Single top computations and generation tools

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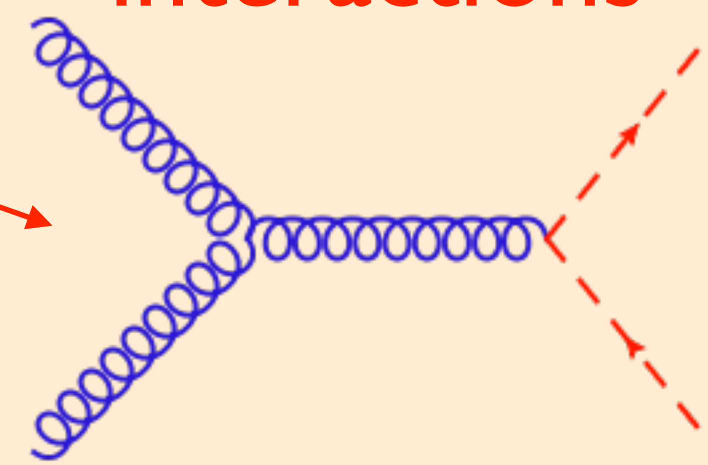
TOP 2014, CANNES, SEP. 29TH 2014

Single-top: EW production of tops

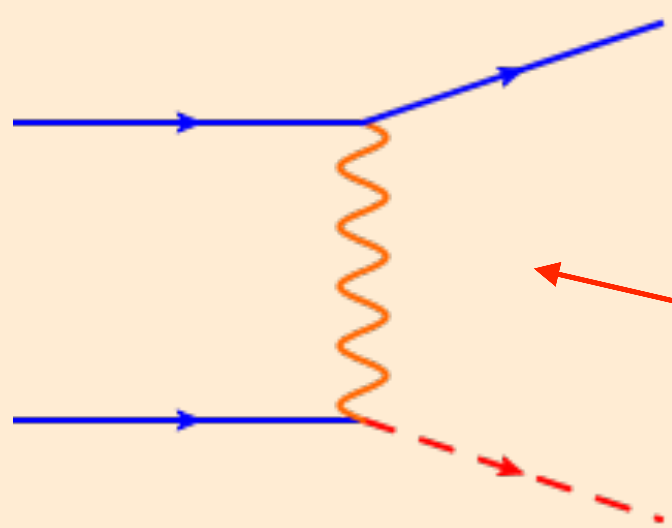
Two main production mechanism
of tops at hadron colliders:

THIS MORNING

Probe strong interactions



Probe weak interactions



FOCUS OF THIS TALK

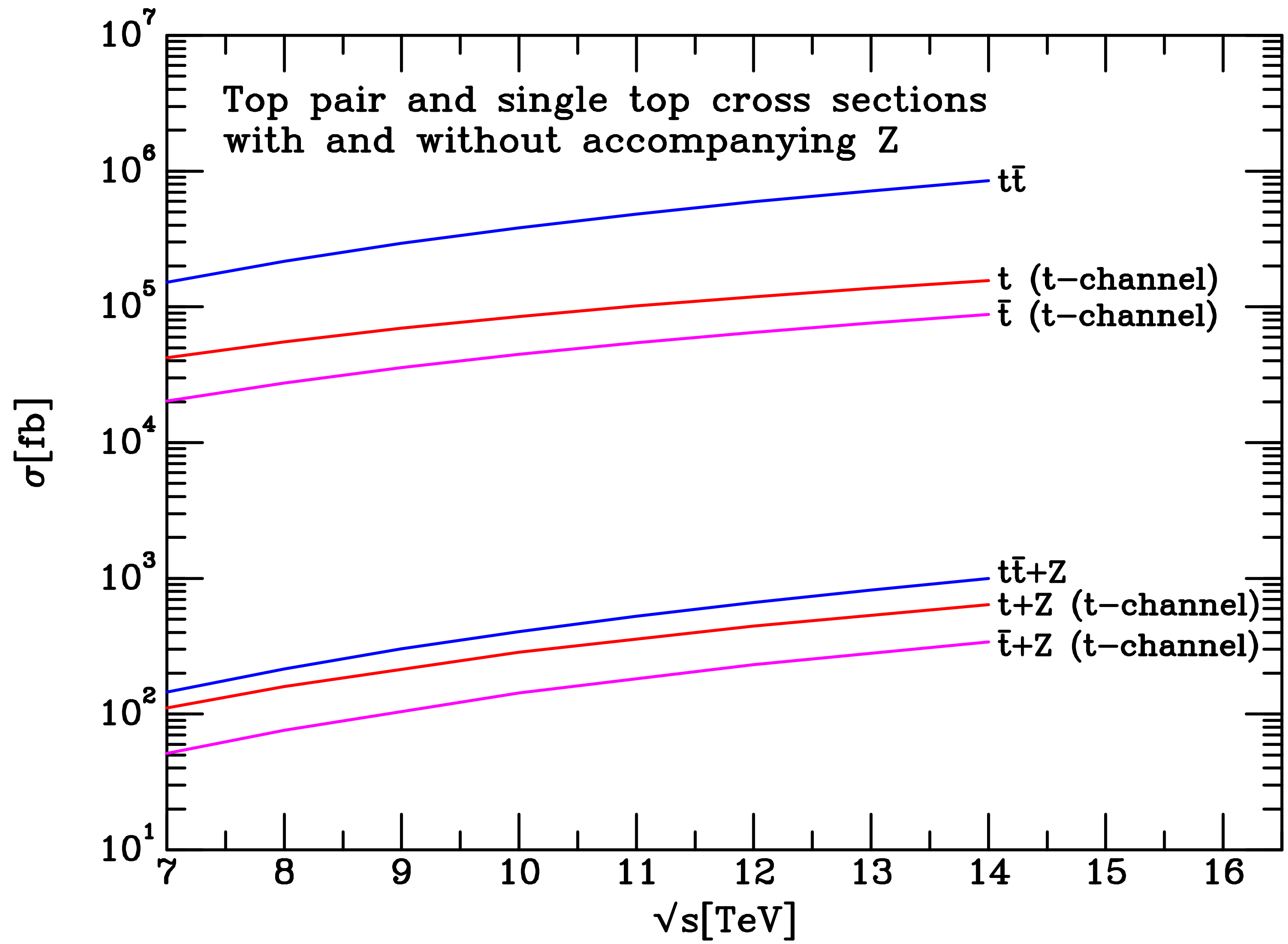
Disclaimer

Extremely biased selection of topics

- Time constraints ->
  presenting everything neither possible nor useful

- Personal expertise ->
  won't discuss at all parton-shower issues,
  although of course very interesting and important

LHC as a top factory

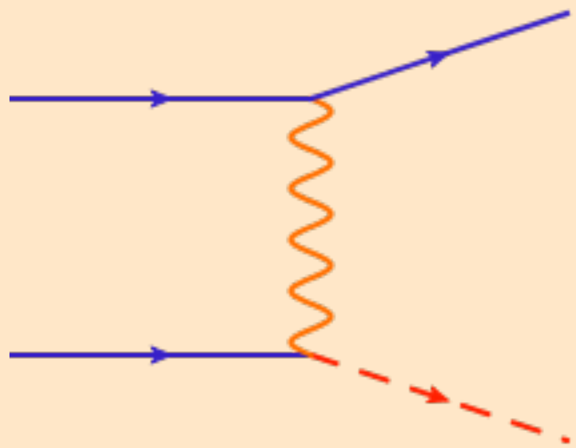


[Campbell, Ellis, Rontsch (2013)]

From discovery to PRECISION PHYSICS

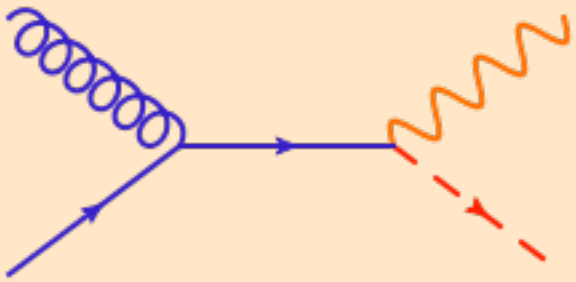
The classical picture: 3 production mechanism

T-CHANNEL



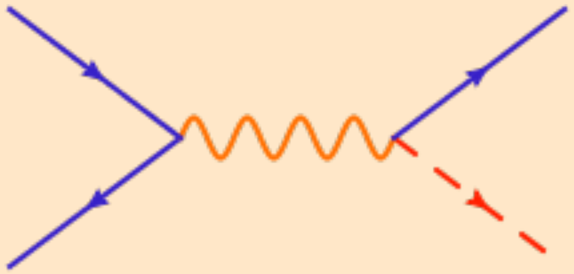
LHC8: ~ 82%
TEV: ~ 65%

ASSOCIATED PRODUCTION



LHC8: ~ 15%
TEV: ~ 0

S-CHANNEL

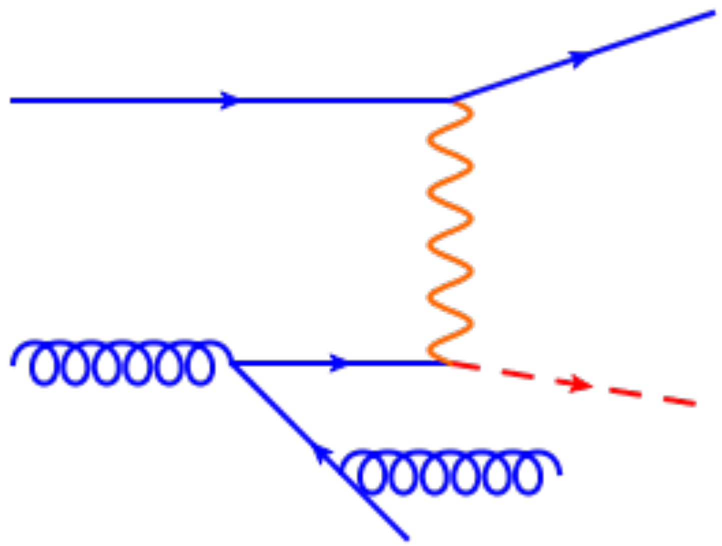


LHC8: ~ 5%
TEV: ~ 33%

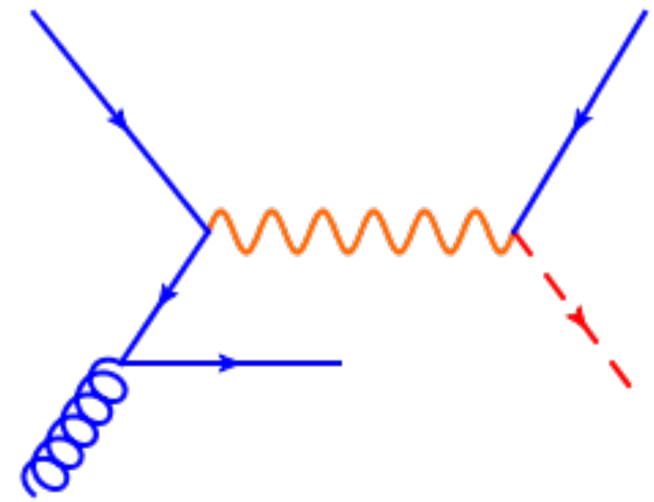
Good for the old 'pioneering' days,
must be taken with care for precision physics

t- vs s- channels: it still makes sense

In principle: beyond LO t- and s- channels same initial/final states -> interferences, no well defined distinction



vs



However in practice:

- interference starts at NNLO (in the 5FNS)
- suppressed (color / kinematics)

CAN STILL TALK MEANINGFULLY ABOUT T (AND S) CHANNEL

Talking about fiducial cross section is much better

Ideally for realistic final states

The quest for precision: t-channel @ NNLO

[Brucherseifer, FC, Melnikov (2013)]

t-channel single top: do we need NNLO?

LOOK AT THE NLO PREDICTION

The total cross section at the 8 TeV LHC:

$$\sigma_{\rm LO} = 53.77 + 3.03 - 4.33 \text{ pb}$$
$$\sigma_{\rm NLO} = 55.13 + 1.63 - 0.90 \text{ pb}$$

NAIVELY:

“Small ~ 2% corrections, no need to go further”

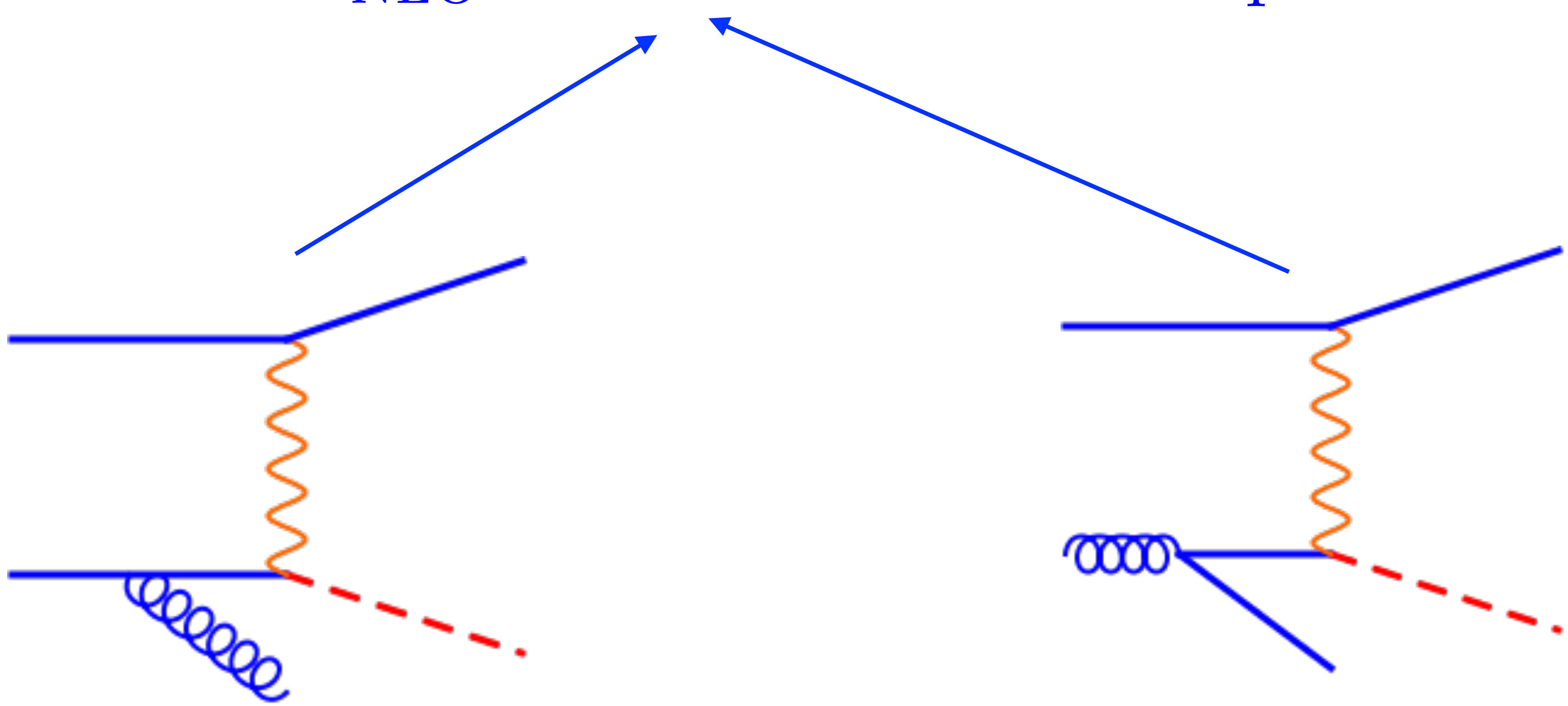
HOWEVER…

t-channel single top: do we need NNLO?

The total cross section at the 8 TeV LHC: A CLOSER LOOK

$$\sigma_{\mathrm{LO}} = 53.77 + 3.03 - 4.33 \text{ pb}$$

$$\sigma_{\mathrm{NLO}} = 55.13 + 1.63 - 0.90 \text{ pb}$$



+12%

-14%

Large cancellations among channels

t-channel single top: do we need NNLO?

The NLO K-factor is Accidentally Small

The pattern of cancellation is (very) phase-space dependent:

$$\sigma(p_{\perp,t} > p_{\perp,cut})$$

$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$
0 GeV	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	$+2.4\%$
20 GeV	$46.6^{+2.5}_{-3.7}$	$48.9^{+1.2}_{-0.5}$	$+4.9\%$
40 GeV	$33.4^{+1.7}_{-2.5}$	$36.5^{+0.6}_{-0.03}$	$+9.3\%$
60 GeV	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	$+13.6\%$

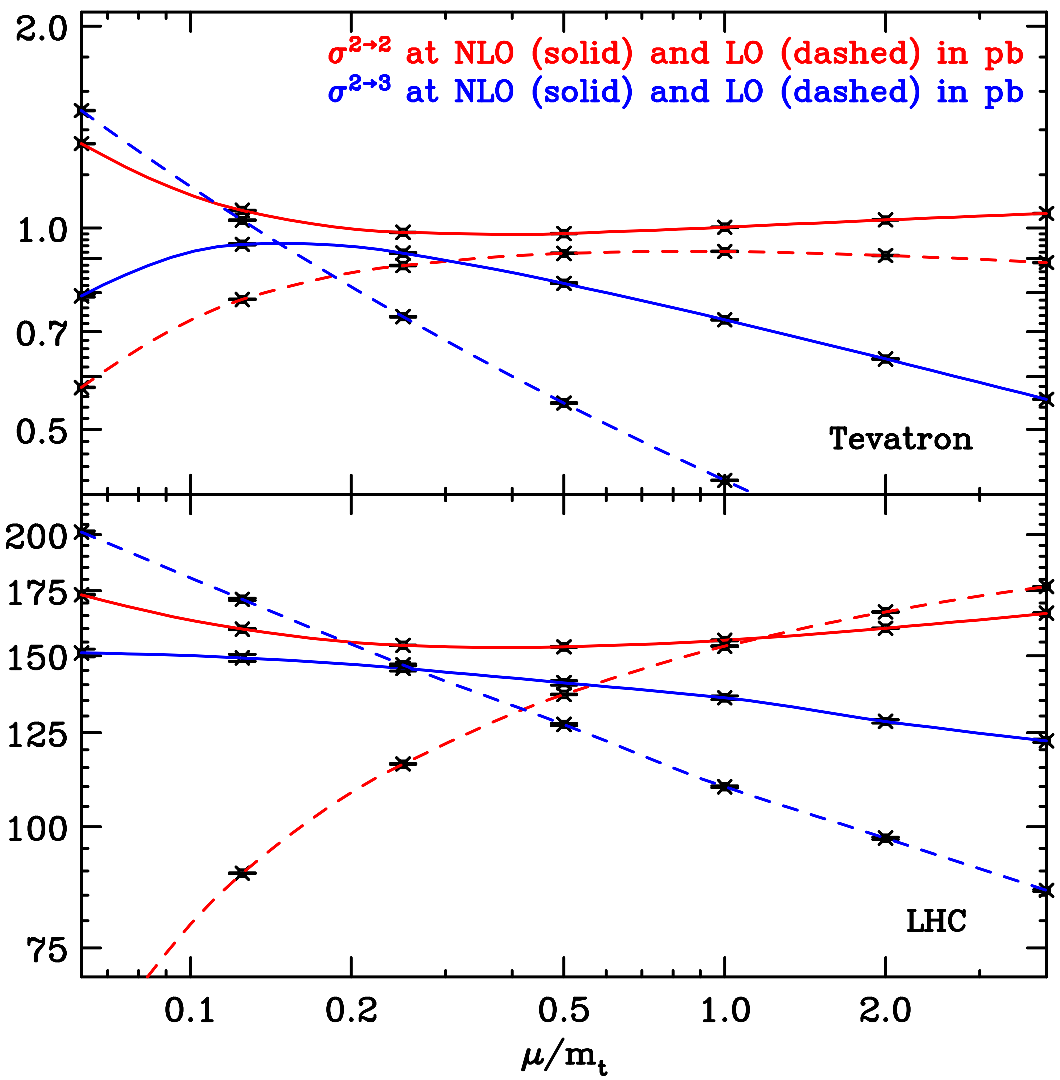
Corrections to more exclusive observables ~ 10%

T-channel single top: do we need NNLO?

The total cross section at the 8 TeV LHC: A CLOSER LOOK

$$\sigma_{\mathrm{LO}} = 53.77 + 3.03 - 4.33 \text{ pb}$$

$$\sigma_{\mathrm{NLO}} = 55.13 + 1.63 - 0.90 \text{ pb}$$



[Campbell et al (2009)]

- Scale variation similar to corrections
- ~ percent difference between 4FNS/5FNS calculations

T-channel single top: do we need NNLO?

The total cross section at the 8 TeV LHC: A Closer Look

$$\sigma_{\mathrm{LO}} = 53.77 + 3.03 - 4.33 \text{ pb}$$

$$\sigma_{\mathrm{NLO}} = 55.13 + 1.63 - 0.90 \text{ pb}$$

- Large (accidental?) cancellations between channels
- Scale variation (~ NNLO!) as large as corrections
- Larger corrections for more exclusive observables

To control single-top production at the percent level:
NNLO Correction to t-channel Production

Anatomy of a NNLO computation

- For a long time, the problem of NNLO computations was how to consistently extract IR singularity from double-real emission/real-virtual emission
- This problem has now been solved both in theory (antenna subtraction, sector decomposition+FKS, semi-analytic subtraction) and in practice (top-pair, dijet, H+jet,…)
- Now the problematic part is computing two-loop amplitudes. State of the art:
  - Numerically: 2->2 with 1 extra mass-scale (tt)
  - Analytically: 2->2 with two external mass scales (VV*)

t-channel single-top @ NNLO

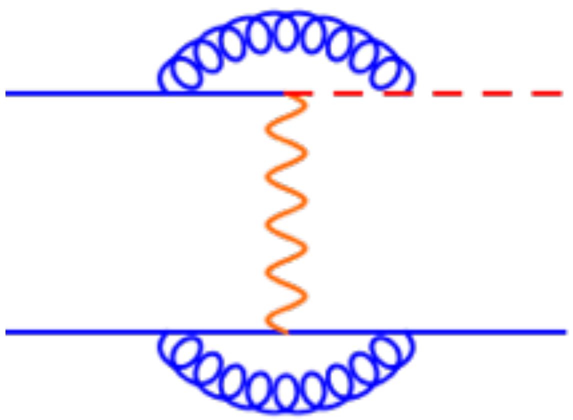
Recent developments in NNLO techniques, allowed us to compute (almost) t-channel single-top corrections.

In particular, for our computation:

- 5FNS@NNLO (2->2) (although almost all nice features of 4FNS@NLO naturally inherited)
- Fully differential (arbitrary cuts on the final state are not a problem)
- For now, top is stable but very easy to implement top decay in the NWA with full spin correlation

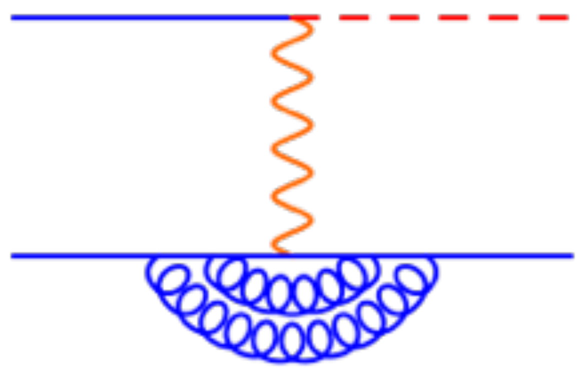
Single-top in the 'factorized' approximation

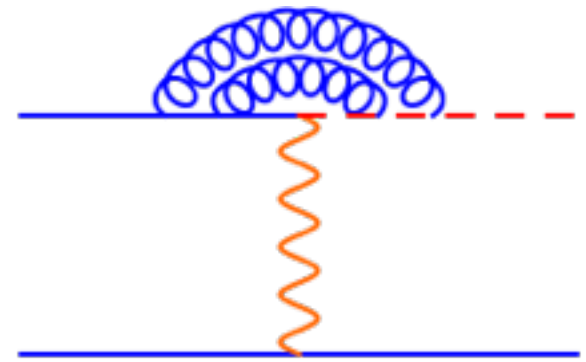
Two-loop amplitudes:



Trivial ($\sim$NLO^2)

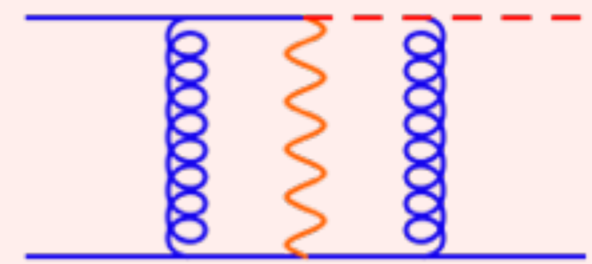
Simple





~OK

(very) hard



Must be interfered with tree-level -> COLOR SINGLET

The 'hard' amplitude contribution is suppressed by $1/N_c^2$

NEGLECTED IN OUR COMPUTATION

[same for s/t interference]

Single-top @ NNLO: total cross section

8 TeV LHC, MSTW2008, m_t = 173.2 GeV

$$\sigma_{\mathrm{LO}} = 53.8^{+3.0}_{-4.3}\ \mathrm{pb} \qquad \sigma_{\mathrm{NLO}} = 55.1^{+1.6}_{-0.9}\ \mathrm{pb}$$

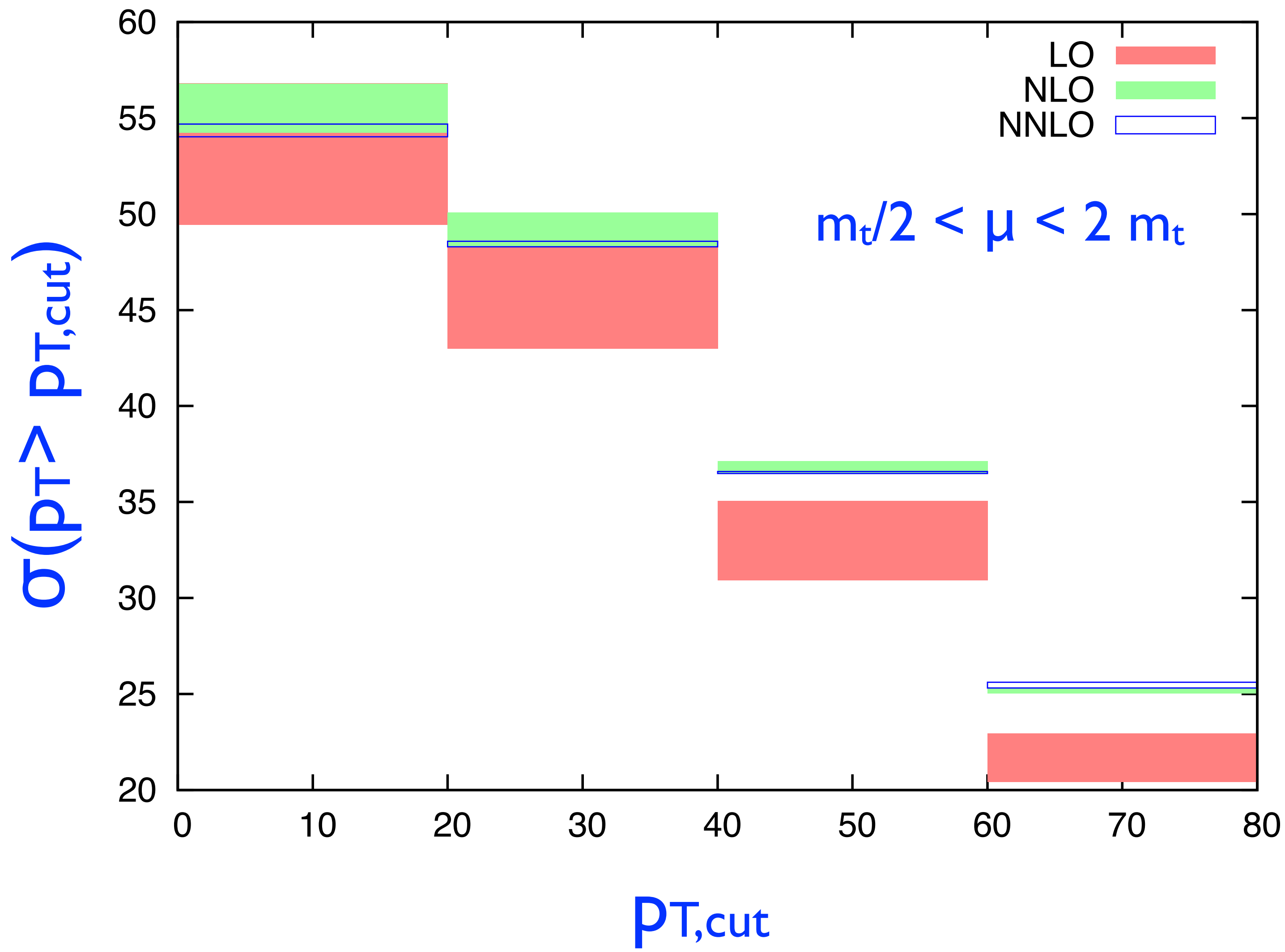
$$\sigma_{\mathrm{NNLO}} = 54.2^{+0.5}_{-0.2}\ \mathrm{pb}$$

(μ_R=μ_F= {m_t/2, m_t, 2 m_t})

- Still delicate interplay/cancellations between different channels -> important to consistently compute corrections to all of them
- Result very close to the NLO (-1.6%), reduced μ dependence -> good theoretical control
- μ dependence dominated by factorization scale (larger scale -> more b)

Single-top @ NNLO: more differential observables

$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
0 GeV	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	$+2.4\%$	$54.2^{+0.5}_{-0.2}$	-1.6%
20 GeV	$46.6^{+2.5}_{-3.7}$	$48.9^{+1.2}_{-0.5}$	$+4.9\%$	$48.3^{+0.3}_{-0.02}$	-1.2%
40 GeV	$33.4^{+1.7}_{-2.5}$	$36.5^{+0.6}_{-0.03}$	$+9.3\%$	$36.5^{+0.1}_{+0.1}$	-0.1%
60 GeV	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	$+13.6\%$	$25.4^{-0.1}_{+0.2}$	$+1.6\%$



- Contrary to NLO, results stable in the full spectrum
- Scale dependence typically improved
- K-factor is small but not constant

Very similar results for anti-top

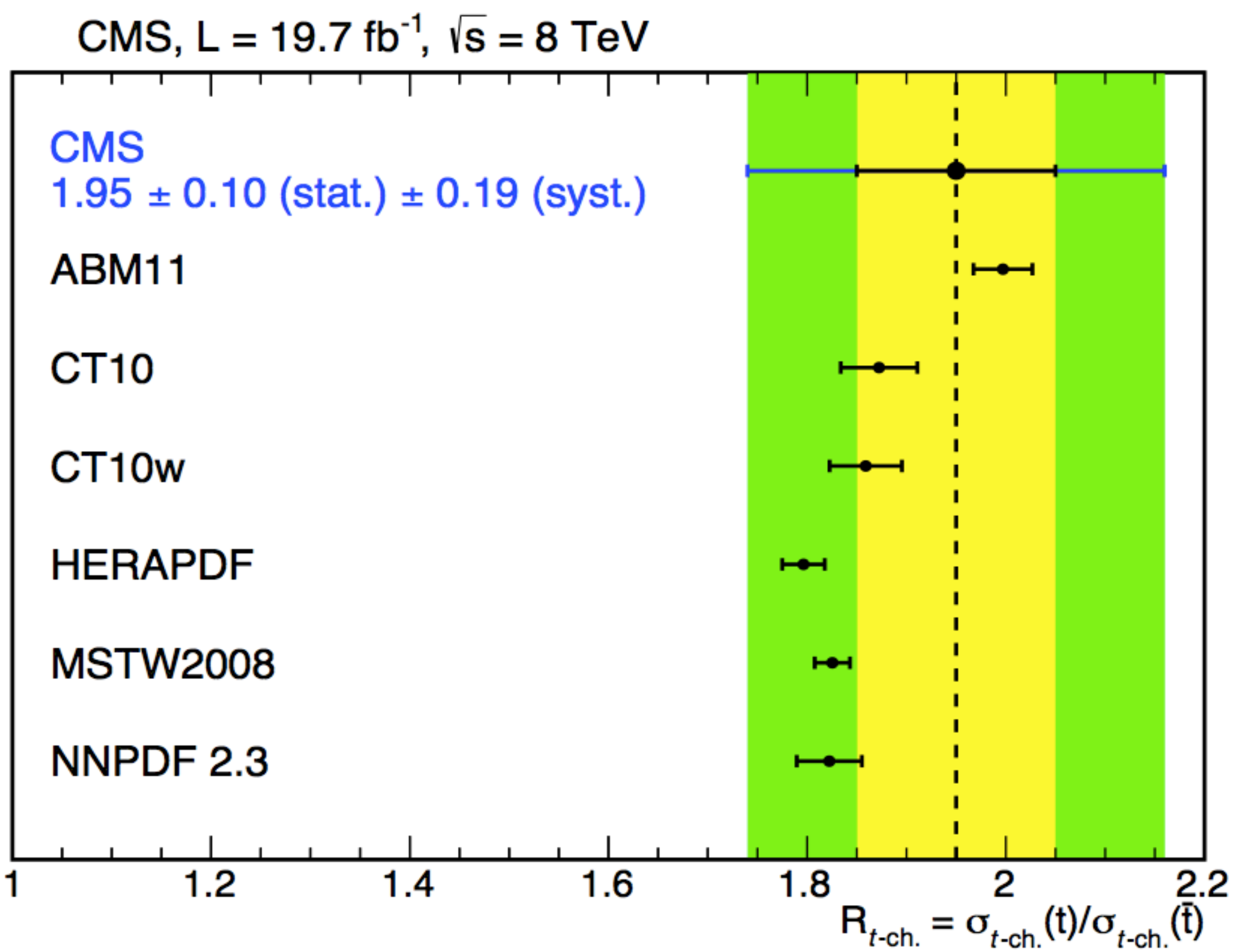
$$\sigma_{\mathrm{NNLO},\bar{t}} = 29.7^{+0.3}_{-0.1}\ \mathrm{pb}$$

$p_\perp$	σ_{LO}, pb	σ_{NLO}, pb	δ_{NLO}	σ_{NNLO}, pb	δ_{NNLO}
0 GeV	$29.1^{+1.7}_{-2.4}$	$30.1^{+0.9}_{-0.5}$	$+3.4\%$	$29.7^{+0.3}_{-0.1}$	-1.3%
20 GeV	$24.8^{+1.4}_{-2.0}$	$26.3^{+0.7}_{-0.3}$	$+6.0\%$	$26.2^{-0.01}_{-0.1}$	-0.4%
40 GeV	$17.1^{+0.9}_{-1.3}$	$19.1^{+0.3}_{+0.1}$	$+11.7\%$	$19.3^{-0.2}_{+0.1}$	$+1.0\%$
60 GeV	$10.8^{+0.5}_{-0.7}$	$12.7^{+0.03}_{+0.2}$	$+17.6\%$	$12.9^{-0.2}_{+0.2}$	$+1.6\%$

- NLO corrections slightly larger, NNLO very similar
- Slightly larger scale variation w.r.t top, NLO scale variation accidentally small

top/anti-top ratio very stable

8 TeV LHC, MSTW2008, m_t = 173.2 GeV



$$\sigma_{t,\mathrm{LO}}/\sigma_{\bar{t},\mathrm{LO}} = 1.85$$

$$\sigma_{t,\mathrm{NLO}}/\sigma_{\bar{t},\mathrm{NLO}} = 1.83$$

$$\sigma_{t,\mathrm{NNLO}}/\sigma_{\bar{t},\mathrm{NNLO}} = 1.83$$

No substantial modification w.r.t. NLO

t-channel@NNLO: what's next

NNLO is ready for serious phenomenology

Easy to do:

- complete error estimates (PDF, μ_R/μ_F)
- m_b effects from PDF evolution
- 7/8/13 TeV ratios
- run with fiducial cuts on the reconstructed top system
- differential distributions at the reconstructed level?

Known in principle (but some work involved):

- interface with top decay in the NWA
- decay@NNLO is known [Gao, Li, Zhu (2012); BCM (2013)]
- realistic final state description@NNLO

A step towards reality: top decay

Top quark decay in single-top predictions

- Top: narrow resonance, decay before hadronization
- To reduce reconstruction biases, it is important to properly include top decay in the theory prediction
- From tt studies, we know consistent treatment of QCD corrections for production and decay is important

- Full computation of pp->WbX much more complicated than pp -> tX
- However, $\Gamma_t/m_t \ll 1$, so (for inclusive enough observables) the situation can be significantly simplified by using the narrow-width-approximation
  - QCD corrections to production/decay do not talk
  - Still, full spin information is retained
  - Error of the NWA parametrically suppressed by Γ_t/m_t [Fadin, Khoze, Martin (1994)]

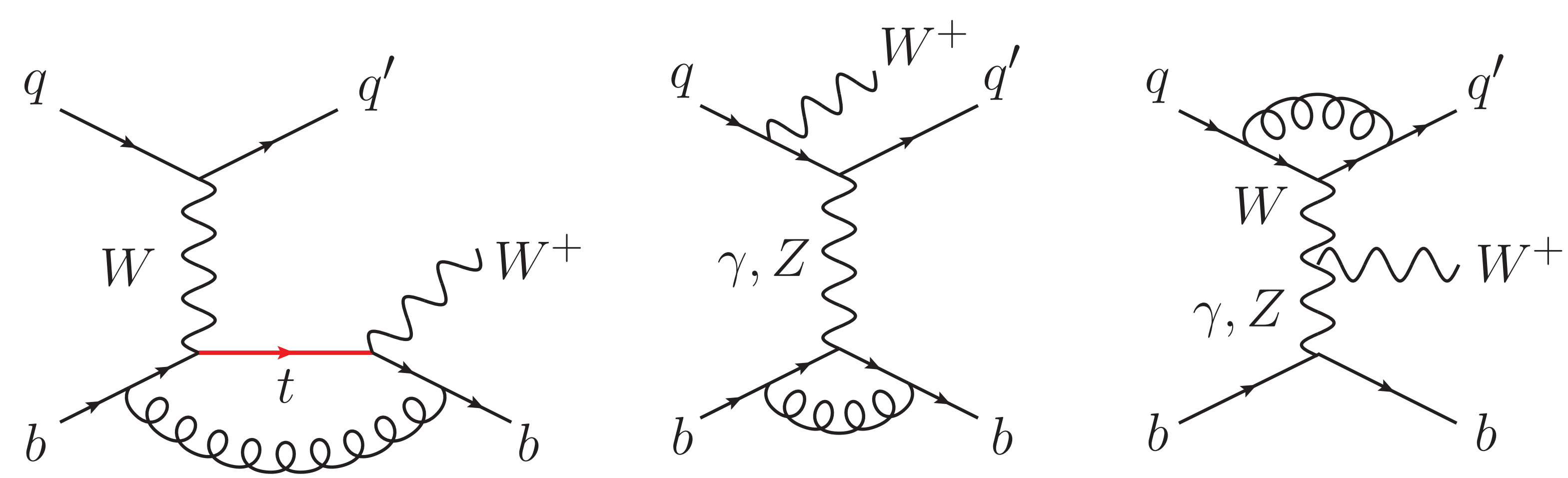
Validating the NWA

For benchmark process (t-channel single top), we now have the tools for validating the NWA at NLO

[First pioneering studies: s-channel, Pittau (1996)]

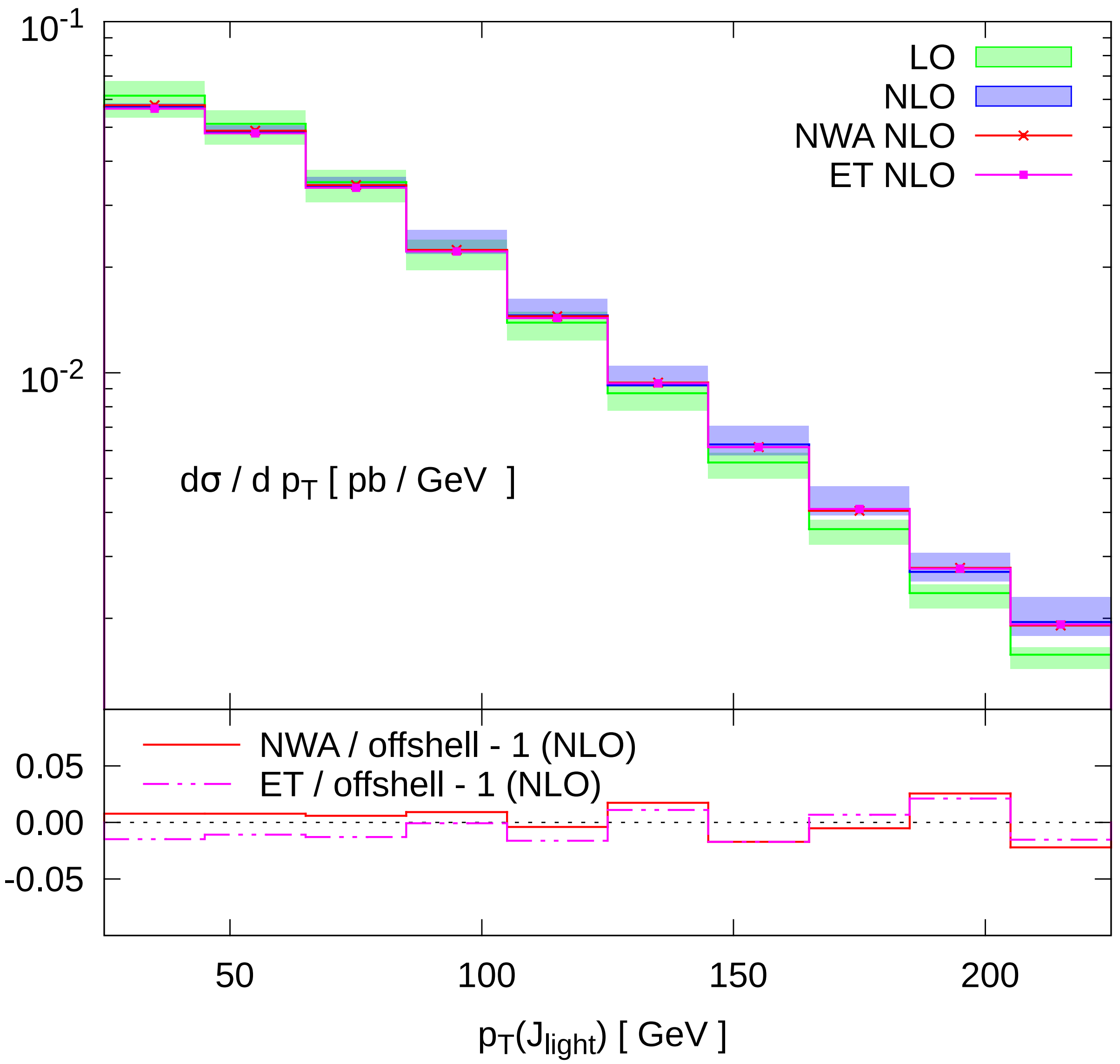
Three increasingly accurate predictions for single top @ NLO

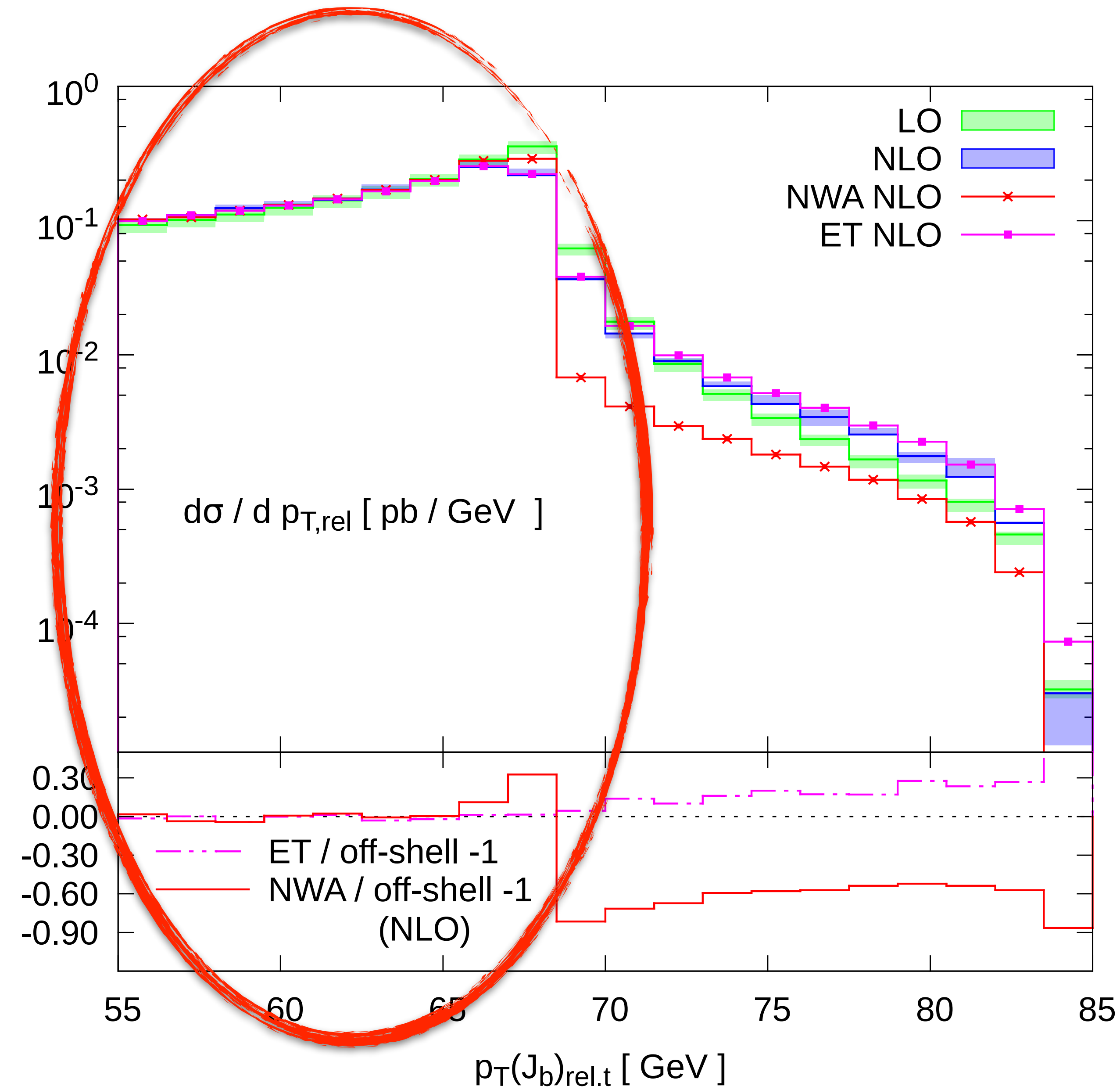
- NWA, NLO in production and decay, $p_t^2 = m_t^2$
  [Campbell, Ellis (2012)]
- EFT for top decay: $p_t^2 \sim m_t^2$
  [Falgari, Mellor, Signer (2010)]
- Full off-shell effects, ~Wbj final state, p_t^2 generic
  [Papanastasiou, Frederix, Frixione, Hirschi, Maltoni (2013)]



How well does the NWA work?

In general, the NWA works extremely well, as expected



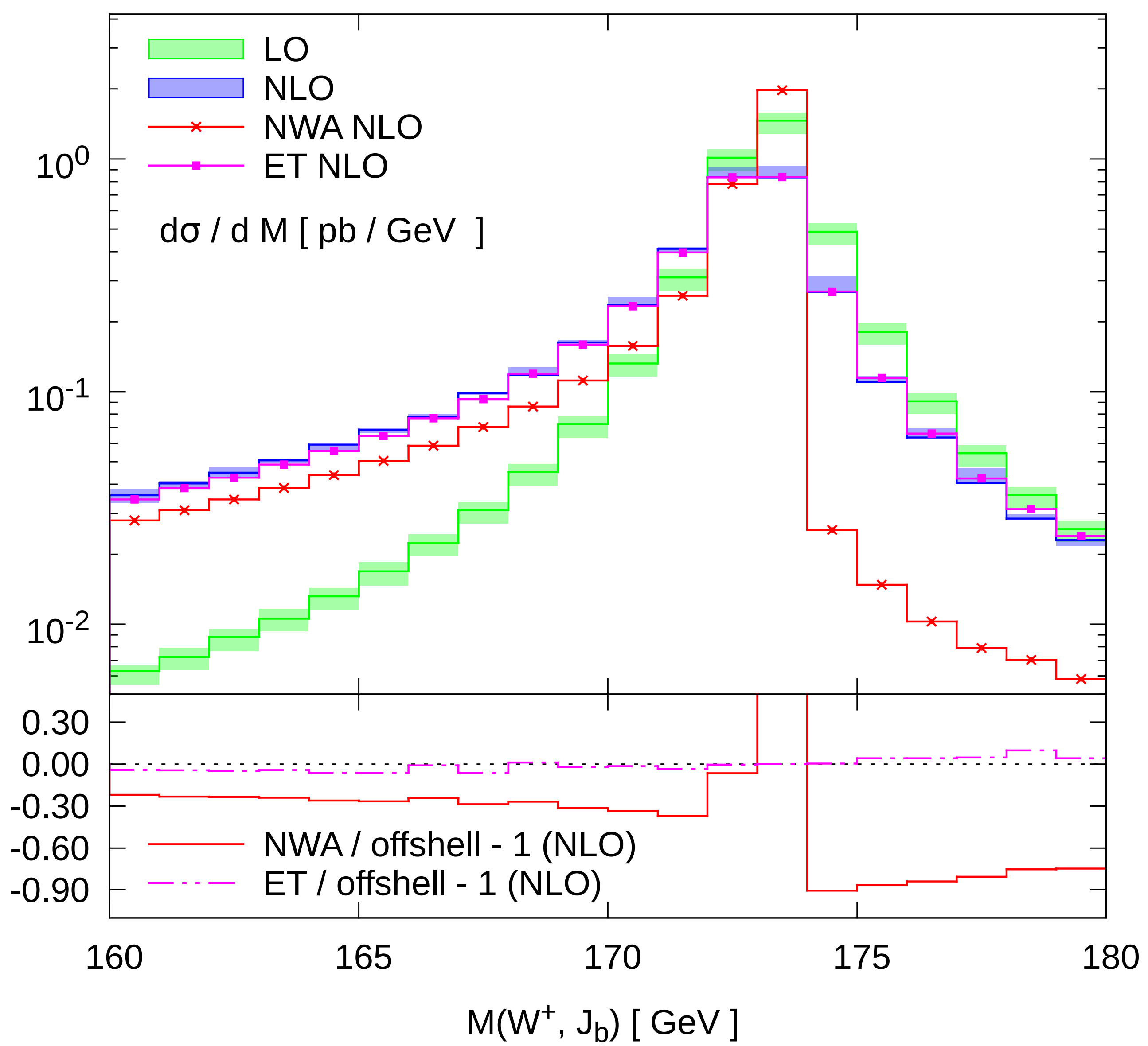


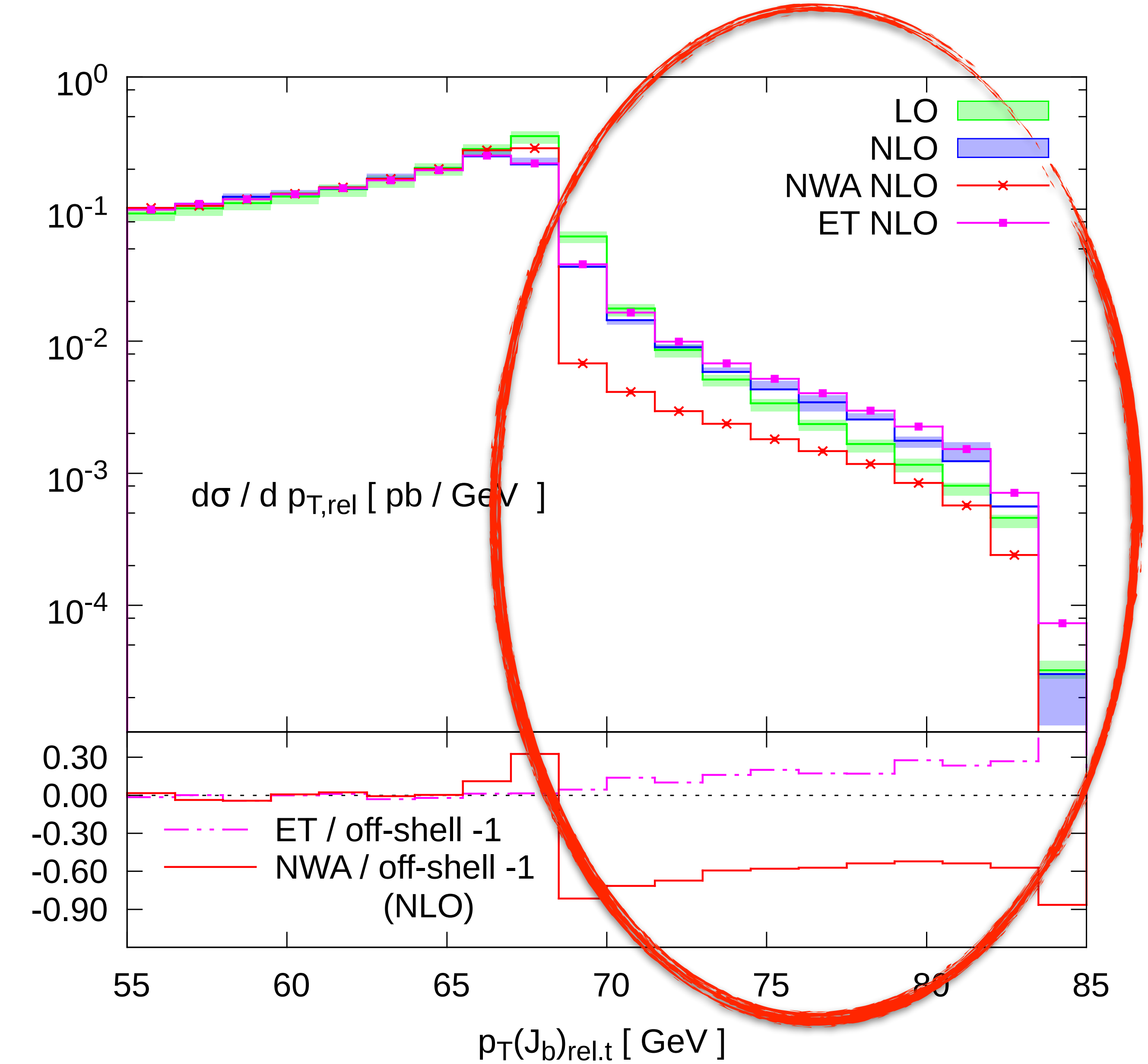
[Papanastasiou, Frederix, Frixione, Hirschi, Maltoni (2013)]

However, be careful

By definition, NWA is not supposed to work:

- for observables sensitive to M_{Wb}
- beyond kinematics edges





And indeed it does not

Top decay, recap:

Thanks to advances in NLO tools, one can validate the NWA approximation on benchmark processes -> WORKS EXACTLY AS EXPECTED

Pioneering studies [s-channel, Pittau (1996)] confirmed

[Papanastasiou, Frederix, Frixione, Hirschi, Maltoni (2013)]

Can confidently use NWA to compute (parton level) predictions with realistic final states for complicated processes

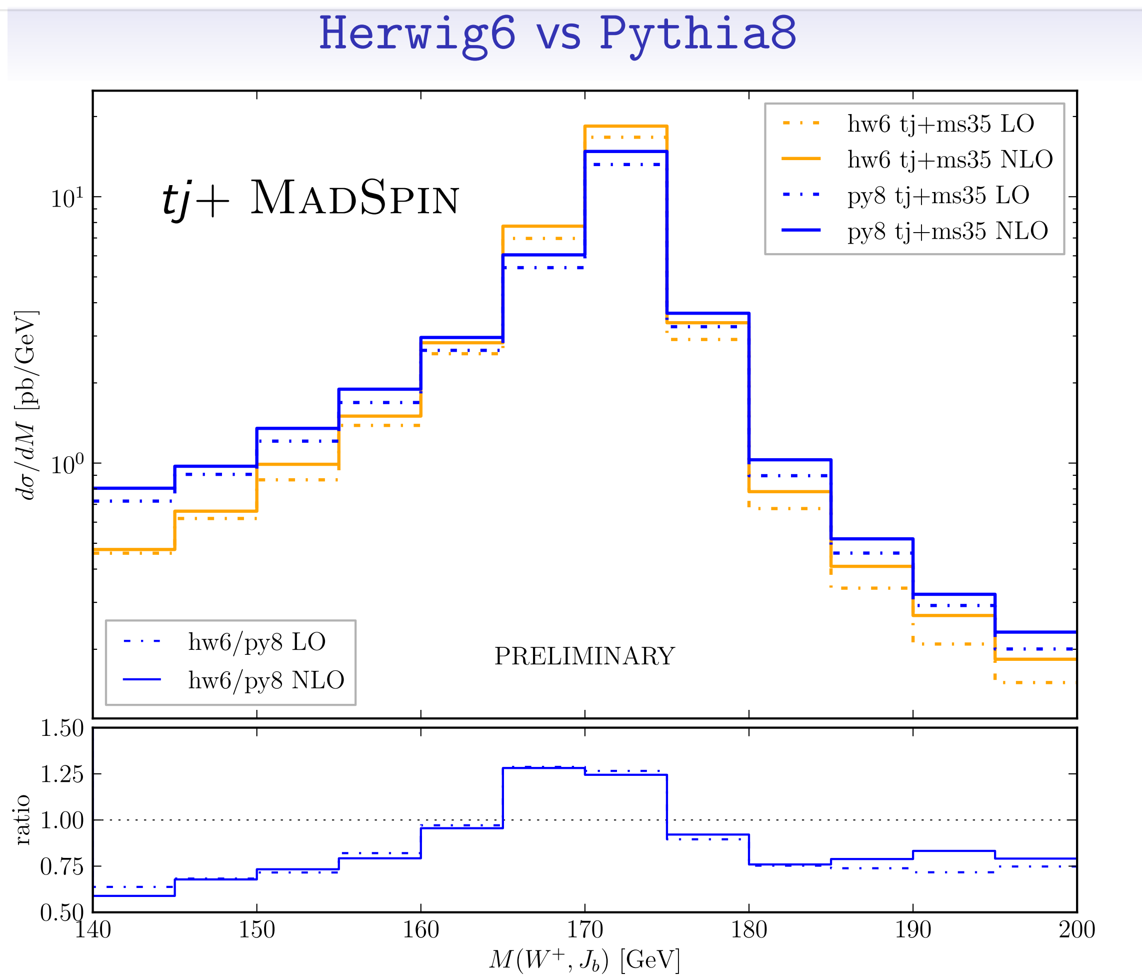
- NNLO
- single-top + X (see e.g. arXiv1302.3856 and talk on Thusrday)

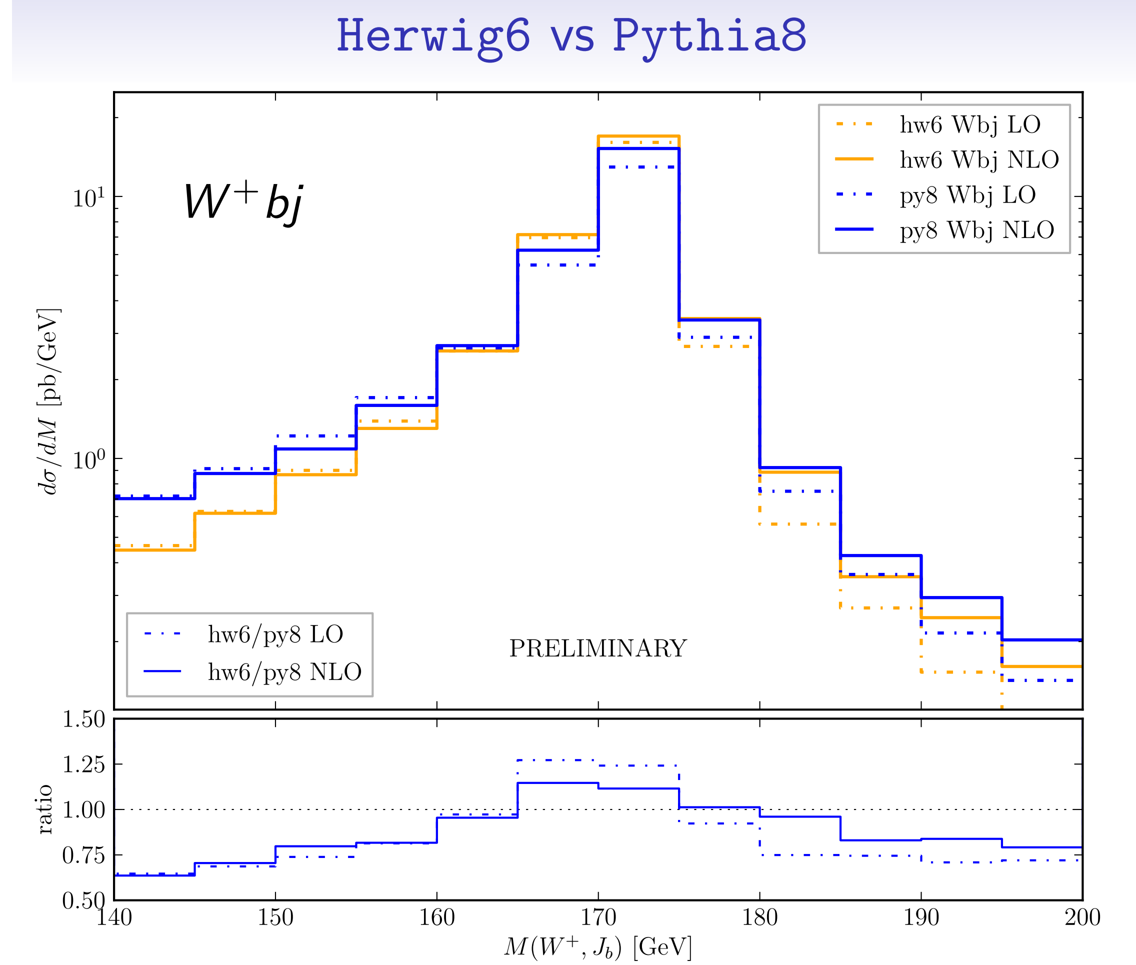
If NWA is not supposed to work for your observable:

- EFT seems to work pretty well
- NLO tools could provide full predictions in the near future

Top decay: interfacing with PS

- Ideally, one wants hadron-level results
- PS with decaying resonances seems tricky
  [see e.g. Stefan Prestel's talk at this conference pre-meeting]





[A. Papanastasiou, TOP LHC WG meeting]

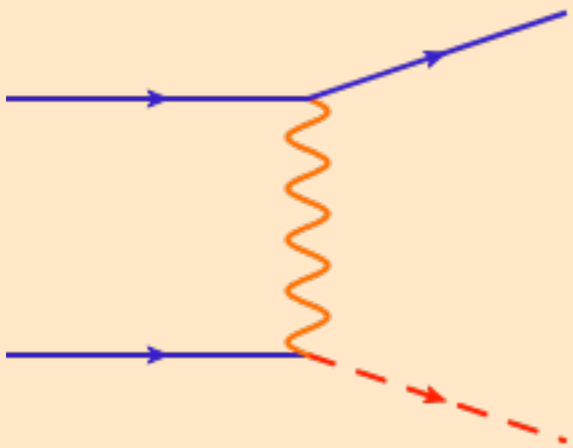
ONGOING WORK, STAY TUNED!

Wt vs WWbb

[see also J. Winter's talk this afternoon]

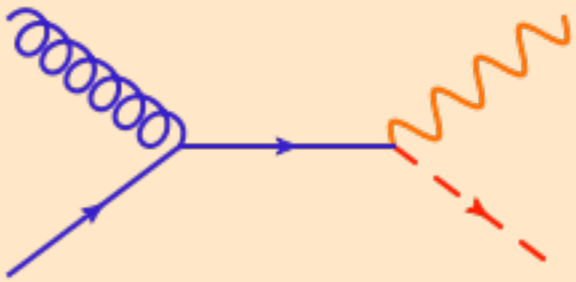
The classical picture: 3 production mechanism

T-CHANNEL



LHC8: ~ 82%
TEV: ~ 65%

ASSOCIATED PRODUCTION



LHC8: ~ 15%
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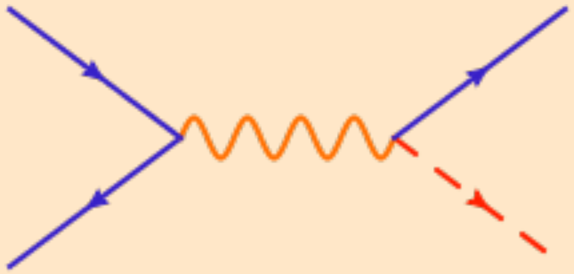
S-CHANNEL

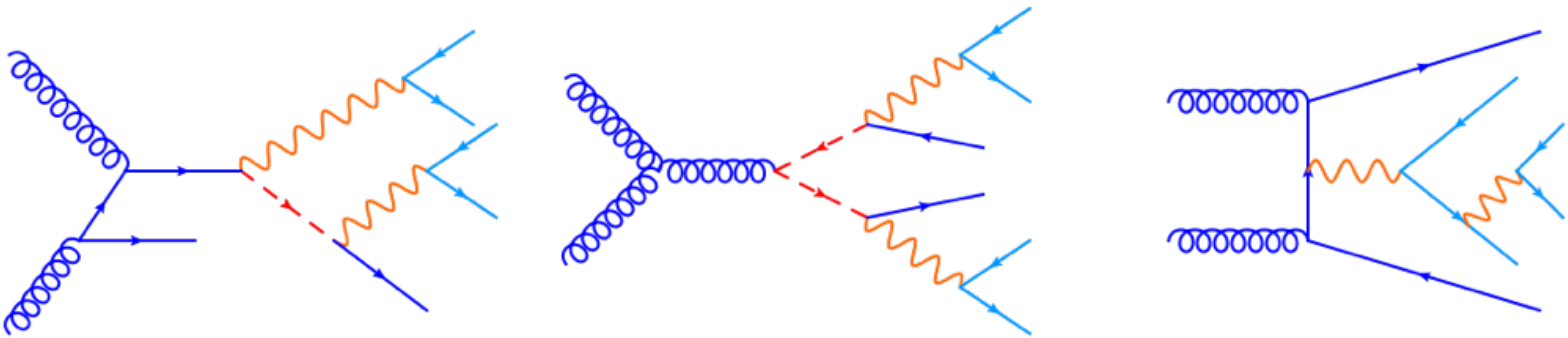


LHC8: ~ 5%
TEV: ~ 33%

Is there ACTUALLY a problem with this picture?

Yes: Wt vs WWbb

Already at NLO, Wt, ttbar and 'background' share the same initial/final states -> interferences, cannot be separated



If you want to consider massive b (good reasons to do it) and work in the 4FNS -> LO problem

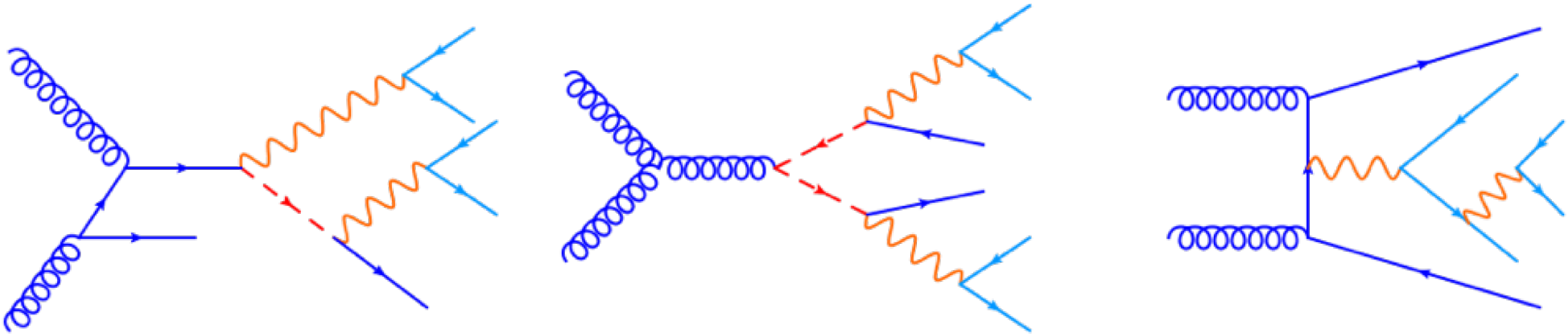
In the past, full computation was out of question -> must cook up some add-hoc recipe to deal with it (DR, DS, PR…)

NONE OF THEM IS THEORETICALLY FULLY SOUND

Wt and tt: unified description

Thanks to modern tools the full (very hard) NLO computation with massive b is now doable

[Frederix (2013), Cascioli, Maierhoefer, Kallweit, Pozzorini (2013)]

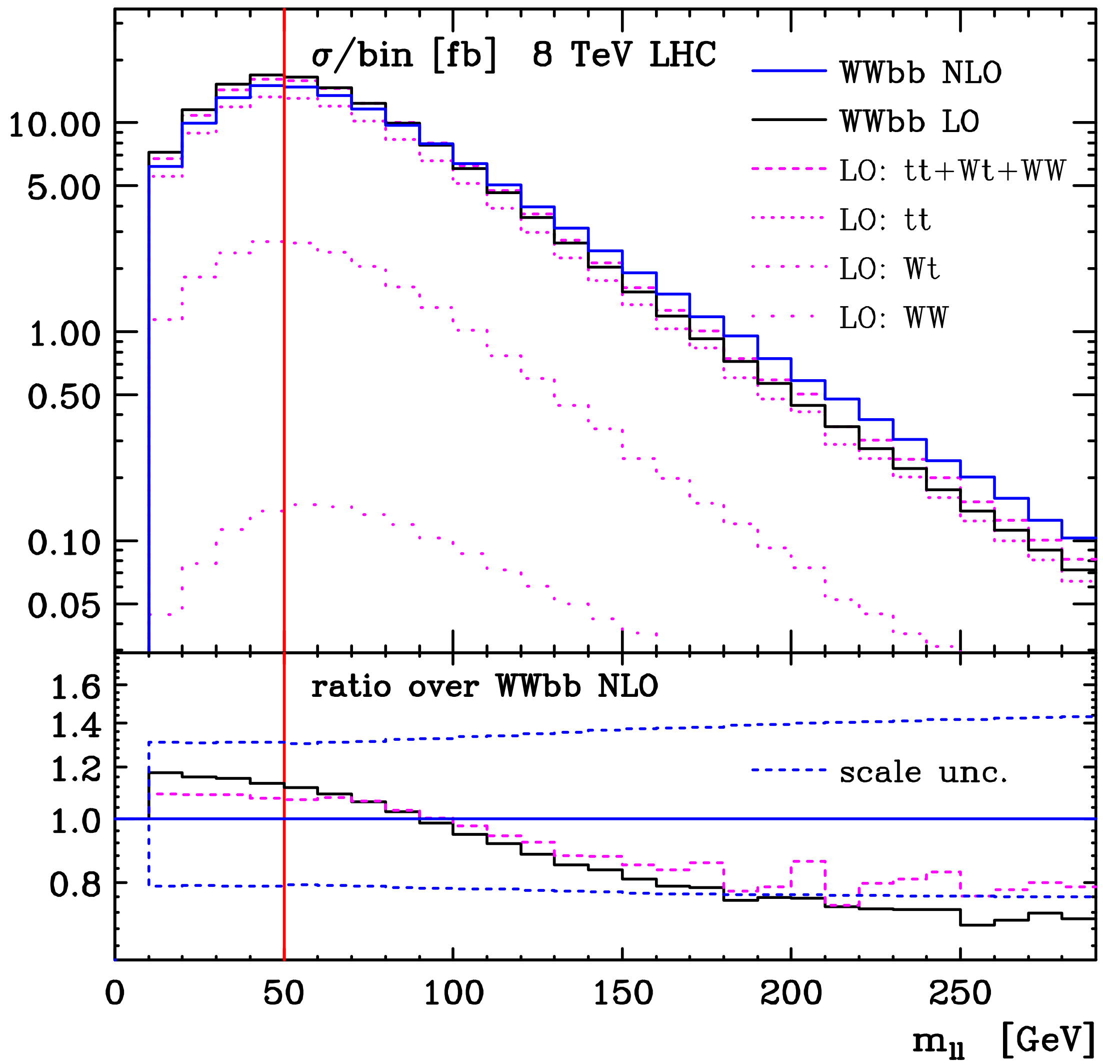


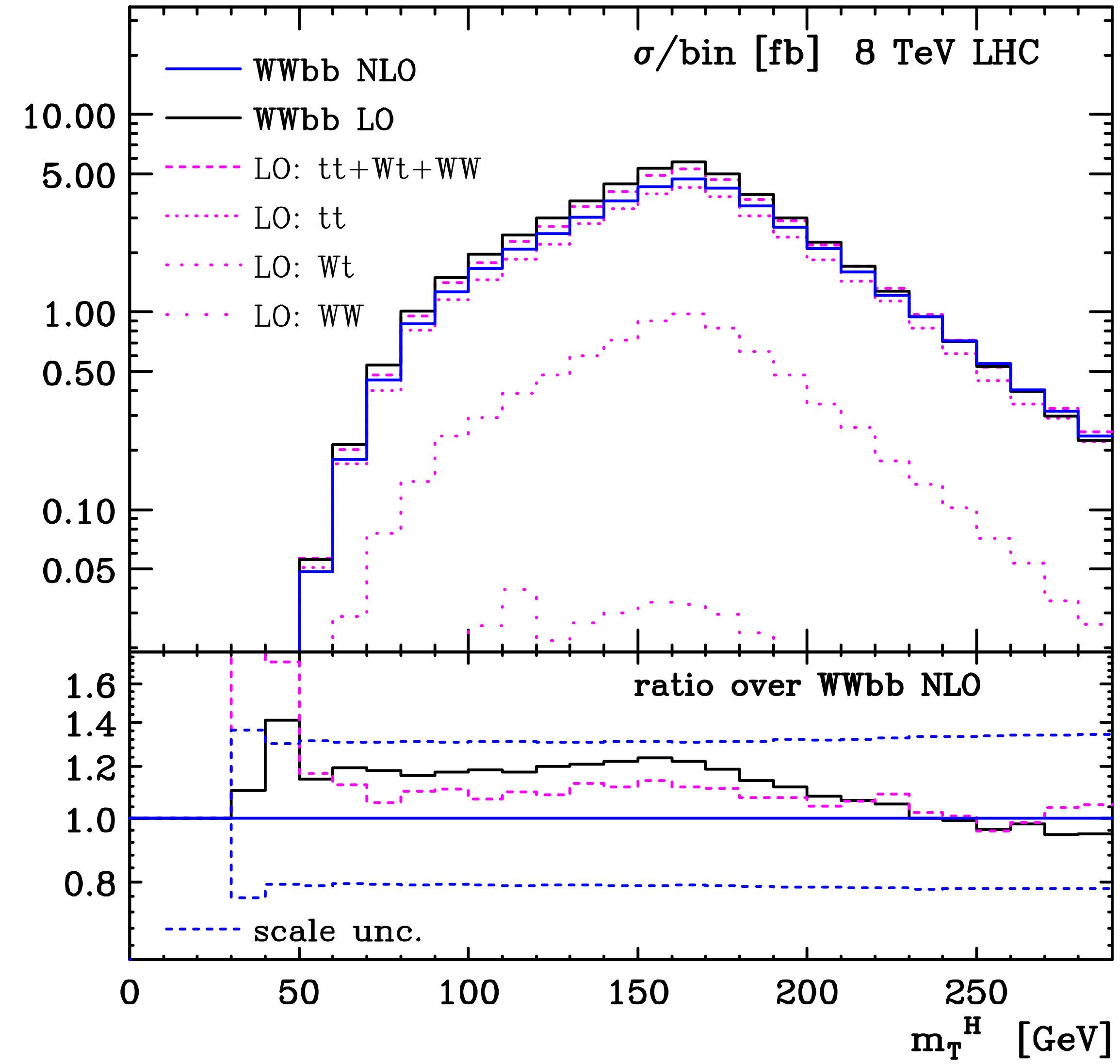
- There is no need (nor reason) to use old strategies any more
- Wt: single resonant contribution of the full process -> enhanced/suppressed with specific cuts
- Again, matching with PS is subtle (under investigation)

Example: Wt/tt as background for H->WW

[Frederix (2013), MadGraph5/aMC@NLO]

- H->WW, 1-jet bin, ATLAS cuts
- ‘Large tt background, ~20% Wt’ -> same process





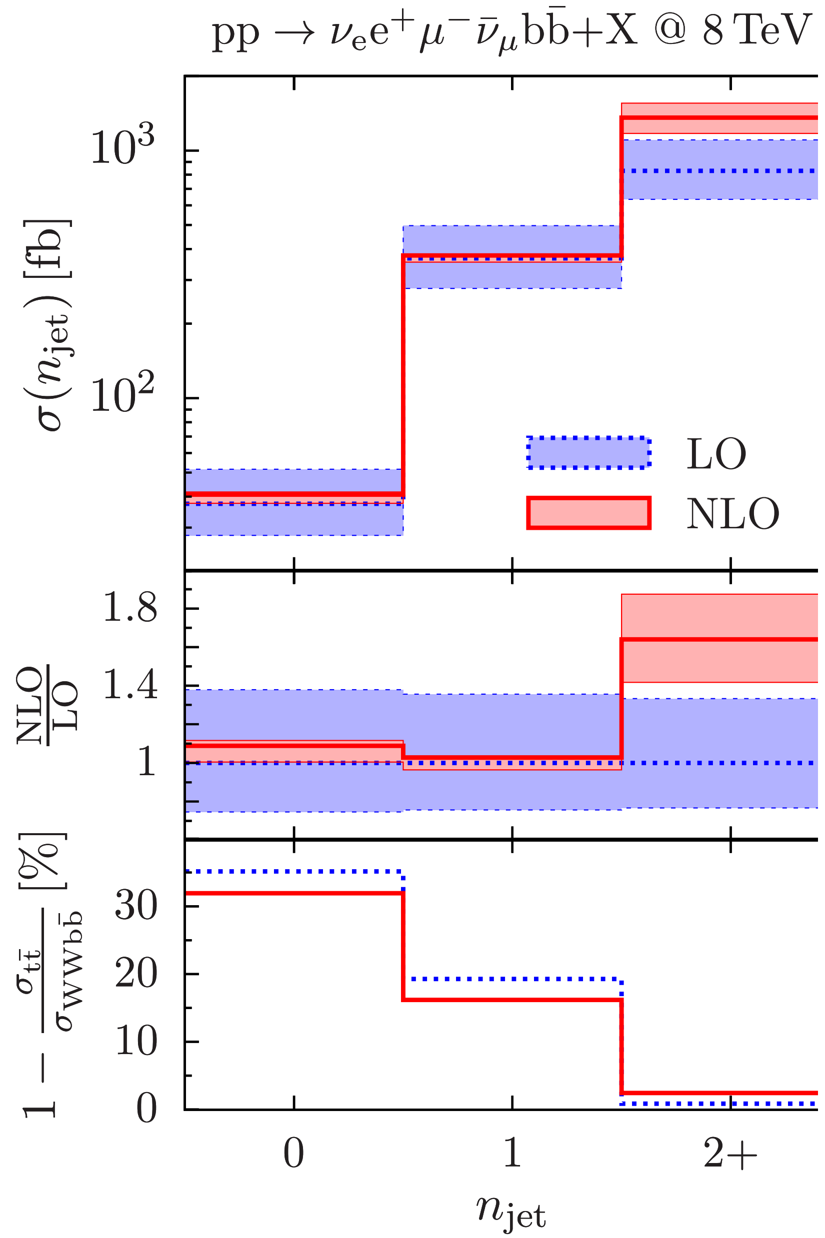
m_{ll}: shape distortion @ NLO

Interferences smaller than NLO, but non-trivial shape

Example: separating tt

[Cascioli, Maierhoefer, Kallweit, Pozzorini (2013), OpenLoops]

Theoretically sound procedure to remove NWA tt contribution from Wt/off-shell effects



NLO(LO) 4F NNPDFSs, $p_{\mathrm{T},j} = 30\,\mathrm{GeV}$

- Non tt effects very jet-bin dependent, concentrated in the 0/1 jet bins
- Large in phase space regions with unresolved b-quarks
- Non tt effects perturbatively stable
- Nice interplay of NLO / Wt and off shell effects

Conclusions

Advances in theory and phenomenology bring predictions closer and closer to experimental reality

- Precision -> fully differential NNLO
  - Corrections as large as NLO on the total rate
  - Differential K-factor non trivial shape, but small
  - Will be interesting to let the top decay (and PS…)
- Realistic final states -> top decay
  - NWA validated by dedicated benchmark computations
  - For simple processes, can go beyond NWA if needed
  - Conceptual work needed for proper PS matching
- Artificial distinctions no longer needed -> Wt vs WWbb
  - Unified description for top as background
  - Theoretically correct separation of tt
  - Again, improvements needed for PS

Thank you for
your attention!