Probing small x dynamics in UPC & pA collisions with help of ZDC information

what have we learned and several promising directions for the near future studies

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This talk primarily based on Alvioli, Guzey, MS. 2402.19060 [hep-ph]

CERN PA WORKSHOP, JULY 4, 2024

Prequel

*Several novel observations in NA **nearly** reached the level of discovery:*

Brahms & STAR observation of suppression forward production in combination with moderate y=0 hadron activity

Claims - due to fractional energy losses in proximity of black disk regime vs color glass condensate

Huge drop of R_{CP} from one to R_{CP} =0.2 in dijet production in large $x_{F.}$ pA collisions

Claim - due to shrinkage o ft transverse size of proton in configurations with large x quark

Mechanism of large gluon shadowing

Need additional handles / selections to reach a discovery level

- ZDC signal seems a promising supplementary tool

Outline

- Small x - how close one to the black limit is in current experiments
- Nuclear shadowing, unitarity, multiplicity fluctuations (only answers no time)
  (Color fluctuation model)
- Number of neutrons hitting ZDC - an estimator of number of wounded nucleons
- Applications of ZDC:

  Studying multiscale structure of photons

  Measuring nuclear gluon gpds

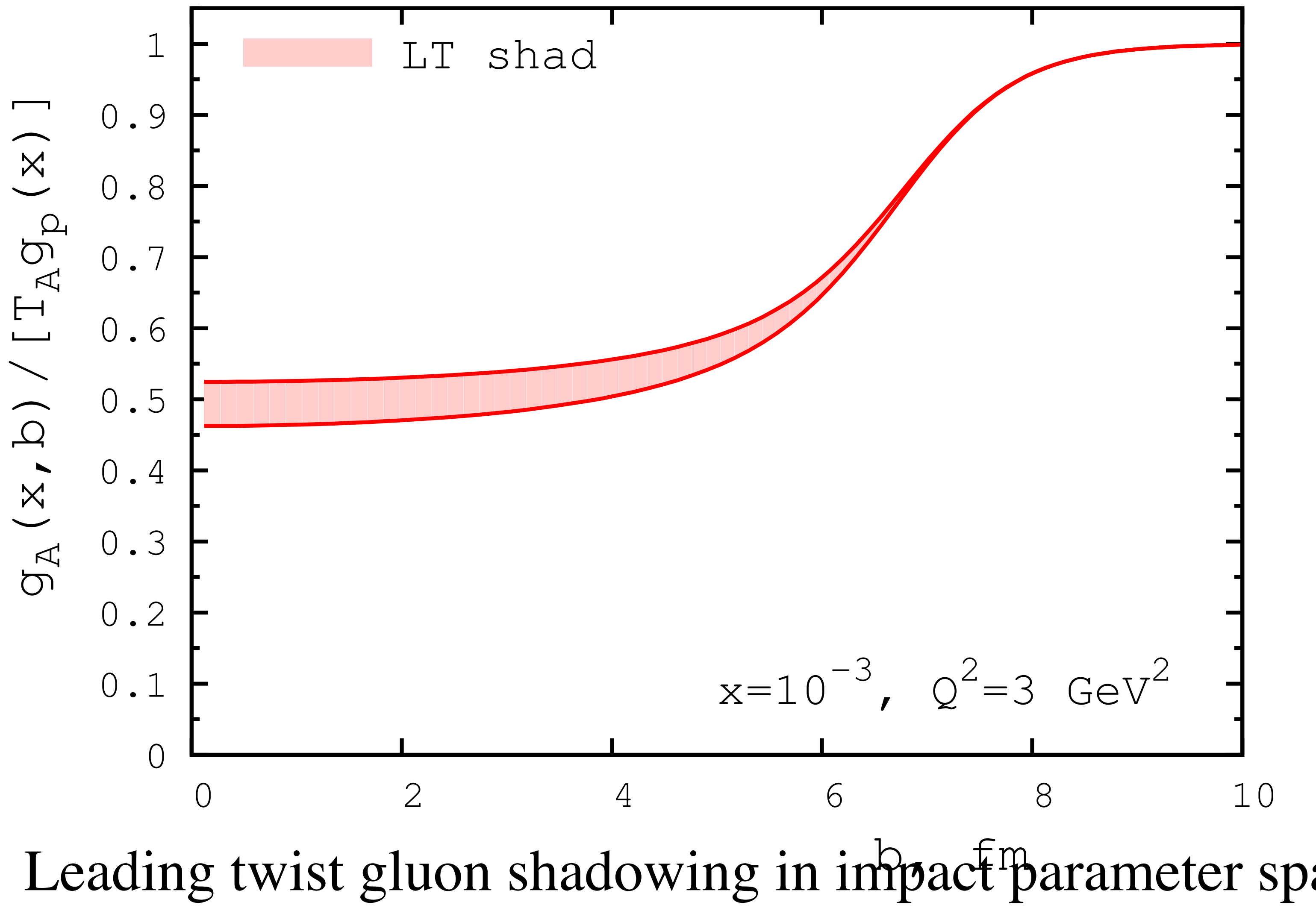
  Looking for onset of nonlinear regime

  Getting insight into dynamics of pA—-> very forward pion & jet prod.

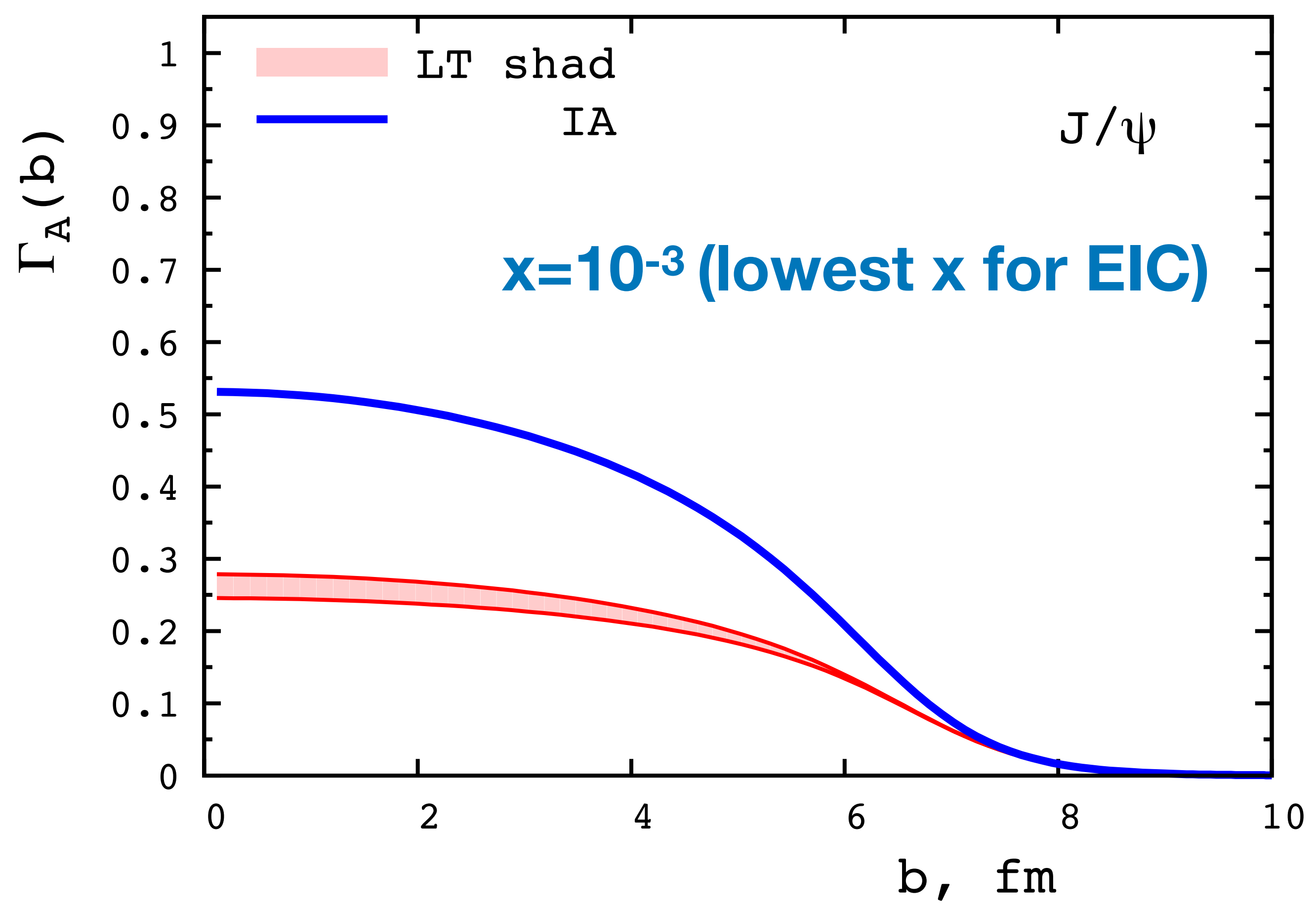
  Observing multiparton interactions in pA collisions

Two major conclusions

from analysis of coherent J/psi production
and forward pion production in deuteron Au



Leading twist gluon shadowing in impact parameter space for coherent J/ψ photoproduction on Pb as a function of impact parameter |b|.



Γ(b)=1 black disk

The scattering amplitude in impact parameter space $\Gamma_A(\vec{b})$ for coherent J/ψ photoproduction on Pb as a function of |b|.

Gluon shadowing changes regime of interaction at $x \sim 10^{-3}$ and small b getting closer to black (probability to interact inelastically)

Fractional energy losses

$1-(1-\Gamma)^2 = 0.45$ $x \sim 10^{-3}$ gray

$1-(1-\Gamma)^2 = 0.64$ $x \sim 10^{-4}$ Blackish

Approach to black regime is much faster for inelastic scattering than for coherent processes

Example of how ZDC signal could have resolved between two models of the BRAHMS effect :

Apparent violation of pQCD factorization in the leading (x_F >0.4) pion production in D A —> Π+X (RHIC)

Scenario I =CGC

Pions from elastic quark scattering off CGC gluon field

Central collisions

More neutrons than minbias

Scenario II Post selection

Fractional energy losses in the black disk regime and BRAHMS effect

Peripheral collisions

Fewer neutrons by a factor ~2

STAR data strongly indicate dominance of a peripheral mechanism of the forward pion production with a strong suppression of the production at central impact parameters.

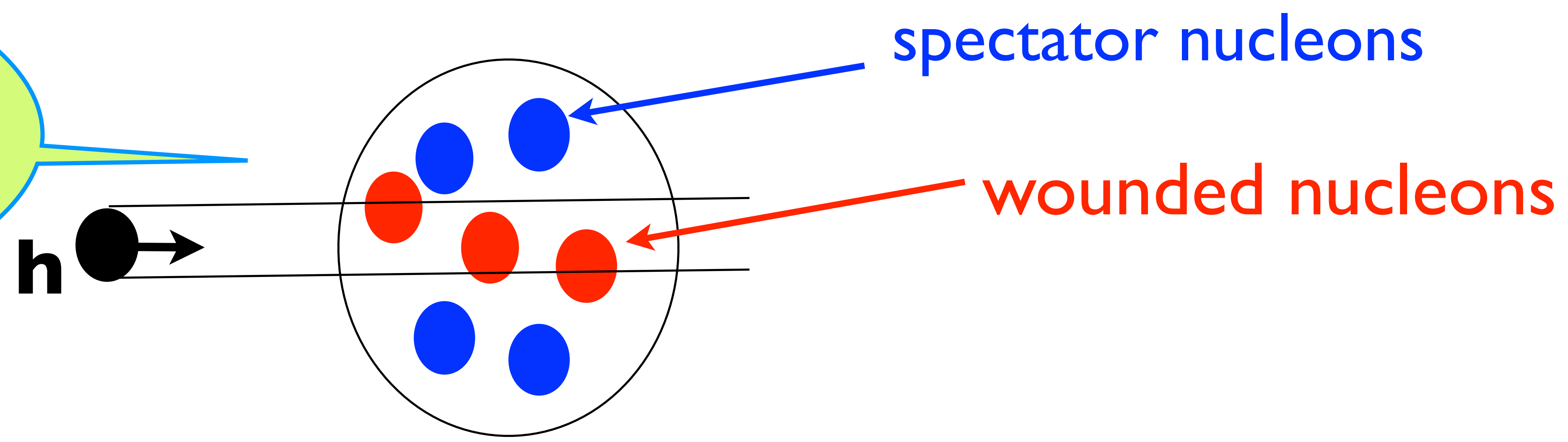
Ultimate test would be measurement of the neutron multiplicity in ZDC

ARE THERE SUCH DATA IN STAR OR PHENIX ARCHIVES???

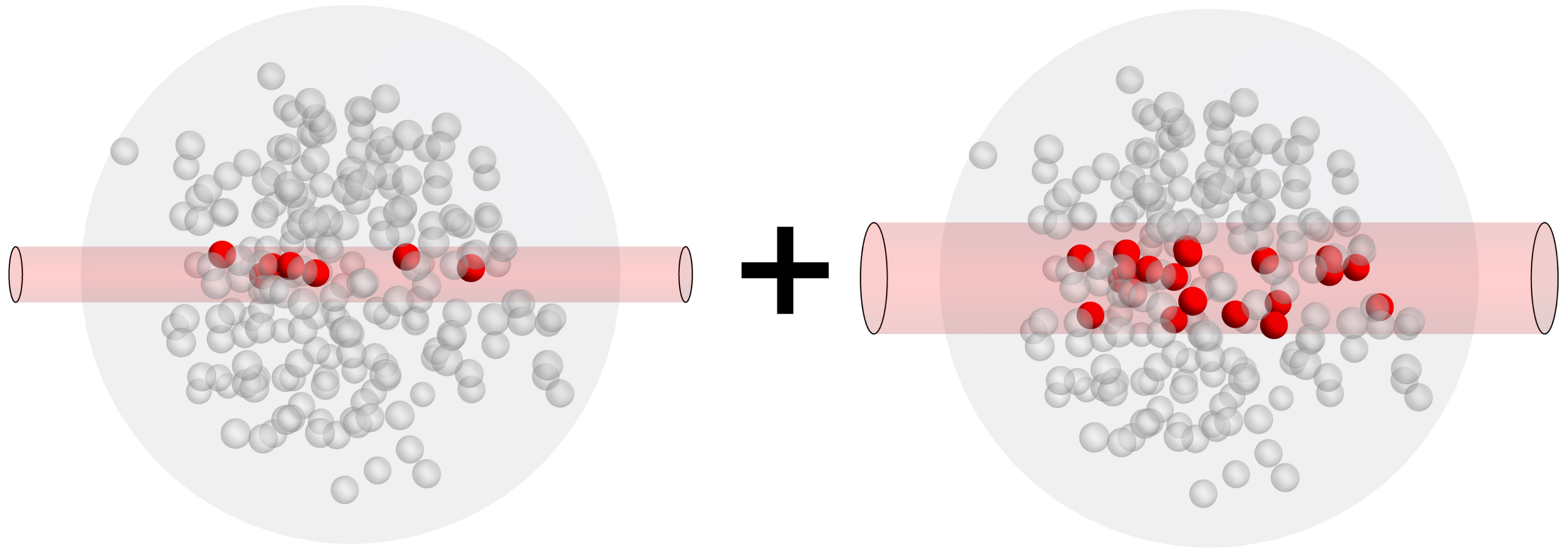
Many observables studied in QCD are of inclusive nature. Fluctuations of parton density transverse size,... are averaged out. At the same time no averaging occurs say in high energy pA scattering

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 of the stick,)

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



Convenient quantity - $P(\sigma)$ -probability that hadron/photon interacts with cross section σ with the target.

$$\int P(\sigma) d\sigma = 1, \qquad \int \sigma P(\sigma) d\sigma = \sigma_{tot},$$

Confer: $P_{MC\ Glauber}(\sigma) = \delta(\sigma - \sigma_{tot})$

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

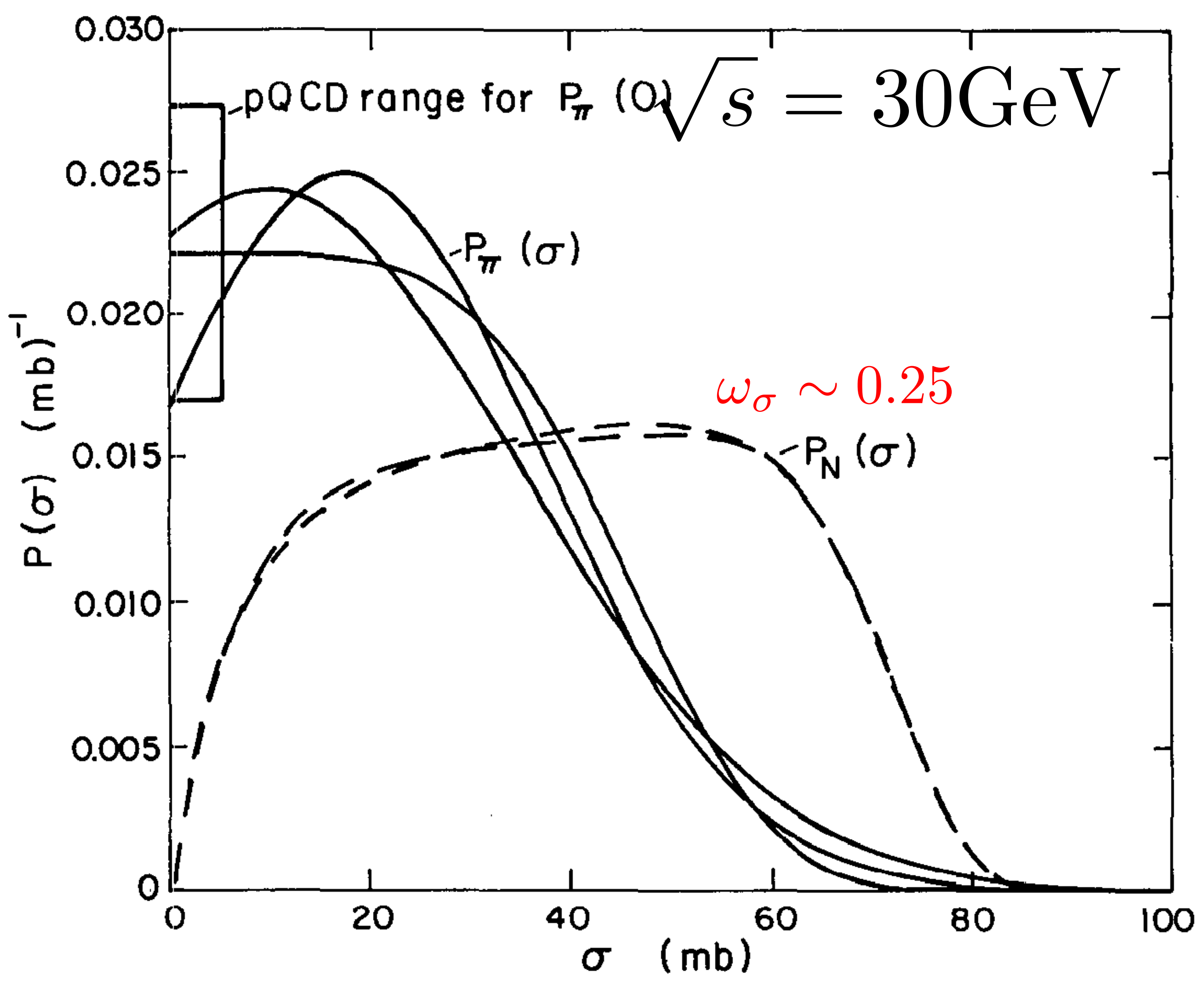
variance

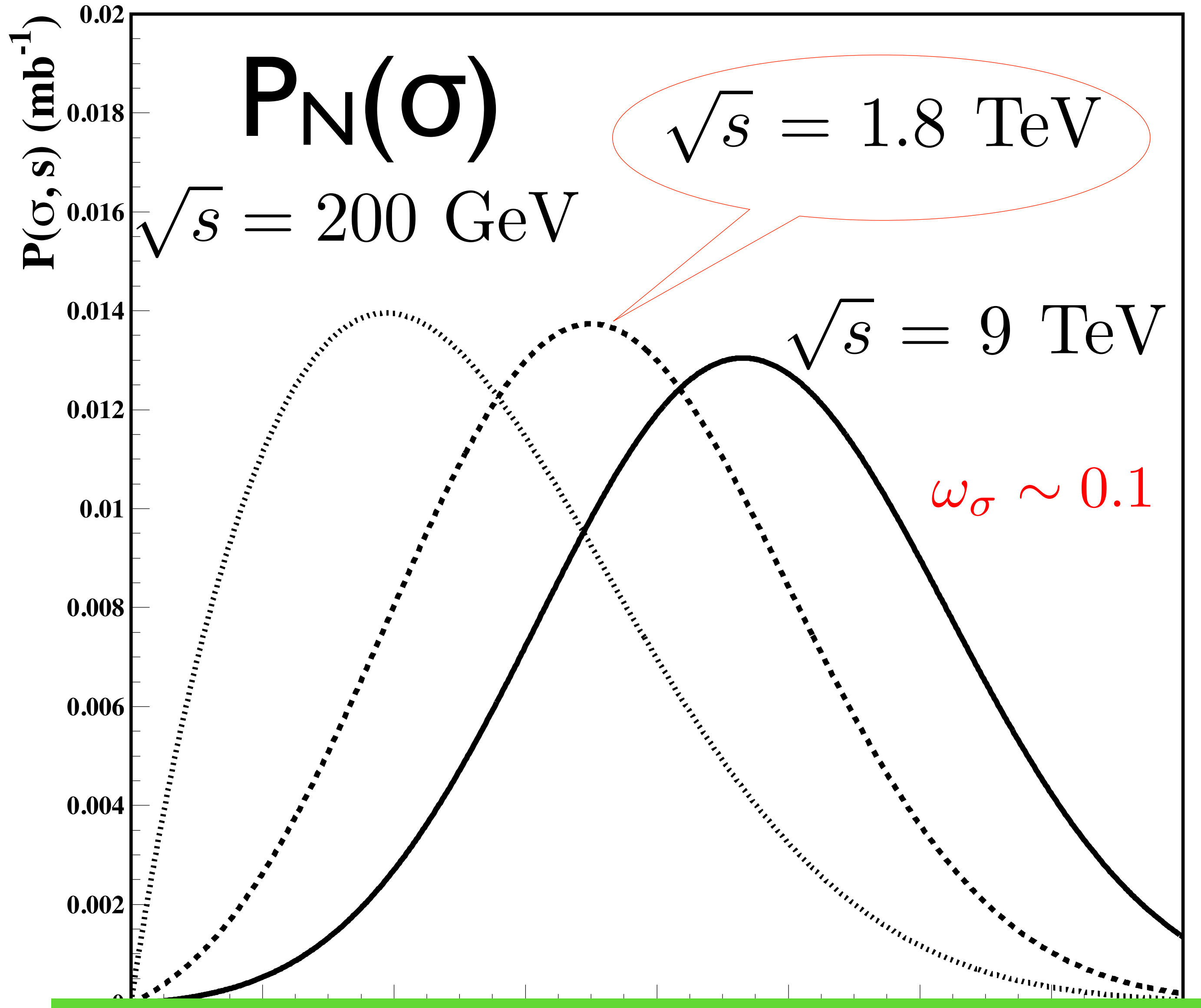
Pumplin &Miettinen

Good - Walker model of coherent scattering Eigen statesl

Warning - connection between fluctuations and inelastic diffraction is a reasonable model for t=0. However at finite t knockout mechanism becomes important and ultimately dominant

Example σ (Deuteron +h —> (pn) +h) = 0 for t=0 in the impulse approximation (no fluctuations) and not suppressed for $-t > 1/r_N^2$ - knockout mechanism





Extrapolation of Guzey & MS before the LHC data

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

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

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

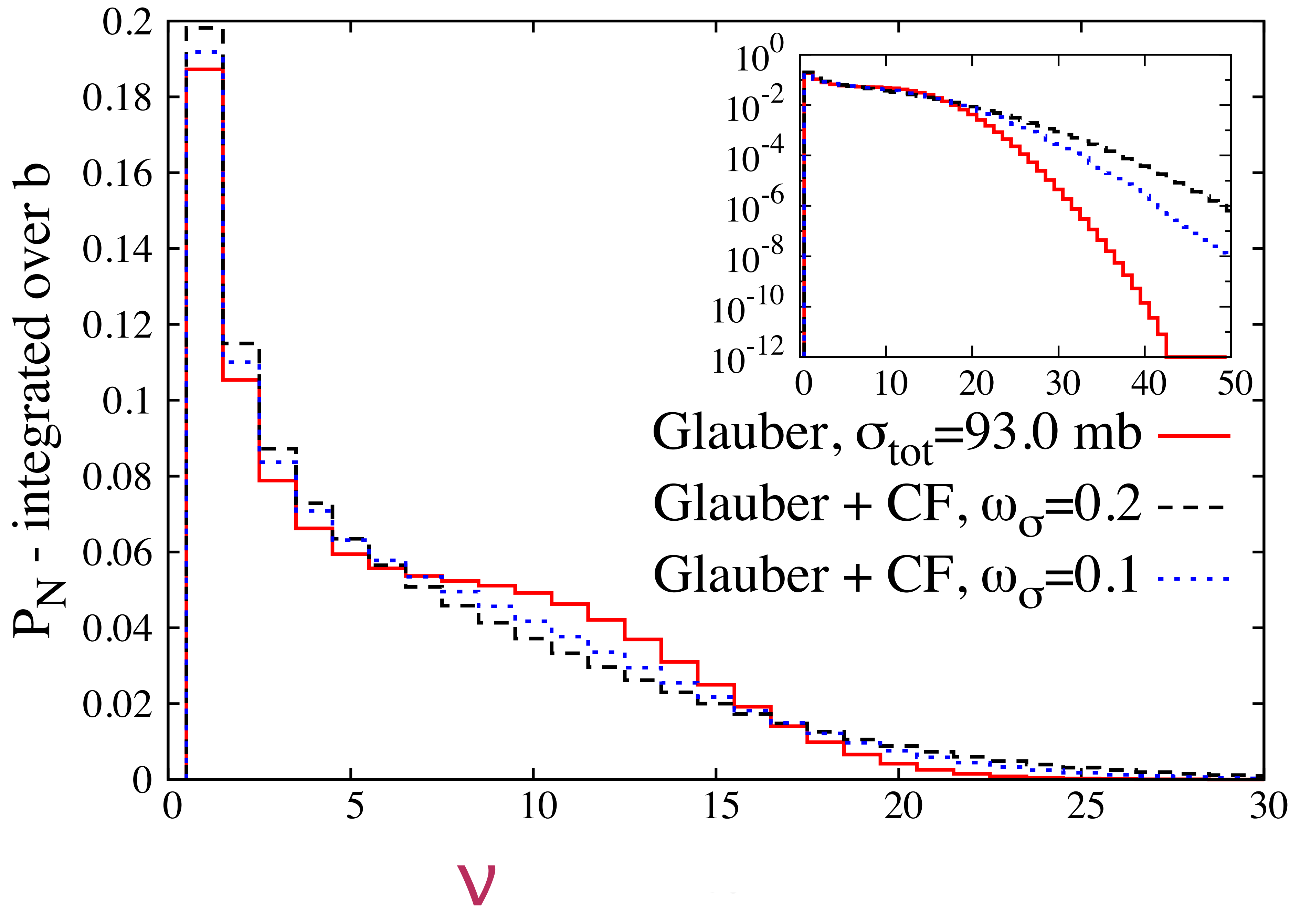
Fast drop of $P_N(\sigma)$ at small σ, with increase of energy pQCD?

Can use P(σ) to implement Gribov- Glauber dynamics of inelastic pA interactions. Baym et al 91-93

$$\sigma_{\rm in}^{\rm NA} = \int d\sigma_{in} P(\sigma_{in}) \int d\vec{b}\, \left[1 - (1-x)^A\right]$$

$$\sigma_n = \int d\sigma_{in} P(\sigma_{in}) \frac{A!}{(A-n)!\,n!} \int d\vec{b}\, x^n (1-x)^{A-n}\,.$$

Probability of exactly n interactions is $P_n = \sigma_n / \sigma_{in}^{hA}$

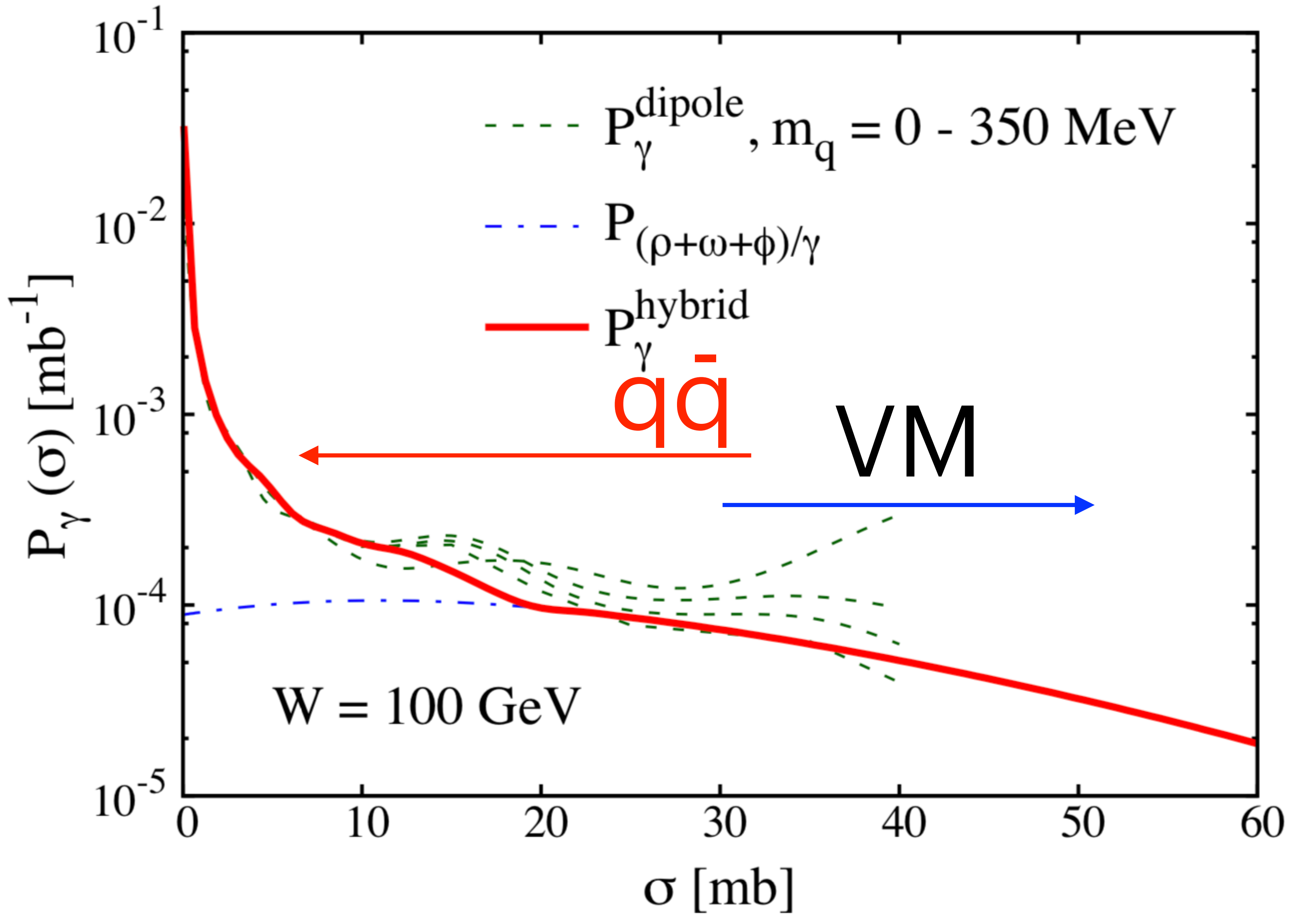


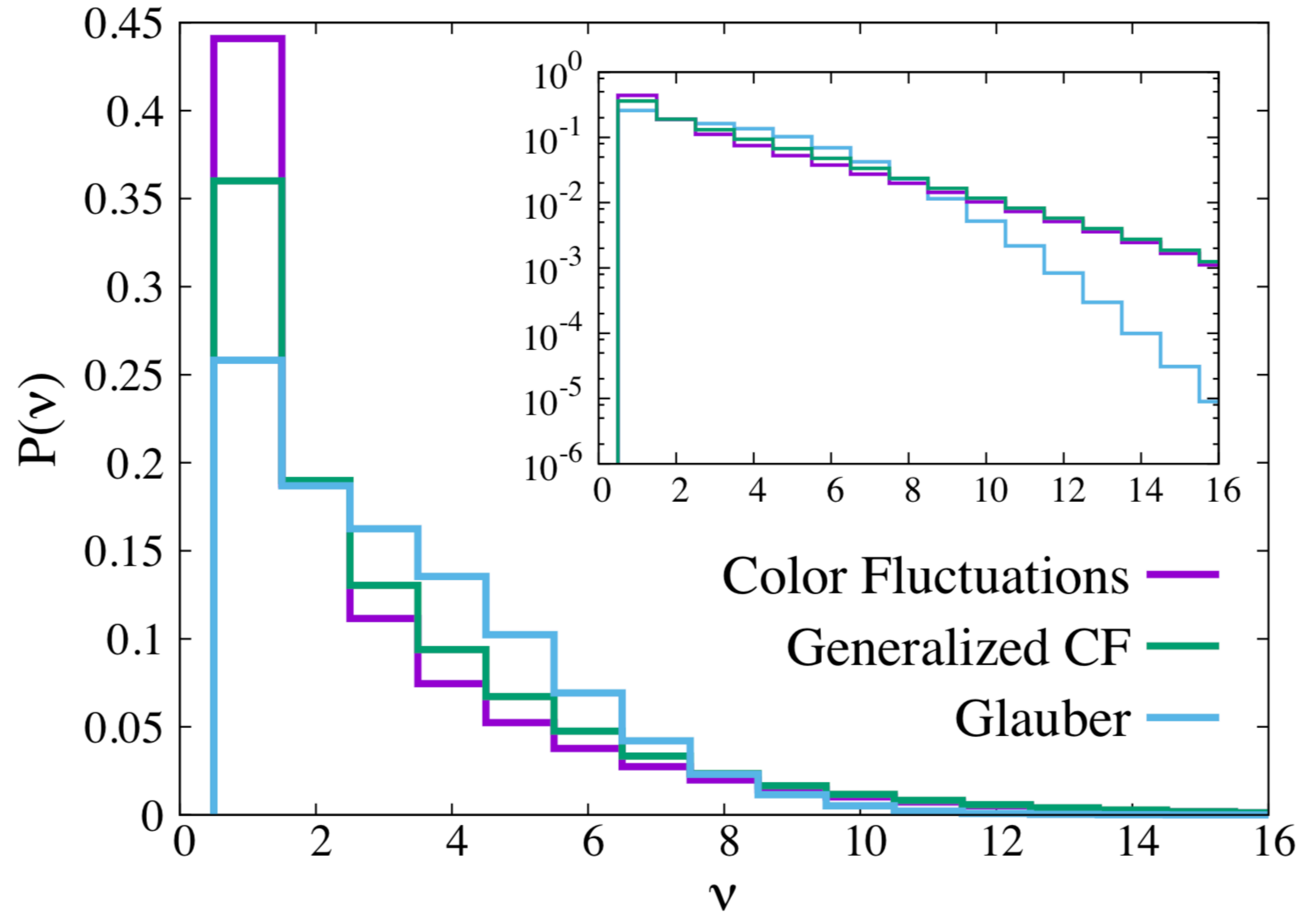
Distribution over ν= N_{coll} is sensitive primarily to the value of variance, ω_σ

ΣE_T^{Pb} distribution as a function of ν: modeling by ATLAS at large negative rapidities -3 >η> -5

Similar effects in photon - nucleus collisions (a broader distribution in number of wounded nucleons) UPC & EIC

We calculated $P_\gamma(\sigma)$





Plenty of predictions for ultraperipheral collisions at LHC

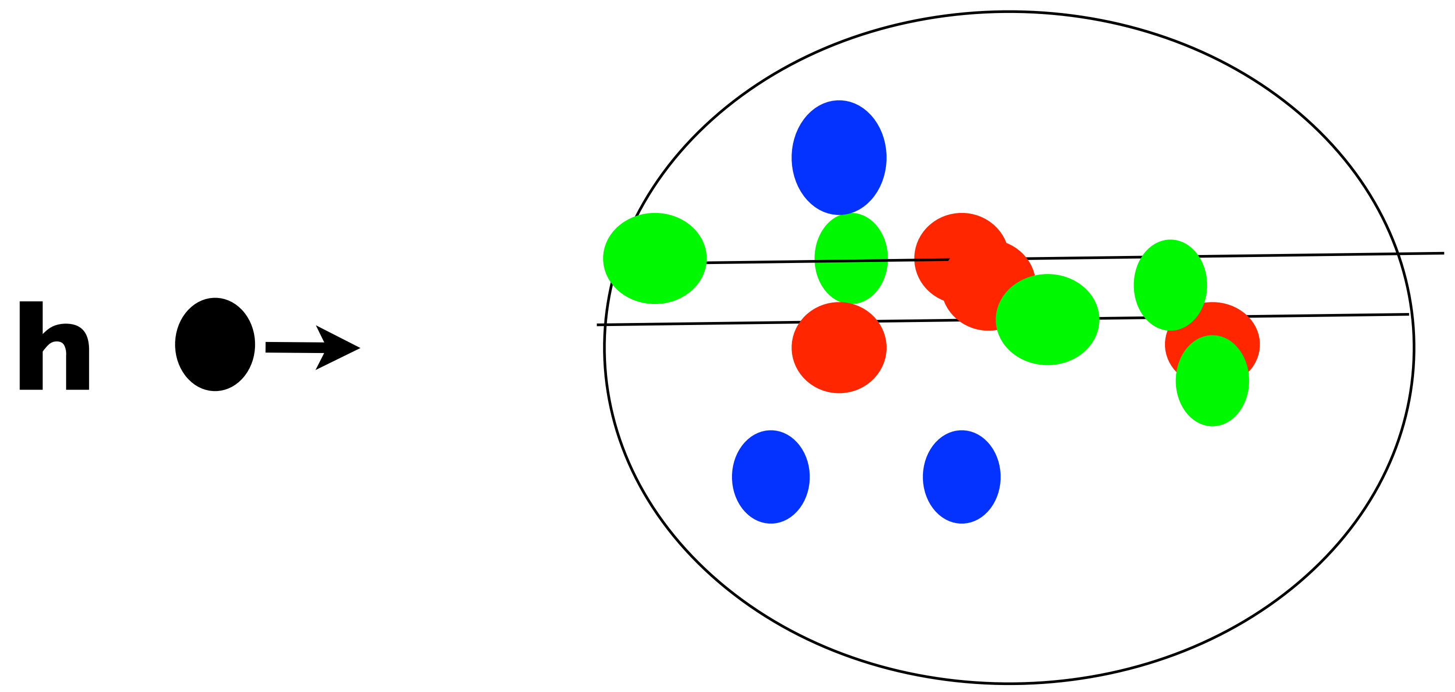
Interesting: smooth matching pQCD and soft interactions

requires m_q= 300 MeV — constituent quark mass

To study dependence of a subprocess on N_{coll} it is desirable to maximize the distance between rapidities where the process is measured and the yrapidity range used for centrality (<b>) determination.

ZDC signal?

A wounded nucleon leaves behind a hole with excitation energy~20 MeV. Results in emission of soft neutrons more or less independently from each wounded nucleon



spectator nucleons

wounded nucleons

Soft neutrons

Average number of soft neutrons is ~ 5 times larger than N_{coll}

Example of a remarkable process in which Glauber model grossly contradicts to the data:

pA —>t wo jets + X

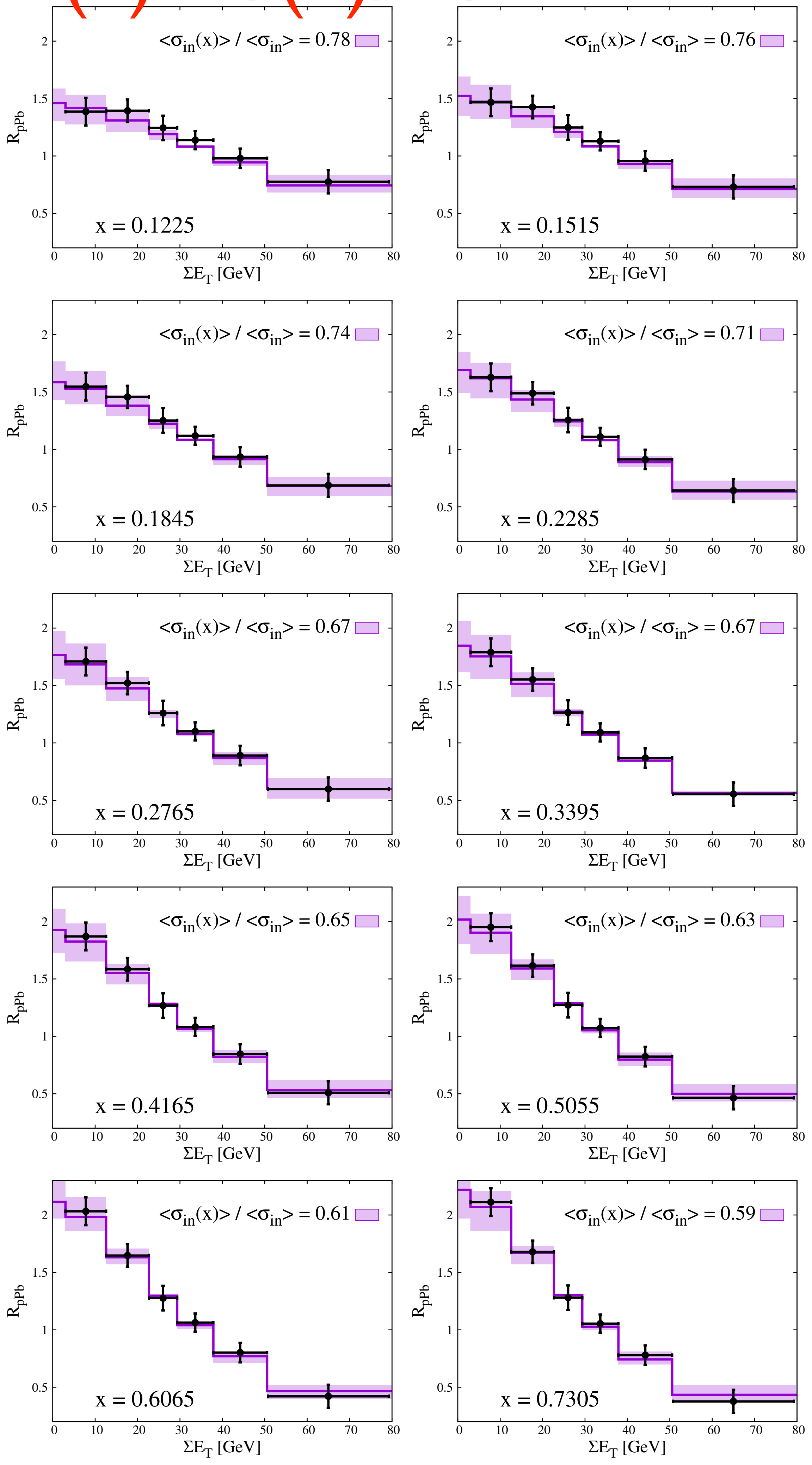
with jets produced along proton direction with momentum fraction $x_F > 0.3$

Inclusive set up - factorization works fine, but strong dependence of the dijet rate on the transverse energy, E_T, produced at far away rapitities.

our 2015 analysis of ATLAS data (extension of 2013)

Alvioli, Frankfurt, Perepelitsa, MS **Phys.Rev. D98 (2018) no.7, 071502**

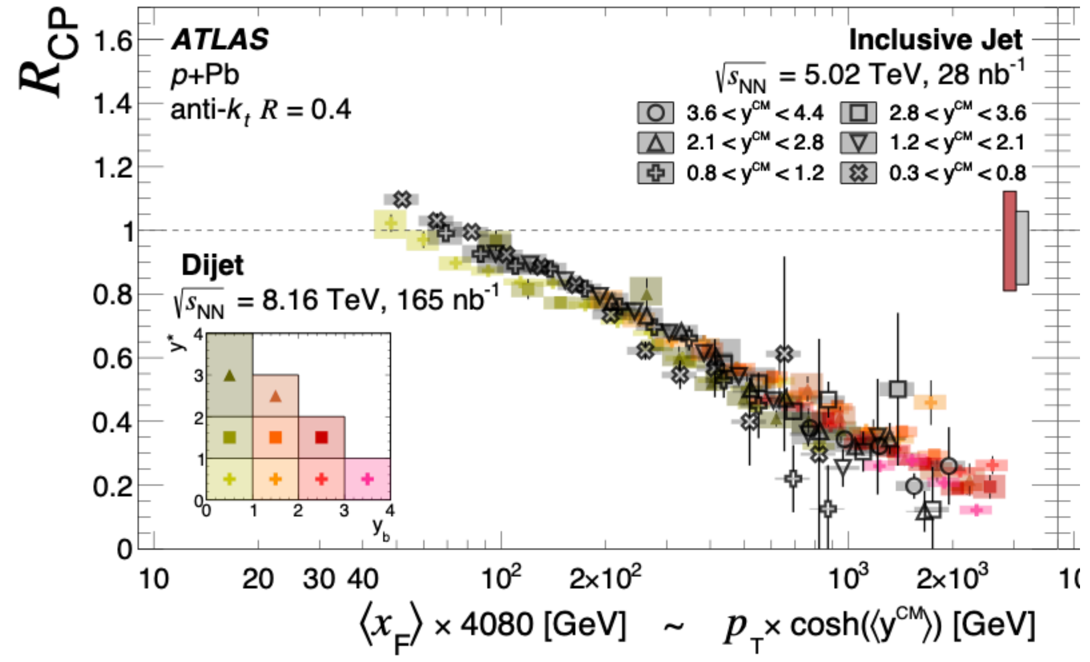
$\lambda(x) = \sigma(x)/\langle\sigma\rangle$



Our explanation in the color fluctuation model : effect is due to decrease of $\langle\sigma_{eff}(x)\rangle/\sigma_{in}$ with increase of x_F.

No alternative explanations proposed a decade after the data were published by CMS and ATLAS

FSI explanation does not count - scaling for inclusive.

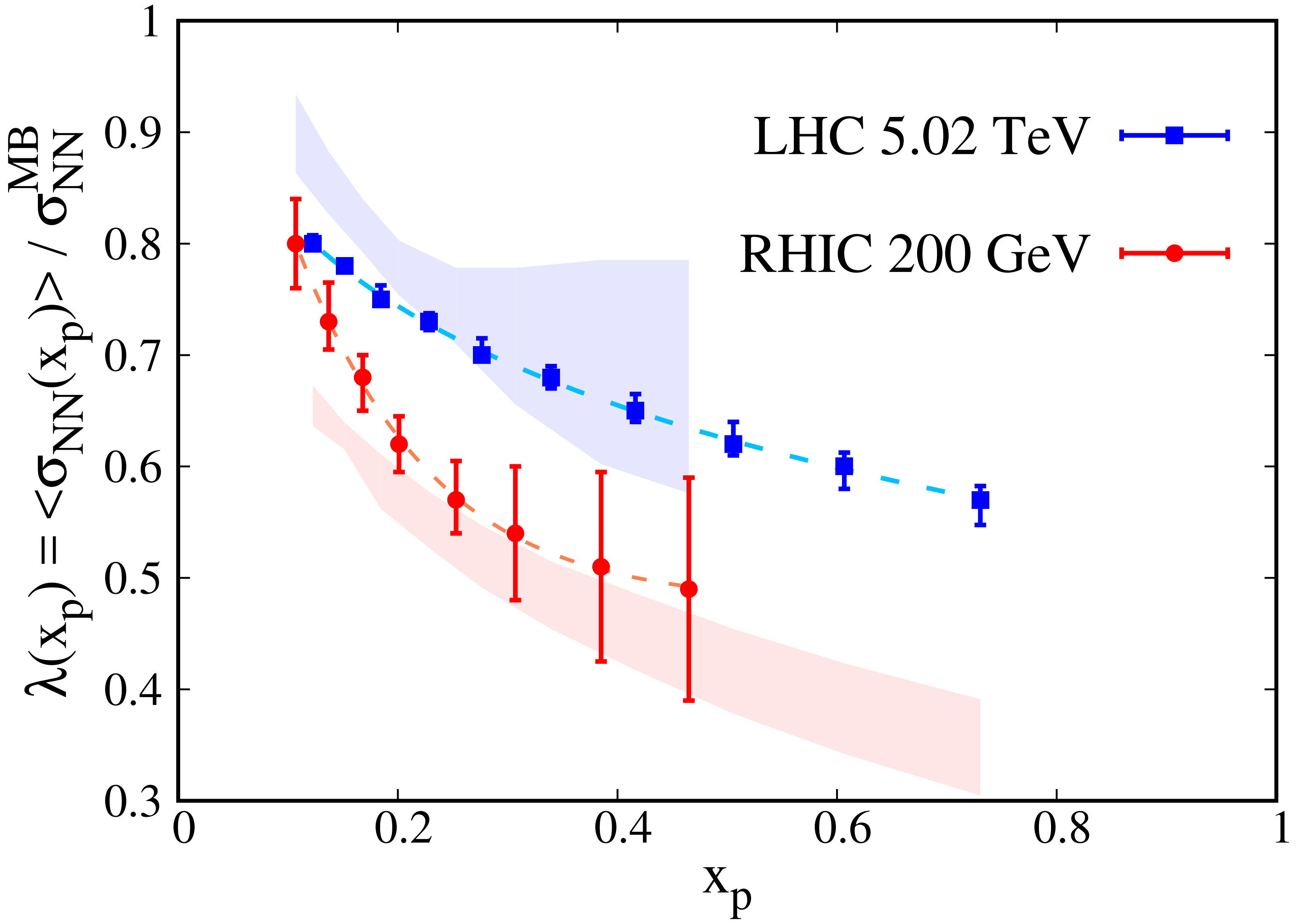


New ATLAS data (2023) confirmed the original data (R.Long talk)

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. (*)



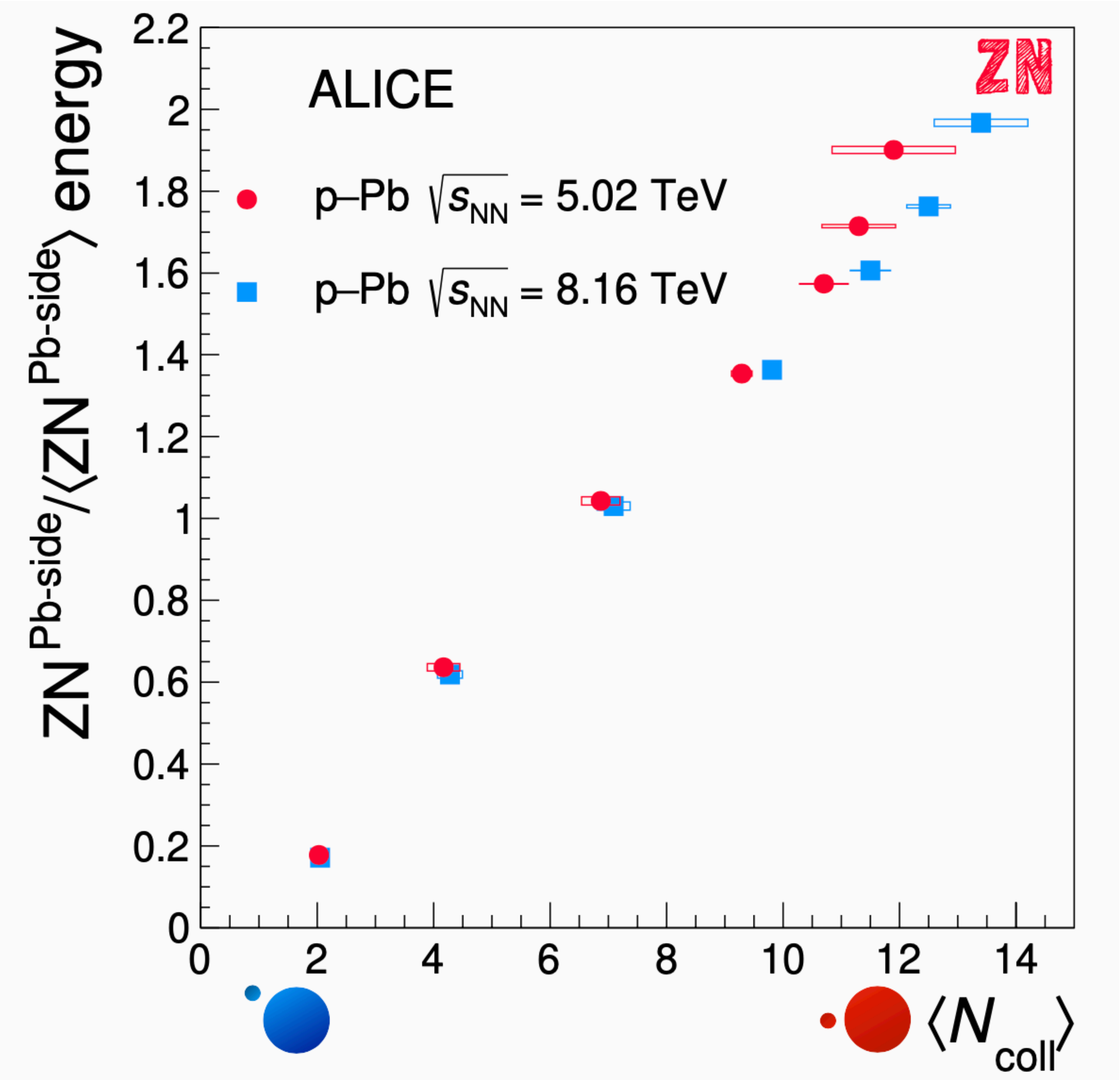
$\lambda(x_p, s)$ grows with s since cross section at higher virtualities of the projectile grows faster with s

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

Eq.(*) suggests $\lambda(x_p{=}0.5$, low energy) ~1/4. Such a strong reduction of interaction strength corresponds to reduction of the transverse size of nucleon at x> 0.5 by a factor > 4

(suppression was predicted in Frankfurt & MS83)

Pb fragmentation vs. collision geometry

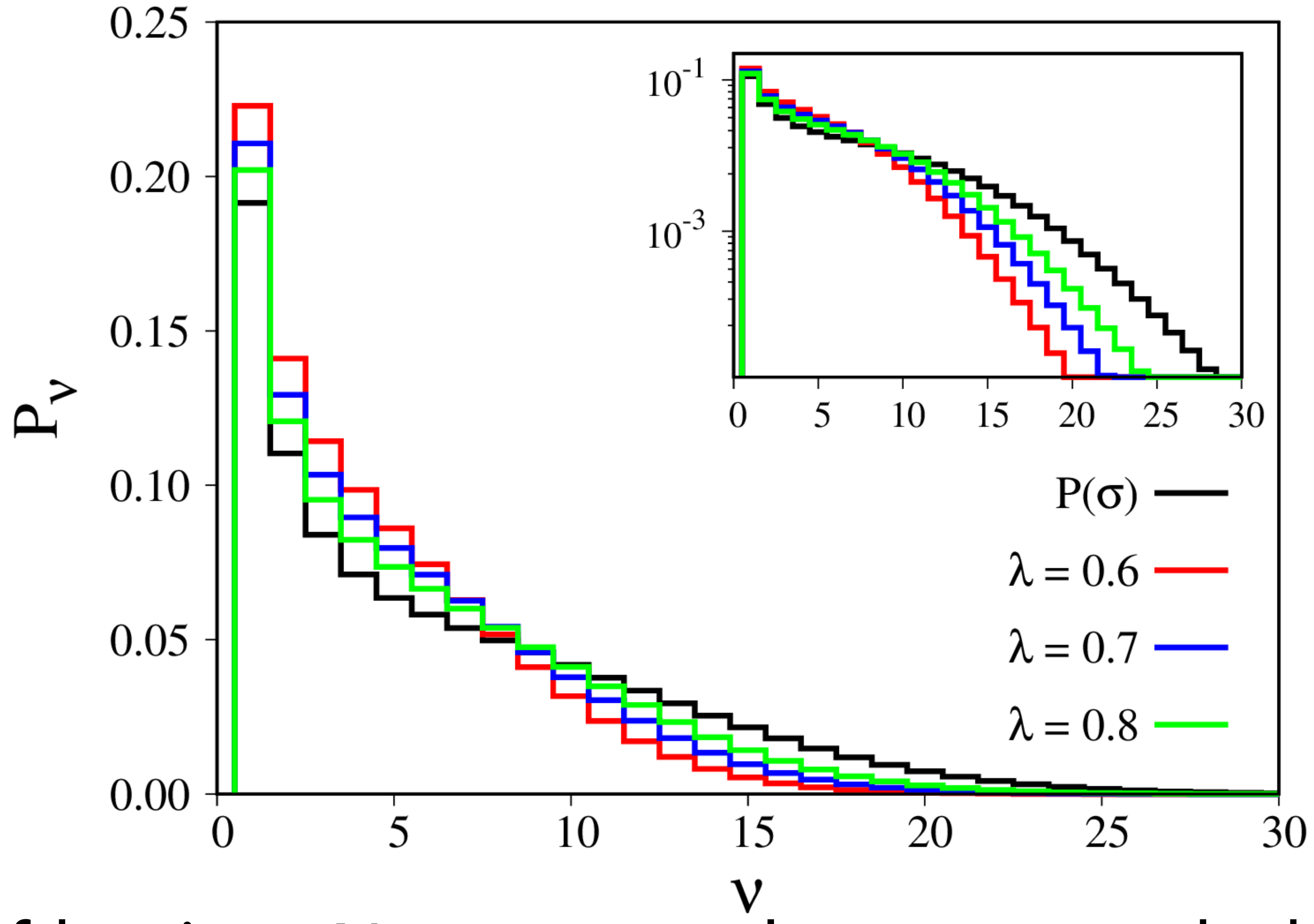


ALICE coll., arXiv 2107.10757

Energy carried by neutrons emitted from the Pb nucleus (slow neutrons) increases linearly with the number of binary N-N collisions (as already observed at smaller energies)

MS: There are corrections to linear dependence of neutron energy/ average neutron energy — need to work on corrections for small N_{coll}, via e.g. quasielastic J/psi

C. Oppedisano, CFNS Ad-hoc Workshop, February 2022



Probability of having $N_{coll} = \nu$ nucleons wounded for a dijet trigger.

Strong reduction of neutron yield for large energy releases in ZDC. Quantitative predictions with reduced uncertainty after kinematics $\nu=1$ is studied in UPC

If prediction is confirmed , establishes a new fundamental property of nucleon wave function: at large x transverse area of nucleons at least factor of four smaller than in average at x> 0.5. Would explain EMC effect (Frabkfurt, MS 1983)

Conclusions and outlook

Use of ZDC information would allow to extend information greatly extend information on small x dynamics which could be derived from UPC. Several examples

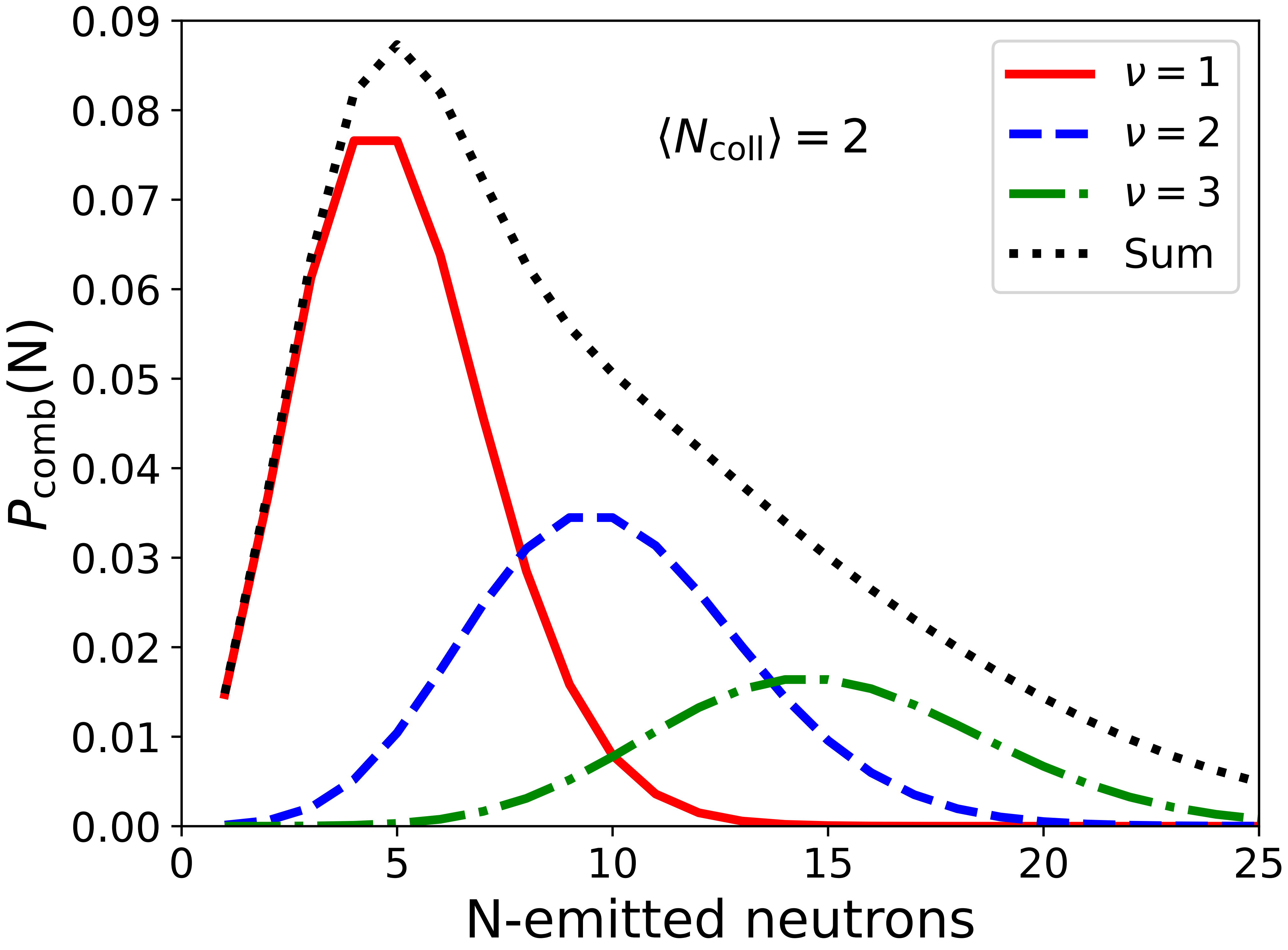
Gluon shadowing (analogies to strategy used to study R_{CP} in pA :

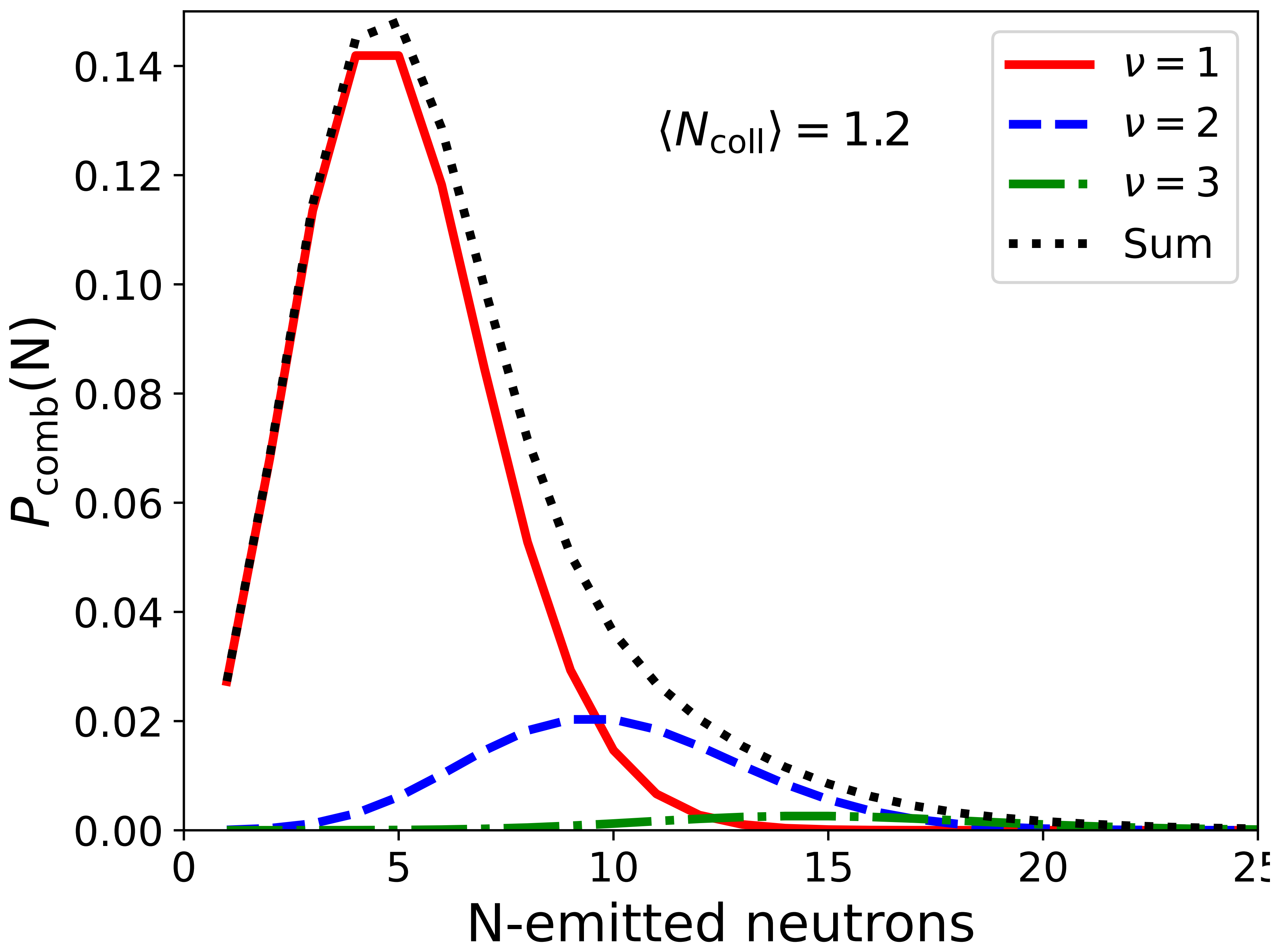
Using ZDC to get samples of events with lowest (15%) and highest (15%) activities

in ZDC with proper normalization of pA samples using jet production at x~0.01.

HIGH /LOW ratio for charm photoproduction (Talk by Innocenti) is directly related to gluon shadowing

Gluon shadowing via photoproduction





20 %. Shadowing of gluon pdf

Charm phttoproduction for

moderate p_t and $x \sim 10^{-4}$

Separation of different N_{coll} contributions would provide detailed info on nuclear shadowing dynamics

UPC: Shadowing and suppression of leading meson (minijets)production with increase of $W_{\gamma N}$ **tests of the approach to the black disk regime**

(1)- fractional energy losses —> decrease of the yield of large x_F particles

(2) increase of average p_T for surviving large x_F hadrons. (Guzey, McDermott, MS, LF. 2000)

These patterns should be stronger for central collisions (higher neutron multiplicities)

Huge rapidity distance between analysed particles in the event and ZDC should minimize trigger bias effects. The strategies don't require knowledge of γp cross sections

pA physics *Are suppression effects observed in leading particle production at RHIC stronger for small b? o b dependence of BRAHNS effect?*

Use of ZDC to observe multiparton interactions in pA

Large enhancement of MPI (double, trople) as compare to pp collisions was predicted by Treleani and MS in 2001 in parton model and in pQCD by Blok, MS, Wiedemann (2017).

Still mot observed

Main reason - uncertainties in calculating 2 —> 4

Possible solution - studying impact parameter dependence of cross section

- Alvioli, Azarkin, Blok,MS *Eur.Phys.J.C* 79 (2019) 6

Use of ZDC allows to cancel out contribution of 2—> 4

Summary

Study of pA and γA collisions at LHC with ZDC information including diffractive photoproduction would lead to a much better understanding of the small x dynamics down to at least $x \sim 10^{-5}$, QCD structure of photons and multiparton structure of nucleons (MPI). EIC would complement by studying smaller x-range $x > 10^{-3}$ but with a higher precision.

Critical to measure as soon as possible emission of neutrons for the case of no shadowing kinematics in γ A, deal with the contribution of giant dipole resonance,...