Parton dynamics and colour condensates

Elena Petreska

Nikhef/VU Amsterdam

How to learn about:

- ⋈ The structure of protons and nuclei when they are accelerated to high velocities.

- ⋈ Phenomena of the strong interactions under extreme conditions, e.g. gluon saturation, quark-gluon plasma formation.

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⋈ The structure of protons and nuclei when they are accelerated to high velocities.

⋈ Phenomena of the strong interactions under extreme conditions, e.g. gluon saturation, quark-gluon plasma formation.

⋈ Factorization theorems of QCD at high energy

From collinear factorization to transverse-momentum-dependent (TMD) factorization

⋈ Effective field theories of QCD at high energy

Color Glass Condensate (CGC) effective theory

Typical proton-proton collision at high energy

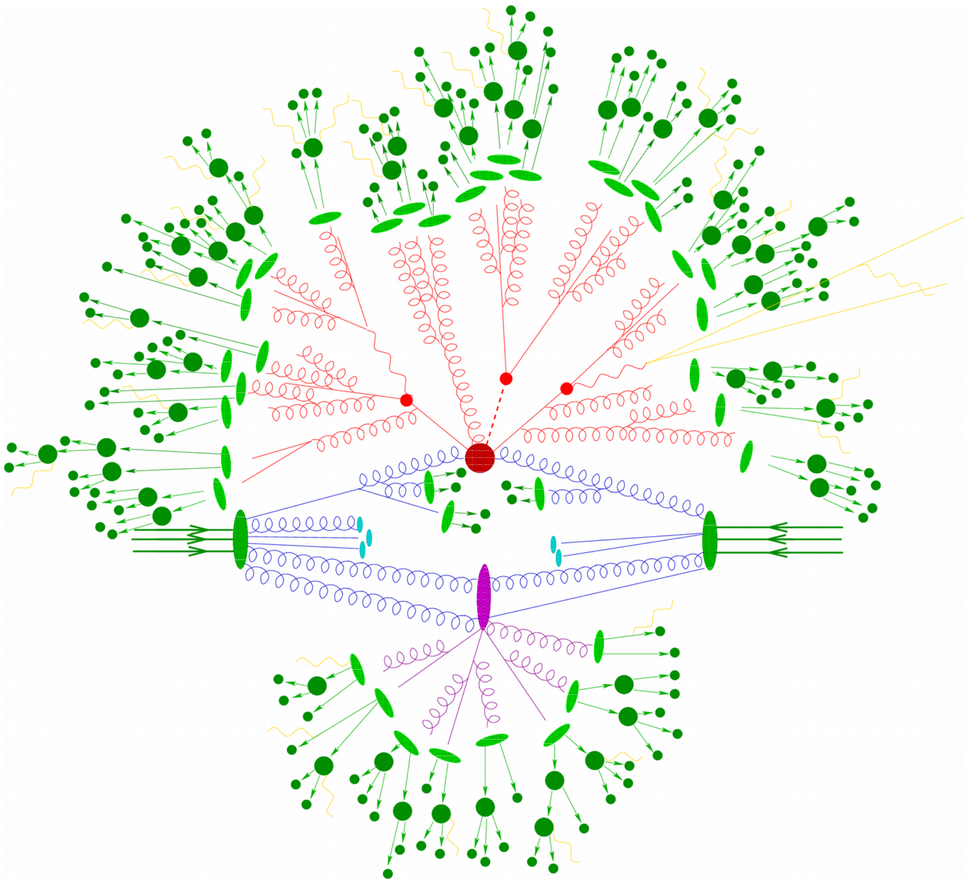
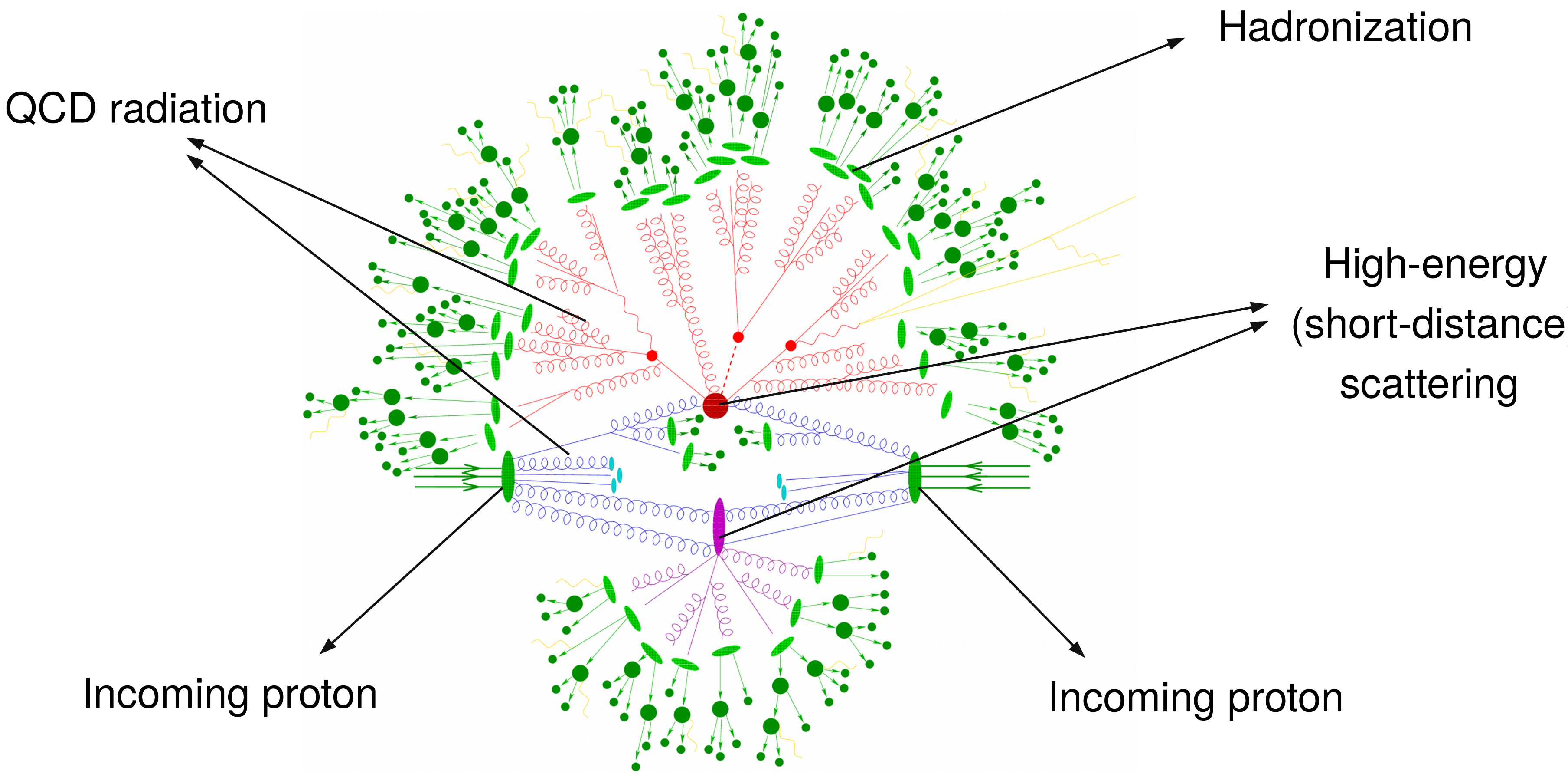


Fig. by Sherpa (R. Teuscher)

Typical proton-proton collision at high energy



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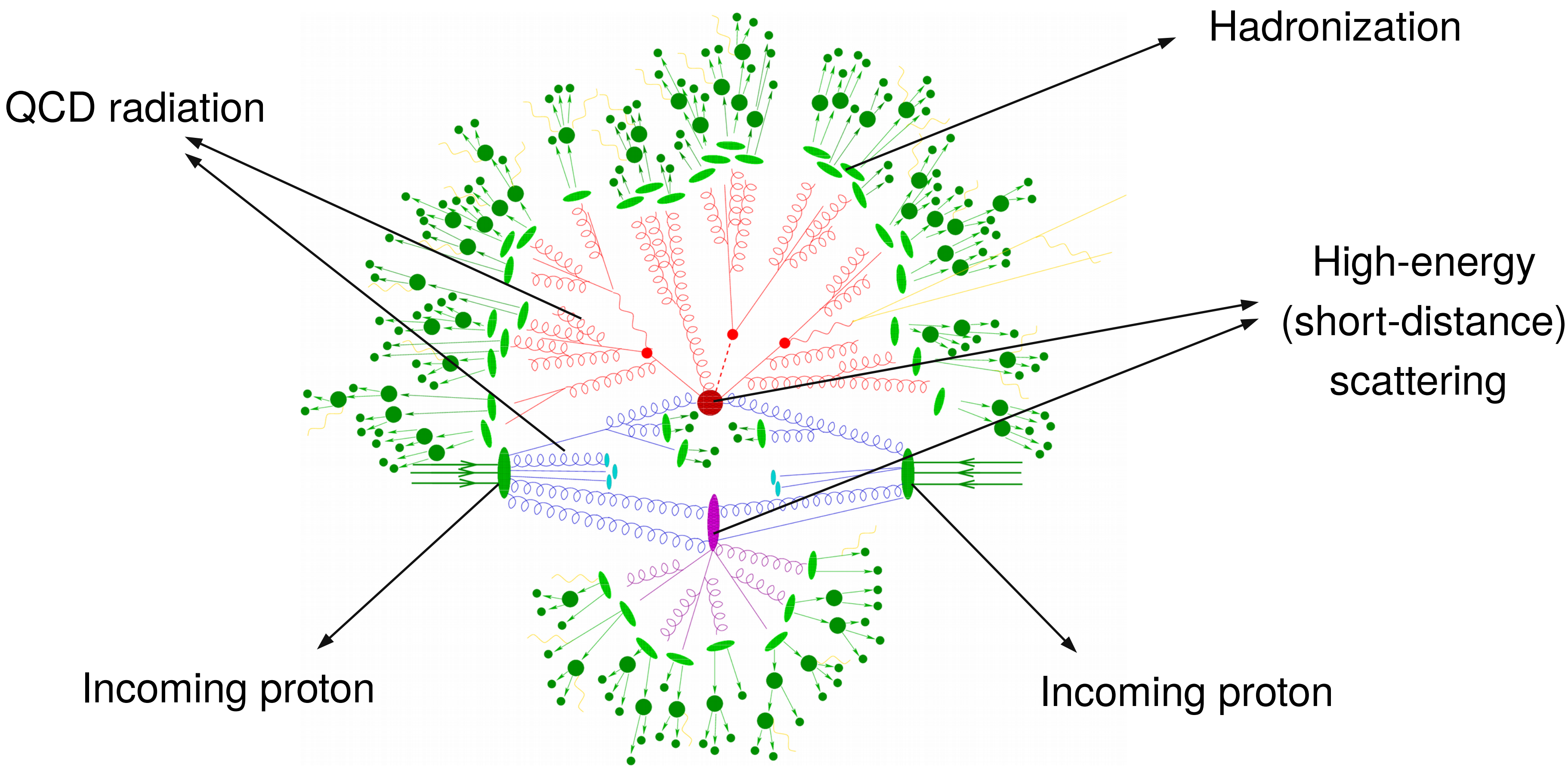

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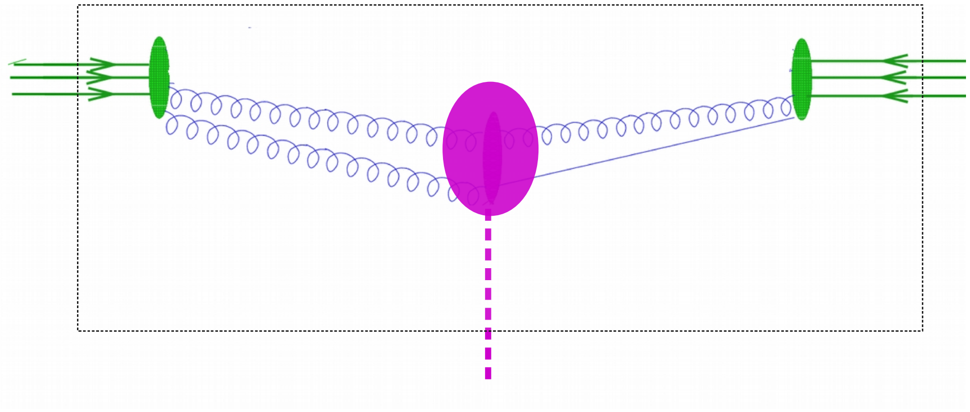
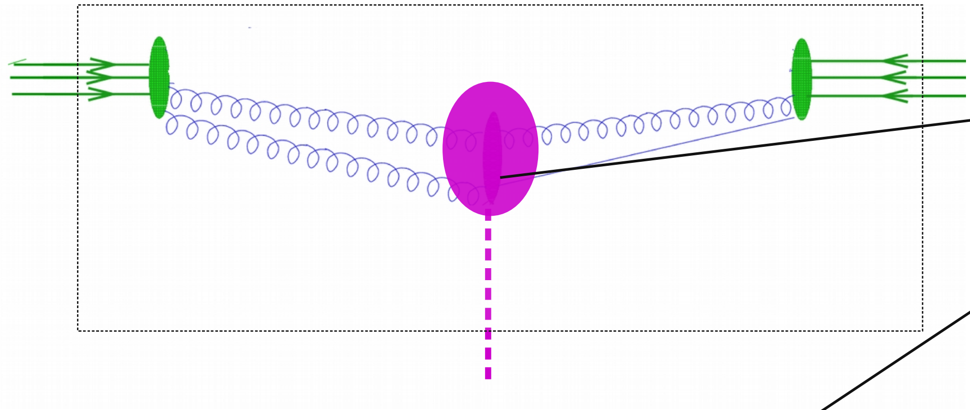
Factorize the cross section

E.g. Higgs production



$$\sigma \sim f_A(x_1) \otimes f_B(x_2) \otimes \sigma_{\text{partonic}} \otimes \text{final state}$$

E.g. Higgs production



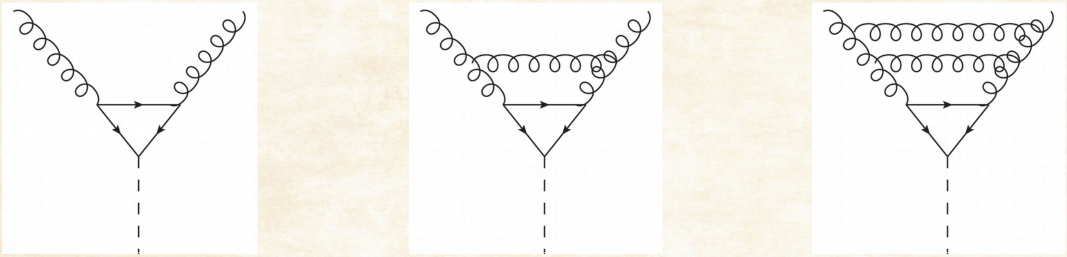
High-energy (short-distance) scattering

$$\sigma \sim f_A(x_1) \otimes f_B(x_2) \otimes \sigma_{\text{partonic}} \otimes \text{final state}$$

Perturbative physics is contained in the short-distance (partonic) cross section:

$$\sigma_{\text{partonic}} \sim \alpha_s^2 \sigma_{\text{partonic}}^{LO} + \alpha_s^3 \sigma_{\text{partonic}}^{NLO} + \alpha_s^4 \sigma_{\text{partonic}}^{NNLO} + \alpha_s^5 \sigma_{\text{partonic}}^{N3LO} + \cdots$$

e.g.



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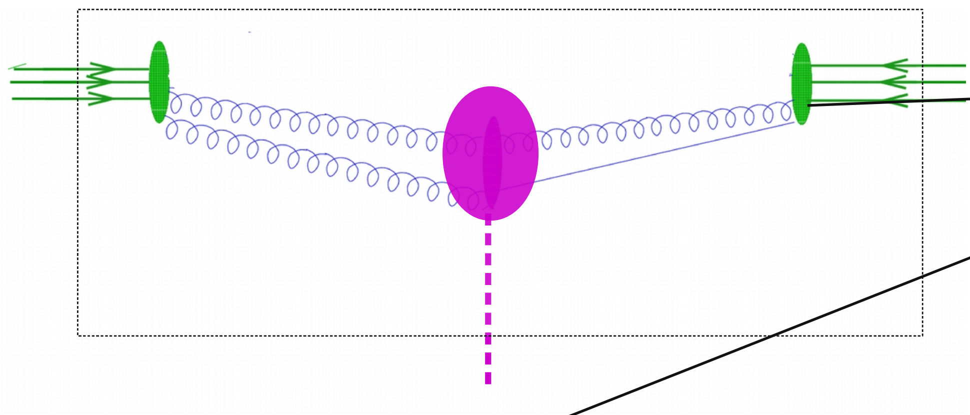


Parton distribution functions (PDFs)

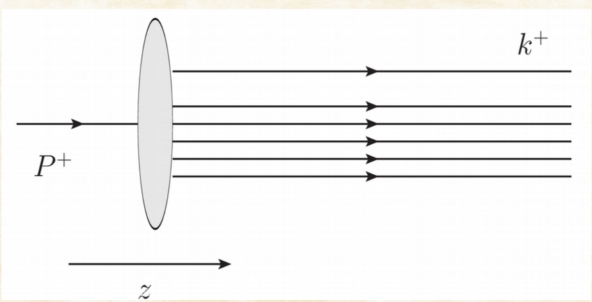
One-dimensional image of the proton

$$\sigma \sim f_A(x_1) \otimes f_B(x_2) \otimes \sigma_{\text{partonic}} \otimes \text{final state}$$

Describe the incoming protons with parton distribution functions (PDFs) → One dimensional

⋈ The PDFs are probability densities for finding a parton (quark, antiquark or gluon) with a longitudinal momentum fraction x in the incoming proton at the resolution scale relevant for the problem.

Infinite momentum frame

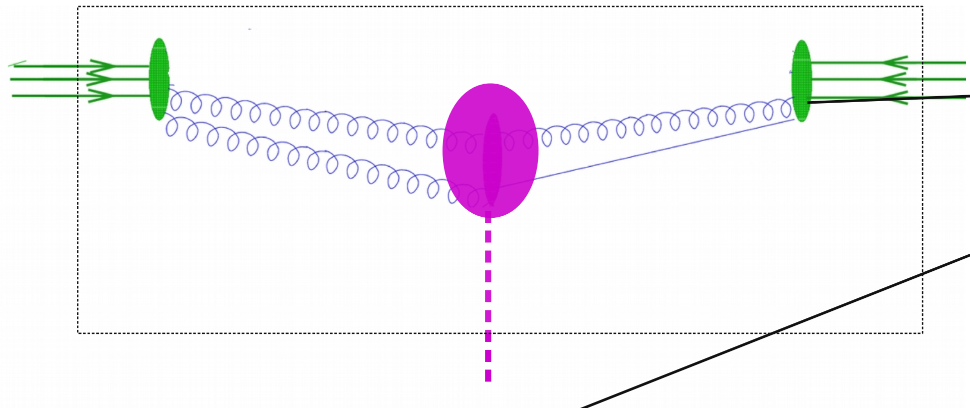


1D :

$$x = \frac{k^+}{p^+}$$

$$f(x)$$

E.g. Higgs production



Parton distribution functions (PDFs)

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Describe the incoming protons with parton distribution functions (PDFs) → One dimensional

⋈ The PDFs are probability densities for finding a parton (quark, antiquark or gluon) with a longitudinal momentum fraction x in the incoming proton at the resolution scale relevant for the problem.

⋈ The PDFs are non-perturbative, they cannot be calculated from first principles.

Collinear factorization

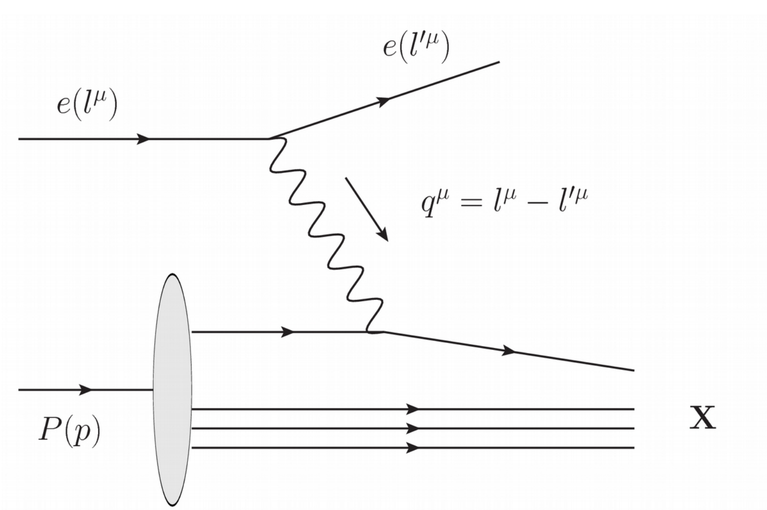
⋈ Factorize the cross section in

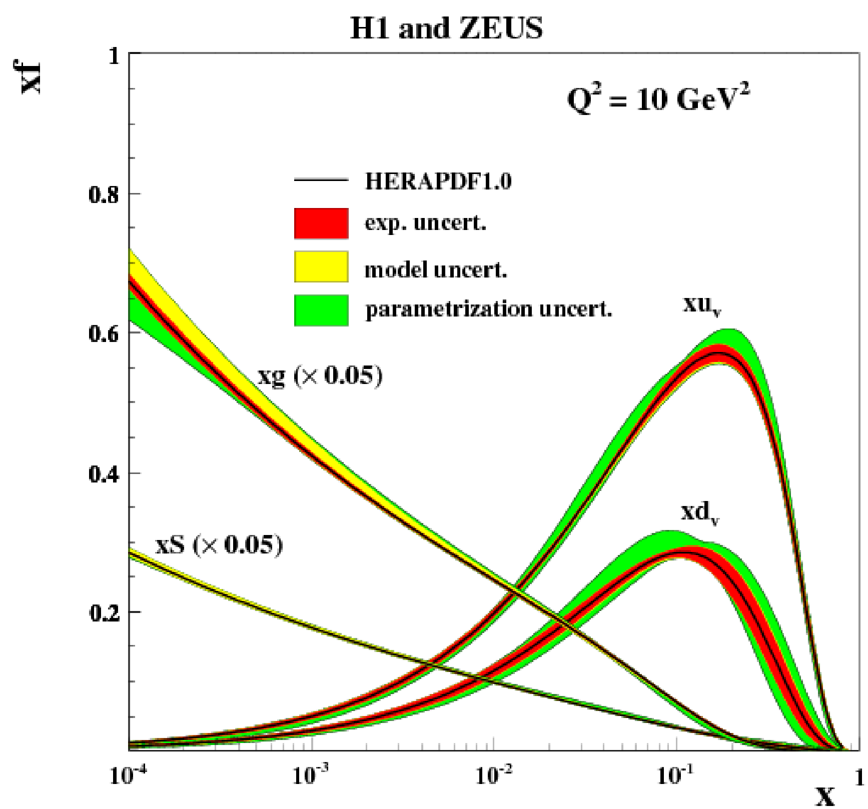
Non-perturbative parton distribution functions (PDFs) ⊗ perturbative partonic cross section.

⋈ Extract PDFs from experiment.

► Learn about the 1D momentum structure of the proton.

From electron-proton deep inelastic scattering
(H1 and ZEUS collaborations 2010)





Collinear factorization

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- ► Learn about the 1D momentum structure of the proton.
- ► Apply the PDFs as an input to another experiment.

How do we know it works?

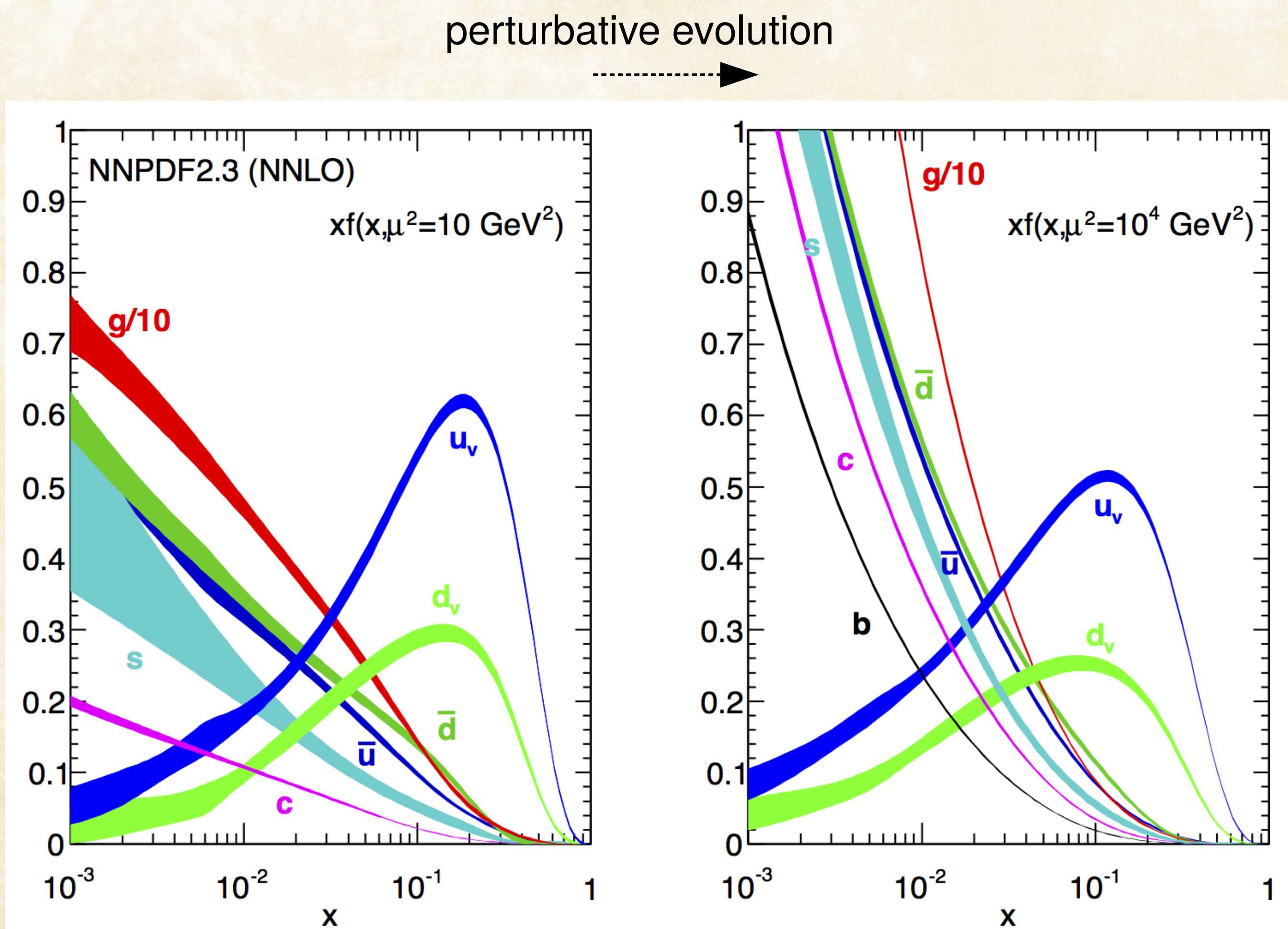
How the PDFs change with changing the resolution scale and the energy of the collision can be calculated perturbatively

+

The PDFs are universal

With factorization we can constrain PDFs from a set of processes and use them to predict other cross sections → test of QCD.

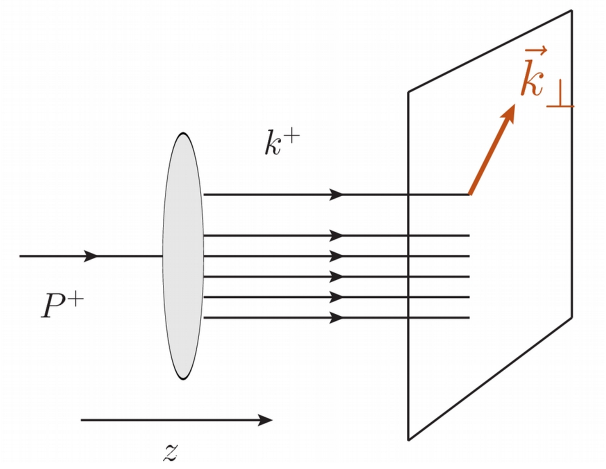
- Use global PDF analysis from different processes and colliders to extract PDFs at scales of a few GeV and perturbative evolution equations to calculate PDFs and make predictions at higher scales.



What about the structure of protons in three dimensions?

Distributions in longitudinal + transverse momentum

What about the structure of protons in three dimensions?
Distributions in longitudinal + transverse momentum



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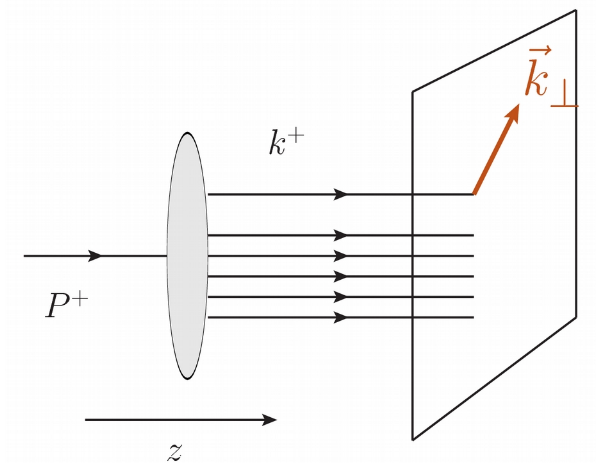
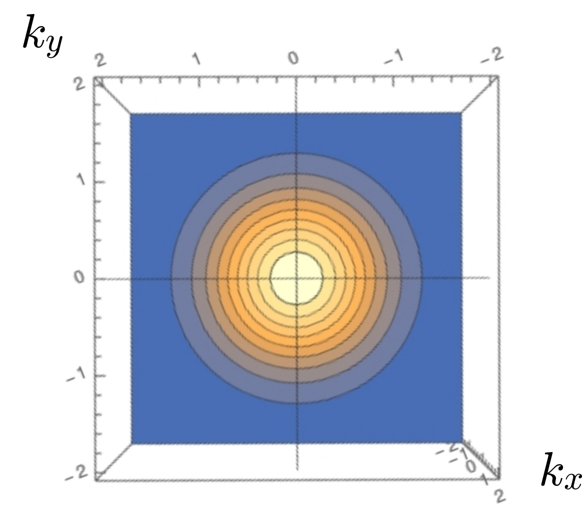


Transverse momentum dependent (TMD) distribution functions

$f(x, k_\perp)$



3D momentum tomography

Def: $\mathcal{F}_q(x, k_\perp, S, T) \sim \int dz^+ d^2\boldsymbol{z} e^{ixP^- z^+ - ik_t\cdot \boldsymbol{z}} \langle PS| \left[\bar{\psi}\left(z^+, \boldsymbol{z}_t\right) U(z,0) \psi\left(0^+, \mathbf{0}_t\right)\right] |PS\rangle$

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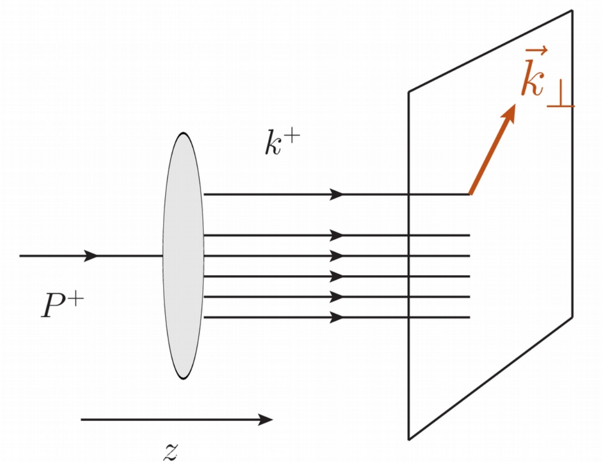
Distributions in longitudinal + transverse momentum



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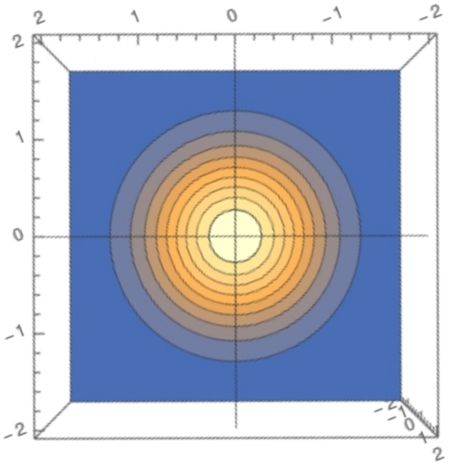

3D momentum tomography

TMD factorization

TMD factorization

⋈ Factorize the cross section in

Non-perturbative transverse momentum dependent (TMD) distributions

$$\otimes$$

perturbative partonic cross section

⋈ Extract TMDs from experiment.

- Learn about the 3D momentum structure of the proton.
- Use the TMDs as an input to another experiment.

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Universality of TMDs?

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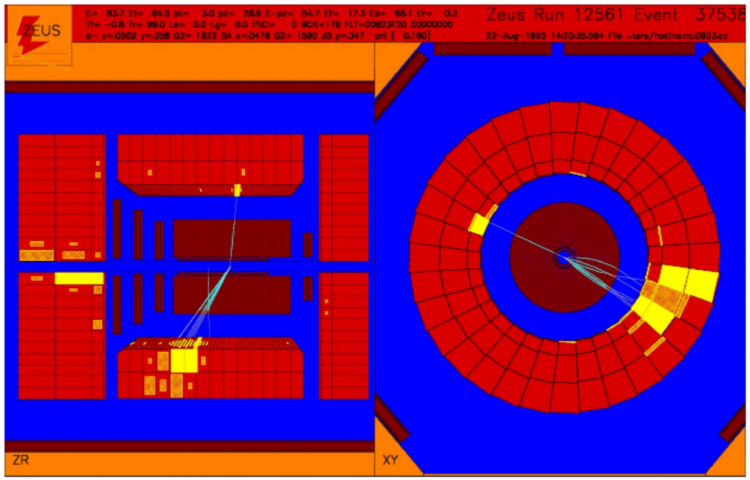
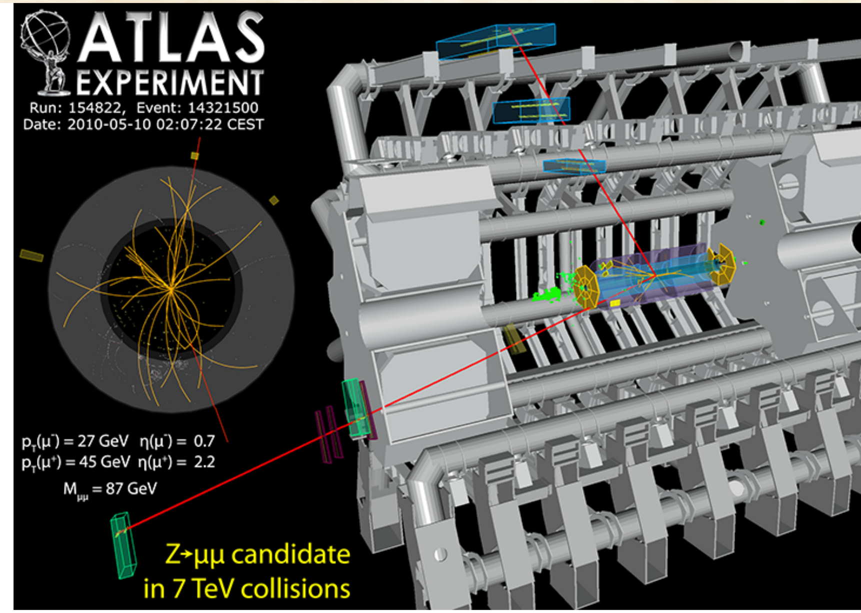
Universality of TMDs?

TMD factorization is not always possible
and
TMDs are not universal

Semi-inclusive deep inelastic scattering in electron-proton collisions:
lepton+proton → lepton+pion



Drell-Yan production:
proton+proton → lepton+antilepton



↔ Non-trivial connection

Non-universality of TMD distributions:
Use to test QCD

J. C. Collins, D. E. Soper, G. F. Sterman, 1983
D. Boer and P. J. Mulders, 2000
J. C. Collins, 2002
J.C Collins, A. Metz, 2004
M.G.A. Buffing, A. Mukherjee, P. J. Mulders, 2012

Semi-inclusive deep inelastic scattering in electron-proton collisions:

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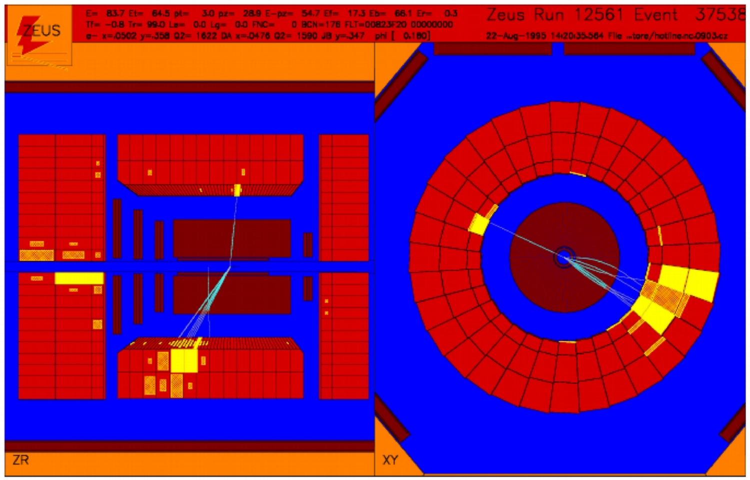

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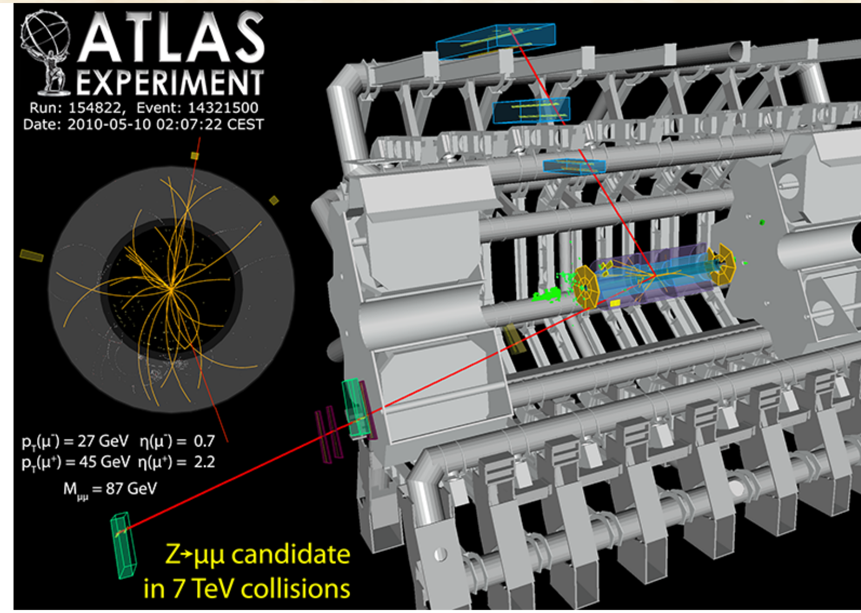

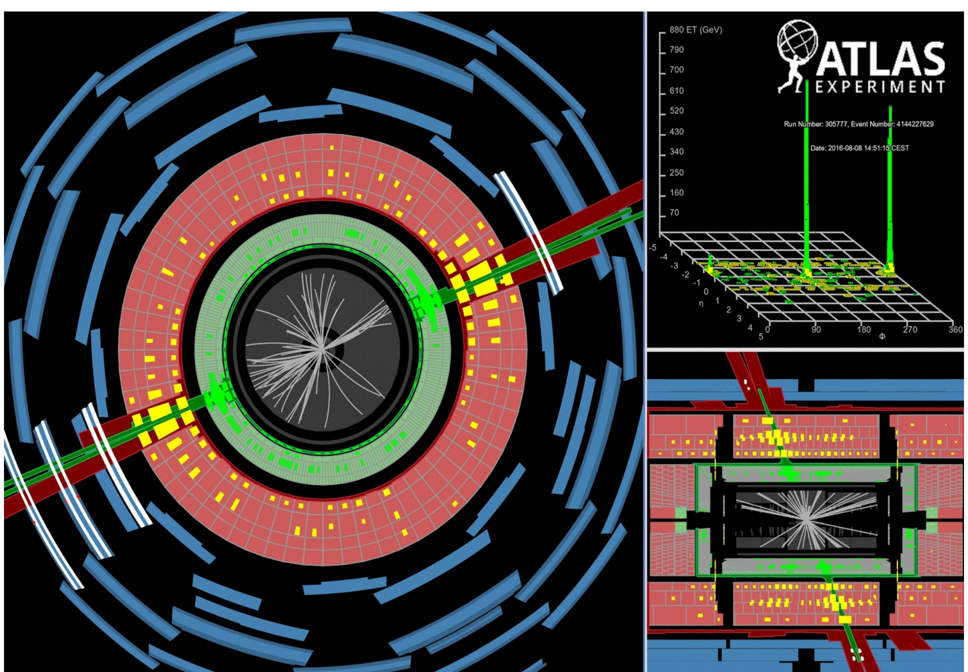

Dijet production in proton-proton collisions

proton+proton → 2 jets

TMD factorization is broken

TMD factorization

⋈ Factorize the cross section in

Non-perturbative transverse momentum dependent (TMD) distributions

$\otimes$

perturbative partonic cross section

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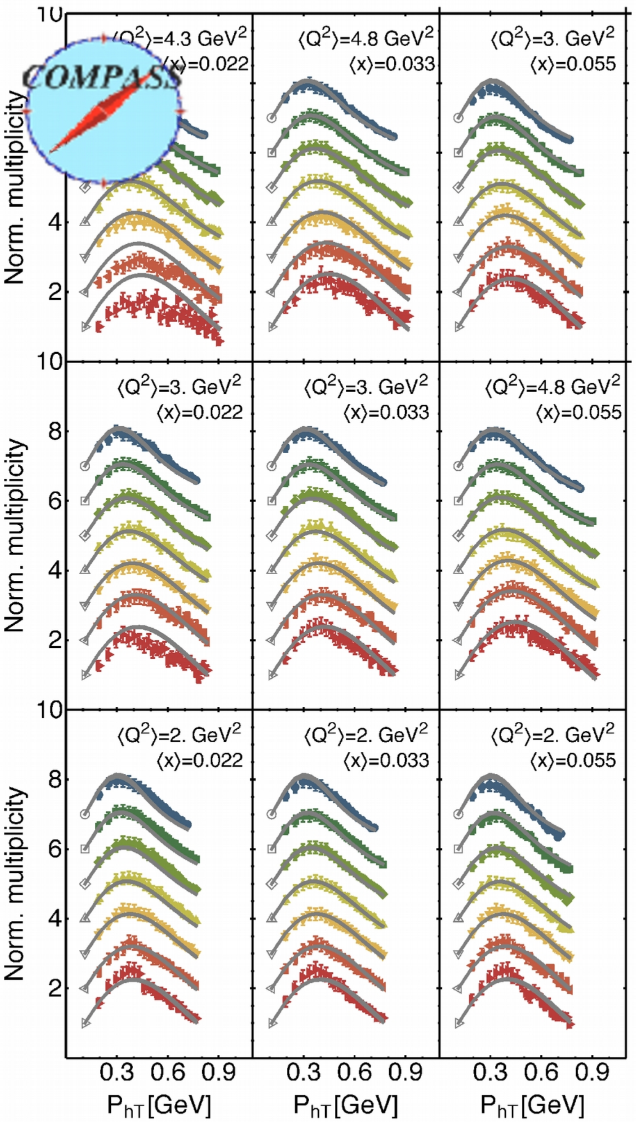
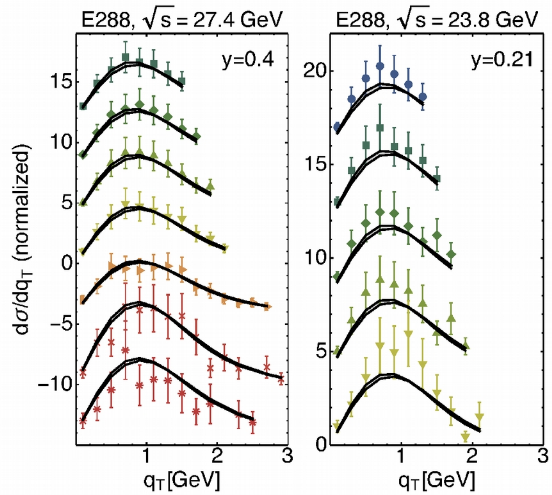
First global fit of TMDs

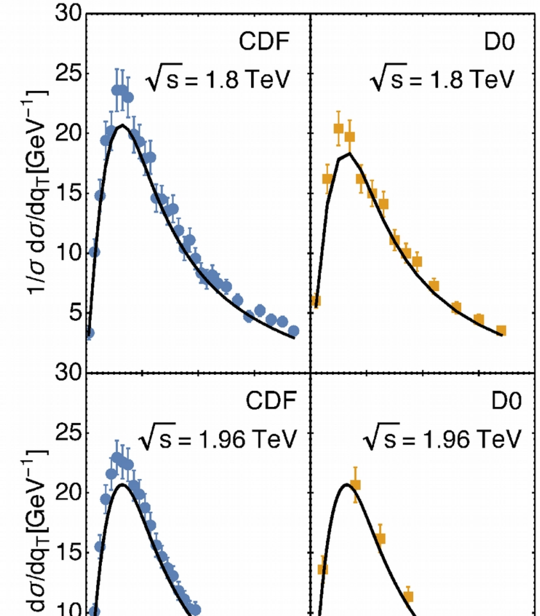
SIDIS



Drell-Yan



Z production



Next-to-Leading Log

Number of data points: 8059

Global χ^2/dof = 1.52

Pavia2016: first fit putting together semi-inclusive DIS, Drell-Yan and Z production

Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

see talk by C. Pisano (Tuesday, WG 6)

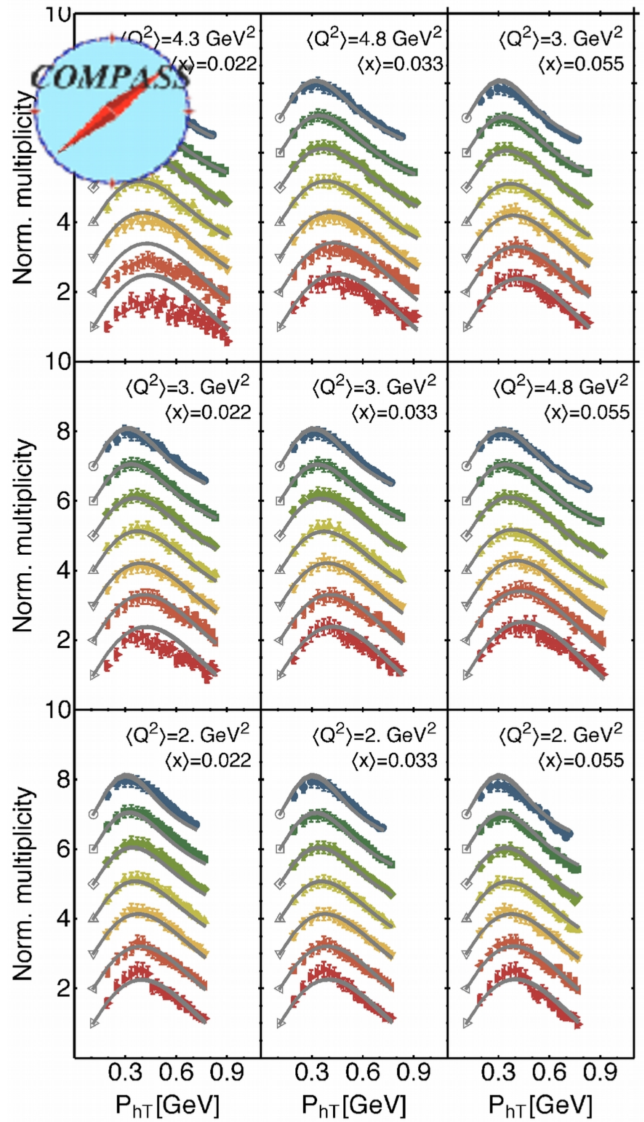
Slide from A. Bacchetta, DIS2017

First global fit of TMDs

To better constrain the TMDs we need:

- More data;
- Improved perturbative calculations (higher orders);
- Improved TMD evolution...

SIDIS



Parallel session: Hadron structure, spectroscopy and dynamics

Talks by:

Mariaelena Boglione, Tuesday 14:30

Simone Rodini, Tuesday 15:10

Next-to

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Slide from A. Bacchetta, DIS2017

What about:

- ⋈ Distributions of gluons in protons at very high energy?
- ⋈ Distributions of gluons in nuclei at very high energy?
- ⋈ Effective factorization in collisions where TMD factorization is broken?
- ⋈ Effective factorization in collisions with nuclei?

What about:

- ⋈ Distributions of gluons in protons at very high energy?
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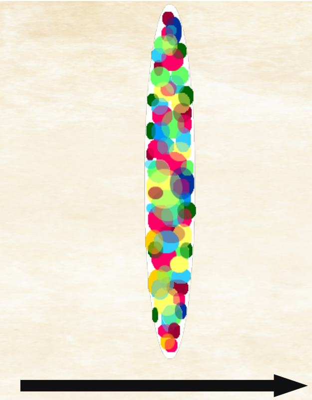
Color Glass Condensate effective field theory

High-energy limit:

center of mass energy squared $s \to \infty$

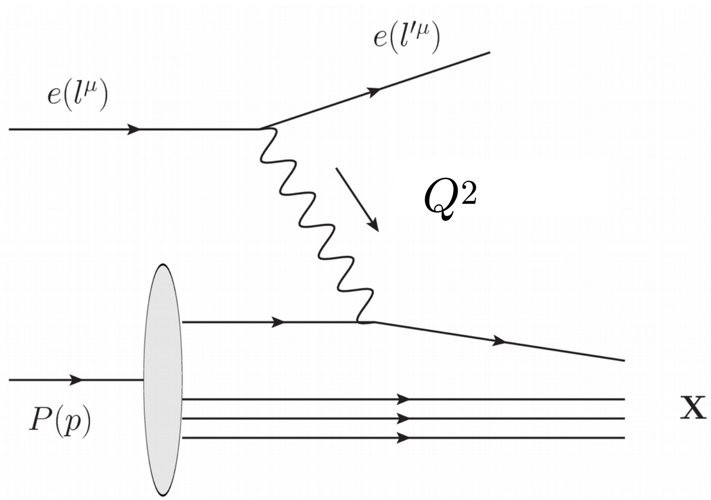
momentum transfer squared Q^2 = fixed

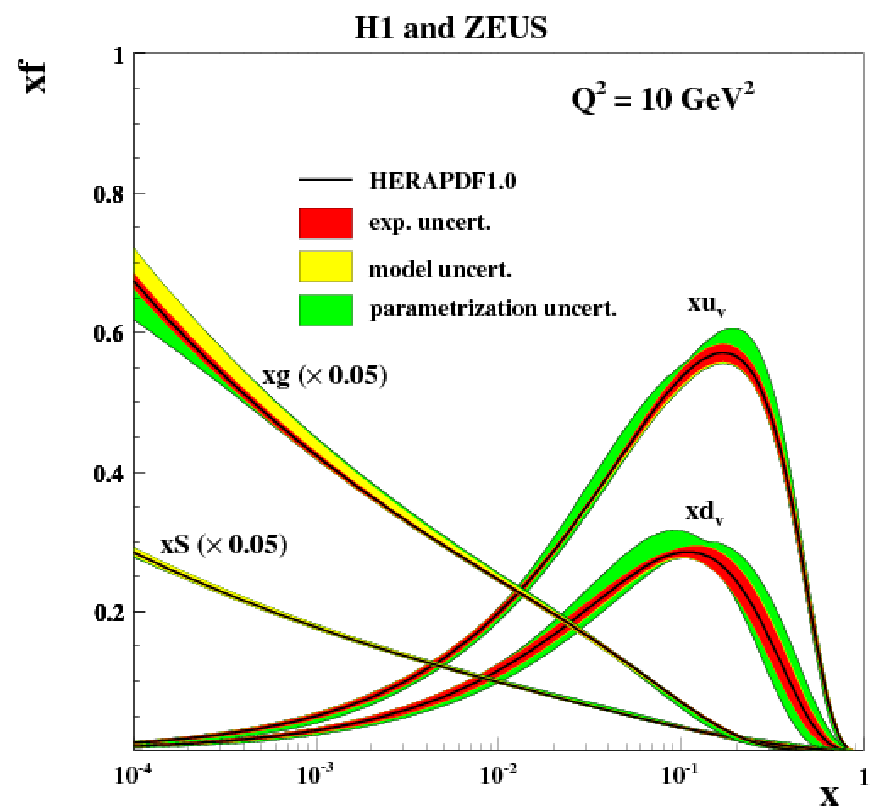
longitudinal momentum fraction $x \to 0$



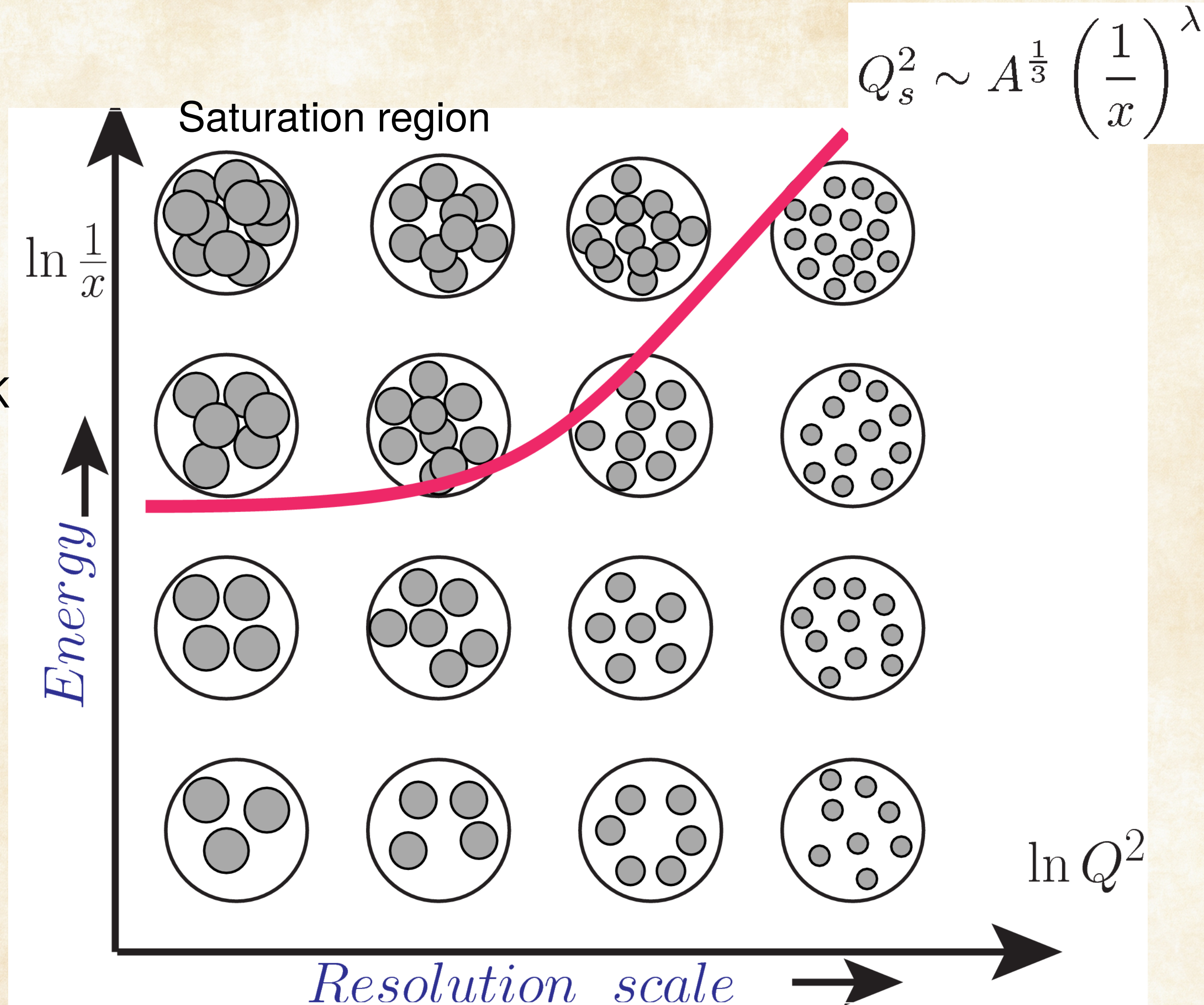
Lorentz contracted dense system of gluons

From electron-proton deep inelastic scattering (H1 and ZEUS collaborations 2010)





Map of high-energy QCD



Non-linear
JIMWLK or BK
evolution

Linear BFKL
evolution

DGLAP evolution

Color Glass Condensate effective theory of QCD at high energy

⋈ Physics of high gluon densities can be formulated as classical effective theory;

⋈ Solve classical Yang-Mills equations for the small-*x* gluon field in the presence of the large-*x* sources;

⋈ Quantum corrections enter through non-linear evolution equations capturing saturation.

L. McLerran and R. Venugopalan, 1994
J. Jalilian-Marian, A. Kovner, A. Leonidov, and H. Weigert, 1997, 1999
E. Iancu, A. Leonidov, and L. D. McLerran, 2001
A. H. Mueller, 2001
E. Ferreiro, E. Iancu, A. Leonidov, and L. McLerran, 2002

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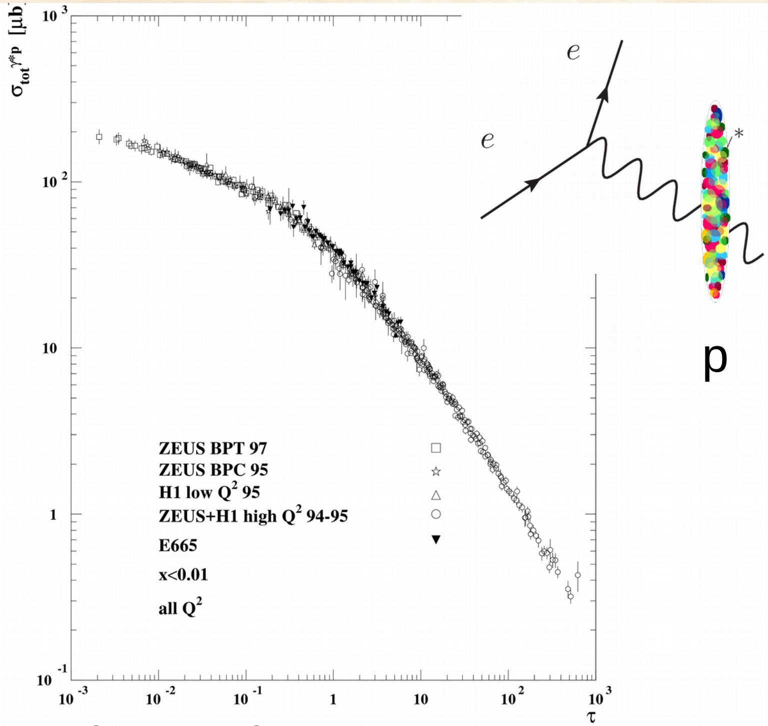
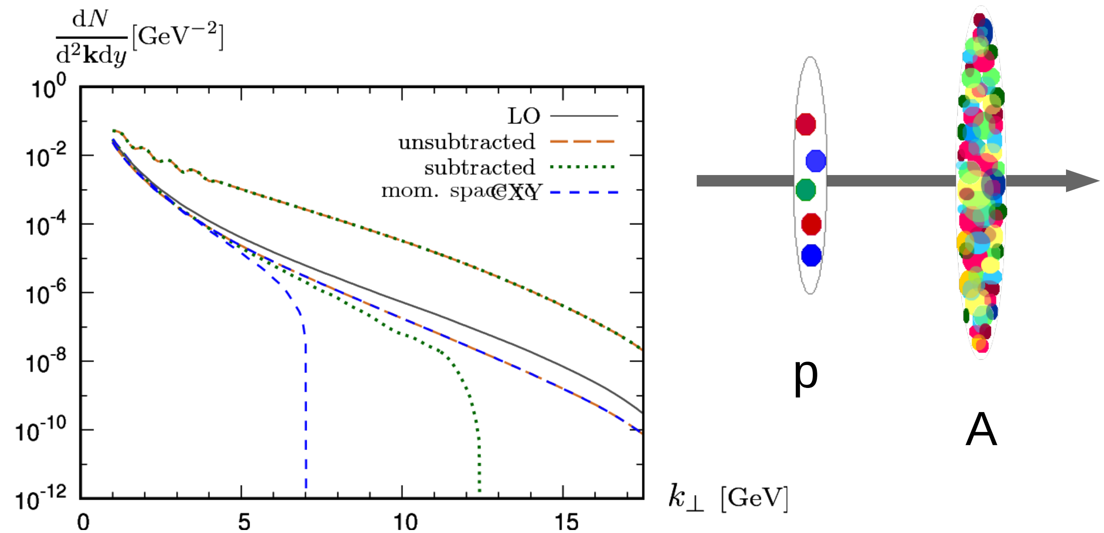
The CGC type of matter is universal for any ultra-relativistic proton or nucleus, independent on the particular scattering process.

Geometric scaling in deep inelastic scattering in electron-proton collisions



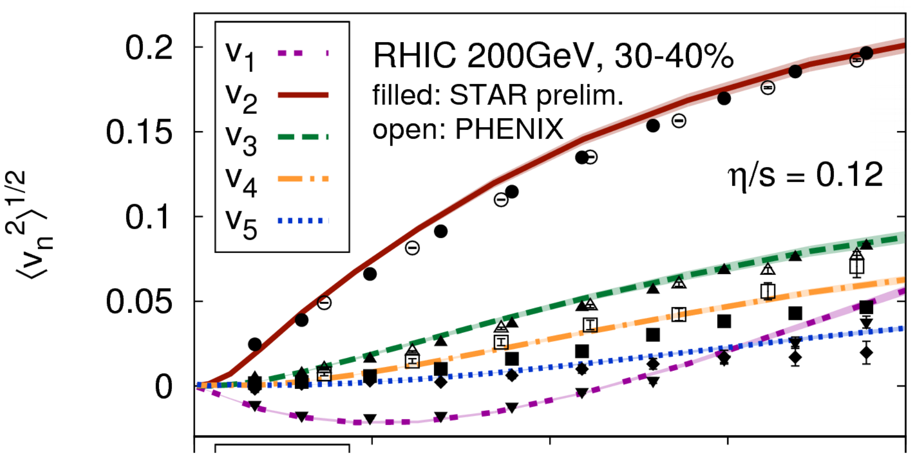
A. M. Stasto, K. Golec-Biernat, J. Kwiecinski, 2001

Forward hadron production in proton-nucleus collisions

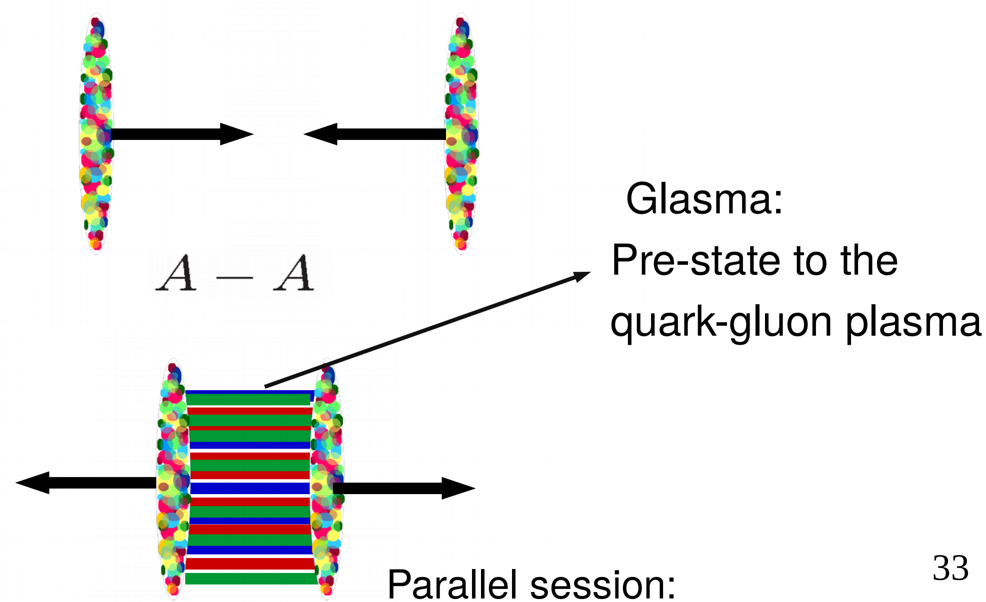


B. Ducloué, T. Lappi, Y. Zhu, 2017

Flow coefficients in nucleus-nucleus collisions

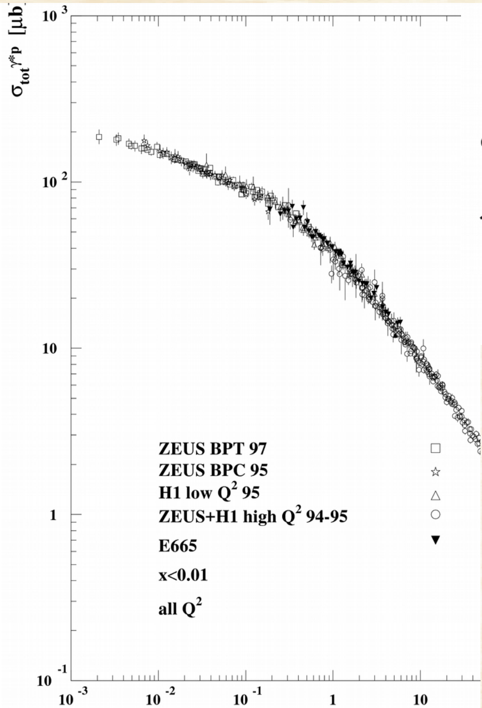


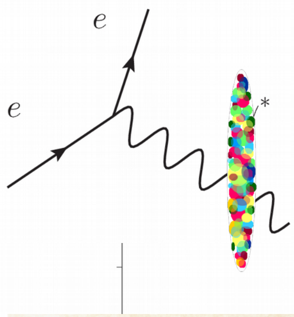
C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, 2013



Parallel session:
Heavy Ion collisions and QCD phases

Geometric scaling in deep inelastic scattering in electron-proton collisions





A. M. Stasto, K. Golec-Biernat, J

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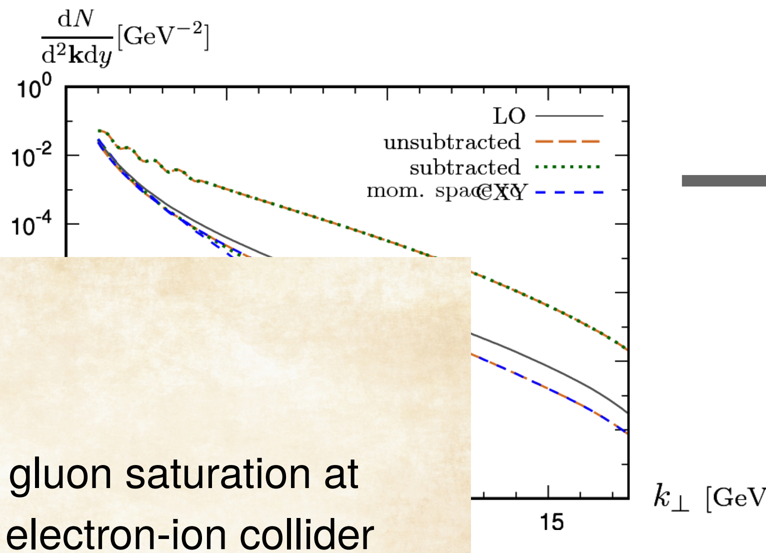
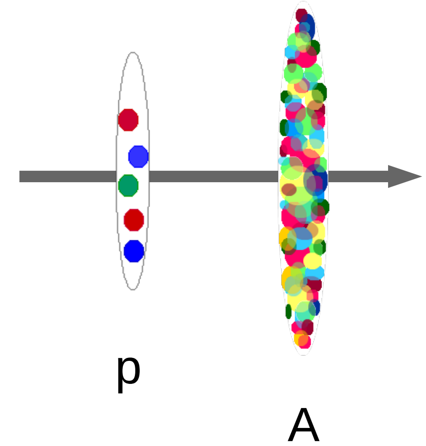
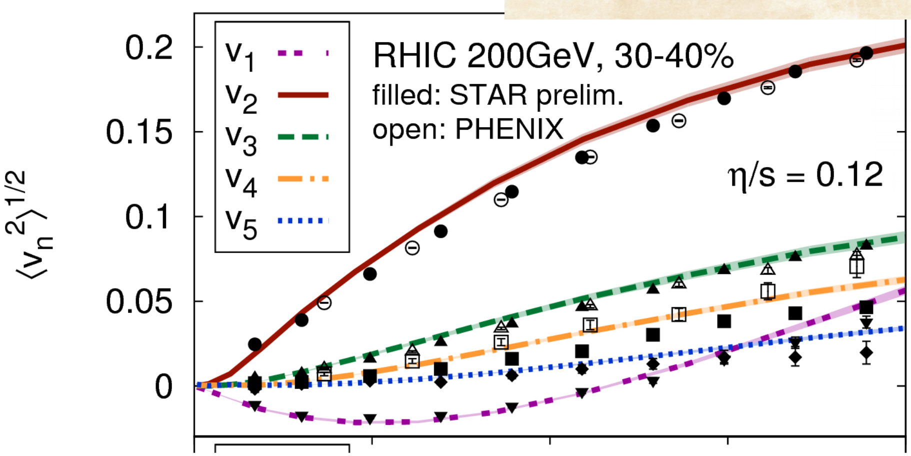




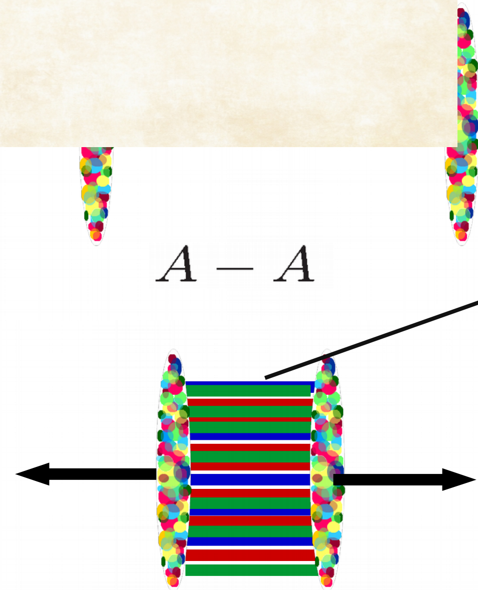
Zhu, 2017

Clean evidence of gluon saturation at the future proposed electron-ion collider (EIC)?

Flow coefficients in nucleus-nucleus collisions



C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, 2013



Glasma:
Pre-state to the quark-gluon plasma

The Color Glass Condensate provides a universal picture of the 3D momentum distribution of gluons in protons and nuclei at small *x*.

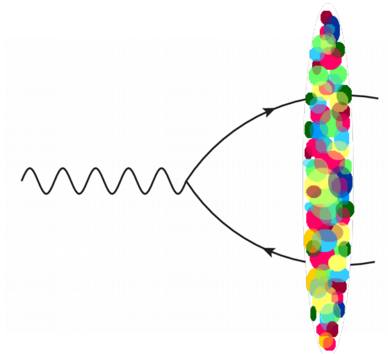
Use CGC to study gluon TMD distributions at small *x*.

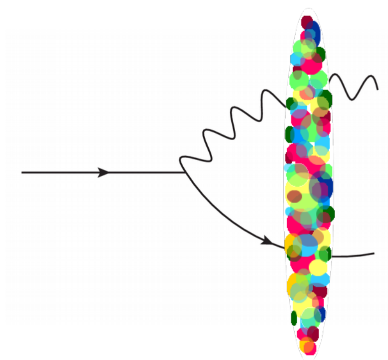
Connection between the TMD factorization and the CGC theory and its possible applications

Connection between the TMD factorization and the CGC theory and its possible applications

⋈ Non-universality of gluon distributions realized independently in both formalisms.

⋈ Origin due to the color flow in the hard part of the process.



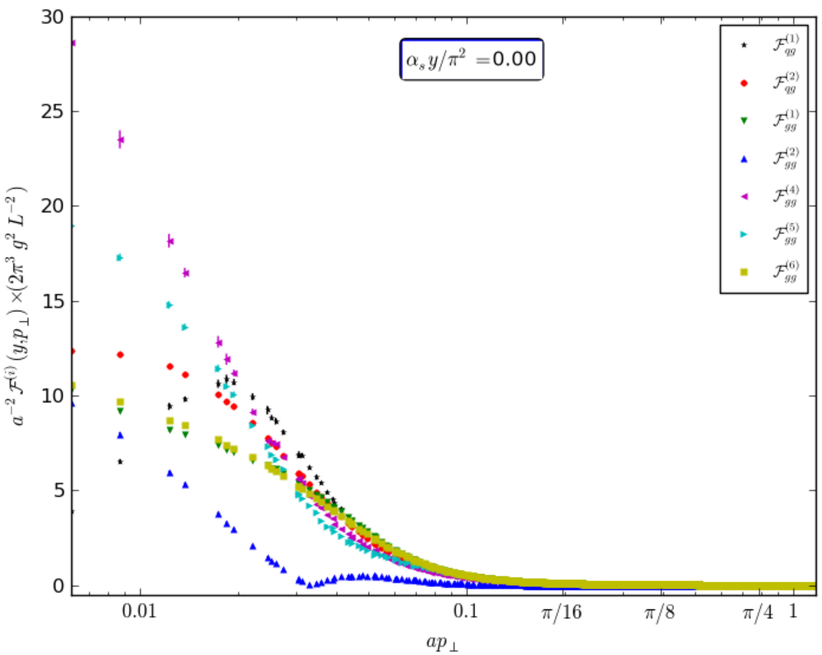


D. Kharzeev, Y. V. Kovchegov and K. Tuchin, 2003
F. Dominguez, B. W. Xiao and F. Yuan, 2011
F. Dominguez, C. Marquet, B. W. Xiao and F. Yuan, 2011

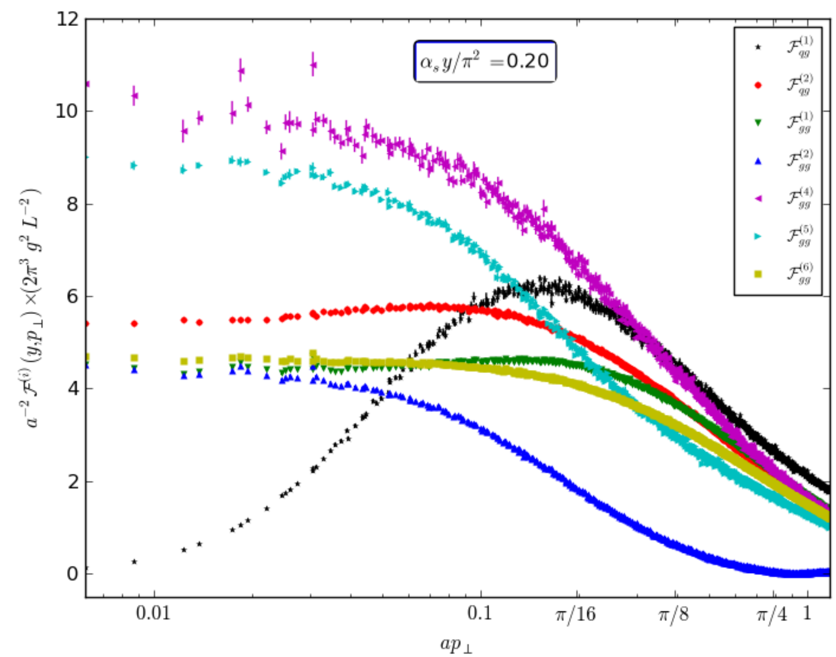
What can we learn about the behaviour of the TMD gluon distributions in the high-energy limit (at small *x*) from the CGC theory?

TMD distributions can be calculated at small-*x* in the CGC formalism.

Different energy scales can be studied through small-*x* evolution equations.



Small-*x* evolution



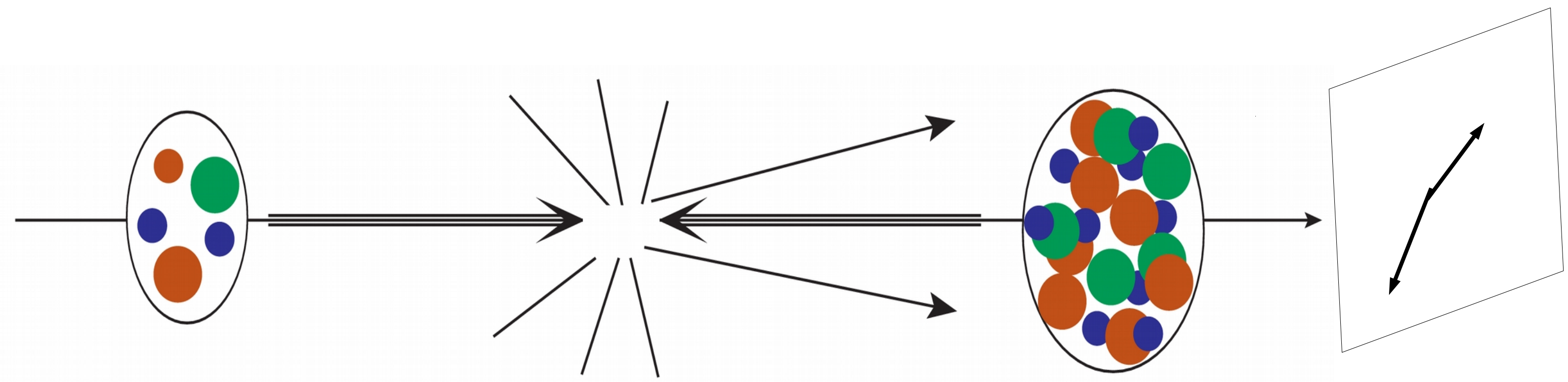
Universality at large transverse momentum

Non-universality at small transverse momentum

Marquet, EP, Roiesnel (2016)

Can we derive effective factorization in the high-energy limit for processes where TMD factorization is broken?

E.g. Forward dijet production in proton-nucleus (or proton-proton) collisions
in the small-*x* limit + back-to-back jets



$$\frac{d\sigma^{pA\to \text{dijets}+X}}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \frac{\alpha_s^2}{(x_1 x_2 s)^2} \sum_{a,c,d} x_1 f_{a/p}(x_1,\mu^2) \sum_i H^{(i)}_{ag\to cd} \mathcal{F}^{(i)}_{ag}(x_2,k_t) \frac{1}{1+\delta_{cd}}$$

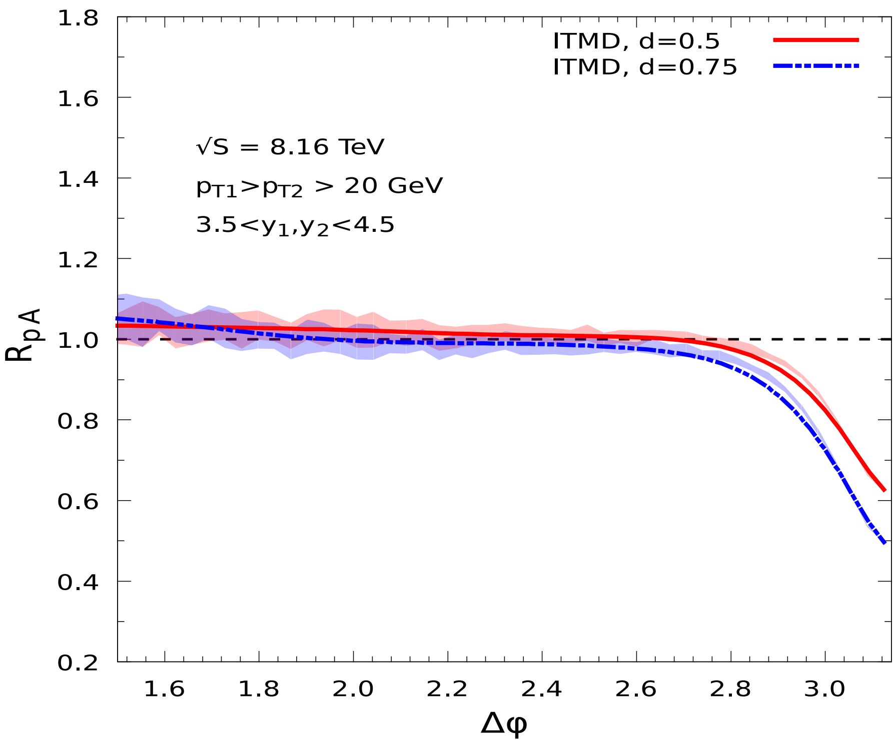
Bomhof, Mulders and Pijlman (2006)
Dominguez, Marquet, Xiao and Yuan (2011)
Kotko, Kutak, Marquet, EP, Sapeta and van Hameren (2015)
Marquet, EP, Roiesnel (2016)

Use effective TMD factorization to study gluon saturation

Can we use effective TMD factorization to study gluon saturation in nuclei which is simpler than the full CGC?

Forward dijet production in
proton-nucleus vs proton-proton

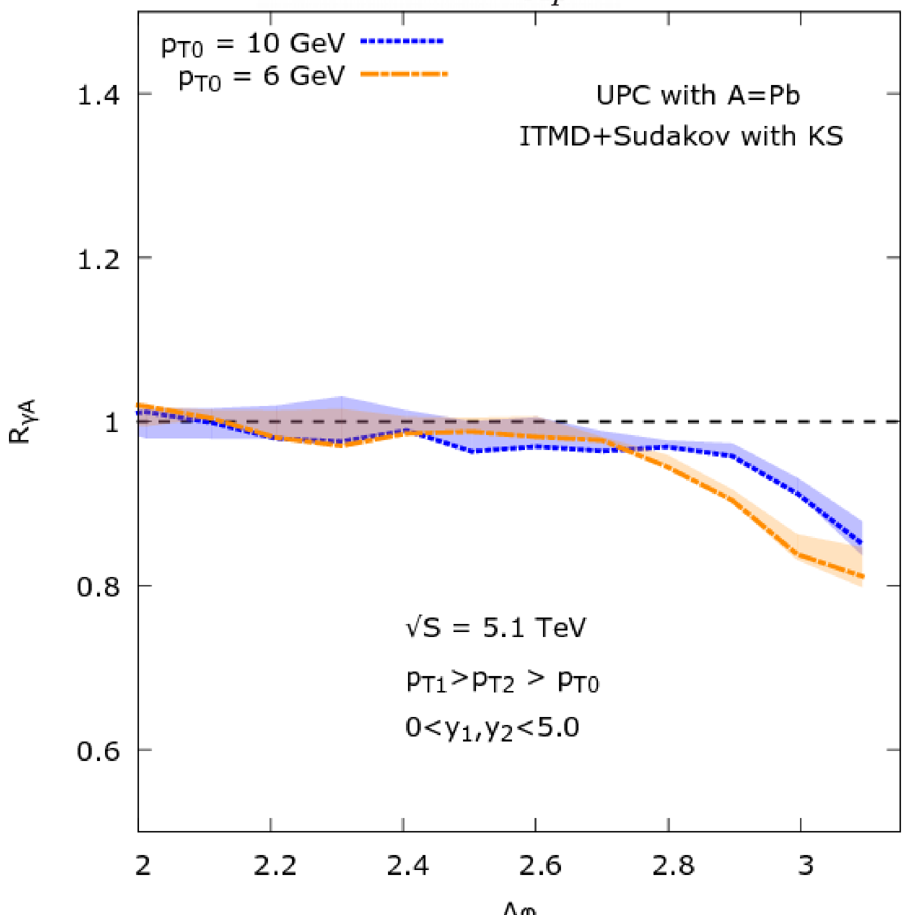
$$R_{\mathrm{pPb}} = \frac{d\sigma^{p+Pb}}{A\ d\sigma^{p+p}}$$



van Hameren, Kotko, Kutak, Marquet,
EP and Sapeta, 2016

Forward dijet production in
ultra-peripheral nucleus-nucleus vs nucleus-proton

$$R_{\gamma \mathrm{A}} = \frac{d\sigma_{AA}^{UPC}}{A\ d\sigma_{Ap}^{UPC}}$$



P. Kotko, K. Kutak, S. Sapeta, A. M. Stasto
and M. Strikman, 2017

Combine TMD evolution with non-linear small-x evolution to calculate gluon TMDs at different scales

⋈ A lot of progress recently, see e.g.

A. H. Mueller, B. W. Xiao and F. Yuan, (2013)
I. Balitsky and A. Tarasov, (2015,2016)
B. W. Xiao, F. Yuan and J. Zhou, (2017)

Conclusions:

⋈ Connections between the TMD factorization method and the CGC theory, in their overlapping domain of validity, can be used for studying the structure of ultra-relativistic protons and nuclei.

⋈ Use CGC to extract gluon TMDs at small-x for processes where TMD factorization is broken.

⋈ Use effective TMD factorization to search for signatures of gluon saturation.

⋈ Combine TMD evolution and small-*x* evolution for an inclusive calculation of the TMD gluon distributions at different scales.

⋈ Make predictions for future experiments based on the combined studies.

⋈ …

⋈ Polarized TMDs in the CGC...
⋈ Distributions in positions space and gluon saturation...