t-channel Single Top Quark Production and Decay at NNLO

Hua Xing Zhu

Massachusetts Institute of Technology
Zhejiang University

In collaboration with **Ed Berger, Jun Gao; + C.-P. Yuan**
Based on: 1606.08463, Phys.Rev. D94 (2016) no.7, 071501
and work to appear soon

52nd Recontres de Moriond QCD 2017

Outline

The goal of this talk:

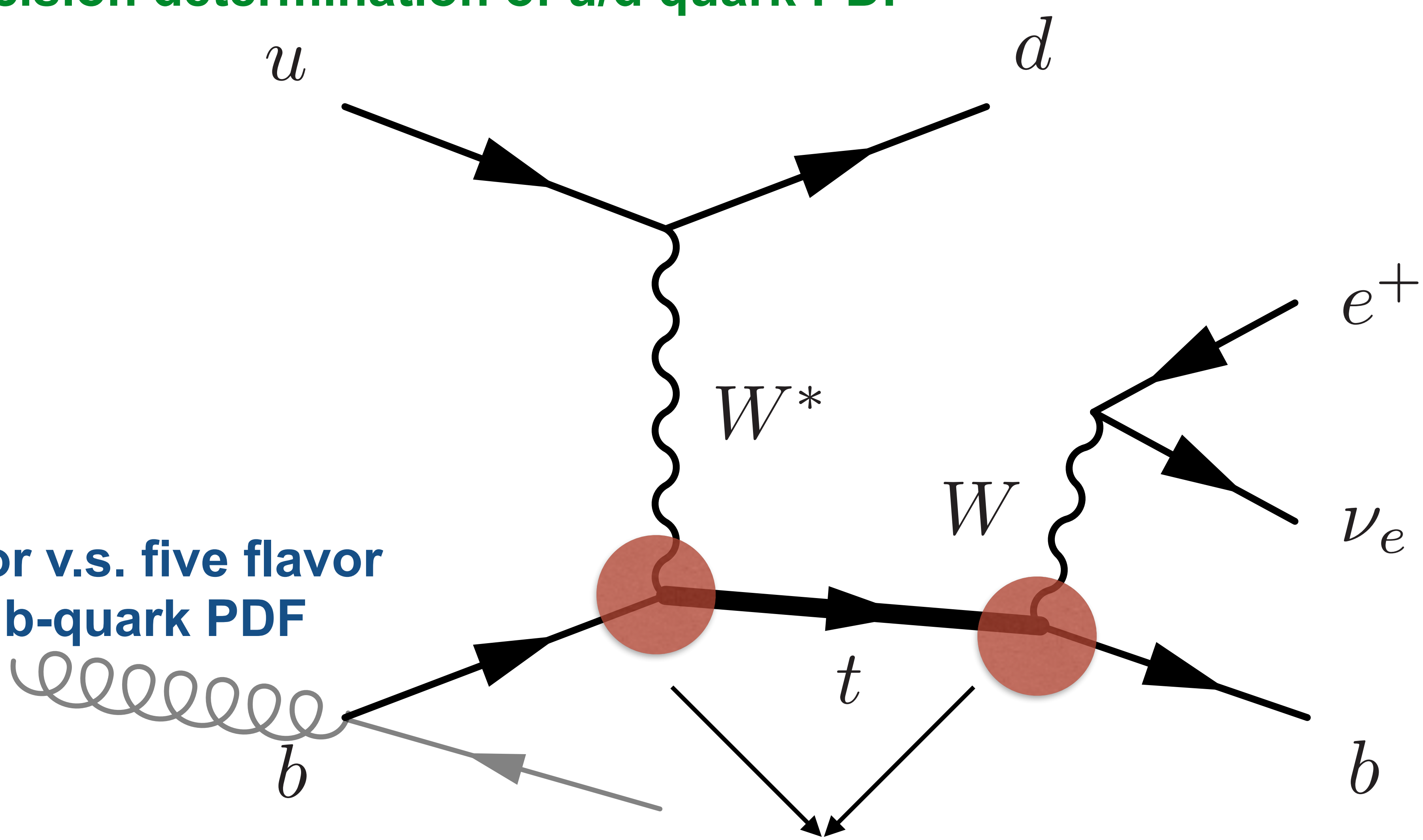
Present a calculation of t-channel single top at NNLO, including NNLO production and NNLO decay, in a fully differential framework, to enable fiducial cuts, and to match the precision of LHC measurements, and to better determine V_{tb}

- **Motivation**
- **Method of the calculation**
- **Results and comparison with data**
- **Summary and outlook**

Electroweak production of top quark — single top production
t-channel production has the largest rate, ~ 200 pb @ 13 TeV

Measurement of σ(t)/σ($\bar{t}$)
precision determination of u/d quark PDF

Four-flavor v.s. five flavor
test of b-quark PDF

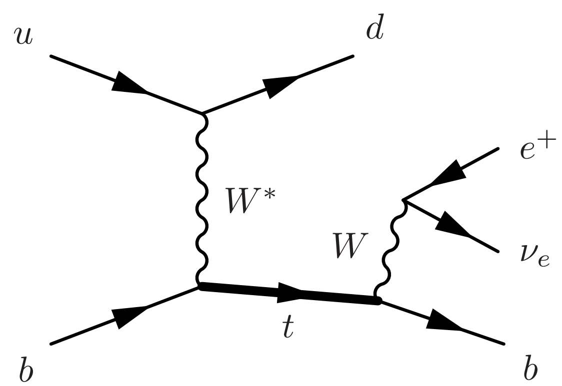


Direct probe of Wtb vertex in *both* production and decay

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + \text{h.c.}$$

Direct measurement of $|V_{tb}|^2$

Experimental measurement strongly rely on theoretical modeling of signal and background



background:
W+jets
$t\bar{t}$
(Z, VV)+jets
multijet

low acceptance,
fiducial v.s. full phase space ~ 1:5

Extrapolation to full phase induces large systematic uncertainties related to MC generators

ATLAS [1702.02859]

Source	$\Delta\sigma_{\text{fid}}(tq)$ / $\sigma_{\text{fid}}(tq)$ [%]	$\Delta\sigma_{\text{fid}}(\bar{t}q)$ / $\sigma_{\text{fid}}(\bar{t}q)$ [%]
Data statistics	± 1.7	± 2.5
Monte Carlo statistics	± 1.0	± 1.4
Background normalisation	< 0.5	< 0.5
Background modelling	± 1.0	± 1.6
Lepton reconstruction	± 2.1	± 2.5
Jet reconstruction	± 1.2	± 1.5
Jet energy scale	± 3.1	± 3.6
Flavour tagging	± 1.5	± 1.8
$E_{\text{T}}^{\text{miss}}$ modelling	± 1.1	± 1.6
$b/\bar{b}$ tagging efficiency	± 0.9	± 0.9
PDF	± 1.3	± 2.2
tq ($\bar{t}q$) NLO matching	± 0.5	< 0.5
tq ($\bar{t}q$) parton shower	± 1.1	± 0.8
tq ($\bar{t}q$) scale variations	± 2.0	± 1.7
$t\bar{t}$ NLO matching	± 2.1	± 4.3
$t\bar{t}$ parton shower	± 0.8	± 2.5
$t\bar{t}$ scale variations	< 0.5	< 0.5
Luminosity	± 1.9	± 1.9
Total systematic	± 5.6	± 7.3
Total (stat. + syst.)	± 5.8	± 7.8

fiducial [pb]	LO	NLO	NNLO
top quark	$4.07^{+7.6\%}_{-9.8\%}$	$2.95^{+4.1\%}_{-2.2\%}$	?
top antiquark	$2.45^{+7.8\%}_{-10\%}$	$1.78^{+3.9\%}_{-2.0\%}$	?

Standard acceptance cut

Large NLO corrections
Scale variation underestimate true uncertainties

Theoretical uncertainty can be dominant
Need further improvement in theoretical prediction!

First NNLO corrections for both production and decay

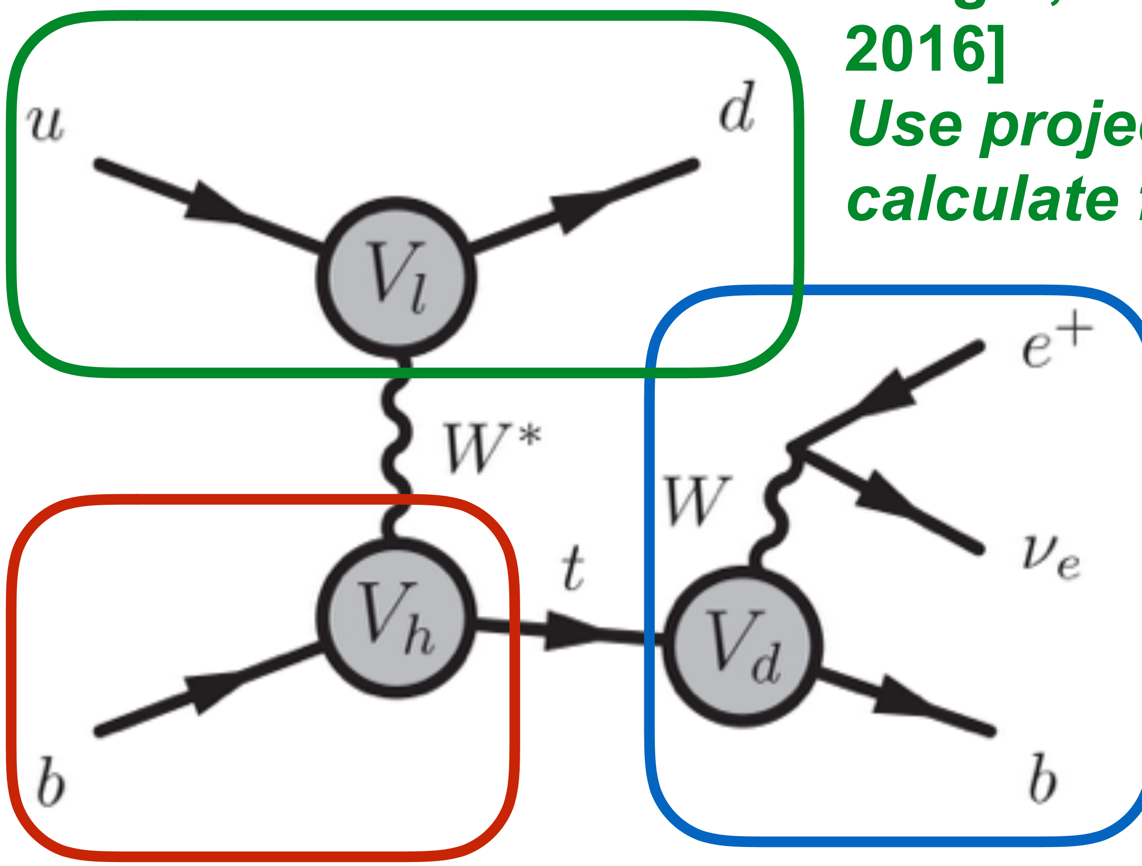
Ed Berger, J. Gao, C.-P. Yuan, HXZ,1606.08463, PRD94 (2016) no.7, 071501
Ed Berger, J. Gao, HXZ, 2017, to appear soon

- Single top quark production + decay at NNLO in (fully differential) structure function approximation
- First calculation with NNLO corrections both to production and decay of top quark
- Fully differential + arbitrary (infrared safe) cut on (2,3,4) jets+l+ν_l. Can directly calculate fiducial cross section
- Retain full spin correlation by computing polarized top production and decay
- Many distribution available in [Ed Berger, J. Gao, HXZ, 2017, to appear soon]
- More distributions can be calculated upon request

- **NNLO in structure function approximation**
  - **NNLO production only [Brucherseifer, Caola, Melnikov, 2014]**
  - **Both production and decay at NNLO [Berger, J. Gao, C.-P. Yuan, HXZ, 2016; Berger, J. Gao, HXZ, to appear soon]**

NNLO corrections to DIS [Ed Berger, J. Gao, C.-P. Yuan, HXZ, 2016]
Use projection-to-born method to calculate fully differential rate

Structure function approximation: ignore QCD cross talk between V_l and V_h



NNLO corrections to DIS-like heavy quark production [Ed Berger, J. Gao, C.S. Li, Z.L. Liu, HXZ, 2016]
Use phase space slicing method with 0-jettiness (inclusive beam jet mass) as resolution variable

NNLO corrections to decay [J. Gao, C.S. Li, HXZ, 2012]
Use phase space slicing method with final-state inclusive jet mass as resolution variable

Master formula to combine production and decay

$$\sigma^{\rm LO} = \frac{1}{\Gamma_t^{(0)}} {\rm d}\sigma^{(0)} \otimes {\rm d}\Gamma_t^{(0)}$$

$$\delta\sigma^{\rm NLO} = \frac{1}{\Gamma_t^{(0)}} \left[{\rm d}\sigma^{(1)} \otimes {\rm d}\Gamma_t^{(0)} + {\rm d}\sigma^{(0)} \otimes \left({\rm d}\Gamma_t^{(1)} - \frac{\Gamma_t^{(1)}}{\Gamma_t^{(0)}} {\rm d}\Gamma_t^{(0)} \right) \right]$$

$$\delta\sigma^{\rm NNLO} = \frac{1}{\Gamma_t^{(0)}} \left[{\rm d}\sigma^{(2)} \otimes {\rm d}\Gamma_t^{(0)} + {\rm d}\sigma^{(1)} \otimes \left({\rm d}\Gamma_t^{(1)} - \frac{\Gamma_t^{(1)}}{\Gamma_t^{(0)}} {\rm d}\Gamma_t^{(0)} \right) \right.$$
$$\left. + {\rm d}\sigma^{(0)} \otimes \left({\rm d}\Gamma_t^{(2)} - \frac{\Gamma_t^{(2)}}{\Gamma_t^{(0)}} {\rm d}\Gamma_t^{(0)} - \frac{\Gamma_t^{(1)}}{\Gamma_t^{(0)}} \left({\rm d}\Gamma_t^{(1)} - \frac{\Gamma_t^{(1)}}{\Gamma_t^{(0)}} {\rm d}\Gamma_t^{(0)} \right) \right) \right]$$

$$ {\rm d}\sigma^{(2)} = {\rm d}\sigma_{\rm h}^{(2)} {\rm d}\sigma_{\rm l}^{(0)} + {\rm d}\sigma_{\rm h}^{(1)} {\rm d}\sigma_{\rm l}^{(1)} + {\rm d}\sigma_{\rm h}^{(0)} {\rm d}\sigma_{\rm l}^{(2)} $$

At NNLO, need to consistently combine *11 different $O(\alpha_s^2)$ terms*.

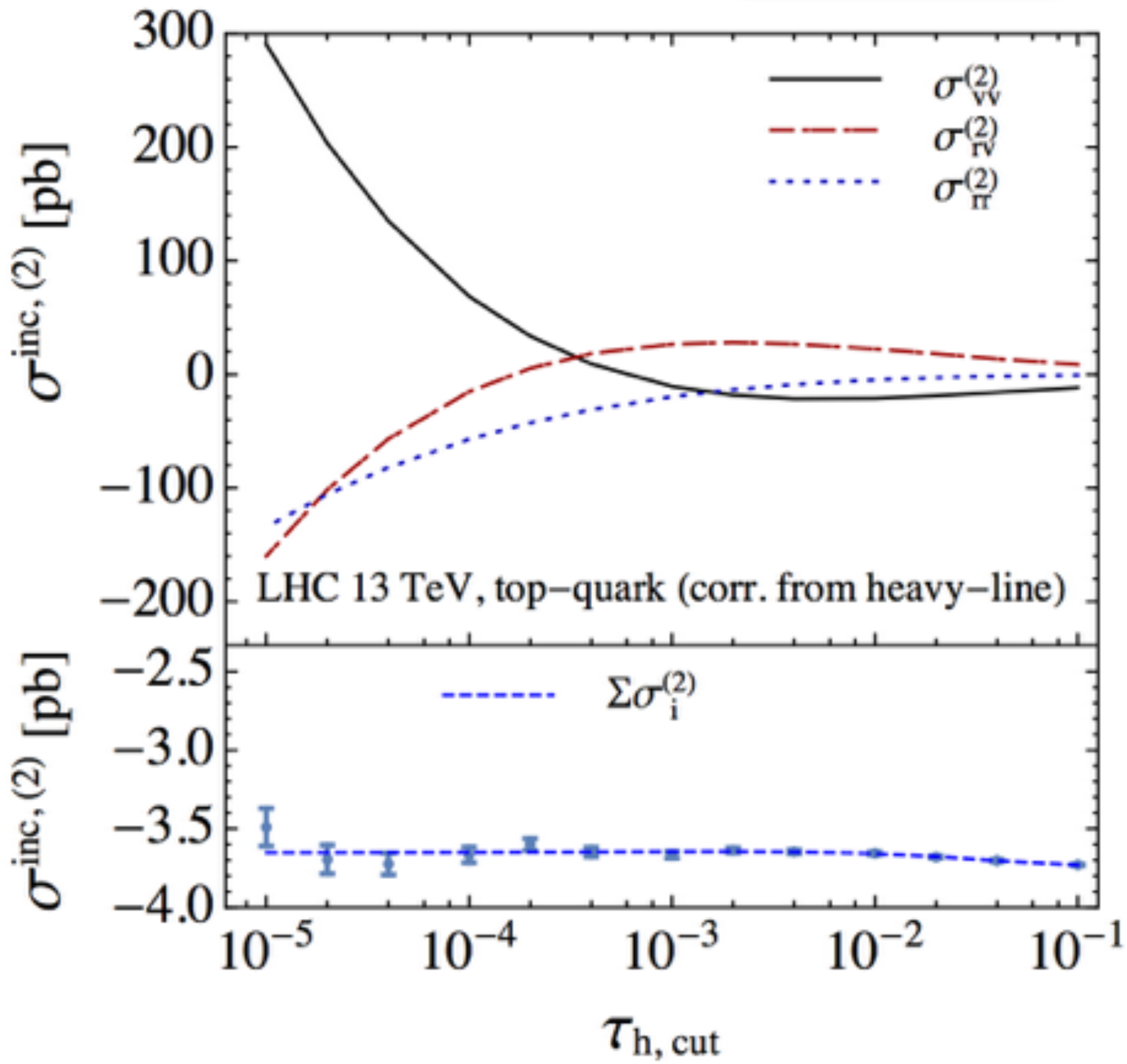
Integrate over the phase space of decay product reproduce inclusive production cross section — an important consistency check

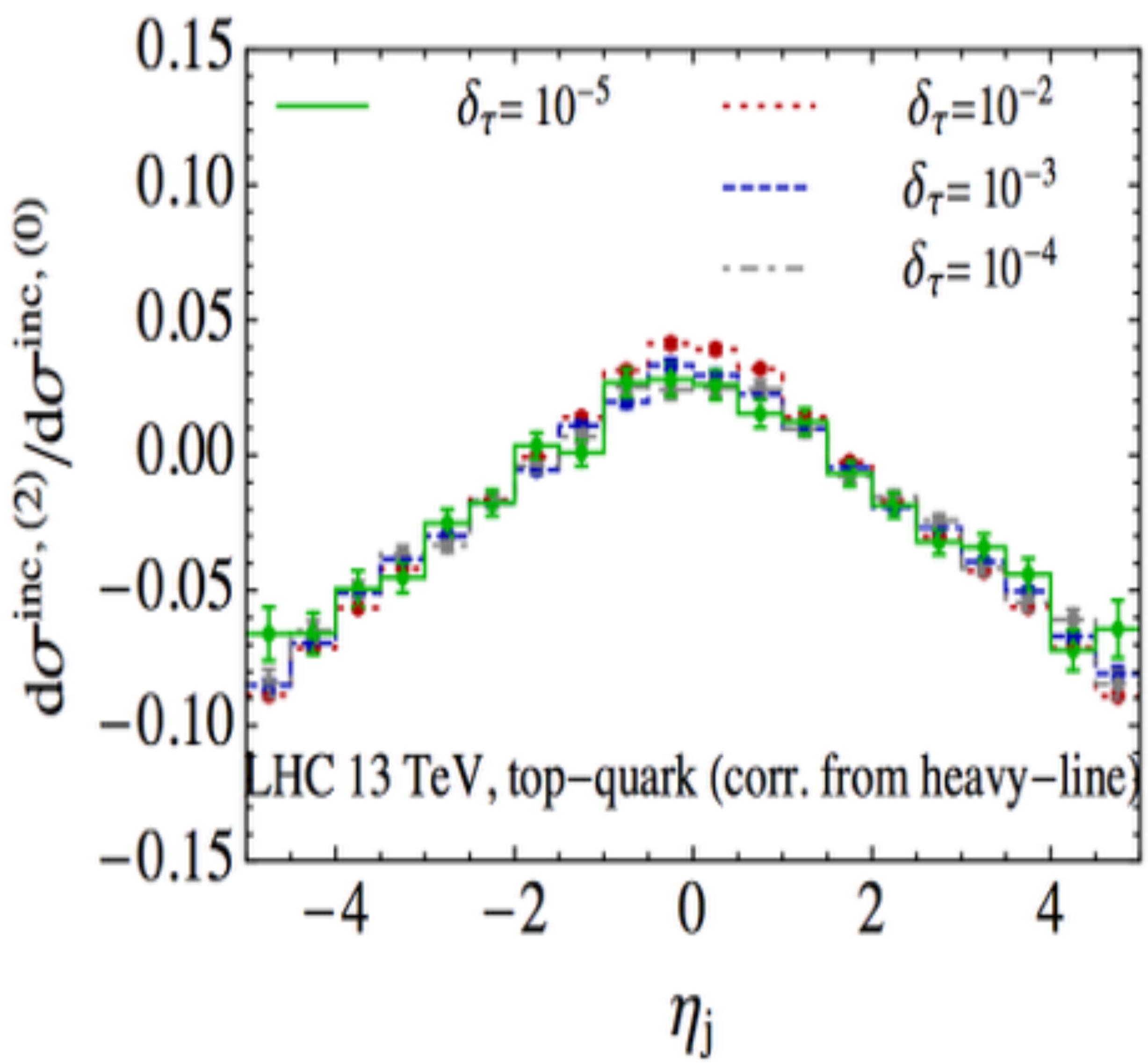
Validation of the calculation

Phase space slicing method introduce non-physical cut-off parameter into the calculation. Cancel between unresolved and resolved contribution.

$$\mathrm{d}\sigma = \int_0^{\tau_{\rm cut}} \mathrm{d}\tau \, \frac{\mathrm{d}\sigma}{\mathrm{d}\tau} + \int_{\tau_{\rm cut}}^{\tau_{\rm max}} \mathrm{d}\tau \, \frac{\mathrm{d}\sigma}{\mathrm{d}\tau}$$

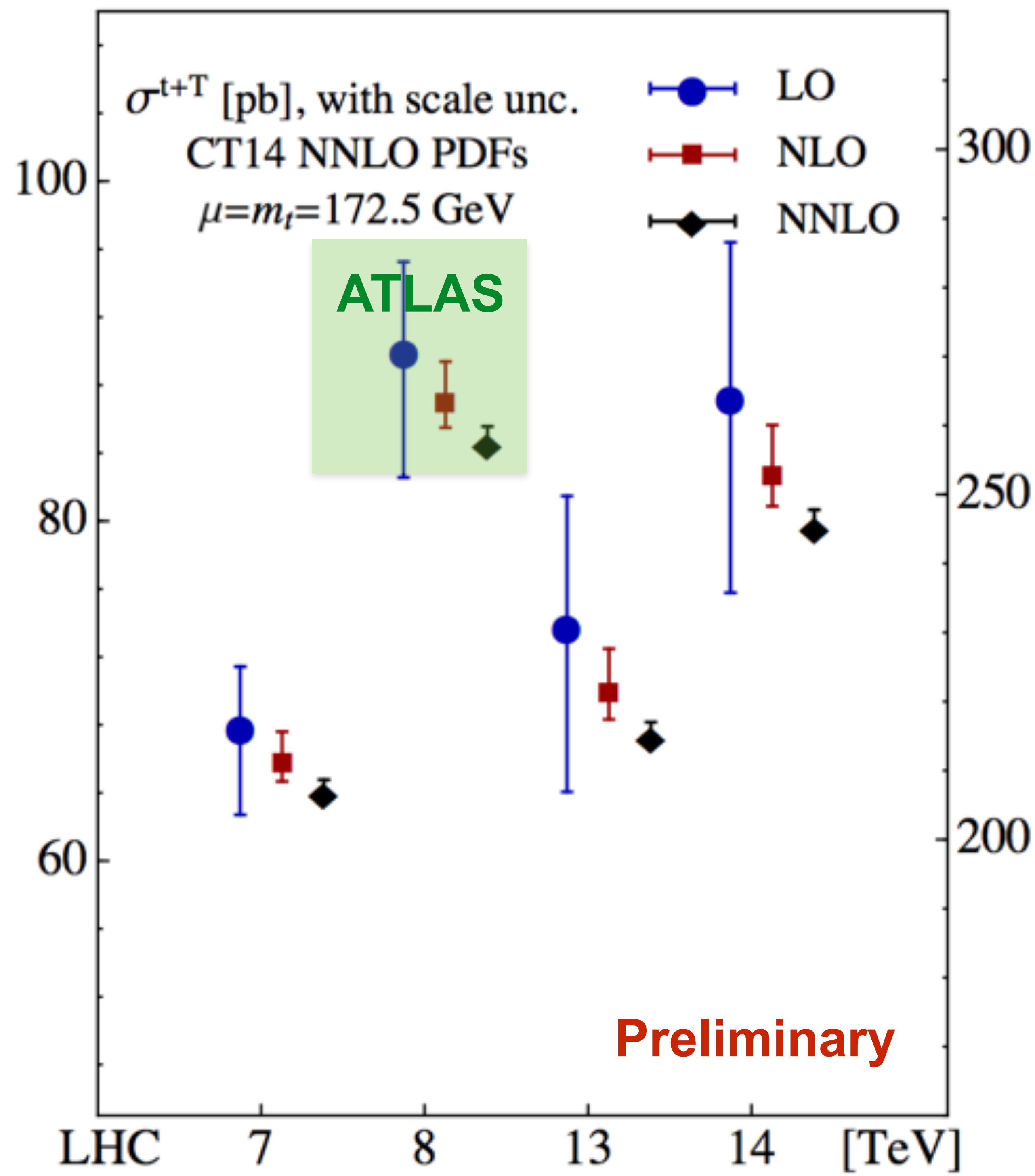
$$\sim \alpha_s^2 \ln^4 \tau_{\rm cut} \qquad \sim -\alpha_s^2 \ln^4 \tau_{\rm cut} - 4\tau_{\rm cut} \ln^3 \tau_{\rm cut} + \text{MC error}$$





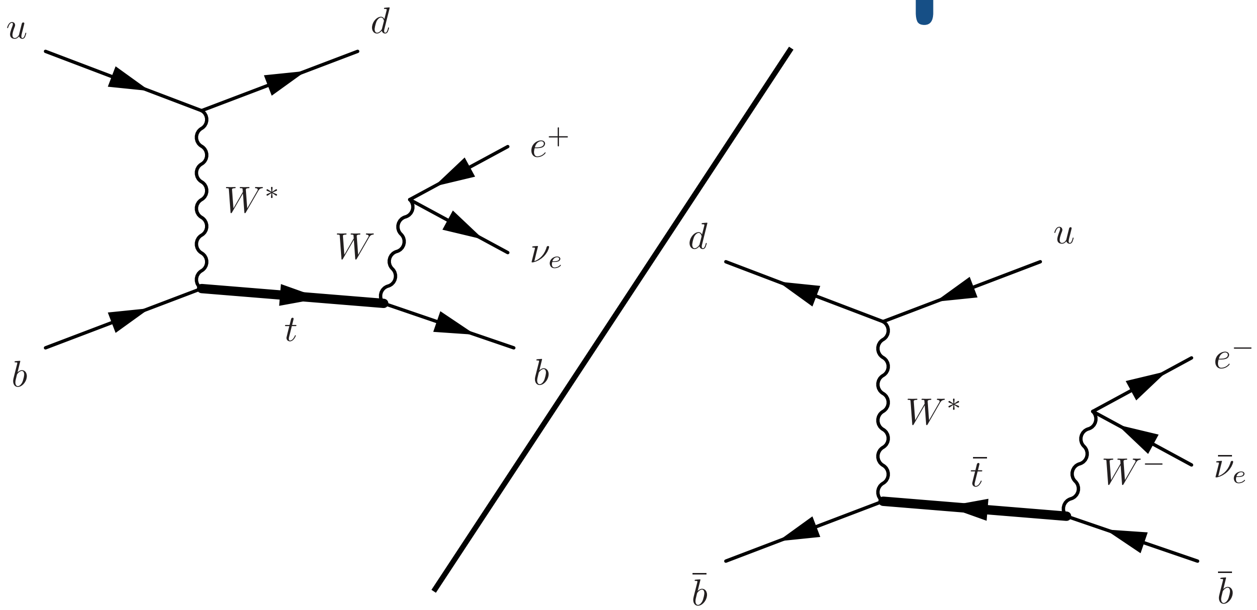
Total cross section at NNLO

- QCD corrections tend to be negative both at NLO and NNLO
- Scale uncertainties estimated from $\mu_r = \mu_f \in [1/2m_t, 2m_t]$
- NLO and NNLO scale band barely overlap
- At 8 TeV, $\sigma_{t+T} = 84.6^{+1.0}_{-0.5}$ pb at NNLO with CT14 NNLO
- ATLAS 8 TeV 20.2fb^{-1} [1702.02859]: $\sigma_{t+T} = 89.6^{+7.1}_{-6.3}$ pb

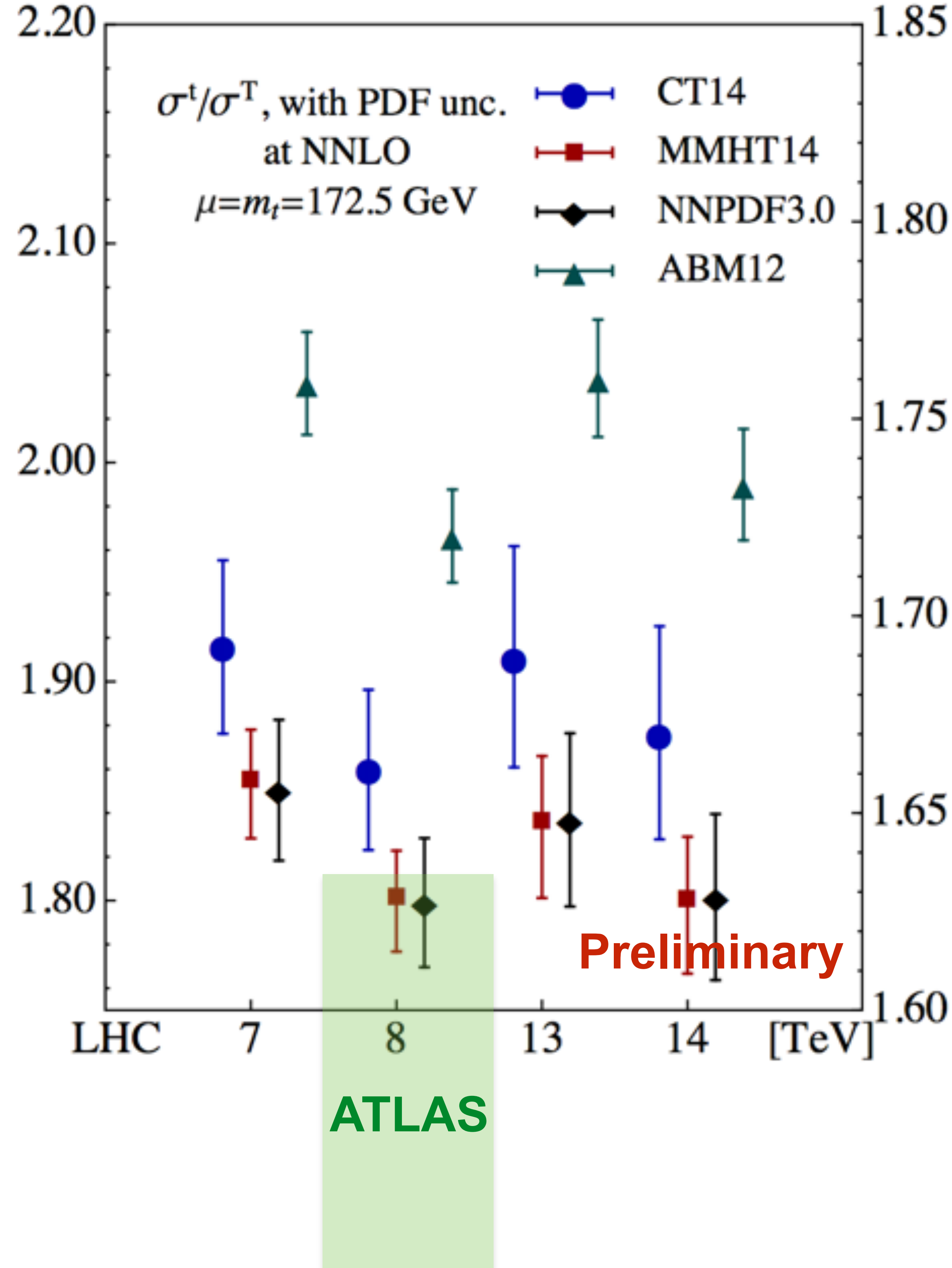


[Ed Berger, J. Gao, H.X. Zhu, 2017]

Top/anti-top ratio



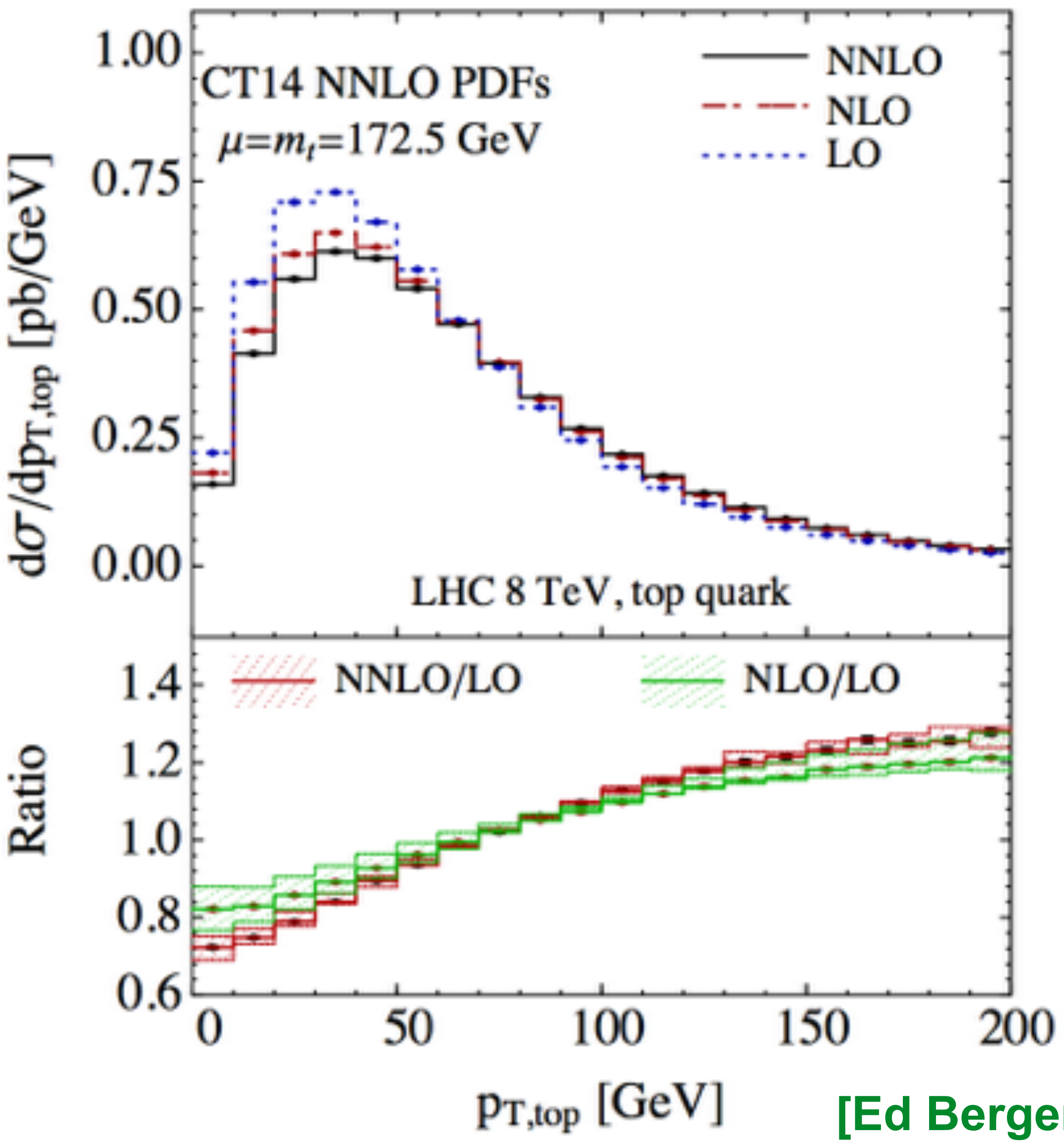
[Ed Berger, J. Gao, H.X. Zhu, 2017]

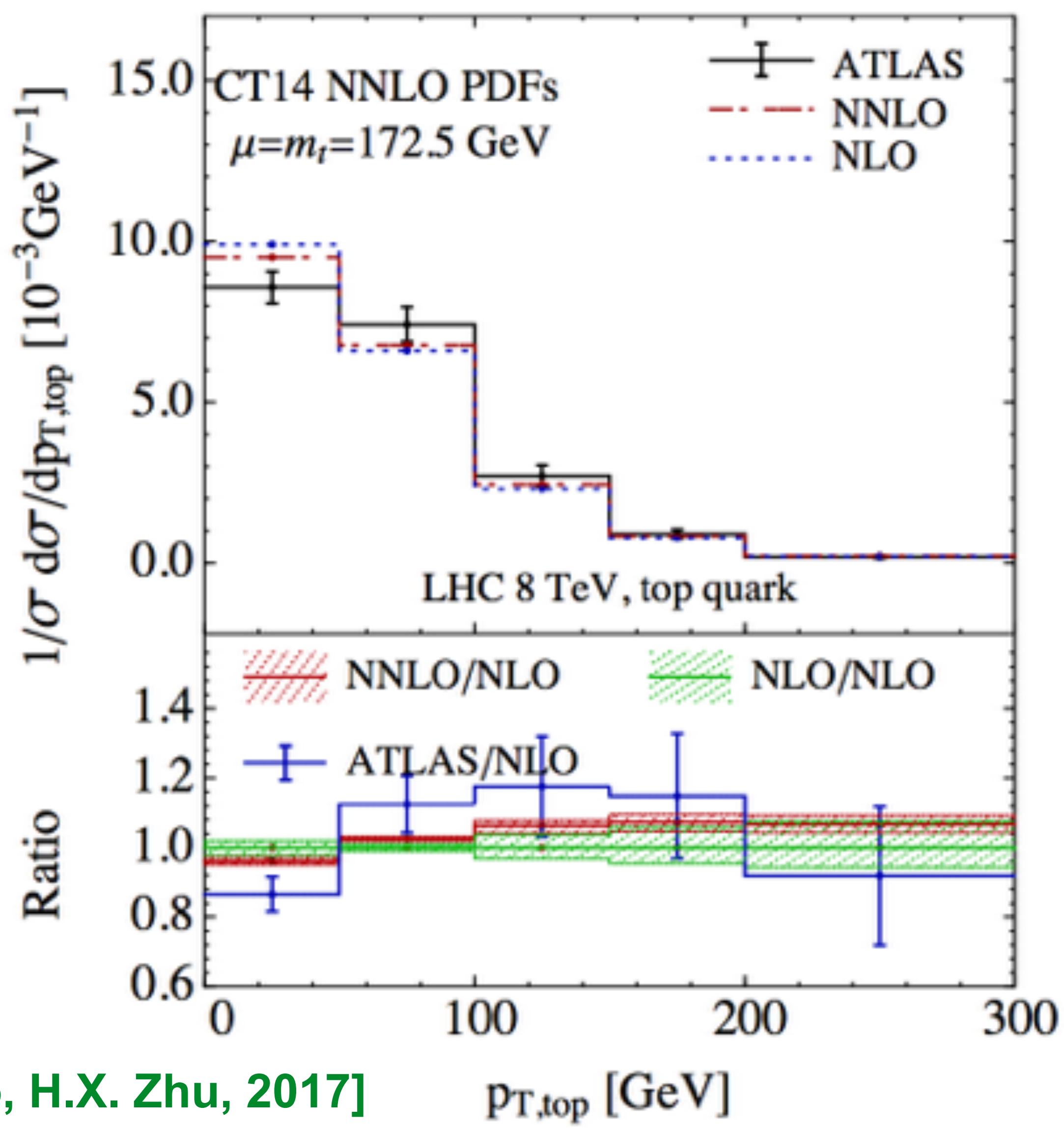


- $R_t = \sigma_t/\sigma_{\bar{t}}$ sensitive to ratio of u/d quark distribution function
- Large spread of predictions from different PDFs
- Relatively well measured due to cancellation of systematics
- ATLAS 8 TeV 20.2fb^{-1} [1702.02859]: $R_t = 1.72 \pm 0.09$

Top quark p_T distribution

- Large corrections at NNLO. Non-trivial shape dependence
- Barely overlap of the NLO and NNLO scale bands
- Better agreement with data at NNLO





[Ed Berger, J. Gao, H.X. Zhu, 2017]

ATLAS distribution taken from [1702.02859]

Fiducial cross section

Ed Berger, J. Gao, C.-P. Yuan, HXZ,1606.08463

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

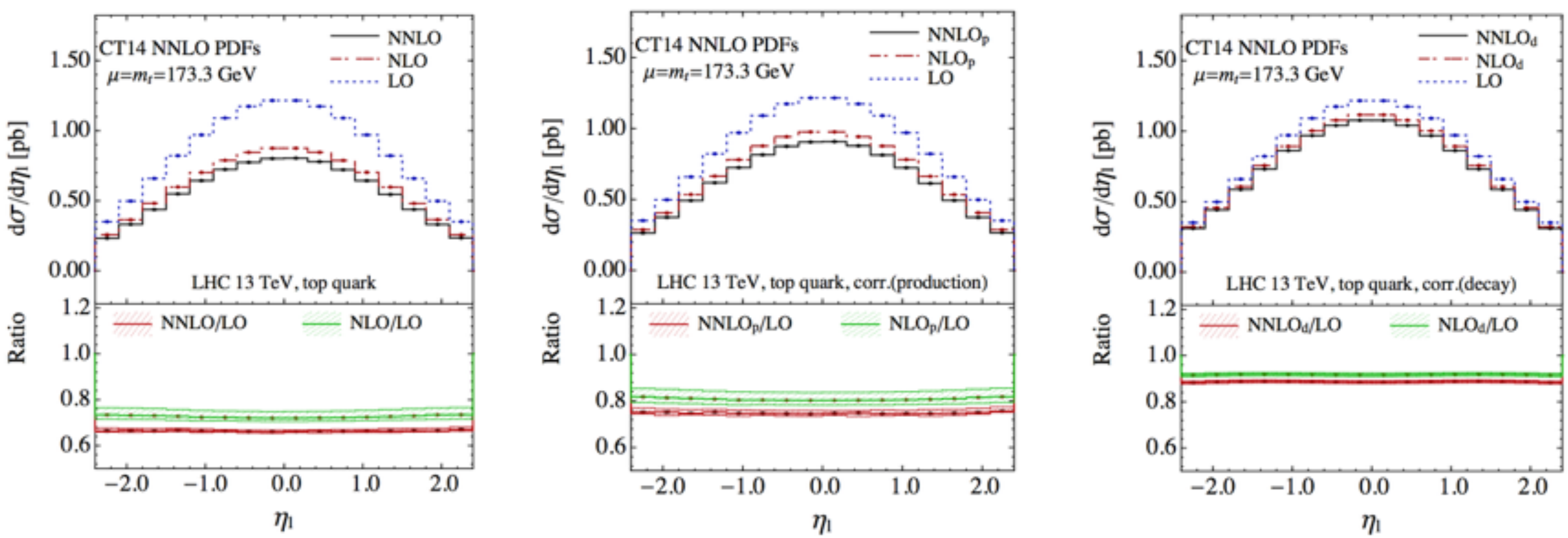
LHC 13 TeV
anti-kT R=0.5
pT_{jet}>40GeV,$|\eta|_{jet}$<5
$|\eta|_{b\text{-}jet}$<2.4
pT_{lepton}>30GeV,$|\eta|_{lepton}$<2.4

Fiducial cross section for decay to only one lepton family

- **Large QCD corrections to fiducial cross section at both NLO and NNLO**
- **NNLO corrections can change the acceptance by 6%, larger than the NLO scale uncertainties estimate. Can propagate to extrapolation of total cross section and extraction of $|V_{tb}|^2$.**
- **Potential large logarithms induced by fiducial cut scale pT_{jet} ~ 40 GeV. Perturbative expansion better behaved if central scale chosen as$(pT_{jet}\, m_t)^{1/2}$**

Importance of decay corrections

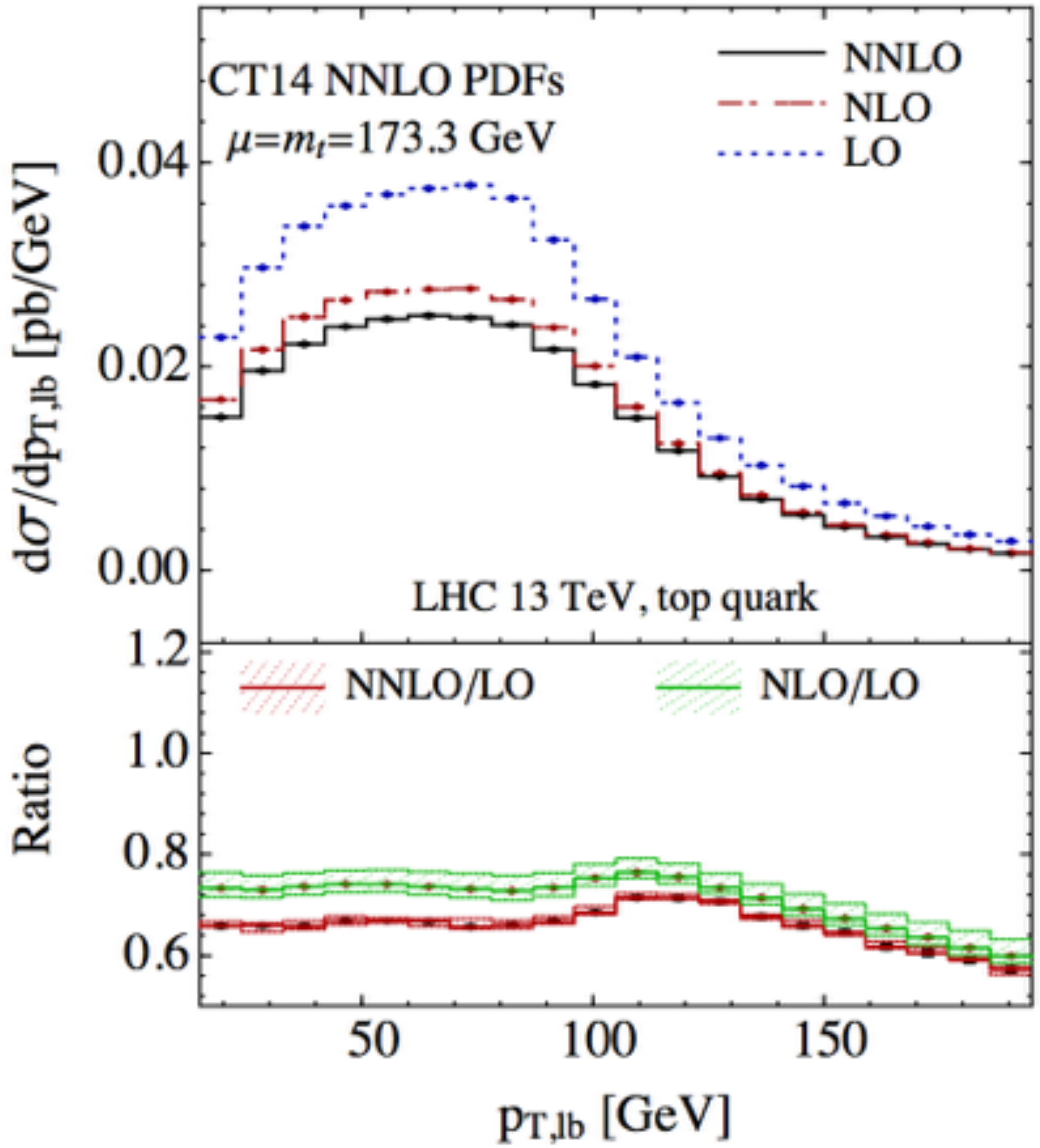
- Lepton rapidity distribution in fiducial volume. Large NNLO corrections (bottom left)
- NNLO corrections from production only(middle bottom) and decay only(bottom right)
- NNLO corrections to top-quark inclusive decay rate small, ~2%
- For differential distribution, the NNLO corrections from decay can reach 4%

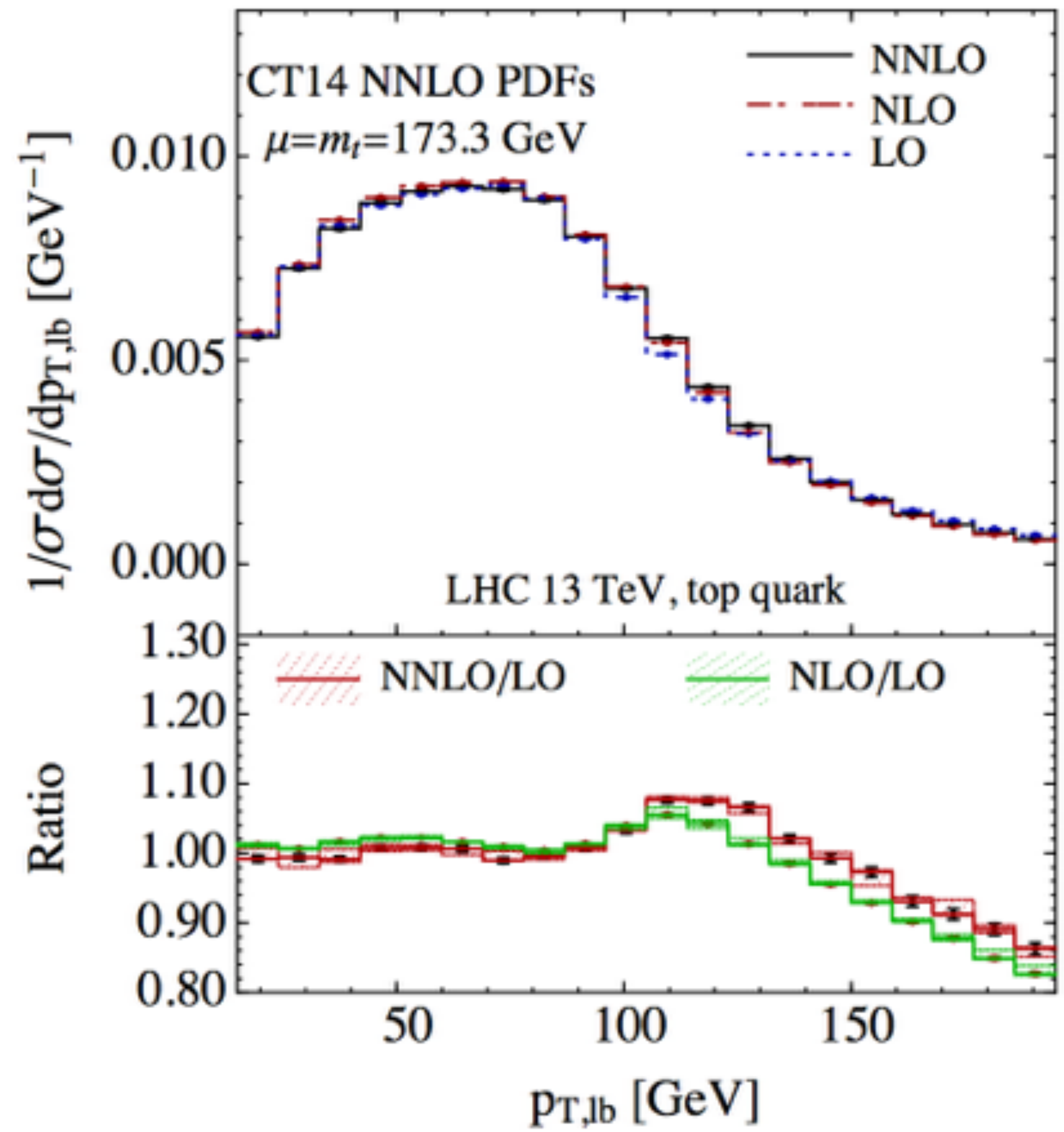


[Ed Berger, J. Gao, H.X. Zhu, 2017]

pT distribution of lepton and b-jet

- Large NNLO QCD corrections for both absolute distribution and normalized distribution
- NLO scale variation clearly fails to estimate the higher order perturbative uncertainties





[Ed Berger, J. Gao, H.X. Zhu, 2017]

Summary

- First results on single top production and decay at NNLO in (fully differential) structure function approximation
- Allow direct comparison of theory and measurement in fiducial volume. Avoid additional systematics from unfolding
- For typical differential distributions, NNLO corrections outside of NLO scale band
- More distributions available upon request
- Future directions
  - s-channel and tW associate production
  - Full NNLO corrections beyond the structure function approximation
  - Interface with parton shower

Thank you very much for your attention!

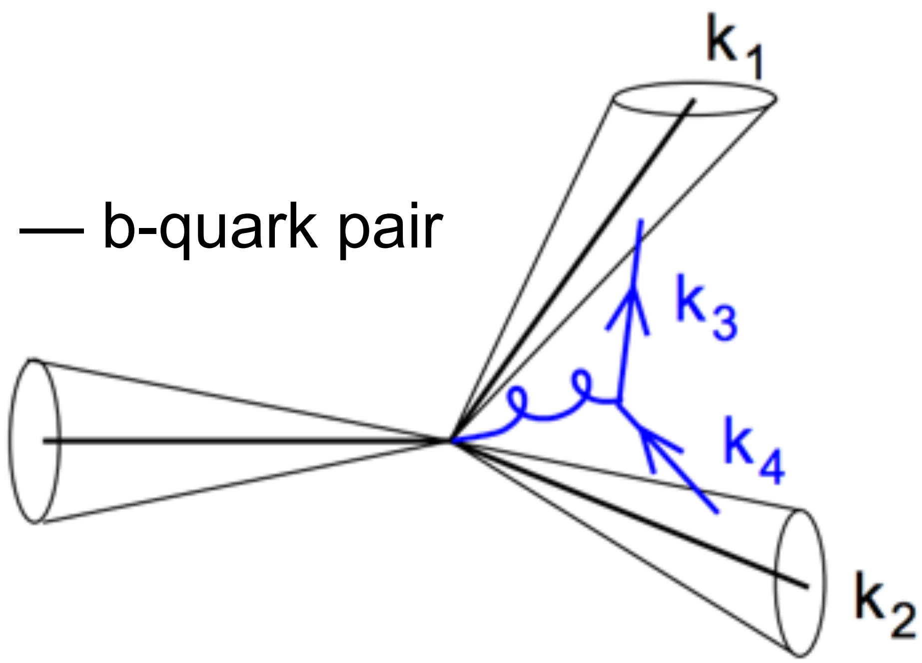
Backup Slides

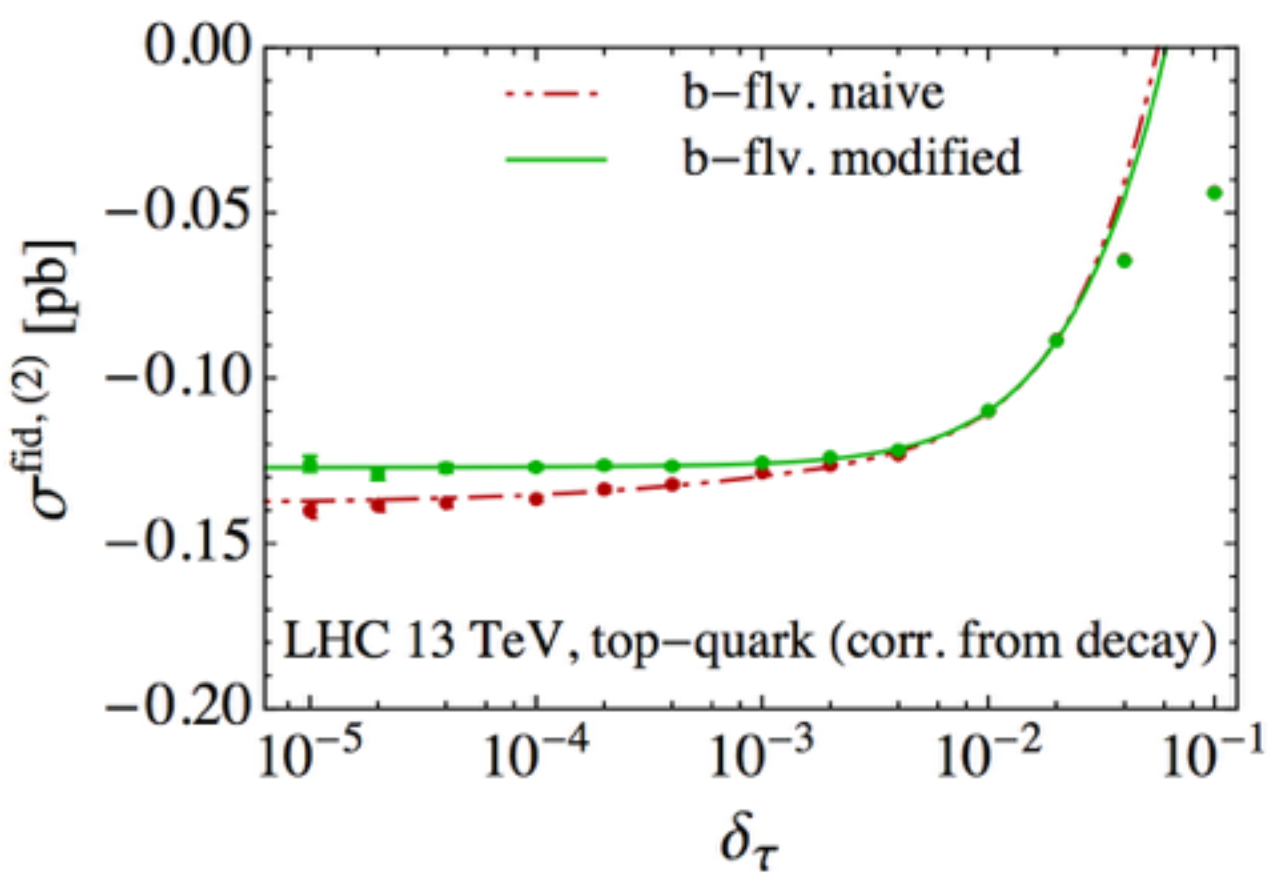
Previous t-channel Single Top Calculation

- NLO production in four-flavor scheme
  - *Campbell, Frederix, Maltoni, Tramontano, 0903.0005*
- NLO production in five-flavor scheme
  - *Bordes, van Eijk, Nucl. Phys. B435 (1995) 23–58*
  - *Stelzer, Sullivan, Willenbrock, hep-ph/9705398*
  - *Harris, Laenen, Phaf, Sullivan, Weinzierl, hep-ph/020705*
  - *Kant, et al., HatHor, 1406.4403*
- NLO production + decay in five-flavor scheme and on-shell top-quark approximation
  - *Campbell, Ellis, Tramontano, hep-ph/0408158*
  - *Q.-H. Cao, Schwienhorst, Benitez, Brock, C.-P. Yuan, hep-ph/0504230*
  - *Schwienhorst, C. P. Yuan, Mueller, Q.-H. Cao, 1012.5132*
- NLO production + decay in five-flavor scheme and beyond on-shell top-quark approximation
  - *Pittau, hep-ph/9603265*
  - *Falgari, Mellor, Signer, 1007.0893*
  - *Falgari, Giannuzzi, Mellor, Signer, 1102.5267*
- Threshold resummation
  - *J. Wang, C. S. Li, J. J. Zhang, HXZ, 1010.4509*
  - *J. Wang, C. S. Li, HXZ, 1210.7698*
  - *Kidonakis, 1103.2792, 1510.06361*
- NLO production interface with parton shower
  - *Frixione, Laenen, Motylinski, Webber, hep-ph/0512250*
  - *Alioli, Nason, Oleari, Re, 0907.4076*
  - *Frederix, E. Re, and P. Torrielli, 1207.5391*
  - *Frederix, Frixione, Papanastasiou, Prestel, Torrielli, 1603.01178*
- NNLO production in (fully differential) structure function approximation
  - *Brucherseifer, Caola, Melnikov, 1404.7116*

Apologize if I miss your work!

Infrared Unsafety of Naive anti-k_T





Mis-cancellation of soft singularity if the parent if either k_1 or k_2 jet is identified as b-jet with the original naive anti-kT algorithm. [Banfi, Salam, Zanderighi, 2006]

Mis-cancellation of soft singularity manifest as non-zero logarithmic phase space cut-off dependence.

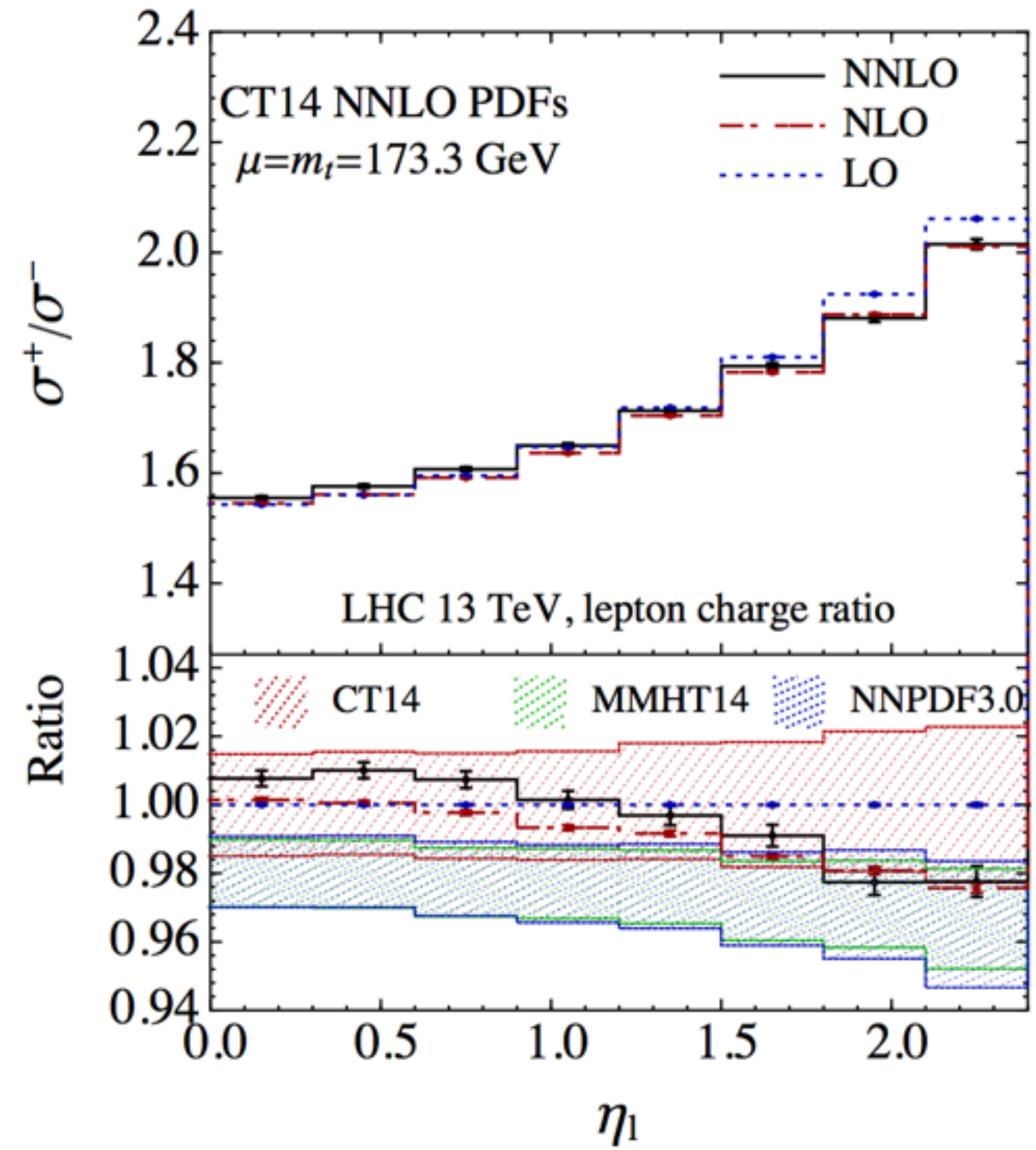
We use a modified anti-kT algorithm in our calculation: always assign the parent gluon of the splitted $b\bar{b}$ pair with zero b-quark number.

For $\tau_{\mathrm{cut}} \sim \frac{m_b^2}{m_t^2} \sim 10^{-4}$

< 1% effects at NNLO.

Charge lepton ratio

- Instead of $R_t = \sigma_t/\sigma_T$, can also use charge lepton ratio in fiducial volume to differentiate PDFs
- Avoid systematics from unfolding and extrapolate to full phase space
- Non-trivial rapidity dependence of higher order corrections
- Bottom panel: PDF uncertainties as ratios to LO prediction using CT14 for three different sets.
- Large spread of predictions from different PDFs



Ed Berger, J. Gao, C.-P. Yuan, HXZ,1606.08463