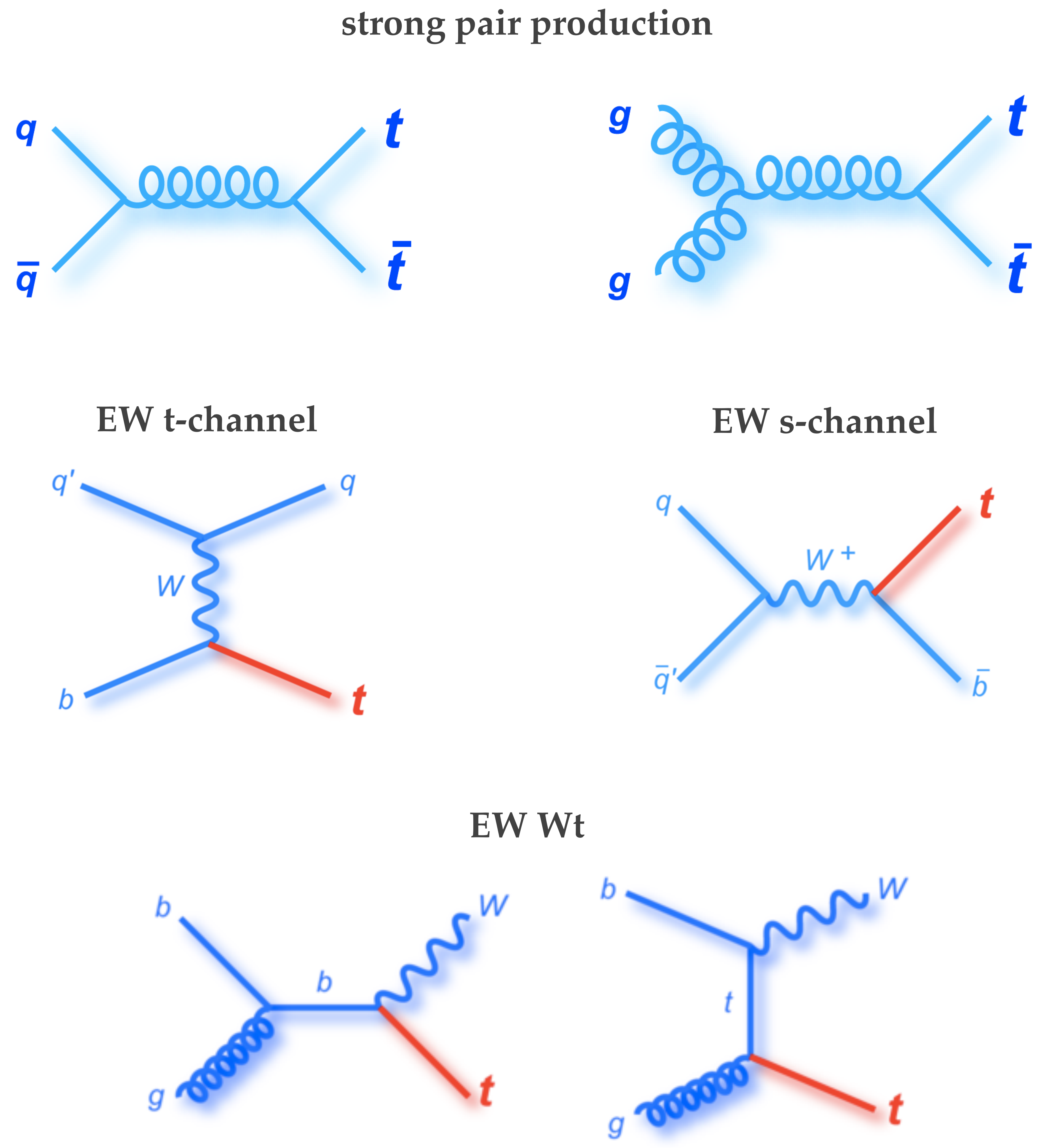
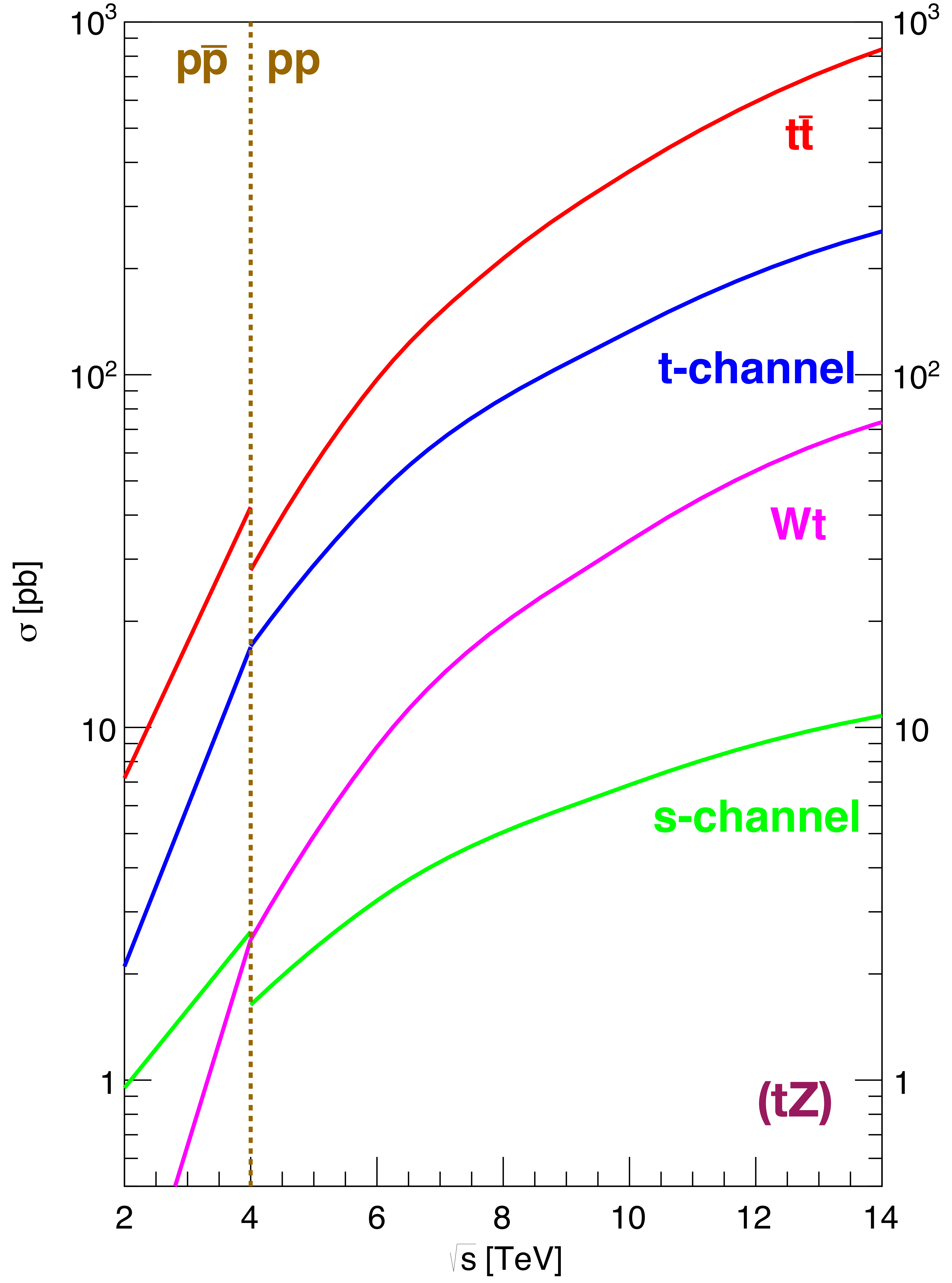
Highlights in single top quark physics

TOP 2021

John Campbell

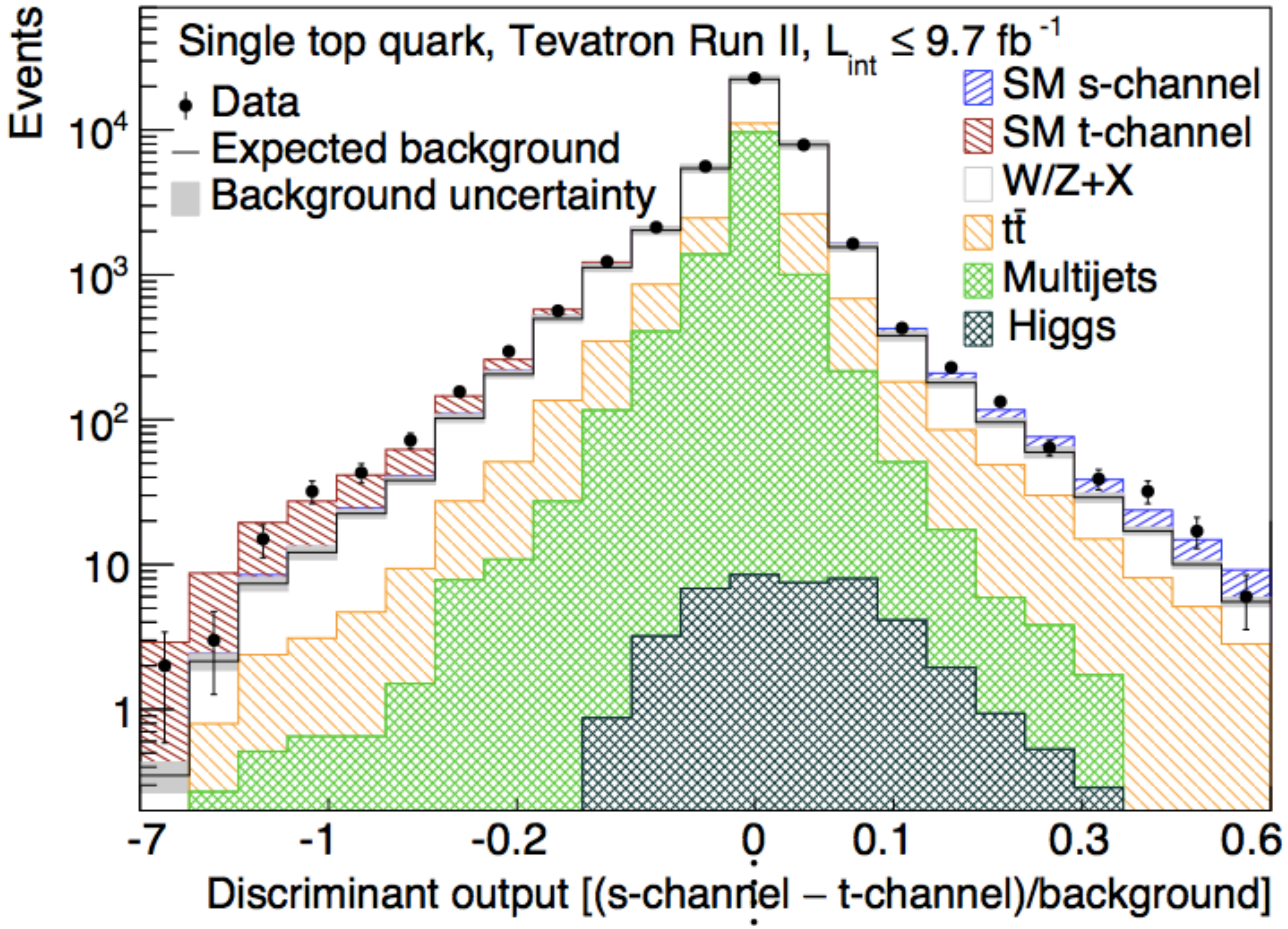
Top production





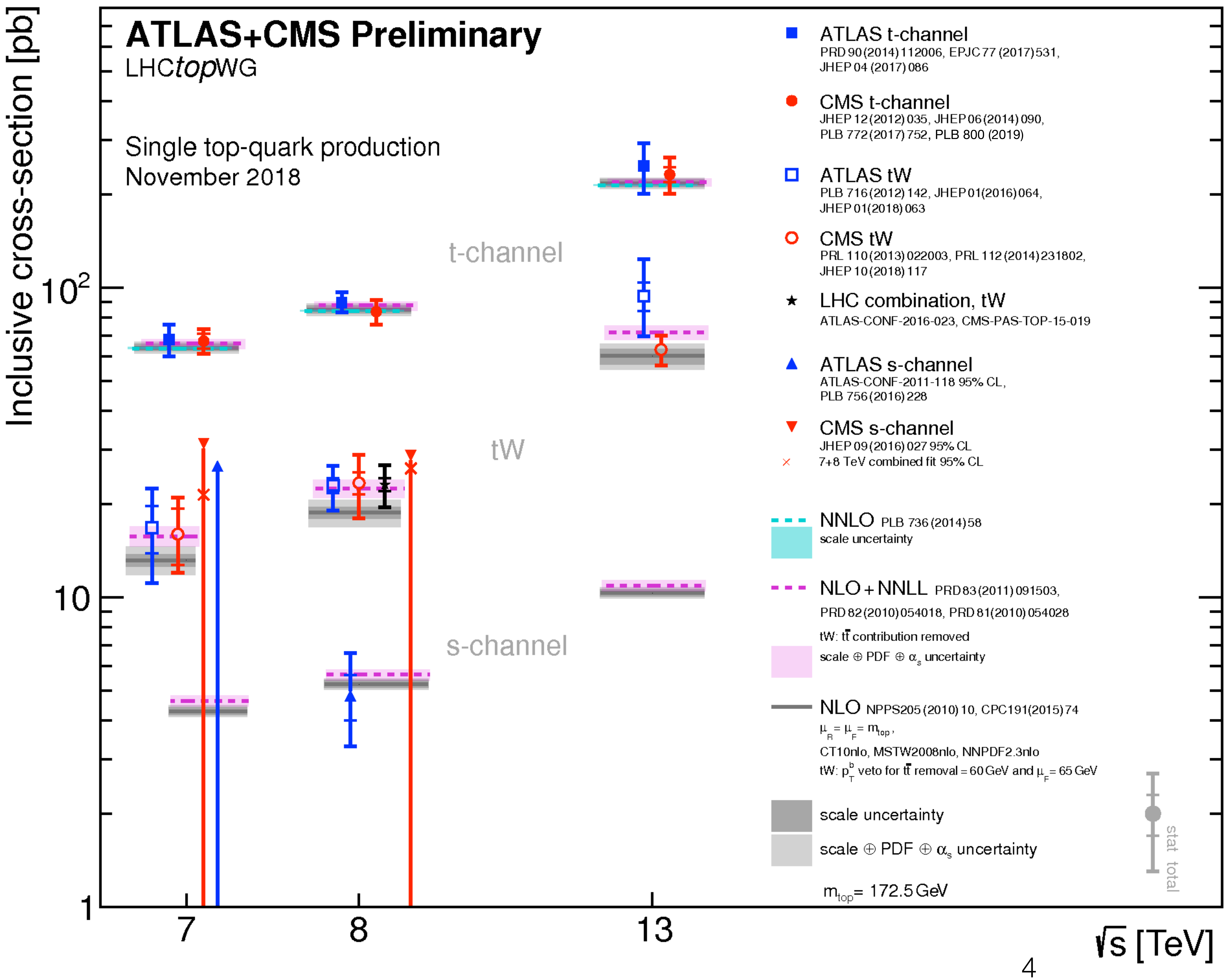
Single-top discovery

- Conclusive observation of single top production at the Tevatron in 2009.
- Impressive coming-together of experimental analysis techniques (e.g. MVA) and theory to overcome formidable backgrounds.
- Provides constraints on SM: V_{tb}, m_t, PDFs, new physics.



Tevatron combination, https://arxiv.org/abs/1503.05027

LHC status



- Not much to update since 2019, notably tW ℓ+jets ATLAS 8 TeV, CMS 13 TeV (not shown here).
- s-channel very tough: small and plentiful backgrounds!
- Theory < expt. uncertainty for s- and t-channel but similar for tW.
- t-channel: relatively large uncertainties at 13 TeV compared to 8 TeV, lots of work ahead
  - t-channel will be precision probe for HL-LHC

Theory status

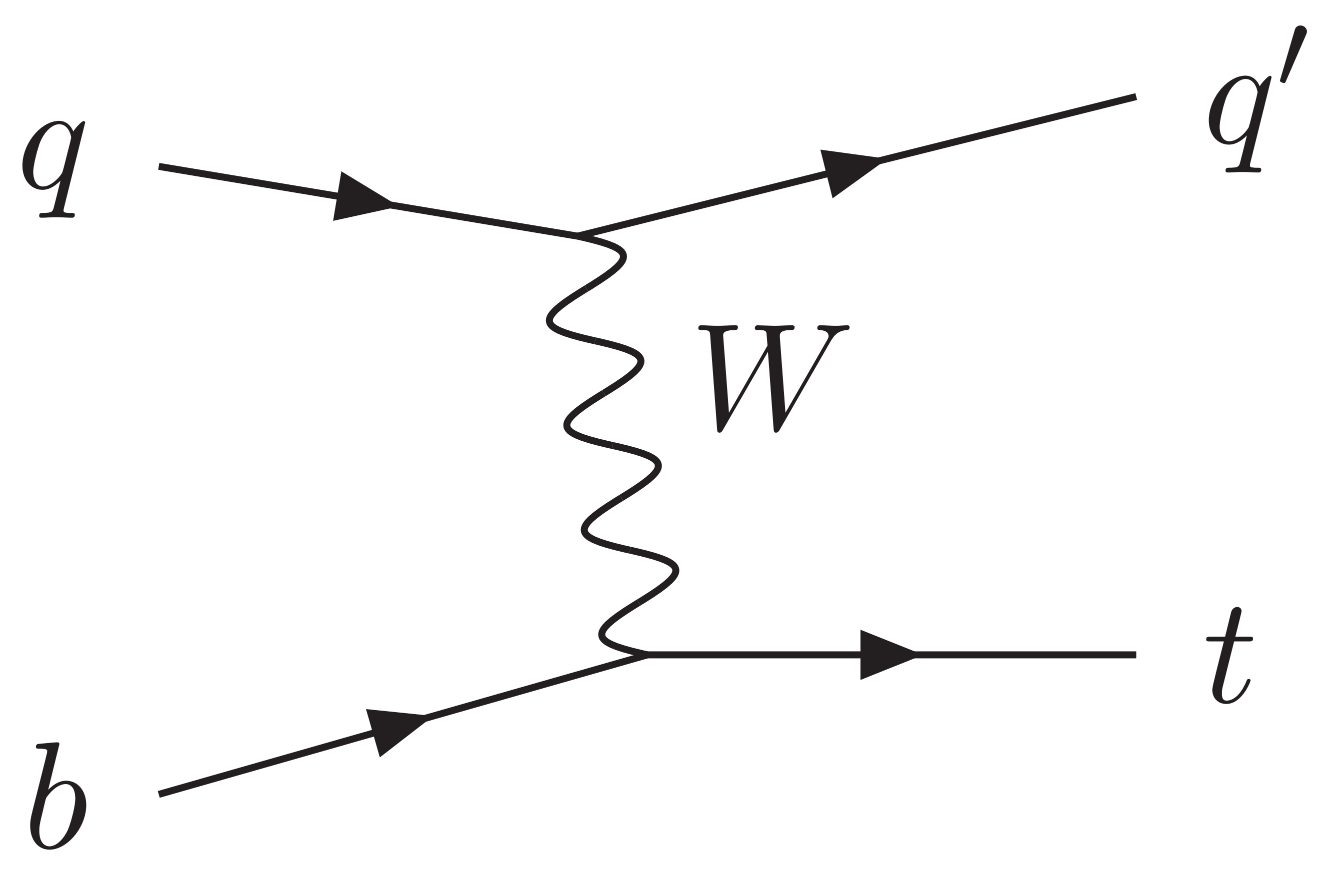
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SingleTopRefXsec

The goal is to provide a common inclusive reference cross section for single-top to be used by the ATLAS and CMS collaborations. Until the newly available *t* channel NNLO prediction and its uncertainties are fully expressed and available for the parameter values of choice, this reference cross section is obtained with automated NLO tools which guarantee flexible and easily configurable settings in order to be in accordance with configurations used for Monte Carlo samples and agreed-on parameter values. Predictions for the *t* channel cross sections at NLO in QCD have been prepared using the Hathor v2.1 program (P. Kant et al., arXiv:1406.4403 and M. Aliev et al., arXiv:1007.1327) in a common ATLAS-CMS effort. The same applies to the *s* channel, while the approx. NNLO predictions of Kidonakis are the reference for Wt.

- Past time for latest NNLO QCD predictions, EW effects, etc. to be exploited for the evaluation of cross-sections and associated parametric, theoretical uncertainties.
- Future-proof the theory input for the expected march to experimental precision.
- This talk: focus on t-channel, highest priority and lots of recent progress.

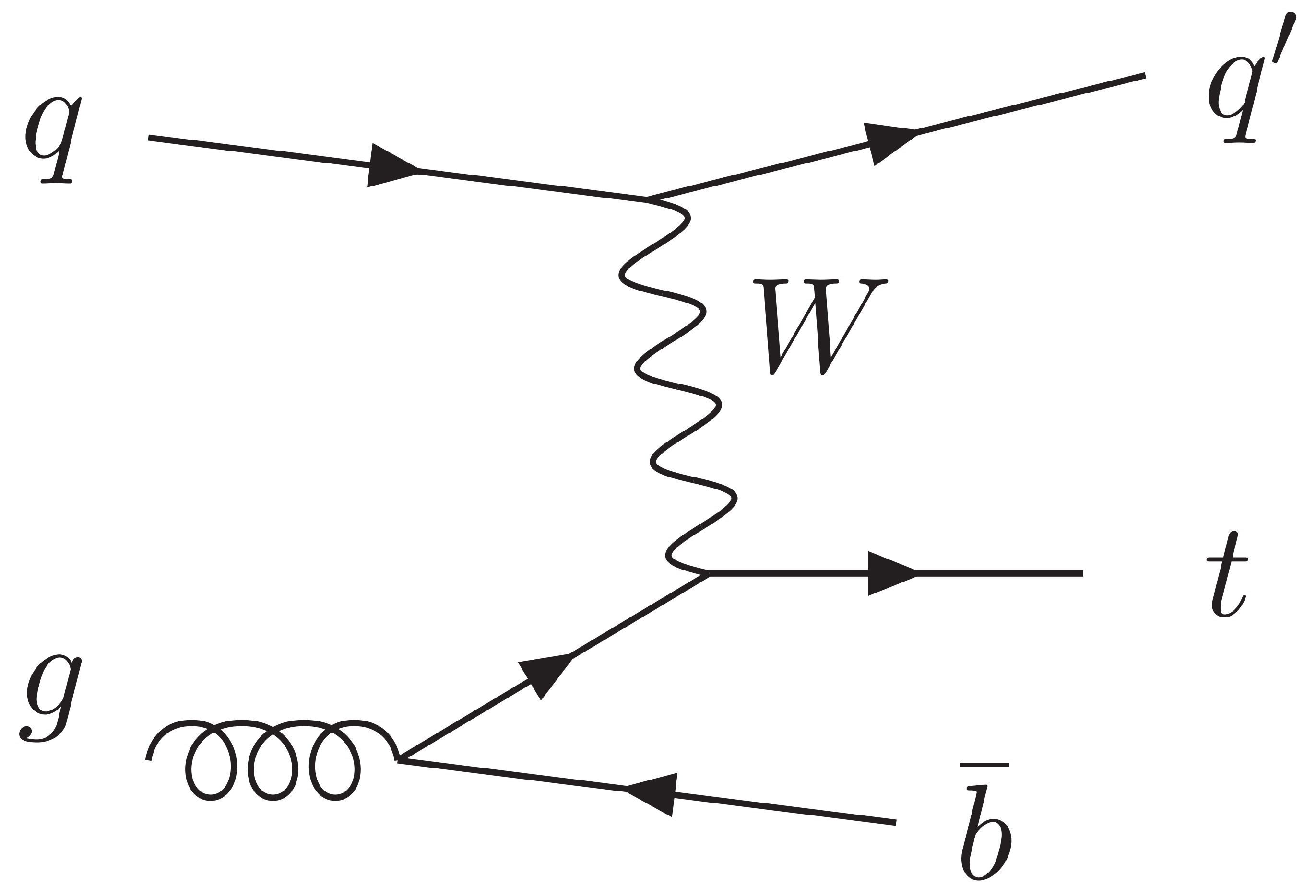
t-channel

5 flavour scheme



- b-pdf (resums large logs)
- simpler (NNLO)

4 flavour scheme



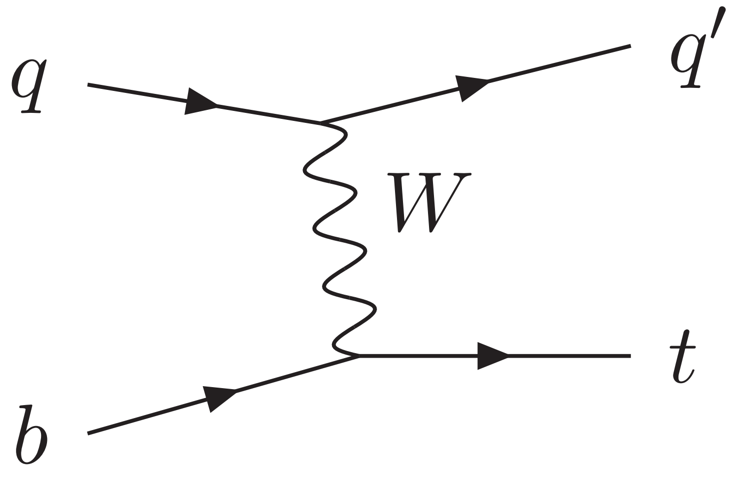
- exposes g→bb splitting, sensitivity to spectator b
- 2→3 with two masses (NLO)

4F vs 5F scheme

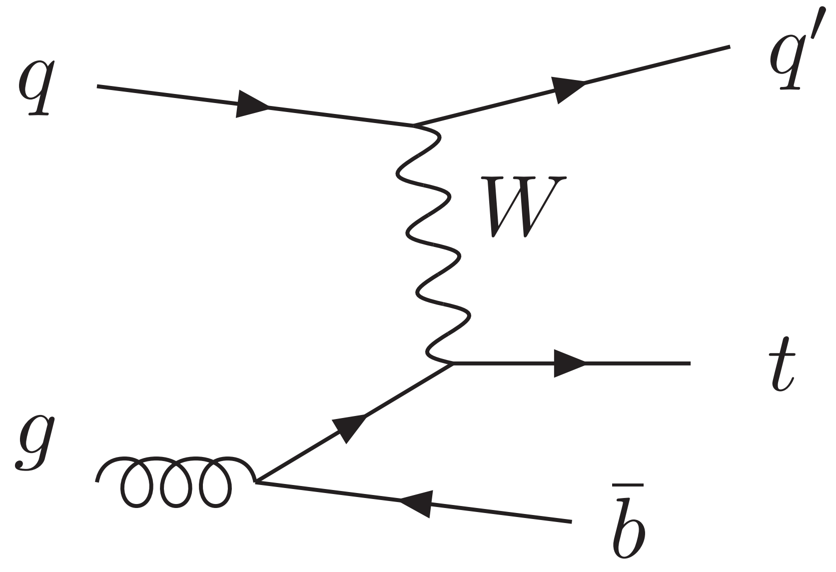
Gao and Berger, https://arxiv.org/abs/2005.12936

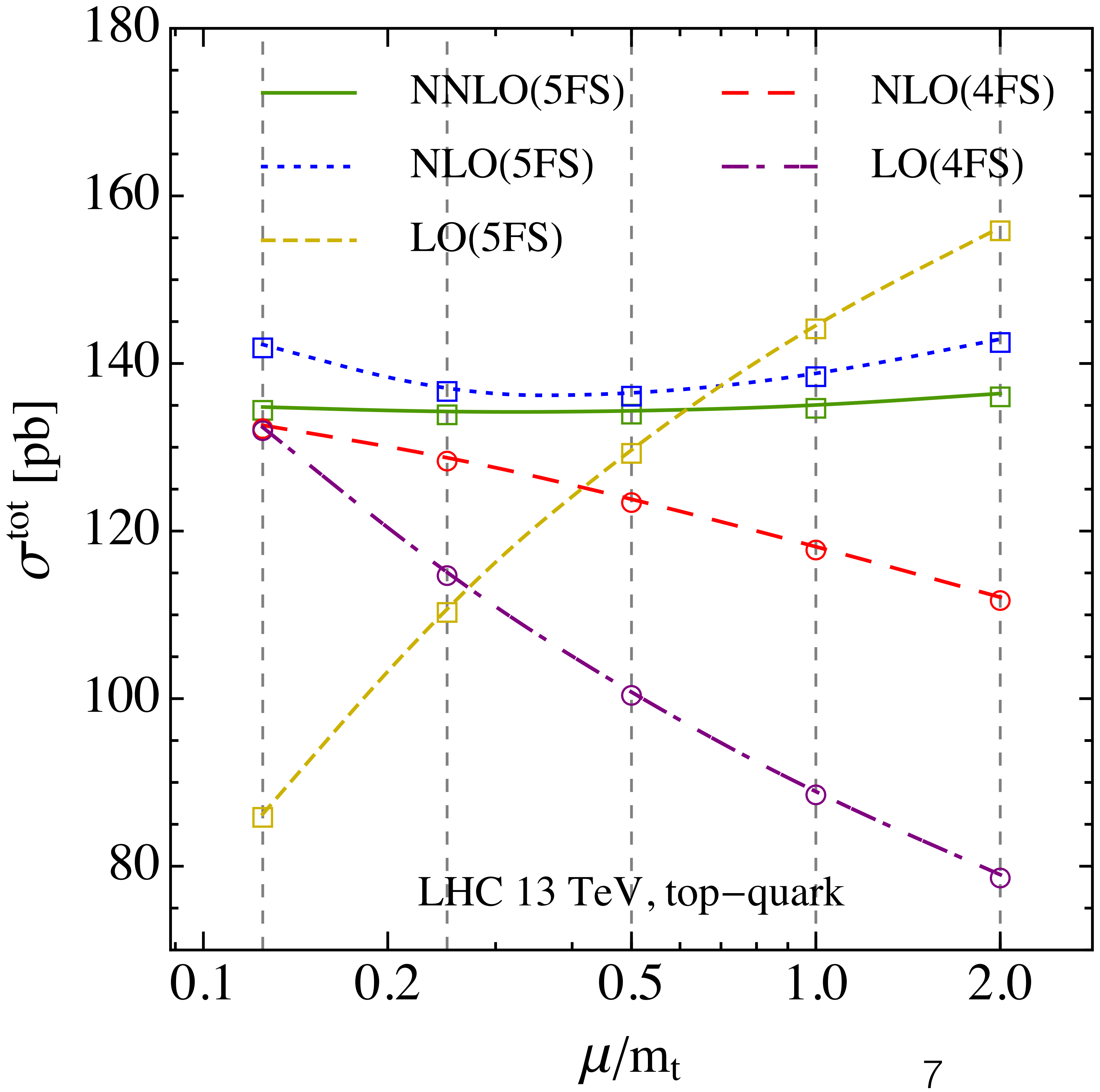
- Good agreement in top-quark distributions, 4FS normalization low except for small scale

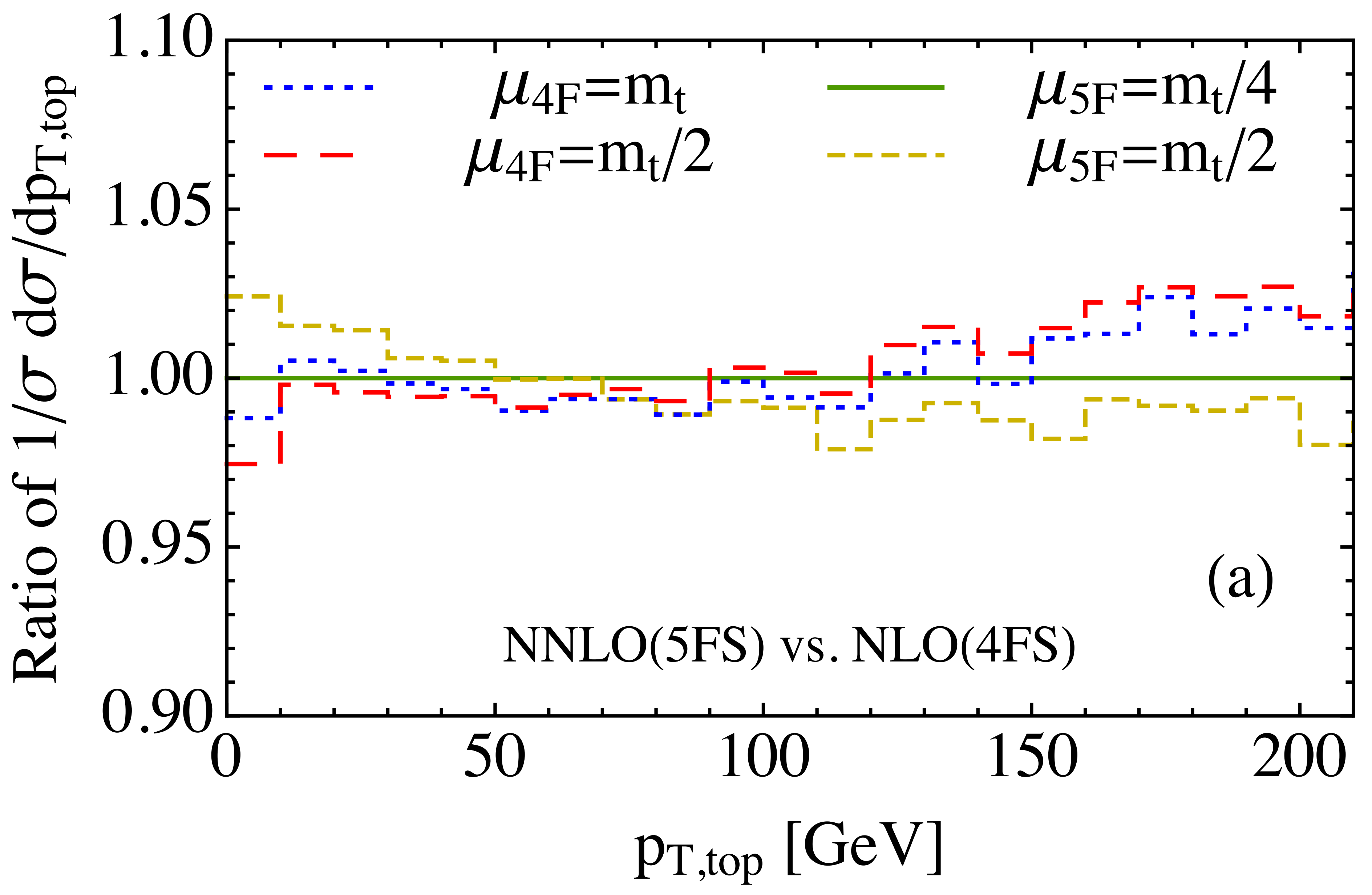
5FS

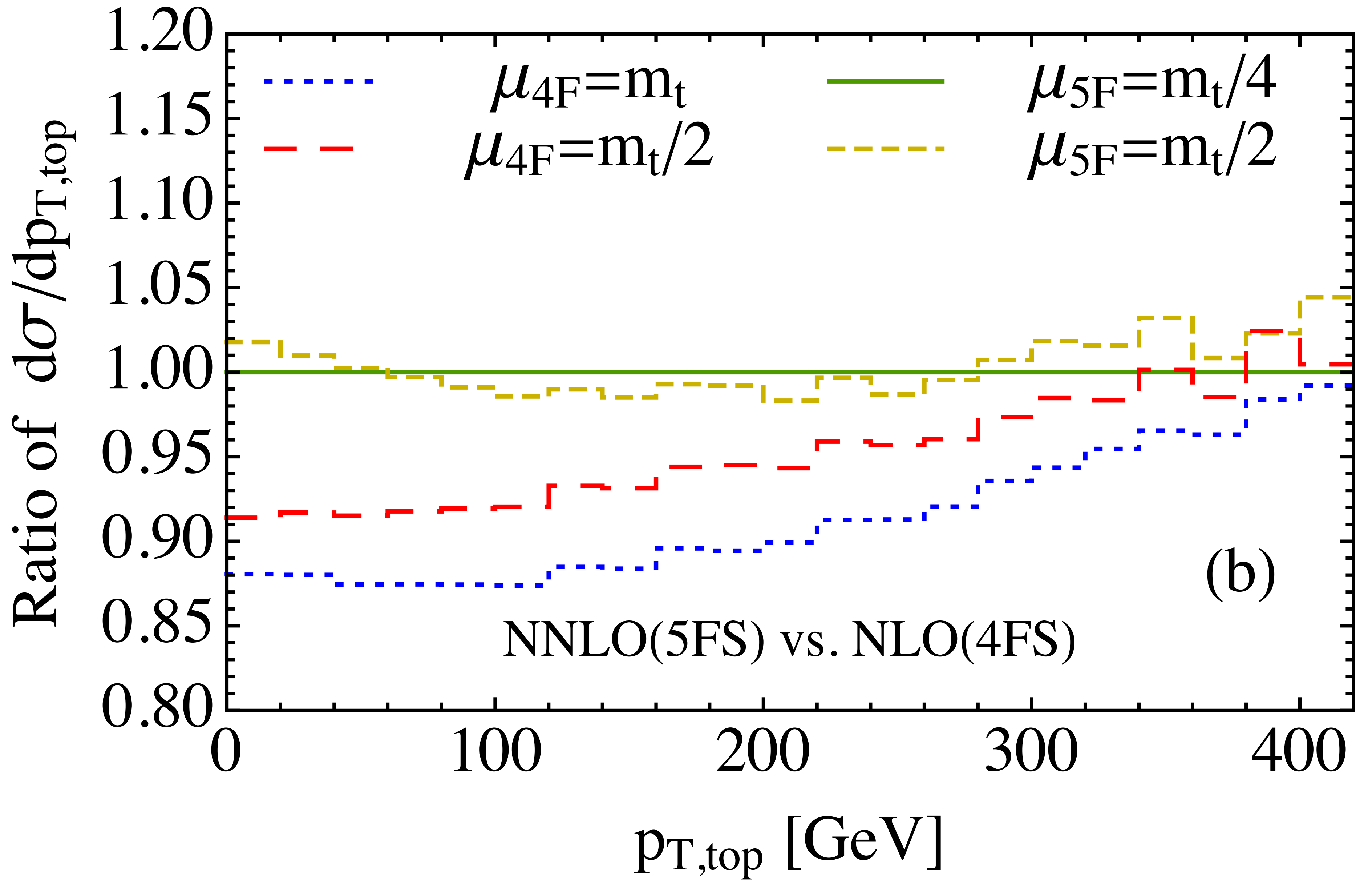


4FS





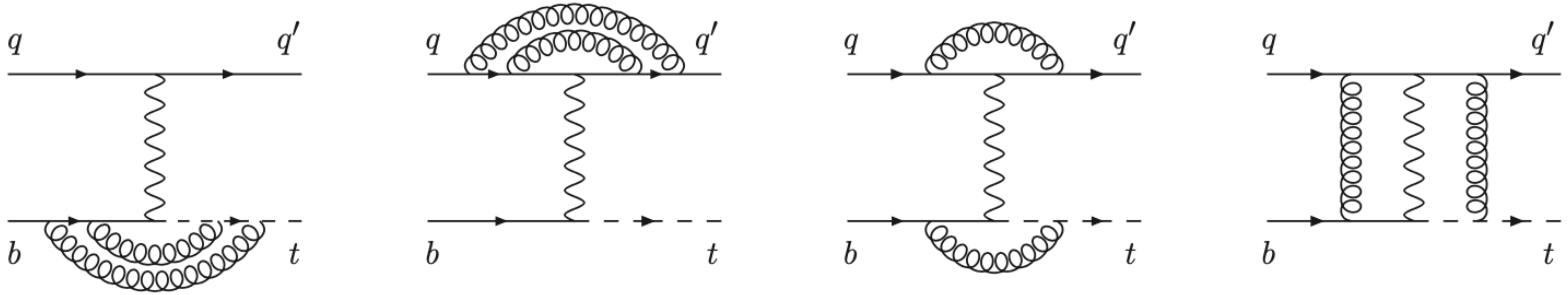




t-channel at NNLO

- First calculated for a stable top-quark using NNLO sector subtraction

Brucherseifer, Caola, Melnikov, https://arxiv.org/abs/1404.7116

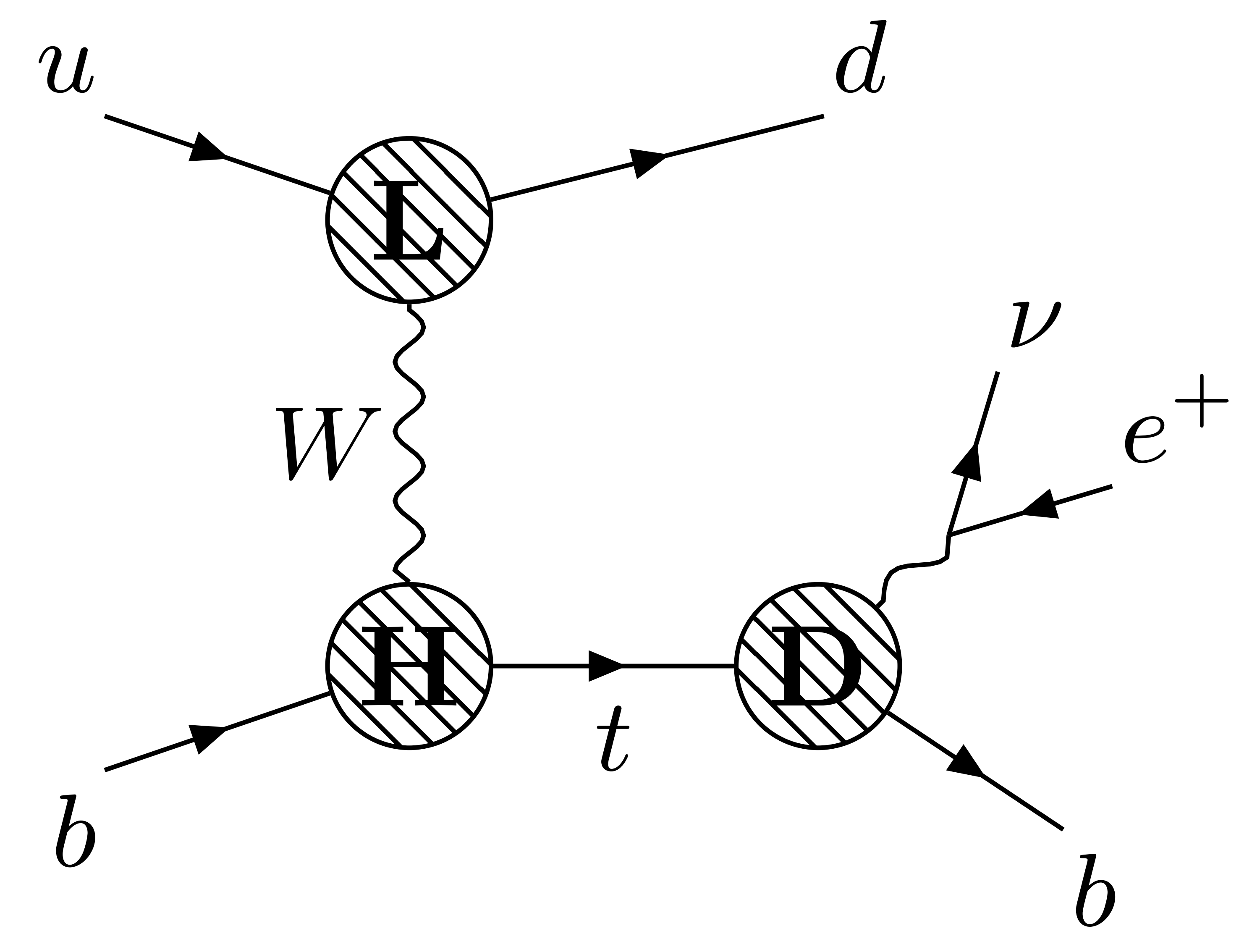


- Structure function approximation — corrections to heavy and light lines separately (NNLO) and interference (NLOxNLO).
  - non-factorizable contributions neglected, relative size $O(\alpha_s^2/N_c^2)$.
- Effect of NNLO on inclusive cross-section and top p_T distribution small ~ [-2%, +2%].

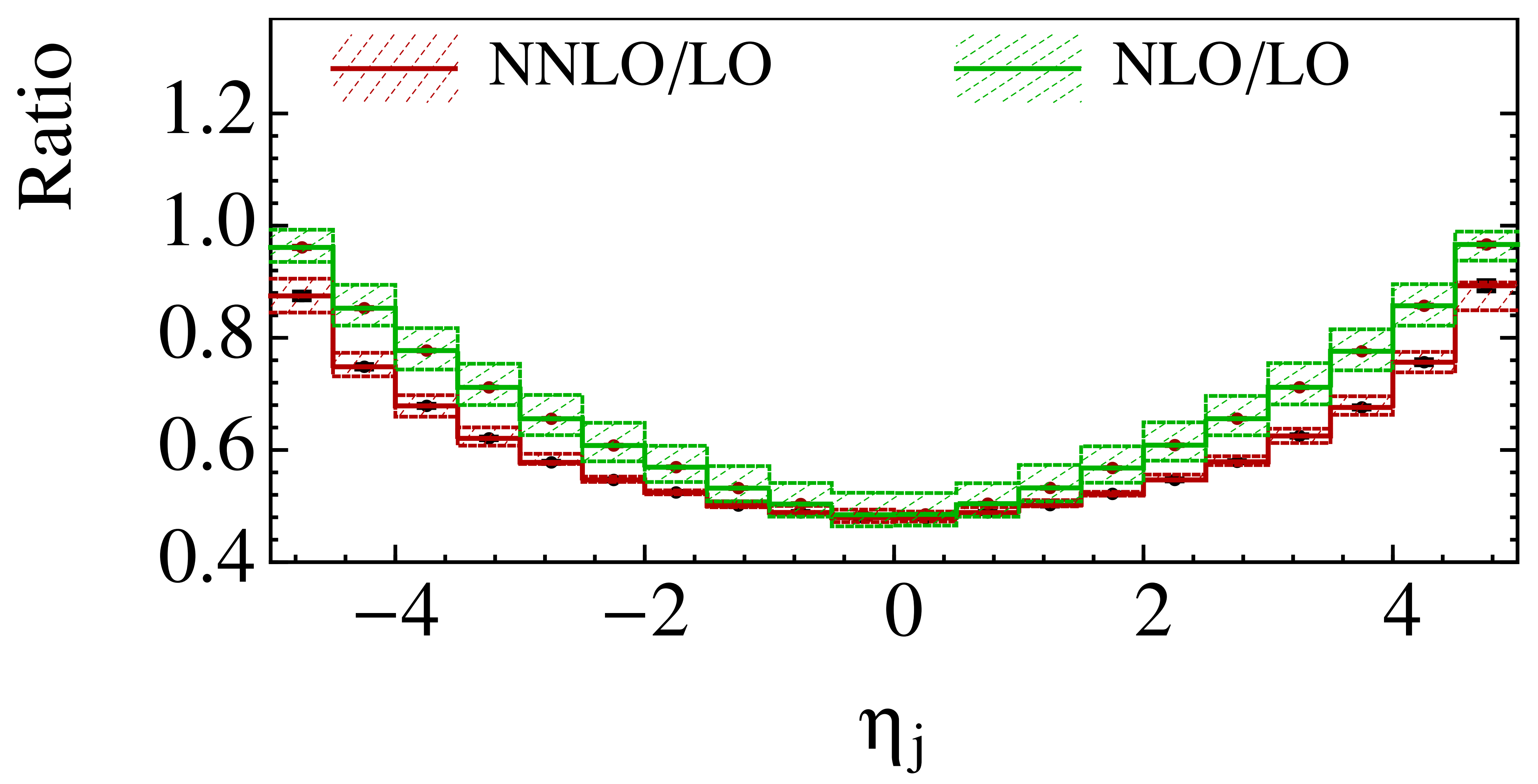
- Extension to top-quark decay in narrow-width approximation, including also NNLO in decay (computed using combination of SCET/jettiness + projection to Born)

Berger, Gao, Yuan, Zhu, https://arxiv.org/abs/1606.08463; https://arxiv.org/abs/1708.09405

(also top decay: BCM, https://arxiv.org/abs/1301.7133)



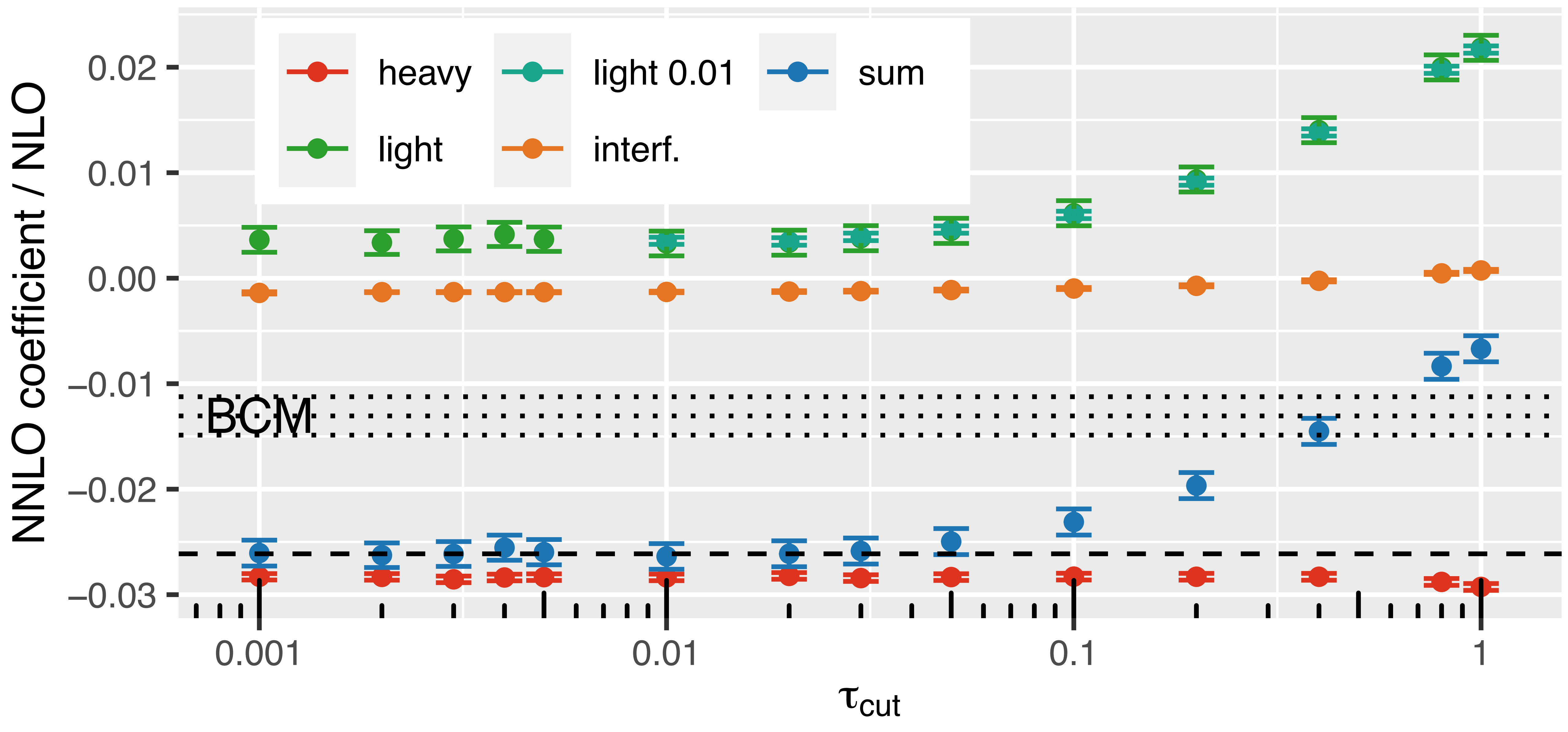
- Larger corrections ~ 10% in regions of some distributions.
- Disagreement with earlier calculation of inclusive cross-section
  - only percent-level on total but O(1) difference in NNLO coefficient



Production and decay at NNLO: redux

- Single top too important to leave theoretical ambiguity unresolved!
- New calculation based on SCET approach, all ingredients re-computed from scratch and independently verified where possible.

JC, Neumann, Sullivan, https://arxiv.org/abs/2012.01574)



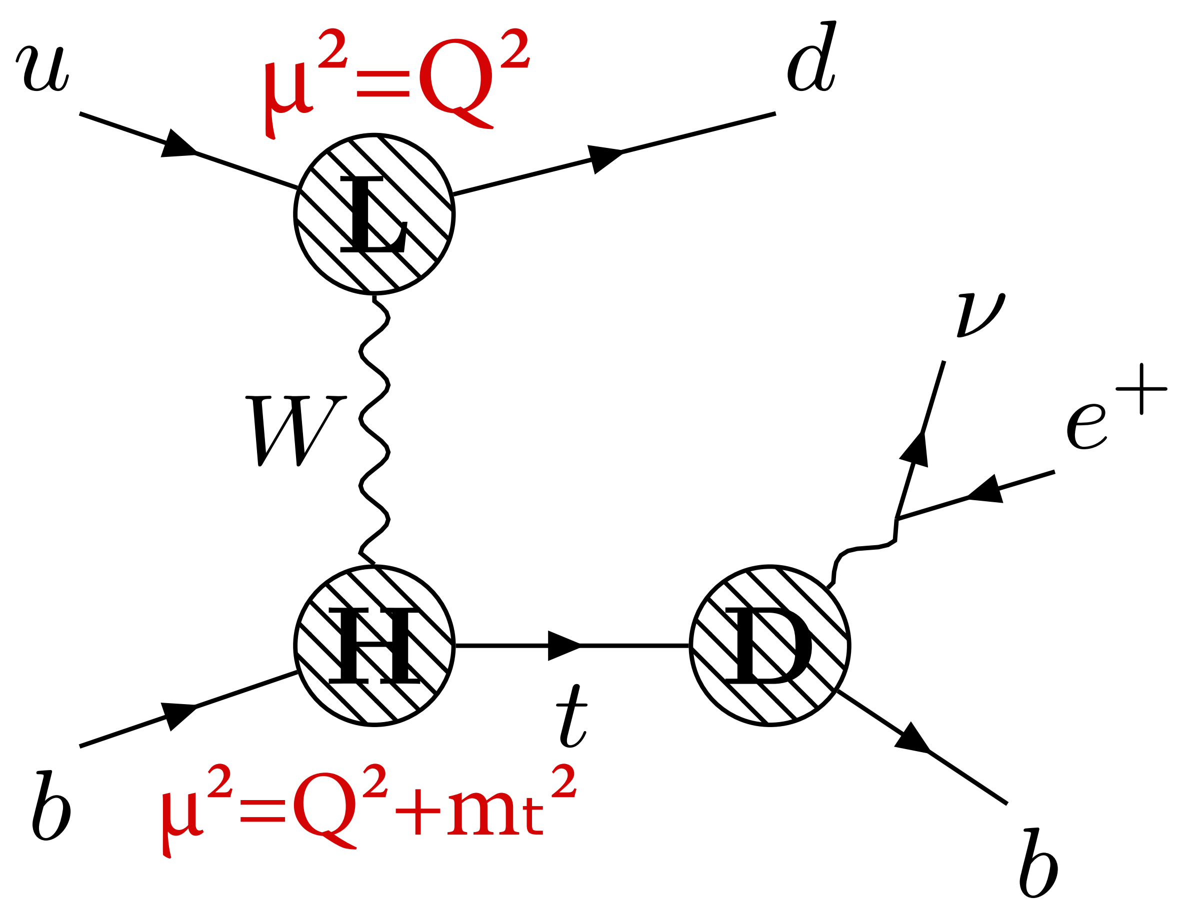
		$\sigma_{\rm NNLO}^{\rm BGZ}$	$\sigma_{\rm NNLO}$
7 TeV	top	$42.05^{+1.2\%}_{-0.6\%}$	$41.99(4)^{+1.4\%}_{-0.7\%}$
	anti-top	$21.95^{+1.2\%}_{-0.7\%}$	$21.90(3)^{+1.4\%}_{-0.8\%}$
14 TeV	top	$153.3^{+1.1\%}_{-0.5\%}$	$153.2(2)^{+1.2\%}_{-0.6\%}$
	anti-top	$91.81^{+1.0\%}_{-0.5\%}$	$91.5(1)^{+1.2\%}_{-0.7\%}$

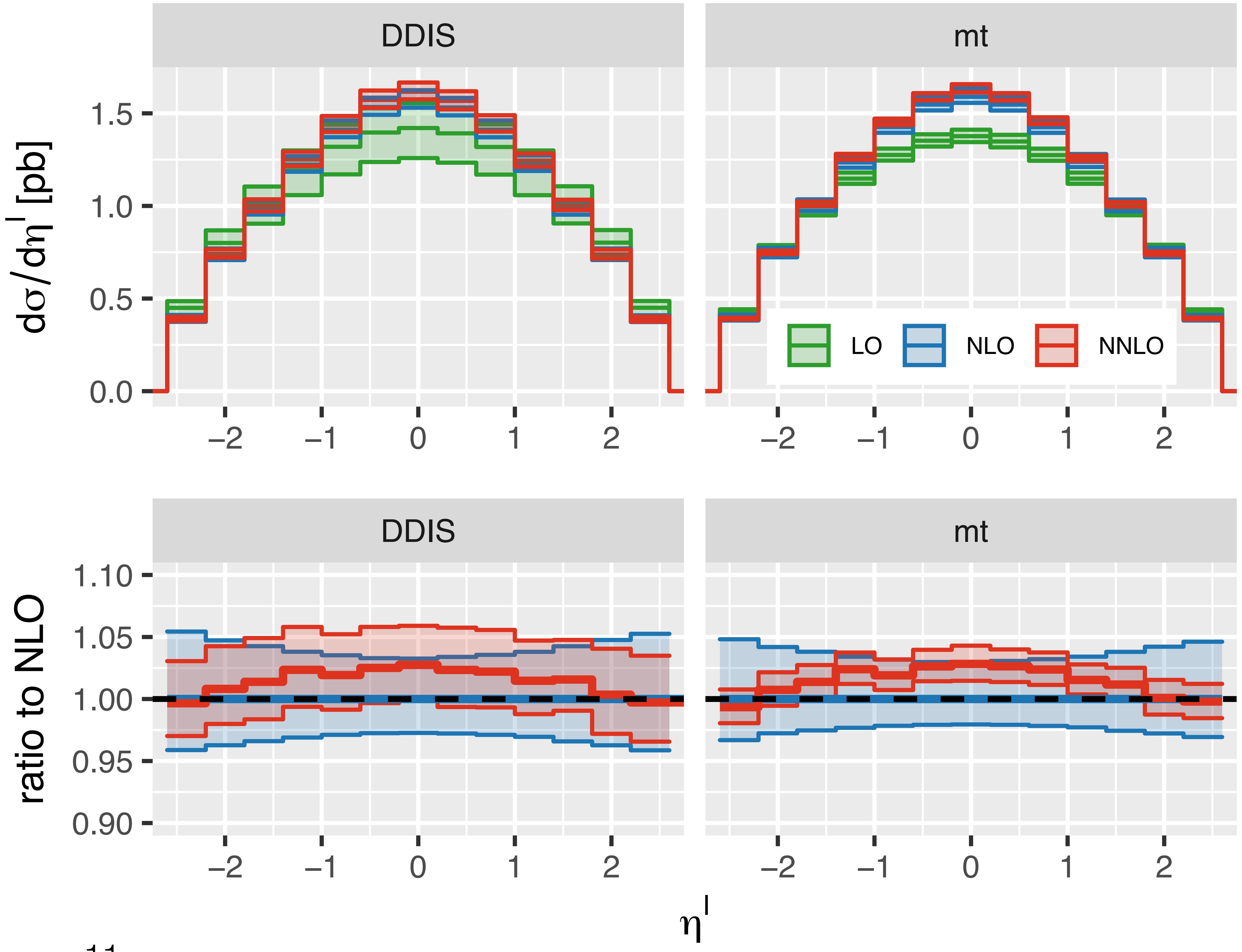
same O(1%) difference with BCM

perfect agreement with BGZ (also in distributions)

Scale choice

- Calculation also allows for double-deep inelastic scattering “DDIS” scales to match extraction of PDFs.



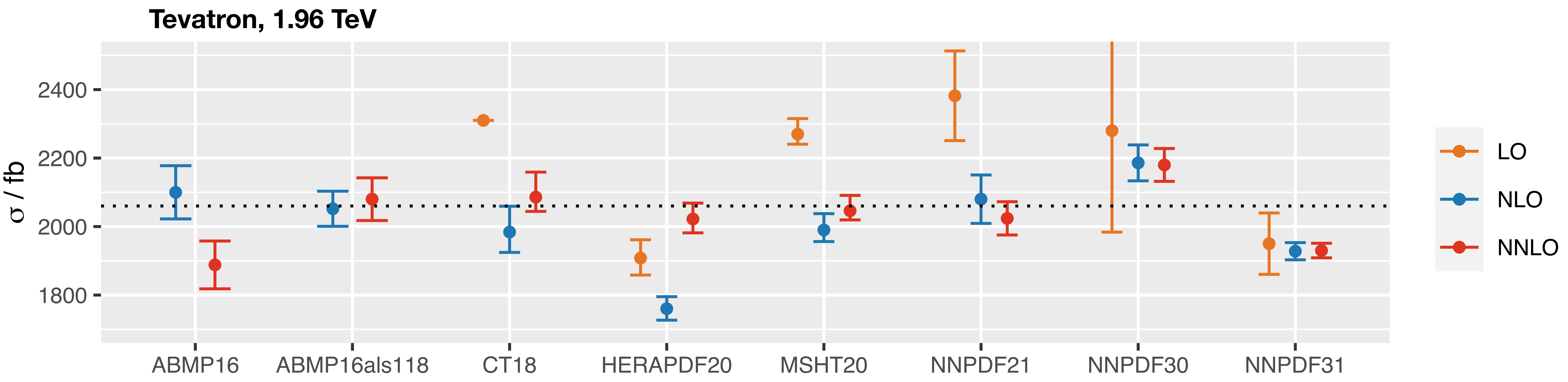


- Scale uncertainties larger (compared to m_t), suggesting more robust choice.

Consistency across orders

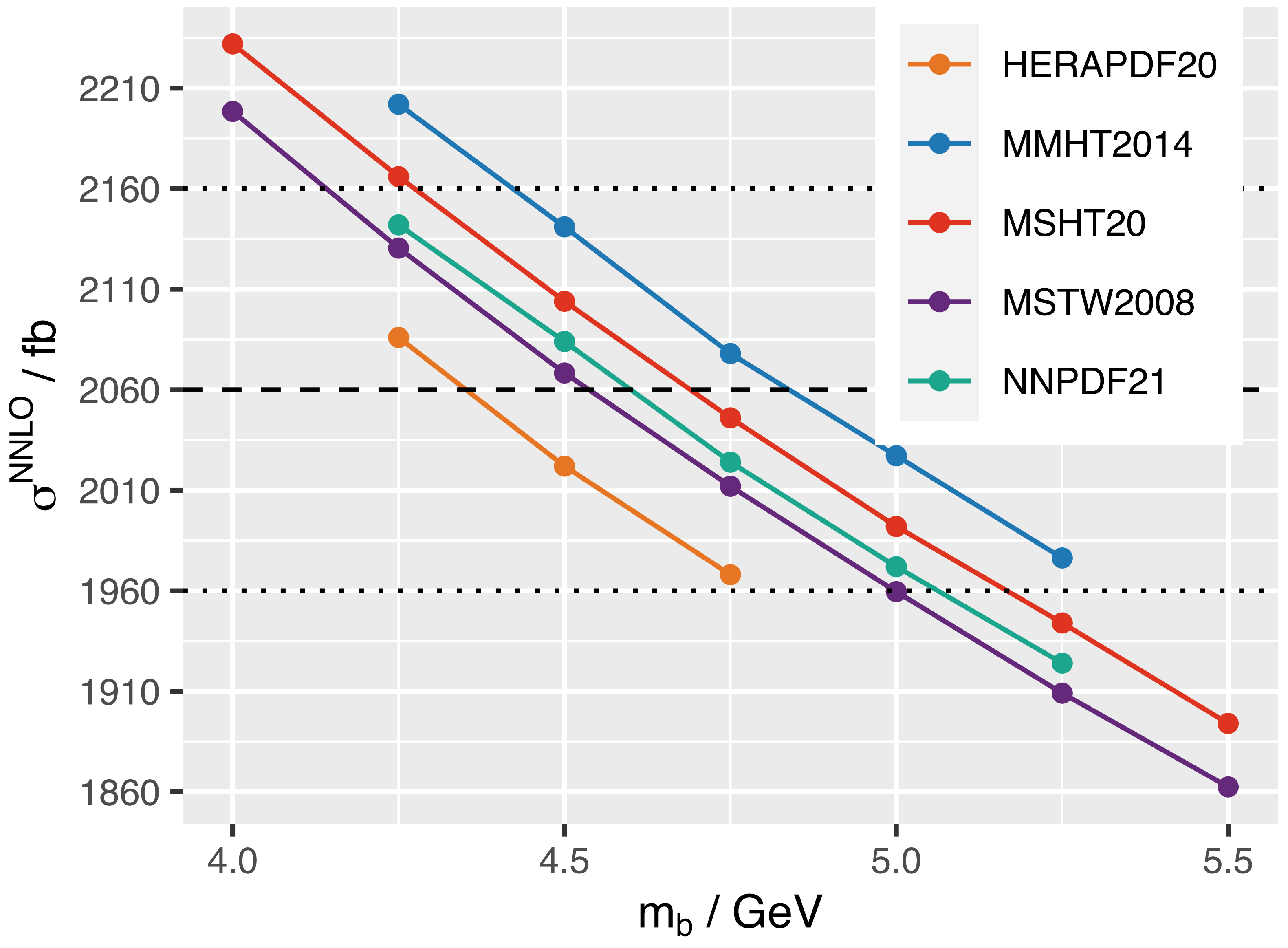
JC, Neumann, Sullivan, to appear

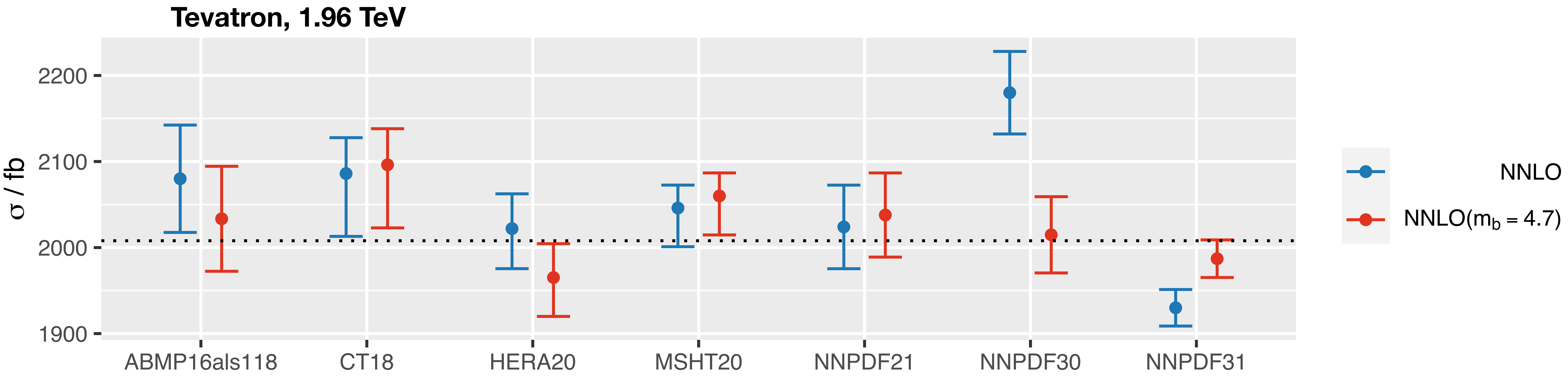
- Many PDF constraints come directly from DIS data → PDFs extracted at each order, combined with fixed-order prediction at same order, should agree
- Using DDIS scales, t-channel single-top tests this directly.
- Mostly consistent at NLO, NNLO; couple of sets minimal/no overlap (ABMP16, HERA2.0)



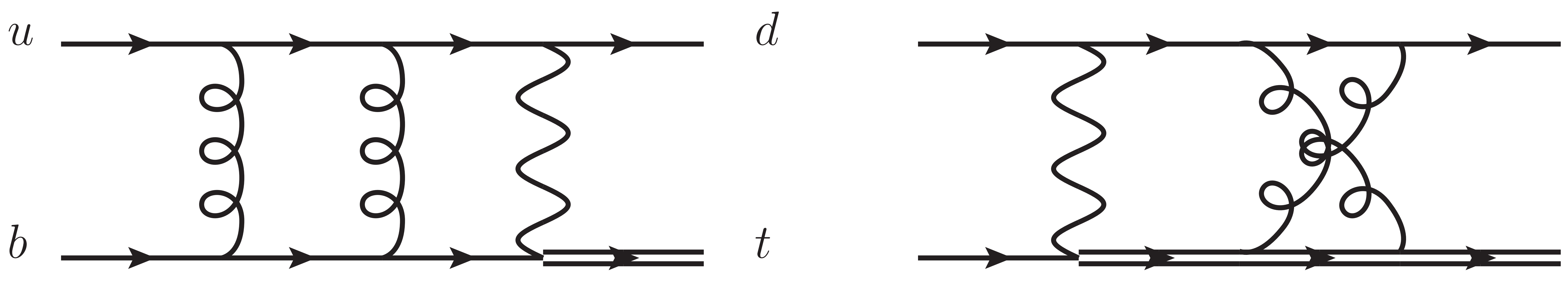
Sensitivity to m_b

- Difference between predictions of PDF fits mostly due to input value of m_b, e.g. NNPDF3.0 (4.18 GeV), NNPDF3.1 (4.92 GeV)
- Much better agreement after rescaling to m_b=4.7 GeV.
- Eventually expt. uncertainties will be small enough to be sensitive to such differences at the LHC → sharpen PDF constraints, effects propagated to other processes via sum rules
  - ideally, include m_b variation in standard uncertainty envelope





Non-factorisable contributions



Bronnum-Hansen et al, https://arxiv.org/abs/2108.09222

Basat et al, https://arxiv.org/abs/2102.08225

(also Assadsolimani et al, https://arxiv.org/abs/1409.3654)

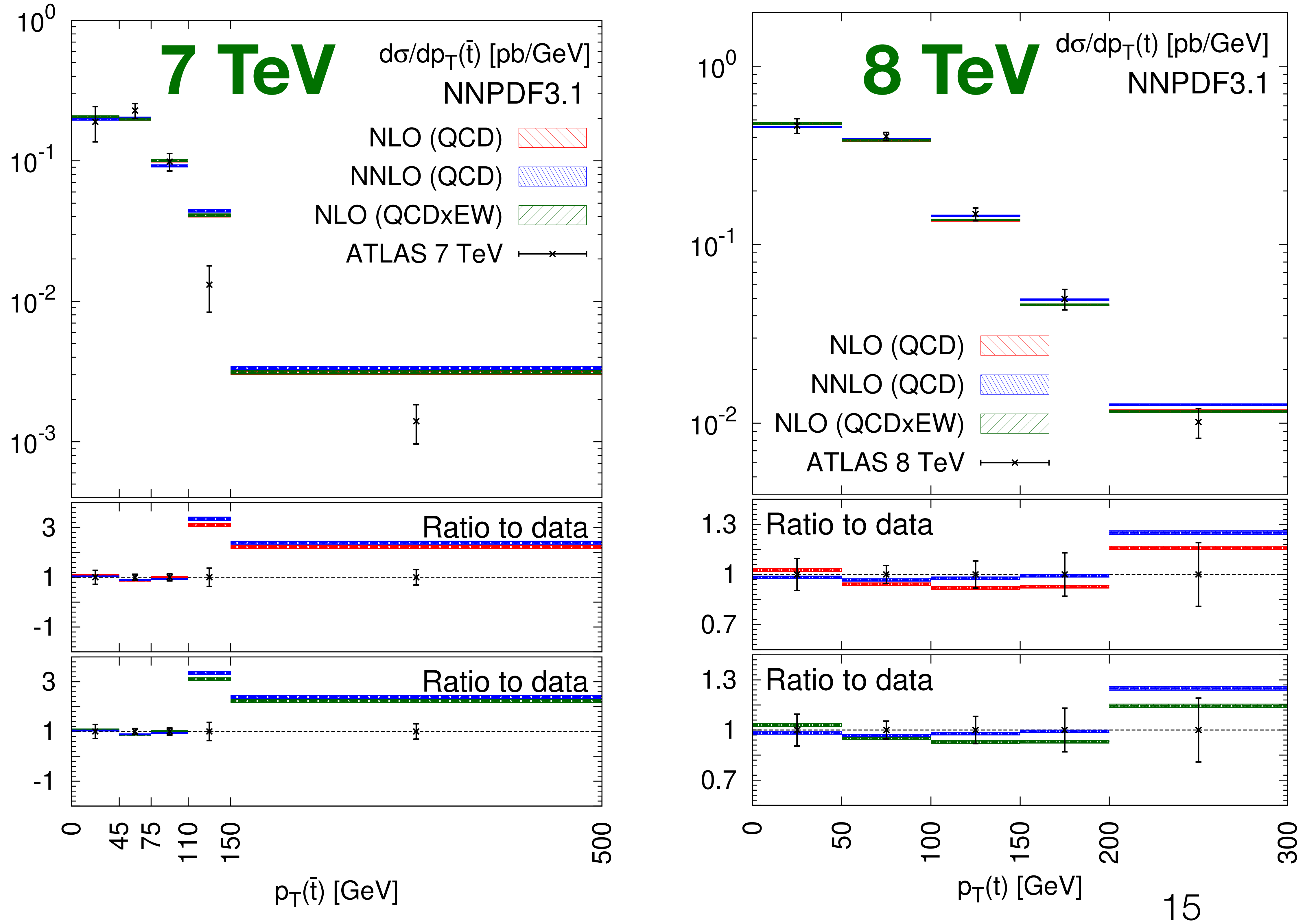
- May not be as suppressed as originally thought, actually proportional to $(\alpha_s \pi / N_c)^2$, c.f. calculation of WBF process. Liu, Melnikov, Penin, https://arxiv.org/abs/1906.10899
- Non-factorisable 2-loop virtual amplitude recently computed analytically with full dependence on m_t. Bronnum-Hansen et al, https://arxiv.org/abs/2108.09222
- Integrals computed numerically, demonstrated to be sufficiently robust for phenomenology.
- Full study on the way, preliminary results indicate size of corrections may be similar to factorisable contribution:

$$\sigma^{ub}_{pp\to dt} = \left(90.3 + 0.3\left(\frac{\alpha_s(\mu_{\rm nf})}{0.108}\right)^2\right)\ \text{pb}$$

Single top in PDF fits

Nocera, Ubiali and Voisey, https://arxiv.org/abs/1912.09543

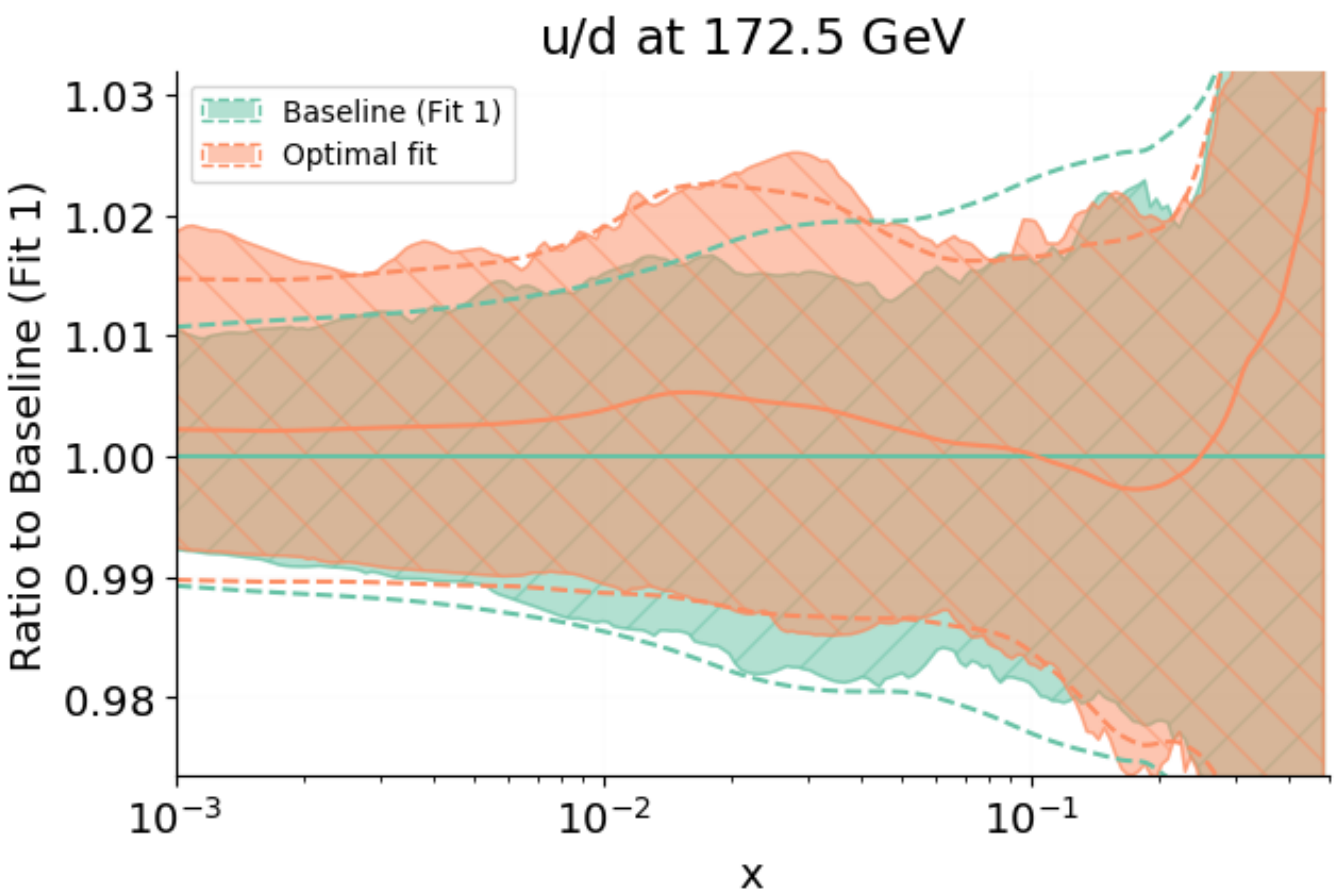
- Based on NNPDF3.1, assessing impact of single-top datasets.
- Most 8, 13 TeV differential data not included — lack of detailed uncertainty/correlation information.
- Some distributions at 7 TeV— notably $p_T(t)$ — not well-described by theory.
  No such disagreement at 8 TeV, perhaps measurement issue?

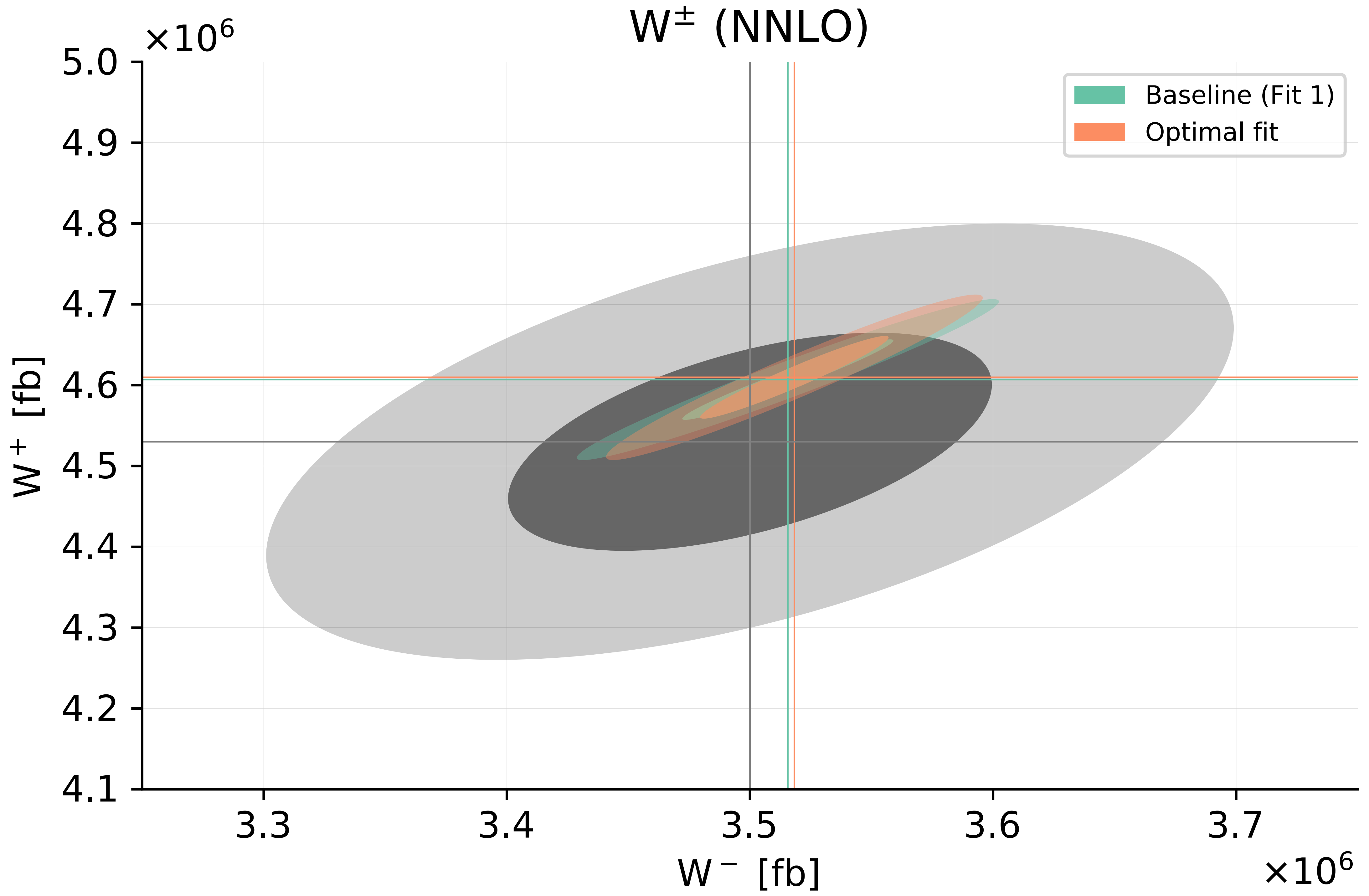


Dataset	Optimal fit
Global baseline	**y**
ATLAS $\sigma_t/\sigma_{\bar{t}}$ 7 TeV	**y**
ATLAS $\sigma_t/\sigma_{\bar{t}}$ 8 TeV	n
ATLAS $\sigma_t/\sigma_{\bar{t}}$ 13 TeV	**y**
CMS $\sigma_t/\sigma_{\bar{t}}$ 8 TeV	**y**
CMS $\sigma_t/\sigma_{\bar{t}}$ 13 TeV	**y**
CMS $\sigma_{t+\bar{t}}$ 7 TeV	**y**
ATLAS $d\sigma/dp_T(t)$ 7 TeV	n
ATLAS $d\sigma/dp_T(\bar{t})$ 7 TeV	n
ATLAS $d\sigma/d\|y(t)\|$ 7 TeV	n
ATLAS $d\sigma/d\|y(\bar{t})\|$ 7 TeV	n
ATLAS $(1/\sigma)d\sigma/dp_T(t)$ 7 TeV	n
ATLAS $(1/\sigma)d\sigma/dp_T(\bar{t})$ 7 TeV	n
ATLAS $(1/\sigma)d\sigma/d\|y(t)\|$ 7 TeV	**y**
ATLAS $(1/\sigma)d\sigma/d\|y(\bar{t})\|$ 7 TeV	**y**

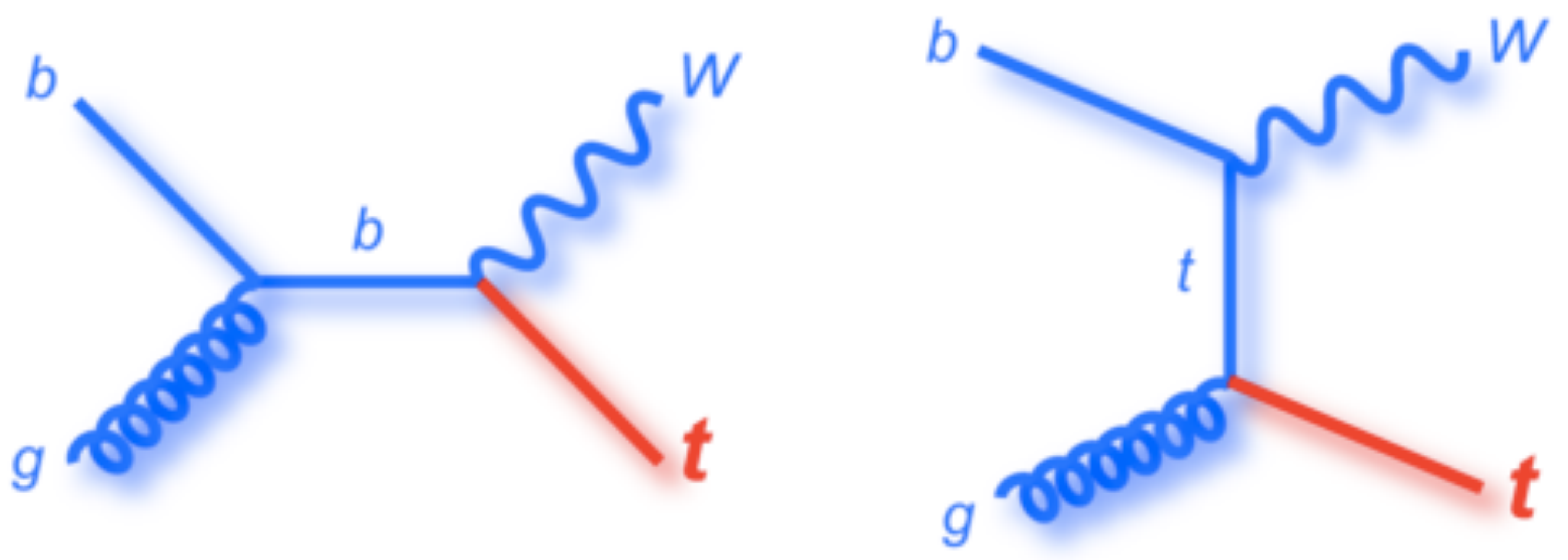
Impact on u/d ratio

- Moderate decrease in uncertainties for *x* ~ [0.01, 0.5], driven by **σ**(t)/**σ**(t̄)
- Reflected in very small shift in **σ**(W^+) and **σ**(W^-), within current expt. uncertainties.





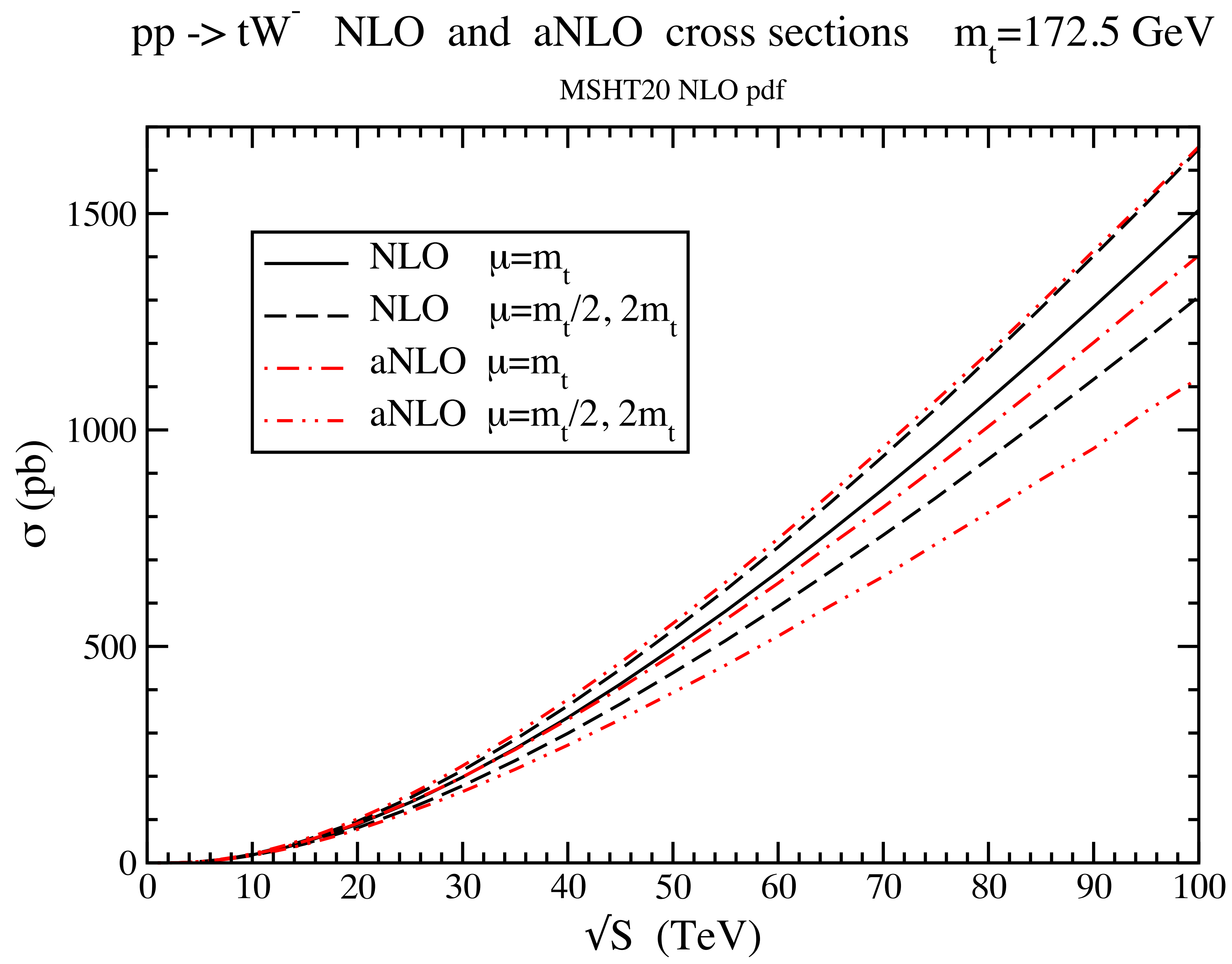
Associated tW production

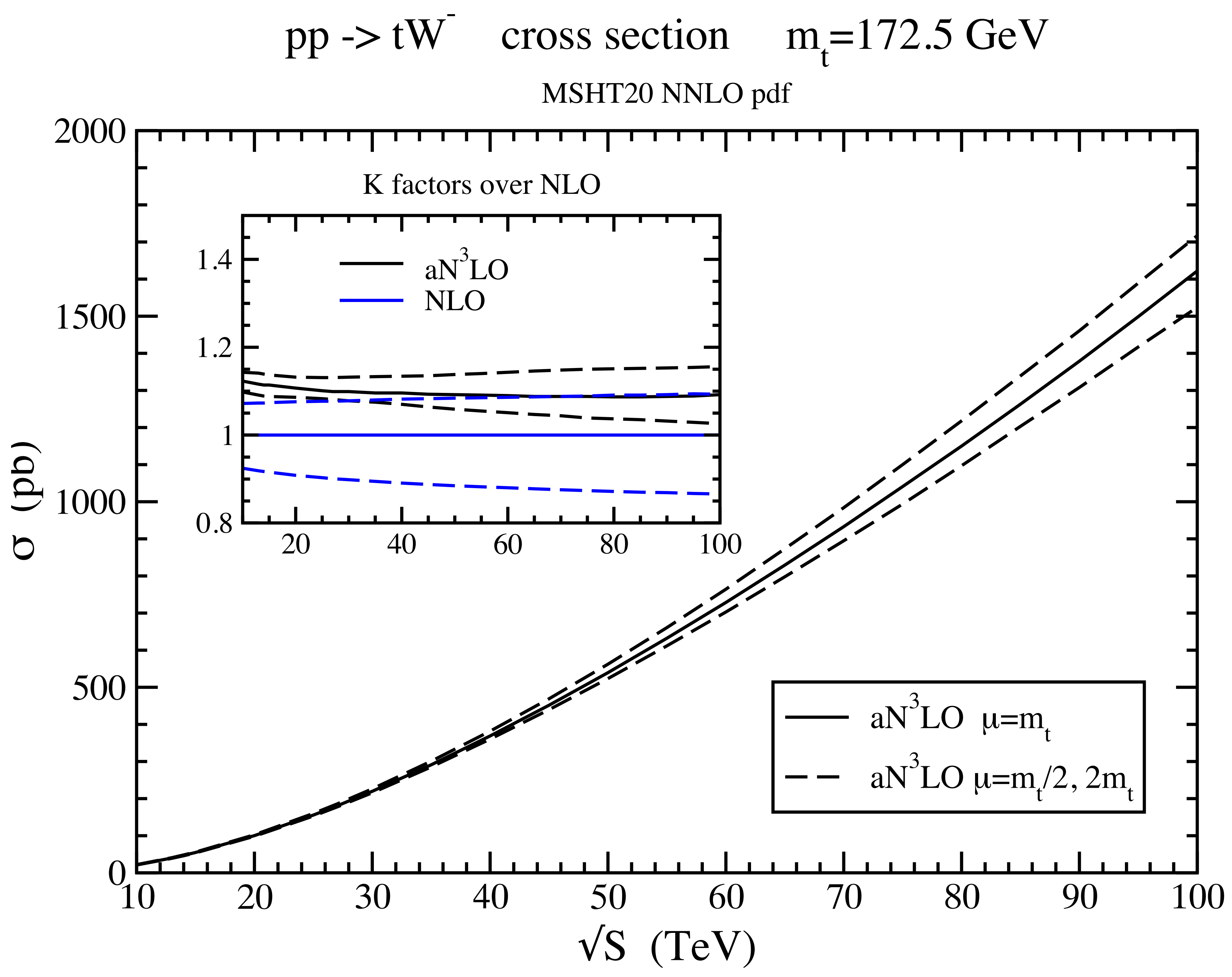


Latest developments

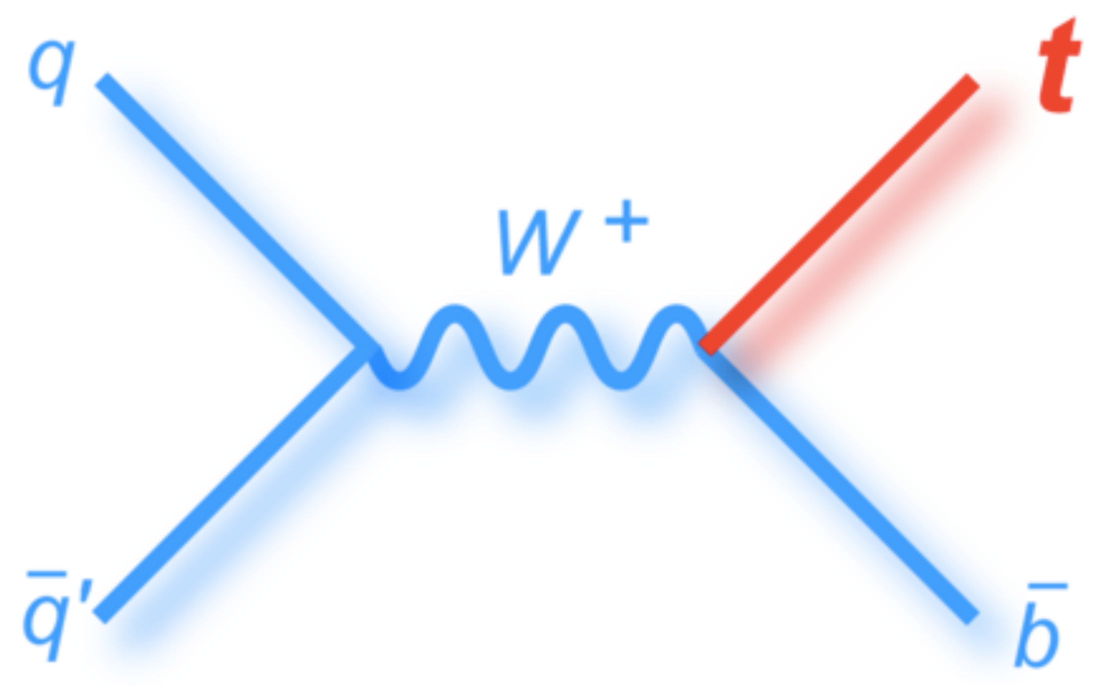
- Not yet known at NNLO — too many masses for current 2-loop methods.
- Approximate approaches fill the gap, can capture salient features of higher-order corrections, e.g. reduced scale uncertainty.
- State-of-the-art: soft-gluon corrections to approximate N³LO — "aN³LO" — for (stable) top + W, underpinned by comparison of aNLO vs. exact NLO (performs extremely well even at 100 TeV).

Kidonakis and Yamanaka, https://arxiv.org/abs/2102.11300





s-channel



Current status

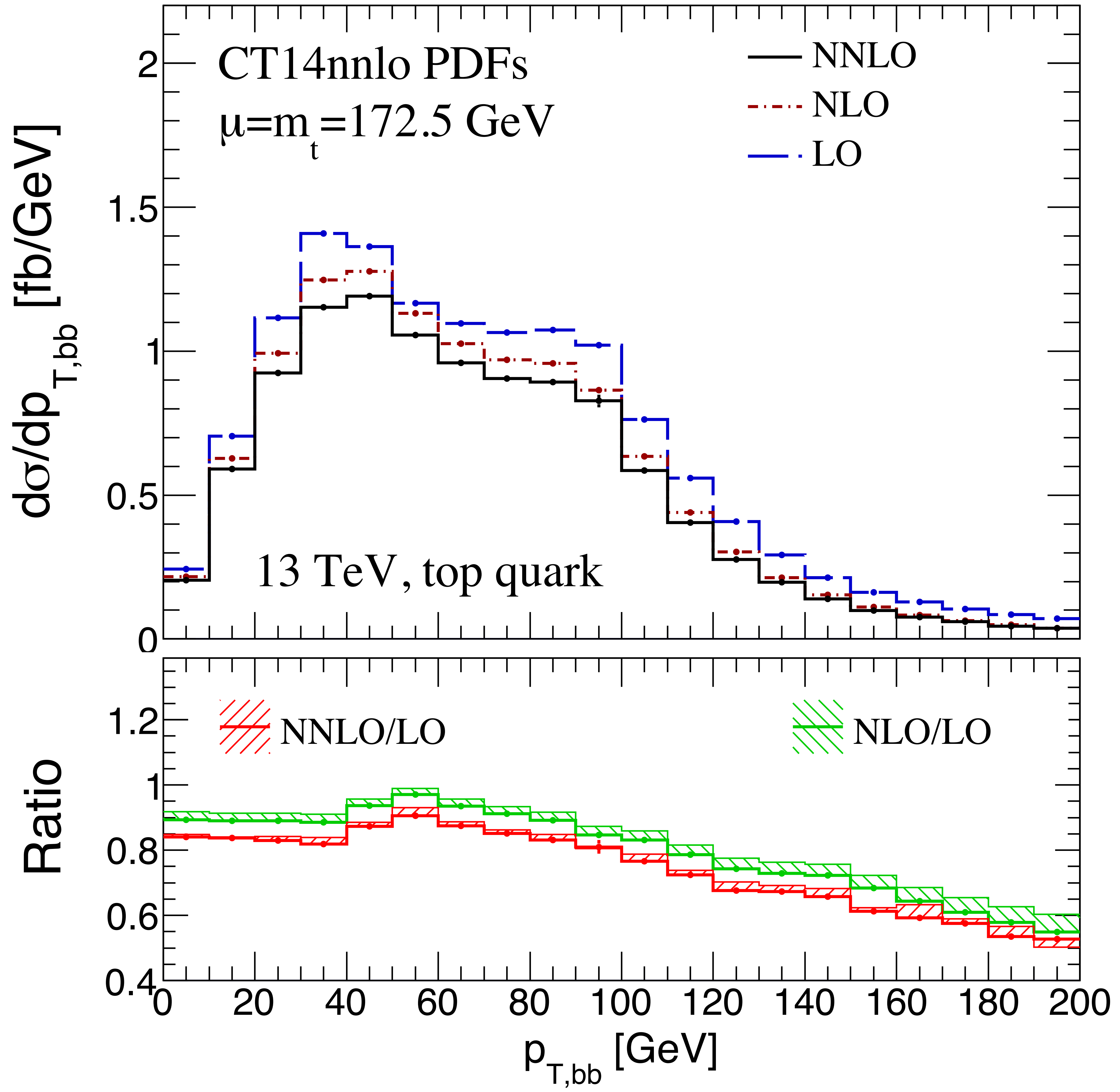
- Current status: NNLO QCD in production and decay (SCET/jettiness)

  Gao, Liu, https://arxiv.org/abs/1807.03835

- Corrections +5% overall, little overlap between orders.

inclusive		LO	NLO	NNLO
13 TeV	$\sigma(t)$ [pb]	$4.775^{+2.69\%}_{-3.50\%}$	$6.447^{+1.39\%}_{-0.91\%}$	$6.778^{+0.76\%}_{-0.53\%}$
	$\sigma(\bar{t})$ [pb]	$2.998^{+2.69\%}_{-3.55\%}$	$4.043^{+1.33\%}_{-0.94\%}$	$4.249^{+0.69\%}_{-0.48\%}$
	$\sigma(t+\bar{t})$ [pb]	$7.772^{+2.69\%}_{-3.52\%}$	$10.49^{+1.36\%}_{-0.92\%}$	$11.03^{+0.74\%}_{-0.51\%}$
	$\sigma(t)/\sigma(\bar{t})$	$1.593^{+0.05\%}_{-0.01\%}$	$1.595^{+0.06\%}_{0.03\%}$	$1.595^{+0.07\%}_{-0.05\%}$

- Decay allows for fiducial cuts, showing opposite (negative) pattern of corrections in “2 jets, 2 b-tags” analysis.

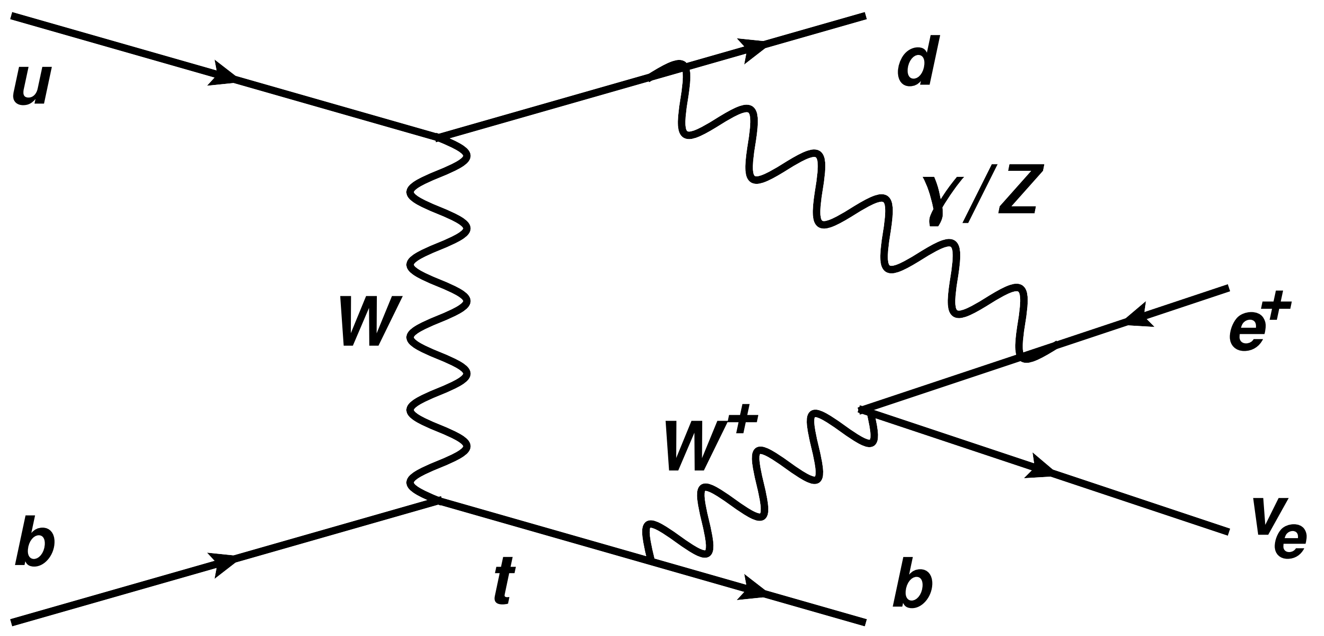


Other developments

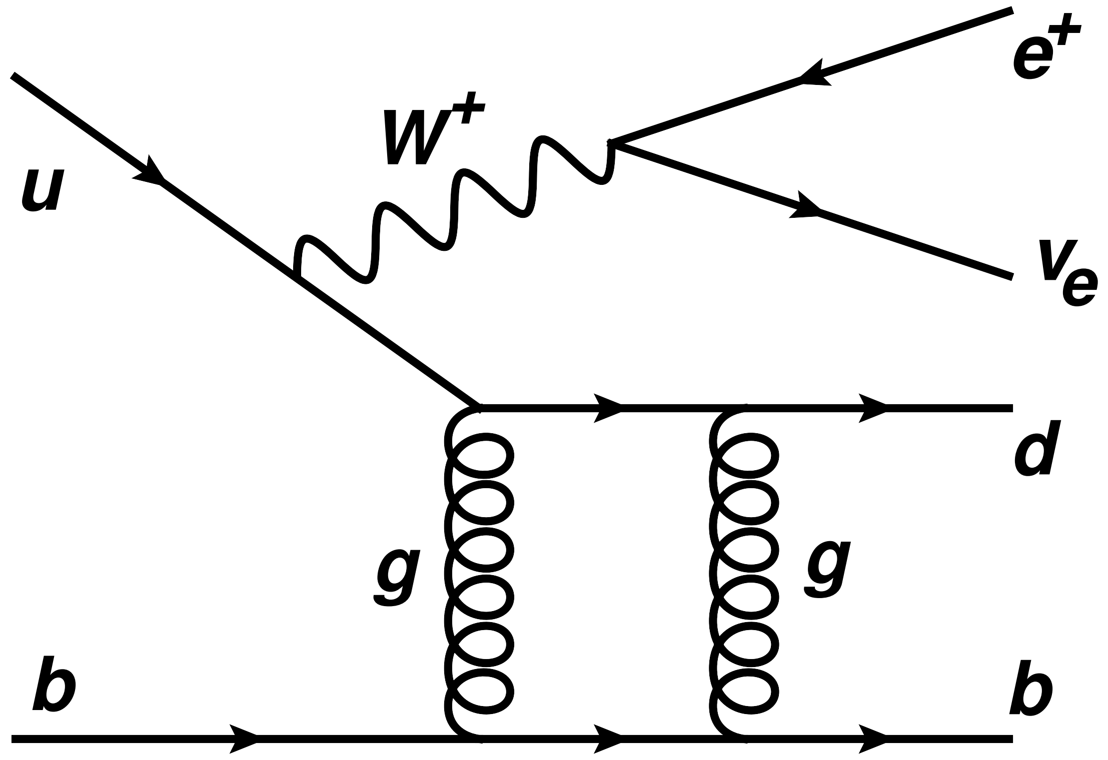
“Complete” single top

- Complementary approach: include all contributions to a given final-state signature (at some order), traditional channels emerge by applying cuts
  - less assumptions, e.g. reliance on narrow-width approximation ✔
  - much more complicated, not highest formal accuracy (no NNLO) ❌
- Study including all NLO QCD and EW effects + QCD shower in MG5_aMC@NLO
  - t-channel signature: lepton, light jet, b-jet, missing E_T

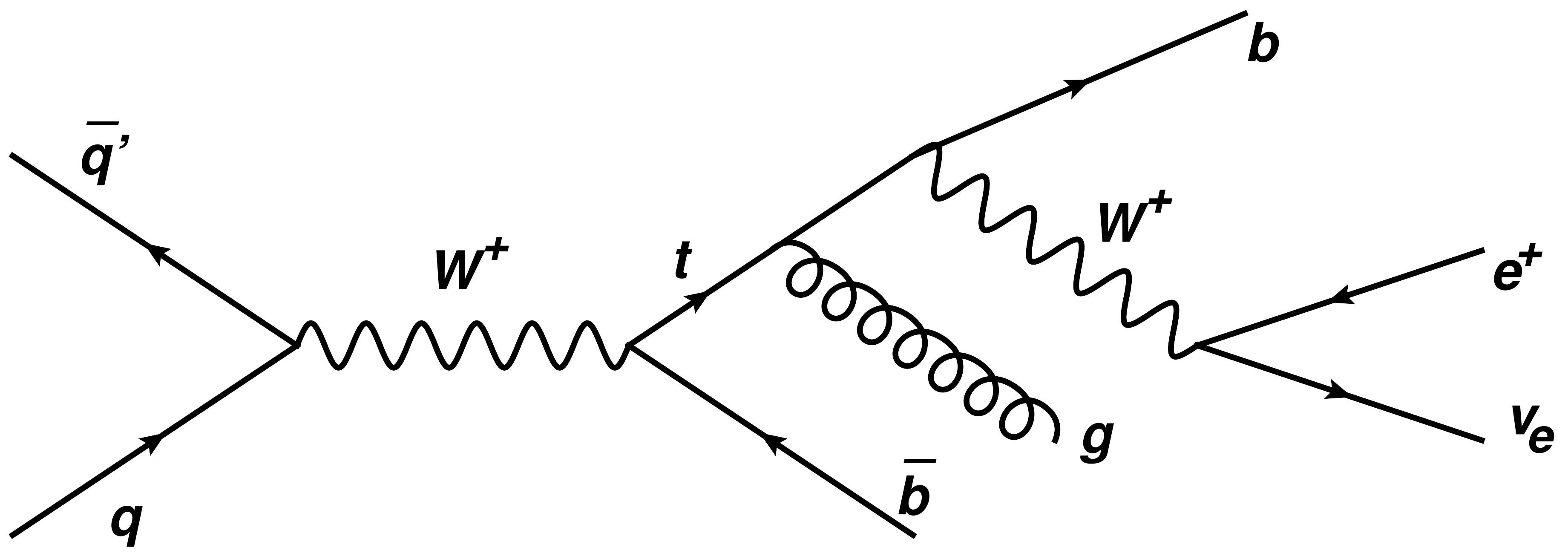
Frederix, Pagani and Tsinikos, https://arxiv.org/abs/1907.12586



“NLO EW t-channel”

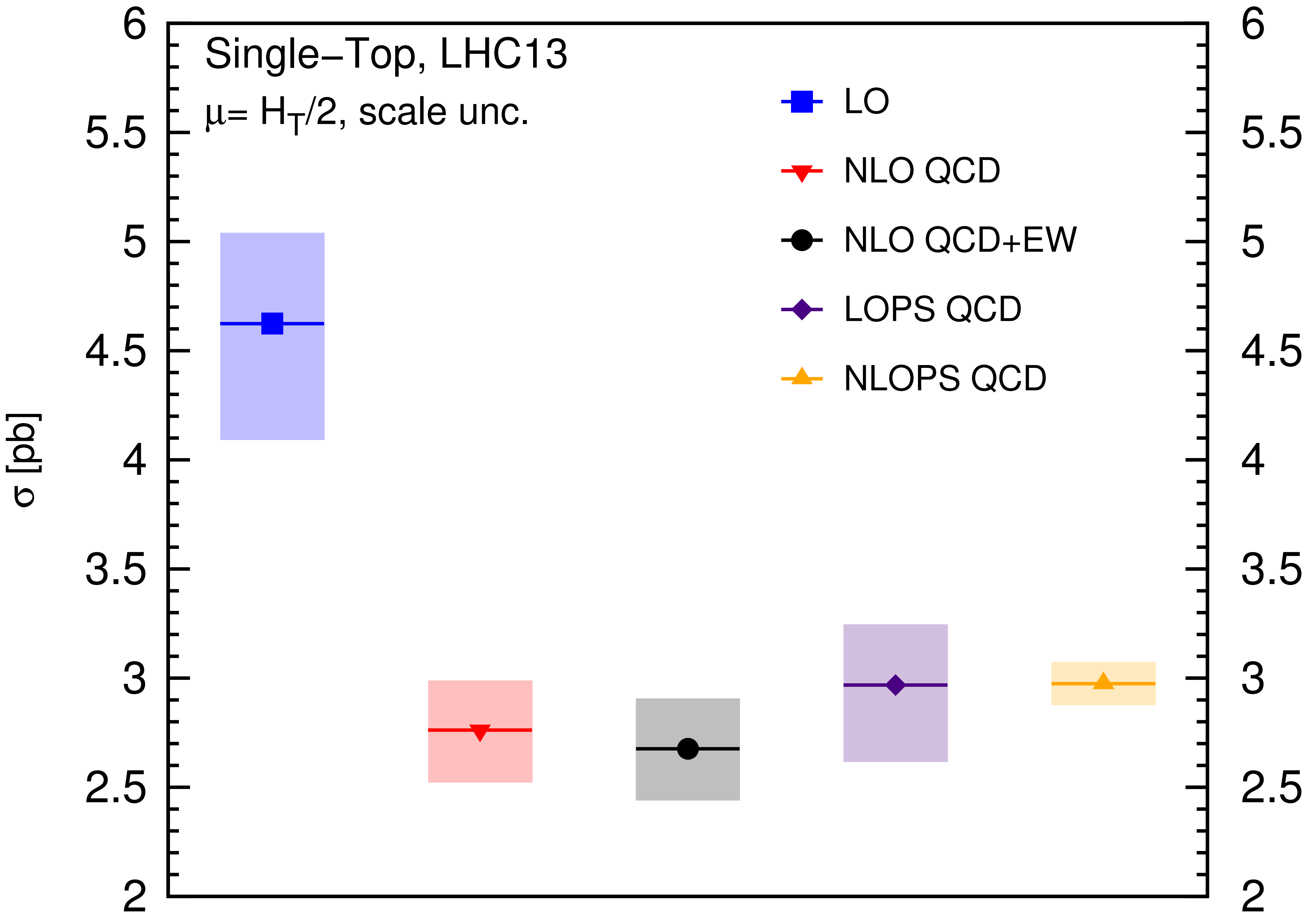


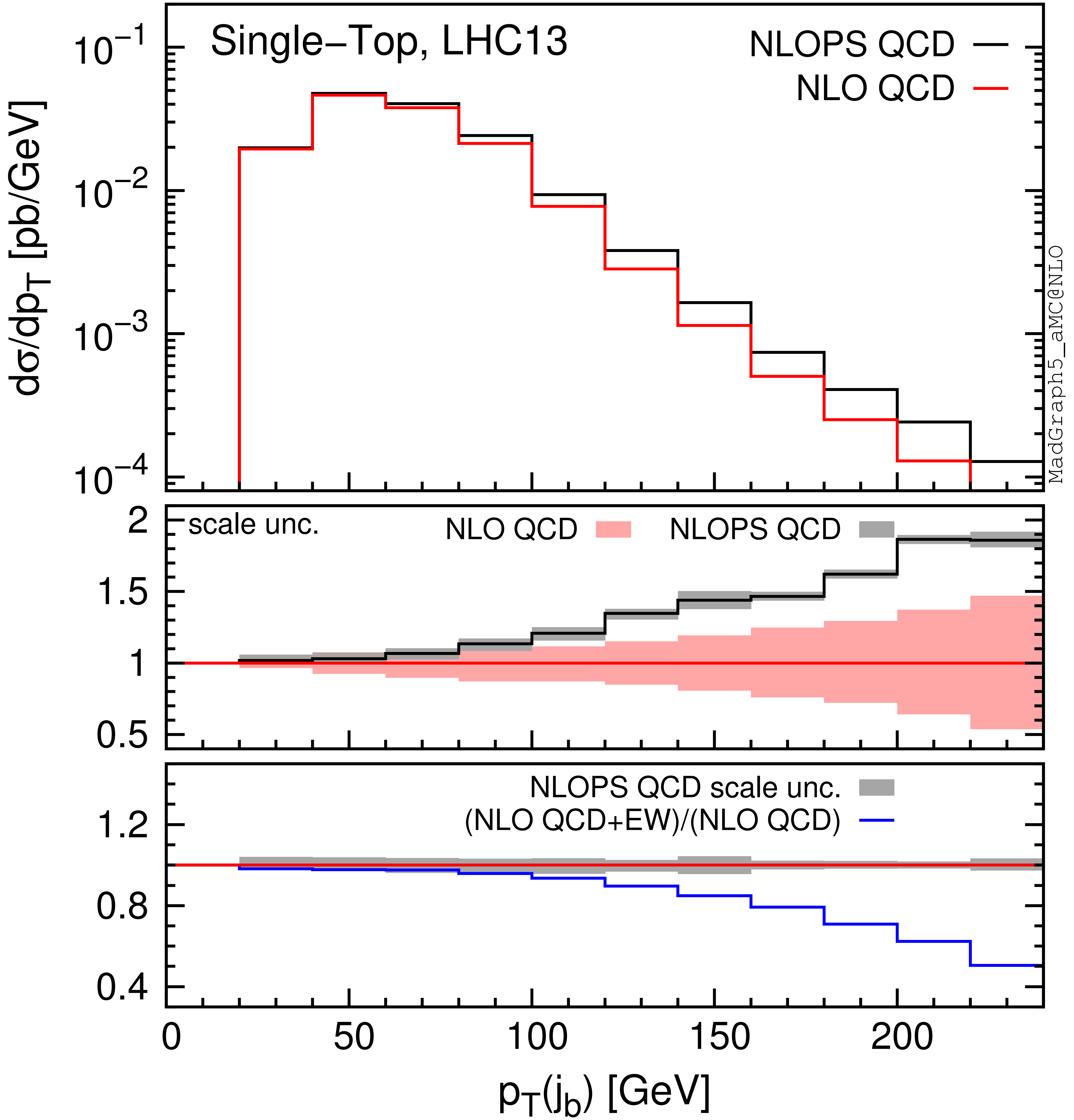
“NLO QCD W+2 jets”



“NLO QCD s-channel”

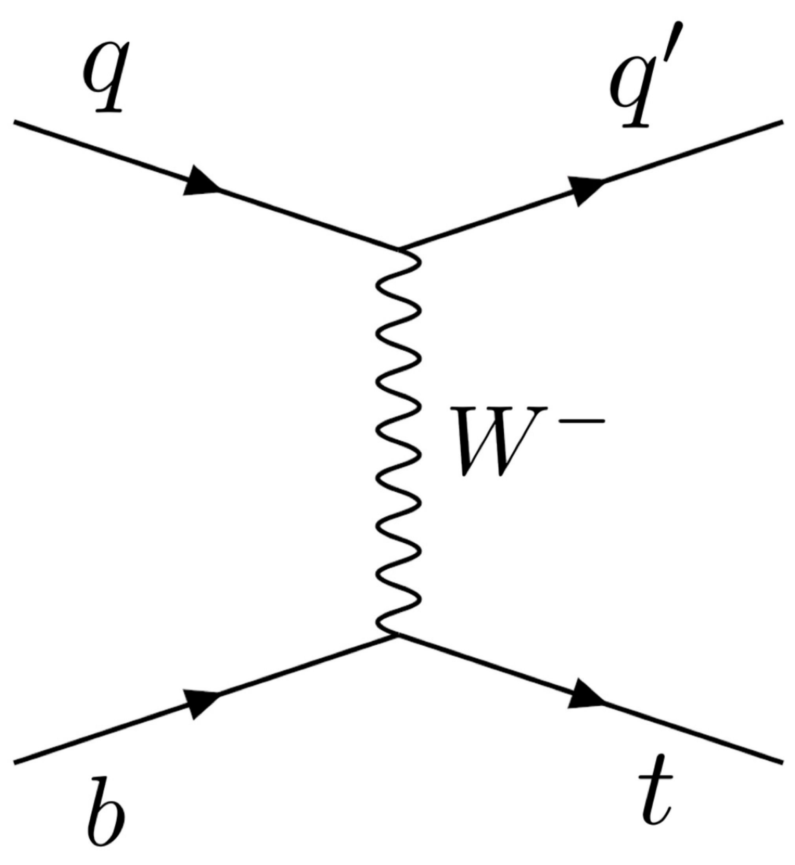
- Large uncertainty at fixed order due to jet veto remedied in NLOPS.
- EW effects substantial in distributions.

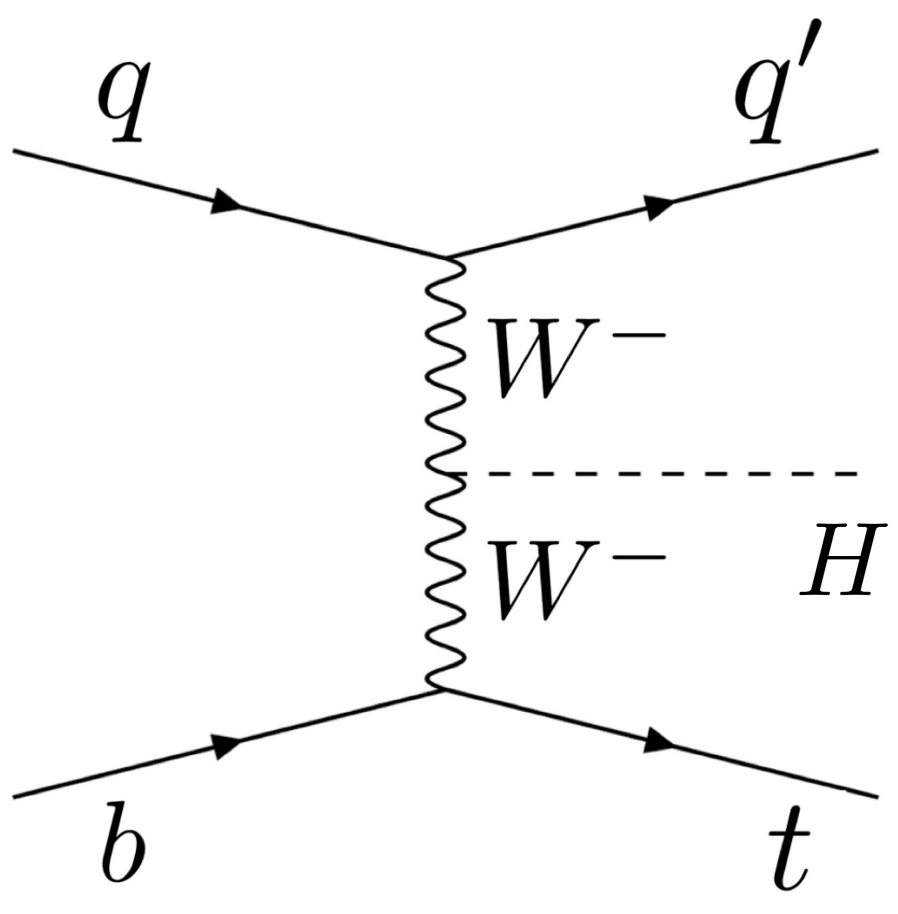


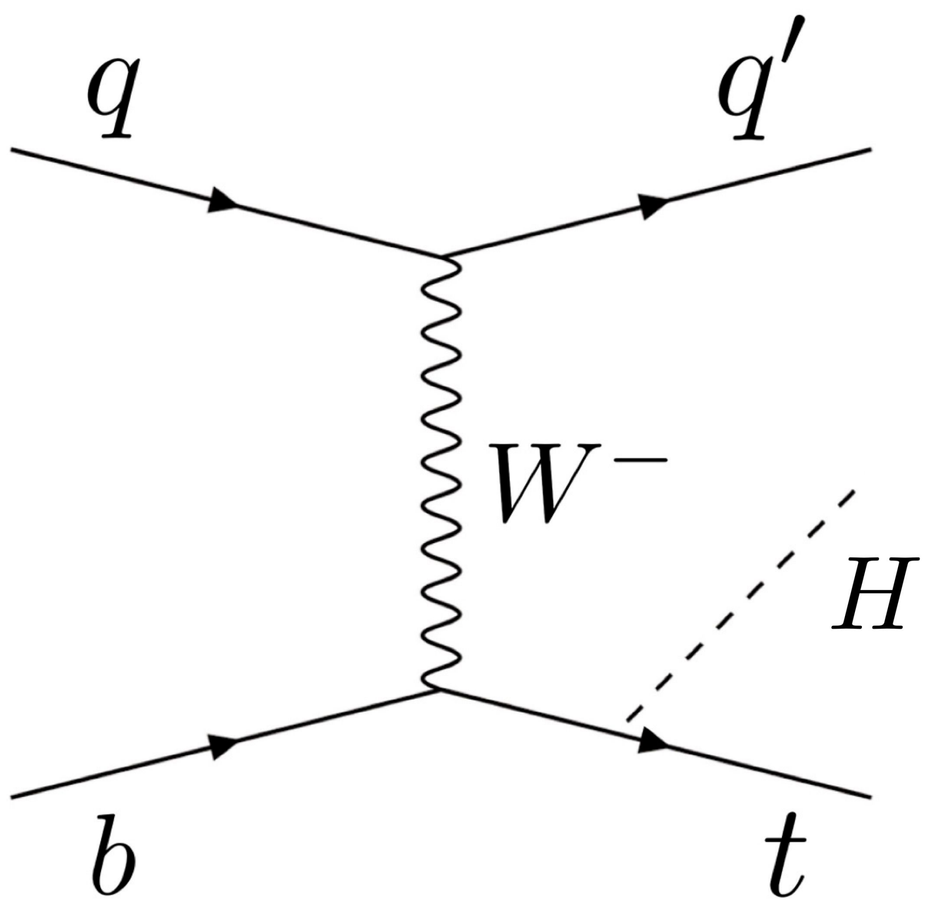


Single top in SMEFT

Cao, Jiang, Zeng, https://arxiv.org/abs/2105.04464







SMEFT: dim-6 analysis:

sensitive to 3 independent operators

$$\sigma_t = \left[214 - 13C_{qq}^{(3)} + 16C_{uW} + 13C_{\phi q3}\right]\,\mathrm{pb}$$

$$\sigma_{\bar{t}} = \left[81 - 4C_{qq}^{(3)} + 5C_{uW} + 5C_{\phi q3}\right]\,\mathrm{pb}$$

sensitive to same 3 operators + highly-constrained and/or suppressed contributions

$$\sigma_{\substack{tHq \\ +\bar{t}Hq'}} = \left[74.3 - 11.3C_{qq}^{(3)} + 22.0C_{uW} - 2.6C_{\phi q3}\right]\,\mathrm{fb}$$

(cross-sections at 13 TeV)

Single top + H constraint

- Probe these three operators by measurement of total t-channel cross section (**σ**), ratio of top to anti-top (R) and forward-backward asymmetry (A).
- Leading-order operator expansion of tH cross-section:

$$\sigma_{\substack{tHq \\ +\bar{t}Hq'}} = \Big[-95.1 - 44.0 \times \frac{\sigma_{t+\bar{t}}}{\sigma_{t+\bar{t}}^{\mathrm{SM}}} - 266.0 \times \frac{A_{\mathrm{FB}}}{A_{\mathrm{FB}}^{\mathrm{SM}}} + 479.4 \times \frac{R_t}{R_t^{\mathrm{SM}}} \Big]$$

current 13 TeV measurements →

$$\sigma_{\substack{tHq \\ +\bar{t}Hq'}} = \big[106.8 \pm 64.8\big]\ \mathrm{fb}$$

vs. direct search

$$\sigma_{\substack{tHq \\ +\bar{t}Hq'}} \leq 900\ \mathrm{fb}$$

CMS, https://arxiv.org/abs/2004.04545

Summary

- Single-top processes offer a wealth of opportunities that are only beginning to be explored.

- High-rate t-channel topology is particularly powerful:
  - probe of SM parameters
  - unique constraints on PDFs
  - limits on new physics

- Theory calculations are well-placed to exploit high-luminosity era
  - NNLO QCD, NLO EW, fewer approximations