Color fluctuation phenomena in pp, pA, and AA collisions

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Several feature of NN interactions at the LHC relevant for pA and AA

two seem to be most important:

- ✱ Fluctuations of overall strength of NN interaction
- ✱ A factor of four difference of the transverse area scales for soft and hard NN interaction

Other fluctuations - gluon density in nucleon, nuclei, LT shadowing effects -- can discuss only during the question part.

Fluctuations of overall strength of high energy NN interaction

- High energy projectile stays in a frozen configuration distances $l_{coh} = c\Delta t$

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

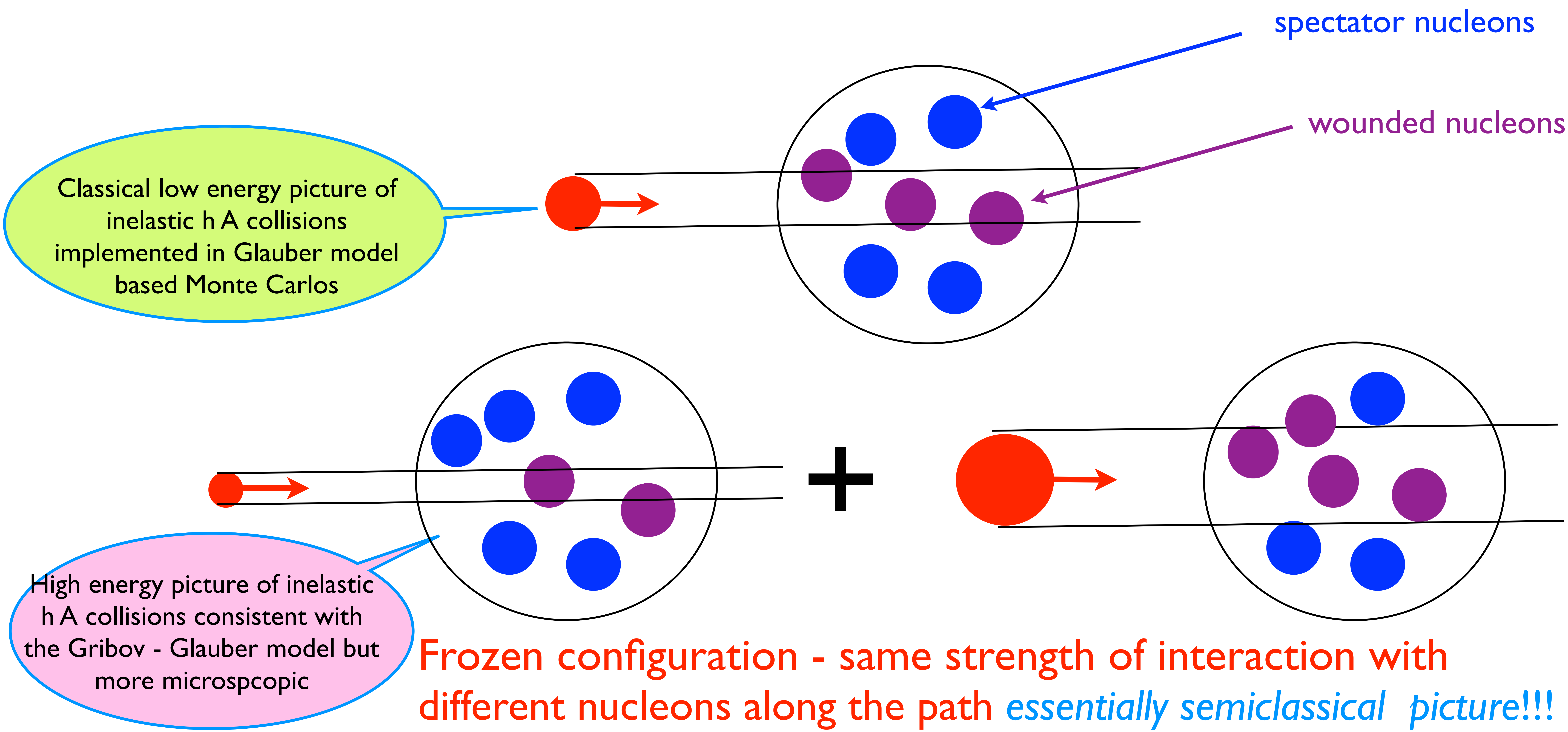
At LHC for $m_{int}^2 - m_h^2 \sim 1\text{GeV}^2$ $l_{coh} \sim 10^7$ fm>> $2R_A$>> $2r_N$

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 <u>interaction of small size color singlet wave package of quarks and gluons.</u>

Constructive way to account for coherence of the high-energy dynamics is
Fluctuations of interaction cross section formalism.



Frozen configuration - same strength of interaction with different nucleons along the path *essentially semiclassical picture*!!!

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

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

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

variance

Pumplin &Miettinen

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

Baym et al from pD diffraction

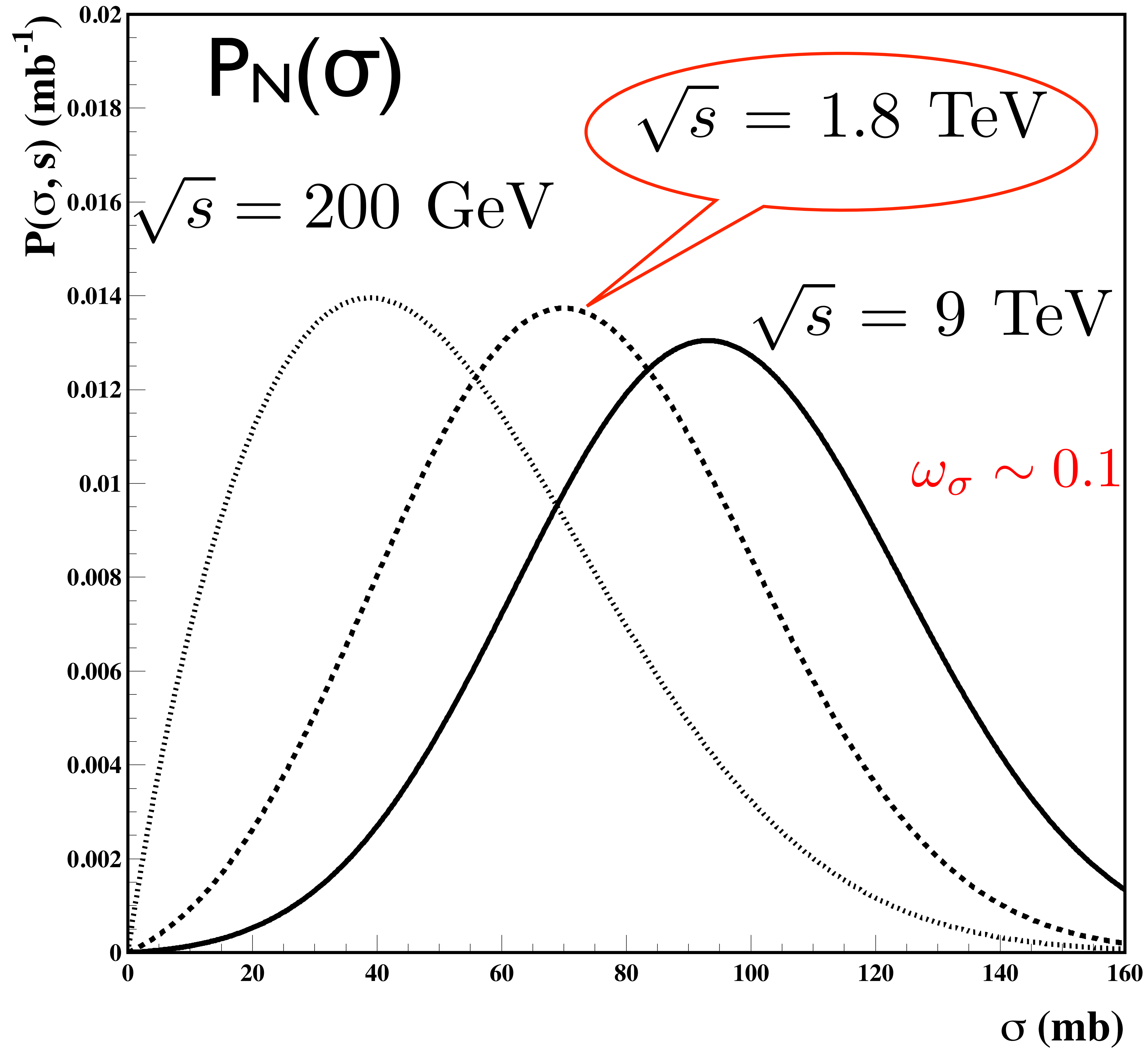
$$P(\sigma)_{|\sigma\to 0} \propto \sigma^{n_q - 2}$$

Baym et al 1993 - analog of QCD counting rules

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

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

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



Extrapolation of Guzey & MS before the LHC data

consistent with LHC data which are still not too accurate

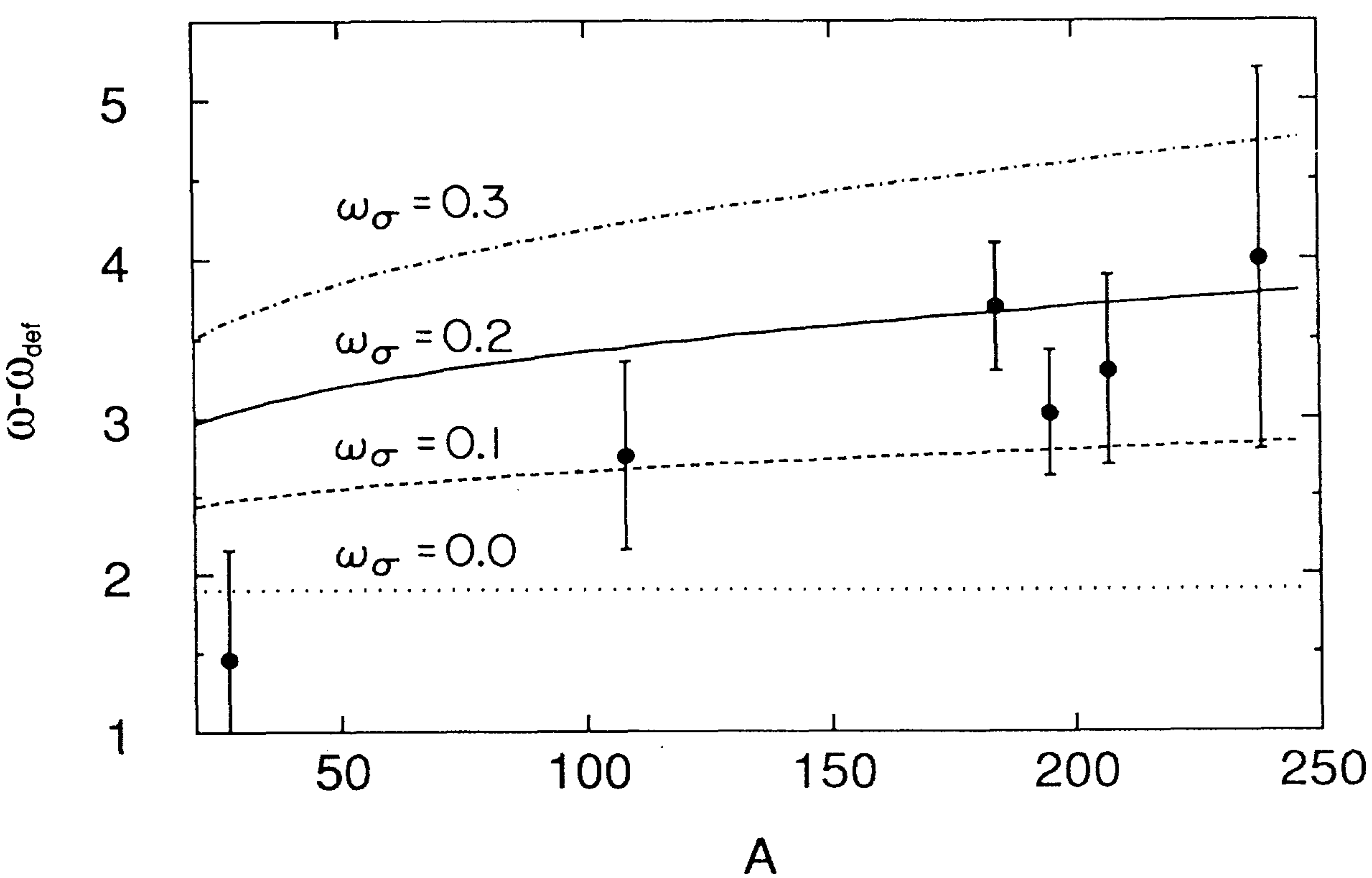
Qualitative expectation: CF increase fluctuations of a number of observables in pA and AB collisions.

First example: study of dispersion of E_T distribution in AB collisions as superposition of emission from binary collisions with variance ω_0:

$$\omega - \omega_{def} = \omega_0 + 2 - \alpha - \beta + (N_{pB} + N_{pA} - \alpha - \beta)\omega_\sigma$$

nucl. deform.

nucl. corr.: $\alpha \sim \beta \sim 0.3$



Dispersion of E_T distribution in central ^{32}S A collisions at SPS at E/A =200 GeV

H. Heiselberg, G. Baym, B. Blattel, L. L. Frankfurt, "' and M. Strikman PRL 1991

Large fluctuations in the number of wounded nucleons at fixed impact parameter

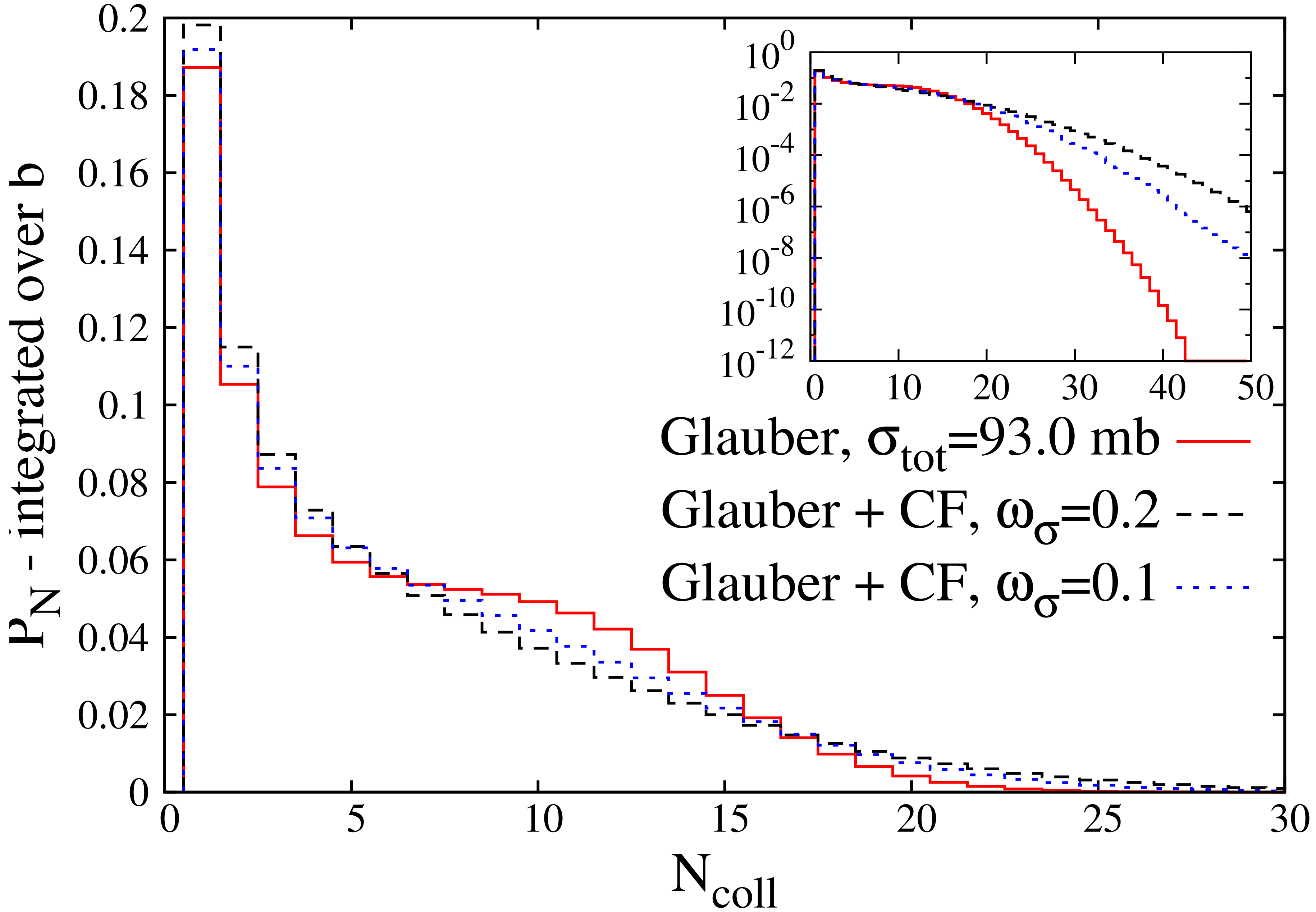
Simple illustration - two component model ≡ quasieikonal approximation:

$$\sigma_{1,2} = (1 \pm \sqrt{\omega_\sigma}) \cdot \sigma_{tot}$$

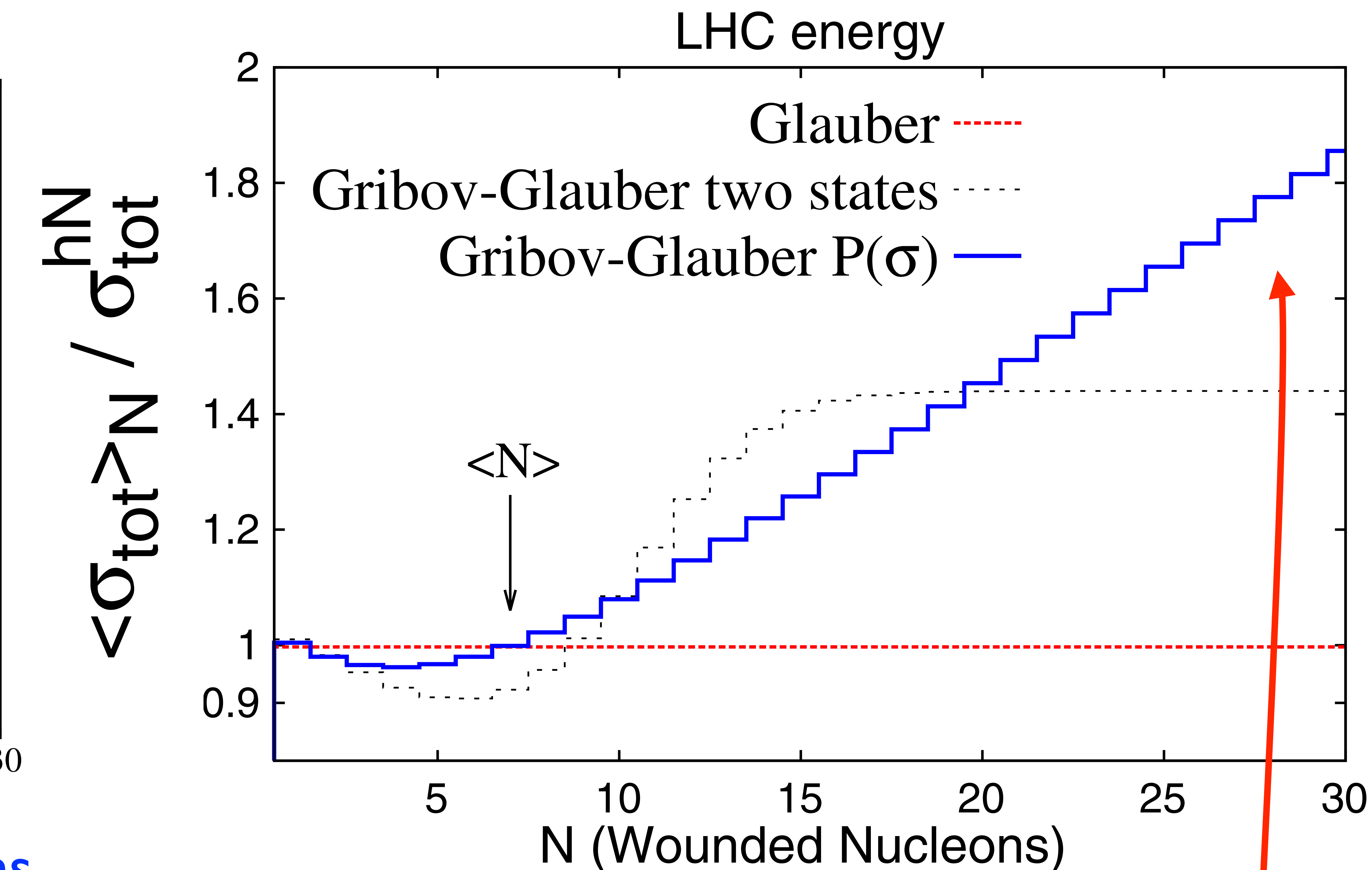
LHC $\sigma_1 = 70\, mb,\ \sigma_2 = 130\, mb$

number of wounded nucleons at small b differs by a factor of 2 !!!

Scattering at b=4 fm with probability ~ 1/2 generates the same number of wounded nucleons as an average collision at b=0. *Smearing of the centrality*



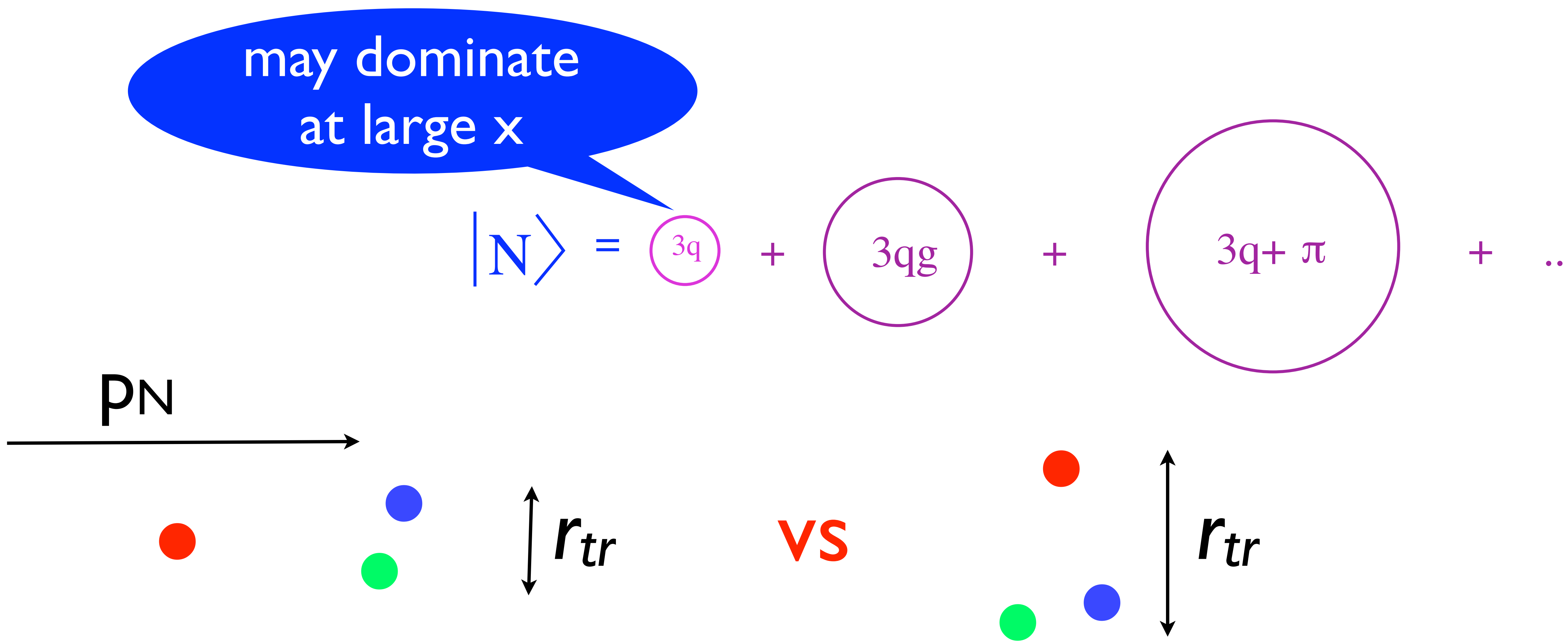
Probability of interaction with N_{coll} nucleons integrated over impact parameter b.

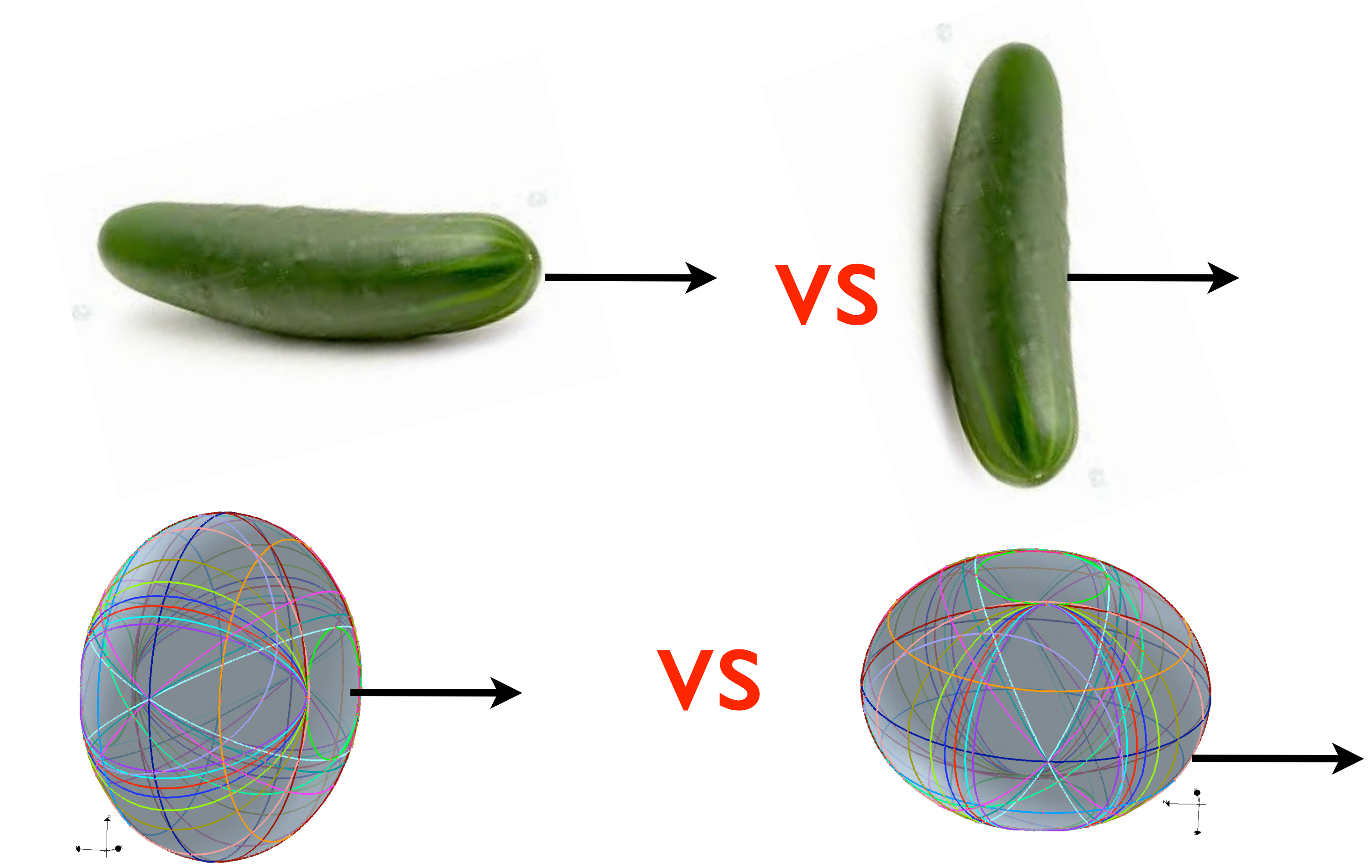


MC calculation of Alvioli and MS Phys.Lett. 13. Accurate account of profile functions on NN interactions and short-range nucleon correlations in nuclei

Fluctuations lead to broadening of the distribution over N_{coll} - number of active nucleons as compared to Glauber model - reported by ATLAS (Cole's talk) and ALICE. Large N_{coll} select configurations with larger σ

There exist a number of dynamical mechanisms of the fluctuations of the strength of interaction of a fast nucleon/pion: fluctuations of the size, number of valence constituents, orientations





Localization of color certainly plays a role - so we refer to the fluctuations generically as color fluctuations.

Studing effects of CFs in pA aims at

(i) Mapping 3-dimensional global structure of the nucleon

(ii) Better understanding of the dynamics of pA and AA collisions

Natural expectation is that there is a correlation between configuration of hard partons in the hadron and strength of interaction of the hadron:

π (ρ)-meson decay constants (f_π,$f_\rho$are determined configuration with essentially no gluon field and of small transverse size

Operational success of quark counting rules -- minimal Fock space configurations dominate at large x. Quarks in these configurations have to be close enough - otherwise generation of Weizsäcker -Williams gluons

IDEA

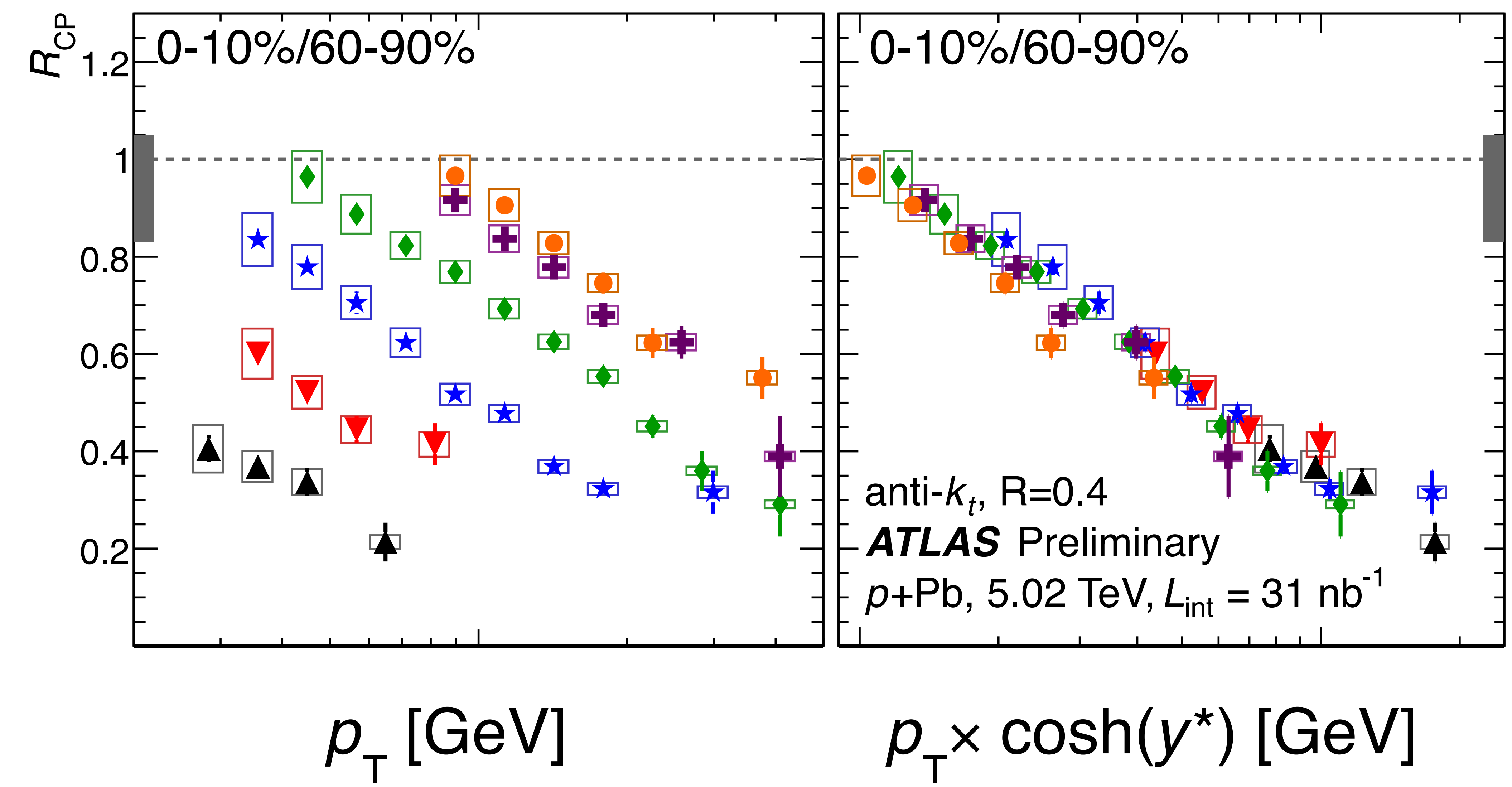
Use the hard trigger (dijet) to determine x of the parton in the proton (x_p) and low p_t hadron activity to measure overall strength of interaction σ_{eff} of configuration in the proton with given x FS83

Expectation: large x ($x \gtrsim 0.5$) correspond to smaller σ → drop of # of wounded nucleons, central multiplicity

Data - ATLAS & CMS on correlation of jet production and activity in forward rapidities - - details are in B.Cole & G. Roland talks tomorrow:

Key relevant observations:

- ✔ pQCD works fine for inclusive production of jets
- ✔ The jet rates for different centrality classes do not match geometric expectations. Discrepancy scales with x of the parton of the proton and maximal for large x_p



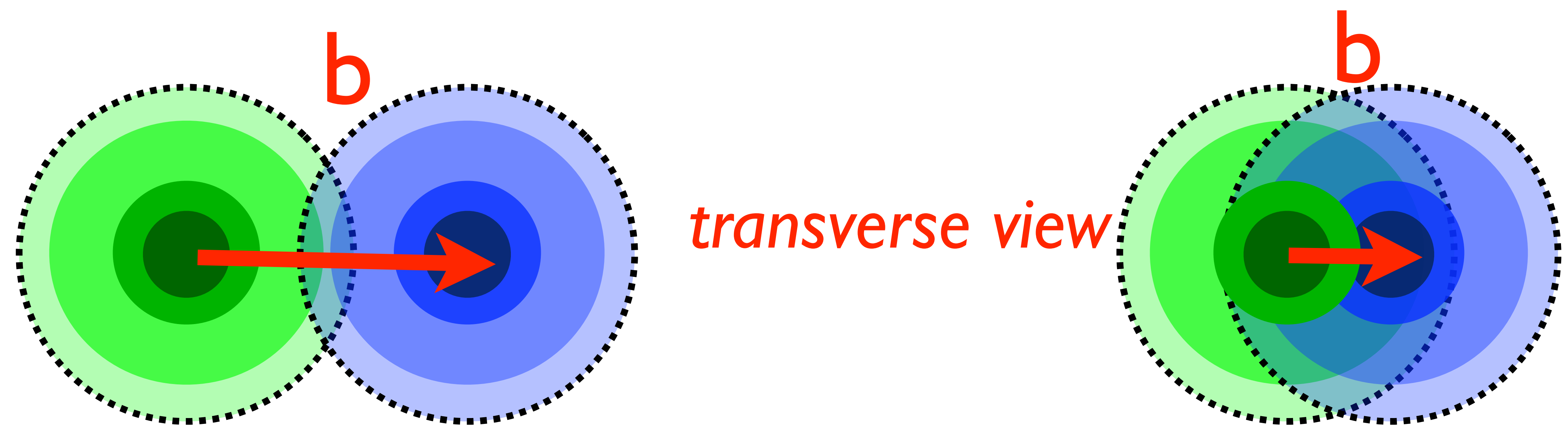
To calculate the expected CF effects accurately it is necessary to take into account grossly different geometry of minimum bias and hard collisions

Two scale transverse dynamics of pp interactions at LHC

LF, MS, Weiss 03

Different intensity of interactions for small and large impact parameters

Peripheral pp collisions

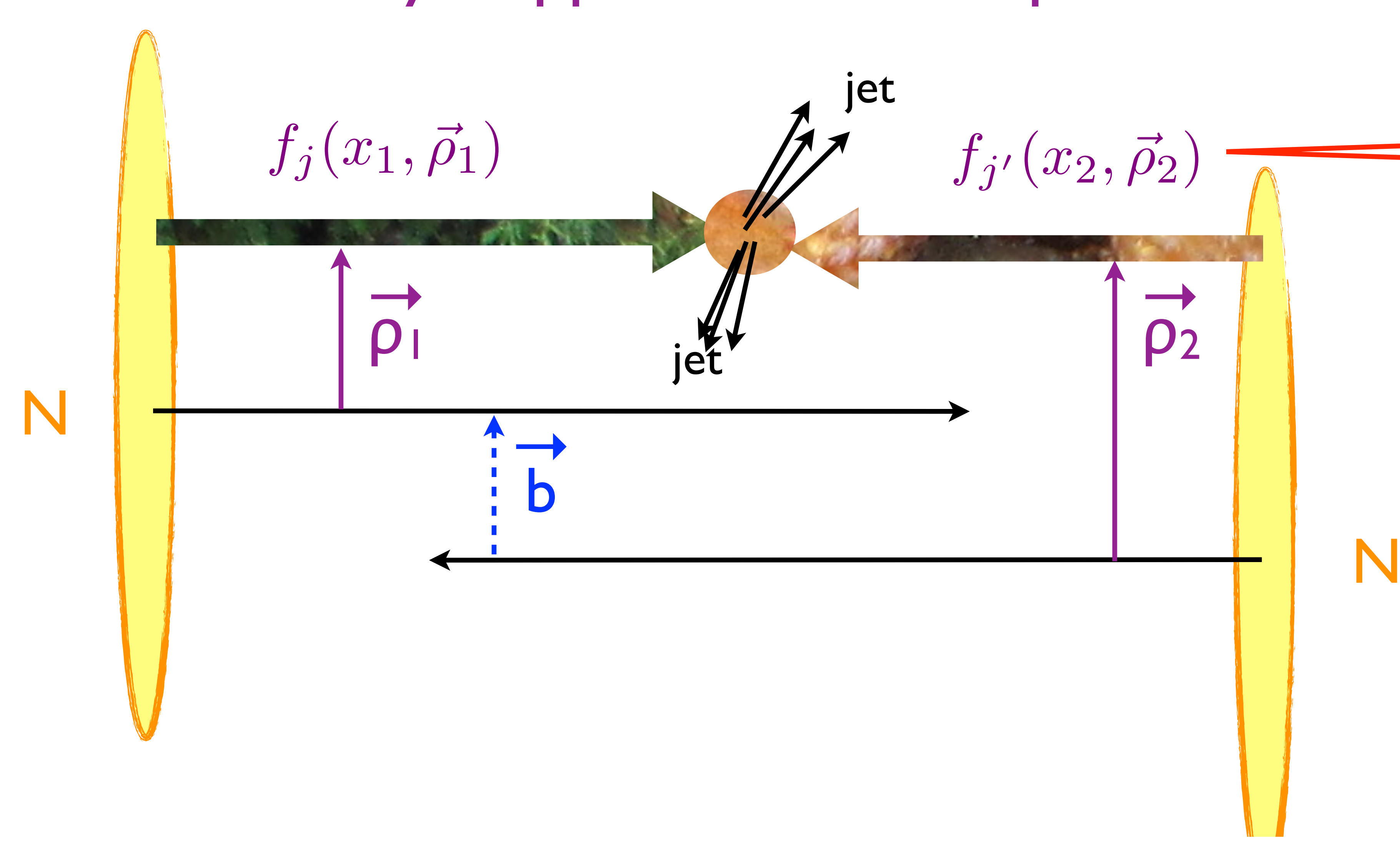


Central pp collisions

Small b ➡ large overlap of $x>10^{-3}$ partons ➡ Large probability of multiparton, soft/hard interactions

Using realistic transverse parton distributions is critical for genuine understanding of pp and pA inelastic interactions

Geometry of pp collision with production of dijet in the transverse plane

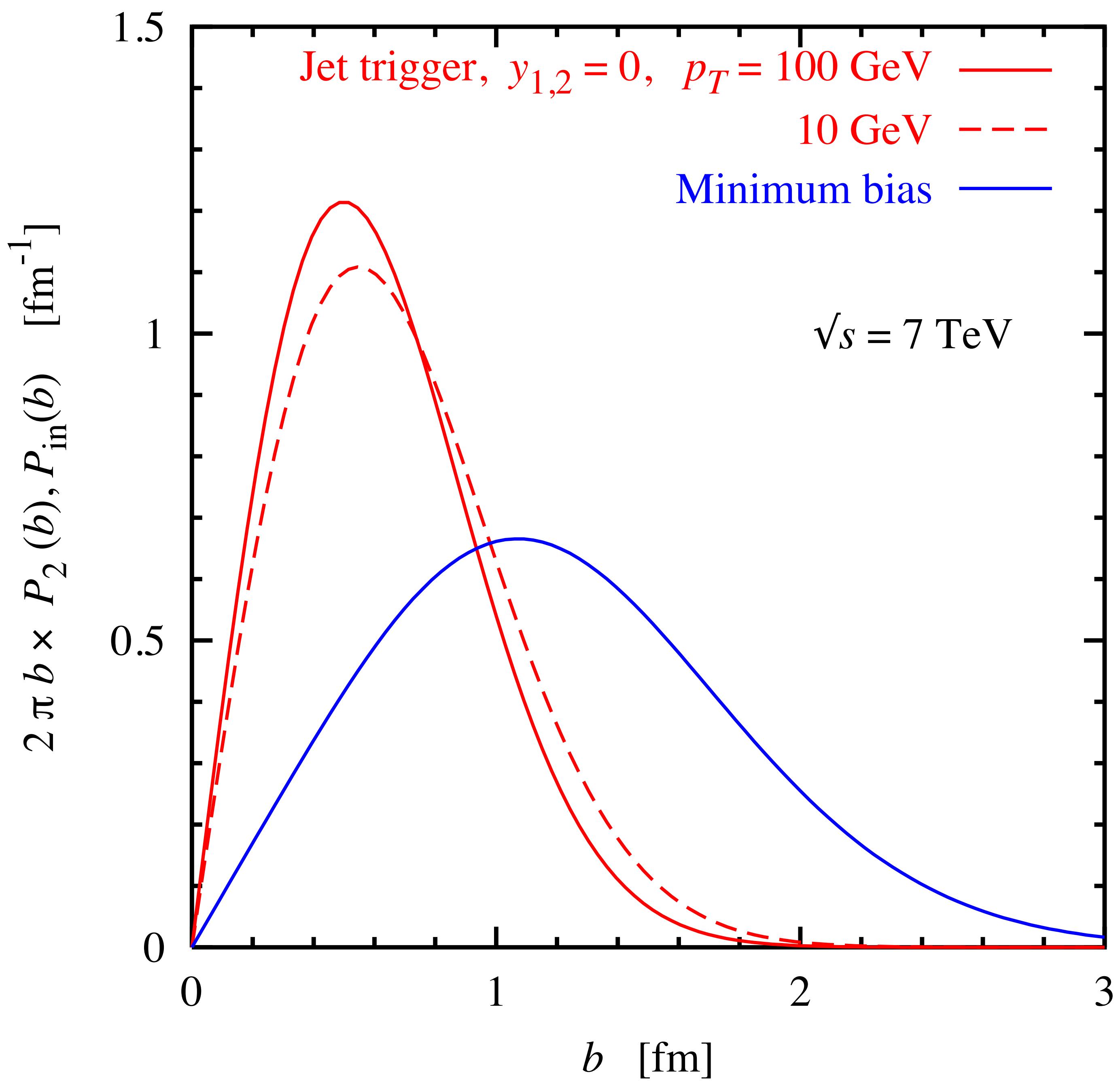


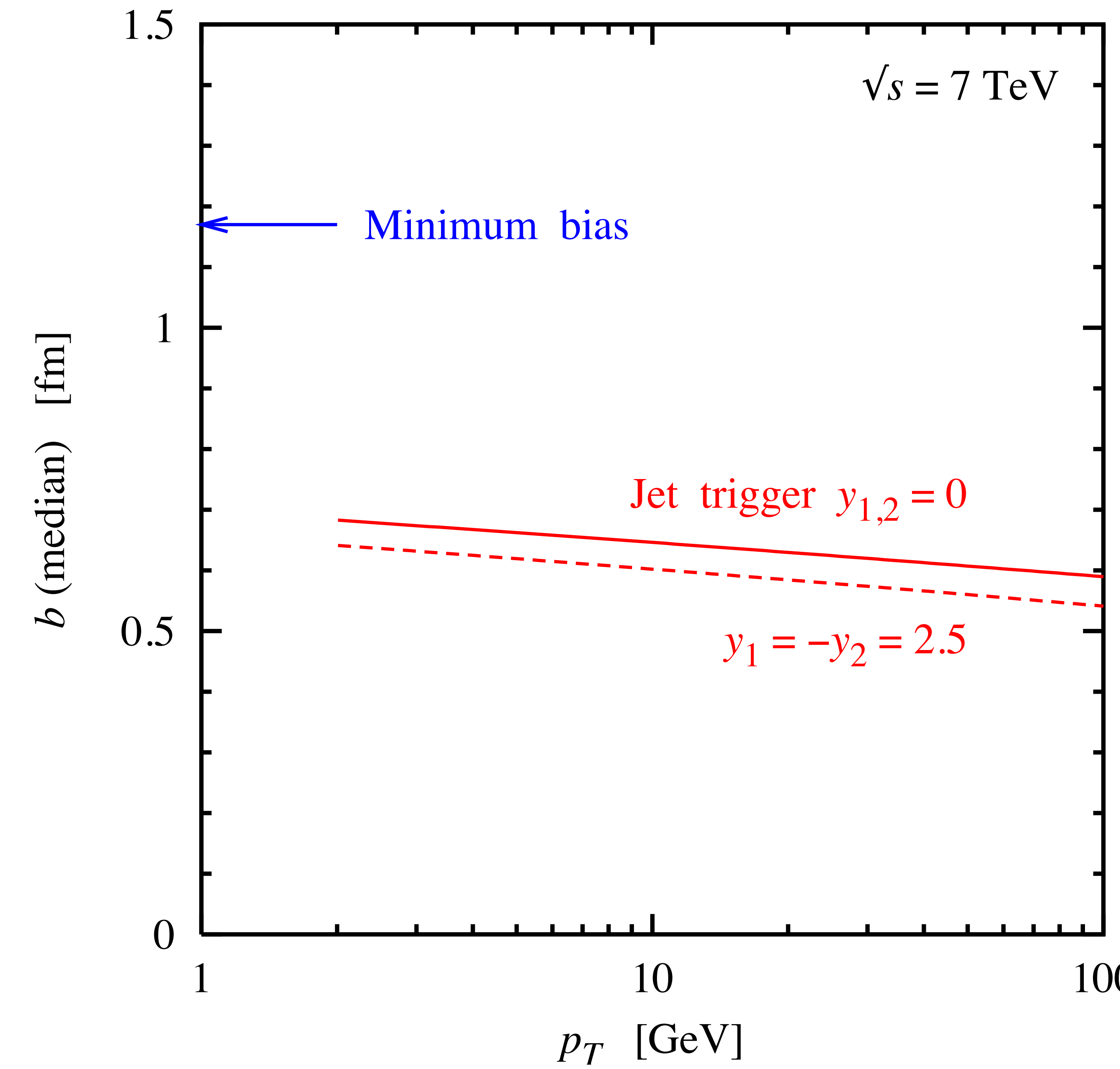
Diagonal Generalized Parton distribution -

For hard collision

$$\vec{\rho}_1 + \vec{b} - \vec{\rho}_2 \propto 1/p_{tjet} \sim 0$$

Comparison of b -distributions for minimum bias and dijet collisions





$$P_2(b) = \frac{m_g^2}{12\pi}\left(\frac{m_g b}{2}\right)^3 K_3(m_g b)$$

Weak dependence of probability of hard interaction occurs at given b on rapidity and p_T of the dijet $m_g^2(x \sim 10^{-2}) \approx 1\text{GeV}^2$

Area in which most of hard interactions occurs is a factor of four smaller than that of minimum bias interactions

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,' arXiv:1402.2868

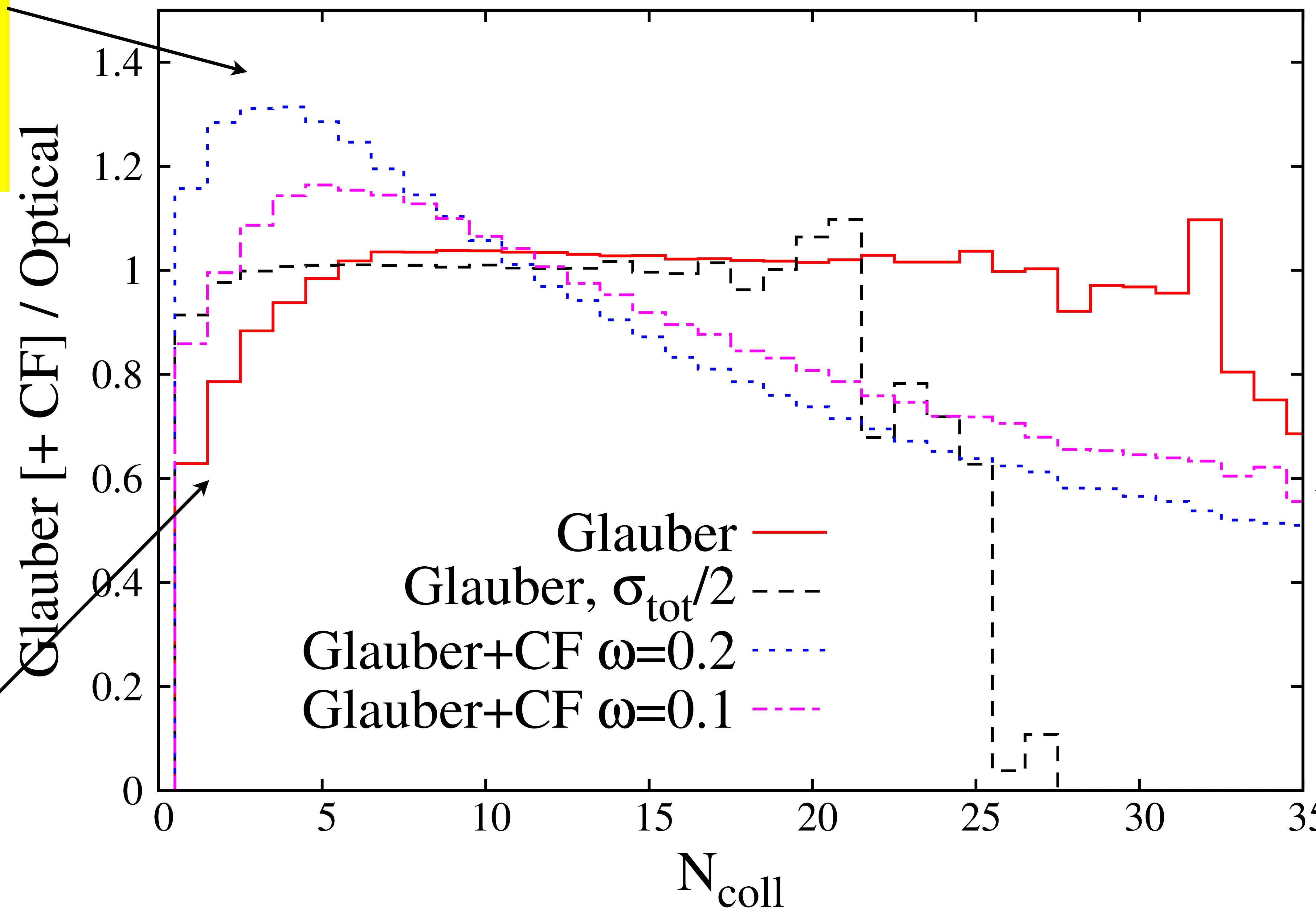
Consider multiplicity of hard events $Mult_{pA}(HT) = \sigma_{pA}(HT + X)/\sigma_{pA}(in)$ as a function of N_{coll}

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:

$$R_{HT}(N_{coll}) \equiv \frac{Mult_{pA}(HT)}{Mult_{pN}(HT)N_{coll}} = 1$$

Accuracy? Significant corrections due to presence of two transverse scale.

increase due to more central interactions of configurations with $\sigma < \sigma_{tot}$



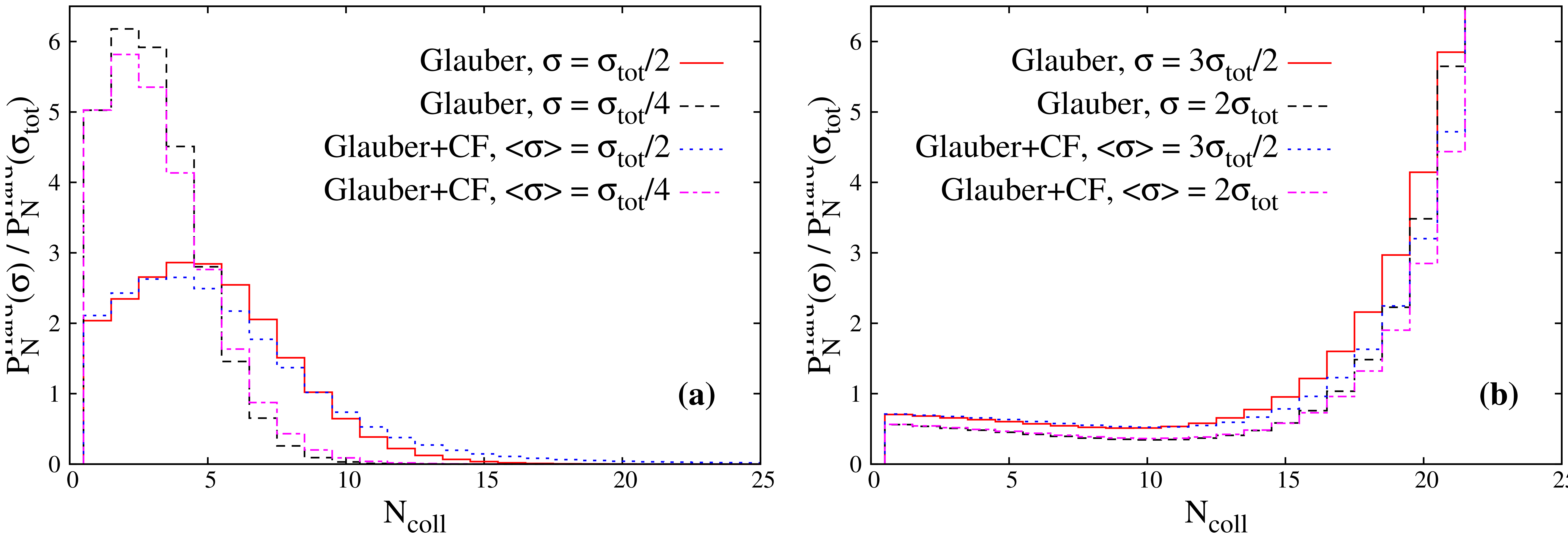
drop due increased role of configurations with $\sigma > \sigma_{tot}$

the cylinder in which interaction occur is larger but local density does not go up as fast in Glauber

Deviation of $R_{HT}(N_{coll})$ from 1

drop due to more localized hard interactions

We conclude from our numerical studies that the main effect is the change of σ_{eff} ; variance place small role if it is modest. Not the case for 1% centrality.



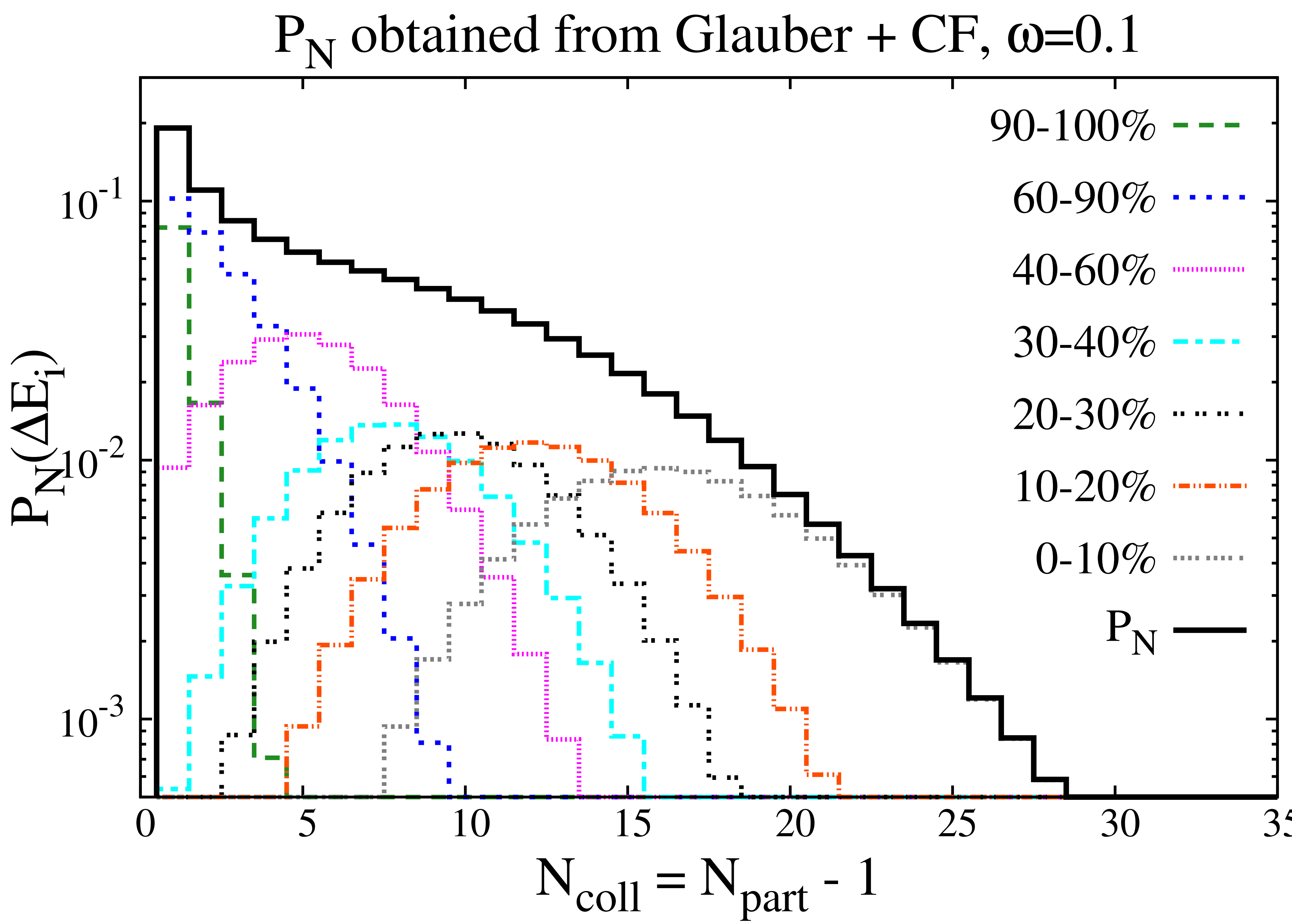
Ratio of the probabilities P_N of having N_{coll} wounded nucleons for scattering of the proton in configuration different values of $\sigma(x)$ and P_N for $\sigma = \sigma_{tot}$ with CF (ω_σ=0.1) and without CF (marked as Glauber)

High sensitivity of the distribution to change of $\sigma(x)$.

Large N_{coll} enriched by large σ and vice versa

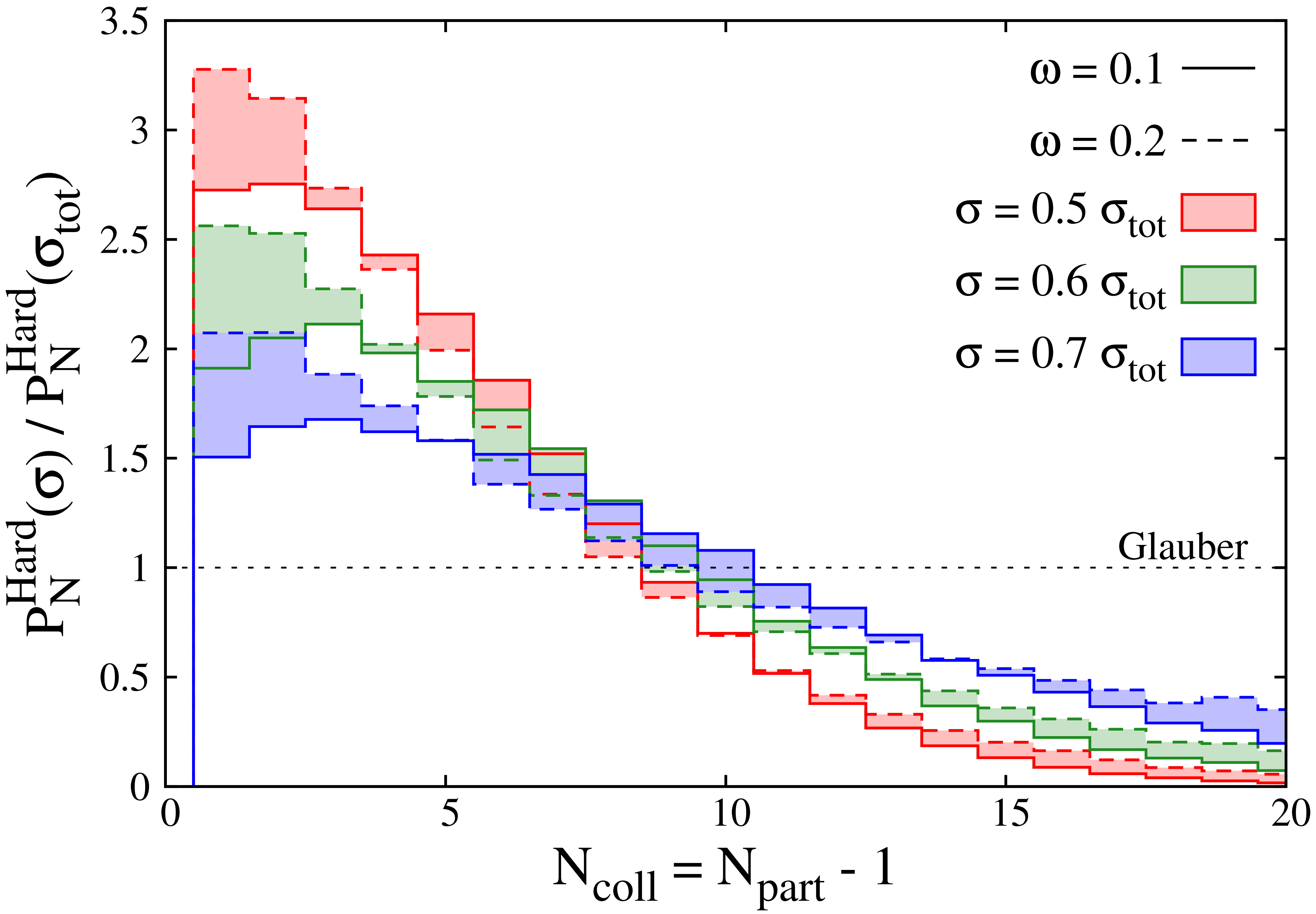
In order to compare with the data we need to use a model for the distribution in E_T^{Pb} as a function of N_{coll}. We use the analysis of ATLAS (B.Cole's talk).

Alvioli, Cole, LF, MS, arXiv:1409.7381



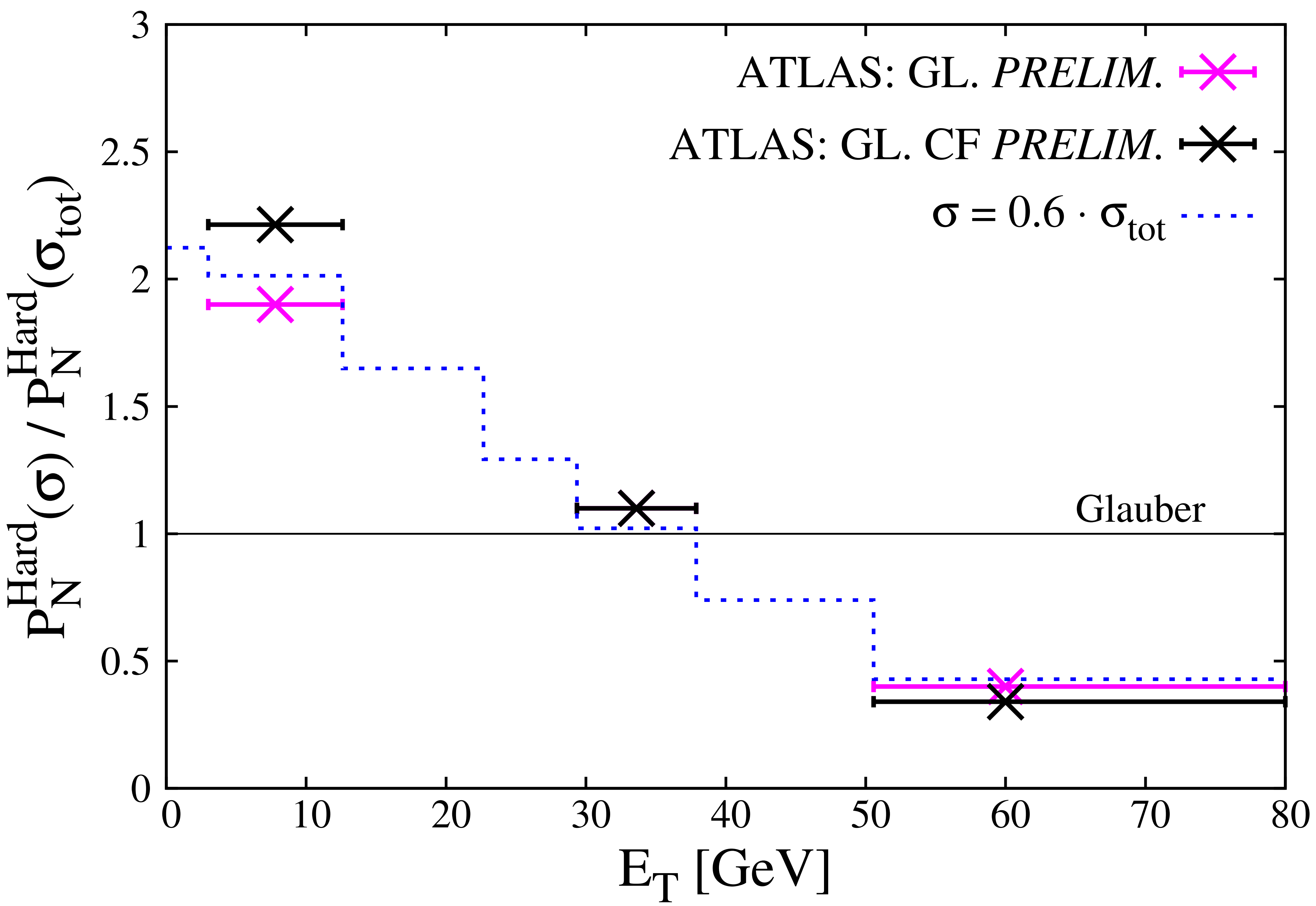
Probabilities, P_N,of interaction with N=Ncoll nucleons and contributions to P_N of different ΔE_T intervals.

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



So we use $\omega_\sigma(x=0.5)=0.1$ for following comparison

$\sigma(x=0.6) \sim \sigma_{tot}/2$ gives a reasonable description of the data



—✕— corrects ATLAS data for difference of N_{coll} in Glauber and Color Fluctuation models

We can estimate $\sigma(x=0.6)/\sigma_{tot}$[fixed target]=1/4

from probability conservation relation: $$\int_0^{\sigma(s_1)} P(\sigma, s_1) d\sigma = \int_0^{\sigma(s_2)} P(\sigma, s_2) d\sigma$$

➡ $x \geq 0.5$ configurations have small transverse size ($\sim 1/2\ r_N$)

➡ Implication for the LHC - different underling event structure than at smaller x

Outlook

- ✱ Observing effects of Large Hadronic Configurations - dijets at small x_p
- ✱ Study of the suppression / enhancement effects as a function of both x_p and x_A

Additional to CF effects which should be included in modeling of pA with jets:

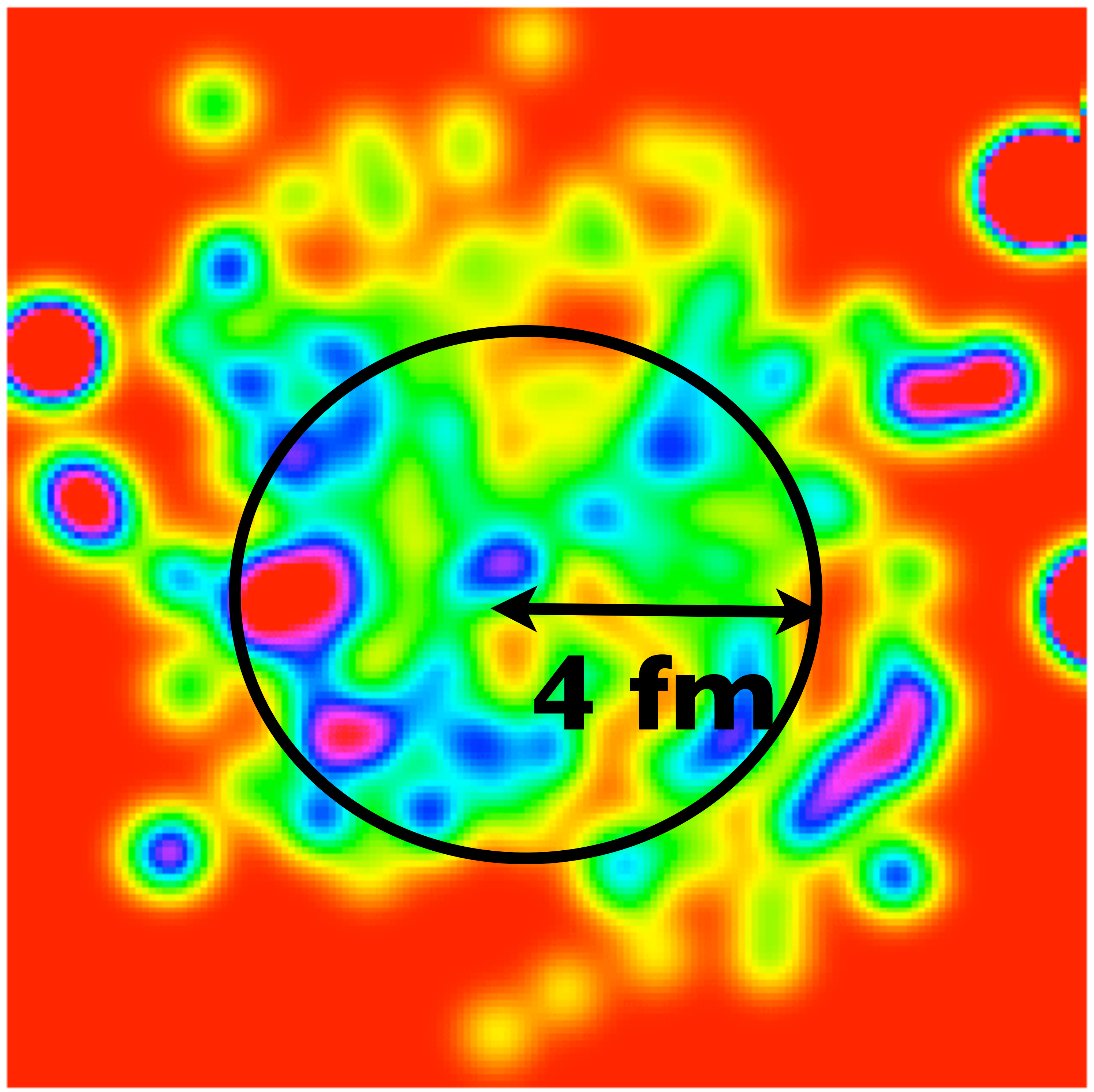
- Fluctuations of small x gluon strength in nucleons: variance $\omega_g(x=10^{-3}) \sim 0.15$
- Strong dependence of the multiplicity on the impact parameter of the pp collision

  (Evidence from pp - supplementary slides)

- Influence of CF on impact parameters of the NN interactions in pA.
- Fluctuations of the gluon fields in nuclei - Swiss cheese

Slides for discussion & supplementary slides

If two (three) nucleons are at a small relative impact parameter (b < 0.6 fm), the gluon shadowing strongly reduces the overall transverse. gluon density. However the thickness of the realistic nuclei is pretty low. So average number of overlapping nucleons is rather small (2.5 for b ~0) and hence fluctuations of the gluon transverse density are large



yellow < 1
1 green <2
2 <cyan < 3
3 <blue <4
4< magenta < 5
5< red

Fluctuations of transverse density of gluons in Pb on event by event basis (Alvioli and MS 09) for x outside the shadowing region

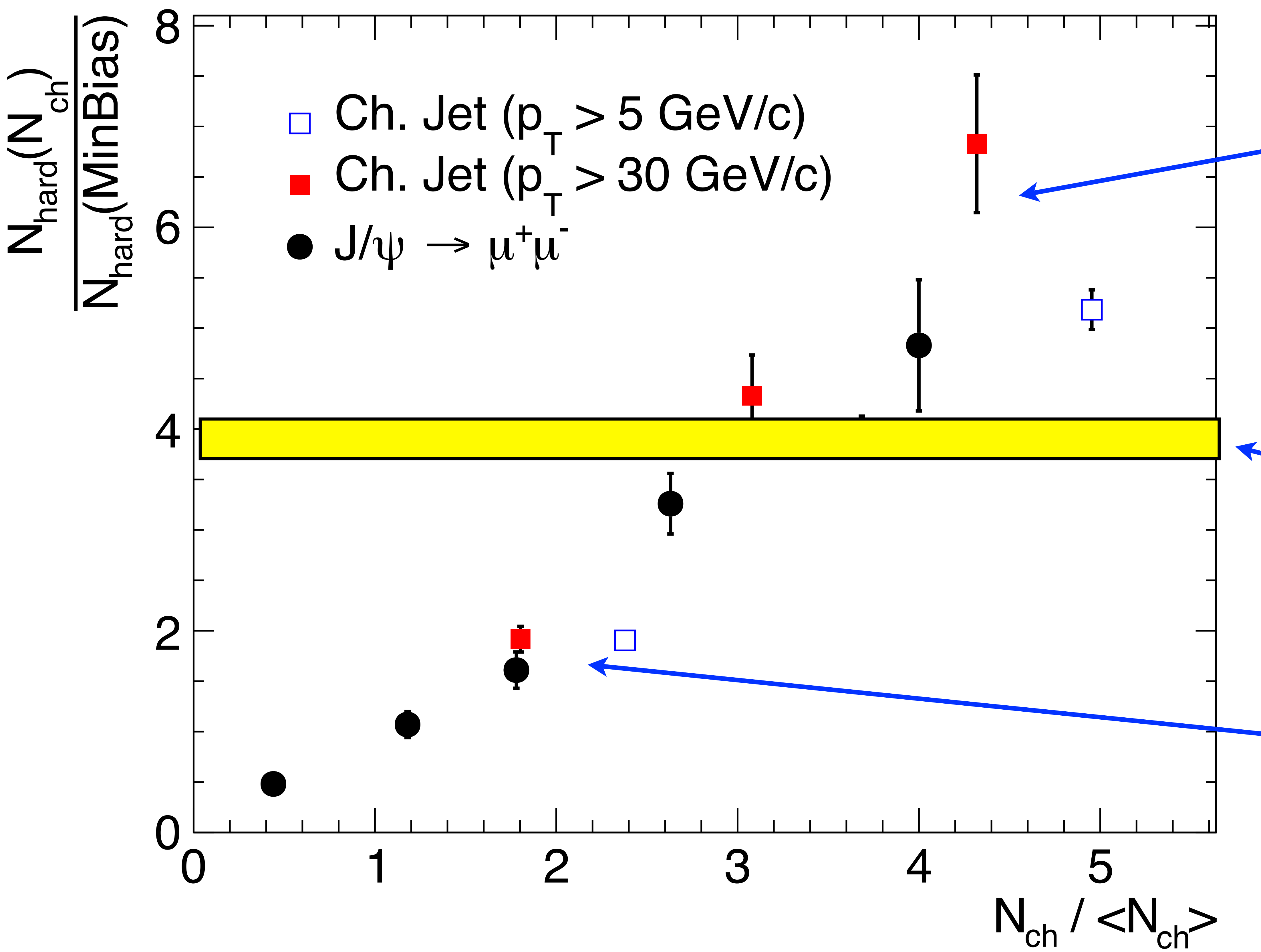
Heavy nuclei are not large enough to suppress fluctuations - A=200 nucleus for gluons with x > 10^{-2} is like a *thin slice of Swiss cheese*.

Far from the A $\rightarrow \infty$ limit.

Leading twist shadowing observed at LHC does suppress some of fluctuations but new types of fluctuations

Universal relationship of soft and hard multiplicity

(Azarkin, Dremin , MS, 14)



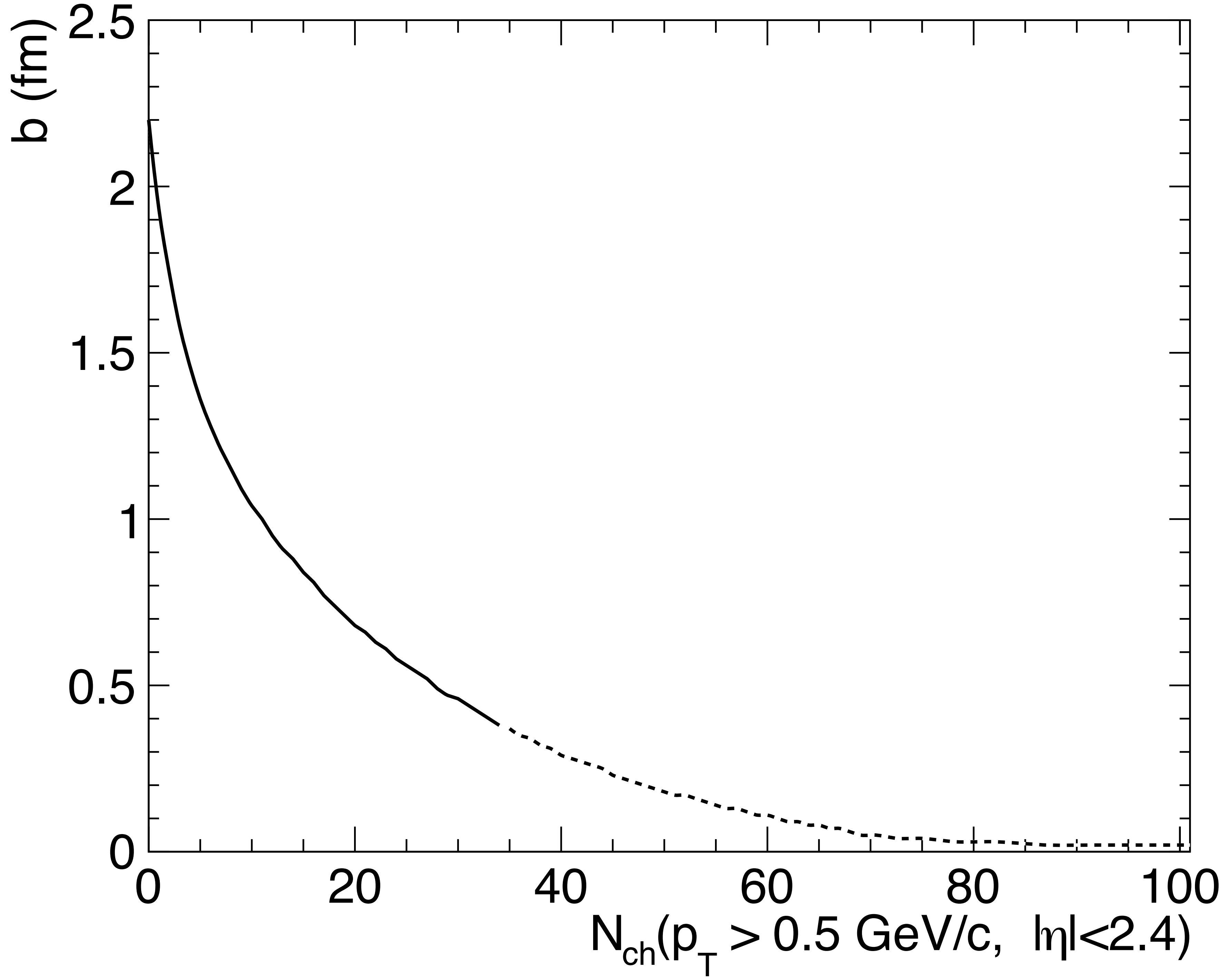
Superhigh multiplicities require special rare configurations in nucleons

max value from geometry

$$R = P_2(0)\sigma_{in}(pp) = \frac{m_g^2}{12\pi}\sigma_{in}(pp)$$

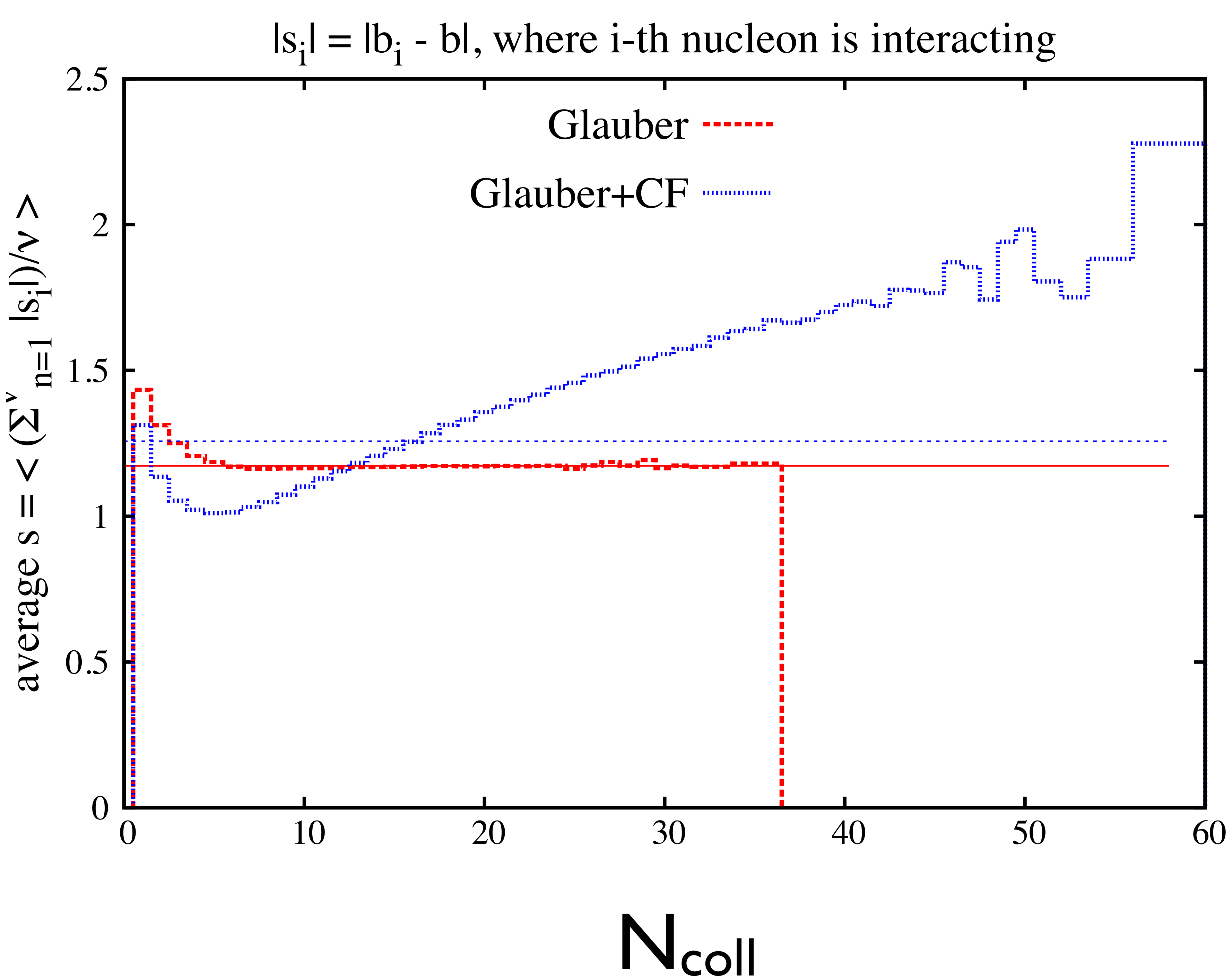
reproduced by $P_2(b)$

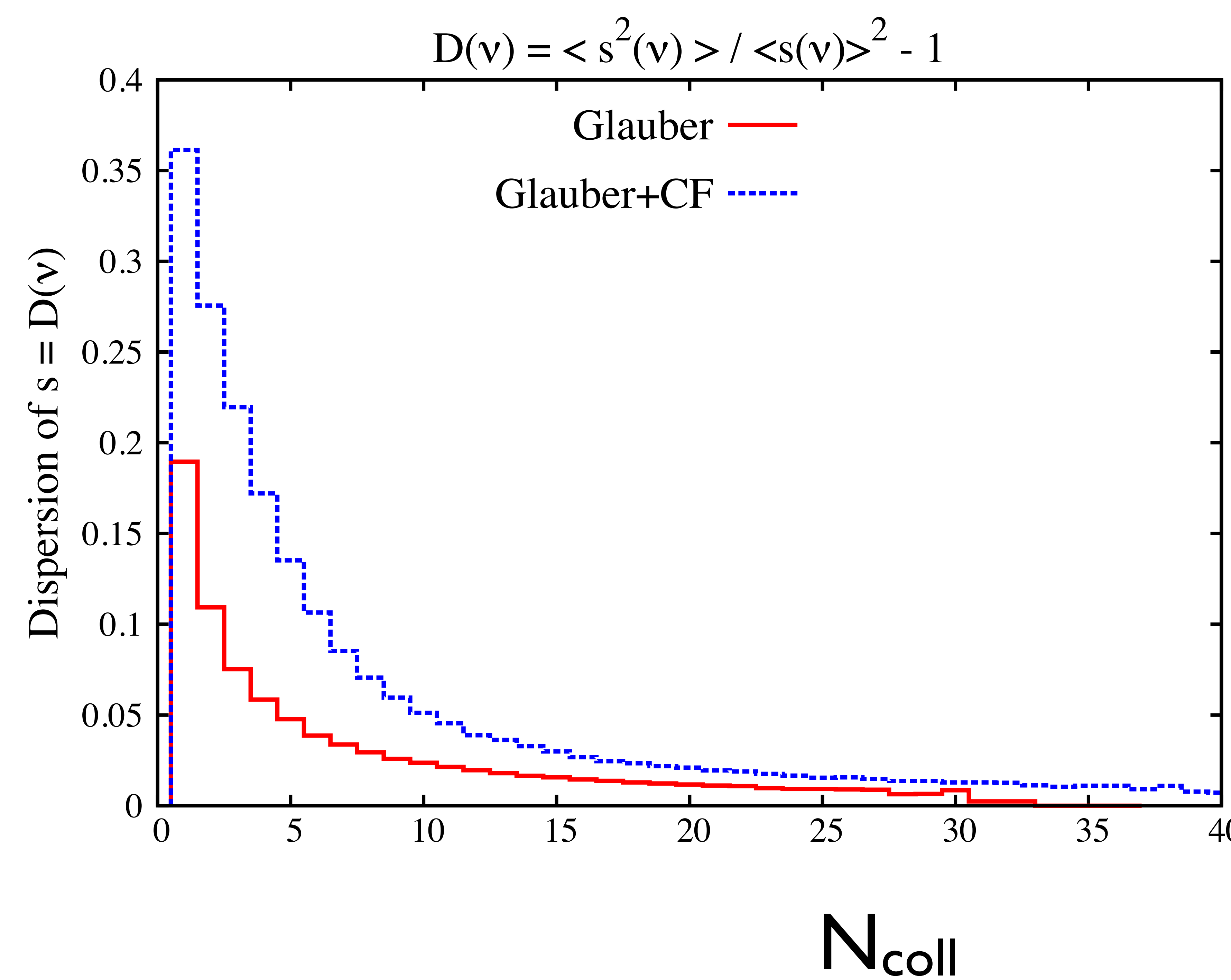
Universality of scaling of for hard processes scales with multiplicity: simple trigger - dijets(CMS) & direct J/ψ , D and B-mesons (Alice)



Correspondence between impact parameter and N_{ch}. N_{ch} is defined here as a number of charged particles with $|\eta| < 2.4$ and $p_T > 0.5$ GeV/c. Since events with $N_{ch} > 35$ are effectively central, the correspondence is not valid there.

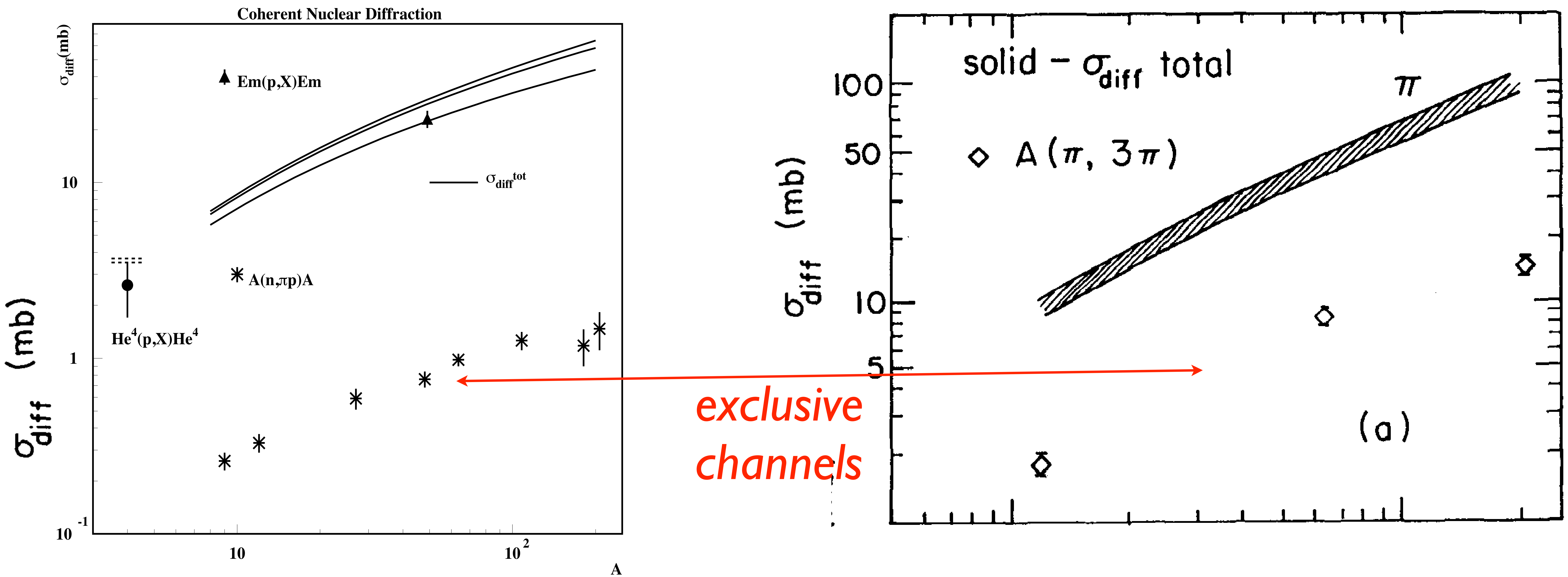
- $b(N_{ch}/\langle N_{ch}\rangle \sim 2) \sim 0.7$ fm
- $b(N_{ch}/\langle N_{ch}\rangle \sim 3) \sim 0.5$ fm
- For $N_{ch}/\langle N_{ch}\rangle \gtrsim 4$ gluon fluctuations are important: jet multiplicity otherwise too high & probability of $N_{ch}/\langle N_{ch}\rangle > 4$ events is much smaller than given by $P_2(b)$.





Average impact parameter, s, for pN interactions as a function of number of wounded nucleons and its dispersion. Average s traces average σ.

Test: Calculate inelastic diffraction off nuclei - no free parameters



The inelastic small t coherent diffraction off nuclei provides one of the most stringent tests of the presence of the fluctuations of the strength of the interaction in NN interactions. The answer is expressed through $P(\sigma)$ - probability distribution for interaction with the strength σ. (Miller &FS 93)

$$\sigma^{hA}_{diff} = \int d^2b \left(\int d\sigma P_h(\sigma) |\langle h|F^2(\sigma,b)|h\rangle| - \left(\int d\sigma P(\sigma) |\langle h|F(\sigma,b)|h\rangle| \right)^2 \right) .$$

Here $F(\sigma,b) = 1 - e^{-\sigma T(b)/2}$, $T(b) = \int_{-\infty}^{\infty} \rho_A(b,z)dz$, and $\rho_A(b,z)$ is the nuclear density.

Reminder -in the limit of small inelastic diffraction and neglecting radius of NN interaction as compared to internucleon distance, Gribov - Glauber model leads to

$$\sigma_{\rm in}^{\rm hA} = \int d\vec{b}\ \left[1-(1-x)^A\right] = \sum_{n=1}^{A} \frac{(-1)^{n+1} A!}{(A-n)!n!} \int d\vec{b}\, x^n$$

where $x = \sigma_{\rm in}^{\rm hN} T(\mathbf{b})/A$ $\qquad \int d\vec{b} T(b) = A$

Series can be rewritten as sum of positive terms corresponding to cross sections σ_n of exactly one, two ... inelastic interactions

Bertocchi, Treleani, 1976

$$\sigma_{\rm in}^{\rm hA} = \sum_{n=1}^{A} \sigma_n, \quad \sigma_n = \frac{A!}{(A-n)!\, n!} \int d\vec{b}\, x^n (1-x)^{A-n}$$

$$\langle N\rangle = \sum_{n=1}^{A} n\sigma_n \Big/ \sum_{n=1}^{A}\sigma_n = \frac{\sigma_{\rm in}^{\rm hN}}{\sigma_{\rm in}^{\rm hA}}\int {\rm d}^2 b \sum_{n=1}^{A}\frac{A!}{(A-n)!(n-1)!}x^n(1-x)^{A-n}$$

$$= \frac{\sigma_{\rm in}^{\rm hN}}{\sigma_{\rm in}^{\rm hA}}\int {\rm d}^2 b\, A\, T(\mathbf{b}) = \frac{A\sigma_{\rm in}^{\rm hN}}{\sigma_{\rm in}^{\rm hA}},$$

Simple geometric interpretation

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 $P_n = \sigma_n/\sigma_{in}^{hA}$