Single Top Production at the LHC

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Outline

- ✓Introduction
- ✓QCD corrections
- ✓t-channel single top production
- ✓s-channel single top production
- ✓tW production
- ✓Conclusion

Introduction

Why top quark?

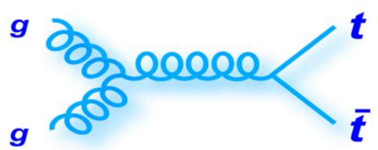
- ✓ Top quark is the heaviest elementary particle in the Standard Model
- ✓ Top-quark mass is related to the strength of the interaction between top-quark and Higgs-boson, which is essential to Higgs boson production at the LHC.
- ✓ Top quark might play a role of electroweak symmetry breaking
- ✓ The measurements at the LHC offer the ultimate precision in top quark physics
- ✓ Top quark is a good probe of new physics

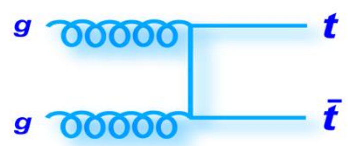
How to produce top quark?

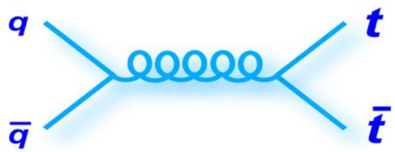
- ✓ Primarily pair production via the **strong interaction**
- ✓ single production via the **Weak-interaction**

Introduction

Top quark pair production

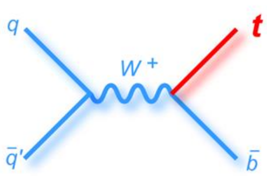




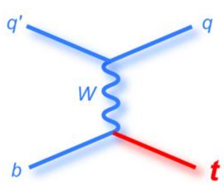


- It has high precision of the experimental measurements of total and differential cross sections
- It is used to study many properties of the top quark

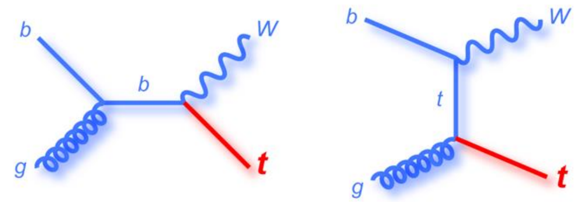
Single top quark production



s-channel



t-channel

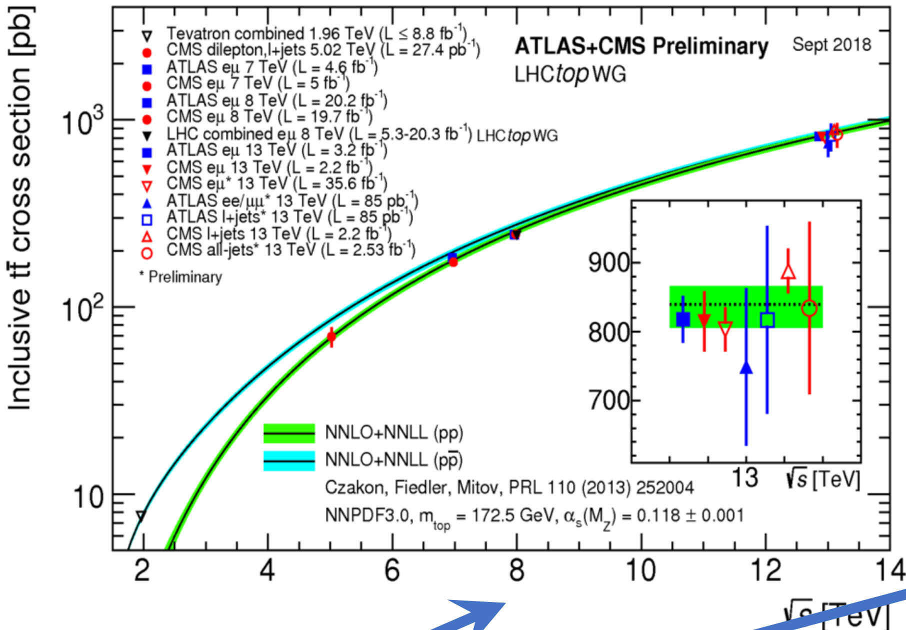


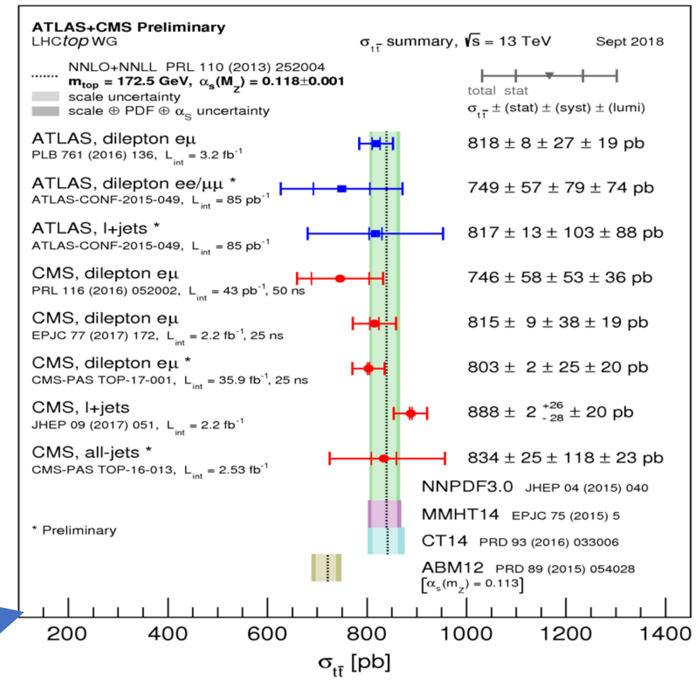
tW production

- It allows measurement of V_{tb} per channel
- It is Easier to check the chiral structure of Wtb vertex than $t\bar{t}$ production
- t-channel can be used to measurement the b quark density
- Sensitive to FCNC (t-channel), or W' resonances (s-channel)

Introduction

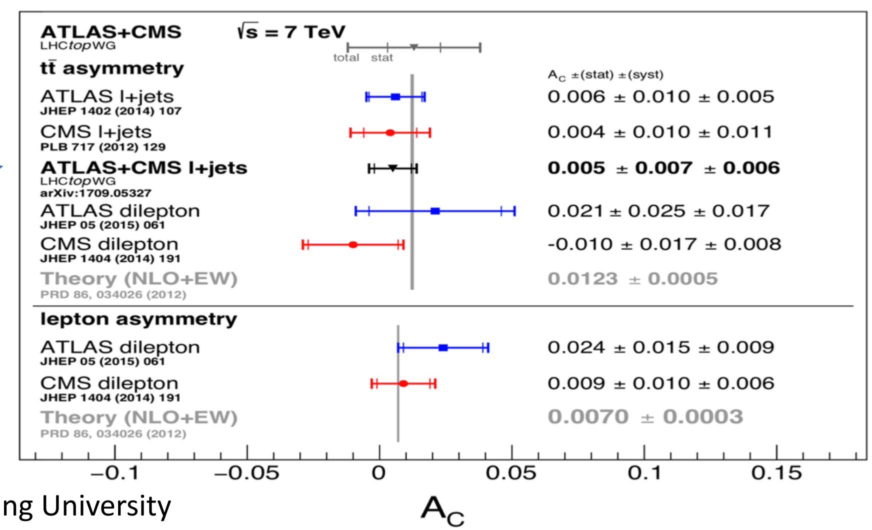
Measurements of top quark pair production





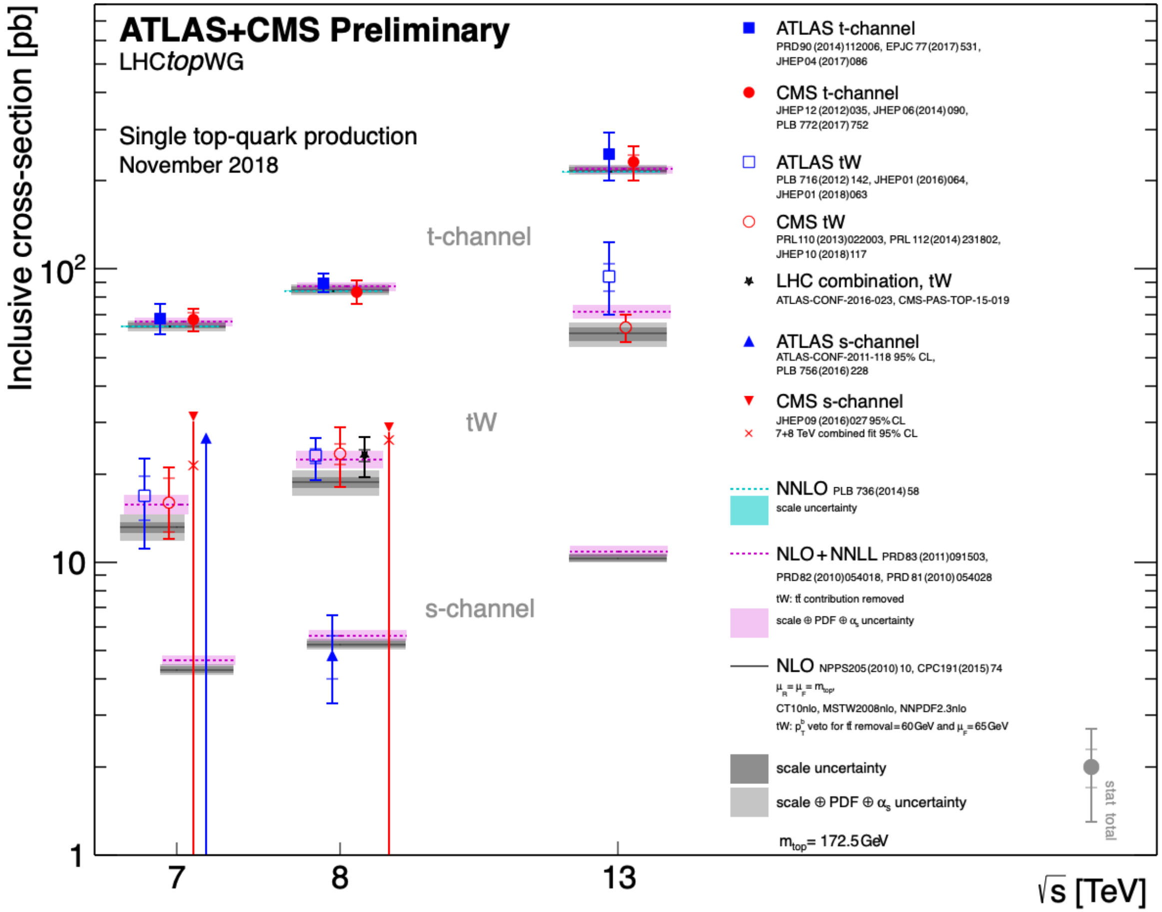
total cross section

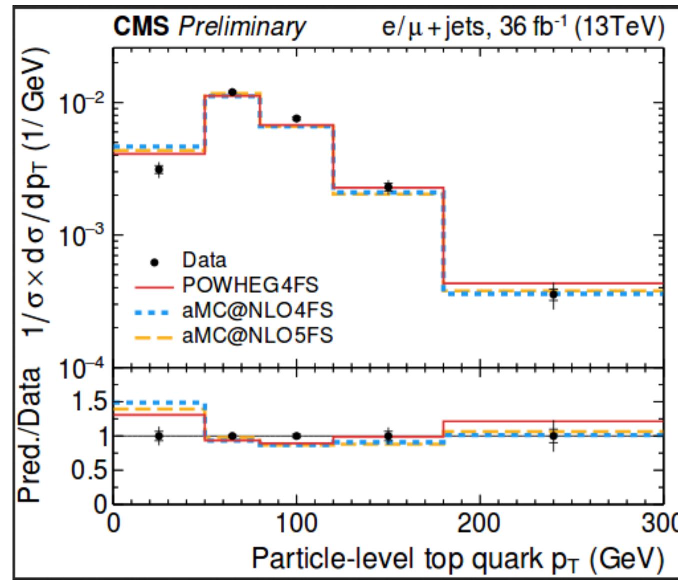
the charge asymmetry measurements



Introduction

Single Top quark production



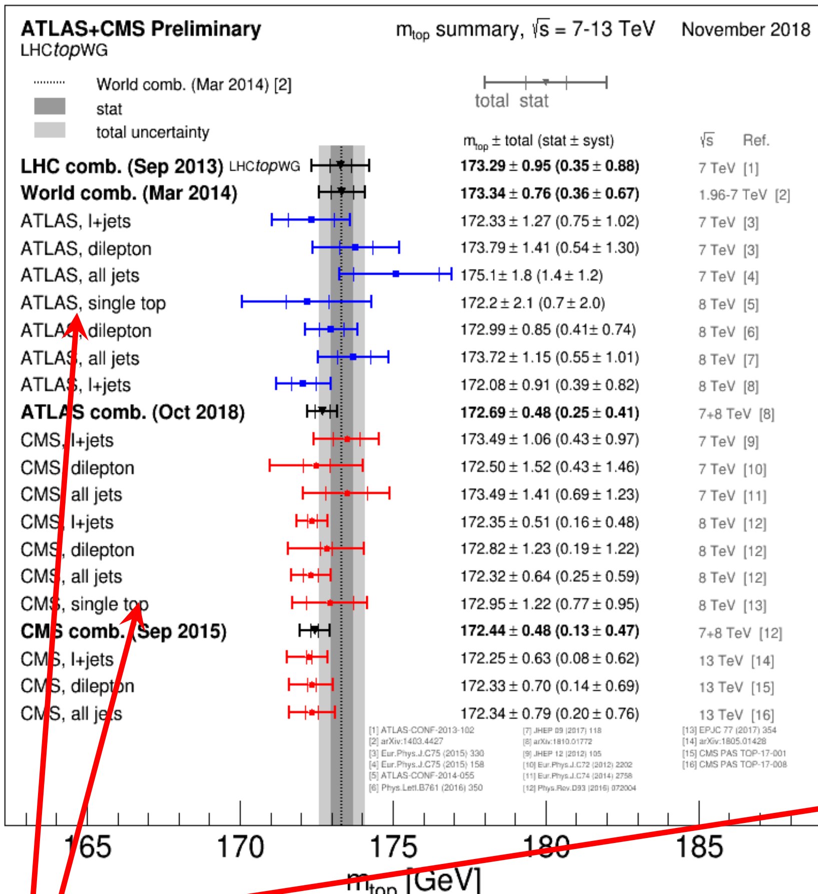


Differential Distributions from t-channel single top measurement
[CMS-PAS-TOP-17-023]()

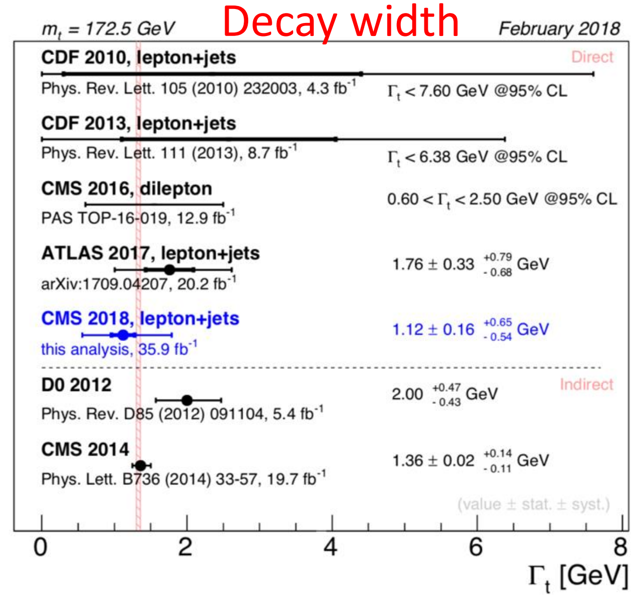
Introduction

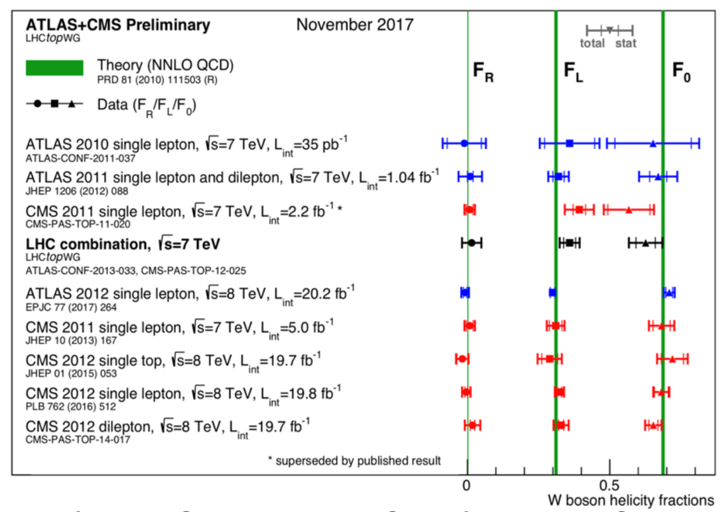
Top quark properties

Top quark mass



Decay width





Single top processes

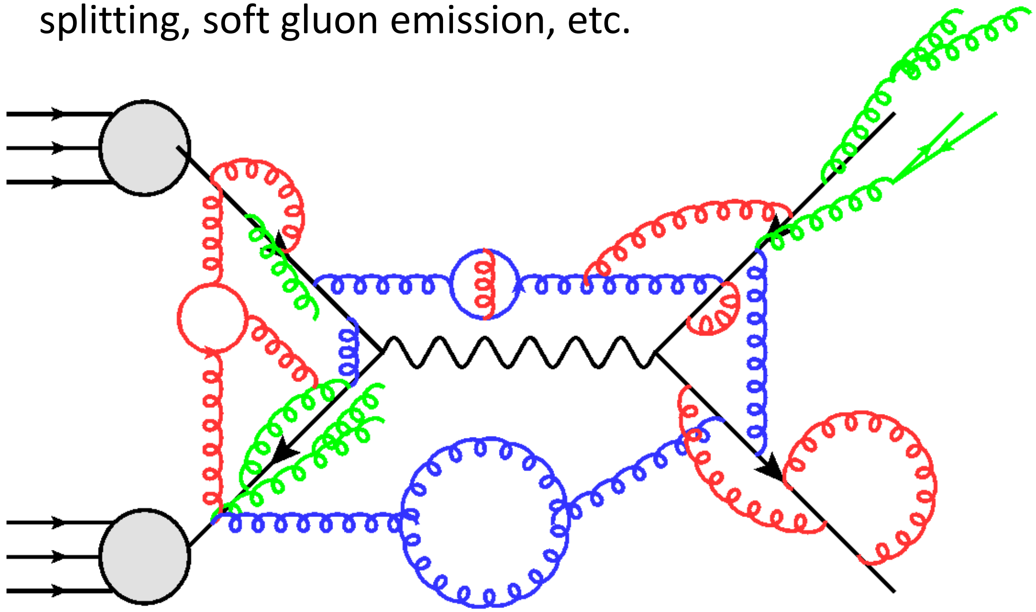
Helicity fractions of W bosons from top quark decays

QCD corrections

Generic Cross Section in pQCD

Take s-channel single top as an example, other channels are similar.

Extremely complicated at higher orders: initial state splitting, final state splitting, soft gluon emission, etc.



hard particles

soft particles

collinear particles

$$\sigma = \frac{1}{2E_{\rm CM}^2}\int \mathcal{D}\omega \frac{d^4p}{(2\pi)^4}\langle I|O^{\dagger}(0)\delta[\omega - \mathcal{E}^0]O(p)|I\rangle$$

ω: final state energy configure

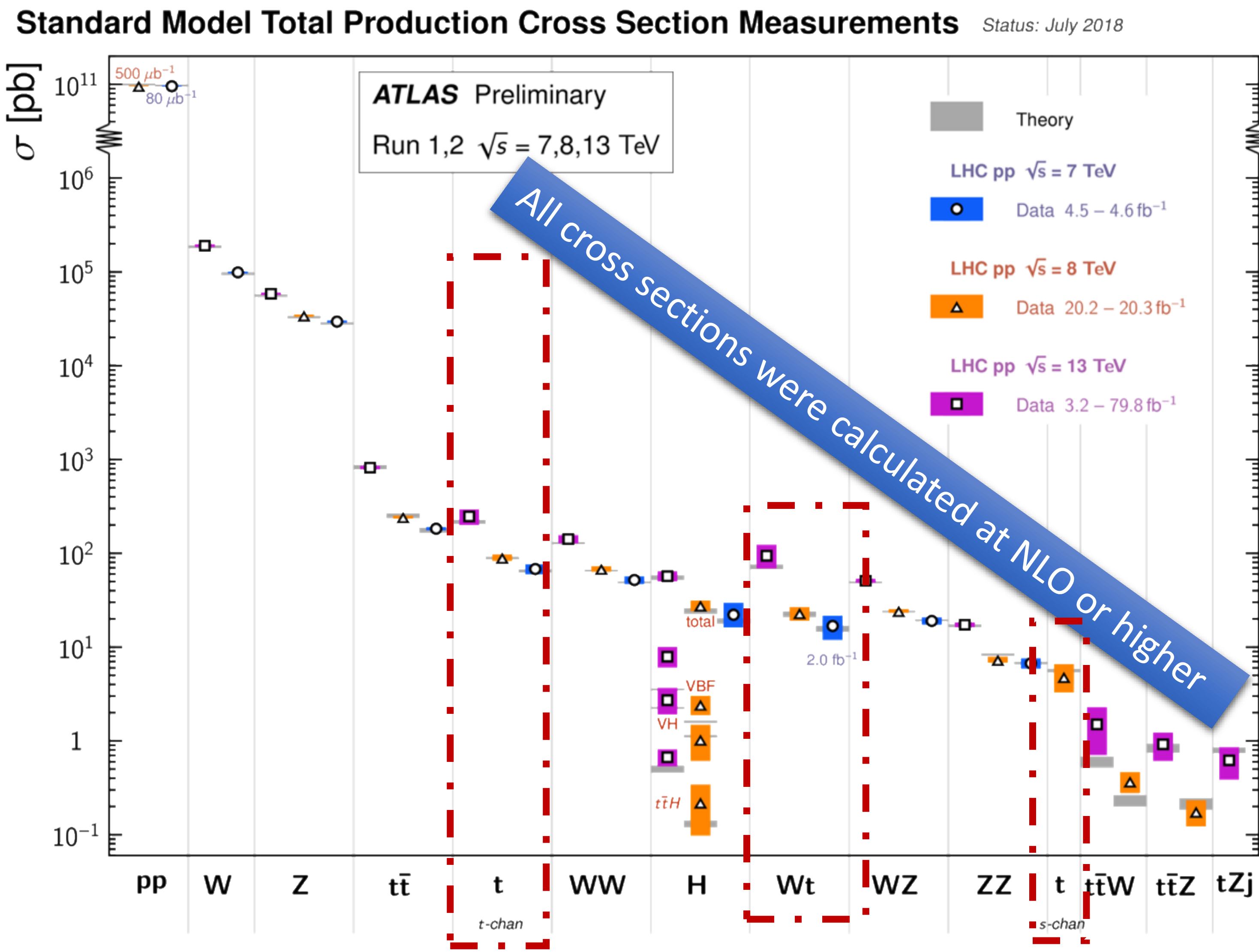
ε^0: energy flow operator

(C. W. Bauer ,et. al., PRD, 2009)

- Fixed order calculations to improve the hard particle radiation
- Resummation is needed for the infrared sensitive radiations

QCD corrections

✓ Impressive agreement between experiment and theory:



QCD corrections

Why resummation?

- ✓ At high energy, α_s is small, and the fixed order calculation is reliable
- ✓ Near the infrared region, there is a scale hierarchy between the high energy scale Q and infrared radiation scale μ_{IR} which produced large logarithmic terms $L = \ln\frac{\mu_{IR}}{Q}$

$$d\sigma \propto \frac{1}{\mu_{IR}}\sum_n C_n \alpha_s^n\, ln^{an+b}\frac{\mu_{IR}}{Q}$$

Breakdown the convergence of the perturbative theory and resummation is needed!

For example the logarithms can be $\frac{\ln^n 1-z}{1-z}$, $\ln\frac{s_4}{M^2}$, $\ln\frac{q_T^2}{M^2}$, ...

$1-\frac{M^2}{s}=z\to 0$ Partonic threshold resumamtion

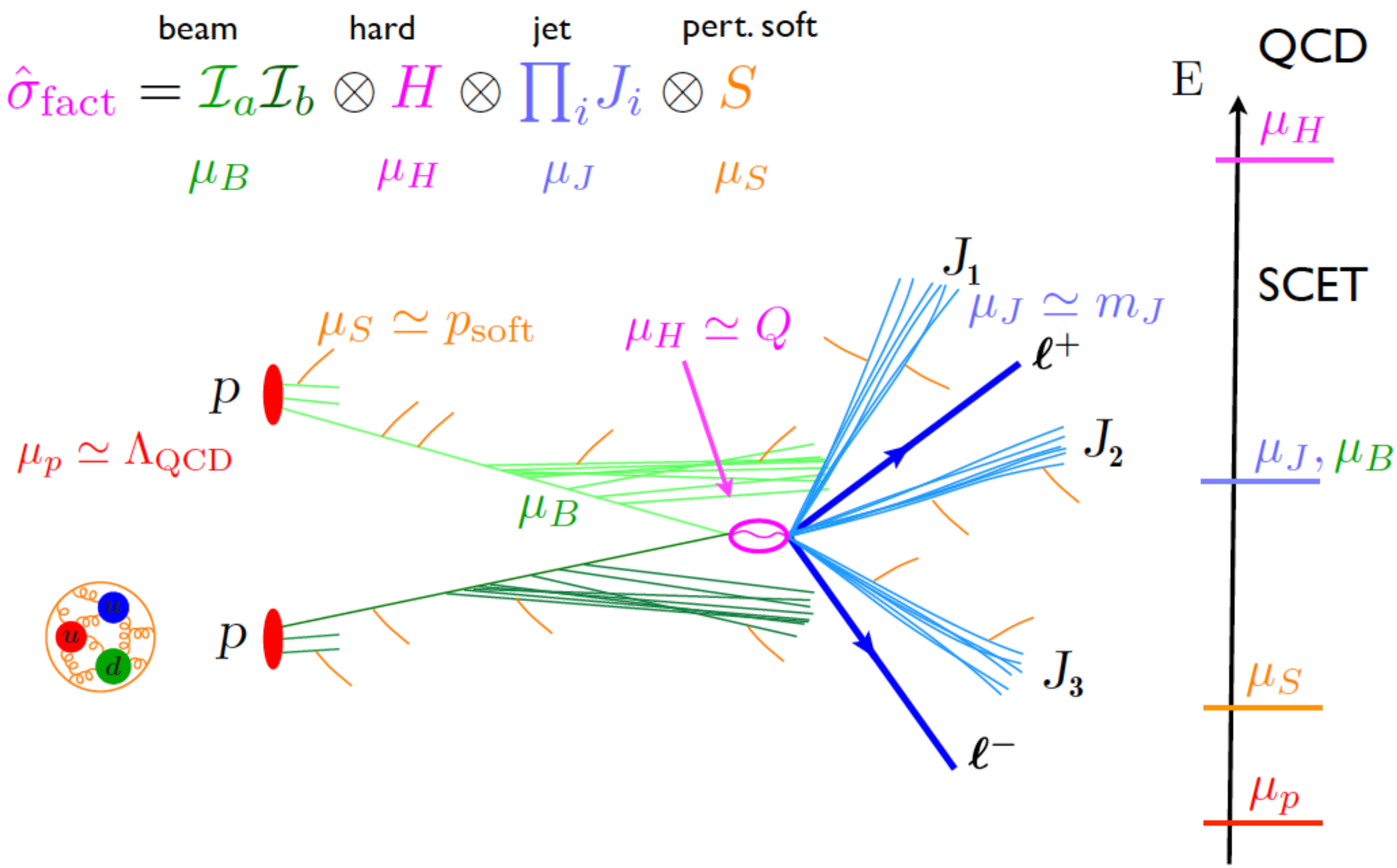
$s+t+u-m_3^2-m_4^2=s_4\to 0$ 1-particle inclusive threshold resummation

$\frac{q_T^2}{s}\to 0$ Transverse momentum resummation

QCD corrections

Factorization in SCET

✓ In general , the cross section can be factorized as (Bauer, Hornig, Tackmann, 2008)



QCD corrections

Resummation in SCET

$$\boldsymbol{\sigma = f_a \otimes f_b \otimes H \otimes J \otimes S}$$

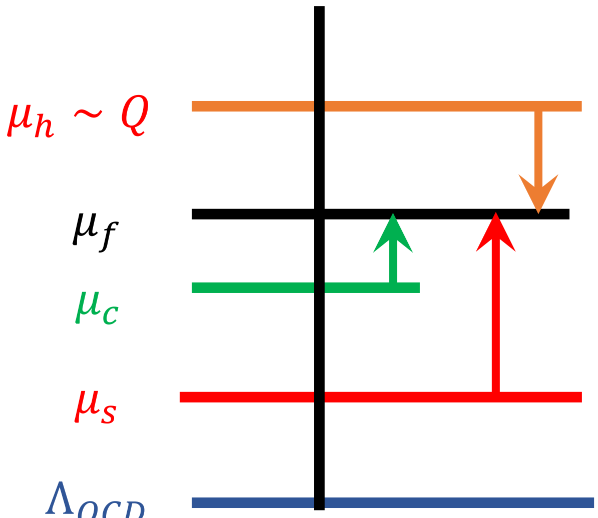
Hard function — Short distance Wilson coefficient, can be obtain from fixed order QCD corrections.

Jet function — Describes final collinear gluon emission from light parton, sensitive to algorithms for jet definition.

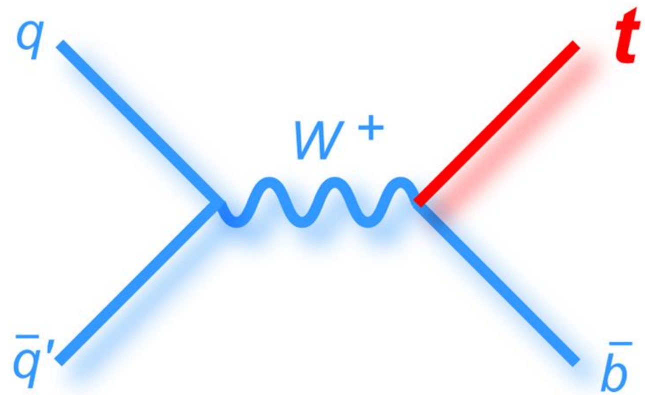
Soft function — Describes soft gluon radiation between energetic jet and heavy quark.

Factorization separates the physics for different scales, which are absorbed into hard, jet and soft functions, respectively.

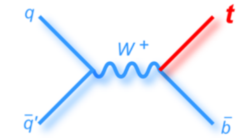
The resummation is achieved by running the hard, soft and jet function to one common factorization scale



s-channel single top production



Fixed order calculations

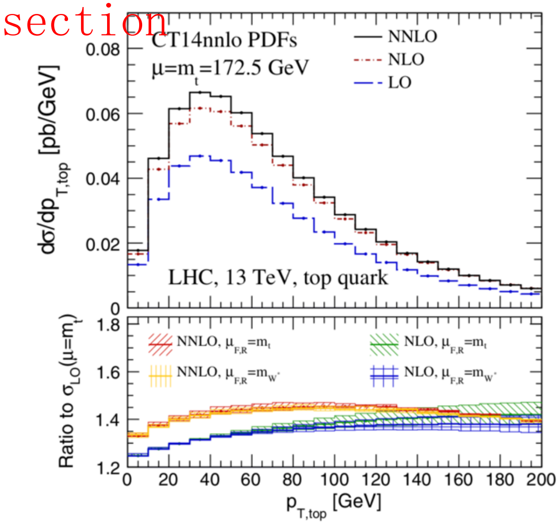


- ✓ NLO QCD corrections for stable top quark — Smith and Willenbrock, arXiv:hep-ph/9604223; Mrenna and Yuan, arXiv:hep-ph/9703224
- ✓ NLO QCD corrections with top quark decay — Campbell et al arXiv:hep-ph/0408158; Cao and Yuan arXiv:hep-ph/0408180
- ✓ NLO QCD corrections + Parton Shower — Frixione et al arXiv:hep-ph/0512250; Frixione et al arXiv:0805.3067; Alioli et al arXiv:0907.4076
- ✓ NNLO QCD corrections without and with top quark decay: neglecting the color correlation between the light and heavy quark lines and in the narrow width approximation — Liu and Gao arXiv:1807.03835

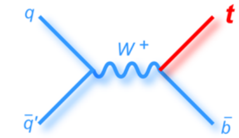
Inclusive cross section

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]	$7.772^{+2.69\%}_{-3.52\%}$	$10.49^{+1.36\%}_{-0.92\%}$	$11.03^{+0.74\%}_{-0.51\%}$
	$\sigma(t)/\sigma(\bar{t})$	$1.593^{+0.05\%}_{-0.01\%}$	$1.595^{+0.06\%}_{0.03\%}$	$1.595^{+0.07\%}_{-0.05\%}$

Differential cross section



Resummed cross section



Threshold limit is defined as $s_4 = s + t + u - m_t^2 \rightarrow 0$

HX. Zhu, C.S. Li, J.Wang, Zhang, arXiv:1006.0681

The cross section is factorized as

$$\sigma = \int_{m_t^2/s}^{1} d\tau \int_{\tau}^{1} \frac{dx_a}{x_a} \int_{m_t^2-\hat{s}}^{0} d\hat{t} \int_{0}^{s_4^{max}} ds_4\, f_{i/N_a}(x_a,\mu_F) f_{j/N_b}(\tau/x_a,\mu_F) \frac{d\hat{\sigma}^{\text{thres}}}{d\hat{t}\, d\hat{u}},$$

where $s_4^{max} = \hat{s} + \hat{t} + m_t^2 \hat{s}/(\hat{t} - m_t^2)$, and

$$\frac{d\hat{\sigma}^{\text{thres}}}{d\hat{t}\, d\hat{u}} = \sum_{ij} \frac{\lambda_{0,ij}}{64\pi N_c^2 \hat{s}^2} \int_0^{s_4/(2E_1)} dk^+\, \mathrm{Tr}[\mathbf{H}_R(\mu) \mathbf{S}_R(k^+,\mu)] J(s_4 - 2E_1 k^+, \mu).$$

Hard function, summing logarithms of the form $\log(\mu_h/\mu)$

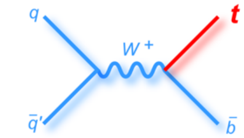
Soft function, summing logarithms of the form $\log(\mu_s/\mu)$

Jet function, summing logarithms of the form $\log(\mu_j/\mu)$

The logarithmic terms at NLO are

$$\sigma^{(1)} \propto \frac{\alpha_s}{4\pi} \int ds_4 \left(c_0 \delta(s_4) + c_{-1} \left(\frac{1}{s_4}\right)_* + c_{-2} \left(\frac{\ln s_4/m_t^2}{s_4}\right)_* \right)$$

Resummed cross section



Zhu, C.S.Li, Wang, Zhang, arXiv:1006.0681

If desired, it can be used to generate higher order expansion of threshold singular terms. For example, the 2-loop singular terms are given by:

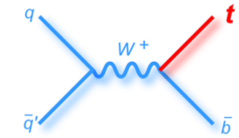
$$
\begin{aligned}
\frac{64\pi \hat{s}^2 d^2\hat{\sigma}_{ij}^{\text{expand}}}{\lambda_{0,ij} d\hat{t}\, d\hat{u}} &= \delta(s_4) + \frac{\alpha_s}{4\pi}\left\{3C_F\gamma^0_{\text{cusp}}\left[\frac{\ln(s_4/m_t^2)}{s_4}\right]_+ + \left(2C_F\gamma^0_{\text{cusp}}L_s + \gamma^0_j - 2\gamma^0_s\right)\right.\\
&\times\left[\frac{1}{s_4}\right]_+ + \left.\left[c^1_h + c^1_j + c^1_s - C_F\gamma^0_{\text{cusp}}\left(\frac{1}{3}L_h^2 + L_s^2 - \frac{1}{4}\pi^2\right) - \frac{2}{3}L_h\gamma^0_h - 2\gamma^0_s L_s\right]\delta(s_4)\right\}\\
&+\left(\frac{\alpha_s}{4\pi}\right)^2\left\{\frac{9}{2}C_F^2(\gamma^0_{\text{cusp}})^2\left[\frac{\ln^3(s_4/m_t^2)}{s_4}\right]_+ + \frac{1}{2}C_F\gamma^0_{\text{cusp}}\left(18C_F\gamma^0_{\text{cusp}}L_s + 9(\gamma^0_J - 2\gamma^0_S) - 5\beta_0\right)\right.\\
&\times\left[\frac{\ln^2(s_4/m_t^2)}{m_t^2}\right]_+ + \Big(-C_F^2L_h^2(\gamma^0_{\text{cusp}})^2 - 2C_FL_h\gamma^0_{\text{cusp}}\gamma^0_h + 7C_F^2(\gamma^0_{\text{cusp}})^2L_s^2\\
&-2C_F\gamma^0_{\text{cusp}}(-2\gamma^0_j + 7\gamma^0_s + 2\beta_0)L_s + 3C_F\gamma^0_{\text{cusp}}(c^1_h + c^1_j + c^1_s) + 3C_F\gamma^1_{\text{cusp}} + \frac{C_F}{N_c}(\Gamma^0_{h,21})^2\\
&+2\Gamma^0_{h,21}\Gamma^0_{h,12} - \frac{9}{4}\pi^2C_F^2(\gamma^0_{\text{cusp}})^2 - 4\gamma^0_j\gamma^0_s - \beta_0\gamma^0_j + (\gamma^0_j)^2 + 4\beta_0\gamma^0_s + 4(\gamma^0_s)^2\Big)\\
&\times\left[\frac{\ln(s_4/m_t^2)}{s_4}\right]_+ + \bigg(\left(\frac{2}{3}C_F\gamma^0_{\text{cusp}}\gamma^0_s - \frac{1}{3}C_F\gamma^0_{\text{cusp}}\gamma^0_j\right)L_h^2 + \bigg(-\frac{C_F}{3N_c}(\Gamma^0_{h,21})^2 - \frac{2}{3}\Gamma^0_{h,21}\Gamma^0_{h,12}\\
&-\frac{2}{3}\gamma^0_j\gamma^0_h + \frac{4}{3}\gamma^0_s\gamma^0_h\bigg)L_h + 2C_F^2(\gamma^0_{\text{cusp}})^2L_s^3 + (\gamma^0_j - 6\gamma^0_s - 2\beta_0)C_F\gamma^0_{\text{cusp}}L_s^2\\
&\Big(2C_F\gamma^0_{\text{cusp}}(c^1_h + c^1_j + c^1_s) - \frac{2}{3}C_F^2(\gamma^0_{\text{cusp}})^2L_h^2 - \frac{3}{2}\pi^2C_F^2(\gamma^0_{\text{cusp}})^2 - \frac{4}{3}C_F\gamma^0_{\text{cusp}}\gamma^0_hL_h\\
&+2C_F\gamma^1_{\text{cusp}} + \frac{C_F}{N_c}(\Gamma^0_{h,21})^2 + 2\Gamma^0_{h,12}\Gamma^0_{h,21} - 2\gamma^0_j\gamma^0_s + 4\beta_0\gamma^0_s + 4(\gamma^0_s)^2\Big)L_s\\
&+(\gamma^0_j - 2\gamma^0_s)(c^1_h + c^1_j + c^1_s) - \beta_0(c^1_j + 2c^1_s) + 9C_F^2(\gamma^0_{\text{cusp}})^2\zeta_3\\
&-\frac{3}{4}\pi^2C_F\gamma^0_{\text{cusp}}\gamma^0_j + \frac{3}{2}\pi^2C_F\gamma^0_{\text{cusp}}\gamma^0_s + \frac{5}{12}\pi^2C_F\beta_0\gamma^0_{\text{cusp}} + \gamma^1_j - 2\gamma^1_s\bigg)\times\left.\left[\frac{1}{s_4}\right]_+\right\}, \qquad (59)
\end{aligned}
$$

Total cross section for single top and anti-top production at the Tevatron and LHC

	σ_{LO}	σ_{NLO}	σ_{expand}	σ_{RES}
Tevatron (top)	$0.318^{+0.029}_{-0.024}$ pb	$0.443^{+0.024}_{-0.020}$ pb	$0.463^{+0.002}_{-0.004}$ pb	$0.467^{+0.010}_{-0.010}$ pb
Tevatron (anti-top)	$0.318^{+0.029}_{-0.024}$ pb	$0.443^{+0.024}_{-0.020}$ pb	$0.463^{+0.002}_{-0.004}$ pb	$0.467^{+0.010}_{-0.010}$ pb
LHC (7 TeV, top)	$2.03^{+0.01}_{-0.01}$ pb	$2.71^{+0.07}_{-0.05}$ pb	$2.82^{+0.06}_{-0.07}$ pb	$2.81^{+0.16}_{-0.10}$ pb
LHC (7 TeV, anti-top)	$1.14^{+0.01}_{-0.01}$ pb	$1.53^{+0.04}_{-0.03}$ pb	$1.60^{+0.03}_{-0.04}$ pb	$1.60^{+0.08}_{-0.05}$ pb
LHC (14 TeV, top)	$5.21^{+0.14}_{-0.18}$ pb	$6.91^{+0.09}_{-0.05}$ pb	$7.17^{+0.20}_{-0.25}$ pb	$7.11^{+0.47}_{-0.35}$ pb
LHC (14 TeV, anti-top)	$3.36^{+0.09}_{-0.12}$ pb	$4.46^{+0.03}_{-0.05}$ pb	$4.64^{+0.10}_{-0.18}$ pb	$4.61^{+0.28}_{-0.24}$ pb

We can see that the resummation effects enhance the NLO cross section by about 3%-5%. The total uncertainties is obtained from varying the hard, soft, jet and factorization scale separately by a factor ½ and 2, and then adding up the individual variations in quadrature.

Resummed cross section

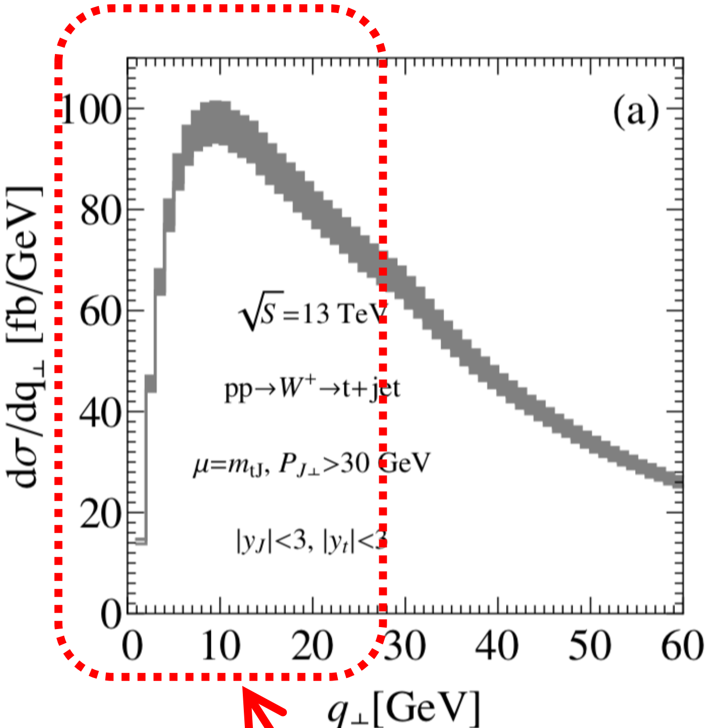


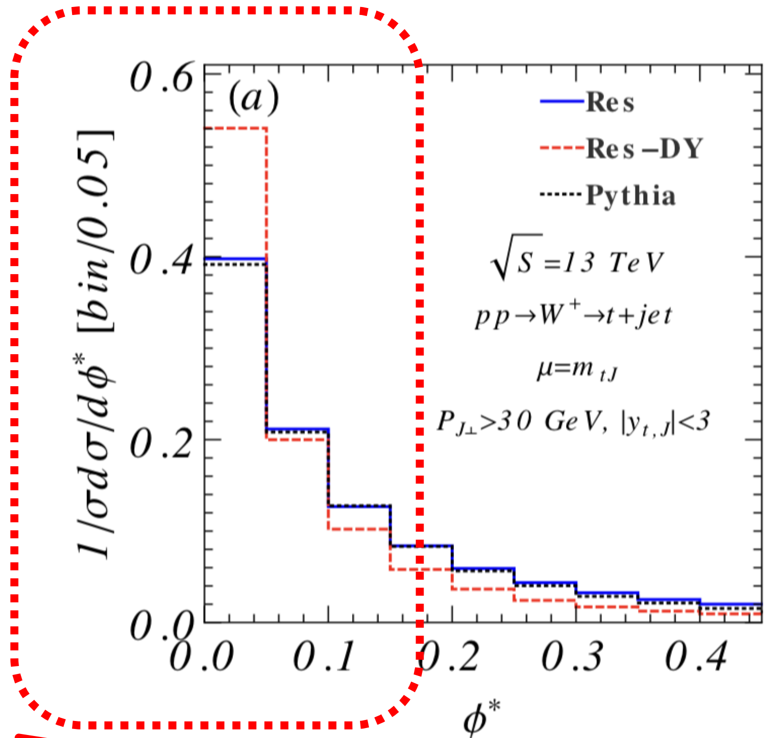
Transverse resummation for s-channel top quark production

Sun, Yan, Yuan, arXiv:1811.01428

They considered $p+p \to t+jet+X$

Resummed the logarithmic terms $\ln\frac{q_T}{Q}$, where $q_\perp = p_{t,\perp} + p_{j,\perp}$

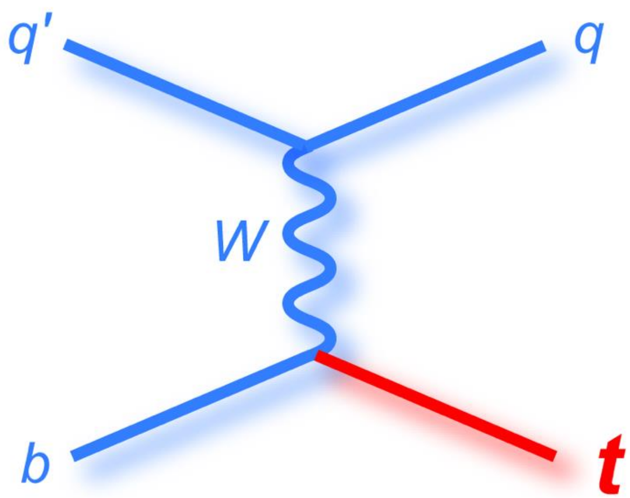




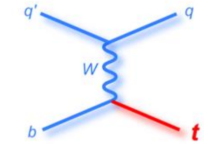
Resummed region

$$\phi^* = \tan\frac{\pi-\Delta\phi}{2}\sin\theta_\eta, \quad \cos\theta_\eta = \tanh\frac{\eta_J-\eta_t}{2}$$

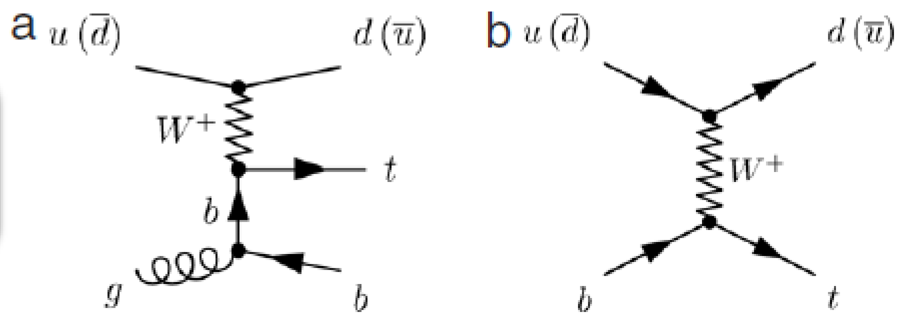
t-channel single top production



T-channel Single Top Quark Production



4-Flavor scheme



5-Flavor scheme

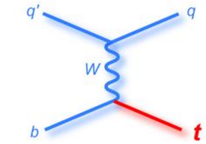
In 4-Flavor scheme,

- ✓ There is no b-quark in the initial state.
- ✓ The LO process for t channel single top production is, for example, $ug \rightarrow d\ t\ b$
- ✓ the gluon splitting process brings $\ln(Q^2 + m_t^2)\ /m_b^2$, which converges rather slowly.

In 5-Flavor scheme,

- ✓ There is b-quark in the initial state.
- ✓ The LO process for t channel single top production is, for example, $\mathrm{ub} \rightarrow d\ t$
- ✓ These logarithms from gluon splitting into $b\bar{b}$ are *resummed* to all orders in the b-quark PDF.
- ✓ It is easier to pursue high order QCD corrections

Fixed order calculations



- ✓ NLO QCD corrections for stable top quark

Bordes 1995, Stelzer 1995, Harris 2002, Sullivan 2004, Campbell 2004, Q.-H. Cao 2005, Campbell 2009

- ✓ NLO QCD corrections + Parton Shower

Frixione 2005, Frederix 2012, Alioli 2009, Bothmann 2017, Carrazza 2018

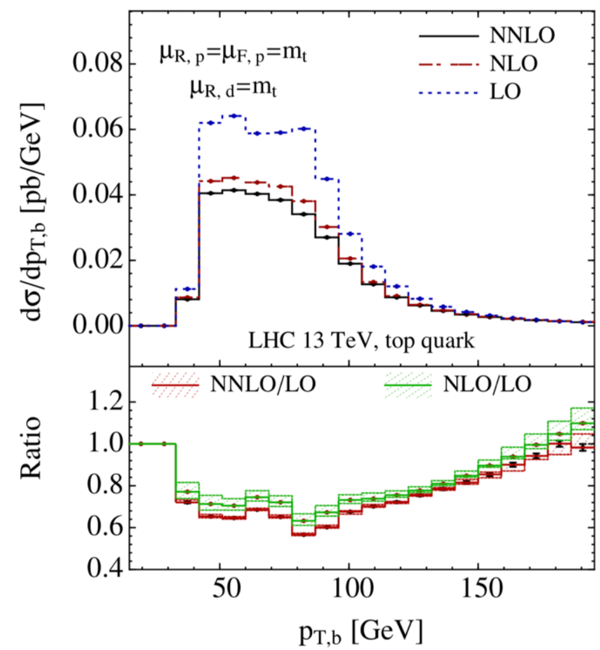
- ✓ NNLO QCD corrections without and with top quark decay neglecting O(αS2) color suppressed interference term

Brucherseifer, Caola, Melnikov, arXiv: 1404.7116
Berger, Gao, Yuan, Zhu, arXiv:1606.08463
Berger, Gao, Zhu, arXiv:1708.09405

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

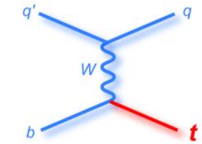
Fiducial cross sections for top (anti-)quark production with decay at 13 TeV

Berger, Gao, Yuan, Zhu, arXiv:1606.08463



Leading b-jet p_T distribution

T-channel Single Top Pro. in SCET



Wang, C.S.Li, Zhu, arXiv:1210.7698

- In SCET, Bauer, et al. 2000,2001,2002, Beneke, et al. 2002, Hill, et al. 2003

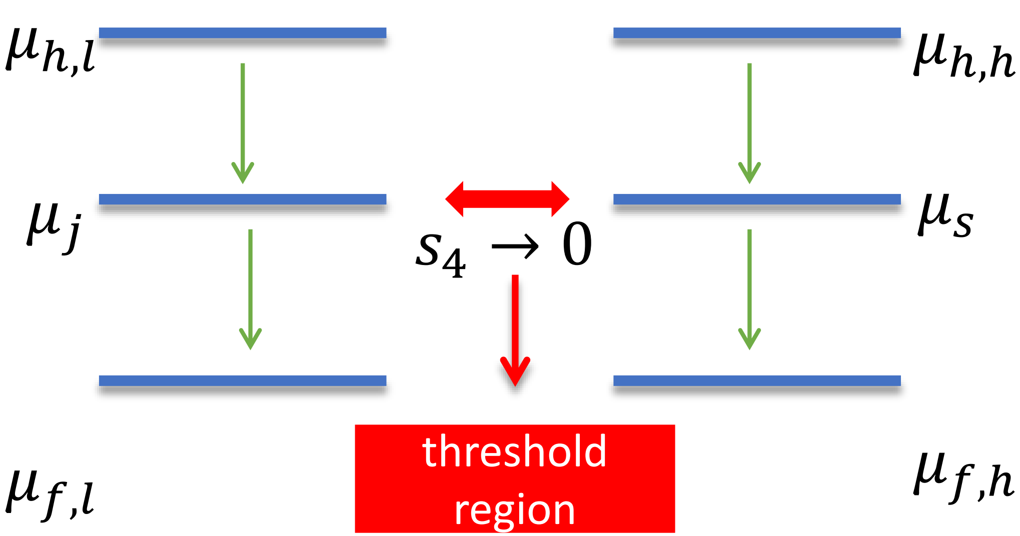
Separate differenct scales → Factorization → Resummation

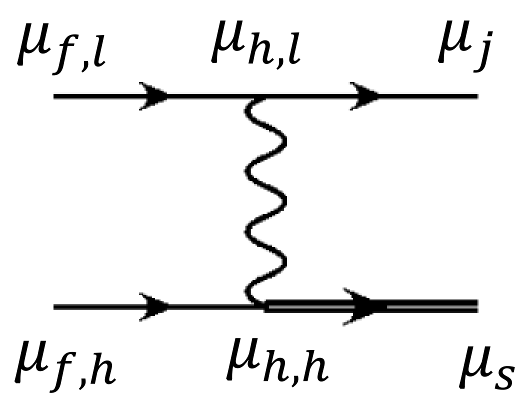
Collinear: $Q(\lambda^2, 1, \lambda)$
Soft: $Q(\lambda, \lambda, \lambda)$
Ultrasoft: $Q(\lambda^2, \lambda^2, \lambda^2)$

$$\sigma = H \times J \times S$$

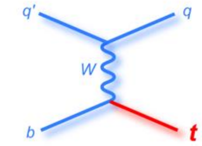
$$H(\mu) = U_h(\mu, \mu_h) H(\mu_h)$$
$$J(\mu) = U_j(\mu, \mu_j) J(\mu_j)$$
$$S(\mu) = U_s(\mu, \mu_s) S(\mu_s)$$

- For t-channel single top production,





$$S_4 = (p_u + p_b - p_t)^2$$



Resummed cross sections

Wang, C.S.Li, Zhu, arXiv:1210.7698

Threshold limit is defined as $s_4 = s + t + u - m_t^2 \to 0$

The resummed differential cross section for t-channel single top production

$$\frac{d\hat{\sigma}^{\rm thres}}{d\hat{t}\,d\hat{u}} = \sum_{ij} \frac{\lambda_{0,ij}}{64\pi N_c^2 \hat{s}^2}$$

hard function evolution

$$\exp\left[4S(\mu_{h,up},\mu_{F,up}) - 2a_{up}^{V}(\mu_{h,up},\mu_{F,up})\right]\left(\frac{-\hat{t}}{\mu_{h,up}^2}\right)^{-2a_\Gamma(\mu_{h,up},\mu_{F,up})} H_{up}(\mu_{h,up})$$

$$\exp\left[2S(\mu_{h,dn},\mu_{F,dn}) - 2a_{dn}^{V}(\mu_{h,dn},\mu_{F,dn})\right]\left(\frac{-\hat{t}+m_t^2}{\mu_{h,dn}m_t}\right)^{-2a_\Gamma(\mu_{h,dn},\mu_{F,dn})} H_{dn}(\mu_{h,dn})$$

$$\exp\left[-4S(\mu_j,\mu_{F,up}) + 2a^{J}(\mu_j,\mu_{F,up})\right]\left(\frac{m_t^2}{\mu_j^2}\right)^{\eta_j}$$

jet function evolution

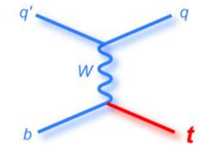
$$\exp\left[-2S(\mu_s,\mu_{F,dn}) - 2a^{S}(\mu_s,\mu_{F,dn})\right]\left(\frac{m_t(-\hat{t}+m_t^2)}{\mu_s(-\hat{u})}\right)^{\eta_s}$$

soft function evolution

$$\widetilde{j}(\partial_\eta + L_j,\mu_j)\,\widetilde{s}(\partial_\eta + L_s,\mu_s)\frac{1}{s_4}\left(\frac{s_4}{m_t^2}\right)^{\eta}\frac{e^{-\gamma_E\eta}}{\Gamma(\eta)},$$

convolution of jet and soft functions

Leading Singular contributions



Wang, C.S.Li, Zhu, arXiv:1210.7698

Expanding the equation in the last slide for all scales equal, we obtain the leading singular contributions.

The logarithmic structure is

$$\left(\frac{\lambda_{0,ij}}{64\pi N_c^2\hat{s}^2}\right)^{-1}\frac{d\hat{\sigma}_{ij}^{\text{thres}}}{d\hat{t}d\hat{u}} = \delta(s_4)+\frac{\alpha_s}{4\pi}\Big\{A_2D_2+A_1D_1+A_0\delta(s_4)\Big\} + \left(\frac{\alpha_s}{4\pi}\right)^2\Big\{B_4D_4+B_3D_3+B_2D_2+B_1D_1+B_0\delta(s_4)\Big\},$$

$$D_n = \left[\frac{\ln^{n-1}(s_4/m_t^2)}{s_4}\right]_+$$

$$A_2 = 3\Gamma_0,$$

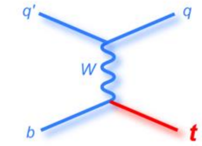
$$A_1 = (L_j+2L_s)\Gamma_0+\gamma_0^J-2\gamma_0^S$$

$$A_0 = \left(-\frac{1}{2}L_{h,up}^2-L_{h,dn}^2+\frac{1}{2}L_j^2+L_s^2-\frac{\pi^2}{4}\right)\Gamma_0-\gamma_{up,0}^V L_{h,up}-2\gamma_{dn,0}^V L_{h,dn}+\gamma_0^J L_j-2\gamma_0^S L_s + c_1^H+c_1^J+c_1^S,$$

For expressions of B_i, see arXiv:1210.7698

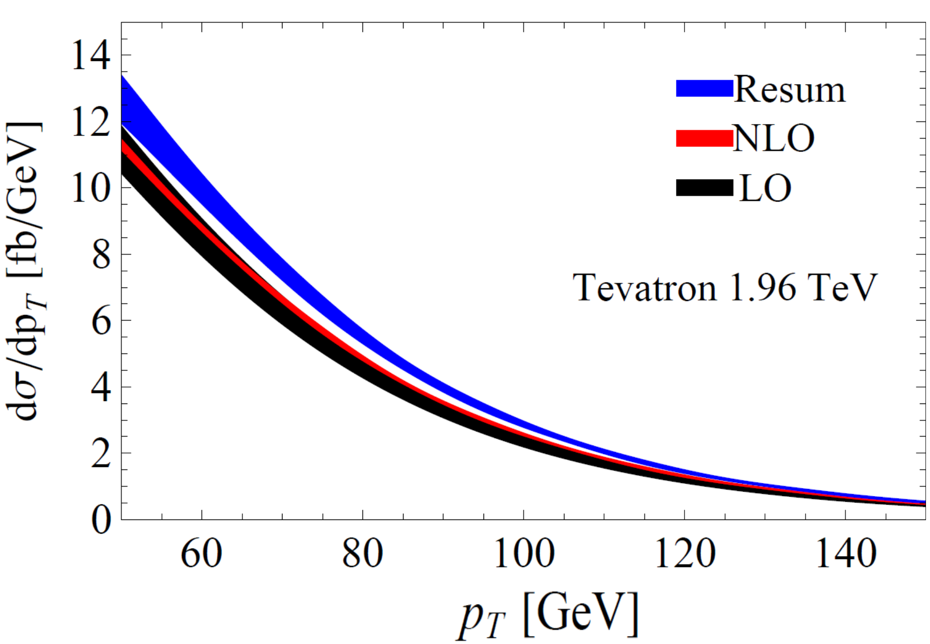
We are going to resum them to all order in α_s

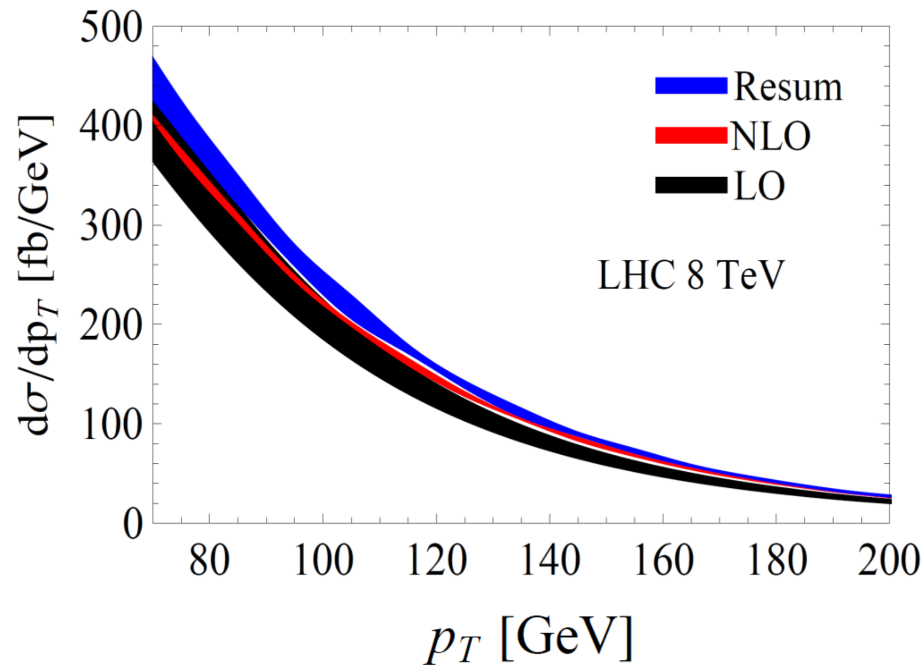
Resummed cross sections



Wang, C.S.Li, Zhu, arXiv:1210.7698

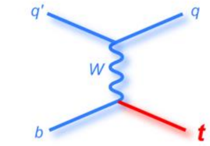
The resumed top quark p_T distribution





- ✓ The resummation for top quark with low transverse momentum is not appropriate.
- ✓ The soft gluon effects can *enhance* the differential cross sections at high transverse momentum of top quark by about 9~13% and 4~9% at the Tevatron and the 8 TeV LHC, respectively.

Other efforts

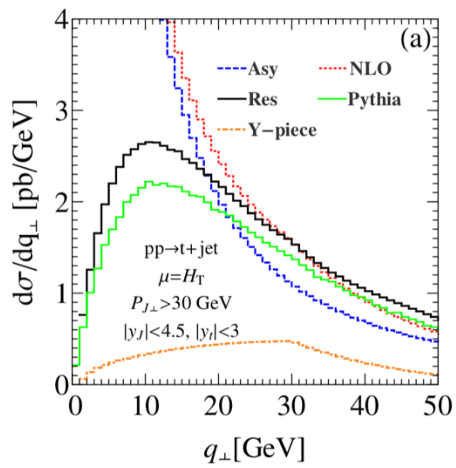


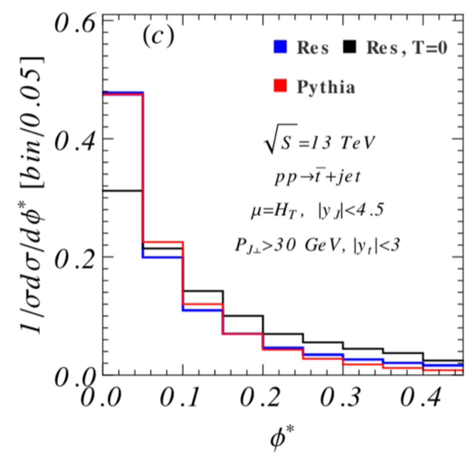
Transverse Momentum Resummation

The process $p + p \to t + jet + X$

$$q_\perp = p_{t,\perp} + p_{j,\perp}$$

$$\phi^* = \tan\frac{\pi - \Delta\phi}{2}\sin\theta_\eta, \quad \cos\theta_\eta = \tanh\frac{\eta_J - \eta_t}{2}$$



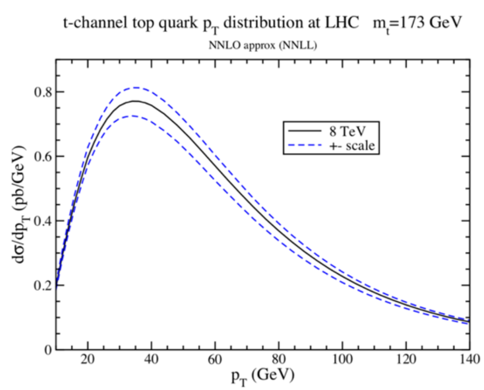


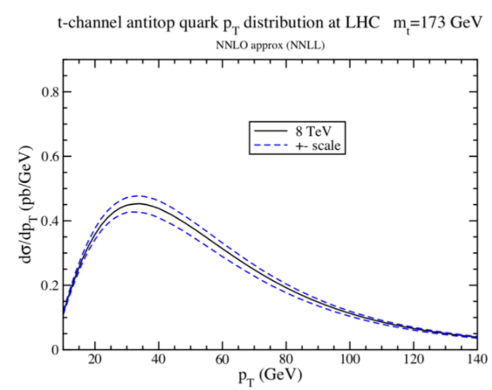
Cao, Sun, Yan, Yuan, Yuan, arXiv:1801.09656, arXiv:1902.09336

Higher order soft gluon effects are calculated in *traditional resummation scheme*

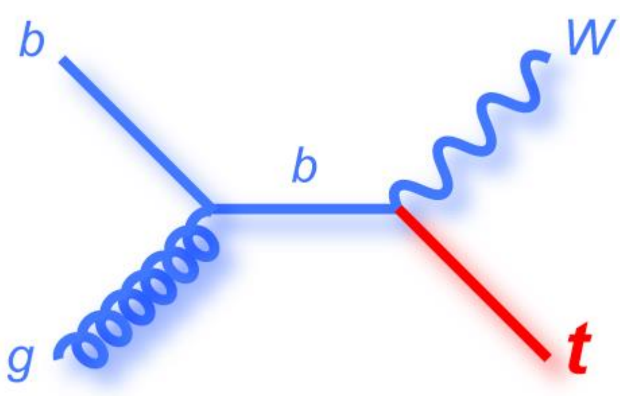
Kidonakis, arXiv:1103.2792, arXiv:1306.3592, arXiv:1510.06361

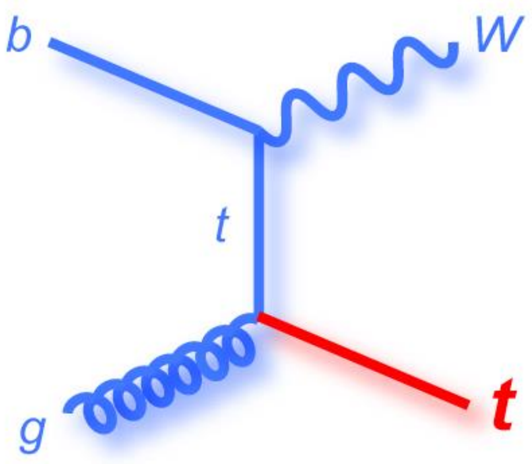
Top-quark transverse-momentum distribution



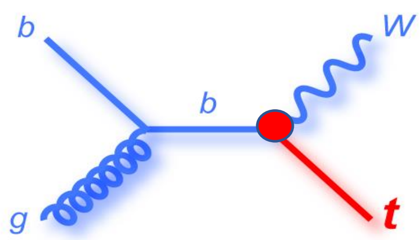


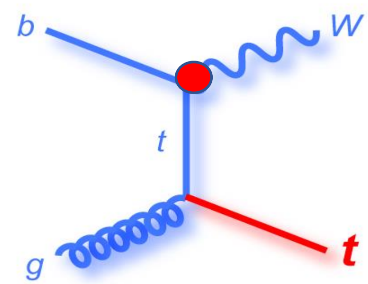
tW production





Theoretical status





tW production

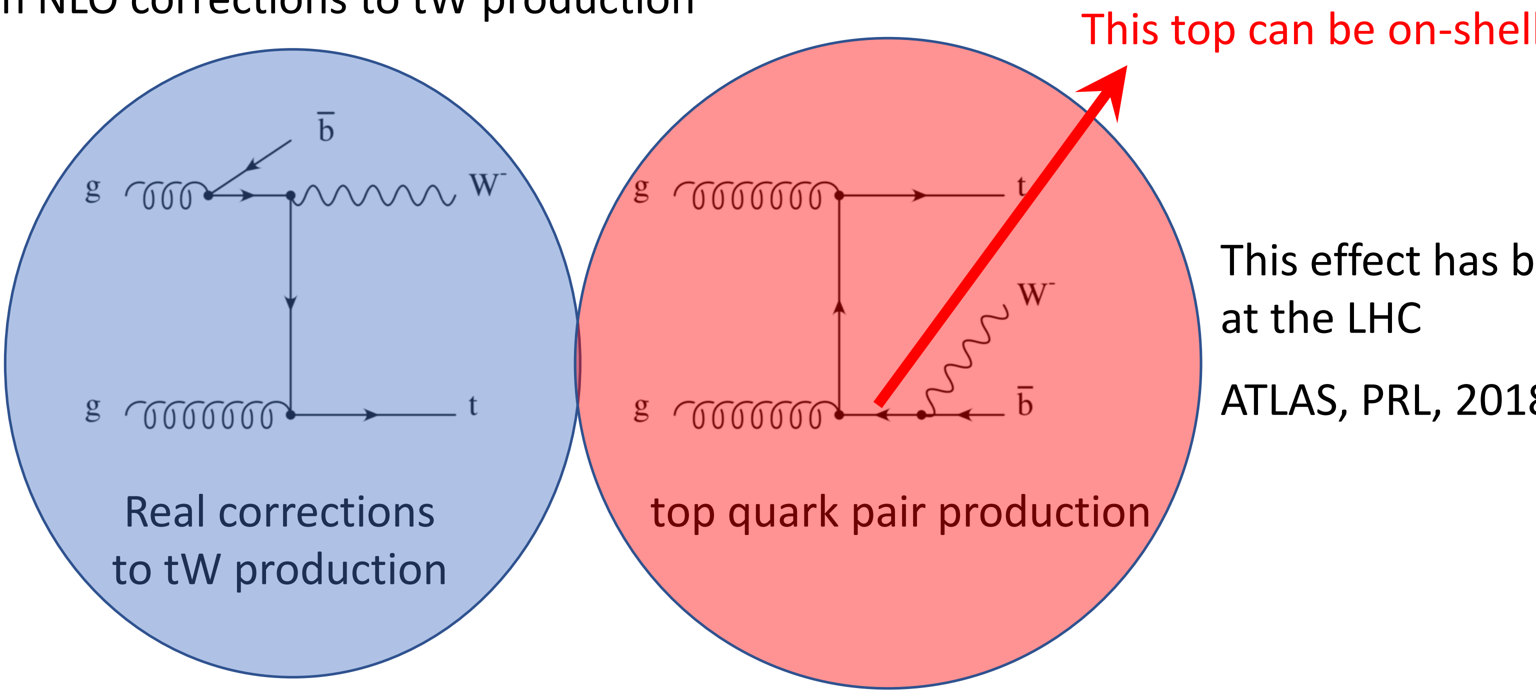
- can be used to direct measurement of the CKM matrix element V_{tb}
- has the second largest cross section in single top production at the LHC
- have been measured directly at the LHC

Theoretical status

- NLO QCD corrections: Giele, Keller, Laenen, 1996; S. Zhu 2001, Campbell and Tramontano, 2005
- NLO QCD with parton shower: Frixione et al 2008; E. Re 2009; Jezo et al 2016
- Resummation and approximated NNLO: Kidonakis, 2006, 2010, 2017

Interference with top quark pair production

In NLO corrections to tW production



This effect has been measured at the LHC

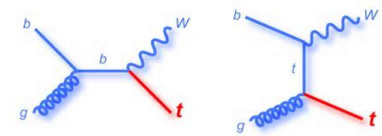
ATLAS, PRL, 2018

We need to find a way to differentiate the two processes or to define tW process properly

- ✓ diagram removal (DR): remove the diagrams for top quark pair production; not gauge invariant
- ✓ diagram subtraction (DS): using a local subtraction term to cancel the matrix element square in the resonance region
- ✓ b-jet veto: together with a careful choice of the factorization scale

Frixione et al 2008
Hollik et al 2012
Campbell et al 2005

Pair invariant mass Limit

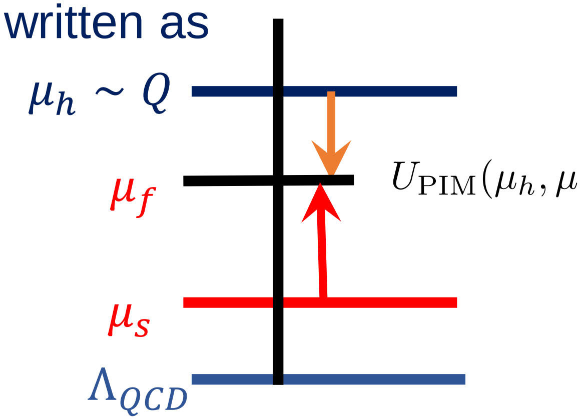


C.S.Li, Li, Shao, Wang, arXiv:1903.01646

Partonic threshold: Pair invariant mass (PIM) $\mathbf{1-z=1-\frac{M_{tW}^2}{s}\to 0}$

The RG improved differential cross section in SCET can be written as

$$\frac{d^2\sigma^{\rm PIM}}{dM^2 d\cos\theta} = \frac{\lambda^{1/2}}{32\pi s M^2}\sum_{ij}\int_\tau^1 \frac{dz}{z}\int_z^1 \frac{dx}{x} f_{i/p}(x,\mu_f) f_{j/p}(z/x,\mu_f) H(\mu_h) U_{\rm PIM}(\mu_h,\mu_s,\mu_f)$$
$$\times \frac{z^{-\eta}}{(1-z)^{1-2\eta}} \tilde{s}_{\rm PIM}\left(\ln\frac{M^2(1-z)^2}{z\mu_s^2}+\partial_\eta,\mu_s\right)\frac{e^{-2\gamma_E\eta}}{\Gamma(2\eta)}\bigg|_{\eta=(C_A+C_F)a_{\gamma^{\rm cusp}}(\mu_s,\mu_f)}$$

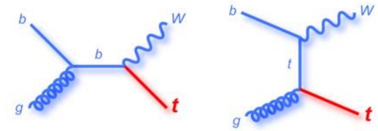


The evolution factor embodies RG running from hard and soft scale to factorization scale, which is expressed as

$$U_{\rm PIM}(\mu_h,\mu_s,\mu_f) = \left(\frac{M^2}{\mu_h^2}\right)^{(C_A+C_F)\,a_{\gamma^{\rm cusp}}(\mu_s,\mu_h)} \exp\Big[2(C_A+C_F)S(\mu_h,\mu_s)$$
$$+\,a_{\gamma^h}(\mu_s,\mu_h)+2\,a_{\gamma^{\phi_q}}(\mu_s,\mu_f)+2\,a_{\gamma^{\phi_g}}(\mu_s,\mu_f)\Big].$$

The factorized cross section captures all the log terms: $\delta(1-z)$, $\left(\frac{1}{1-z}\right)_+$, $\left(\frac{\ln 1-z}{1-z}\right)_+$ … …

One Particle Inclusive limit

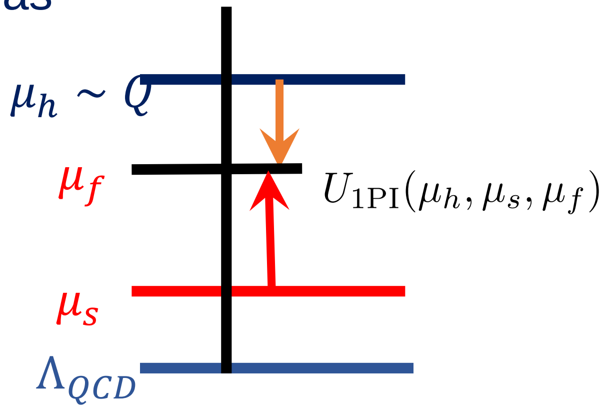


C.S.Li, Li, Shao, Wang, arXiv:1903.01646

Partonic threshold: One-particle inclusive (1PI) $s_4 = s + t + u - m_t^2 - m_W^2 \to 0$

The RG improved differential cross section can be written as

$$\frac{d^2\sigma^{1\mathrm{PI}}}{dp_T^2 dy} = \frac{1}{16\pi s} \sum_{ij} \int_{x_1^{\min}}^{1} \frac{dx_1}{x_1} \int_0^{s_4^{\max}} \frac{ds_4}{s_4 + M_W^2 - m_t^2 - x_1 t_1} f_{i/p}(x_1, \mu_f) f_{j/p}(x_2, \mu_f)$$
$$\times H(\mu_h) U_{1\mathrm{PI}}(\mu_h, \mu_s, \mu_f) \tilde{s}_{1\mathrm{PI}}(\partial_\eta, \mu_s) \frac{1}{s_4} \left(\frac{s_4}{M_W \mu_s} \right)^{2\eta} \frac{e^{-2\gamma_E \eta}}{\Gamma(2\eta)}$$



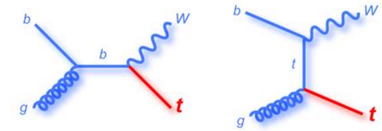
The evolution factor is

$$U_{1\mathrm{PI}}(\mu_h, \mu_s, \mu_f) = \left(\frac{M^2}{\mu_h^2} \right)^{(C_A + C_F) a_{\gamma^{\mathrm{cusp}}}(\mu_s, \mu_h)} \exp \Big[2(C_A + C_F) S(\mu_h, \mu_s) + a_{\gamma^h}(\mu_s, \mu_h)$$
$$+ 2\, a_{\gamma^{\phi_q}}(\mu_s, \mu_f) + 2\, a_{\gamma^{\phi_g}}(\mu_s, \mu_f) + a_{\gamma^{\mathrm{cusp}}}(\mu_s, \mu_f) \left(C_A \ln \frac{M_W^2 \mu_s^2}{(\hat{t}_1^W)^2} + C_F \ln \frac{M_W^2 \mu_s^2}{(\hat{u}_1^W)^2} \right) \Big].$$

Different RG factor

In principle, these two definitions describe the same physics in the soft limits.
However, they include different power suppressed corrections when the radiation is not exactly soft.

Leading contribution



C.S.Li, Li, Shao, Wang, arXiv:1903.01646

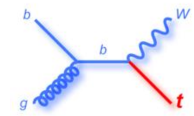
The fixed-order total cross section and the power corrections in different schemes

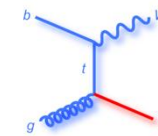
[pb]	PIM			1PI		
	b-veto	DS	DR	b-veto	DS	DR
LO		$6.96^{+5\%}_{-6\%}$			$7.21^{+5\%}_{-4\%}$	
NLO bg		$12.0^{-6\%}_{+2\%}$			$11.7^{-8\%}_{+4\%}$	
NLO leading		$11.2^{-5\%}_{+2\%}$			$11.5^{-3\%}_{+0\%}$	
NLO	$9.31^{+0\%}_{-1\%}$	$9.92^{+2\%}_{-2\%}$	$10.0^{+2\%}_{-2\%}$	$9.32^{-1\%}_{+0\%}$	$10.0^{+1\%}_{-2\%}$	$10.2^{+2\%}_{-2\%}$
power corr.	$-1.87^{+0.5}_{-0.25}$	$-1.26^{+0.75}_{-0.40}$	$-1.17^{+0.76}_{-0.43}$	$-2.14^{+0.30}_{-0.05}$	$-1.46^{+0.53}_{-0.21}$	$-1.29^{+0.63}_{-0.27}$

- ✓ There is huge corrections (29% ~ 44%) for the total cross section from LO to NLO
- ✓ the leading power terms of the bg channel can approximate the total result of the bg channel very well
- ✓ The power corrections are negative and around −20% ~ −12% in PIM and −23% ~ −13% in 1PI kinematic scheme depending on the methods

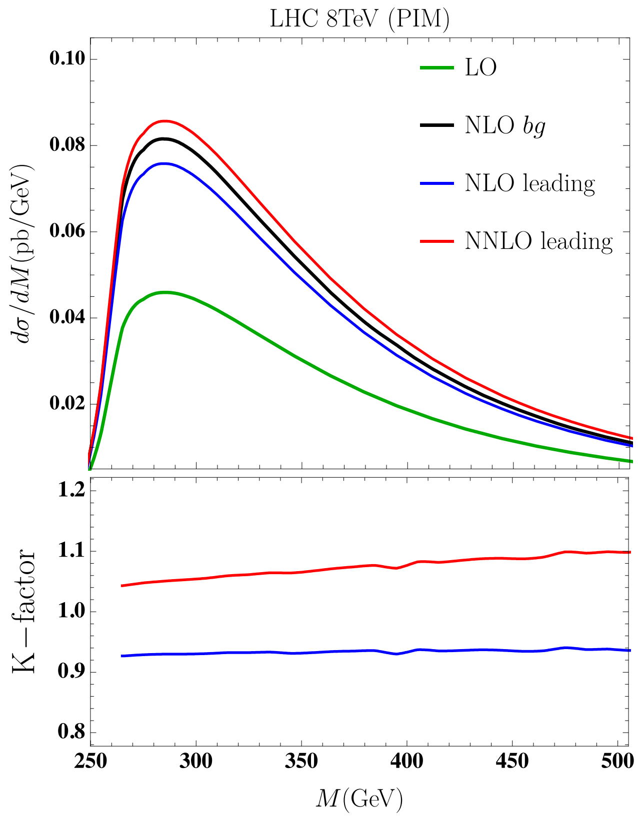
The contributions of the higher order power corrections can be obtained by calculating the full NNLO QCD corrections or by making use of the next- to-leading power factorization and resummation.

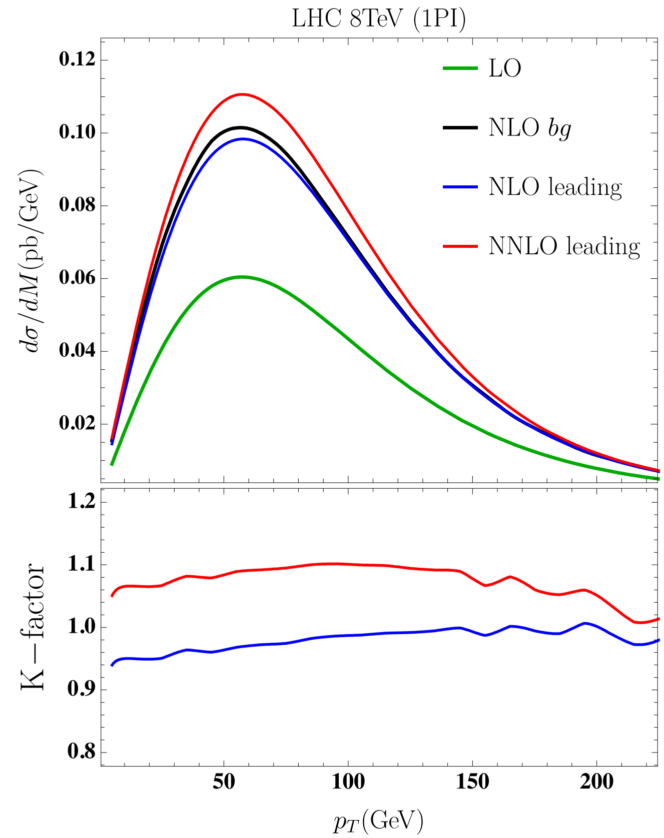
Leading contribution





C.S.Li, Li, Shao, Wang, arXiv:1903.01646

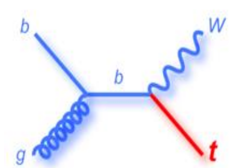


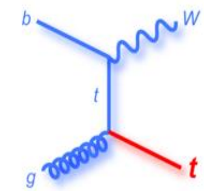


- ✓ There is huge corrections from, LO to NLO
- ✓ The leading power terms are dominant in all the invariant mass or the top p_T regions, as in the case of total cross sections.
- ✓ The NNLO leading terms increase the NLO leading cross section by about 10% in most of the region.

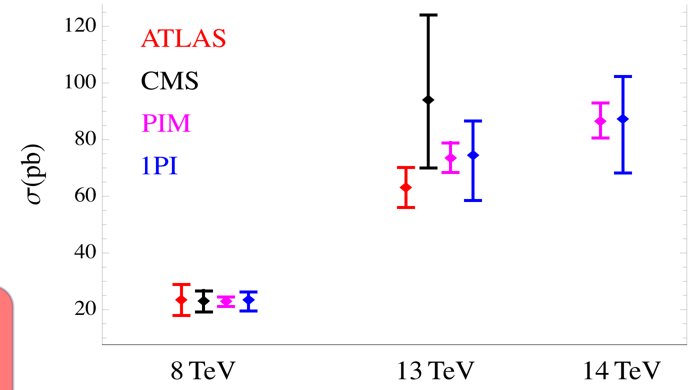
Resummed cross section

C.S.Li, Li, Shao, Wang, arXiv:1903.01646



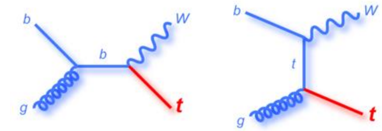


[pb]	PIM		1PI	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
LO	$7.0^{+5\%}_{-6\%}$	$22.4^{+5\%}_{-2\%}$	$7.2^{+5\%}_{-4\%}$	$22.9^{+3\%}_{-1\%}$
NLO	$9.92^{+2\%}_{-2\%}$	$32.8^{+1\%}_{-1\%}$	$10.0^{+1\%}_{-2\%}$	$33.0^{+1\%}_{-1\%}$
aNNLO	$11.6^{+4\%}_{-5\%}$	$37.1^{+5\%}_{-5\%}$	$11.2^{+6\%}_{-6\%}$	$35.9^{+7\%}_{-6\%}$
NLO+NNLL	$11.4^{+7\%}_{-7\%}$	$36.7^{+7\%}_{-7\%}$	$11.7^{+12\%}_{-17\%}$	$37.3^{+16\%}_{-21\%}$
aNNLO/NLO	1.16	1.13	1.12	1.09
(NLO+NNLL)/NLO	1.15	1.12	1.17	1.13



- ✓ The NLO+NNLL predictions increase the NLO total cross section by 12% ~ 17% depending on the collider energy and the threshold variable, but with larger scale uncertainties
- ✓ These large uncertainties are mainly from the variation of the factorization scale μ_f
- ✓ The NLO+NNLL predictions are in good agreement with the data at the 8 TeV and 13 TeV LHC

Comments on future directions



C.S.Li, Li, Shao, Wang, arXiv:1903.01646

The NNLO QCD corrections can be achieved making use of the ***N-jettiness subtraction method***

$$\sigma(X) = \int_0 \mathrm{d}\mathcal{T}_N \frac{\mathrm{d}\sigma(X)}{\mathrm{d}\mathcal{T}_N} = \boxed{\int_0^{\mathcal{T}_N^{\rm cut}} \mathrm{d}\mathcal{T}_N \frac{\mathrm{d}\sigma(X)}{\mathrm{d}\mathcal{T}_N}} + \boxed{\int_{\mathcal{T}_N^{\rm cut}} \mathrm{d}\mathcal{T}_N \frac{\mathrm{d}\sigma(X)}{\mathrm{d}\mathcal{T}_N}}$$

It was first used in top decay and has been applied to many processes in hadronic collisions

Gao, C.S.Li, Zhu, arXiv:1210.2808
Boughezal et al arXiv:1504.02131
Gaunt et al arXiv:1505.04794

Predicted by the factorized cross section in SCET

Predicted by the standard NLO QCD corrections

$$\sigma(\mathcal{T}_N < \mathcal{T}_N^{cut}) = \int H \otimes B \otimes B \otimes S \otimes \left[\prod_n^N J_n\right]$$

- ✓ The NNLO beam functions are available
  Gaunt, Stahlhofen, Tackmann arXiv:1405.1044, arXiv:1401.5478
- ✓ The NNLO N-jettiness soft function for this process is also available *Li, Wang arXiv:1611.02749, arXiv:1804.0635*
- ✓ The only missing part is the two-loop hard function

NNLO massive N-jettiness soft function

Hai Tao Li, Jian Wang, Phys.Lett.B.784(2018)397

- So far, N-jettiness slicing method is successful for the NNLO differential calculation of jet production at hadron colliders.
- How about massive colored particle production, ttbar or tW?

$$\frac{d\sigma}{d\mathcal{O}} = \boxed{\frac{d\sigma}{d\mathcal{O}}\bigg|_{\mathcal{T}_N<\Delta}} + \frac{d\sigma}{d\mathcal{O}}\bigg|_{\mathcal{T}_N>\Delta}$$

$$\mathcal{T}_N = \sum_k \min_i \{n_i \cdot q_k\} \,,$$

$$\frac{d\sigma}{dY\,d\tau} = \int d\Phi_2 \frac{d\hat{\sigma}_0}{d\Phi_2} \int dt_a dt_b d\tau_s H(\beta_t, \cos\theta_t, \mu) B_1(t_a, x_a, \mu) B_2(t_b, x_b, \mu)$$

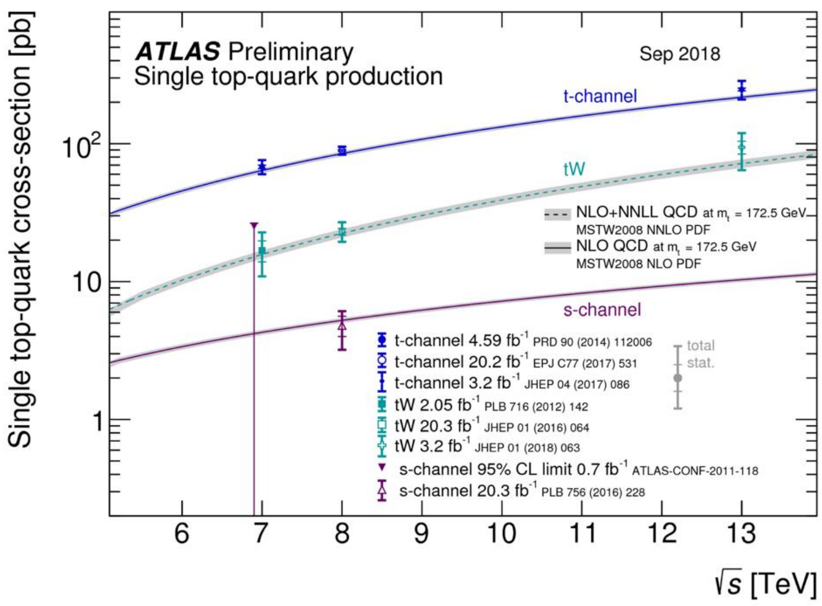
$$\times \boxed{S(\tau_s, \beta_t, \cos\theta_t, \mu)}\, \delta\left(\tau - \tau_s - \frac{t_a + t_b}{\sqrt{\hat{s}}}\right)\left(1 + \mathcal{O}\left(\frac{\tau}{\sqrt{\hat{s}}}\right)\right)$$

$$\sum_{X_s} \left\langle 0 \middle| \bar{\mathbf{T}} Y_n^\dagger Y_{\bar{n}} Y_v \middle| X_s \right\rangle \delta\left(\tau - \sum_k \min\left(n \cdot \hat{P}_k, \bar{n} \cdot \hat{P}_k\right)\right) \left\langle X_s \middle| \mathbf{T} Y_n Y_{\bar{n}}^\dagger Y_v^\dagger \middle| 0 \right\rangle$$

$$v^+ = \frac{1 - \beta_t \cos\theta_t}{\sqrt{1 - \beta_t^2}}, \quad v^- = \frac{1 + \beta_t \cos\theta_t}{\sqrt{1 - \beta_t^2}}, \quad |v_\perp| = \frac{\beta_t \sin\theta_t}{\sqrt{1 - \beta_t^2}},$$

Conclusion

- ✓ Reviewed the measurements for top quark production at the LHC
- ✓ Discussed how to include higher order QCD corrections for the process at the LHC, especially resummation in SCET approach
- ✓ Presented the theory predictions for s-channel, t-channel single top production
- ✓ Show our recent work on the soft gluon resummation for tW production at the LHC



Thank you !