Going off-shell: matrix element, parton densities and shower

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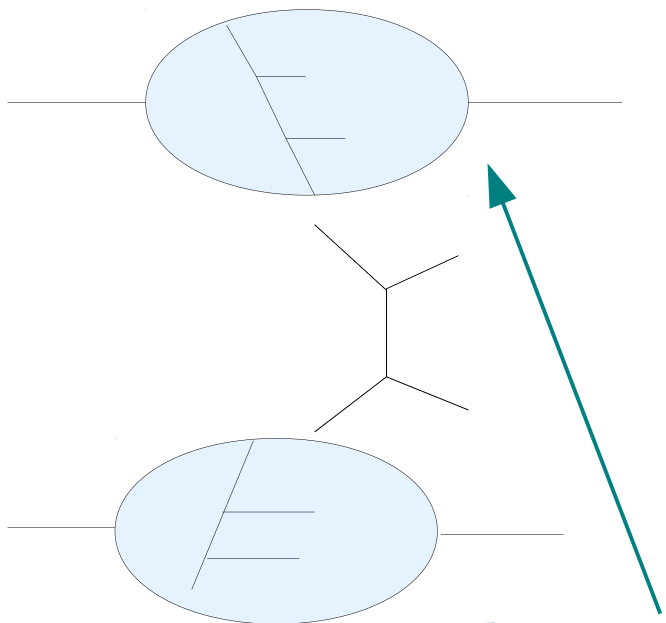
NCN

HORIZON 2020

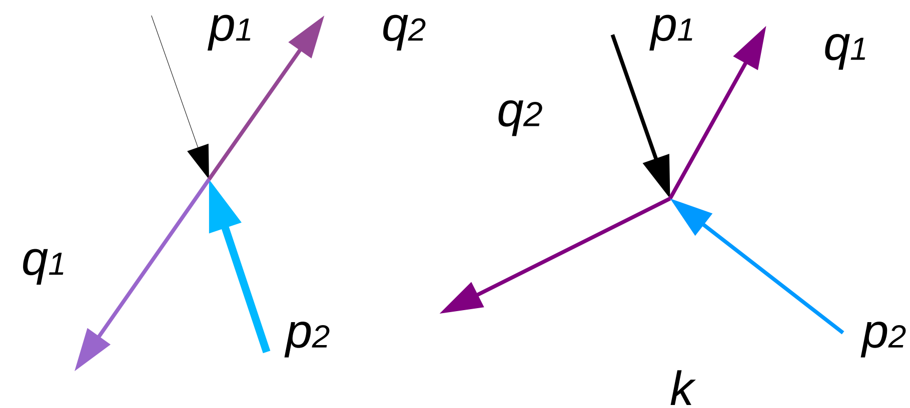
Based on projects with:
E. Blanco, M. Deak, F. Hautmann, M. Hentschinski, A. Kusina, L. Keersmaekers, O. Lelek, P. Van Mechelen, A. Van Hameren, H. Van Haevermaet, H. Jung, M. Serino, P. Kotko

k_T - factorization

QCD at high energies – k_T factorization



Strongly decreasing
Longitudinal momentum
fractions of off-shell partons



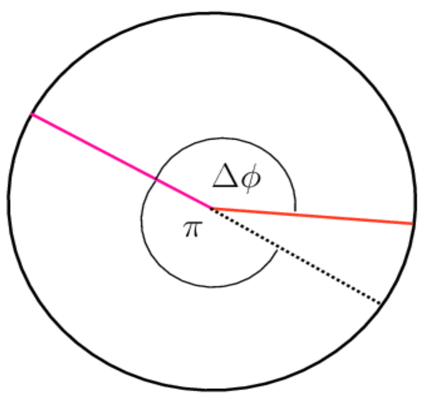
$p_1+p_2=q_1+q_2$

$p_1+p_2=q_1+q_2+k$

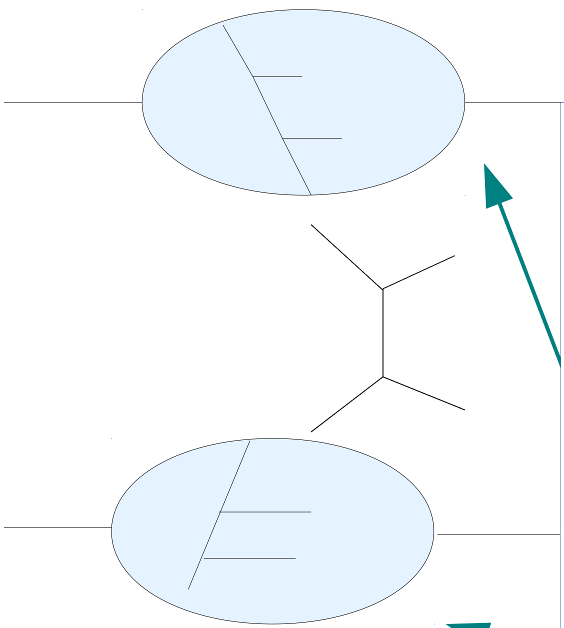
$$\frac{d\sigma}{dPS} \propto \mathcal{F}_{a^*}(x_1, k_{\perp 1}) \otimes \hat{\sigma}_{ab\to cd}(x_1, x_2) \otimes \mathcal{F}_{b^*}(x_2, k_{\perp 2})$$

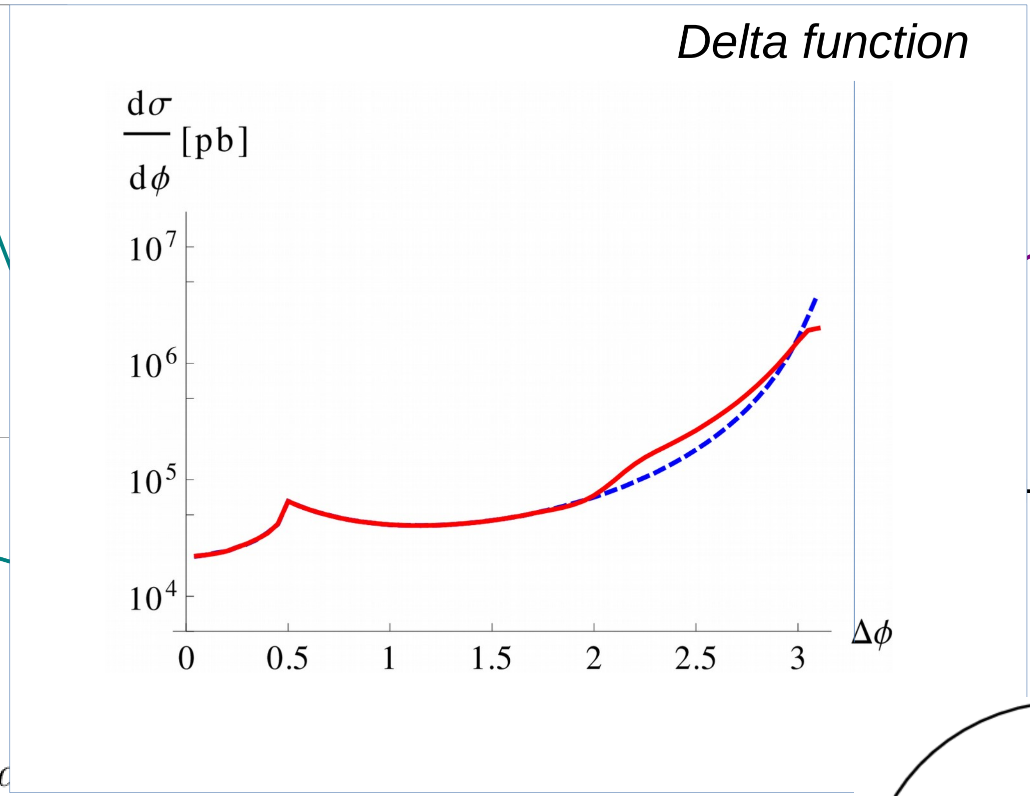
Ciafaloni, Catani, Hautman '93
Collins, Ellis '93

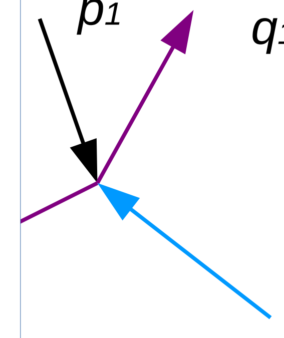
New helicity based methods for ME
Kotko, K.K, van Hameren, '12



QCD at high energies – k_T factorization

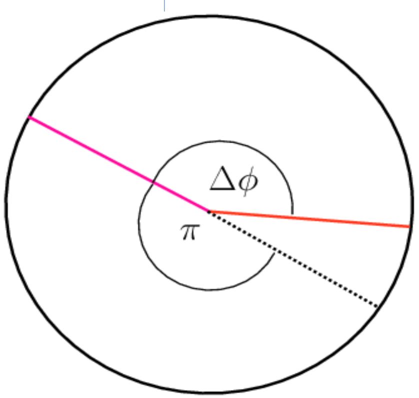






$$\frac{d\sigma}{dPS} \propto \mathcal{F}_{a^*}(x_1, k_{\perp 1}) \otimes \hat{\sigma}$$

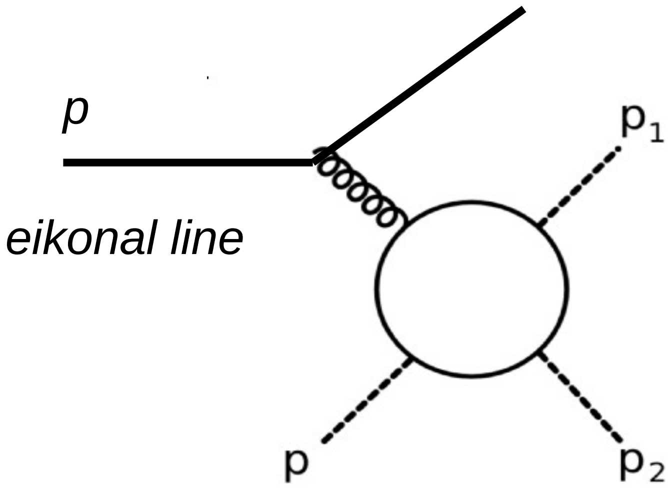
Ciafaloni, Catani, Hautman '93
Collins, Ellis '93



New helicity based methods for ME

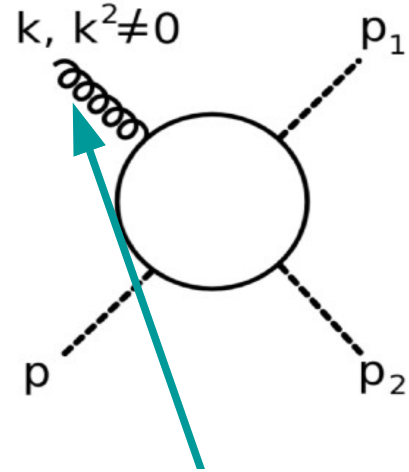
Kotko, K.K, van Hameren, '12

Example of matrix element for hybrid factorization



Decomposition
of polarization sum

$$g_{\mu\nu} = g_{\mu\nu\perp} + \frac{p_{A\mu}p_\nu + p_{A\nu}p_\mu}{s}$$



$$k = x\,p_A + k_T$$

$$\epsilon^0_\mu = \frac{i\sqrt{2}\,x}{|k_t|}p_{A\,\mu}$$

Polarization sum
for onshell gluons

$$\sum_{\lambda=\pm}\epsilon^\lambda_\mu\epsilon^{\lambda *}_\nu = g_{\mu\nu} - \frac{p_{A\mu}q_\nu + q_\mu p_{A\nu}}{q^\rho p_{A\rho}}$$

Polarization of off-shell gluon
One applies usual methods
but polarization summ deiffers

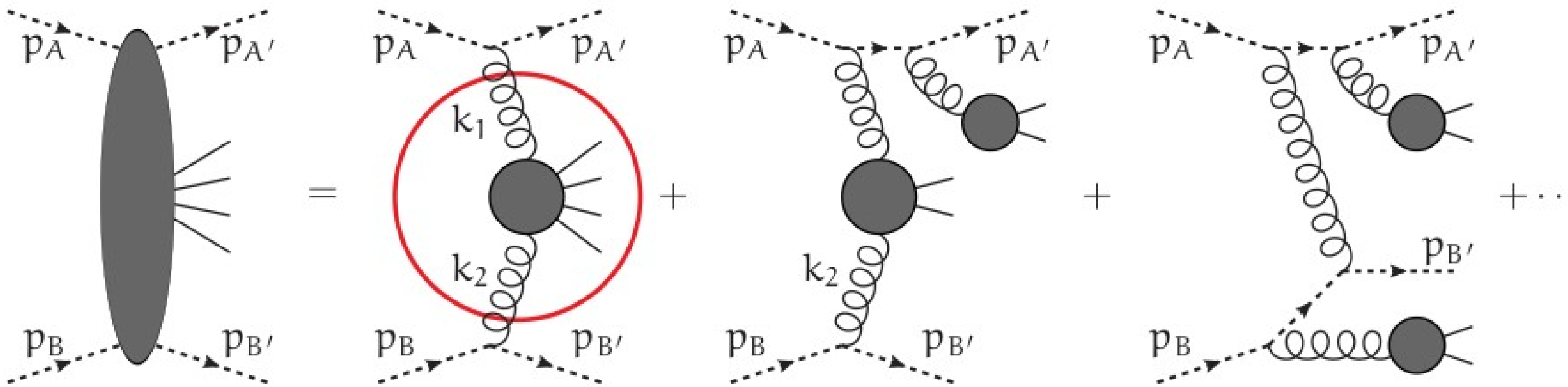
Effective action based approach
Lipatov 95, Lipatov, Vyazovsky 2000

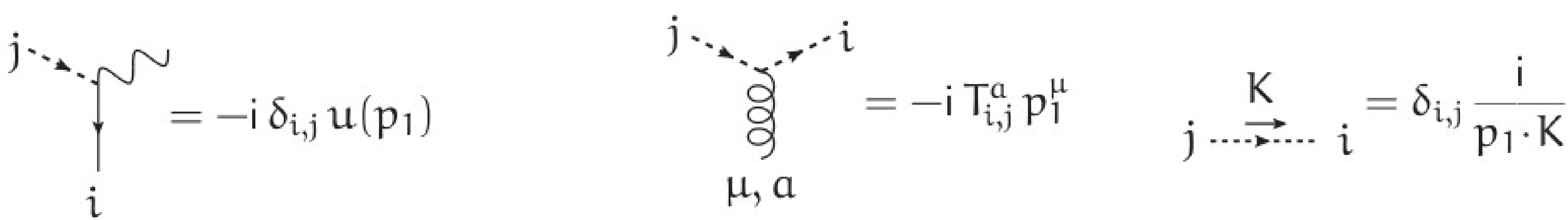
Gauge link based derivation
Kotko'14

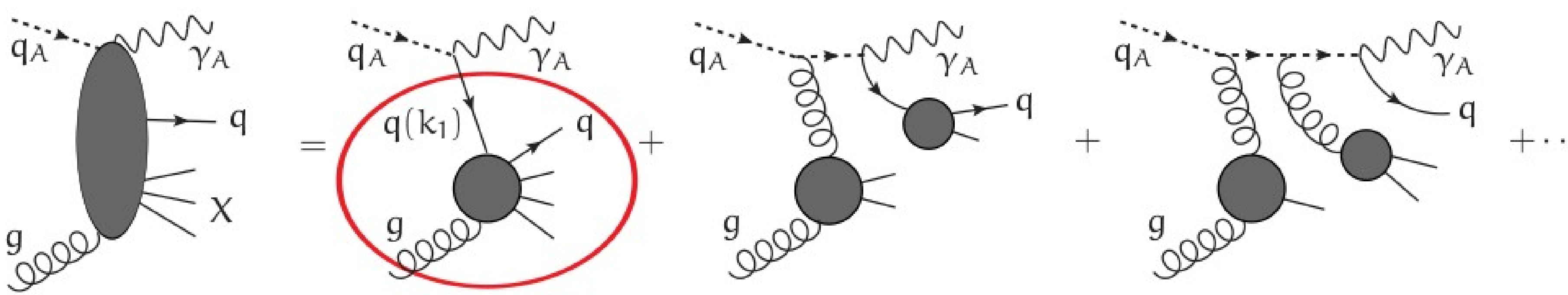
Hard coefficient functions in kt factorization:

One consider embedding off-shell amplitude in on-shell and introduces eikonal lines

Kotko, KK, van Hameren 2013,
KK, Salwa, van Hameren 2013



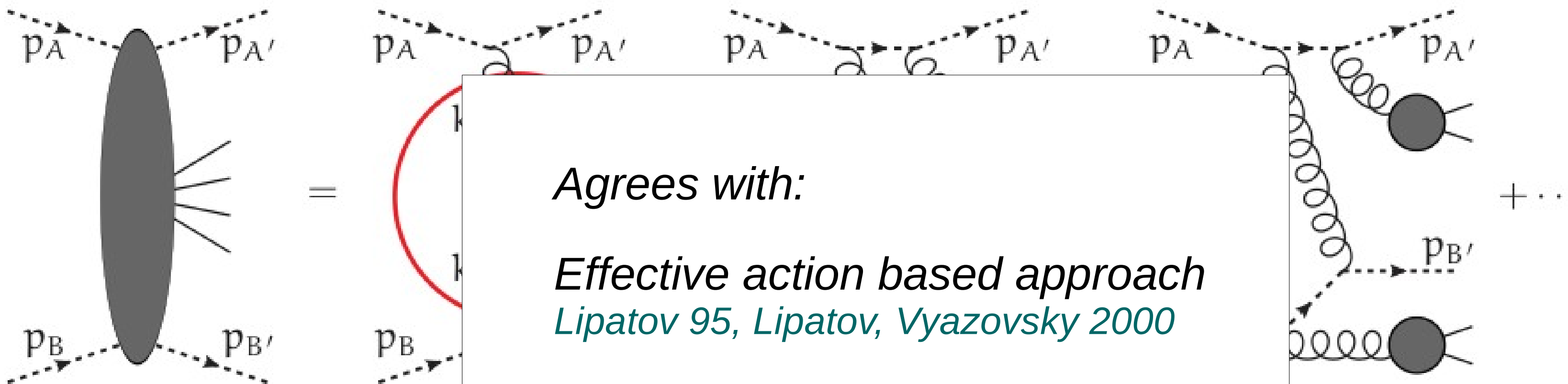




Hard coefficient functions in HEF:

Kotko, KK, van Hameren 2013,
KK, Salwa, van Hameren 2013

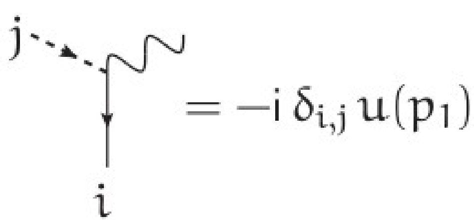
Implemented in KaTie Monte Carlo

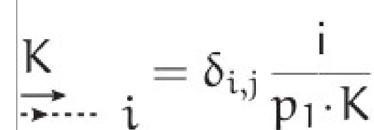


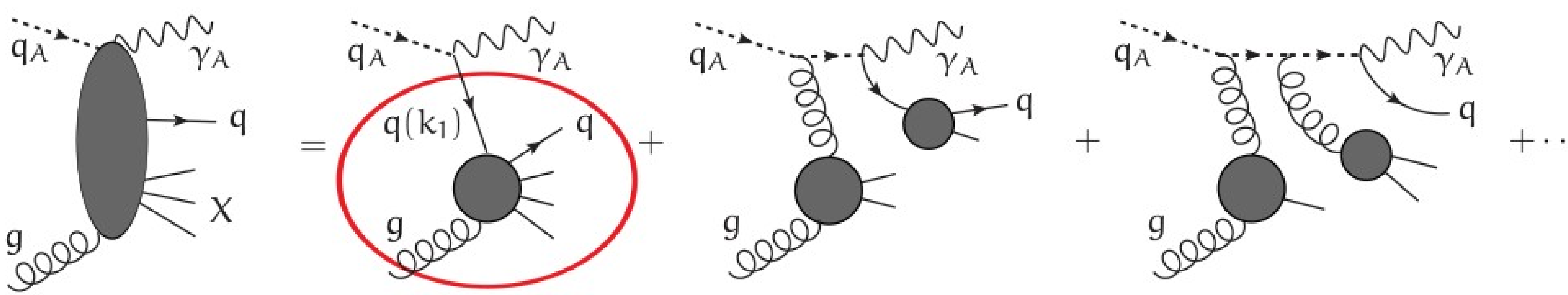
Agrees with:

Effective action based approach
Lipatov 95, Lipatov, Vyazovsky 2000

Gauge link based derivation
Kotko'14





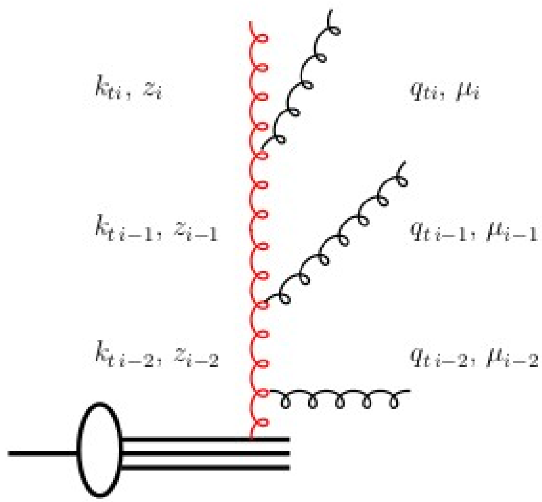


Monte Carlo – parton branching method

The idea: construct such parton shower that gives also TMD dependent paton density.
On integrated level the pdf obeys DGLAP equation.

A. Bermudez Martinez, P. Connor, H. Jung, A. Lelek, R. Žlebčík, F. Hautmann, V. Radescu
Phys.Rev. D99 (2019) no.7, 074008

See talks by
Bermudez Martinez
S. Taheri



$$\mathcal{A}_a(x,\mathbf{k},\mu^2) = \Delta_a(\mu^2)\,\mathcal{A}_a(x,\mathbf{k},\mu_0^2) + \sum_b \int \frac{d^2\mathbf{q}'}{\pi\mathbf{q}'^2}\,\frac{\Delta_a(\mu^2)}{\Delta_a(\mathbf{q}'^2)}\,\Theta(\mu^2-\mathbf{q}'^2)\,\Theta(\mathbf{q}'^2-\mu_0^2)$$
$$\times \int_x^{z_M} \frac{dz}{z}\,P_{ab}^{(R)}(\alpha_s,z)\,\mathcal{A}_b\left(\frac{x}{z},\mathbf{k}+(1-z)\mathbf{q}',\mathbf{q}'^2\right)$$

The method provides first consistent and complete set of TMD's which are applicable in Monte Carlo simulations and can be generalized to account for small x effects at least in linear regime. Applies in the regime above saturation scale.

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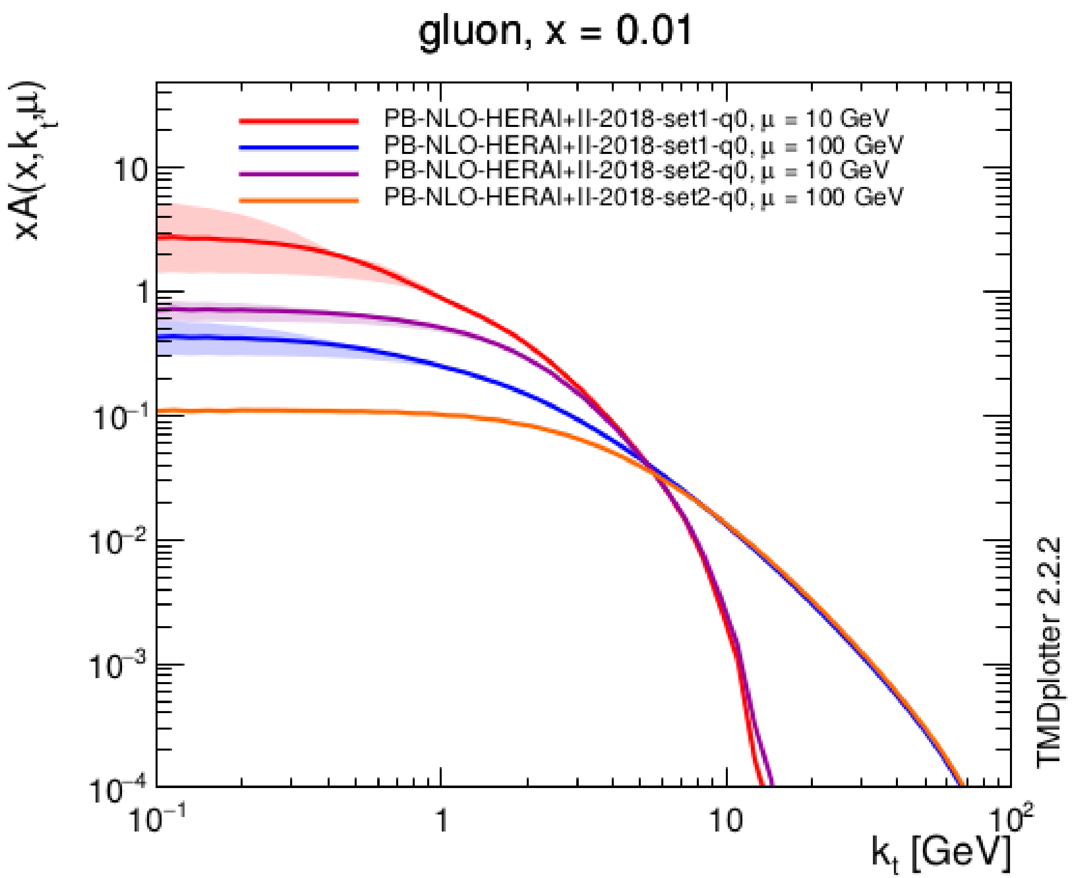


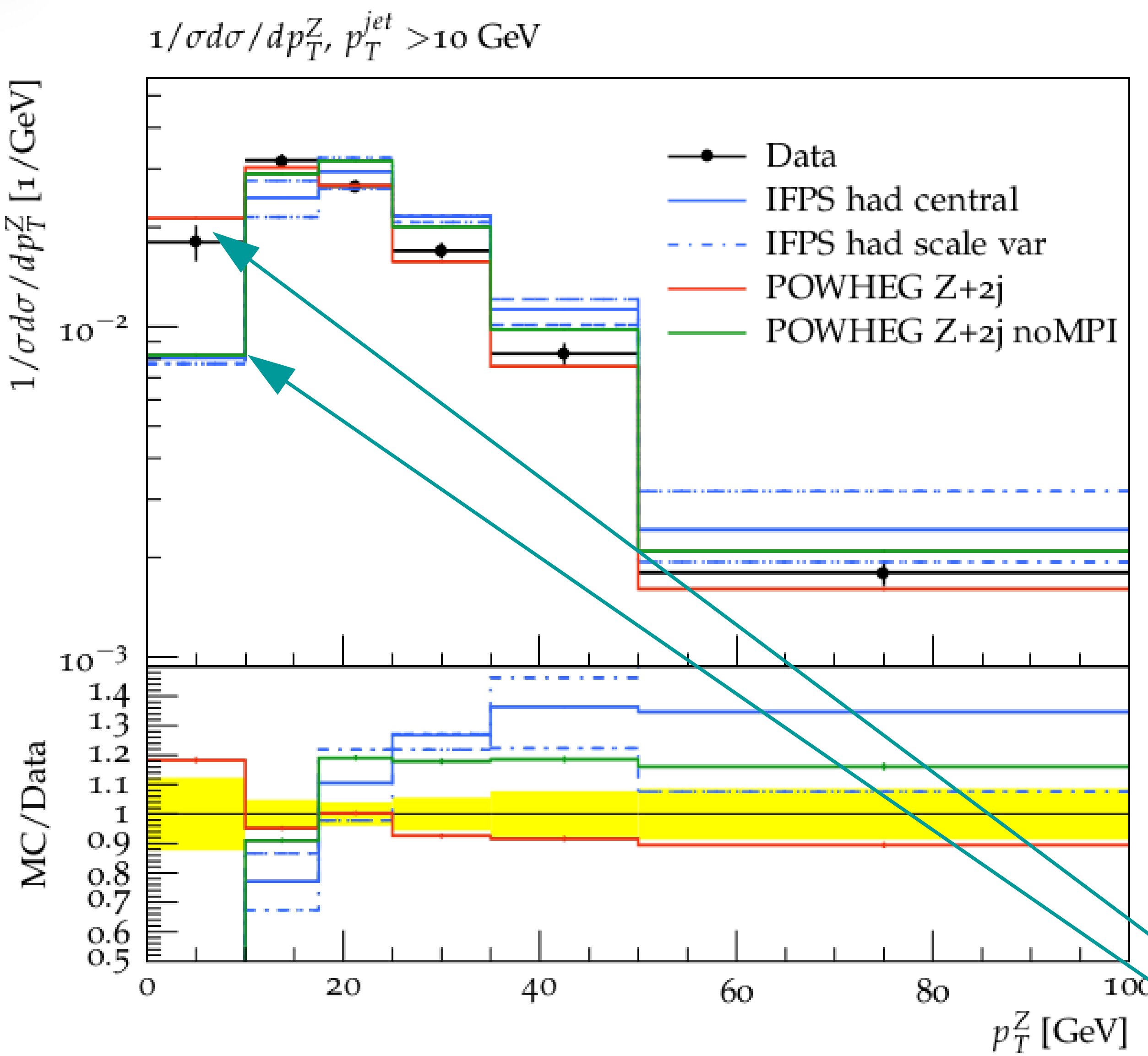
$\mathcal{A}_a(x, \mathbf{k}, \mu^2) \quad = \quad \ldots - \mu_0^2)$

$\times$

The method provides first consistent and complete set of TMD's which are applicable in Monte Carlo simulations and can be generalized to account for small x effects at least in linear regime. Applies in the regime above saturation scale.

Example: Z+jet: p_T of Z

van Hameren, Deak, Jung, Kusina, Kutak, M. Serino ‘18



Simulation in KaTie+ CASCADE

Parton Branching pdfs used

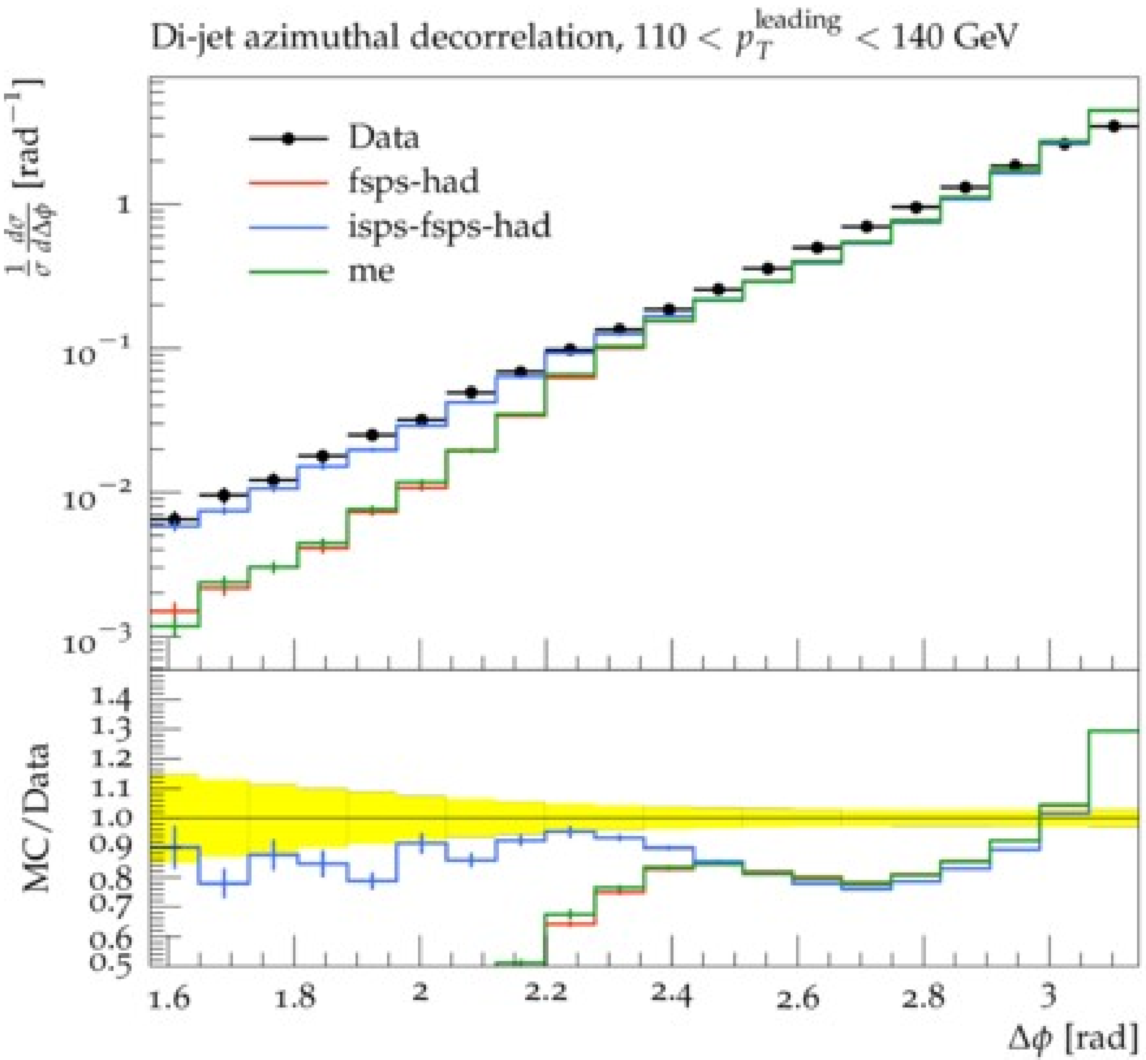
Together with off-shell ME as obtained from

KaTie ME generator

Large contribution from MPI in POWHEG

Example- dijets- azimuthal angle correlations – central region

M. Bury, A. van Hameren, H. Jung, KK, S. Sapeta, M. Serino '17



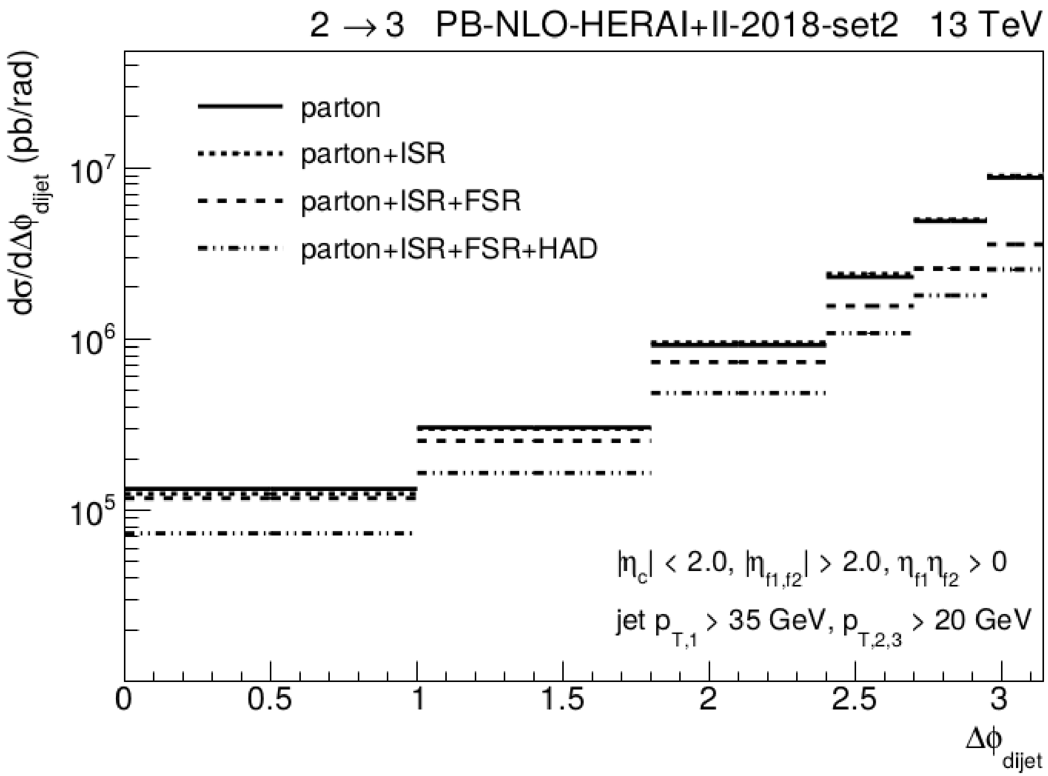
Simulation in KaTie+ CASCADE

KMR pdfs used unintegrated DGLAP based

Together with off-shell ME

as obtained from KaTie ME generator

Decorelations 3 jets forward-central

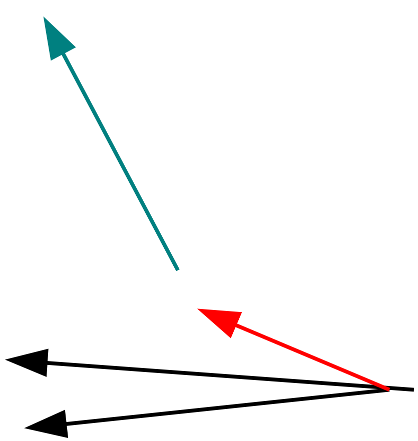


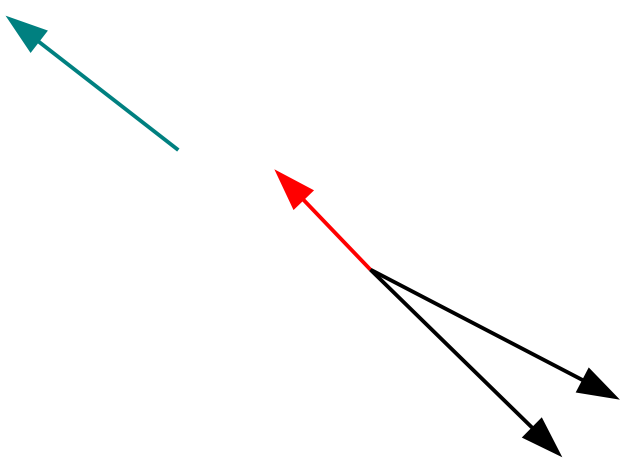
H. Van Haevermaet,
Van Hameren, Kotko, K.Kutak, Van
Mechelen '20

Results obtained within
kt factorization calculations
+ ISR are on top
on kt factorization without ISR
e used Parton Branching TMDs

Hautmann, H. Jung, A. Lelek, V.
adescu and R. Zlebcik '18

Bermudez Martinez, P. Connor, H.
ng, A. Lelek, R. Zlebcik, F. Hautmann '19





Parton branching method for lead unintegrated pdfs

$$x\mathcal{A}_a^{\rm Pb}(x,k_t^2,\mu^2) = \int dx'\mathcal{A}_{0,b}^{\rm Pb}(x',k_{t,0}^2,\mu_0^2)\frac{x}{x'}\ \mathcal{K}_{ba}\left(\frac{x}{x'},k_{t,0}^2,k_t^2,\mu_0^2,\mu^2\right)$$

$$\mathcal{A}_{0,b}^{\rm Pb}(x,k_{t,0}^2,\mu_0^2) = f_{0,b}^{\rm Pb}(x,\mu_0^2)\cdot\ \exp(-|k_{t,0}^2|/\sigma^2)$$

$$\sigma^2 = q_0^2/2$$

$$q_0 = 0.5\ \text{GeV}$$

Momentum conservation → exact kinematics

The splitting function → NLO DGLAP

The shower is consistent with the transversal momentum dependent distribution it uses

Available collinear nuclear PDFs

Multiplicative correction factor

$$f_i^{p/A}(x_N, \mu_0) = R_i(x_N, \mu_0, A)\ f_i^{\text{free proton}}(x_N, \mu_0)$$

HKN: Hirai, Kumano, Nagai [PRC 76, 065207 (2007)]
DSSZ: de Florian, Sassot, Stratmann, Zurita [PRD 85, 074028 (2012)]
EPS09: Eskola, Paukkunen, Salgado [JHEP 04 (2009) 065]
EPPS16: Eskola, Paakkinen, Paukkunen, Salgado [EPJC 77 (2017) 163]
KT16: Khanpour, Tehrani [PRD 93, 014026 (2016)]

Native nuclear PDFs

$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$
$$f_i(x_N, A = 1, \mu_0) \equiv f_i^{\text{free proton}}(x_N, \mu_0)$$

nCTEQ15: Kovarik, Kusina, Jezo, Clark, Keppel, Lyonnet, Morfin, Olness, Owens, Schienbein, Yu [PRD 93, 085037 (2016), arXiv:1509.00792]

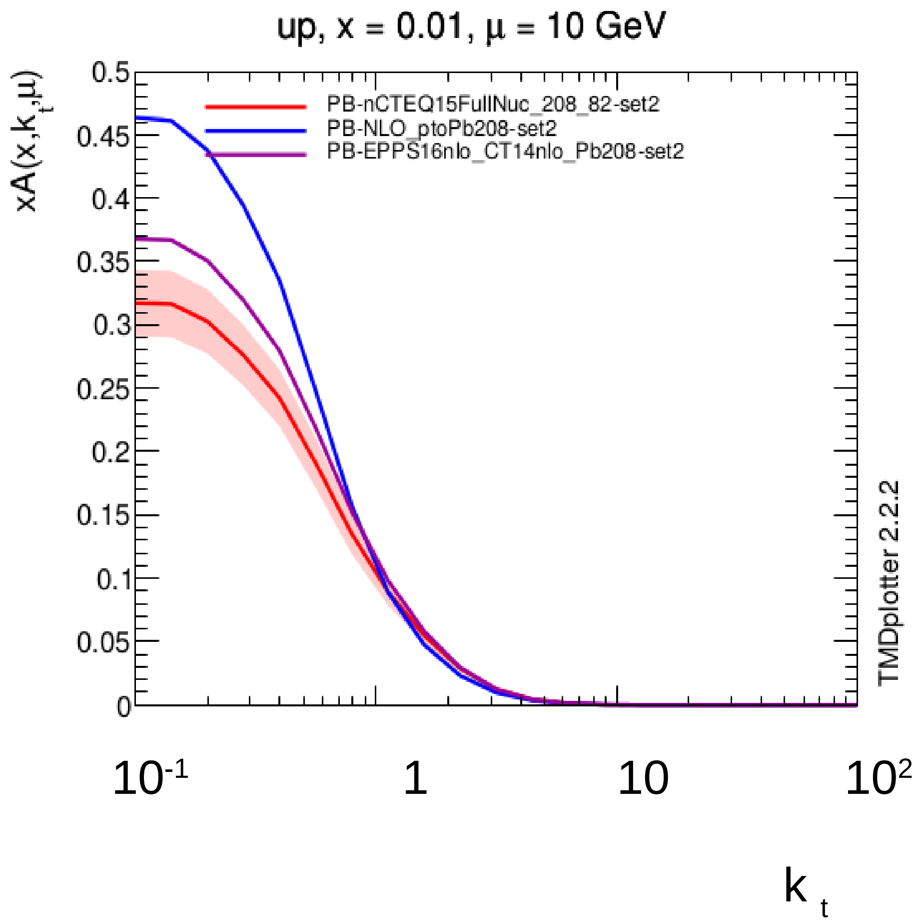
NNPDF Khalek, Ethier, Rojo arXiv:1904.00018

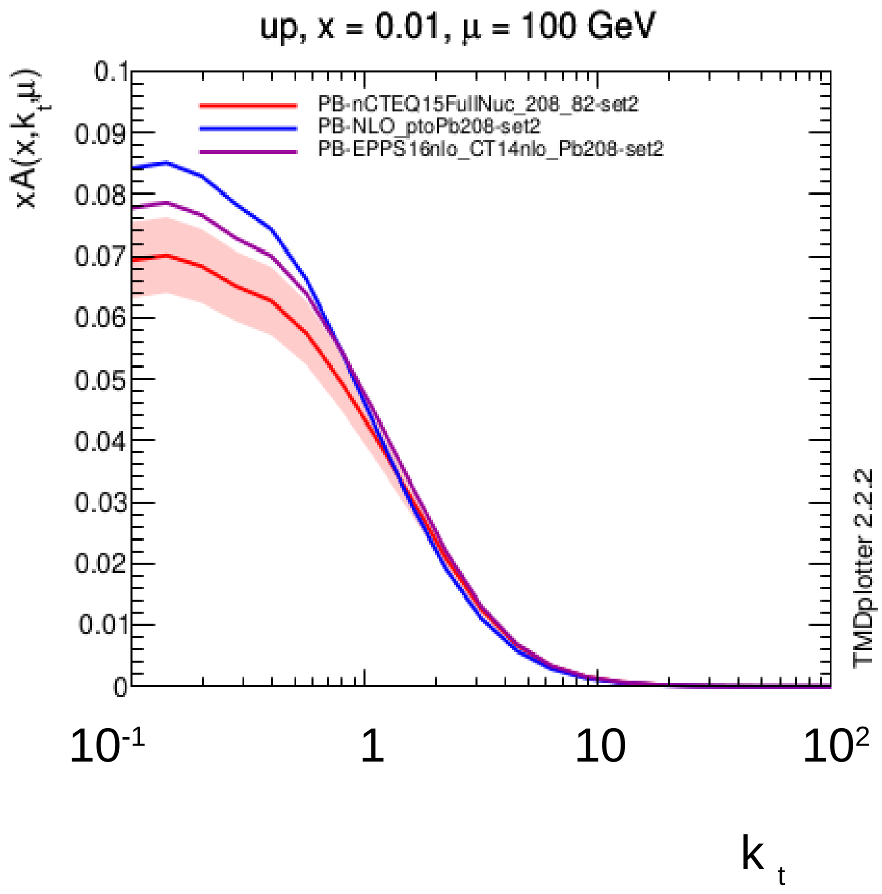
WHV Marina Walt, Ilkka Helenius, Werner Vogelsang arXiv:1908.03355

See also talks by
V. Guzey
M. Zurita

Transverse momentum dependence

Blanco, Jung, Van Hameren, Kusina, Kutak '19

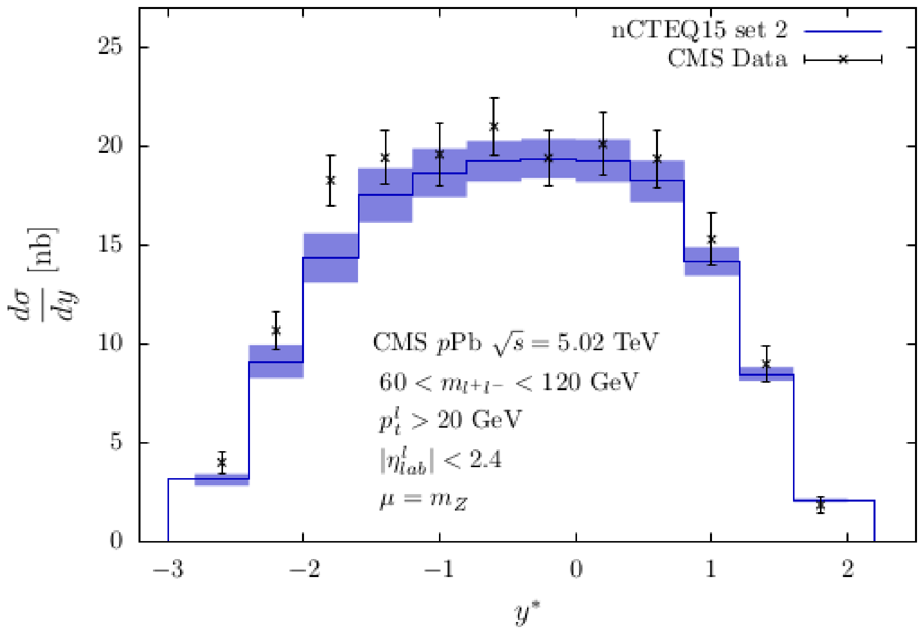


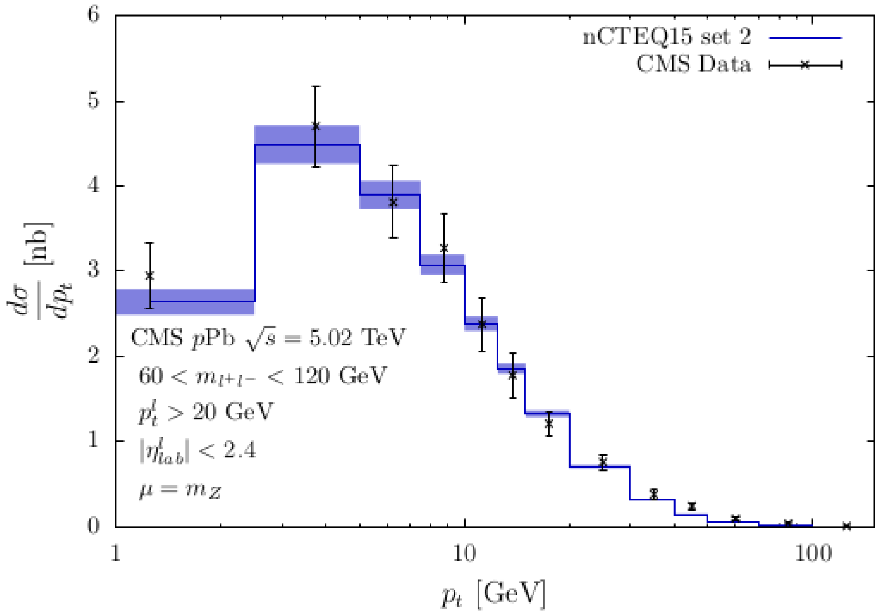


Drell-Yan – with PDF uncertainty

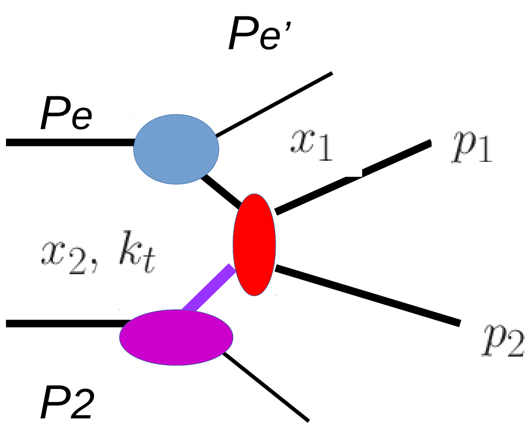
Blanco, Jung, Van Hameren, Kusina, Kutak '19

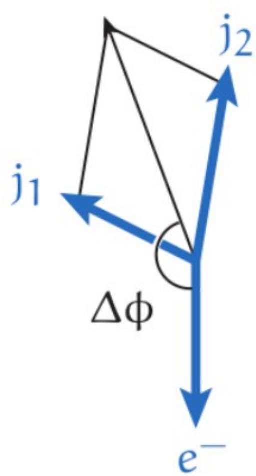
$$p + Pb \to Z^* \to \mu^+ + \mu^-$$

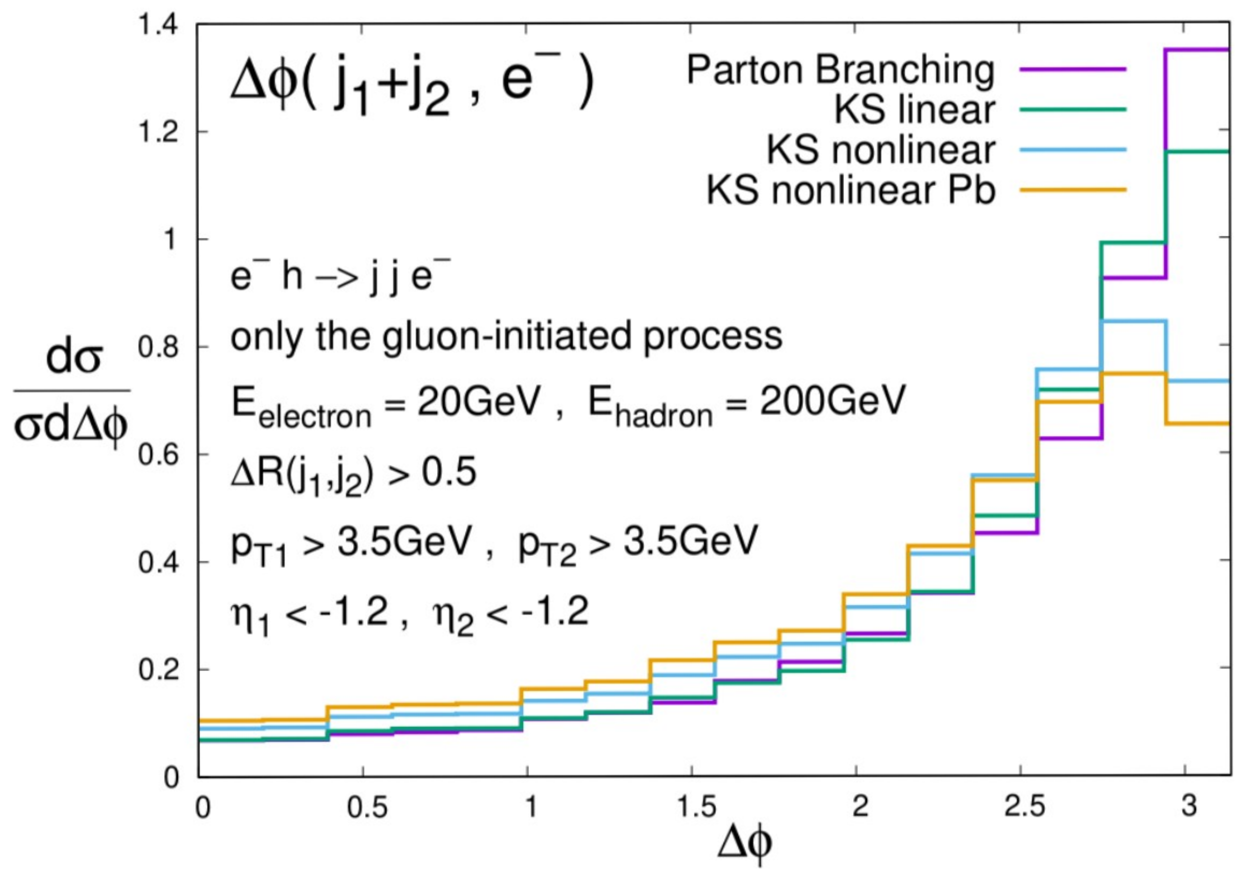




Preliminary: towards DIS in Electron Ion Collider







from A. Van Hameren

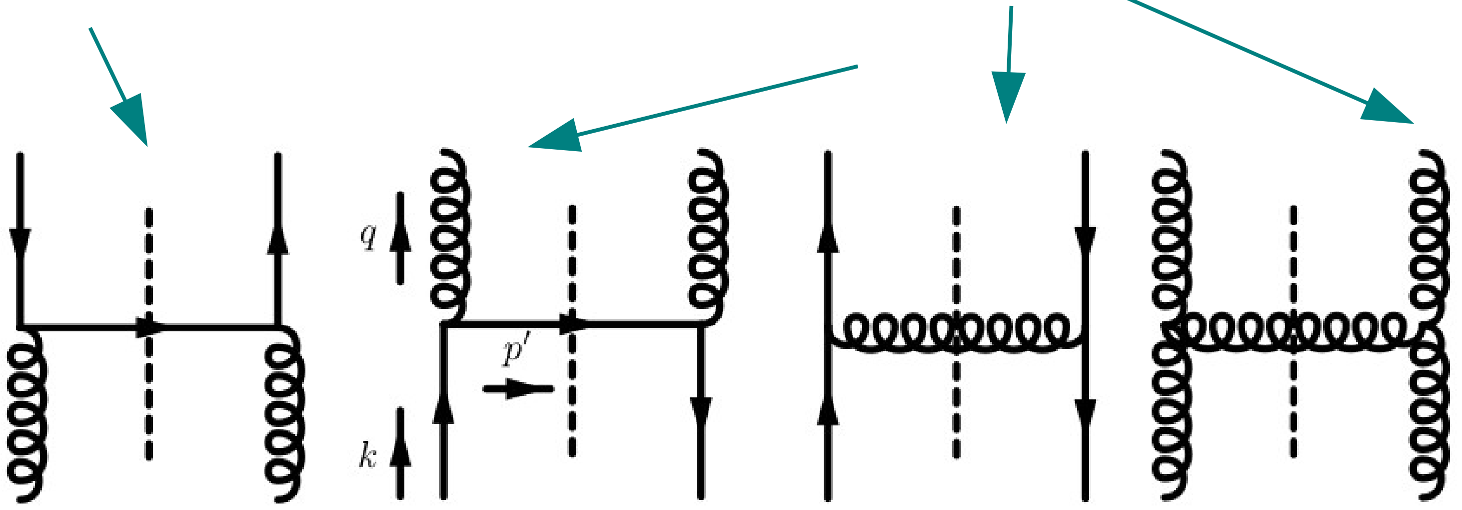
Kernels with kt dependent splittings

In the collinear physics based Monte Carlo's the k_T dependence is generated by kinematcs. However, by using low x methods one can obtain kernels that depend on transverse momentum.

Real emission kernels obtained in

Catani and Hautmann '94

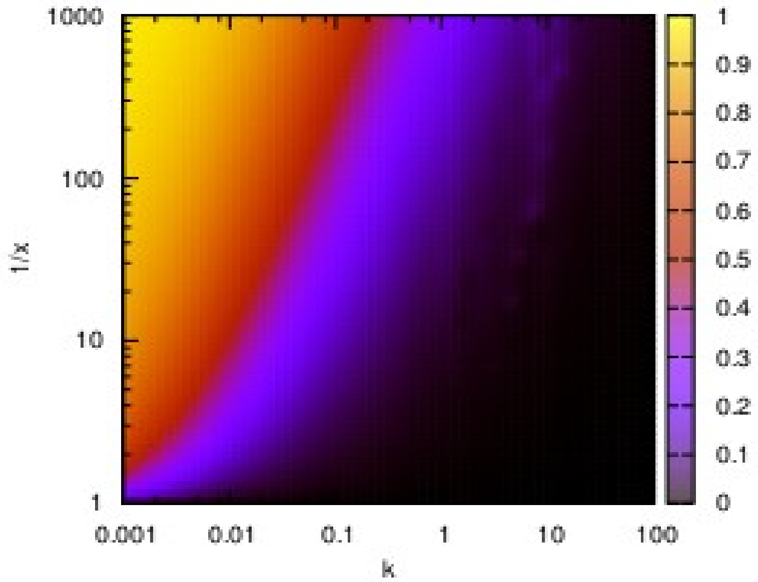
O. Gituliar, M. Hentschinski, K.K; JHEP 1601 (2016) 181
Hentschinski, Kusina, KK, Serino '17



At present we have a conjecture for complete kernels.
However, the results distributions are still to be obtained.

Saturation

Saturation



Saturation – state where number of gluons stops growing due to high occupation number. Way to fulfill unitarity requirements in high energy limit of QCD.

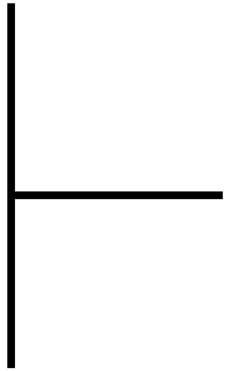
L.V. Gribov, E.M. Levin, M.G. Ryskin
Phys.Rept. 100 (1983) 1-150

Larry D. McLerran, Raju Venugopalan
Phys.Rev. D49 (1994) 3352-3355

On microscopic level it means that gluon apart splitting recombine

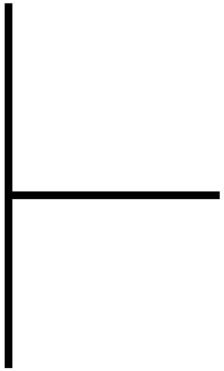
Linear evolution equation BFKL

splitting



Nonlinear evolution equations

splitting



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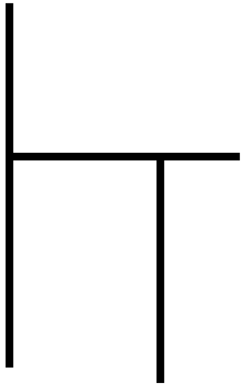
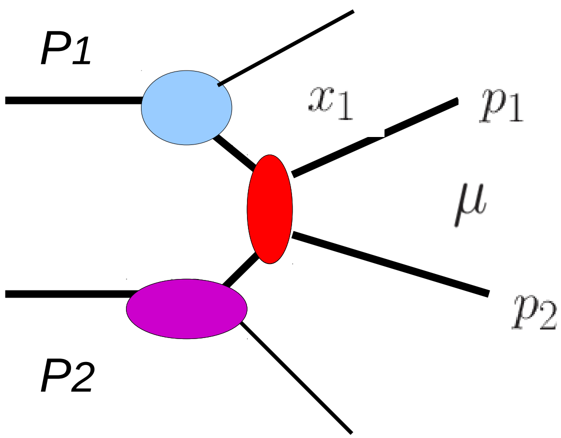
recombination



Improved Transversal Momentum Dependent Factorization

$$\frac{d\sigma_{\rm SPS}^{P_1P_2\rightarrow {\rm dijets}+X}}{dy_1dy_2dp_{1t}dp_{2t}d\Delta\phi} = \frac{p_{1t}p_{2t}}{8\pi^2(x_1x_2s)^2}\sum_{a,c,d} x_1 f_{a/P_1}(x_1,\mu^2)\,|\overline{\mathcal{M}_{ag^*\rightarrow cd}}|^2 \quad \mathcal{F}_{g/P_2}(x_2,k_t^2)\frac{1}{1+\delta_{cd}}$$



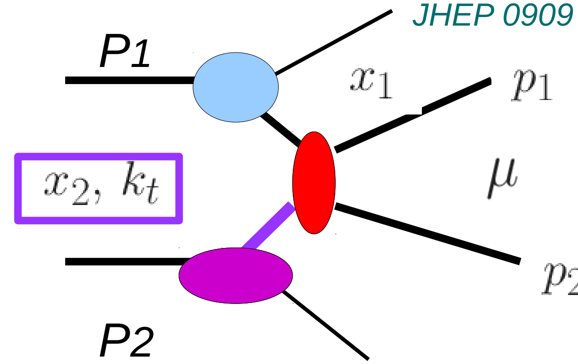
Generalization of hybrid formula but no kt in ME

Fabio Dominguez, Bo-Wen Xiao, Feng Yuan Phys.Rev.Lett. 106 (2011) 022301

F. Dominguez, C. Marquet, Bo-Wen Xiao, F. Yuan Phys.Rev. D83 (2011) 105005

Appropriate in back-to-back configuration

A, Dumitru, A. Hayashigaki J. Jalilian-Marian Nucl.Phys. A765 (2006) 464-482M. Deak, F. Hautmann, H. Jung, K. Kutak JHEP 0909 (2009) 121



Using HEF motivated sum over polarization for low x gluons we included kt in ME

Conjecture P. Kotko K. Kutak , C. Marquet , E. Petreska , S. Sapeta, A. van Hameren, JHEP 1509 (2015) 106

Appropriate in any configuration

Can be obtained from CGC

T. Altinoluk, R. Boussarie, Piotr Kotko JHEP 1905 (2019) 156

gauge invariant amplitudes with kt and TMDs

Example for g g → g g*

$$\frac{d\sigma^{pA\rightarrow ggX}}{d^2P_td^2k_tdy_1dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\; x_1 f_{g/p}(x_1,\mu^2)\sum_{i=1}^{6}\mathcal{F}_{gg}^{(i)}H_{gg\rightarrow gg}^{(i)}$$

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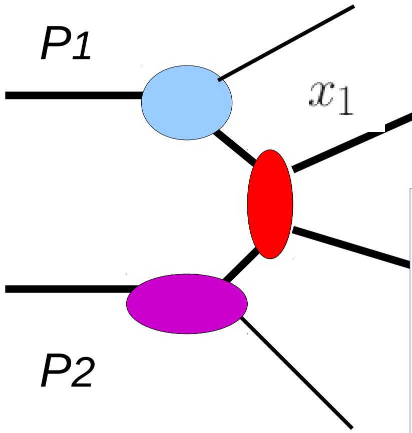

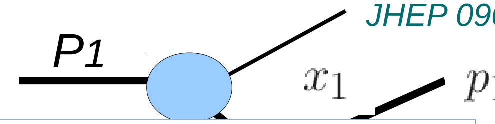

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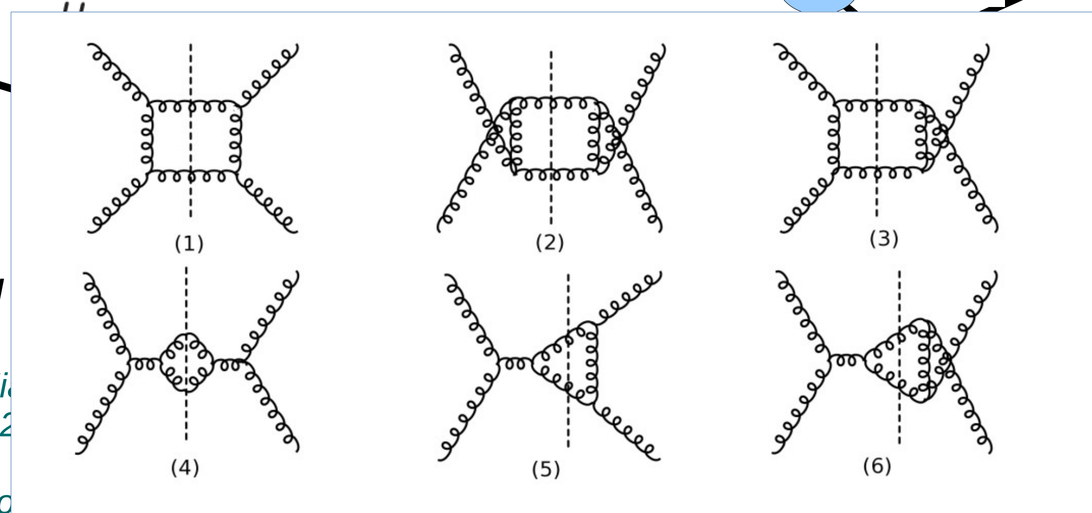

Generalization of hybrid
ME

Fabio Dominguez, Bo-Wen Xi
Phys.Rev.Lett. 106 (2011) 022

F. Dominguez, C. Marquet, Bo
Phys.Rev. D83 (2011) 105005

Appropriate in back-to-back configuration

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Marquet , E. Petreska , S. Sapeta,
A. van Hameren, JHEP 1509 (2015) 106

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T. Altinoluk, R. Boussarie, Piotr Kotko JHEP 1905 (2019) 156

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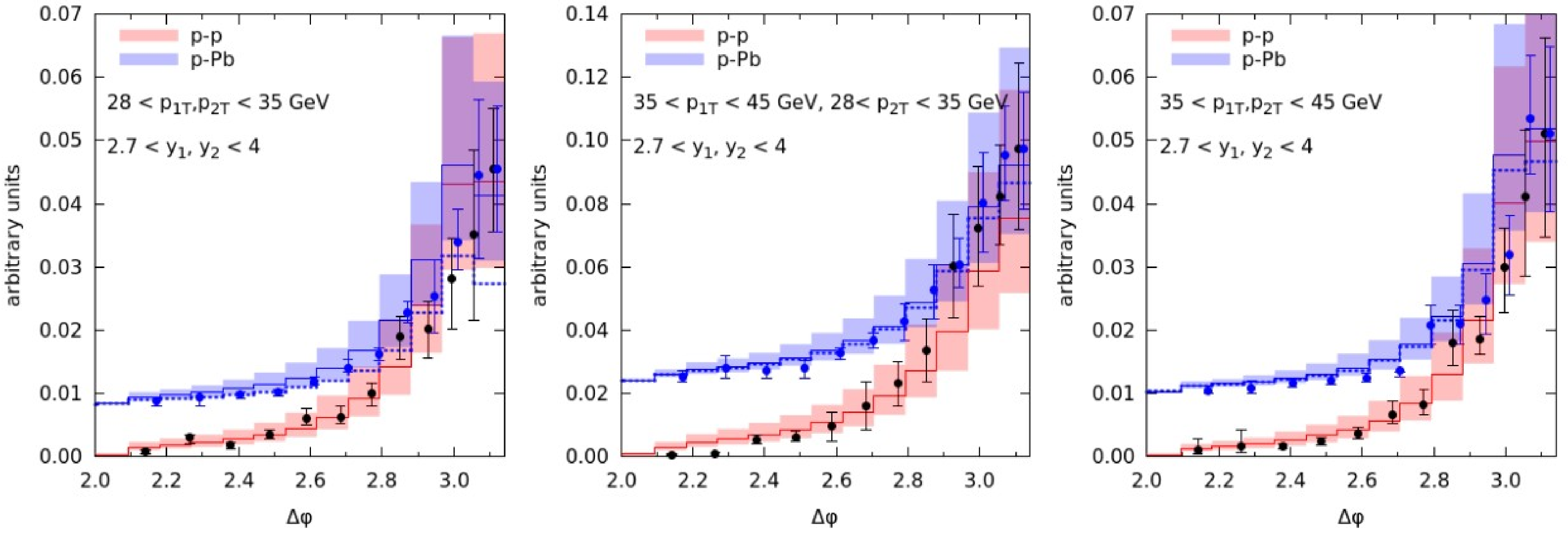
Signature of broadening in forward-forward dijets

ATLAS Phys.Rev. C100 (2019) no.3, 034903

A. Hameren, P. Kotko, K. Kutak, S. Sapeta
Phys.Lett. B795 (2019) 511-515



Data: number of dijets normalized to number of single inclusive jets. We can not calculate that.
We can compare shapes.
Procedure: fit normalization to p-p data.
Use that both for p-p and p-Pb. Shift p-Pb data
The procedure allows for visualization of broadening

Summary

- *New TMD introduced: i.e. nTMD’s using PB method*
- *Good description of data within kt factorization*
- *Parton branching shower works well*
- *Some steps towards generalization of splittings done*
- *Preliminary results for DIS*
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