Transverse Momentum Resummation in Top Quark Pair Production

Li Lin Yang
Peking University

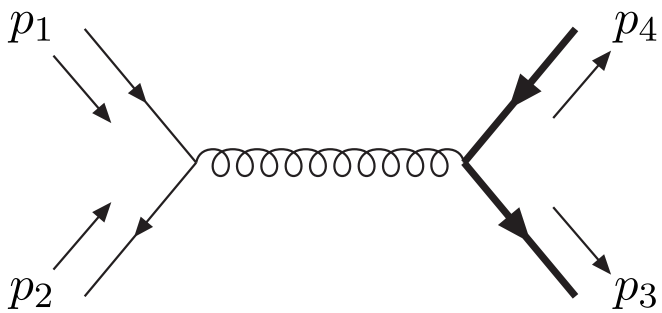
In collaboration with C. S. Li, H. T. Li, D. Y. Shao, H. X. Zhu

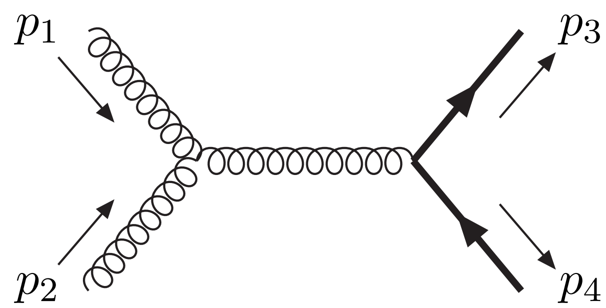
The first three years of the LHC, Mainz, March 2013

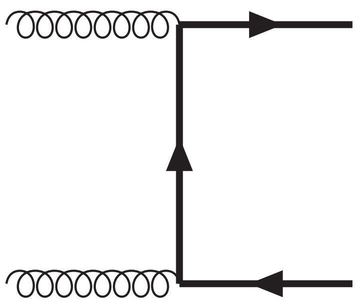
Outline

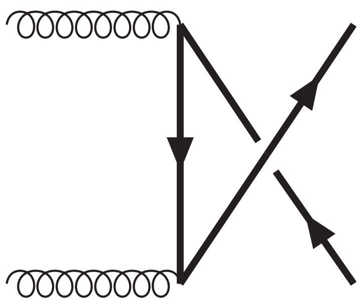
- Introduction: top quark pair production
- Introduction: Q_T resummation
- Q_T resummation in top quark pair production
- Summary

Top quark pair production









- Main production mechanism of top quarks at hadron colliders
- NNLO results for total cross section emerging

Bärnreuther, Czakon, Mitov: 1204.5201
Czakon, Mitov: 1207.0236 & 1210.6832
waiting for the *gg* channel...

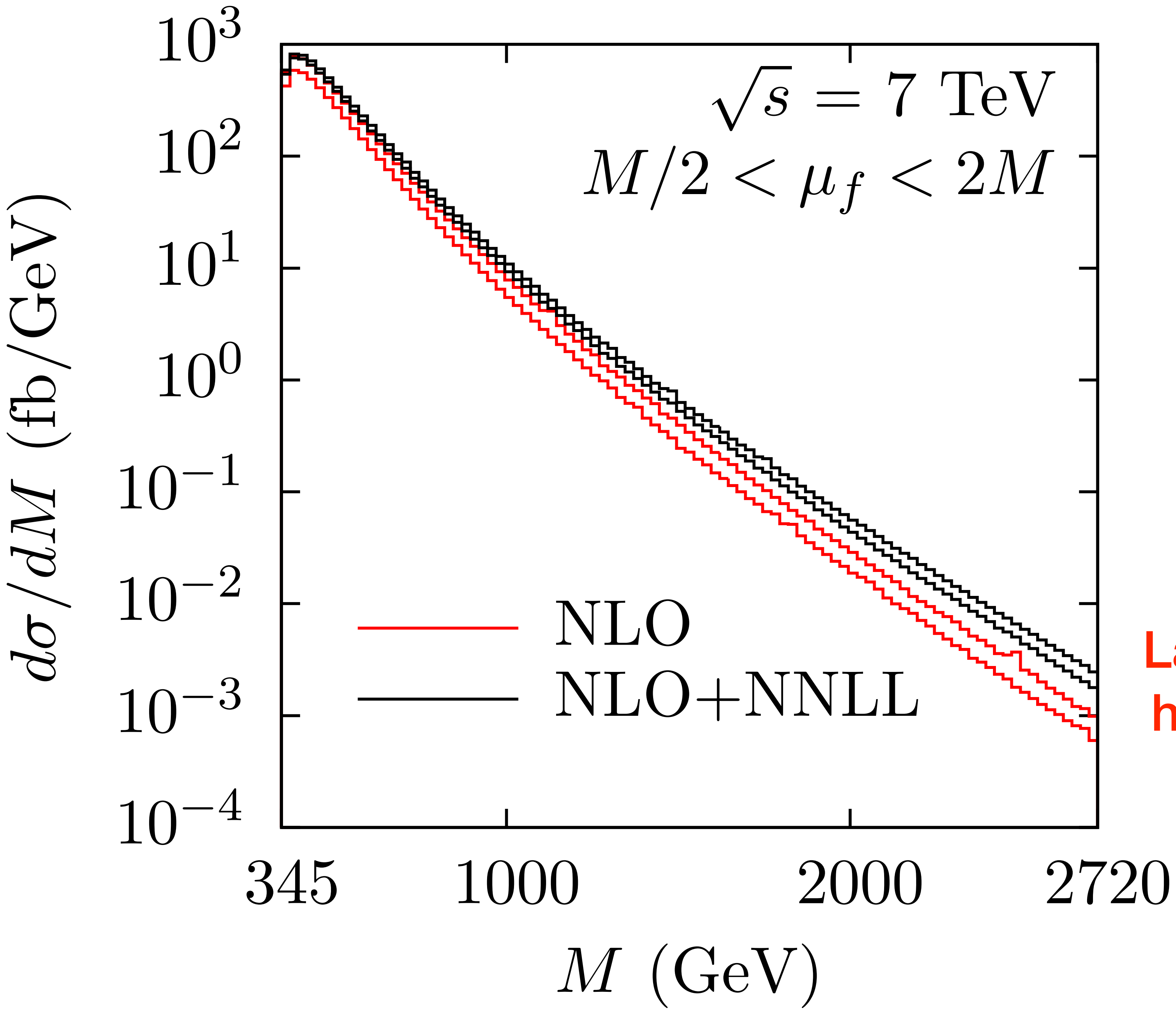
- Pair differential distributions interesting
  - Searching for new resonances in the invariant mass distribution
  - Forward-backward asymmetry shows intriguing dependence on the invariant mass and the transverse momentum of the pair

M Q_T

Invariant mass distribution

Ahrens, Ferroglia, Neubert, Pecjak, LLY: 1003.5827

- NLO+NNLL threshold resummed prediction



Large corrections at high invariant mass

Invariant mass distribution in the boosted regime

- For ***M*** much larger than $\boldsymbol{m_t}$, may simultaneously resum threshold logs and mass logs

- Framework set up **Ferroglia, Pecjak, LLY: 1205.3662**

$$C_{ij}(z, M, m_t, \cos\theta, \mu_f) = C_D^2(m_t, \mu_f)\,\mathrm{Tr}\left[\boldsymbol{H}_{ij}(M, t_1, \mu_f)\,\boldsymbol{S}_{ij}(\sqrt{\hat{s}}(1-z), t_1, \mu_f)\right]$$

$$\otimes C_{ff}^{ij}(z, m_t, \mu_f) \otimes C_{t/t}(z, m_t, \mu_f) \otimes C_{t/t}(z, m_t, \mu_f)$$

$$\otimes S_D(m_t(1-z), \mu_f) \otimes S_D(m_t(1-z), \mu_f) + \mathcal{O}(1-z) + \mathcal{O}\left(\frac{m_t}{M}\right)$$

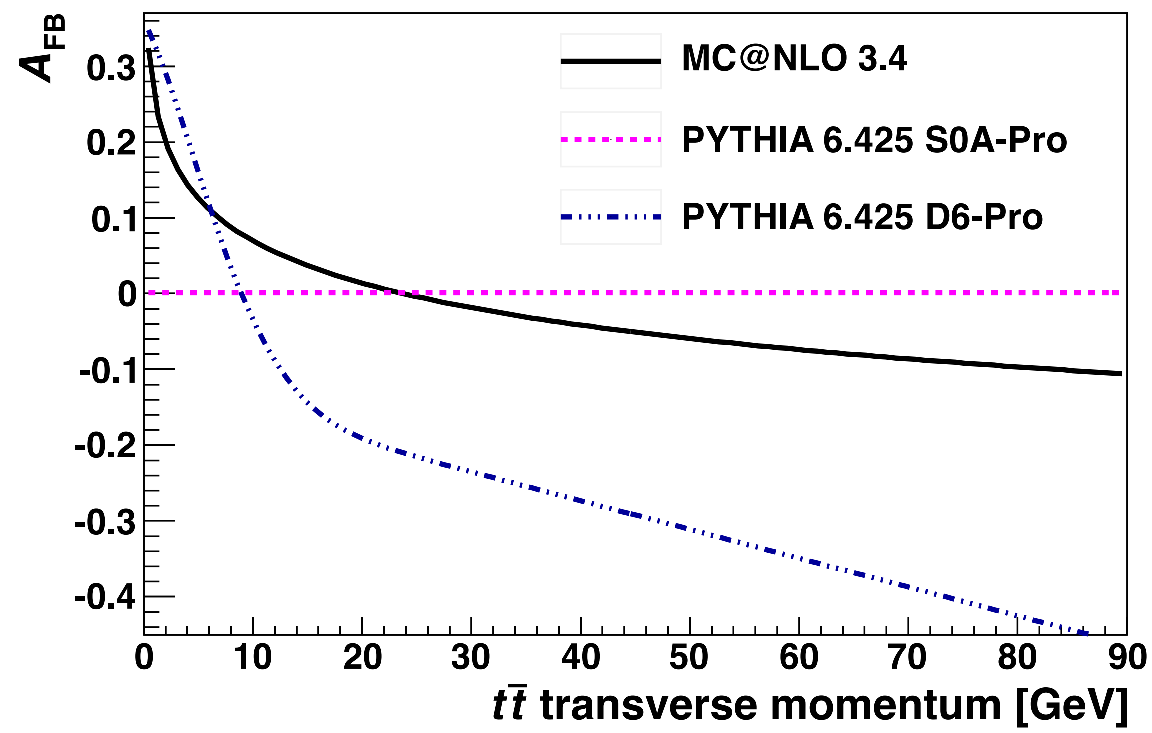
partonic cross section

- NNLO massless soft function calculated — allows soft+virtual at NNLO
  Ferroglia, Pecjak, LLY: 1207.4798

- Phenomenological studies in progress

Small Q_T region

- Suppress the gluon channel — enhance the forward-backward asymmetry
- Theoretically challenging — fixed-order divergent, resummation necessary
- Existing parton shower tools need to be validated in this region by analytic calculations



D0 Collaboration: 1107.4995

Q_T resummation

- Originally developed by Collins, Soper, Sterman (CSS)

  Collins, Soper, Sterman: Nucl. Phys. B 250, 199 (1985)

- Refinement by Catani, de Florian, Grazzini

  Catani, de Florian, Grazzini: hep-ph/0008014

- New SCET based approaches

  - Becher, Neubert: 1007.4005

  - Chiu, Jain, Neill, Rothstein: 1104.0881

  - Echevarria, Idilbi, Scimemi: 1111.4996

Applied to color-neutral final states so far!

Q_T resummation in Higgs production

Becher, Neubert, Wilhelm: 1212.2621

$$d\sigma = \sigma_0(\mu)\, C_t^2(m_t^2,\mu)\, \left|C_S(-m_H^2,\mu)\right|^2 \frac{m_H^2}{\tau s}\, dy\, \frac{d^2q_\perp}{(2\pi)^2} \int d^2x_\perp\, e^{-iq_\perp\cdot x_\perp}$$
$$\times\, 2\mathcal{B}_c^{\mu\nu}(\xi_1,x_\perp,\mu)\,\mathcal{B}_{\bar{c}\,\mu\nu}(\xi_2,x_\perp,\mu)\,\mathcal{S}(x_\perp,\mu)\,,$$

transverse PDFs

transverse soft function
trivial with analytic regulator

$$\bar{C}_{gg\leftarrow ij}(z_1,z_2,q_T^2,m_H^2,\mu) = \frac{1}{2}\int_0^\infty dx_T\, x_T\, J_0(x_T q_T)\, \exp\left[g_A(\eta,L_\perp,a_s)\right]$$
$$\times \sum_{n=1,2} \bar{I}_{g\leftarrow i}^{(n)}(z_1,L_\perp,a_s)\, \bar{I}_{g\leftarrow j}^{(n)}(z_2,L_\perp,a_s)\,,$$

See Becher's talk for details

Q_T subtraction

Catani, Grazzini: hep-ph/0703012

- Closely related to Q_T resummation
- Exploits behavior at small Q_T to subtract IR divergences
- Works in principle for any process where Q_T resummation is available
- One of the first subtraction methods applied successfully at NNLO

$$d\sigma^F_{(N)NLO} = \mathcal{H}^F_{(N)NLO} \otimes d\sigma^F_{LO} + \left[d\sigma^{F+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO} \right]$$

Q_T resummation in $t\bar{t}$ production

- Early attempts — naively supplementing the CSS formalism with final state interactions

  Berger, Meng: hep-ph/9310341
  Mrenna, Yuan: hep-ph/9606361

  - Results don't agree between the two works!
  - (Partial) NLL only. No initial-final interference.

- New SCET based systematic factorization/resummation framework

  Li, Li, Shao, LLY, Zhu: 1208.5774

  - Works in principle to all orders

    Rest of this talk!

  - NNLL numerical results

Factorization formula

- An all-order factorization formula is proposed

$$\frac{d^4\sigma}{dQ_T^2\,dy\,dM\,d\cos\theta} = \frac{\pi\beta_t}{sM}\int\frac{d^2x_\perp}{4\pi}\,e^{-iQ_\perp\cdot x_\perp}$$
$$\times\,\mathrm{Tr}\left[\boldsymbol{H}(M,\cos\theta,m_t,\mu)\,\boldsymbol{S}(L_\perp,M,\cos\theta,m_t,\mu)\right]$$
$$\times\,\mathcal{B}(\xi_1,L_\perp,\mu)\,\bar{\mathcal{B}}(\xi_2,L_\perp,\mu)$$

new transverse soft function matrix in color space

same as in threshold resummation

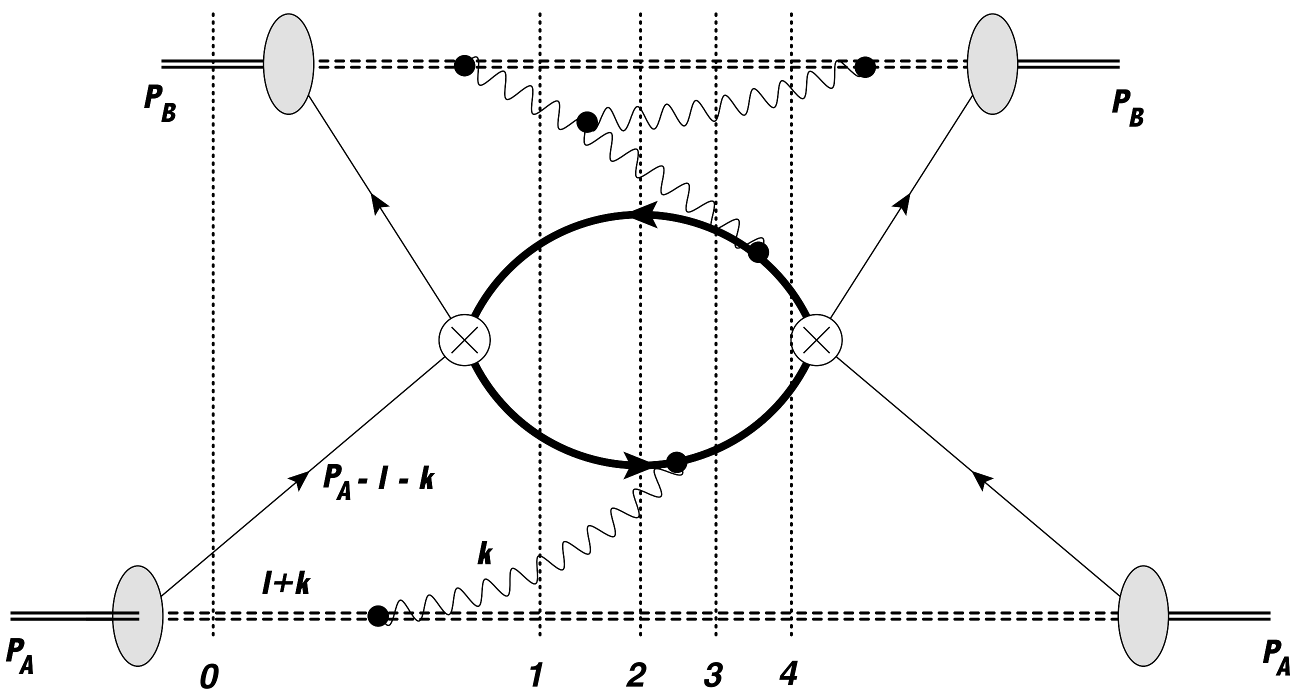
Ahrens, Ferroglia, Neubert, Pecjak, LLY: 1003.5827

same as in DY and Higgs

Becher, Neubert, Wilhelm: 1109.6027 & 1212.2621

Possible factorization breaking effects

Mitov, Sterman: 1209.5798



- Due to interactions among top quarks and spectators

See also
Collins, Qiu: 0705.2141
Rogers, Mulders: 1001.2977

- Numerical impacts unclear
- We focus on the partonic cross section (neglecting spectators)

The transverse soft function

$$\boldsymbol{S}(L_\perp, M, \cos\theta, m_t, \mu) = \frac{1}{d_R} \sum_{X_s} \int \frac{d\phi_t}{2\pi}\, d^2Q_\perp\, e^{iQ_\perp \cdot x_\perp}$$

$$\times \langle 0|Y_n^\dagger Y_{\bar{n}}^\dagger Y_t^\dagger Y_{\bar{t}}^\dagger|X_s\rangle\, \delta^{(2)}(Q_\perp + \hat{P}_\perp)\, \langle X_s|Y_n Y_{\bar{n}} Y_t Y_{\bar{t}}|0\rangle$$

- Definition similar to the threshold one, but calculation much more complicated due to the presence of the transverse vector
- We had to integrate over the azimuthal angle — calculation for the more exclusive case failed ideas?

NLO soft function

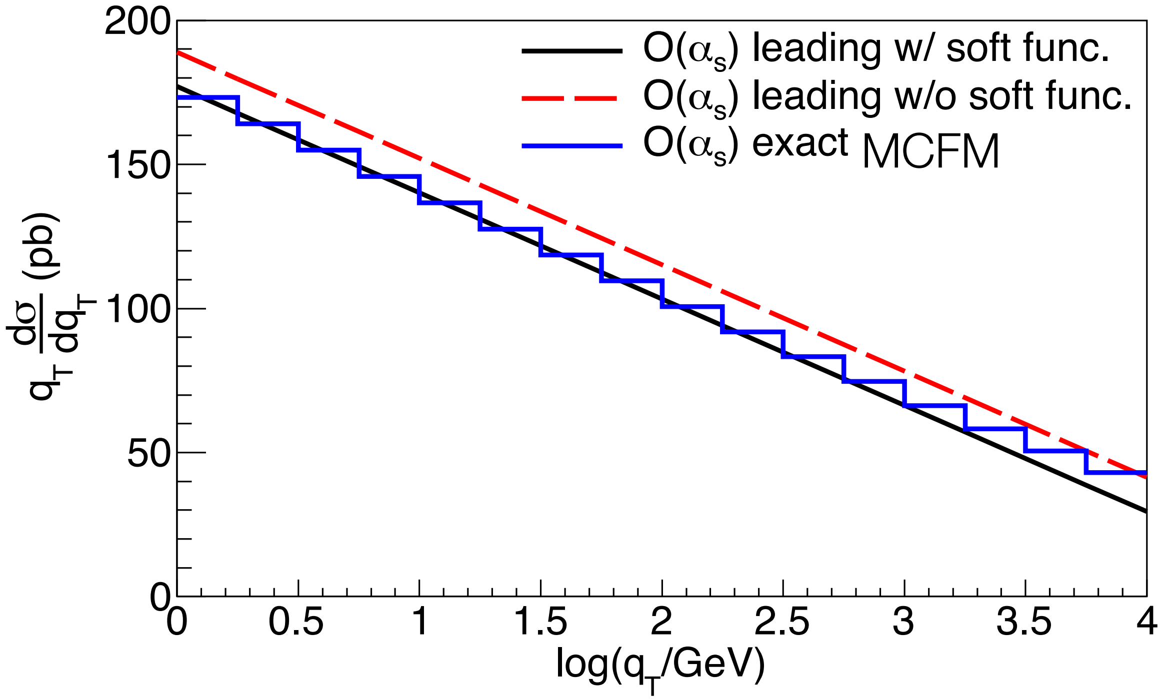
$$\boldsymbol{S}^{(1)}_{i\bar{i}} = 4L_\perp \left(2\boldsymbol{w}^{13}_{i\bar{i}} \ln \frac{-t_1}{m_t M} + 2\boldsymbol{w}^{23}_{i\bar{i}} \ln \frac{-u_1}{m_t M} + \boldsymbol{w}^{33}_{i\bar{i}} \right)$$
$$- 4 \left(\boldsymbol{w}^{13}_{i\bar{i}} + \boldsymbol{w}^{23}_{i\bar{i}} \right) \mathrm{Li}_2 \left(1 - \frac{t_1 u_1}{m_t^2 M^2} \right) + 4\boldsymbol{w}^{33}_{i\bar{i}} \ln \frac{t_1 u_1}{m_t^2 M^2}$$
$$- 2\boldsymbol{w}^{34}_{i\bar{i}} \frac{1+\beta_t^2}{\beta_t} \left[L_\perp \ln x_s + f_{34} \right],$$

$$f_{34} = -\mathrm{Li}_2 \left(-x_s \tan^2 \frac{\theta}{2} \right) + \mathrm{Li}_2 \left(-\frac{1}{x_s} \tan^2 \frac{\theta}{2} \right) + 4 \ln x_s \ln \cos \frac{\theta}{2} .$$

- Rapidity divergence in intermediate steps regularized using method in Becher, Bell: 1112.3907
- No rapidity divergence in the final soft function (as expected)
- Dependence on the scattering angle cannot be written as simple functions of the invariants t_1 and u_1 (unlike the threshold soft function)

Consistency checks

- NLO expansion compared with exact result at small Q_T
- Soft function important for the nice agreement
- Constant term checked by reproducing the NLO total cross section
- Would be great to compare the NNLO expansion with the NLO $t\bar{t}$+jet code



Resummation formula

$$C_{i\bar{i}\leftarrow ab}(z_1, z_2, q_T, M, \cos\theta, m_t, \mu) = \frac{1}{2}\int_0^\infty db\, b\, J_0(bq_T)$$
$$\times \exp\left[g_i(\eta_i, L_\perp, \alpha_s)\right]\Big[\bar{I}_{i/a}(z_1, L_\perp, \alpha_s)\,\bar{I}_{\bar{i}/b}(z_2, L_\perp, \alpha_s)$$
$$+\,\delta_{gi}\,\bar{I}'_{g/a}(z_1, L_\perp, \alpha_s)\,\bar{I}'_{g/b}(z_2, L_\perp, \alpha_s)\Big]$$
$$\times \mathrm{Tr}\Big[\boldsymbol{H}_{i\bar{i}}(M, \cos\theta, m_t, \mu_h, \mu)\,\boldsymbol{S}_{i\bar{i}}(L_\perp, M, \cos\theta, m_t, \mu)\Big]$$

- Scale choices follow Becher, Neubert, Wilhelm for DY and Higgs

$$\mu_i = q_i^* + Q_T$$

- Much weaker dependence on non-perturbative physics due to larger mass — protected all the way down to $Q_T = 0$

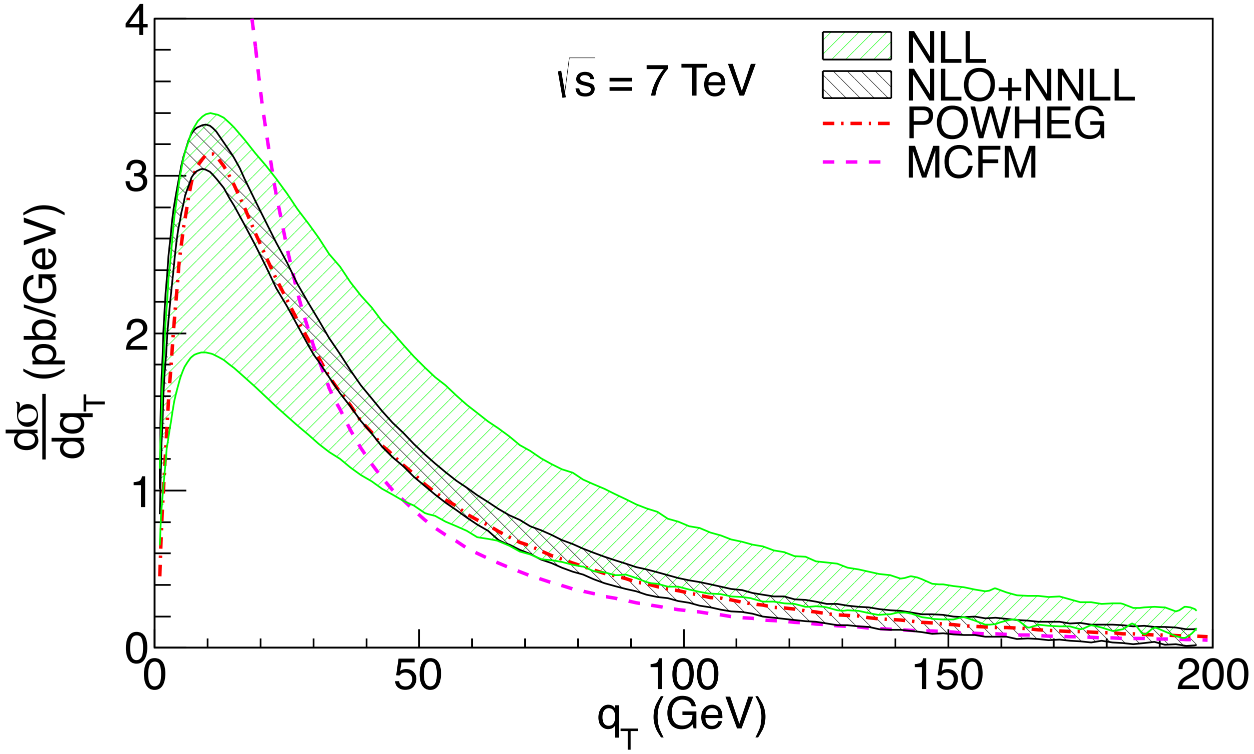
$$q_q^* \gtrsim 3.0\mathrm{GeV} \qquad q_g^* \gtrsim 14.0\mathrm{GeV}$$

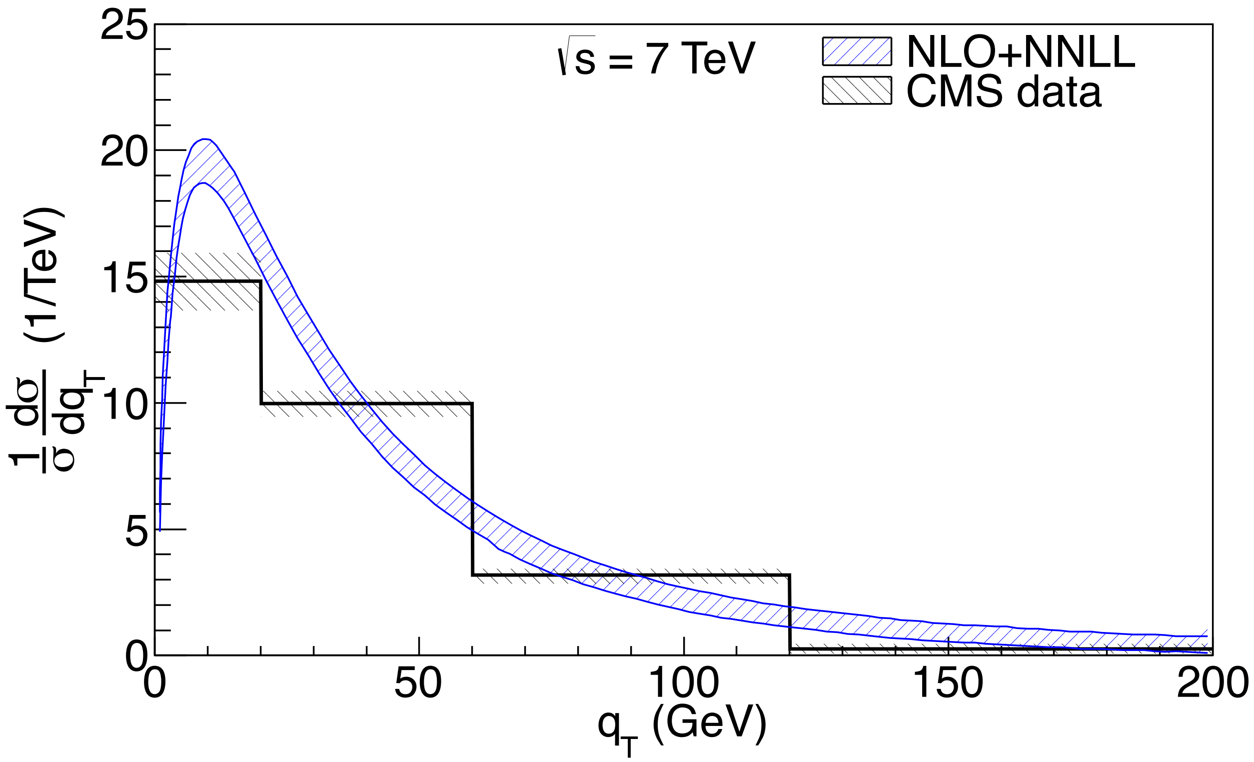
- Evolution of the hard function given in

Ferroglia, Neubert, Pecjak, LLY: 0907.4791 & 0908.3676
Ahrens, Ferroglia, Neubert, Pecjak, LLY: 1003.5827

Resummed prediction

- Good perturbative convergence, significantly reduced scale dependence from NLL to NNLL
- Consistent with NLO parton shower results
- Agree well with existing data. More data required to check the shape in the low Q_T region!





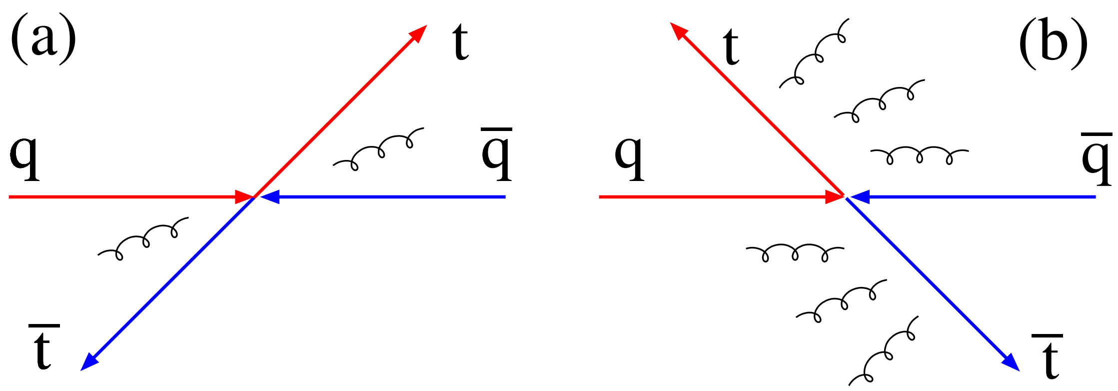
Forward-backward asymmetry

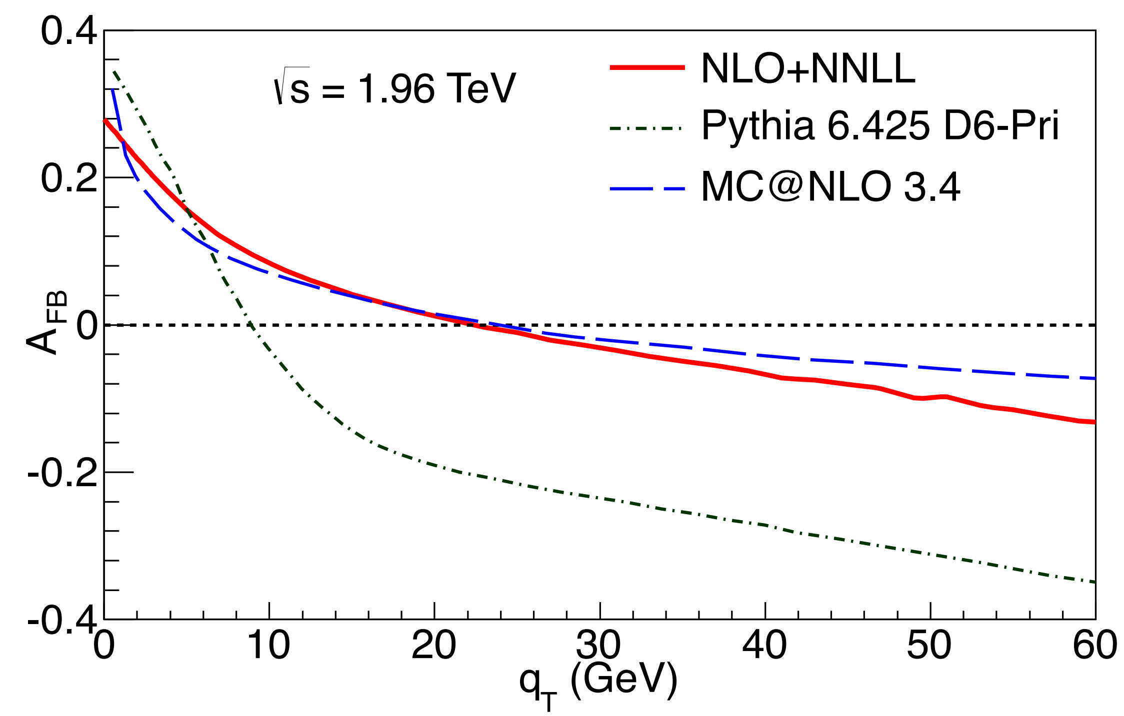
- LO parton shower can generate non-zero asymmetry due to color coherence

  Skands, Webber, Winter: 1205.1466

- In our framework, color coherence is built into the soft function

- Our prediction agrees well with NLO parton shower





NNLO Q_T subtraction in $t\bar{t}$ production?

$$\frac{d^4\sigma}{dQ_T^2\,dy\,dM\,d\cos\theta} = \frac{\pi\beta_t}{sM}\int\frac{d^2x_\perp}{4\pi}\,e^{-iQ_\perp\cdot x_\perp}$$
$$\times\,\mathrm{Tr}\Big[\boldsymbol{H}(M,\cos\theta,m_t,\mu)\,\boldsymbol{S}(L_\perp,M,\cos\theta,m_t,\mu)\Big]$$
$$\times\,\mathcal{B}(\xi_1,L_\perp,\mu)\,\bar{\mathcal{B}}(\xi_2,L_\perp,\mu)$$

???

Gehrmann, Lübbert, LLY
1209.0682 and work in progress

Summary

- An all-order Q_T resummation framework for top quark pair production is proposed for the first time
- Numerical results are given at NLO+NNLL accuracy
- Consistent with NLO parton shower tools and with experimental data
- May provide an alternative NNLO subtraction method for $t\bar{t}$ production
- Towards matching at NNLO

Thank you!