Inclusive forward jet and dijet production at the LHC

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Outline

- Introduction
- High Energy Factorization
- Transverse momentum dependent parton densities
- Forward jet production
- Forward dijet production
- Conclusions

Introduction

- Forward particle production - opportunity to study the dynamics of QCD at small x, in particular saturation
- New results:
  - diagrams with off-shell quarks
  - double parton scattering
  - final state radiation

High Energy Factorization (k_T-factorization)

Catani, Ciafaloni, Hautmann | Collins, Ellis

$$\sigma_{AB\to q\bar{q}} = \int d^2k_{T\,A}\frac{dx_A}{x_A}\mathcal{F}\left(x_A, k_{T\,A}\right)\, d^2k_{T\,B}\frac{dx_B}{x_B}\,\mathcal{F}\left(x_B, k_{T\,B}\right)\,\hat{\sigma}_{g^*g^*}\left(\frac{m^2}{x_A x_B s}, \frac{k_{T\,A}}{m}, \frac{k_{T\,B}}{m}\right)$$

- reduces to collinear factorization for $s \gg m^2 \gg k_T^2$, but holds also for $s \gg m^2 \sim k_T^2$
- allows for higher-order kinematical effects at leading order

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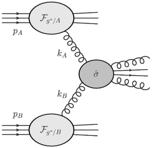
- allows for higher-order kinematical effects at leading order
- requires matrix elements with *off-shell* initial-state partons with $k_i^2 = k_{iT}^2 < 0$



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$$k_B^\mu = x_B p_B^\mu + k_{T\,B}^\mu$$

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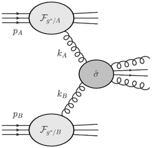

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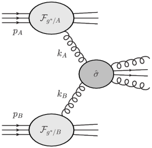

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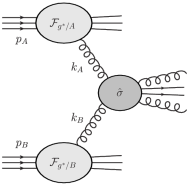
- k_T-dependent $\mathcal{F}$ may satisfy BFKL, CCFM, BK, KGBJS evolution equations
- typically associated with small-x and forward physics, saturation, heavy-ions

Hybrid High Energy Factorization

Forward particle production

- one of the protons is probed at large x - collinear factorization applies for that proton
- the other proton is probed at small x and high energy factorization applies



$$k_A^\mu = x_A p_A^\mu$$

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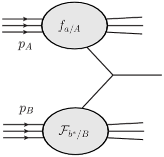
$$d\sigma_{AB\to X} = \int \frac{d^2 k_{T\,B}}{\pi} \int \frac{dx_B}{x_B} \int dx_A \mathcal{F}(x_B, k_{T\,B}, \mu) f_{a/A}(x_A, \mu) d\sigma_{ab^*\to X}(x_A, x_B, k_{T\,B}, \mu)$$

- collinear PDF $f_{a/A}(x_A, \mu)$
- unintegrated PDF $\mathcal{F}(x_B, k_{T\,B}, \mu)$
- off-shell matrix elements reside in $d\sigma_{ab^*\to X}(x_A, x_B, k_{T\,B}, \mu)$

Transverse momentum dependent parton densities

Distributions used for the off-shell partons:

- The *KS nonlinear* Kutak, Sapeta - gluon density from an extension of the BK equation (include complete splitting functions, contributions from sea quarks, energy conservation formulated by Kutak, Kwiecinski)
- The *KS linear* - linearized version of the above
- The *KS hardscale nonlinear* Kutak - gluon density from the *KS nonlinear* + Sudakov resummation
- The *KS hardscale linear* - linearized version of the above
- *DLC2016* Kutak, Maciula, Serino, Szczurek, van Hameren - gluon and quarks distributions from collinear PDFs using the KMR prescription Kimber, Martin, Ryskin (angular ordering, Sudakov form factor).



- The hybrid, HEF cross section, $x_A \gg x_B$

$$\frac{d\sigma}{dy_{jet}dp_{t,\,jet}} = \frac{1}{2}\frac{\pi\, p_{t,\,jet}}{(x_A x_B s)^2}\sum_{a,b,c}\overline{|\mathcal{M}_{ab^*\to c}|}^2 x_A f_{a/A}(x_A,\mu^2)\,\mathcal{F}_{b/B}(x_B,p_{t,\,jet}^2,\mu^2)$$

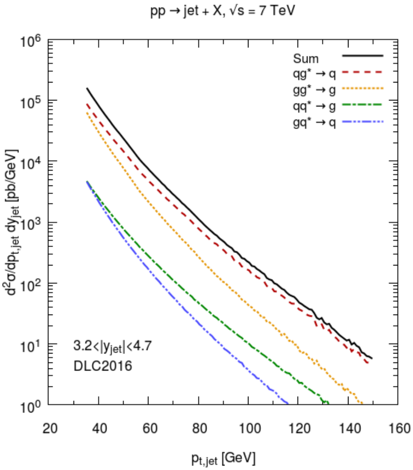
- The longitudinal kinematic variables

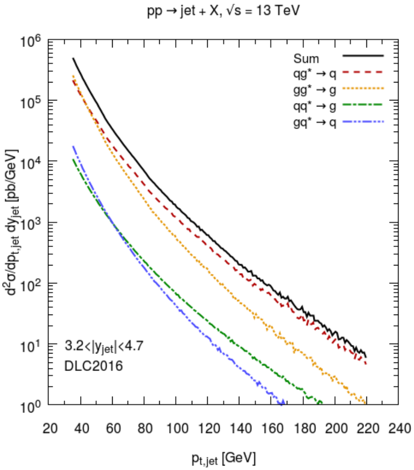
$$x_A = {}^1\!/\!\sqrt{s}\, p_{t,jet}\, e^{y_{jet}} \qquad x_B = {}^1\!/\!\sqrt{s}\, p_{t,jet}\, e^{-y_{jet}}$$

- Contributing channels

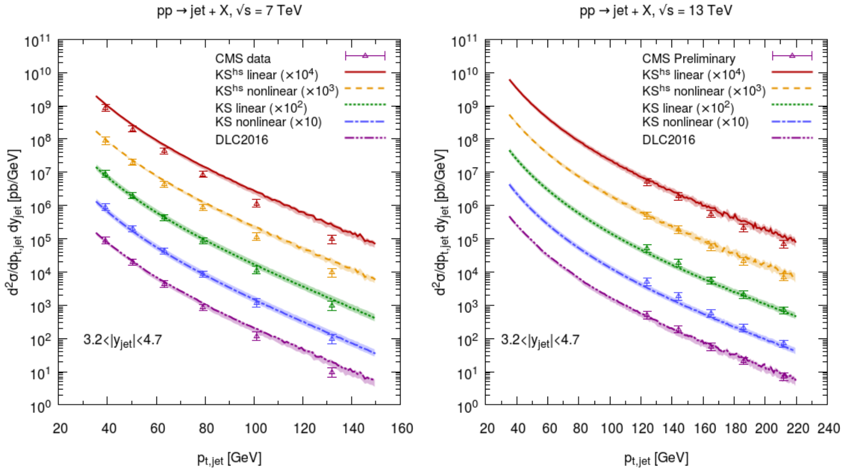
$$gg^* \to g \qquad qg^* \to q \qquad gq^* \to q \qquad \bar{q}q^* \to g$$

Single inclusive forward jet production - channels





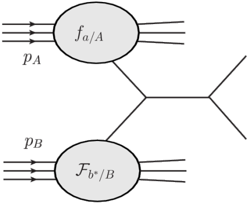
Single inclusive forward jet production - distributions

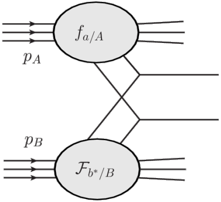


Forward dijet production

- Dijets can be produced in two ways

– *Single parton scattering* (SPS) – *Double parton scattering* (DPS)





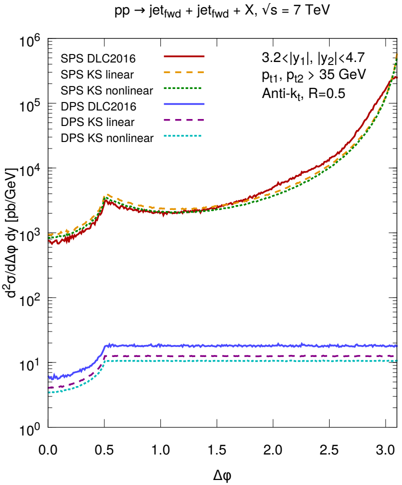
- Cross section formula for SPS

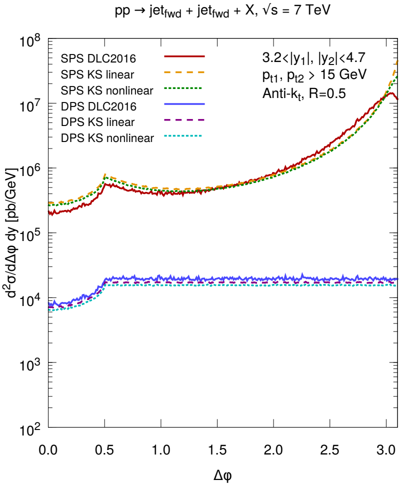
$$d\sigma_{\text{SPS}}^{pA\to\text{dijets}+X} = \frac{p_{1t}p_{2t}}{8\pi^2(x_Ax_Bs)^2}\sum_{a,c,d} x_A f_{a/p}(x_A,\mu^2)\,|\overline{\mathcal{M}_{ag^*\to cd}}|^2\mathcal{F}_{g/A}(x_B,k_t^2)\frac{1}{1+\delta_{cd}}$$

- Cross section formula for DPS (factorized assumption)

$$\frac{d\sigma_{\text{DPS}}^{pA\to\text{dijets}+X}}{dy_1d^2p_{1t}dy_2d^2p_{2t}} = \frac{1}{\sigma_{\text{eff}}}\frac{d\sigma}{dy_1d^2p_{1t}}\frac{d\sigma}{dy_2d^2p_{2t}}$$

Forward dijet production - SPS vs. DPS





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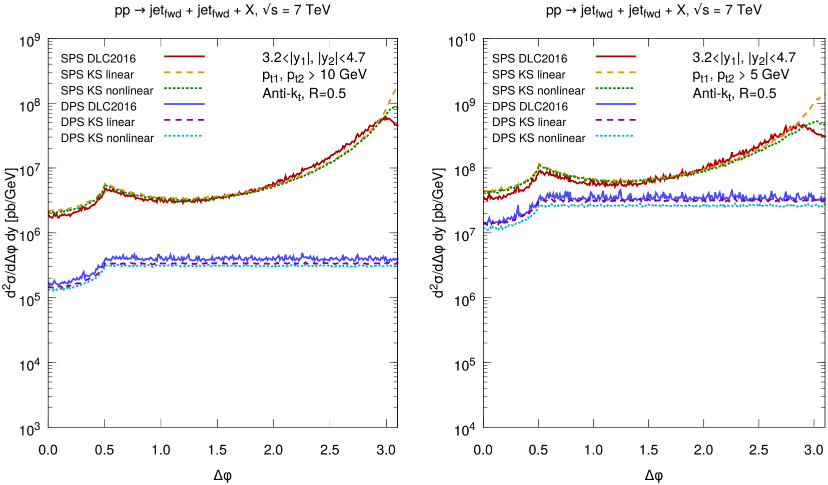
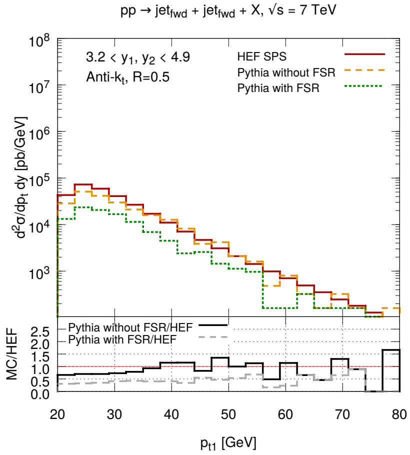
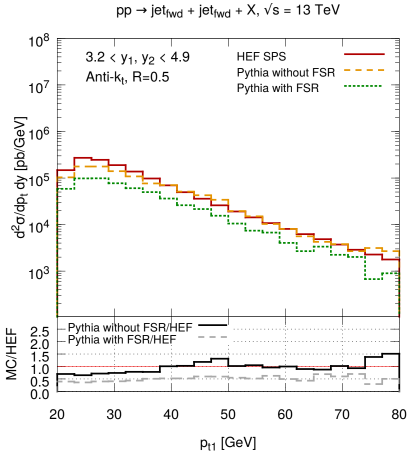


Forward dijet production - HEF vs. Pythia





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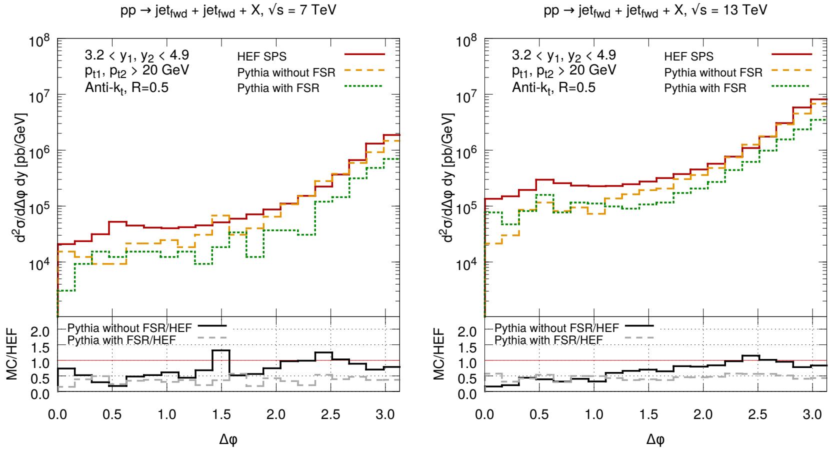

Conclusions

- The HEF framework provides a good description of the single inclusive forward jet production at the LHC, the main uncertainty comes from the unintegrated parton distributions.
- Contribution from off-shell quarks is negligible for forward jet production.
- The double parton scatering contributions to inclusive dijet production precesses are significantly smaller than single parton scattering at experimentally relevant phase space region.
- The effect of final state radiation is not negligible and leads to change of normalization of differential distributions in forward dijet production.

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Backup

Amplitudes with off-shell partons

- $gg^* \to g$

$$\overline{|\mathcal{M}_{gg^*\to g}|}^2 = 4g_s^2 \frac{C_A}{N_c^2-1}\frac{(k\cdot q)^2}{k_t^2}$$

- $qg^* \to q$

$$\overline{|\mathcal{M}_{qg^*\to g}|}^2 = 4g_s^2 \frac{C_F}{N_c^2-1}\frac{(k\cdot q)^2}{k_t^2}$$

- $gq^* \to q$

$$\overline{|\mathcal{M}_{gq^*\to g}|}^2 = g_s^2 \frac{C_F}{N_c^2-1}(k\cdot q)$$

- $\bar{q}q^* \to g$

$$\overline{|\mathcal{M}_{\bar{q}q^*\to g}|}^2 = g_s^2 \frac{C_F}{N_c}(k\cdot q)$$

k - off-shell momentum　　k_t -transverse component of the off-shell momentum
q - on-shell momentum　　g_s - strong coupling
C_i - colour factor of the emitter: C_F for a quark, C_A for a gluon
$C_A = 3$, $C_F = \frac{4}{3}$