Saturation effects in QCD and its phenomenological implications

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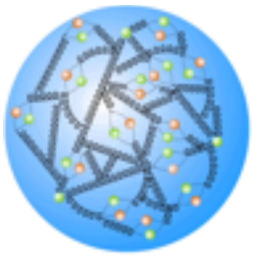
Outline

- PART I: Gluon saturation in high-energy QCD scattering (a brief overview)
- PART II: Searching for saturation in experimental data (some selected topics):
  - Deep Inelastic scattering (HERA)
  - p+p and p+A collisions (RHIC & LHC)
  - Heavy ion collisions
  - Astroparticles
  - The future

High collision energy ⇄ Small Bjorken-x

$$x \sim \frac{p_\perp}{\sqrt{s}}\, e^y$$

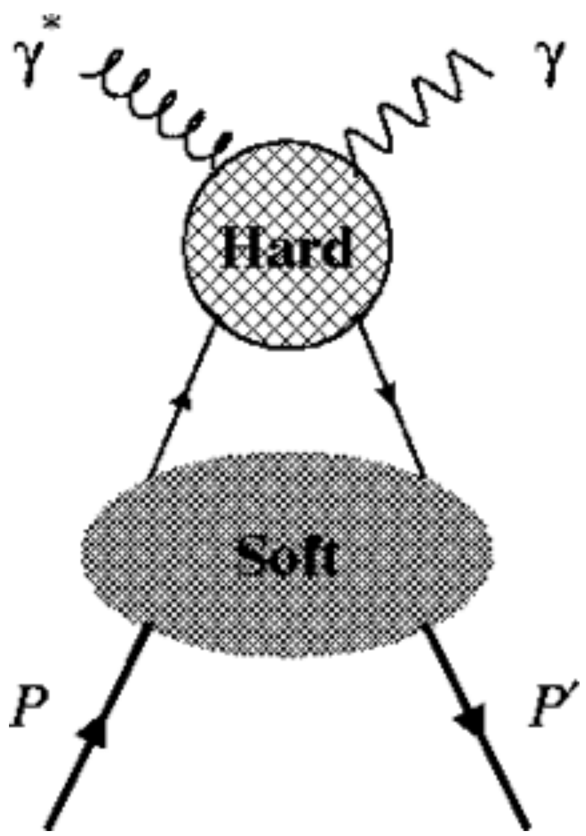


Particle production in hadronic collisions. General structure of factorisation theorems

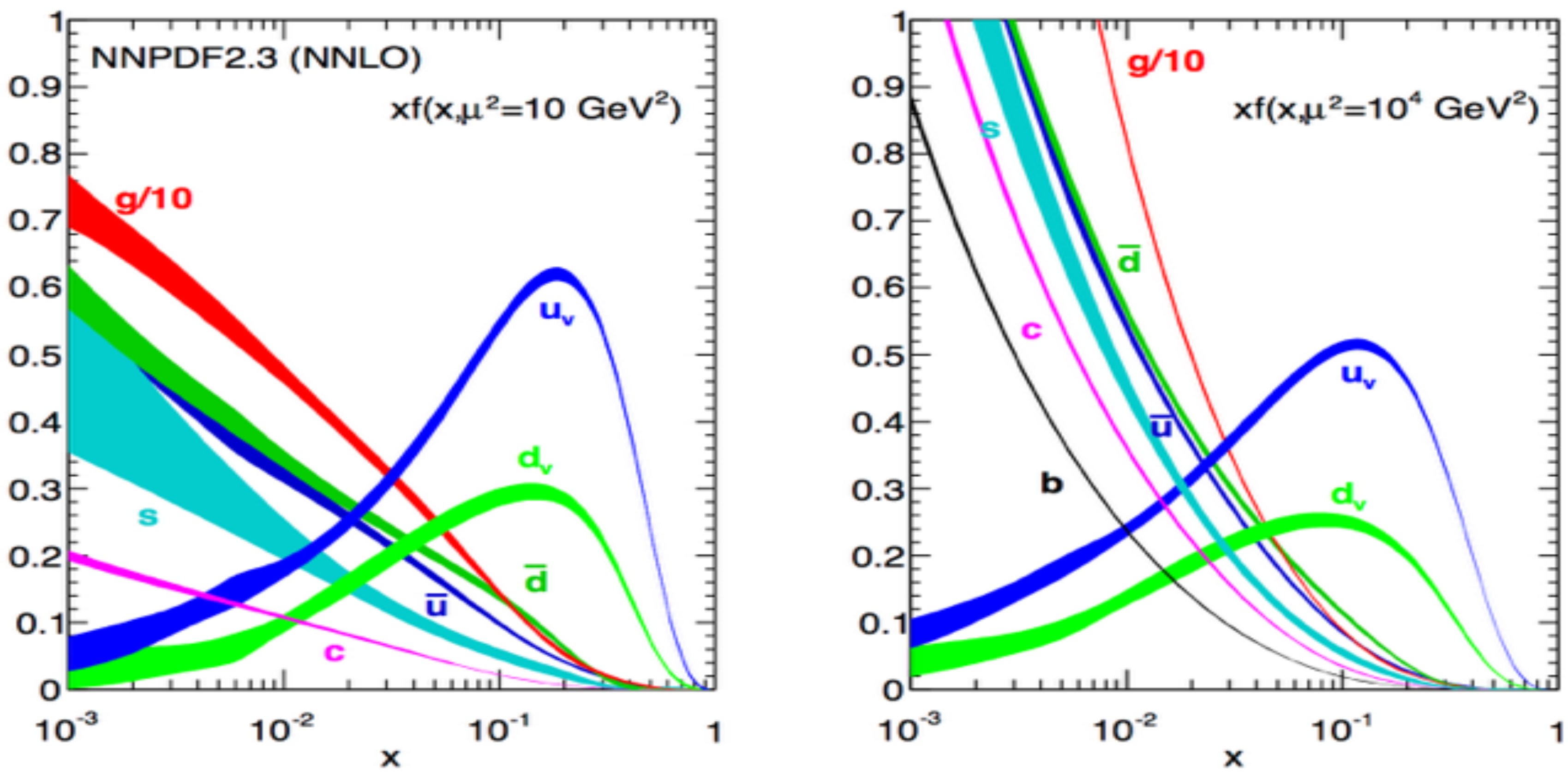
$$\sigma \sim \underbrace{\left(\begin{array}{c}\text{Probability of} \\ \text{finding a quark/gluon} \\ \text{in nucleon}\end{array}\right)}_{\text{Low energy QCD}} \otimes \underbrace{\sigma^{q/g-\nu}}_{\text{Perturbative}}$$

$\left(\ \dots\ \right)$: Parton Distribution Function,

Unintegrated Gluon Distribution



• Parton densities (PDF's, UGD's, TMD's) are ultimately non-perturbative quantities.
• They depend on the observation scales (x,Q2). Why?: Only the fluctuations that are longer lived and of the same size as the external probe participate in the interaction process



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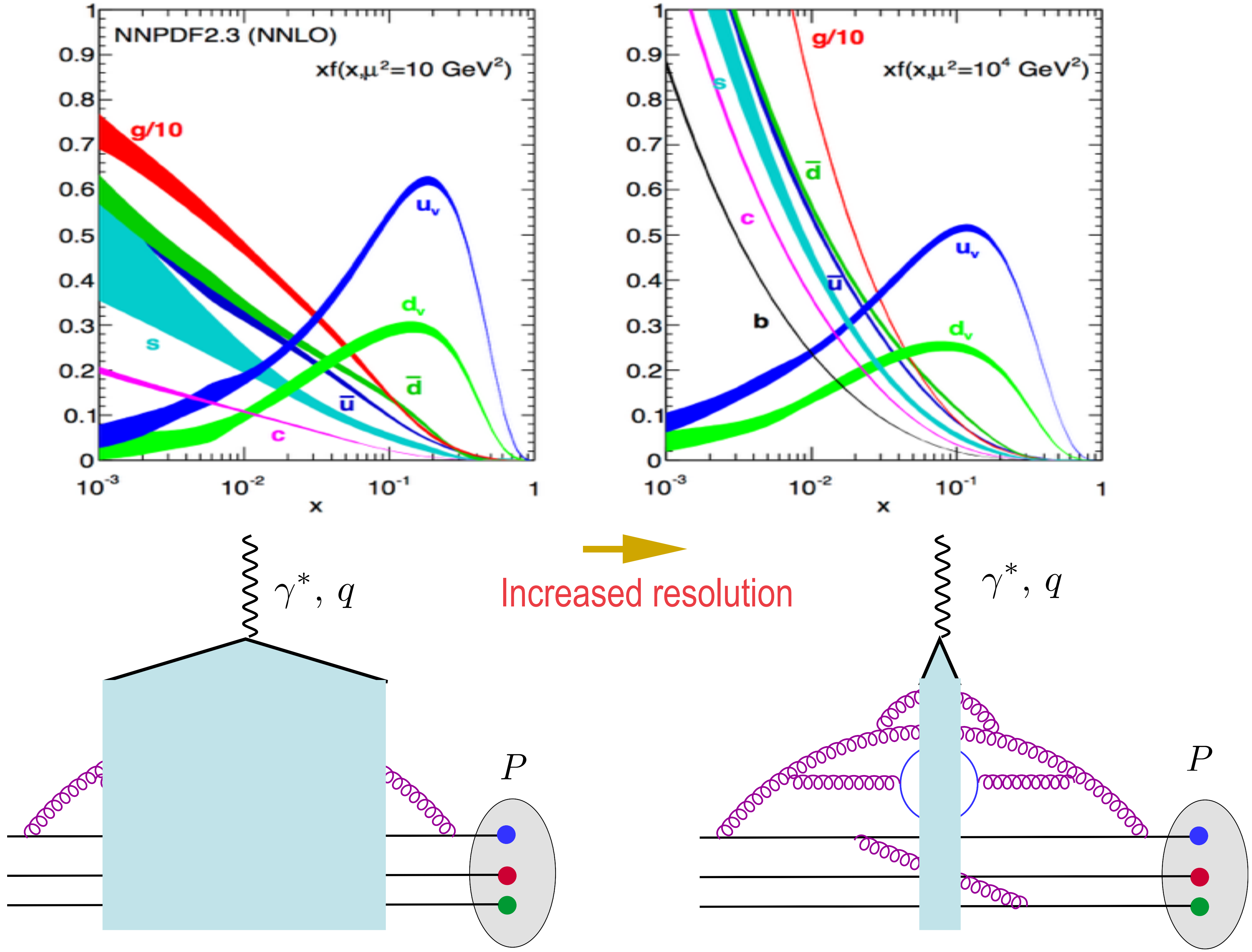
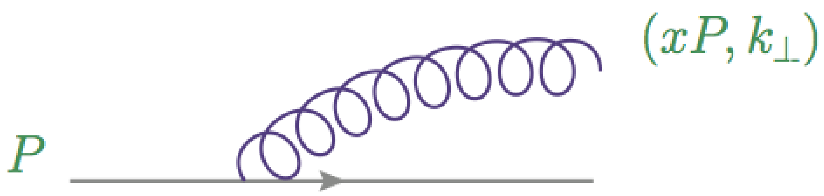


pQCD evolution equations of the parton densities

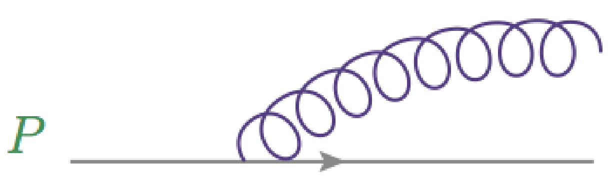


$$\mathrm{d}P_{q/g\to g} = \frac{\alpha_s C_{F/A}}{\pi}\frac{\mathrm{d}x}{x}\frac{\mathrm{d}k_\perp^2}{k_\perp^2}$$

$x \to 0$: soft divergences

$k_\perp \to 0$: collinear divergences

pQCD evolution equations of the parton densities



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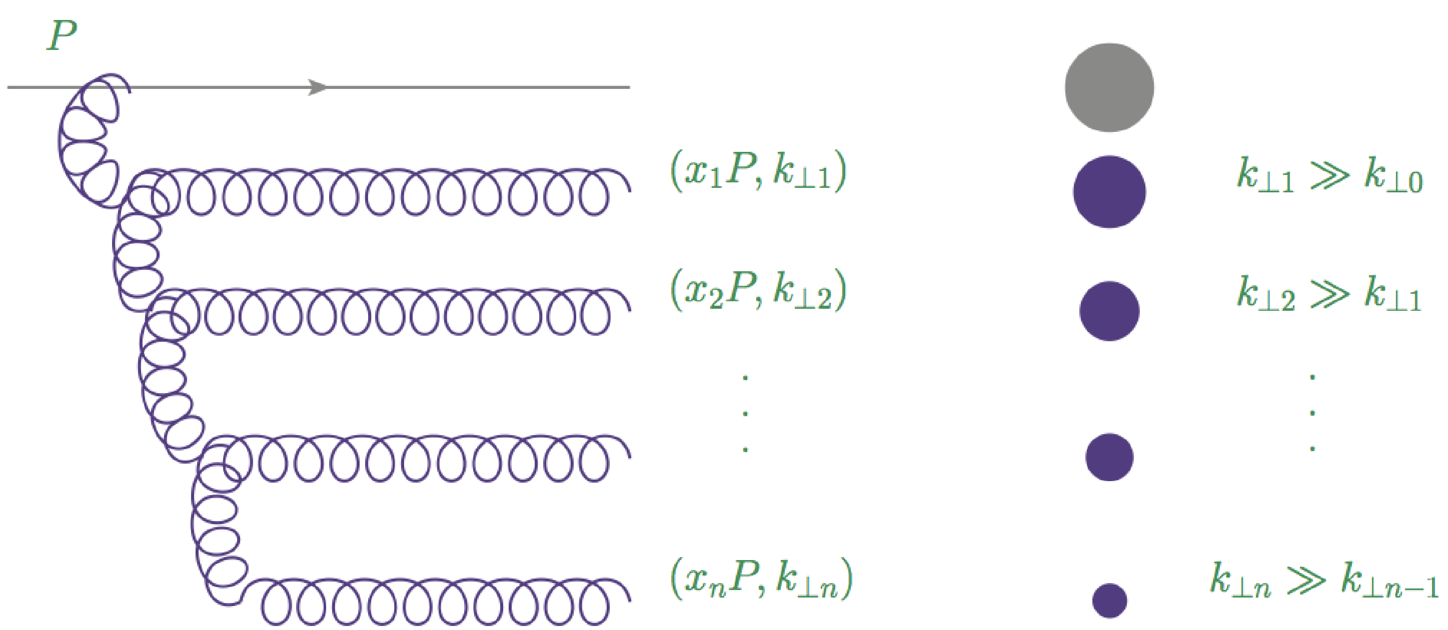
One gluon, two gluons, three gluons… pQCD evolution equations resum parton emissions to all orders



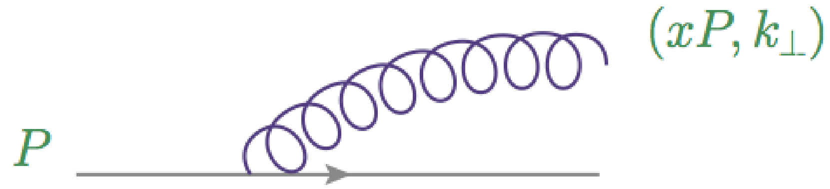
transverse momentum ordering

$$\mathrm{d}P_n \sim \left[\alpha_s(Q^2)\ln\left(\frac{Q^2}{Q_0^2}\right)\right]^n$$

DGLAP evolution:

$$\frac{\partial \mathrm{PDF}(\mathrm{x}, Q^2)}{\partial \ln Q^2} \propto \mathcal{P} \otimes \mathrm{PDF}(\mathrm{x}, Q^2)$$

pQCD evolution equations of the parton densities



$$dP_{q/g\to g} = \frac{\alpha_s C_{F/A}}{\pi}\frac{dx}{x}\frac{dk_\perp^2}{k_\perp^2}$$

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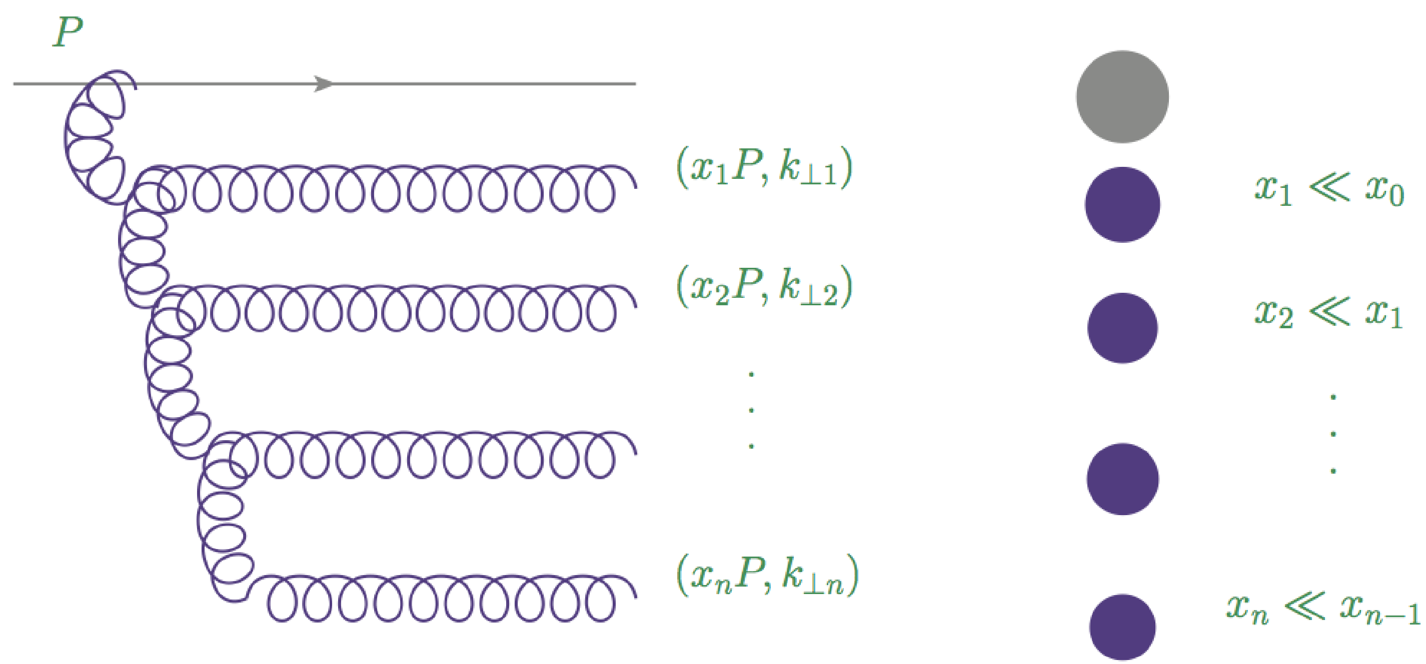

longitudinal momentum ordering

$$dP_n \sim \left[\alpha_s(Q^2)\ln\left(\frac{Q^2}{Q_0^2}\right)\right]^n$$

DGLAP evolution:

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$$dP_n \sim \left[\alpha_s(Q^2)\ln\left(\frac{x_0}{x}\right)\right]^n$$

BFKL evolution:

$$\frac{\partial \phi(x,k_\perp)}{\partial \ln(1/x)} \propto \mathcal{K}\otimes \phi(x,k_\perp)$$

- DGLAP and BFKL are LINEAR evolution equations: “exponential” growth of the gluon distributions at small-x

DGLAP evolution: $$\frac{\partial \mathrm{PDF}(x,Q^2)}{\partial \ln Q^2} \propto \mathcal{P} \otimes \mathrm{PDF}(x,Q^2)$$

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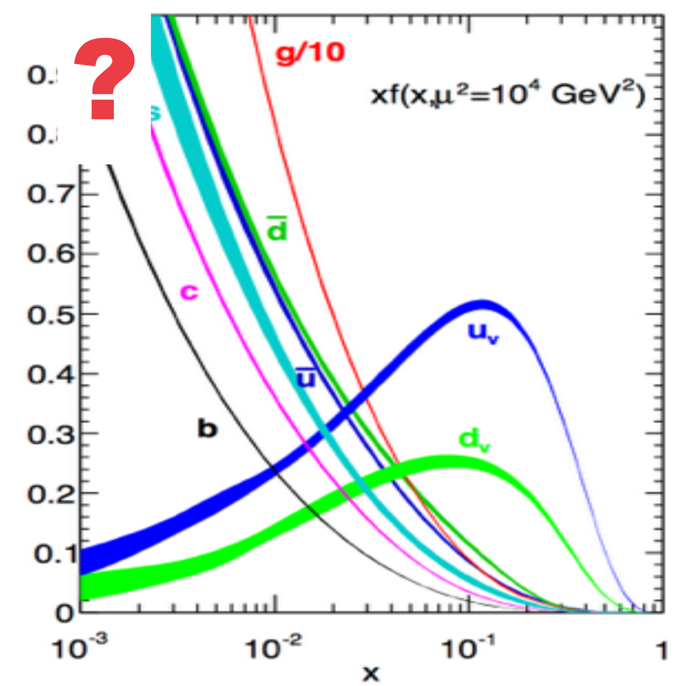

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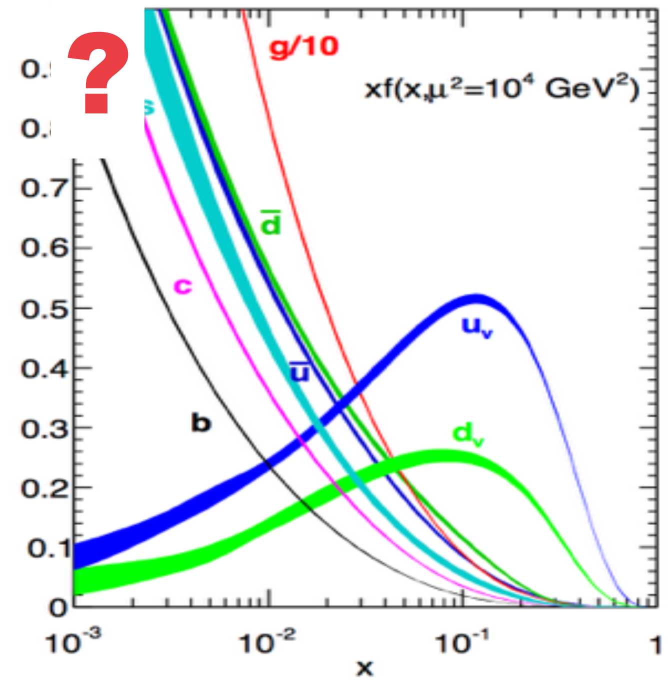


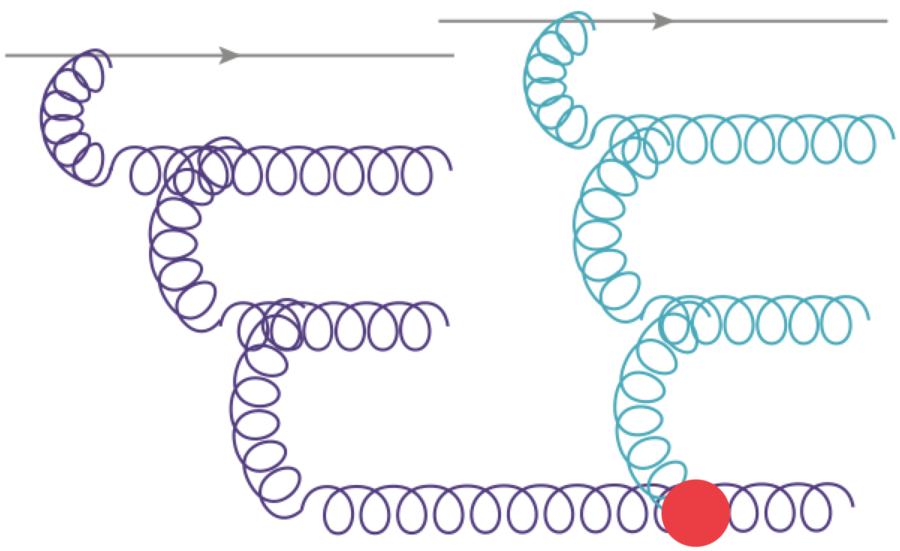
- At very small-x NON-LINEAR, gluon recombination terms that tame the growth of gluon densities become equally important. UNITARITY!!!

$$\frac{\partial \phi(\mathbf{x},\mathbf{k}_\perp)}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x},\mathbf{k}_\perp) - \phi(\mathbf{x},\mathbf{k}_\perp)^2$$

radiation recombination

$$\mathbf{k_t} \lesssim \mathbf{Q_s}(\mathbf{x})$$

"BK-JIMWLK" evolution equations

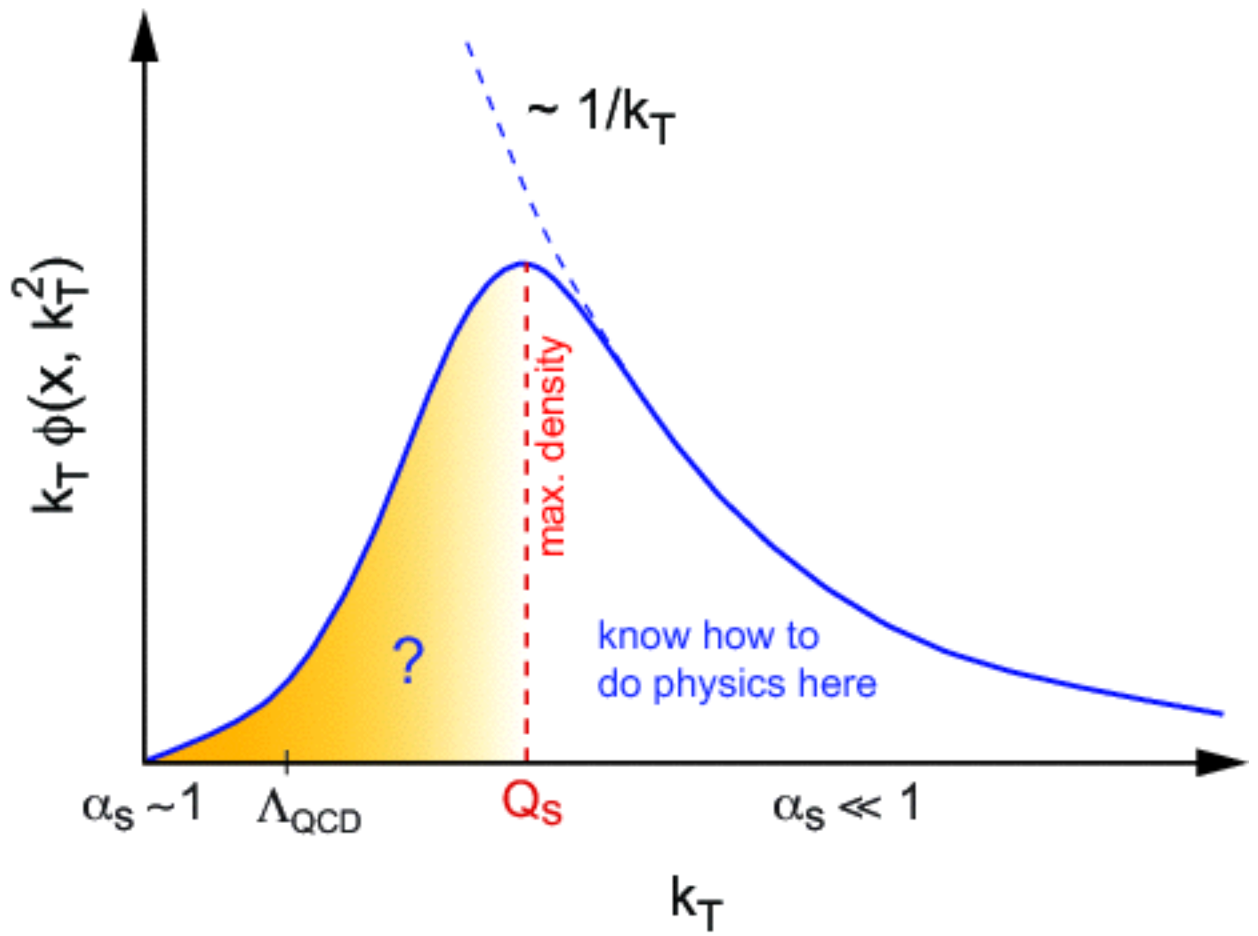


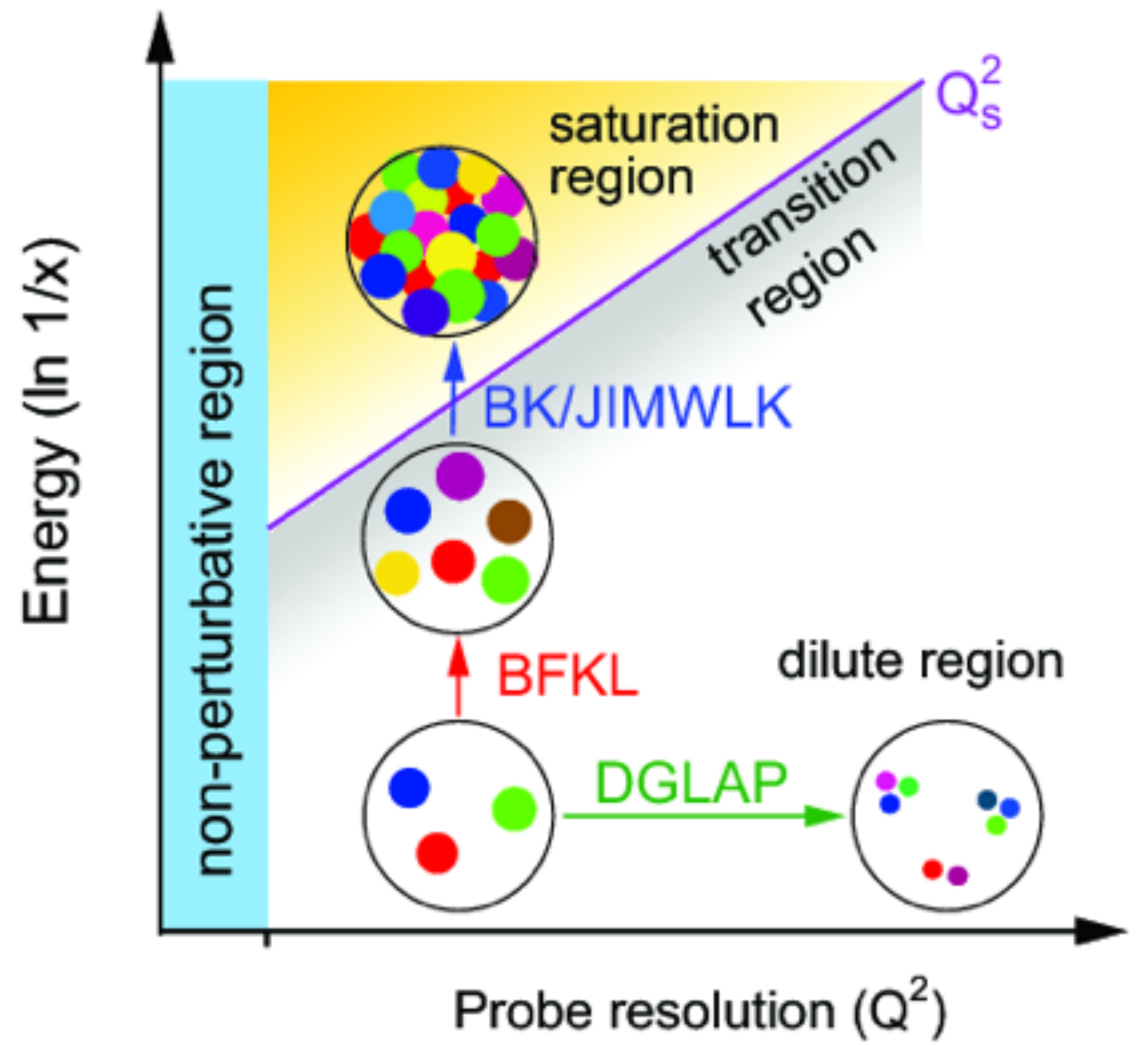
- **Saturation scale:** Transverse momentum scale that determines the onset of non-linear corrections in QCD evolution equations

$$\mathbf{Q^2_{sat}(x) \sim Q_0^2\, A^{1/3} \left(\frac{x_0}{x}\right)^{\lambda}}$$

- The saturation domain is characterized by large gluon densities or strong gluon fields

$$\phi(\mathbf{x}, \mathbf{k}_\perp \lesssim \mathbf{Q_s(x)}) \sim \frac{\mathbf{1}}{\alpha_\mathbf{s}} \Longrightarrow \mathcal{A}(\mathbf{k} \lesssim \mathbf{Q_s}) \sim \frac{\mathbf{1}}{\mathbf{g}} \qquad \mathbf{g}\mathcal{A} \sim \mathcal{O}(\mathbf{1})$$





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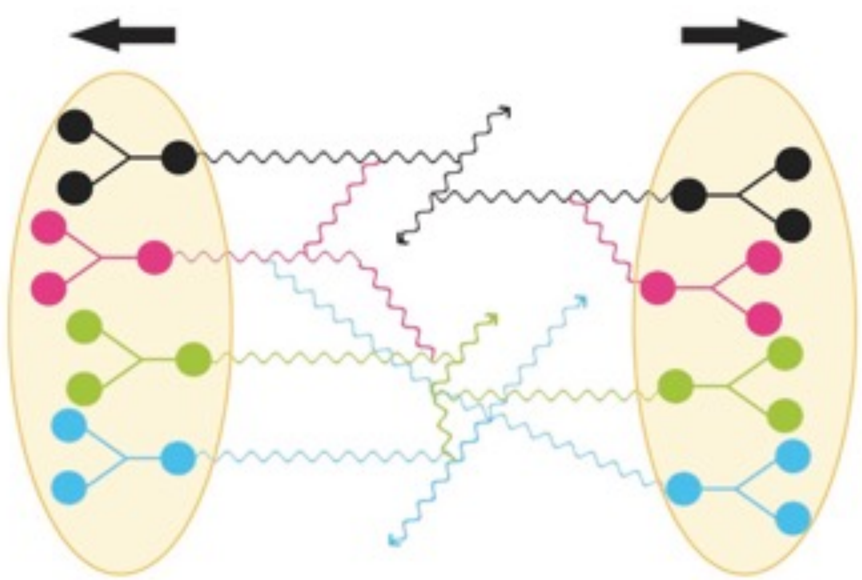
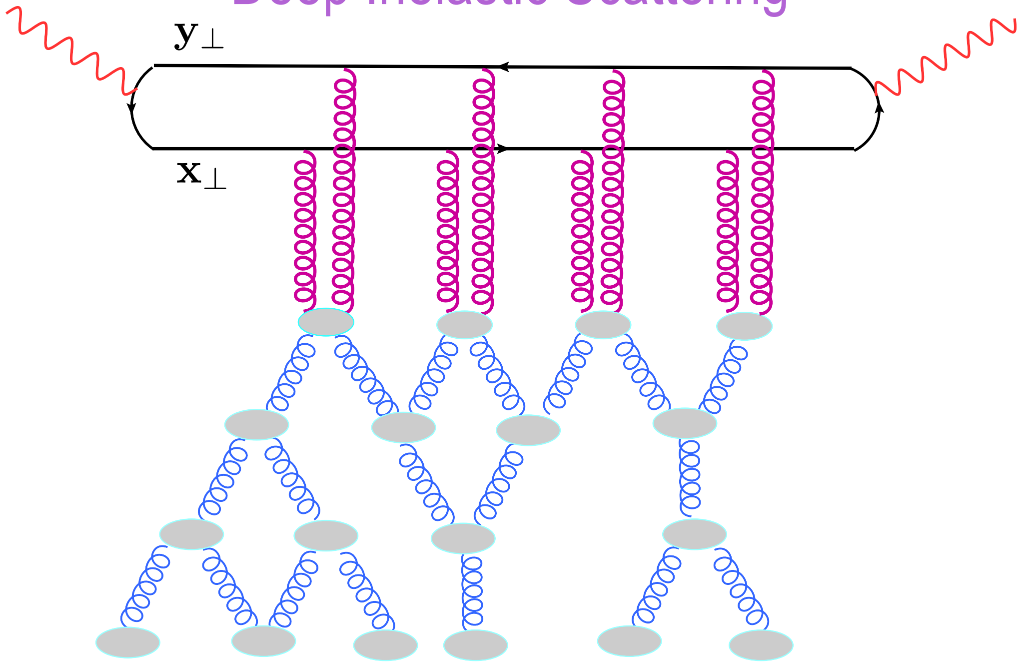
- Breakdown of independent particle production: resummation of multiple scatterings:

hadron-hadron



Deep Inelastic Scattering

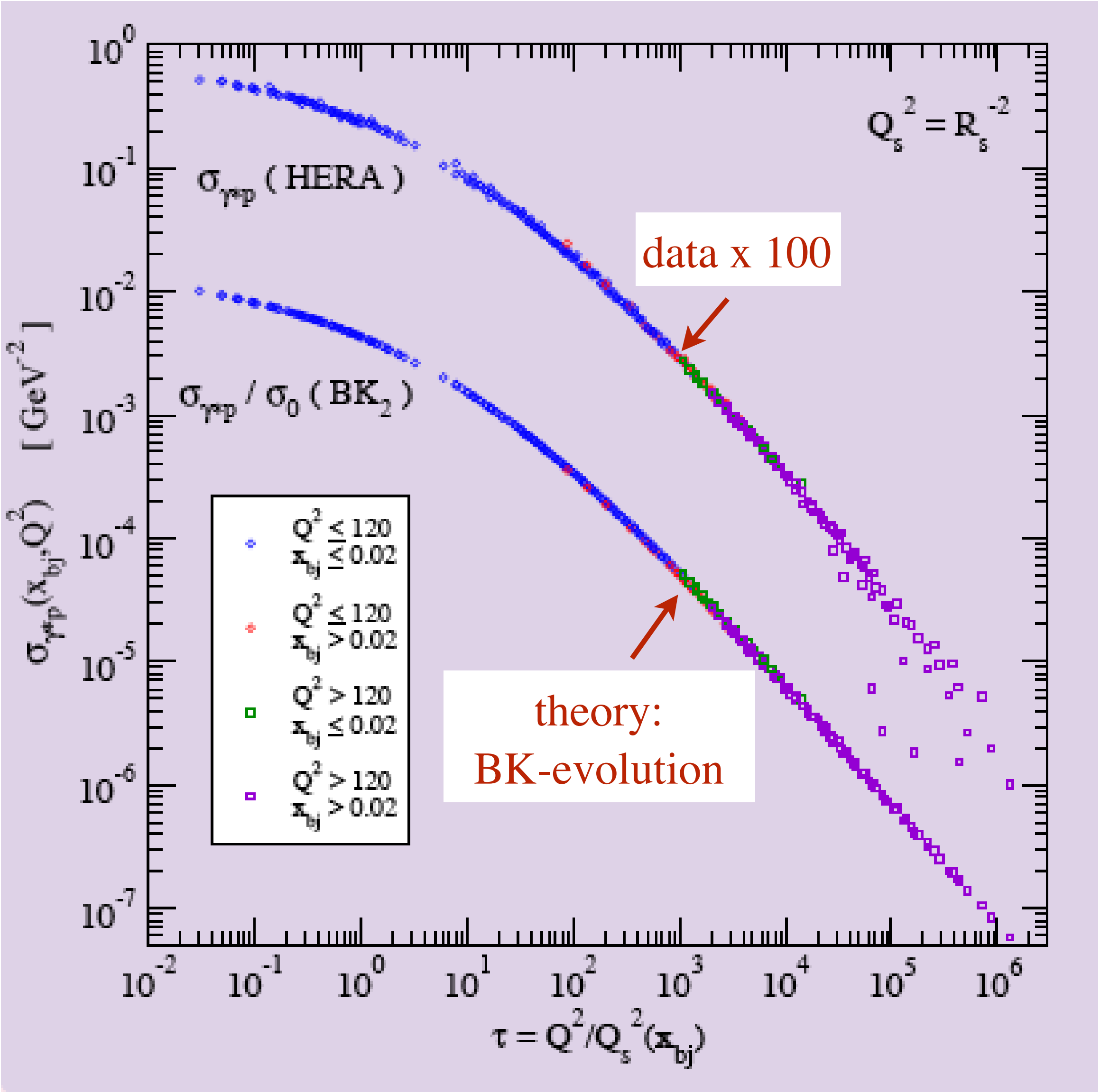


- PART II: Searching for saturation in experimental data

• Deep Inelastic electron-proton scattering

- Geometric Scaling of structure functions in DIS data at small-x ($x<10^{-2}$)

$$\sigma^{\gamma^* h}(x, Q^2) \to \sigma^{\gamma^* h}(\tau = Q^2/Q_s^2(x)) \qquad Q^2_{\rm sat}(x) = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$$



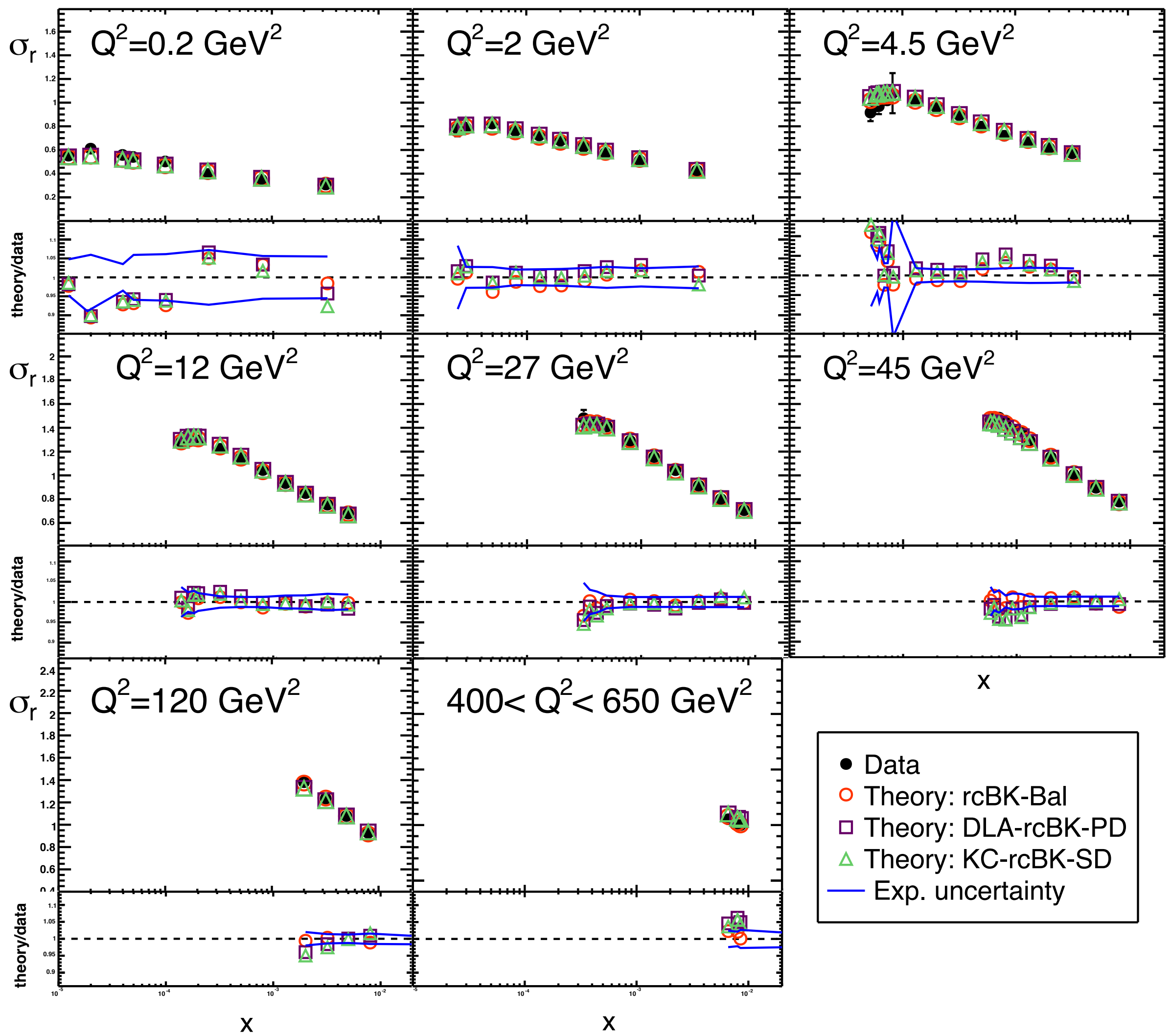
Stasto Golec-Biernat Kwicinski (2000) Plot by H. Weigert

• Deep Inelastic electron-proton scattering

- Overall, very good description of all available small-x data ($x<10^{-2}$) via non-linear pQCD dynamics
- DGLAP based fits show tensions at small values of $Q^2 <$10-15 GeV^2

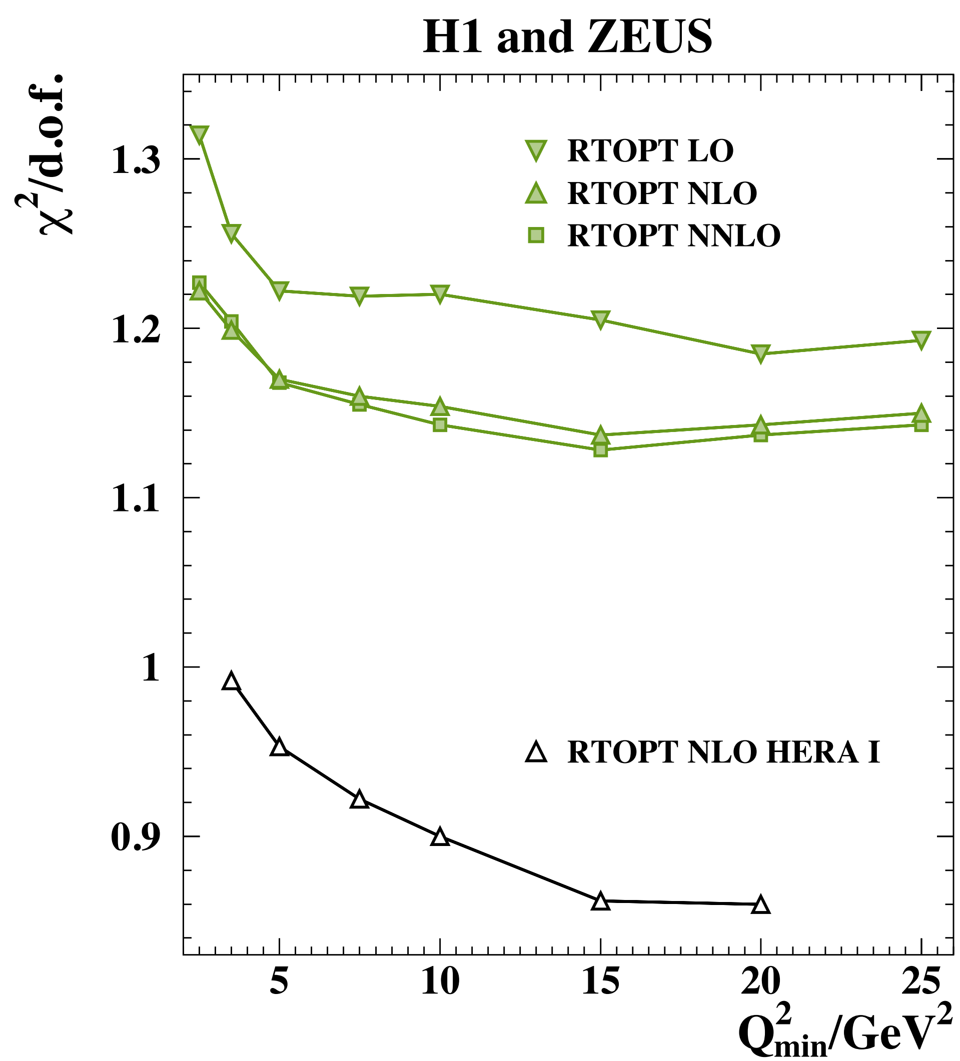
Global fits to ep x-sections via non-linear BK equation

$$\frac{\partial \phi(\mathbf{x},\mathbf{k}_\perp)}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x},\mathbf{k}_\perp) - \phi(\mathbf{x},\mathbf{k}_\perp)^2$$



JLA 1507.07120

DGLAP HERAPDF fit to H1 and ZEUS run II combined analysis. Sensitivity of χ^2/dof to minimum Q^2 value in the fit

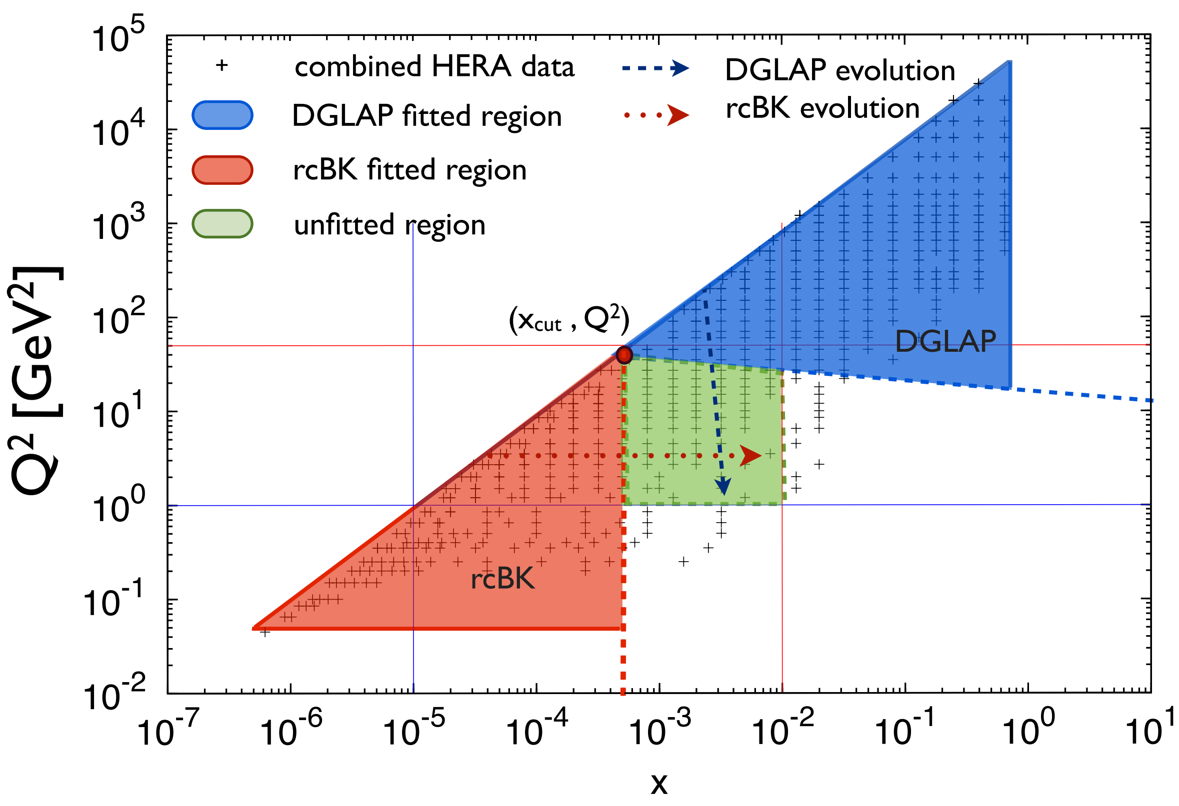


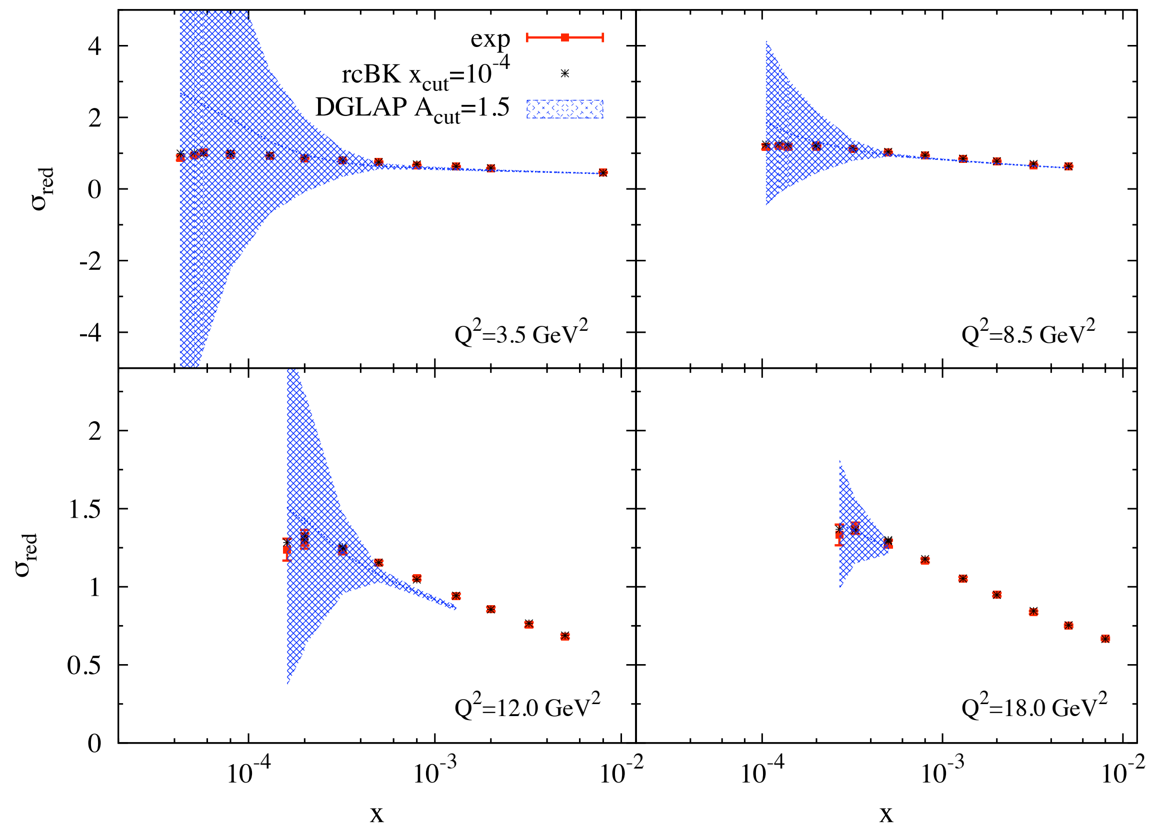
H Abramowicz et al 1506.06042

• DGLAP (linear) vs BK (non-linear) approaches at HERA

JLA, J.G Milhano, P. Quiroga and J Rojo

• What approach yields a better description of data at moderates values of (x,Q2)?





• rcBK fits are more stable than DGLAP ones!!!!

• Hadron-hadron collisions

Schematic structure of (most of) Monte Carlo event generators (PYTHIA, HERWIG…) for p+p and A+A collisions

soft sector: Regge theory, DPM …

$$\sigma_{soft} \propto s^{\alpha_{\mathcal{P}} \sim 0.08} + \ldots$$

hard sector: 2 →2 pQCD x-sections

$$\sigma = \mathrm{pdf} \otimes \sigma_{hard} \otimes \mathrm{FF}$$

$$\sigma_{\mathrm{hard}}(p_{\perp\mathrm{min}}) = \int_{p^2_{\perp\mathrm{min}}}^{s} \frac{d\sigma}{dp^2_\perp} dp^2_\perp$$

$p_{\perp\mathrm{min}}$

transverse momentum

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$p_{\perp\mathrm{min}} \sim 1\,\mathrm{GeV}$

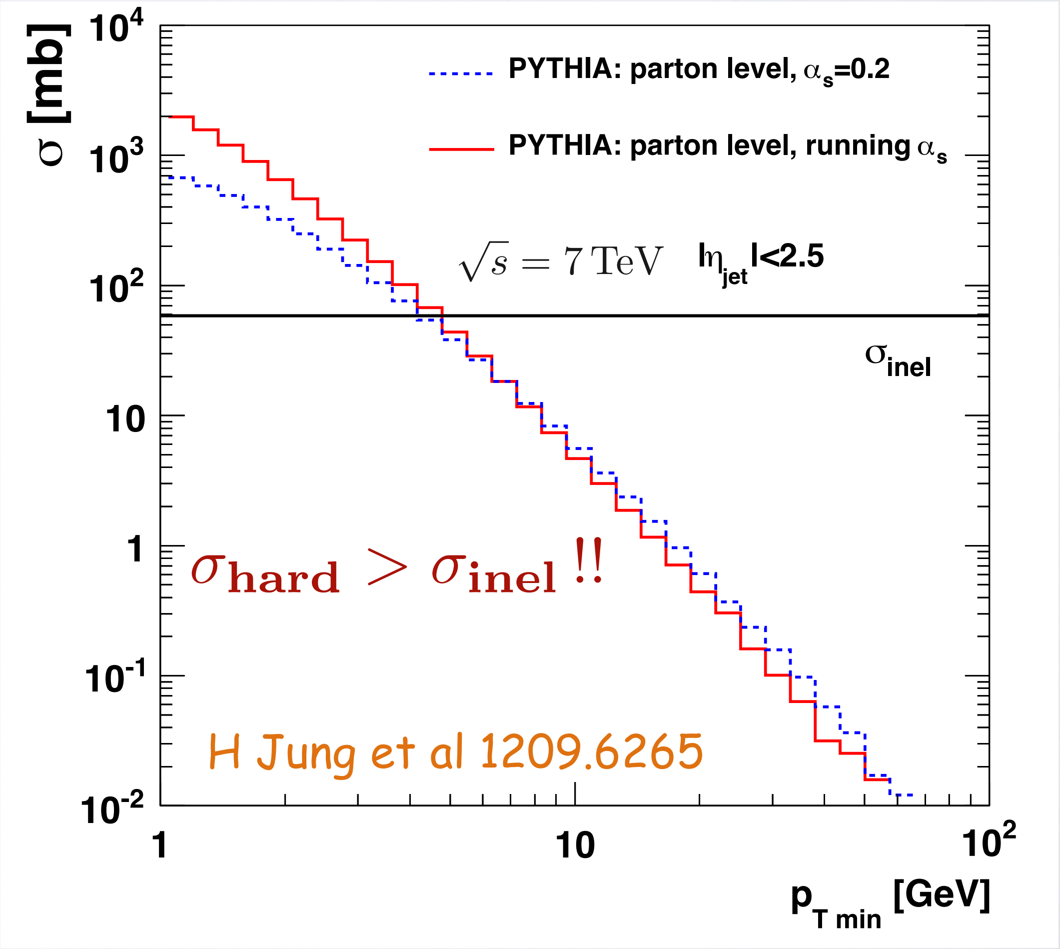
transverse momentum

Strong growth of gluon distributions to small-x results in a violation of unitarity for perturbatively large p_{tmin} values

This problem is (partly) solved by letting p_{tmin} grow with increasing collision energy

$$p_{\perp\mathrm{min}} \sim \sqrt{s}^{\lambda \approx 0.2} \sim Q_{\mathrm{sat}}$$

Collinear factorisation is relaxed to allow for intrinsic transverse momentum of the colliding partons



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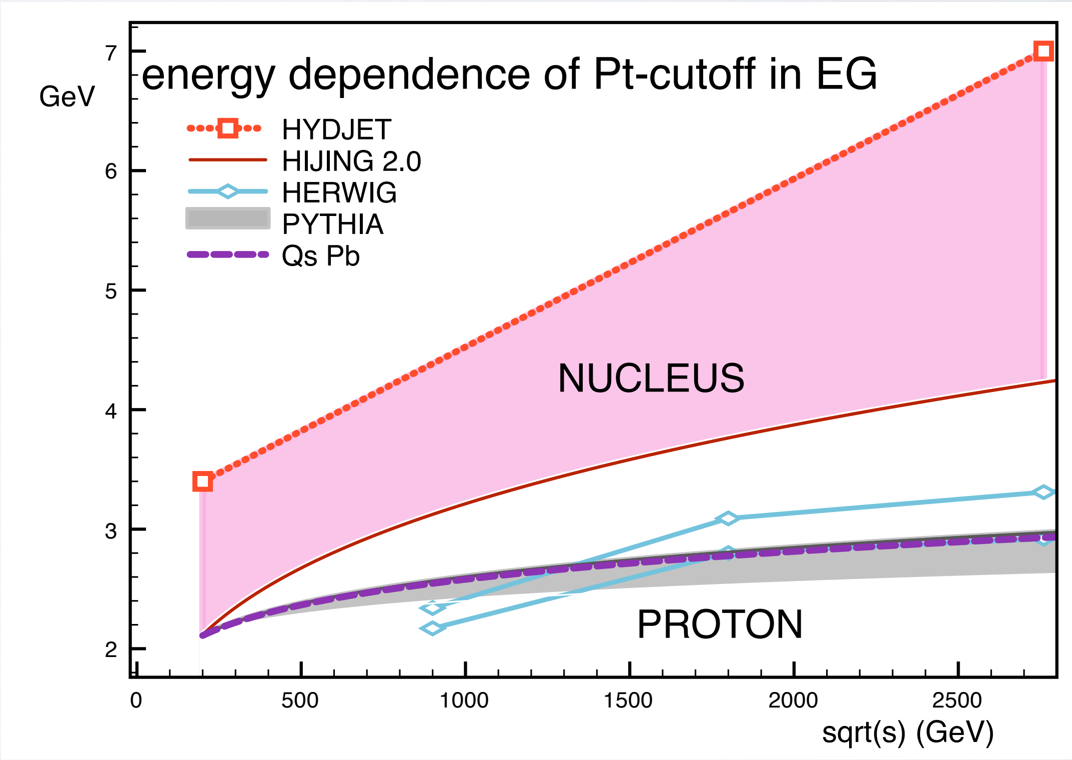

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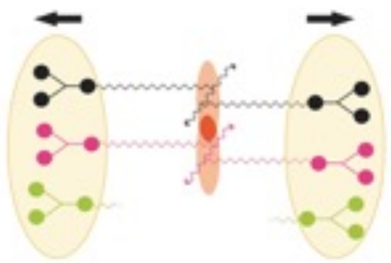
$$\sigma_{soft} \propto s^{\alpha_{\mathcal{P}} \sim 0.08} + \ldots$$

Breakdown of independent scattering approximation



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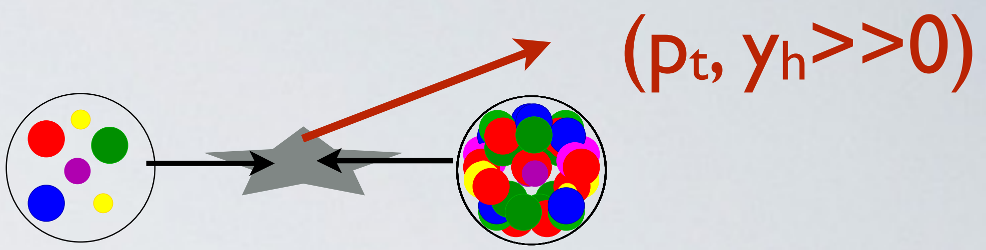
transverse momentum

Open theoretical problem: To find a unified formalism to describe QCD dynamics in all the (perturbative) kinematic plane.

This problem translates to MC event simulators and others

• proton-Nucleus collisions

$$\mathbf{Q^2_{sat}(x) \sim Q_0^2\, A^{1/3} \left(\frac{x_0}{x}\right)^{\lambda}} \qquad x_{1(2)} \sim \frac{m_t}{\sqrt{s}} \exp(\pm\, y_h)$$

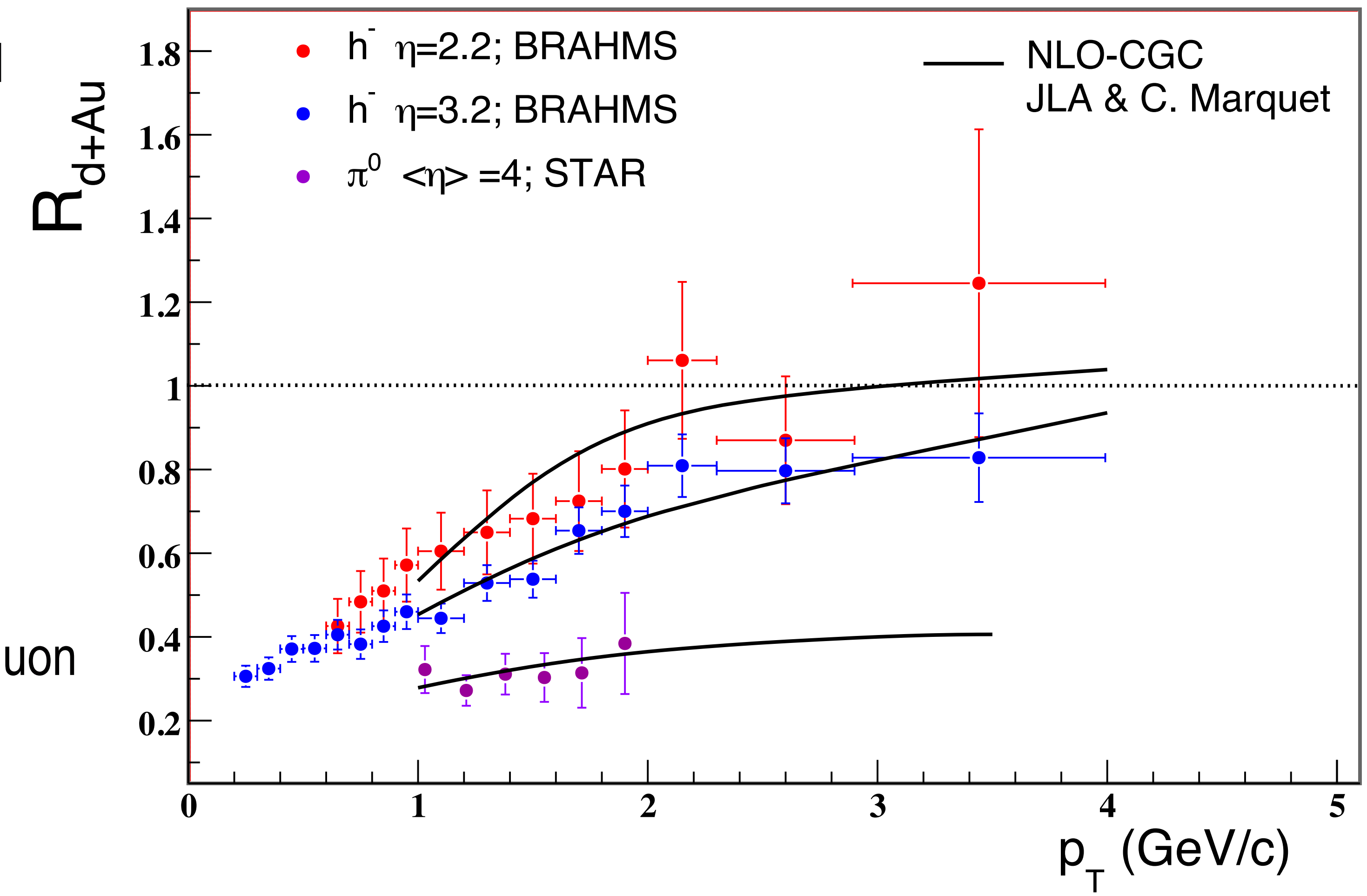


• Forward suppression phenomena in p-A collisions at RHIC:

• Less particles per nucleon produced in the forward region in p+Au than in p+p collision:

$$R_{pPb} = \frac{1}{N_{\rm coll}} \frac{dN_h^{pPb}}{dy_h\, d^2p_t} \Big/ \frac{dN_h^{pp}}{dy_h\, d^2p_t}$$

• Such suppression was predicted within the high gluon densities framework.



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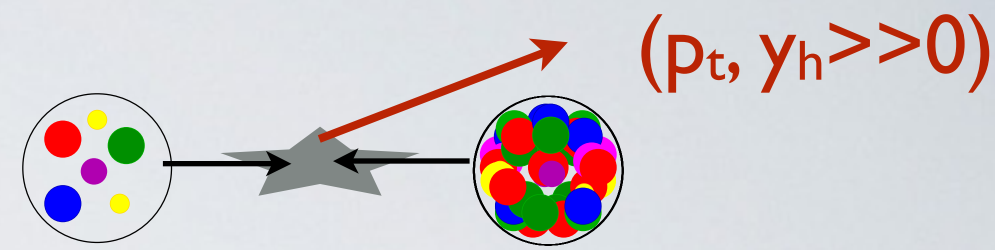
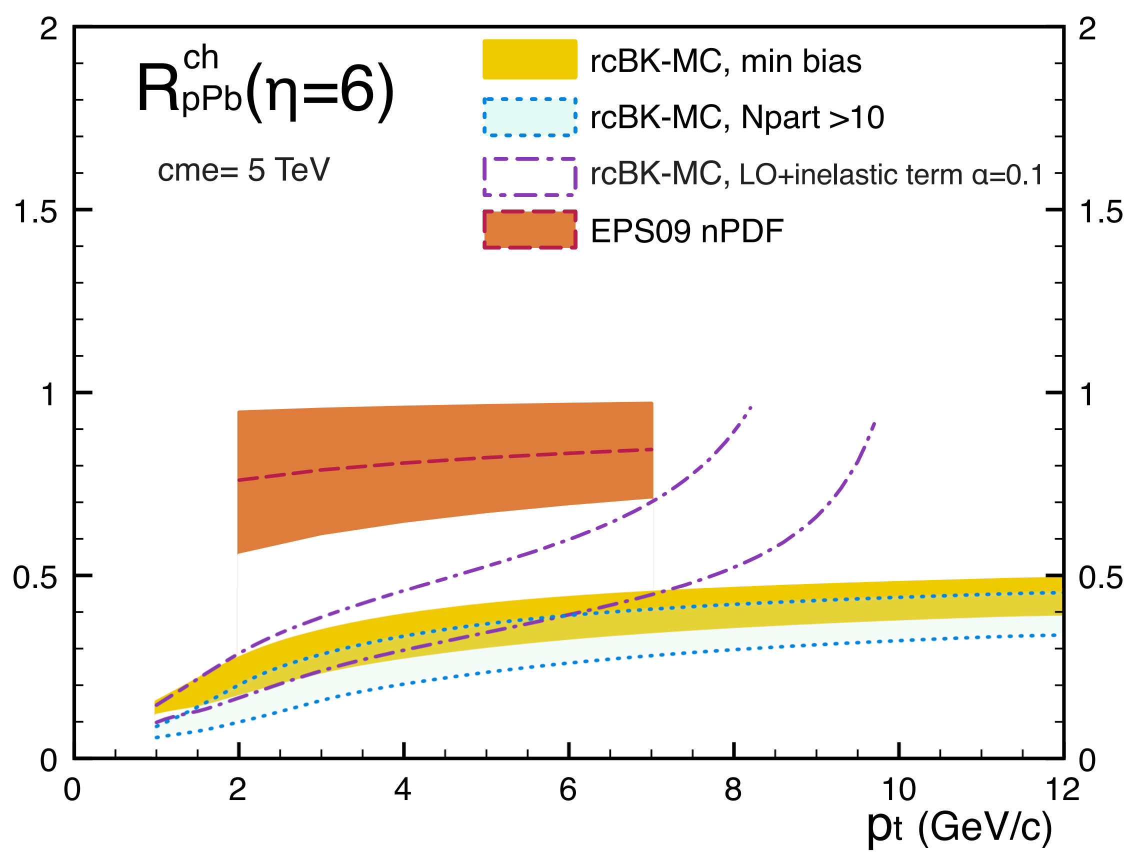


• **Forward suppression phenomena in p-A collisions at LHC:**



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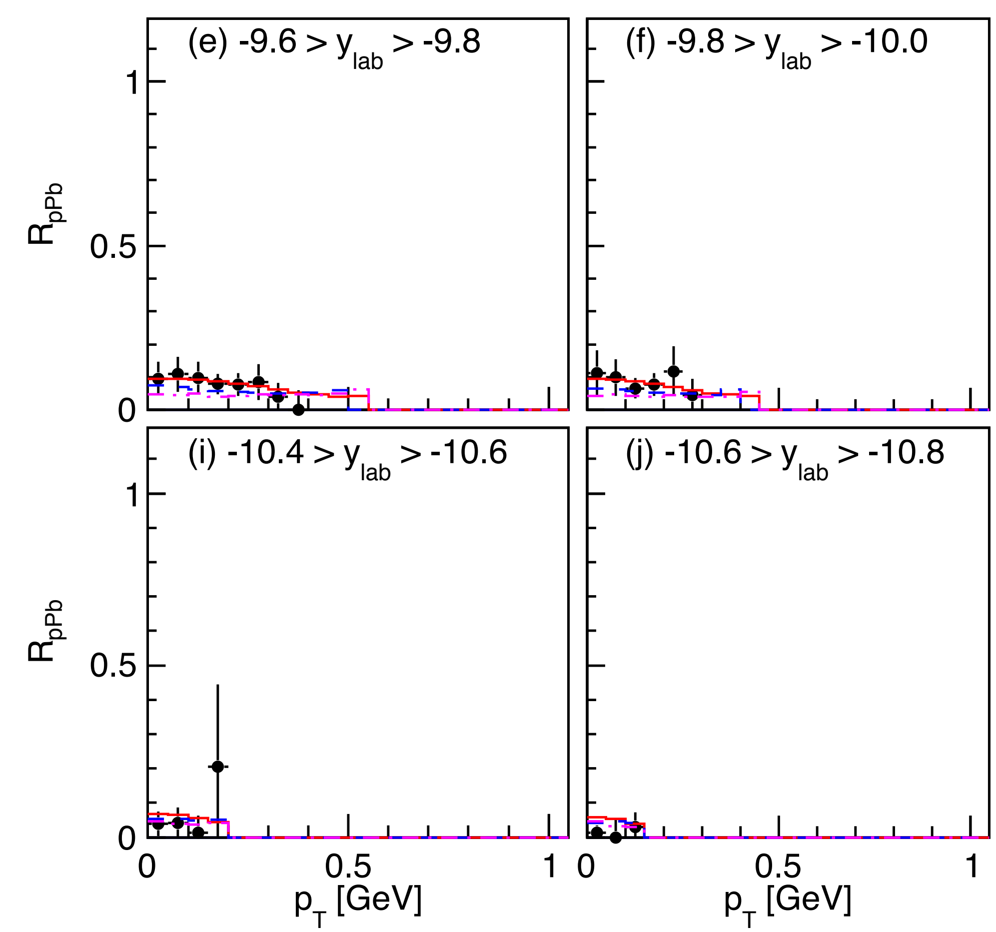
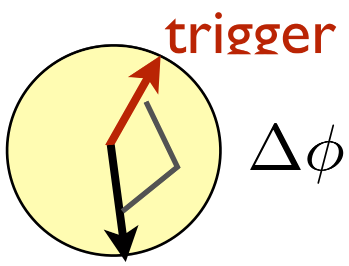


p+Pb @LHC
LHCf coll.

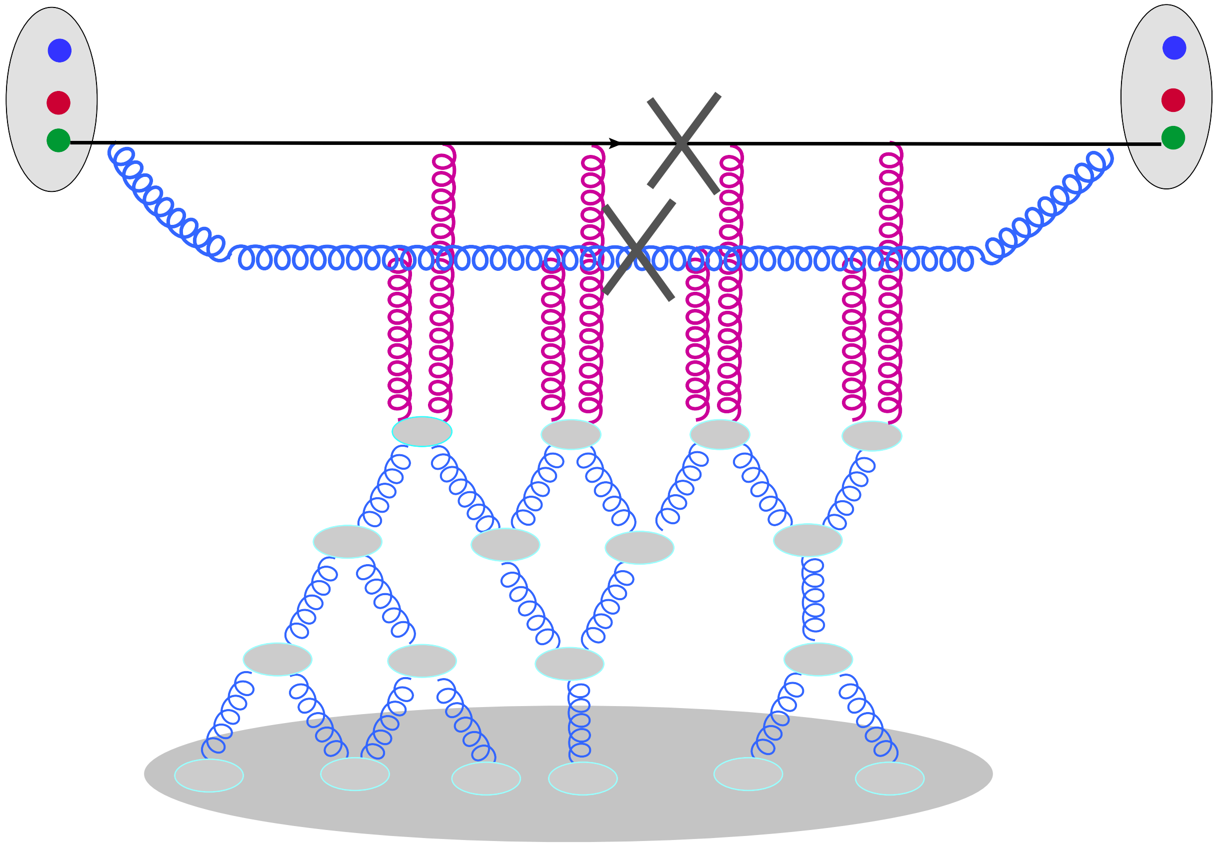
• proton-Nucleus collisions

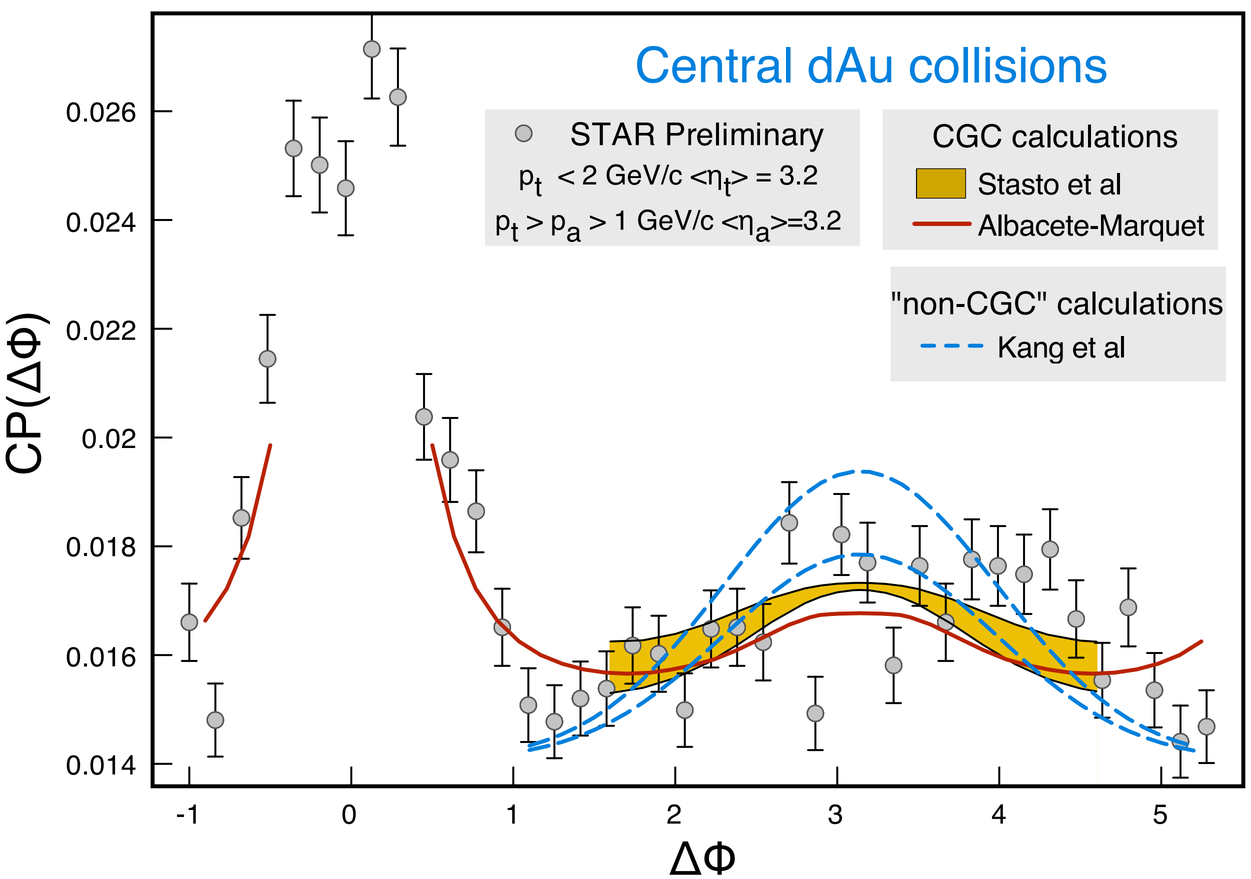
Suppression of angular correlations in forward particle production



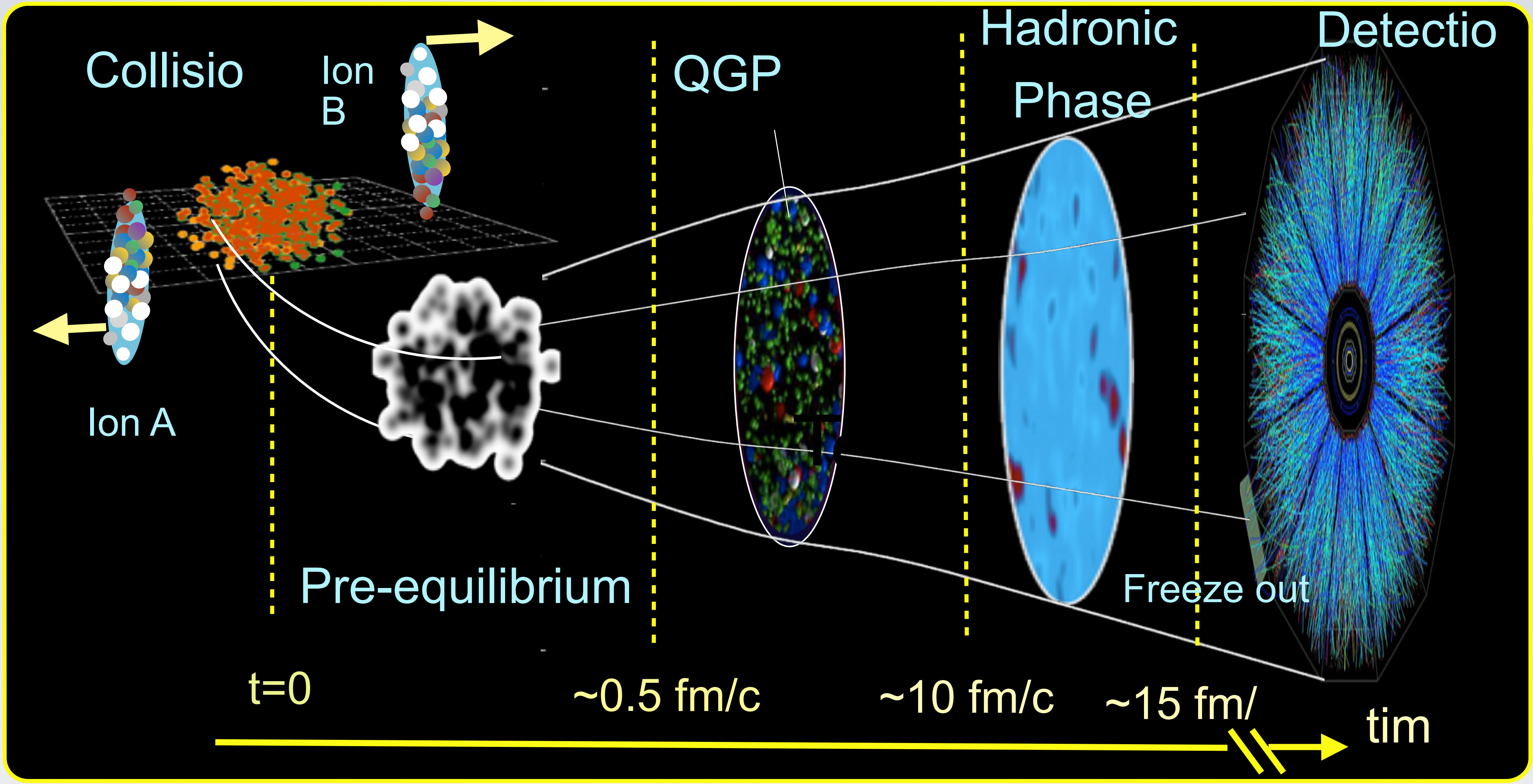
Angular decorrelation happens if $\mathbf{Q_s^{Pb}(x_A)} \sim (\mathbf{k_1}, \mathbf{k_2})$

$$CP(\Delta\phi) = \frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\phi}$$





The "little bang": Heavy ion collisions at RHIC and the LHC



"The abundant, saturated gluons in the wave function of the colliding ions seed the formation of a new, deconfined state of QCD matter: the Quark Gluon Plasma"

99% of the particles produced in a heavy ion collisions have relatively small transverse momentum

$$p_t \sim 1 \div 2\,\text{GeV}$$

RHIC: $\sqrt{s_{NN}} = 200\text{GeV}$ $\quad x \sim 10^{-2}$

LHC: $\sqrt{s_{NN}} = 2.76\text{TeV}$ $\quad x \sim 10^{-4}$

- Total multiplicities in heavy ion collisions:

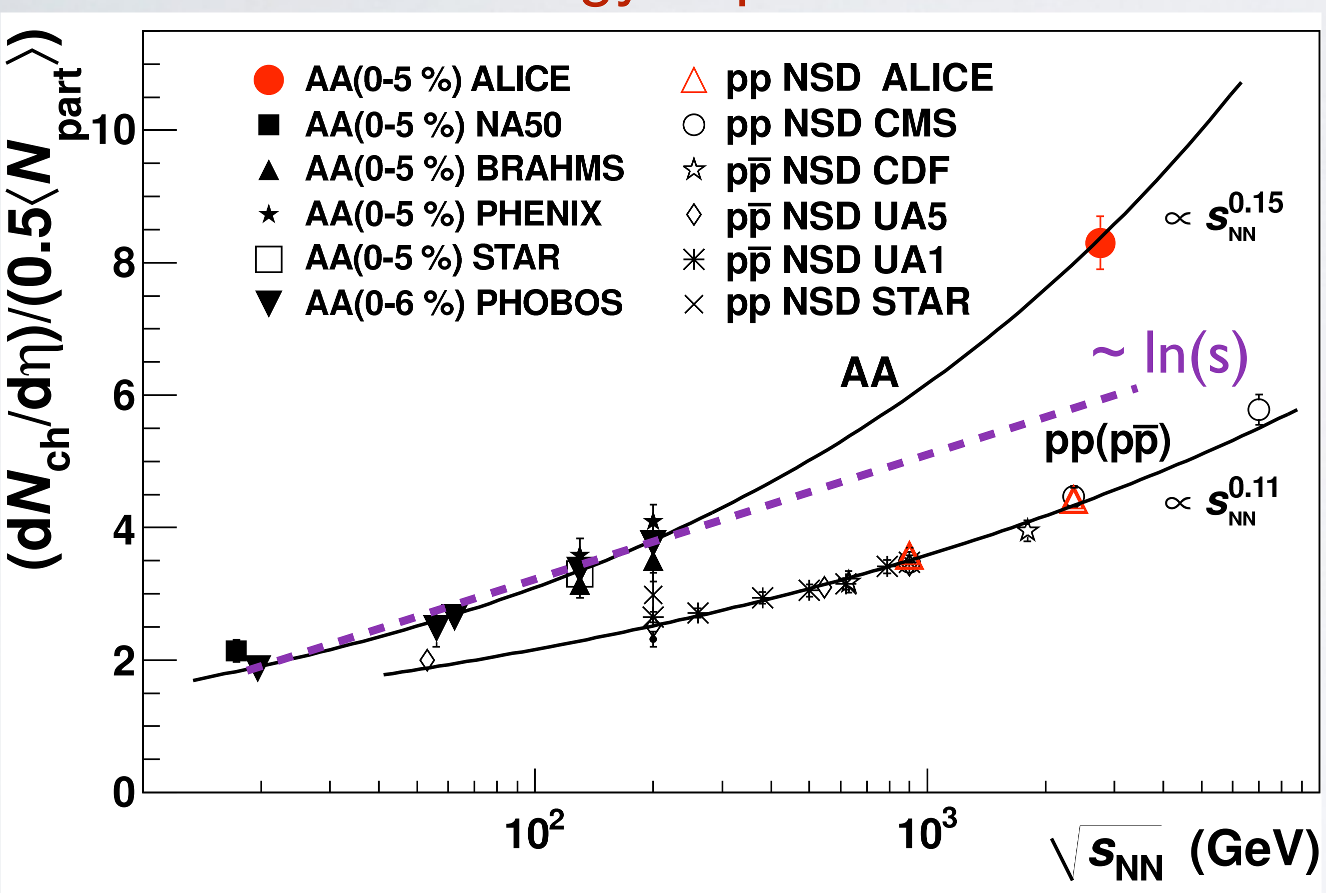
Theory

$$\left.\frac{dN^{ch}}{d\eta}\right|_{\eta=0} = \frac{2}{3}K\left.\frac{dN^{g}}{d\eta}\right|_{\eta=0} \propto Q_s^2(\sqrt{s},b) \sim \sqrt{s/s_0}^{\lambda} N_{part}$$

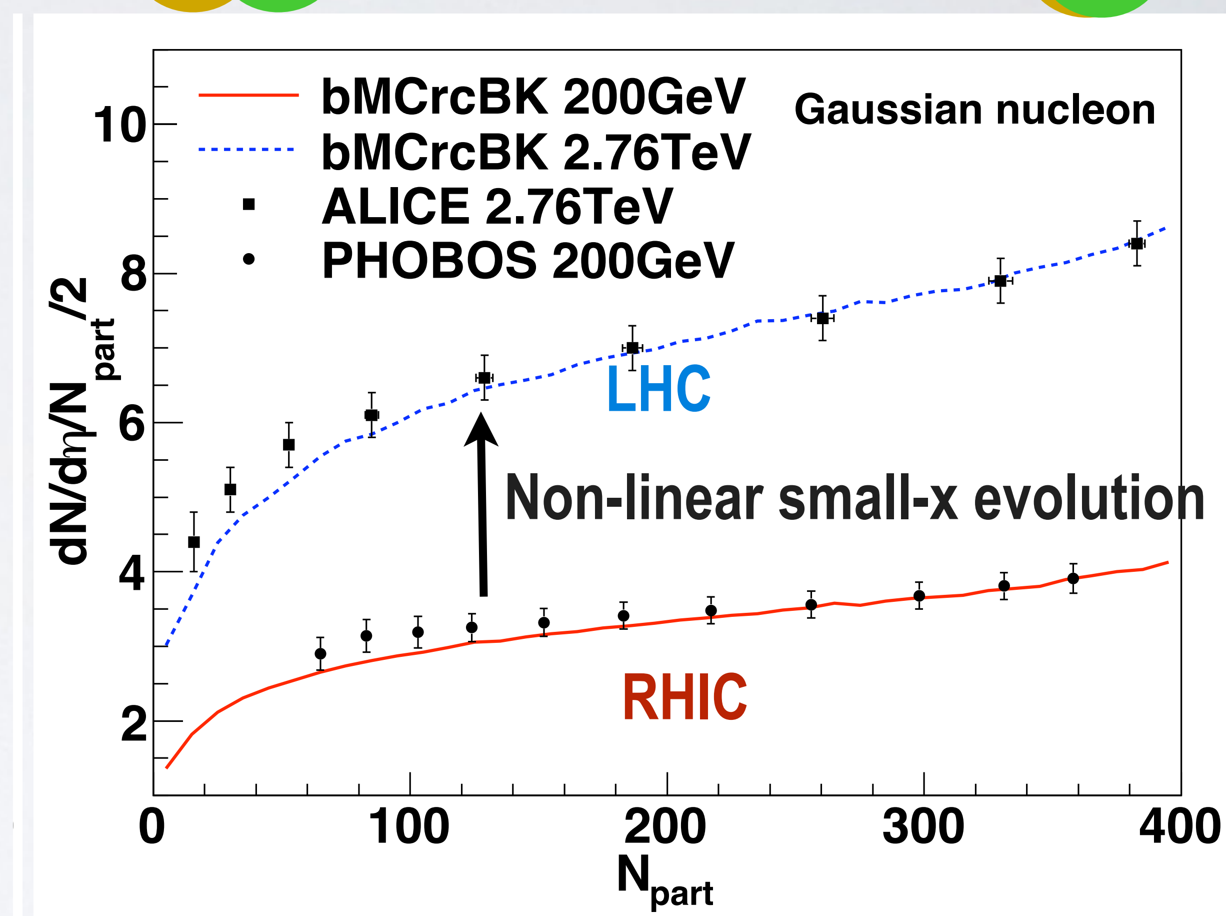
Data

$$\left.\frac{dN^{ch}}{d\eta}\right|_{\eta=0} \approx \sqrt{s}^{0.3} \times f(N_{part})$$

Energy dependence



Centrality dependence



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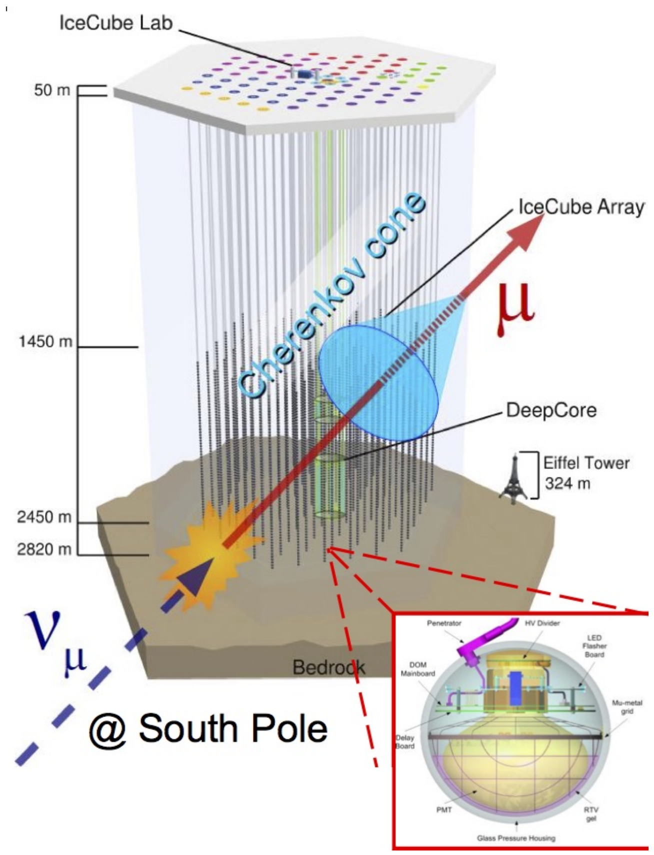
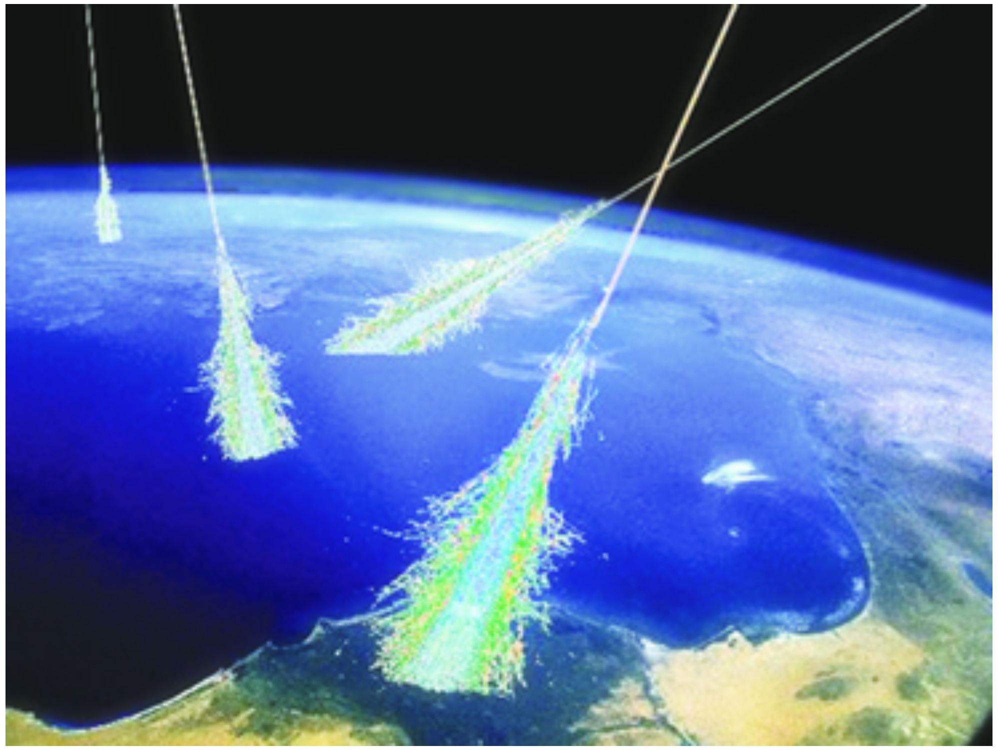
Up in the skies…

Neutrino observatories



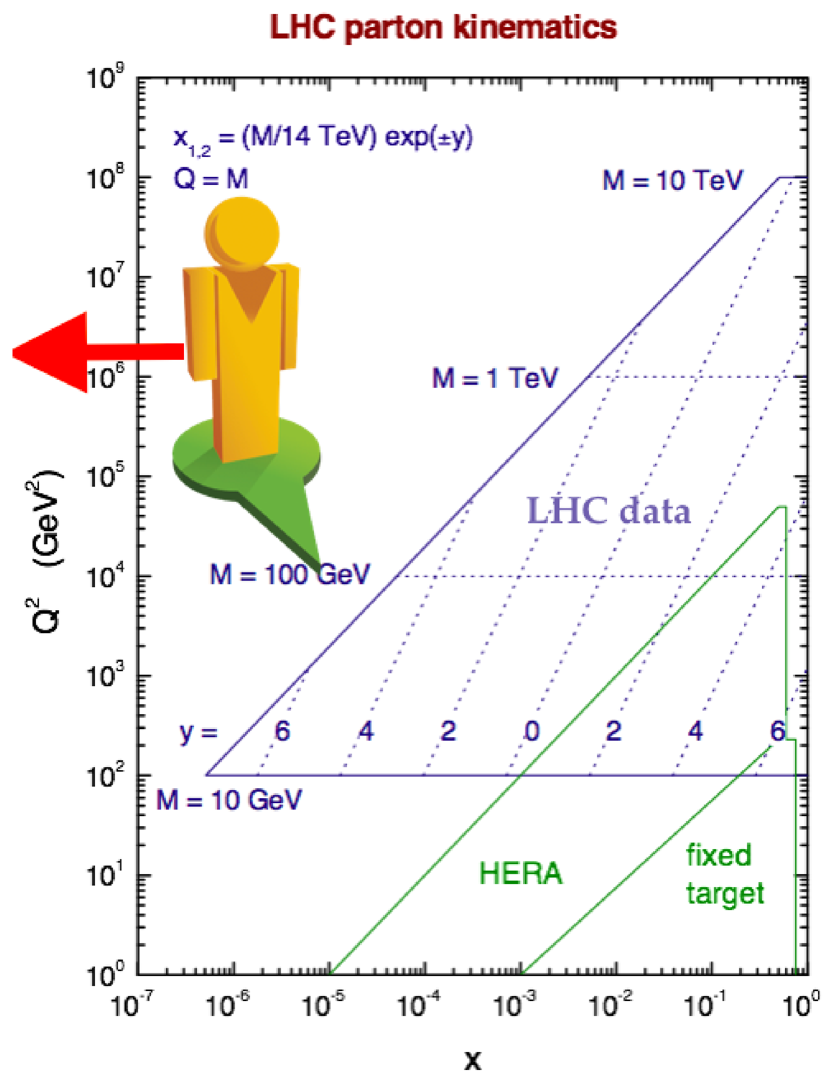
IceCube: $E_\nu = 2\ 10^9$ eV
Anita $E_\nu = 10^{11}$ eV
Lunaska $E_\nu = 10^{12}$ eV

Cosmic rays



Cosmic rays of $E_{CR} \sim 10^{20}$ eV
measured in Auger $\sqrt{s_{GZK}} \sim 300\,\mathrm{TeV}$

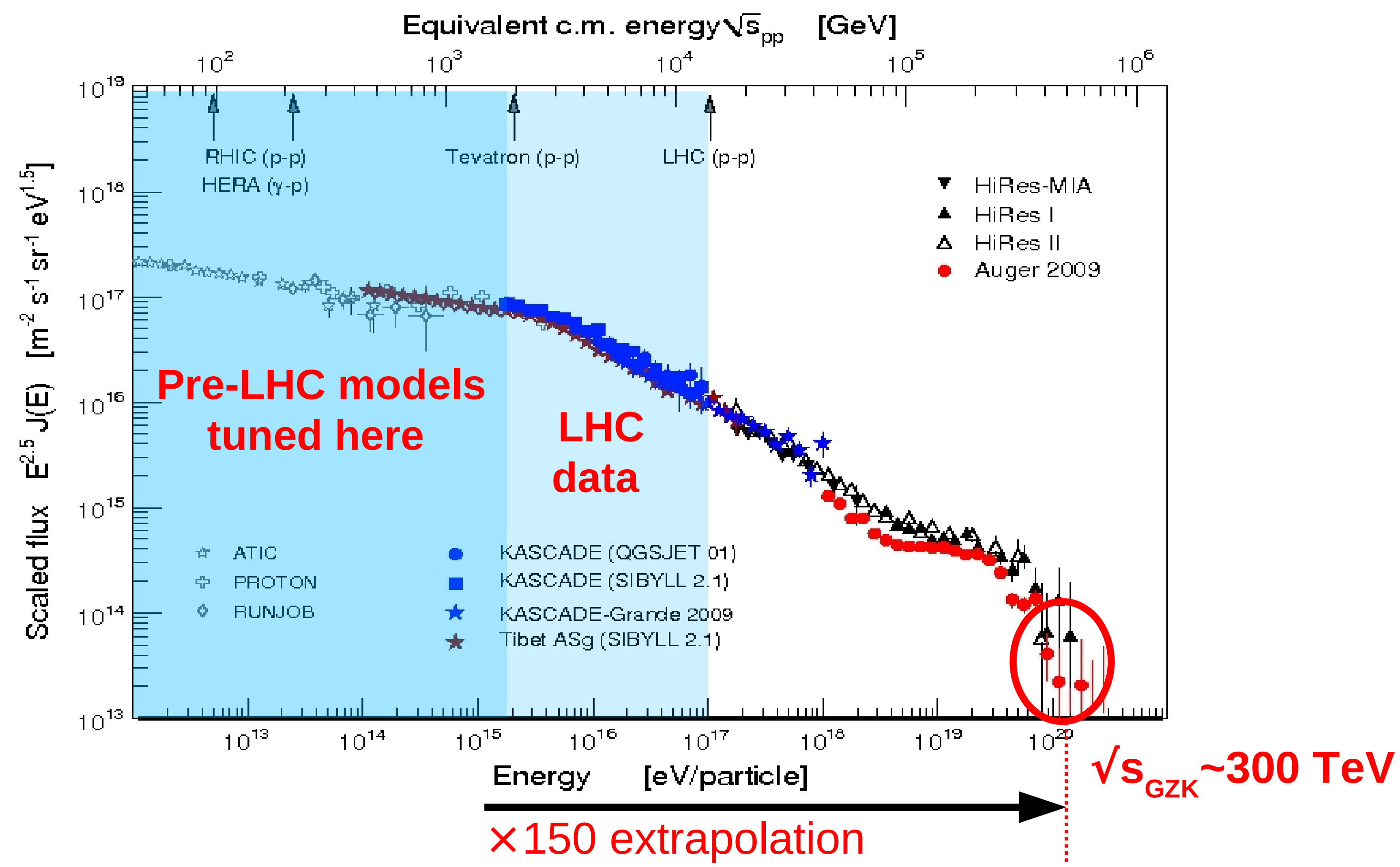
Uncharted territory: kinematic extrapolations



$$Q^2 \sim M_i^2 \sim 10^4\ \mathrm{GeV}^2$$

&

$$10^{-11} \lesssim x \lesssim 10^{-5}$$

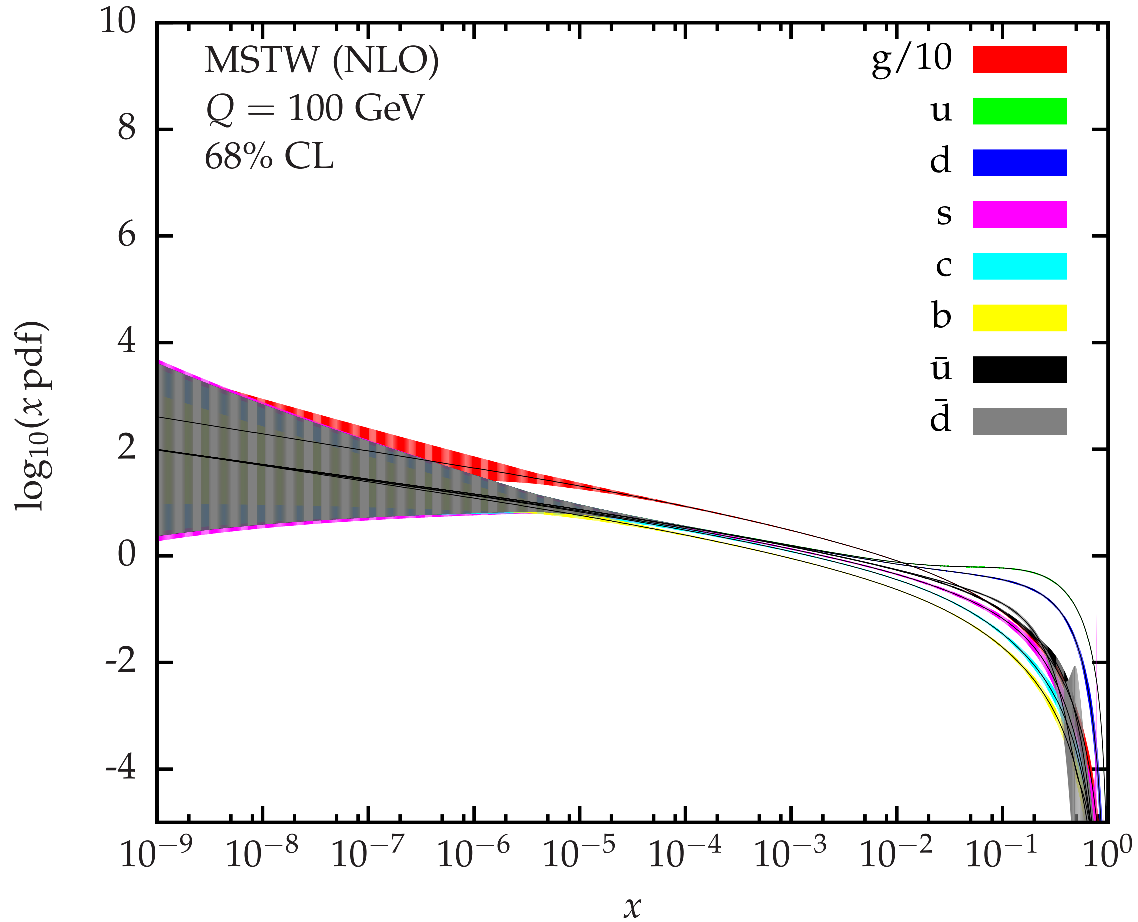


The study of UHE CR's imply the extrapolation of hadronic Monte Carlo event generators by a factor ~150 wrt to LHC energies

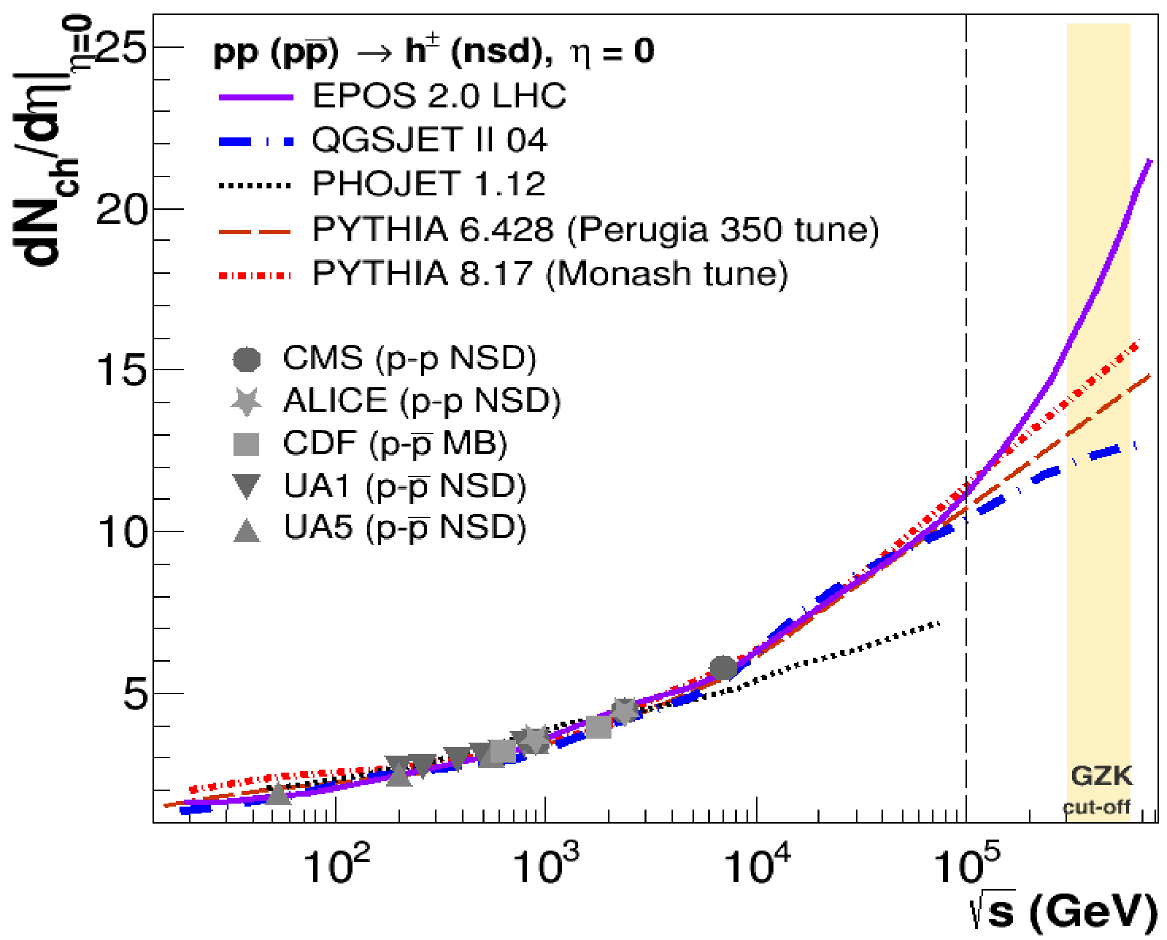
Similarly, the relevant kinematic region for νN scattering in IceCube and others fall several orders of magnitude beyond the reach of LHC or HERA

Reliable theoretically-based extrapolations are needed!

Uncharted territory: kinematic extrapolations



Extrapolation of fitted pdf sets to x-values relevant in UHE νN scattering



Extrapolation of hadronic MC's to UHE CR energies (multiplicities)

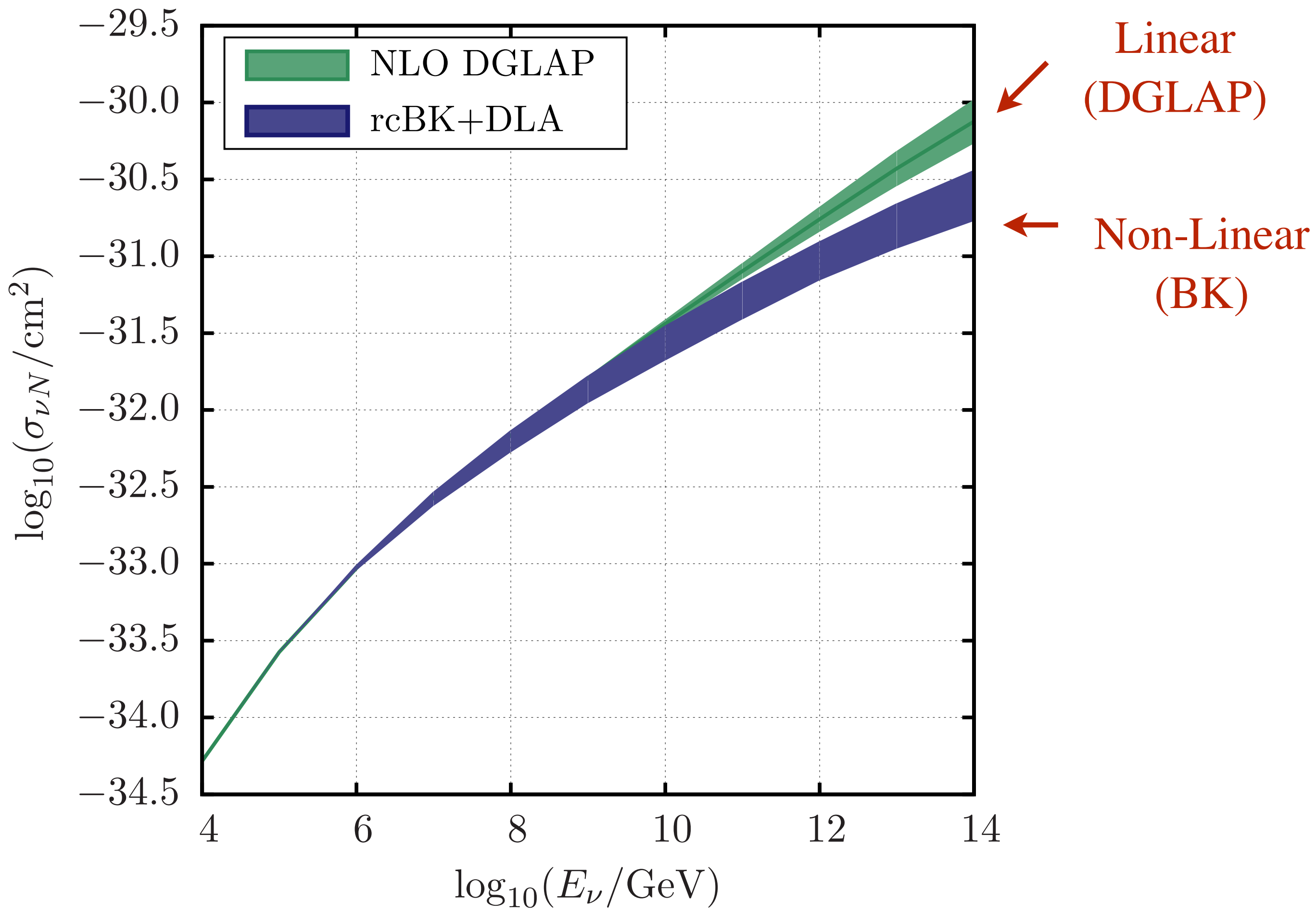
Reliable theoretically-based extrapolations are needed!

Limits on neutrino fluxes

Bounds on the neutrino fluxes are sensitive to the value of the νN cross-section

$$\frac{dN}{dE} \sim \phi_\nu \cdot \sigma_{\nu N}$$

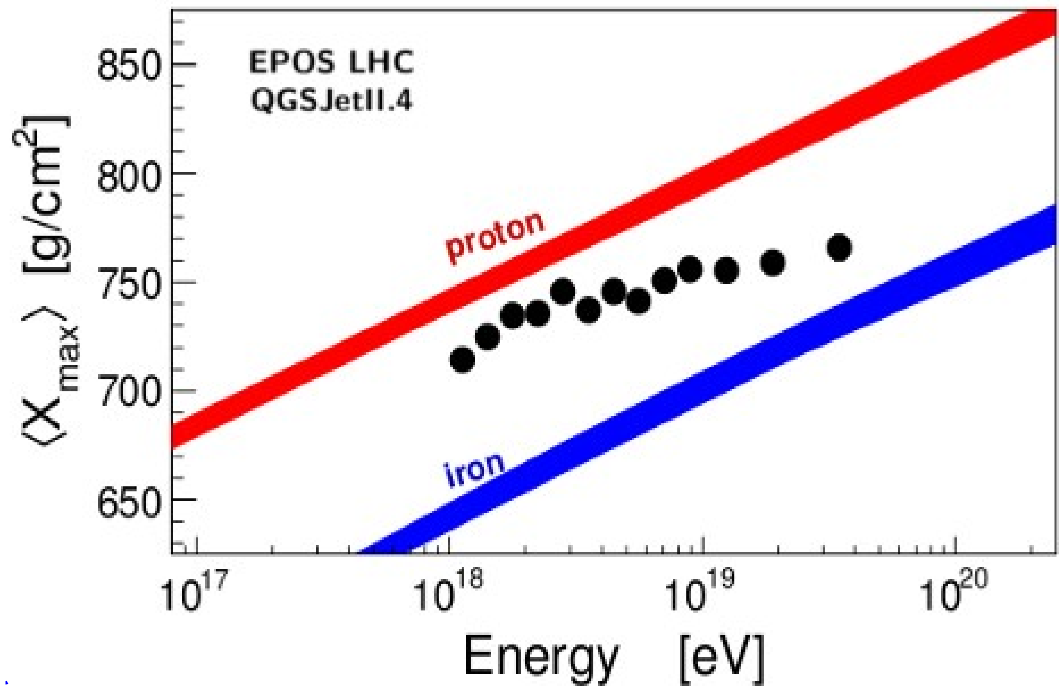
Theoretical uncertainty: non-linear QCD effects reduce the x-section and increase the flux.



$$\frac{d\phi_\nu}{dE_\nu} = k\,E_\nu^{-2} \Rightarrow k_{90} < \frac{N_{\rm up}}{\int dE_\nu\, E_\nu^{-2} \mathcal{E}_{\rm tot}(E_\nu)} = 6.4 \times 10^{-9}\ \mathrm{GeV\,cm^{-2}\,sr^{-1}\,s^{-1}}$$ P. Auger

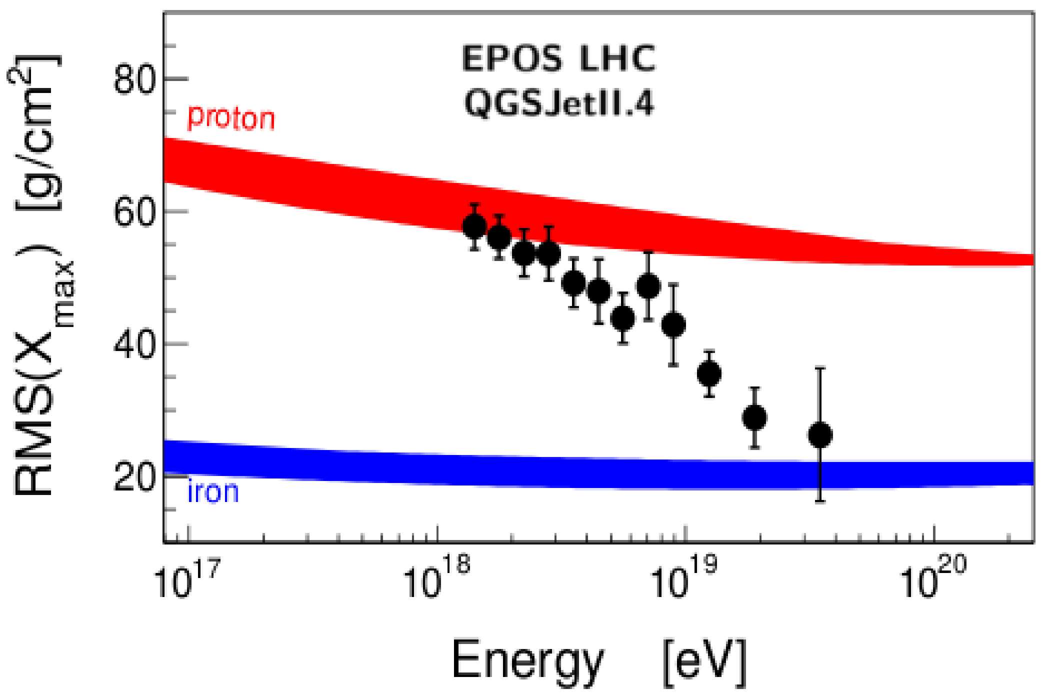
P. Auger	$E_\nu = 10^9$ GeV.	$k_{90} \sim 1.4 \times k_{90}$
ANITA	$E_\nu \sim 10^{11}$ GeV	$k_{90} \sim 1.5 \times k_{90}$
Lunaska	$10^{12} < E_\nu < 10^{14}$ GeV	$k_{90} \sim (2.5 \div 4.5) \times k_{90}$

Some open problems in the study of UHE **Cosmic Rays** where saturation physics may play a role…



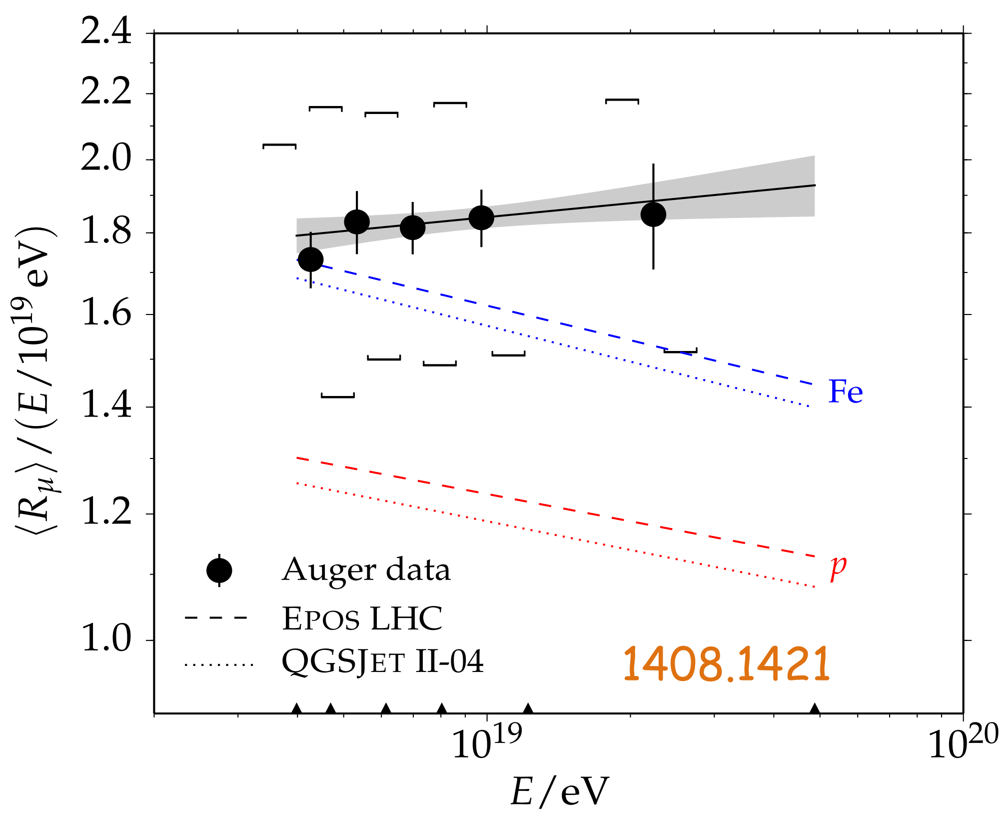
Features of the cosmic ray shower are very sensitive to hadronic interactions: $\sigma, \frac{dN}{dy}, < y >$

Xmax: Extrapolations of the hadronic Monte Carlo simulations to UHE CR energies yield an inconclusive situation on the atomic mass composition of the primary CR's



Plots by R. Ulrich (KIT)

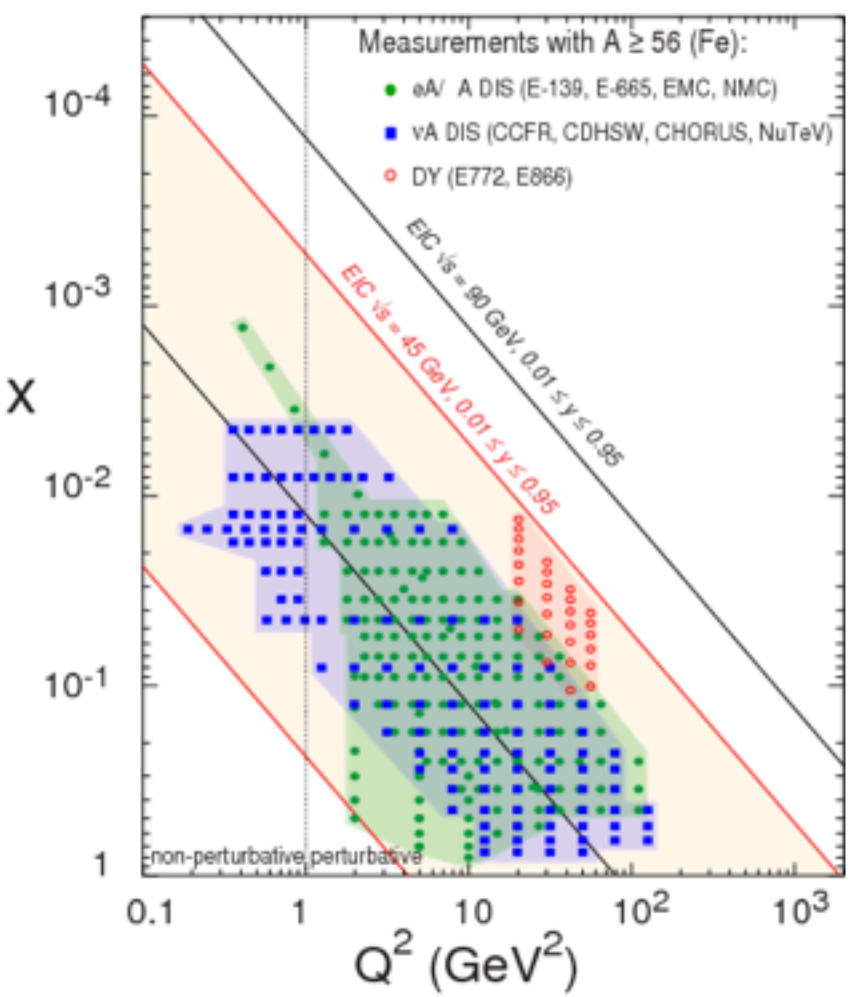
Muons: More muons observed than expected…



Pushing the energy frontier: Future (?) facilities

Electron Ion collider

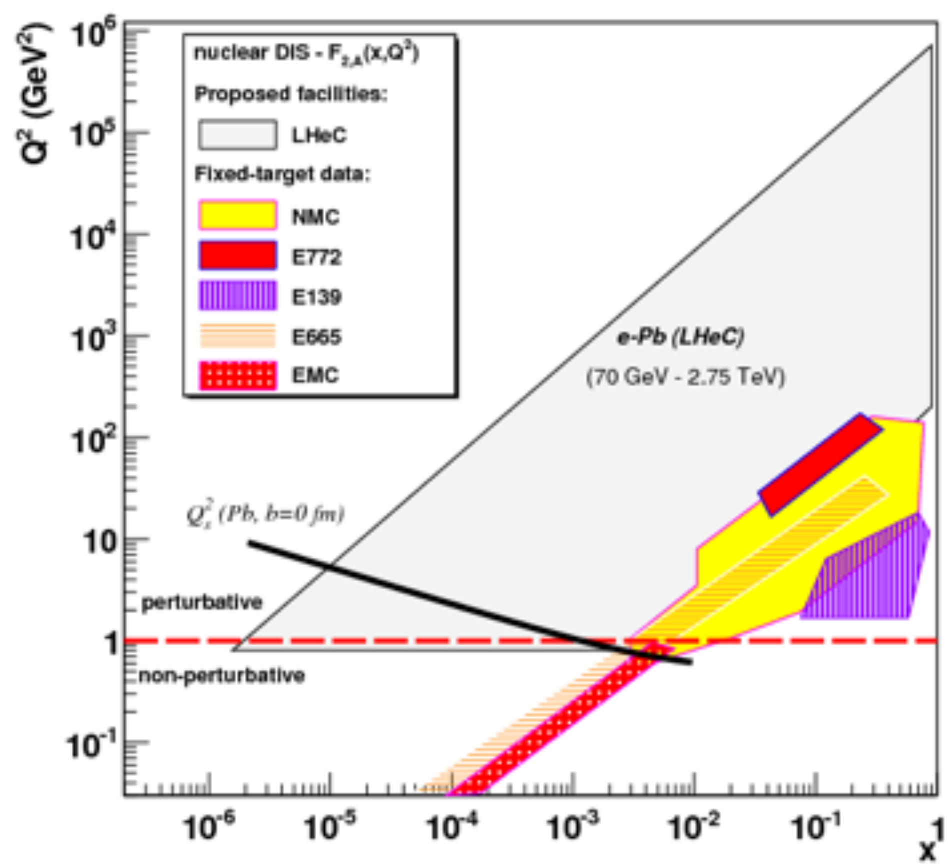
e+p,A ~ 100 GeV
polarized



NSAC, October 16th: "We recommend a high-energy high-luminosity polarized EIC as the **highest priority for new facility construction** following the completion of FRIB."

LHeC

e+p,A ~ 1 TeV



Future Circular Collider
100 TeV

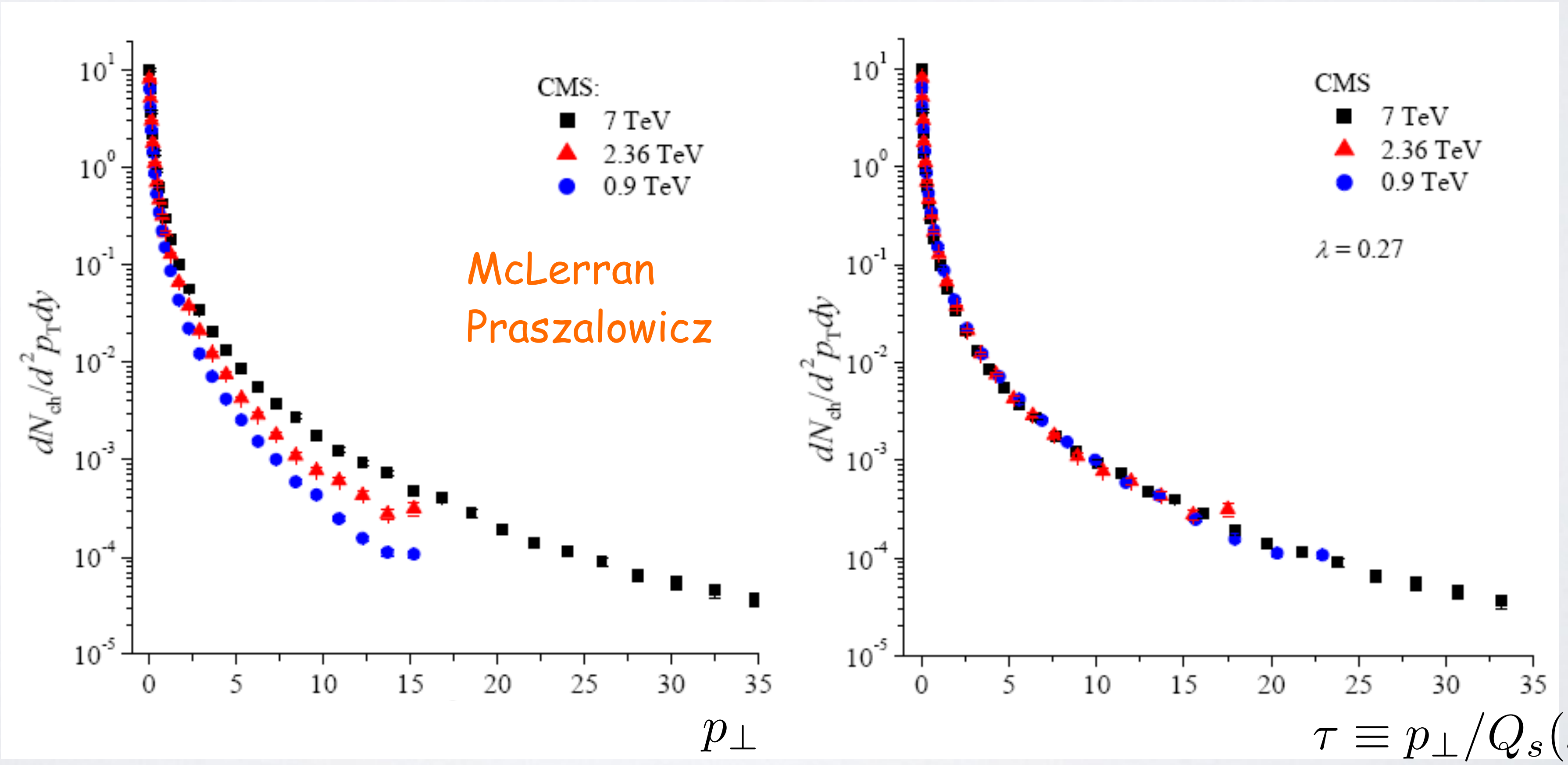
The Future Circular Collider study has an emphasis on proton-proton and electron-positron (lepton) high-energy frontier machines. It is exploring the potential of hadron and lepton circular colliders, performing an in-depth analysis of infrastructure and operation concepts and considering the technology research and development programs that would be required to build a future circular collider. A conceptual design report will be delivered before the end of 2018 , in time for the next update of the European Strategy for Particle Physics.

Instead of conclusions …

While no definitive conclusion can be extracted from the analyses of presently available data, it is fair to say that many observables from a variety of collision systems find their natural explanation and a good quantitative description in terms of non-linear dynamics associated to the presence of large gluon densities.

• Energy dependence of multiplicities well described in saturation formalisms

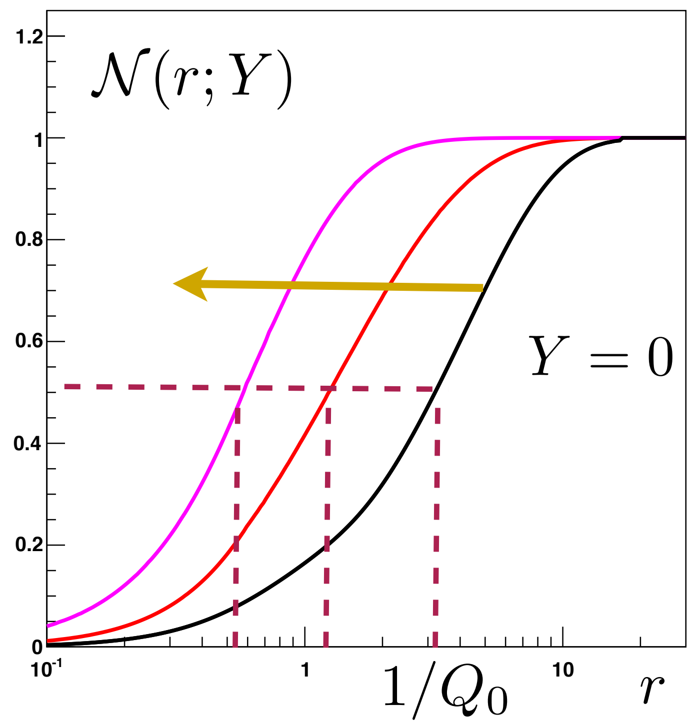
• Related Geometric Scaling features identified in p+p collisions at different collision energies $\frac{dN_{\mathrm{ch}}}{dy dp_{\mathrm{T}}^2}(s, p_{\mathrm{T}}) = \frac{1}{Q_0^2} F(\tau)$



✓ Saturation: Unitarity at work

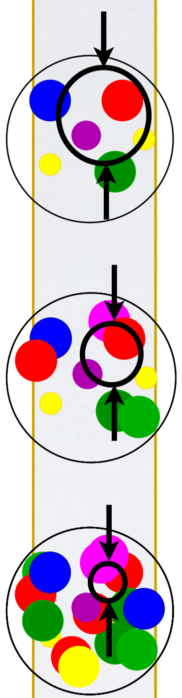
$Y = \ln \frac{1}{x}$

COORDINATE SPACE

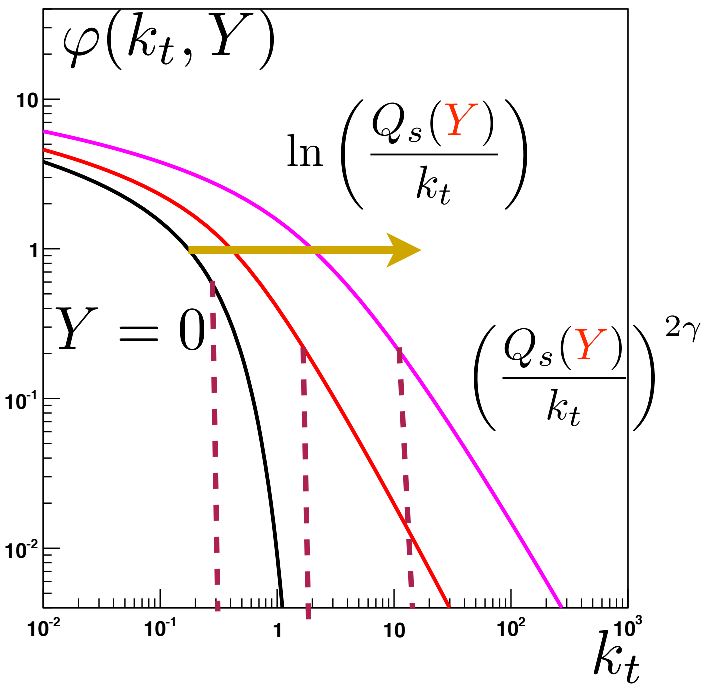


Black disc limit preserved $\mathcal{N}(r,Y) \leq 1$

BFKL yields $\mathcal{N}(r,Y) > 1$



MOMENTUM SPACE

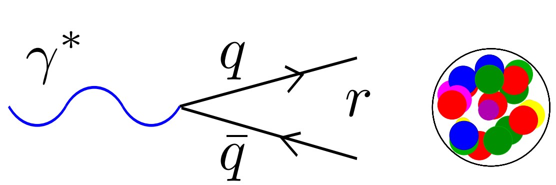


Infrared diffusion suppressed

- The non-linear terms are essential for preserving unitarity of the theory!!

Dipole scattering amplitude ⟷ Unintegrated gluon distribution

$$S(r;Y) = 1 - \mathcal{N}(r;Y)$$



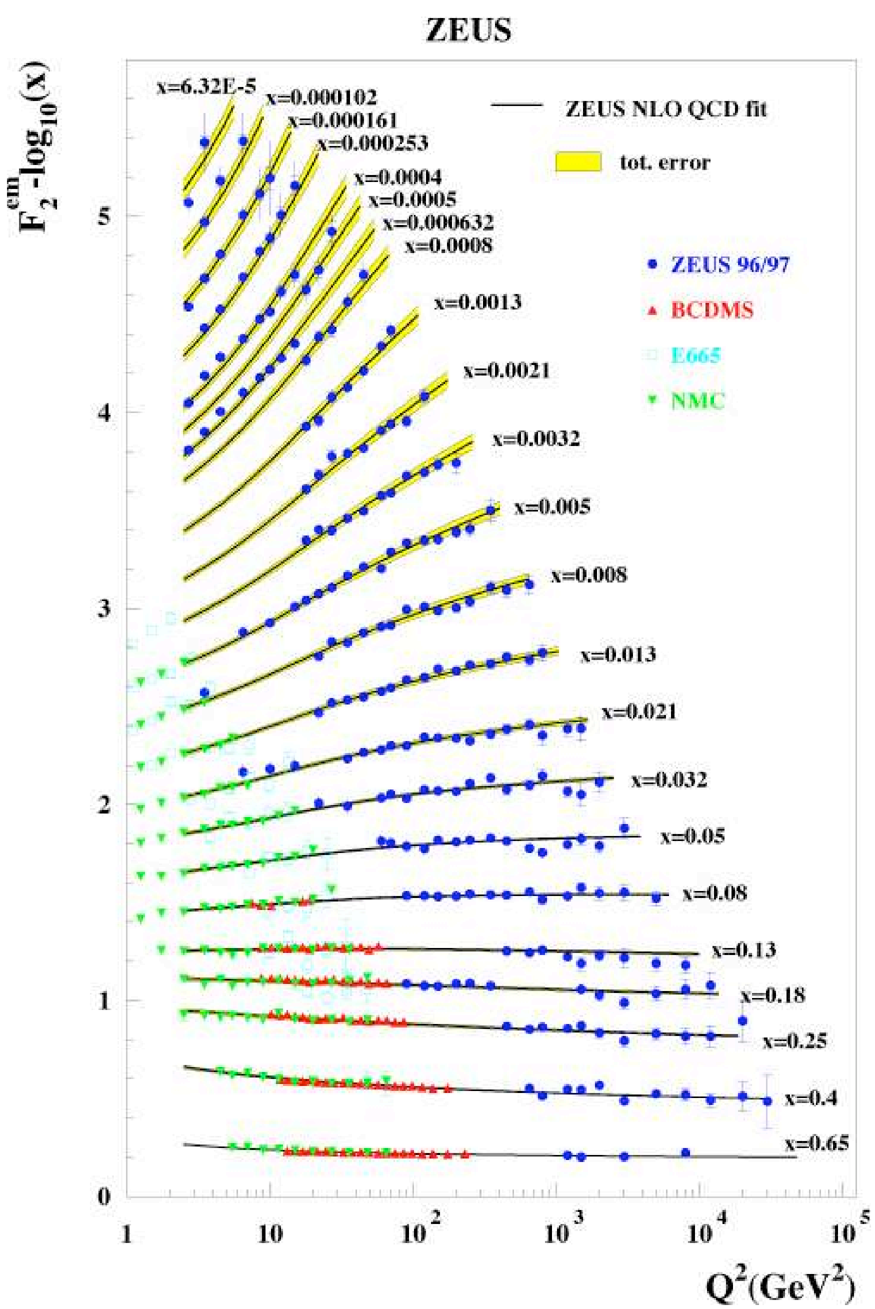
$$\varphi(k,Y) = \int \frac{d^2r}{2\pi r^2} \exp[i\underline{k}\cdot\underline{r}]\,\mathcal{N}(r;Y)$$

↓

$$xG(x,Q^2) = \int^{Q^2} d^2k\; \varphi(k,Y)$$

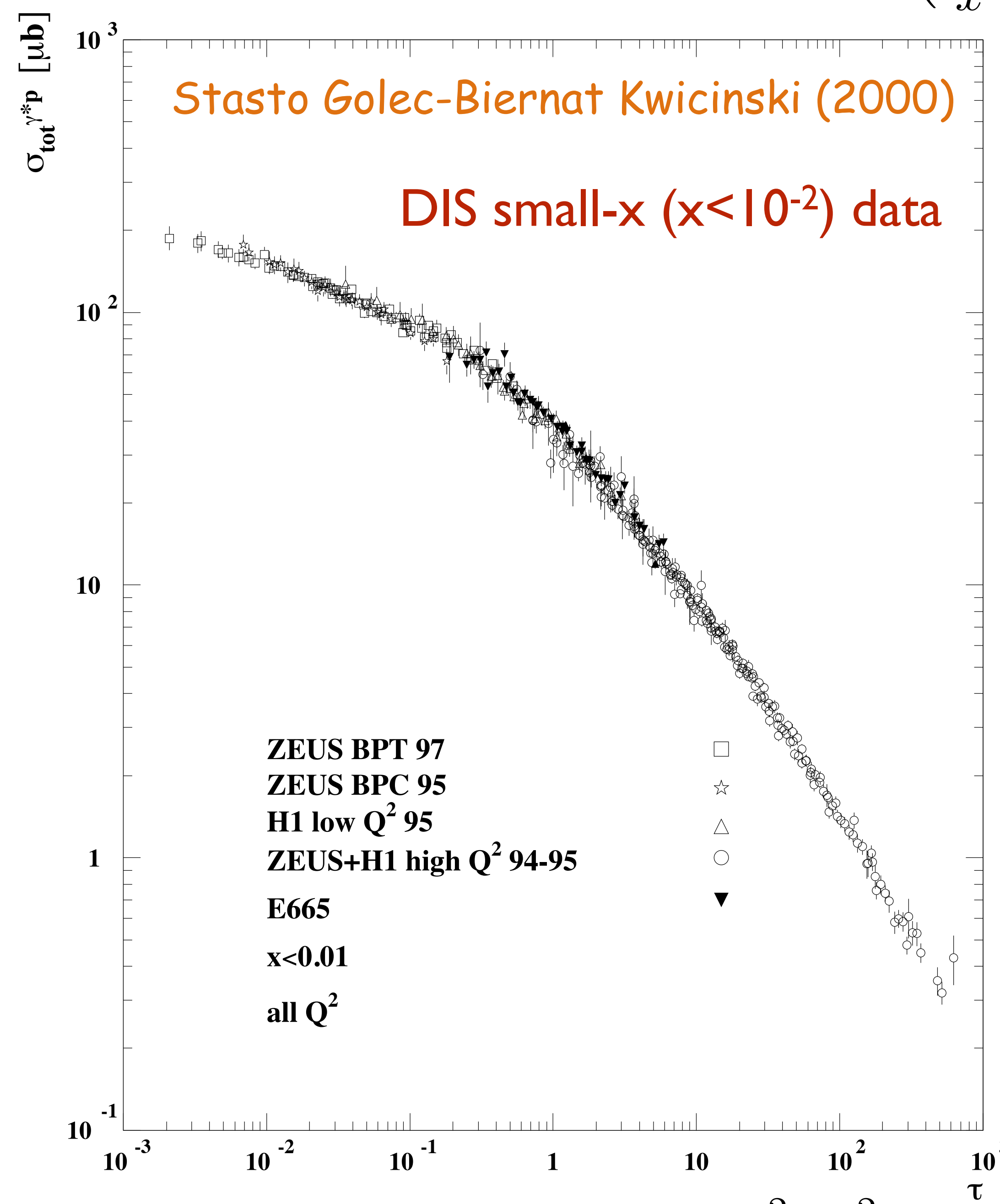
• Geometric scaling in DIS

HERA data as a function of x and Q2:



Rescaled data: $\sigma^{\gamma^* h}(x, Q^2) \to \sigma^{\gamma^* h}(\tau = Q^2/Q_s^2(x))$

$$Q_s^2(x) \sim Q_0^2 \left(\frac{x_0}{x}\right)^{\lambda \sim 0.3}$$



$\tau = Q^2/Q_s^2(x)$

HERA data clearly shows the emergence of a dynamical, semi-hard scale in small-x data: Saturation scale

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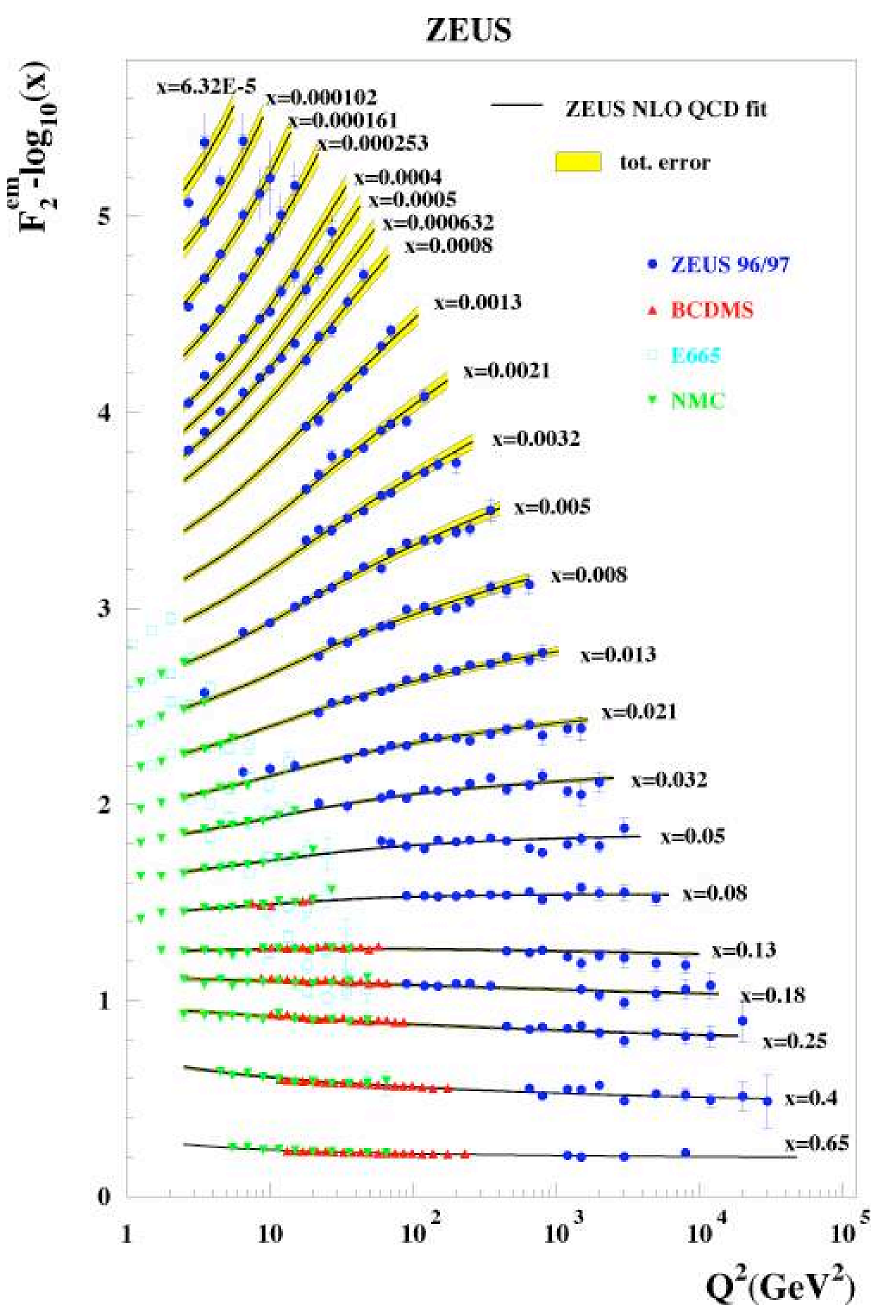
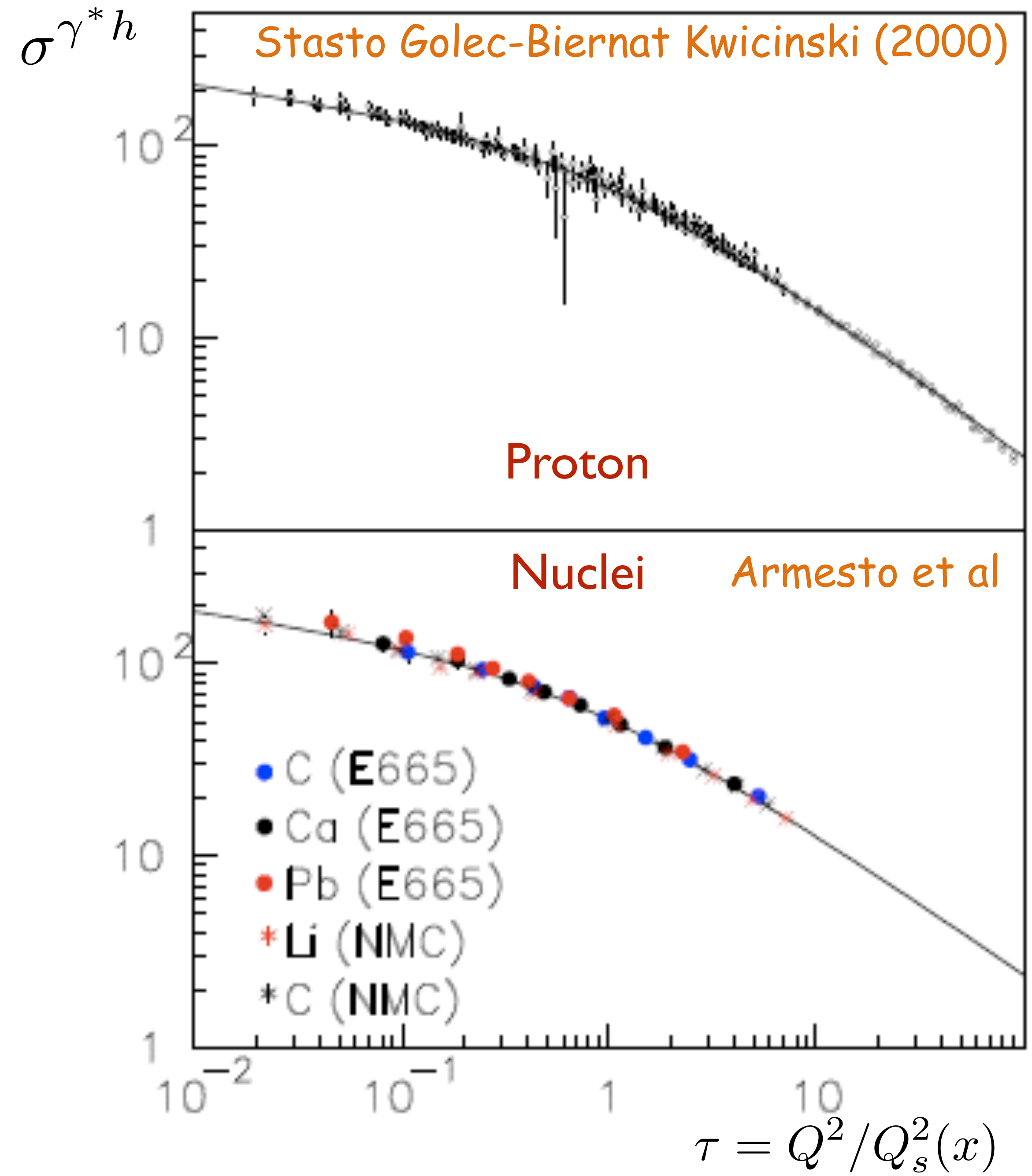


DIS small-x ($x<10^{-2}$) data

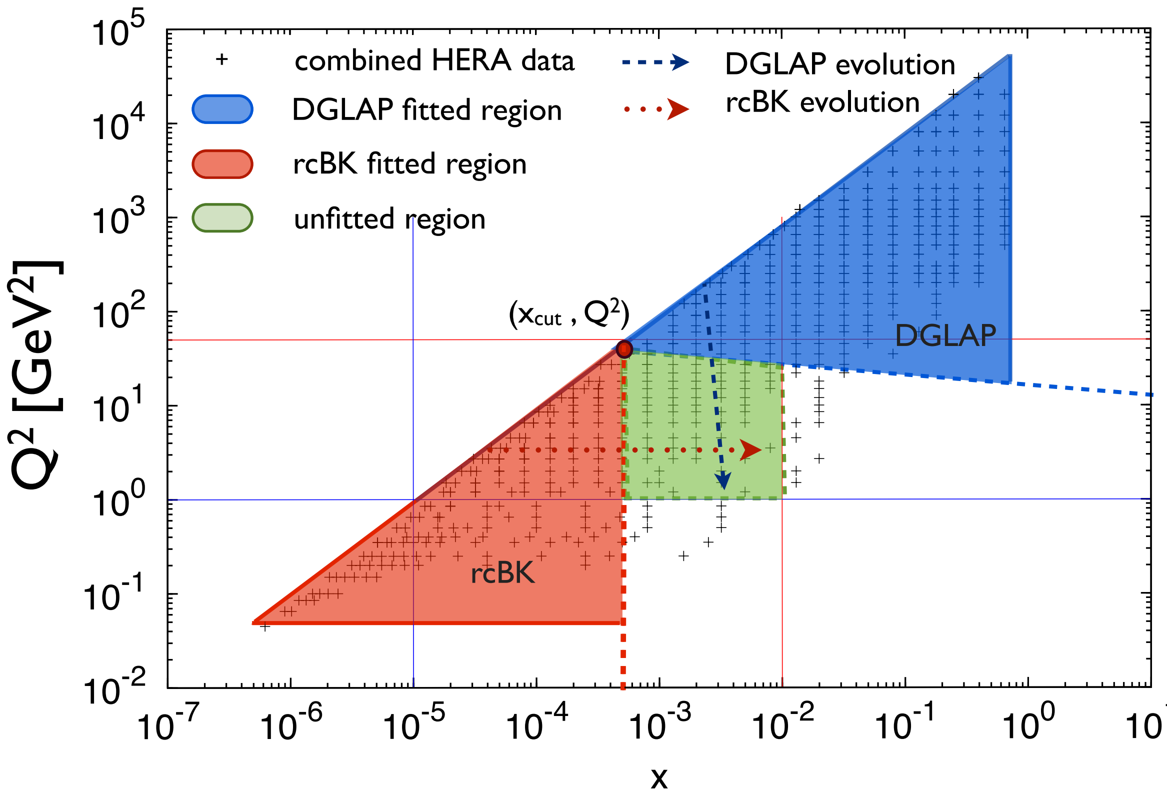


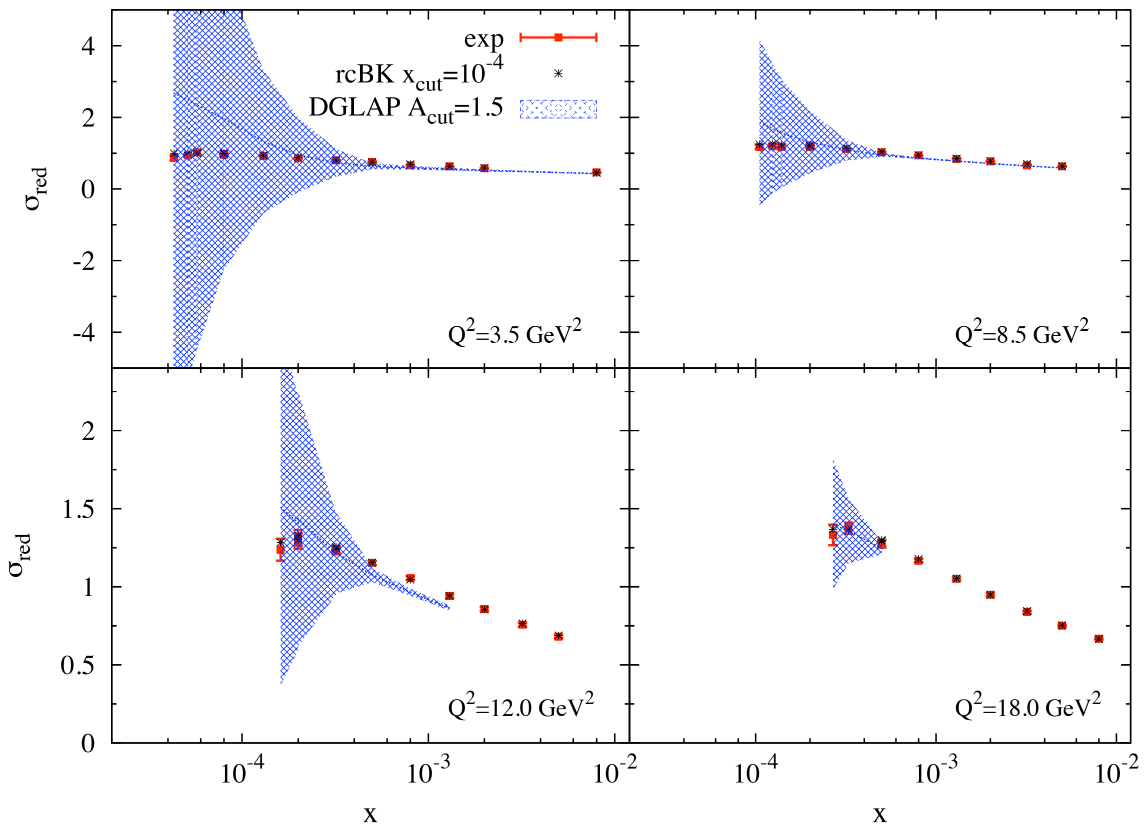
HERA data clearly shows the emergence of a dynamical, semi-hard scale in small-x data: Saturation scale

• DGLAP (linear) vs BK (non-linear) approaches at HERA

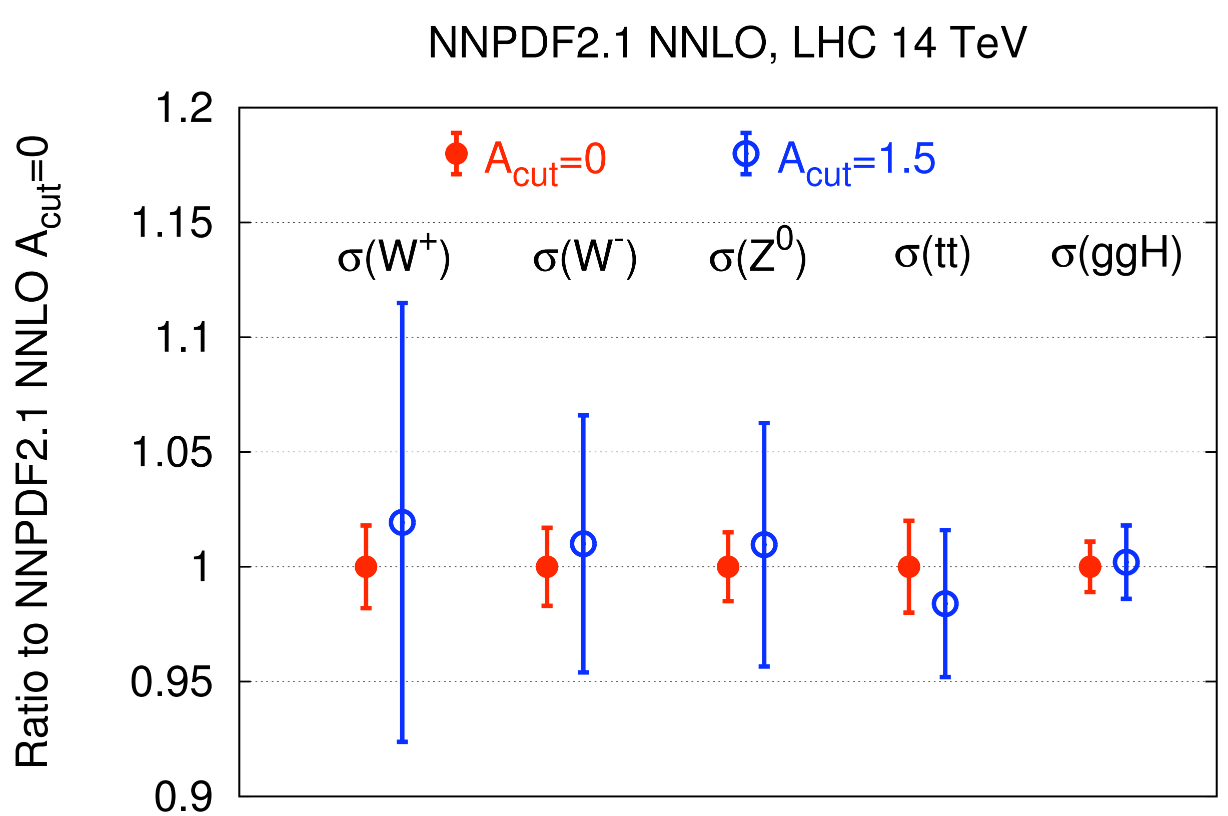
JLA, J.G Milhano, P. Quiroga and J Rojo

• What approach yields a better description of data at moderates values of (x,Q2)?



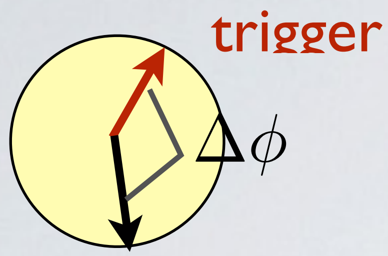


• rcBK fits are more stable than DGLAP ones. Excluding small-x data in DGLAP fits affects predictions for high-Q2 processes at the LHC:

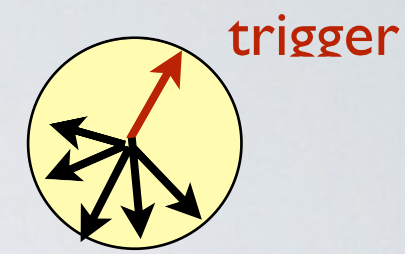


- **Disappearence of angular di-hadron correlations:**

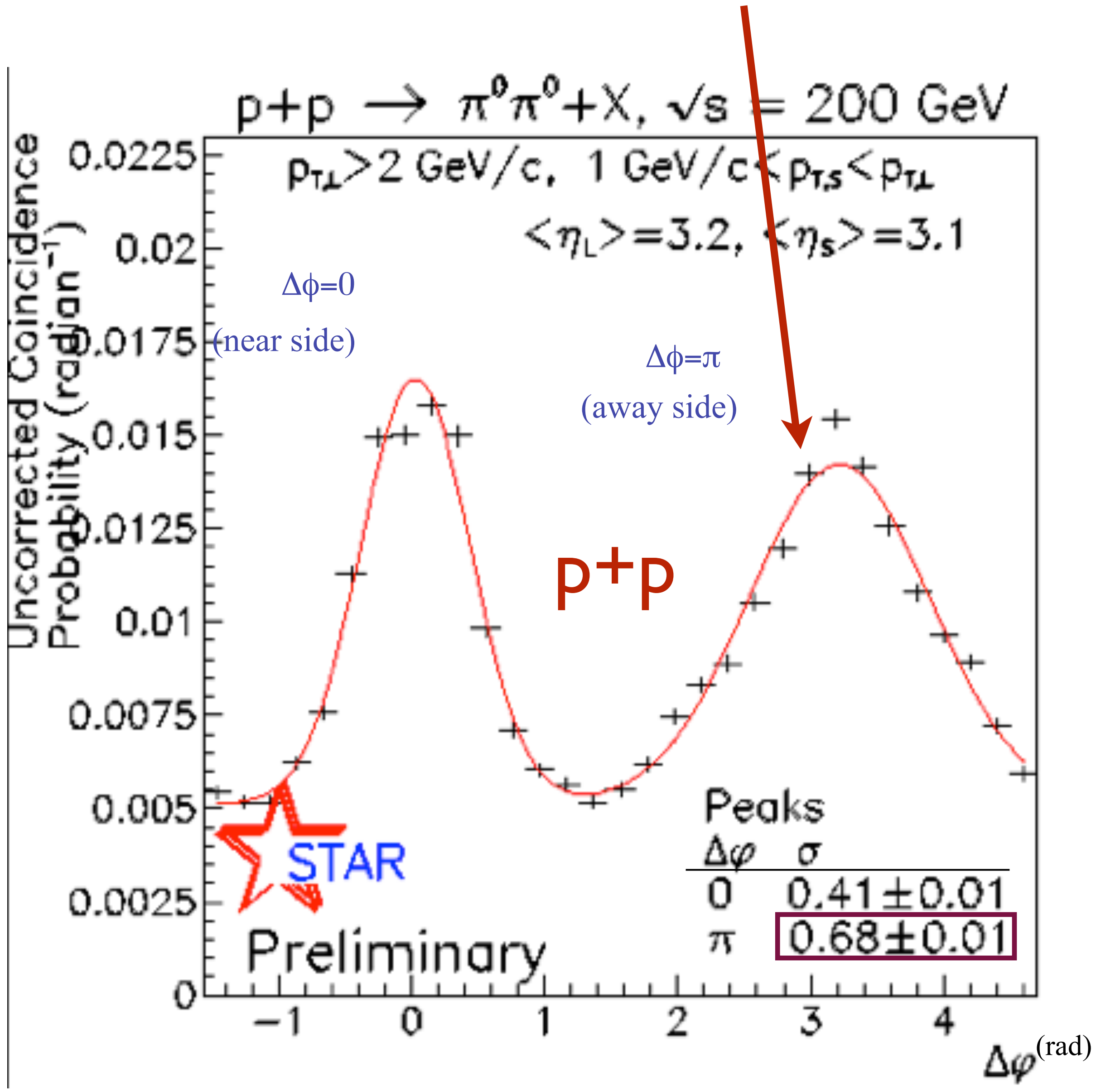
➡ "Coincidence probability" at measured by STAR Coll. at forward rapidities:



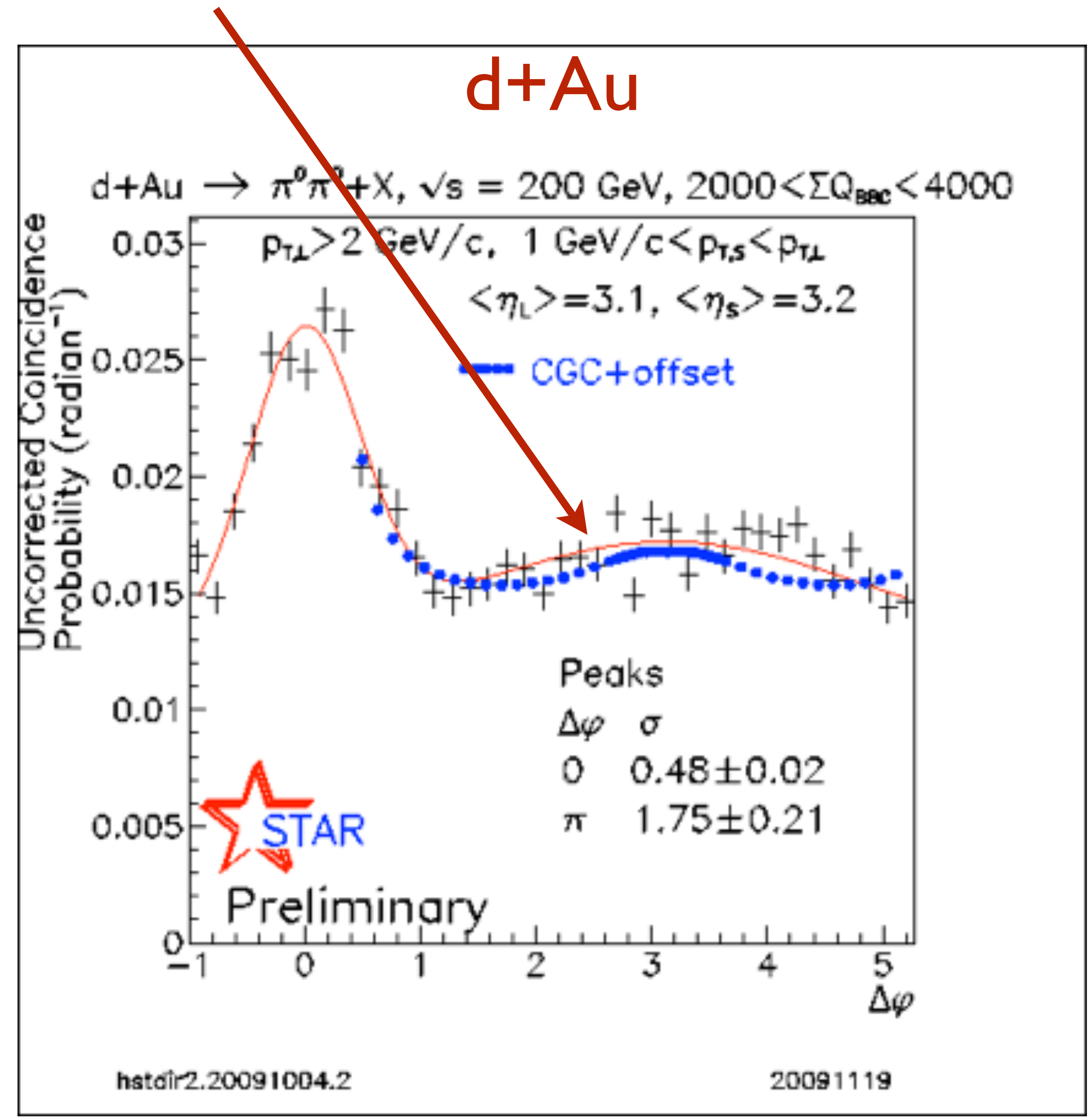
$$CP(\Delta\phi) = \frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\phi}$$



➡ Away peak is present in p+p coll.



➡ Absence of away particle in d+Au coll.



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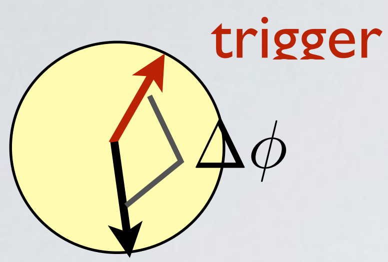

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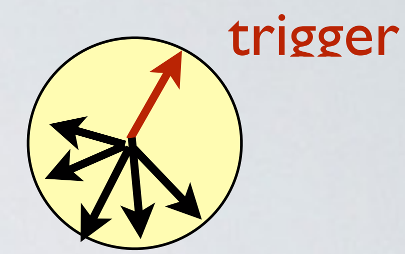

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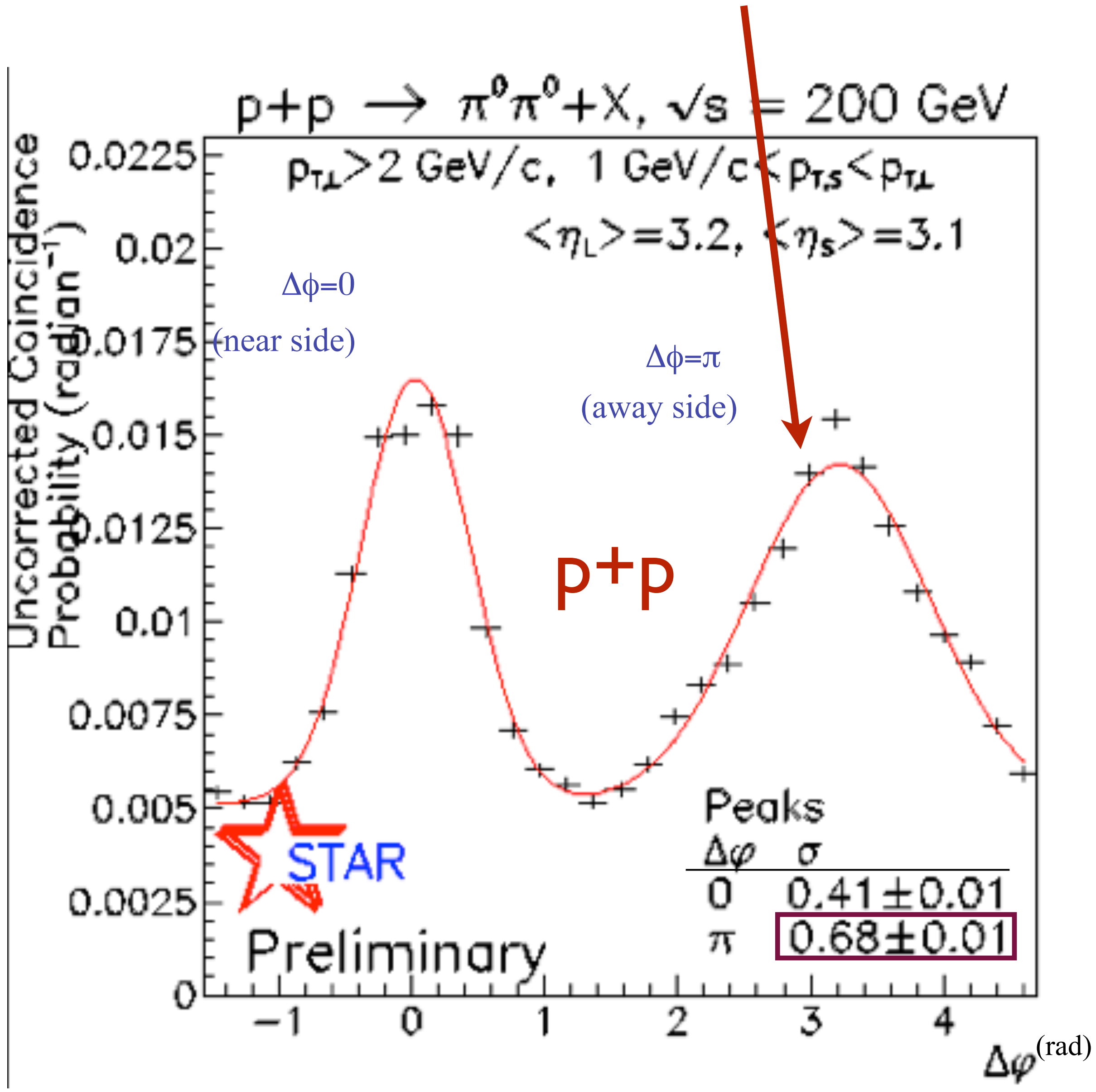

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