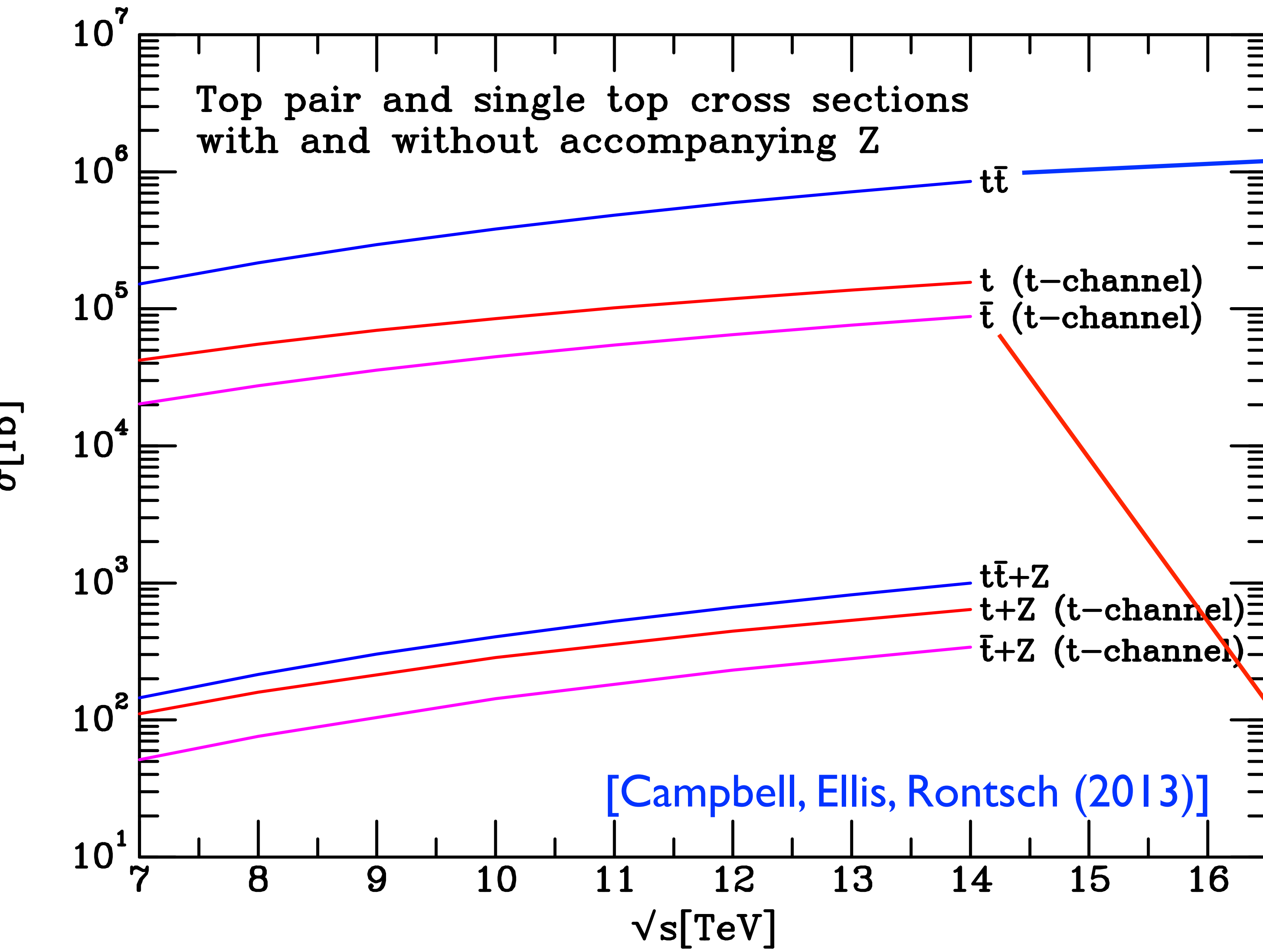
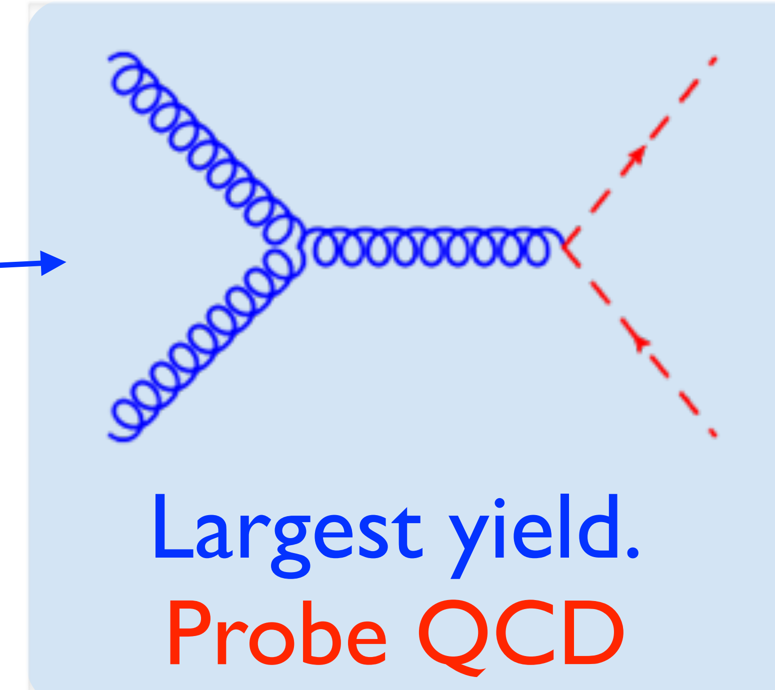
(Some) recent advances in single-top theory

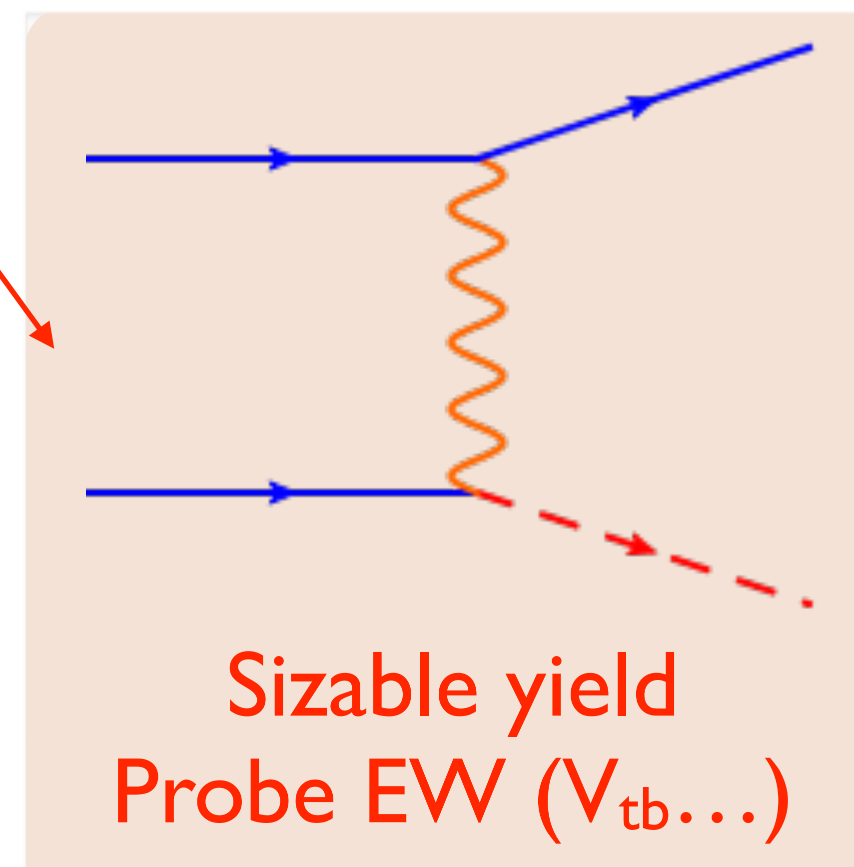
Fabrizio Caola, CERN

2ND CMS SINGLE-TOP WORKSHOP, NAPOLI, DEC. 4TH 2014

LHC as a top factory







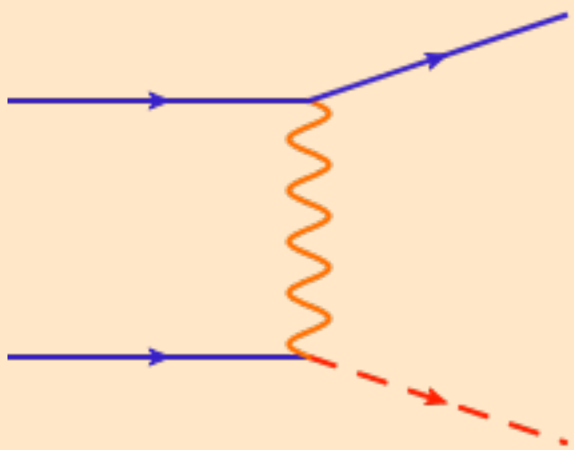
Single-top@LHC: PRECISION PHYSICS

- Complementary w.r.t. top pair
- Associated production within reach

The price of precision

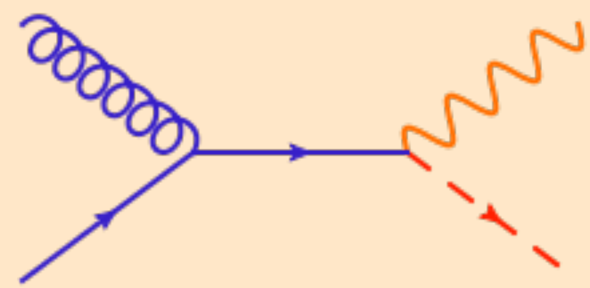
Classical picture: 3 production mechanism

T-CHANNEL



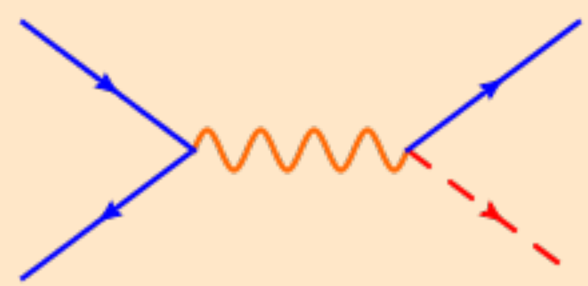
LHC8: ~ 82%

ASSOCIATED PRODUCTION



LHC8: ~ 15%

S-CHANNEL



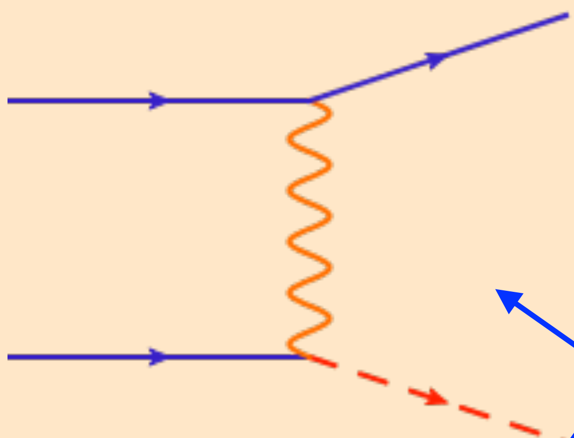
LHC8: ~ 5%

With stable tops and at tree-level:
clear separation / hierarchy among different channels

The price of precision

Mixing at the quantum level

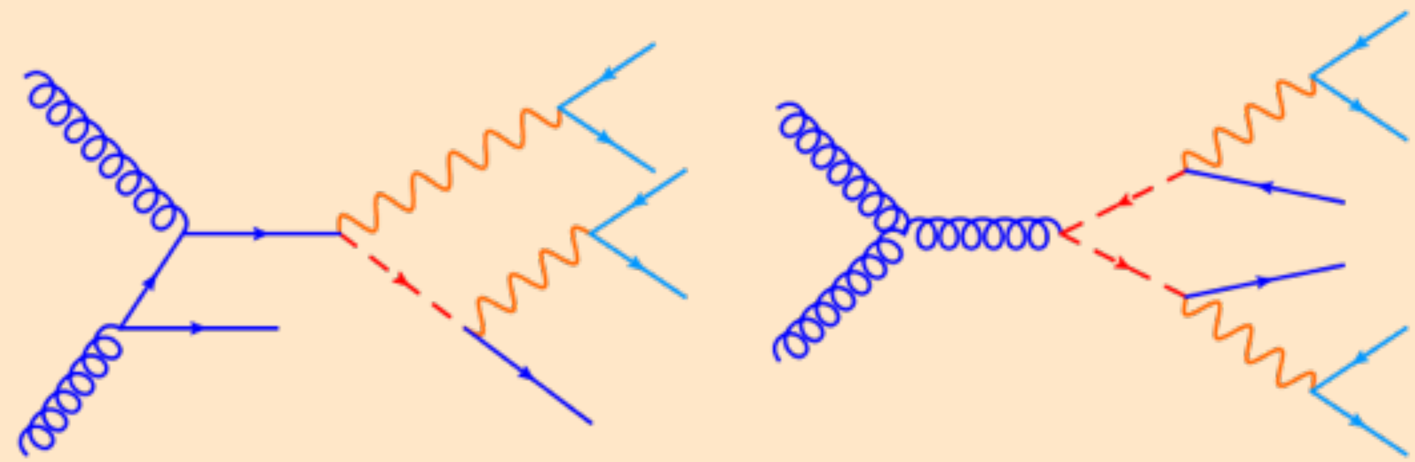
T-CHANNEL



LHC8: ~ 82%

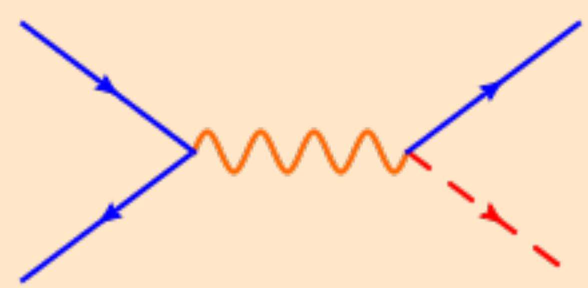
INTERFERENCE

ASSOCIATED PRODUCTION



SAME FINAL STATE OF TOP-PAIR

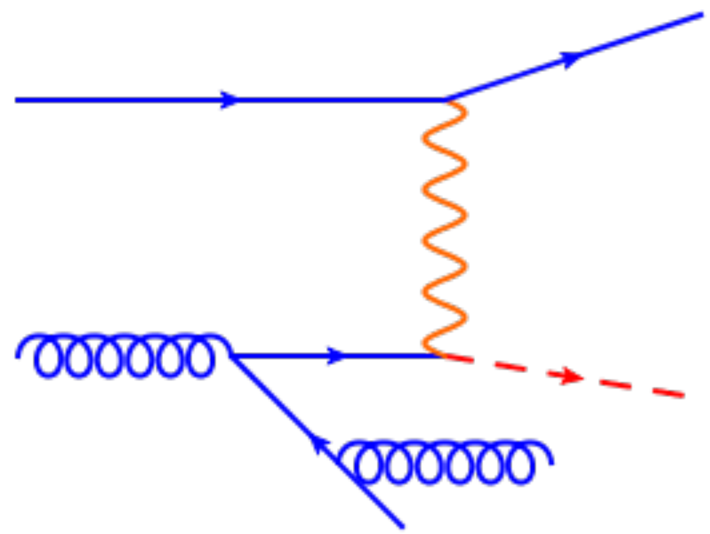
S-CHANNEL



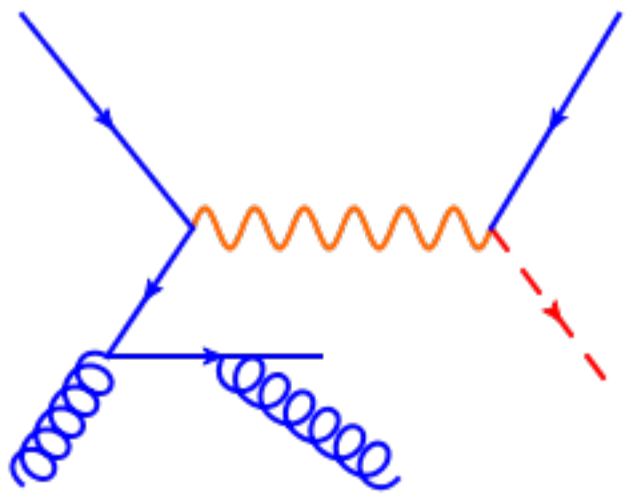
LHC8: ~ 5%

Rigid separation: good for the old ‘pioneering’ days, must be taken with care for precision physics

t- vs s- channels: it still makes sense



vs



In principle:

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

However in practice:

- thanks to color, 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:

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

NAIVELY:

"Small ~ 2% corrections, no need to go further"

If 'genuine' NLO corrections are at the percent level:

- NNLO in the per-mill range
- Irrelevant w.r.t. other sources of uncertainties (PDFs, m_b, m_t…)

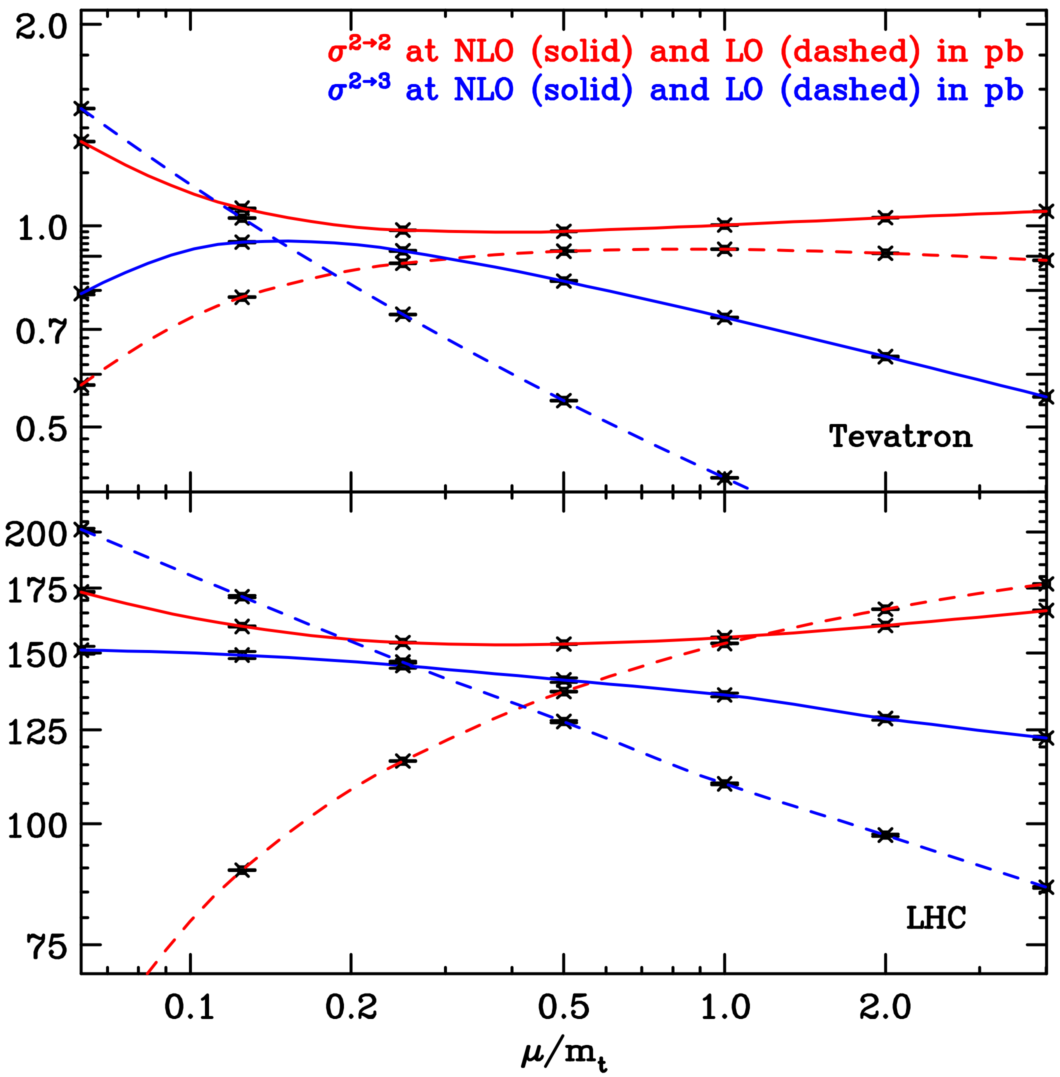
HOWEVER…

T-channel single top: do we need NNLO?

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

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

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



[Campbell et al (2009)]

- Scale variation (-> h.o. est.) similar to corrections
- ~ percent difference between 4FNS/5FNS calculations

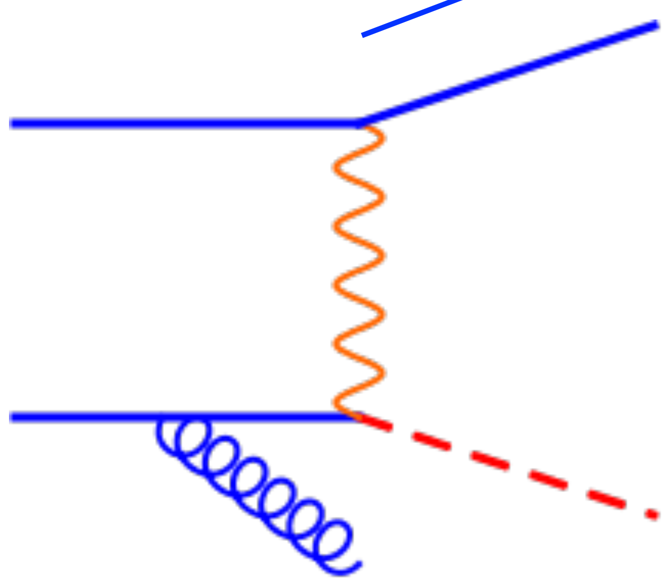
Residual perturbative uncertainty at the percent-level

t-channel single top: do we need NNLO?

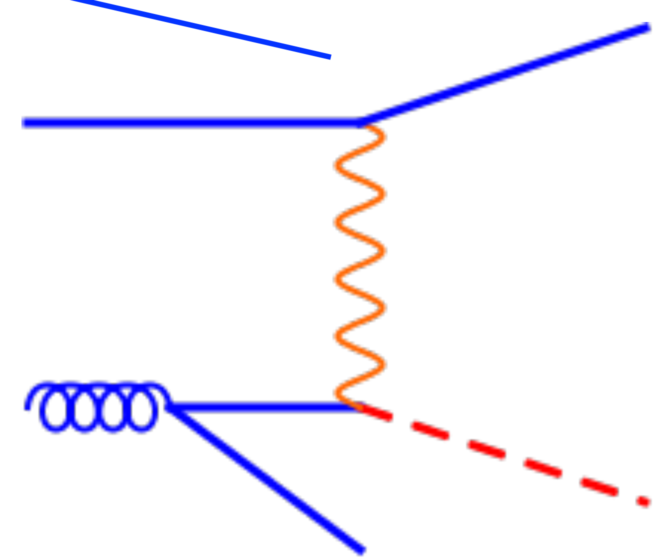
'Typical' NLO corrections are much more ~10%

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

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



+12%



-14%

Large cancellations among channels

(beware of approximations only considering one channel)

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

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

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

- 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. Colorful 2->2 has been achieved (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

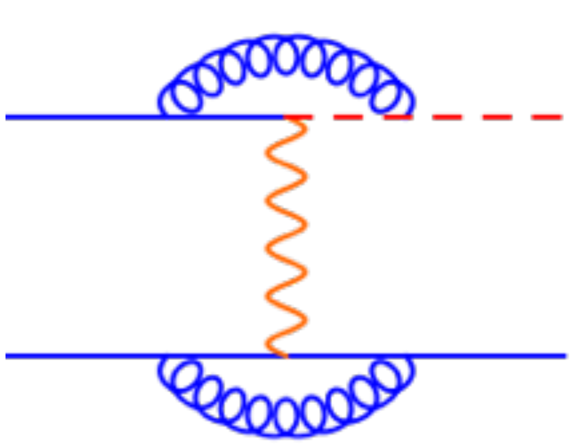
Recent developments in NNLO techniques, allowed us to compute (almost) t-channel single-top corrections.

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 -> fiducial region)
- For now, top is stable but in principle possible to implement top decay in the NWA with full spin correlation (polarization studies…)

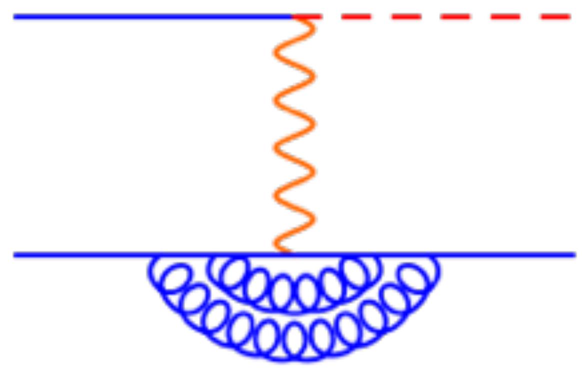
Single-top in the 'factorized' approximation

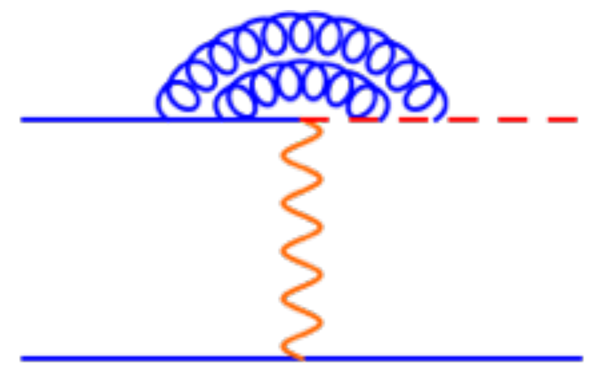
Two-loop amplitudes:



Trivial (~NLO^2)

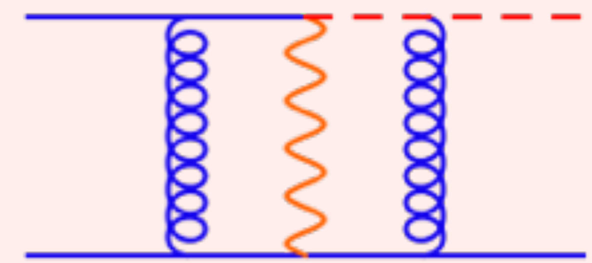
Simple





~OK

(very) hard



Preliminary investigations:
[Uwer et al (2014)]

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

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

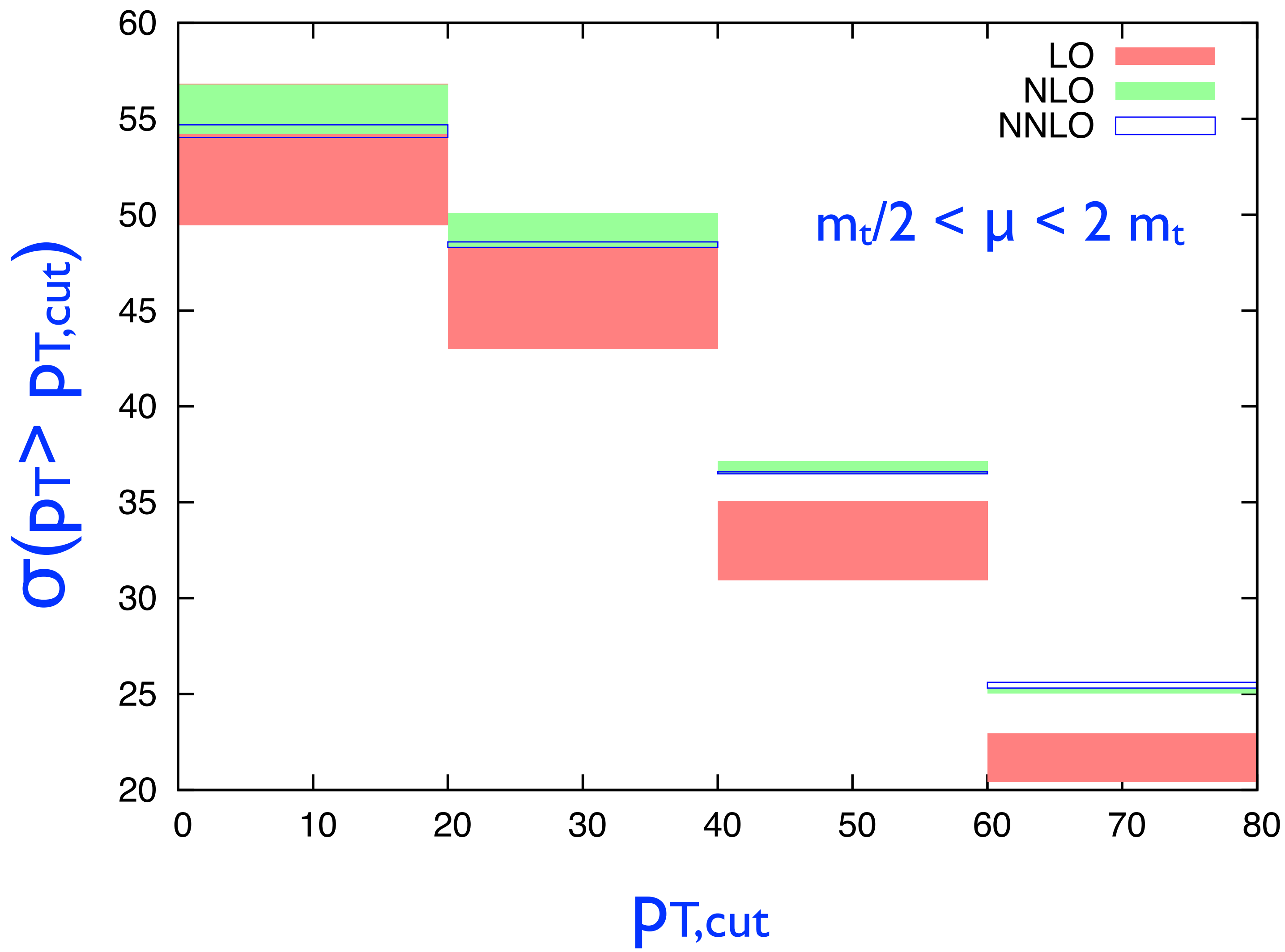
$$\sigma_{\mathrm{NNLO}} = 54.2^{+0.5}_{-0.2}\ \mathrm{pb}$$

($\mu_R = \mu_F = \{m_t/2, m_t, 2\, m_t\}$)

- 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
- For some cuts, slightly larger scale variation w.r.t top, NLO scale variation can be accidentally small (fake result from channel cancellations)

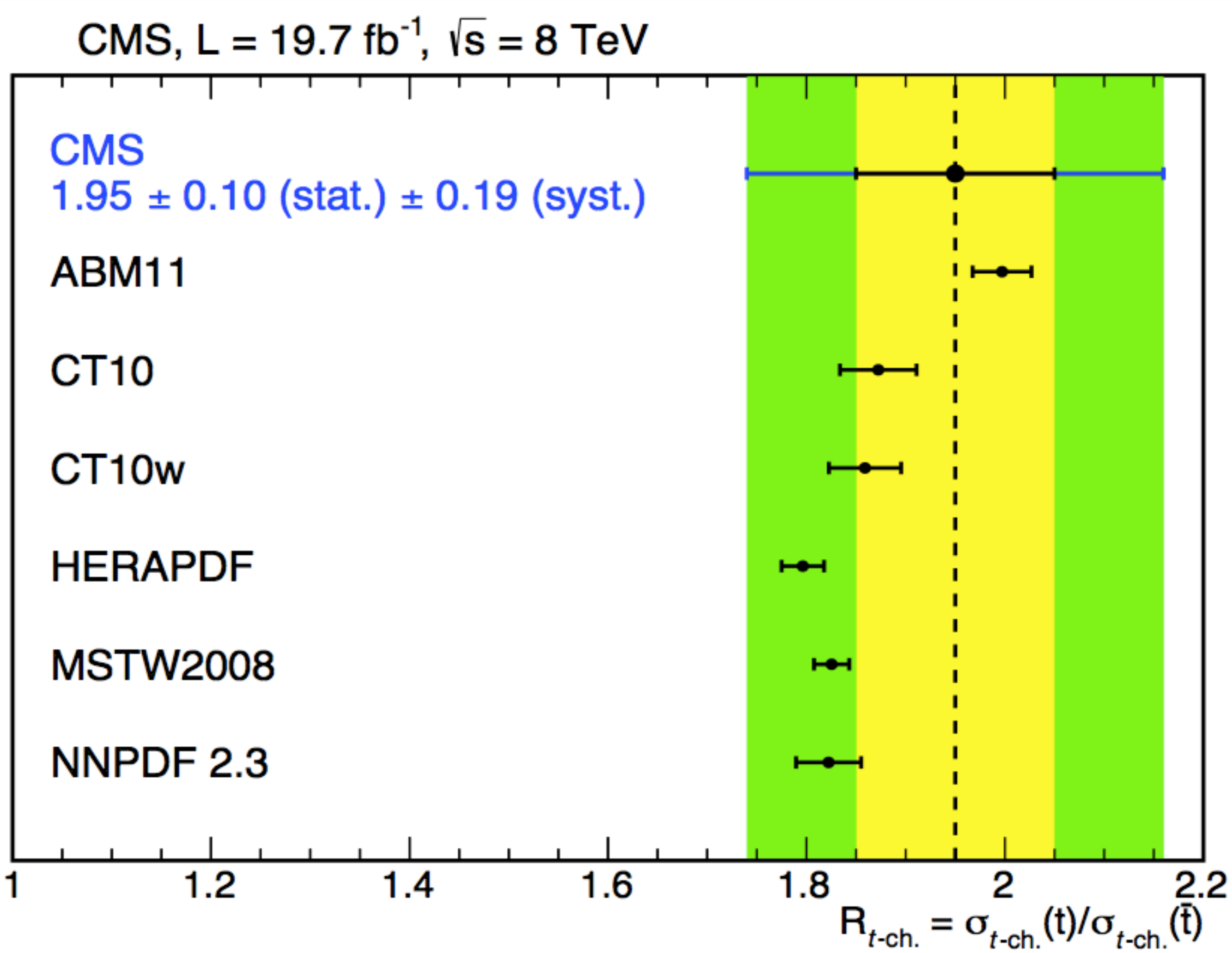
Single-top total cross section, NNLO QCD

8 TeV LHC, MSTW2008, m_t = 173.2 GeV

$$\sigma^{\rm NLO}_{t+\bar{t}} = 85.2^{+2.5}_{-1.4}\ {\rm pb}, \qquad \sigma^{\rm NNLO}_{t+\bar{t}} = 83.9^{+0.8}_{-0.3}\ {\rm pb} \qquad ({\rm scale\ only})$$

$$\sigma^{\rm ATLAS}_{t+\bar{t}} = 82.6 \pm 1.2\ ({\rm stat.}) \pm 11.4\ ({\rm syst.}) \pm 3.1\ ({\rm PDF}) \pm 2.3\ ({\rm lumi})$$

$$\sigma^{\rm CMS}_{t+\bar{t}} = 83.6 \pm 2.3\ ({\rm stat.}) \pm 7.4\ ({\rm syst.}){\rm pb}$$



top/anti-top ratio very stable

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

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

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

No substantial modification w.r.t. NLO -> handle on PDF?

t-channel@NNLO: what's next

NNLO is ready for serious phenomenology

Easy to do (=*almost* only computer time):

- 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
Study parton without worrying about hadronization
Great playground for perturbative QCD

Predictions including decay: pro

- To reduce reconstruction biases, it is important to properly include top decay in the theory prediction
- Top characterization (helicity fraction, polarization…)
- From tt studies, we know consistent treatment of QCD corrections for production and decay is important

Predictions including decay: contra

- COMPUTING pp->WbX MUCH HARDER THAN pp -> tX

Top quark decay in single-top predictions

A compromise: decay in the Narrow Width Approximation

Physics intuition: $\Gamma_t/m_t << 1$, so
QCD corrections to production / decay do not talk
Factorized approach, NWA

Advantages of the NWA

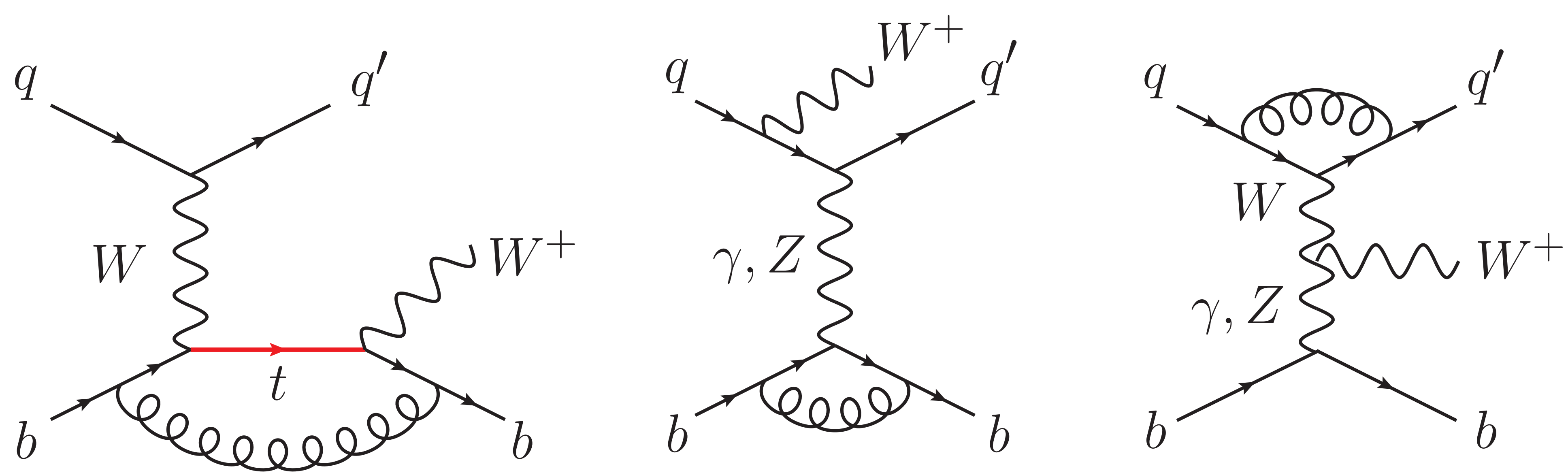
- Production/decay separated -> computations much easier
- Still, full spin information is retained
- For inclusive enough observables, error of the NWA parametrically suppressed by Γ_t/m_t [Fadin, Khoze, Martin (1994)]

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)]

Validating the NWA

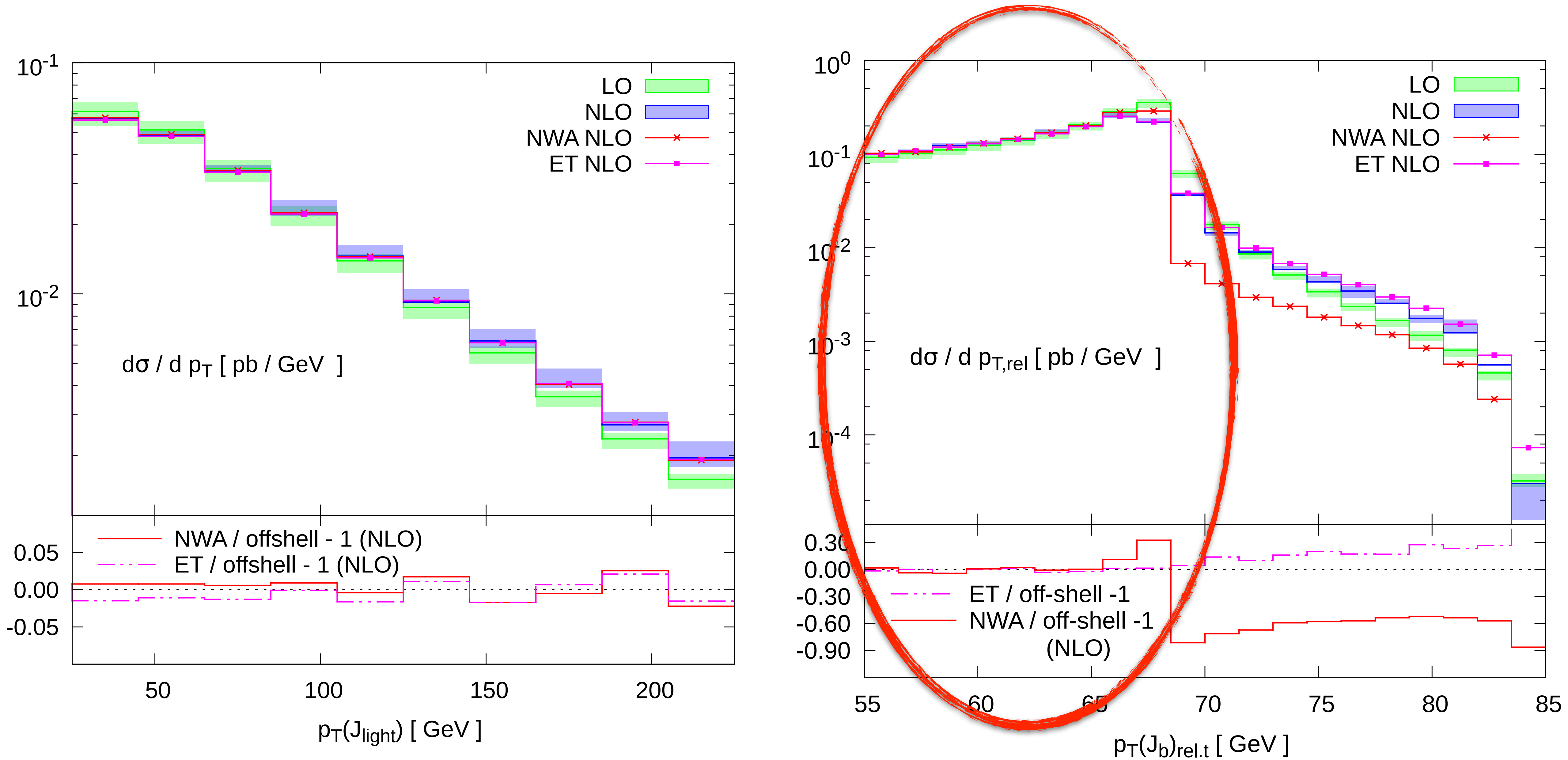
Three increasingly accurate predictions for single top @ NLO

- 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

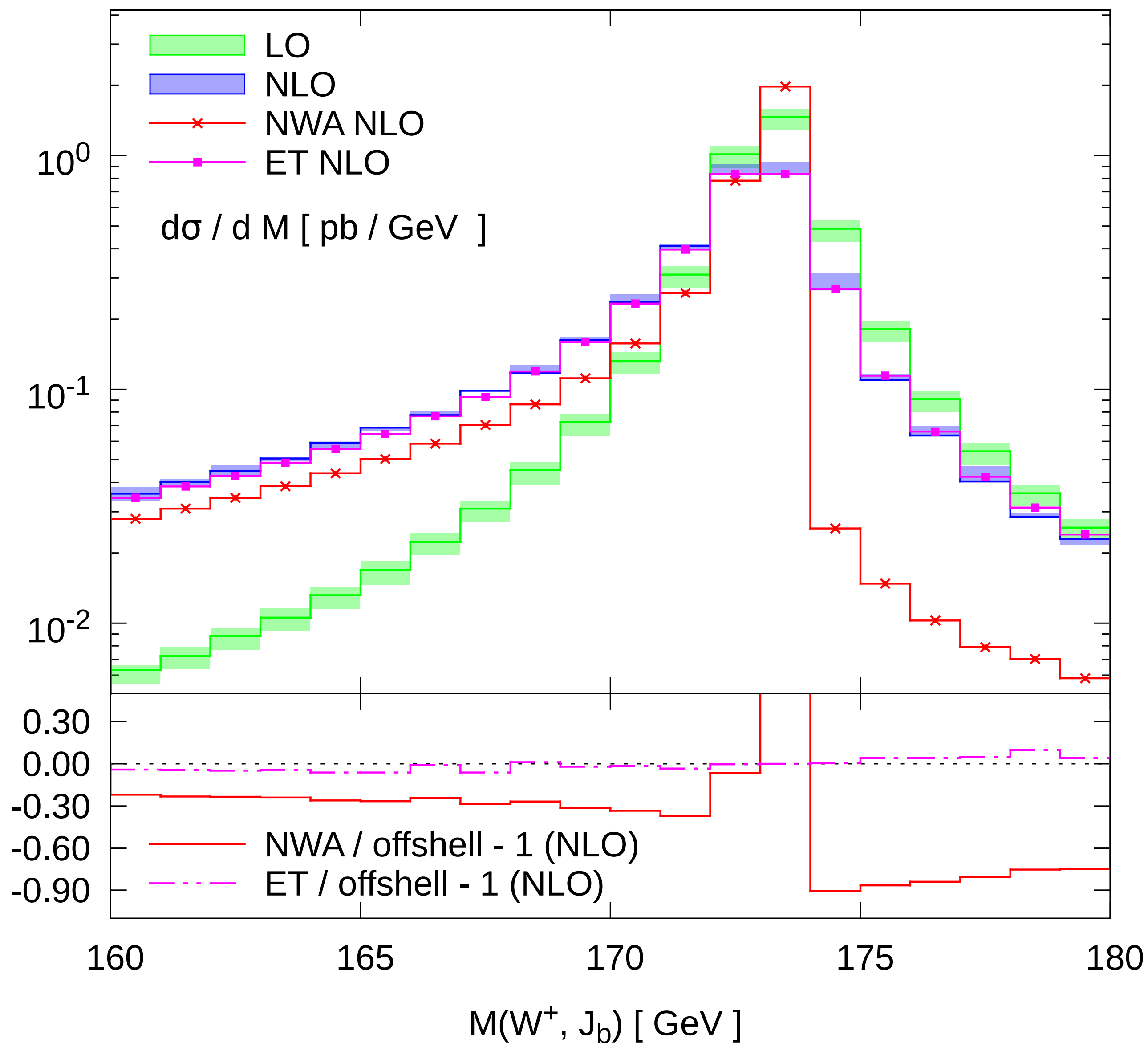


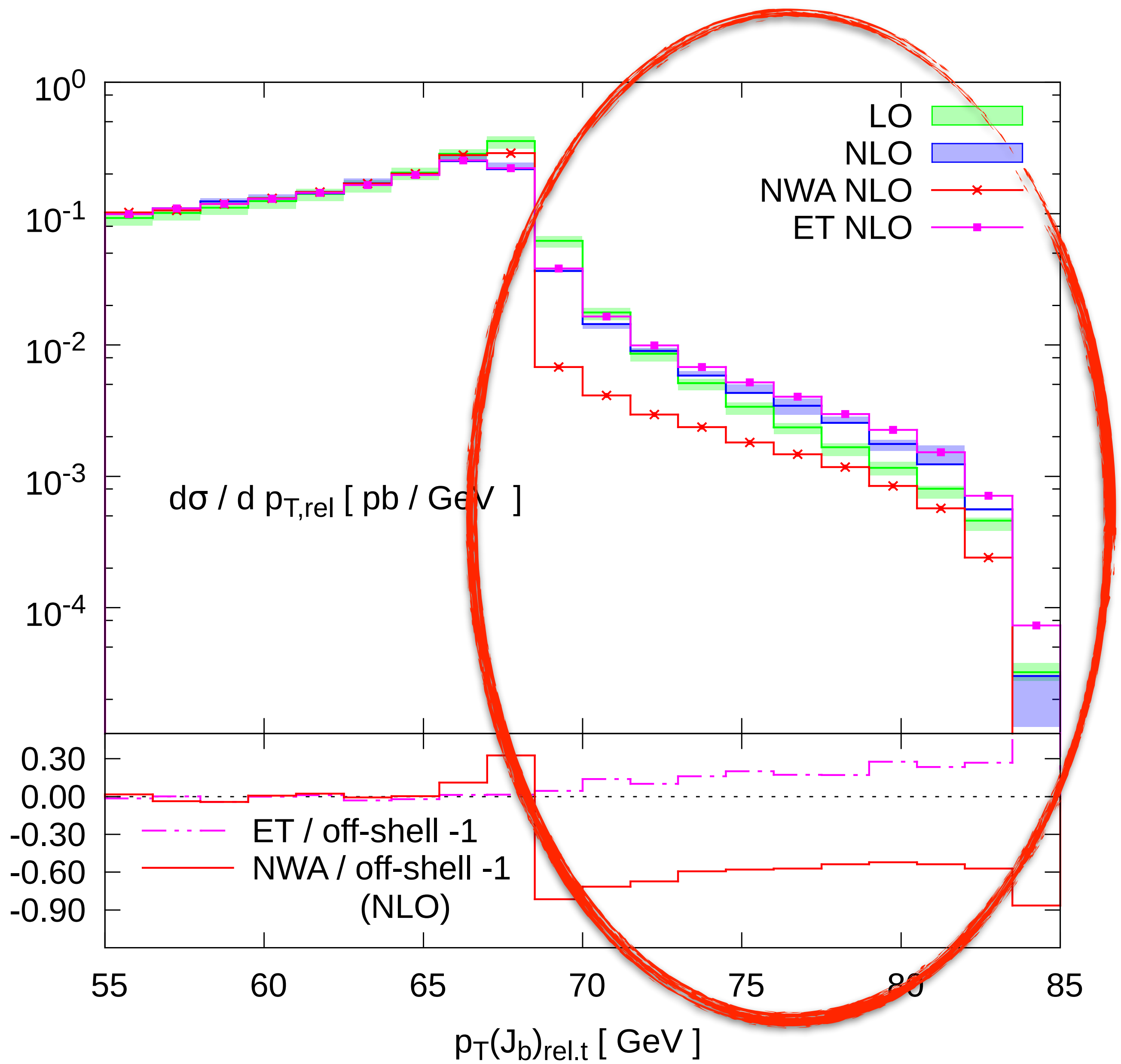
[Papanastasiou, Frederix, Frixione, Hirschi, Maltoni (2013)]

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

(OK apart from m_{Wb}-sensitive // past kinematic thresholds)

Can CONFIDENTLY USE NWA to compute predictions with REALISTIC FINAL STATES for complicated processes

- NNLO
- single-top + X (see e.g. arXiv1302.3856)

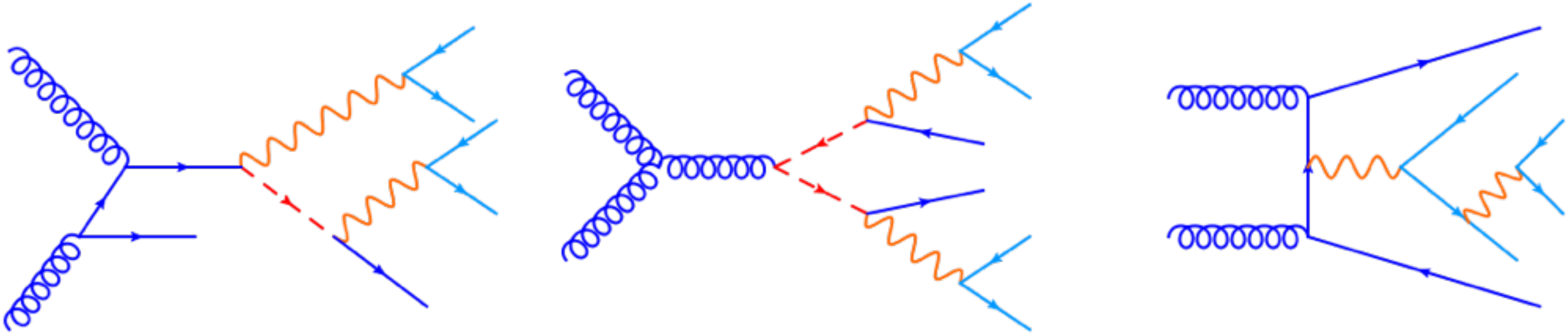
If NWA is not supposed to work for your observable:

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

Wt vs WWbb

The problem with Wt: Wt vs WWbb

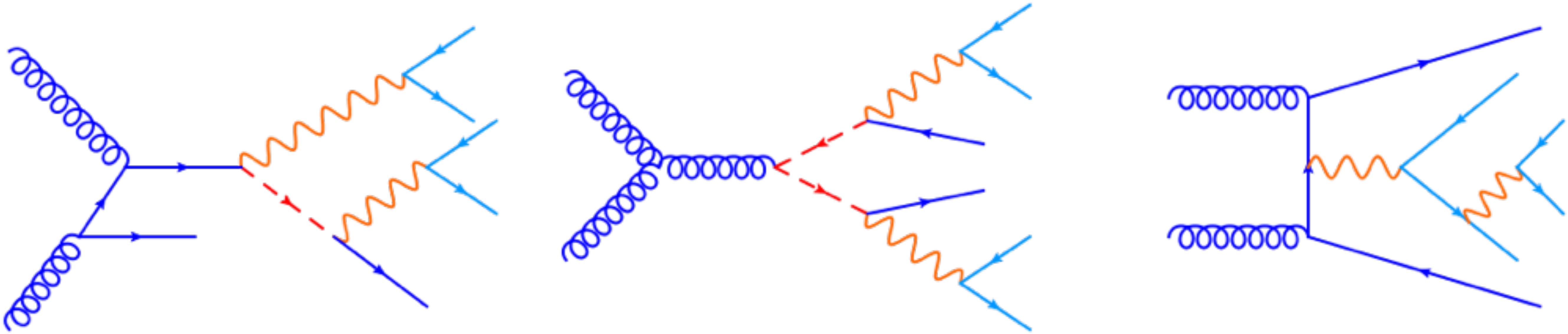
Already at NLO, Wt, ttbar and ‘background’ share the same initial/final states -> interferences, cannot be separated



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

The problem with Wt: Wt vs WWbb



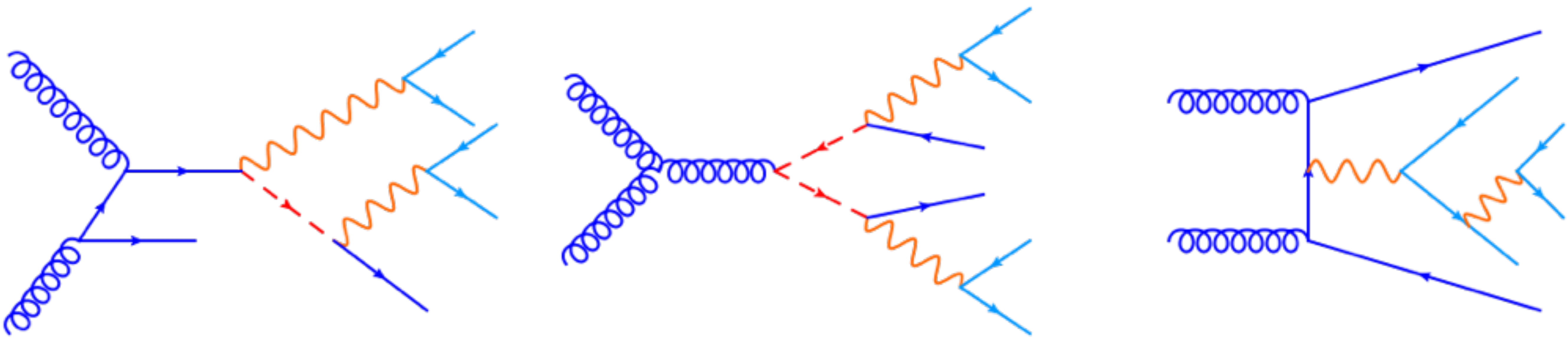
In practice, this means:

- Wt perfectly defined at LO -> O(20%) accuracy
- Traditional (DR, PR, DS…) ways of 'fixing' the problem suffer from conceptual issues (gauge invariance, RGE, arbitrariness…), *i.e.* they are AFFECTED BY A SYSTEMATIC THEORETICAL ERROR WHICH CANNOT GO DOWN, *INTRINSICALLY*

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)]

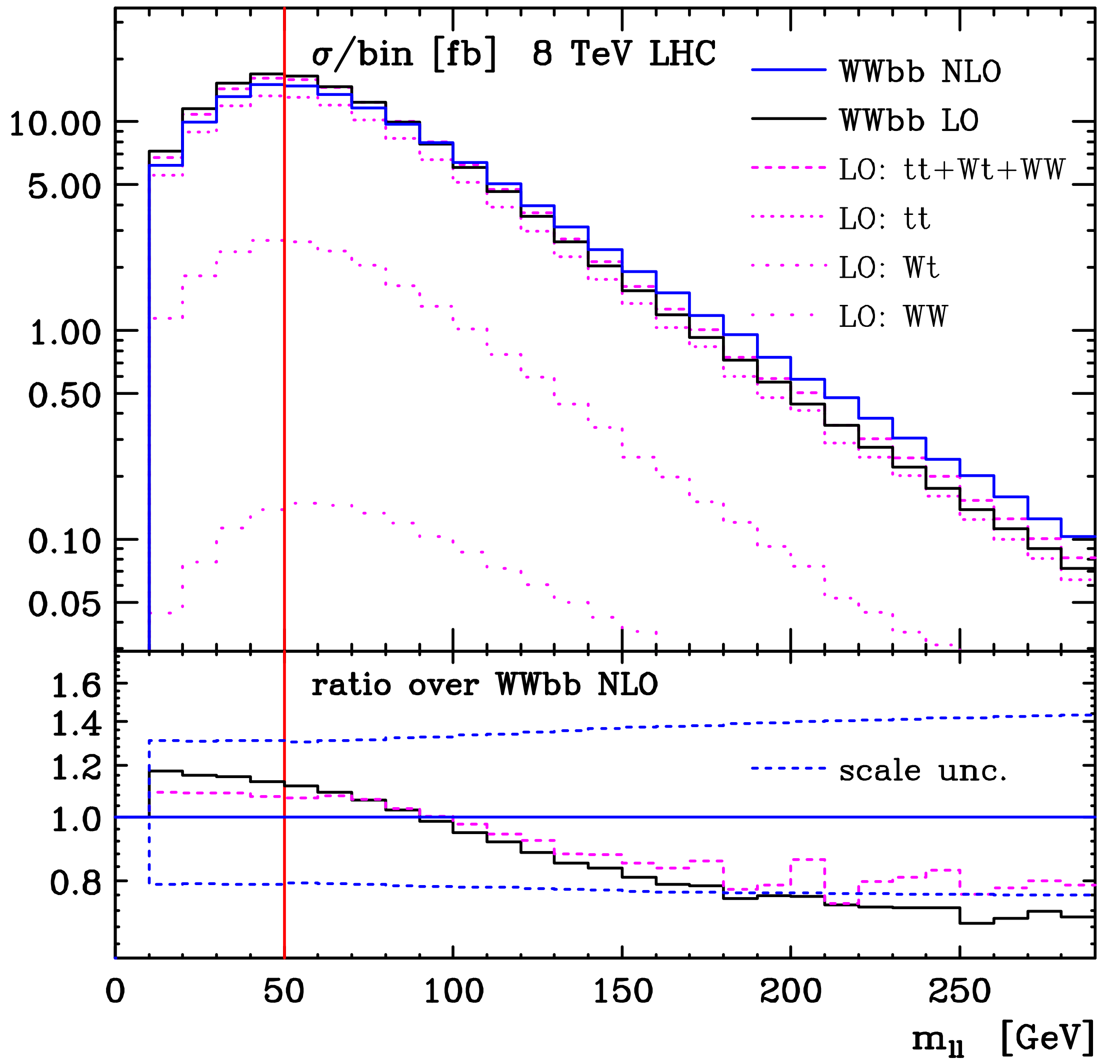


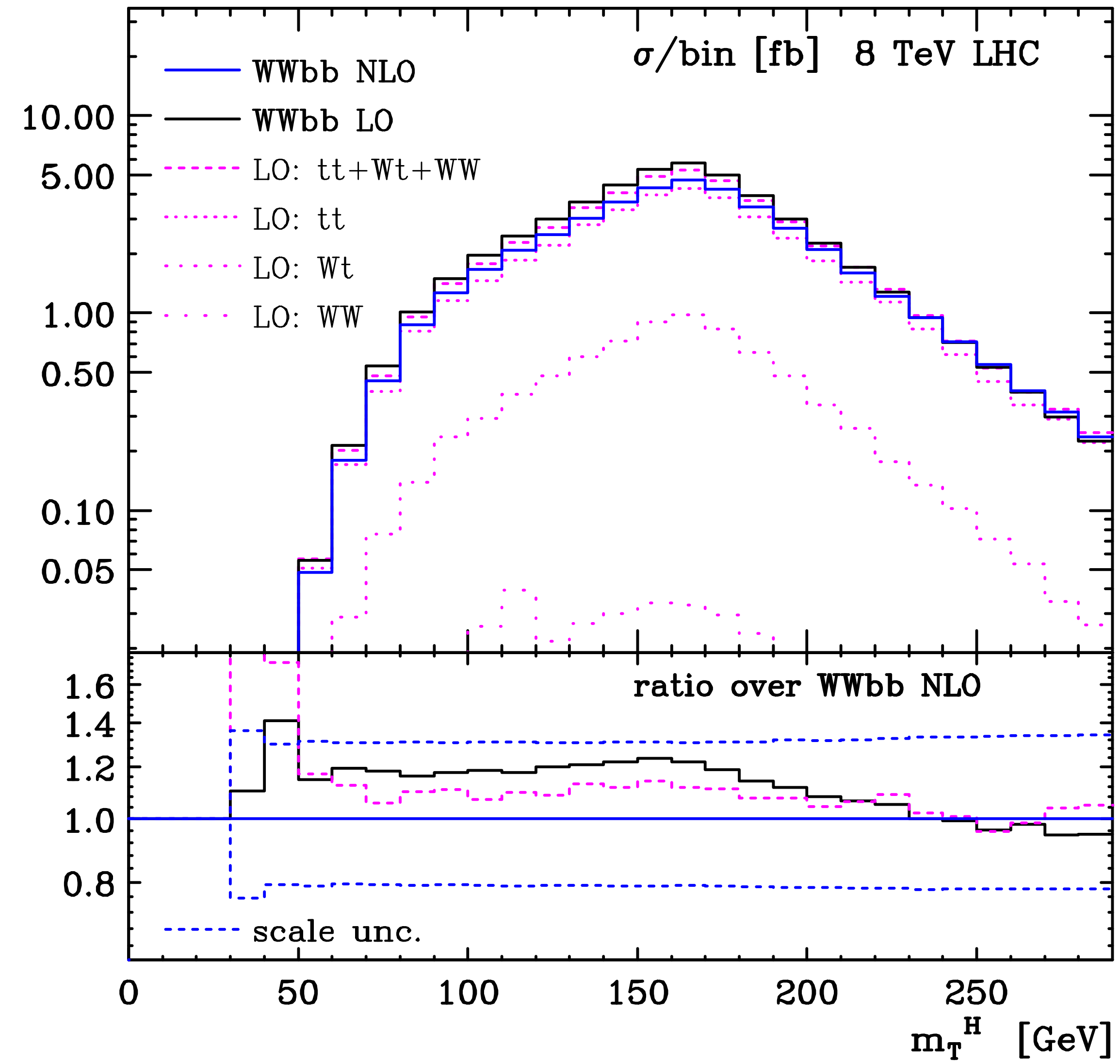
- There is no need (nor reason) to use old strategies any more
- Wt: single resonant contribution of the full process -> enhanced/suppressed with specific cuts
- *(Some caveats: PS however is not yet there…)*

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





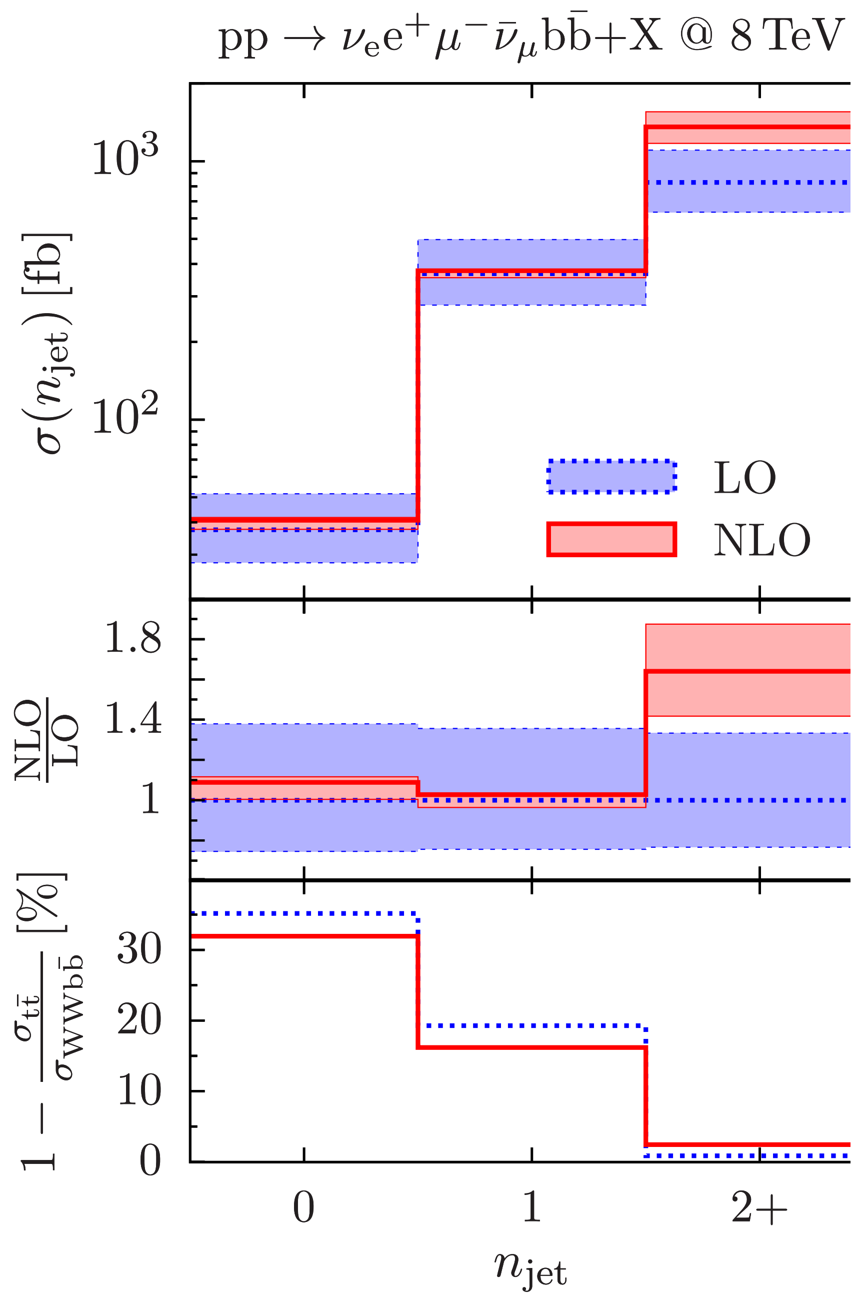
m_{ll}: shape distortion @ NLO

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, $p_{\mathrm{T},j} = 30\,\mathrm{GeV}$

$$d\sigma_{WWb\bar{b}} \sim \frac{1}{\Gamma_t^2} d\sigma_{t\bar{t}} + \frac{1}{\Gamma_t} d\sigma_t + d\sigma_{bkg}$$

Devise cuts to enhance single-resonant region

- Non tt effects very jet-bin dependent, concentrated in the 0/1 jet bins
- Large in phase space regions with unresolved b-quarks

Put physical intuition on a precise quantitative level

Conclusions

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

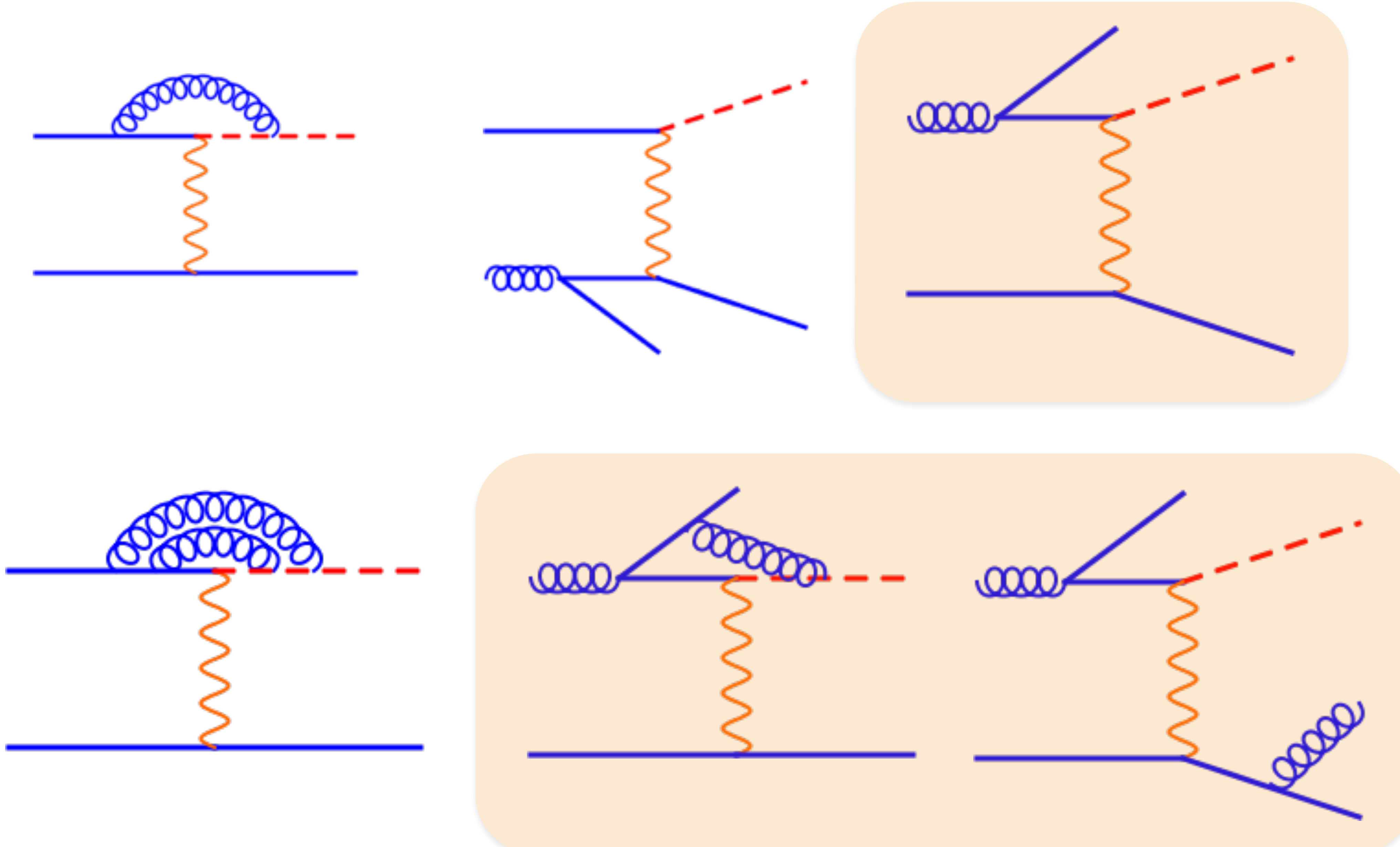
- Precision -> fully differential NNLO
  - Corrections as large as NLO on the total rate
  - Small (non-constant) K-factor, (differential) NLO stable
  - Will be interesting to let the top decay
- Realistic final states -> top decay
  - NWA validated by dedicated benchmark computations
  - For simple processes, can go beyond NWA if needed
- Artificial distinctions no longer needed -> Wt vs WWbb
  - Unified description for top as background
  - Theoretically correct separation of tt/t/non-resonant
- Relatively recent progress, conceptual novelties
  - Be patient for PS implementations…

Thank you for your attention!

single-top @ NNLO: 5FNS vs 4FNS@NLO

NLO

NNLO



Inside NNLO 5FNS: ~ NLO 4FNS

- collinear regulator: MSbar vs m_b (log resummed, p.s.t. neglected)
- SLC light/heavy interference neglected in our computation
- 'Nice' features of 4FNS NLO (B-JET MODELING) inherited