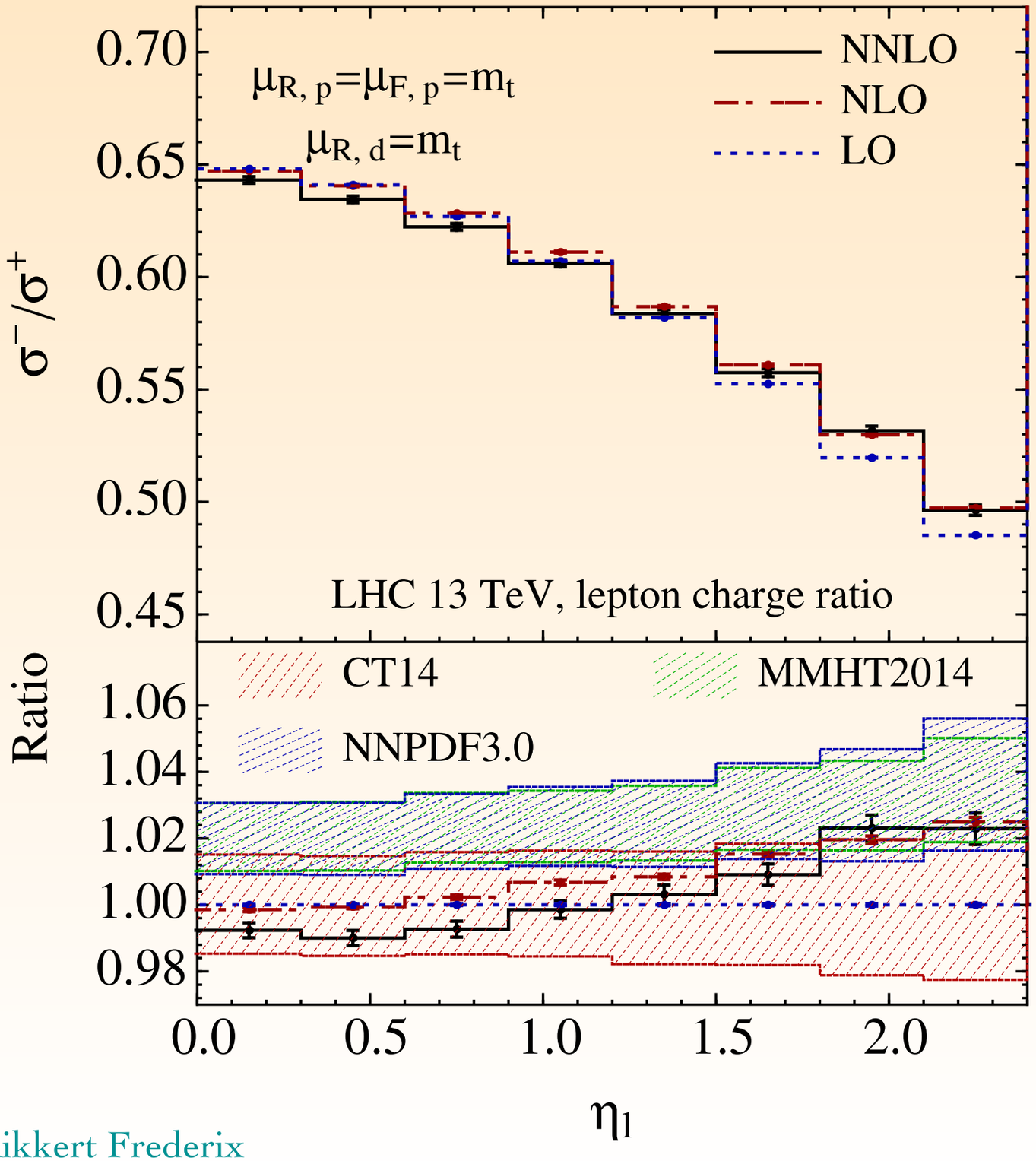
[Berger, Gao, Yuan, Zhu 2016]

- Total inclusive rate essentially identical to NNLO single top (without decay). Rather good convergence of perturbative series
- Fiducial region: require exactly 2 jets (anti-kT, R=0.5, p_T>40 GeV, |η|<5), of which one is b-tagged (|η|<2.4)
- p_T(lepton)>30 GeV, $|\eta_l|$<2.4
- LHC 13 TeV
- ren. & fac. scales equal to top mass
- Rather poor perturbative convergence in fiducial region
  - LO->NLO: -19% correction
  - NLO->NNLO: -8% correction
  - Large logarithms that need to be resummed from jet-veto?

fiducial [pb]		LO	NLO	NNLO
t quark	total	$4.07^{+7.6\%}_{-9.8\%}$	$2.95^{+4.1\%}_{-2.2\%}$	$2.70^{+1.2\%}_{-0.7\%}$
	corr. in pro.		-0.79	-0.24
	corr. in dec.		-0.33	-0.13
$\bar{t}$ quark	total	$2.45^{+7.8\%}_{-10\%}$	$1.78^{+3.9\%}_{-2.0\%}$	$1.62^{+1.2\%}_{-0.8\%}$
	corr. in pro.		-0.46	-0.15
	corr. in dec.		-0.21	-0.08

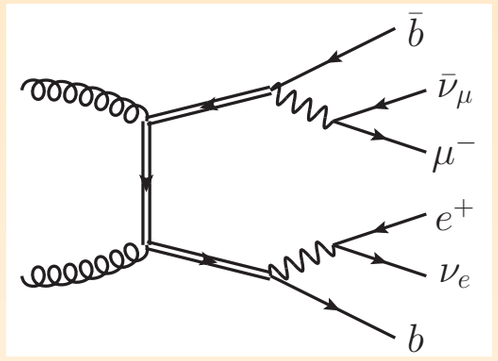
NNLO SINGLE TOP: DIFF. DISTRIBUTION

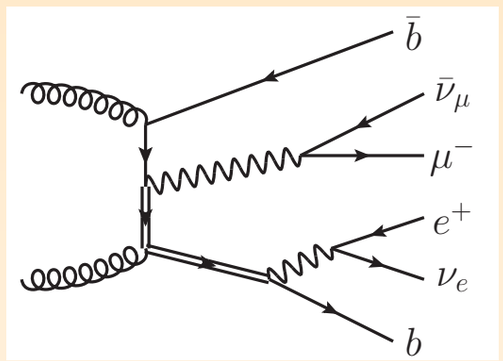
[Berger, Gao, Yuan, Zhu 2016]

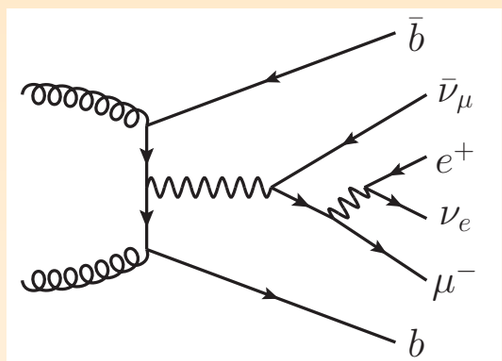


- Ratio of diff. fiducial cross sections for top and anti-top production as a function of the lepton rapidity
- Sensitive to b quark PDF

TTBAR WITH NON-ZERO WIDTH EFFECTS

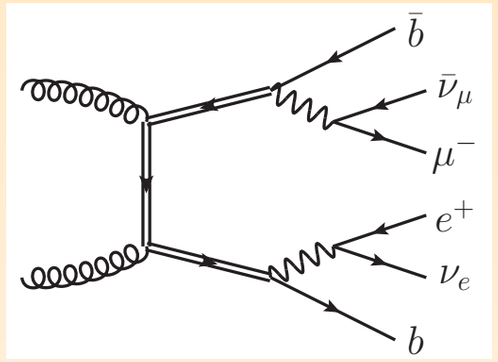


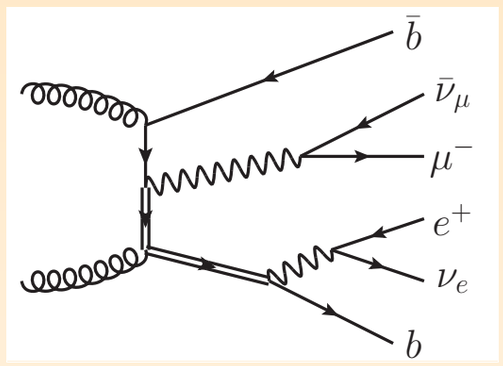


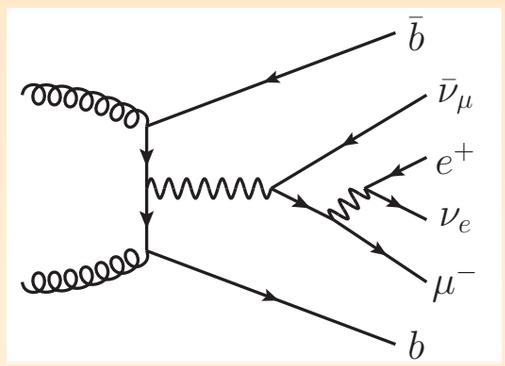


- Top quark pair production including decay
  - Complex mass scheme used to include width in gauge invariant way [Denner, Dittmaier]
- Important conceptual difference between use of 5-flavour scheme and 4-flavour scheme!

TTBAR WITH OFF-SHELL EFFECTS







✦ 5 flavour scheme

- ✦ Use a zero b quark mass
- ✦ Initial state b-quark contributions usually ignored
- ✦ Simpler calculation, because no b quark mass
- ✦ Can only be used when both b-quark/jets are tagged
  [Bevilacqua et al. (2011); Denner et al. (2011,2012)]

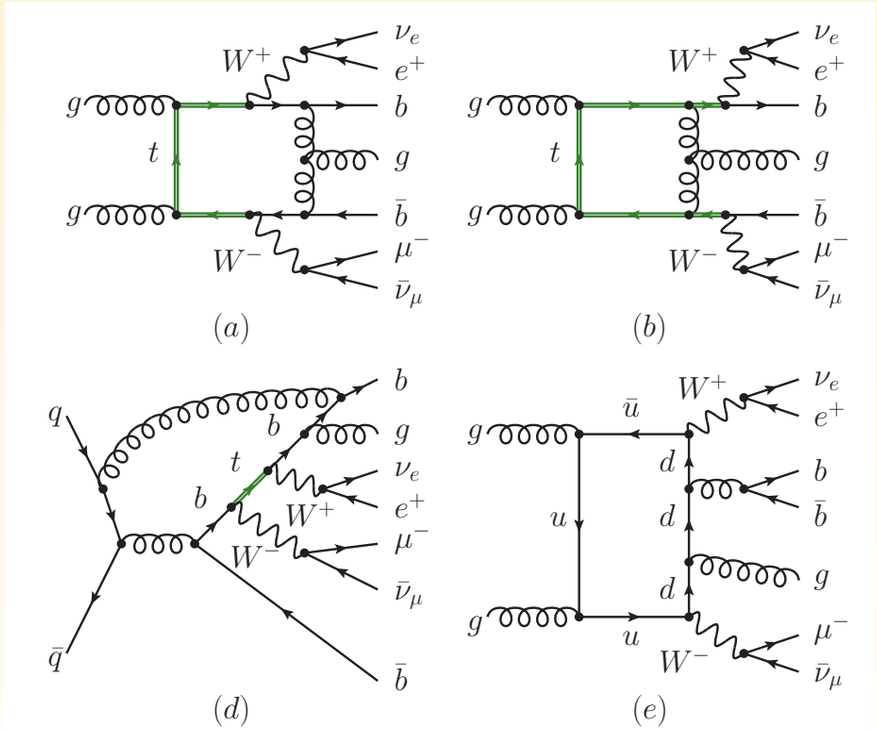
✦ 4 flavour scheme

- ✦ Non-zero b quark mass
- ✦ No initial state b-quark contributions: need 4FS PDFs for consistency
- ✦ Also consistent when b-quark/jets escape detection
- ✦ Contains tW production (and b-quark induced WW pair production) fully consistently
  [RF (2013); Cascioli et al. (2013)]

TTBAR OFF-SHELL 5FS: TTBAR+JET @NLO

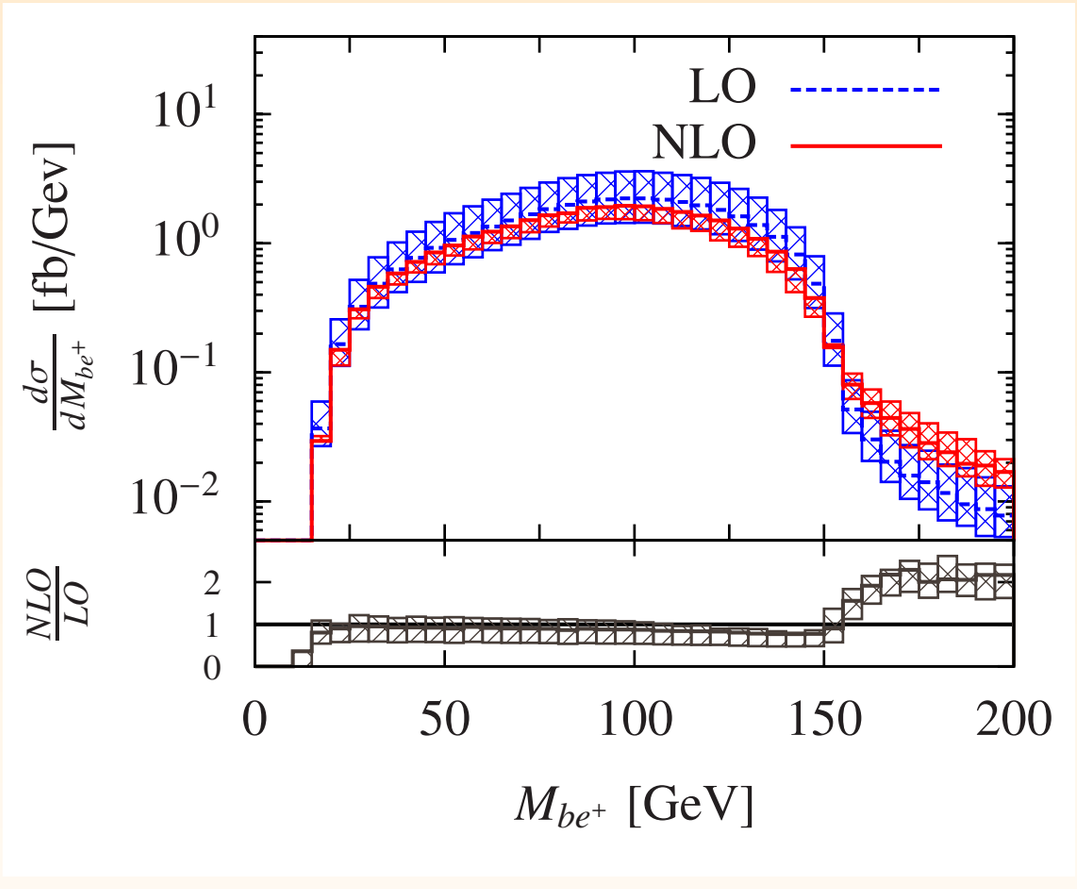
[Bevilacqua, Hartanto, Kraus, Worek (2015)]

- New NLO calculation for top pair + jet + di-lepton decay (and off-shell) effects
- Contains double, single and non-resonant contributions
- Particularly important when not fully inclusive over reconstructed top mass
  - signature:
    - charged lepton pair (different flavour)
    - missing energy
    - 3 jets (of which some b-tagged)
  - major background in e.g. SUSY searches
- Helac-NLO framework
- Talk by Hartanto



TTBAR OFF-SHELL 5FS: TTBAR+JET @NLO — RESULTS

[Bevilacqua, Hartanto, Kraus, Worek (2015)]

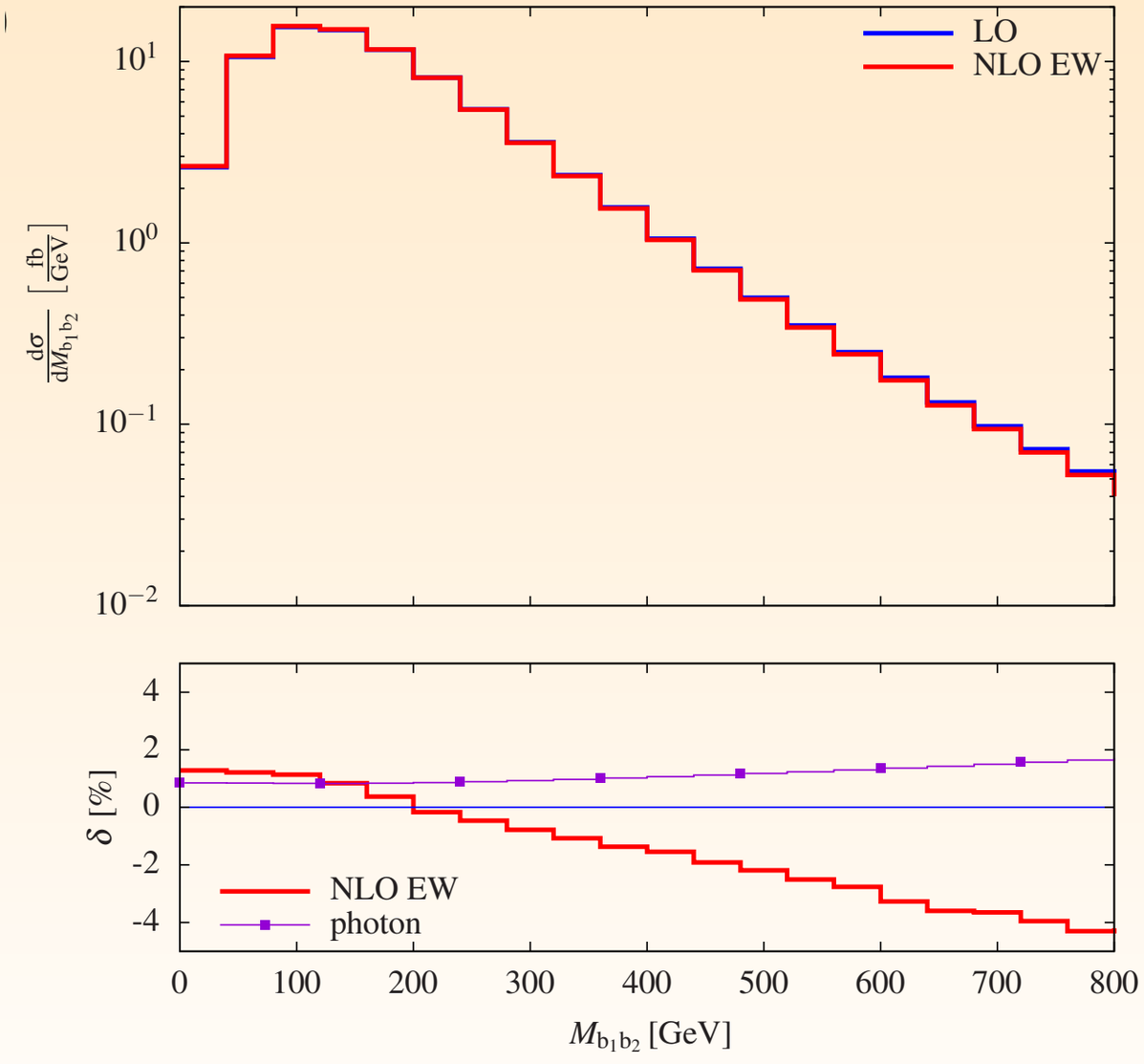


- As expected, effects on total rate are negligibly small
- Some large effects in shapes of distributions
  - e.g., lepton+b-jet invariant mass. Kinematical cut 153.3 GeV if tops and W-boson exactly on-shell
- Difference can be attributed mostly to radiation in production or decay smearing out the distribution
  - Genuine off-shell effects are smaller
  - Would be interesting to compare to NLO computation in the NWA [Melnikov, Scharf, Schulze (2011)] or parton shower

TTBAR OFF-SHELL 5FS: NLO EW

[Denner, Pellen 2016]

- NLO EW corrections have also been computed for ttbar+decay (incl. off-shell)
- Typically, EW corrections are small, but grow (negatively) in high-energy tails of distributions
- Just as for EW corrections to on-shell top pair production, they remain modest even in high-energetic tails
- Talk by Pellen



TTBAR OFF-SHELL 4FS: NLO+PS

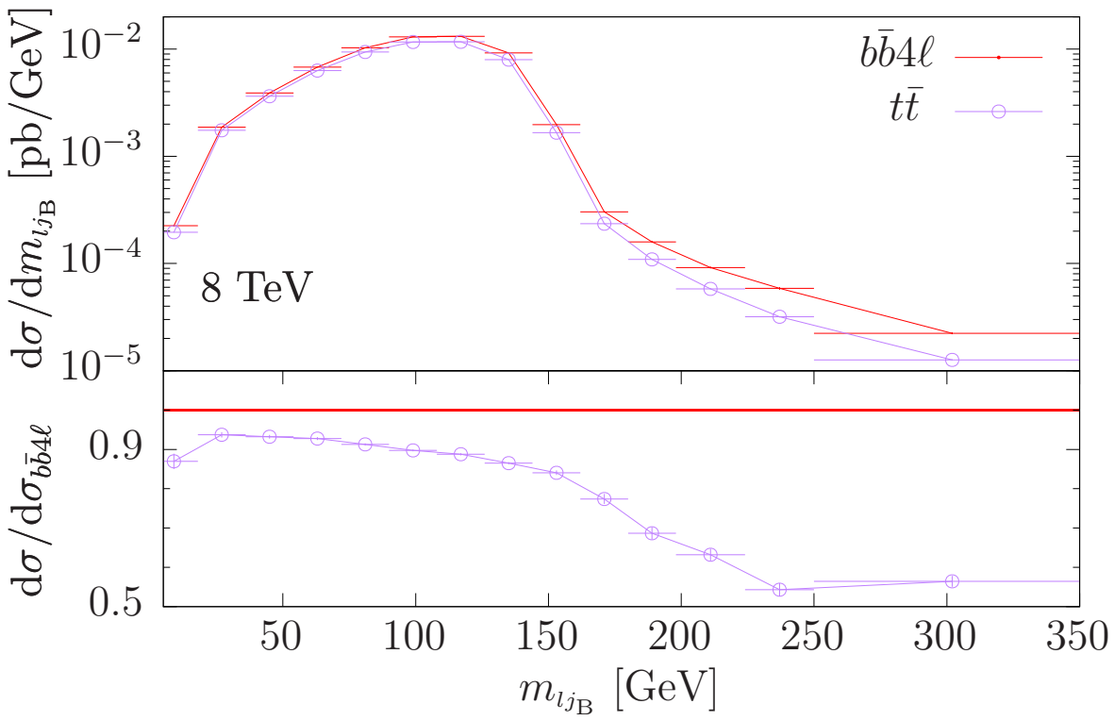
- In the 4 flavour scheme WWbb production contains ttbar and Wt production in a consistent way
- New result: NLO+PS for complete WWbb process
  - Requires special "resonance-aware" extension in the matching
    - Need consistency in "reconstructed" top quark mass between Born, real, shower (and shower subtraction terms), i.e., if the shower keeps mass fixed in emissions, so should it be at the level of the hard matrix elements
- Extensions to POHWEG and MC@NLO matching algorithms developed for single top in POWHEG-BOX-RES [Jezo, Nason 2015] and MadGraph5_aMC@NLO [RF, Frixione, Papanastasiou, Prestel, Torrielli 2016]
- Talks by Torrielli and Lindert

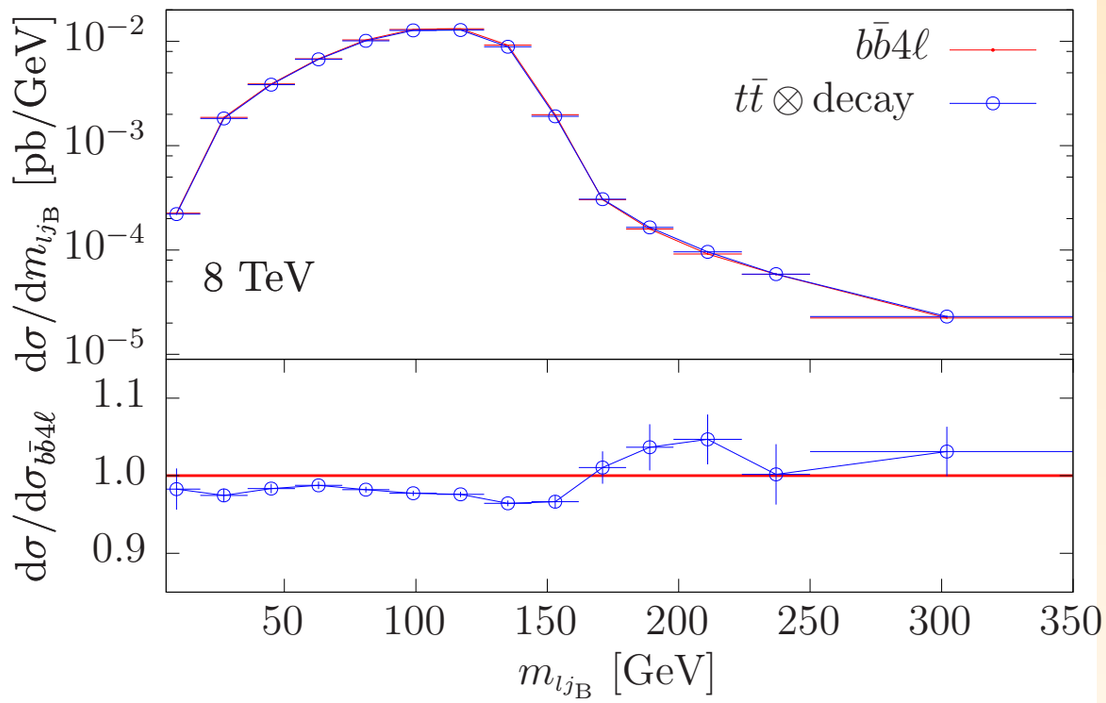
TTBAR IN POWHEG BOX

- Three levels of sophistication in POWHEG BOX for top pair production
  - ttbar NLO+PS; decays at LO [Frixione, Nason, Rudolf 2007]
  - ttbar and decay at NLO+PS; Reweighing with LO bb4l matrix elements [Campbell, Ellis, Nason, Re 2015]
  - bb4l NLO+PS-RES [Jezo, Lindert, Nason, Oleari, Pozzorini 2016]
- Differences are small for inclusive observables
- But very relevant for top quark mass extraction

Important effects for top quark mass extraction

[Jezo, Lindert, Nason, Oleari, Pozzorini 2016]





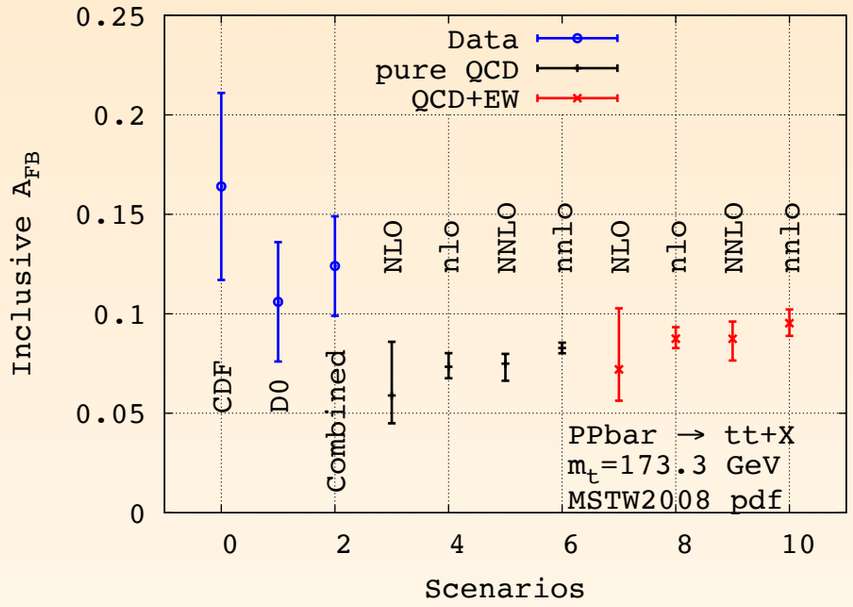
- Significant shape distortions between current LHC default and best predictions
- Might be 500 MeV effect on top mass extraction

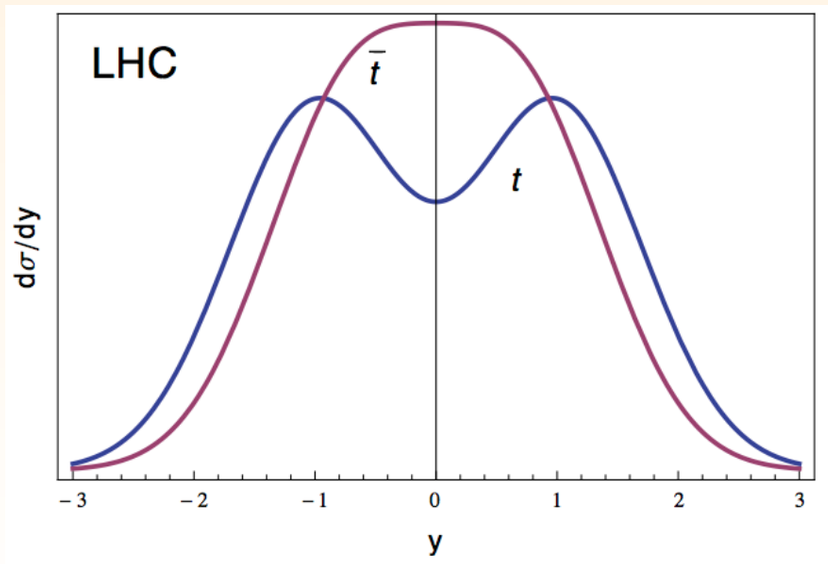
- Also differences between the two recent more sophisticated methods
- Might be 100 MeV effect on top quark mass

Top quark charge asymmetry

- QCD has interesting non-trivial effects beyond lowest order in perturbation theory
  - Tests of SM
  - A typical example is the top quark charge asymmetry
  - Extensively studied at Tevatron due to tension between theory and data. Latest NNLO results show much better agreement with data
  - At LHC effect is visible in difference in rapidities for tops and anti-tops
- Another non-trivial effect that appears beyond lowest order is the naive-T-odd asymmetry

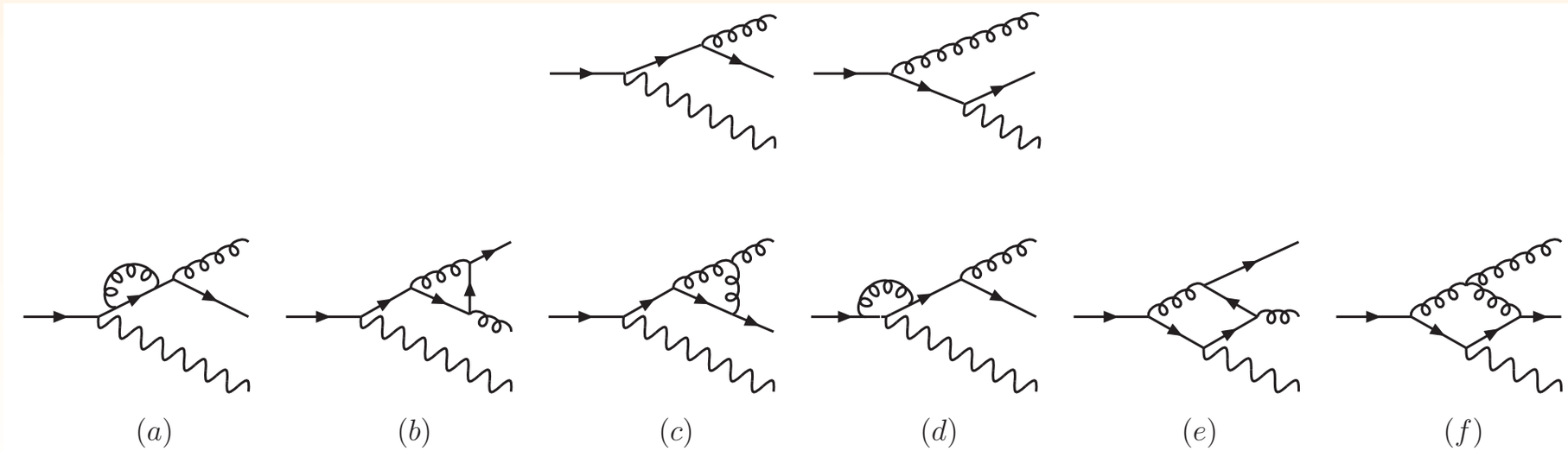
[Kuhn & Rodrigo; Bernreuther & Si; Czakon, Fiedler & Mitov]





Naive-T-odd asymmetries in radiative top decays - I

- Interference between tree-level and one-loop contributions gives rise to naive-T-odd asymmetries
  - Naive-T-odd observables change sign under operation of reversing both spatial momenta and spin of all particles, but not interchanging initial with final state
  - Effect coming from abortive part of scattering amplitudes
  - Never been measured at hadron colliders
- Should also appear in top quark decays + 1 jet

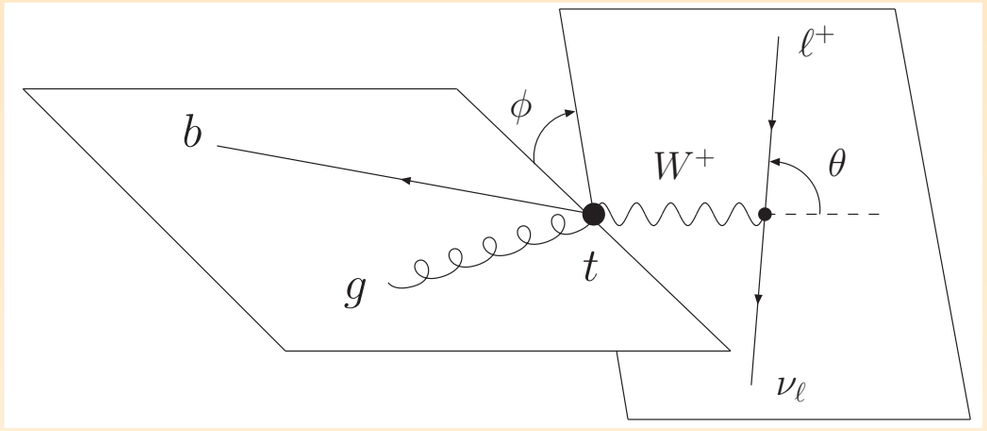


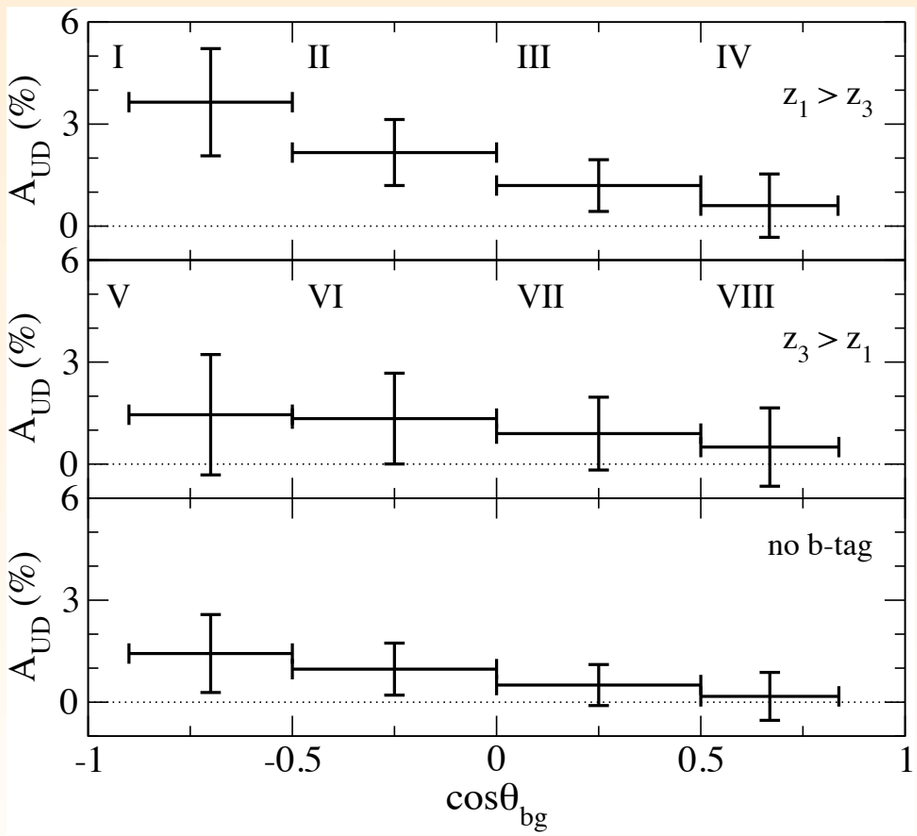
Naive-T-odd asymmetries in radiative top decays - II

- Where to look?
  - Probably easiest to see by considering the top decay plane
  - There should be an asymmetry in the decay plane of the W-boson: not the same number of events with $0<\phi<\pi$ and $\pi<\phi<2\pi$

$$A_{\mathrm{UD}} \equiv \left[N(0<\phi<\pi) - N(\pi<\phi<2\pi)\right] / N_{\mathrm{sum}}$$

- Effect is a couple of percent, depending on the angle between the bottom and the gluon
- Errors are statistical only for 800k top quark events
  - Interesting to see what can be done with current data set
- Similar asymmetry also appears in W/Z+jets [RF, Hagiwara, Yamada, Yokoya, 2014]





[Hagiwara, Mawatari, Yokoya 2007]

Summary

- Highly accurate measurement need to be accompanied by similarly accurate theoretical calculation
- Some tension remains in the top p_T spectrum even with NNLO results. Needs to be understood…
- Many interesting new theoretical calculations
  - ttbar+3jets at NLO
  - combined NNLO QCD and NLO EW corrections
  - Single top NNLO + decay at NNLO in NWA
  - Many results for tops including off-shell effects
    - including matching to parton showers
  - and many more …
- Might have enough top events to look at very small effects, such as the naive-T-odd asymmetry in the decay