



Transverse Momentum Resummation for single top quark production at the LHC

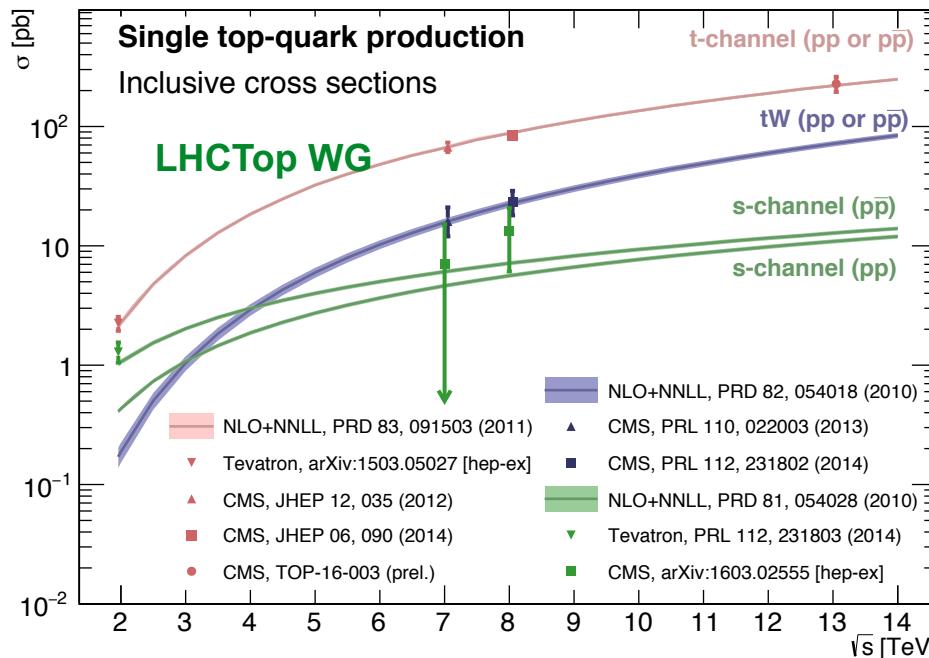
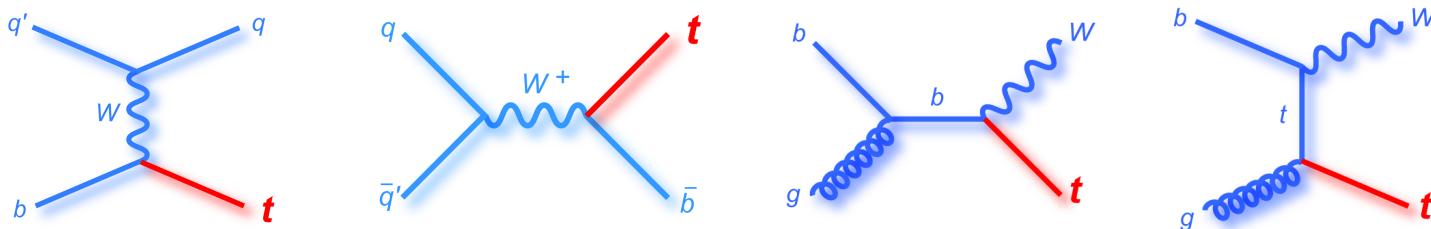
C.-P. Yuan
Michigan State University

**Jan. 16, 2018 @ Fermilab
Top quark physics at the precision frontier**

In collaboration with Qing-Hong Cao , Peng Sun, Bin Yan and Feng Yuan

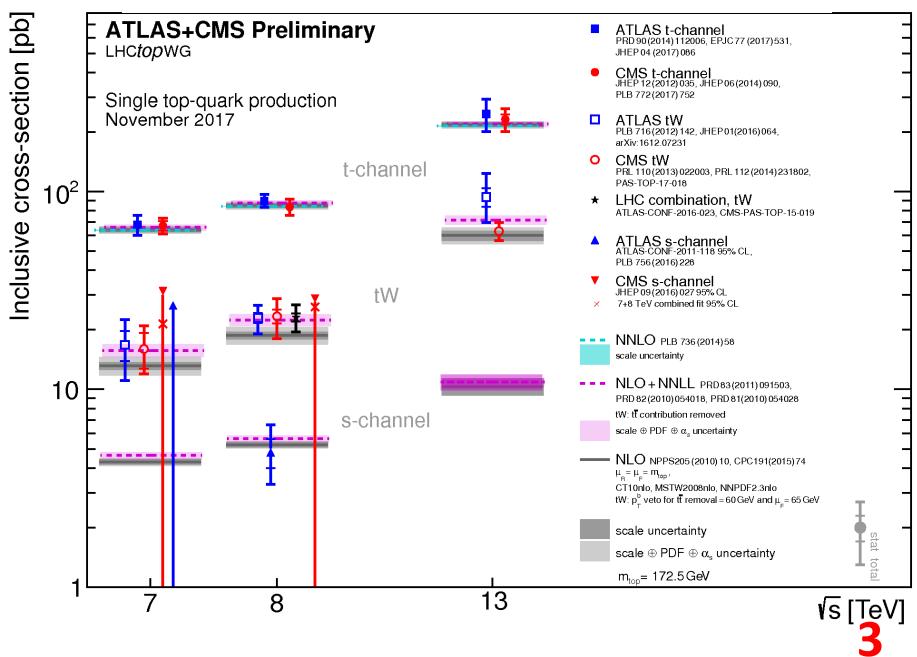
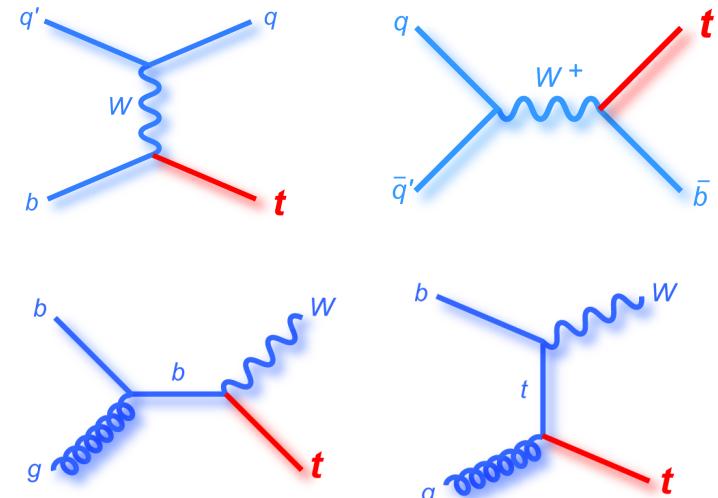
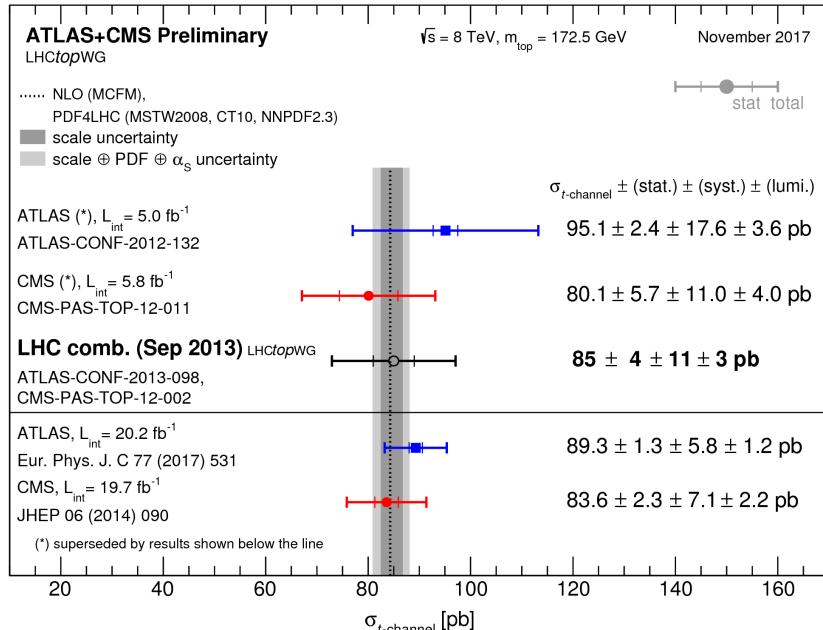
Single top-quark production

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



- ★ probing EW coupling (V_{tb})
- ★ polarized top-quark production
- ★ test of heavy-quark scheme
- ★ constraining parton distributions
- ★ measuring top-quark mass
- ★ sensitive to various new physics

State of the art: single top quark production



Better understanding and further improvements on the theory are needed

State of the art: single top quark production

NLO:

G. Bordes and B. Van Eijk, Nucl. Phys. B435 (1995)23-58
R. Pttau, Phys. Lett. B386(1996)397-402
T. Stelzer, Z. Sullivan, and S. Willenbrock, PRD56(1997)5919-5927, PRD58(1998)094021
B.W. Harris, E. Laenen, L. Phaf, Z. Sullivan and S. Weinzier, Int. J. Mod. Phys.A16S1A(2001)379-381
PRD66(2002)054024
Z. Sullivan, PRD70(2004)114012, PRD72(2005)094034
P. Falgari, P. Mellor and A. Signer, PRD82(2010)054028
R. Schwienhorst, C. P. Yuan, C. Mueller and Q. H. Cao, PRD83(2011)034019
J. M. Campbell, R. Frederix, F. Maltoni, and F. Tramontano, PRL102(2009)182003
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Q.-H. Cao, R. Schwienhorst, J.A. Benitez, R. Brock and C.-P. Yuan, PRD72(2005)094027
....

Matching with Parton Shower:

S. Frixinoe, E. Laenen, P. Motylinski and B. R. Webber, JHEP03(2006)092
S. Alioli, P. Nason, C. Oleari and E. Re, JHEP09(2009)111
S. Frederix, E. Re and P. Torrielli, JHEP 09 (2013)130

NNLO:

M. Brucherseifer, F. Caola and K. Melnikov, PLB736(2014)58-63
E. L. Berger, J. Cao, C. P. Yuan and H. X. Zhu, PRD94(2016),no.7, 071501
E. L. Berger, J. Cao and H. X. Zhu, arxiv:1708,09405

Apologize if missing your works!

Soft-gluon resummation: (threshold)

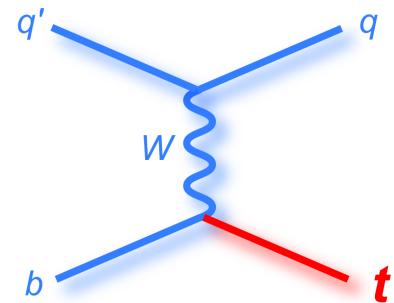
J. Wang, C.S. Li, H.X. Zhu, and J,J, Zhang, arxiv:10010.4509
N. Kidonakis, 2011-2016
J. Wang, C.S. Li, and H. X. Zhu, PRD87(2013)no.3, 034030
Alekhin, Moch, Their, 2016

Kinematic distribution and resummation

Single top quark events @ LHC

detection efficiency of the events, after imposing the needed kinematic cuts

Variable	Definition
$ \eta(j) $	pseudorapidity of the light quark (un-tagged) jet (j)
$m(\ell vb)$	top-quark mass reconstructed from the charged lepton, neutrino and b -quark jet
$m(jb)$	invariant mass of the tagged (b) and light quark jet (j)
$m_T(W)$	transverse mass of the reconstructed W boson
$m(\ell b)$	invariant mass of the lepton (ℓ) and the tagged jet (b)
$\eta(lv)$	pseudorapidity of the reconstructed W -boson
$\cos \Theta(\ell, j)_{\ell vb \text{ r.f.}}$	cosine of the angle θ between the charged lepton and the light quark (un-tagged) jet (j) in the rest frame of the reconstructed top quark
$H_T(l, \text{jets}, E_T^{\text{miss}})$	scalar sum of the transverse momenta of the jets, the charged lepton and the missing transverse momentum
E_T^{miss}	transverse missing momentum
$\Delta R(\ell vb, \ell)$	ΔR of the reconstructed top quark and the charged lepton
$p_T(\ell v)$	transverse momentum of the reconstructed W -boson
$\eta(\ell vb)$	pseudorapidity of the reconstructed top quark
$\eta(b)$	pseudorapidity of the b -quark jet (b)
$p_T(\ell vb)$	transverse momentum of the reconstructed top quark



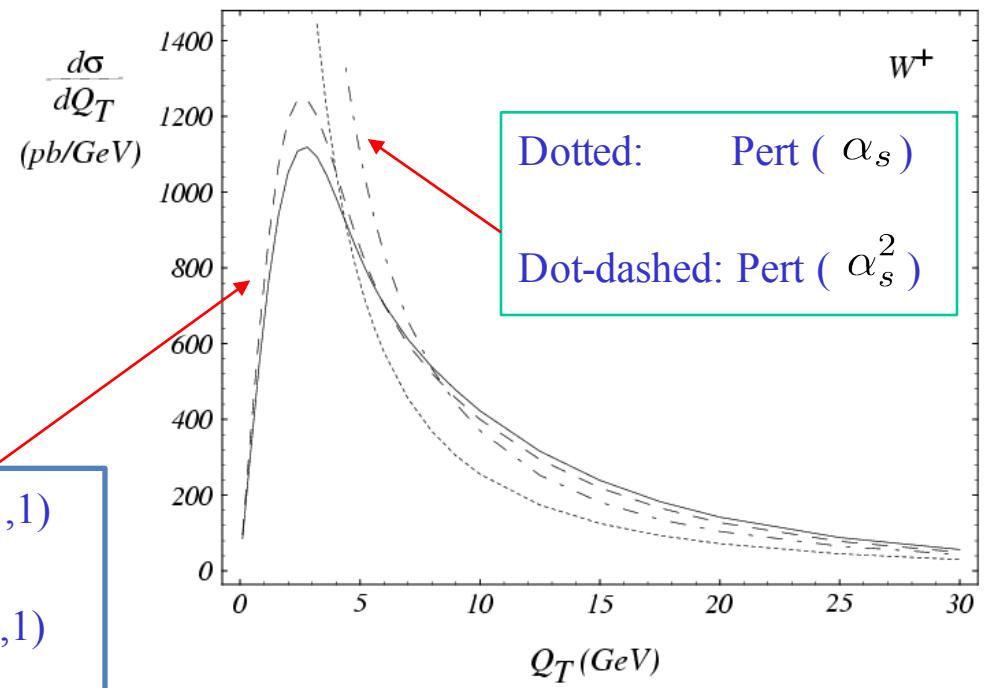
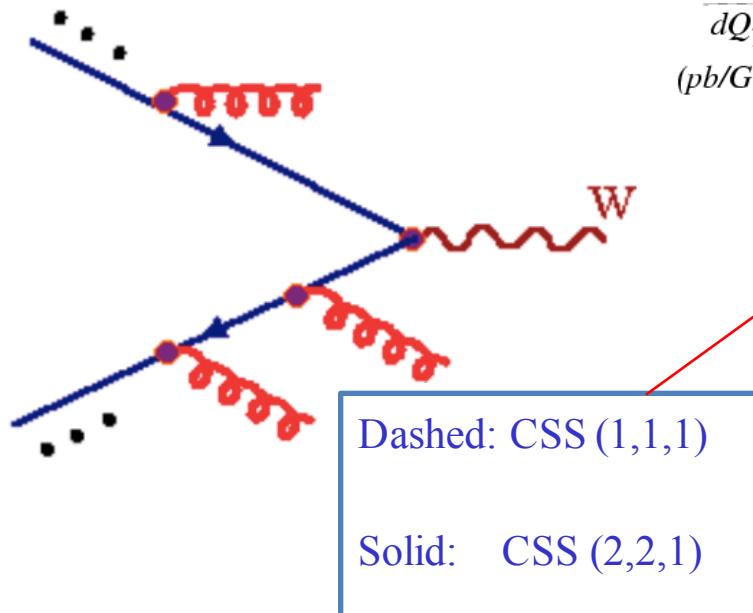
Resum large $\log \ln \frac{Q^2}{q_\perp^2}$ to improve the kinematic distribution

CSS Formalism (For Drell-Yan-like processes)

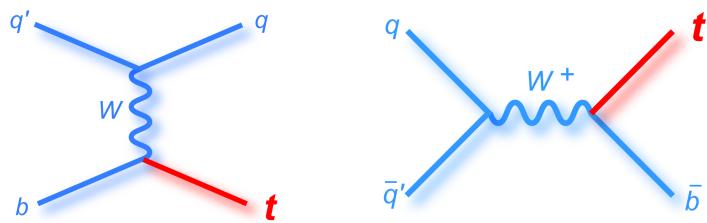
The large logs will be resummed into the exponential form factor:

$$W(Q, b) = e^{-\int_{1/b}^Q \frac{d\mu}{\mu} \left(\ln \frac{Q}{\mu} A + B \right)} C \otimes f_1 C \otimes f_2$$

Only for initial state soft gluon resummation



Single top quark vs. Drell-Yan process

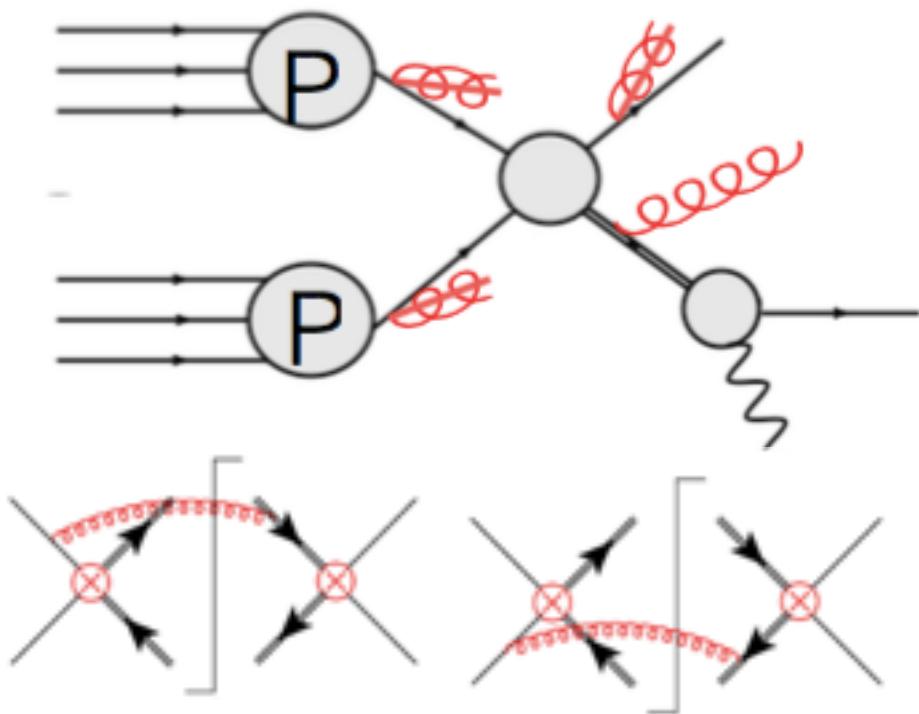


A. Final states carry color,
Soft gluon radiation from final state
will contribute

B. Jet algorithm will enter into the
calculations as well

Only out of the cone radiation
contributions to the imbalance
between the top quark and jet
system

C. Color coherence effects
between the initial and final states
are important (t-channel)



t-channel Single top quark

Resummation Formalism

$$\frac{d^4\sigma}{dy_t dy_J dP_{J\perp}^2 d^2 q_\perp} = \sum_{ab} \left[\int \frac{d^2 \vec{b}}{(2\pi)^2} e^{-i \vec{q}_\perp \cdot \vec{b}} W_{ab \rightarrow tJ}(x_1, x_2, \mathbf{b}) + Y_{ab \rightarrow tJ} \right]$$

$$W_{ab \rightarrow tJ}(x_1, x_2, \mathbf{b}) = x_1 f_a(x_1, \mu_F = b_0/b_*) x_2 f_b(x_2, \mu_F = b_0/b_*) e^{-S_{\text{Sud}}(Q^2, \mu_{\text{Res}}, b_*)} e^{-\mathcal{F}_{NP}(Q^2, \mathbf{b})} \\ \times \text{Tr} \left[\mathbf{H}_{ab \rightarrow tJ}(\mu_{\text{Res}}) \exp \left[- \int_{b_0/b_*}^{\mu_{\text{Res}}} \frac{d\mu}{\mu} \gamma^{s\dagger} \right] \mathbf{S}_{ab \rightarrow tJ}(b_0/b_*) \exp \left[- \int_{b_0/b_*}^{\mu_{\text{Res}}} \frac{d\mu}{\mu} \gamma^s \right] \right]$$

$$S_{\text{Sud}}(Q^2, \mu_R, b_*) = \int_{b_0^2/b_*^2}^{\mu_R^2} \frac{d\mu^2}{\mu^2} \left[\ln \left(\frac{Q^2}{\mu^2} \right) A + B + D_1 \ln \frac{Q^2 - m_t^2}{P_{J\perp}^2 R^2} + D_2 \ln \frac{Q^2 - m_t^2}{m_t^2} \right]$$

From final state radiation

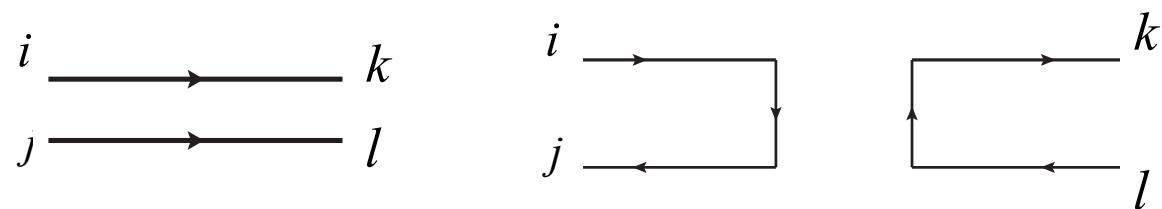
$$A = C_F \frac{\alpha_s}{\pi}, B = -2C_F \frac{\alpha_s}{\pi}, D_1 = D_2 = C_F \frac{\alpha_s}{2\pi}$$

Resummation Formalism

$$\frac{d^4\sigma}{dy_t dy_J dP_{J\perp}^2 d^2 q_\perp} = \sum_{ab} \left[\int \frac{d^2 \vec{b}}{(2\pi)^2} e^{-i \vec{q}_\perp \cdot \vec{b}} W_{ab \rightarrow tJ}(x_1, x_2, \mathbf{b}) + Y_{ab \rightarrow tJ} \right]$$

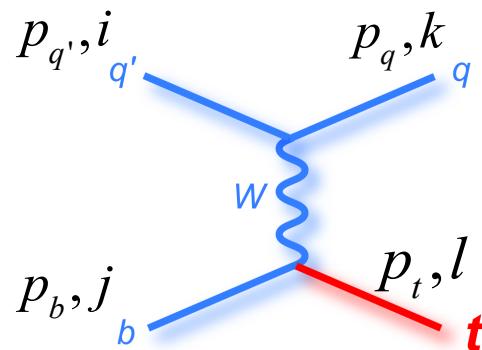
Color Space

$$C_{1kl}^{ij} = \delta_{ik}\delta_{jl}, \quad C_{2kl}^{ij} = T_{ik}^{a'} T_{jl}^{a'}$$



Hard Function

$$\mathbf{H} = \begin{bmatrix} H^{(0)} + H^{(1)} & H_{12}^{(1)} \\ H_{12}^{(1)} & 0 \end{bmatrix}$$

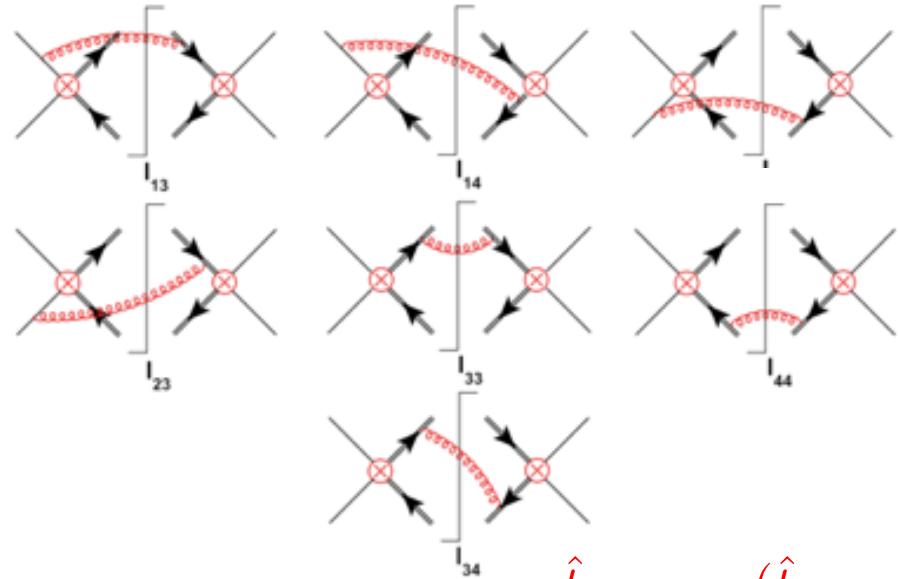
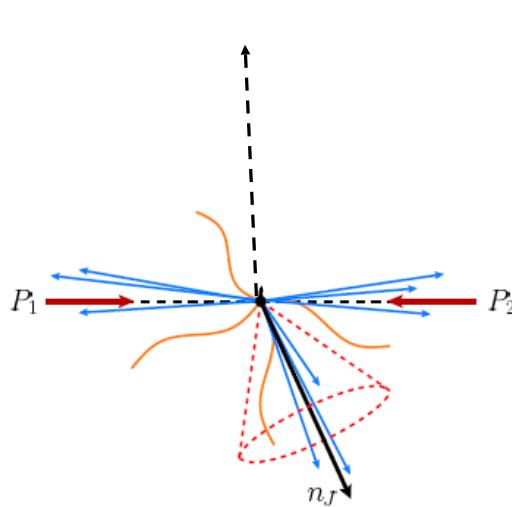


$$\hat{s} = (p_{q'} + p_b)^2 \quad \hat{u} = (p_{q'} - p_t)^2$$

$$\hat{t} = (p_{q'} - p_q)^2$$

Resummation Formalism

$$S_{IJ} = \int_0^\pi \frac{d\phi}{\pi} C_{Iii'}^{bb'} C_{Jll'}^{aa'} \langle 0 | \mathcal{L}_{vcb'}^\dagger(b_*) \mathcal{L}_{\bar{v}bc'}(b_*) \mathcal{L}_{\bar{v}c'a'}^\dagger(0) \mathcal{L}_{vac}(0) \mathcal{L}_{nji}^\dagger(b_*) \mathcal{L}_{\bar{n}i'k}(b_*) \mathcal{L}_{\bar{n}kl}^\dagger(0) \mathcal{L}_{nl'j}(0) | 0 \rangle$$



Example:

$$\gamma^{\mathbf{s}}_{ub \rightarrow dt} = \frac{\alpha_s}{\pi} \begin{bmatrix} C_F T & C_F/C_A U \\ U & \frac{1}{2}(C_A - 2/C_A)U - \frac{1}{2C_A}T \end{bmatrix} \quad \begin{aligned} T &= \ln \frac{-\hat{t}}{\hat{s}} + \ln \frac{-(\hat{t} - m_t^2)}{\hat{s} - m_t^2} \\ U &= \ln \left(\frac{-\hat{u}}{\hat{s}} \right) + \ln \left(\frac{-(\hat{u} - m_t^2)}{\hat{s} - m_t^2} \right). \end{aligned}$$

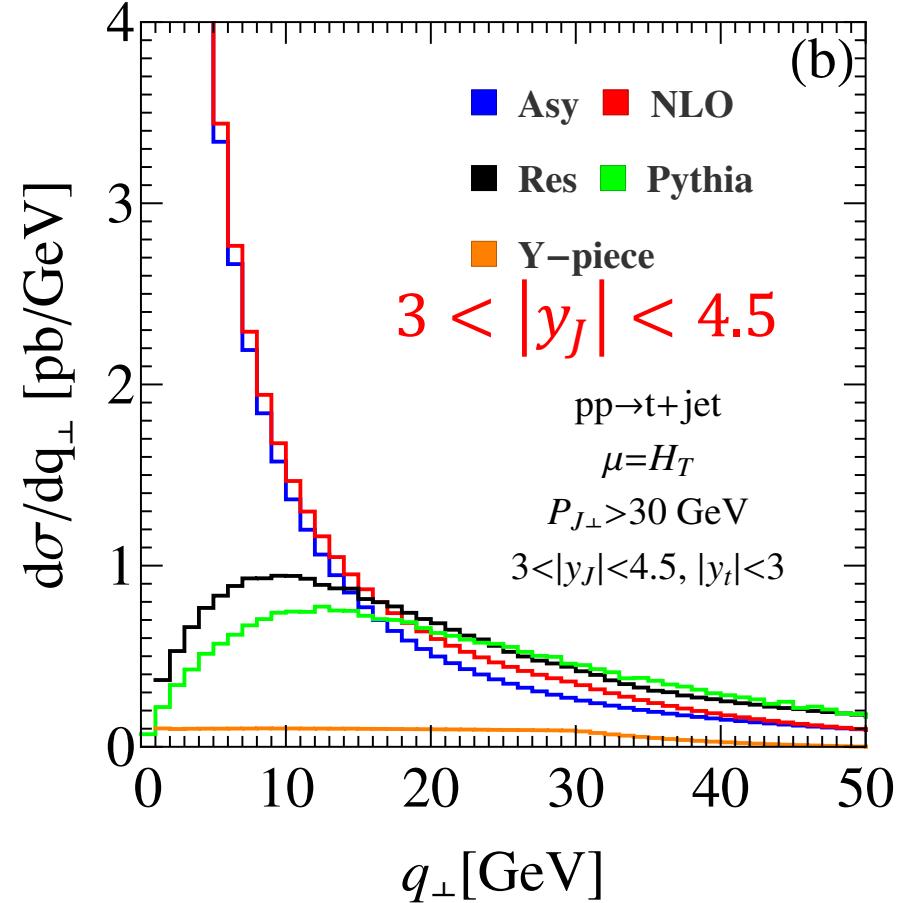
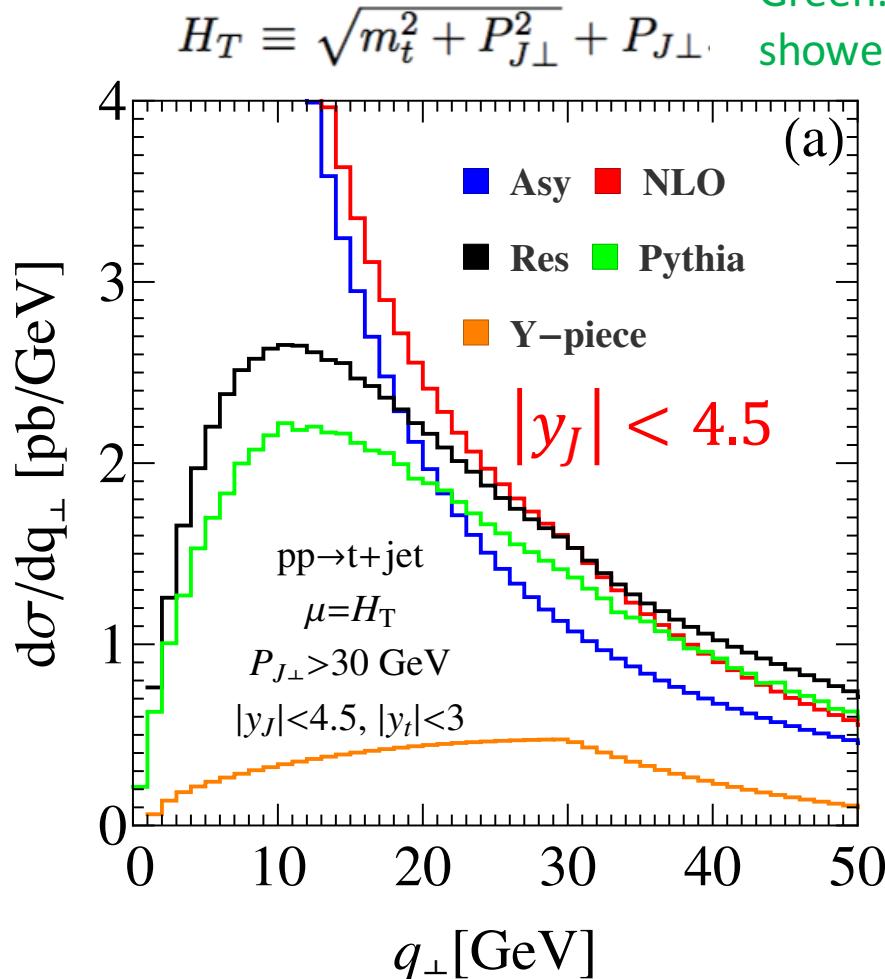
Subleading logs in this process would be enhanced in the jet forward region $|\hat{t}| \rightarrow 0$

Phenomenological results

Resummation scale:

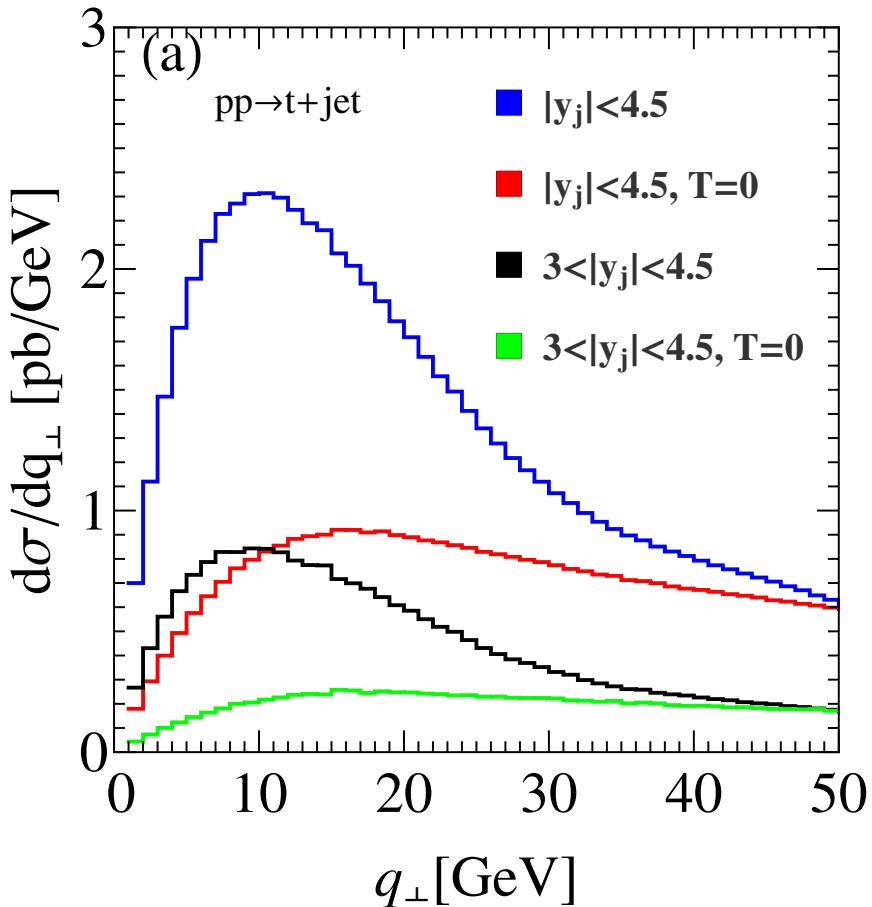
Black: resummation calculation

Green: leading order matrix element with parton showers by Pythia

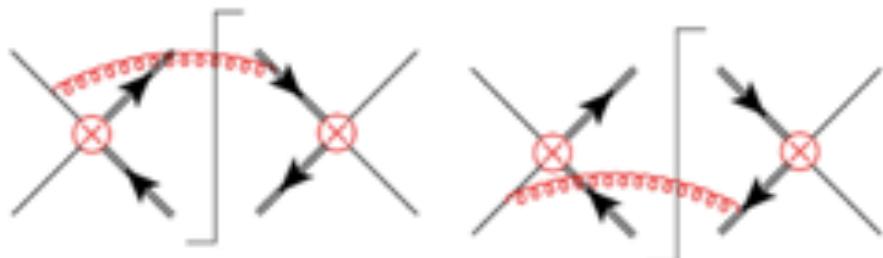


Blue: Asymptotic part ; Red: NLO calculation ; Orange: Y-piece

Color coherence effects



color coherence effects



$$T = \ln \frac{-\hat{t}}{\hat{s}} + \ln \frac{-(\hat{t} - m_t^2)}{\hat{s} - m_t^2}$$

Blue: $|y_J| < 4.5$

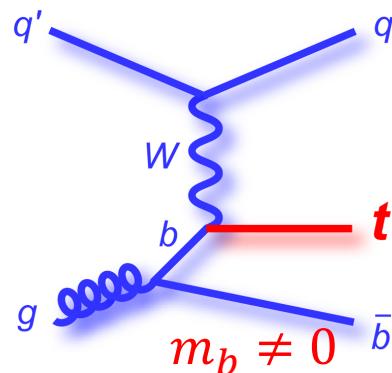
Red: $|y_J| < 4.5$, turn off the color coherence factor T

Black: $3 < |y_J| < 4.5$

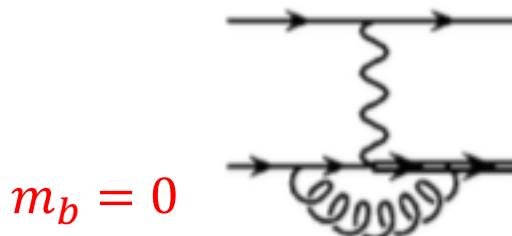
Green: $3 < |y_J| < 4.5$, turn off the color coherence factor T

Finite bottom quark mass

S-ACOT scheme:



M. A. G. Aivazis, J. C. Collins, F.I. Olness and W.-K Tung,
 PRD50,3085(1994), PRD50,3102(1994)
 J. C. Collins, PRD58,094002(1998)
 M. Kramer, F.I. Olness and D.E. Soper, PRD 62,096007(2000)



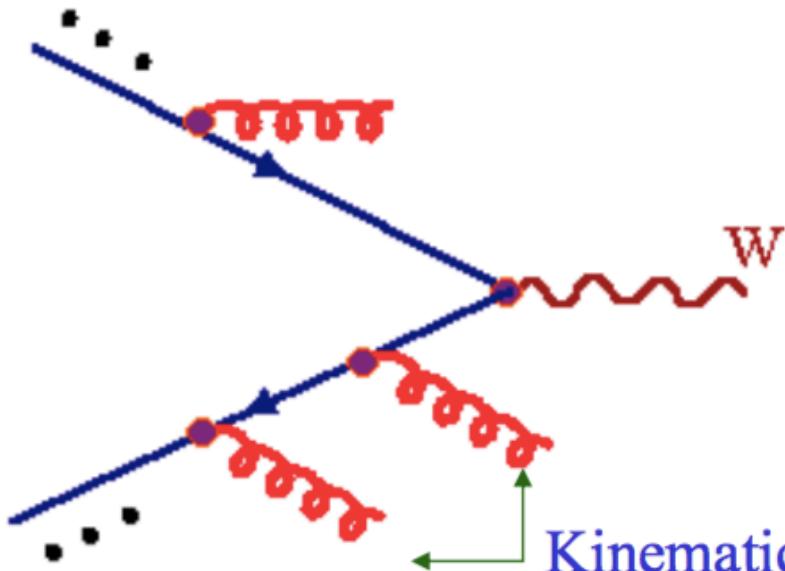
A. Belyaev, P. M. Nadolsky and C.-P. Yuan, JHEP04,004(2006)

$$\begin{aligned} \mathcal{C}_{b/g}^{(1)}(x, b, m_b, \mu_F) &= T_R x (1-x) b m_b K_1(b m_b) \\ &+ P_{q/g}^{(1)}(x) \left[K_0(b m_b) - \theta(\mu_F - m_b) \ln\left(\frac{\mu_F}{m_b}\right) \right], \end{aligned}$$

$$\lim_{b m_b \rightarrow 0} \mathcal{C}_{b/g}^{(1)}(x, b, m_b, \mu_F) = T_R x (1-x) - \ln\left(\frac{\mu_F b}{b_0}\right) P_{q/g}^{(1)}(x),$$

Monte-Carlo Approach (Pythia)

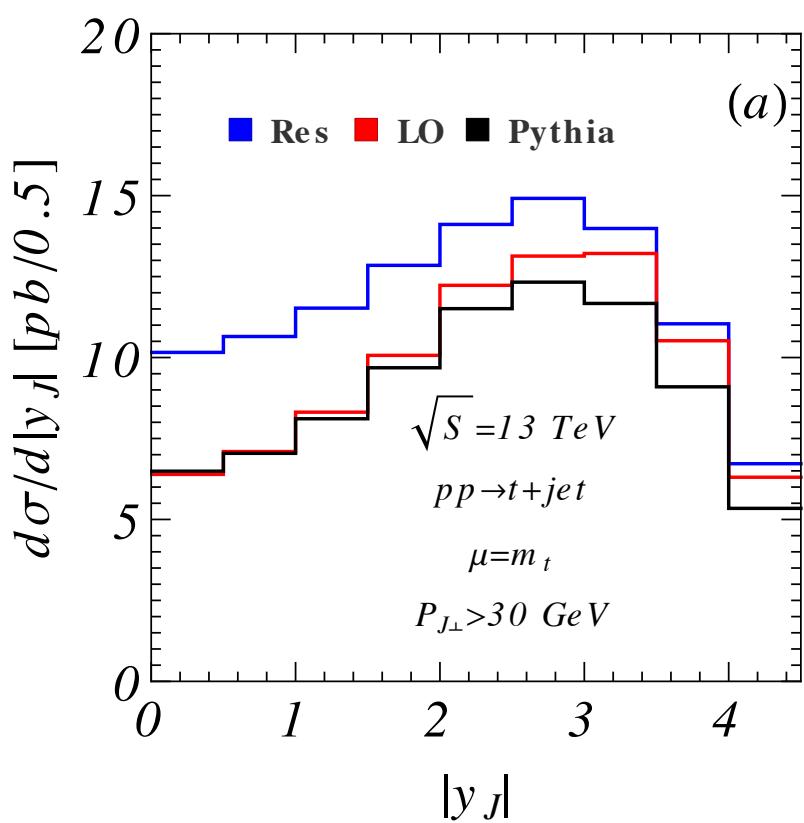
Parton showers



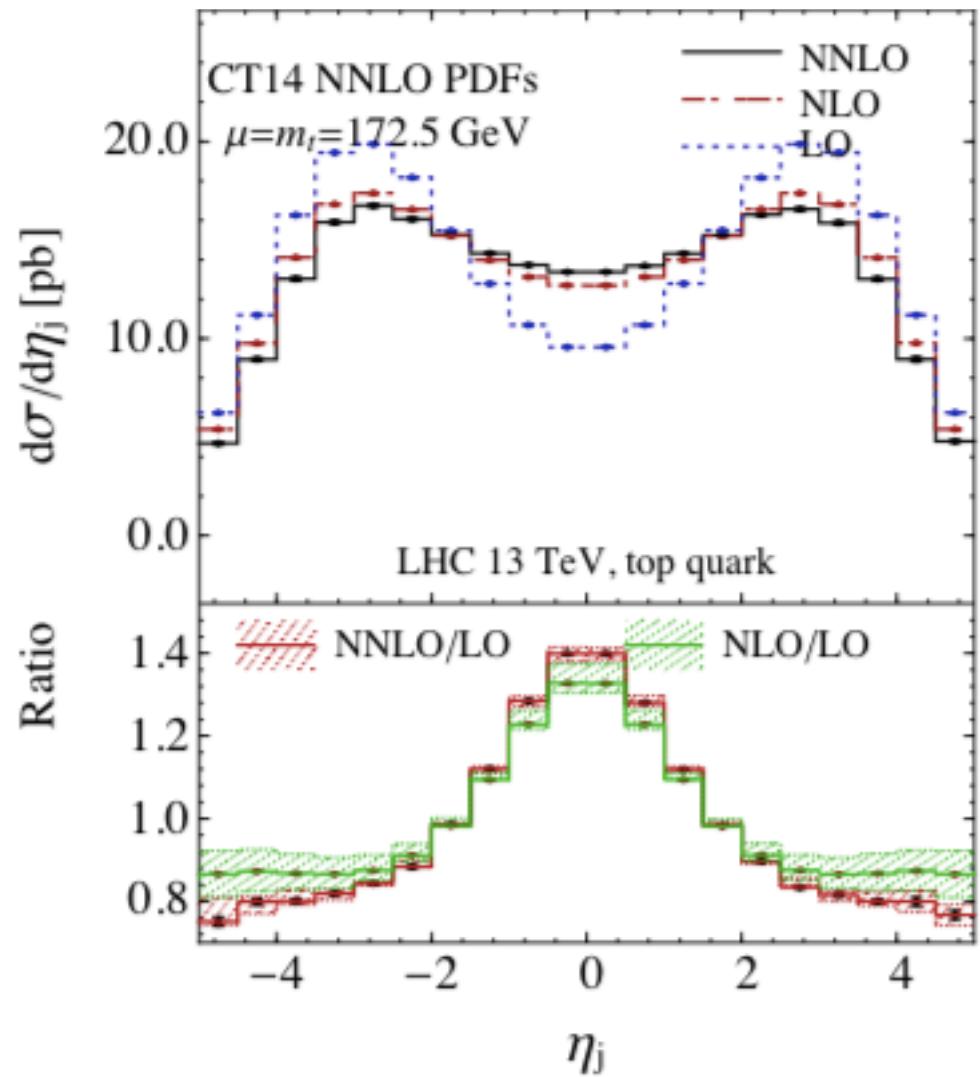
Backward Radiation
(Initial State Radiation)

Kinematics of the radiated gluon, controlled by Sudakov form factor with some arbitrary cut-off.
(In contrast to perform integration in impact parameter space, i.e., b space.)

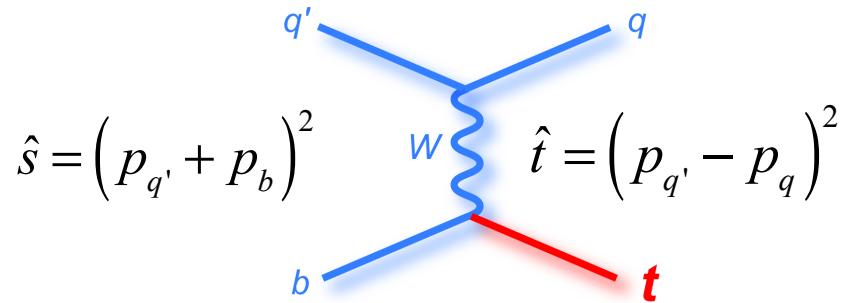
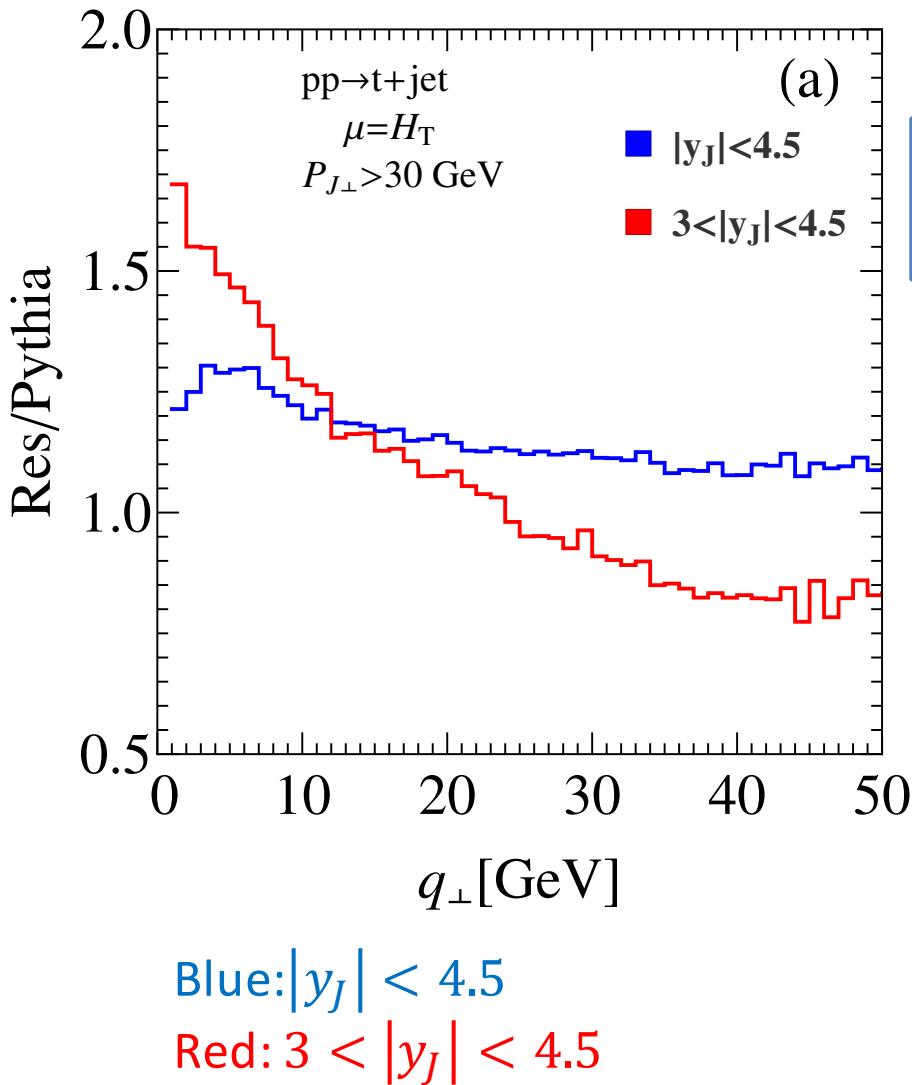
Pseudorapidity distribution of the leading-jet



CT14LO PDF is used in
the Pythia prediction

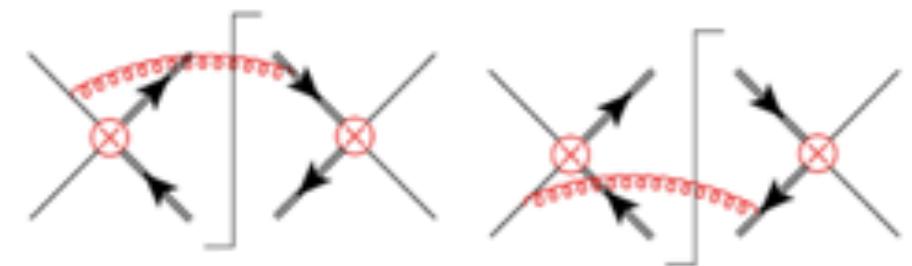


Compared to Pythia



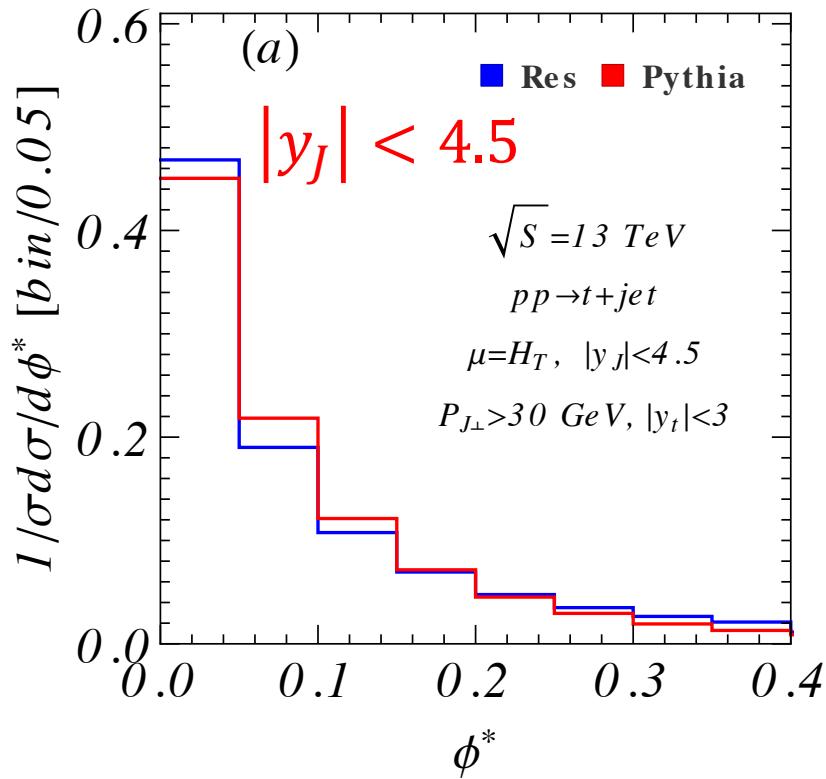
The resummation prediction is different from Pythia when $3 < |y_J| < 4.5$

color coherence factor plays an important role

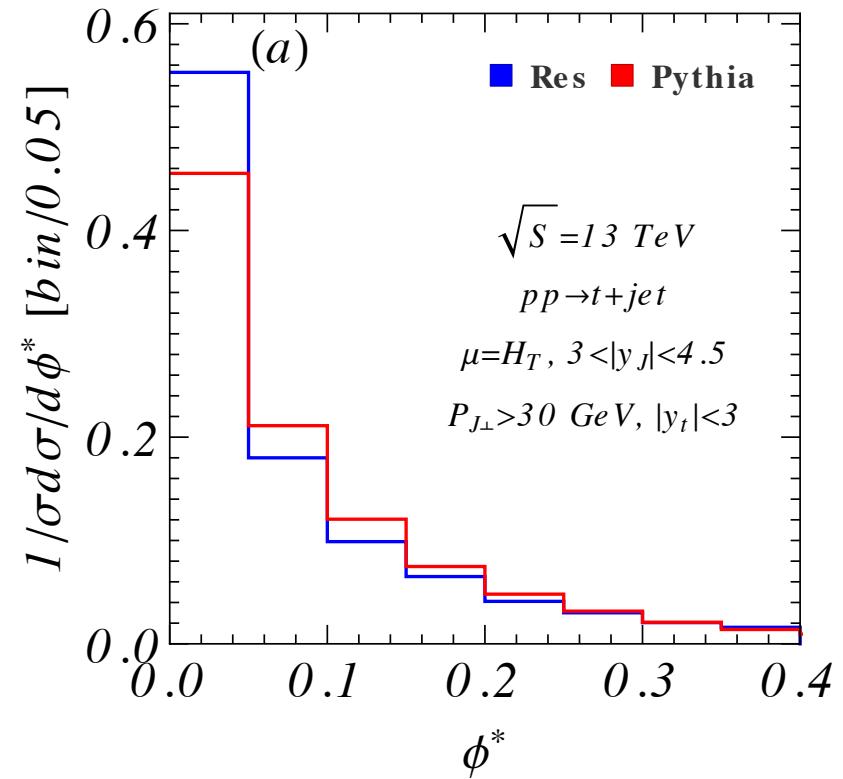


$$T = \ln \frac{-\hat{t}}{\hat{s}} + \ln \frac{-(\hat{t} - m_t^2)}{\hat{s} - m_t^2}$$

Phistar distribution



$$\phi^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \sin\theta_\eta^*,$$



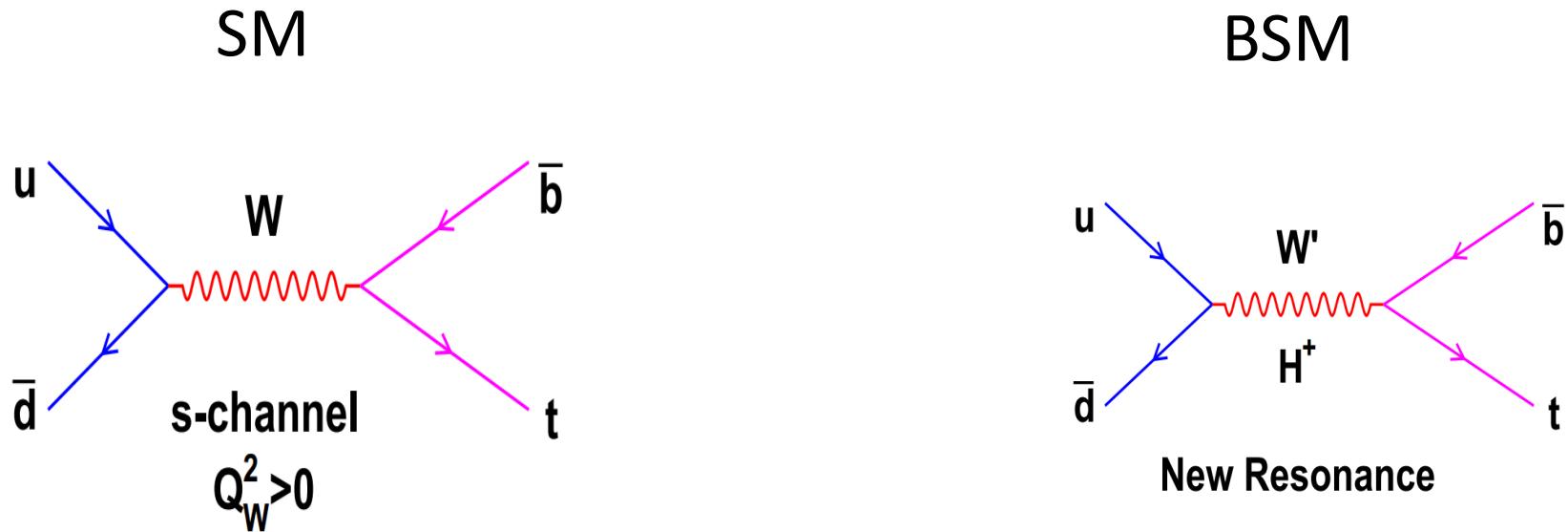
$$\cos\theta_\eta^* = \tanh\left[\frac{\eta_J - \eta_t}{2}\right],$$

Only depends on the jet and top quark moving directions, not their energies

s-channel Single top quark

PS, BY, CPY, FY, work in progress

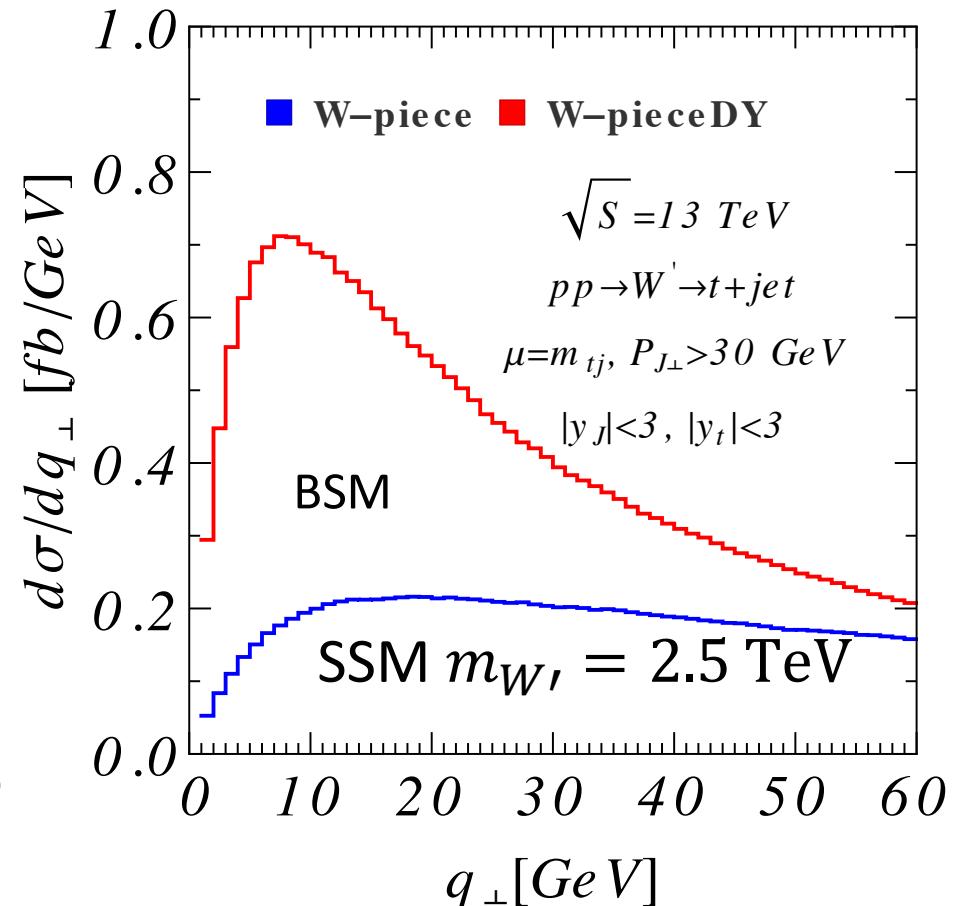
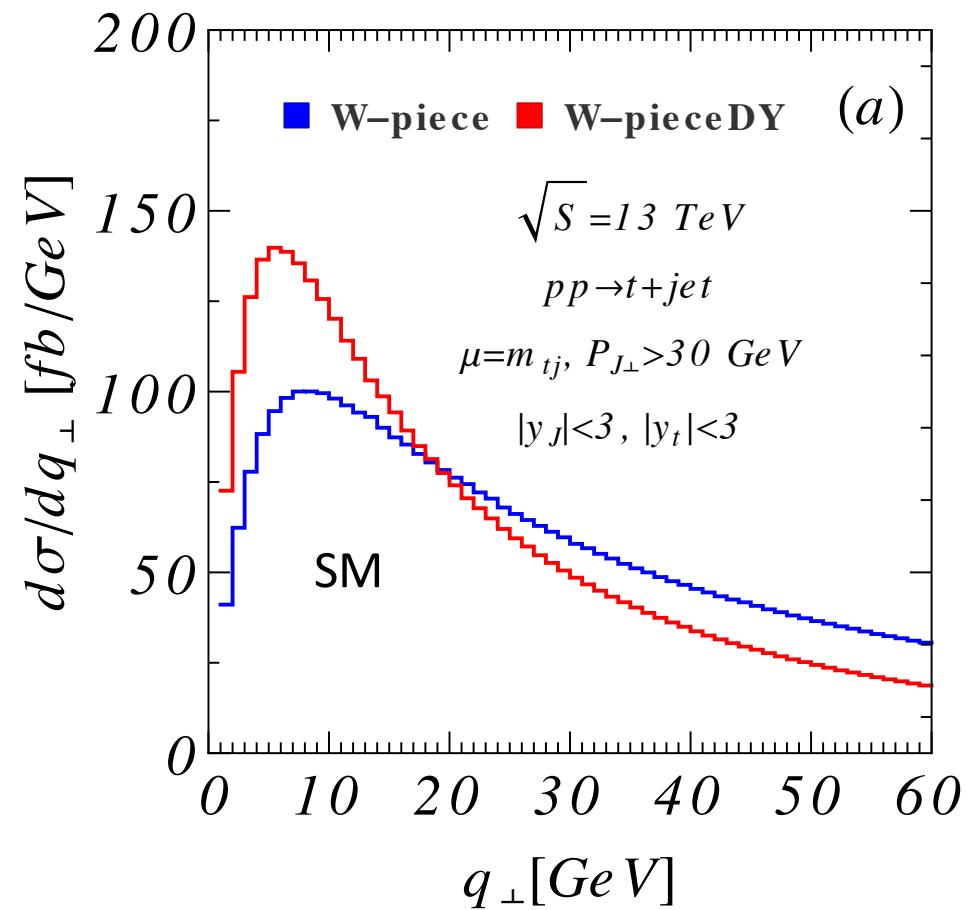
s-channel single top quark production



$$S_{\text{Sud}}(Q^2, \mu_R, b_*) = \int_{b_0^2/b_*^2}^{\mu_R^2} \frac{d\mu^2}{\mu^2} \left[\ln \left(\frac{Q^2}{\mu^2} \right) A + B + D_1 \ln \frac{Q^2 - m_t^2}{P_{J\perp}^2 R^2} + D_2 \ln \frac{Q^2 - m_t^2}{m_t^2} \right]$$

Resummation effects of final state:

Red curve: turn off final state radiation



$$S_{\text{Sud}}(Q^2, \mu_R, b_*) = \int_{b_0^2/b_*^2}^{\mu_R^2} \frac{d\mu^2}{\mu^2} \left[\ln \left(\frac{Q^2}{\mu^2} \right) A + B + D_1 \ln \frac{Q^2 - m_t^2}{P_{J\perp}^2 R^2} + D_2 \ln \frac{Q^2 - m_t^2}{m_t^2} \right]$$

Summary:

Soft gluon resummation are important for the single top quark production.

Color coherence effects:

