

# s-channel single top quark production and decay at NNLO in QCD

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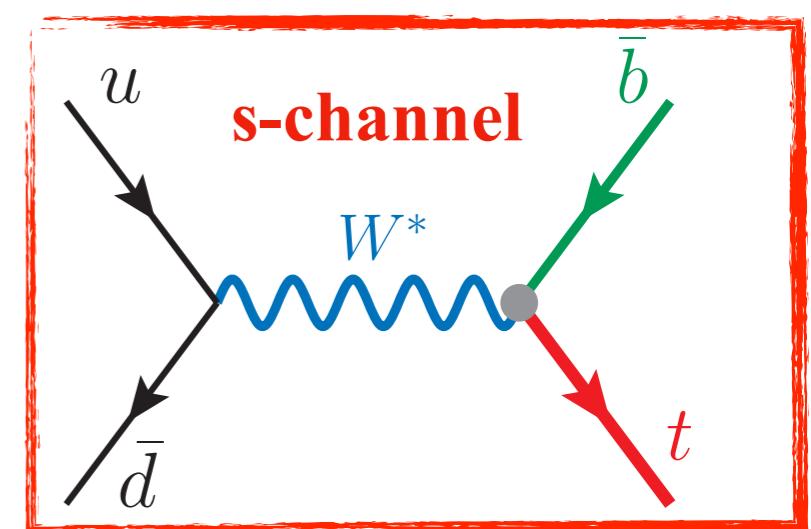
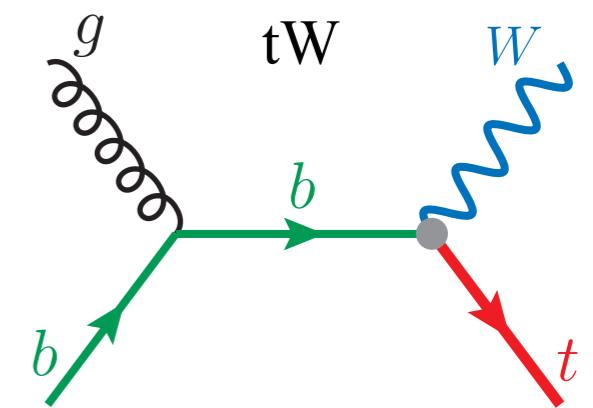
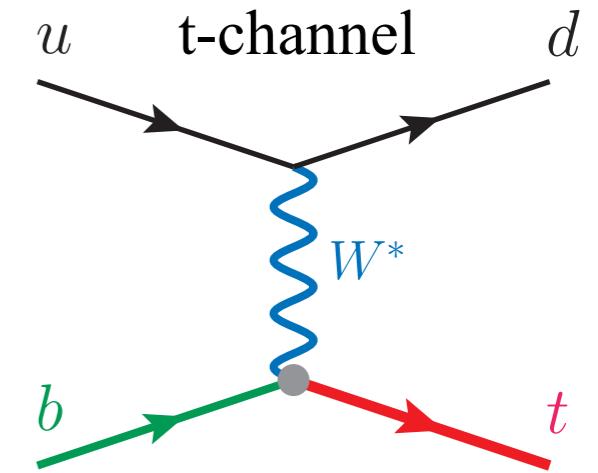
arXiv:1807.03835 with Jun Gao

DESY Theory Workshop  
26 September 2018  
DESY, Hamburg

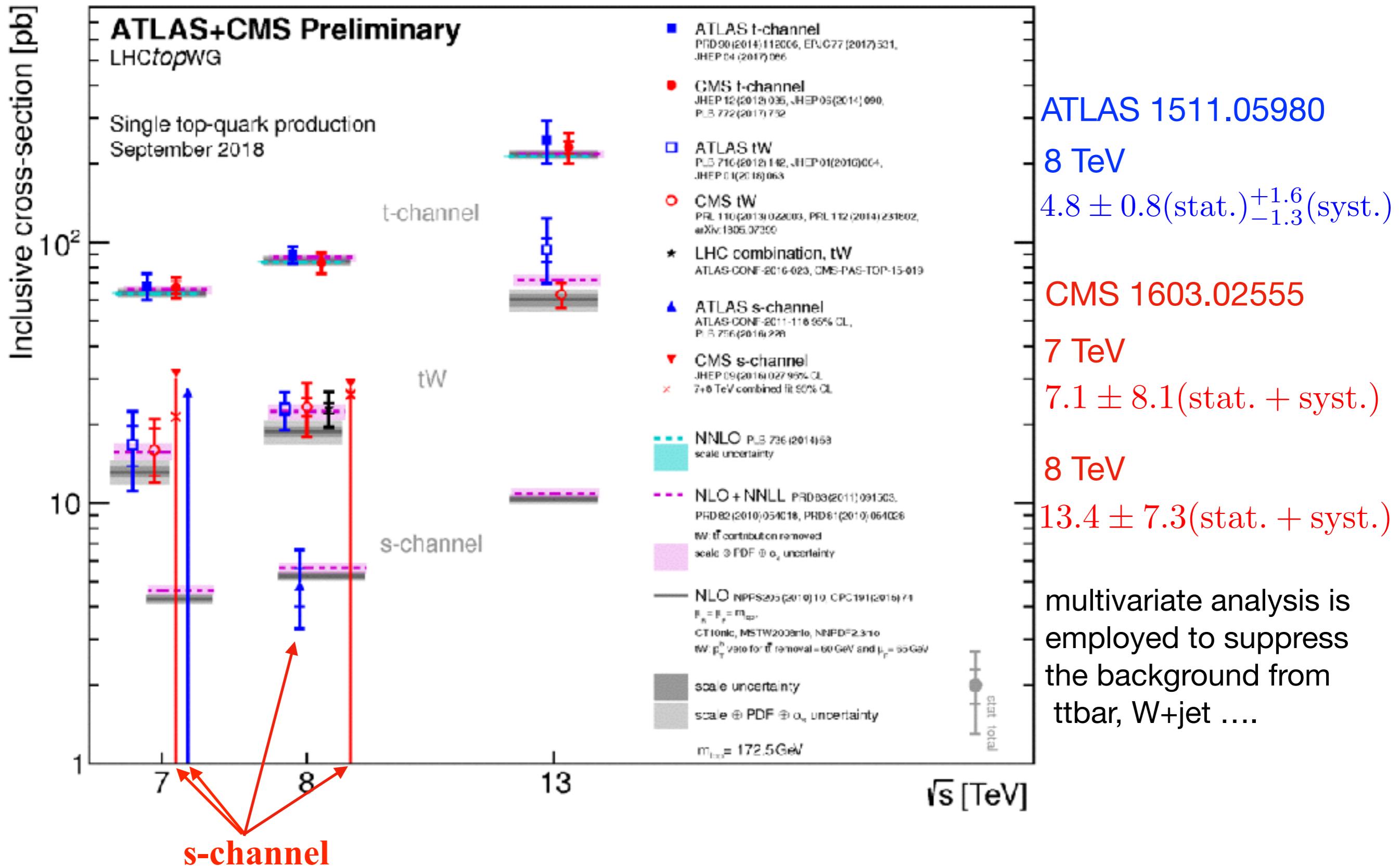
# Motivation

single top production at the LHC: 3 modes

- Precision test of the SM
  - ▶ top quark weak coupling:  $|V_{tb}|$
  - ▶ top quark mass
- Background to Higgs and BSM studies
  - ▶ **s-channel**: have the same final states with  $pp \rightarrow H(b\bar{b})W(l\nu)$
  - ▶ **s-channel**: sensitive to new heavy resonances such as  $W'$  and  $H^\pm$
  - ▶  $Wtb$  anomalous couplings
- Constrain PDFs
  - ▶ **s-channel**: sensitive to u/d ratio in PDF
  - ▶ t-channel & tW: b quark PDF



# Measurements @ LHC



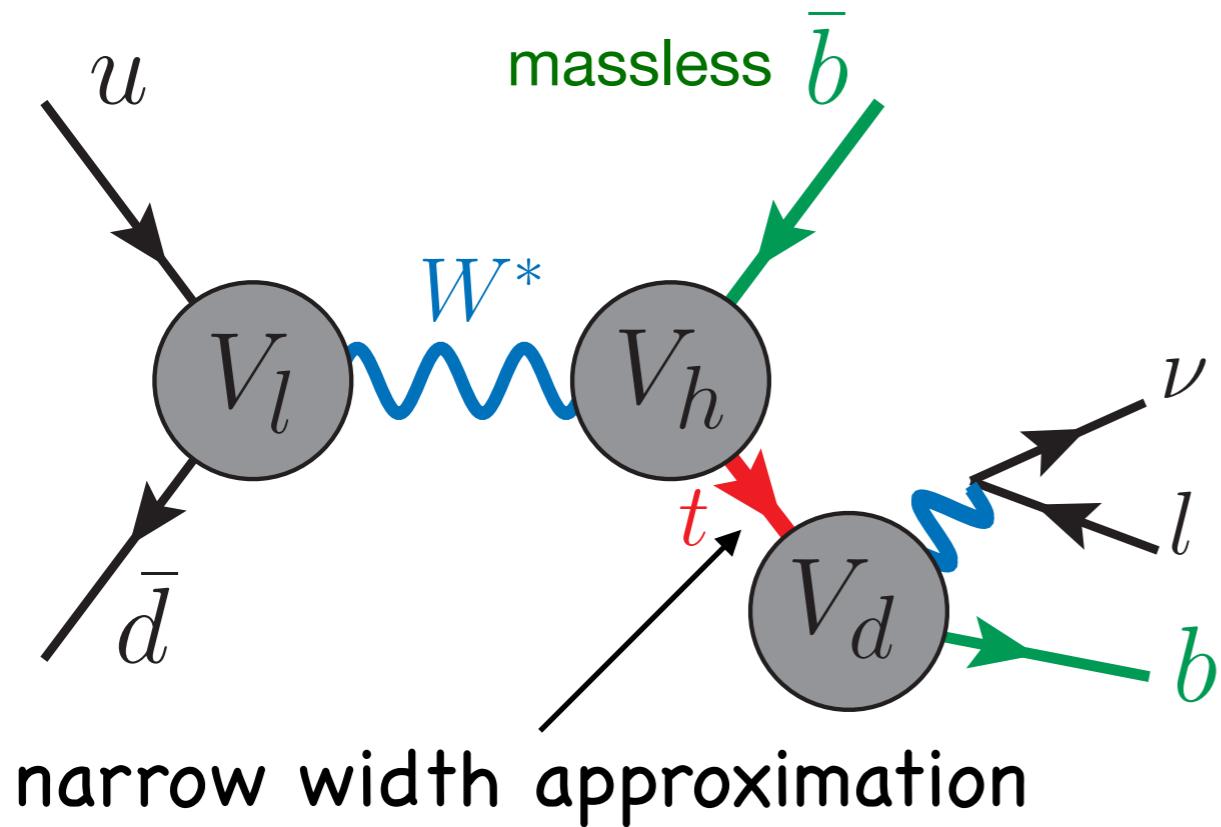
# Theory status

- Fixed-order Calculations
  - ▶ NLO: stable top production  
Bordes, Eijk, 95; Smith, Willenbrock, 96; Zhu, 01;  
Harris, Laenen, Phaf, Sullivan, Weinzierl, 02; Sullivan, 04
  - ▶ NLO: top production + decay  
Campbell, Ellis, Tramontano, 04; Cao, Yuan, 04;  
Cao, Schwienhorst, Yuan, 05; Heim, Cao, Schwienhorst, Yuan, 09;
  - ▶ NLO matched with parton shower  
Frixione, Laenen, Motylinski, Webber, 05; Alioli, Nason, Oleari, Re, 09;
  - ▶ NNLO: only for t-channel  
Brucherseifer, Caola, Melnikov, 14;  
Berger, Gao, Yuan, Zhu, 16; Berger, Gao, Zhu, 17 (with top decay @ NNLO)
- Soft gluon resummation @ NNLL+NLO  
Kidonakis, 10-16; Zhu, Li, Wang, Zhang, 10; Wang, Li, Zhu, 12;

We aim at NNLO QCD corrections for s-channel

- ▶ K-factor @ NNLO
- ▶ Fully differential distribution
- ▶ cross section with fiducial cuts

# Method



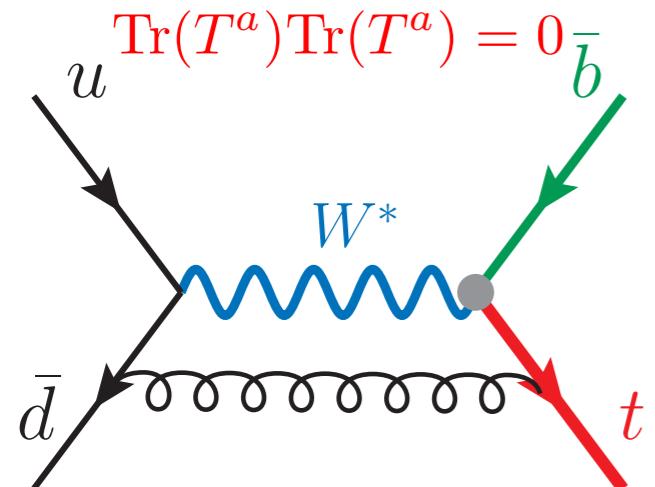
light quark line: Drell-Yan like  
 heavy quark line: off-shell W boson decay

top decay: available @ NNLO

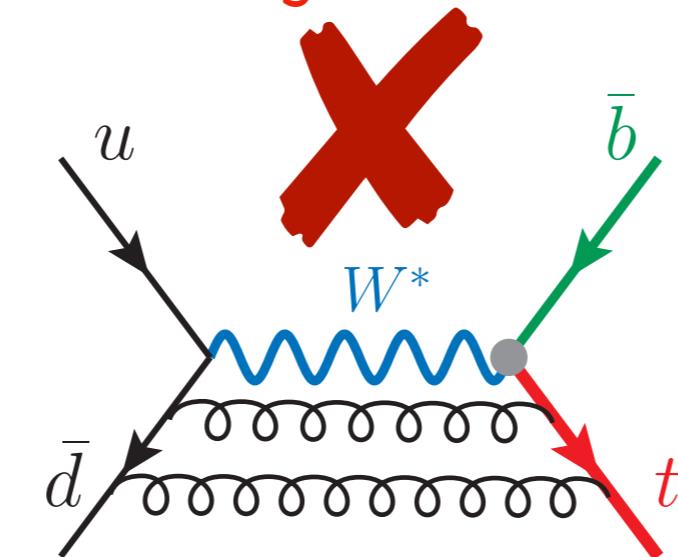
Gao, Li, Zhu, 12;  
 Brucherseifer, Caola, Melnikov, 13

separately gauge invariance  
 and infra-red safe

vanish due to



subleading color contribution: suppressed by  $1/N_c^2$



far from application due to  
 the complexity of the multi-scale Feynman integrals

$$I_{2\text{box}}(s, t, m_t, m_W)$$

Assadsolimani, Kant, Tausk, Uwer, 14  
 Meyer, 16

# Method

# N-jettiness subtraction is employed

Boughezal, Focke, Liu, Petriello, '15;  
Gaunt, Stahlhofen, Tackmann, Walsh, '15

**N-jettiness:**  $\tau_N = \frac{2}{Q^2} \sum_k \min \{q_a \cdot p_k, q_b \cdot p_k, q_1 \cdot p_k, \dots, q_N \cdot p_k\}$

Phase space cut:  $\sigma(X) = \int_0^{\tau_N} d\tau_N \frac{d\sigma(X)}{d\tau_N} + \int_{\tau_N^{\text{cut}}} d\tau_N \frac{d\sigma(X)}{d\tau_N}$

unresolved, IR safe      resolved, IR safe

In the limit  $\tau_N^{\text{cut}} \ll 1$ , all the radiations should be soft or collinear to a beam or jet axis, and the cross section can be factorized in SCET

$$\frac{d\sigma}{d\tau_N} = \int dt_a B_a(t_a, x_a, \mu) \int dt_b B_b(t_b, x_b, \mu) \prod_{k=1}^N \int dp_k^2 J(p_k^2, \mu) \\ \times H(\{p_a, p_b, p_k\}, \mu) S(\mathcal{T}_s, \{\hat{p}_a, \hat{p}_b, \hat{p}_k\}, \mu) \delta \left( \tau_N - \frac{t_a + t_b + Q\mathcal{T}_s + \sum p_k^2}{Q^2} \right) + \mathcal{O}(\tau_N)$$

@ NNLO, resolved part = X+1 jet @ NLO

Various progresses have been made on subleading power corrections to improve the numerical stability Moult, Rothen, Stewart, Tackmann, Zhu 16,17; Boughezal, Liu, Isqr, Petriello, 16, 18; Ebert, Moult, Stewart, Tackmann, Vita, Zhu 18

# Method : light quark line

## 0-jettiness (beam thrust) subtraction

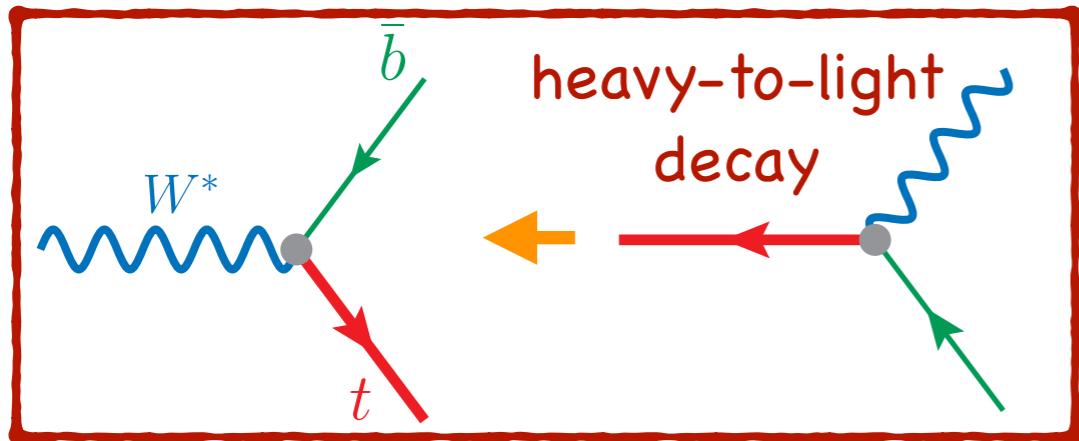
$$\tau_l = \frac{e^Y B_a^+(Y) + e^{-Y} B_b^+(Y)}{Q}$$

Stewart, Tackmann, Waalewijn 10

- ▶ unresolved part:  $\sigma_l \sim H \otimes B \otimes B \otimes S$ 
  - ▶ Hard function: virtual correction – 2-loop massless form factor Idilbi, Ji, Yuan, 06; Becher, Neubert, Pecjak, 06
  - ▶ Soft function: Kelly, Schwartz, Schabinger, Zhu 11; Monni, Gehremann, Luisoni 11
  - ▶ Beam function: Gaunt, Stahlhofen, Tackmann, 14
- ▶ resolved part:  $p p \rightarrow W^*(b\bar{t}) + j$  @ NLO
  - ▶ to control the IR divergence: dipole subtraction Catani, Seymour, 98
  - ▶ 1-loop virtual correction can be obtained from  $e^+ e^- \rightarrow q\bar{q}g$  by crossing Gehrmann Remiddi, 02
  - ▶ with  $m_t=0$ , can be cross checked with  $p p \rightarrow W + j$  @NLO
- ▶ NNLO result for light quark line has been cross checked with **DYNNLO** by setting  $m_t=0$

# Method : heavy quark line

1-jettiness (inclusive jet mass) subtraction without initial states



- unresolved part:

$$\sigma_h \sim f \otimes f \otimes H \otimes J \otimes S$$

- Hard function: Bonciani, Ferroglia 08;

Asatraining, Greub, Peckjak, 08; Beneke, Huber, Li, 08; Bell 08

- Soft function: Becher, Neubert, 05

- Jet function: Becher, Neubert, 06

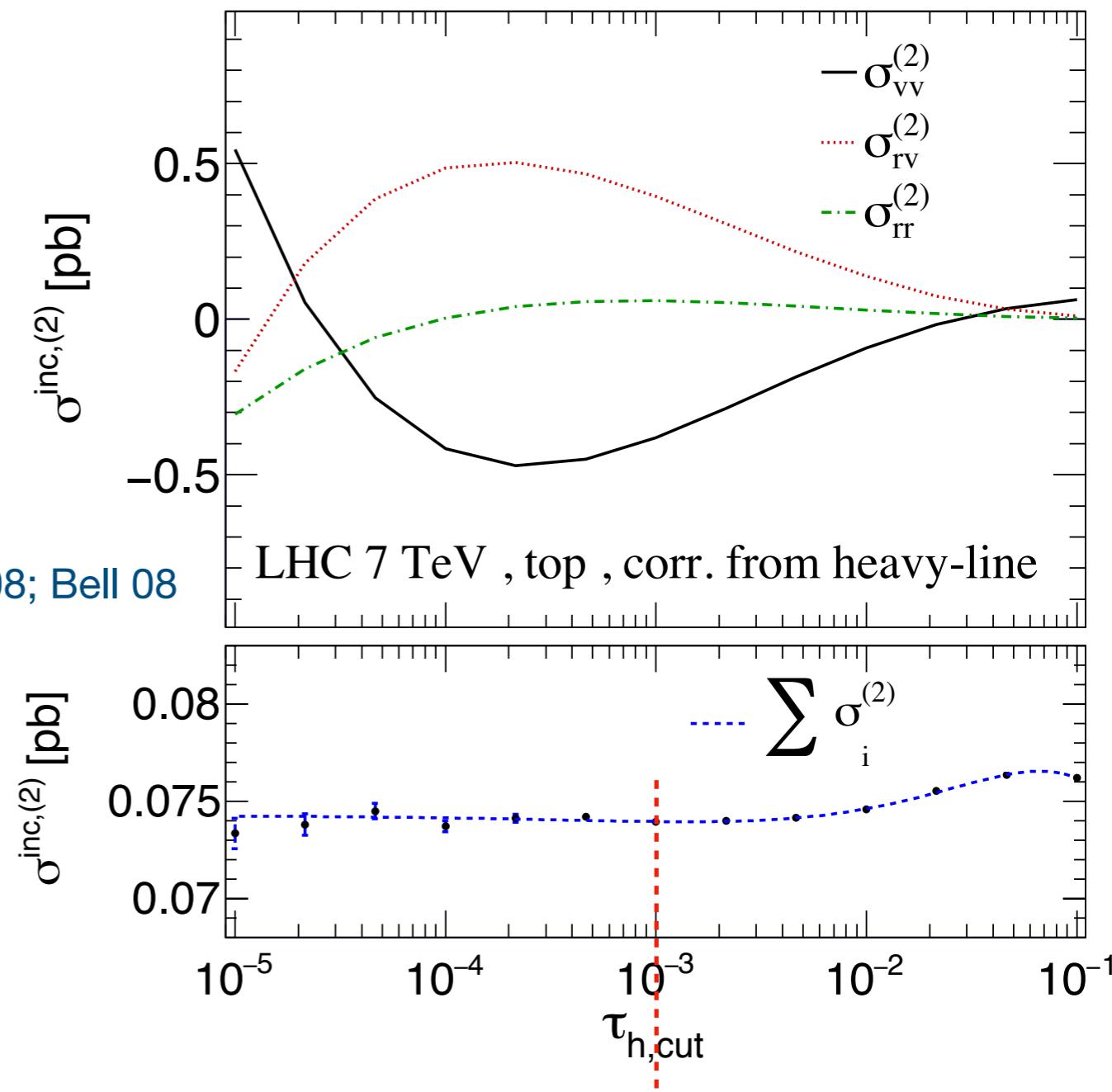
- resolved part:  $W^* \rightarrow \bar{b} + t + j$

- massive dipole subtraction**

Catani, Dittmaier, Seymour, Trocsanyi, 02

- NLO virtual correction is obtained by analytical continuation from  $g + b \rightarrow W + t$

Campbell, Tramontano, 06

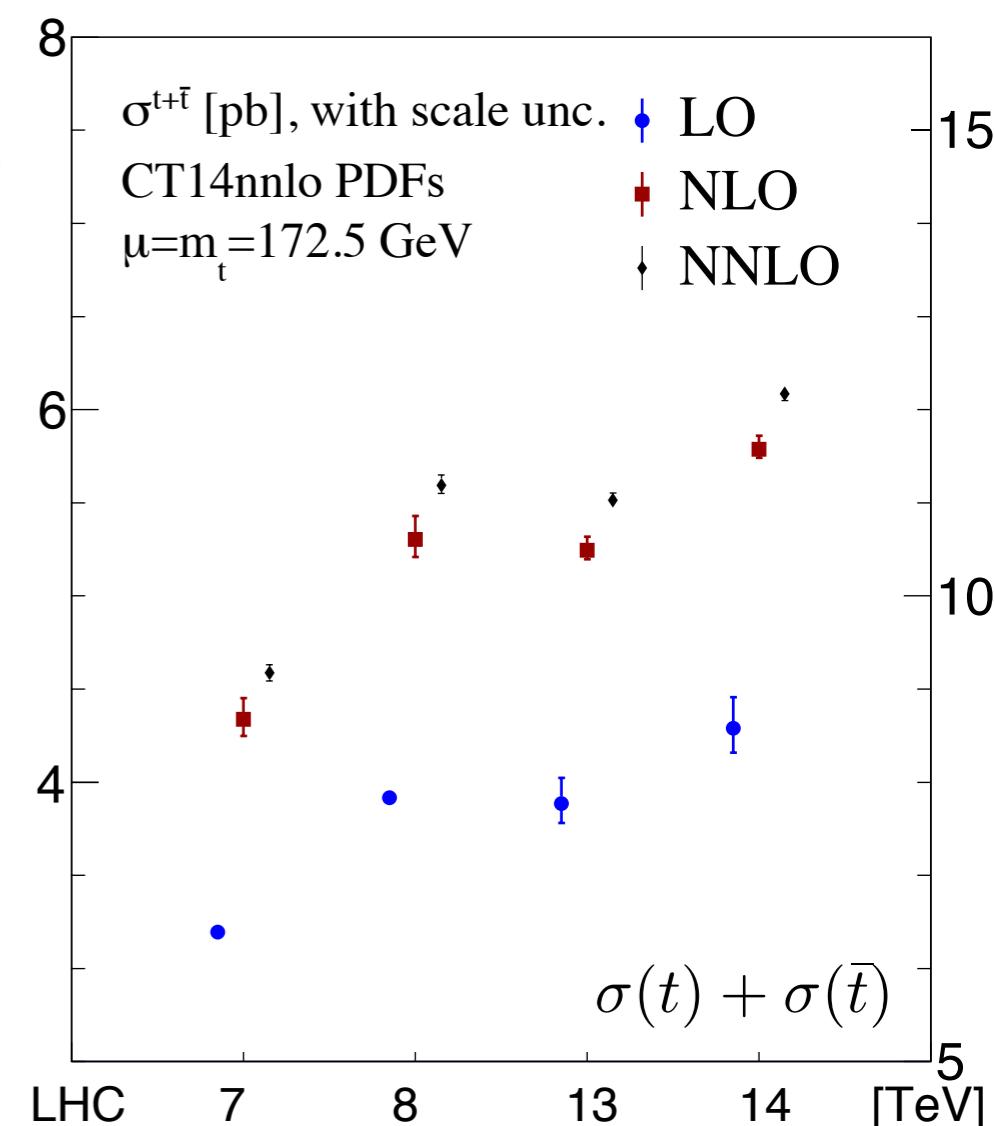


to balance the subleading power correction and numerical stability

# Numerical Results

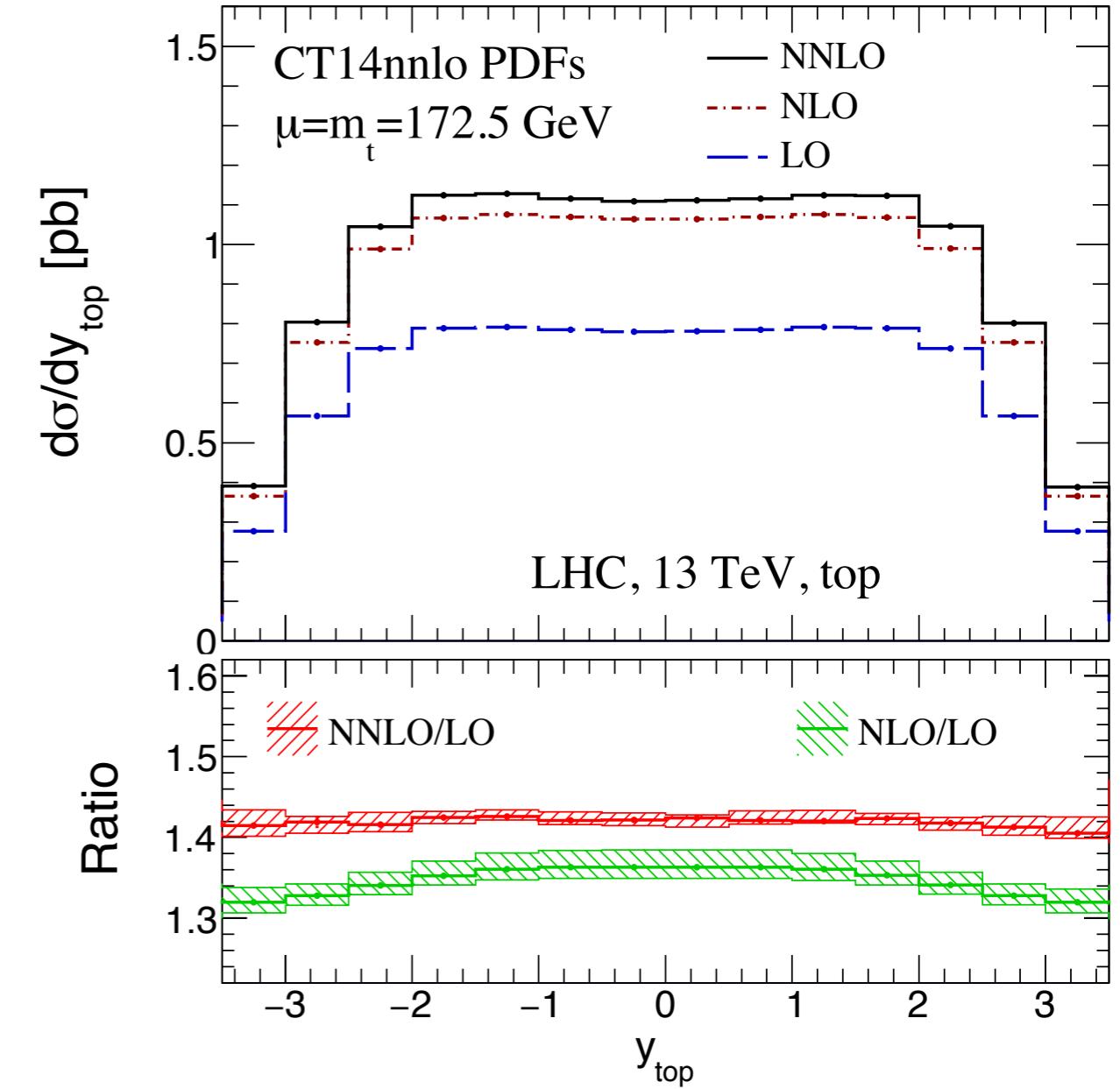
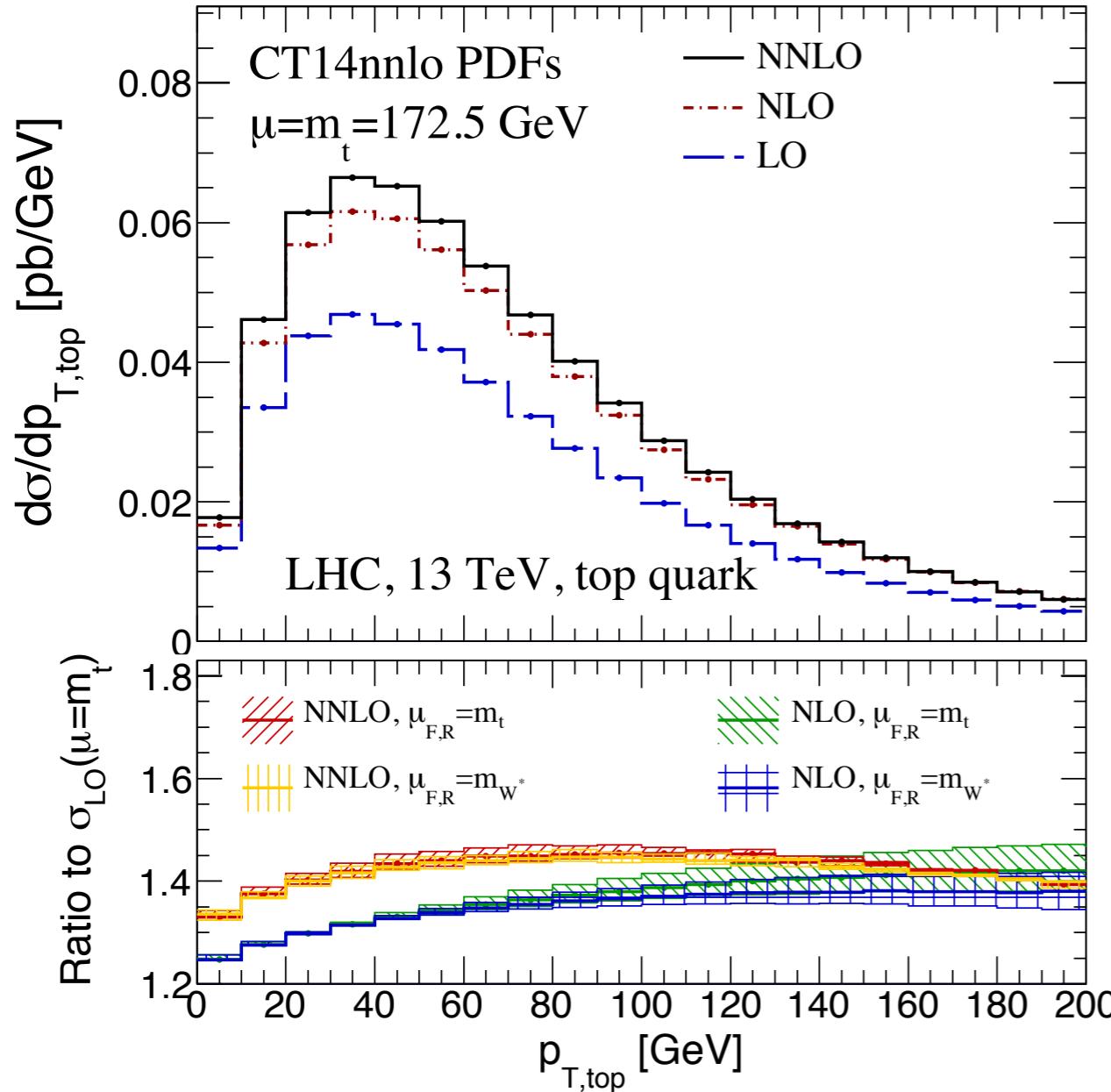
Inclusive cross sections:

inclusive	LO	NLO	NNLO	
8 TeV	$\sigma(t)$ [pb]	$2.498^{+0.17\%}_{-0.74\%}$	$3.382^{+2.36\%}_{-1.81\%}$	$3.566^{+0.95\%}_{-0.78\%}$
	$\sigma(\bar{t})$ [pb]	$1.418^{+0.12\%}_{-0.73\%}$	$1.922^{+2.37\%}_{-1.81\%}$	$2.029^{+1.07\%}_{-0.83\%}$
	$\sigma(t + \bar{t})$ [pb]	$3.916^{+0.15\%}_{-0.73\%}$	$5.304^{+2.36\%}_{-1.81\%}$	$5.595^{+0.99\%}_{-0.80\%}$
	$\sigma(t)/\sigma(\bar{t})$	$1.762^{+0.04\%}_{-0.01\%}$	$1.760^{+0.00\%}_{-0.02\%}$	$1.757^{+0.05\%}_{-0.12\%}$
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]	$7.772^{+2.69\%}_{-3.52\%}$	$10.49^{+1.36\%}_{-0.92\%}$	$11.03^{+0.74\%}_{-0.51\%}$
	$\sigma(t)/\sigma(\bar{t})$	$1.593^{+0.05\%}_{-0.01\%}$	$1.595^{+0.06\%}_{-0.03\%}$	$1.595^{+0.07\%}_{-0.05\%}$



- ★ NLO corrections  $\sim 35\%$ ; NNLO corr.  $\sim 7\%$ , indicating good perturbative convergence!
- ★ NNLO corrections are **underestimated** by NLO scale variation
- ★ scale uncertainties are **reduced** by NNLO corrections

# Distributions of top quark



- ★ fixed vs dynamic scale choice: very close to each other
- ★ NNLO corrections can be as large as 10% in low pT and large rapidity region of top

# Fiducial Cross Section

Setup: based on CMS

1. assume top 100% decay to bW
2. branching ratio = 0.1086 for leptonic decay of W boson
3. charged lepton:  $p_{T,l} > 24 \text{ GeV}$   $|\eta| < 2.1$
4. pre-selection for jets: anti-kT,  $R = 0.5$   $p_T > 20 \text{ GeV}$   $|\eta| < 4.5$
5. “2-jets 2-tags”: exactly two b-tagged jets with  $p_T > 40 \text{ GeV}$   $|\eta| < 2.4$

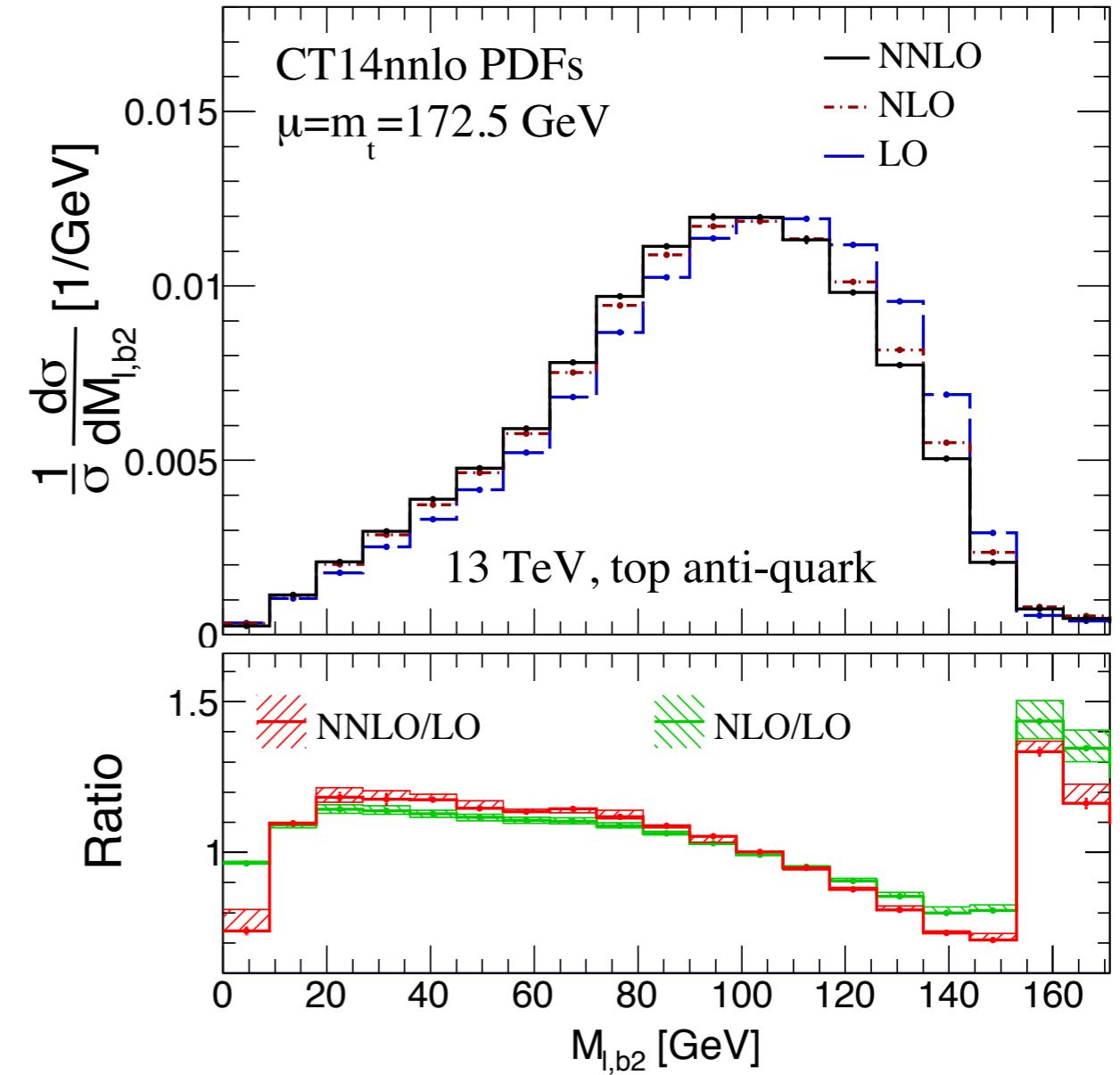
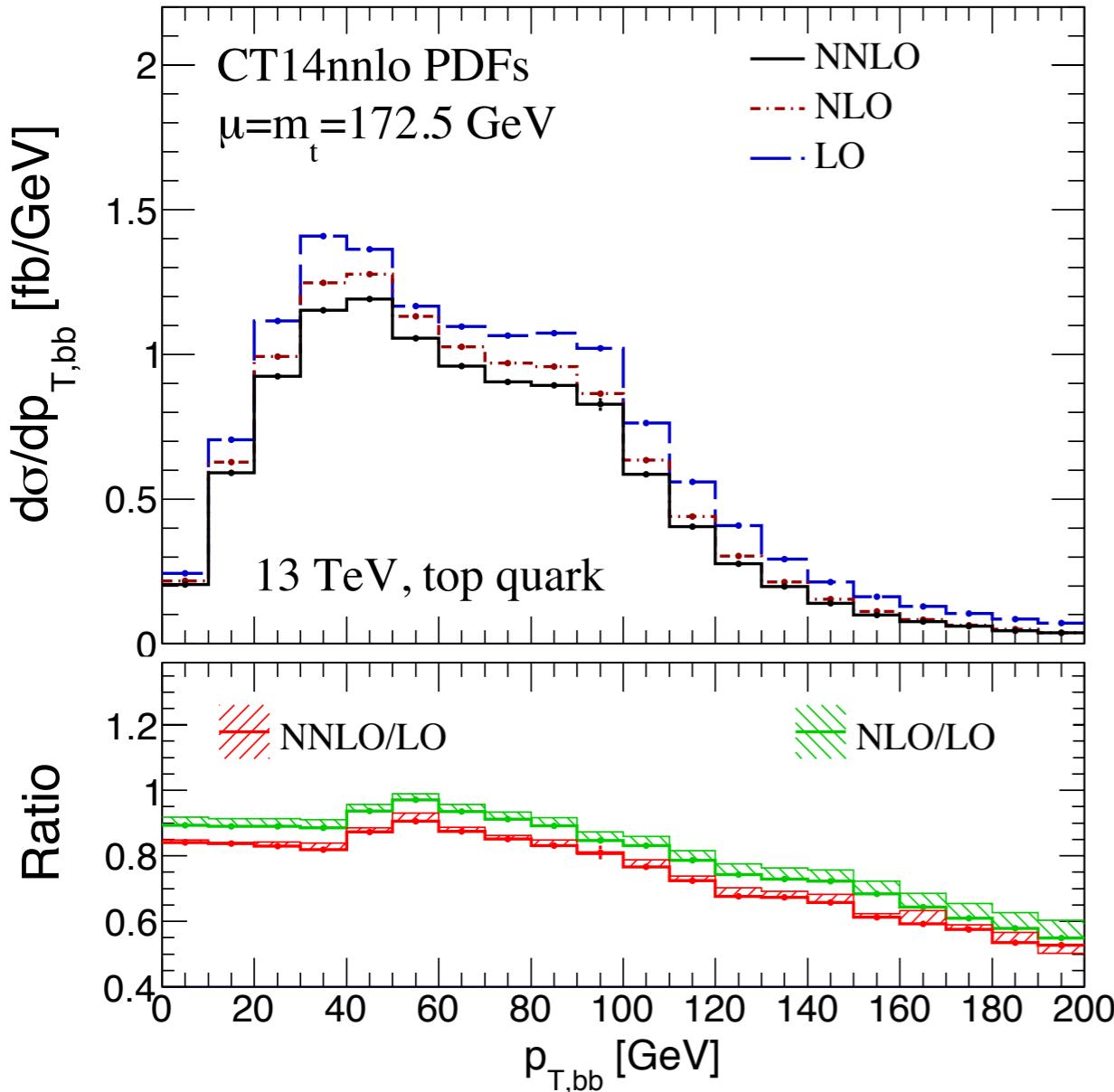
To suppressed background from ttbar

Total cross section with fiducial cuts @ 13 TeV LHC

fiducial [pb]		LO	NLO	NNLO
$t$ quark	total	$0.1348^{+2.6\%}_{-3.4\%}$	$0.1156^{+3.1\%}_{-3.0\%}$	$0.1071^{+2.2\%}_{-0.8\%}$
	corr. in pro.		-0.0121	-0.0065
	corr. in dec.		-0.0071	-0.0026
$\bar{t}$ quark	total	$0.0907^{+2.5\%}_{-3.4\%}$	$0.0745^{+3.6\%}_{-3.4\%}$	$0.0663^{+2.5\%}_{-1.3\%}$
	corr. in pro.		-0.0066	-0.0051
	corr. in dec.		-0.0096	-0.0035

- ★ NLO and NNLO corrections are negative
- ★ NLO  $\sim -15\%$ ; NNLO  $\sim -8\%$
- ★ scale uncertainties are reduced by NNLO corrections
- ★ QCD corrections from top decay are comparable to those from top production

# Distribution with Fiducial Cuts



- ★ two important inputs to multivariate analysis
- ★ NNLO corrections are **underestimated** by scale variation @NLO
- ★ For  $M_{l,b2}$ , the peak is shifted to lower mass by higher order corrections

# Summary

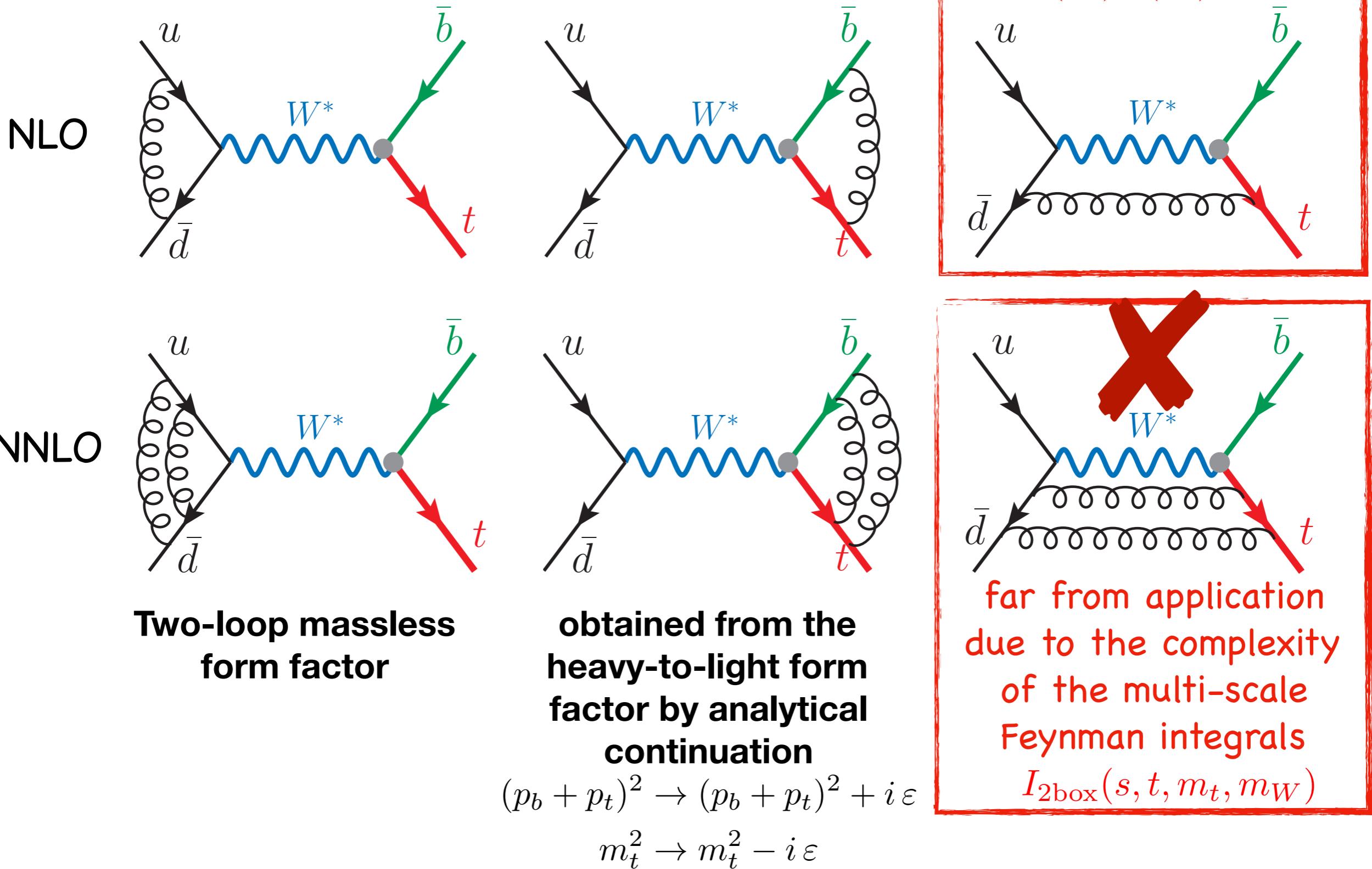
1. First calculation for s-channel @ NNLO QCD
2. NNLO corr.  $\sim 7\%$  for inclusive cross section
3. For the fully differential cross section, NNLO corr. can reach  $10\%$  in some kinematic regions
4. Scale uncertainties are reduced
5. Fiducial cross section: compare with exp. data without unfolding procedures

## In further:

- Towards the full results : cross-talk between light-heavy
  - ▶ 2-box Feynman integrals
  - ▶ 1-jettiness soft function with initial states and a massive spector @ NNLO
- pT veto resummation
- Soft gluon Resummation @ NNNLL + NNLO

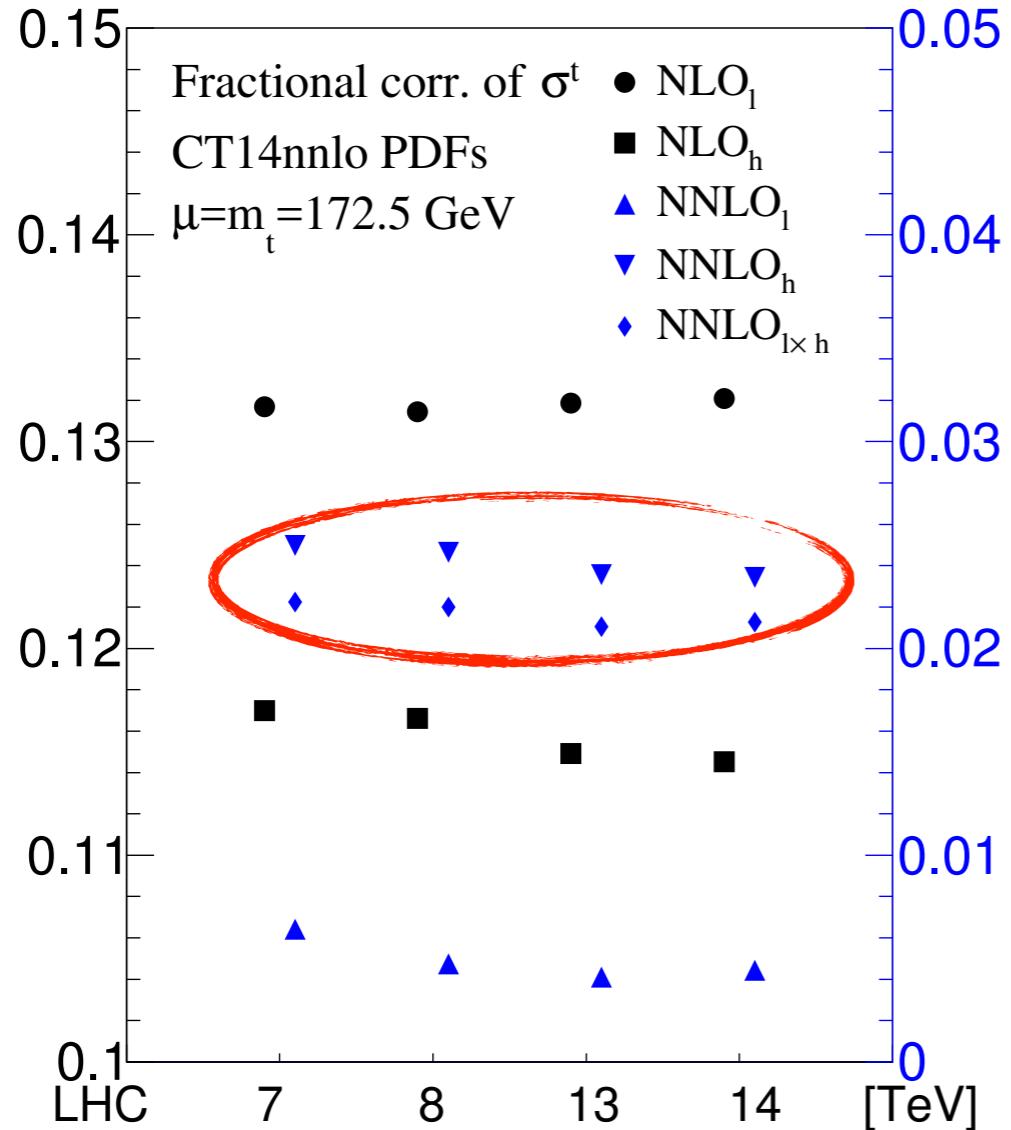
Thanks for your attention!

# Backup



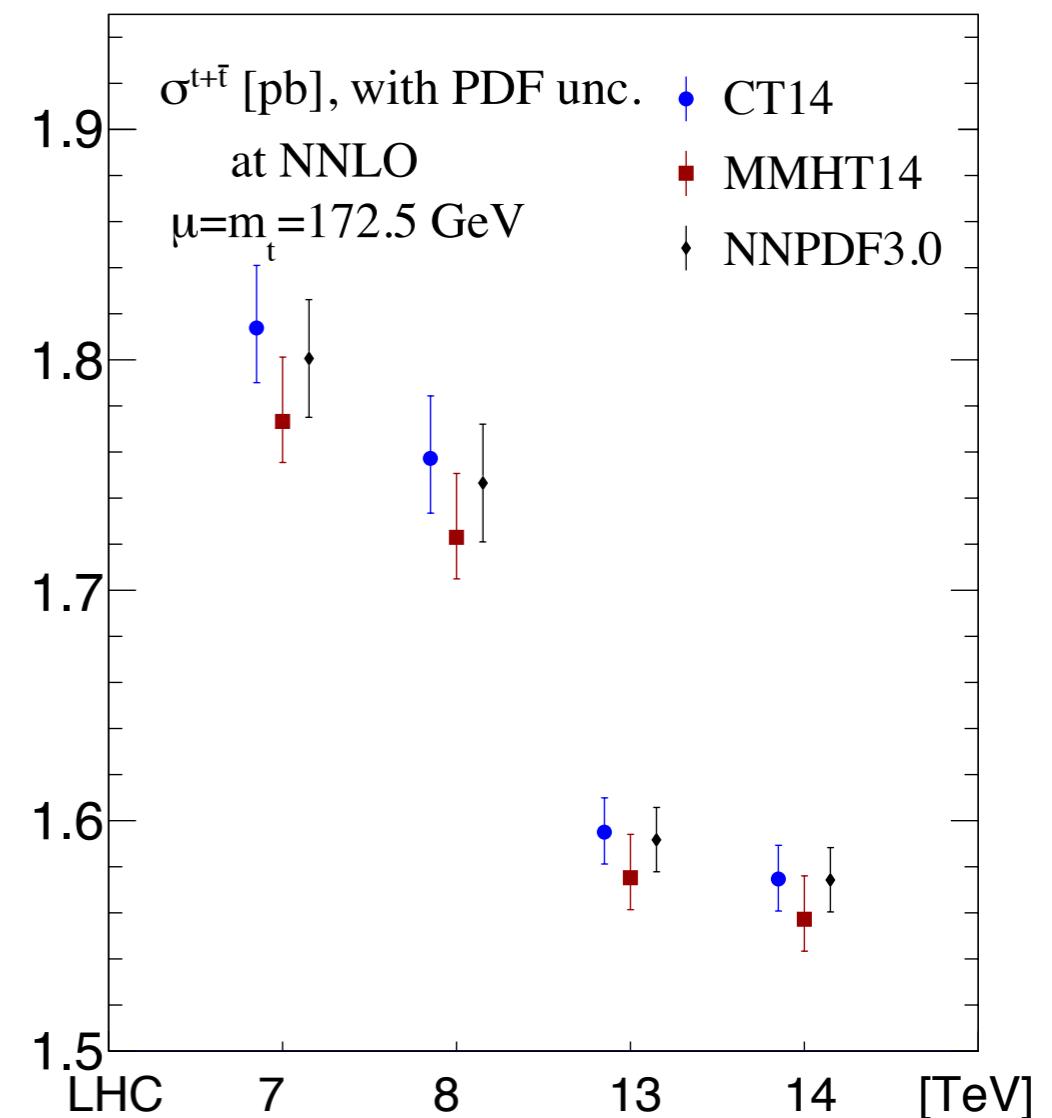
# Numerical Results

corrections from different components



- NNLO correction from light quark line is less than 1%
- NNLO corrections from heavy quark line and the product of light and heavy @NLO are more than 2%

PDF uncertainties of  $\sigma(t)/\sigma(\bar{t})$



- constrain PDFs
- ★ sensitive to the difference of valence u & d quark distributions at low Bjorken-x