Physics opportunities with a polarized pA@RHIC

Mark Strikman, PSU

The Physics of p↑+A Collisions at RHIC, 01/07/13

General remarks

Amazingly little is known about pA at collider energies.

- dependence of various observables on nuclear thickness - T(b). Hardly possible to study in a clean way using dA. Possible in pA if running with several nuclei - defining centrality classes of events in pAu cannot be trusted as it is based on low energy Glauber picture

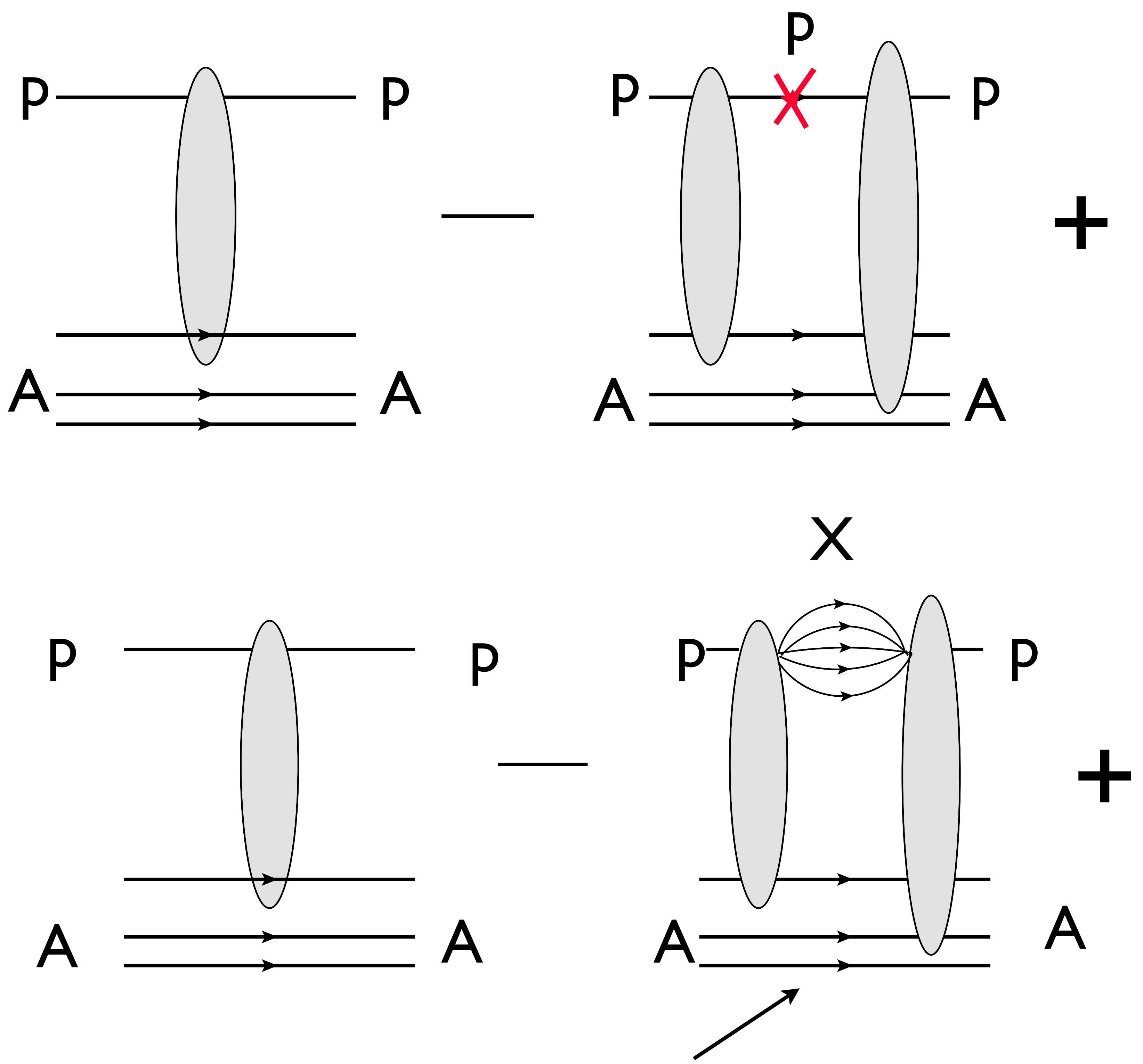
- T(b) -dependence of forward large p_t pion production - e.g. how big is suppression for central pAu collisions.

- Are the low pt forward neutron & pion spectra are qualitatively different for central and peripheral collisions

- Forward physics in pA at LHC and RHIC --- change in x by a factor ~ 600 - comparison will be of great help for understanding small x dynamics.

- *Polarization - icing on the cake.*

High energy space-time picture of soft pA - Gribov - Glauber fundamentally different from low energy Glauber picture



Glauber model

in rescattering proton in intermediate state - zero at high energy - cancelation of planar diagrams (Mandelstam & Gribov)- no time for a proton to come together between nucleons. Violates energy conservation for cut through two exchanges

High energies = Gribov -Glauber

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

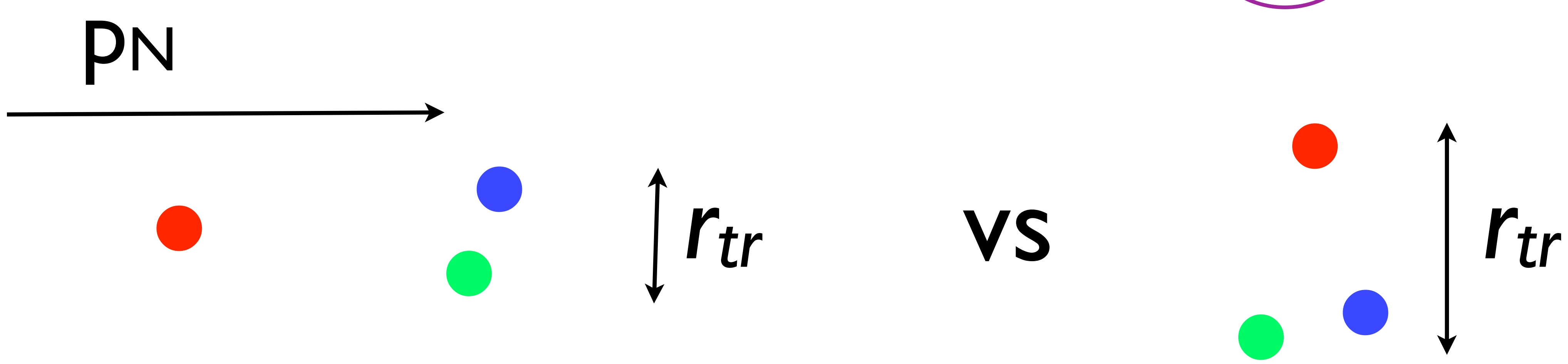
$$\sigma_2 \propto \int dt F_A^2(t) \frac{d\sigma(p+p \to p + X(p + \ inel \ diff))}{dt}$$

Deviations from Glauber for σ_{in}(pA) are small for Einc ~ 10 GeV as inelastic diffraction is still small. They stay small for heavy nuclei for all energies. But for pD at ISR at large t effect is large ~40%. An effective way to implement Gribov-Glauber picture of high energy pA interactions is the concept of color fluctuations

Color fluctuations in the nucleon wave function & 3-dimensional mapping of the nucleon

Are there global fluctuations of the strength of interaction of a fast nucleon, for example due to fluctuations of the size /orientation. Extreme case - color transparency.

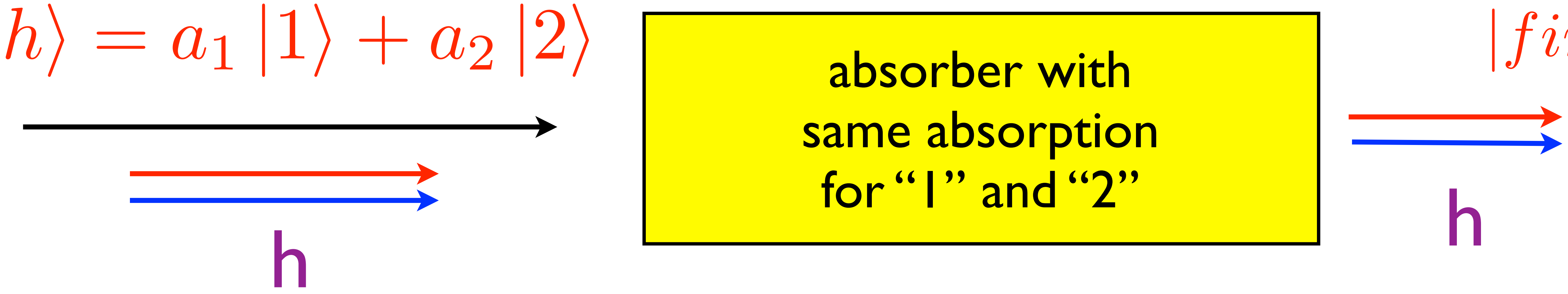
$$|N\rangle = 3q + 3qg + 3q + \pi + \ldots$$



Due to a slow space-time evolution of the fast nucleon wave function one can treat the interaction as a superposition of interaction of configurations of different strength - Pomeranchuk & Feinberg, Good and Walker, Pumplin &Miettinen. In QCD this is reasonable for total cross sections and for diffraction at very small t.

If there were no fluctuations of strength - there will be no inelastic diffraction at t=0:

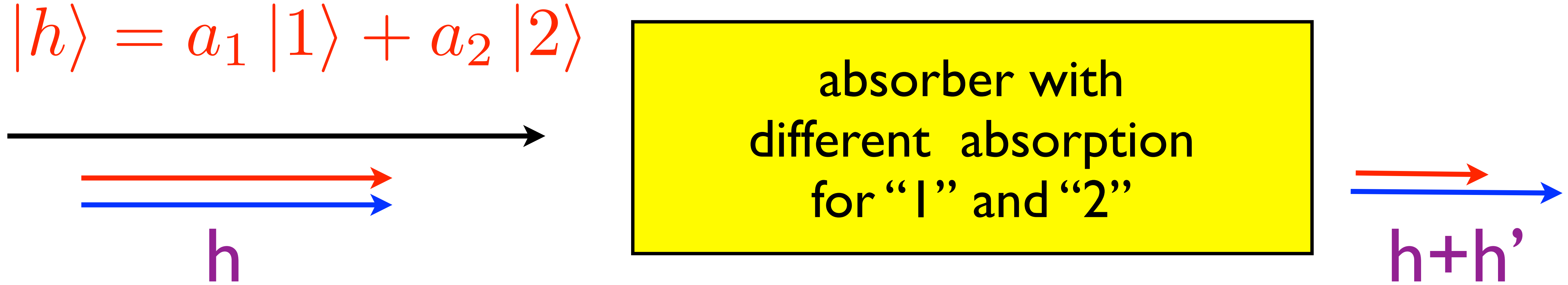
$$|h\rangle = a_1\,|1\rangle + a_2\,|2\rangle$$



$$|final\rangle = \lambda(a_1\,|1\rangle + a_2\,|2\rangle) = \lambda\,|h\rangle$$

only elastic scattering

$$|h\rangle = a_1\,|1\rangle + a_2\,|2\rangle$$



$$|final\rangle = \lambda_1 a_1\,|1\rangle + \lambda_2 a_2\,|2\rangle)$$
$$= c_1\,|h\rangle + c_2\,|h'\rangle$$

elastic scattering
+inelastic diffraction

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

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

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

variance

Pumplin &Miettinen

ω_σ(RHIC)=0.25 ω_σ(LHC)=0.20 - more data are coming from LHC

A very rough model illustrating scale of the effect

$$P(\sigma) = \frac{1}{2}\delta(\sigma - \sigma_{tot}(1-\sqrt{\omega_\sigma})) + \frac{1}{2}\delta(\sigma - \sigma_{tot}(1+\sqrt{\omega_\sigma}))$$

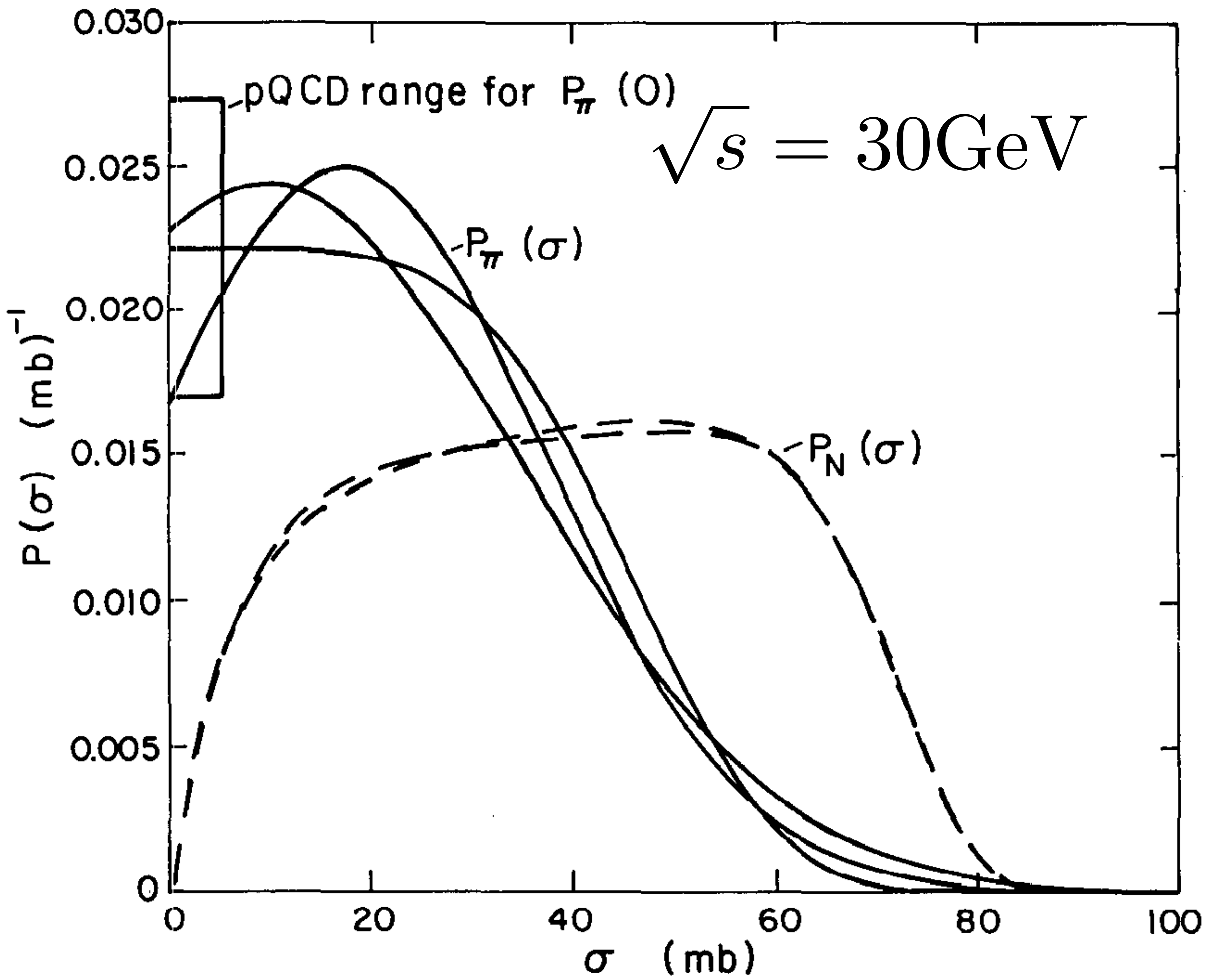
for $\omega_\sigma=0.25$, $\sigma_1=0.5\sigma_{tot}$; $\sigma_2=1.5\sigma_{tot}$

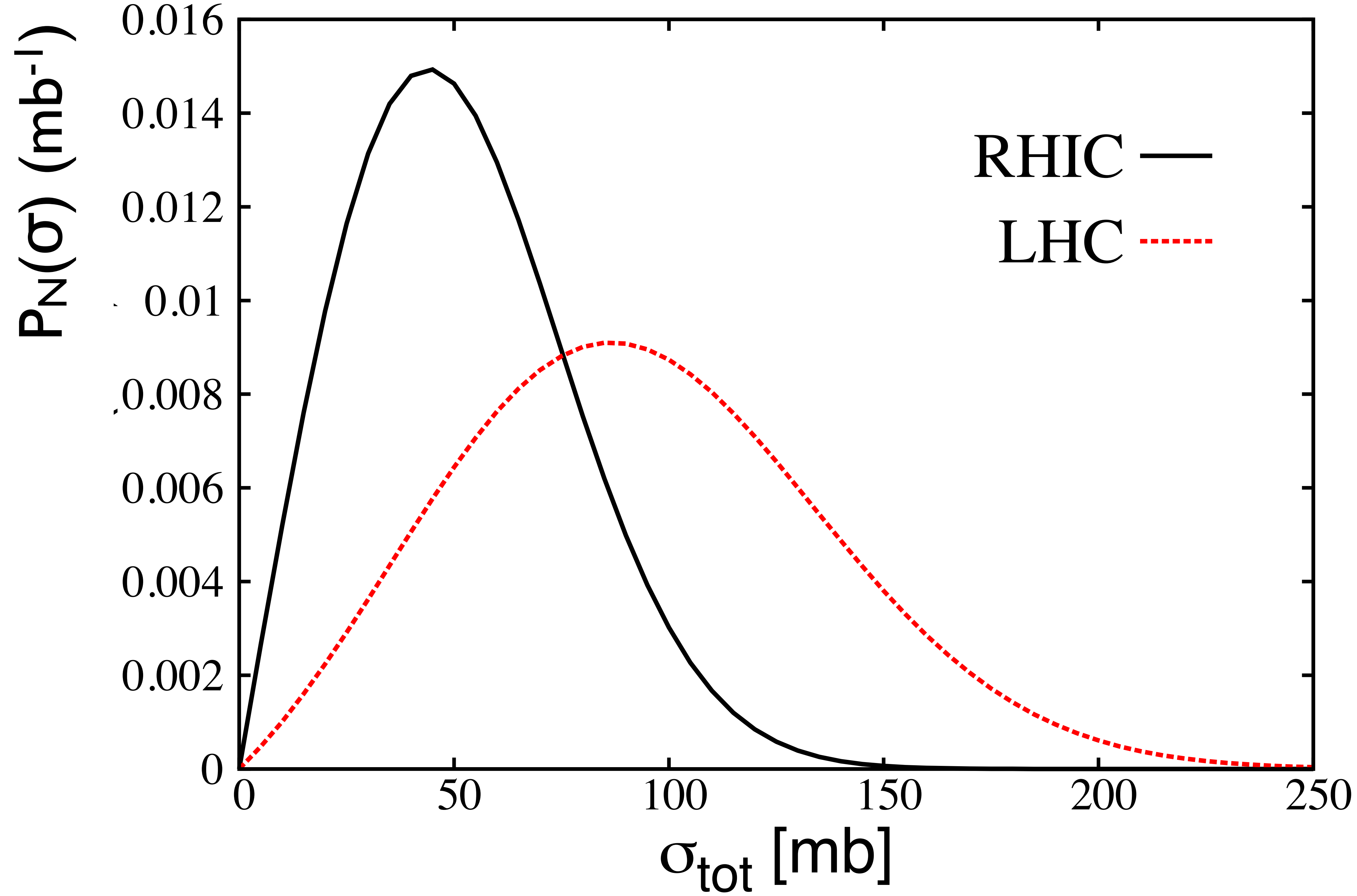
$\int (\sigma - \sigma_{tot})^3 P(\sigma) d\sigma = 0$,

Baym et al from pD diffraction

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

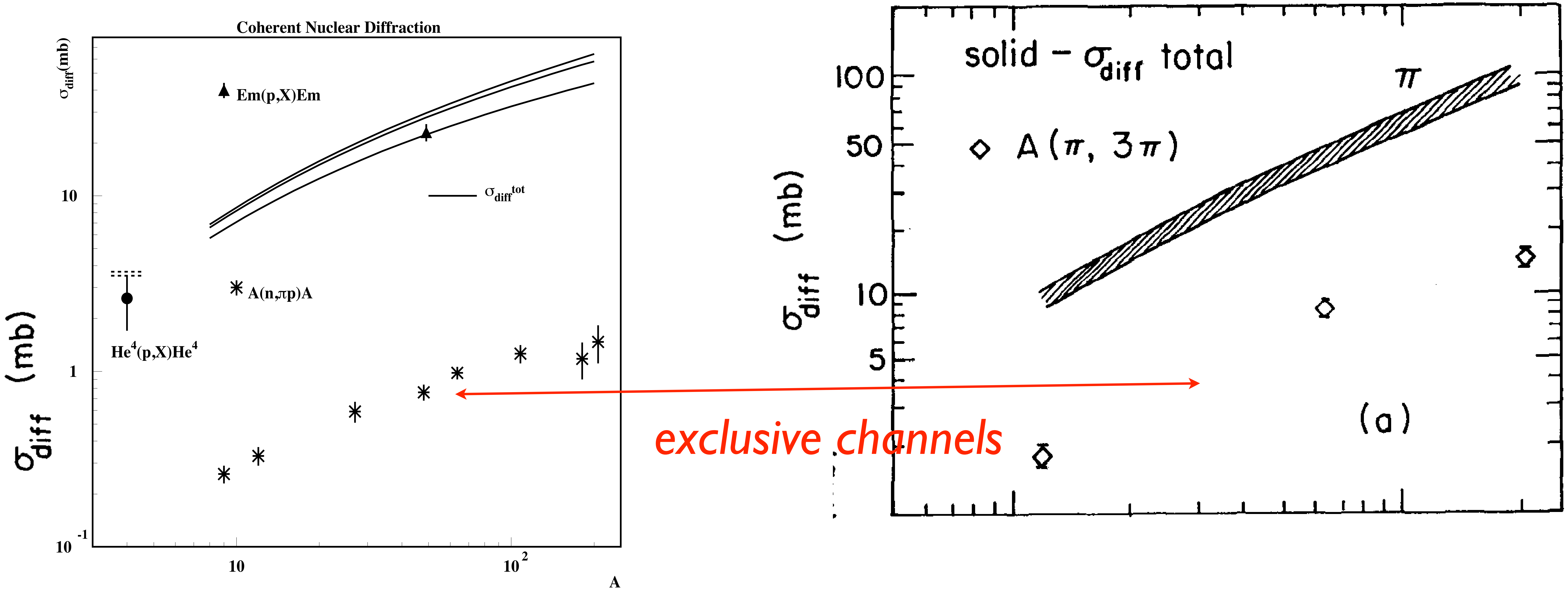
Baym et al 1993





$P_N(\sigma)$ extracted from pp,pd diffraction Baym et al 93. $P_\pi(\sigma)$ is also shown

Extrapolation of Guzey & MS to higher energy using diffractive data

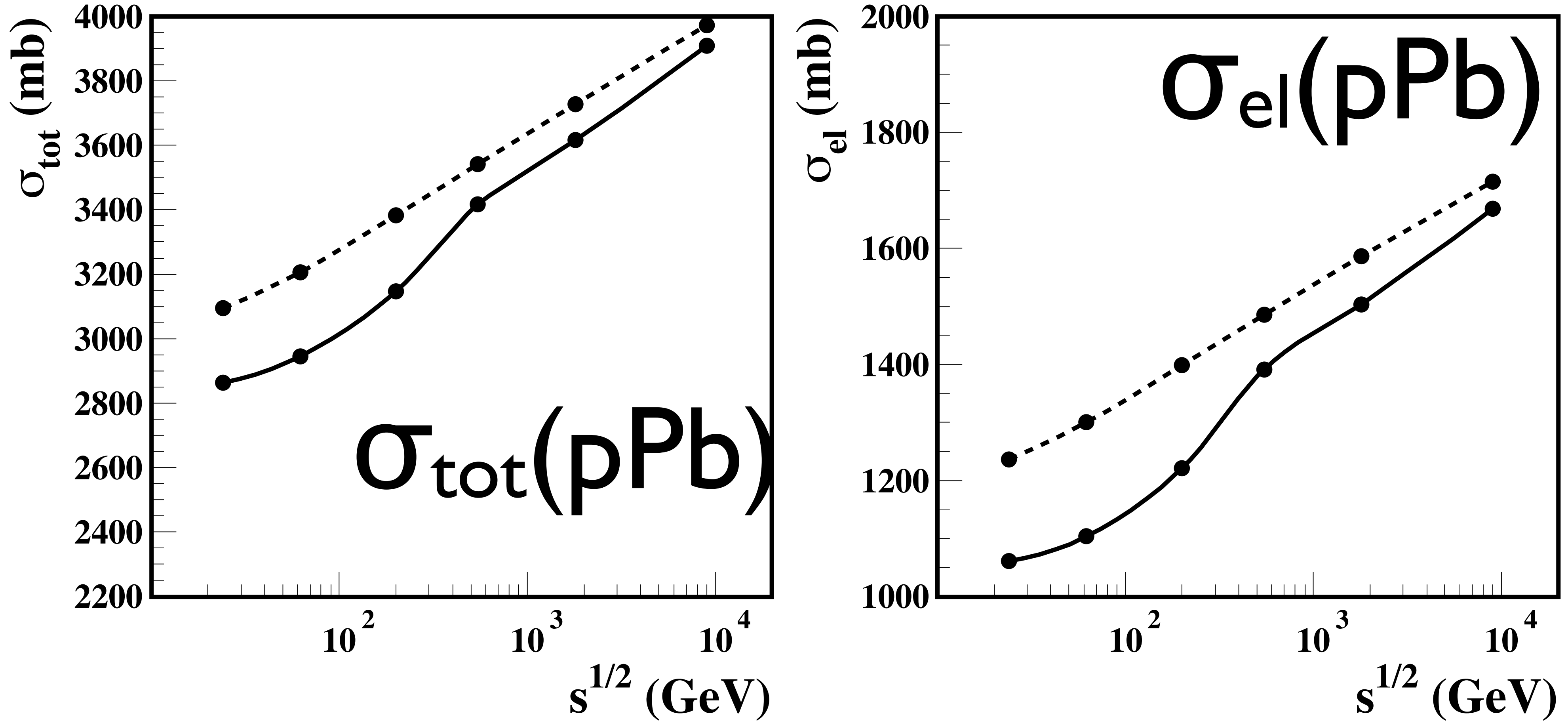


The inelastic small t coherent diffraction off nuclei provides one of the most stringent tests of the presence of the fluctuations of the strength of the interaction in NN interactions. The answer is expressed through $P(\sigma)$ - probability distribution for interaction with the strength σ. (Miller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

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

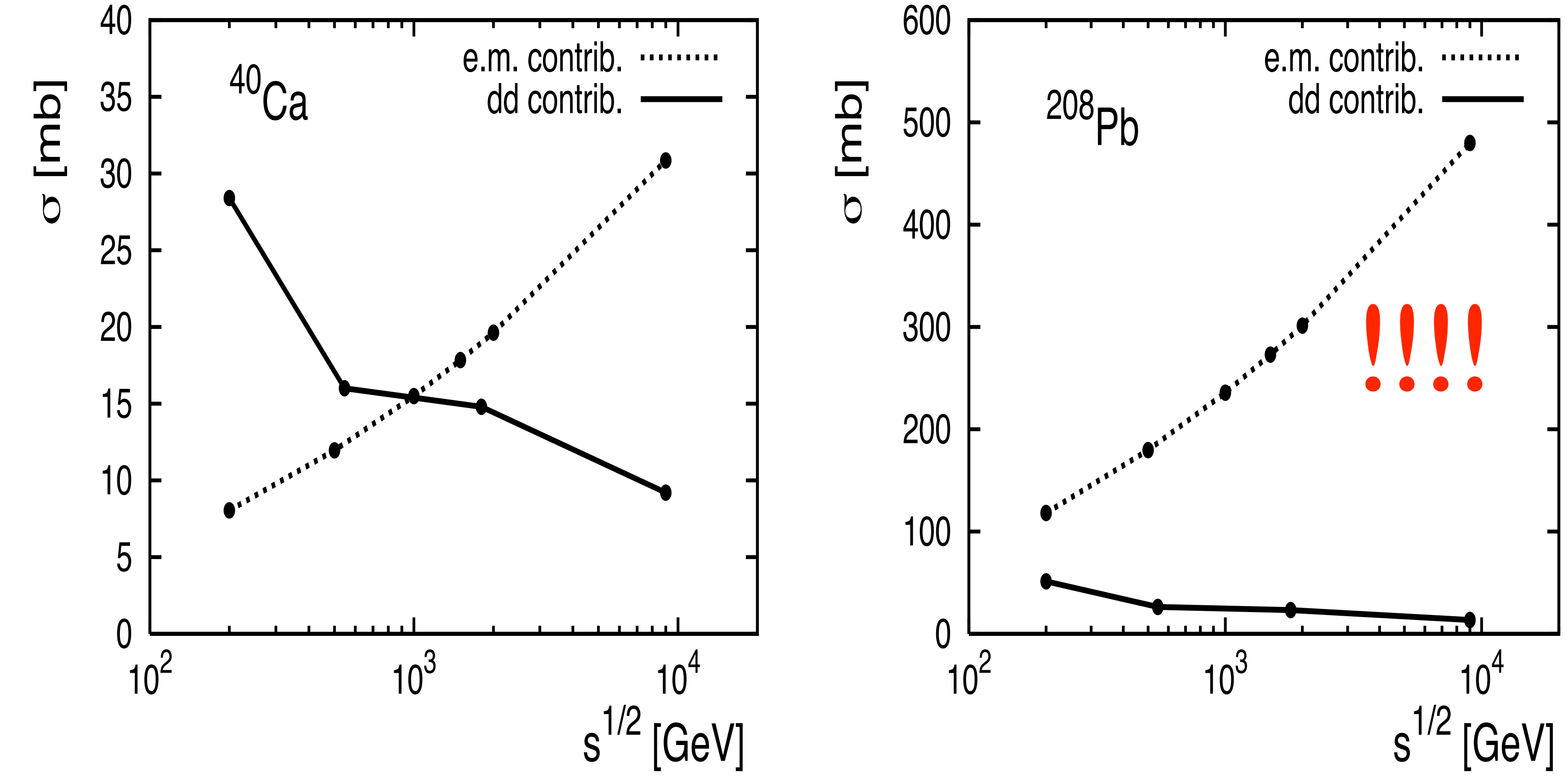
Here $F(\sigma,b) = 1 - e^{-\sigma T(b)/2}$, $T(b) = \int_{-\infty}^{\infty} \rho_A(b,z)dz$, and $\rho_A(b,z)$ is the nuclear density.

Color fluctuations/inelastic shadowing



Guzey & MS

$\sigma_{diff}(pA \to XA)$



⇒ E.M. interaction dominates by far in diffraction above RHIC true for hard diffraction as well (Guzey, MS)

⇒ For RHIC for A=200 comparable contributions, for A=40, e.m. contribution is a small correction. A unique opportunity for RHIC. Use ZDC?

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

Simple illustration - two component model ≡ quasieikonal approximation:

RHIC $\sigma_1 = 25\, mb,\ \sigma_2 = 75\, mb$

number of wounded nucleons at small b differs by a factor of 3 !!!

LHC $\sigma_1 = 60\, mb,\ \sigma_2 = 140\, mb$

Scattering at b=4.6 fm with probability ~ 1/2 generates the same multiplicity as collision at b=0. *Smearing of the centrality*

color fluctuations lead to addition dispersion as compared to the geometrical model

Color fluctuation model implementation of the Gribov - Glauber approximation in optical limit

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

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

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

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

Numerical calculations (Alvioli and MS arXiv:1301.0728) - event generator using our set of nucleon configuration with short-range correlations (small effect) and finite radius of NN interaction.

For NN scattering $P_{inel}(b) = 1 - |1 - \Gamma(b)|^2$

We also took σ/B= const for fluctuations (corresponding to σ_{el}/σ_{tot}=const)

B is t-slope of elastic cross section

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

with parameters fixed to satisfy sum rules

	Monte Carlo			Optical Model		
energy/model	$\langle N \rangle$	$\langle N^2 \rangle$	ω_N	$\langle N \rangle$	$\langle N^2 \rangle$	ω_N
RHIC, Glauber	4.6	31.6	0.51	5.0	35.9	0.46
RHIC, GG2	4.7	38.9	0.74	5.1	45.3	0.71
RHIC, GG $P(\sigma)$	4.8	39.2	0.72	5.2	45.6	0.70
LHC, Glauber	6.7	72.4	0.59	7.6	88.0	0.51
LHC, GG2	6.8	84.2	0.80	7.8	106.2	0.75
LHC, GG $P(\sigma)$	6.8	82.1	0.77	7.8	106.4	0.74

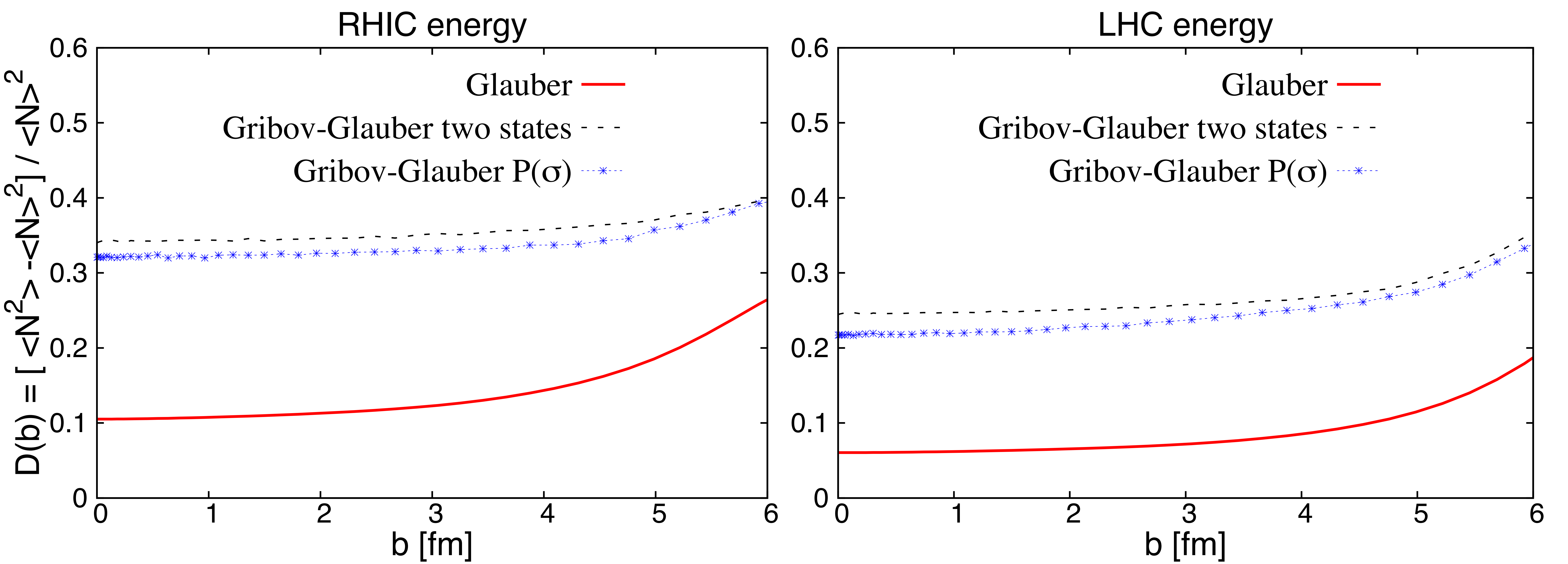
$$\omega_N \equiv \frac{\langle N^2 \rangle}{\langle N \rangle^2} - 1$$

Small effect for <N>

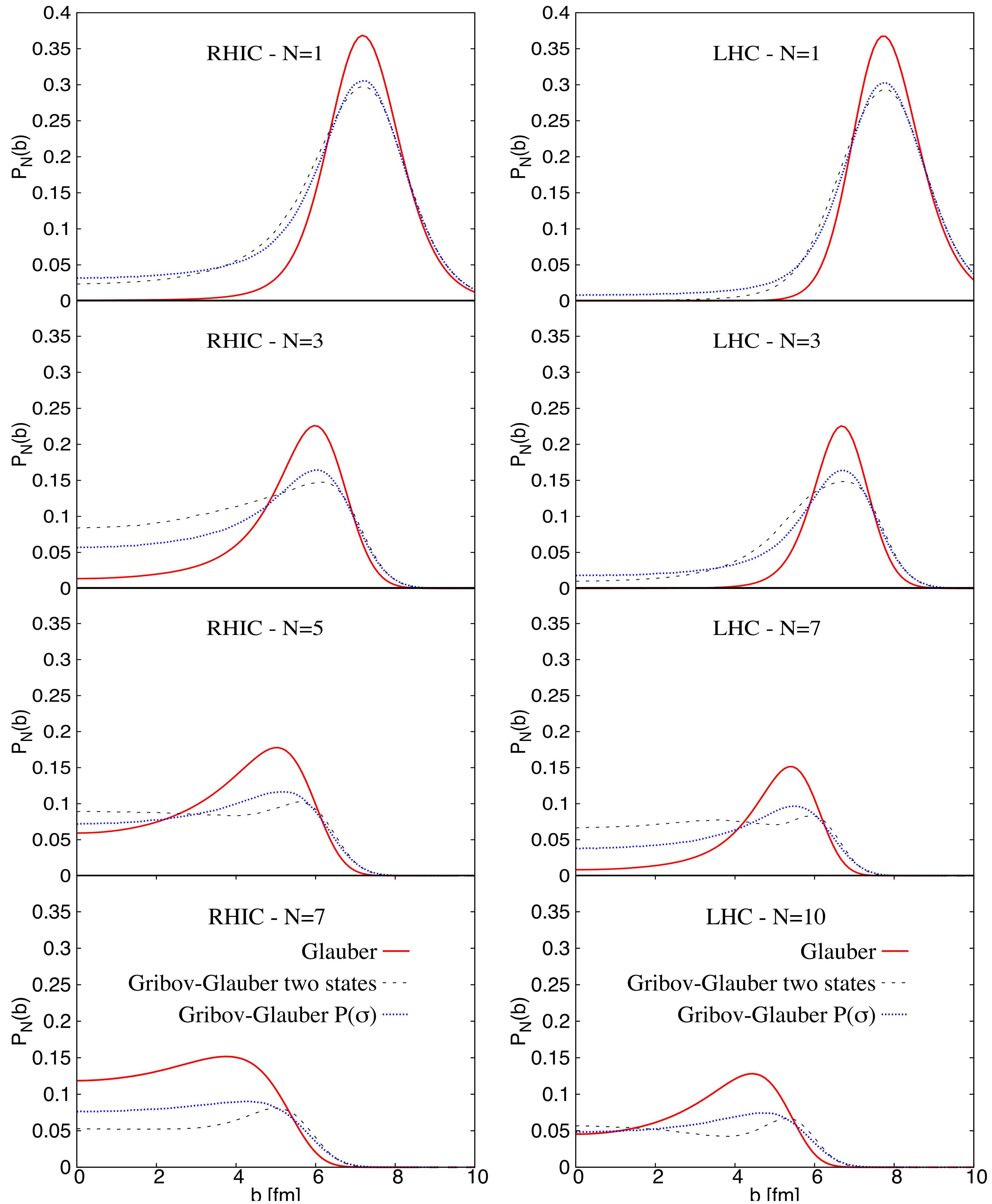
Large for dispersion even though in dispersion one integrates over impact parameters

GG= Gribov- Glauber,

GG2= Gribov- Glauber two component

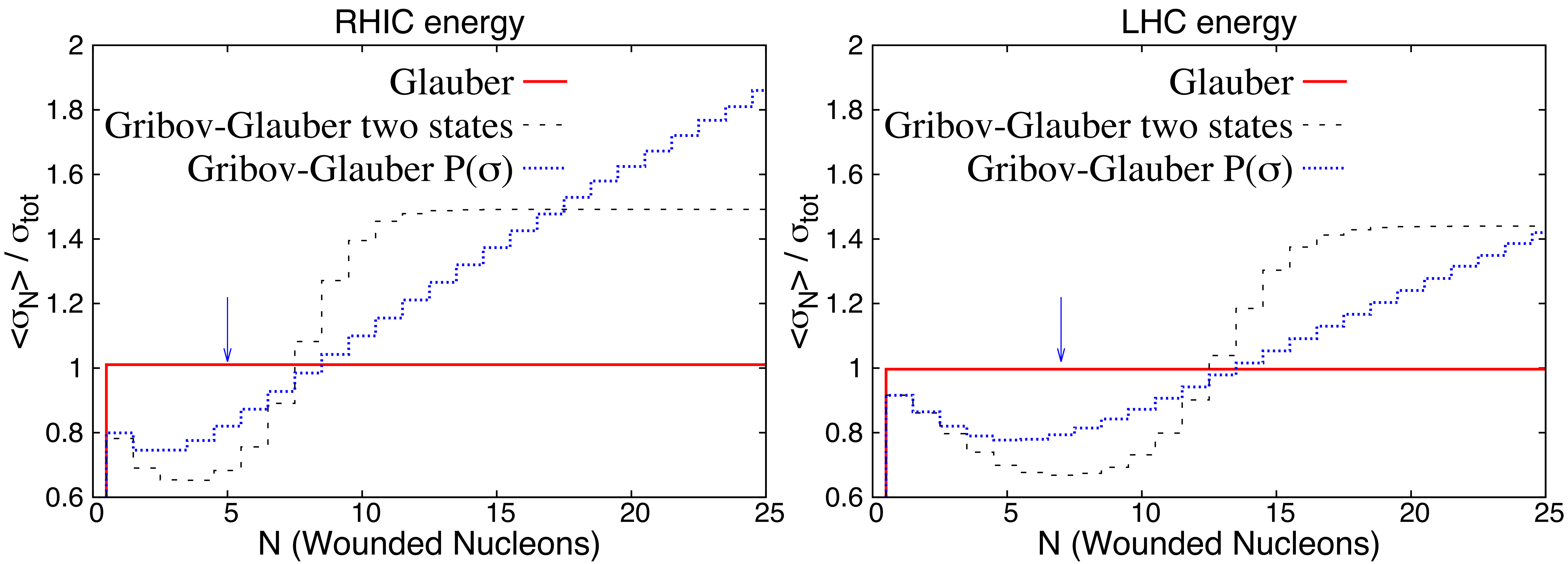


Color fluctuations give dominant contribution to fluctuations of the number of wounded nucleons for fixed b



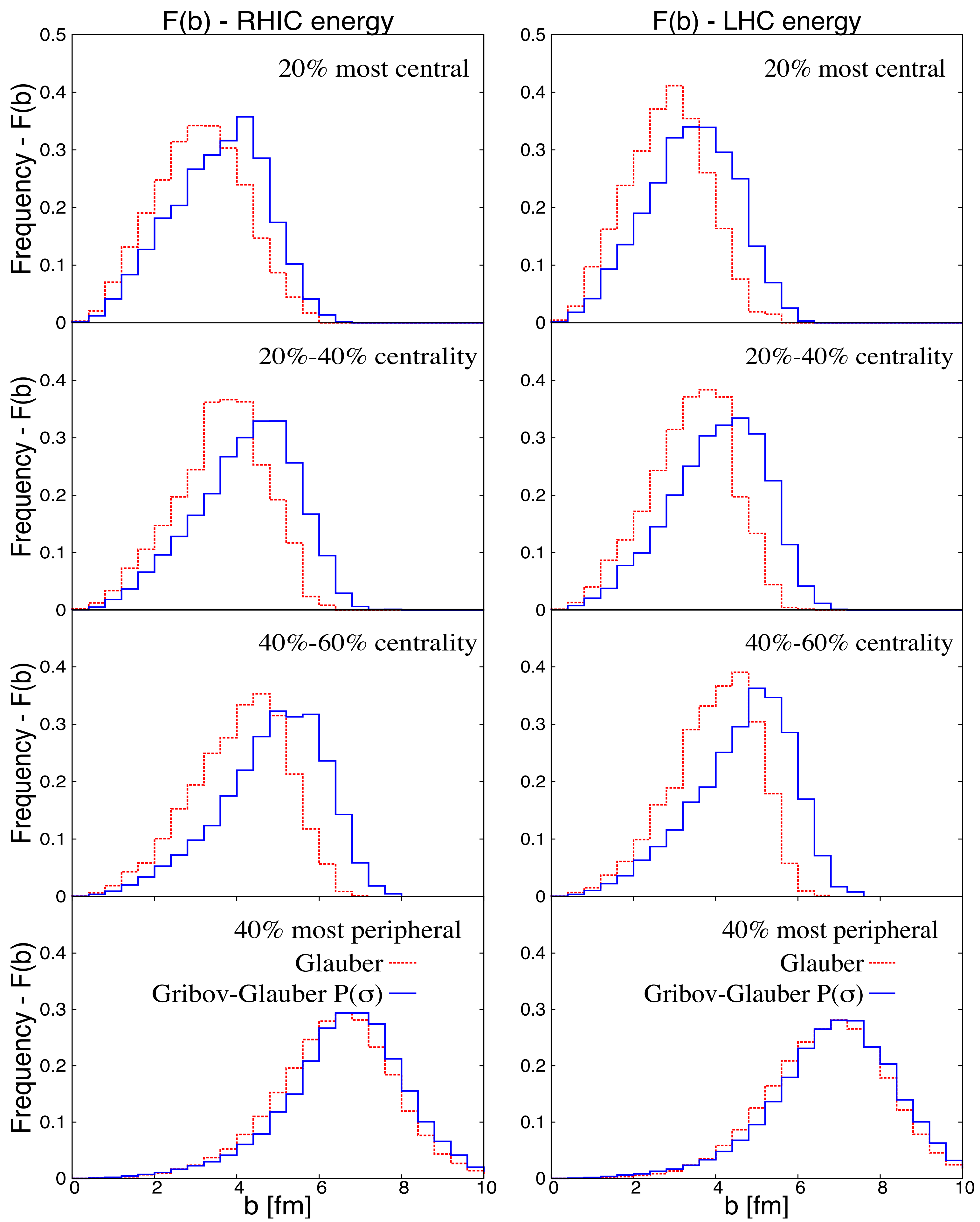
The probability P_N (b) of having N inelastically interacting (wounded) nucleons in a pA collision, vs. impact parameter b, when using simple Glauber (red curves) and a distribution P (σ) (green curves); We show the probabilities P_N (b) for N=1 (top row) for both energies and the curves for N corresponding to ⟨N⟩ and ⟨N⟩±0.5⟨N⟩ (remaining panels); ⟨N⟩ is 5 and 7 for RHIC and LHC energies, respectively

Large deviations from Glauber model



Effect of fluctuations on the event-by-event fluctuating values of cross section. Small numbe of wounded nucleons, N, selects $\sigma < \sigma_{in}$; large N --- - $\sigma > \sigma_{in}$

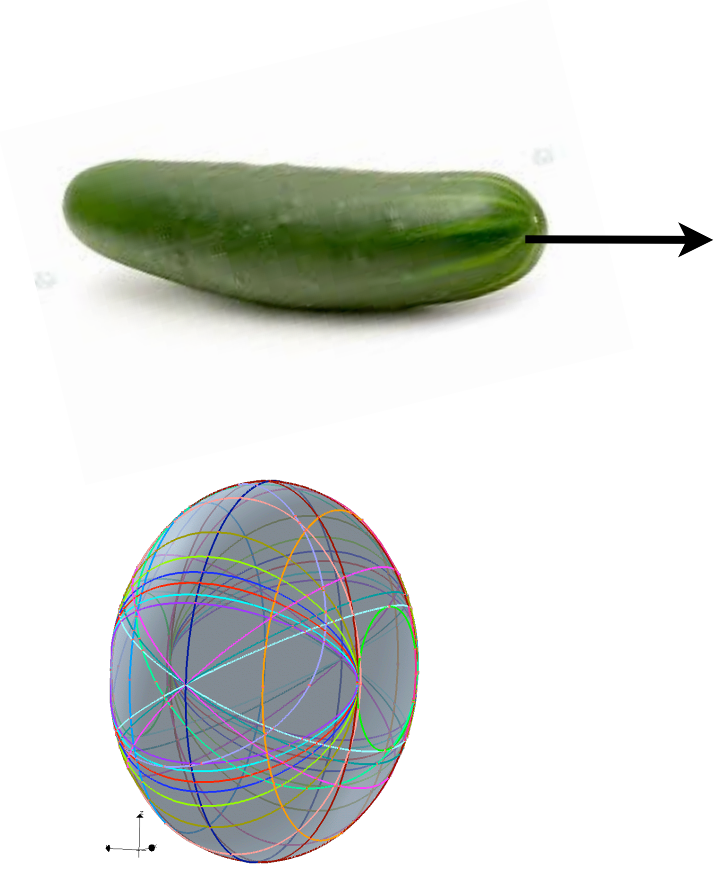
Note that since RHIC studied so far d-Au - smaller effect of fluctuations for hard trigger.

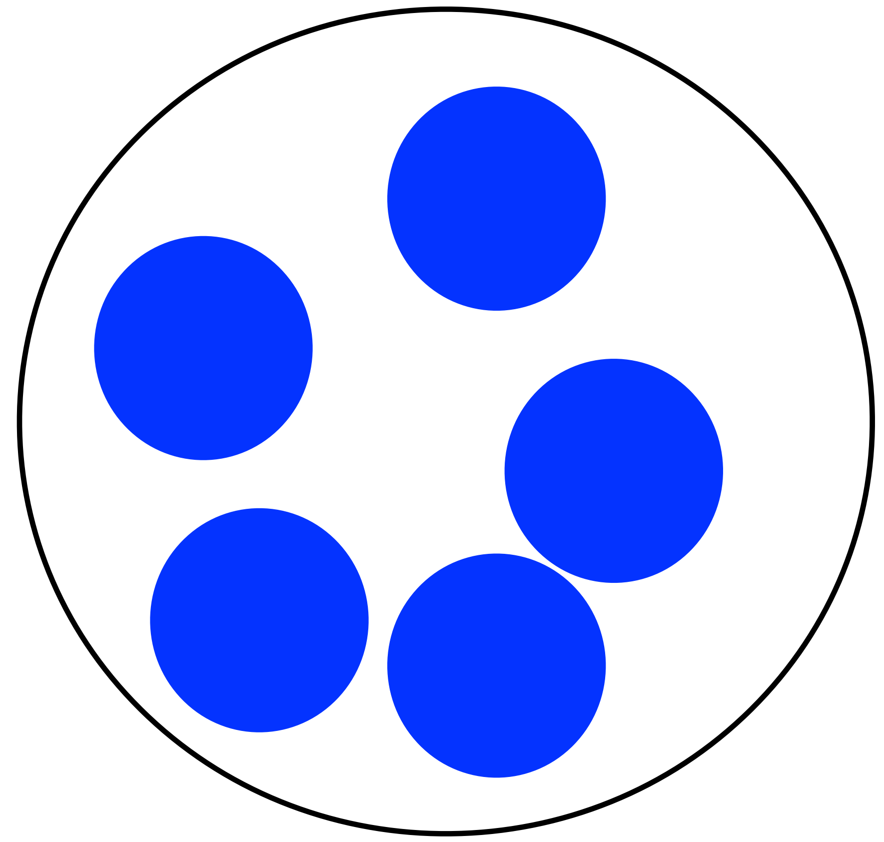


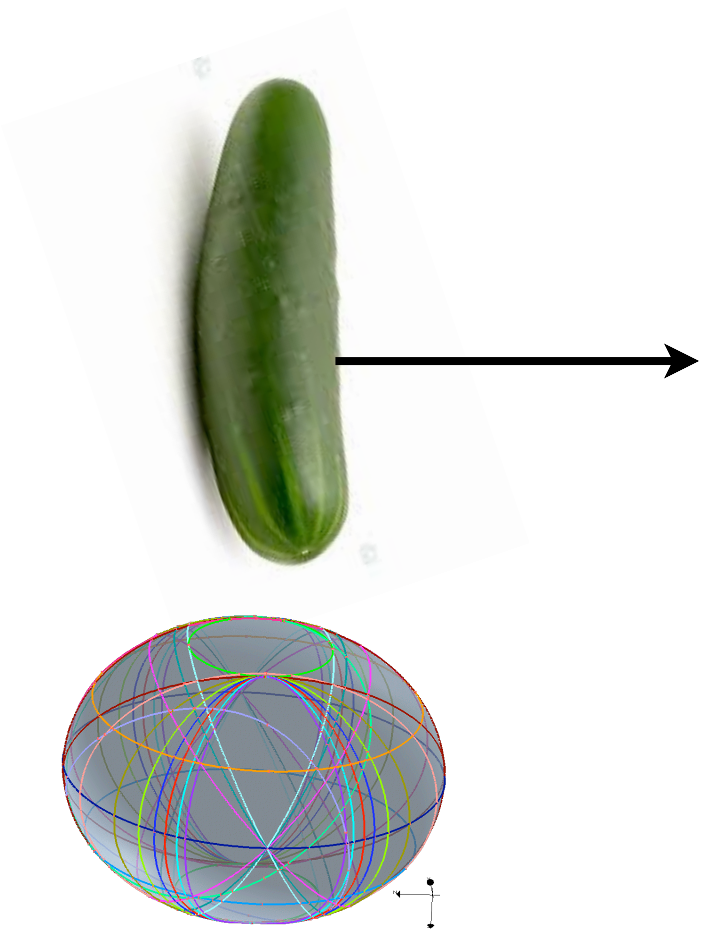
The distribution over impact parameter, calculated with our Monte Carlo, of the different centrality classes 20% most central (first row), 20%-40% (second row), 40%-60% (third row), 40% most peripheral (last row), both for RHIC (left) and LHC (right) energies. Red: Glauber result; blue: Gribov - Glauber color fluctuations with P(σ) distribution.

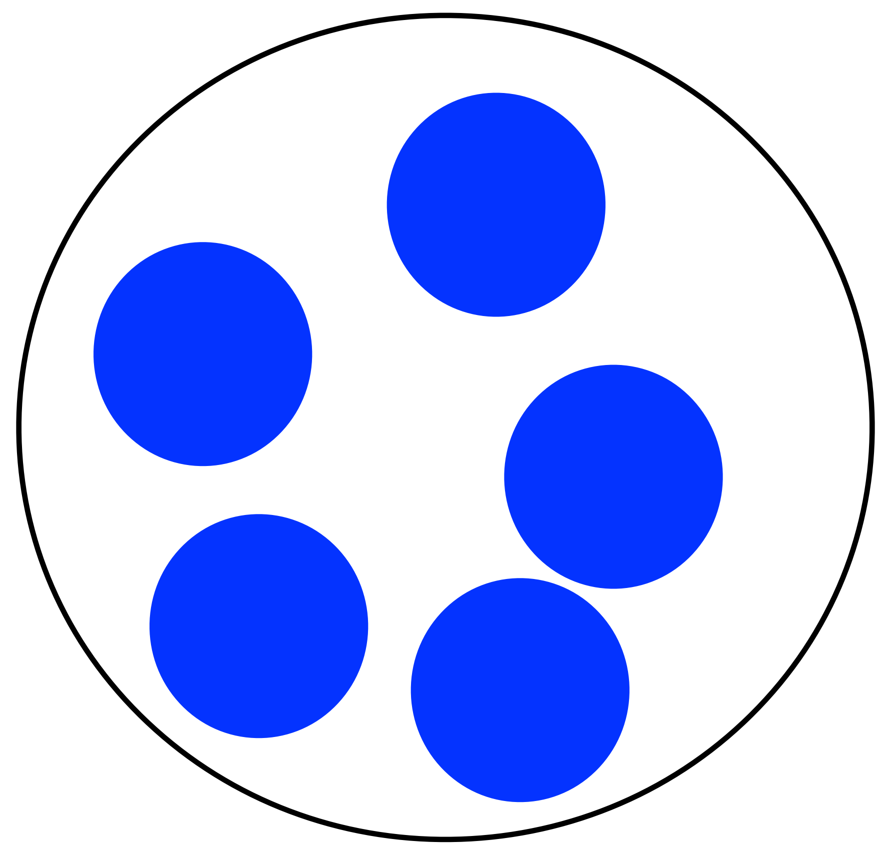
If one wants to perform a precision measurement of dependence of spin effect on nuclear thickness, measurements with a set of nuclei are necessary.

Different σ's --- different size, different shape, different parton densities









Correlation between the hard and soft components of the pA interaction.

Idea:

Use the hard trigger to determine x_p and low p_t hadrons to measure overall strength of interaction σ_{eff} of configuration in the proton with given x_p FS83

LHC - jets with large p_t - -- practically no nuclear shadowing effects

RHIC ? statistics, acceptance?

Expectation: Larger the size, more gluon radiation, softer the x distribution

Illustration $G(x, Q^2\,|\sigma) \;=\; G(x, \xi Q^2) \qquad \xi(Q^2) \;\equiv\; (\sigma/\langle\sigma\rangle)^{\alpha_s(Q_0^2)/\alpha_s(Q^2)}$

$where\, Q_0^2 \sim 1\,\mathrm{GeV}^2$

gives a reasonable magnitude of fluctuations of the gluon density

would result in different parton distribution in nucleons measured with different number of wounded nucleons, with no change in the inclusive case

Alternative strategy - use a hard trigger which selects rare configurations in nucleon which are small size or large size

Example: The presence of a quark with large $x>0.6$ requires three quarks to exchange rather large momenta, one may expect that these configurations have a smaller transverse size (+ few gluons & sea quarks at low Q scale) and hence interact with the target with a smaller effective cross section: σ_{eff}.

Note: if $x>0.6$ configurations do have a size smaller than average, it would explain the EMC effect (FS83)

Selection of such x seems feasible at LHC but a challenge at RHIC - need a better acceptance in forward region.

Forward pion production: Summary of the challenge

☞ For pp - pQCD works both for inclusive pion spectra and for correlations (will discuss later)

☞ Suppression of the pion spectrum for fixed p_t increases with increase of η_N.

Independent of details - the observed effect is a strong evidence for breaking pQCD approximation. Natural suspicion is that this is due to effects of strong small x gluon fields in nuclei as the forward kinematics sensitive to small x effects.

The key question: what is the mechanism of the suppression of the dominant pQCD contribution of quark scattering off gluons with $x_A > 0.01$ where shadowing effects are very small.

CGC scenario - assumes ☟ LT $x_A > 0.01$ mechanism becomes negligible, though experimentally nuclear pdf = A nucleon pdf for such x (assumes that somehow suppression of the LT mechanism should be >> than observed suppression of inclusive spectrum), ✌ 2 → 1 mechanism dominates

Post-selection scenario - LT $x_A > 0.01$ mechanism is suppressed but still *dominates inclusive cross section*

✔ *Post-selection (effective energy losses) in proximity to black disk regime (BDR)* - usually only finite energy losses discussed (BDMPS) (QCD factorization for LT) - hence a very small effect for partons with energies 10^4 GeV in the rest frame of second nucleus. Not true in black disk regime - post selection - energy splits before the collision - effectively 10- 15 % energy losses decreasing with increase of k_t. at k_t. > k_t(BDR) Large effect on the pion rate since x_q's, z's are large,

$$\Downarrow$$

dominant yield from scattering at peripheral impact parameters

$$\Downarrow$$

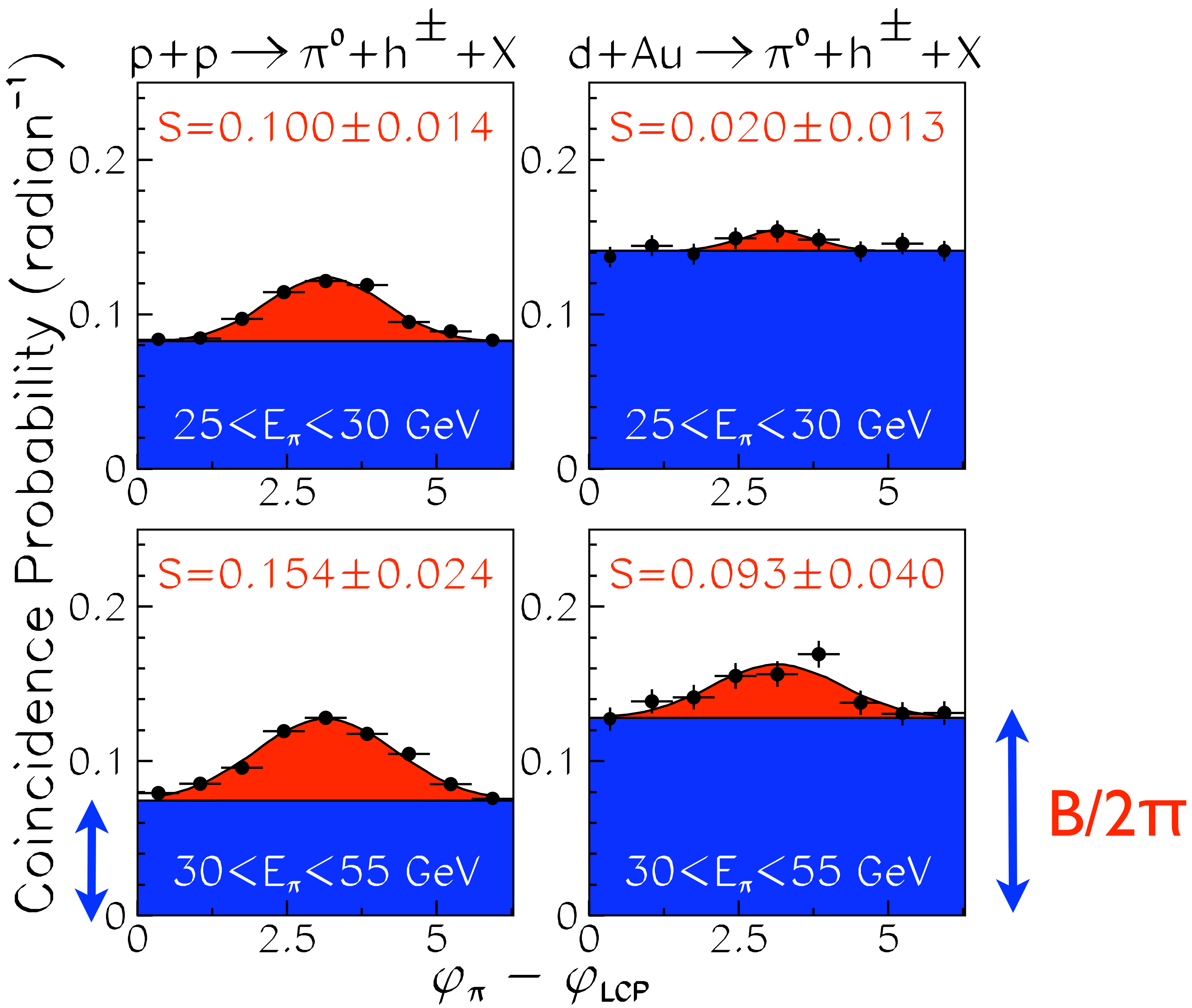
In the first approximation polarization effects are the same in pp and pA

Analysis of the STAR correlation data of 2006

Forward central correlations - kinematics corresponding to $x_A \sim 0.01$ - main contribution in 2→2

Leading charge particle (LCP) analysis picks a midrapidity track with $|\eta_h| \leq 0.75$ with the highest $p_T \geq 0.5$ GeV/c and computes the azimuthal angle difference $\Delta\varphi = \varphi_{\pi^0} - \varphi_{LCP}$ for each event. This provides a coincidence probability $f(\Delta\varphi)$. It is fitted as a sum of two terms - a background term, $B/2\pi$, which is independent of $\Delta\varphi$ and the correlation term $\Delta\varphi$ which is peaked at $\Delta\varphi = \pi$. By construction,

$$\int_0^{2\pi} f(\Delta\phi)d\Delta\phi = B + \int_0^{2\pi} S(\Delta\phi)d\Delta\phi \equiv B + S \leq 1$$



Coincidence probability versus azimuthal angle difference between the forward π^0 and a leading charged particle at midrapidity with $p_T > 0.5$ GeV/c. The curves are fits of the STAR. S is red area.

Obvious problem for central impact parameter scenario of π^0 production is rather small difference between low p_T production in the $\eta=0$ region (blue), in pp and in dAu - (while for b=0, $N_{coll} \sim 16$)

Detailed analysis using BRAHMS result: central multiplicity $\propto N^{0.8}$. Our results are not sensitive to details though we took into account of the distribution over the number of the collisions, energy conservation in hadron production, different number of collisions with proton and neutron.

average number of wounded nucleons in events with leading pion: $\langle N\rangle \cong 3$

We find $S(dAu) \approx 0.1$ assuming no suppression of the second jet. Data: $S(dAu) = 0.093 \pm 0.040$

Thus, the data are consistent with no suppression of recoil jets. PHENIX analysis which effectively subtracts the soft background - similar conclusion. In CGC - 100% suppression - no recoil jets at all. Moreover for a particular observables of STAR dominance of central impact parameters in the CGC mechanism would lead to $(1-B-S) < 0.01$, $S < 0.01$ since for such collisions $N_{coll} \sim 16$. This would be the case even if the central mechanism would result in a central jet.

Test of our interpretation - ratio, R, of soft pion multiplicity at $y \sim 0$ with π^0 trigger and in minimal bias events.

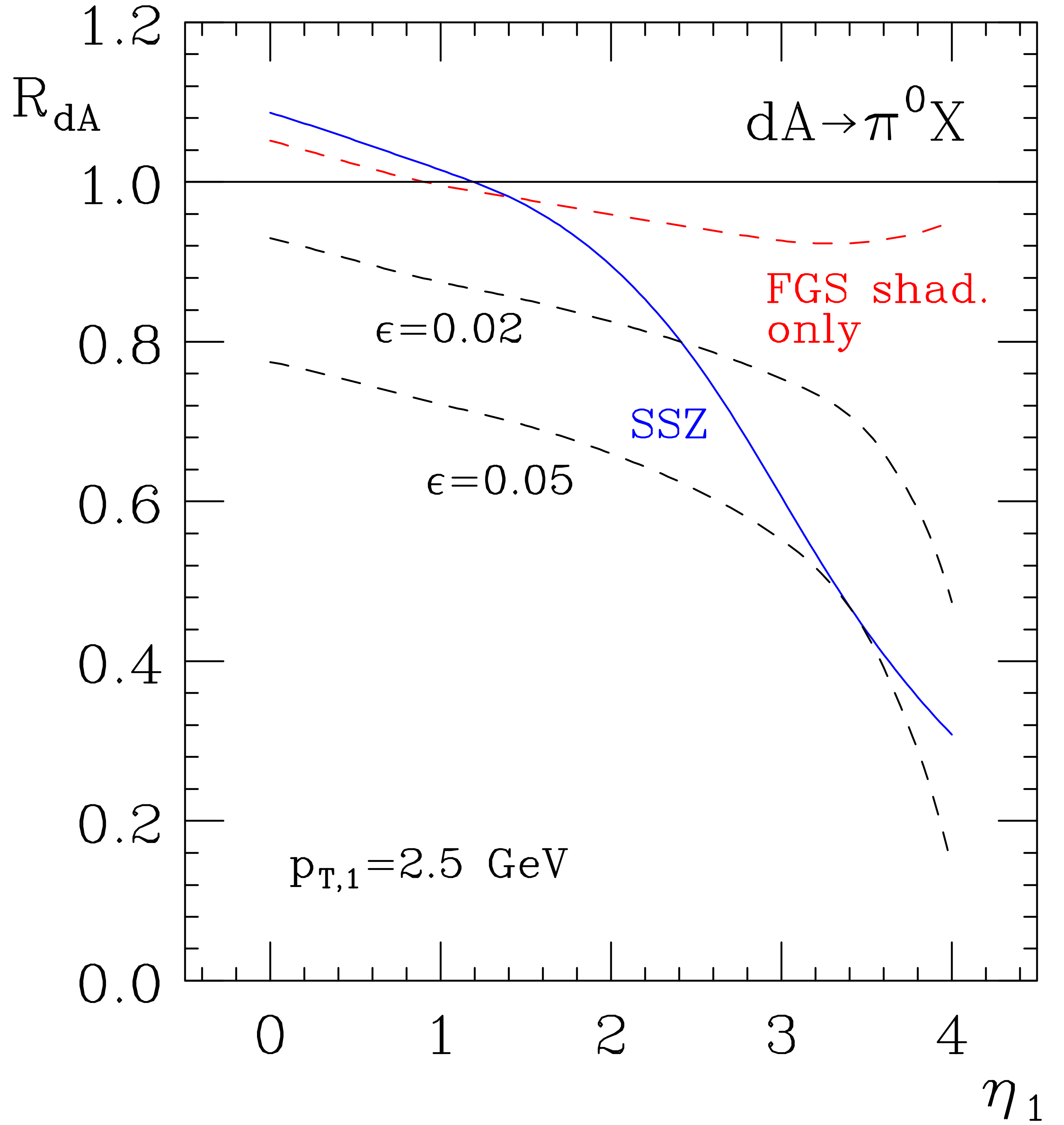
In CGC scenario R ~ 1.3

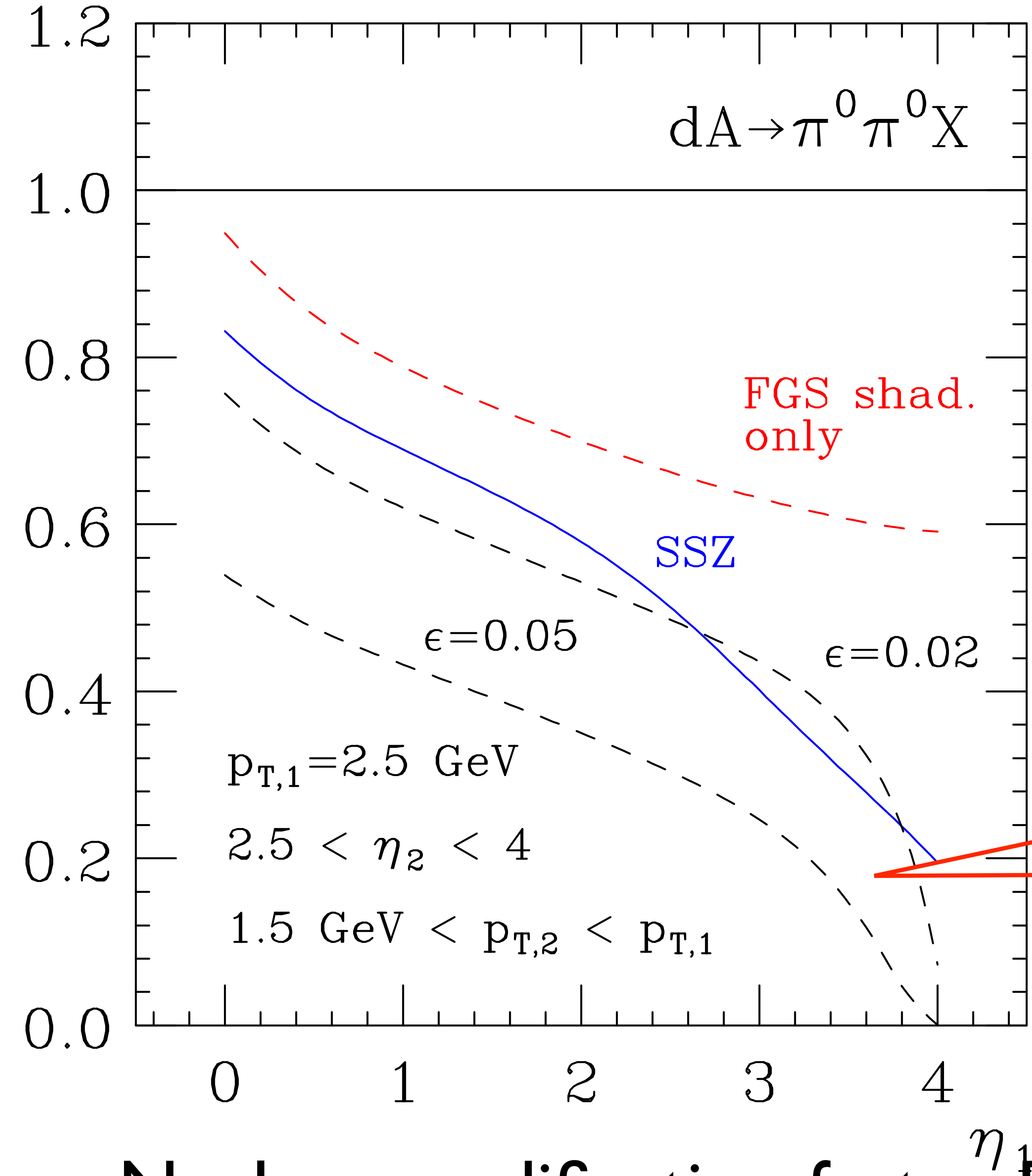
In BDR energy loss scenario we calculated R ~ 0.5

STAR - R ~0.5 Gregory Rakness - private communication

$\langle\eta\rangle = 0$ corresponds to $x_A = 0.01 \Rightarrow$ lack of suppression proves validity of $2 \rightarrow 2$ for dominant x_A region.

Correlation data appear to rule out CGC $2 \rightarrow 1$ mechanism as a major source of leading pions in inclusive setup $\Rightarrow$ NLO CGC calculations of inclusive yield grossly overestimates $2 \rightarrow 1$ contribution.





Vogelsang & MS 2011)

typical suppression of recoil peak ~ 3-- 5

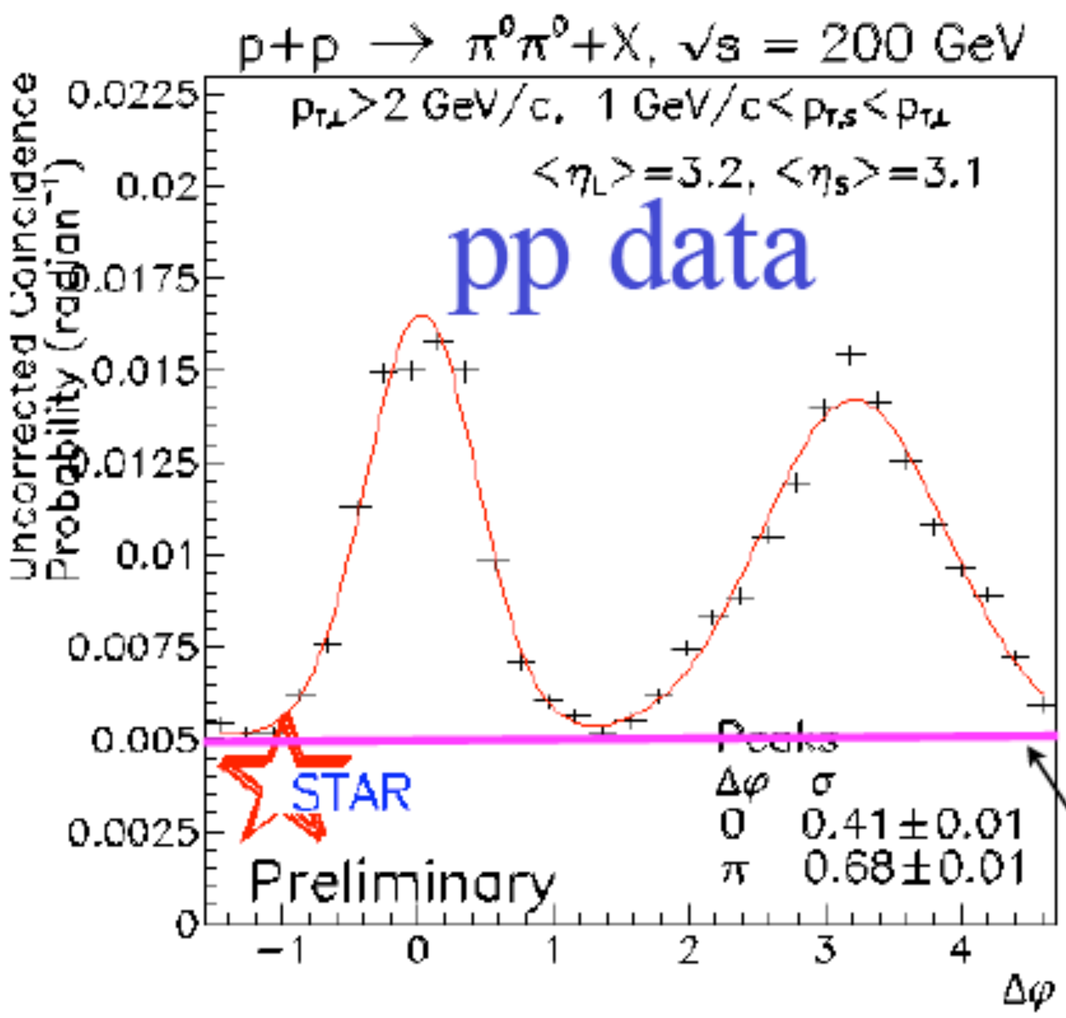
Left: Same for single-inclusive pion production - much larger suppression effect - because average x_q are closer to 1

Nuclear modification factor R_{dA} for double-inclusive leading-twist pion production as a function of rapidity η_1 at $p_{T,1}$ = 2.5 GeV. The upper dashed line shows the effect of leading-twist shadowing for the Frankfurt-Guzey-Strikman (FGS) nuclear parton distributions. The solid line includes shadowing and the "medium-modified" fragmentation functions of Sassot-Stratmann-Zurita (SSZ). The lower dashed lines show the results for two simple energy-loss models.

Accounting for fractional energy losses effect, and LT gluon shadowing reduces (4→4)/ (2→2) ratio:

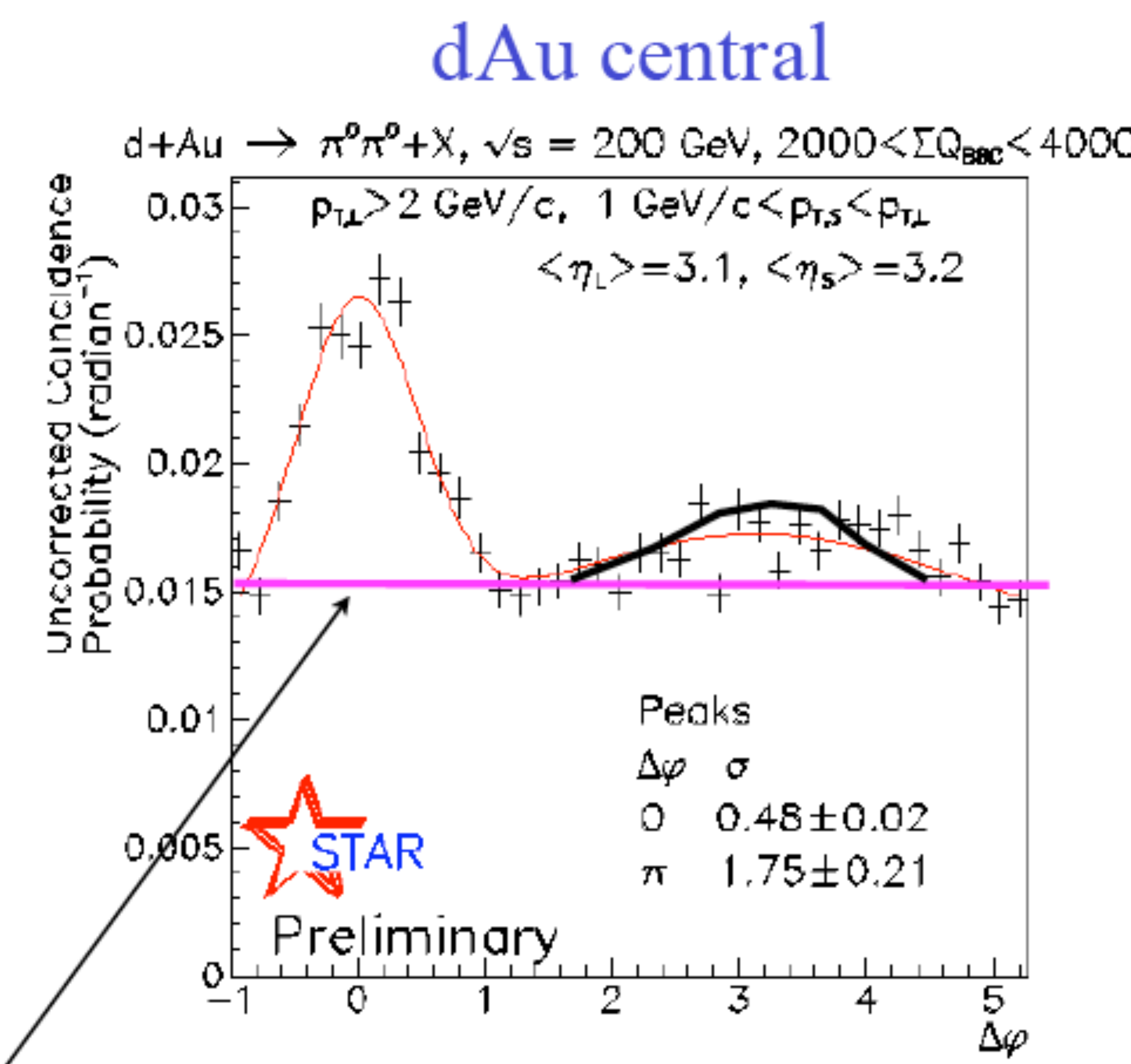
- ✶ Δϕ independent pedestal in dA is 2.5 ÷ 4 times larger in pp
- ✶ Suppression of Δϕ =180° peak by a factor ~ three --four

Main effect - disappearance from large x - perhaps also some broadening due to elastic rescattering



1 : 3

pedestal



Black curve is the pp data peak above pedestal for Δφ ~π scaled down by a factor of 4

Overall suppression of f-f (dAu/pp) is about a factor of 10; hardly could be much larger - since the probability of fluctuations in the nucleus wave function leads to a probability of punch through of 5 - 10% (Alvioli + MS).

No suppression for Δφ ~ 0 - fragmentation of the same quark

Subtle points which are difficult to see in dA.

a) In peripheral collisions (defined as events with small number of wounded nucleons)

$\langle \sigma \rangle < \sigma_{in}$ enhancement of the forward pion production

If polarization is related to primordial p_t ➔ enhancement of polarization

b) In central collisions defined through number of wounded nucleons there is additional suppression due to selection of large size configurations

c) In central collisions defined through use of a set of nuclei - possible scenario - dominance of fluctuations into point -like configurations which have >> probability to propagate through the center and interact once. May lead to larger polarization !!!

Leading hadron production in the central pA(pp) collisions

Expectation: The leading particle spectrum should be strongly suppressed in the central pA collisions as compared to minimal bias pp collisions since each leading parton gets large transverse momentum and hence fragments independently and may also split into a couple of partons with comparable energies. The especially pronounced suppression for nucleons: for $z \geq 0.1$ the differential multiplicity of pions should exceed that of nucleons. This model neglects additional suppression due to finite fractional energy losses in BDR

$$\frac{1}{N}\left(\frac{dN}{dz}\right)^{pA\to h+X} = \sum_{a=q,g}\int dx\, x f_a^{(p)}(x, Q^2_{\rm eff}) D_{h/a}(z/x, Q^2_{\rm eff})$$

The limiting curve of leading particles from hadron-nucleus collisions at infinite A

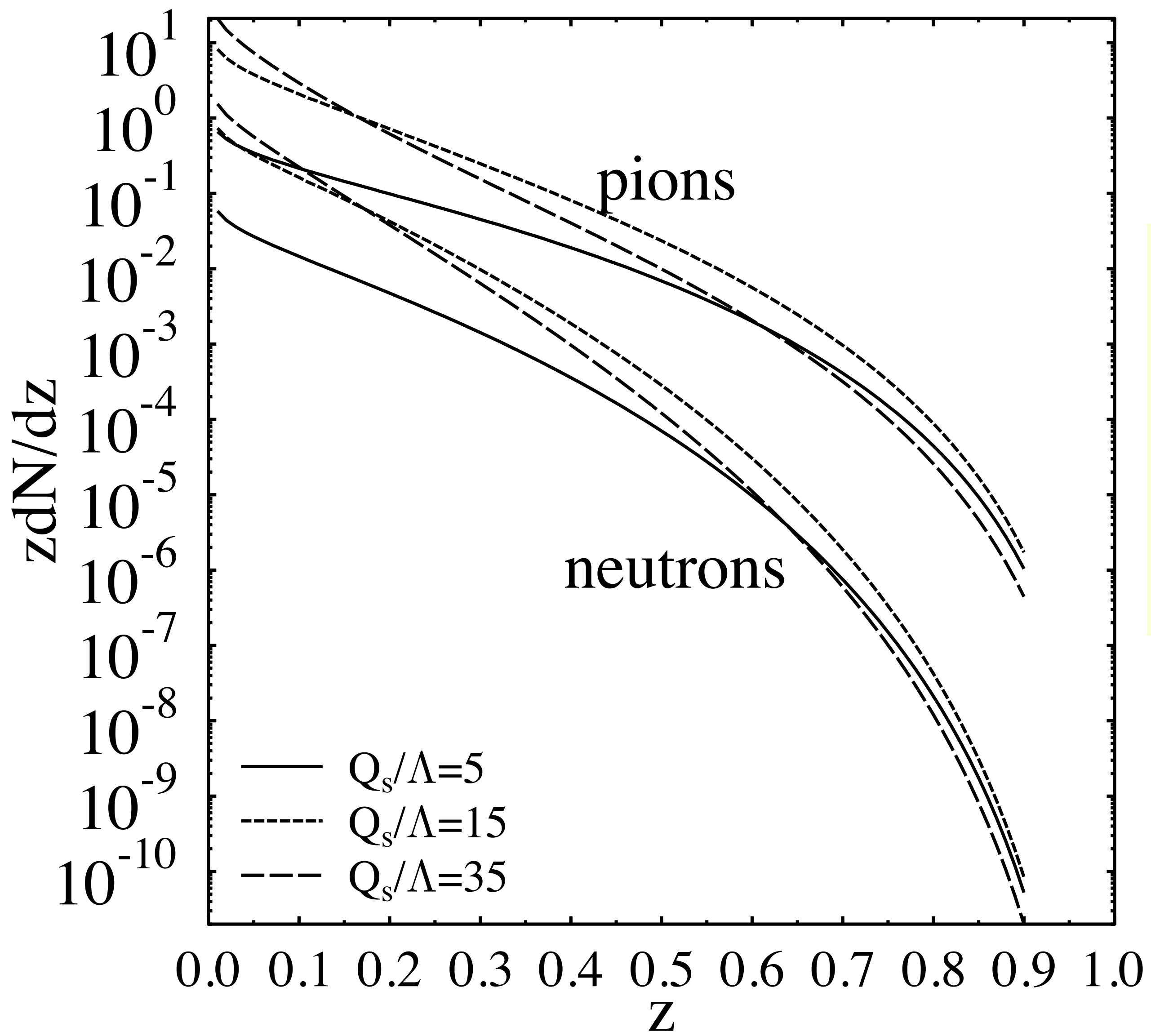
A. Berera[a,1], M. Strikman[a], W.S. Toothacker[b], W.D. Walker[c], J.J. Whitmore[a]

Physics Letters B 403 (1997) 1–7

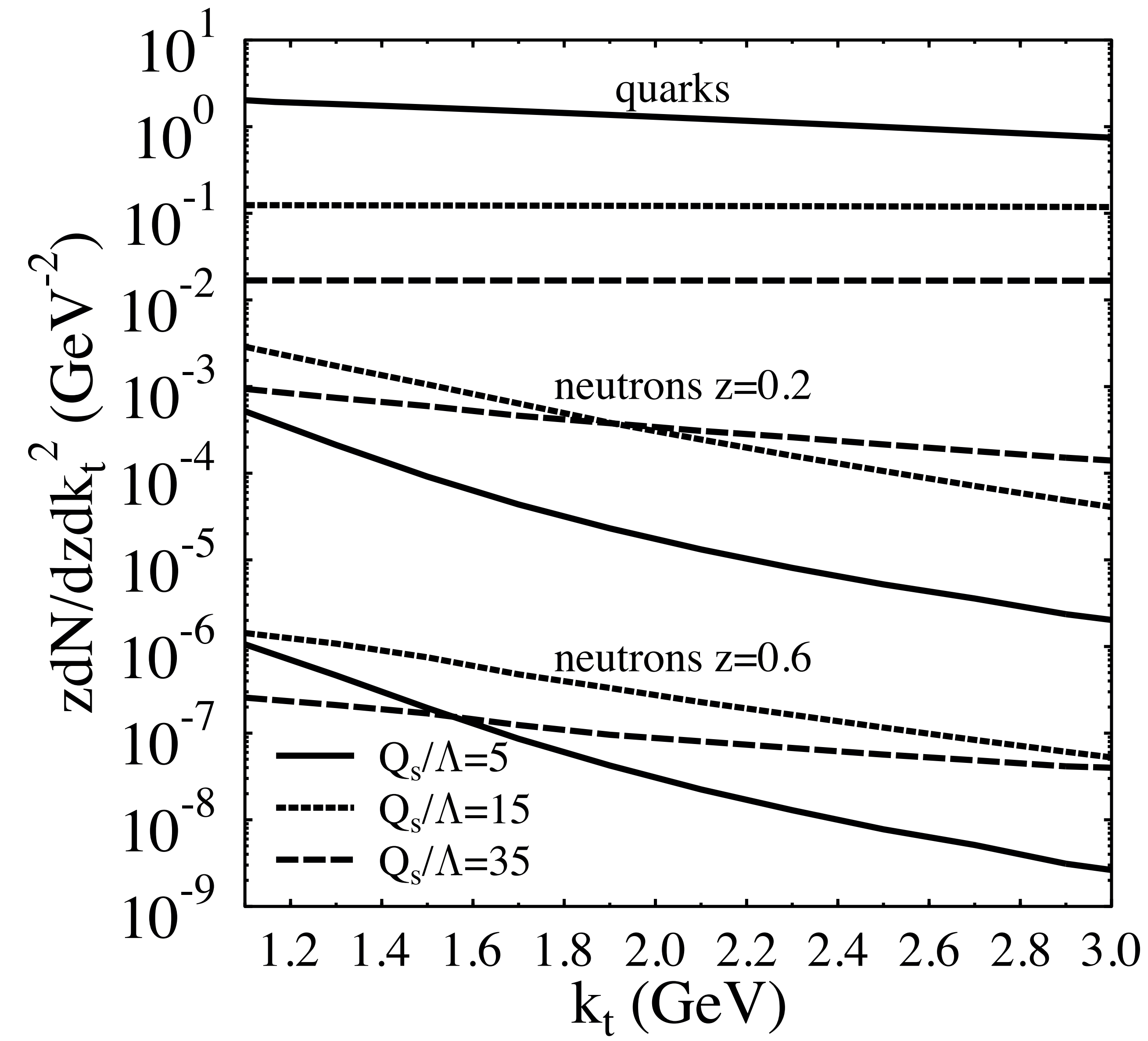
Simple model of p_t broadening - eikonal rescattering model with saturation (Boer, Dumitru 2003), effective energy losses (mentioned before) are neglected

$$C(k_t) \sim \frac{1}{Q_s^2 \log \frac{Q_s}{\Lambda_{QCD}}} \exp(-\frac{\pi k_t^2}{Q_s^2 \log \frac{Q_s}{\Lambda_{QCD}}}) \, .$$

Quark gets a transverse momentum of the order Q_s but does not loose significant energy. Use of the convolution formula for fixed transverse momentum of the produced hadron using $C(k_t)$ - Dumitru, Gerland, MS -PRL03. Other calculations with similar logic -Gelis, Stasto, Venugopalan (06)



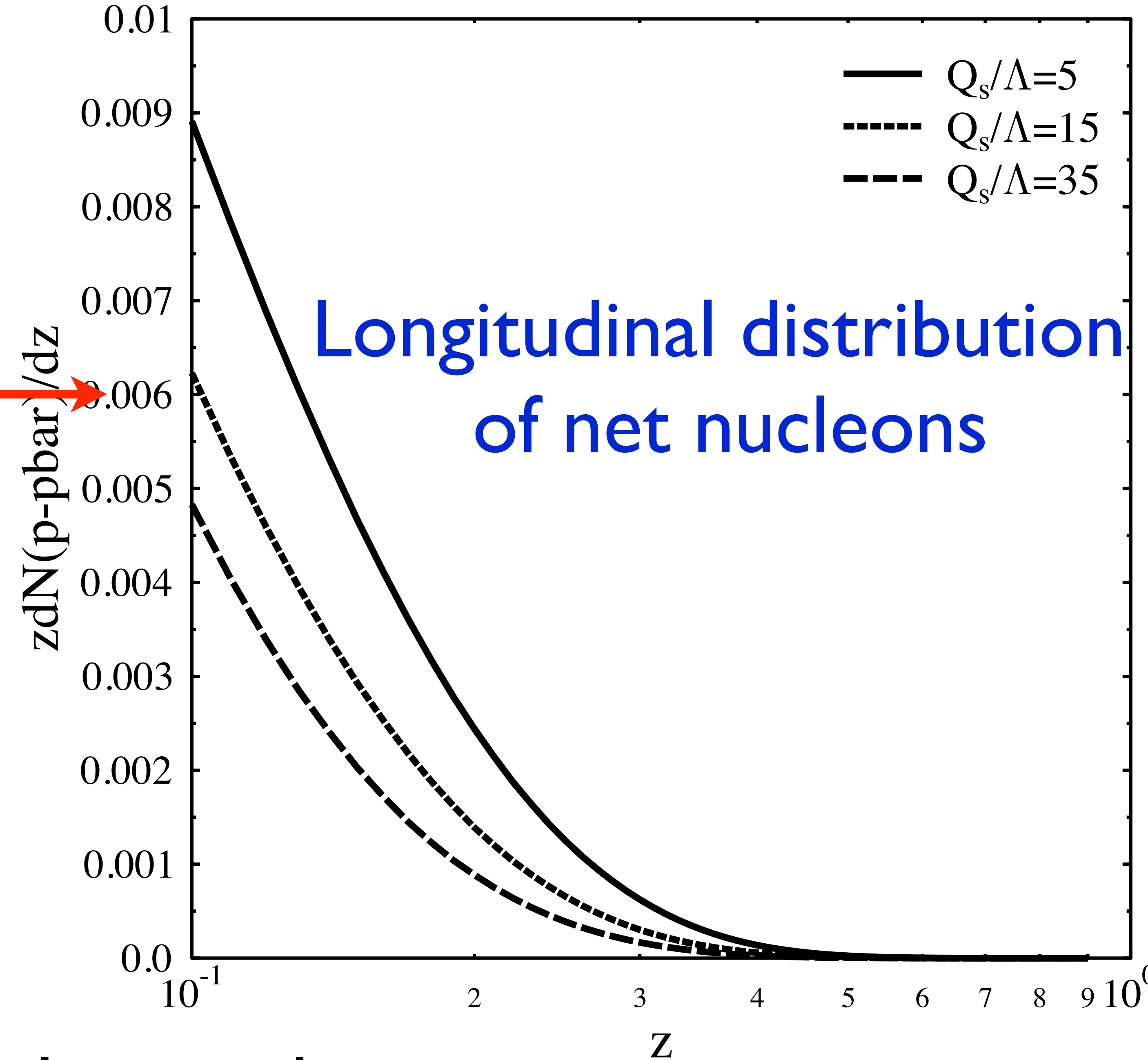
Steep fall with z, strong E_{inc} dependence



Weak p_t dependence, becomes weaker with increase of E_{inc}

Longitudinal (integrated over p_t) and transverse distributions in Color Glass Condensate (CGC) model for central pA collisions. Spectra for central pp - the same trends.

Very few forward baryons in central collisions!!!



Large flow of energy to central rapidities
- obvious implications for AA

Warnings: Parton carrying a fraction y of the quark momentum carries $y\, p_t$ part of the quark's transverse momentum. Condition for independent fragmentation $y\, p_t > 1/r_N$ ~.3 - 0.5 GeV/c

For RHIC (LHC) independent fragmentation is probably safe for $z > 0.2$ (0.1)

➠ Photon - proton contribution has to be subtracted!!!

Experimental prospects (perhaps too optimistic for LHC)

pA run at LHC: TOTEM: $x_F \geq 0.8$ broad range of p_t can check both suppression and p_t broadening neutrons from ZDC (CMS, ALICE, LHCf); π^0+ (LHCf) -large z , moderate p_t

RHIC: need pA run preferably at different energies and for several nuclei to avoid model dependent procedure for determining centrality of collision. Spin effect for neutrons ???

Warning: Color fluctuations in nucleon and nucleon density in nucleus may reduce the suppression

Conclusions on physics opportunities of pA:

- ☛ Will produce a novel information on strong interactions in the high gluon density kinematics for fixed nuclear thickness as a function of energy:
  parton , groups of partons propagation through media in soft and hard regime including spin effects

- ☛ Will complement pA run at LHC - critical for understanding how small x dynamics changes with energy

- ☛ Will allow to measure inelastic diffraction at the highest energy where it is still comparable/larger than e.m. contribution

- ☛ Check the color fluctuation dynamics for generic inelastic pA collisions