Dijet azimuthal correlations in multi-jets production at high energy in k_T-factorization

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Outline.

Introduction

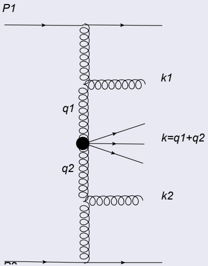
I will continue discussion of PRA and it's application for jet production at large transverse momenta at high energy

Some additional remarks on PRA

- PRA is tool for hard processes in multi-Regge-Kinematics (MRK)
- When energy ($\sqrt{S}$) grows at fixed hard scale μ, MRK works better and better.
- MRK factorization formula formally coincide with k_T-factorization master formula
- Kimber-Martin-Ryskin (KMR) model for unintegrated PDF (or TMD PDF) corresponds MRK approximation
- Conception of Reggeized partons as fields of gauge invariant Lipatov's effective theory also based on MRK approximation

Parton Reggeization Approach

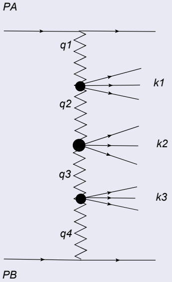
Schematic representation of the amplitude in CPM



$$k_{T1,2} \sim q_{T1,2} \sim 0$$

$$x_{1,2} \leq 1$$

Schematic representation of the amplitude in MRK



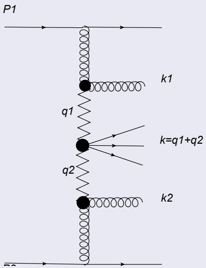
$$0 \ll q_{T1} \sim q_{T2} \sim q_{T3} \sim q_{T4} \ll \sqrt{S}$$

$$0 \ll |q_1^2| \sim |q_2^2| \sim |q_3^2| \sim |q_4^2| \ll S$$

$$y_A \gg y_1 \gg y_2 \gg y_3 \gg y_B$$

Parton Reggeization Approach

Schematic representation of the amplitude in PRA



$$0 \ll k_{T1,2} \sim q_{T1,2} \ll \sqrt{S}$$

$$0 \ll |q_1^2| \sim |q_2^2| \sim |q_3^2| \sim |q_4^2| \ll S$$

$$x_{1,2} \ll 1$$

$$q^{\mu}_{1,2} = x1,2P^{\mu}_{1,2} + q^{\mu}_{T1,2}$$

Parton Reggeization Approach smoothly interpolates between CPM and QMRK limit of QCD

Old results for single-jet production in PRA

PHYSICAL REVIEW D **84,** 074017 (2011)

Single jet and prompt-photon inclusive production with multi-Regge kinematics: From Tevatron to LHC

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(Received 7 July 2011; published 13 October 2011)

Old results for single-jet production in PRA

The Fadin-Kuraev-Lipatov effective $\mathcal{R}\mathcal{R}g$ vertex reads [2,19]:

$$C^{g,\mu}_{\mathcal{R}\mathcal{R}}(q_1,q_2) = -\sqrt{4\pi\alpha_s} f^{abc} \frac{q_1^+ q_2^-}{2\sqrt{t_1 t_2}} \left[(q_1-q_2)^\mu + \frac{(n^+)^\mu}{q_1^+}(q_2^2 + q_1^+ q_2^-) - \frac{(n^-)^\mu}{q_2^-}(q_1^2 + q_1^+ q_2^-) \right], \quad (1)$$

where α_s is the strong-coupling constant, a and b are the color indices of the Reggeized gluons with incoming four-momenta q_1 and q_2, and f^{abc} are the structure constants of the color gauge group SU(3). The squared amplitude of the partonic subprocess $\mathcal{R}+\mathcal{R}\to g$ is straightforwardly found from Eq. (1) to be

$$\overline{|\mathcal{M}(\mathcal{R}+\mathcal{R}\to g)|^2} = \frac{3}{2}\pi\alpha_s \mathbf{p}_T^2. \quad (2)$$

Old results for single-jet production in PRA

$$\frac{d\sigma}{dp_T dy}(p\bar{p}\to j+X)=\frac{1}{p_T^3}\int d\phi_1\int dt_1\Phi_g^p(x_1,t_1,\mu^2)$$
$$\times\Phi_g^{\bar{p}}(x_2,t_2,\mu^2)\overline{|\mathcal{M}(\mathcal{R}\mathcal{R}\to g)|^2},\tag{6}$$

where ϕ_1 is the azimuthal angle enclosed between $\mathbf{q}_{1T}$ and $\mathbf{p}_T$,

$$x_{1,2}=\frac{p_T\exp(\pm y)}{\sqrt{S}},\quad t_2=t_1+p_T^2-2p_T\sqrt{t_1}\cos\phi_1.\tag{7}$$

Old results for single-jet production in PRA

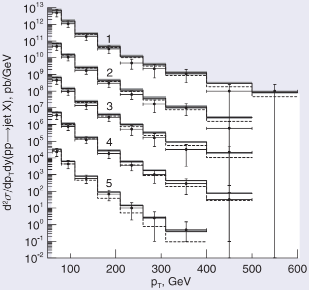
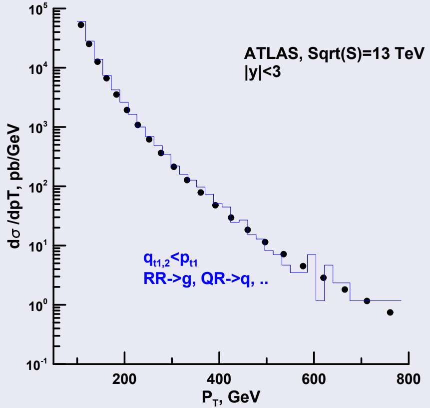


FIG. 5. The transverse-momentum distributions of single jet inclusive hadroproduction measured in the rapidity intervals (1) $|y| < 0.3$ ($\times 10^8$), (2) $0.3 < |y| < 0.8$ ($\times 10^6$), (3) $0.8 < |y| < 1.2$ ($\times 10^4$), (4) $1.2 < |y| < 2.1$ ($\times 10^2$), and (5) $2.1 < |y| < 2.6$ by the ATLAS Collaboration at the LHC [17] are compared with our LO MRK predictions evaluated in the KMR (solid histograms) and B (dashed histograms) approaches using the MRST PDFs. The shaded bands indicate the scale uncertainties in the KMR evaluations.

Recent results for single-jet production in PRA



Old results for dijet production in PRA

PHYSICAL REVIEW D **87,** 094030 (2013)

Dijet azimuthal decorrelations at the LHC in the parton Reggeization approach

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(Received 12 April 2013; published 28 May 2013)

Old results for dijet production in PRA

$$R + R \longrightarrow g + g, \tag{1}$$

$$R + R \longrightarrow q + \bar{q}, \tag{2}$$

$$Q + R \longrightarrow q + g, \tag{3}$$

$$Q + Q \longrightarrow q + q, \tag{4}$$

$$Q + Q' \longrightarrow q + q', \tag{5}$$

$$Q + \bar{Q} \longrightarrow q + \bar{q}, \tag{6}$$

$$Q + \bar{Q} \longrightarrow q' + \bar{q}', \tag{7}$$

$$Q + \bar{Q} \longrightarrow g + g, \tag{8}$$

Old results for dijet production in PRA

Effective vertex $RR \to gg$

$$C^{gg,cd,\mu\nu}_{RR,ab}(q_1,q_2,k_1,k_2) = g_s^2 \frac{q_1^+ q_2^-}{4\sqrt{t_1 t_2}}\Big(T_1 s^{-1}\Gamma^{(+-)_\sigma}(q_1,q_2)\gamma_{\mu\nu\sigma}(-k_1,-k_2) + T_3 t^{-1}\Gamma^{\sigma\mu-}(q_1,k_1-q_1)\Gamma^{\sigma\nu+}(k_2-q_2,q_2)$$
$$- T_2 u^{-1}\Gamma^{\sigma\nu-}(q_1,k_2-q_1)\Gamma^{\sigma\mu+}(k_1-q_2,q_2) - T_1(n^-_\mu n^+_\nu - n^-_\nu n^+_\mu) - T_2(2g_{\mu\nu} - n^-_\mu n^+_\nu)$$
$$- T_3(-2g_{\mu\nu} + n^-_\nu n^+_\mu) + \Delta^{\mu\nu+}(q_1,q_2,k_1,k_2) + \Delta^{\mu\nu-}(q_1,q_2,k_1,k_2)\Big), \qquad (14)$$

where

$$T_1 = f_{cdr}f_{abr}, \qquad T_2 = f_{dar}f_{cbr}, \qquad T_3 = f_{acr}f_{dbr}, \qquad T_1+T_2+T_3=0,$$
$$\Delta^{\mu\nu+}(q_1,q_2,k_1,k_2) = 2t_2 n^+_\mu n^+_\nu\left(\frac{T_3}{k_2^+ q_1^+} - \frac{T_2}{k_1^+ q_1^+}\right), \qquad \Delta^{\mu\nu-}(q_1,q_2,k_1,k_2) = 2t_1 n^-_\mu n^-_\nu\left(\frac{T_3}{k_1^- q_2^-} - \frac{T_2}{k_2^- q_2^-}\right),$$

Old results for dijet production in PRA

Squared amplitude $RR \to gg$

$$\overline{|\mathcal{M}|^2} = \pi^2 \alpha_S^2 A \sum_{n=0}^{4} W_n S^n,$$

1. $RR \to gg$

$$\begin{aligned}
A &= \frac{18}{a_1 a_2 b_1 b_2 s^2 t^2 u^2 t_1 t_2},\\
W_0 &= x_1 x_2 s^2 t u t_1 t_2 (x_1 x_2 (tu + t_1 t_2) + (a_1 b_2 + a_2 b_1) tu),\\
W_1 &= x_1 x_2 s t_1 t_2 [t^2 u (a_1 b_2 (a_2 b_2 + a_1 x_2)(t_1 + t_2) - a_2 b_1 (a_1 b_1 t_1 + a_2 b_2 t_2) + (x_2 (a_1^2 b_2 + a_2^2 b_1)\\
&\quad + a_1 a_2 (b_1 - b_2)^2) u + x_1 x_2 a_1 b_2 t)] + [a_1 \leftrightarrow a_2, b_1 \leftrightarrow b_2, t \leftrightarrow u],\\
W_2 &= a_1 a_2 b_1 b_2 t u (x_1^2 x_2^2 [2(t_1 + t_2)(t^2 u + t_1 t_2 (s + u - t)) + tu((t_1 - t_2)^2 + t(u + 2t))]\\
&\quad + x_1 x_2 t t_1 t_2 (4(x_1 b_1 + x_2 a_2)(s + u) - (a_1 b_1 + a_2 b_2) u) + tu (x_1^2 b_2 (2 x_2 t - b_1 t_1) t_1 + x_2^2 a_1 (2 x_1 t - a_2 t_2) t_2))\\
&\quad + (a_1 \leftrightarrow a_2, b_1 \leftrightarrow b_2, t \leftrightarrow u),\\
W_3 &= x_1 x_2 a_1 a_2 b_1 b_2 [t^2 u (2 a_1 b_2 (x_1 x_2 (t_1 + t_2)(2t - u - s) - (x_1 b_2 t_1 + x_2 a_1 t_2)(u + s))\\
&\quad + [x_1 t_1 (2(a_1 b_2^2 + a_2 b_1^2) + 3 x_1 b_1 b_2) + x_2 t_2 (2(a_1^2 b_2 + a_2^2 b_1) + 3 a_1 a_2 x_2)] u + 4 x_1 x_2 t ((a_1 b_2 + a_2 b_1) u + a_1 b_2 t))]\\
&\quad + [a_1 \leftrightarrow a_2, b_1 \leftrightarrow b_2, t \leftrightarrow u],\\
W_4 &= x_1^2 x_2^2 a_1 a_2 b_1 b_2 [t (a_1 a_2 b_1 b_2 u (t_1 + t_2)(t - u - s) + (a_1 b_2 + a_2 b_1)^2 t u^2 - 2 a_1 b_2 t (s + u)(2 a_2 b_1 u - a_1 b_2 s))]\\
&\quad + [a_1 \leftrightarrow a_2, b_1 \leftrightarrow b_2, t \leftrightarrow u].
\end{aligned} \tag{A1}$$

Old results for dijet production in PRA

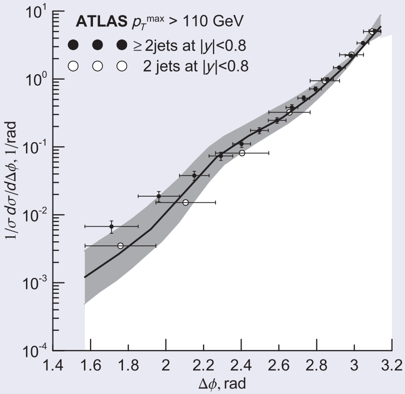


FIG. 3. Normalized $F(\Delta\phi)$ distribution for 2 (open circles) and ≥ 2 (black circles) jets with $p_T > 100$ GeV, $|y| < 0.8$, $p_T^{\max} > 110$ GeV and $\sqrt{S} = 7$ TeV. The data are from the ATLAS Collaboration [3]. The curve corresponds to the LO parton Reggeization approach.

Old results for dijet production in PRA

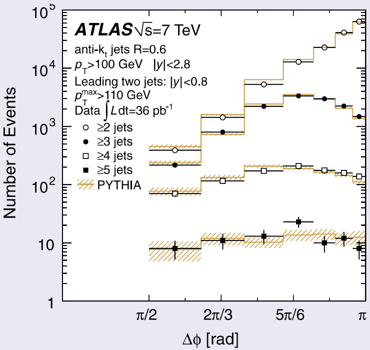


FIG. 1 (color online). The $\Delta\phi$ distribution for ≥ 2, ≥ 3, ≥ 4, and ≥ 5 jets with $p_T > 100$ GeV. Overlaid on the calibrated but otherwise uncorrected data (points) are results from PYTHIA processed through the detector simulation (lines). All uncertainties are statistical only.

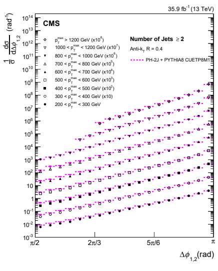
New CMS data for azimuthal correlation between two leading jets in multi-jets events

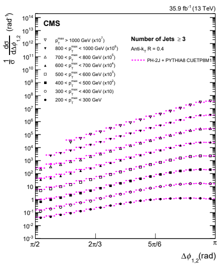
CERN-EP-2017-290
2018/07/12

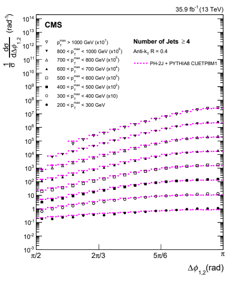
CMS-SMP-16-014

Azimuthal correlations for inclusive 2-jet, 3-jet, and 4-jet events in pp collisions at $\sqrt{s} = 13\,\text{TeV}$

New CMS data for azimuthal correlation between leading jets in multi-jet events



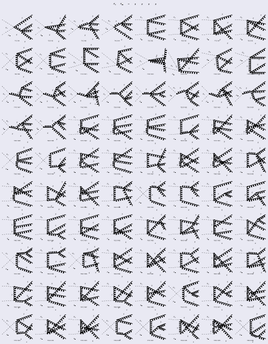




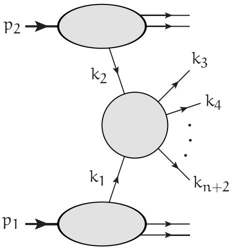
PRA versus / together KaTie

To study CMS data we should calculate off-shell amplitudes with 2, 3, 4 and, may be, more final partons.
We use original model-file `ReggeQCD` for `FeynArts` to explore Feynman's rules of Lipatov's EFT.

$R + R \to 4g$, 227 diagrams.



MC event generator KaTie



KaTie : For parton-level event generation with k_T-dependent initial states

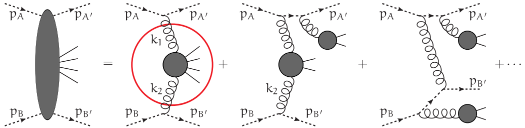
- A. van Hameren, KaTie : For parton-level event generation with k_T-dependent initial states // Comput.Phys.Commun. 224 (2018) 371-380.
- A. van Hameren, P. Kotko, and K. Kutak, Helicity amplitudes for high-energy scattering, JHEP, 01(2013), 078, 1211.0961.
- A. van Hameren, K. Kutak, and T. Salwa, Scattering amplitudes with off-shell quarks, Phys. Lett., B727(2013), 226, 1308.2861.

MC event generator KaTie

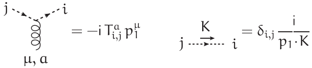
AVHLIB

Dyson-Schwinger recursion was devised by Britto, Cachazo, Feng, and Witten (BCFW). This recursion was implemented in AVHLIB for off-shell amplitudes.

Embed the process in an on-shell process with auxiliary partons and eikonal Feynman rules.



$$\left.\begin{aligned} p_A^\mu &= \Lambda p_1^\mu - \frac{\kappa_1^*}{2}\,\varepsilon_1^{*\mu} \\ p_{A'}^\mu &= -(\Lambda - x_1)p_1^\mu - \frac{\kappa_1}{2}\,\varepsilon_1^\mu \\ \Lambda &\to \infty \end{aligned}\right\} \Rightarrow$$



PRA versus / together KaTie

As it was shown earlier, Reggeized amplitudes in PRA totally agree with off-shell amplitudes from the AVHLIB

We have checked this statement for production of two (*) and three jets (**).

(*)*K. Kutak, R. Maciula, M. Serino, A. Szczurek and A. van Hameren, Four-jet production in single- and double-parton scattering within high-energy factorization, JHEP* **1604** *(2016) 175.*

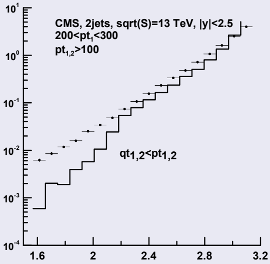
(**) *A. V. Karpishkov, M. A. Nefedov and V. A. Saleev, $B\bar{B}$ angular correlations at the LHC in parton Reggeization approach merged with higher-order matrix elements, Phys. Rev. D* **96** *(2017) no.9, 096019.*

Calculations of hard cross sections use MC event generator KaTie with KMR unPDFS should coincide with semi-analytical calculations in PRA

Our final calculations have been done with KaTie MC event generator.

Azimuthal angle difference spectra

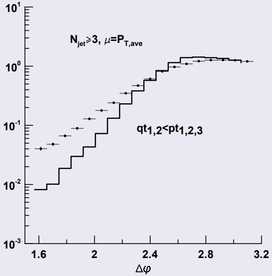
$N_{jet} \geq 2$, LO $2 \to 2$



$$RR \to gg, RR \to q\bar{q}, QR \to qg, QQ \to qq, Q\bar{Q} \to q\bar{q}, Q\bar{Q} \to gg, \ldots$$

Azimuthal angle difference spectra

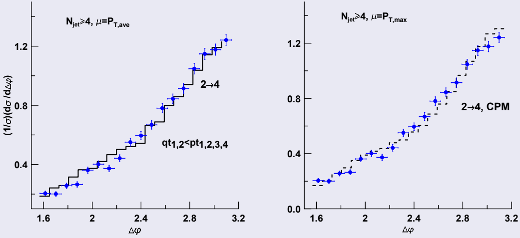
$N_{jet} \geq 3$, LO $2 \to 3$



$$RR \to ggg, RR \to q\bar{q}g, QR \to qgg, QR \to qq\bar{q}, QQ \to qqg, Q\bar{Q} \to q\bar{q}g,$$
$$Q\bar{Q} \to ggg, Q\bar{Q} \to q\bar{q}g, \ldots$$

Azimuthal angle difference spectra

$N_{jet} \geq 4$, LO $2 \to 4$

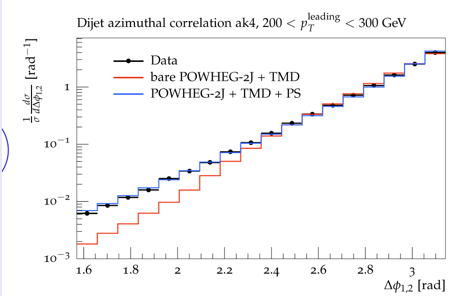


$$RR \to gggg, RR \to q\bar{q}gg, RR \to q\bar{q}gg, RR \to q\bar{q}q\bar{q}, QR \to qggg, QR \to qq\bar{q}g,$$

$$Q\bar{Q} \to q\bar{q}gg, Q\bar{Q} \to gggg, Q\bar{Q} \to q\bar{q}q\bar{q}, \ldots$$

Azimuthal angle difference spectra

$N_{jet} \geq 2$, Talk at REF-2018, Krakow
"Determination and application of TMDs obtained by the Parton Branching method"by A. Bermudez Martinez in collaboration with P.Connor, F. Hautmann, H. Jung, A. Lelek, V. Radescu, R. Zlebcik



Merging of HO contributions with LO in PRA

Azimuthal $B\bar{B}$ correlations, CMS data at 7 TeV (2011)

PHYSICAL REVIEW D **96,** 096019 (2017)

$B\bar{B}$ angular correlations at the LHC in the parton Reggeization approach merged with higher-order matrix elements

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(Received 14 July 2017; published 21 November 2017)

Merging of HO contributions with LO in PRA

LO $(R + R \to b + \bar{b})$ + NLO $(R + R \to b + \bar{b} + g)$

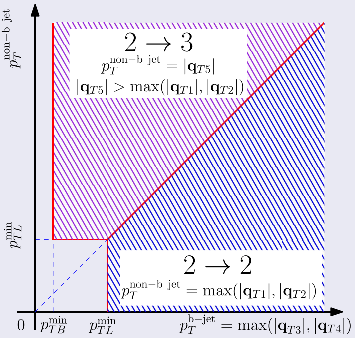
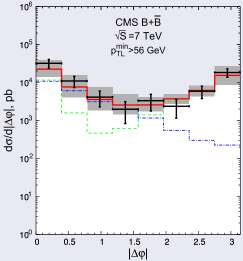
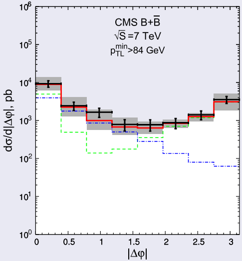


FIG. 6. The kinematic cuts for the $2 \to 2$ contribution (20) and $2 \to 3$ contribution (21) in the space of transverse momentum of the leading b-jet in the event ($p_T^{\text{b-jet}}$) vs transverse momentum of the leading light-quark/gluon jet in the same event ($p_T^{\text{non-b jet}}$).

Azimuthal $B\bar{B}$ correlations, CMS data at 7 TeV (2011)

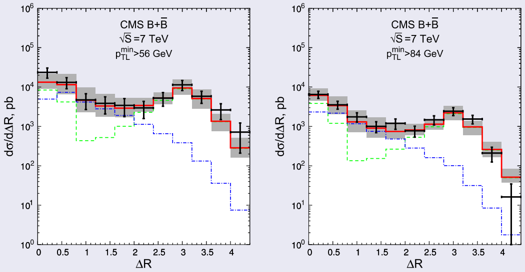
LO $(R + R \to b + \bar{b})$ + NLO $(R + R \to b + \bar{b} + g)$





Angular $B\bar{B}$ correlations, $\Delta R = \sqrt{\Delta\phi^2 + \Delta y^2}$

LO $(R + R \to b + \bar{b})$ + **NLO** $(R + R \to b + \bar{b} + g)$



Merging of HO contributions with LO in PRA

Consistent treatment of charm production in higher-orders at tree-level within k_T-factorization approach

PHYSICAL REVIEW D **100,** 054001 (2019)

Consistent treatment of charm production in higher-orders at tree-level within k_T-factorization approach

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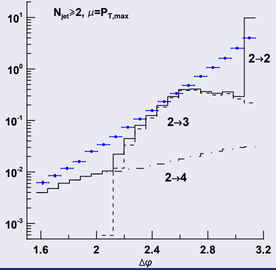
(Received 5 July 2019; published 3 September 2019)

Merging of HO contributions with LO in CPM

CPM calculations with KaTie



Master formula for cross section

$$\frac{d\sigma^{\geq 2}}{d\triangle\phi_{12}} = \sum_{N_{jet}\geq 2} \frac{d\sigma^{N_{jet}}}{d\triangle\phi_{12}} = \frac{d\sigma^{2}}{d\triangle\phi_{12}} + \frac{d\sigma^{3}}{d\triangle\phi_{12}} + \frac{d\sigma^{4}}{d\triangle\phi_{12}} + ...$$

Merging of HO contributions with LO in PRA, the case of $N_{jet} \geq 2$

LO $(2 \to 2)$ + **NLO** $(2 \to 3)$ + **NNLO** $(2 \to 4)$ ...

Old scheme is based on LO approximation for hard part of process:

$$2 \to 2, \qquad q_{T1,2} < p_{T1,2}$$

New scheme with merging of HO contributions:

$$2 \to 2, \qquad q_{T1,2} < p_{TM}, \qquad p_{TM}$$

$$2 \to 3, \qquad q_{T1,2} < p_{TM}, \qquad p_{T3} > p_{TM}$$

$$2 \to 4, \qquad q_{T1,2} < p_{TM}, \qquad p_{T3,4} > p_{TM}$$

Merging of HO contributions with LO in PRA, the case of $N_{jet} \geq 2$

Isolation-cone conditions

$$R_{12} = R_{exp} = 0.4$$

$$R_{13,23} = R_{exp} = 0.4$$

$$R_{14,24} = R_{exp} = 0.4$$

$$R_{34} = ...$$

Sudakov form-factor and collinear singularity

Our choice follows from regularization of collinear singularities in the initial state the same as in KMR unPDFs

$$T_i(s,\mu^2) = \exp\left[-\int_s^{\mu^2} \frac{ds'}{s'}\frac{\alpha_s(s')}{2\pi} J_i(\Delta(s',\mu^2))\right]$$

$$J_i(\Delta) = \sum_j \int_0^{1-\Delta} dzz \cdot P_{ij}(z)$$

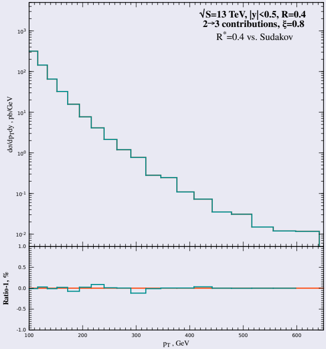
$$\Delta(s_{12}) = \frac{s_{12}}{\mu_s^2}, \qquad \mu_s \sim \mu$$

$$J_q(\Delta) = -2C_F \log\Delta - \frac{3C_F}{2} + \mathcal{O}(\Delta)$$

$$J_g(\Delta) = -2C_A \log\Delta - \frac{\beta_0}{2} + \mathcal{O}(\Delta), \qquad \beta_0 = \frac{11C_A}{3} - \frac{2n_F}{3}$$

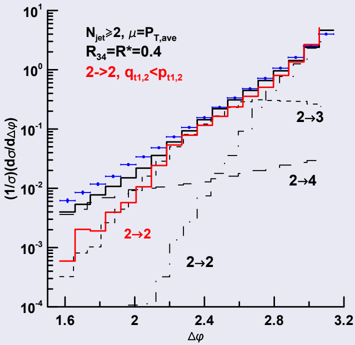
Sudakov form-factor and collinear singularity

FFS and effective R^*



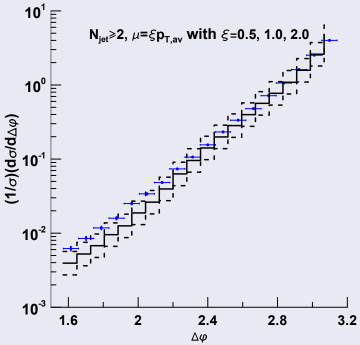
Azimuthal angle correlations, $N_{jets} \geq 2$

LO versus LO+HO



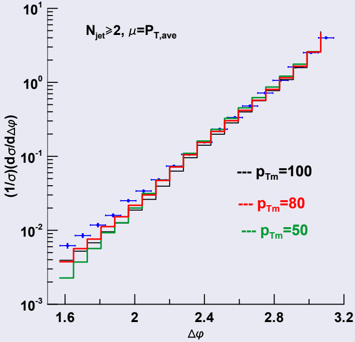
Azimuthal angle correlations, $N_{jets} \geq 2$

Scale dependence, $\mu = \xi' p_{T,ave}$, $\xi' = 0.5, 1.0, 2.0$



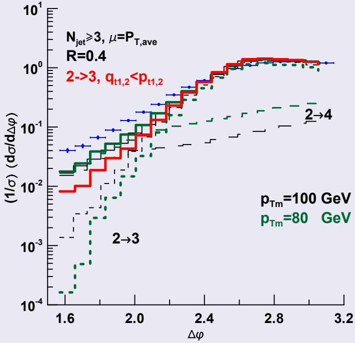
Azimuthal angle correlations, $N_{jets} \geq 2$

Different choices of p_{TM}



Azimuthal angle correlations, $N_{jets} \geq 3$

LO versus LO+HO



Conclusions

- We suggest scheme for merging of tree-level HO corrections with LO calculation in k_T-factorization (PRA)
- We obtain very good agreement with data for angular correlations in $B\bar{B}-$pair production
- We describe data for azimuthal correlations between two leading jets in events with $N_{jets} \geq 2$ (rather good), $N_{jets} \geq 3$ (so so), $N_{jets} \geq 4$ (very good)
- Our results are important for comparison of different models of unPDFs and relative role of PS contribution.
- Our results are important for search of signal from DPS.