Color fluctuation phenomena in high energy hadron & photon-A collisions

Mark Strikman, PSU

Thanks to M.Alvioli, B.Cole, V.Guzey, L.Frankfurt, D.Perepelitsa, M.Zhalov

MPI15, Trieste

Outline

- Coherence in high energy scattering and color fluctuations in hadrons

- Exploring global 3D structure on nucleon in pA
  Evidence for x -dependent color fluctuations

- Exploring photon 3 D at LHC(Ultra Peripheral collisons), ...

Fluctuations of overall strength of high energy h(γ)N 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 $m_{int}^2 - m_h^2 \sim 1\mathrm{GeV}^2$ l_{coh} ~ 10^7 fm>> $2R_A$>> $2r_N$

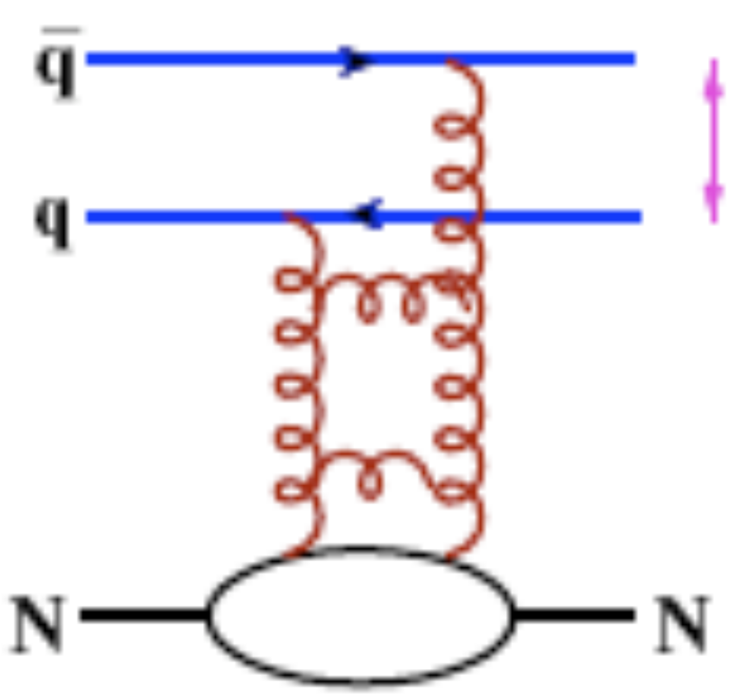
coherence up to $m_{int}^2 \sim 10^6 \mathrm{GeV}^2$

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 quark - antiquark dipole:



$$\sigma(d,x) = \frac{\pi^2}{3}\alpha_s(Q_{eff}^2)d^2\left[xG_N(x,Q_{eff}^2) + \frac{2}{3}xS_N(x,Q_{eff}^2)\right]$$

$$Q_{eff}^2 = \lambda/d^2, \lambda = 4 \div 10$$

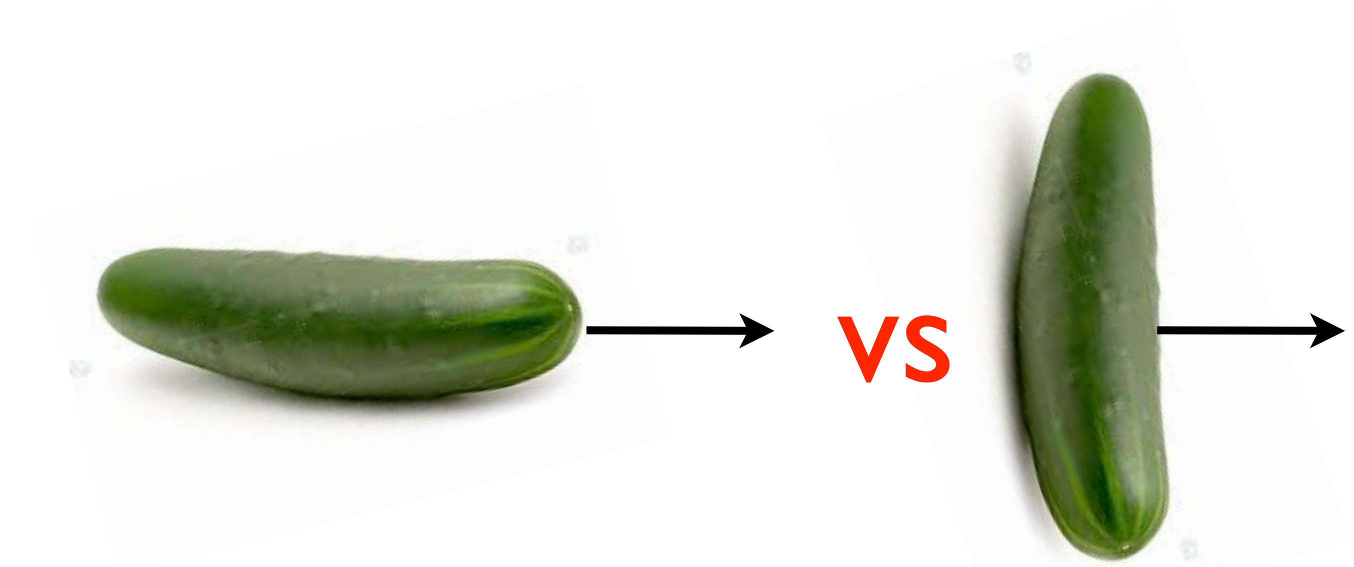
Baym, Blättel, Frankfurt, MS, 93;
Frankfurt,Miller, MS 93

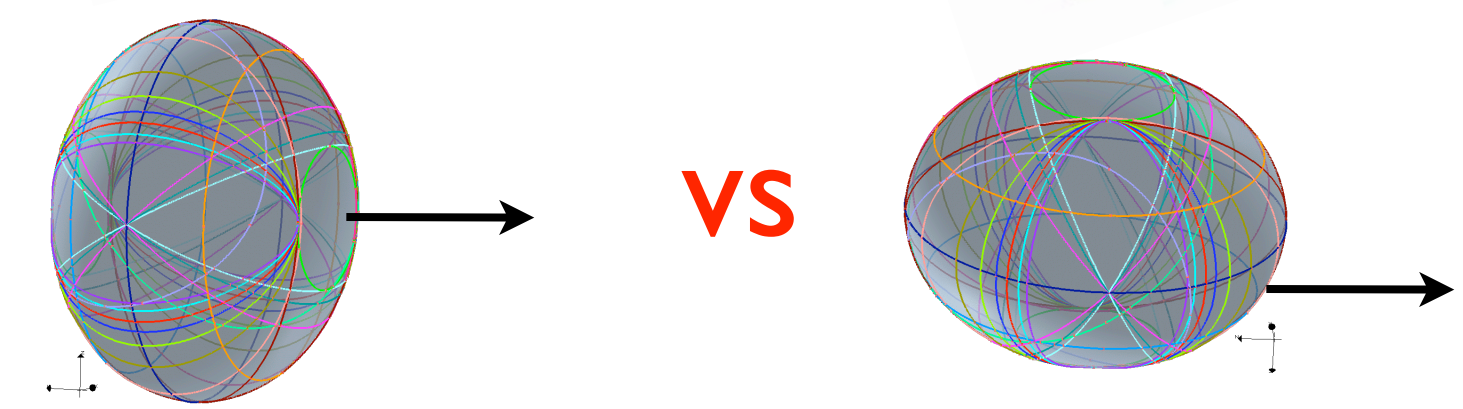
compare: $\sigma(d,x) = cd^2$ in QED or two gluon exchange model of Low - Nussinov (1975)

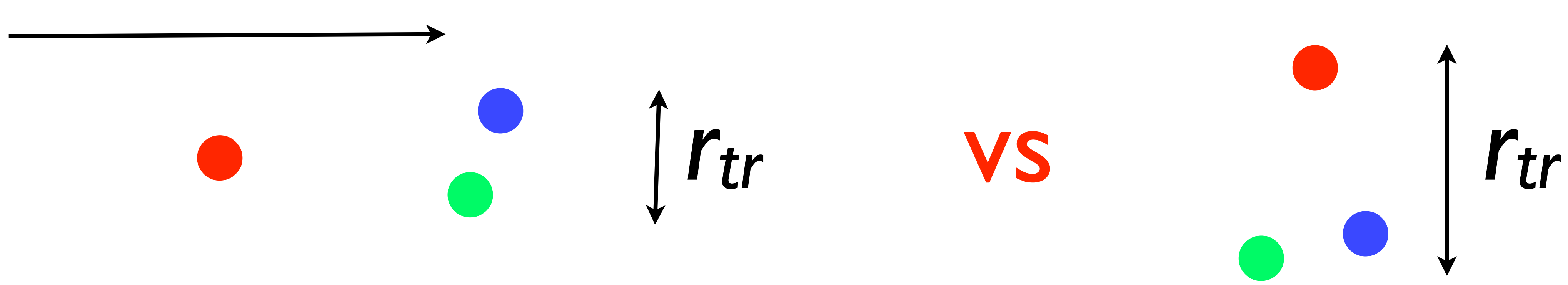
There exist a number of dynamical mechanisms of the fluctuations of the strength of interaction of *a fast nucleon/pion/photon*: fluctuations of the size, number of valence constituents, orientations

may dominate at large x

$|N\rangle = (3q) + (3qg) + (3q + \pi) + \ldots$







p_γ → "ρ,ω,φ" + aligned jet (small k_t) $q\bar{q}$ + small size (large k_t)$q\bar{q}$

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

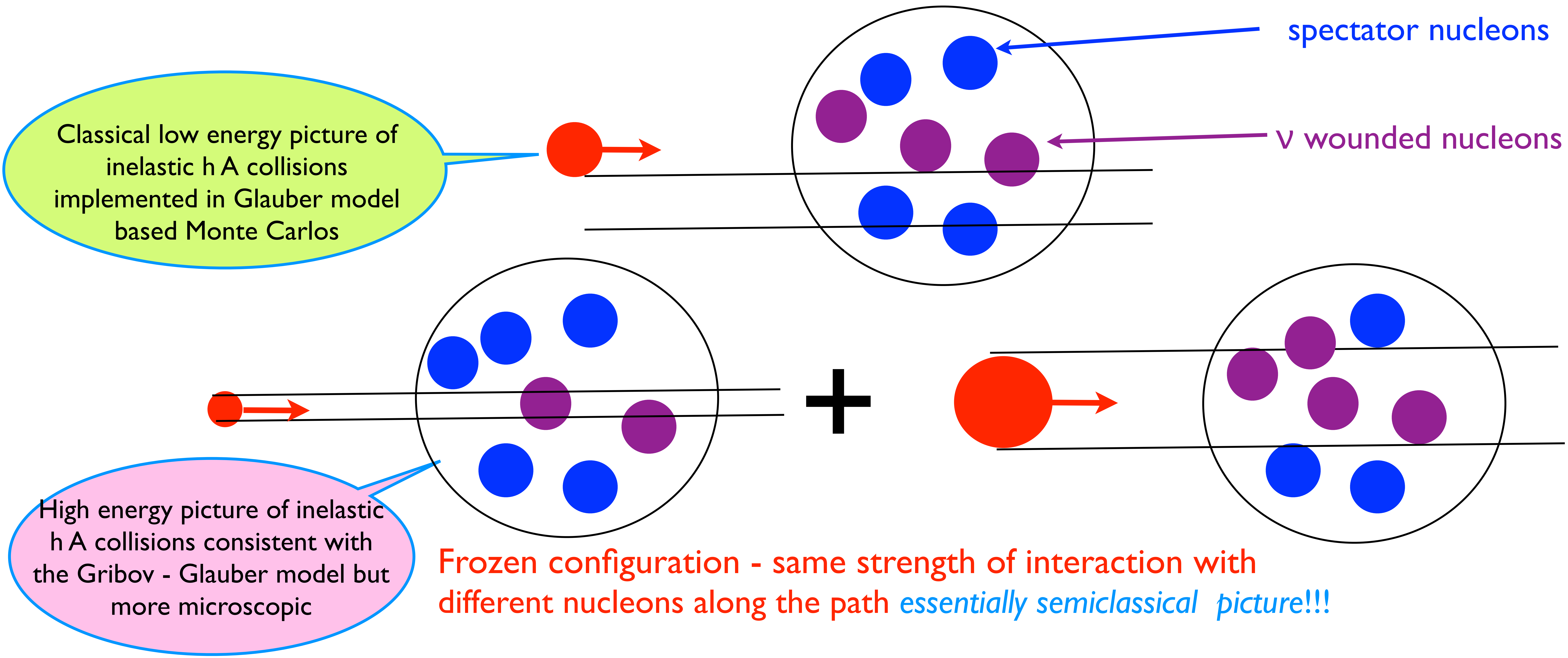
Studying effects of CFs in pA (and soon in γA at the LHC) aims at

(i) Mapping 3-dimensional global quark-gluon structure of the nucleon and photon

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

Constructive way to account for coherence of the high-energy dynamics is

Fluctuations of interaction cross section formalism which we developed in 90's



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

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

Formally introduced via Good Walker eigenstates for total cross sections.

Note that Good Walker assumption that there exist scattering eigenstates for the scattering amplitudes at t away from t=0 is wrong in QCD.

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

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

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
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*

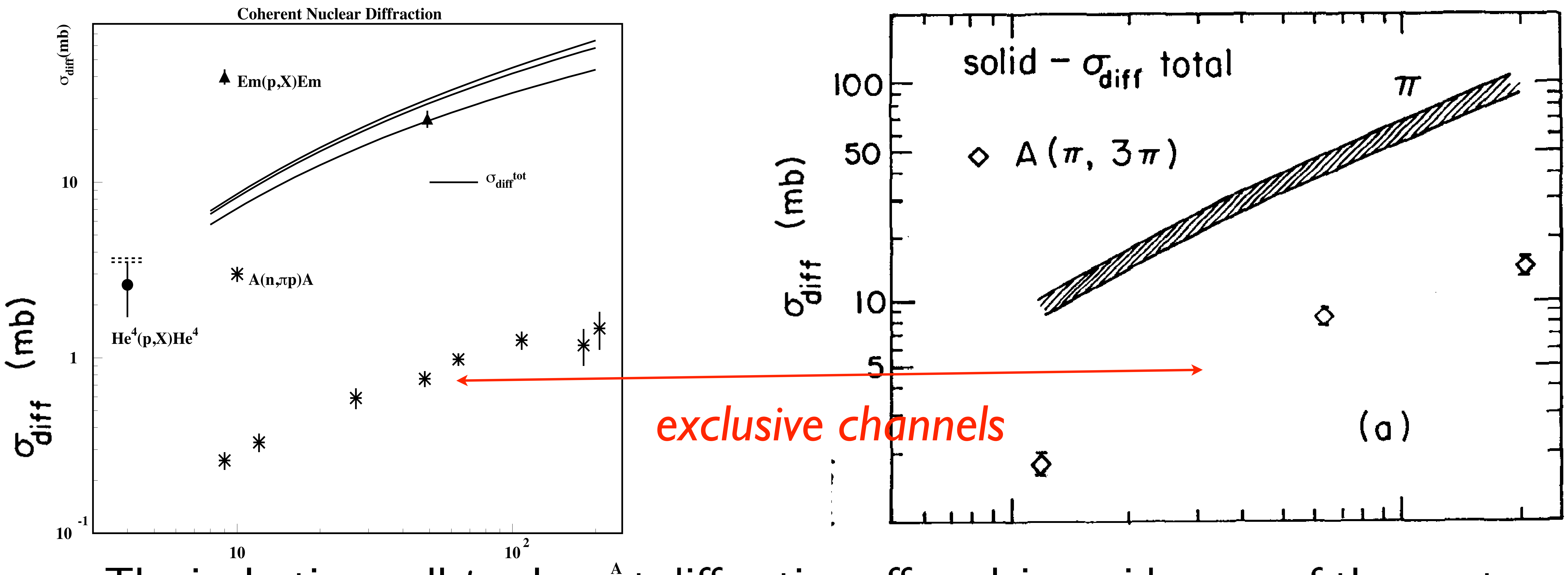
$P_\pi(\sigma \to 0)$ expressed through f_π agrees with phenomenological determination

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

$P_\gamma(\sigma)_{|\sigma\to 0} \propto \sigma^{-1}$ γ =mix of small $q\bar{q}$ and mesonic size configurations

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

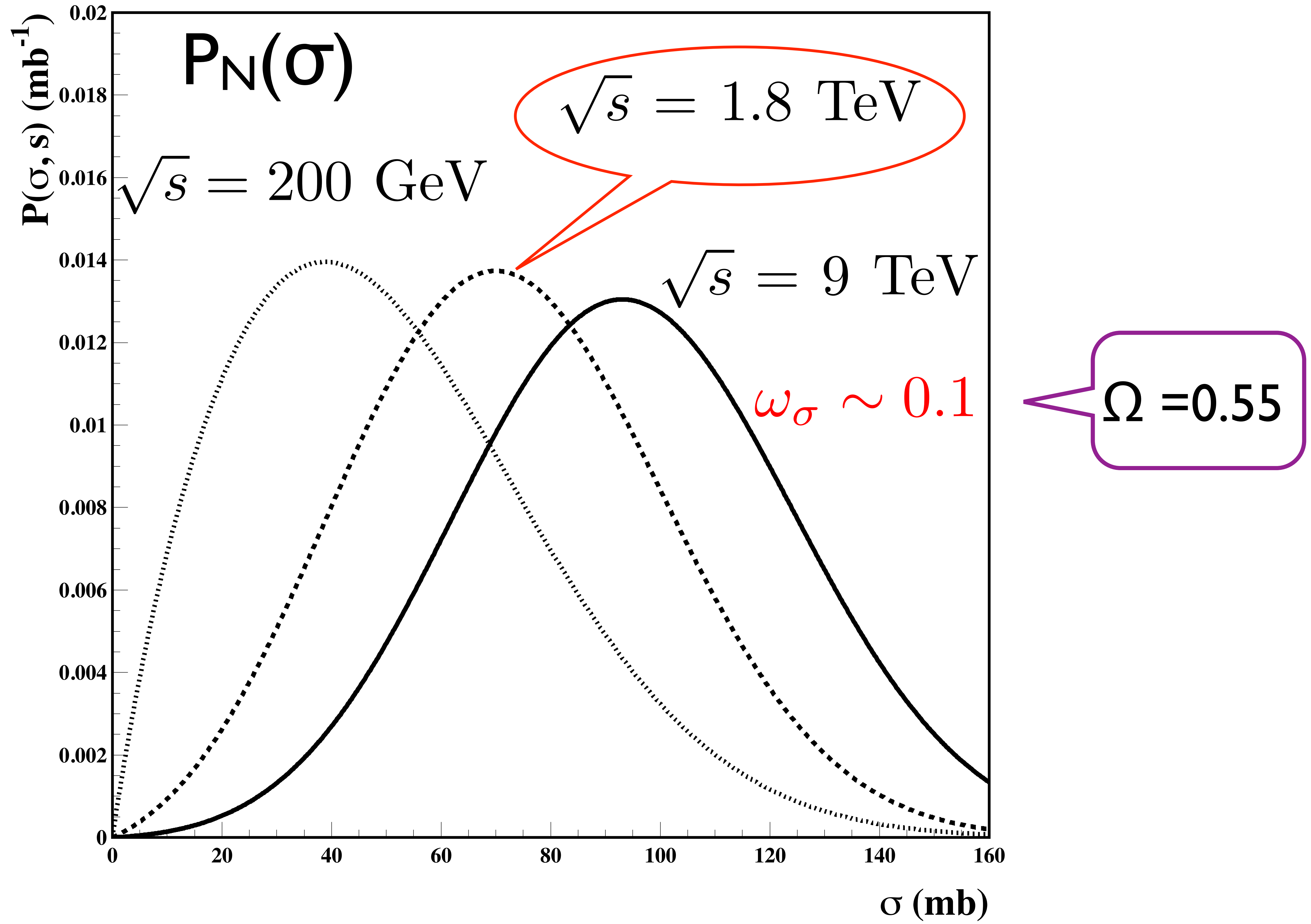
Test: Calculate inelastic diffraction off nuclei - no free parameters



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.



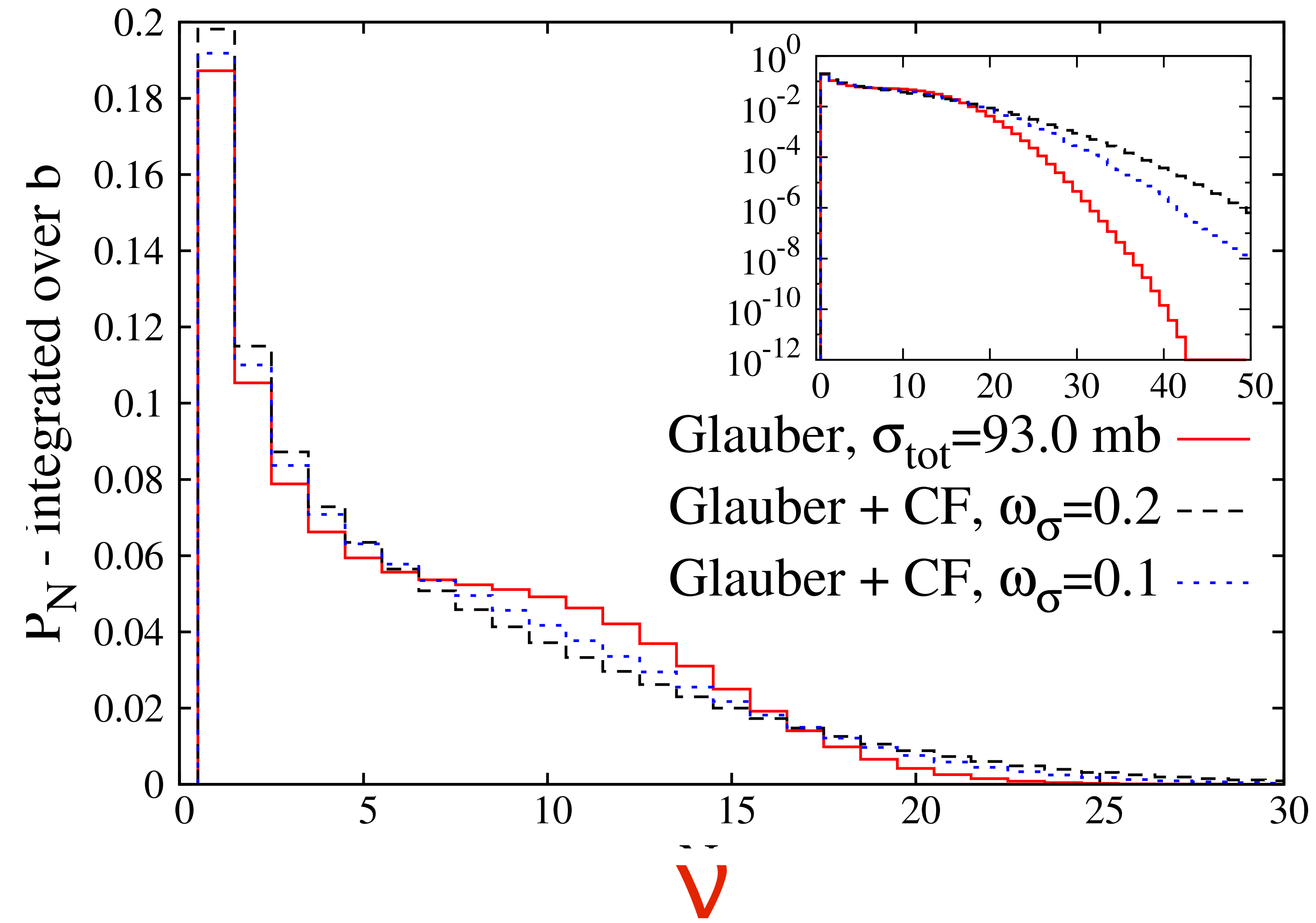
Extrapolation of Guzey & MS before the LHC data

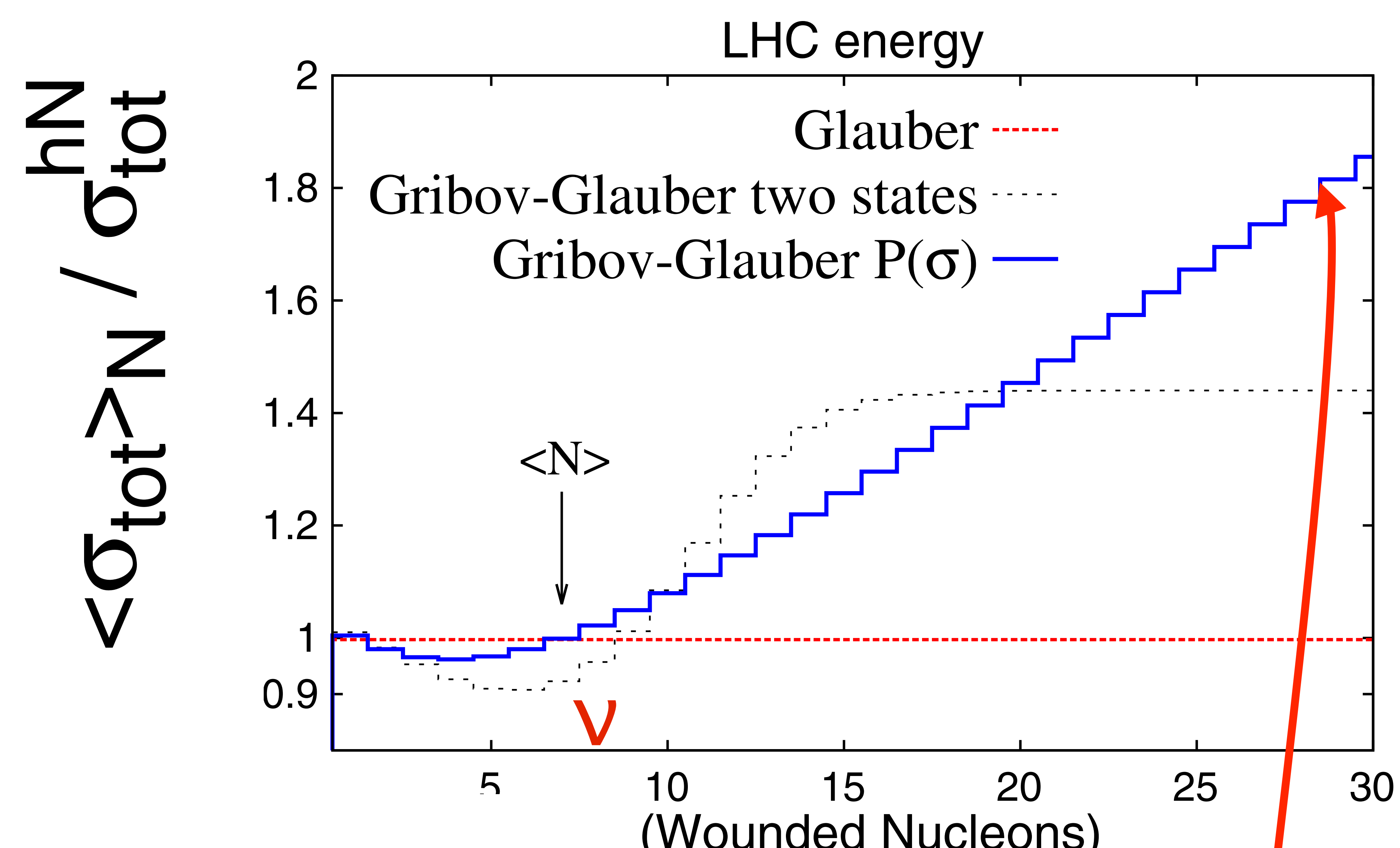
consistent with LHC data which are still not too accurate *simplified expression(optical limit) for cross section of inelastic interaction with exactly ν nucleons*

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

σ_ν includes incoherent single and double diffractive final states (affects mostly ν=1)

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





Probability of interaction with ν nucleons integrated over impact parameter b.

Fluctuations lead to broadening of the distribution over - ν- number of active nucleons as compared to Glauber model - reported by ATLAS and ALICE.

Large ν select configurations with larger σ.

New/old question: *is there a correlation between configuration of hard partons in the hadron and strength of interaction of the hadron?*

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

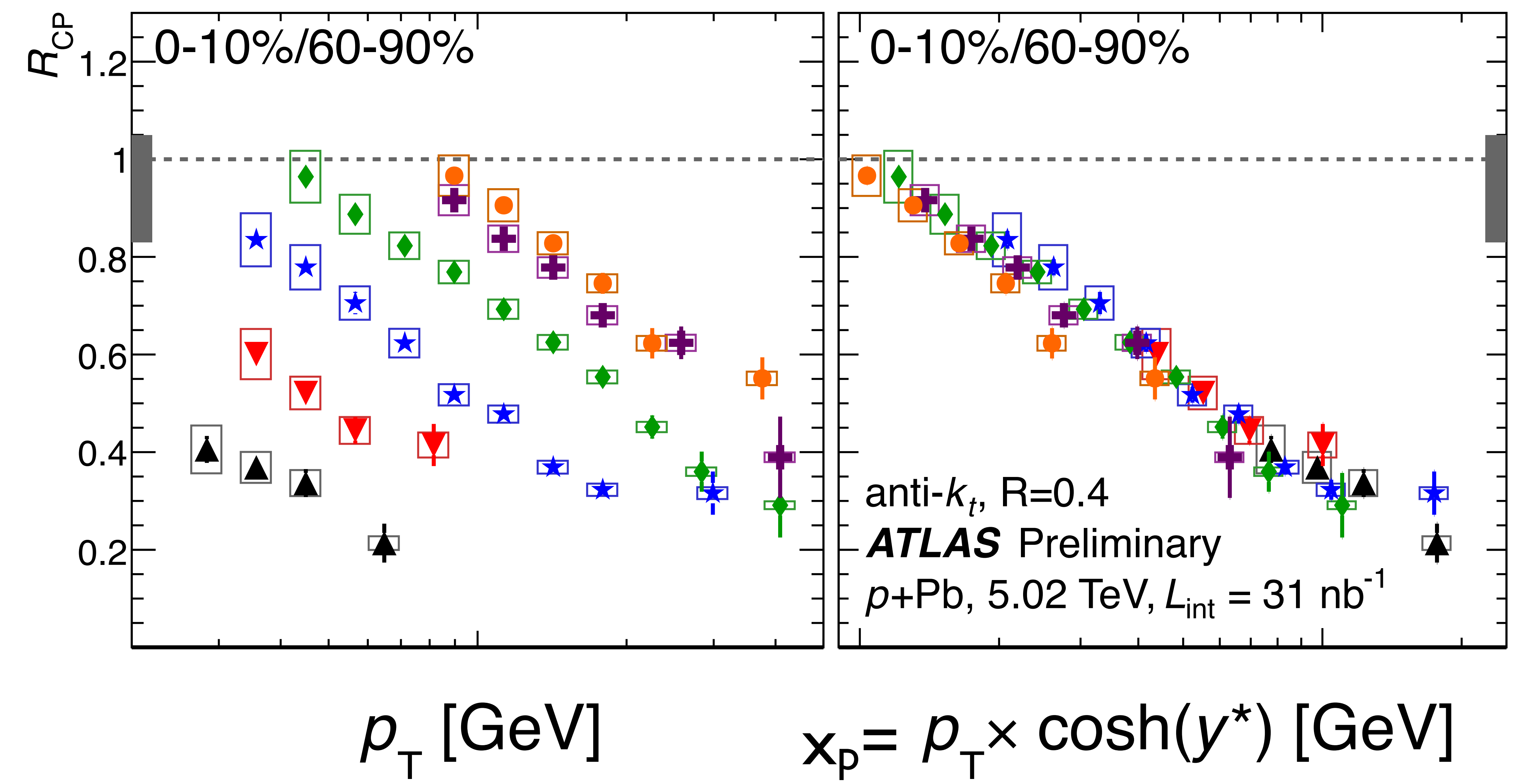
Use the hard trigger (dijet) to determine x of the parton in the proton (x_p) and low p_t hadron activity to measure overall strength of interaction σ_{eff} of configuration in the proton with given x FS83

Expectation: large x ($x \gtrsim 0.5$) correspond to much smaller σ → drop of # of wounded nucleons & overall hadron multiplicity for central collisions

Data - ATLAS & CMS on correlation of jet production and activity in forward rapidities

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 NN collisions

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

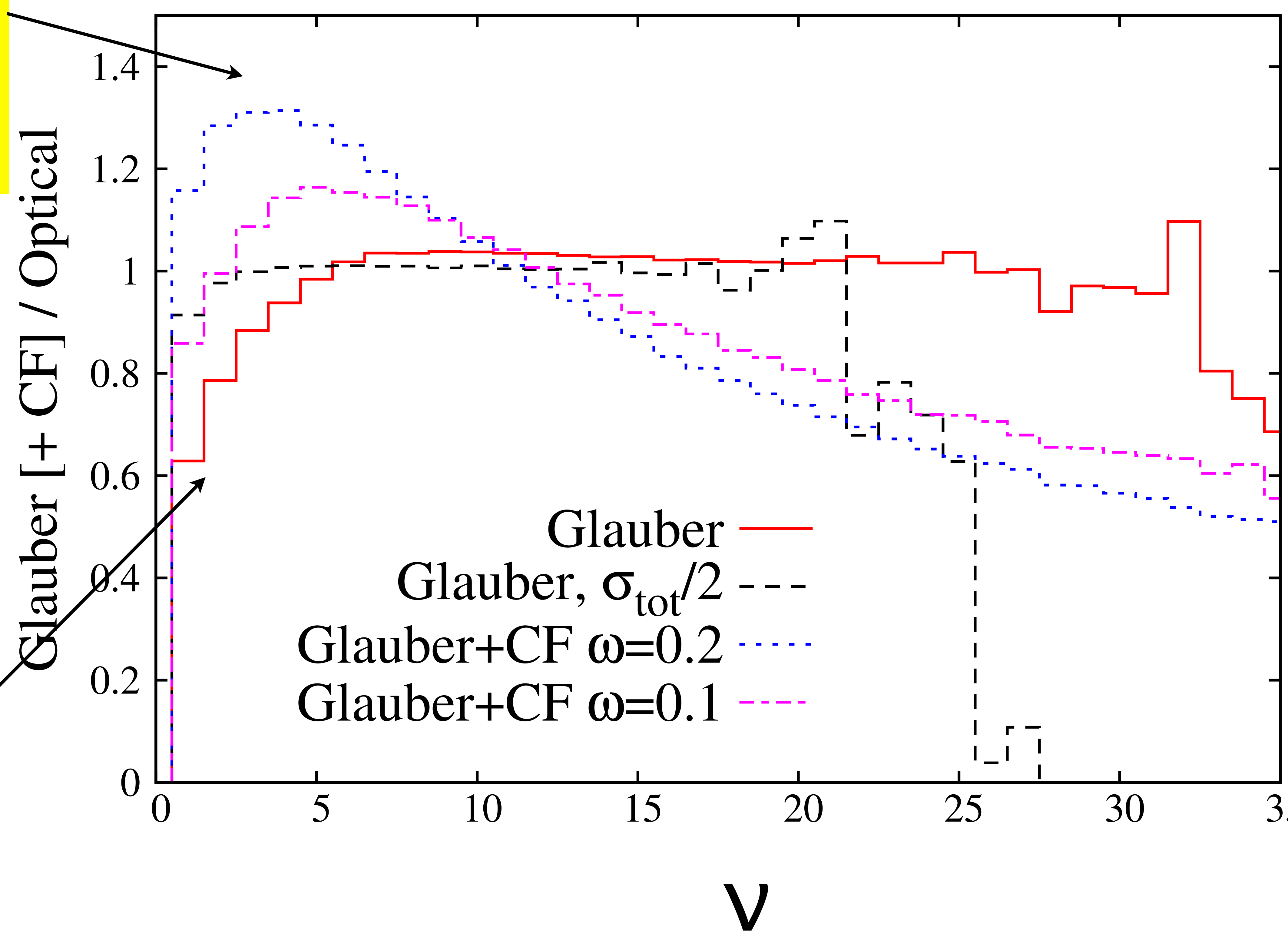
M.Alvioli, L.Frankfurt,V.Guzey and M.Strikman, ``Revealing nucleon and nucleus flickering in pA collisions at the LHC,' Phys.Rev. C90 (2014) 3, 034914 arXiv 1402.2868

Consider multiplicity of hard events $Mult_{pA}(HT) = \sigma_{pA}(HT + X)/\sigma_{pA}(in)$ as a function of ν -- number of collisions

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:

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

Accuracy? Significant corrections due to smaller transverse scale of hard collisions than soft collisions increase due to more central interactions of configurations with $\sigma < \sigma_{tot}$



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

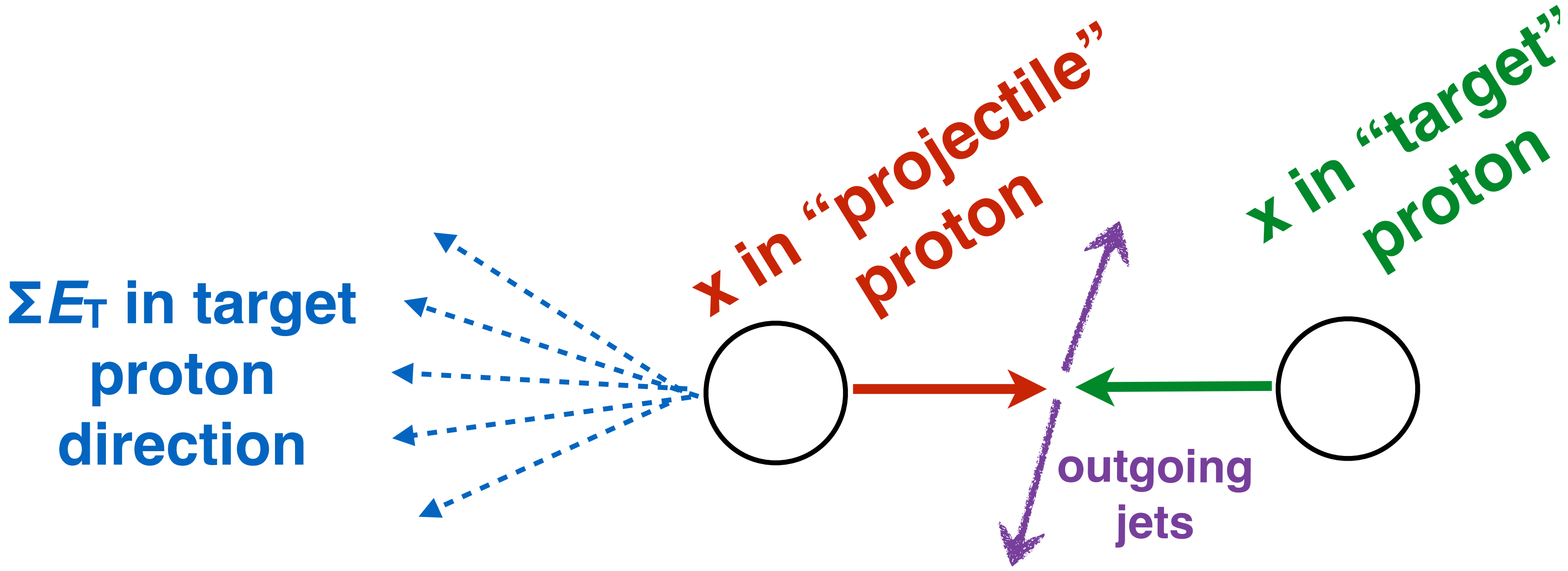
the cylinder in which interaction occur is larger but local density does not go up as fast in Glauber

drop due to more localized hard interactions

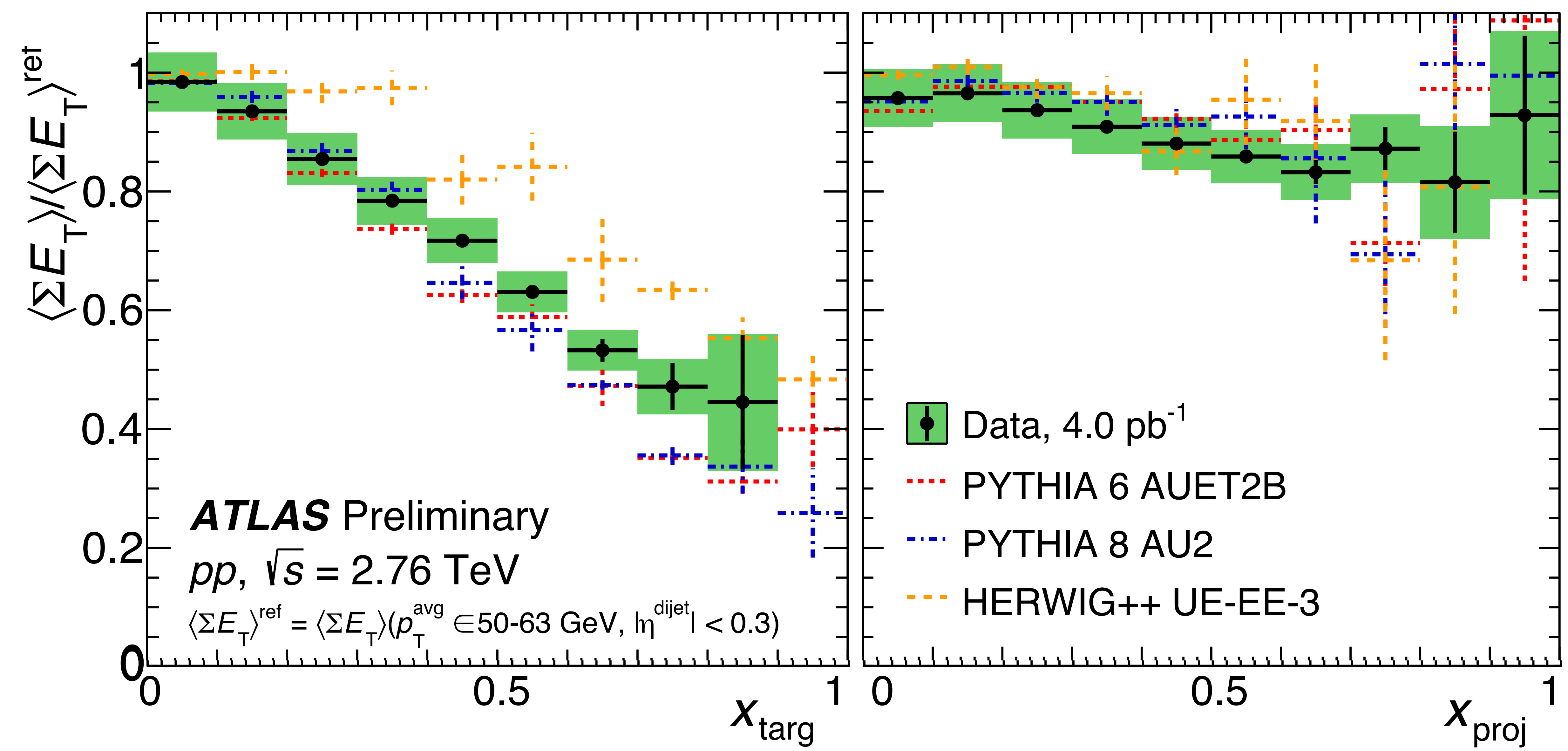
Deviation of $R_{HT}(\nu)$ from 1

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 (-3 ÷ -5) which minimizes the effects of energy conservation (production of jets with large x_p)

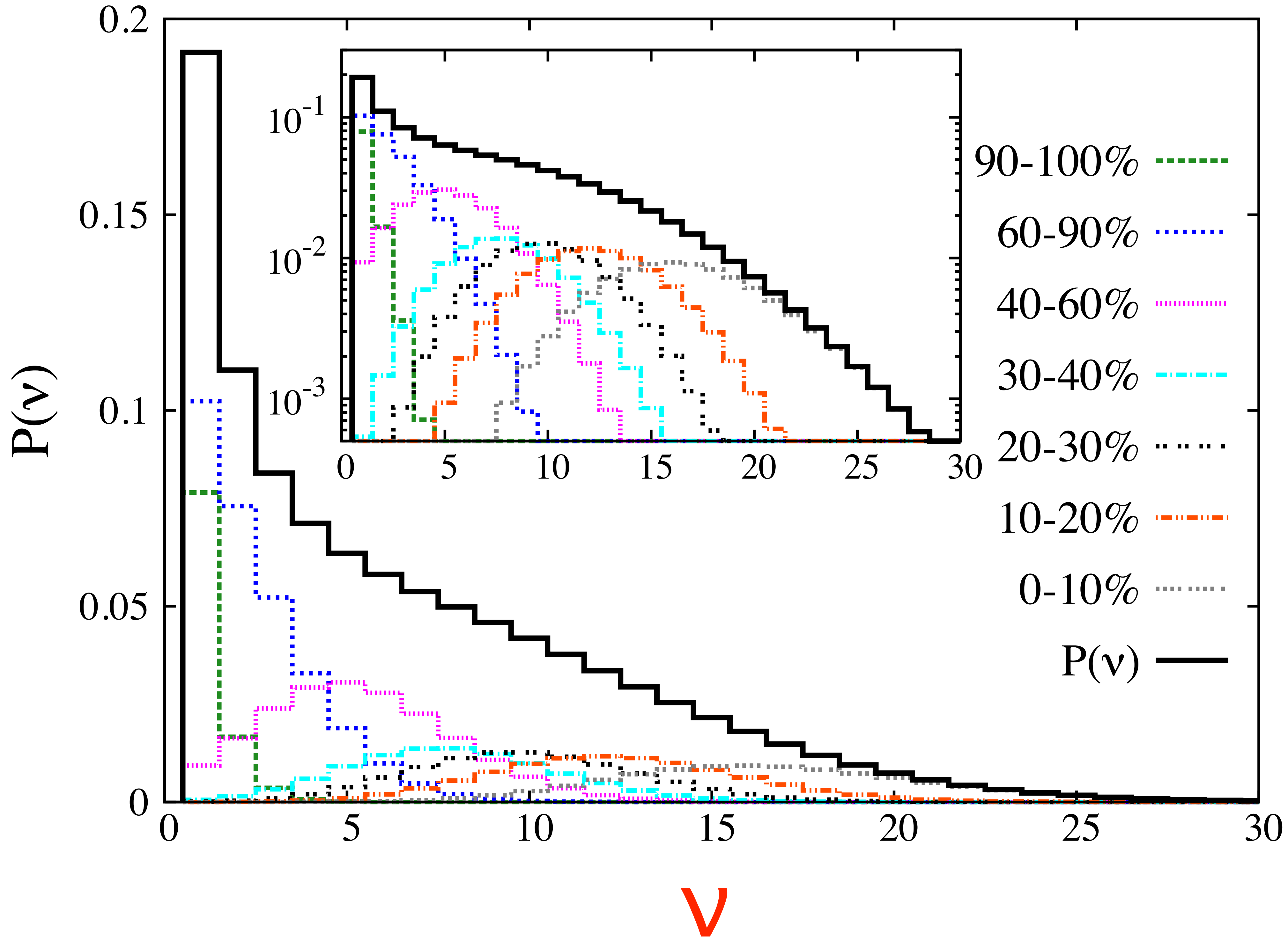
ATLAS-CONF-2015-019 analysis of pp data confirms this expectation



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

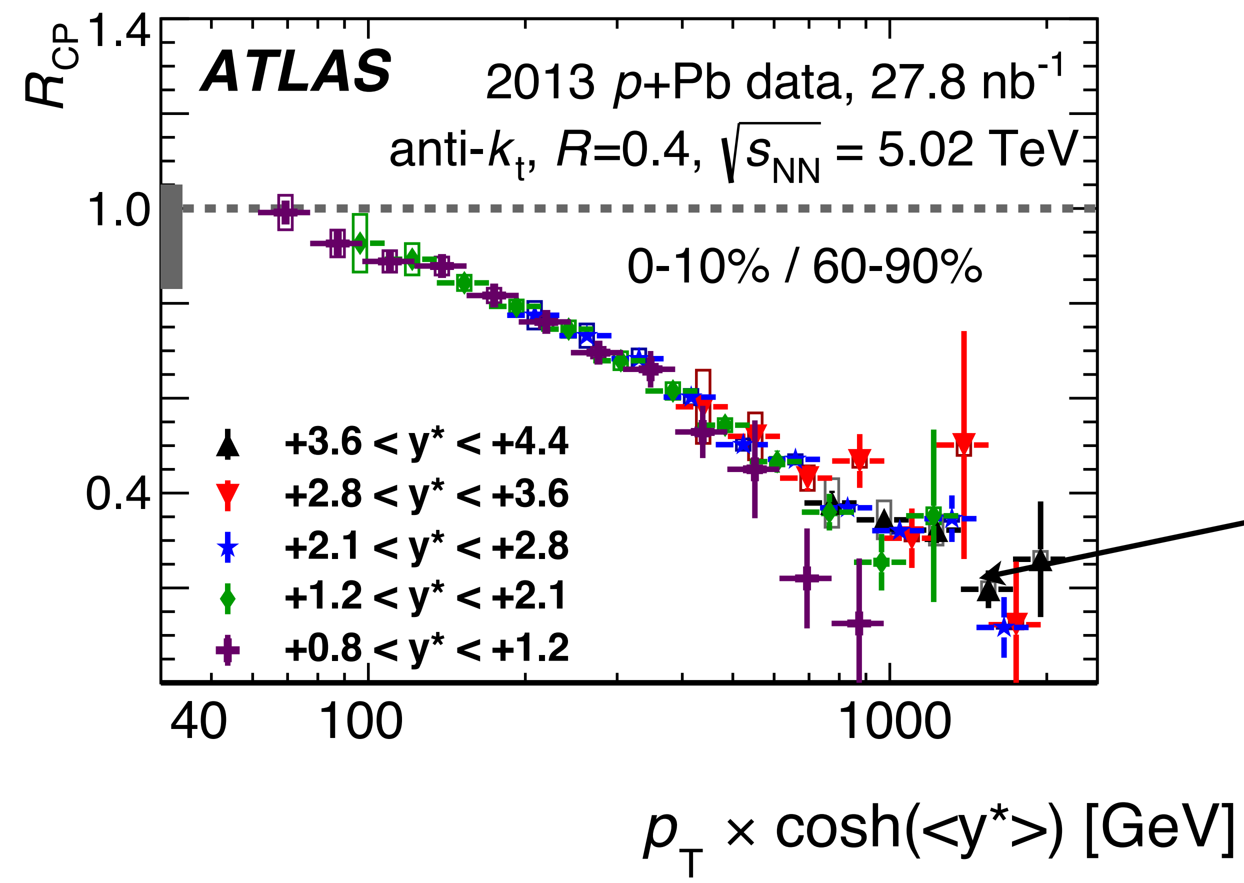


Dependence on x_{proj} and x_{targ}



Alvioli, Cole, LF, Perepelitsa,MS, arXiv:1409.7381

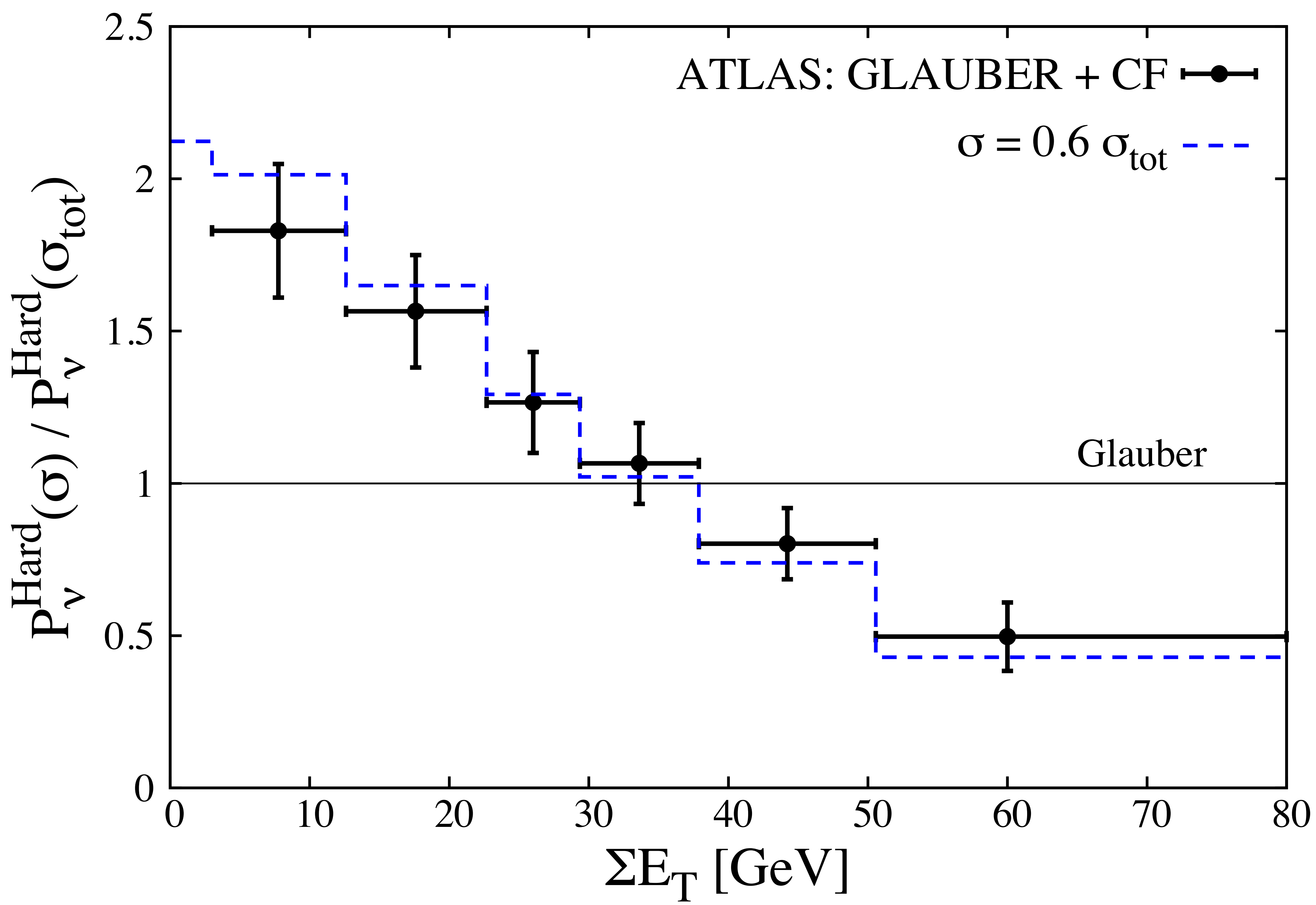
Probability distributions in ν proton-nucleus collisions in all pA collisions and in those selected by different ΣE_T, or centrality, ranges. Note that ΣE_T, reasonably tracks ν's



x_p =0.6

We focus on large x_p where effect is largest and hence corrections for transverse geometry are small (though we do include them).

Sensitivity to ω_σ for studied configurations is small, so we use ω_σ =0.1 for comparison with the data

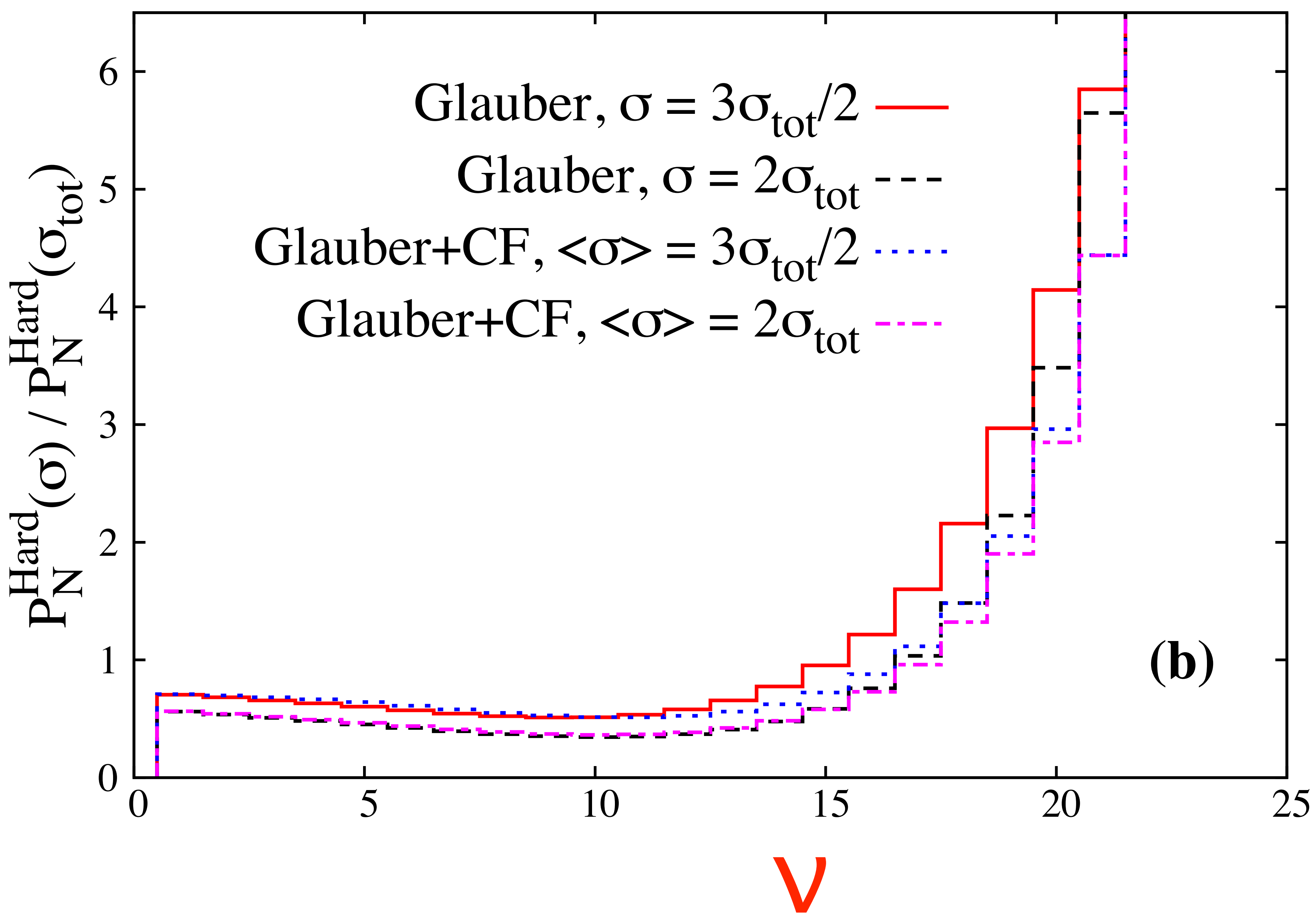


R^{hard} for $x = E_{jet}/E_p = 0.6$ for centrality bins extracted from the ATLAS data using ν's of the CF model. Errors are combined statistical and systematic errors. The solid line is the Glauber model expectation.

We can estimate

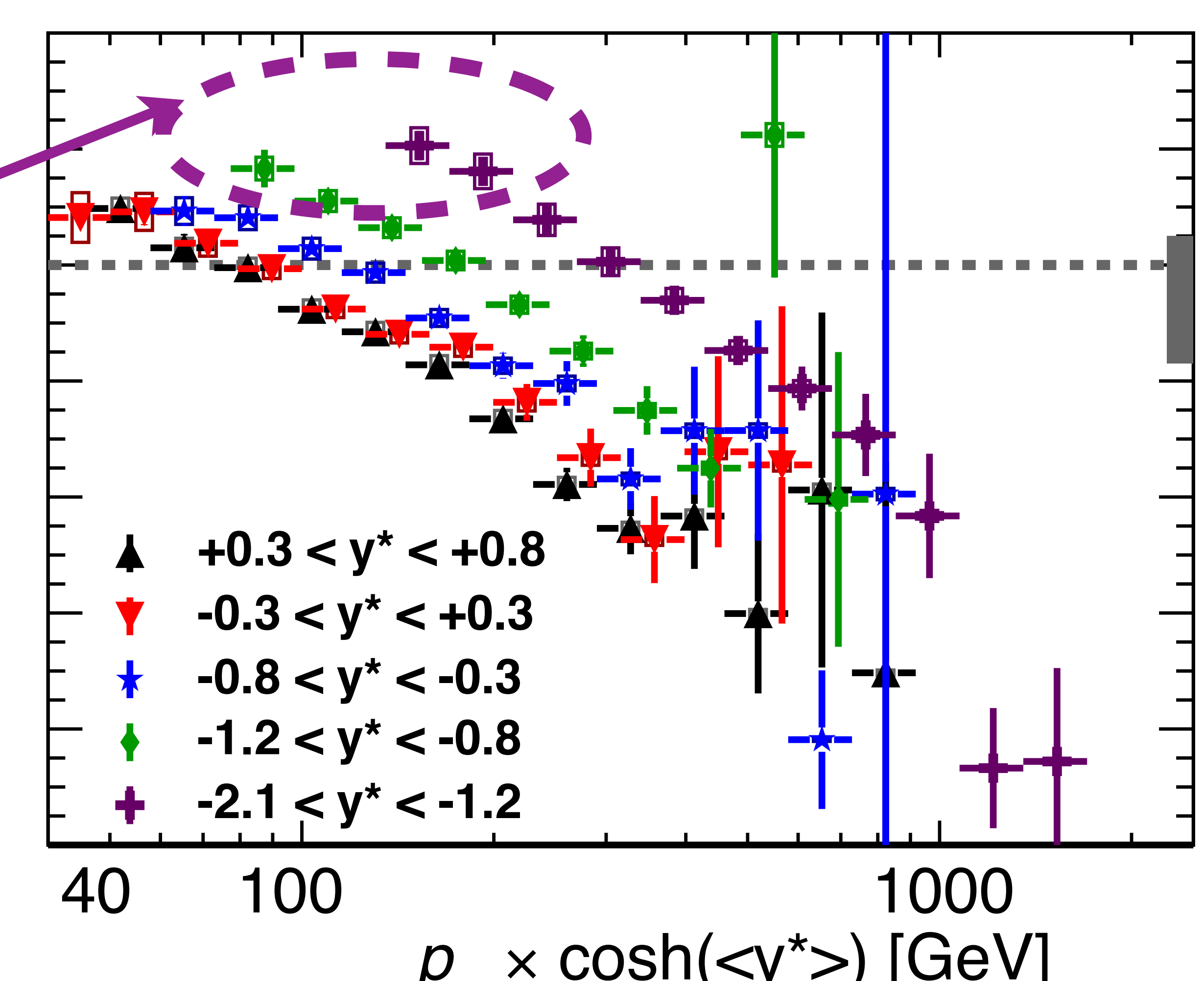
$\sigma(x=0.6)/\sigma_{tot}$[RHIC]=0.4 ÷0.5

For σ > <σ> dependence on centrality is reversed



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

Transition to dominance of larger than average size - $x < 10^{-1}$?

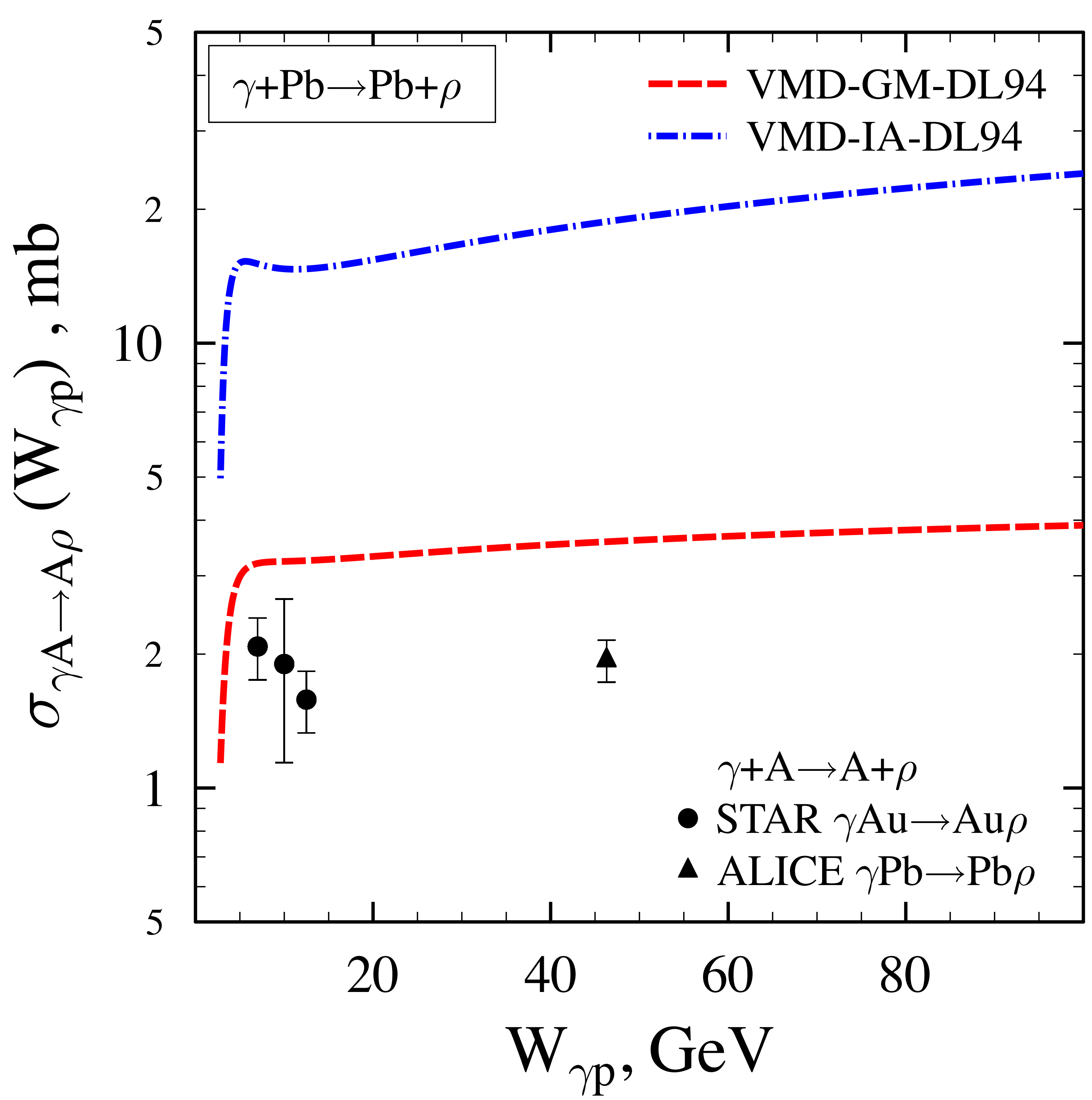


New experimental observation relevant for color fluctuation phenomenon: coherent photoproduction of ρ-meson in ultraperipheral heavy ion collisions at LHC (ALICE): $\gamma + A \to \rho + A$

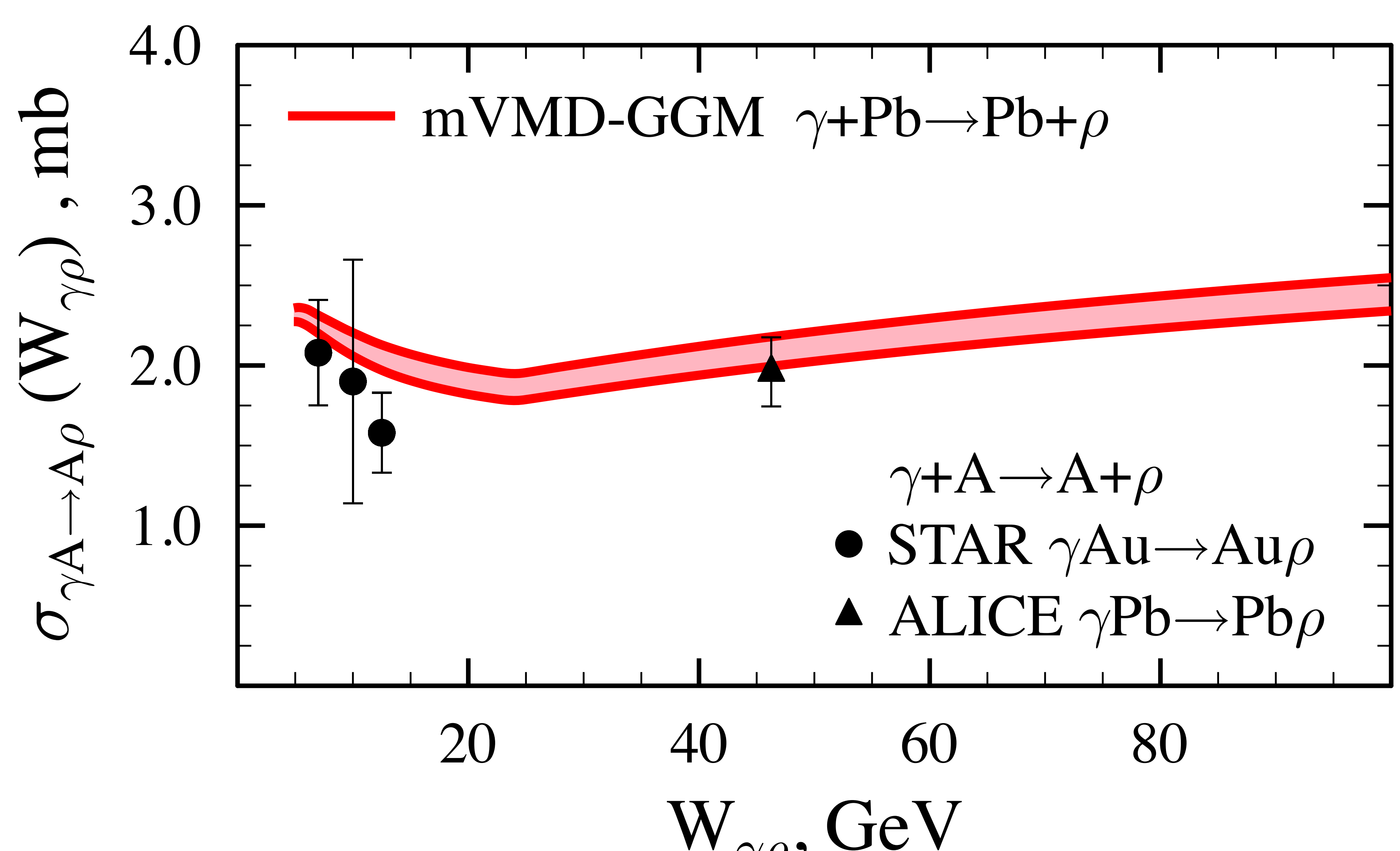
Guzey, Frankfurt, MS, Zhalov 2015 (1506.07150):

- *Vector meson dominance overestimates* $\sigma(\gamma + p \to \rho + p)$ by a factor of 1.3

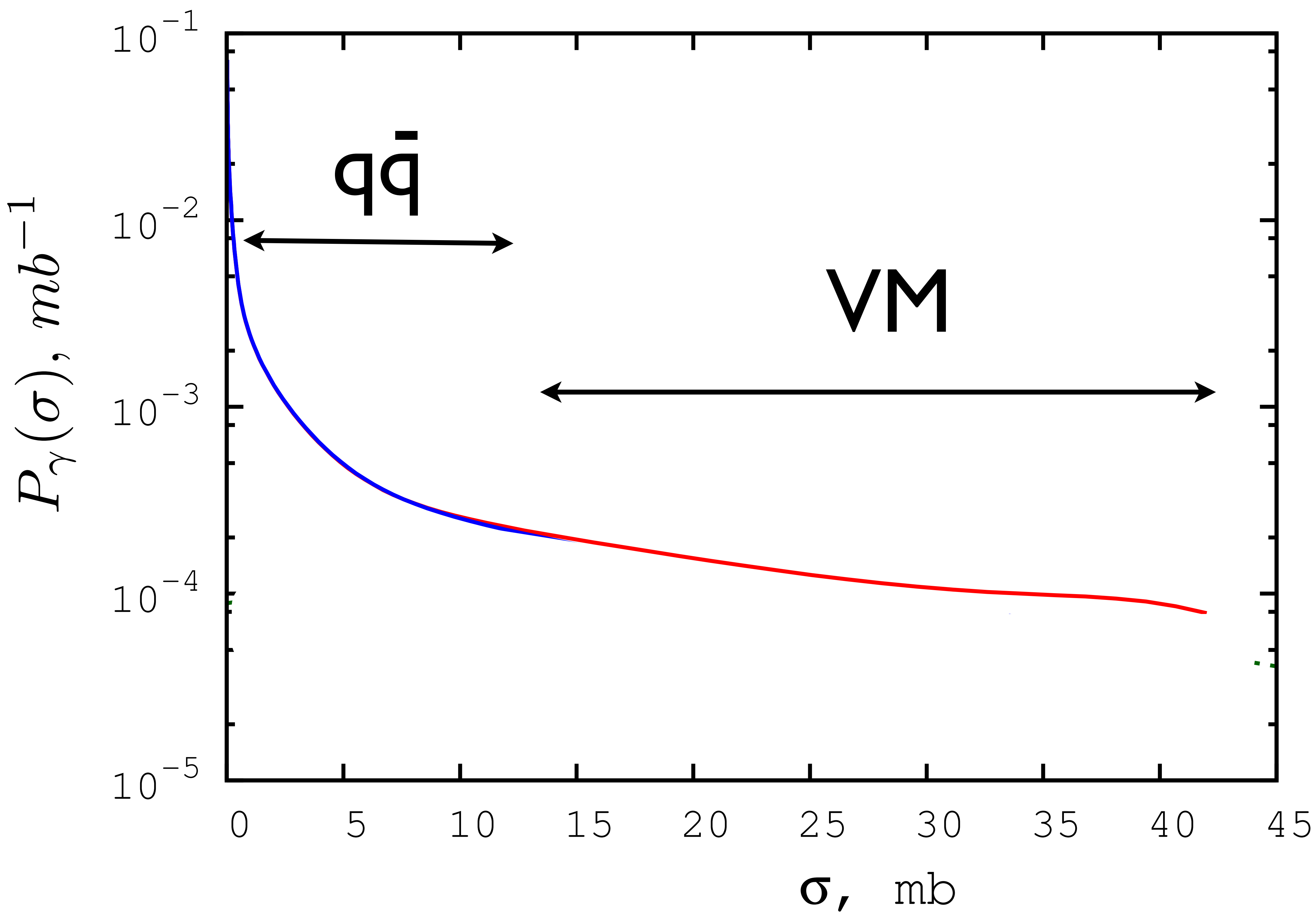
- Glauber model crossly overestimates the cross section



- Gribov - Glauber model with cross section fluctuations. Large $\omega_\sigma \sim 0.5$

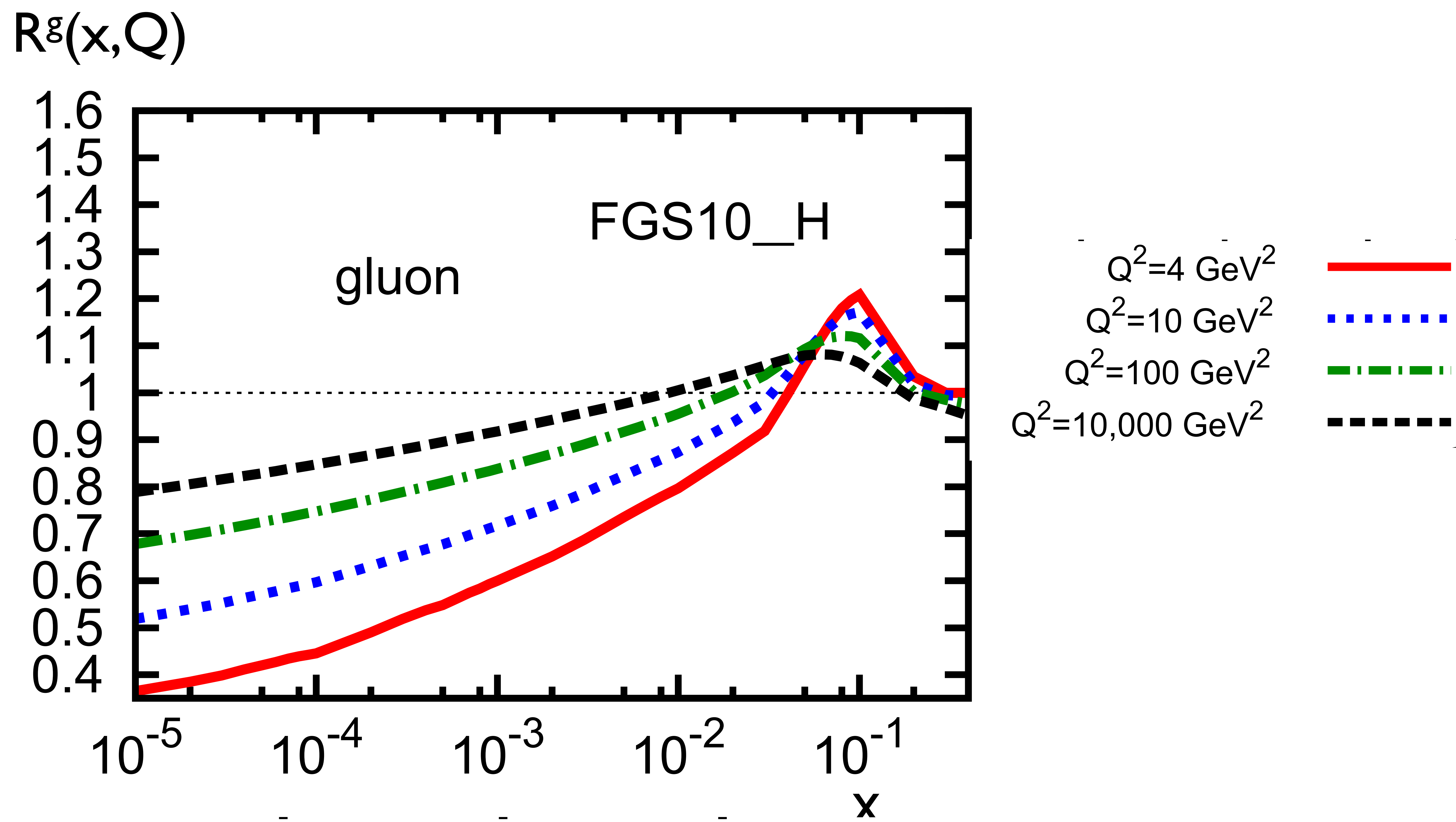


Modeled P_γ



Special situation for small σ: $\frac{\sigma(\text{"}small\ dipole\text{"} - A)}{A\sigma(\text{"}small\ dipole\text{"} - N)} = \frac{G_A(x,Q^2}{AG_N(x,Q^2)} < 1$

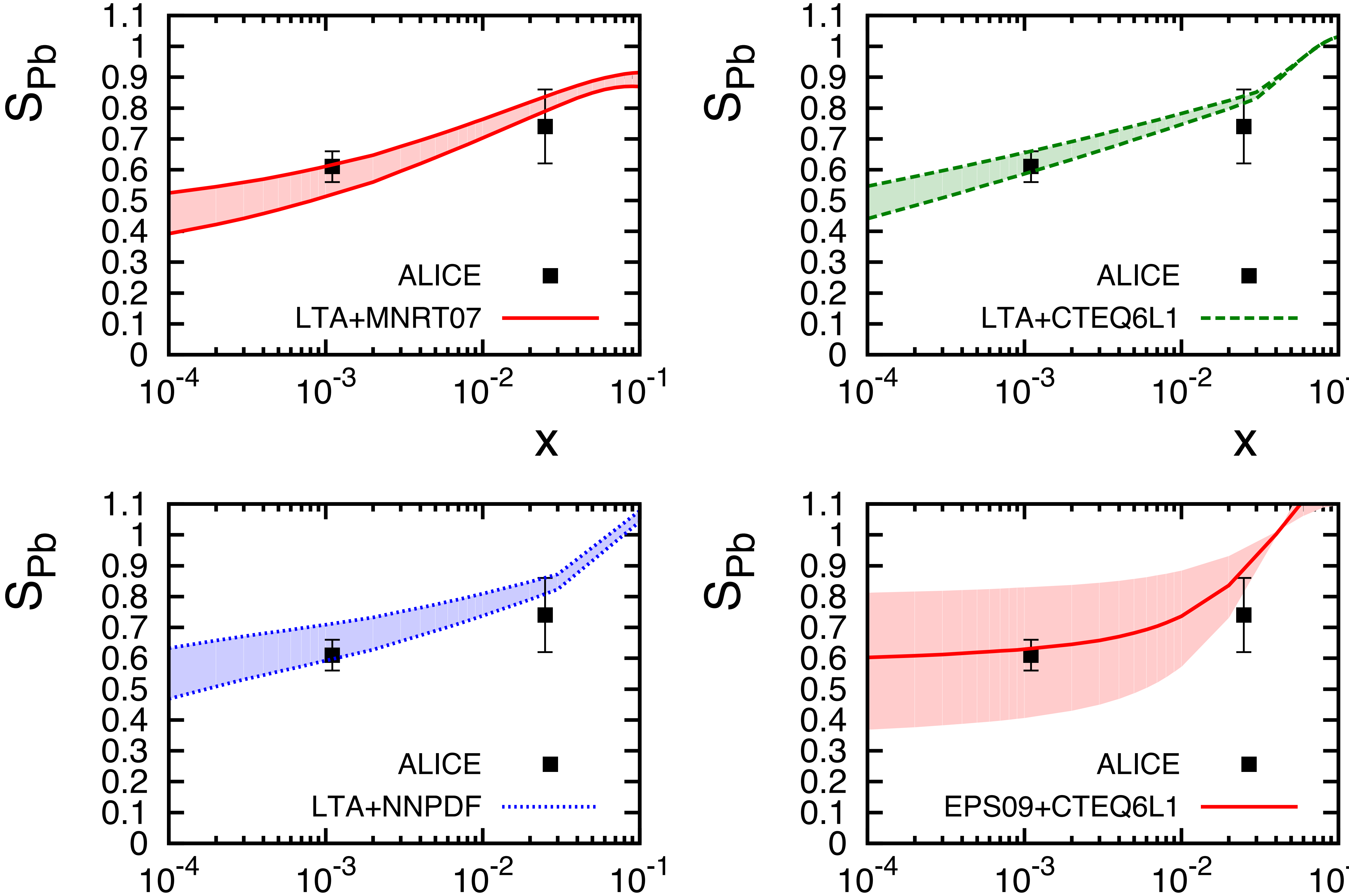
Prediction of the LT theory of nuclear shadowing based on factorization theorem for diffraction and AGK

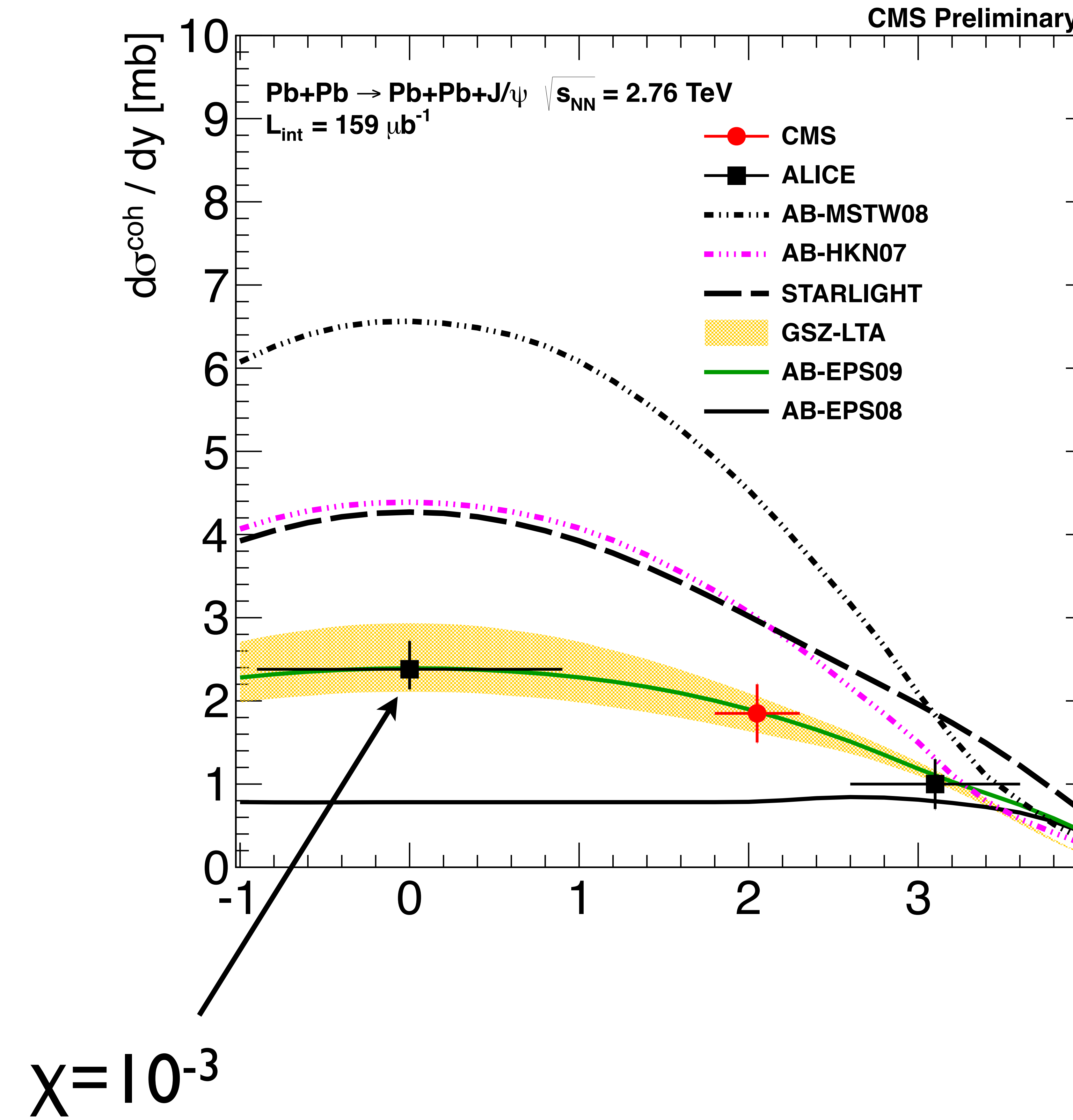


Strong reduction of nuclear shadowing at fixed x with increase of Q due to the DGLAP flow of partons from larger x

Test: Strong suppression of coherent J/ψ production observed by ALICE confirms our prediction of significant gluon shadowing on the $Q^2 \sim 3\ GeV^2$

$$S_{Pb} = \left[\frac{\sigma(\gamma A \to J/\psi + A)}{\sigma_{imp.approx.}(\gamma A \to J/\psi + A)} \right]^{1/2} = \frac{g_A(x,Q^2)}{g_N(x,Q^2)}$$

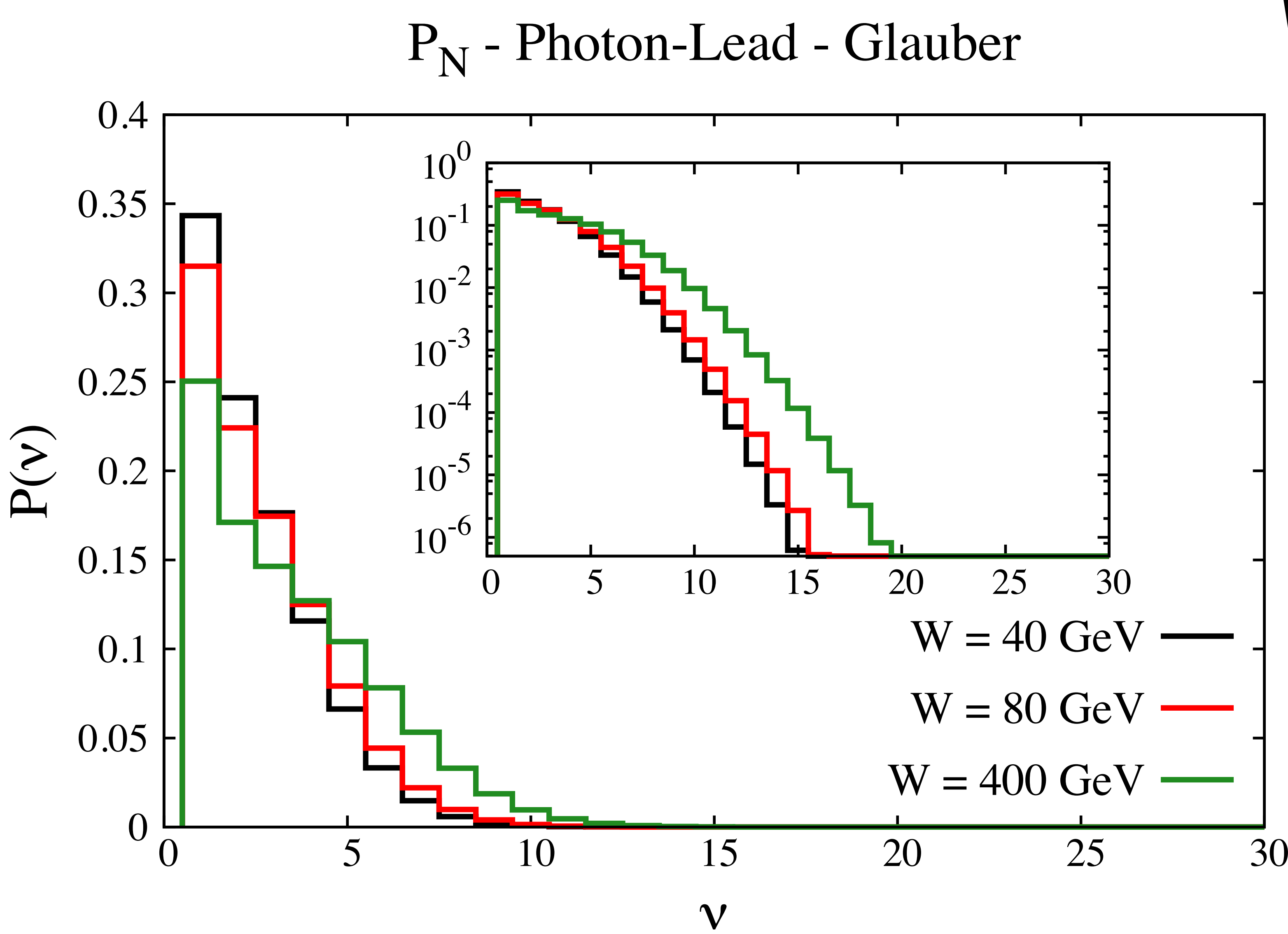


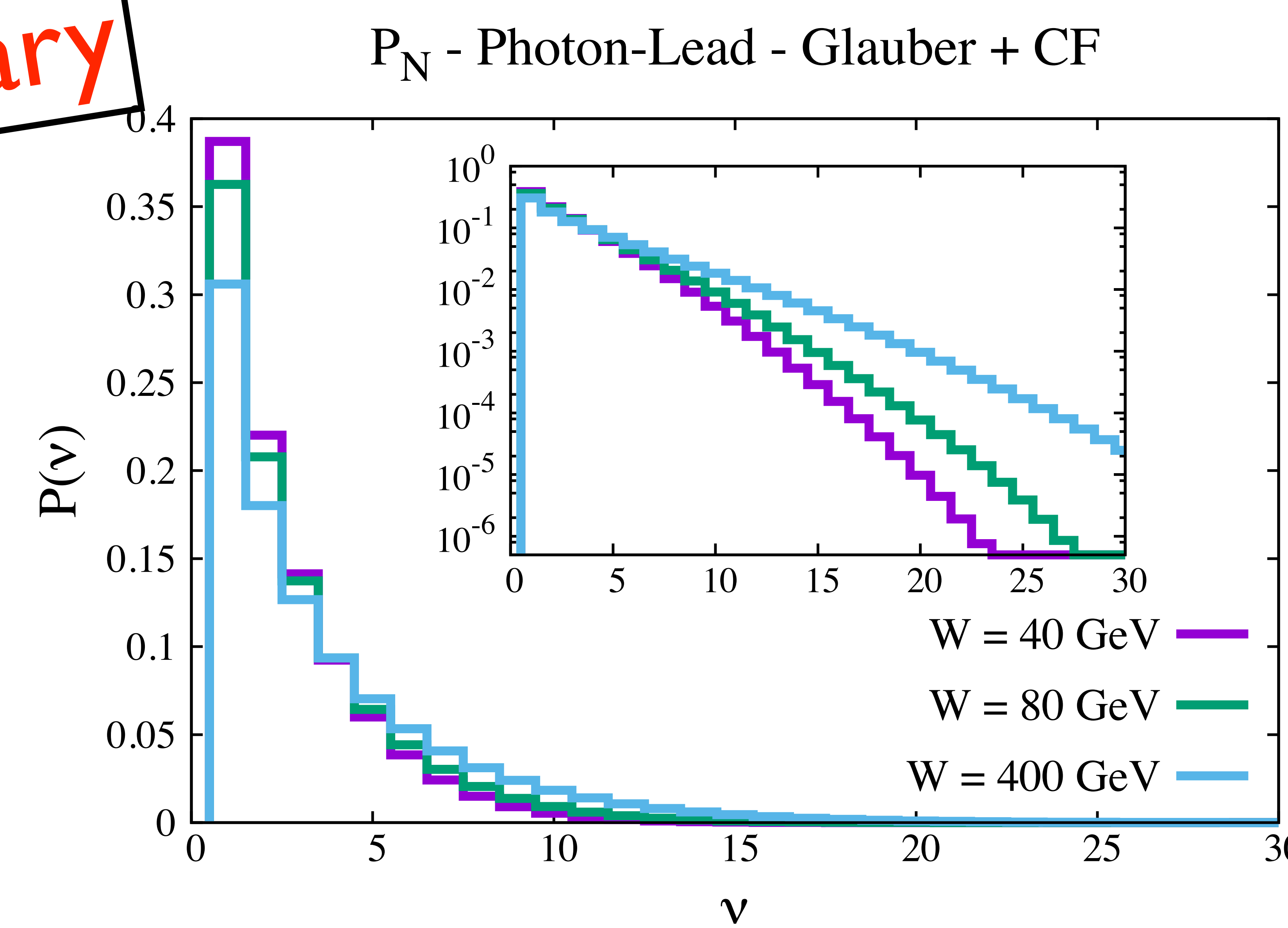


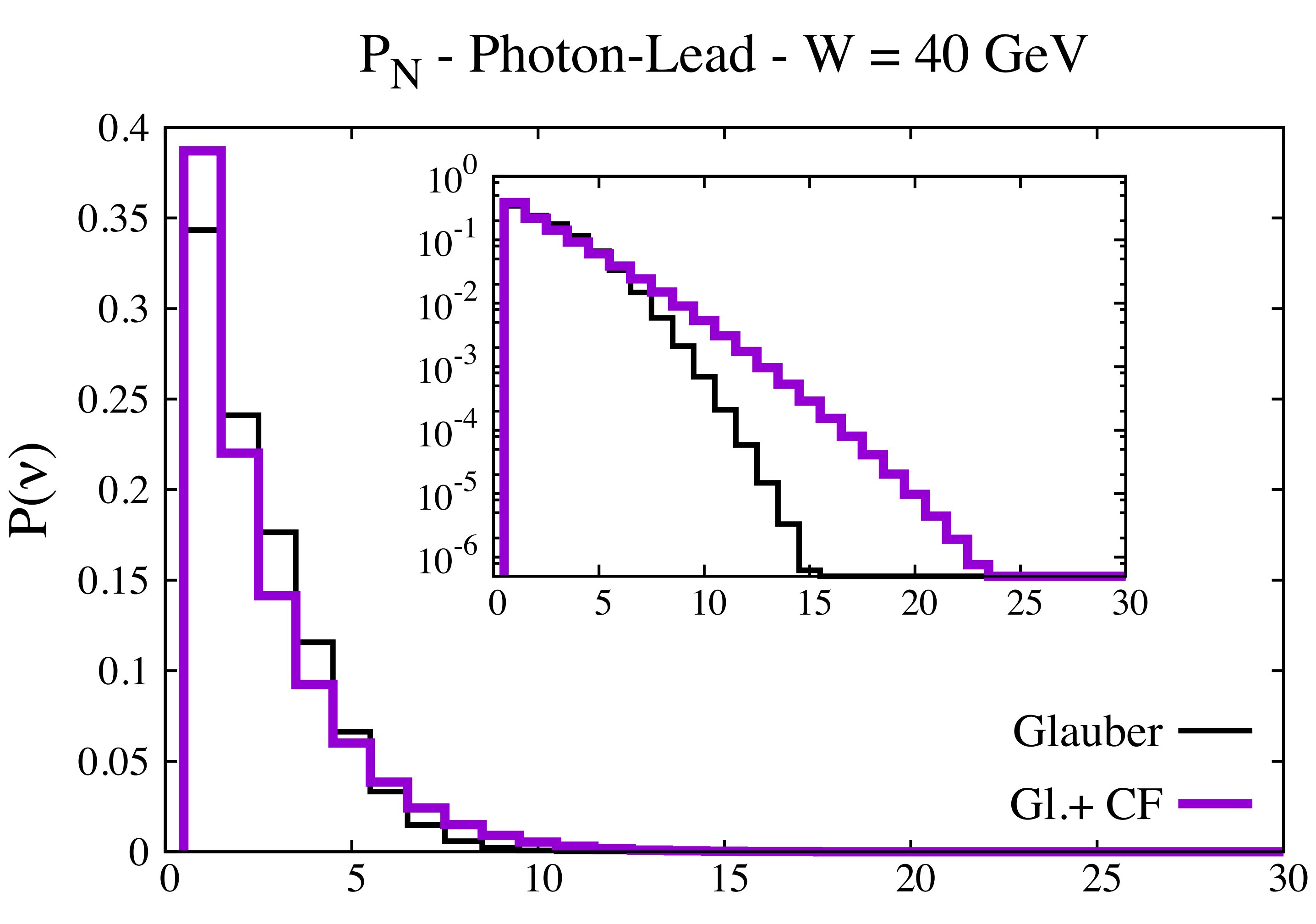
Points - experimental values of S extracted by Guzey et al (arXiv:1305.1724) from the ALICE data; Curves - analysis with determination of Q -scale by Guzey and Zhalov arXiv:1307.6689; JHEP 1402 (2014) 046.

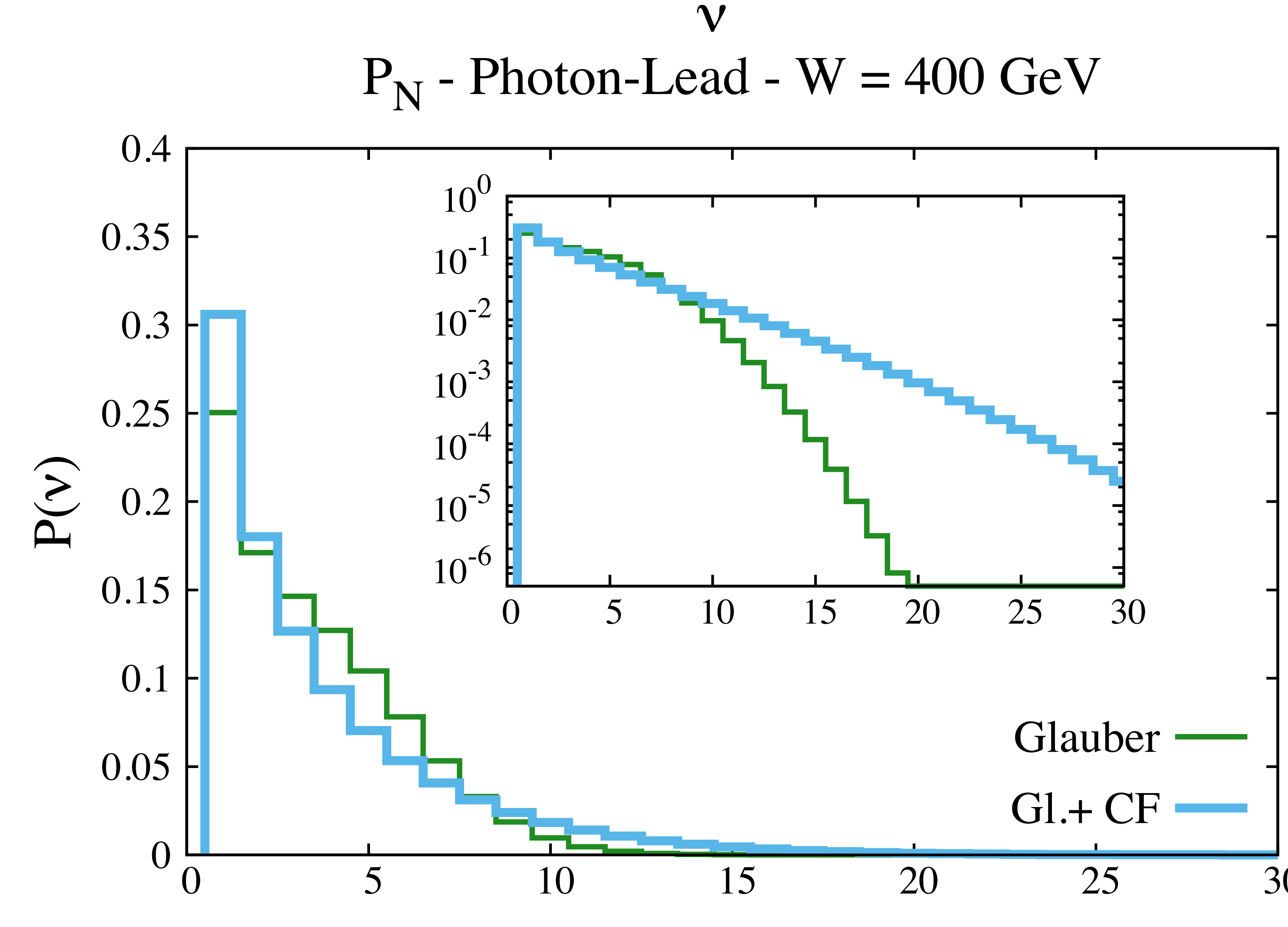
CF broaden very significantly distribution over ν. “pA ATLAS/CMS like analysis” using energy flow at large rapidities would test both presence of configurations with large σ ~40 mb, and weakly interacting configurations.

Preliminary









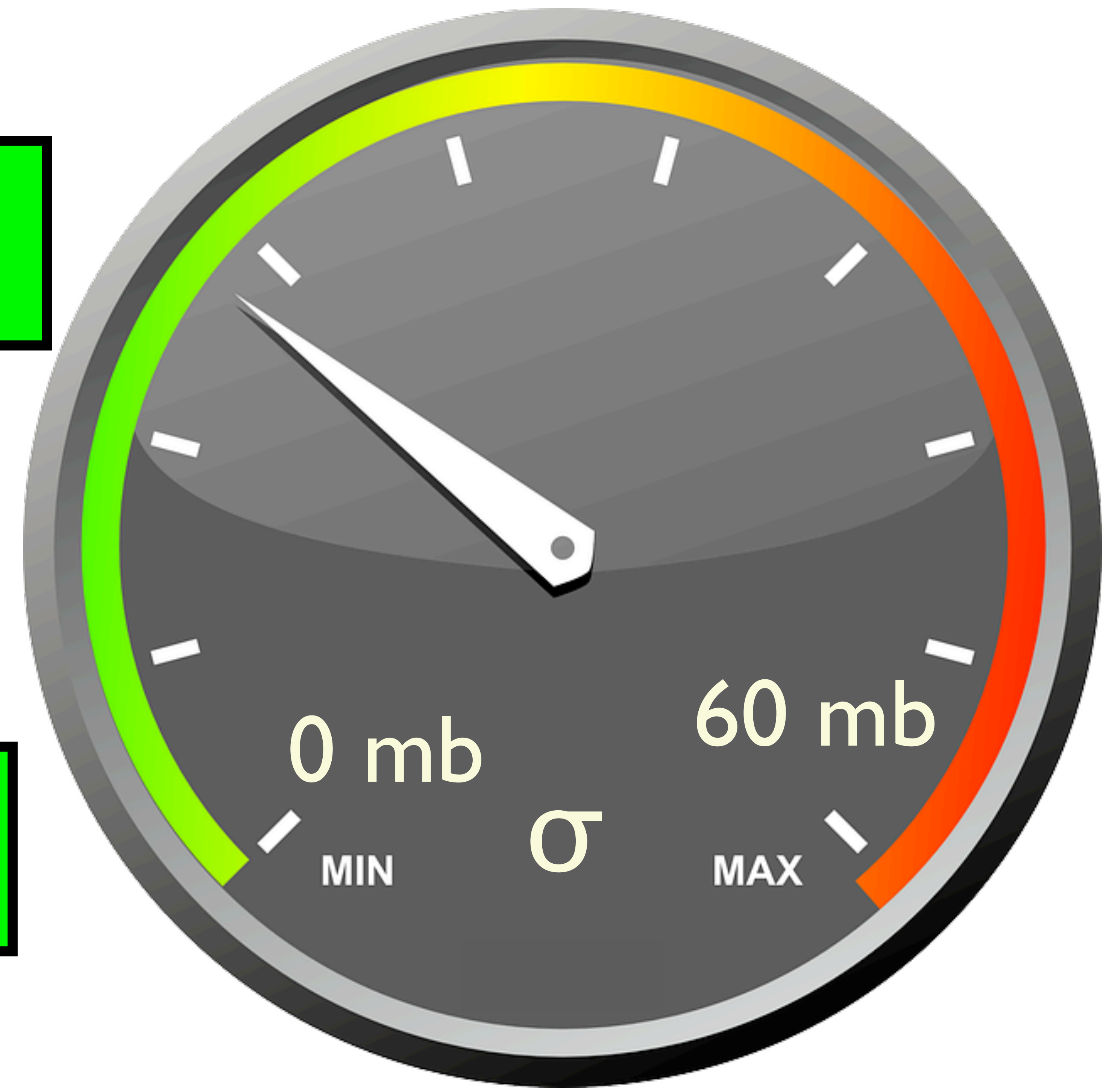
Ultraperipheral collisions at LHC ($W_{\gamma N}$< 500 GeV)

Tuning strength of interaction of configurations in photon

Min bias

Charm
x~ 10^{-3}

Leading strangeness
x~ 10^{-3}



Direct photon dijets
x> 10^{-2}

Low transverse
momentum events

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

Novel way to study dynamics of γ &γ interactions with nuclei*

Conclusions

Color fluctuations are an important component of high energy dynamics

Color fluctuation with large x - have smaller size

Opportunities for study global 3D structure of nucleon and photon

Slides for discussion & supplementary slides

ΣE_T^{Pb} distribution: modeling by ATLAS

Transverse energy distributions in p+p collisions are typically well described by gamma distributions

$$\text{gamma}(x;k,\theta) = \frac{1}{\Gamma(k)}\frac{1}{\theta}\left(\frac{x}{\theta}\right)^{k-1} e^{-x/\theta}$$

gamma distribution has convolution property:

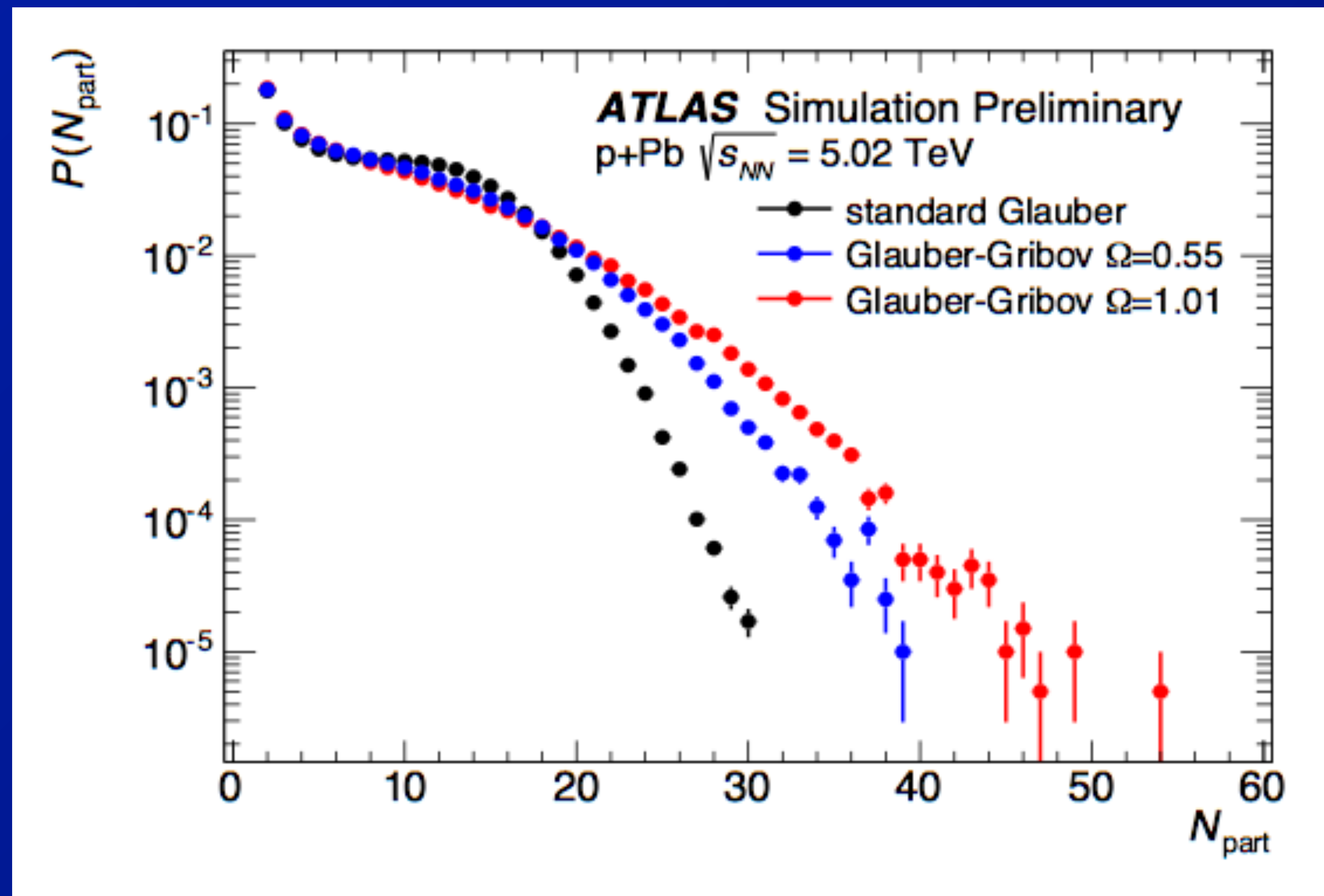
$$k\left(N_{\text{part}}\right) = k_0 + k_1\left(N_{\text{part}} - 2\right),$$

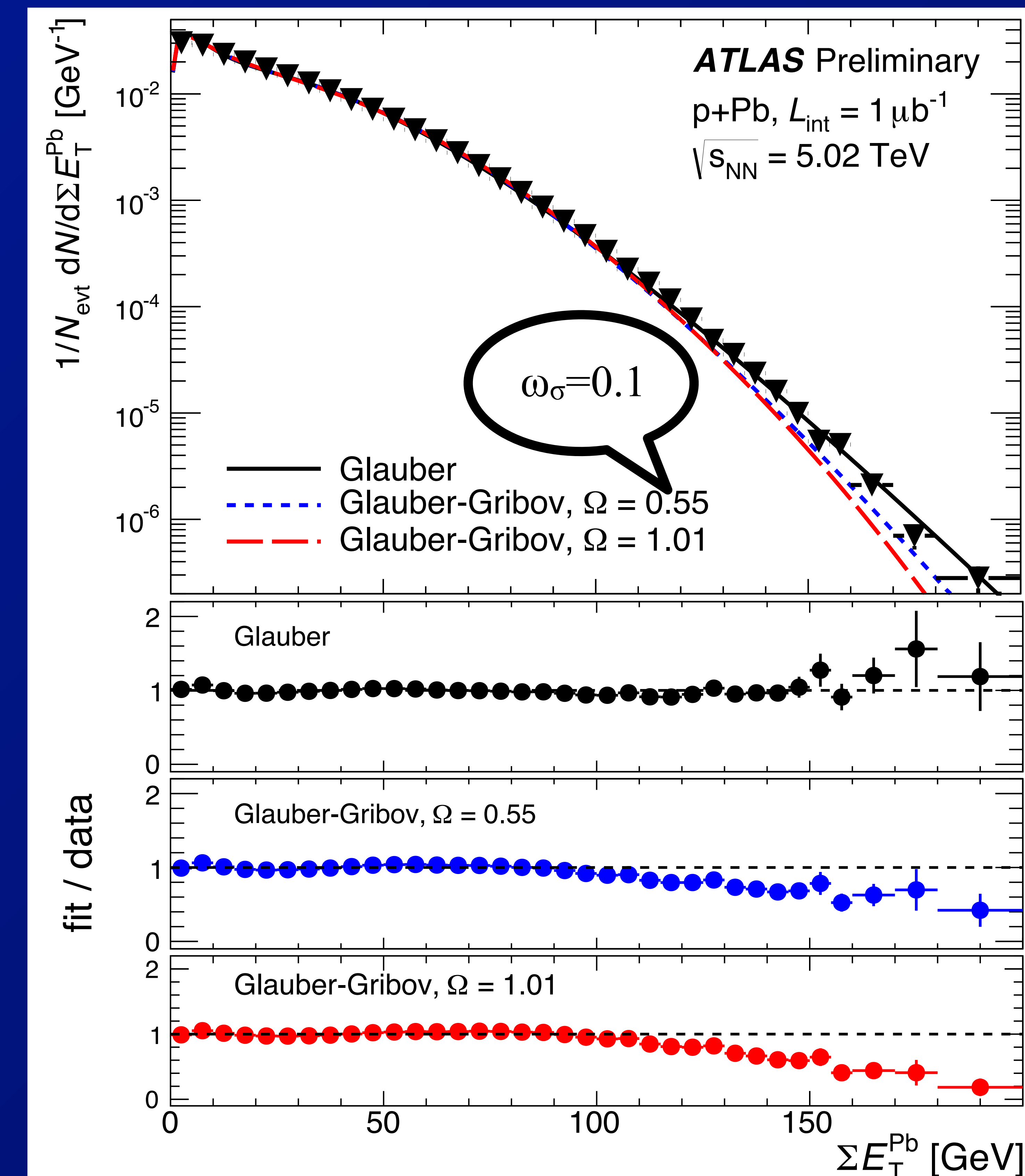
$$\theta\left(N_{\text{part}}\right) = \theta_0 + \theta_1 \log\left(N_{\text{part}} - 1\right).$$

N-fold conv. of gamma(x,k,θ)= $gamma(x,k,\theta) \equiv \frac{1}{\Gamma(Nk)}\frac{1}{\theta}\left(\frac{x}{\theta}\right)^{Nk-1} e^{-x/\theta}$

Note: for k = 1, gamma distribution is exponential, k < 1 is “super-exponential”

Glauber and Glauber-Gribov analysis





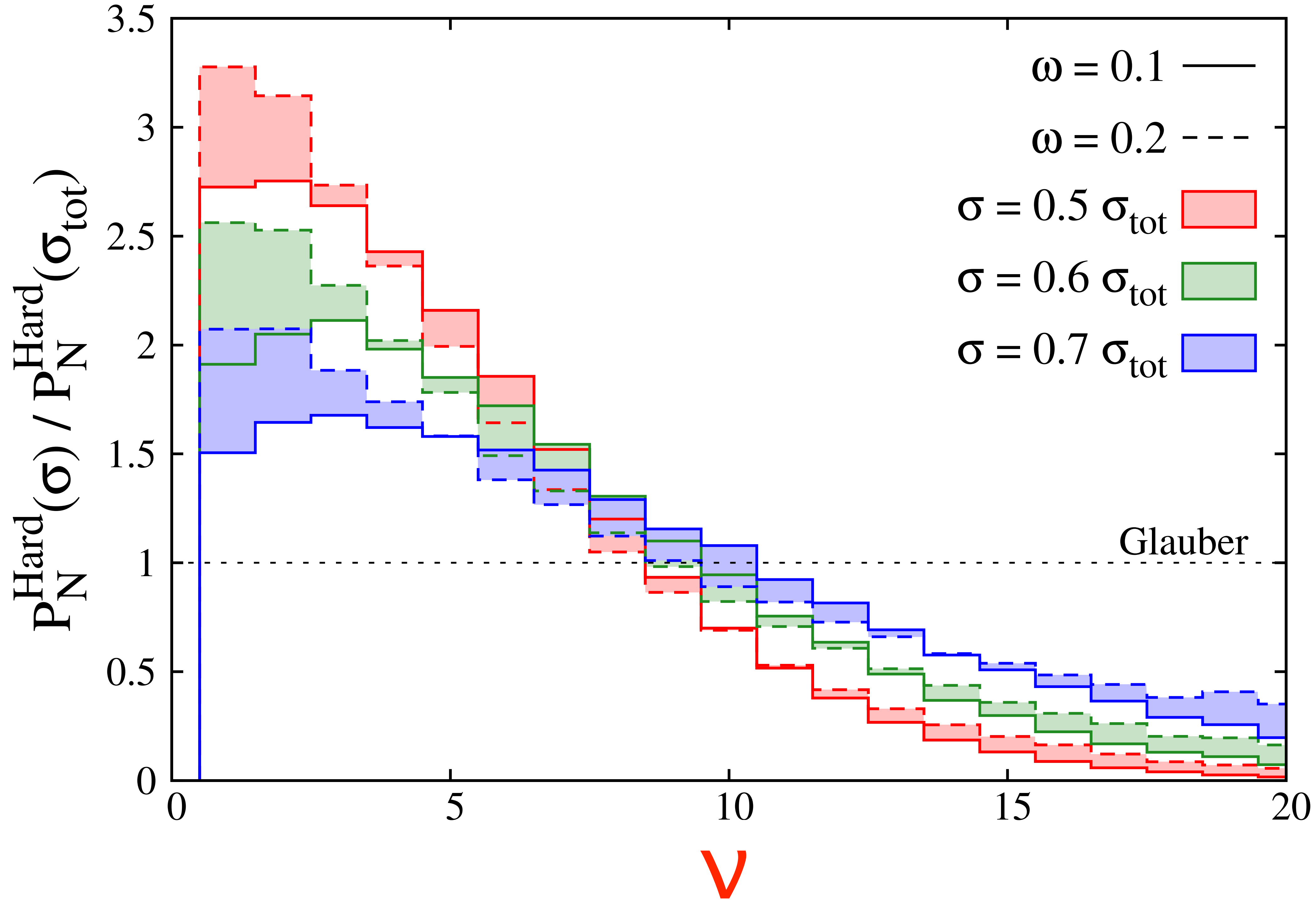
- With Glauber-Gribov N_{part} distribution, the best fits become more WN-like

–e.g. for $\Omega = 0.55$, $k_1 = 0.9$ ($0.64\ k_0$), $\theta_1 = 0.07$

From B.Cole

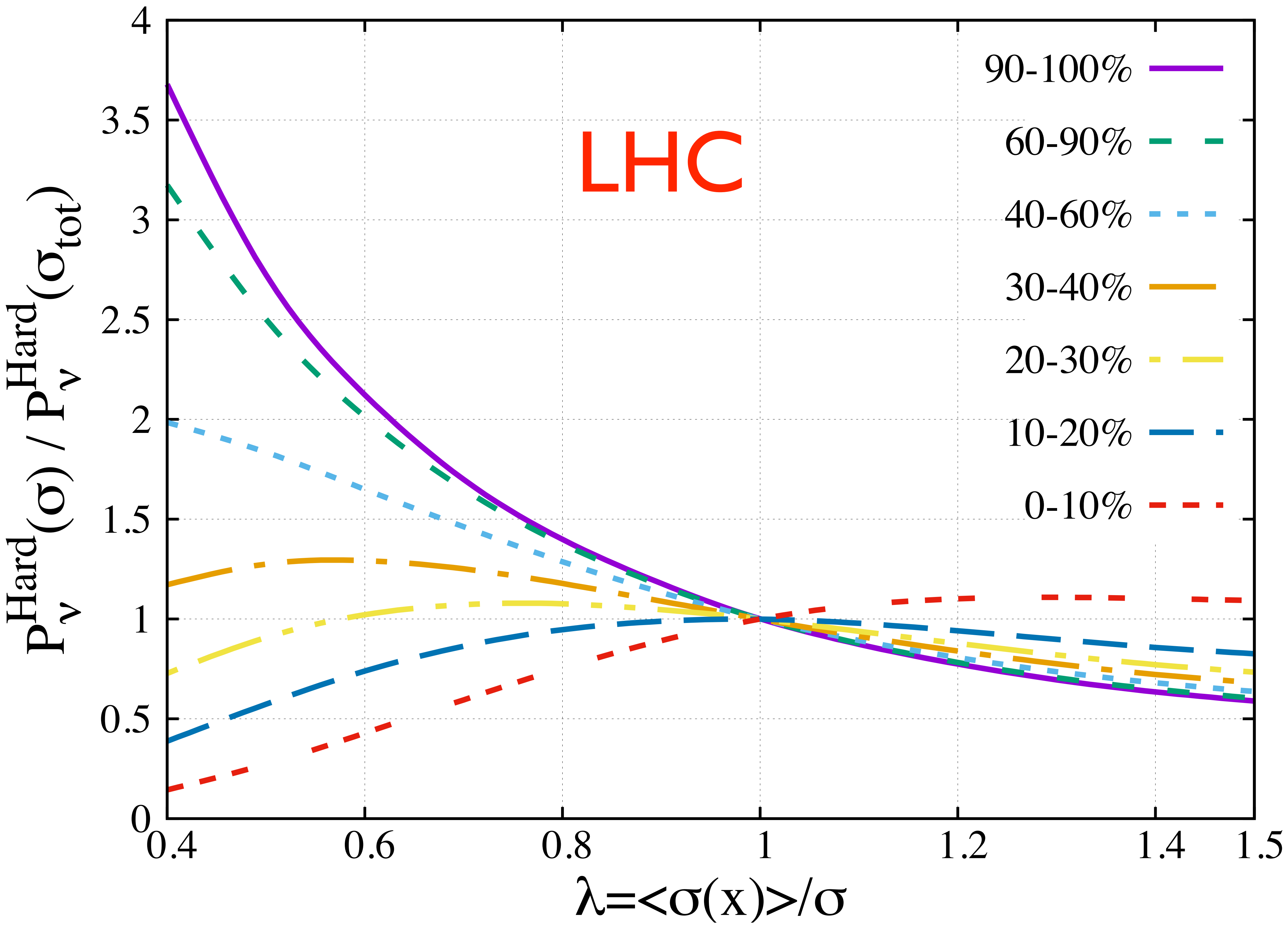
⇒Glauber-Gribov smooths out the knee in the N_{part} distribution

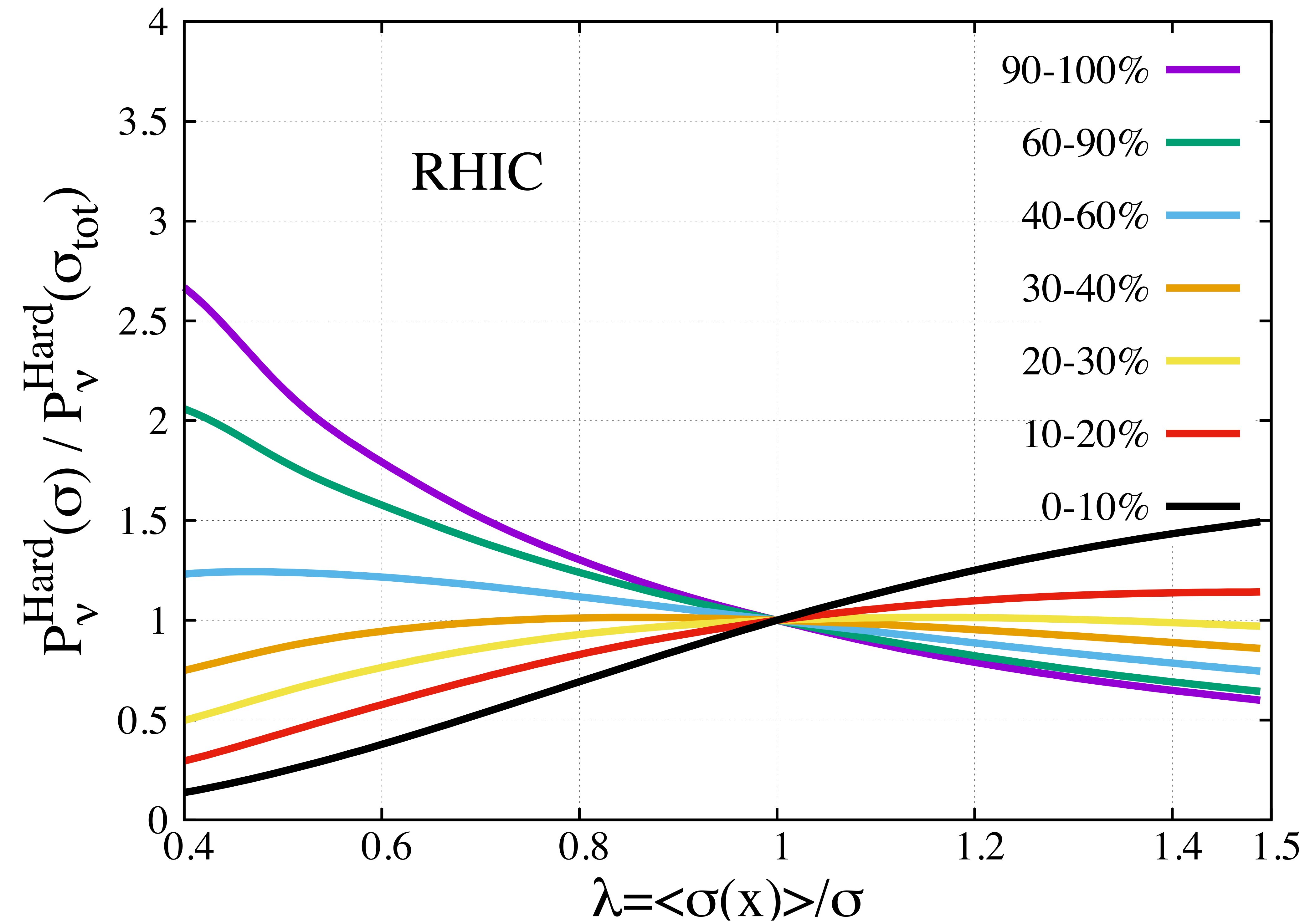
Fluctuations for configurations with small σ maybe different than for average one so we considered both $\omega_\sigma(x\sim0.5)$ =0.1 & 0.2



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

R_{hard} for different centralities is calculated as a function of one x-dependent parameter $\lambda = \sigma(x)/<\sigma>$





We can estimate $\sigma(x=0.6)/\sigma_{tot}[RHIC]=0.4\text{--}0.5$

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 ($\sim r_{N}/2$)

Small size configurations suppressed in bound nucleons (F83) ➠ explanation of the EMC effect

First rough estimates for smaller x:

$\sigma(x=0.2)/\langle\sigma\rangle=0.8$ gluon contribution sets in (smaller size than quarks for same x?)

$\sigma(x=0.1)/\langle\sigma\rangle=1.0$

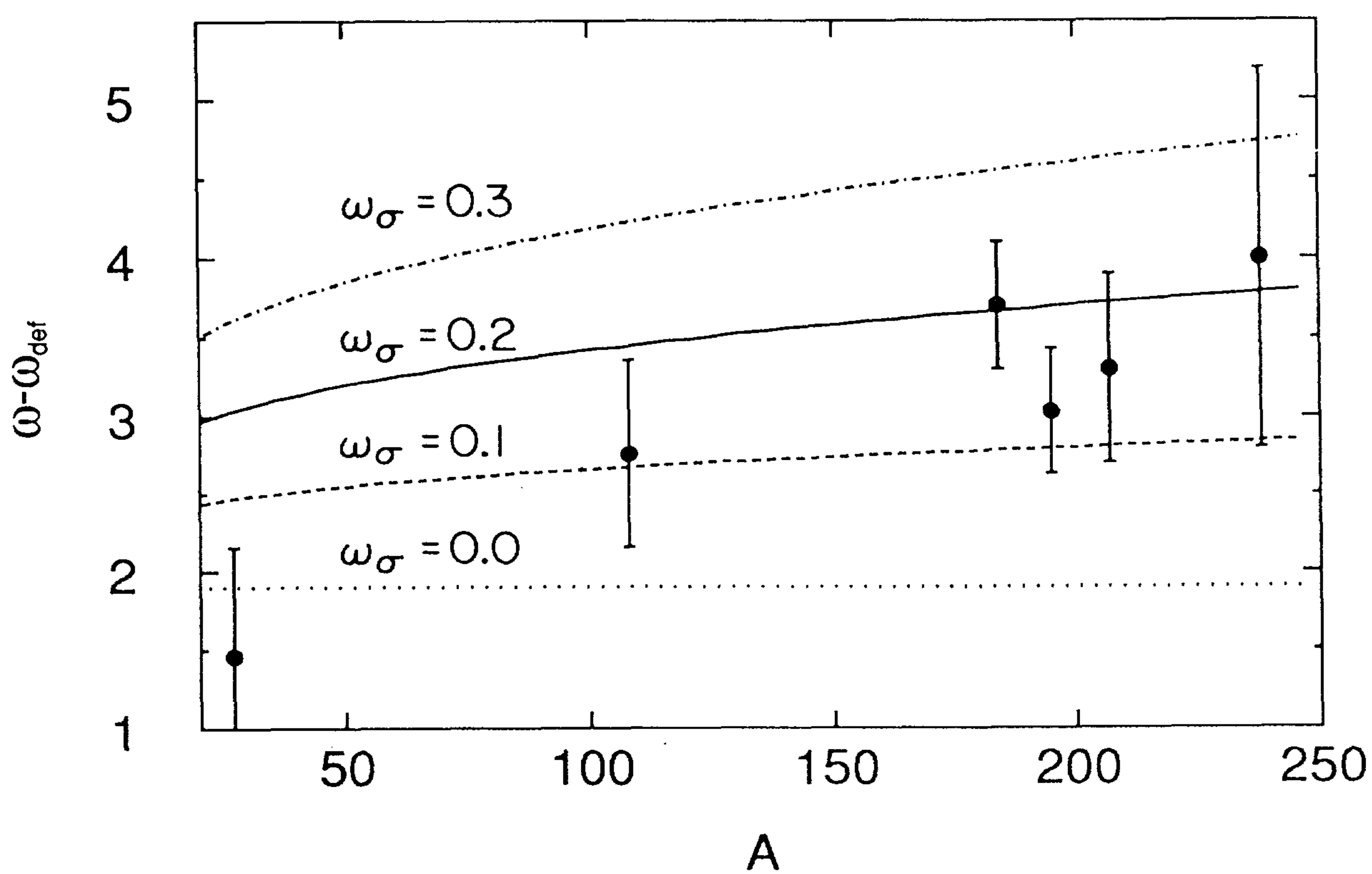
Qualitative expectation: CF increase fluctuations of a number of observables in pA and AB collisions.

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



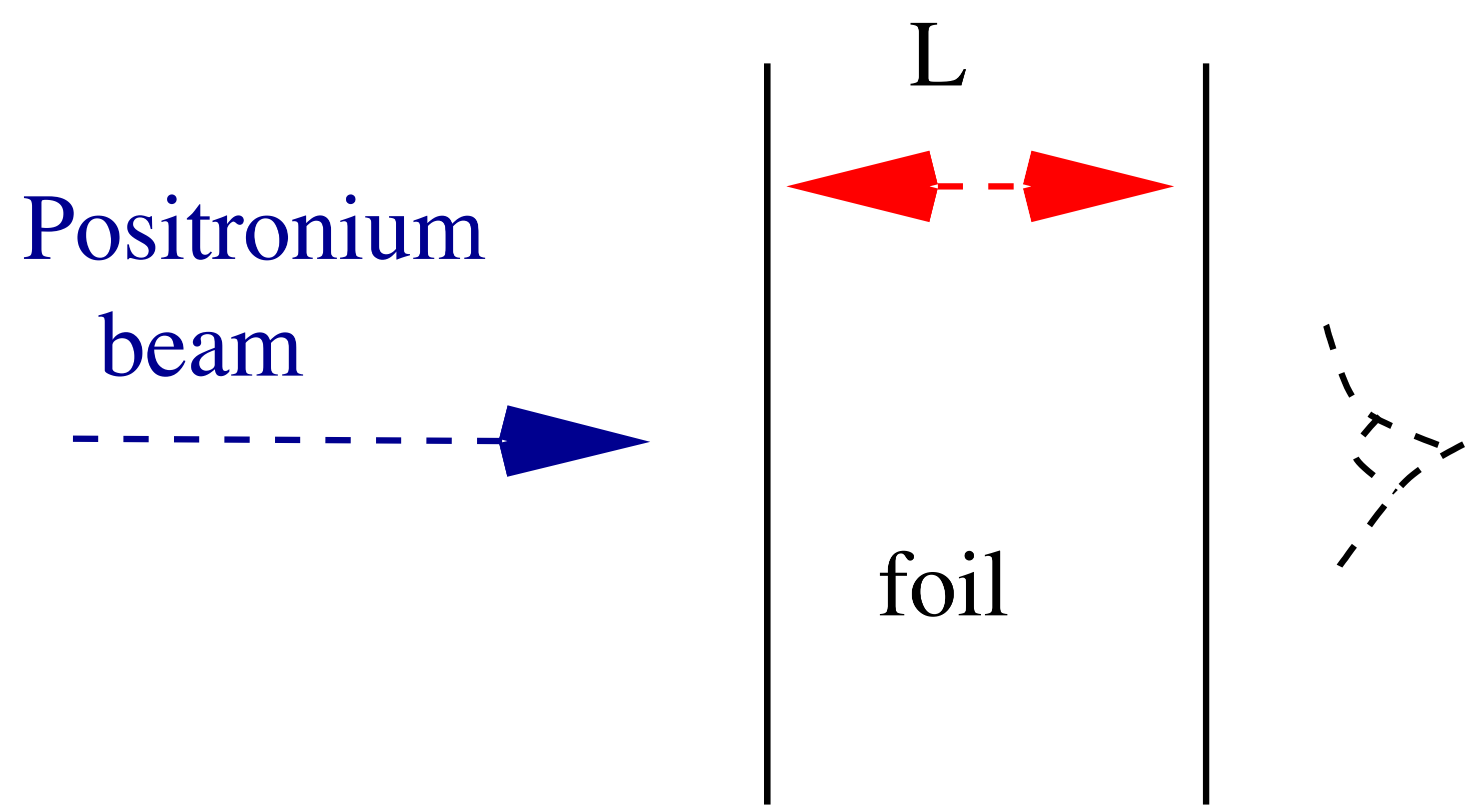
Dispersion of E_T distribution in central ^{32}S A collisions at SPS at E/A =200 GeV

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

Instructive example: propagation of a very fast positronium (bound state of electron and positron) through a foil

$$\frac{P_{pos}}{2m_e} \cdot \frac{1}{\Delta E(\sim few\ m_e\alpha^2)} \gg L(foil)$$

first qualitative discussion - Nemenov, 1981, quantitative treatment Frankfurt and MS 91)



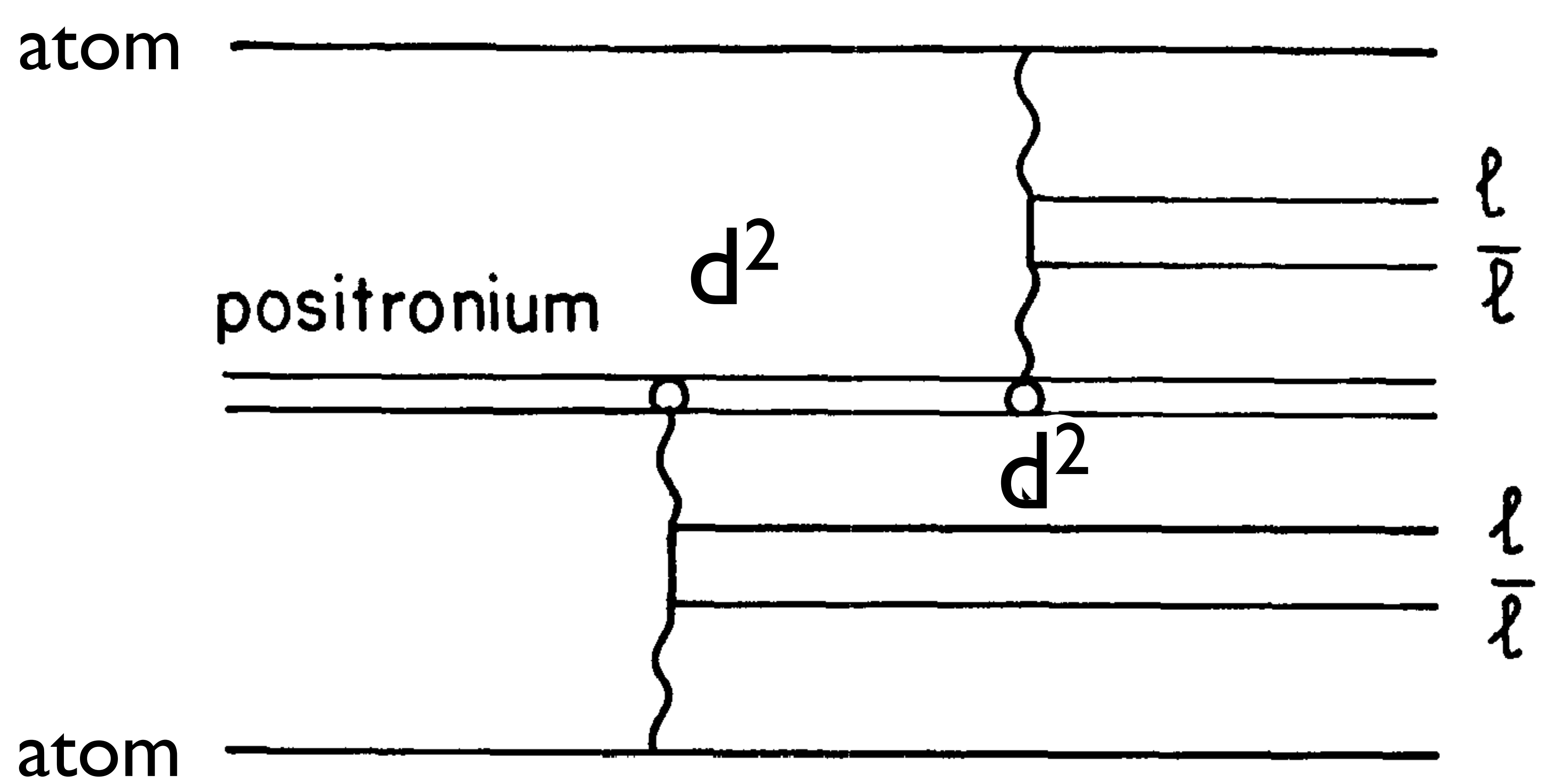
For the positronium at high energies transverse size is frozen during traversing through the foil - so interaction is of dipole-dipole type $\sigma(d) \propto d^2$ where $d = r_t^e - r_t^{e^+}$

Amplitude of i → f transition: $$|M_{if}| = \left[\int d^3r \Psi_{pos} \Psi_f^* \exp(-\sigma(d)\rho L/2)\right]^2$$

For large L: survival probability $\frac{16}{(<\sigma>\rho L)^2}$ absorption is not exponential !!!

Even larger probability to transform to electron - positron pair of the same momentum as positronium $\frac{2}{<\sigma>\rho L}$

Can we instead trigger on larger than average size configuration in positronium?

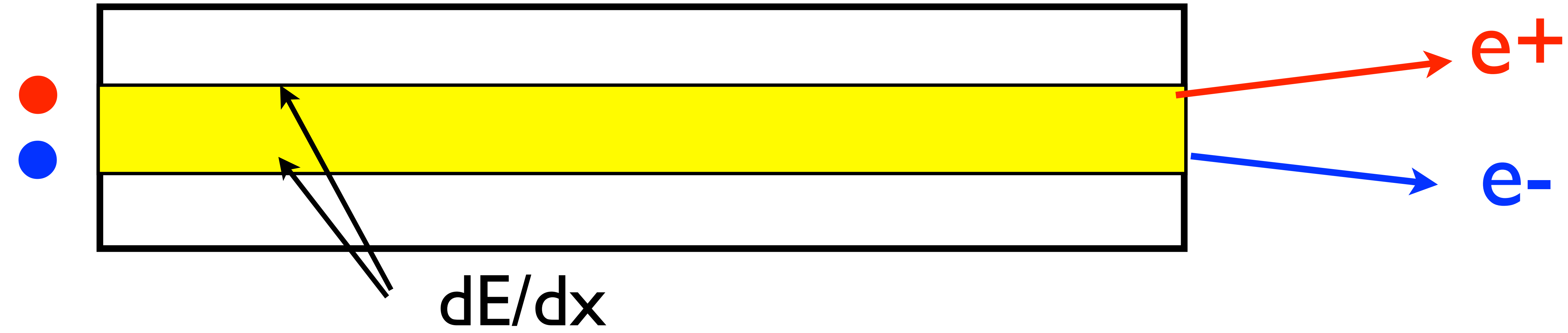


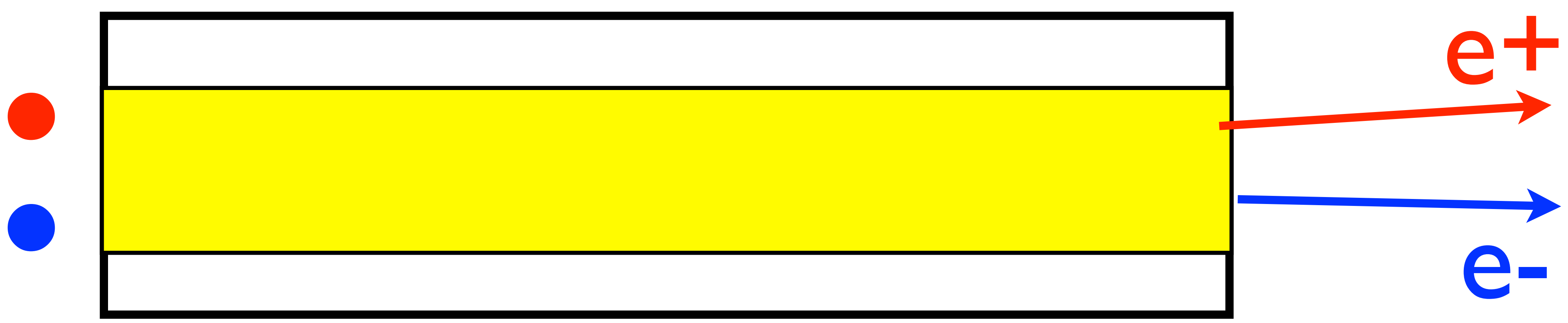
Consider production of one (two) lepton pairs with small momenta in the center of mass:
<d²> for these events is larger than in $\Psi^2_{pos}(d) = \int \Psi^2_{pos}(r)dz$ ➡ $\langle d^2_{2l\bar{l}} \rangle > \langle d^2_{l\bar{l}} \rangle > \langle d^2 \rangle$

Effects:

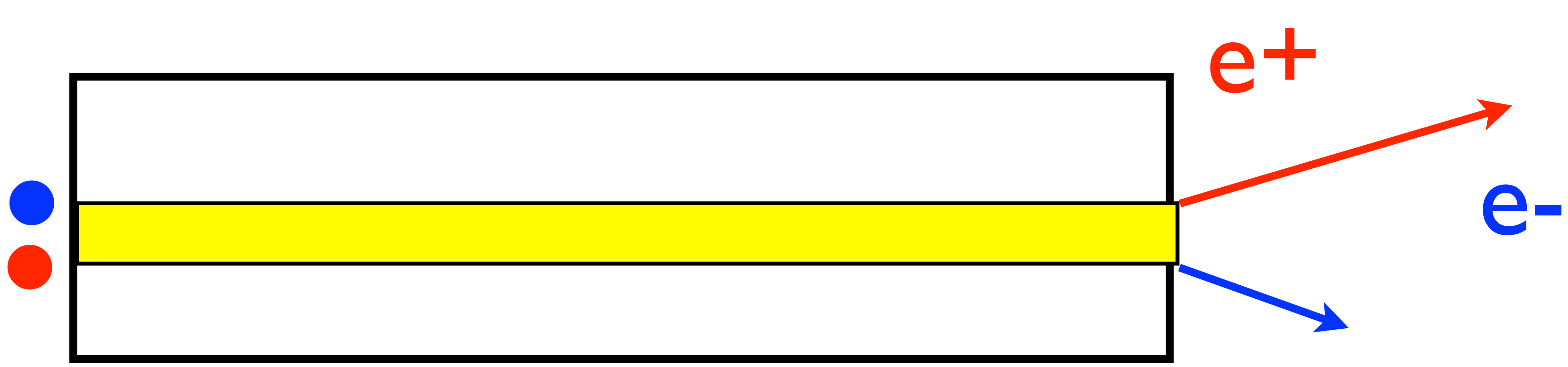
- *Positive correlation between production of one and two pairs*
- *Correlation between energy release along the positronium path and final momenta of e- e+ (next slide)*

Average configuration of incoming positronium





Post selection /Trigger on large d - large energy release along the path in the media -selects smaller than average transverse and longitudinal momenta in positronium - longitudinal momenta of electrons in the positronium fragmentation are softer (x-1/2 closer to 0)- looks as energy loss - but actually post selection.



Trigger on high p_t electron or electron with $x > 1/2$ (fraction of momentum of positronium carried by electron post selects events where excitations along the path were small.

Will discuss later similar effects for proton - nucleus interactions

$\Rightarrow$ The non exponential behavior is a manifestation of high energy coherence - slow down of space-time evolution

$\Rightarrow$ Various triggers allow to change proportion of small and large configurations in the data sample

$\Rightarrow$ *Inelastic processes are sensitive to presence of large & small size configurations in projectile - longer the target (nucleus) --higher the sensitivity*.

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

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