Portraying global 3D nucleon structure via study of the centrality dependence of the forward jet production in pA/DA collisions

Mark Strikman, PSU

Outline

- Intro: Color fluctuations in hadrons - new pattern of high energy hadron - nucleus scattering - going beyond single parton structure of nucleon.

- Evidence for x -dependent color fluctuations in nucleons -nucleon squeezing

- A new frontier : probing color fluctuations in photon in γA collisions starting with UPC data from LHC (pre-sequel of EIC & LHeC studies)

2018 workshop on probing quark-gluon matter with jets, July 24

Fluctuations of overall strength of high energy NN interaction

High energy projectile stays in a frozen configuration distances l_{coh} =cΔt

$$\Delta t \sim 1/\Delta E \sim \frac{2p_h}{m_{int}^2 - m_h^2}$$

At LHC for $m_{int}^2 - m_h^2 \sim 1\mathrm{GeV}^2$ l_{coh} ~ 10^7 fm>> $2R_A$>> $2r_N$

coherence up to $m_{int}^2 \sim 10^6\mathrm{GeV}^2$

Hence system of quarks and gluons passes through the nucleus interacting essentially with the same strength but changes from one event to another different strength

Strength of interaction of white small system is proportional to the area occupies by color.

QCD factorization theorem for the interaction of small size color singlet wave package of quarks and gluons.

For small quark - antiquark dipole $\sigma(q\bar{q}T) = \frac{\pi^2}{3} r_{tr}^2 x g_T(x, Q^2 = \lambda/r_{tr}^2)\alpha_s(Q^2)$

small but rapidly growing with energy

For small 3 quark tripole

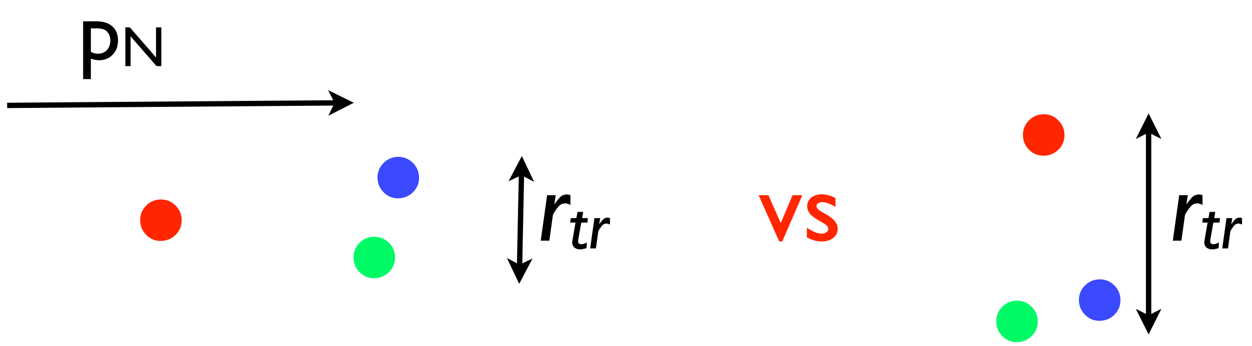
$$r_{tr}^2 \to (r_1 - (r_2 + r_3)/2)^2 + (r_2 - (r_1 + r_3)/2)^2 + (r_3 - (r_1 + r_2)/2)^2$$

dependence of $\sigma_{tot}(hN)$ on size holds in the nonperturbative regime

$$\sigma_{tot}(KN) < \sigma_{tot}(\pi N)$$

Global fluctuations of the strength of interaction of a fast nucleon/pion/photon, can originate from fluctuations of the overall size /shape, number of constituents.

Example: quark -diquark model of nucleon (same for constituent quark model

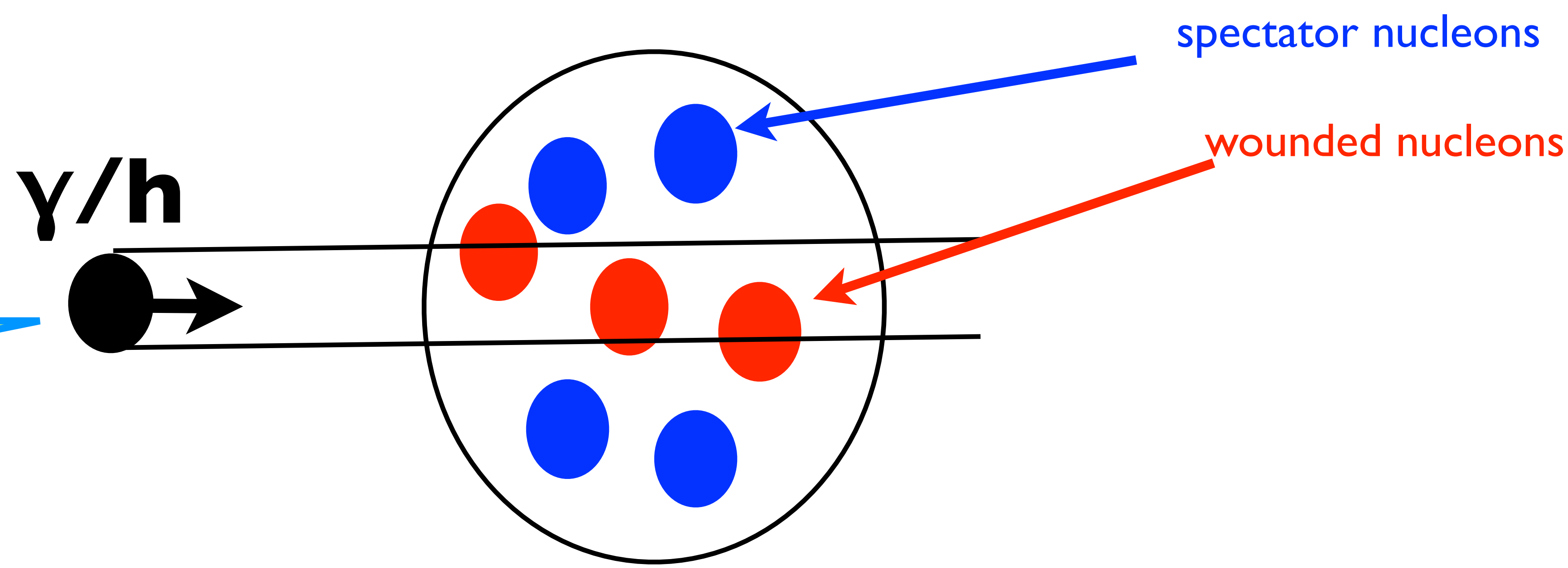


We will refer fluctuations of the strength of interaction of nucleon, photon,.. as color fluctuations of interaction strength - studying them allows to go beyond single parton 3-D mapping of the nucleon.

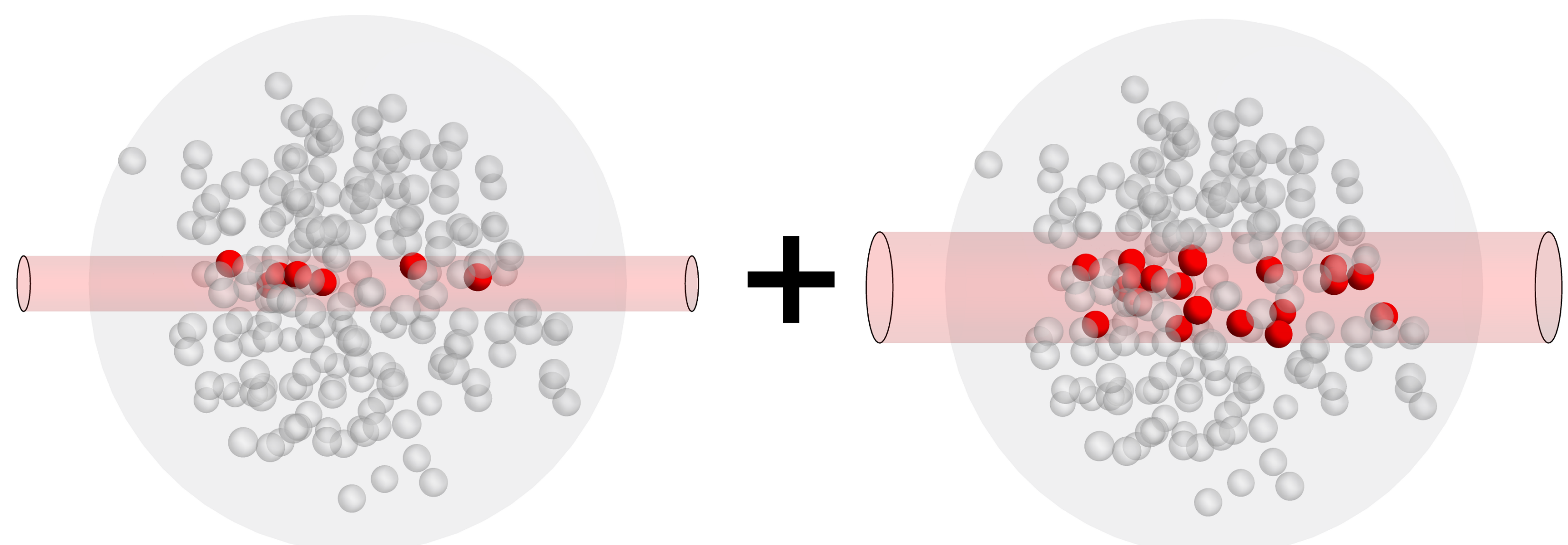
Comment: maybe relevant in pp for underlying event, multiparton interactions

Constructive way to account for coherence of the high-energy dynamics is Fluctuations of interaction = cross section fluctuation formalism. Analogy: consider throwing a stick through a forest - with random orientation relative to the direction of motion. (No rotation while passing through the forest - large $l_{coh.}$) Different absorption for different orientations.

Classical low energy picture of inelastic h A collisions implemented in Glauber model based Monte Carlos

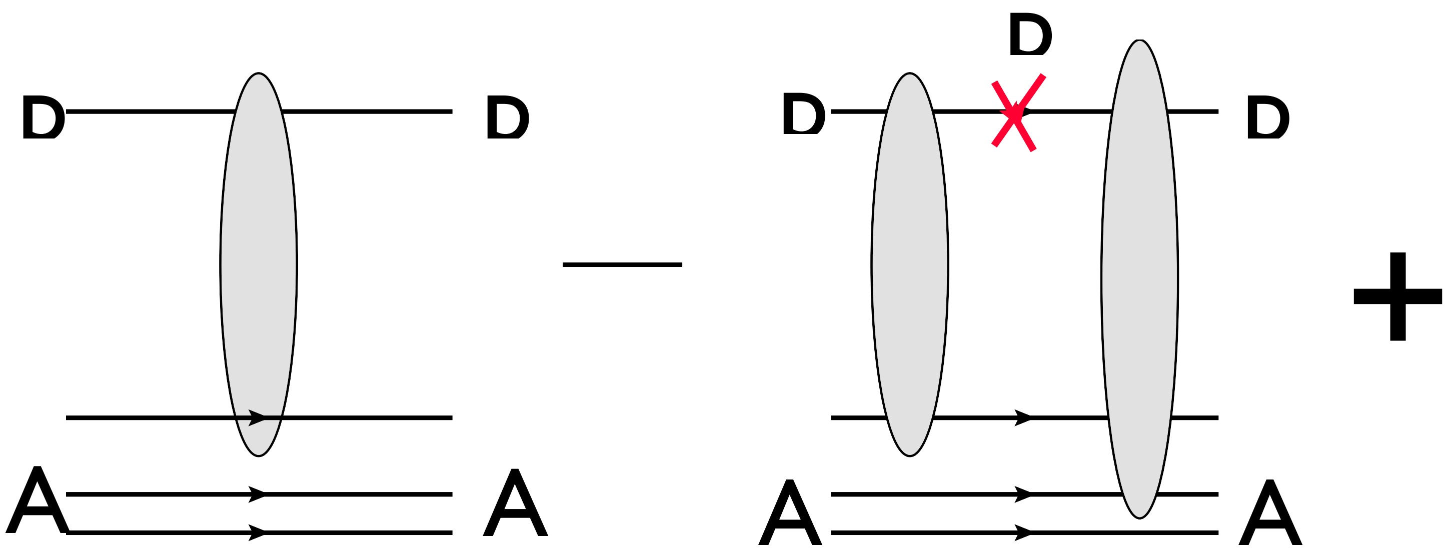


High energy picture of inelastic h A collisions consistent with the Gribov - Glauber model - interaction of frozen configurations



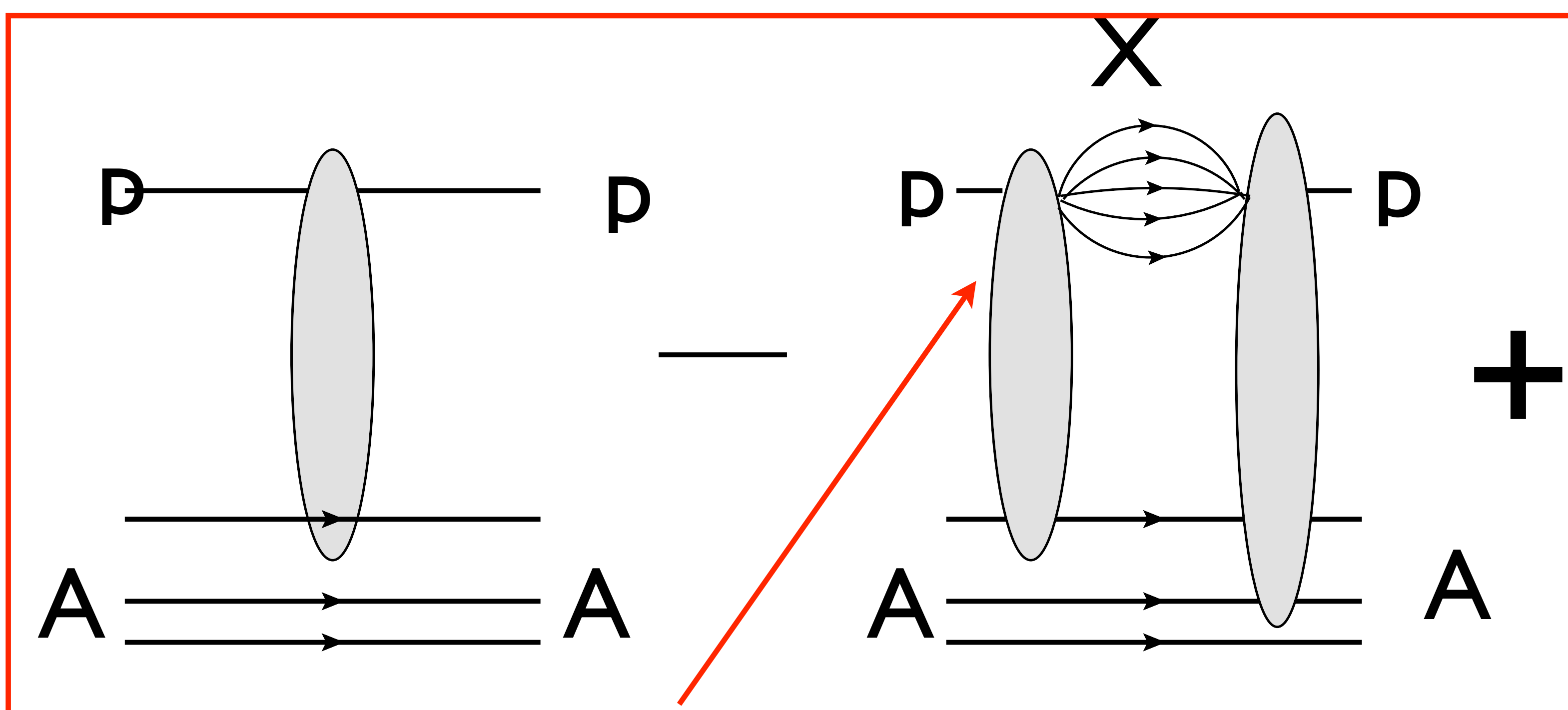
Expect effects similar positronium example = correlation between size and number of wounded nucleons

Formal account of large l_{coh} ➟ different set of diagrams describing p A scattering:



Glauber model

in rescattering diagrams proton propagates in intermediate state - zero at high energy - cancelation of planar diagrams (Mandelstam & Gribov)- no time for a proton to come back between interactions.



High energies = Gribov -Glauber model

X= set of frozen intermediate states the same as in pN diffraction

deviations from Glauber are small for E_{inc} < 10 GeV as inelastic diffraction is still small.

$$\sigma_2 \propto \int dt F_A^2(t) \frac{d\sigma(p+p \to p + X(p + \ inel \ diff))}{dt}$$

Convenient quantity - $P(\sigma)$ -probability that hadron/photon interacts with cross section σ with the target. $\int P(\sigma) d\sigma = 1$, $\int \sigma P(\sigma) d\sigma = \sigma_{tot}$,

cf $P_{MCGlauber}(\sigma) = \delta(\sigma - \sigma_{tot})$

$$\left.\frac{\frac{d\sigma(pp\to X+p)}{dt}}{\frac{d\sigma(pp\to p+p)}{dt}}\right|_{t=0} = \frac{\int(\sigma-\sigma_{tot})^2 P(\sigma) d\sigma}{\sigma_{tot}^2} \equiv \omega_\sigma$$

variance

Pumplin &Miettinen

$\int (\sigma - \sigma_{tot})^3 P(\sigma) d\sigma = 0$,

Baym et al from pD diffraction

$$P(\sigma)_{|\sigma\to 0} \propto \sigma^{n_q - 2}$$

Baym et al 1993 - analog of QCD counting rules probability for all constituents to be in a small transverse area

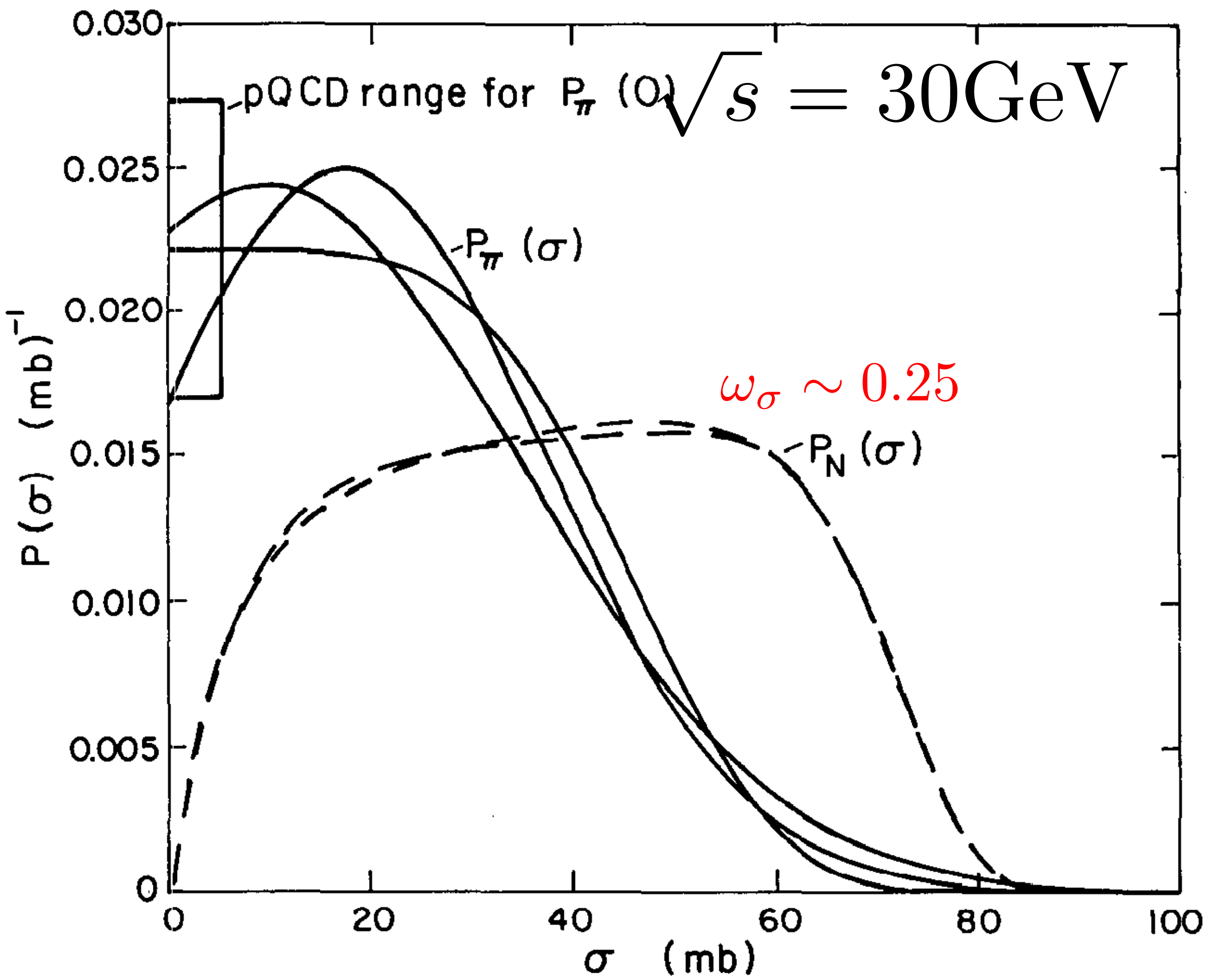
+ additional consideration that *for a many body system fluctuations near average value should be Gaussian*

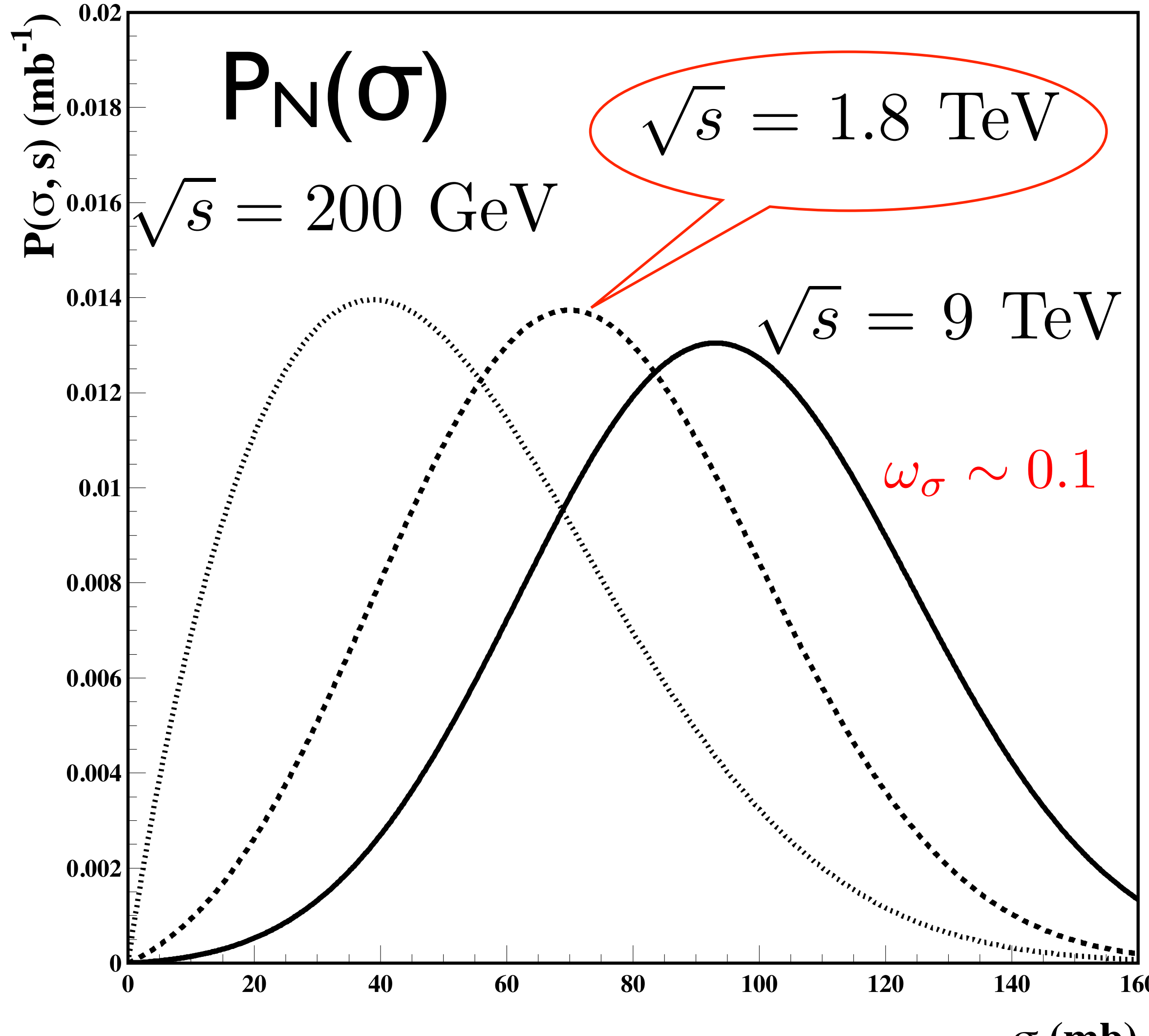
$$P_N(\sigma_{tot}) = r\frac{\sigma_{tot}}{\sigma_{tot} + \sigma_0} exp\{-\frac{(\sigma_{tot}/\sigma_0 - 1)^2}{\Omega^2}\}$$

$$P_\gamma(\sigma)_{|\sigma\to 0} \propto \sigma^{-1}$$

γ =mix of small $q\bar{q}$ and mesonic configurations

Test: calculation of coherent diffraction off nuclei: $\pi A \to XA$, $p A \to XA$ through $P_h(\sigma)$ ✔





$P_N(\sigma)$ extracted from pp,pd diffraction and $P_\pi(\sigma)$; Baym et al 93

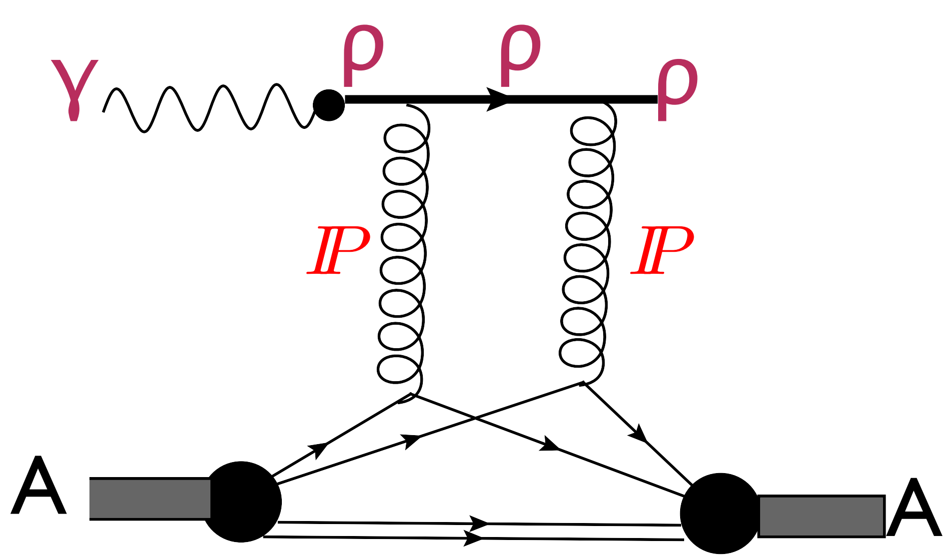
Extrapolation of Guzey & MS before the LHC data

Flat $P_N(\sigma)$ in a wide range of σ - can suggests few effective constituents at this energy scale like in quark - diquark model.

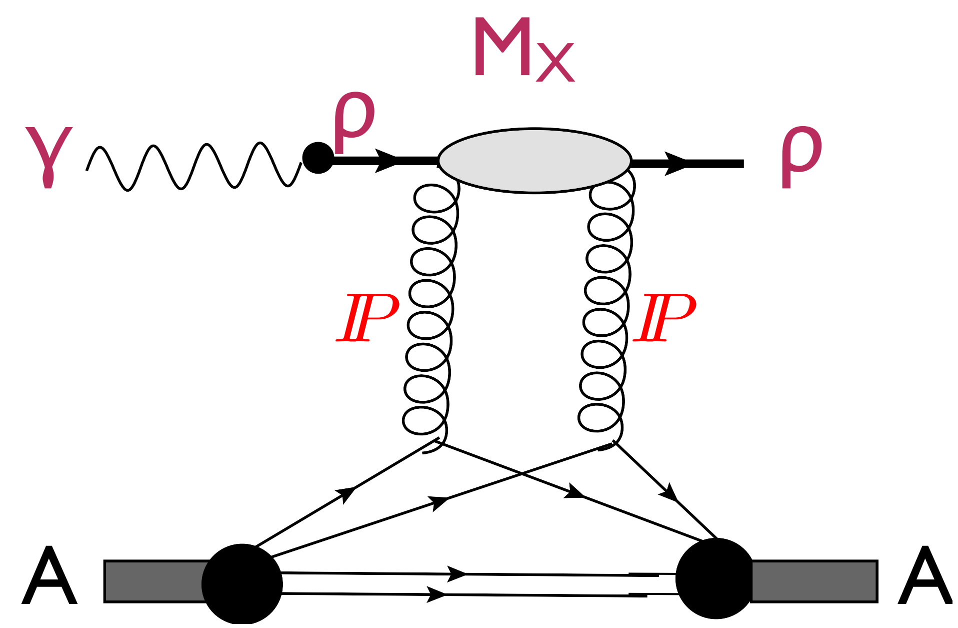
Variance drops with increase of energy, overall shift of distribution to larger σ

Fast drop of $P_N(\sigma)$ at small σ, with increase of energy pQCD?

In the case of proton projectile CF effects for total/ elastic cross section are small (interactions close to black). However Gribov type inelastic shadowing which is practically equivalent to CFs is enhanced in processes involving small elementary cross section - fluctuations grow with decrease of projectile - nucleon cross section. We estimate $\omega_{\gamma\to\rho} \sim 0.5$ and model $P_{\gamma\to\rho}(\sigma)$ - distribution of configurations in transition over σ



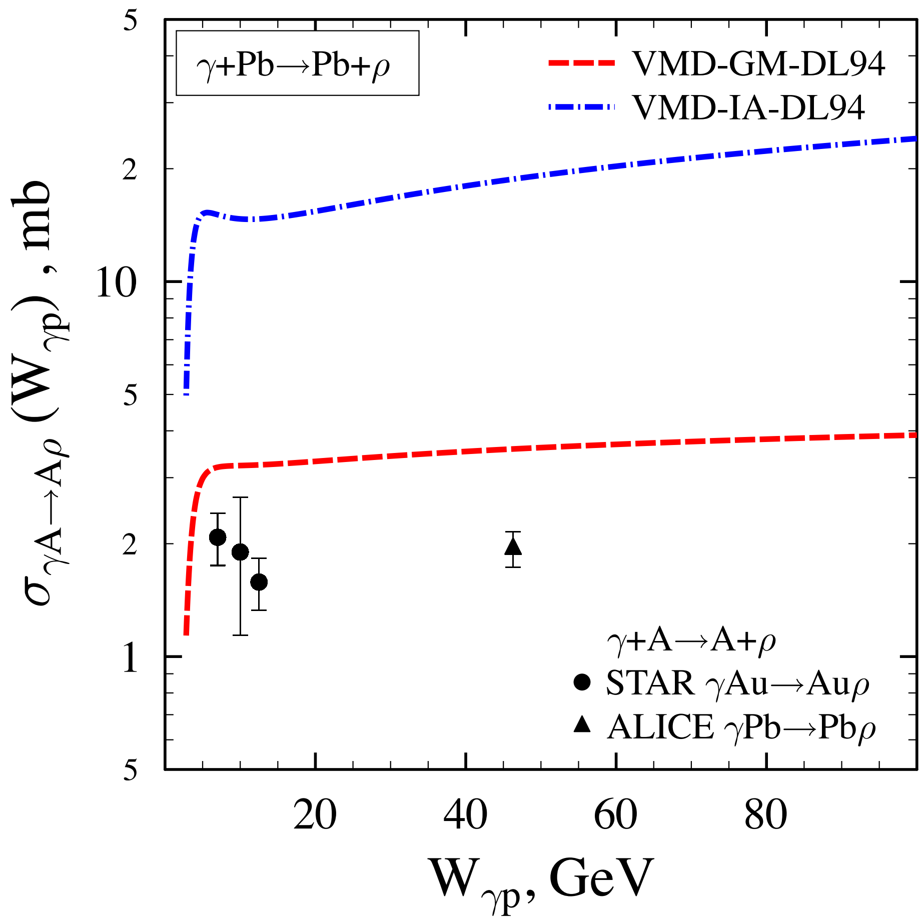
Glauber double scattering



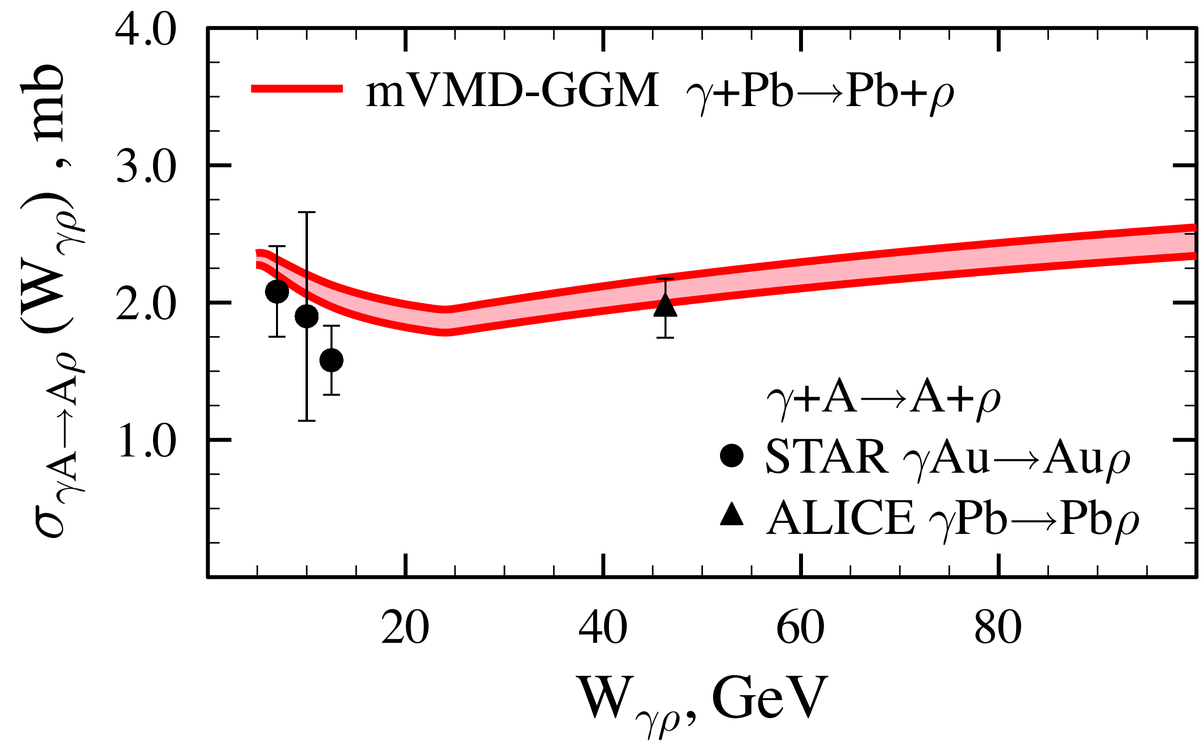
Gribov inelastic shadowing

❖ We use $P_{\gamma\to\rho}(\sigma)$ to calculate coherent ρ production. Several effects contribute to suppression a) large fluctuations, b) enhancement of inelastic shadowing is larger for smaller σ_{tot}. for the same W, c) effect for coherent cross section is square of that for σ_{tot}.

- Glauber model grossly overestimates the cross section (at LHC factor ~2)



- Gribov - Glauber model with cross section fluctuations



Distribution over the number of wounded nucleons in the CF approximation

In pA case fluctuations show much more prominently in inelastic processes

$$\sigma_\nu = \int d\sigma P_h(\sigma) \cdot \frac{A!}{(A-\nu)!\,\nu!} \cdot \int d\boldsymbol{b}\,(\sigma T(b)/A)^\nu\,[1-\sigma T(b)/A]^{A-\nu}$$

simplified expression (optical limit)

Actual calculation is based on MC model of Alvioli and MS which includes

* Short-range NN correlations in the nucleus wave function
* Correct impact profile of soft NN interactions
* Difference of the impact parameter ranges of soft and hard interactions

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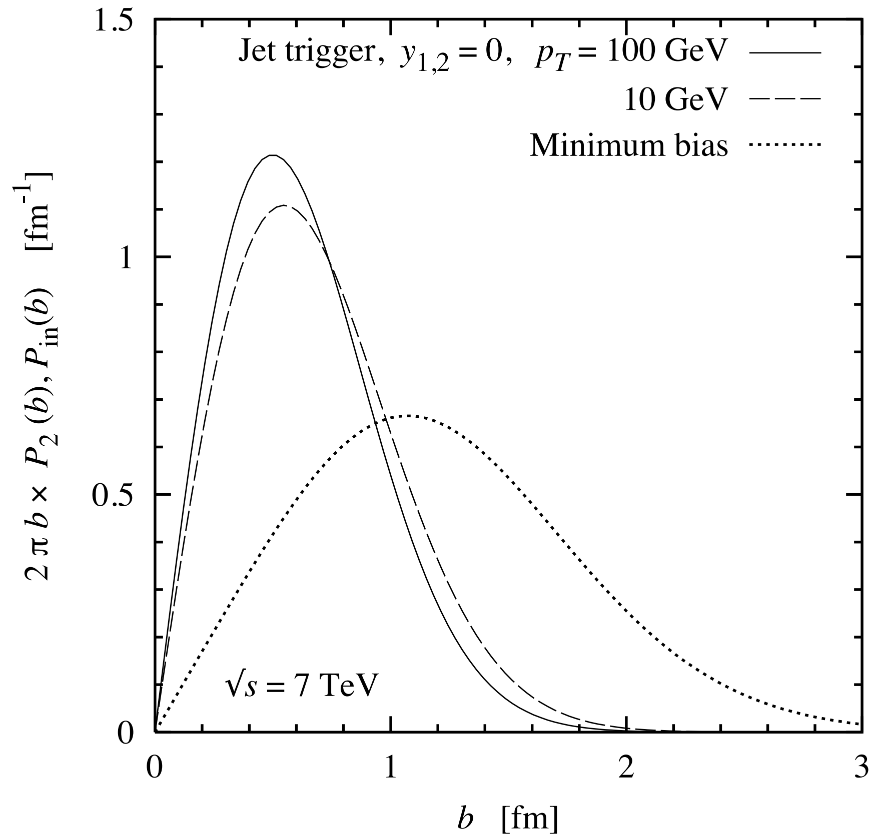
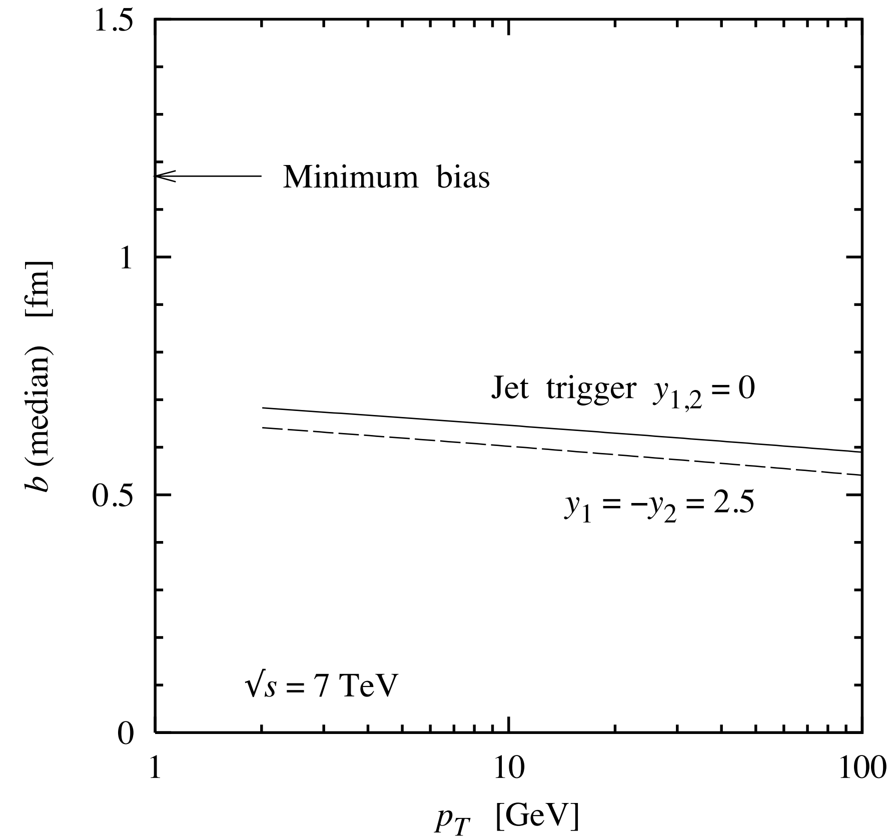
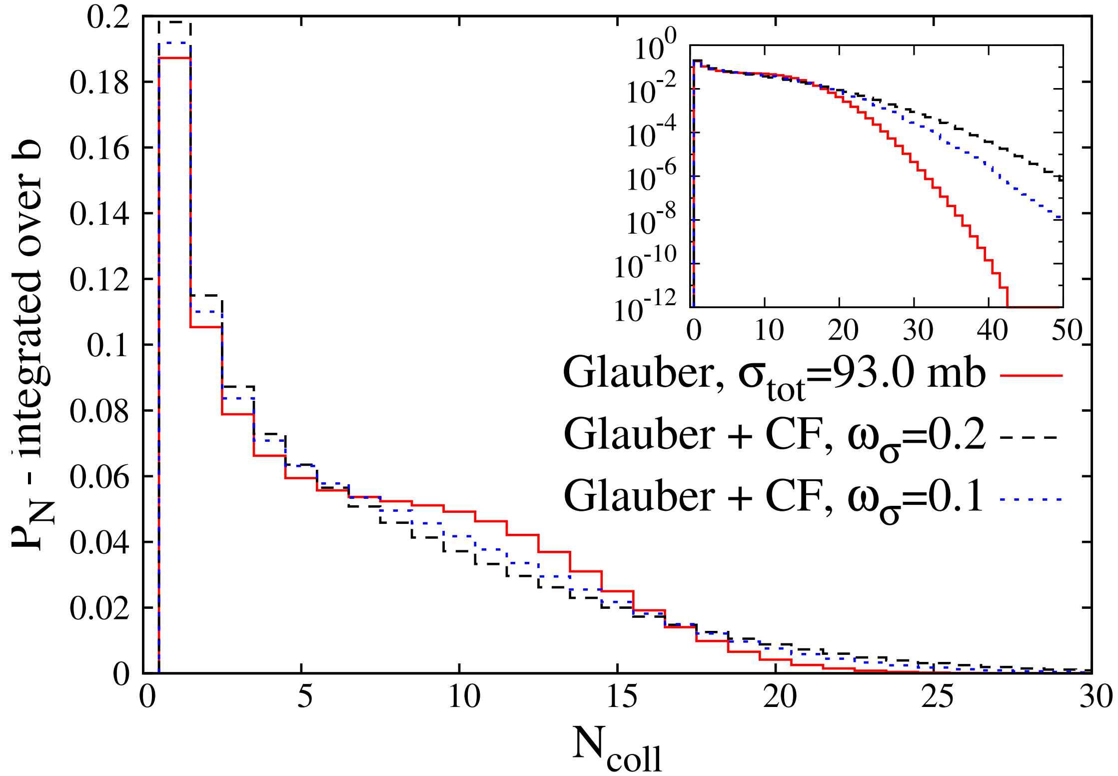
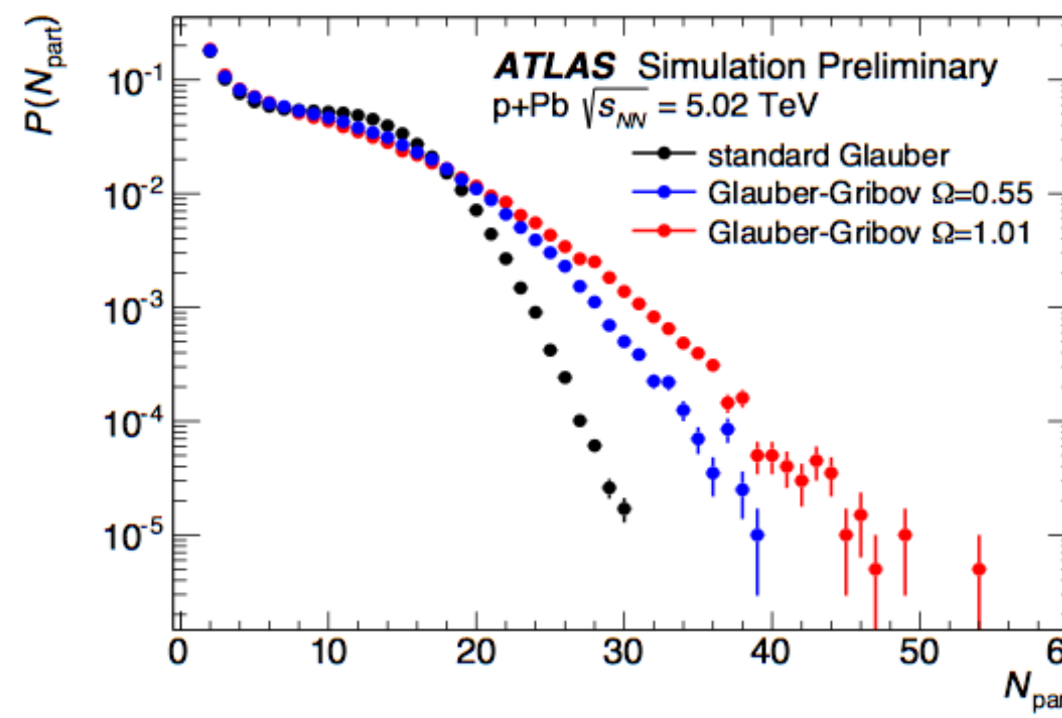




Impact parameter distributions of inelastic pp collisions at $\sqrt{s}$ = 7TeV. Solid (dashed) line: Distribution of events with a dijet trigger at zero rapidity, $y_{1,2} = 0$, c, for p_T = 100 (10) GeV . Dotted line: Distribution of minimum–bias inelastic events (which includes diffraction).

Median impact parameter b(median) of events with a dijet trigger, as a function of the transverse momentum p_T , cf. left plot. Solid line: Dijet at zero rapidity $y_{1,2} = 0$. Dashed line: Dijet with rapidities $y_{1,2} = \pm 2.5$. The arrow indicates the median b for minimum–bias inelastic events.





Probability of interaction with N_{coll} nucleons integrated over impact parameter b.

Fluctuations lead to broadening of the distribution over number of active nucleons as compared to Glauber model for ν~10- 15 with ω_σ=0.1 which is close to the LHC data.

DISTRIBUTION OVER THE NUMBER OF COLLISIONS FOR PROCESSES WITH A HARD TRIGGER

M.Alvioli, L.Frankfurt, V.Guzey and M.Strikman, ``Revealing nucleon and nucleus flickering in pA collisions at the LHC,' (2014)

Consider multiplicity of hard events $Mult_{pA}(HT) = \sigma_{pA}(HT + X)/\sigma_{pA}(in)$

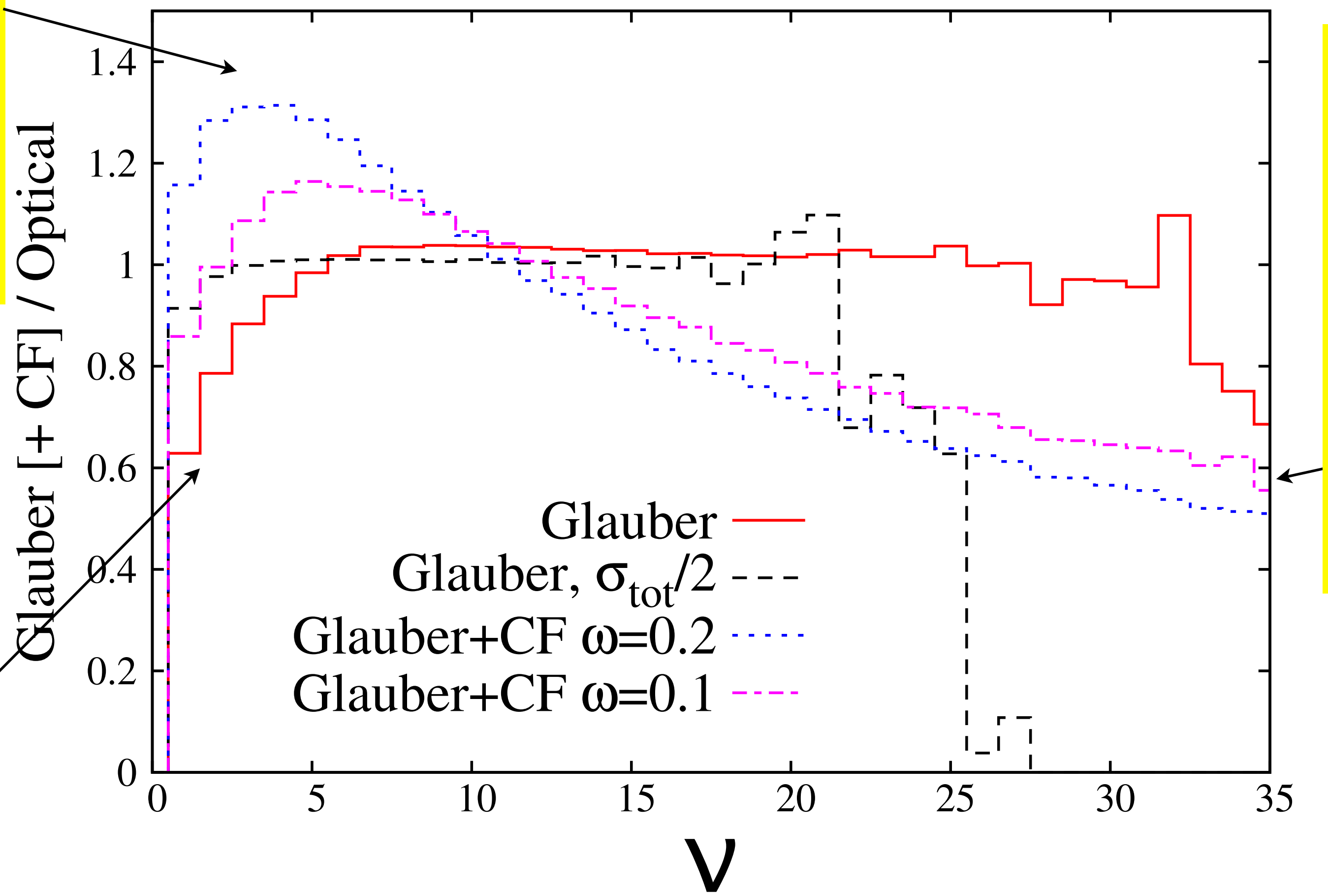
as a function of ν.

If the radius of strong interaction is small and hard interactions have the same distribution over impact parameters as soft interactions multiplicity of hard events:

$$R_{HT}(\nu) = \frac{Mult_{pA}(HT)}{Mult_{pN}(HT)\nu} = 1$$

Accuracy?

Two effects: Two scale dynamics of pp interaction at the LHC, large radius of NN interaction increase due to more central interactions of configurations with $\sigma < \sigma_{tot}$



drop due increased role of configurations with $\sigma > \sigma_{tot}$ the cylinder in which interaction occur is larger but local density does not go up as fast in Glauber

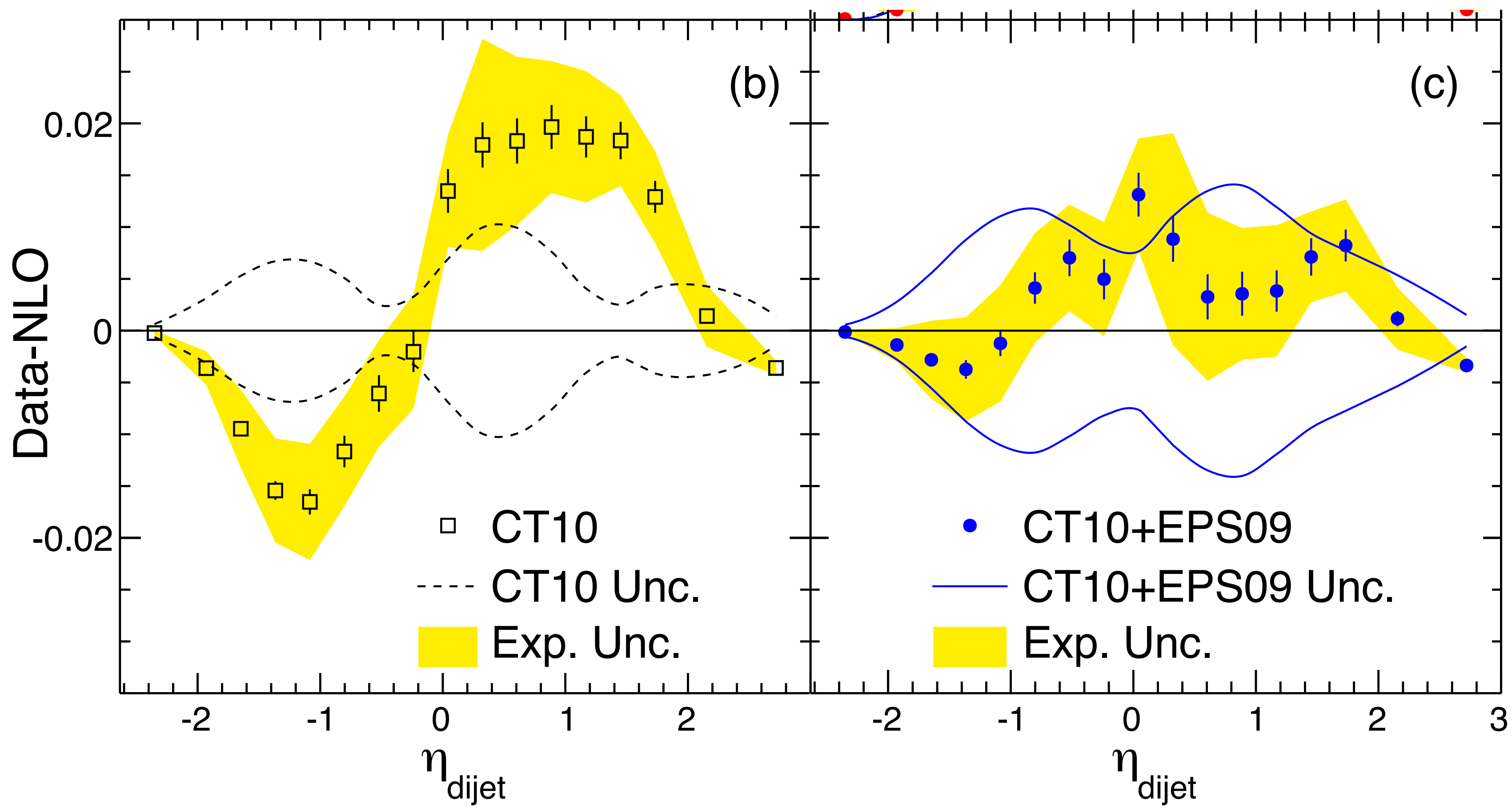
Deviation of $R_{HT}(\nu)$ from 1

drop due to more localized hard interactions

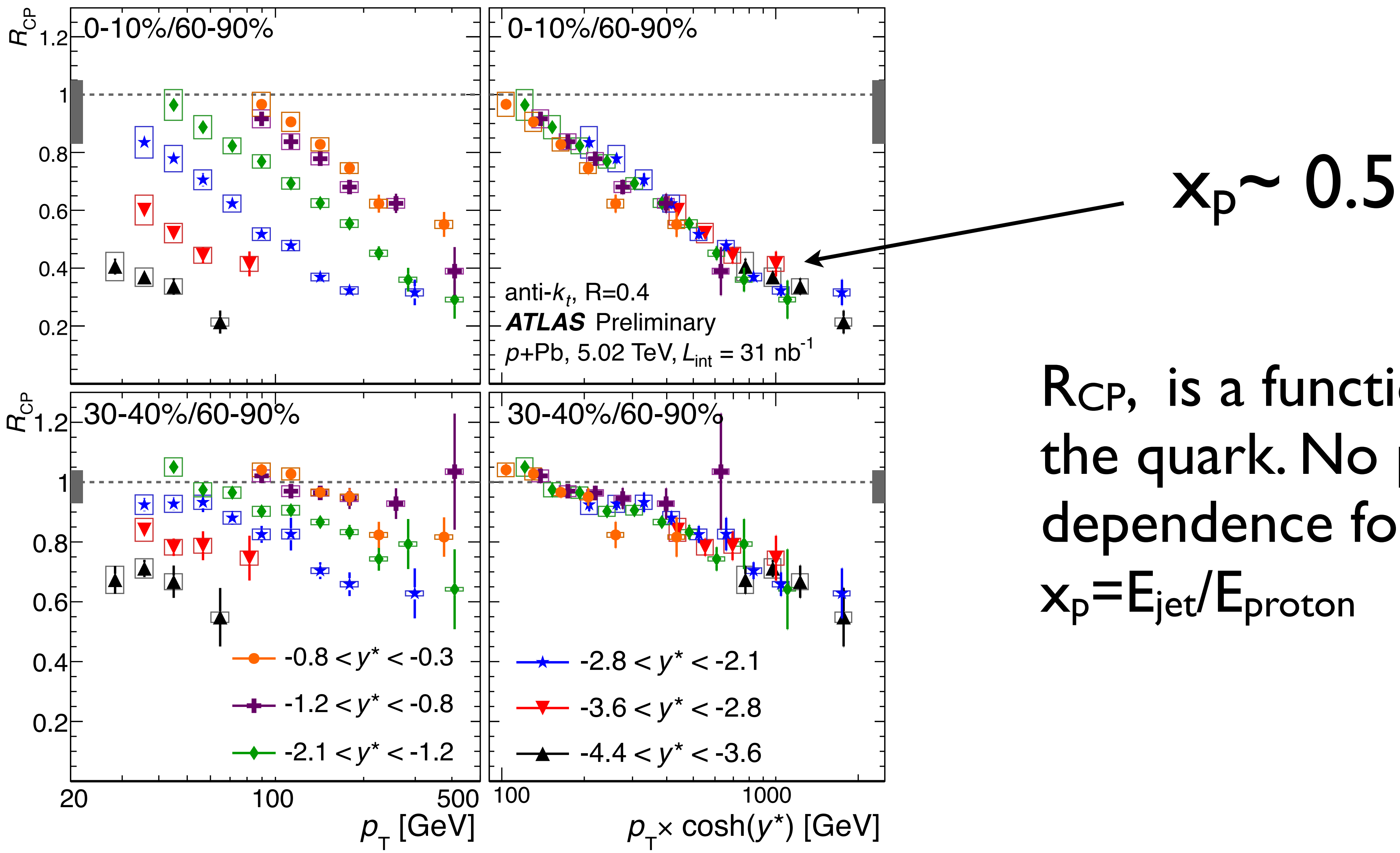
Jet production in pA collisions - possible evidence for x -dependent color fluctuations

Summary of some of the relevant experimental observations of CMS & ATLAS

- Inclusive jet production is consistent with pQCD expectations (CMS)



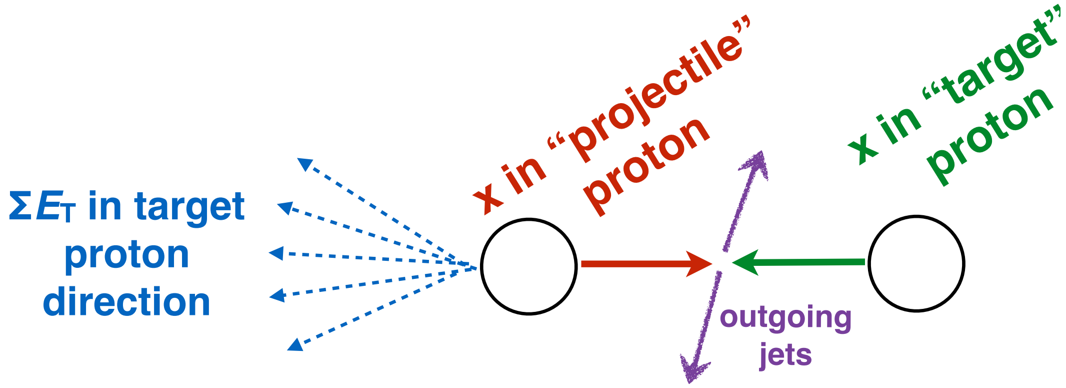
ATLAS and CMS studied dijet production in pA at the LHC. Both observed very small nuclear effects for inclusive dijet production (for reported bins) which rules out energy loss interpretation of the data. However nuclear effects are strong function of ν which was estimated using E_T of particle produced at negative rapidities. Forward jet production in central collisions is strongly suppressed - suppression is mainly function of x_p. and not p_t of the jet. Consistent with expectation that configurations in protons with large x -belong to configurations which are smaller and interact with $\sigma < \sigma_{tot}$.



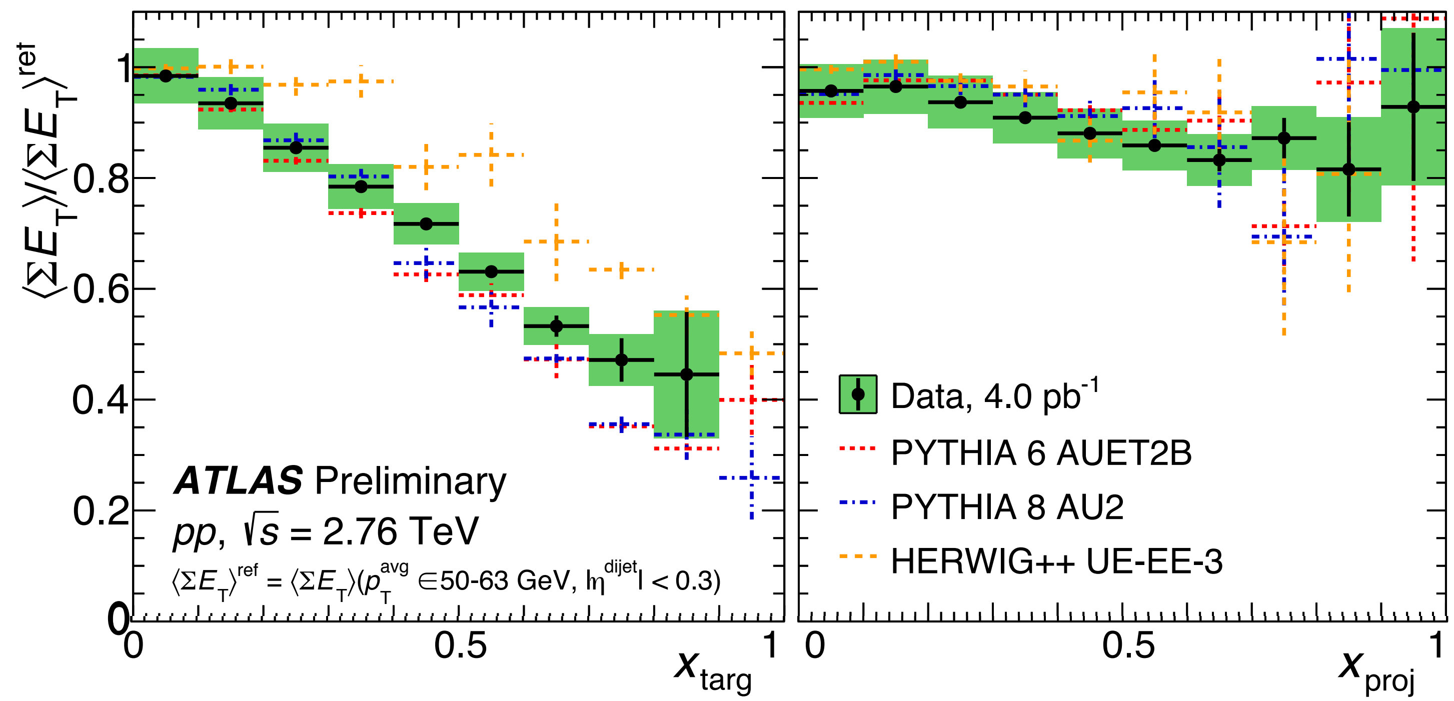
R_{CP}, is a function of x of the quark. No p_T dependence for fixed $x_p = E_{jet}/E_{proton}$

In order to compare with the data we need to use a model for the distribution in E_T^{Pb} as a function of ν. We use the analysis of ATLAS . Note that E_T^{Pb} was measured at large negative rapidities which minimizes the effects of energy conservation (production of jets with large x_p) suggested as an explanation of centrality dependence

ATLAS-CONF-2015-019 analysis of pp data confirms this expectation

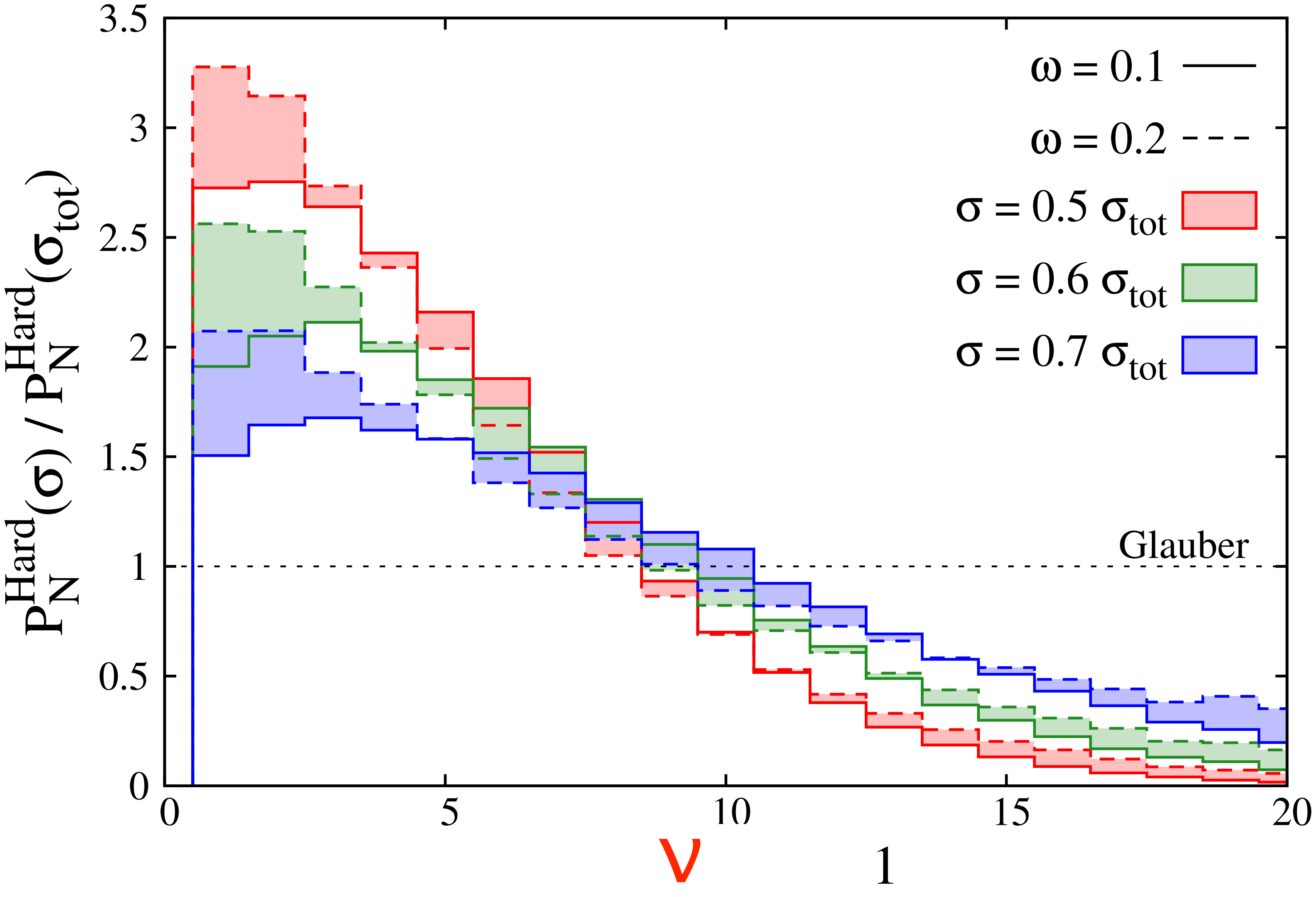


Measure ΣE_T at large pseudorapidity vs.
x in the **projectile** proton (moving away)
x in the **target** proton (moving towards)



Dependence on x_{proj} and x_{targ}

Fluctuations for configurations with small σ maybe different than for average one so we considered both $\omega_\sigma(x\sim 0.5)$ =0.1 & 0.2

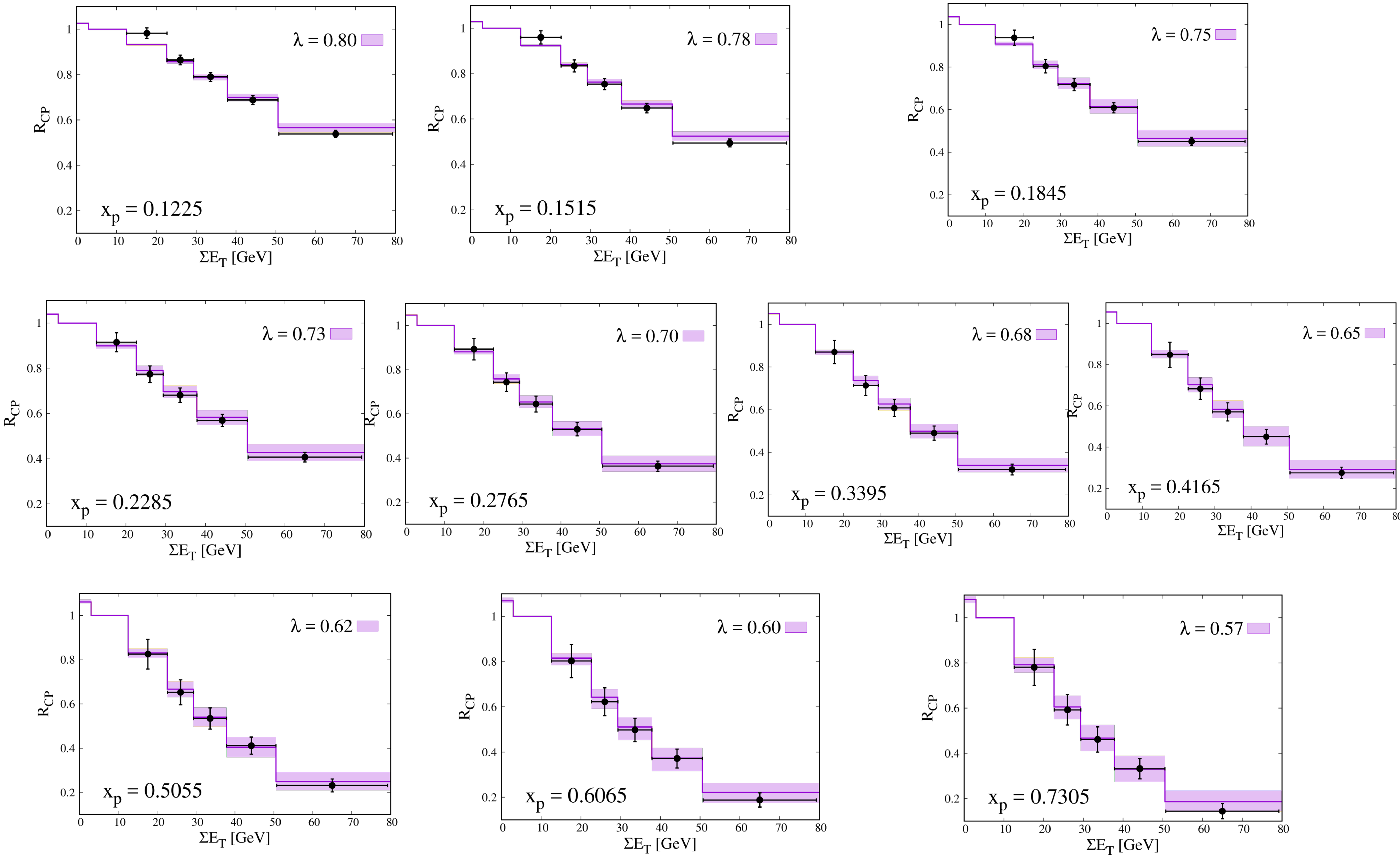


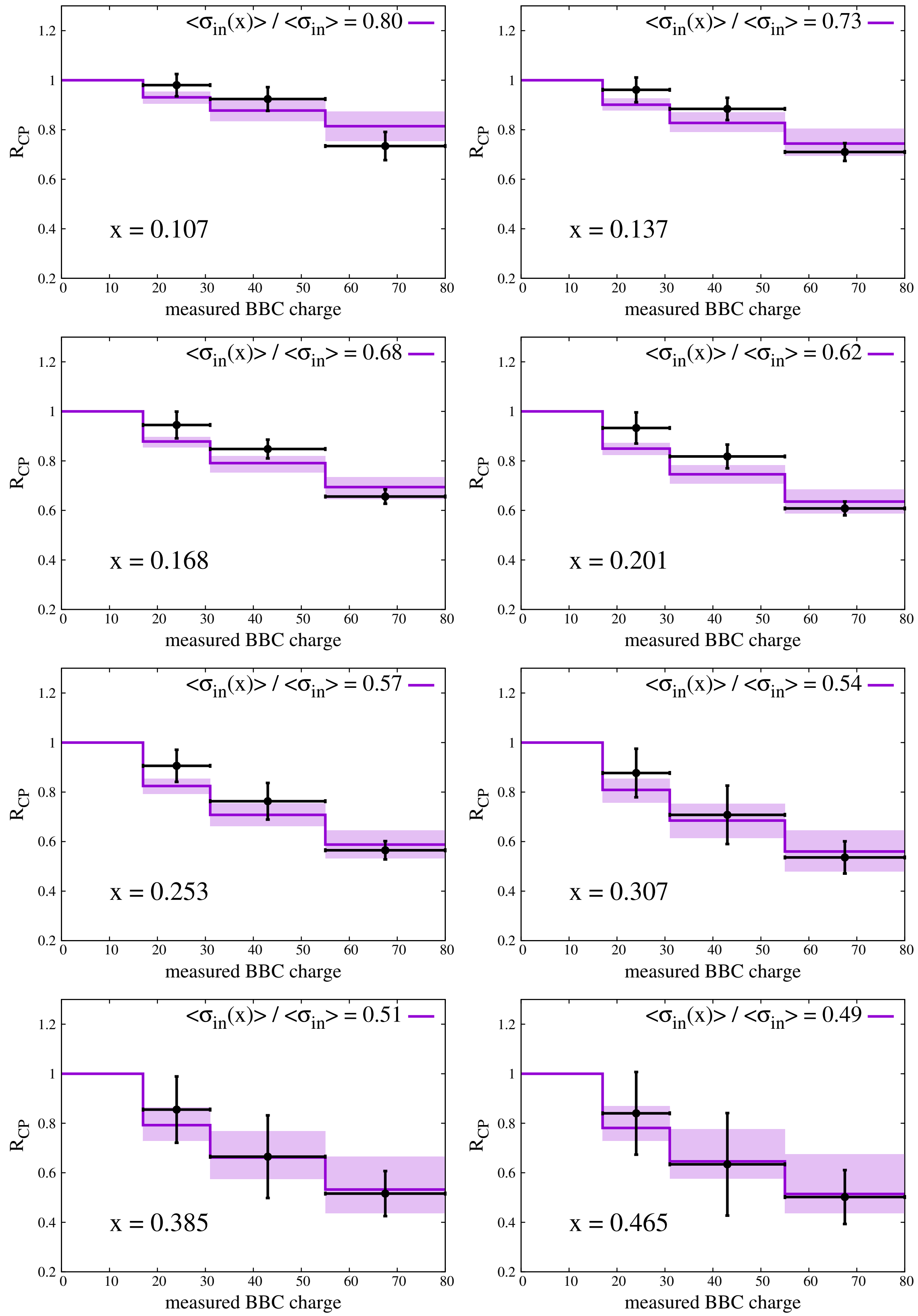
Sensitivity to ω_σ is small, so we use ω_σ =0.1 for following comparisons

We extended our 2015 analysis of ATLAS data and extracted $R_{CP}(x)$

$\lambda(x) = \sigma(x)/\langle\sigma\rangle$

Alvioli, Frankfurt, Perepelitsa, MS



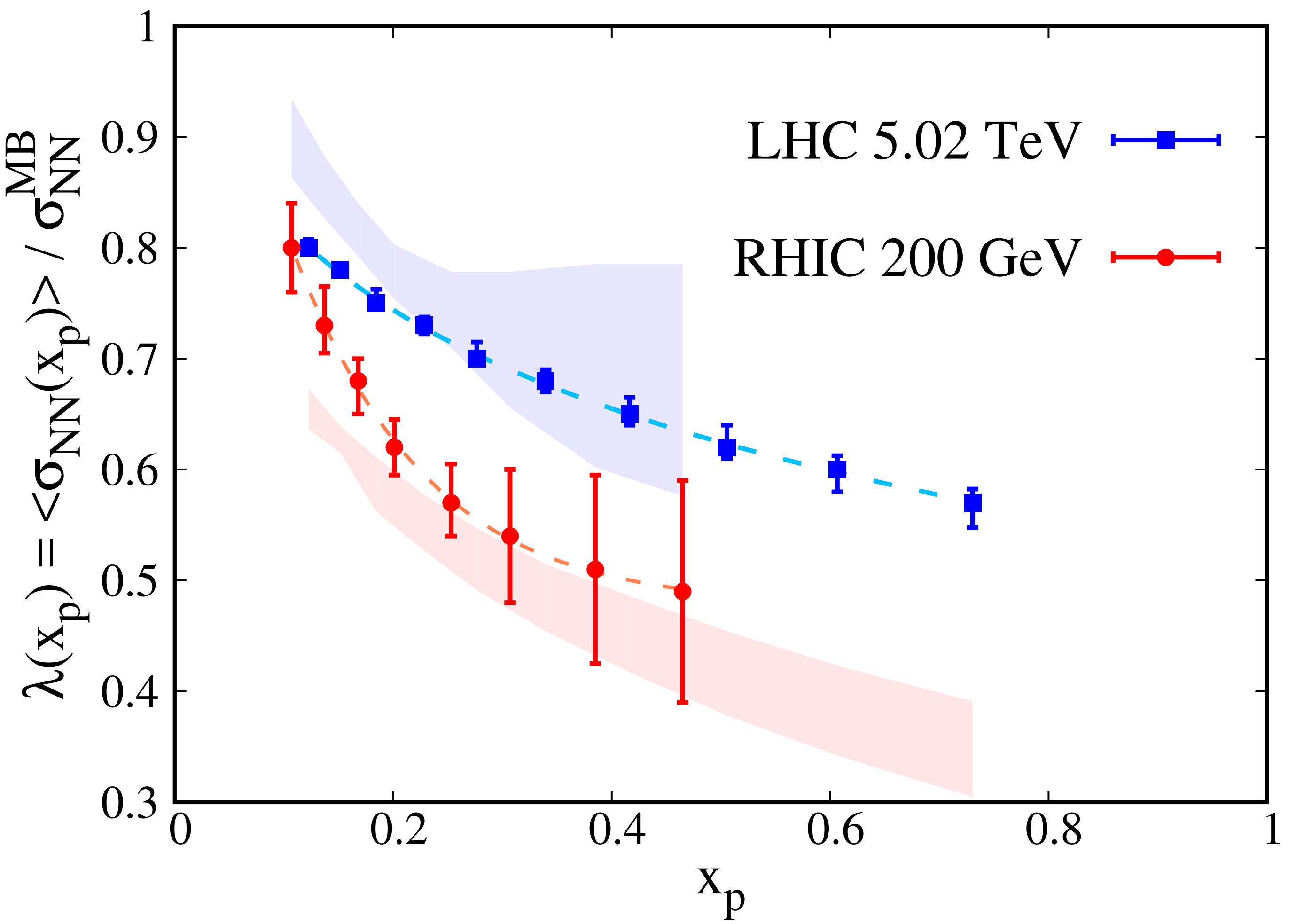


DAu PHENIX data at y=0 and large transverse momenta of the jets, R_{CP}, $\lambda(x)= \sigma(x)/\langle\sigma\rangle$ .Very different kinematics from the one studied at the LHC

Implicit eqn. for relation of $\lambda(x_p, s_1)$ and $\lambda(x_p, s_2)$

$$\int_0^{\lambda(x_p;\sqrt{s_1})\sigma_{tot}(\sqrt{s_1})} d\sigma\, P_N(\sigma;\sqrt{s_1}) = \int_0^{\lambda(x_p;\sqrt{s_2})\sigma_{tot}(\sqrt{s_2})} d\sigma\, P_N(\sigma;\sqrt{s_2})$$

Eq. (*)



$\lambda(x_p, s)$ grows with s since cross section at higher virtualities of the projectile grows faster with s

Highly nontrivial consistency check of interpretation of data at different energies and in different kinematics

Eq.(*) suggests $\lambda(x_p=0.5$, low energy) ~1/4. Such a strong suppression results in the EMC effect of reasonable magnitude due to suppression of small size configurations in bound nucleons (Frankfurt & MS83)

Implication for the quark - gluon level nucleus structure

Color fluctuation effects in nuclei

Introducing in the wave function of the nucleus explicit dependence of the internal variables we find for weakly interacting configurations in the first order perturbation theory using closure and equations of motion

probability of weakly interacting configurations in bound nucleon as compared to free nucleon is a factor of

$$\delta_A(p) = 1 - 4(p^2/2m + \epsilon_A)/\Delta E_A$$

smaller. Here $\Delta E \sim m_{N^*} - m_N \sim 600 - 800\, MeV$

average excitation energy in the energy denominator.

The largest effect is for nucleon momenta above Fermi surface which mostly belong to proton - neutron short-range correlations.

OPEN QUESTIONS

- *How to look for large size configuration - $x_P < 0.1$?*
- *bins in x_P for intervals in x_A*
- *small size configurations for large x_p gluons connection for EMC effects for gluon*
- *tests of centrality modeling — several nuclei*

portraying photon at LHC
Ultraperipheral AA collisions at LHC and CF in photons.

- Modeling $P_\gamma(\sigma)$

For

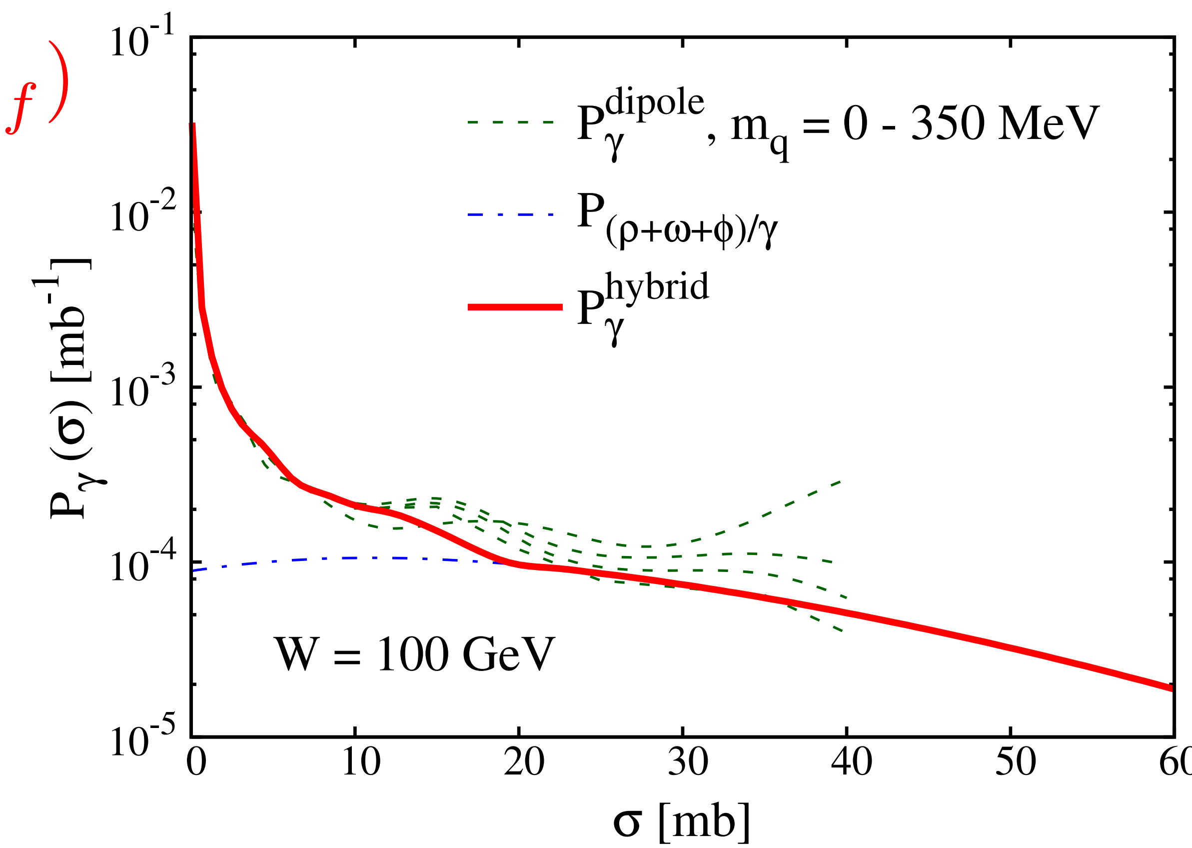
$$\sigma > \sigma(\pi N), P_\gamma(\sigma) = P_{\gamma\to\rho}(\sigma) + P_{\gamma\to\omega}(\sigma) + P_{\gamma\to\phi}(\sigma)$$

For $\sigma \leq 10mb$ (cross section for a J/ψ -dipole) use pQCD for $\psi_\gamma(q\bar{q})$

$$\sigma(d,x) = \frac{\pi^2}{3}\alpha_s(Q^2_{eff})d^2 x G_N(x, Q^2_{eff})$$

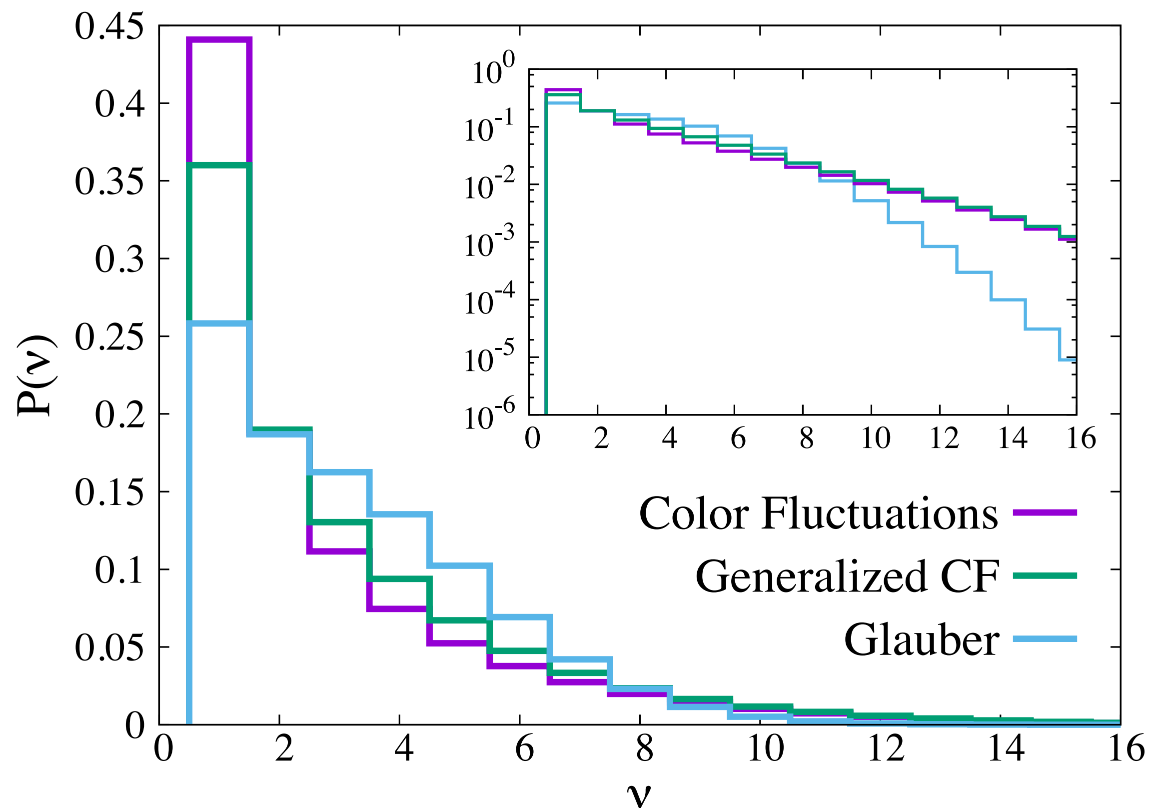
+ smooth interpolation in between

Smooth matching for m_q~ 300 MeV



Ultraperipheral minimum bias γA at the LHC ($W_{\gamma N} < 0.5$ TeV)

Huge fluctuations of the number of wounded nucleons, ν, in interaction with both small and large dipoles



Alvioli, Guzey, Zhalov, LF, MS

Phys.Lett. B767 (2017) 450-457

distribution over the number of wounded nucleons in γA scattering, W ~ 70 GeV

CF broaden very significantly distribution over ν.
"pA ATLAS/CMS like analysis" using energy flow at large rapidities would test both presence of configurations with large σ ~40 mb, and weakly interacting configurations.

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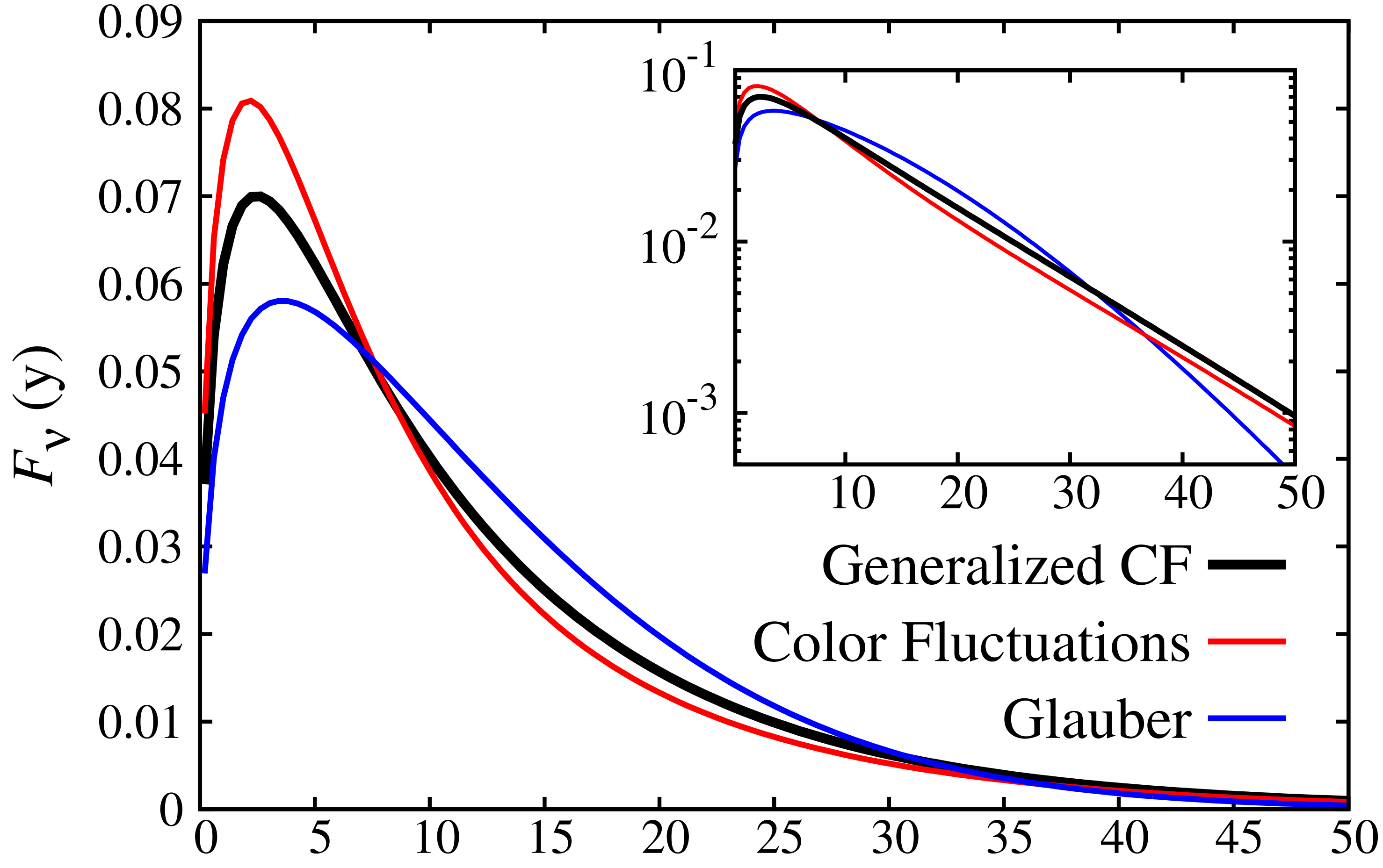


$$y = \Sigma E_T / \langle \Sigma E_T(hN) \rangle$$

The probability distributions over the transverse energy in the Generalized Color Fluctuations (GCF) model assuming distribution over y is the same for pA and γA collisions for same ν.

Using CASTOR for centrality via measurement of "y" advantageous : larger rapidity interval - smaller kinematical/ energy conservation correlations. For using ΣET for centrality determination one needs $\Delta y > 4$

$\gamma A \rightarrow$ jets + X

1) *Direct photon & x_A> 0.01, ν=1?*

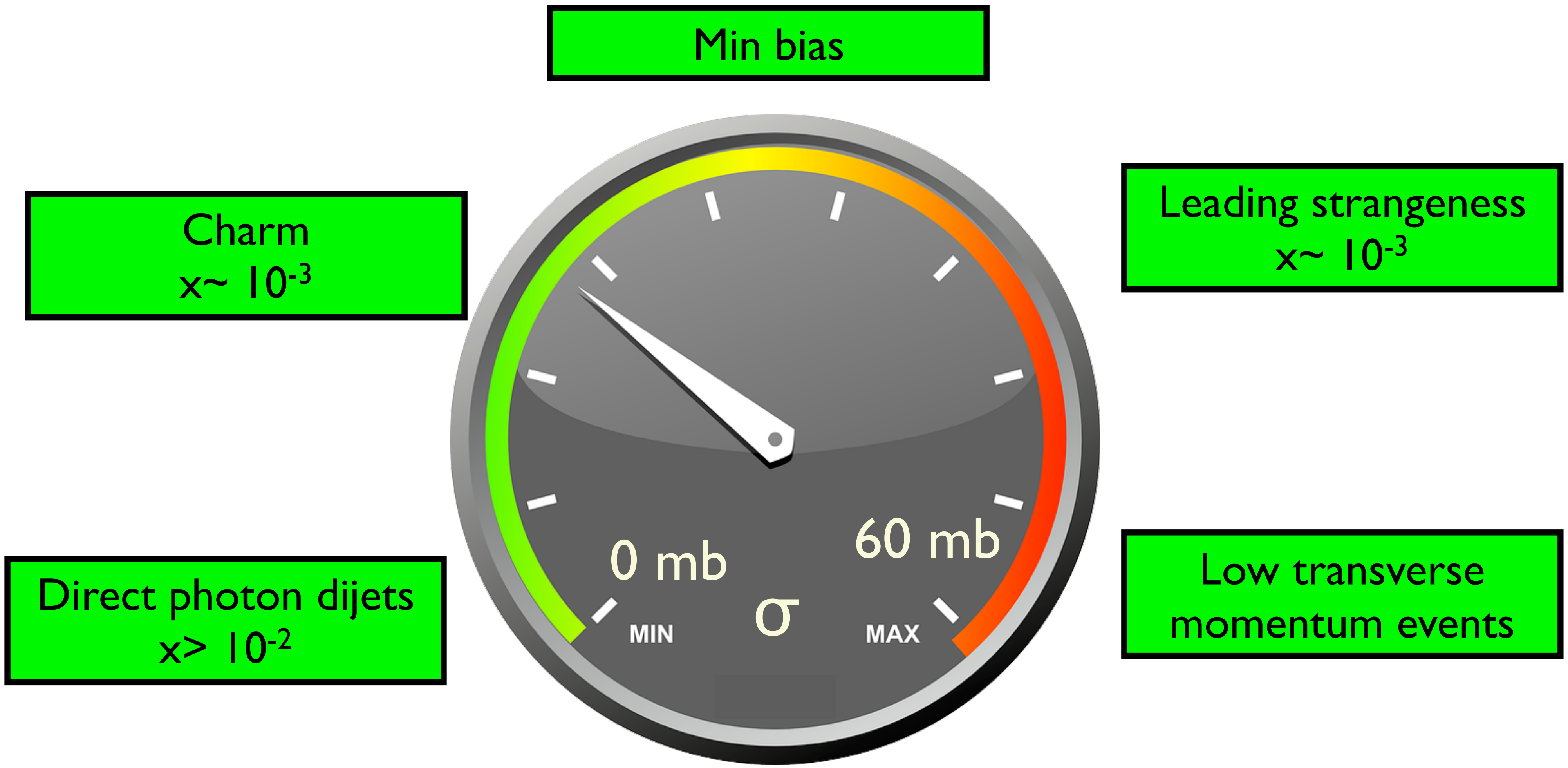
Color change propagation through matter.
Color exchanges ? ➠ nucleus excitations, ZDC & CASTOR

2) *Direct photon & x_A< 0.005 - nuclear shadowing increase of ν*

3) *Resolved photon - increase of ν with decrease of x_γ and x_A* W dependence

portraying transverse size of resolved photon

Tuning strength of interaction of configurations in photon using forward (along γ information) .   Novel way to study dynamics of γ &γ interactions with nuclei*



"2D strengthonometer"   - EIC & LHeC - Q^2 dependence - decrease of role of "fat" configurations, multinucleon interactions due to LT nuclear shadowing

Comment: Forward γA & γp physics at the LHC mostly within acceptance of central ATLAS, CMS detectors

Summary

- Color fluctuations are a regular feature of high energy nucleon, photon collisions... Effects in very central AA collisions are present.

- Gross violation of the Glauber approximation for photoproduction of vector mesons due to CFs

- Jet production at RHIC and LHC produced first glimpse of the global quark - gluon structure of nucleons as a function of x. Nucleon becomes smaller at large x. Interact weaker than in average, but faster grows with energy. Need to separate gluons and quarks in hard processes at x ~0.1.

- Nontrivial link between nuclear DIS, and centrality jet physics in pA. Strong discriminator of the models of the EMC effect. Link to physics of the cores of neutron stars.