NNLO predictions for t-channel single-top

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Work done in collaboration with M. Brucherseifer and K. Melnikov

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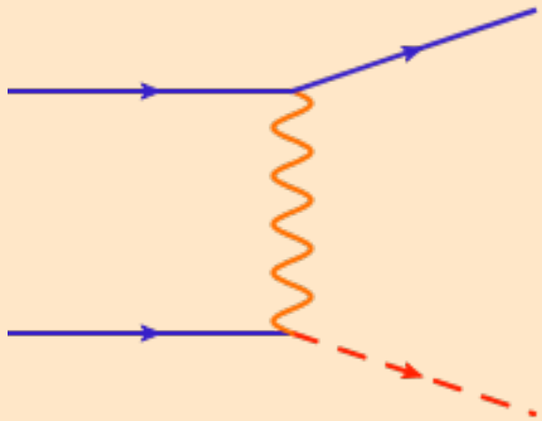
TOP LHC WG MEETING, MAY 20TH 2015

Single-top: the price of precision

At the LHC: single-top is precision physics

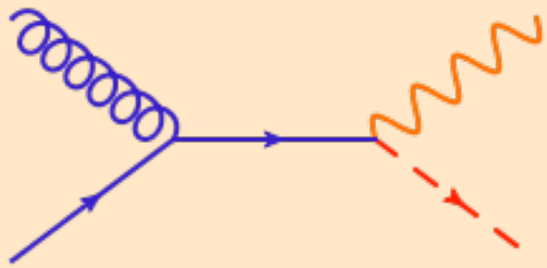
Classical picture: 3 production mechanisms

T-CHANNEL



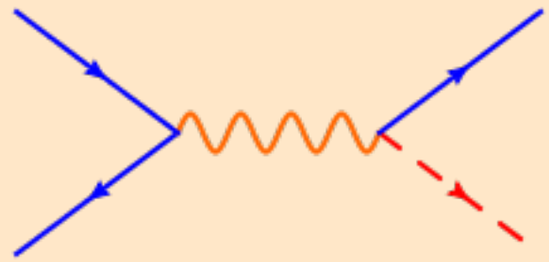
LHC8: ~ 82%

ASSOCIATED PRODUCTION



LHC8: ~ 15%

S-CHANNEL



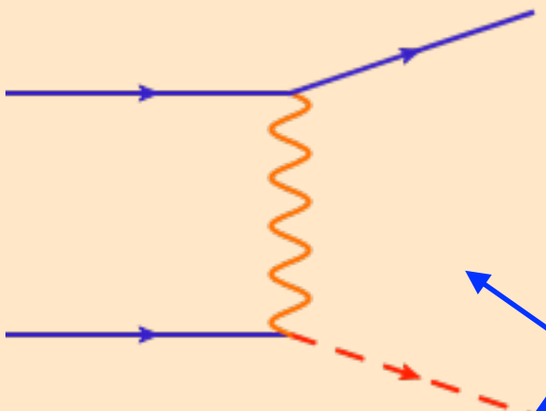
LHC8: ~ 5%

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

The price of precision

Mixing at the quantum level

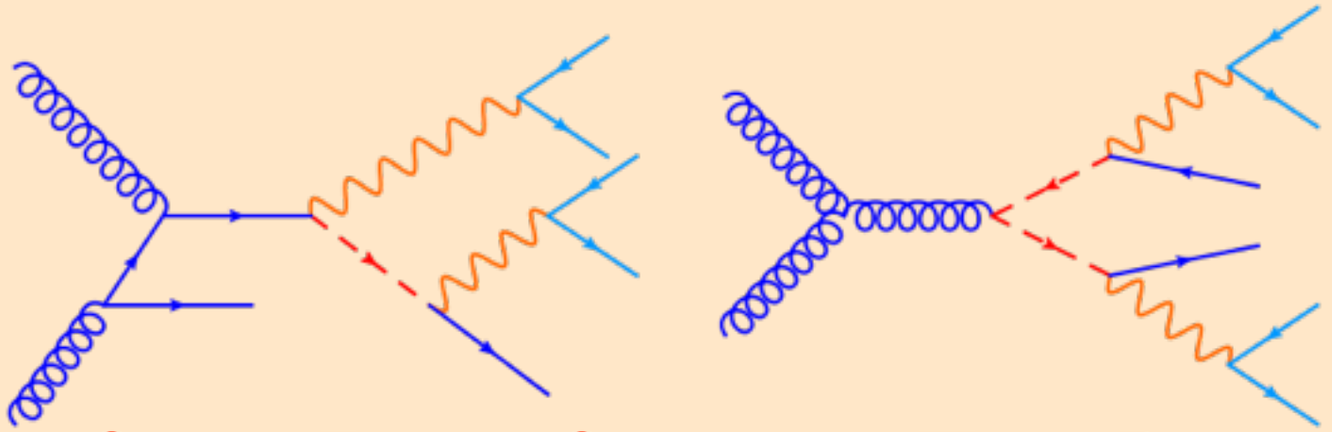
T-CHANNEL



LHC8: ~ 82%

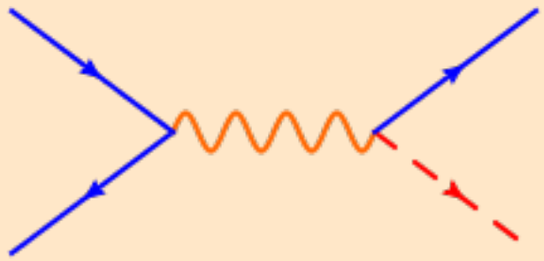
INTERFERENCE

ASSOCIATED PRODUCTION



SAME FINAL STATE OF TOP-PAIR

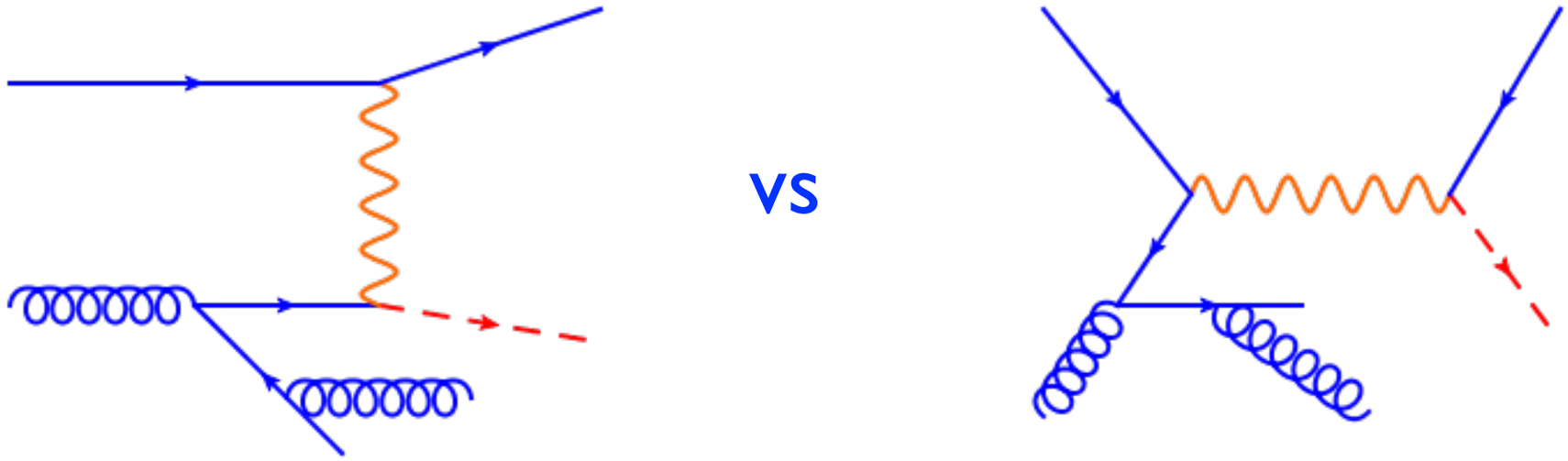
S-CHANNEL



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



IN PRINCIPLE:

- beyond LO: 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

[Situation much more tricky for Wt/WWbb]

The quest for precision: t-channel @ NNLO

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"

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…)

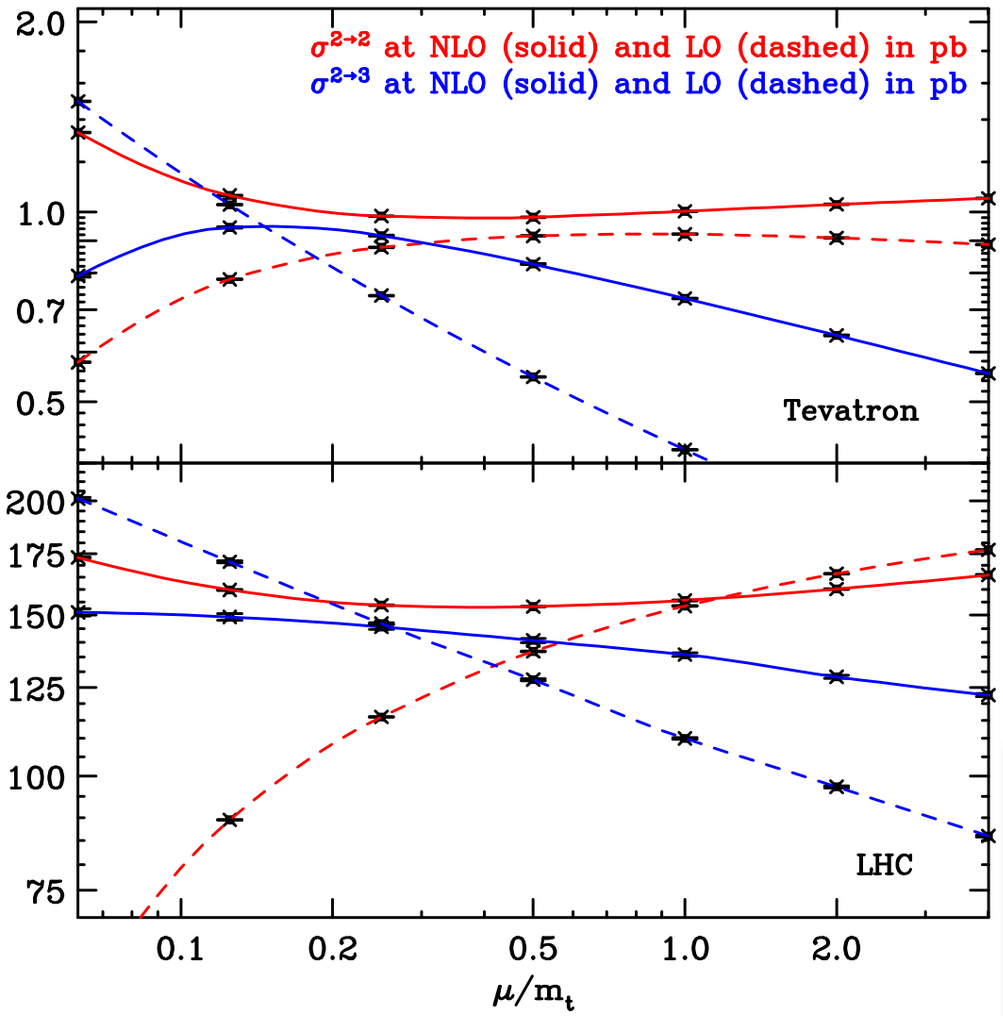
HOWEVER…

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

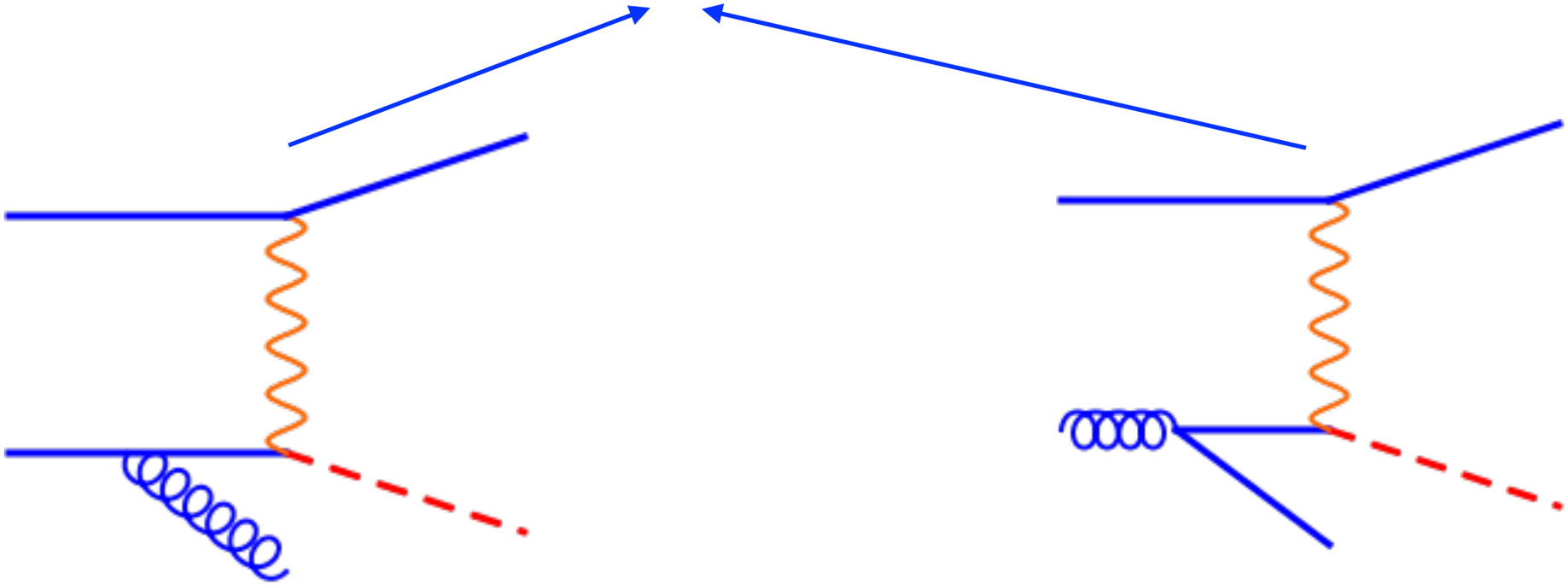
Residual perturbative uncertainty at the percent-level

t-channel single top: do we need NNLO?

‘Typical’ NLO corrections are much more ~10%

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

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



+12%

-14%

Large cancellations among channels

(beware of approximations only considering one channel)

T-channel single top: do we need NNLO?

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

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

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

- 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, q_T) 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

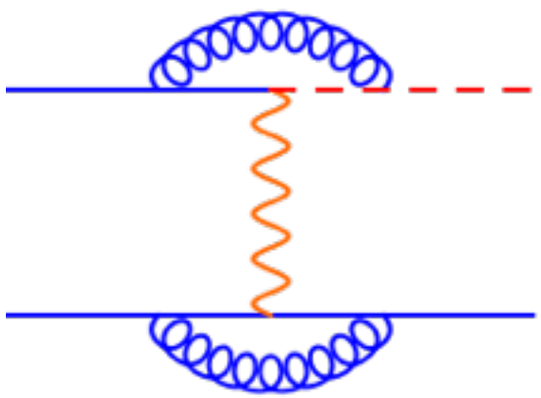
Recent developments in NNLO techniques, allowed us to compute (almost) t-channel single-top corrections.

In particular, for our computation:

- Sector-decomposition+FKS [Czakon (2010); Boughezal, Melnikov, Petriello(2011); Czakon, Heymes (2014)]
- 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…)

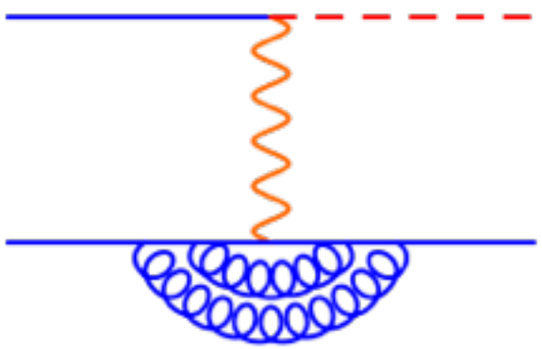
Single-top in the 'factorized' approximation

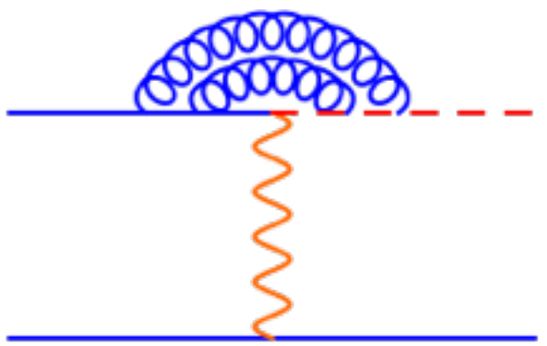
Two-loop amplitudes:



Trivial (~NLO^2)

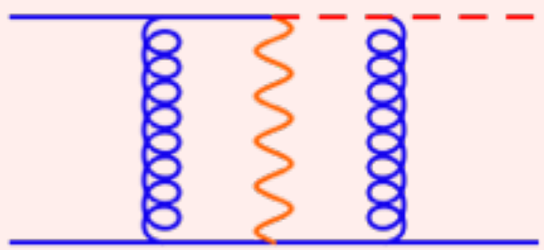
Simple





~OK

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: setup and comments

In the following, I will present PRELIMINARY results with

- m_t = 172.5 GeV, MSTW2008 (Top WG reference)
- on-shell renormalization, pole mass
- error computed from 7-point scale variation
- very CPU intensive -> precomputed grids now implemented

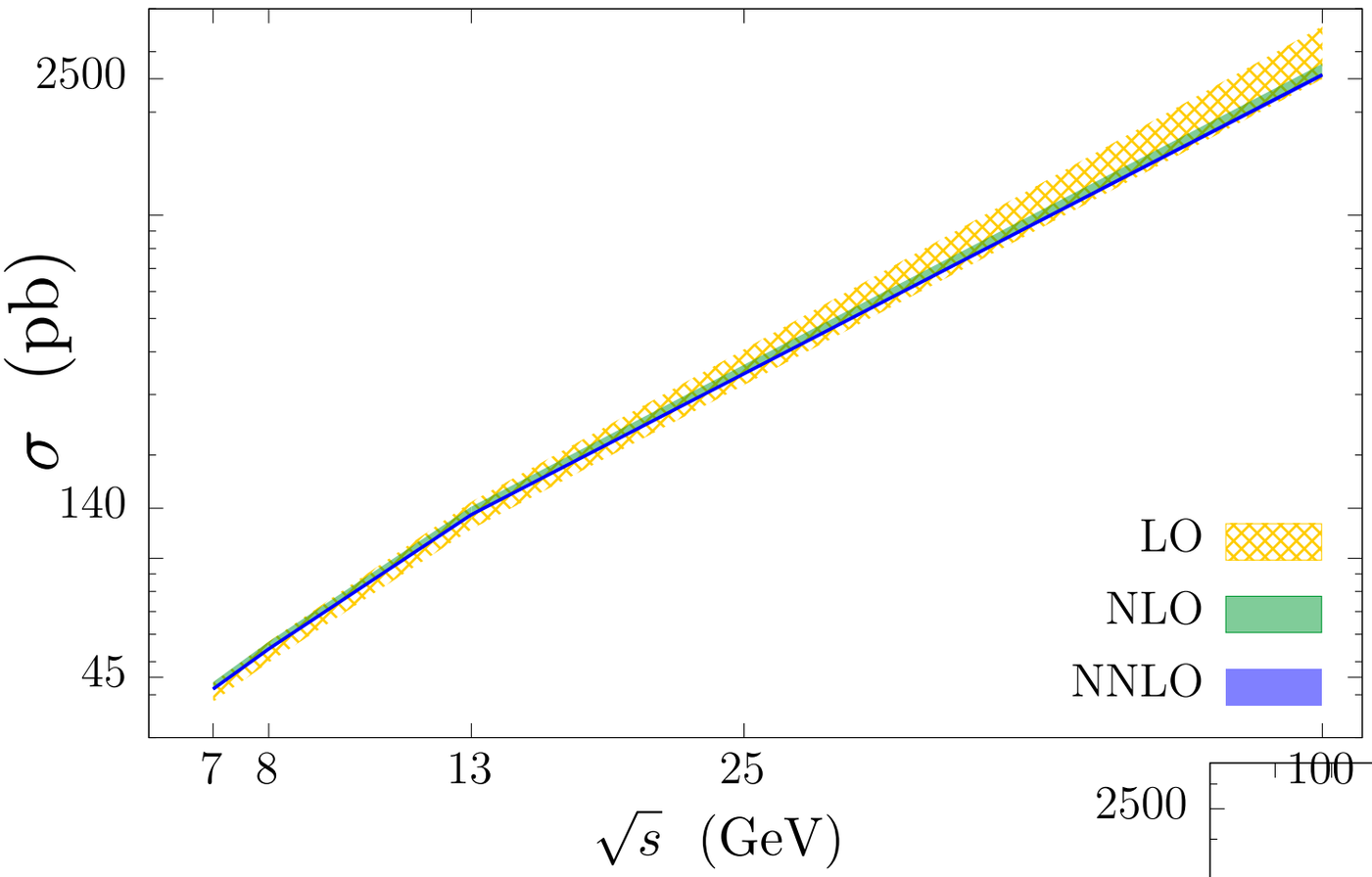
Ideally, one would like to compare fiducial measurements

- definition issues minimized
- less theoretical bias

The total cross-section however can be useful

- thorough error estimates
- similar error analysis not (yet) possible at the differential level (CPU-time)
- focus of this talk

Results: total cross section at different energies



$$\sigma_{t,\mathrm{NNLO}}(7\ \mathrm{TeV}) = 41.6^{+0.3}_{-0.1}\ \mathrm{pb}$$

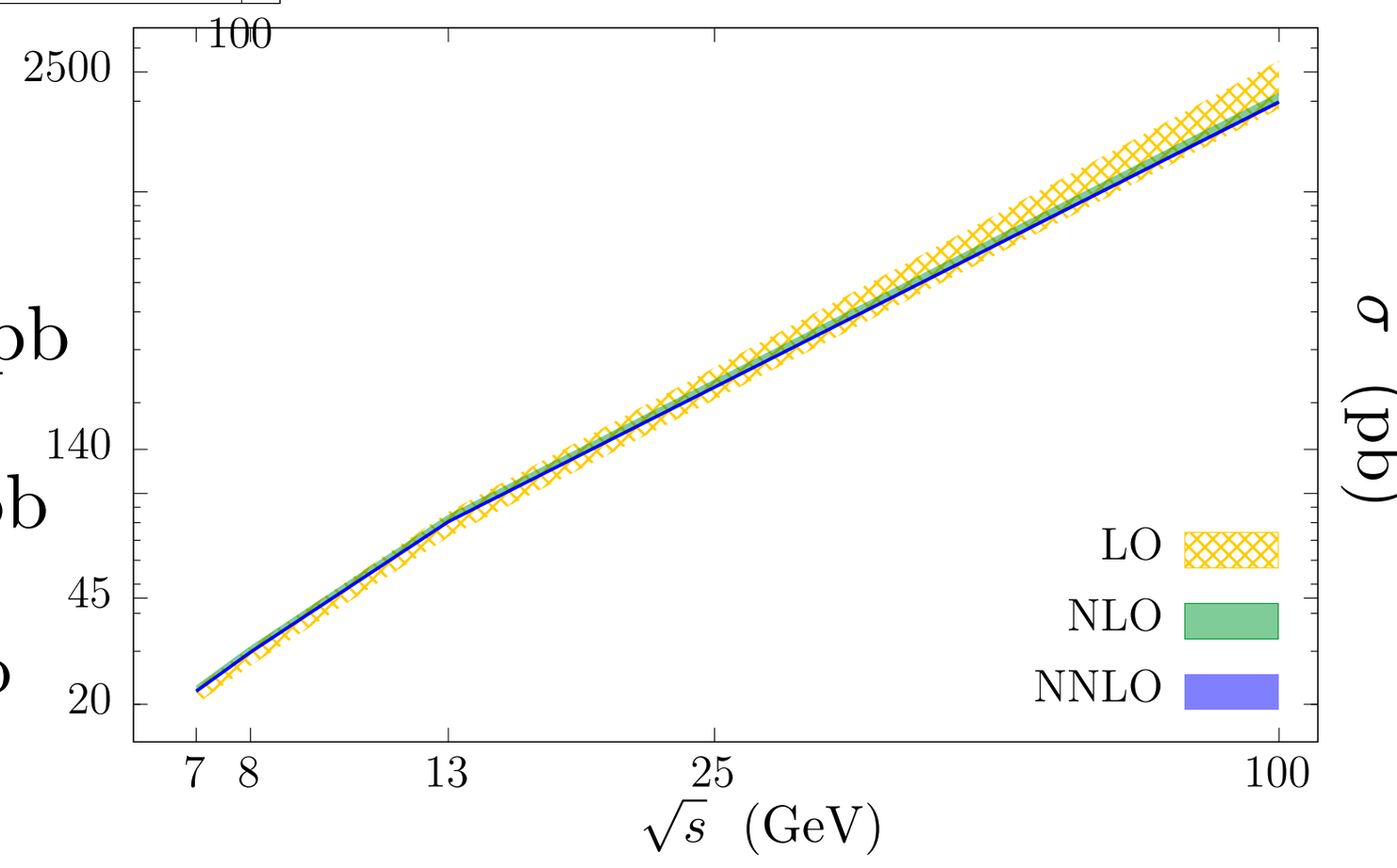
$$\sigma_{t,\mathrm{NNLO}}(8\ \mathrm{TeV}) = 54.4^{+0.4}_{-0.2}\ \mathrm{pb}$$

$$\sigma_{t,\mathrm{NNLO}}(13\ \mathrm{TeV}) = 134.0^{+0.7}_{-0.6}\ \mathrm{pb}$$

$$\sigma_{\bar{t},\mathrm{NNLO}}(7\ \mathrm{TeV}) = 22.1^{+0.1}_{-0.1}\ \mathrm{pb}$$

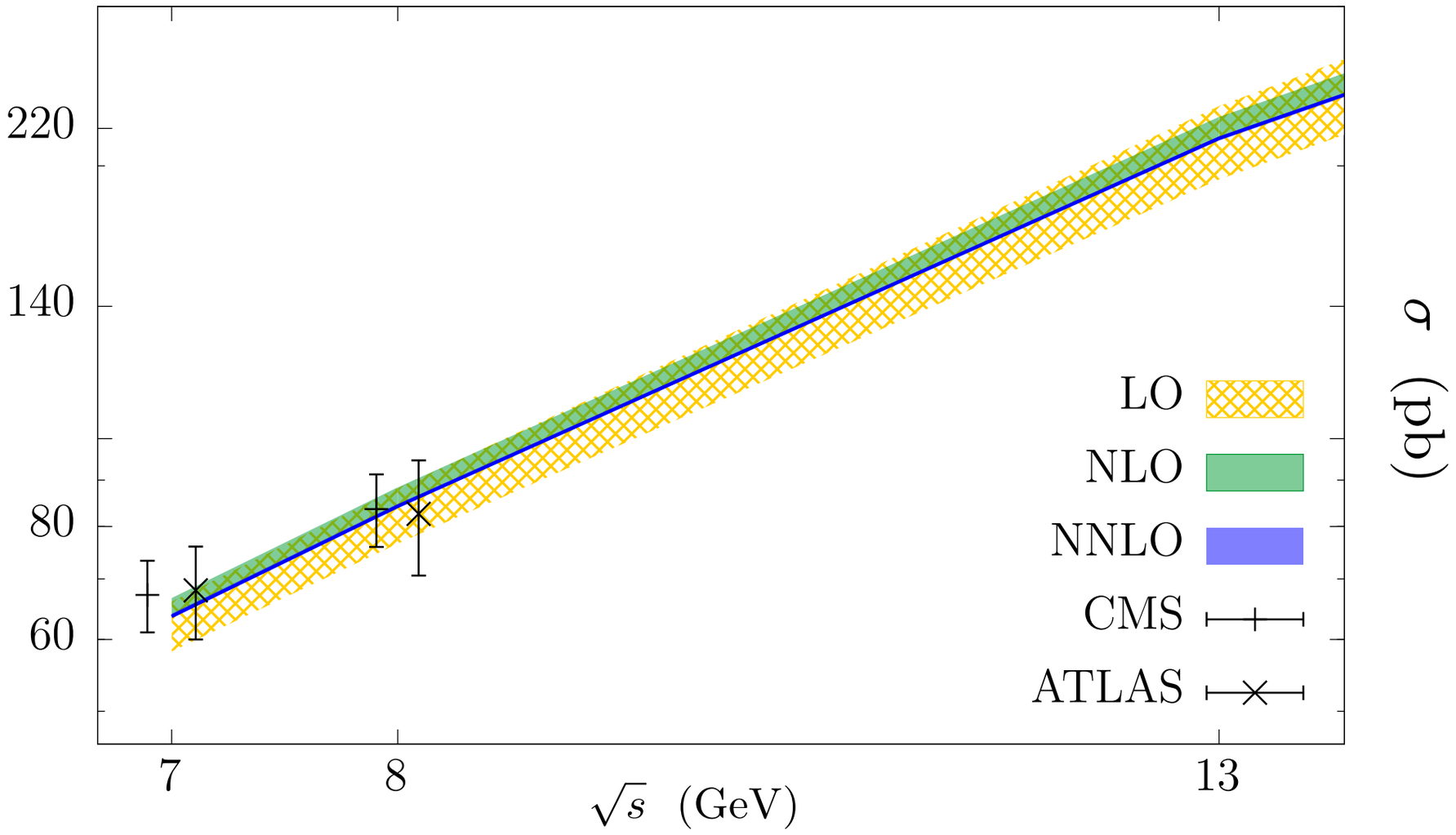
$$\sigma_{\bar{t},\mathrm{NNLO}}(8\ \mathrm{TeV}) = 29.8^{+0.1}_{-0.2}\ \mathrm{pb}$$

$$\sigma_{\bar{t},\mathrm{NNLO}}(13\ \mathrm{TeV}) = 80.5^{+0.3}_{-0.6}\ \mathrm{pb}$$



Results: total cross section at different energies

Combining top and anti top:



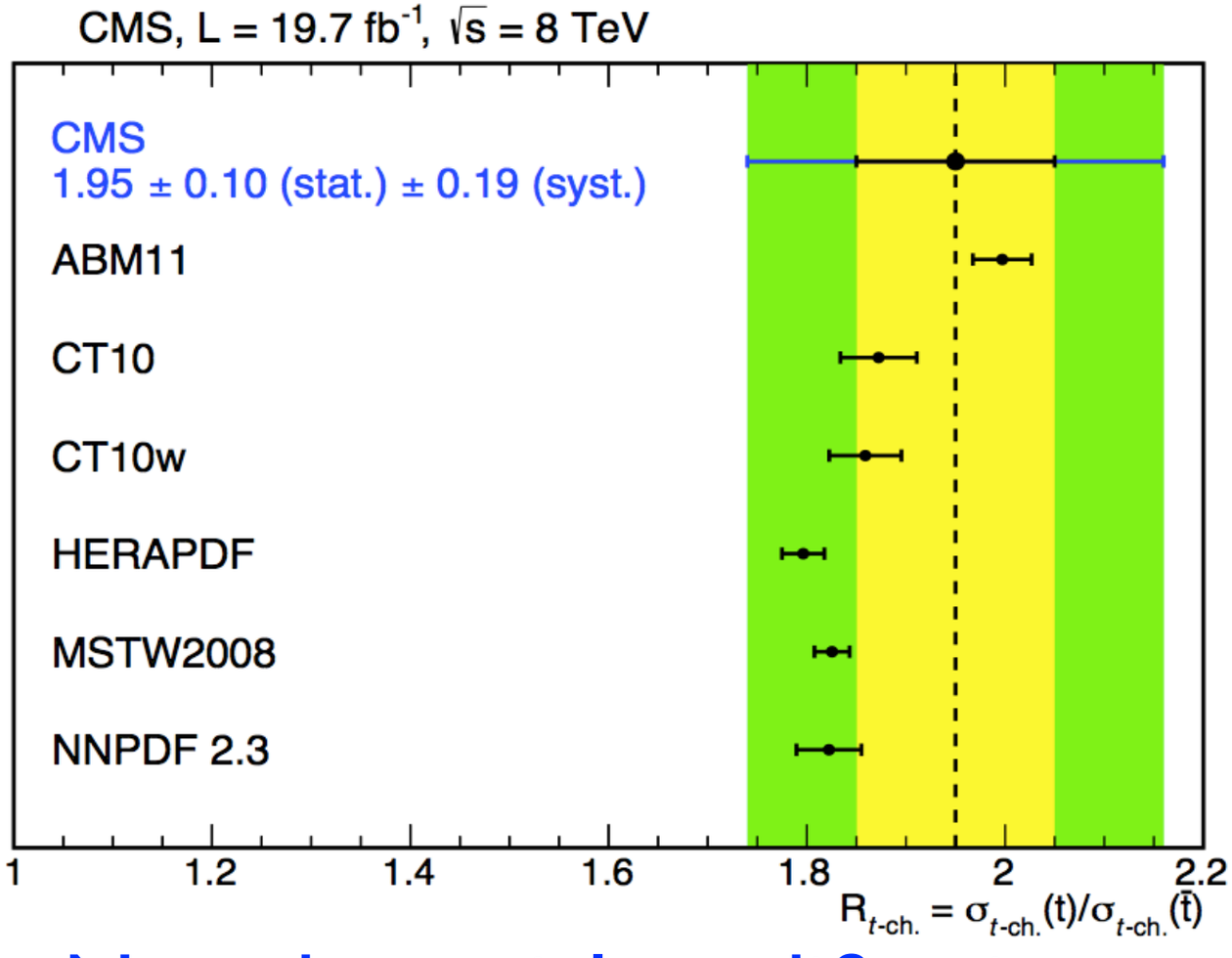
- Excellent agreement with measurements at both LHC7/8
- Tiny scale uncertainty (dominated by μ_F)

Single-top total cross section, NNLO QCD

$$\sigma_{t+\bar{t},\mathrm{NLO}} = 85.8^{+2.7}_{-1.7}\ \mathrm{pb}, \quad \sigma_{t+\bar{t},\mathrm{NNLO}} = 84.2^{+0.5}_{-0.3}\ \mathrm{pb} \quad \text{(scale)}$$

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

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



top/anti-top ratio very stable

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

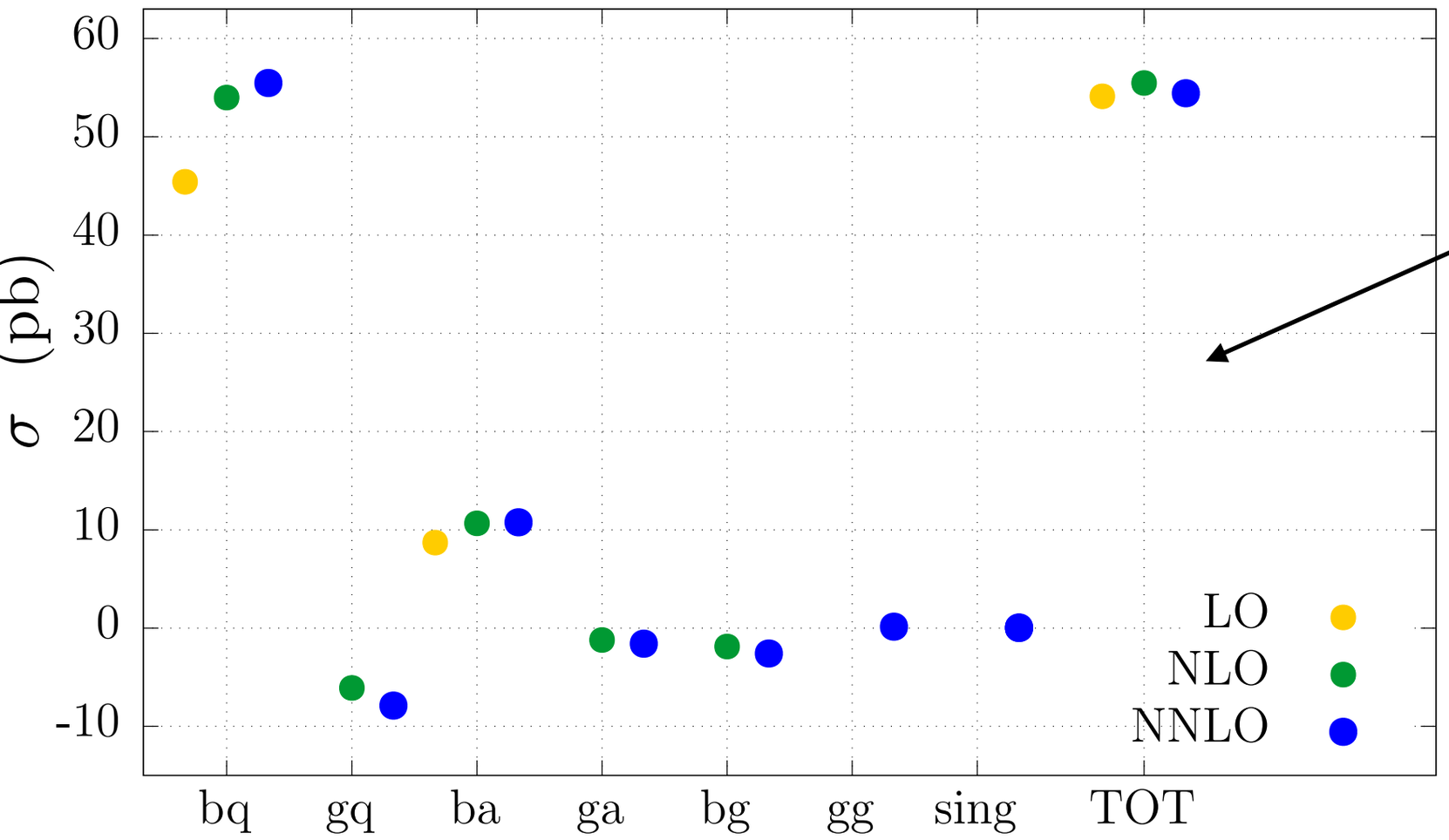
$$\sigma_{t,\mathrm{NLO}}/\sigma_{\bar{t},\mathrm{NLO}} = 1.83$$

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

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

Results: channel separation

Dressing with soft gluons the LO channels is dangerous



Top, 8TeV LHC

Quark and gluon channels: competing effects

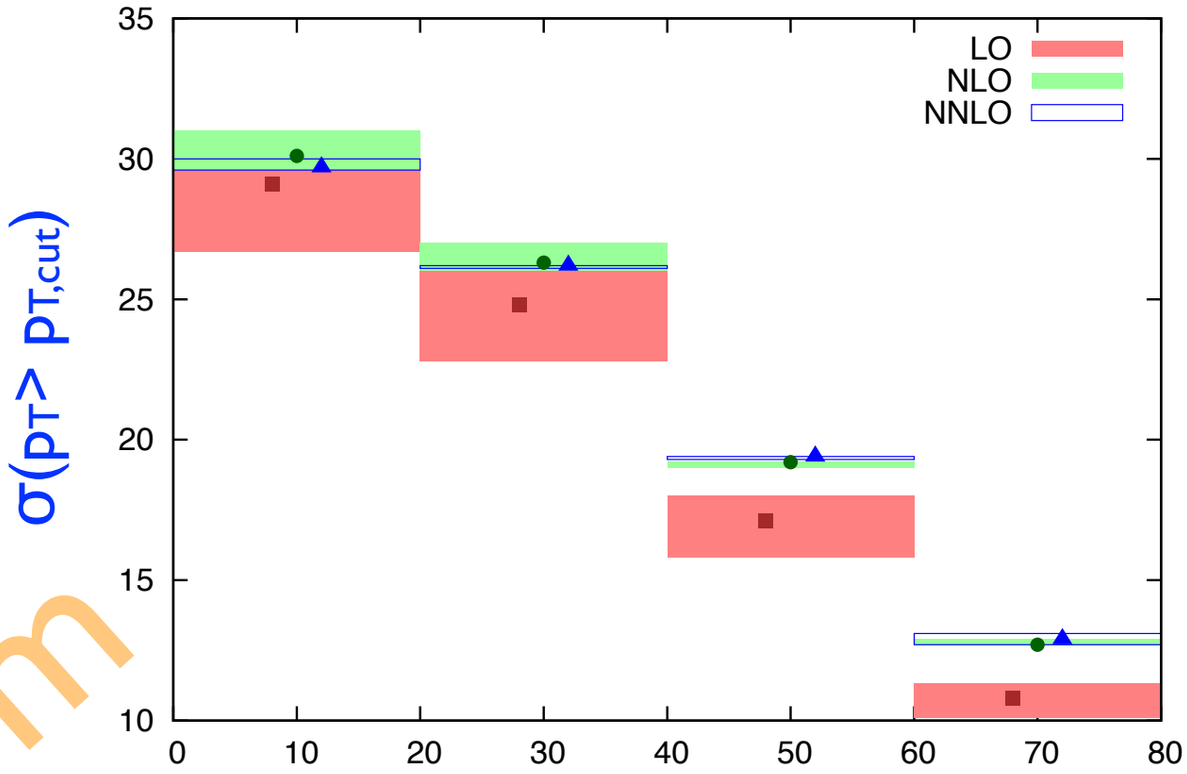
Cancellation patterns among different channels (big at NLO, under control at NNLO)

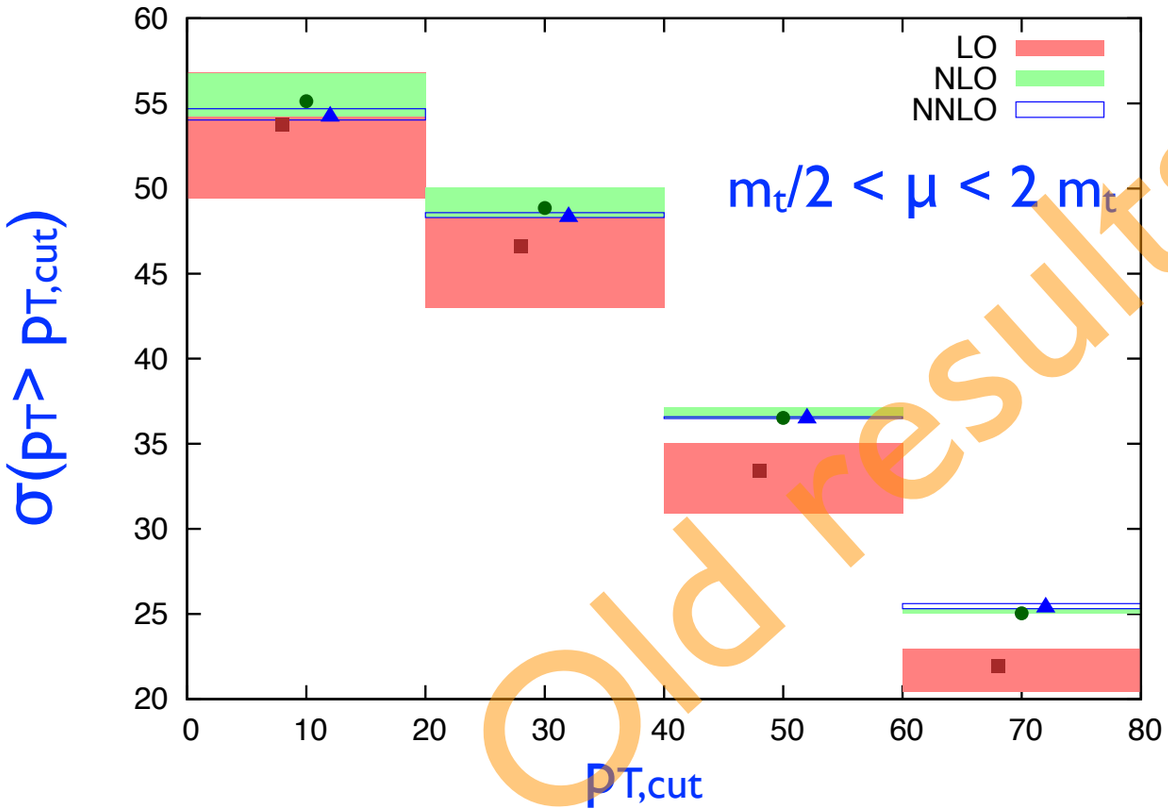
NLO seems to do a pretty good job though

NNLO small also for more differential quantities

$p_\perp$	$\sigma_{\rm LO}$, 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	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	$+13.6\%$	$25.4^{-0.1}_{+0.2}$	$+1.6\%$

Top, 8TeV LHC





Anti-Top, 8TeV LHC

$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
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	$10.8^{+0.5}_{-0.7}$	$12.7^{+0.03}_{+0.2}$	$+17.6\%$	$12.9^{-0.2}_{+0.2}$	$+1.6\%$

Conclusions

Single-top: from discovery to precision physics

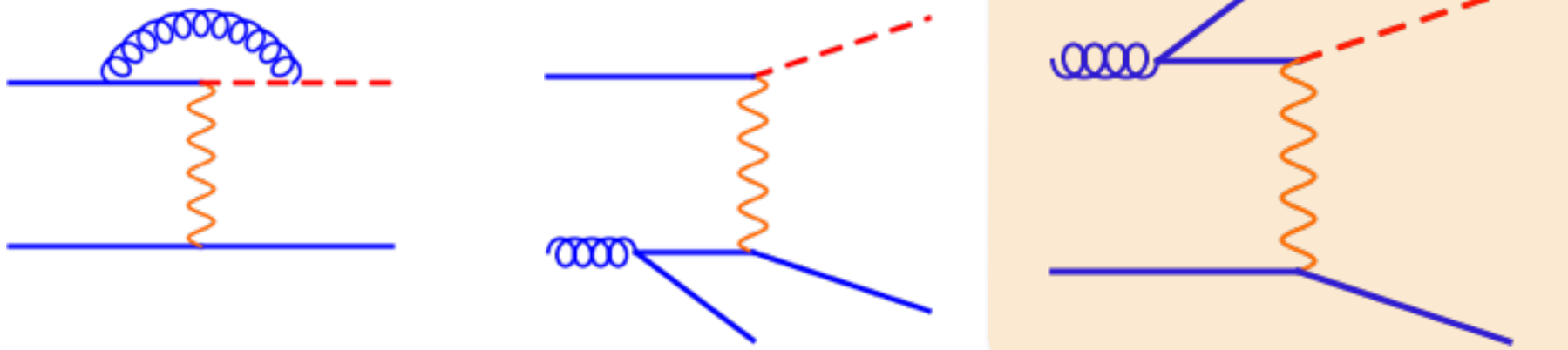
- Increasing experimental precision demands for accurate theory predictions. One important ingredient: NNLO corrections for t-channel production

- Future work
  - Complete / validate benchmark cross-sections (PDF error well underway)
  - Comparisons in the fiducial region
  - Ideally, with realistic final states -> top decay
  - Matching with PS

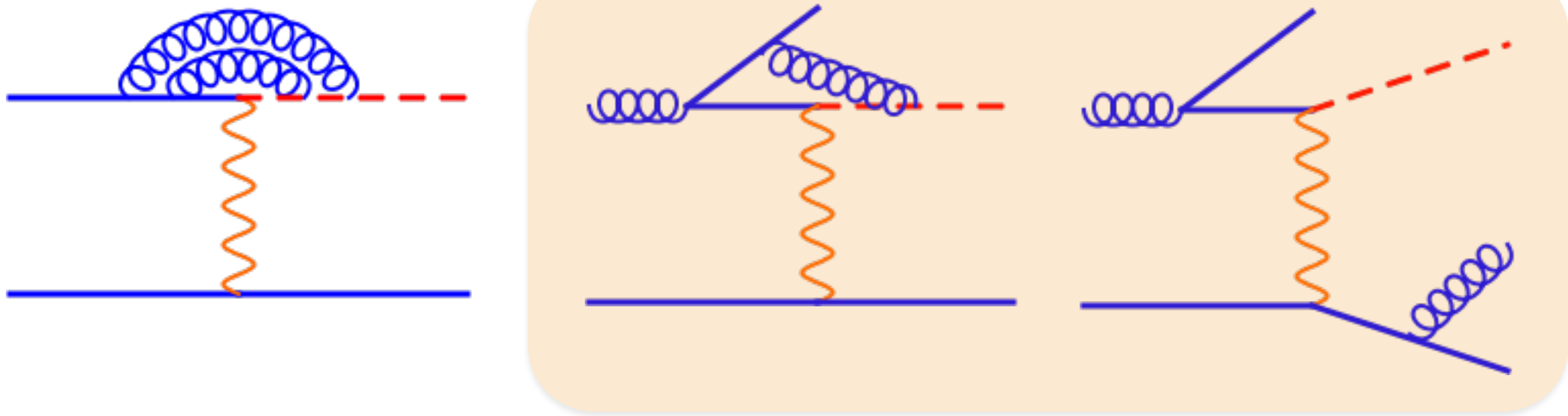
Thank you for your attention!

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