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NCN

TMD distributions and jet physics predictions

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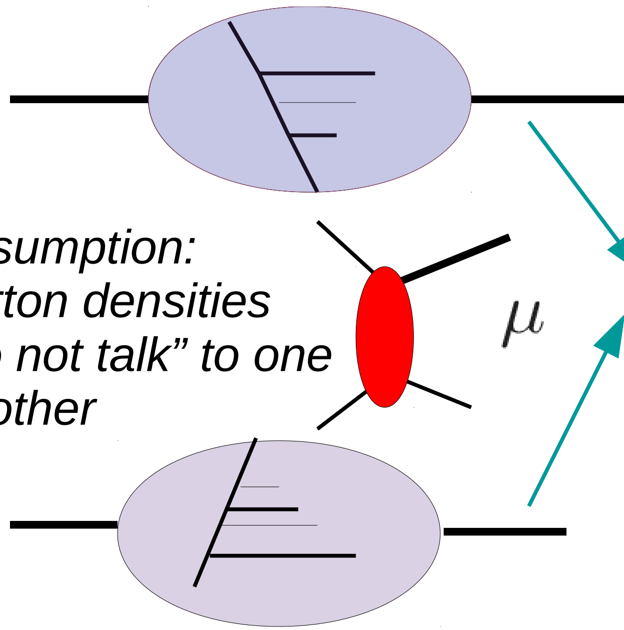
High Energy Factorization

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \sum_{c,d} \int \frac{d^2k_{1t}}{\pi}\frac{d^2k_{2t}}{\pi}\frac{1}{16\pi^2(x_1x_2s)^2}\overline{|\mathcal{M}_{g^*g^*\to cd}|}^2\ \mathcal{F}_A(x_1,k_{1t}^2,\mu^2)\,\mathcal{F}_B(x_2,k_{2t}^2,\mu^2)\,\frac{1}{1+\delta_{cd}}$$

originally derived for gg → QQ

rapidities and pt of produced jets



Assumption: parton densities “do not talk” to one another

Decreasing longitudinal momentum fractions of off-shell partons BFKL like

Decreasing longitudinal momentum fractions of off-shell partons BFKL like

μ *hard scale e.g. sum of pt of jets, used in DGLAP too*

k_t *transversal momentum of incoming gluon*

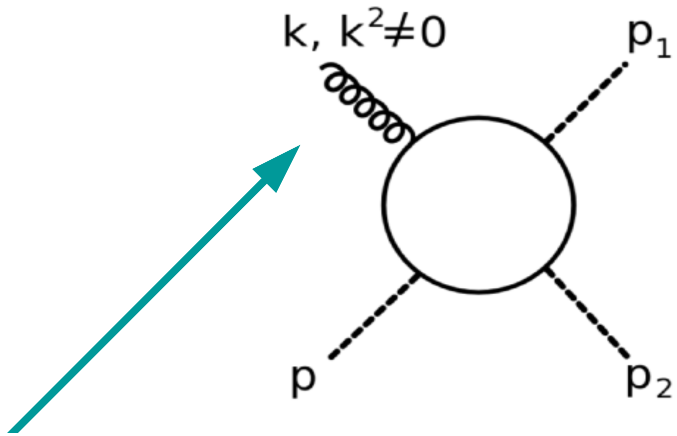
x *longitudinal momentum of incoming gluon In this framework of x of comparable values*

Gribov, Levin, Ryskin '81
Ciafaloni, Catani, Hautman '93

Does not take into account MPI as formulated in DGLAP i.e. emissions from independent chains

Helicity based method for any process
KK, Kotko, van Hameren '13
Further formal advancements by Serino , van Hameren '15

Off-shell matrix elements – old method



apply standard rules
to get matrix elements

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

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

Polarization of off-shell gluon

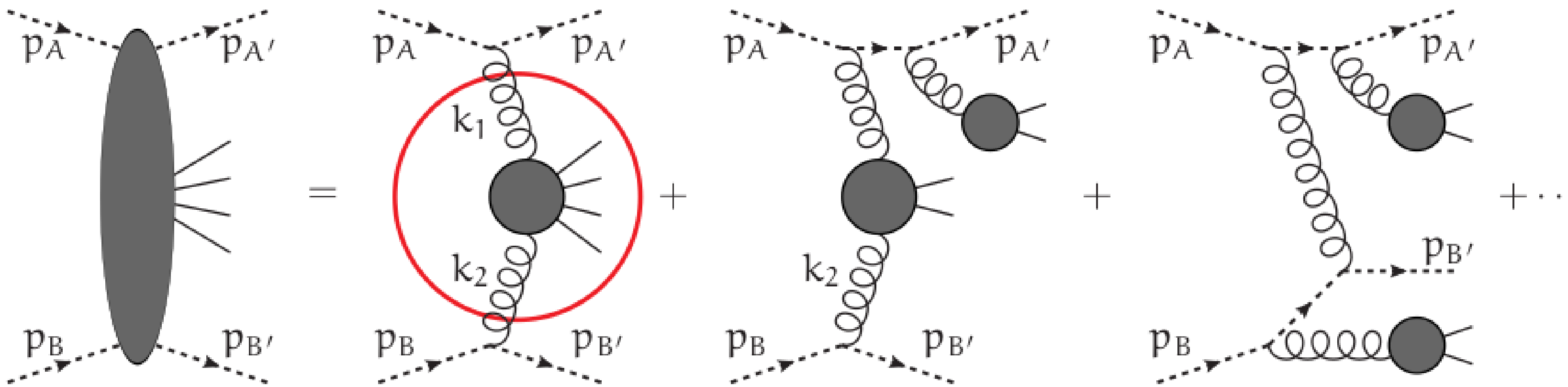
Effective action based approach
Lipatov 95, Lipatov, Vyazovsky 2000

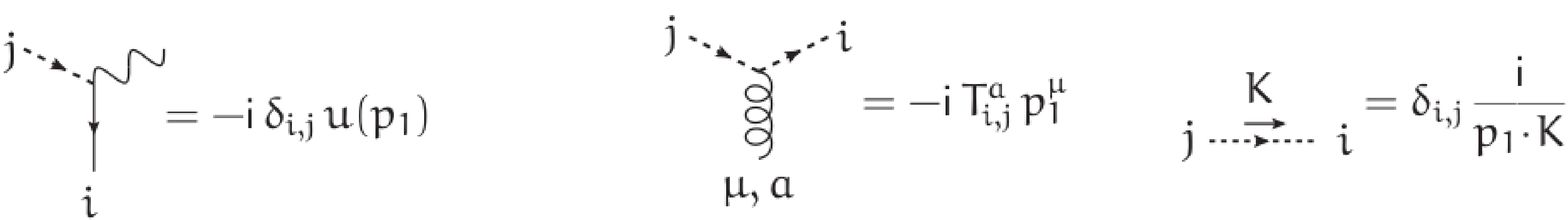
New gauge link based derivation
Kotko'14

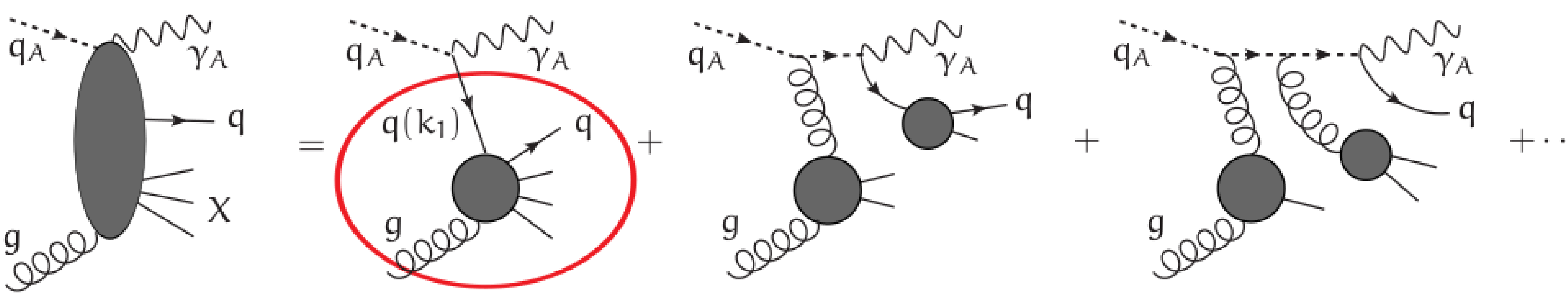
Off-shell matrix elements – modern method

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

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

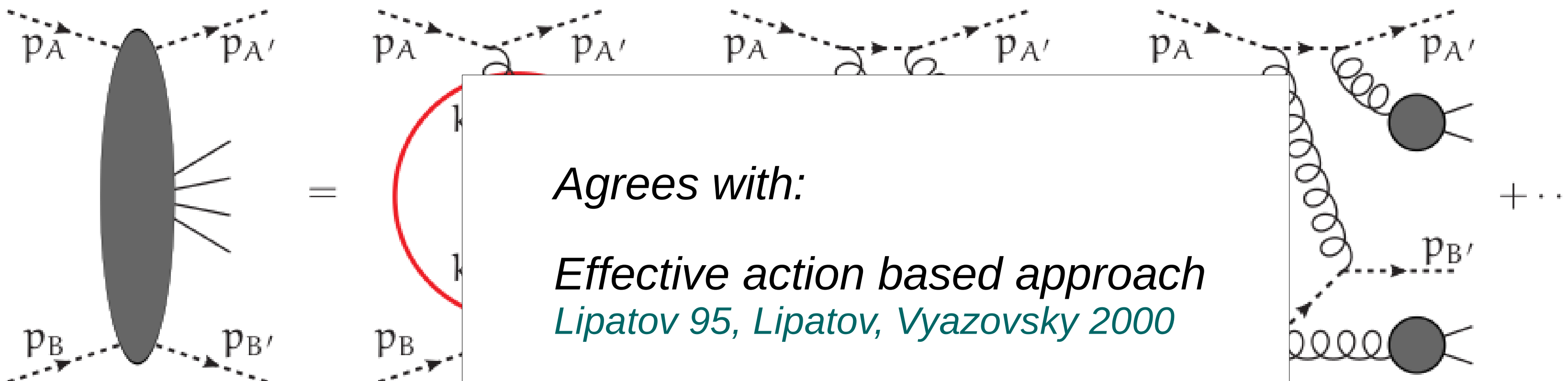






Off-shell matrix elements

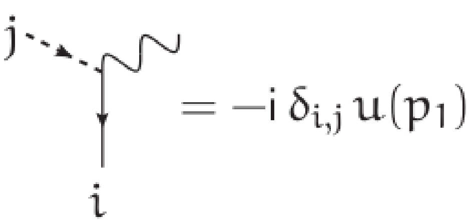
Kotko, KK, van Hameren 2013,
KK, Salwa, van Hameren 2013

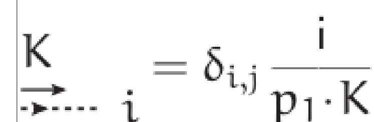


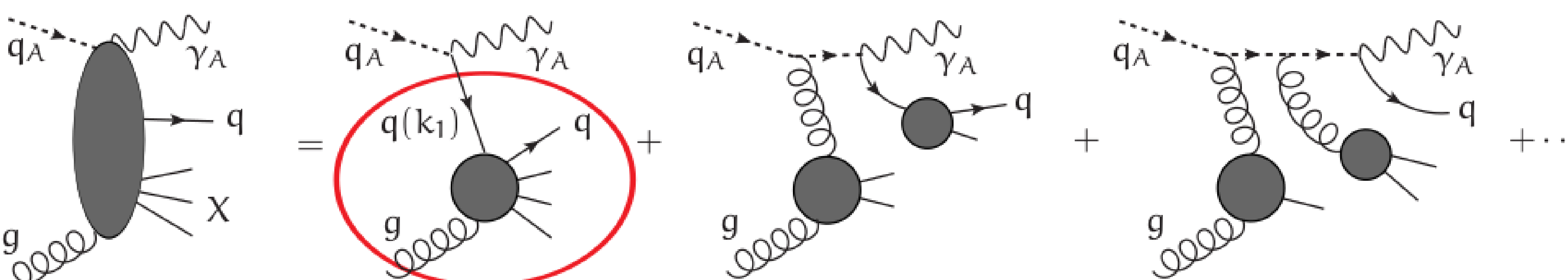
Agrees with:

Effective action based approach
Lipatov 95, Lipatov, Vyazovsky 2000

Gauge link based derivation
Kotko'14



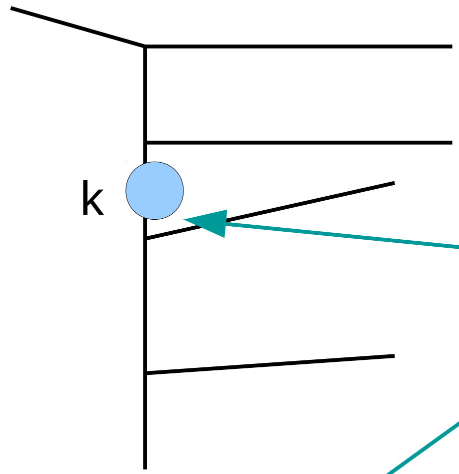




UPDF - Kimber Martin Ryskin Watt

The relevance in low x physics at linear level recognized by:
Catani, Ciafaloni, Fiorani, Marchesini; Kimber, Martin, Ryskin; Collins, Jung

μ and k_t



μ *hard scale*

Survival probability of the gap without emissions

Survival probability of the gap without emissions

Kimber, Martin, Ryskin, Watt procedure :

$$T_s(\mu^2, k^2) = \exp\left(-\int_{k^2}^{\mu^2} \frac{dk'^2}{k'^2} \frac{\alpha_s(k'^2)}{2\pi} \sum_{a'} \int_0^{1-\Delta} dz' P_{a'a}(z')\right)$$

$$\mathcal{F}(x, k^2, \mu^2) \sim \partial_{\lambda^2}(T(\lambda^2, \mu^2) x g(x, \lambda^2))|_{\lambda^2 = k^2}$$

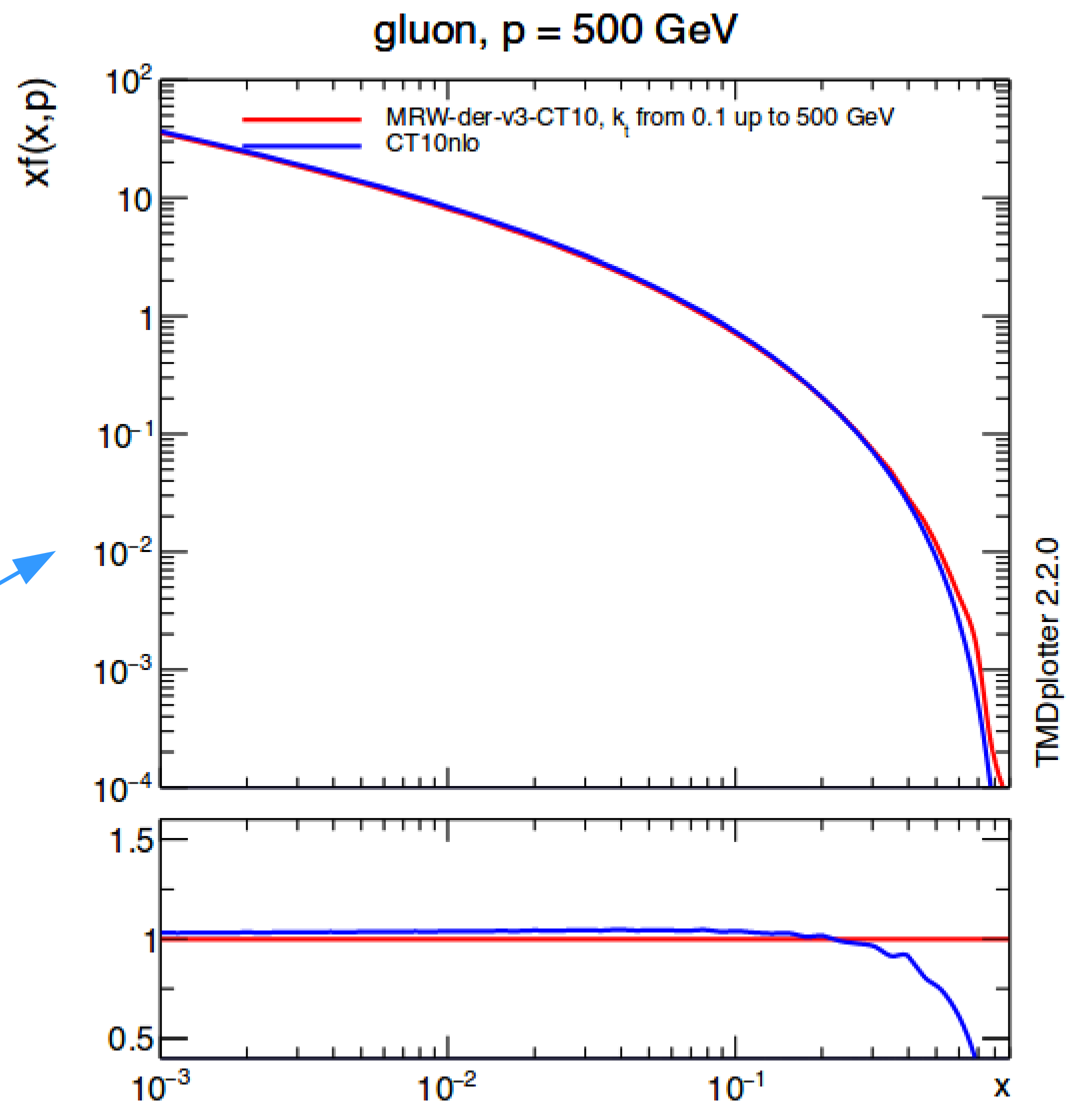
$$\Delta = \frac{\mu}{\mu + k}$$

One can also use TMD's recently obtained in 1708.03279 by *Jung, Hautmann, Lelek, Zlebcik*

Kimber Martin Ryskin Watt - uPDF

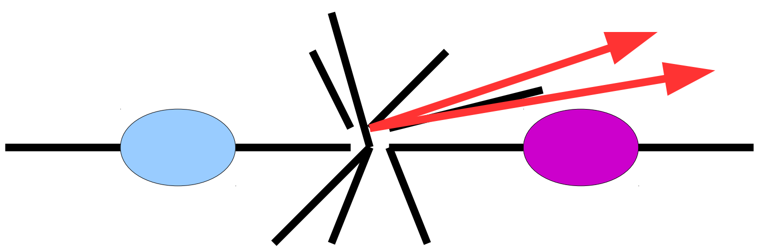
We have now program to obtain TMD PDFS using KMRW procedure both at LO and NLO accuracy.

The program has been written by PhD student Marcin Bury



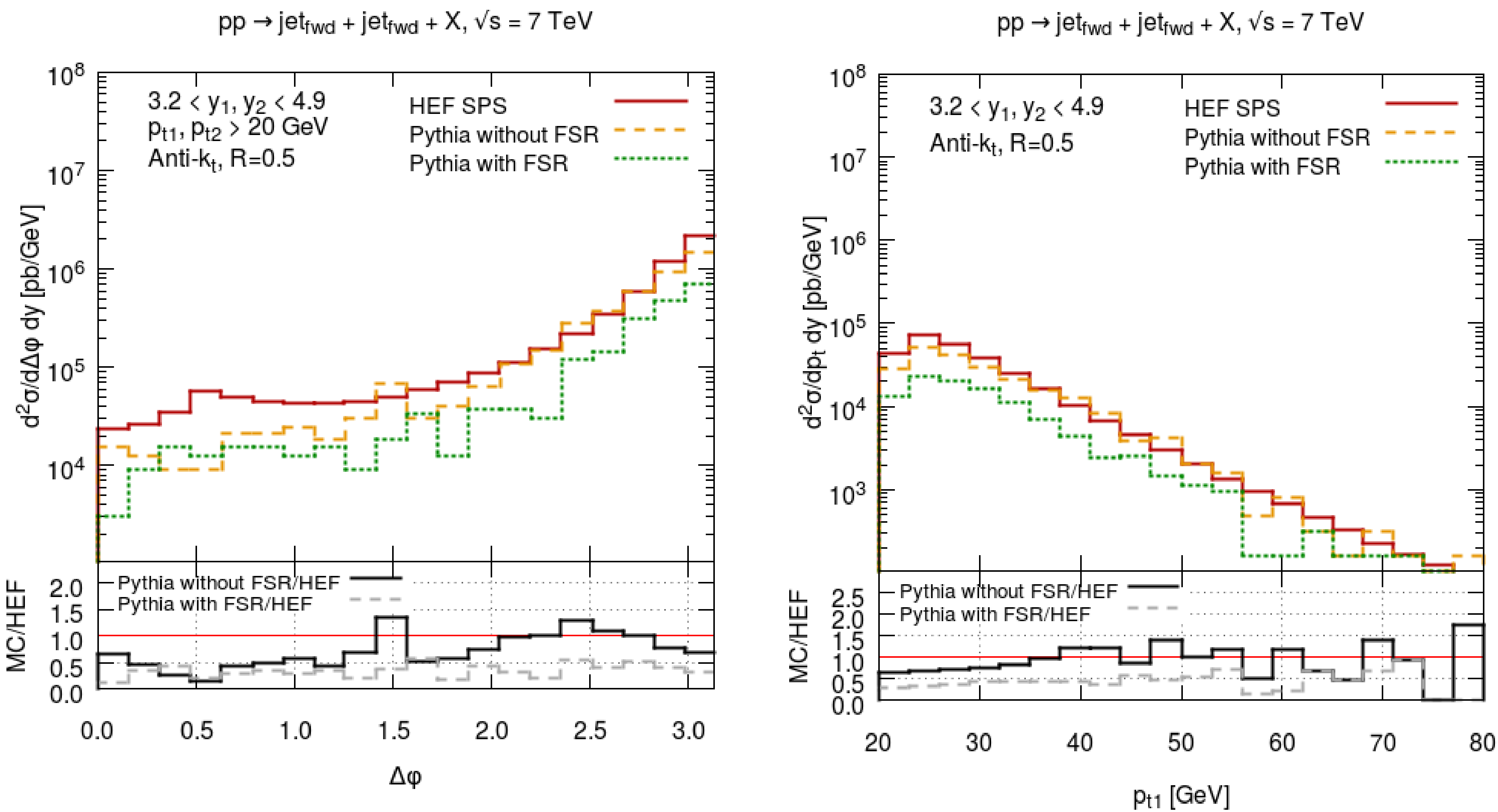
Integrating the gluon we get back collinear PDF

Forward-forward di-jets



HEF vs. PYTHIA: effect of FSR - forward-forward dijets

Bury, Deak , K.K, Sapeta '16



HEF framework with KMR PDFS → compatible with ISR in PYTHIA at moderate and large angles. Wide angle soft emissions lower cross section for hard jets

HEF with Monte Carlo tools

Matrix elements part

KaTie (A. van Hameren) 1611.00680

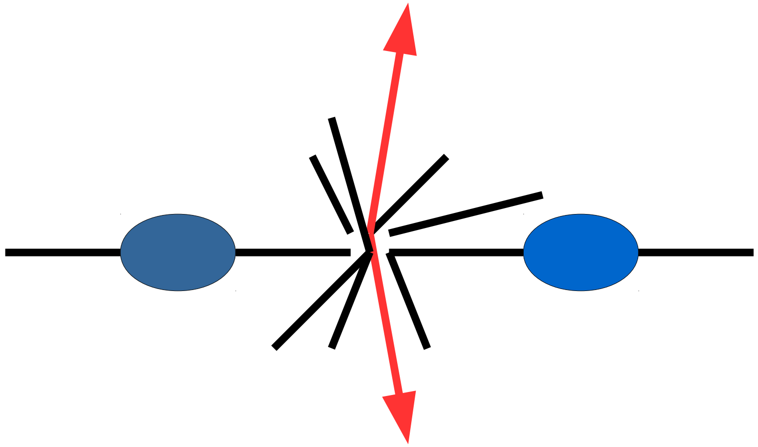
- *complete Monte Carlo program for tree-level calculations*
- *any process within the Standard Model*
- *any initial-state partons on-shell or off-shell*
- *employs numerical Dyson-Schwinger recursion to calculate helicity amplitudes*
- *automatic phase space optimization*

Shower part

CASCADE (H. Jung)

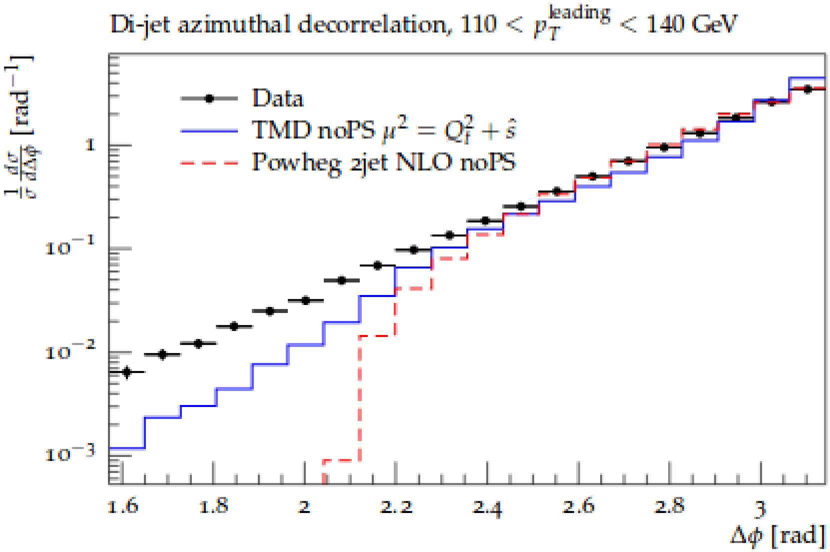
- k_t *factorization based Monte Carlo, program doing ISR and FSR.*
- *Can generate events using CCFM or KMRW pdfs. Uses PYTHIA for hadronization and FSR.*
- *Shower for quarks and gluons*

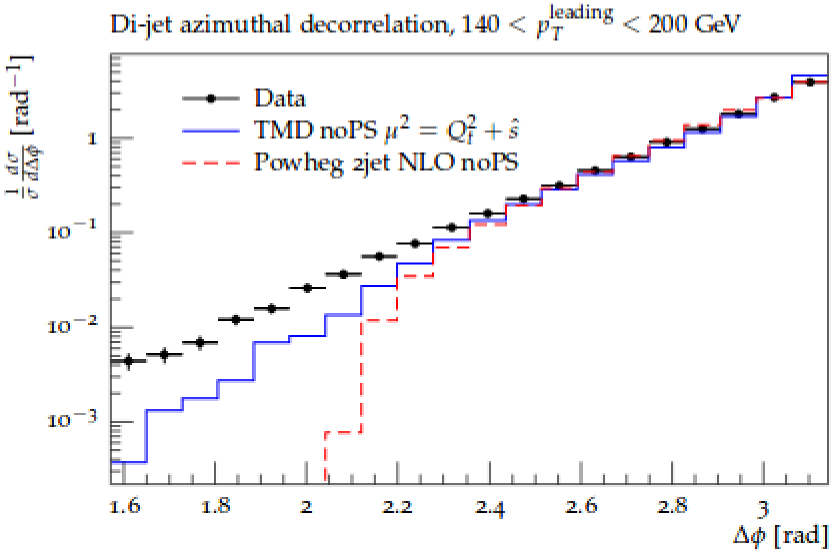
Central-central di-jets



Azimuthal angle correlations – no shower in HEF and Powheg

1712.05932 M. Bury, A. van Hameren, H. Jung, KK, S. Sapeta, M. Serino



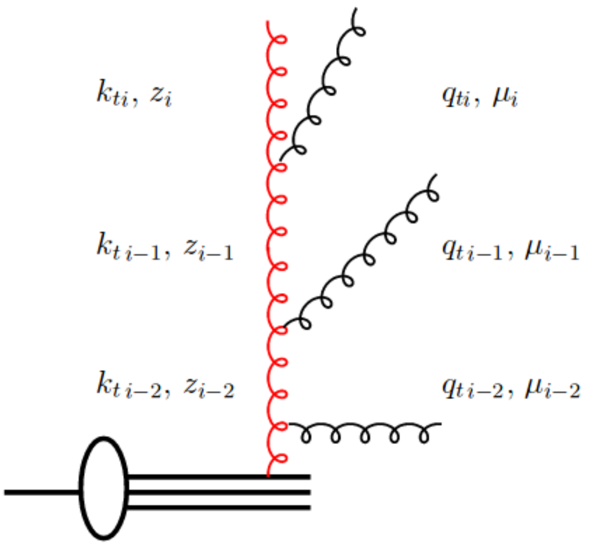


Too few high pt emissions in HEF

Momentum conservation prevents reaching larger angles in Powheg

Central-central dijets HEF including shower

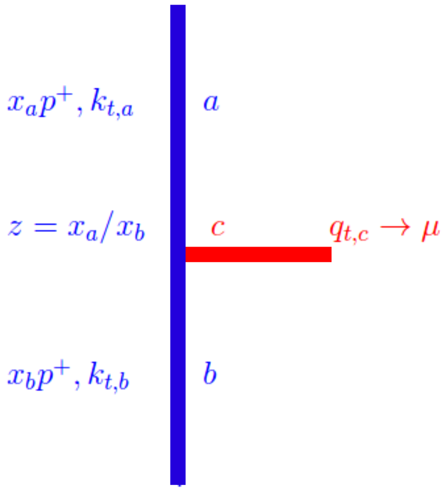
1712.05932 M. Bury, A. van Hameren, H. Jung, KK, S. Sapeta, M. Serino



Backward evolution and branching

- *Starting with hard scale the parton shower algorithm searches for next scale at which resolvable branching occurs. This scale is chosen from Sudakov form factor*

$$\Delta_S(x,\mu_i,\mu_{i-1}) = \exp\left[-\int_{\mu_{i-1}}^{\mu_i}\frac{d\mu'}{\mu'}\frac{\alpha_s(\tilde{\mu}')}{2\pi}\sum_a\int dz P_{a\to bc}(z)\frac{x'\mathcal{A}_a(x',k_t',\mu')}{x\mathcal{A}_b(x,k_t,\mu')}\right]$$

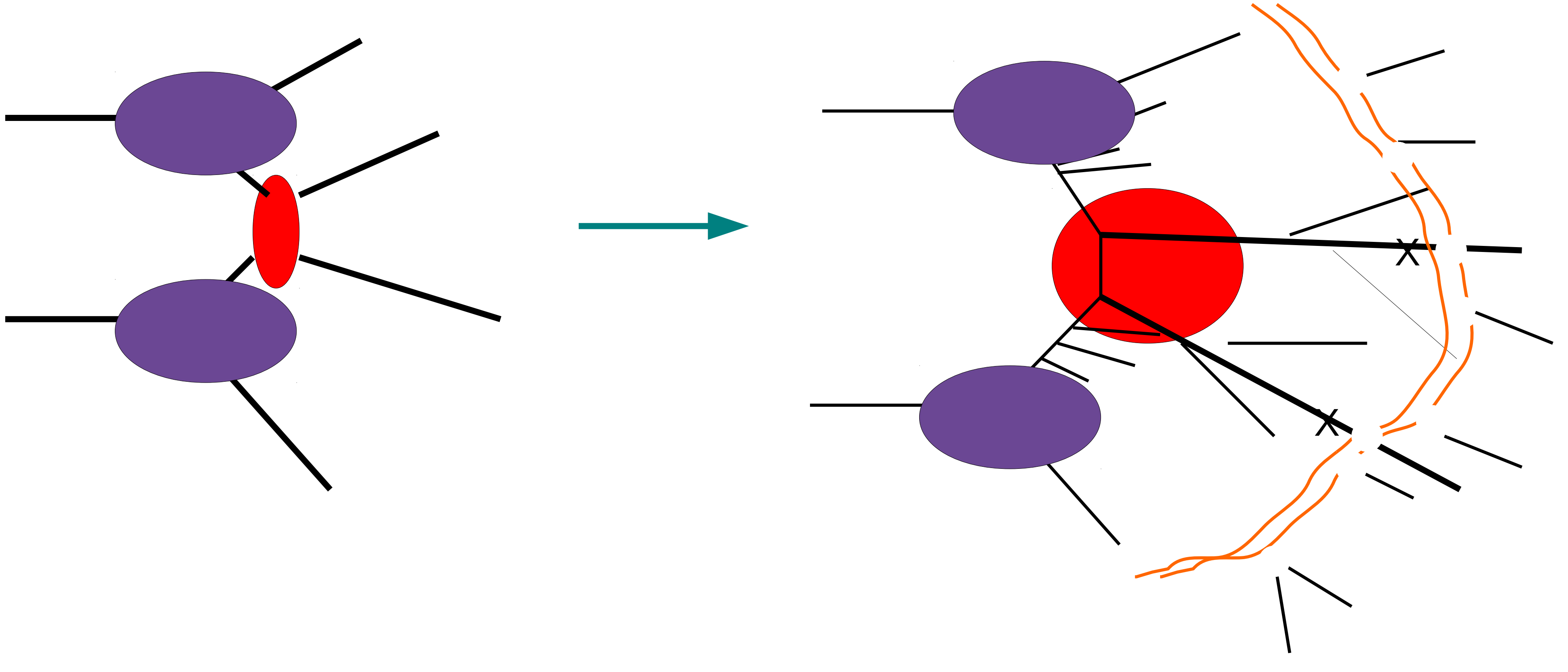


- *The transverse momentum can be obtained by giving physical interpretation to the evolution scale which is associated with angle of emission.*

- *Once the transversal scale of emitted gluon is known one can obtain the kt of exchanged gluon*

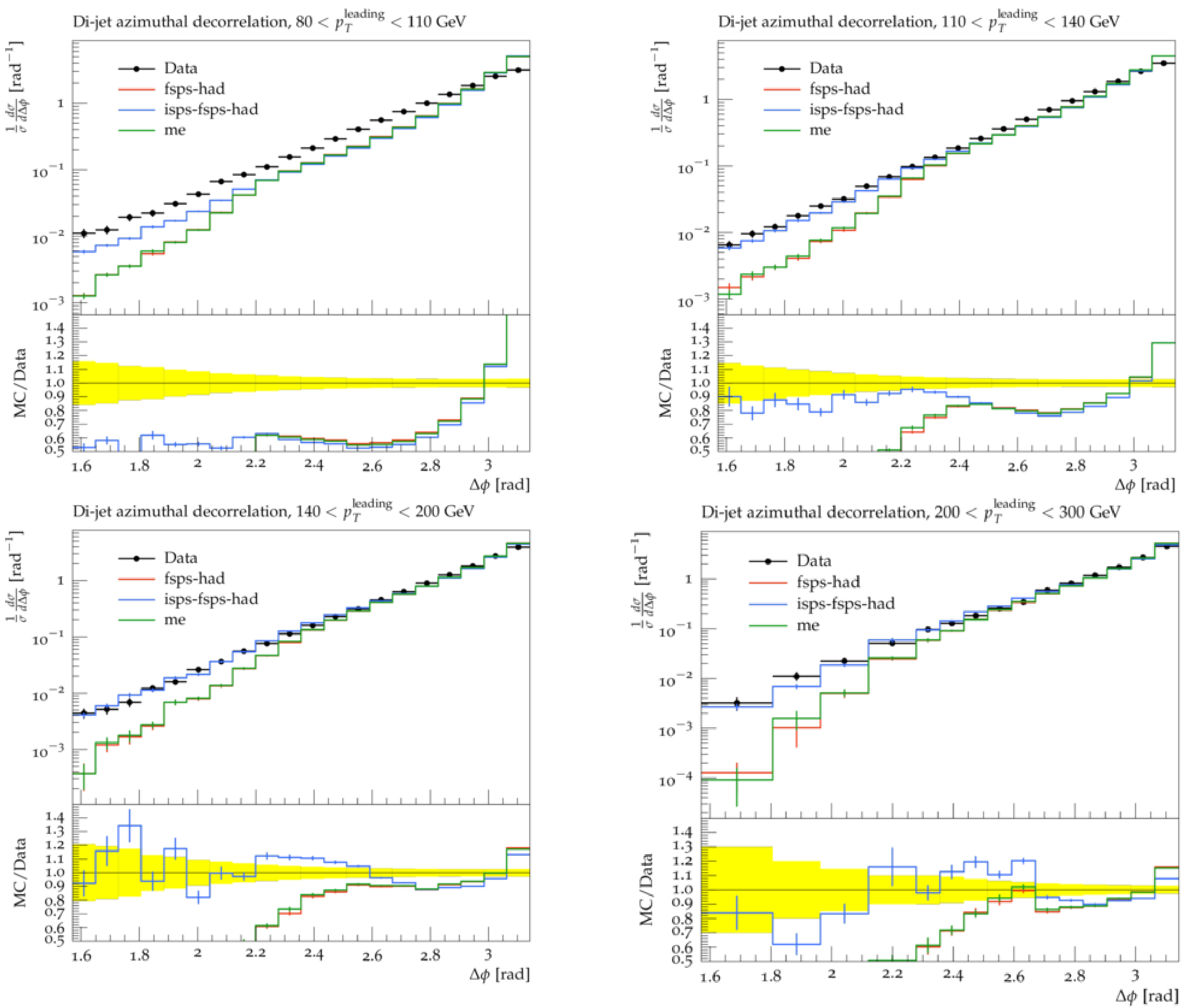
- *The whole procedure continues until cutoff (lowest scale) is reached*

Central-central dijets HEF including shower



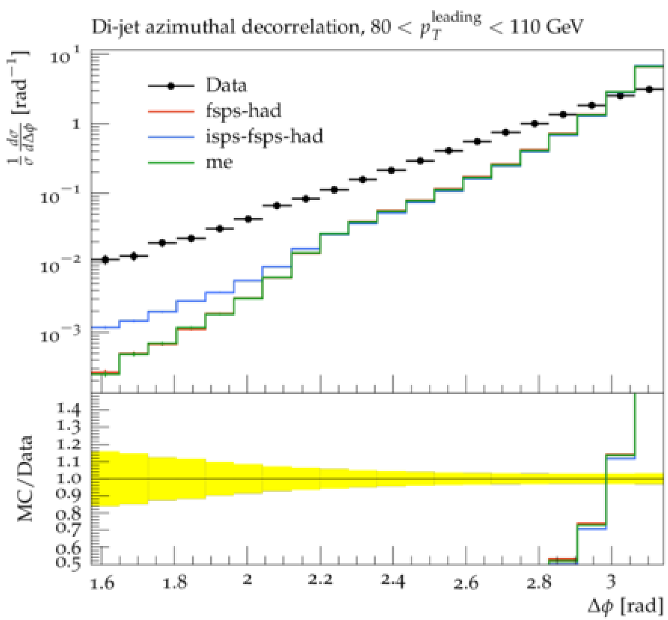
Azimuthal angle correlations - angular scale choice

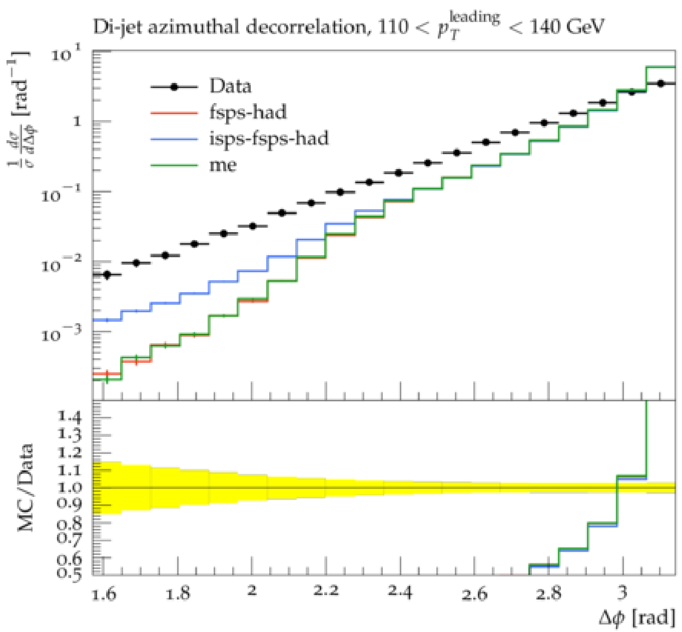
1712.05932 M. Bury, A. van Hameren, H. Jung, KK, S. Sapeta, M. Serino

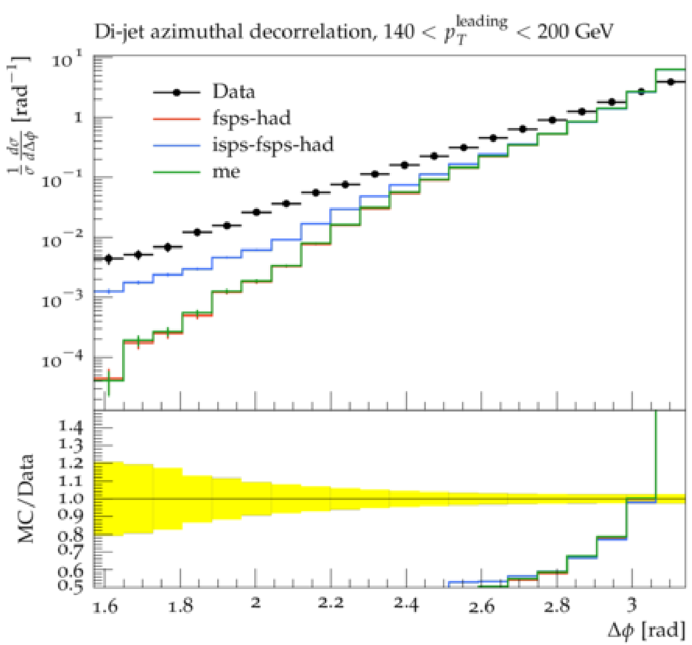


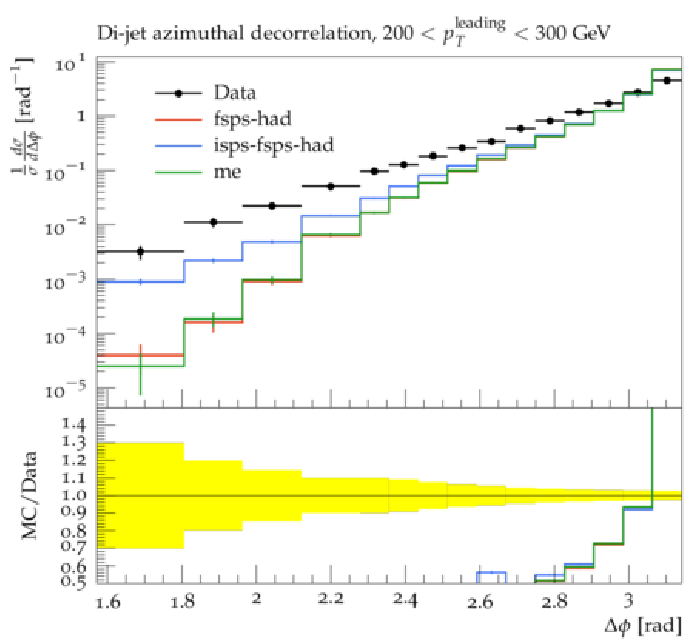
Azimuthal angle correlations – p_T ordering

1712.05932 M. Bury, A. van Hameren, H. Jung, KK, S. Sapeta, M. Serino



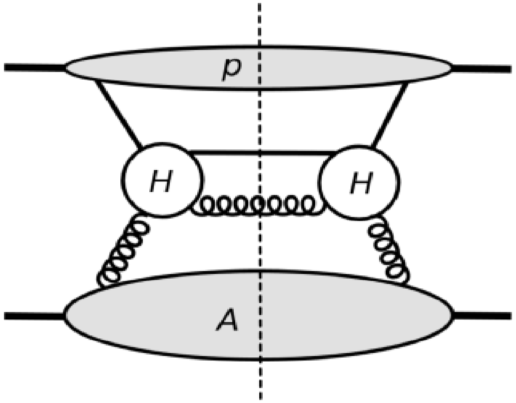






Theory developments TMD for dijets

The used factorization formula for dijets is strictly valid for large transversal momentum and was obtained in a specific gauge. Ultimately we want to go beyond this

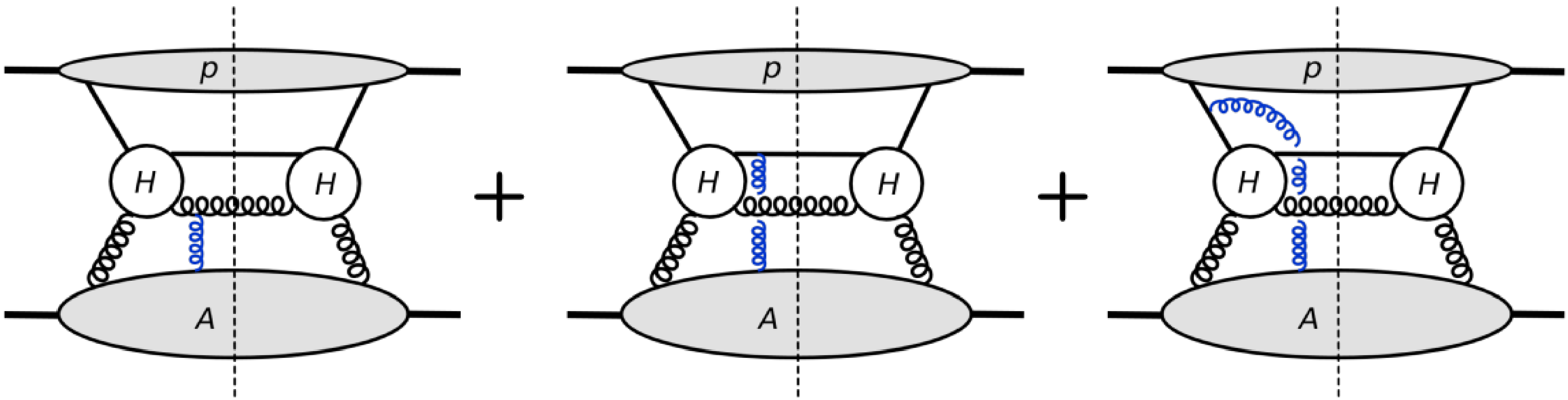


$$\mathcal{F}_{g/A}(x_2, k_t) \overset{\text{naive}}{=} 2 \int \frac{d\xi^+ d^2\boldsymbol{\xi}_t}{(2\pi)^3 p_A^-} e^{i x_2 p_A^- \xi^+ - i k_t \cdot \boldsymbol{\xi}_t} \langle A | \mathrm{Tr} \left[F^{i-} \left(\xi^+, \boldsymbol{\xi}_t \right) F^{i-}(0) \right] | A \rangle$$

Gauge link formulation leads to following generalization of formula above...

Bomhof, Mulders and Pijlman '16.

Towards TMD for dijets in pA – gauge link



+ similar diagrams with 2,3,….gluon exchanges.

Bomhof, Mulders, Pijlman 06

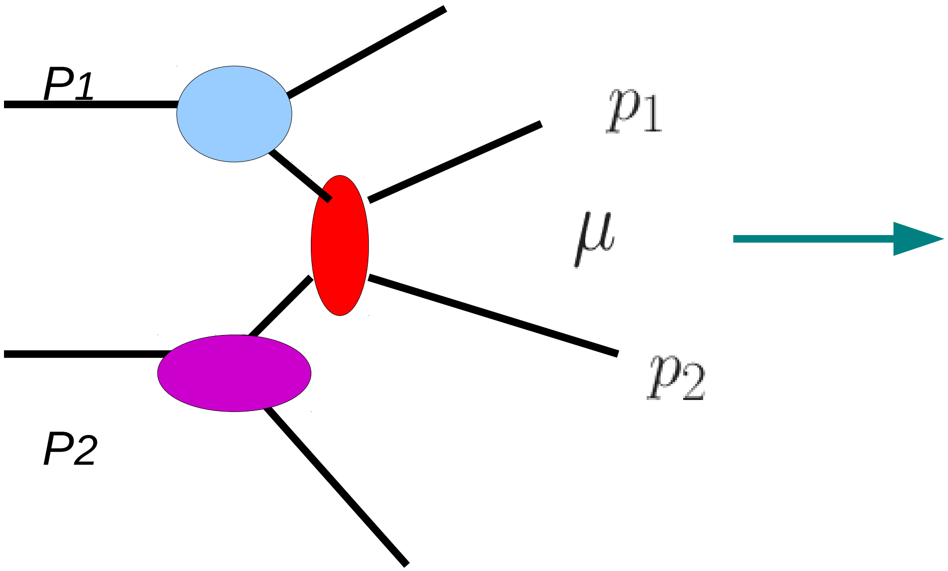
All this need to be resummed

This is achieved via gauge link which renders the gluon density gauge invariant

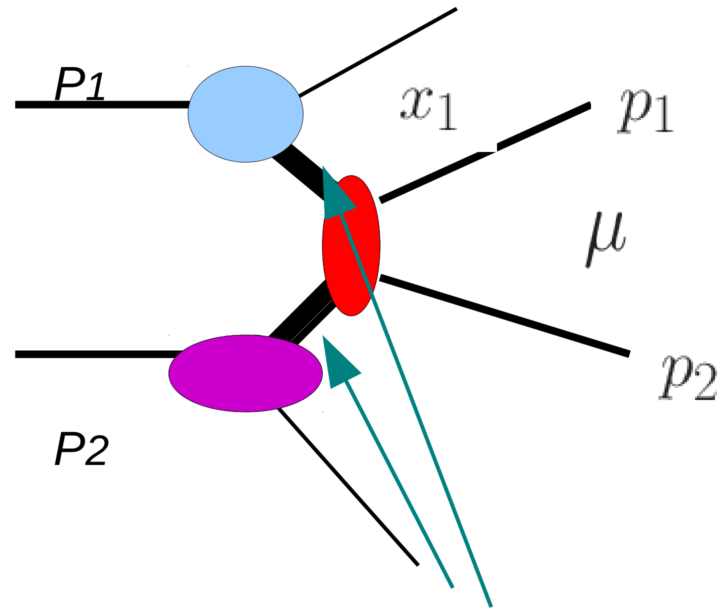
$$\mathcal{P}\exp\left[-ig\int_{\alpha}^{\beta} d\eta^{\mu} A^{a}(\eta) T^{a}\right]$$

$$\mathcal{F}_{g/A}(x_2, k_t) = 2\int \frac{d\xi^{+} d^{2}\boldsymbol{\xi}_t}{(2\pi)^3 p_A^{-}} e^{ix_2 p_A^{-}\xi^{+} - ik_t\cdot\boldsymbol{\xi}_t} \langle A|\mathrm{Tr}\left[F^{i-}\left(\xi^{+}, \boldsymbol{\xi}_t\right) U_{[\xi,0]} F^{i-}(0)\right]|A\rangle$$

Improved TMD for dijets



can be be used for estimates of saturation effects.



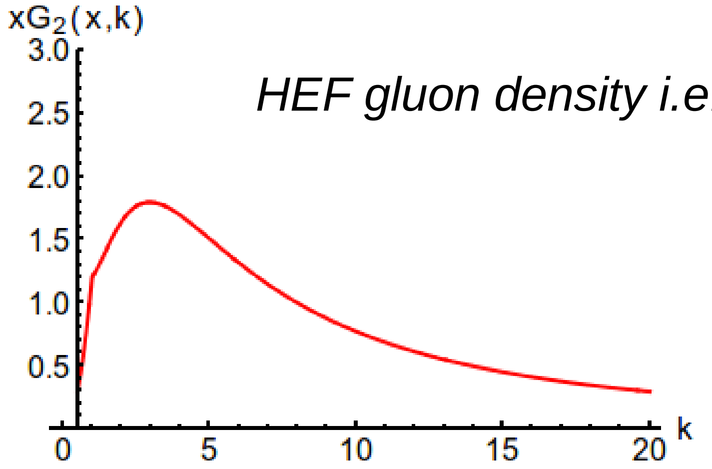
Application to low x in saturation region
Dominguez, Marquet, Xiao, Yuan '11

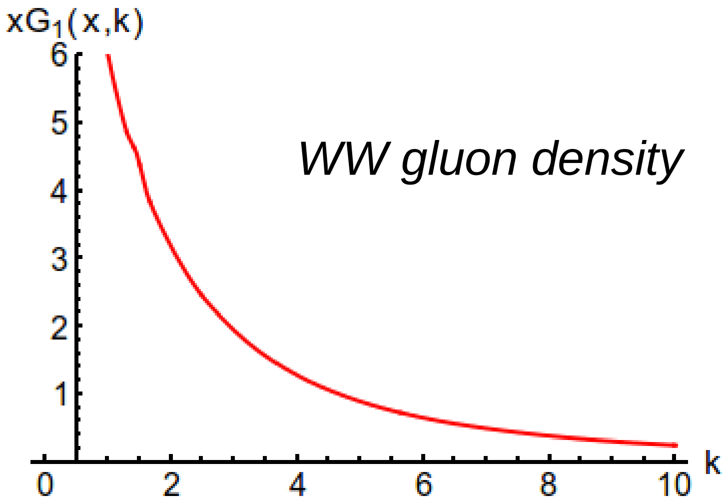
Extension to account for kt in ME
Kotko, KK, Marquet, Petreska, Sapeta, van Hameren '16

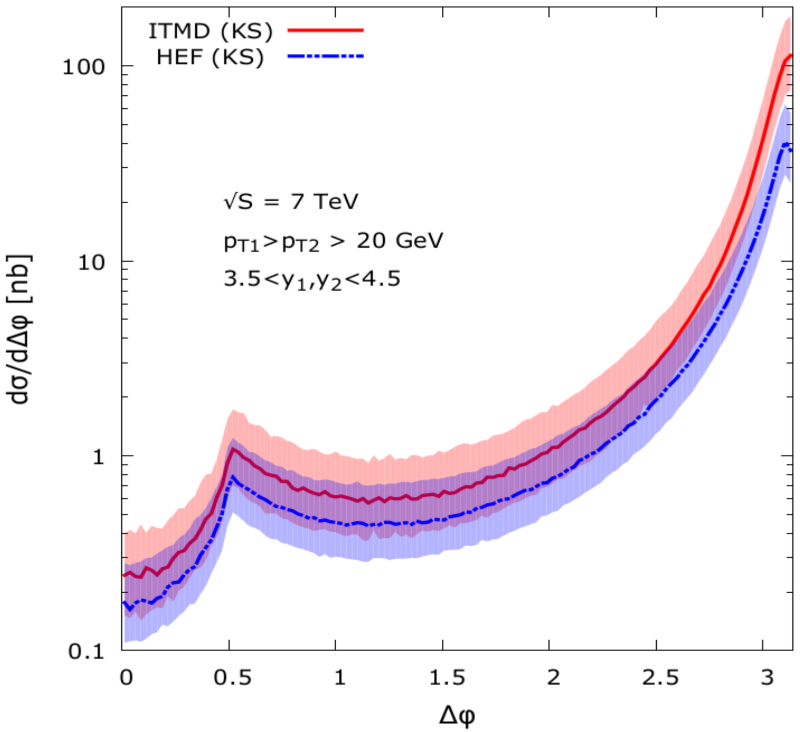
color exchanges between target and hard part resummed in terms of gauge links

Glimpse on the first results – HEF vs. ITMD

Kotko, KK, Marquet, Petreska, Sapeta, van Hameren '16







In large Nc on can express WW UGD in terms of dipole UGD. We use this approximation

Outlook

More extensive comparison to already accumulated data for p+p, and p+A using KaTie + CASCADE

Refinement of used TMDs i.e. fits to latest data

Study of performance of the shower i.e. comparison of 2 –> 4 using ME or using
2 – > 2 +shower

Corrections of higher orders to ME

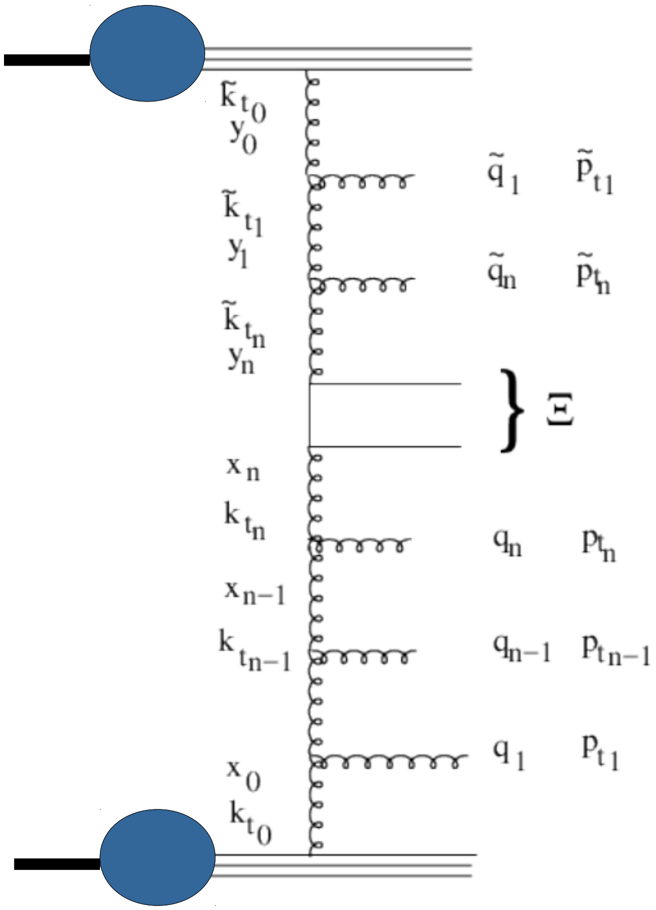
Ongoing development for p+A, A+A

Parton densities from system of evolution equations for TMD PDFs

Later today detailed KaTie presentation by Andreas van Hameren and tutorial on usage KaTie and CASCADE

Back up

Angular ordered parton shower



$$p_q + p_{\bar{q}} = \Upsilon(p^{(1)} + \Xi p^{(2)}) + Q_t$$

$$Y = \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right) = \frac{1}{2}\log\left(\frac{1}{\Xi}\right)$$

$$\begin{aligned} E &= E_q + E_{\bar{q}}\,, p_z = p_{q\,z} + p_{\bar{q}\,z} \\ \Rightarrow & \quad E + p_z = \Upsilon\sqrt{s}\,, E - p_z = \Upsilon\Xi\sqrt{s} \end{aligned}$$

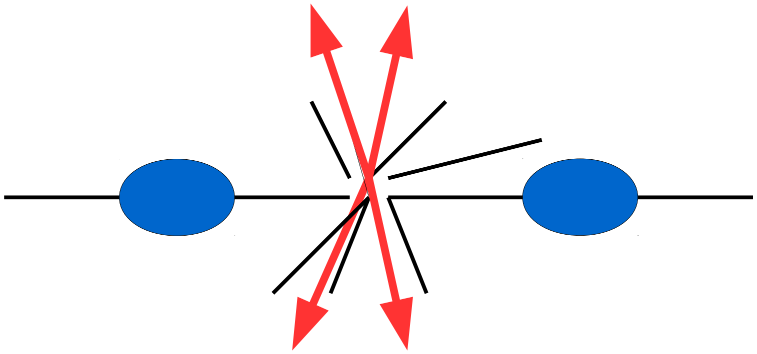
$$\begin{aligned} p_i &= \upsilon_i(p^{(1)} + \xi_i p^{(2)}) + p_{ti}\,, \\ \xi_i &= \frac{p_{ti}^2}{s\upsilon_i^2}\,, \upsilon_i = (1-z_i)x_{i-1}\,, x_i = z_i x_{i-1} \end{aligned}$$

$$\xi_0 < \xi_1 < \cdots < xi_n < \Xi$$

$$z_{i-1}q_{i-1} < q_i\,, q_i = x_{i-1}\sqrt{s\xi_i} = \frac{p_{ti}}{1-z_i}$$

$$\mu^2 \equiv Q^2 = \Upsilon^2\,\Xi\, s = \hat{s} + Q_t^2 = (p_q + p_{\bar{q}})^2 + Q_t^2$$

4 inclusive central jets



Azimuthal angle correlations – p_T ordering

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