Single Top Production and Decay: QCD and LHC

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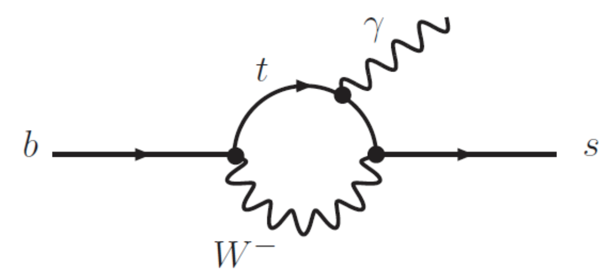
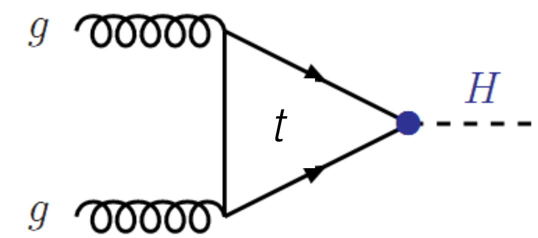
SHANGHAI JIAO TONG UNIVERSITY Department of Physics
INPAC INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

Top quark as a unique probe

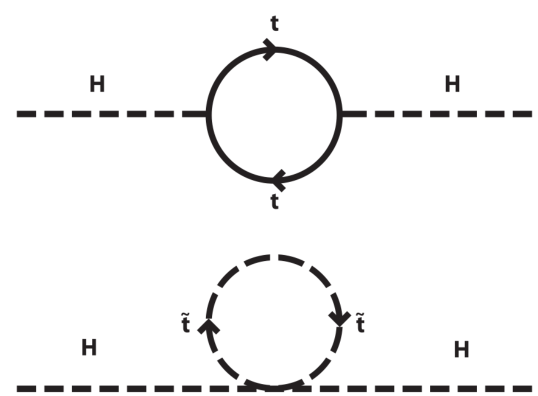
- Top quark is unique in the SM and provides access to physics beyond the standard model through measurements on its production and decays

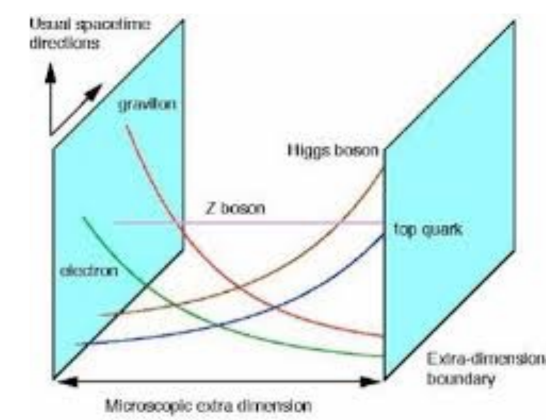
- large mass, ~173 GeV; flavor physics, EW precision fit, Higgs physics



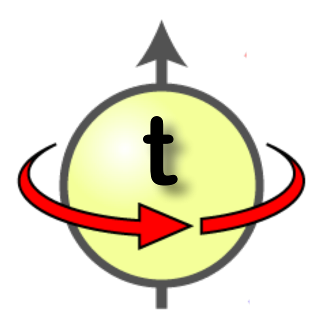


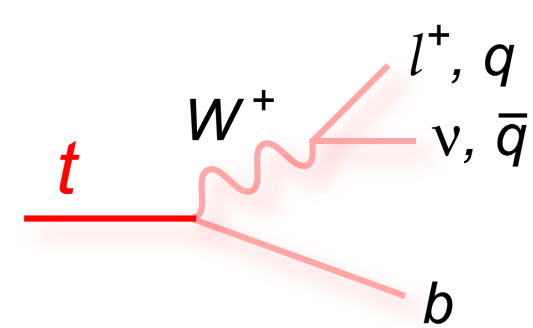
- Important role in various extensions of the SM, e.g., SUSY, extra dimensions





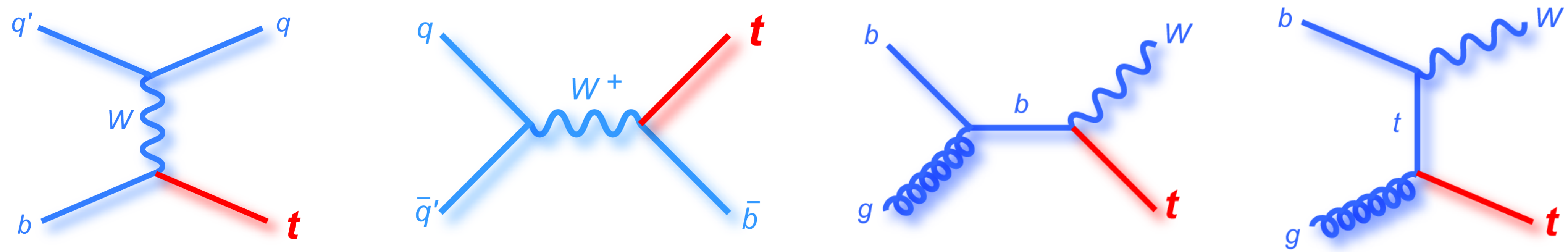
- short life time, decay before QCD hadronization and depolarization; clean exp. signature

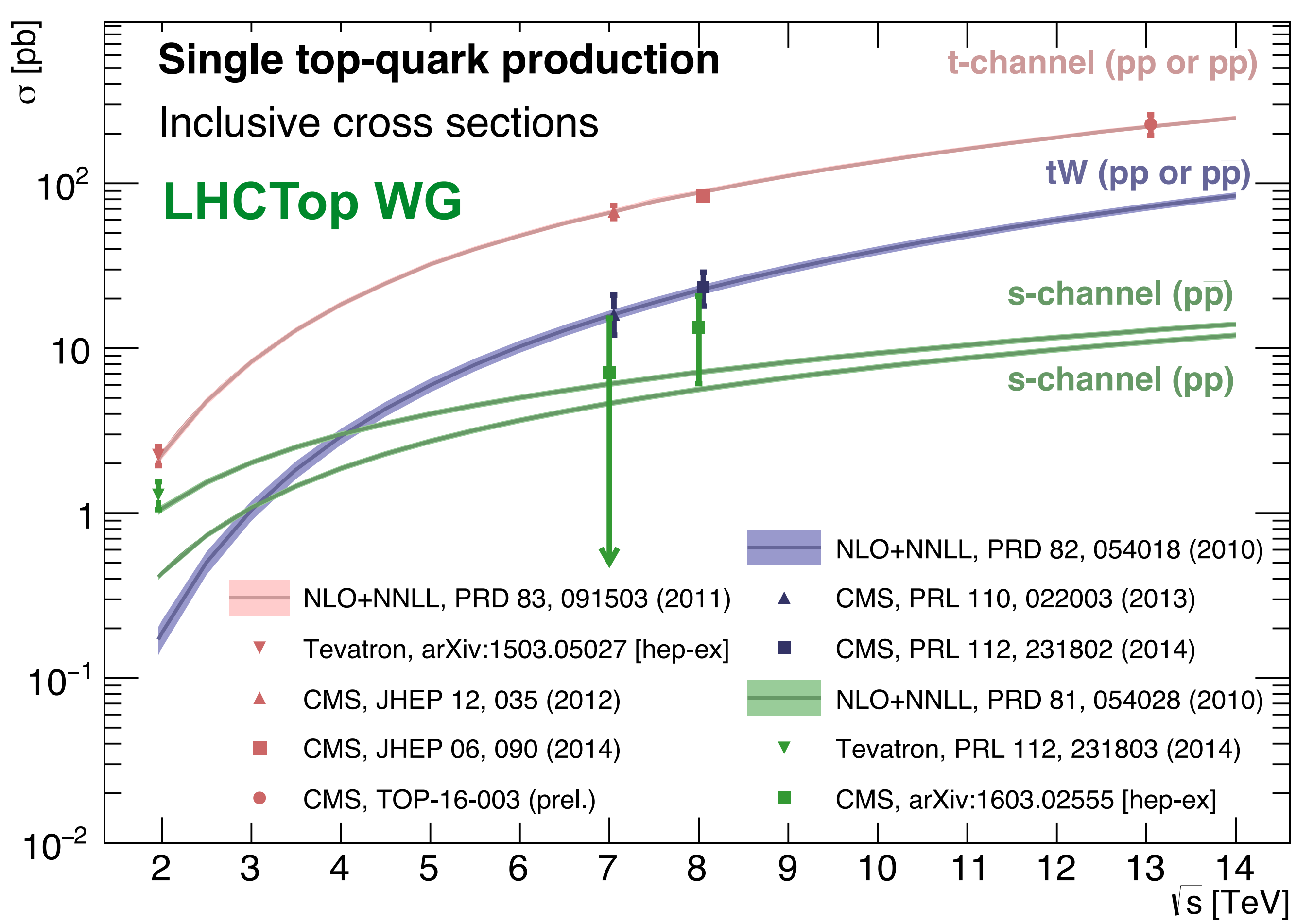




Single top-quark production

- Top quark can be produced singly at LHC via electroweak interactions, including t-channel, s-channel, and associated production

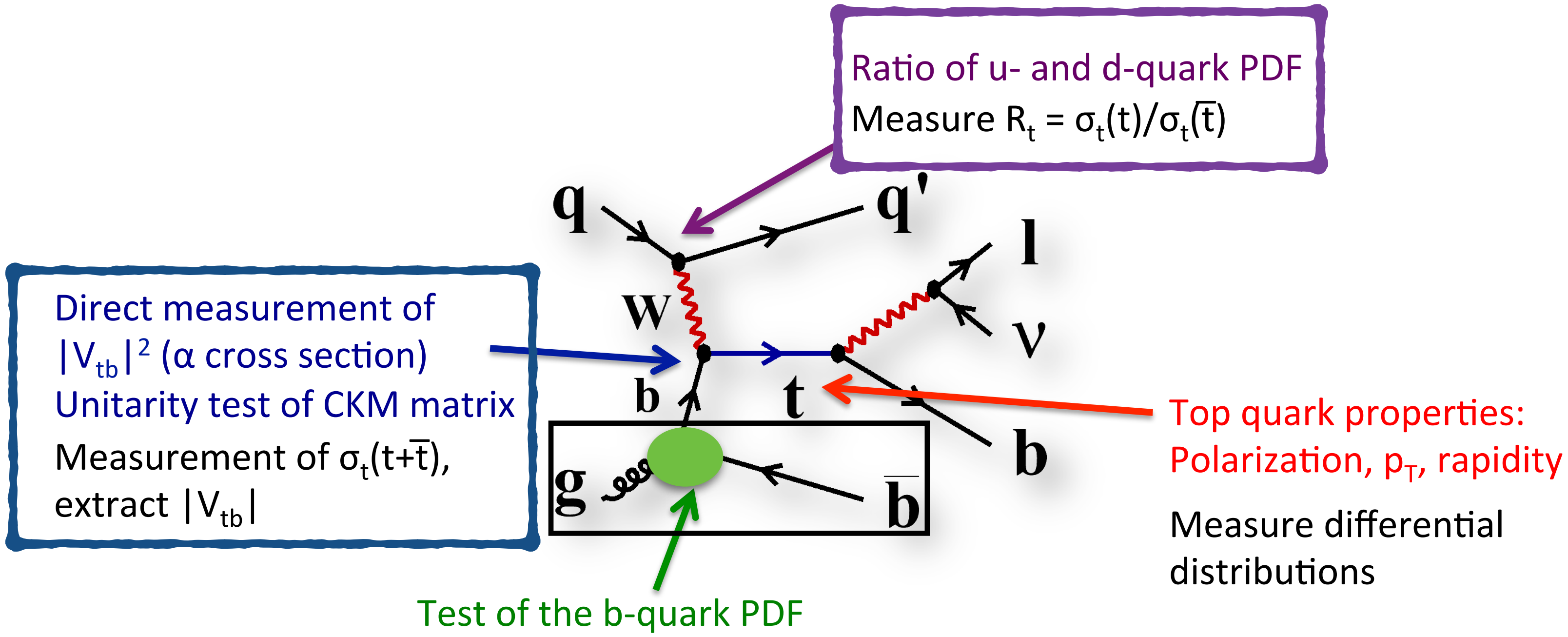




- large cross section, ~300 pb at the LHC 13 TeV; probing EW coupling
- polarized top-quark production due to V-A structure
- sensitive to new charged-current or flavor-changing neutral-current interactions

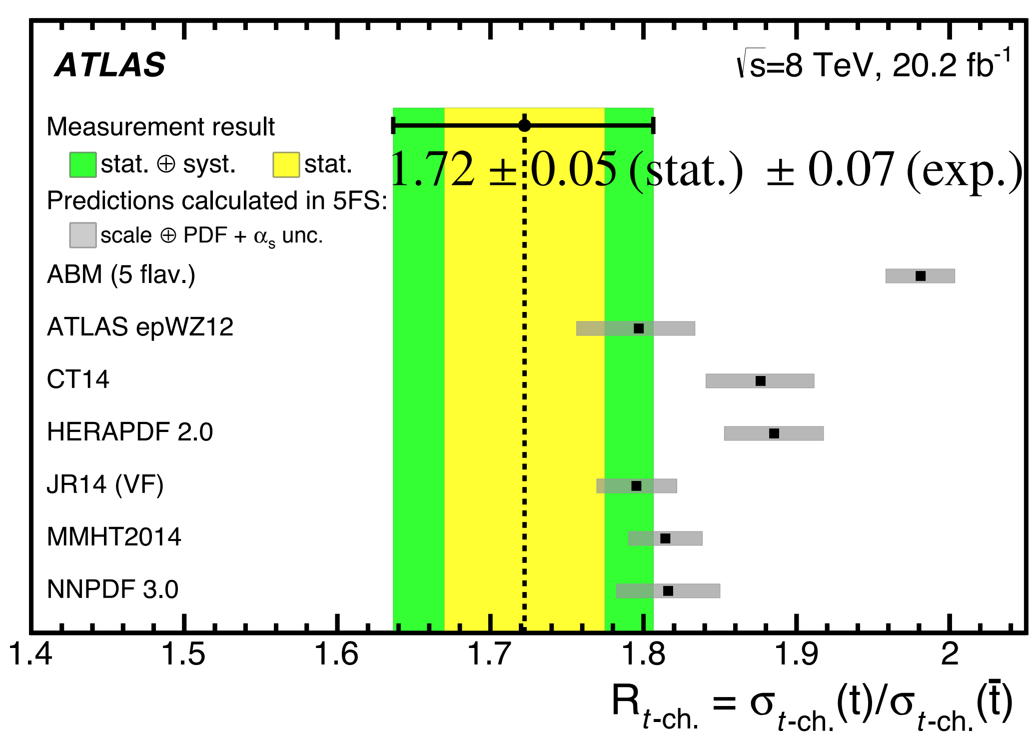
t-channel production

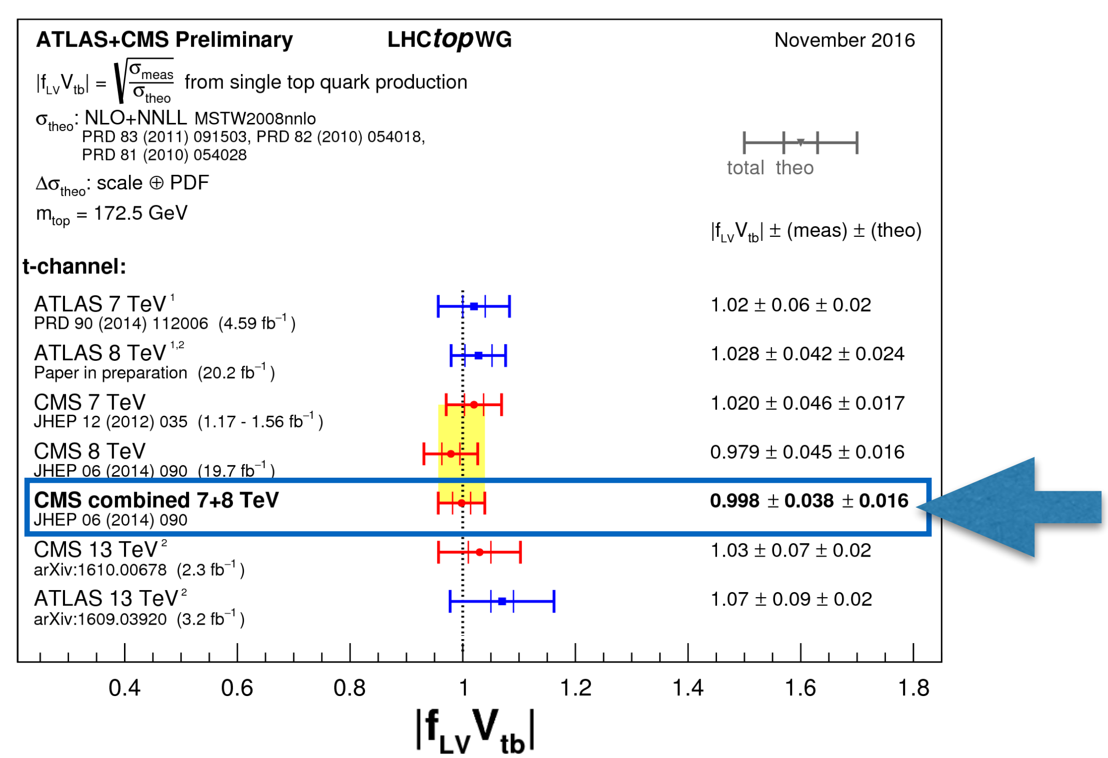
- t-channel production mode enjoys special interest for its large cross section and several strong physics motivations



☆ charge ratio

☆ CKM matrix element, $|V_{tb}|$

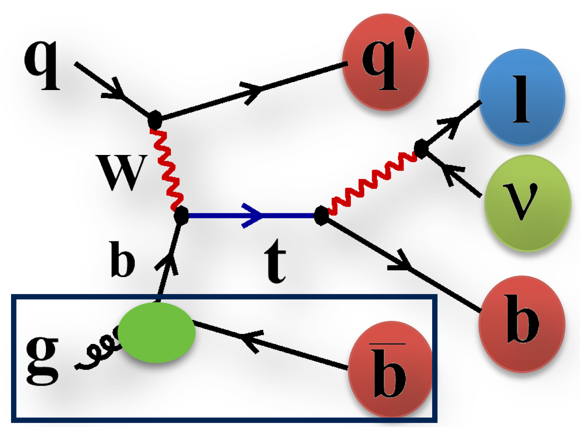




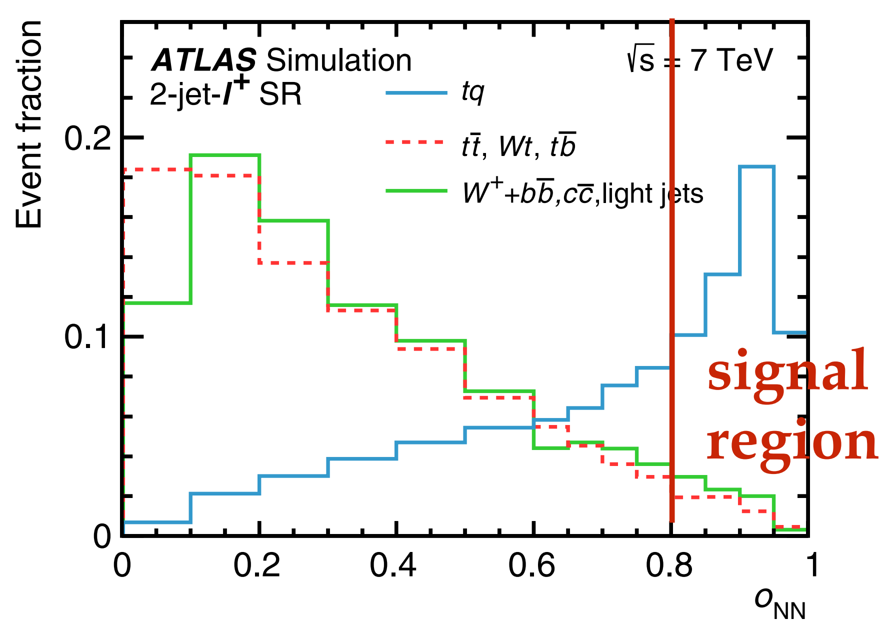
Experimental challenges

- Experimental measurements rely strongly on theoretical modeling of the signal and backgrounds

  - low acceptance, fiducial vs. full phase-space (~1/5)



basic acceptance cuts



further multivariate selection

  - theoretical unc. can be dominant

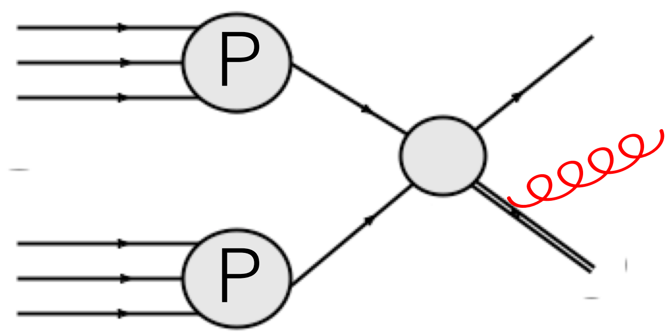
CMS 13 TeV 2.3 fb^{-1}, unfolded

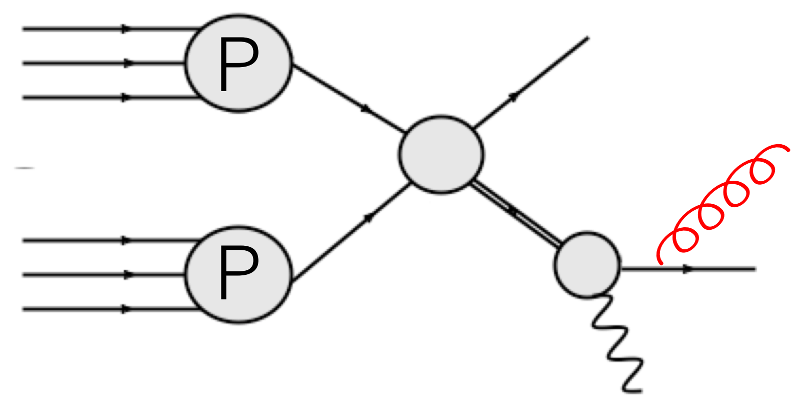
Uncertainty source	$\Delta\sigma_{t\text{-ch.},t}/\sigma^{\text{obs}}_{t\text{-ch.},t}$	$\Delta\sigma_{t\text{-ch.},\bar{t}}/\sigma^{\text{obs}}_{t\text{-ch.},\bar{t}}$	$\Delta R_{t\text{-ch.}}/R_{t\text{-ch.}}$
Statistical uncert.	±5.3%	±11.5%	±9.7%
Profiled exp. uncert.	±5.7%	±4.9%	±3.3%
Total fit uncert.	±7.8%	±12.5%	±10.3%
Integrated luminosity	±2.7%	±2.7%	-
Signal modelling	±8.2%	±8.5%	±5.3%
$t\bar{t}$ modelling	±4.3%	±4.5%	±4.0%
W+jets modelling	−1.6/+2.3%	−2.5/+2.3%	−1.7/+2.0%
μ_R/μ_F scale t-channel	−5.7/+5.2%	−7.2/+5.1%	−0.7/+1.2%
μ_R/μ_F scale $t\bar{t}$	−3.5/+4.1%	−4.7/+3.1%	−1.1/+1.0%
μ_R/μ_F scale tW	−0.6/+0.8%	−1.1/+0.7%	−0.2/+0.1%
μ_R/μ_F scale W+jets	−3.5/+3.0%	−4.9/+3.8%	−1.2/+0.9%
PDF uncert.	−2.1/+1.6%	−1.8/+2.1%	−2.2/+2.5%
Top quark p_T modelling	±0.2%	±0.2%	±0.1%
Total theory uncert.	−12.2/+12.1%	−13.6/+12.9%	±7.5%
Total uncert.	±14.7%	−18.7/+18.2%	±12.7%

signal modeling suffers from large QCD uncertainties and is the major limitation on the measurement

Theory predictions

- There have been extensive efforts on improving the predictions on t-channel production through various perturbative QCD approaches





- Next-to-leading order (NLO) corrections to production known for long time
  - Bordes, van Eijk, 95
  - Pittau, 96
  - Stelzer, Sullivan, Willenbrock, 97
  - Harris, Laenen, Phaf, Sullivan, Weinzierl, 02
  - Sullivan, 04
  - Campbell, Frederix, Maltoni, Tramontano, 09

- NLO production + decay in narrow width approximation
  - Campbell, Ellis, Tramontano, 04
  - Cao, Schwienhorst, Benitez, Brock,Yuan, 04
  - Falgari, Mellor, Signer, 10

- off-shell effects
  - Falgari, Giannuzzi, Mellor, Signer, 11
  - Papanastasiou, Frederix, Frixione, Hirschi, Maltoni, 13
  - Frederix, Frixione, Papanastasiou, Prestel, Torrielli, 16

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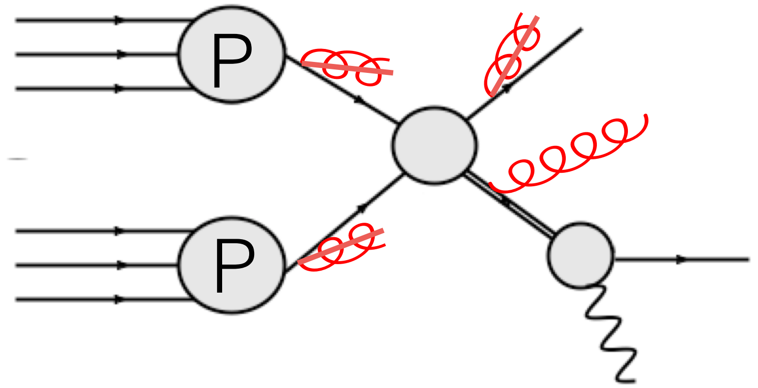


- NLO matched with parton shower
  - **Frixione, Laenen, Motylinski, Webber, 2005**
  - **Alioli, Nason, Oleari, Re, 2009**
  - **Frederix, Re, Torrielli, 2012**
- Threshold resummation
  - **Kidonakis, 2011-2016**
  - **Wang, Li, Zhu, Zhang, 2010**
  - **Wang, Li, Zhu, 2013**

- NLO prediction is insufficient

ATLAS 13 TeV 3.2 fb^{-1}, unfolded

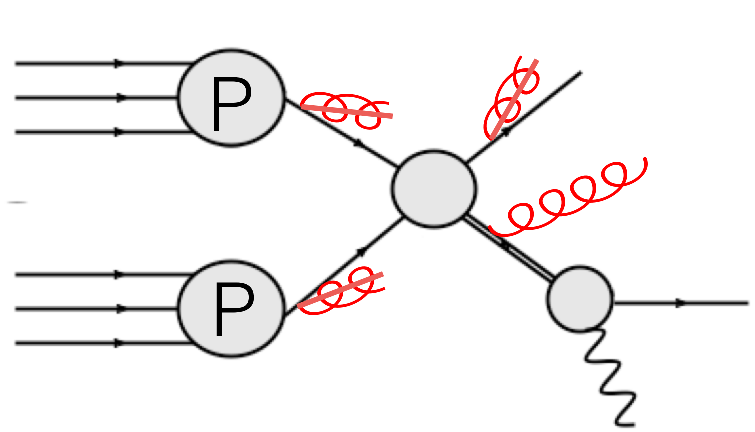
Source	$\frac{\Delta\sigma(tq)}{\sigma(tq)}$ [%]	$\frac{\Delta\sigma(\bar{t}q)}{\sigma(\bar{t}q)}$ [%]	$\frac{\Delta R_t}{R_t}$ [%]
Data statistics	± 2.9	± 4.1	± 5.0
Monte Carlo statistics	± 2.8	± 4.2	± 5.1
Reconstruction efficiency and calibration uncertainties			
Muon uncertainties	± 0.8	± 0.9	± 1.0
Electron uncertainties	< 0.5	± 0.5	± 0.7
JES	± 3.4	± 4.1	± 1.2
Jet energy resolution	± 3.9	± 3.1	± 1.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	± 0.9	± 1.2	< 0.5
b-tagging efficiency	± 7.0	± 6.9	< 0.5
c-tagging efficiency	< 0.5	± 0.5	± 0.6
Light-jet tagging efficiency	< 0.5	< 0.5	< 0.5
Pile-up reweighting	± 1.5	± 2.2	± 3.8
Monte Carlo generators			
tq parton shower generator	± 13.0	± 14.3	± 1.9
tq NLO matching	± 2.1	± 0.7	± 2.8
tq radiation	± 3.7	± 3.4	± 3.7
Total systematic uncertainty	± 17.5	± 20.0	± 10.2
Total uncertainty	± 17.8	± 20.4	± 11.4

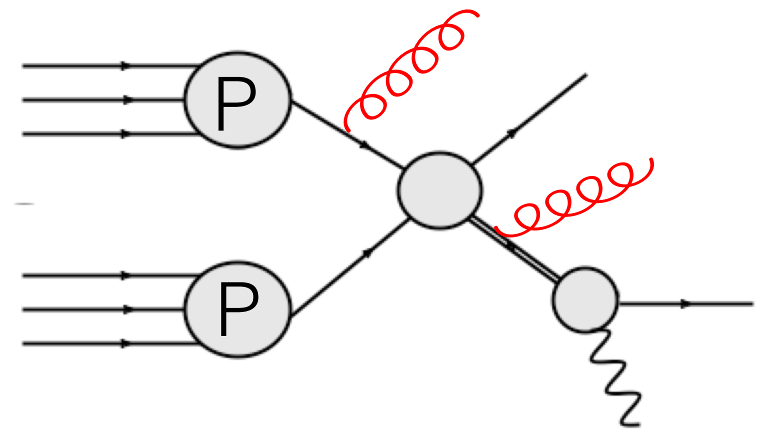
$$f_{\mathrm{LV}} \cdot |V_{tb}| \;=\; 1.07 \pm 0.01\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst.}) \pm 0.02\,(\mathrm{theor.}) \pm 0.01\,(\mathrm{lumi.})$$

NLO corrections are large in the fiducial region inducing dominant uncertainties

Theory predictions

- There have been extensive efforts on improving the predictions on t-channel production through various perturbative QCD approaches





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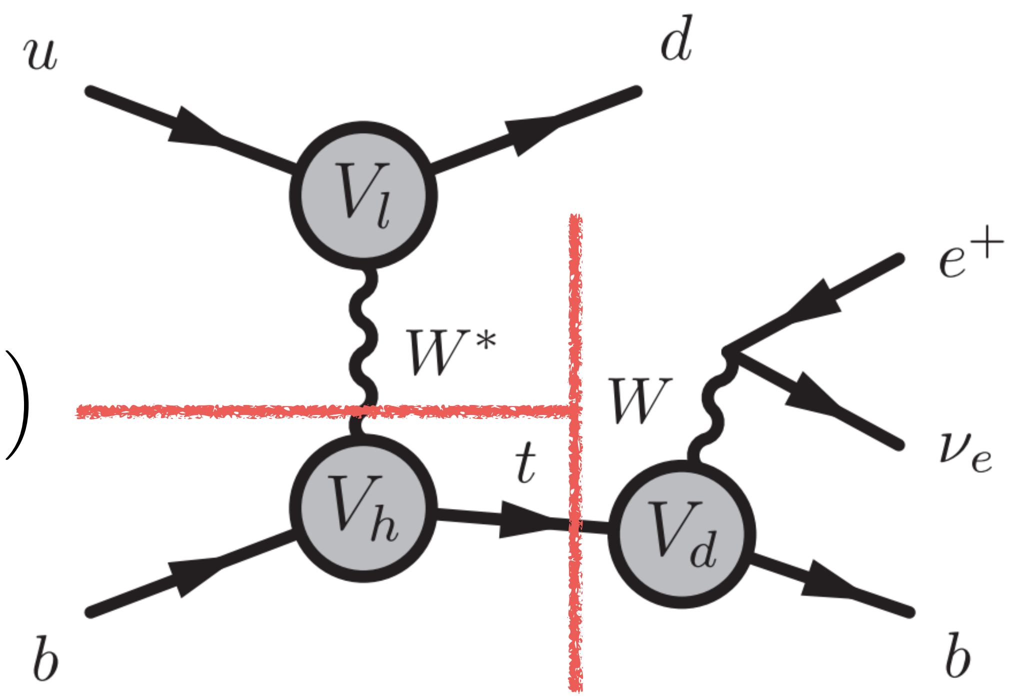
- Threshold resummation
  - **Kidonakis, 2011-2016**
  - **Wang, Li, Zhu, Zhang, 2010**
  - **Wang, Li, Zhu, 2013**
- NNLO production of stable top quark
  - **Brucherseifer, Caola, Melnikov, 2014**
- NNLO production + decay in narrow width approximation
  - **Berger, JG, Yuan, Zhu, 2016**

achieving a realistic NNLO simulation at parton level

Factorization at NNLO

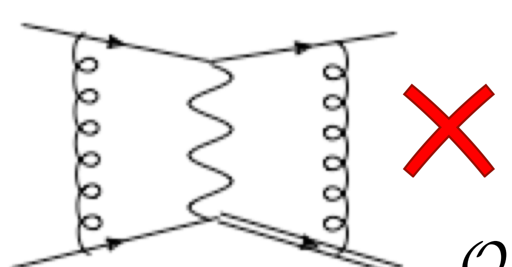
- The perturbative QCD corrections can be factorized into three parts, at the light-quark vertex, heavy-quark vertex, and decay

Double DIS $\mathcal{O}\left(\alpha_s^2 \frac{1}{N_c^2}\right)$



NWA $\mathcal{O}\left(\frac{\Gamma_t}{m_t}\right)$

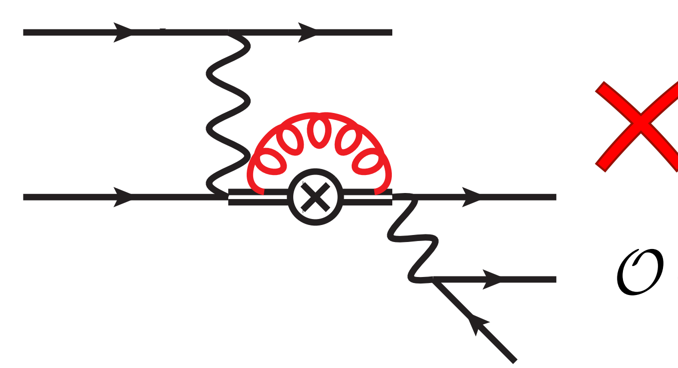
- double deep inelastic scattering (DIS) approximation



$\mathcal{O}\left(\alpha_s^2 \frac{1}{N_c^2}\right)$

violation start at NNLO

- narrow width approximation (NWA)

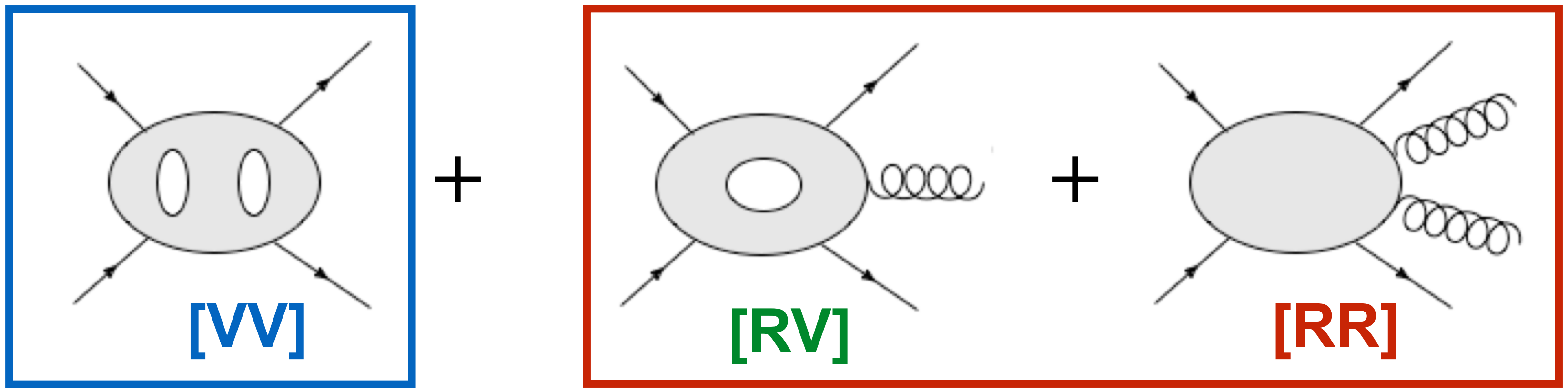


$\mathcal{O}\left(\frac{\Gamma_t}{m_t}\right)$

off-shell effects known to NLO small in general

Factorization at NNLO

- Infrared singularities from double-unresolved phase-space regions prevent a direct evaluation of the fiducial cross sections at NNLO

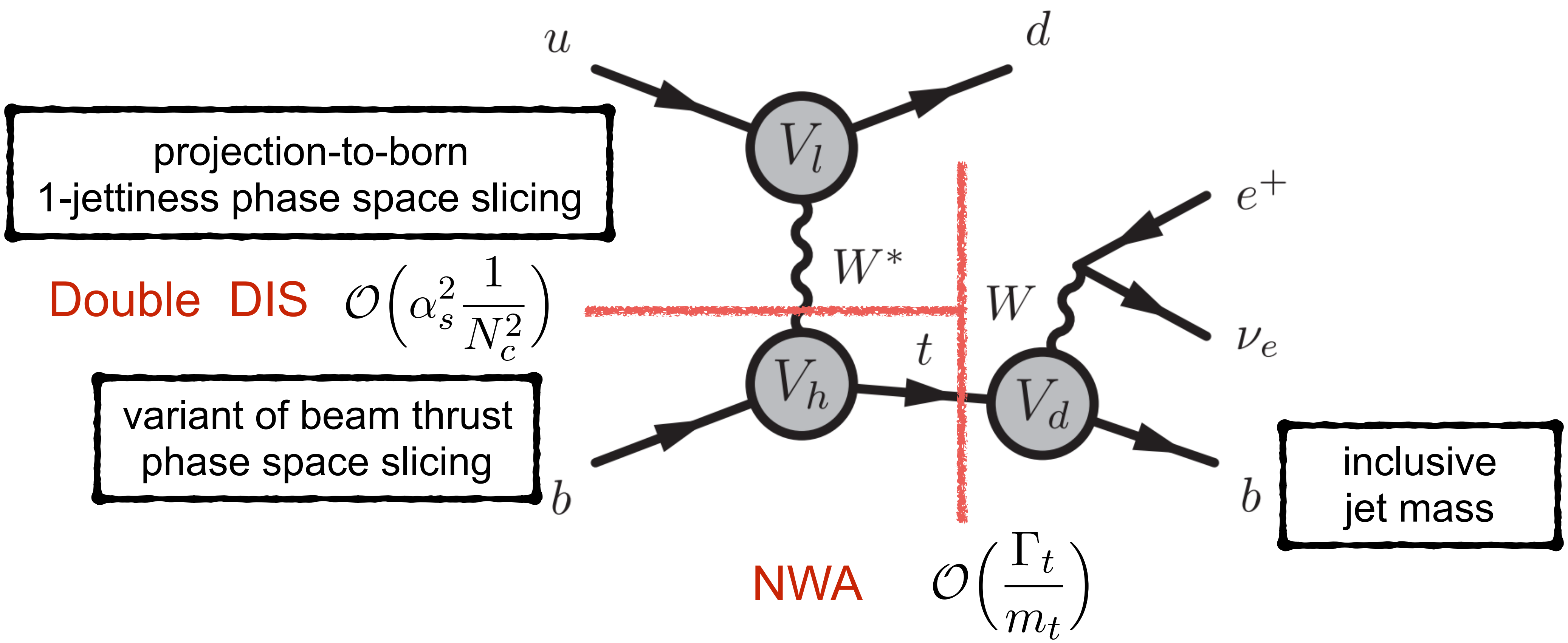


- direct two-loop calculation by integrating out loop momentum
  - DIS form factor **[Kramer, Lampe, 1987]**
  - vertex t→ bW* **[Bonciani, Ferroglia, 2008; Asatrian, Greub, Pecjak, 2008; Beneke, Huber, X.-Q. Li, 2008; Bell, 2008]**

- singularities entangled with phase-space integration of QCD partons
  - Antenna subtraction **[Gehrmann-De Ridder, Gehrmann, Glover], inclusive jet production**
  - Sector-Improved FKS subtraction **[Czakon], top-quark pair production**
  - Phase-space slicing **[Catani; JG, Zhu, Li; Boughezal, Liu, Petriello], vector boson pair production; top production and decay; vector boson plus jet production**
  - Projection-to-Born **[Cacciari, Dreyer, Karlberg, Salam, Zanderighi], WBF Higgs boson production**

Factorization at NNLO

- The perturbative QCD corrections can be factorized into three parts, at the light-quark vertex, heavy-quark vertex, and decay



- light-quark vertex
  - **projection-to-born method (P2B)**
  - **phase-space slicing with 1-jettiness**
- heavy-quark vertex
  - **phase-space slicing with beam thrust**

  [Berger, JG, Li, Liu, Zhu, 2016]
- top-quark decay
  - **phase-space slicing with jet mass**

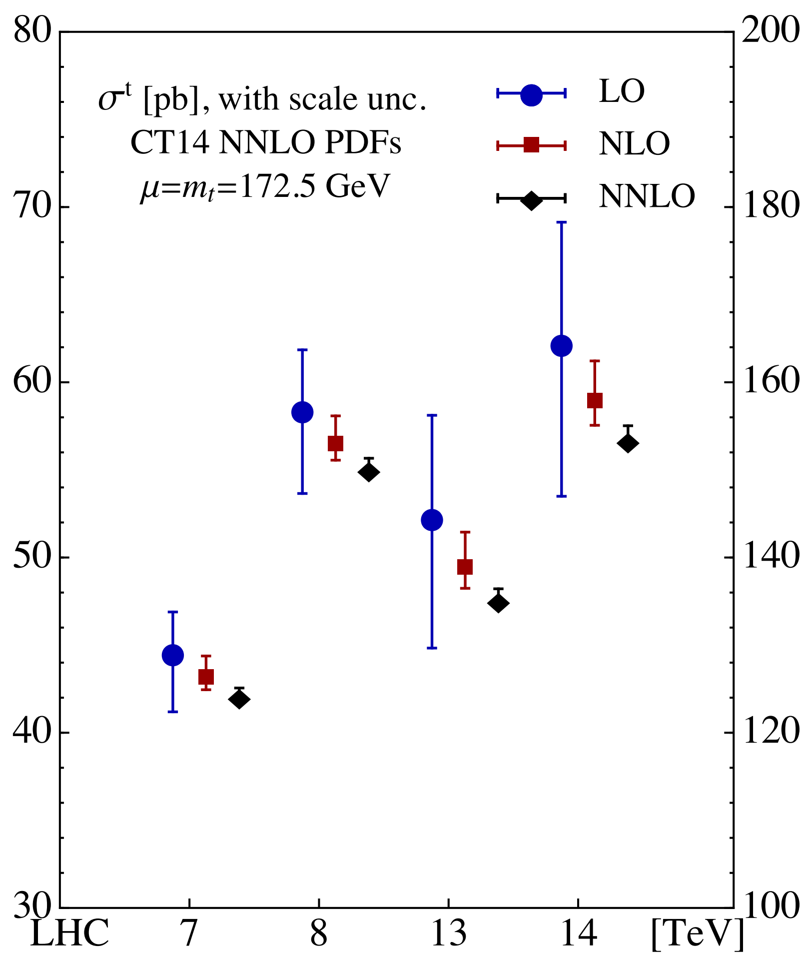
  [JG, Li, Zhu, 2013]

method used for isolating out the infrared singularities

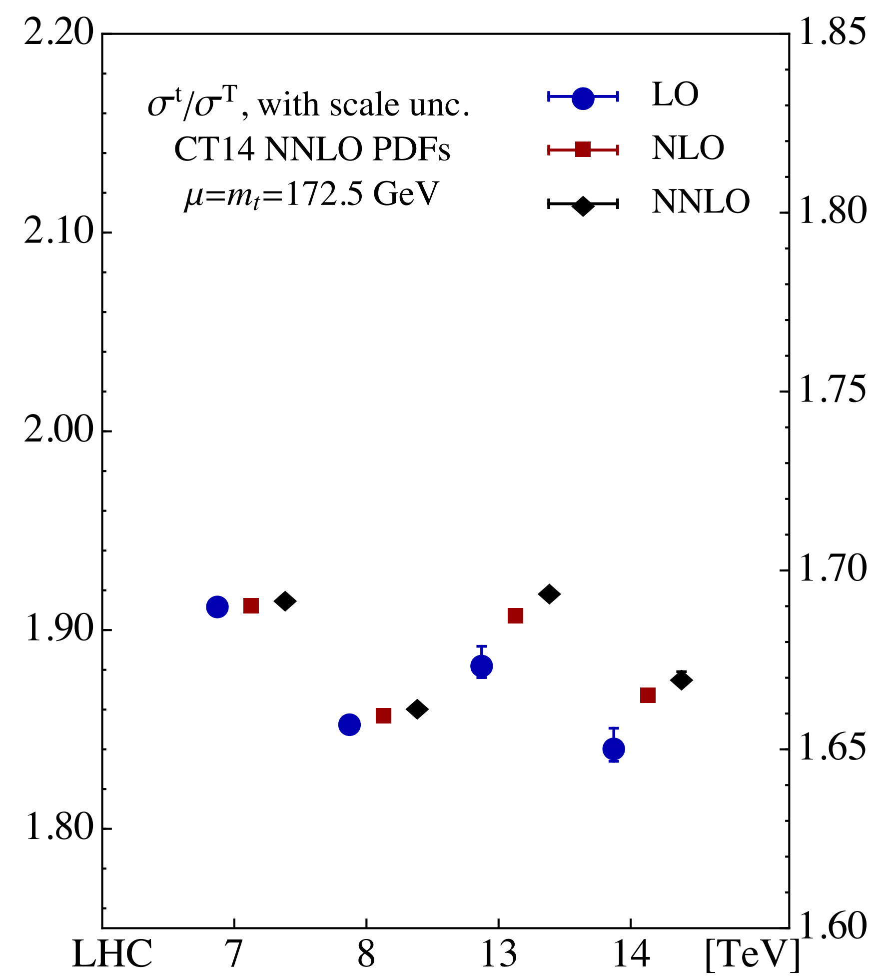
Inclusive cross sections

- Total inclusive cross sections for LHC 7, 8 TeV(left axis), and 13, 14 TeV(right axis) with QCD scale choice in [$m_t/2$, $2m_t$]

☆ total rate, top quark



☆ charge ratio



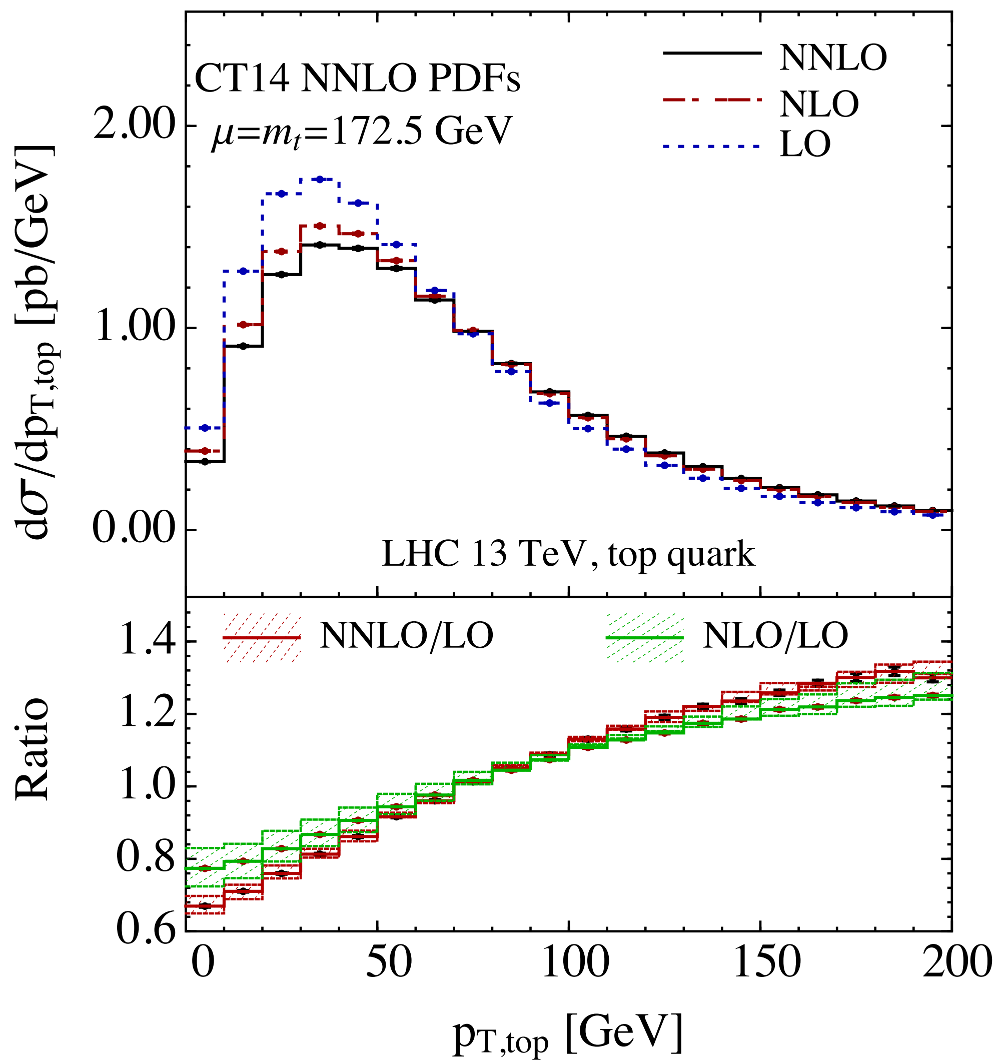
moderate negative corrections, ~5% for NLO, ~3% for NNLO; scale variations reduced to within 1%

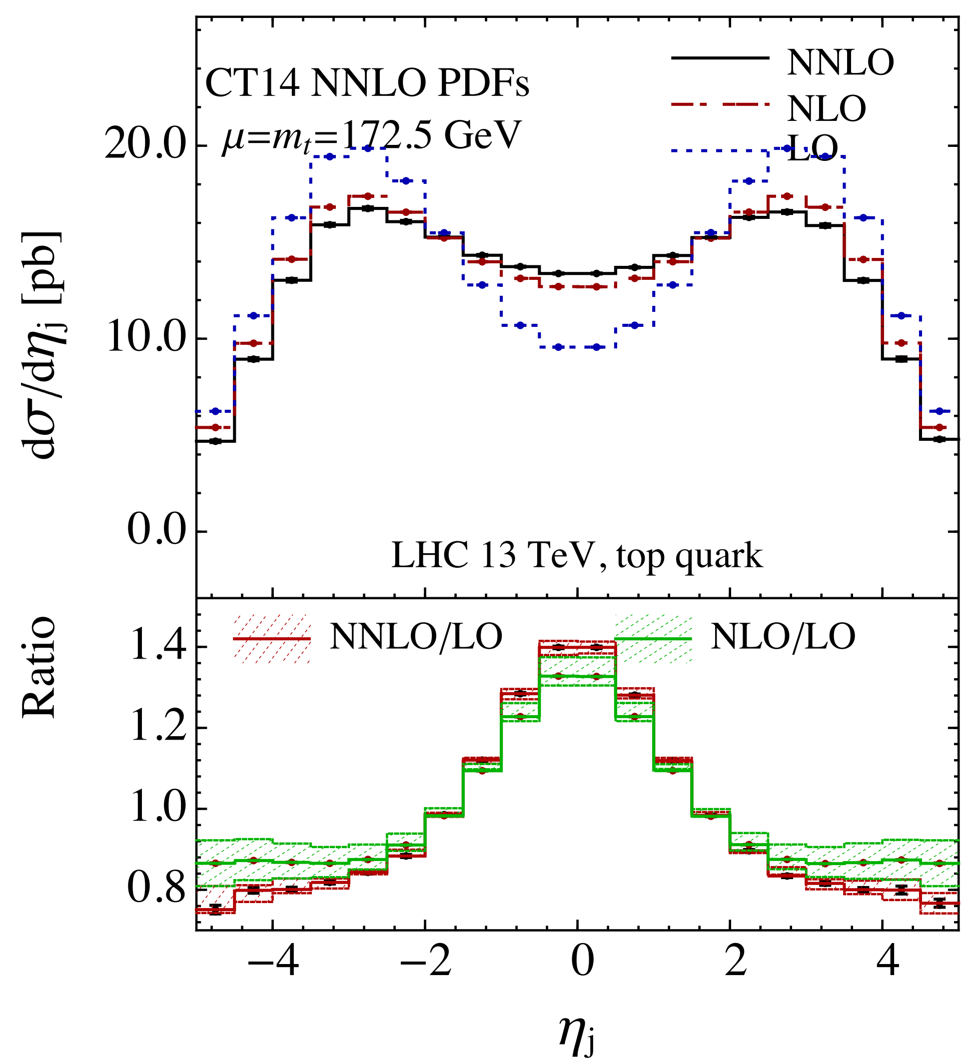
small corrections, within 1%, scale variations almost vanish

Inclusive cross sections

- Differential inclusive cross sections for top-quark at LHC 13 TeV with QCD scale choice in [$m_t/2$, $2m_t$]

  - top-quark transverse momentum
  - leading jet pseudo-rapidity



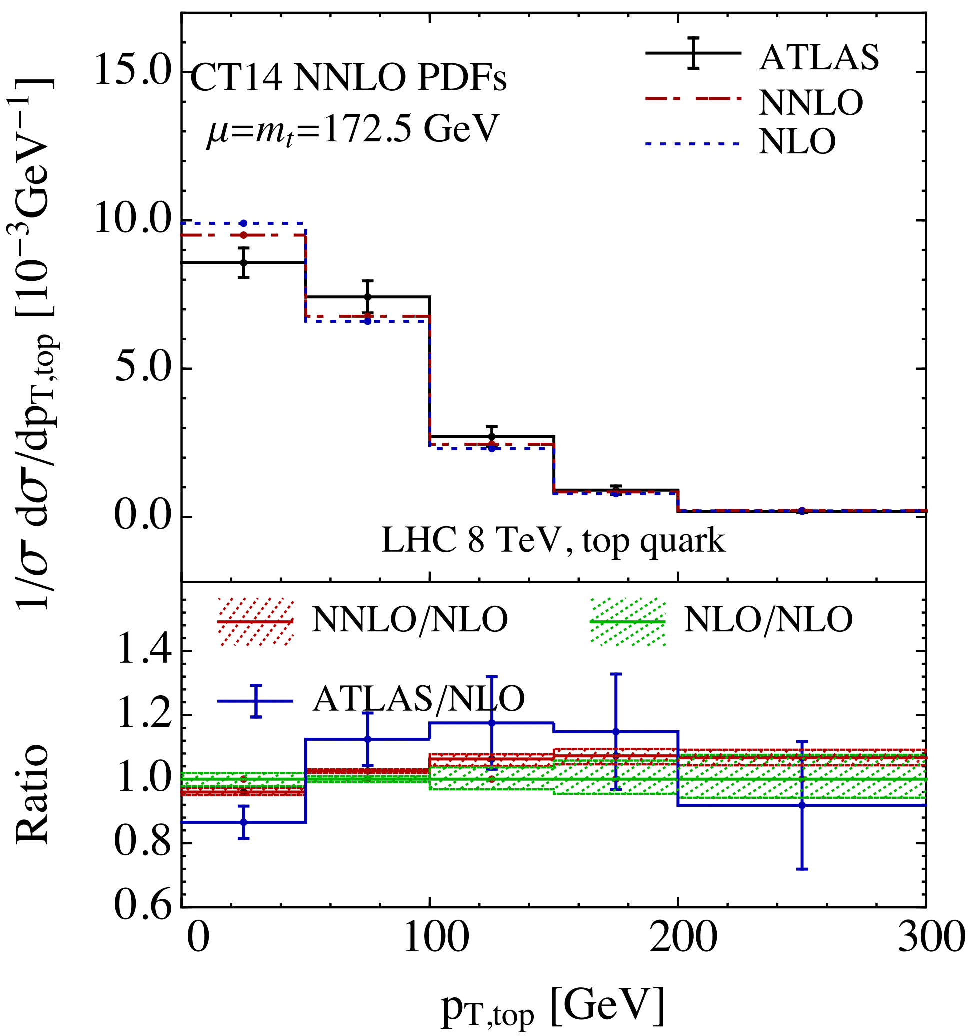


QCD corrections change the shapes significantly and NNLO show a large reduction of the scale uncertainties

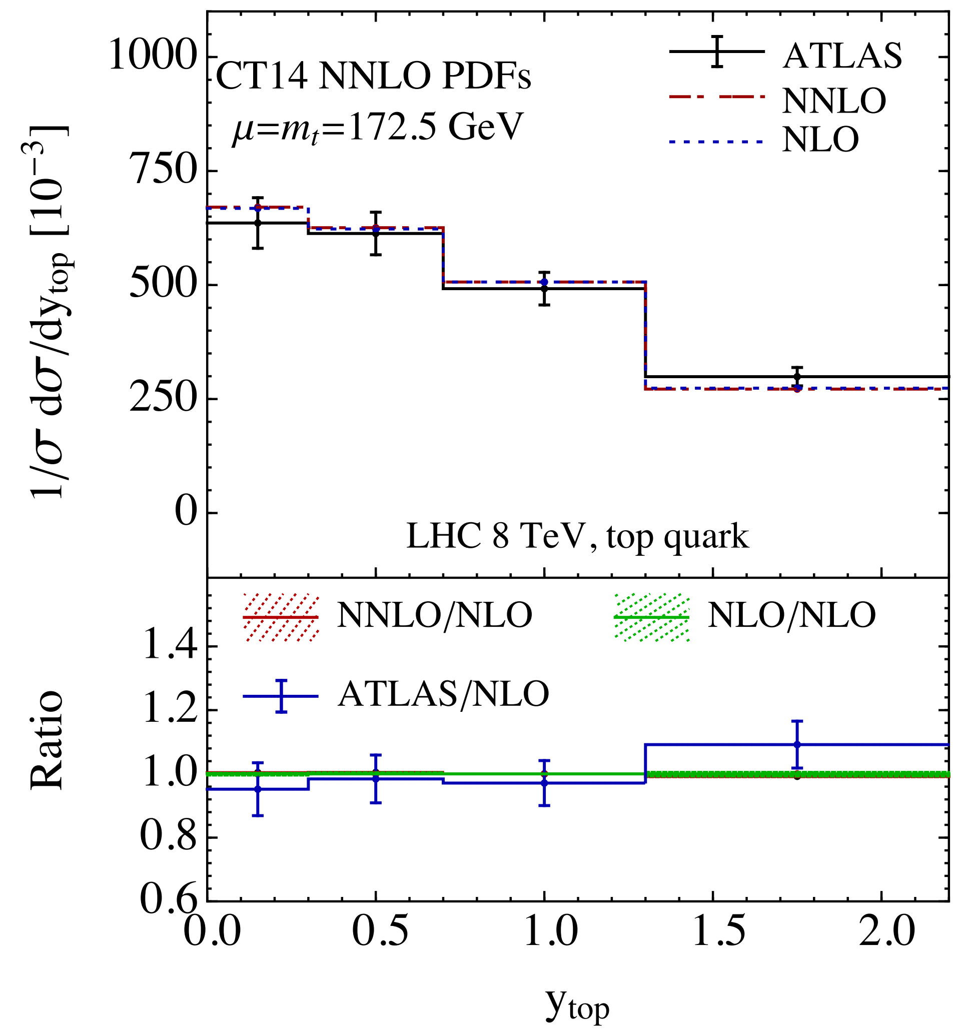
Inclusive cross sections

- Differential inclusive cross sections for top-quark at LHC 8 TeV with QCD scale choice in $[m_t/2, 2m_t]$; **vs. ATLAS data** [1702.02859]

  - top-quark transverse momentum



  - top-quark rapidity



improved agreement to data on the normalized transverse momentum distribution of top quark at NNLO

Fiducial cross sections

- Effects of QCD corrections on cross sections within an experimental fiducial volume at LHC 13 TeV

- fiducial volume (1 family)

$$\text{jet } p_T > 40\,\text{GeV},\ |\eta| < 5$$

exactly 2 jets, 1 b-jet

$$\text{charged lepton } p_T > 30\,\text{GeV}$$

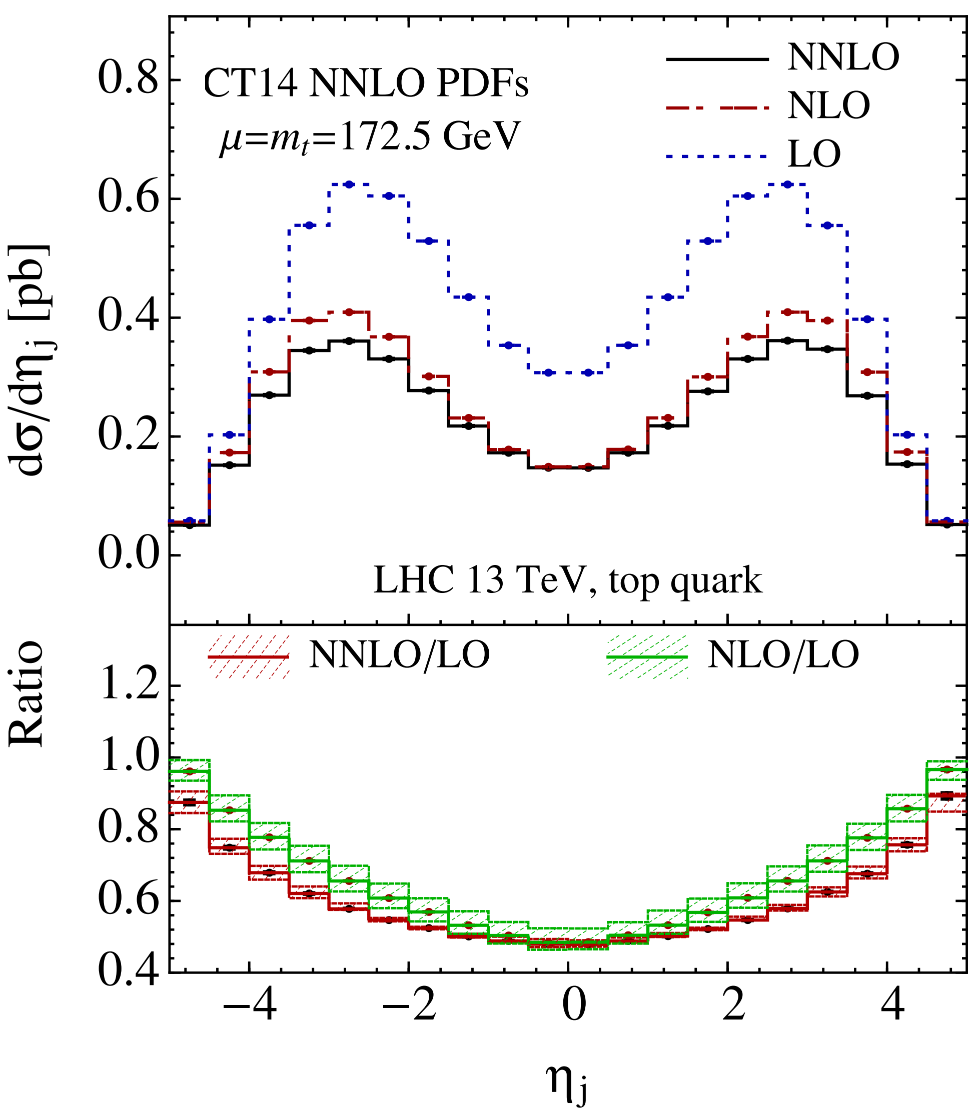
$$|\eta_b| < 2.4,\ |\eta_l| < 2.4$$

- total rate

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

large negative corrections, acceptance LO 0.0283, NLO 0.0214, NNLO 0.0201

- spectator jet pseudo-rapidity

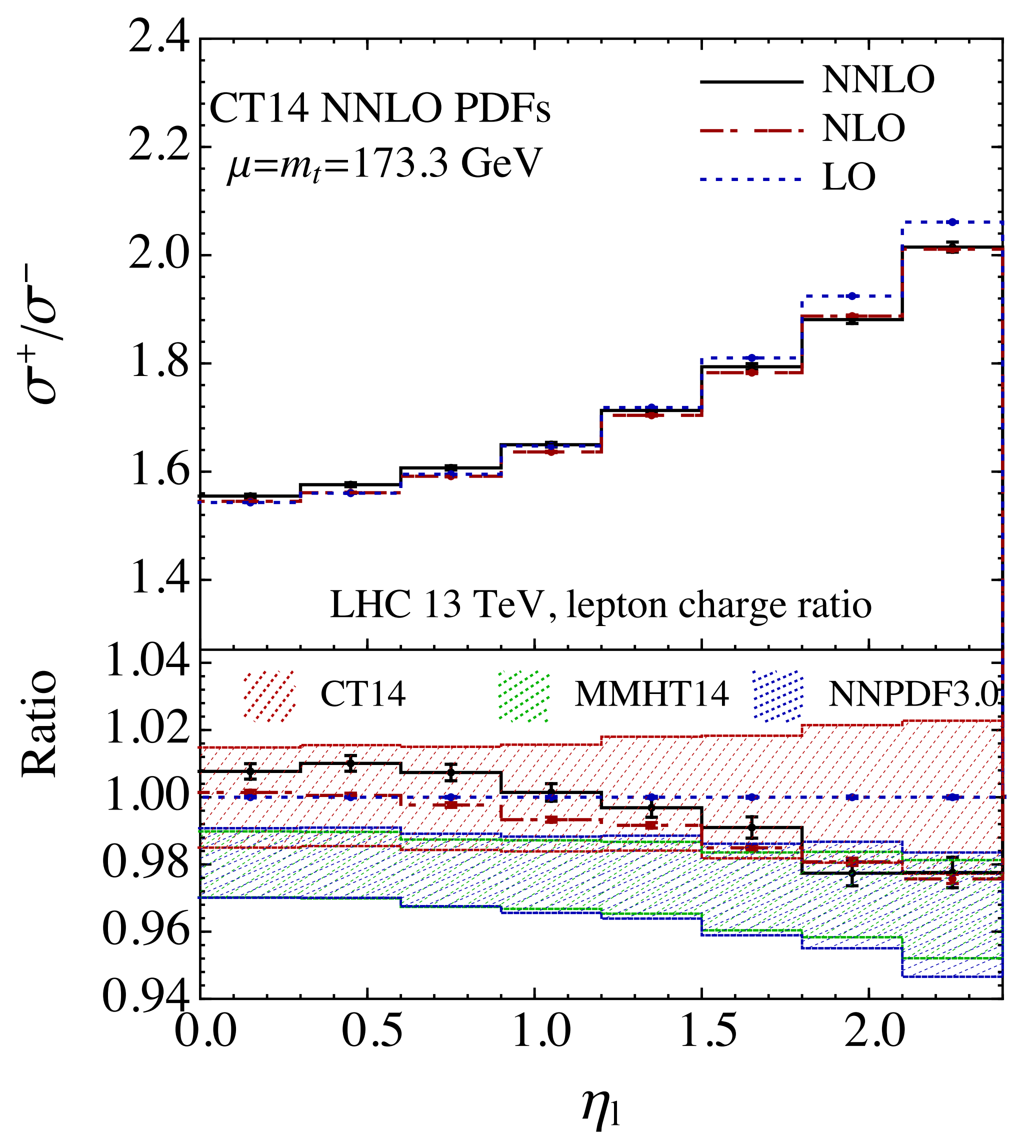


QCD corrections show a very different shapes wrt. inclusive case

Fiducial cross sections

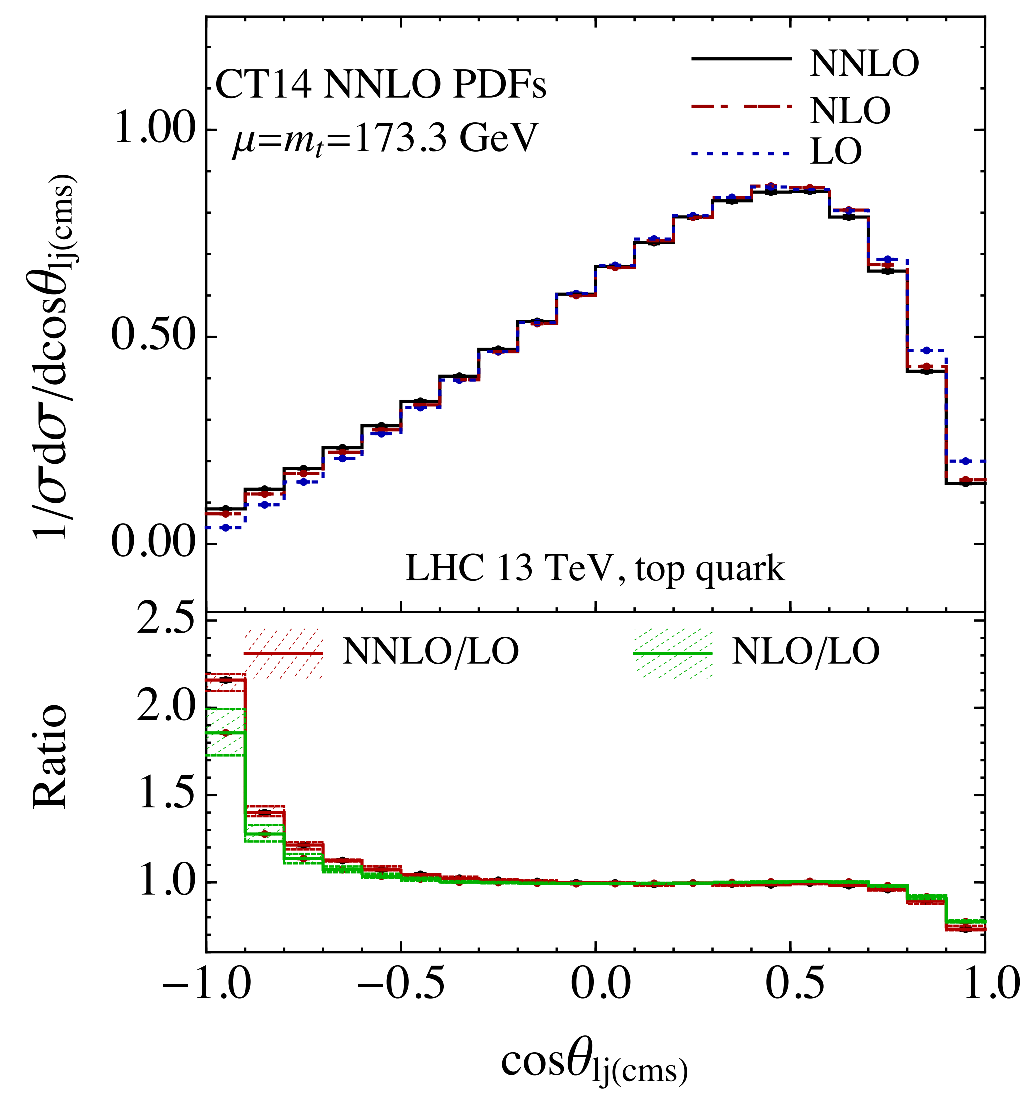
- Effects of QCD corrections on cross sections within an experimental fiducial volume at LHC 13 TeV

  - lepton charge ratio as a function of pseudo-rapidity



NNLO QCD corrections within 1%

  - cosine of angle between lepton and spectator jet



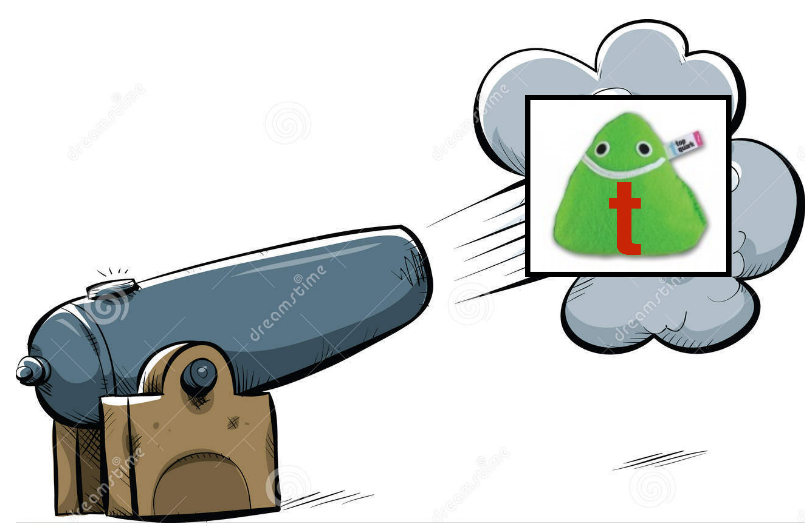
FB asymmetry, A_{LO}=0.383(0), A_{NLO}=0.362(5), A_{NNLO}=0.346(3)

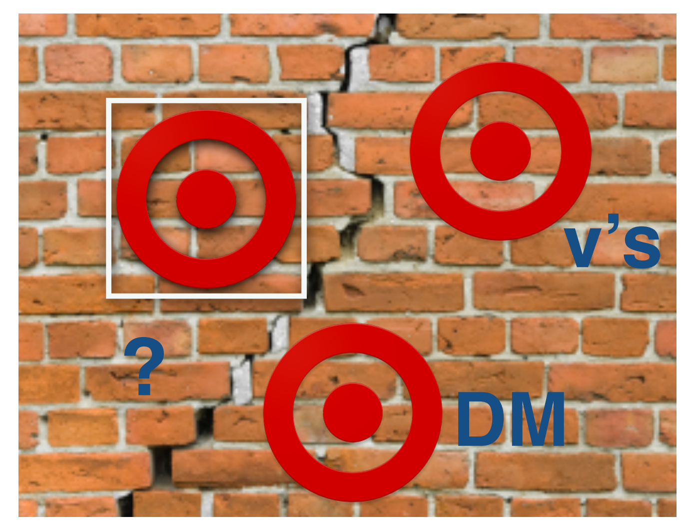
Summary

- Top quark is unique for test of standard model including quantum chromodynamics and as a probe of new physics beyond standard model

- Large Hadron Collider is a top-quark factory and has demonstrated a great success of precision top-quark measurements, e.g., on pair production and single top-quark production; and …

- Improvements on theoretical predictions are still needed to match the precision of ongoing projects at LHC Run 2, e.g., NNLO QCD corrections further matched with parton showering and hadronization, and can be crucial for the measurements of SM and searches for new physics beyond

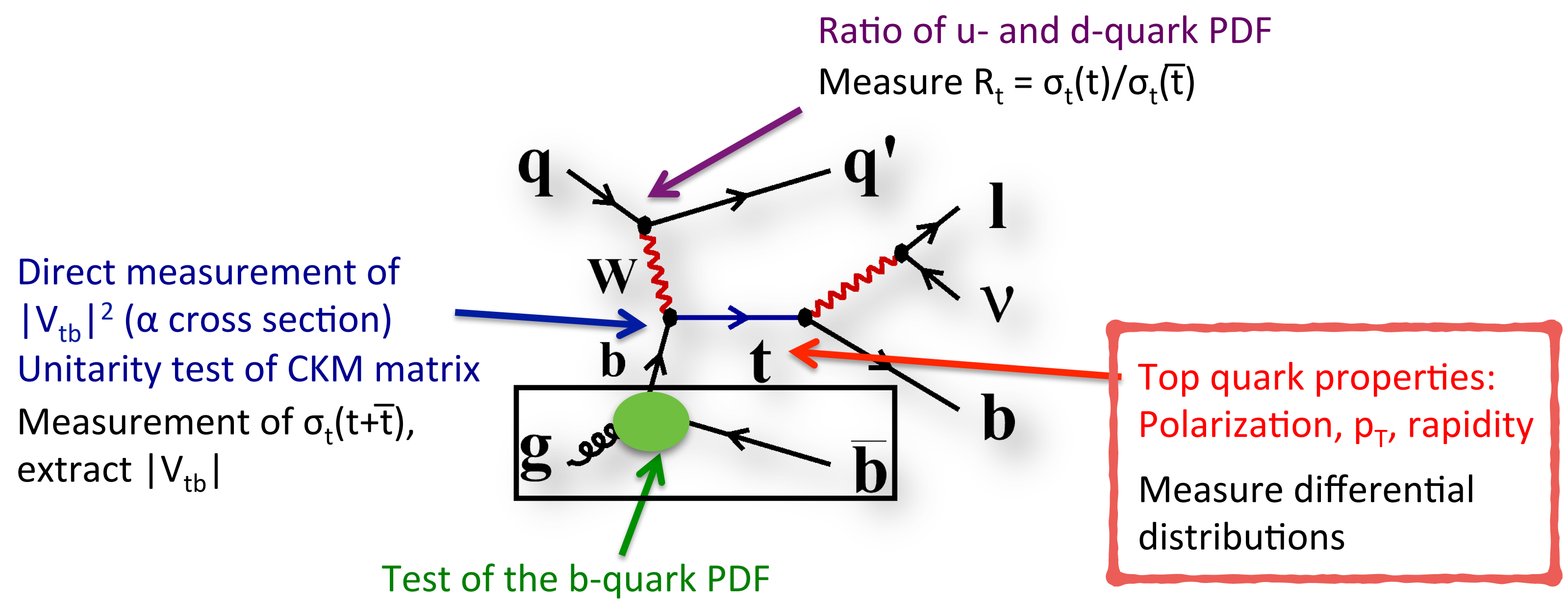




Thank you for your attention!

t-channel production [Backups]

- t-channel production mode enjoys special interest for its large cross section and several strong physics motivations

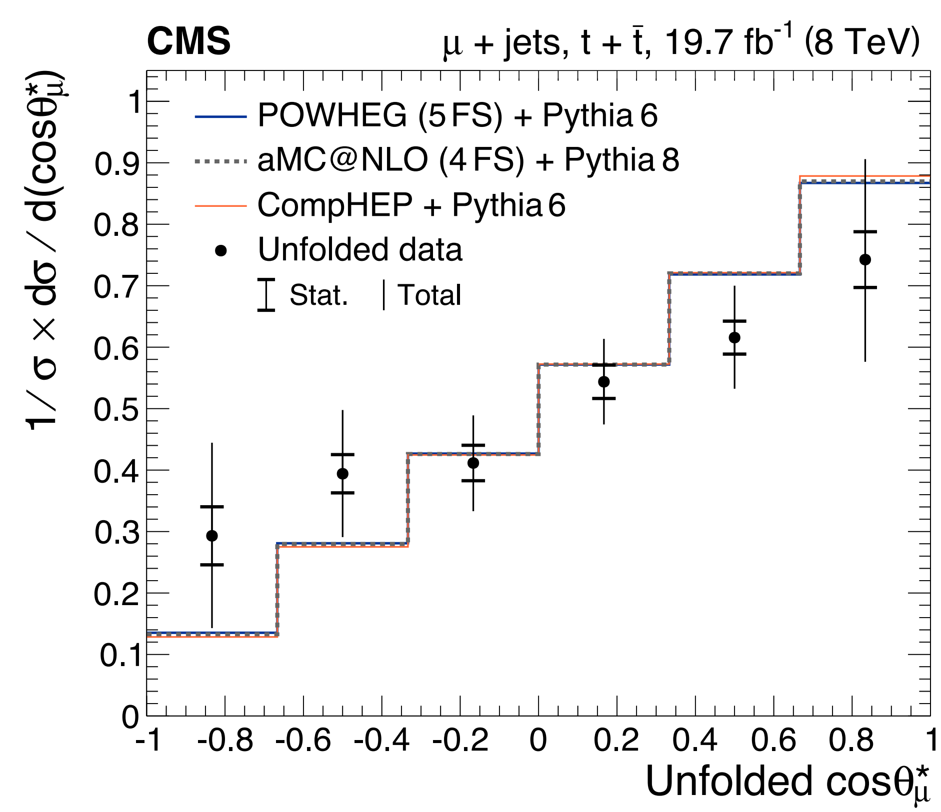


- Polarization: angular distribution in top quark rest frame wrt. spectator quark

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_X} = \frac{1}{2}(1 + P_t^{(\vec{s})}\alpha_X\cos\theta^*_X) = \left(\frac{1}{2} + A_X\cos\theta^*_X\right)$$

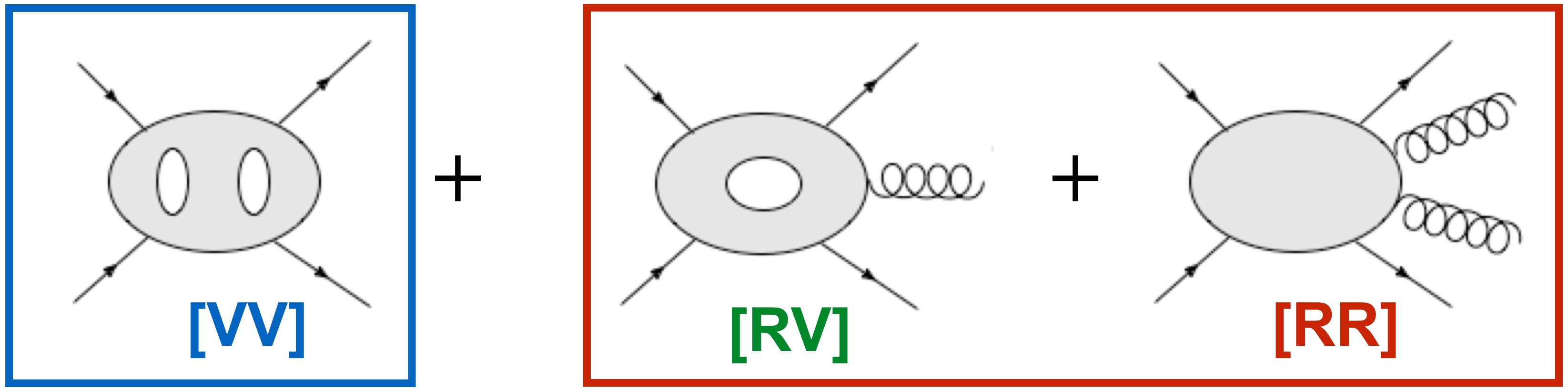
$$A_\mu(t) = 0.29 \pm 0.03\,(\text{stat}) \pm 0.10\,(\text{syst}) = 0.29 \pm 0.11$$
$$A_\mu(\bar{t}) = 0.21 \pm 0.05\,(\text{stat}) \pm 0.13\,(\text{syst}) = 0.21 \pm 0.14$$
$$A_\mu(t+\bar{t}) = 0.26 \pm 0.03\,(\text{stat}) \pm 0.10\,(\text{syst}) = 0.26 \pm 0.11$$

SM NLO prediction on angular asymmetry A_l, 0.44



Factorization at NNLO [Backups]

✦ Infrared singularities from double-unresolved phase-space regions prevent a direct evaluation of the fiducial cross sections at NNLO



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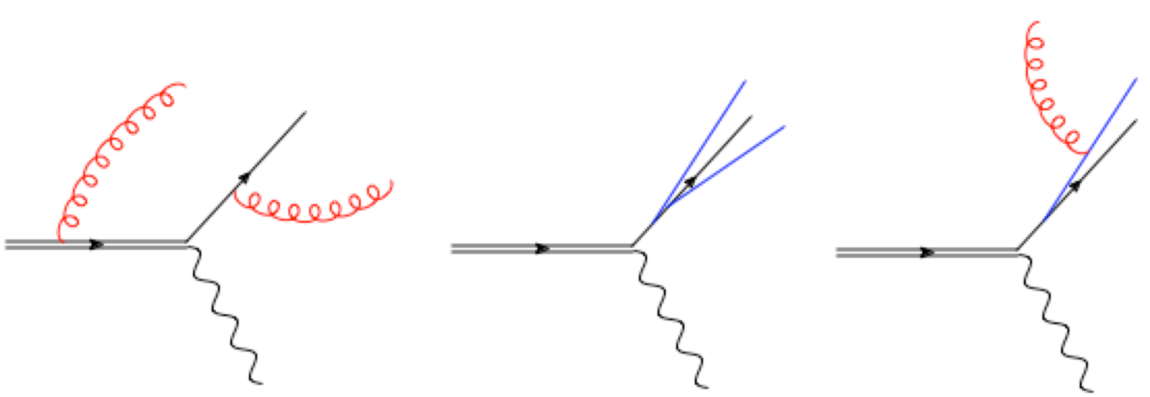
- singularities entangled with phase-space integration of QCD partons

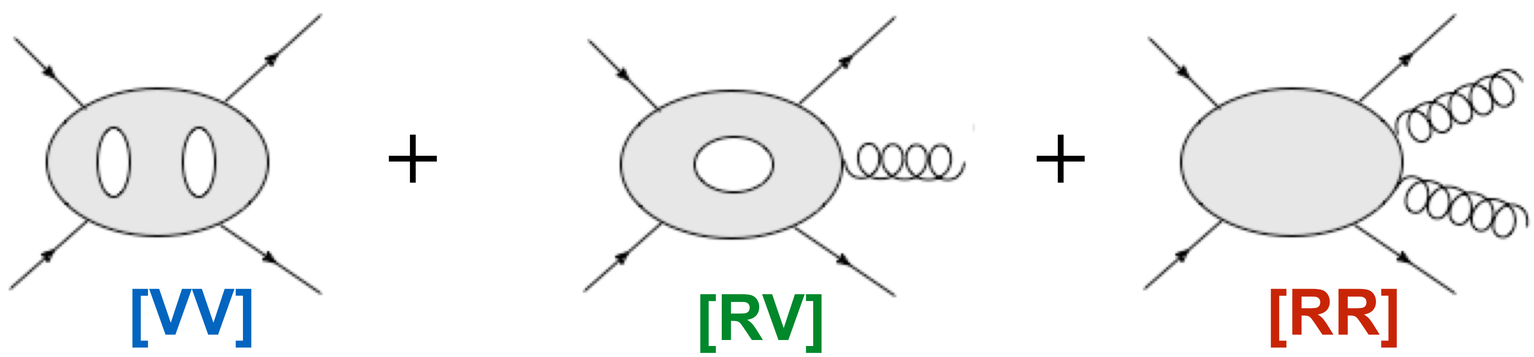
double-unresolved singularities

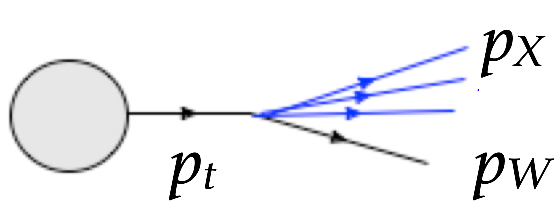
double soft   triple collinear   mixed soft-coll.



Phase space slicing **[Backups]**

- A generalization of phase-space slicing method to NNLO is utilized for QCD corrections in top-quark decay **[JG, Li, Zhu, 2013]**





phase space slicing (in top-quark decay)

$$\tau = \frac{(\sum_X p_X)^2}{m_t^2}$$ slicing variable

- for $\tau > \tau_{\rm cut}$, at most singly-unresolved, can be dealt with NLO techniques

  [RV] + [RR]

- for $\tau < \tau_{\rm cut}$, QCD radiations are unresolved, $\Gamma_t\big|_{\rm unres.}$

  [VV] + [RV] + [RR]

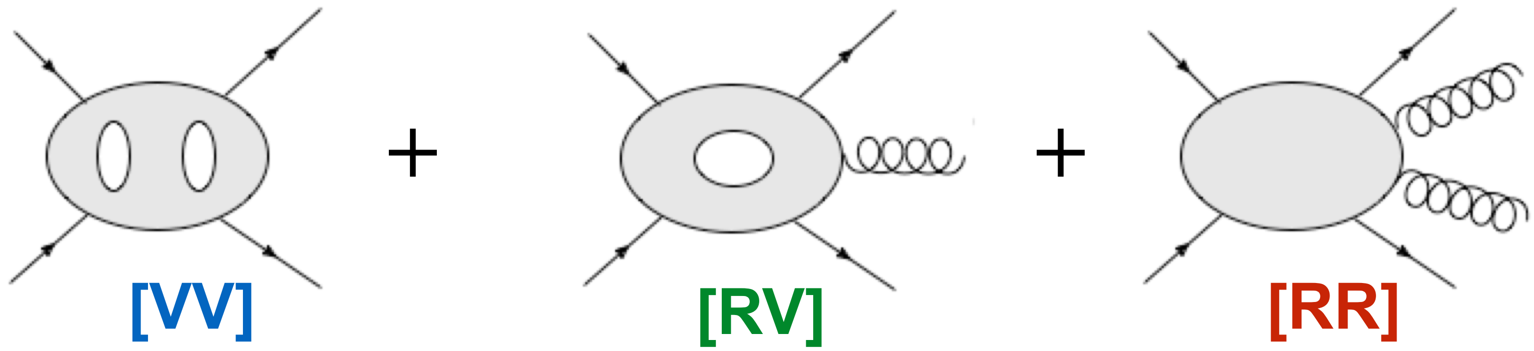
Hard function — Jet function — Soft function

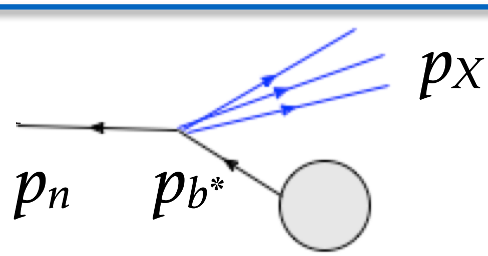
$$\Gamma_t\big|_{\rm unres.} = \Gamma_t^{(0)} H(m_W^2/m_t^2,\mu) \int_0^{\tau_{\rm cut}} d\tau \int d\tau_s \int d\tau_c J(\tau_c,\mu) S(\tau_s,\mu) \delta(\tau - \tau_c - \tau_s)$$

$$+\mathcal{O}(\tau_{\rm cut} \ln^k \tau_{\rm cut})$$ factorization in soft-collinear effective theory

Phase space slicing [Backups]

- A generalization of phase-space slicing method to NNLO is utilized for QCD corrections in heavy-quark vertex **[Berger, JG, Li, Liu, Zhu, 2016]**





phase space slicing
(in heavy-quark vertex)

$$\tau = \frac{2\, p_X \cdot p_n}{Q^2 + m_t^2}$$ slicing variable

- for $\tau > \tau_{\mathrm{cut}}$, at most singly-unresolved, can be dealt with NLO techniques

  [RV] + [RR]

- for $\tau < \tau_{\mathrm{cut}}$, QCD radiations are unresolved, $\sigma\big|_{\mathrm{unres.}}$

  [VV] + [RV] + [RR]

Hard function Beam function Soft function

$$\sigma\big|_{\mathrm{unres.}} = \int_0^{\tau_{\mathrm{cut}}} d\tau \int_0^1 dz\, \hat{\sigma}_0(z) H(Q, m_t, \mu) \int d\tau_c\, d\tau_s B_q(\tau_c, z, \mu) S(\tau_s, \mu) \delta(\tau - \tau_c - \tau_s)$$

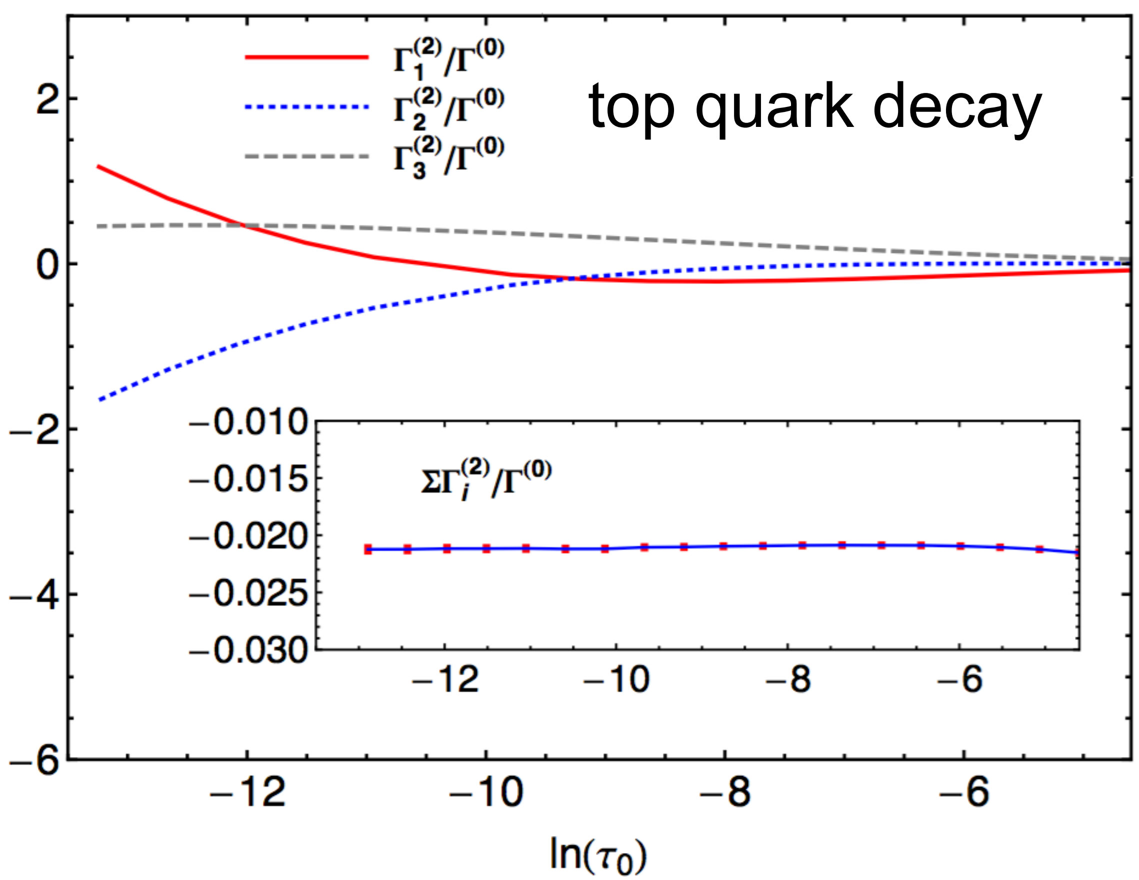
$$+\mathcal{O}(\tau_{\mathrm{cut}} \ln^k \tau_{\mathrm{cut}})$$ factorization in soft-collinear effective theory

Numerical validation **[Backups]**

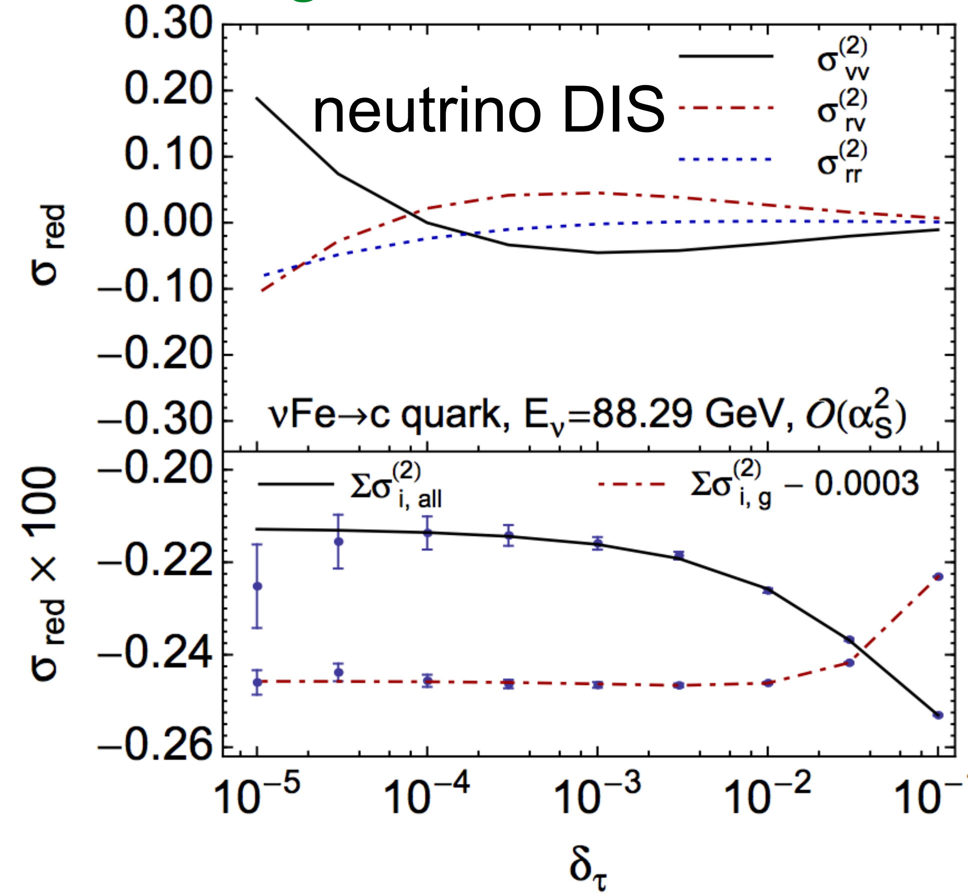
- Residual dependence on the arbitrary cutoff parameter can serve as a good test of the method; vanishes when cutoff small enough

  - dependence on the cutoff

[JG, Li, Zhu, 2013]



[Berger, JG, Li, Liu, Zhu, 2016]



in practice a cutoff ~10^{-4} is found to be sufficiently small to converge to true NNLO results while keeping the MC integrations stable

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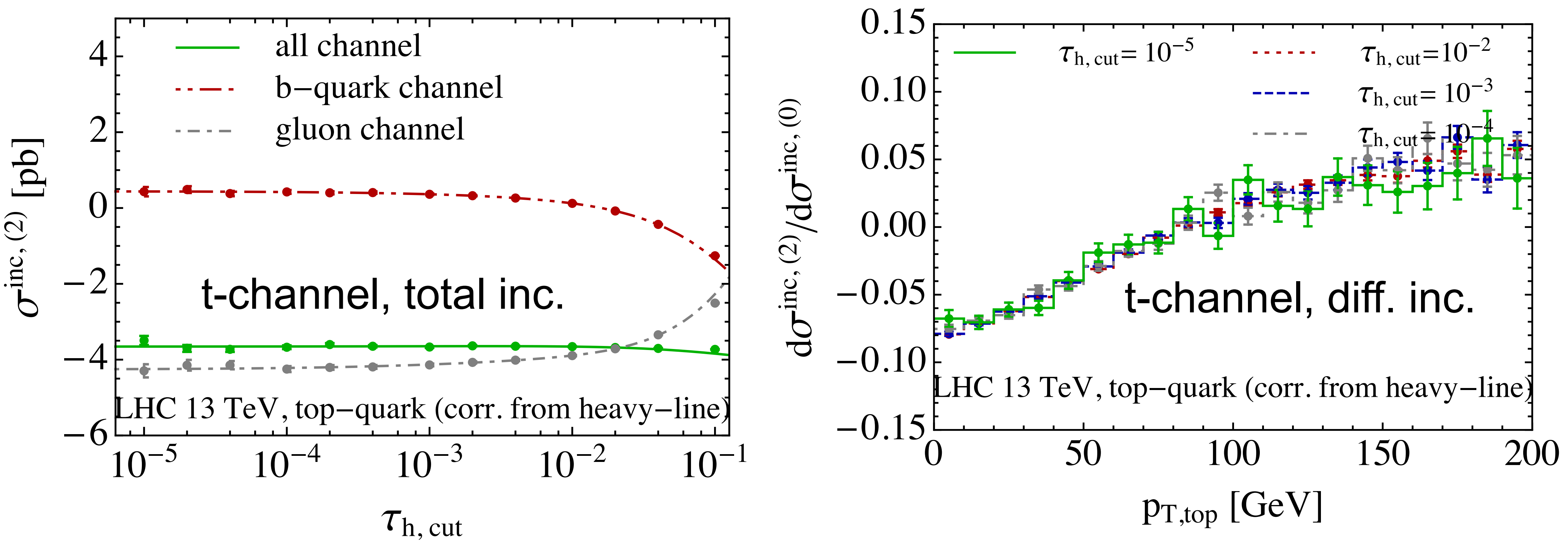
[JG, Berger, Zhu, 2017]



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