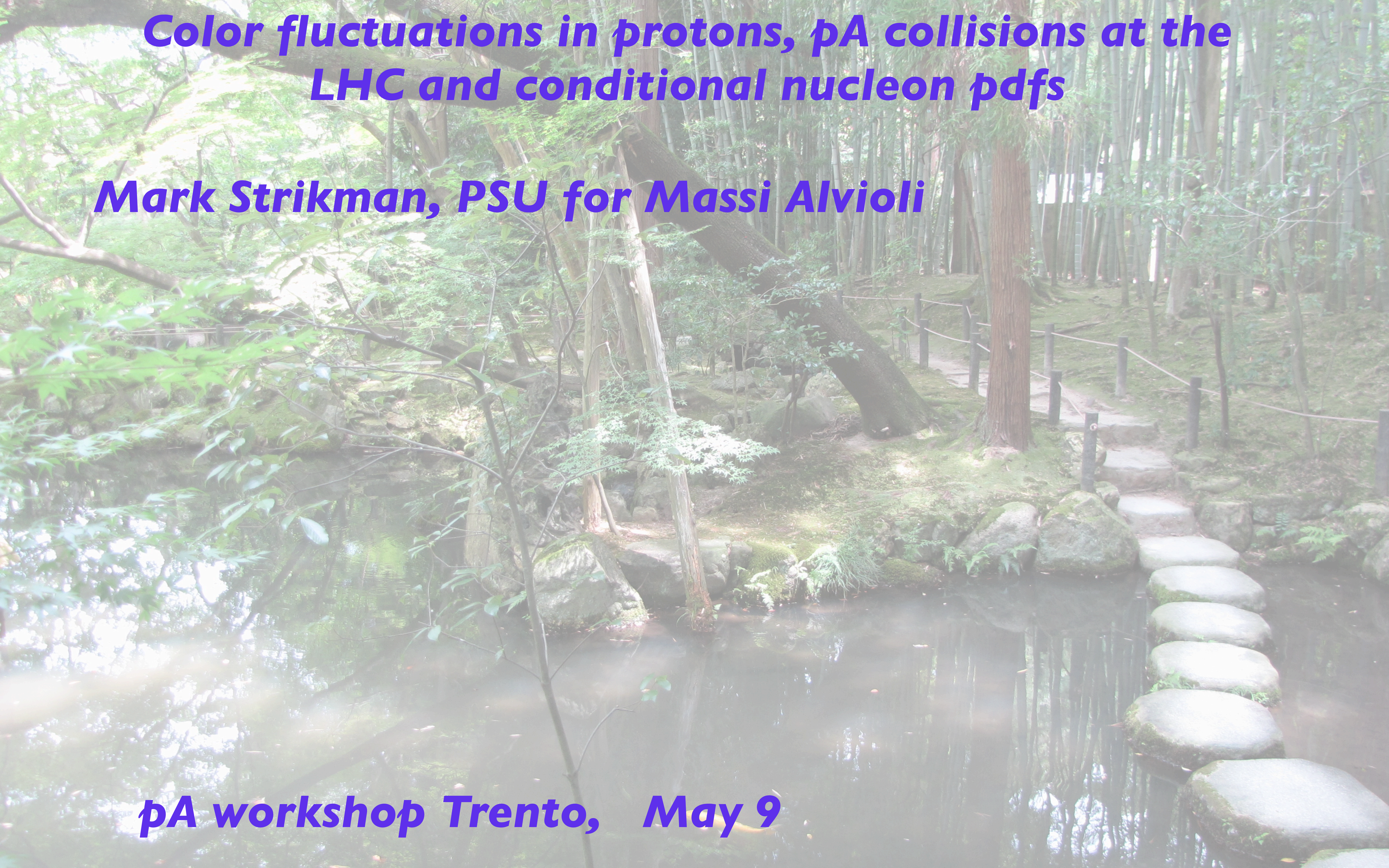

Color fluctuations in protons, pA collisions at the LHC and conditional nucleon pdfs

Mark Strikman, PSU for Massi Alvioli

pA workshop Trento, May 9

Outline

- Importance of coherence in high energy scattering example: positronium propagation through the medium

- Color fluctuations and soft diffraction

- Qualitative difference of Gribov-Glauber theory from low energy Glauber model.

- Color fluctuations in pA collisions with implications for pA @LHC.

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Color fluctuation effects in proton–nucleus collisions

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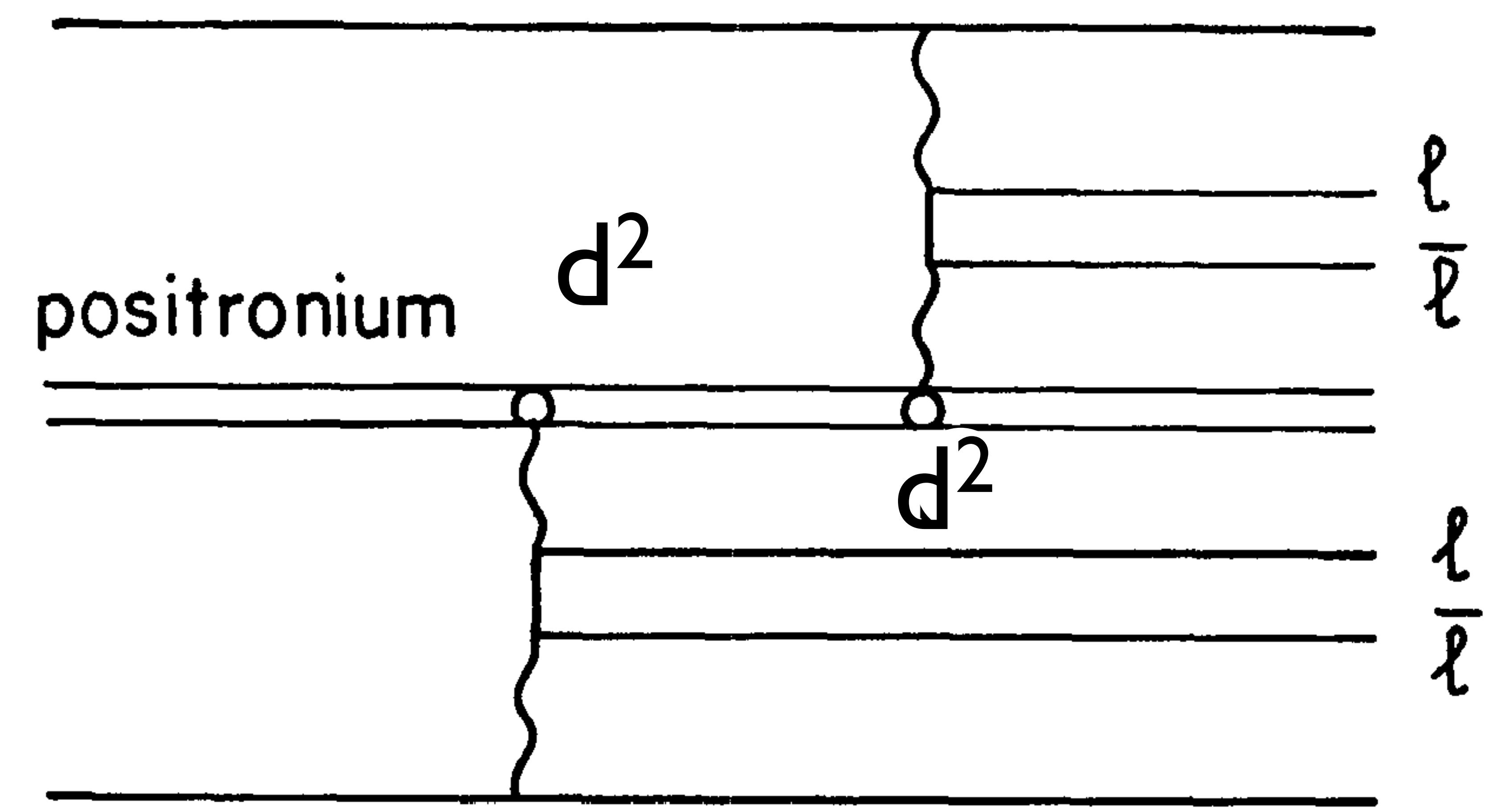
A number of important high energy QCD phenomena (not all) in the hadron - nucleon/nucleus scattering can be illustrated using example of propagation of ultra relativistic positronium through media. One can trigger on small size configuration is fast positronium by looking at e-e+ pairs which passed through a media.

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: $\langle d^2 \rangle$ for these events is larger than in $\Psi^2_{pos}(d) = \int \Psi^2_{pos}(r) d^z$

$$\langle d^2_{2l\bar{l}} \rangle > \langle d^2_{l\bar{l}} \rangle > \langle d^2 \rangle$$



Effects: *Positive correlation between production one and two pairs*

Large b select smaller than average transverse and longitudinal momenta in positronium - longitudinal momenta of electrons in the positronium fragmentation are softer - looks as energy loss - but actually post-selection.

From QED to QCD - similarities and differences

Can a meson/baryon build of light quarks collapse to a small volume?

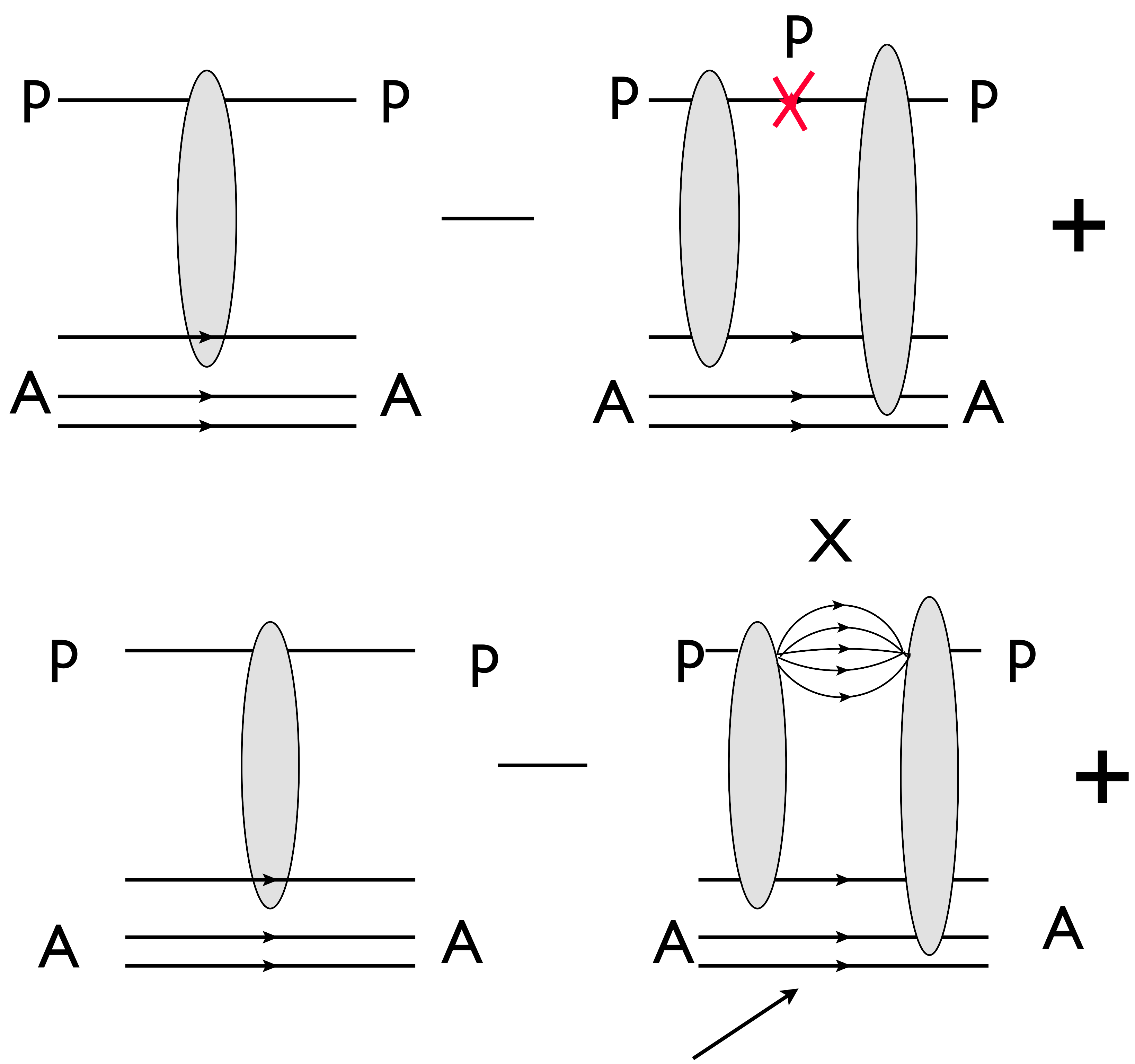
Would such configuration interact weakly with the nuclear medium?

yes - governed by pQCD

How often fluctuations to large hadron configurations (LHC) occur?

Key difference with QED - fast energy dependence of the strength of interaction

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



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

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

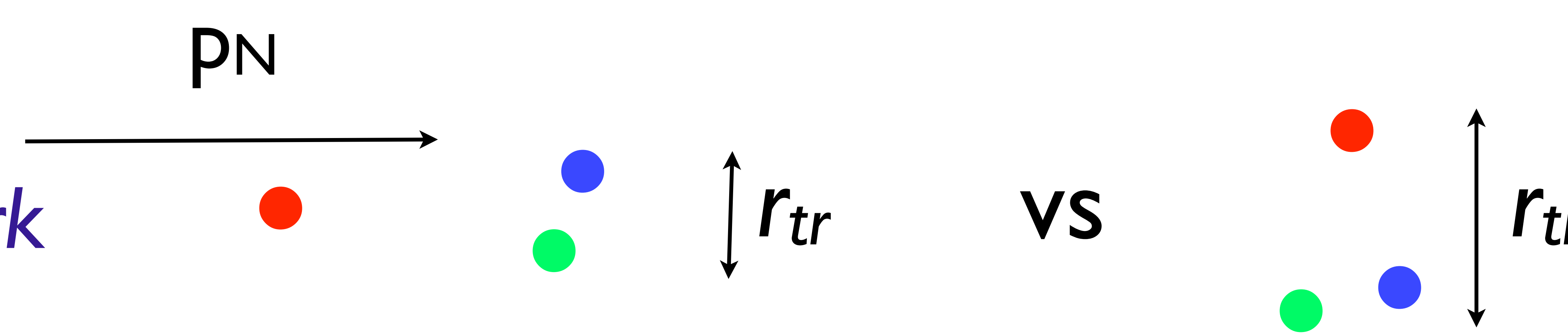
X= set of intermediate states the same as in pN diffraction

Deviations from Glauber for $\sigma_{in}(pA)$ 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.

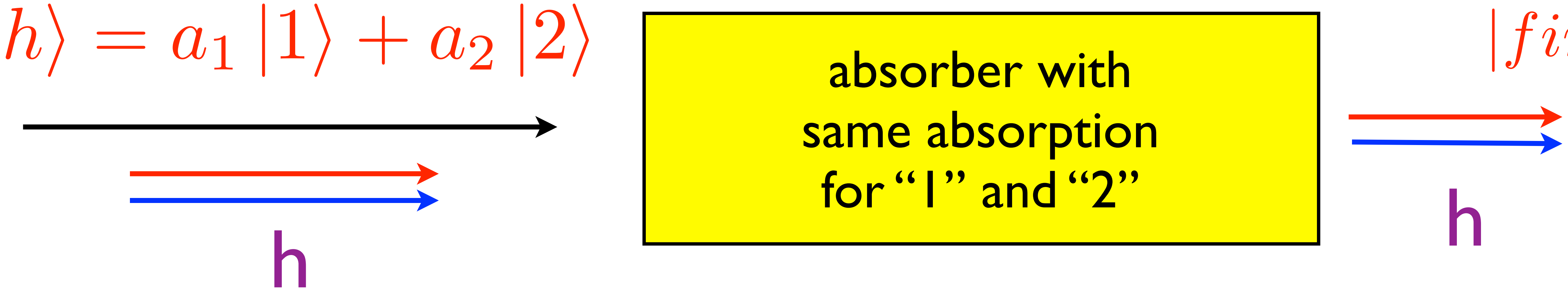
proton= quark + diquark



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:

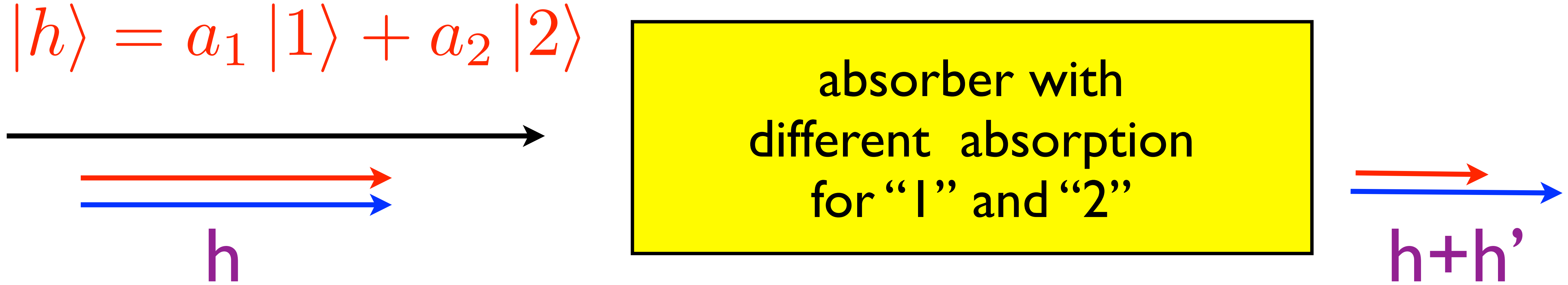
$$|h\rangle = a_1\,|1\rangle + a_2\,|2\rangle$$



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

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

$\omega_\sigma(RHIC)=0.25$ $\omega_\sigma(LHC)=0.20$ - more data are coming from LHC

A very rough model illustrating scale of the effect

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

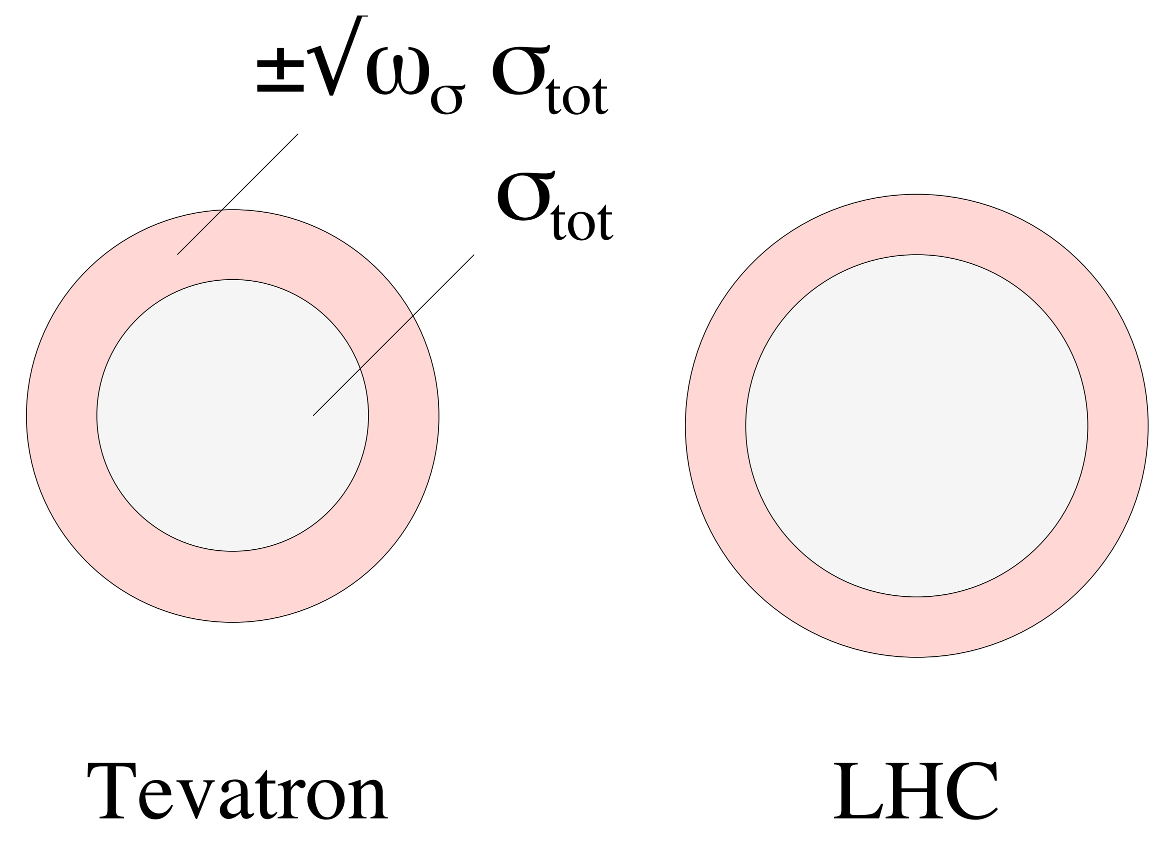
for RHIC $\omega_\sigma=0.25$, $\sigma_1=0.5\sigma_{tot}$; $\sigma_2=1.5\sigma_{tot}$ for LHC $\omega_\sigma=0.2$, $\sigma_1=60$mb ; $\sigma_2=140$mb

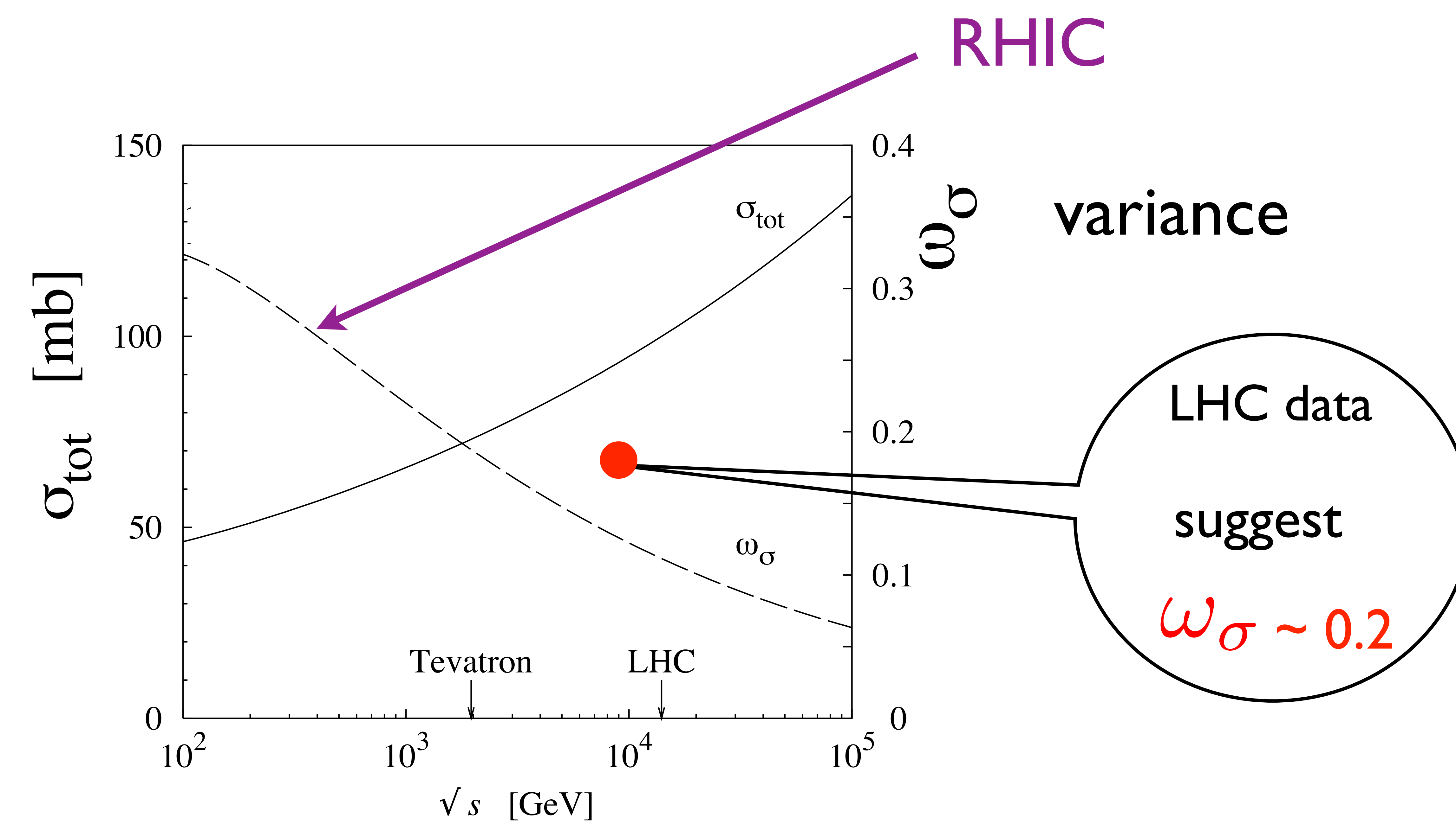
$\int (\sigma - \sigma_{tot})^3 P(\sigma) d\sigma = 0$,

Baym et al from pD diffraction

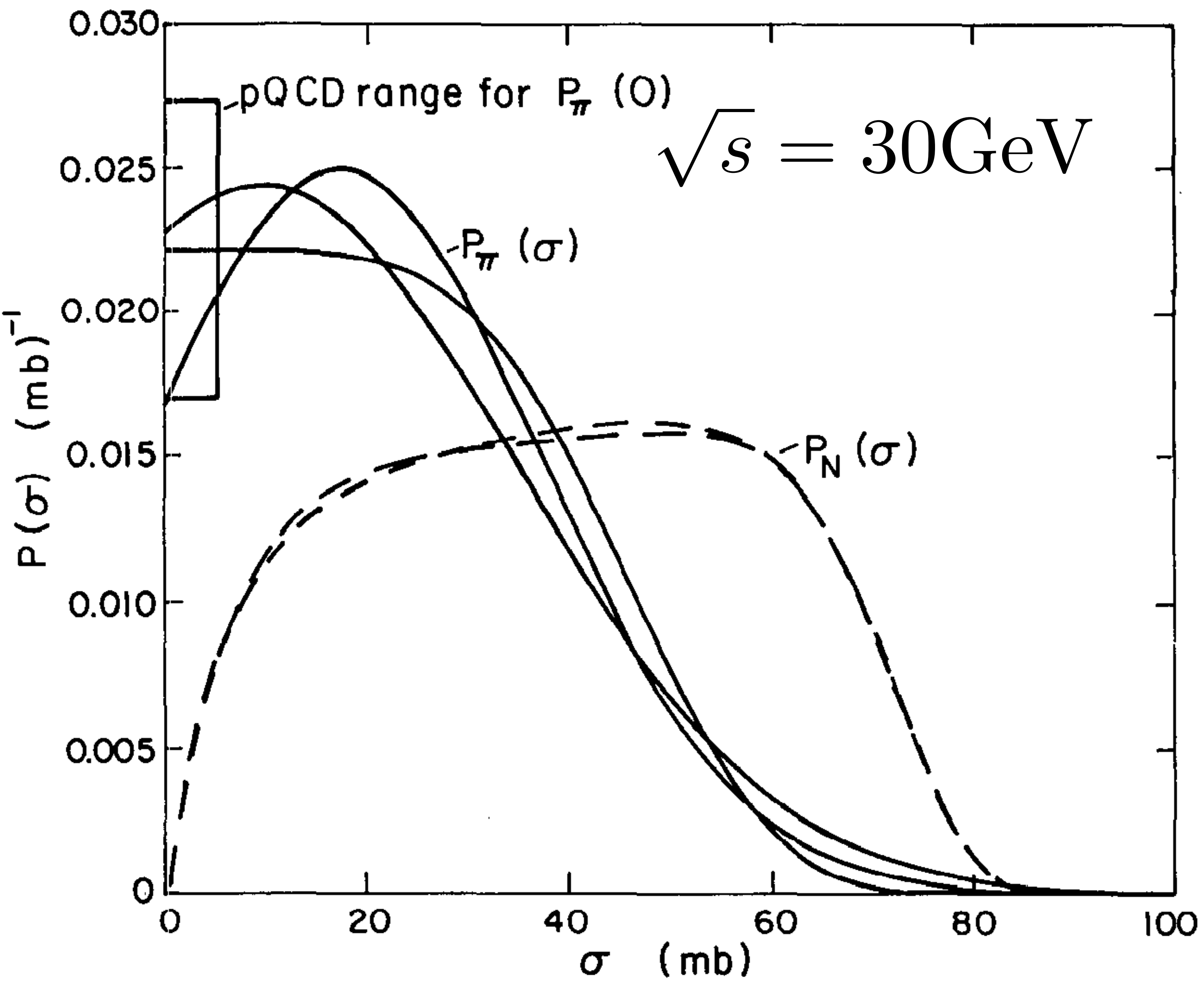
$$P(\sigma)_{|\sigma\to 0} \propto \sigma^{n_q - 2}$$

Baym et al 1993

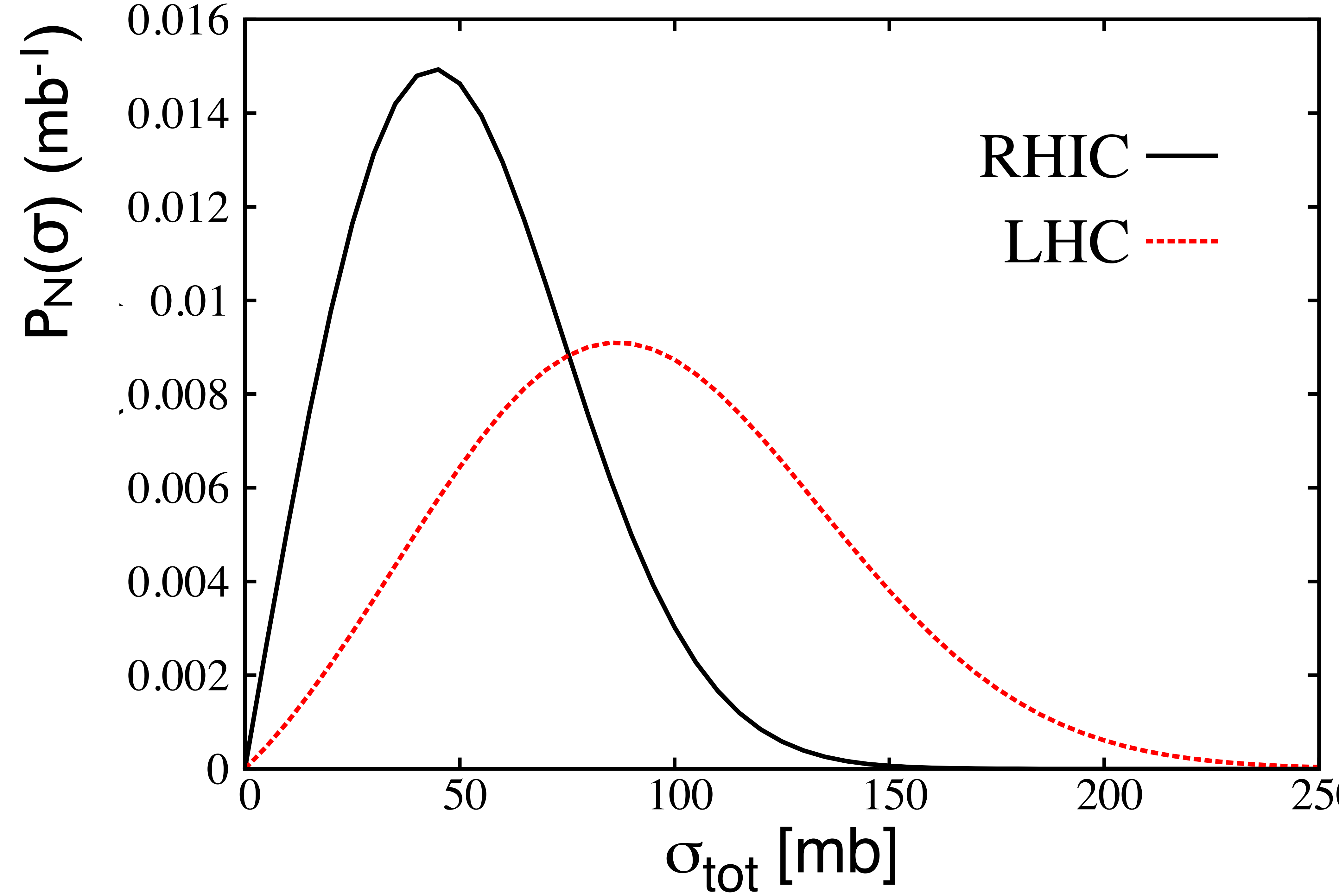




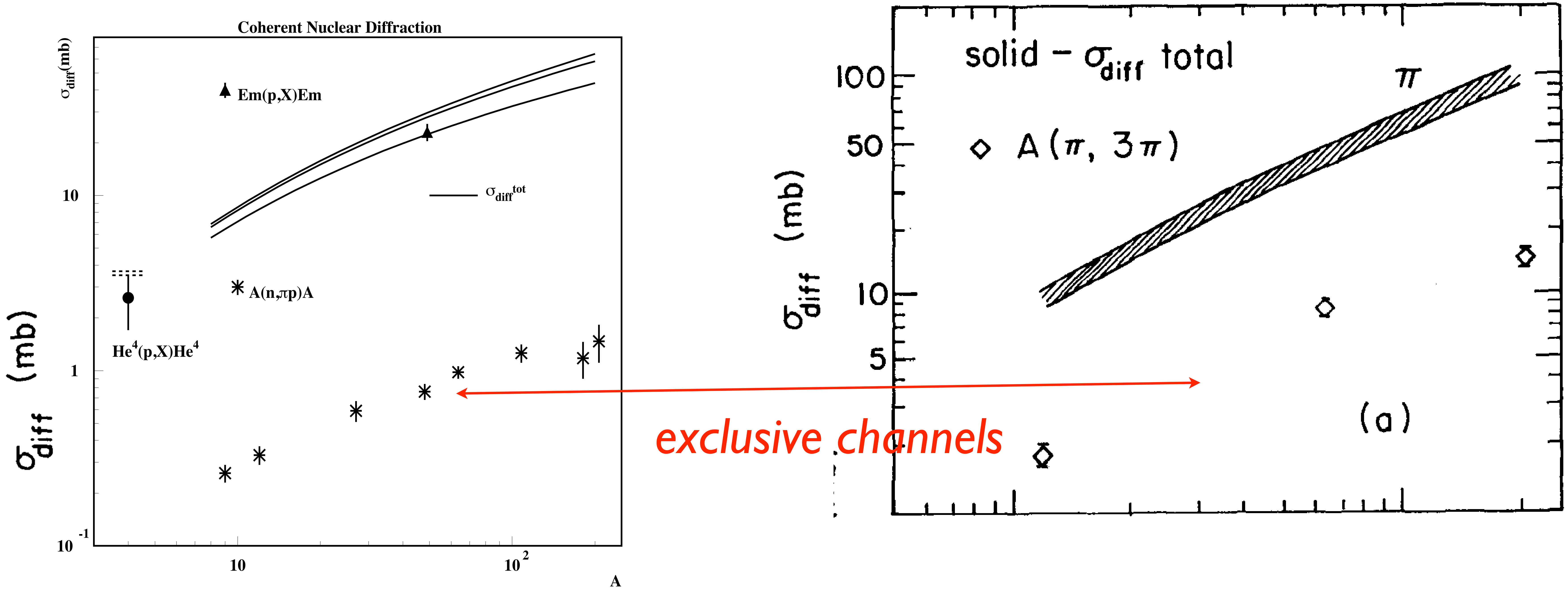
Both small and large configurations grow a periphery - still there is a correlation between σ and parton distributions -smaller σ, harder quark distribution (will discuss implications for pA later)



$P_N(\sigma)$ 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

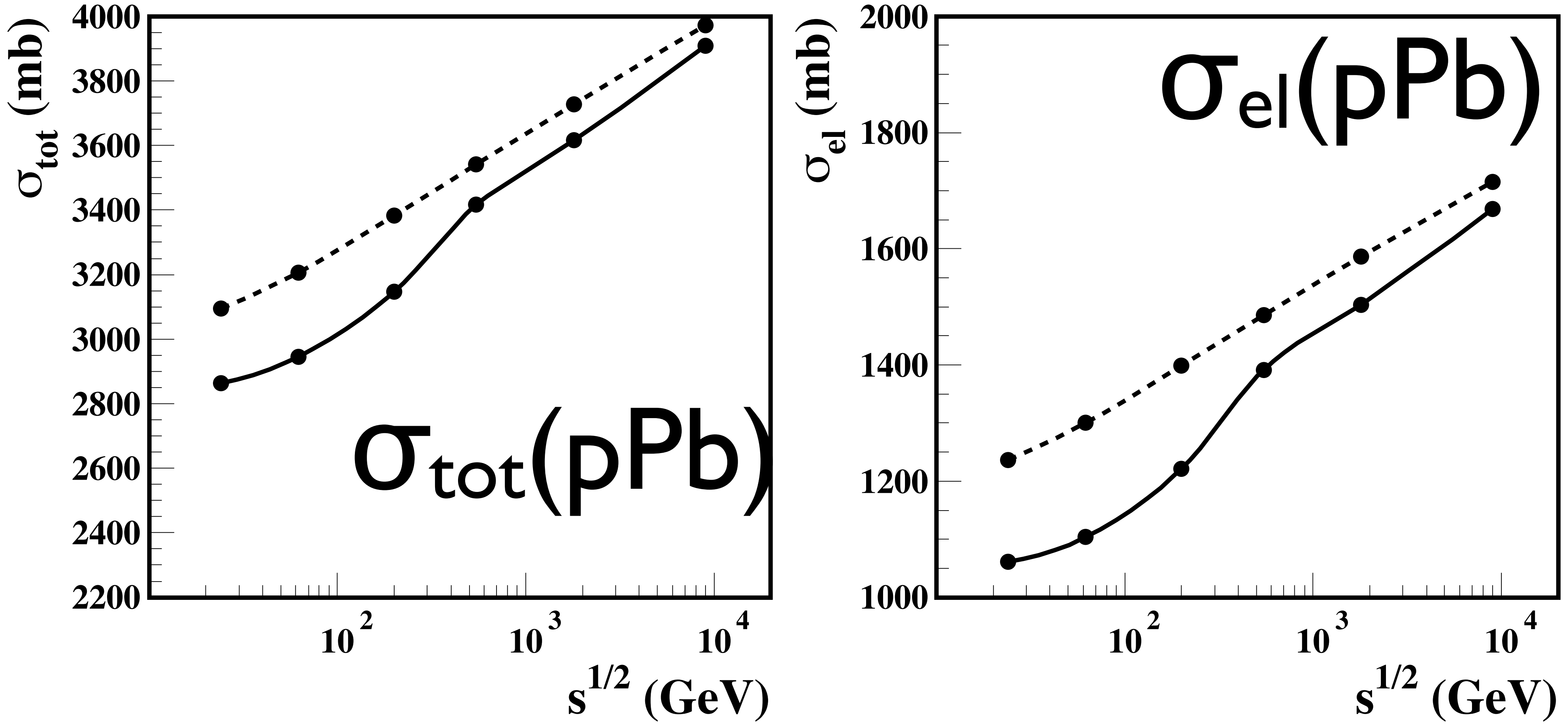


The inelastic small t coherent diffraction off nuclei provides one of the most stringent tests of the presence of the fluctuations of the strength of the interaction in NN interactions. The answer is expressed through $P(\sigma)$ - probability distribution for interaction with the strength σ. (Miller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

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

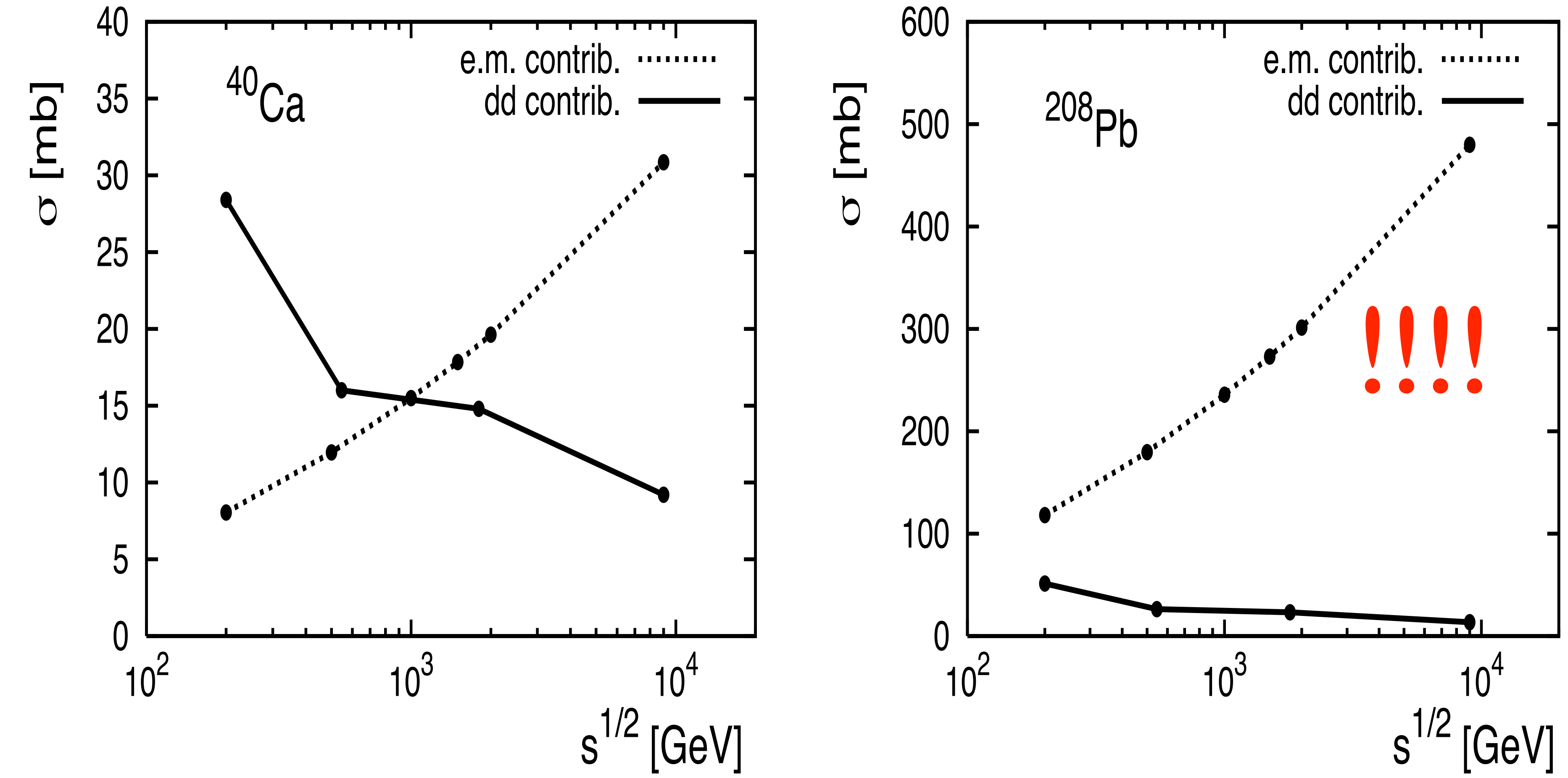
Here $F(\sigma,b) = 1 - e^{-\sigma T(b)/2}$, $T(b) = \int_{-\infty}^{\infty} \rho_A(b,z)dz$, and $\rho_A(b,z)$ is the nuclear density.

Color fluctuations/inelastic shadowing



Guzey & MS

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



⇒ E.M. interaction dominates by far in diffraction above RHIC energies

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 to suppress break up?

Potential problem for Gribov- Glauber approximation:
average impact factor <b> at LHC ~ 1.3 fm ⇒

$2\langle b\rangle > r_{NN} \sim 1.7$ fm ⇒

projectile proton can hit two nucleons at the same time.

Convenient picture of diffraction -

Good - Walker scattering eigen state formalism $\sigma_n |n\rangle = T|n\rangle$
leads to the picture of hA interactions similar to Gribov - Glauber

B. Z. Kopeliovich and L. I. Lapidus, 1978

Can use P(σ) to model Gribov- Glauber dynamics of inelastic pA interactions. -
-probability that nucleon interacts with cross section, Baym et al 91-93

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

$\Delta\omega = \omega_\sigma$ in pA

$\Delta\omega = 2\ \omega_\sigma$ in AA

Numerical calculations (Alvioli and MS) - event generator using our sets of nucleon configurations in nuclei with short-range correlations (small effect) and finite radius of NN interaction.

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

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

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

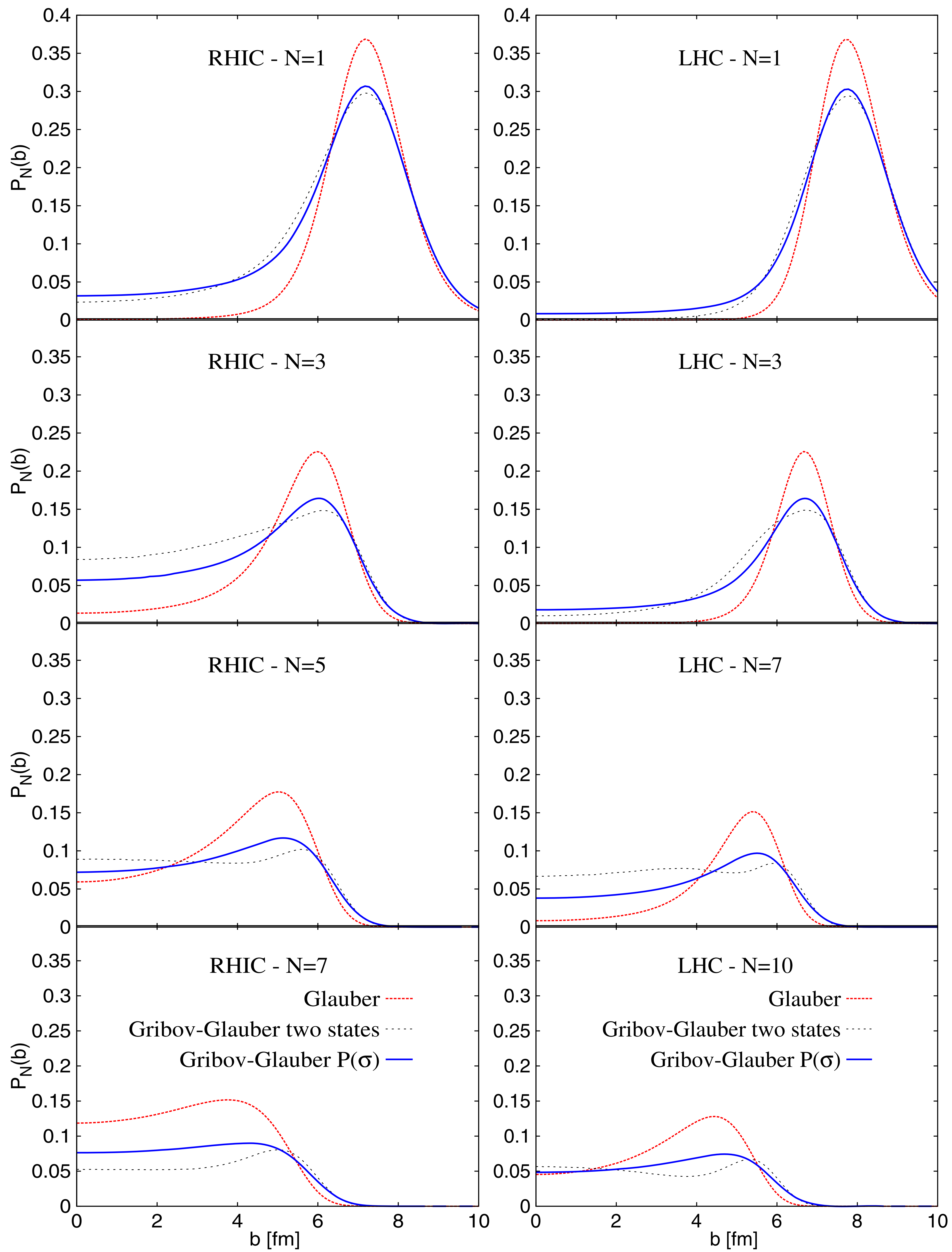
with parameters fixed to satisfy sum rules

Energy/model	Monte Carlo		
	$\langle N \rangle$	$\langle N^2 \rangle$	ω_N
RHIC, Glauber	4.6	31.6	0.51
RHIC, GG2	4.7	38.9	0.74
RHIC, GG $P_h(\sigma_{tot})$	4.8	39.2	0.72
LHC, Glauber	6.7	72.4	0.59
LHC, GG2	6.8	84.2	0.80
LHC, GG $P_h(\sigma_{tot})$	6.8	82.1	0.77

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

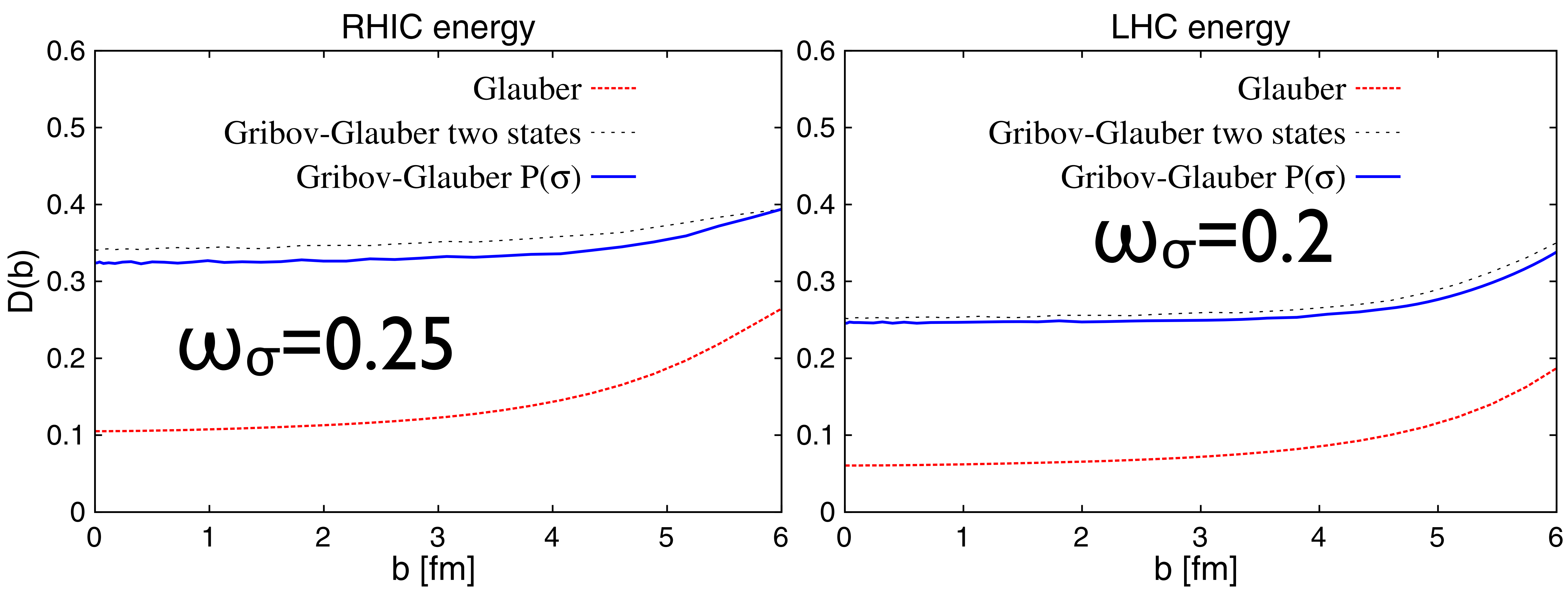
Small effect for <N>

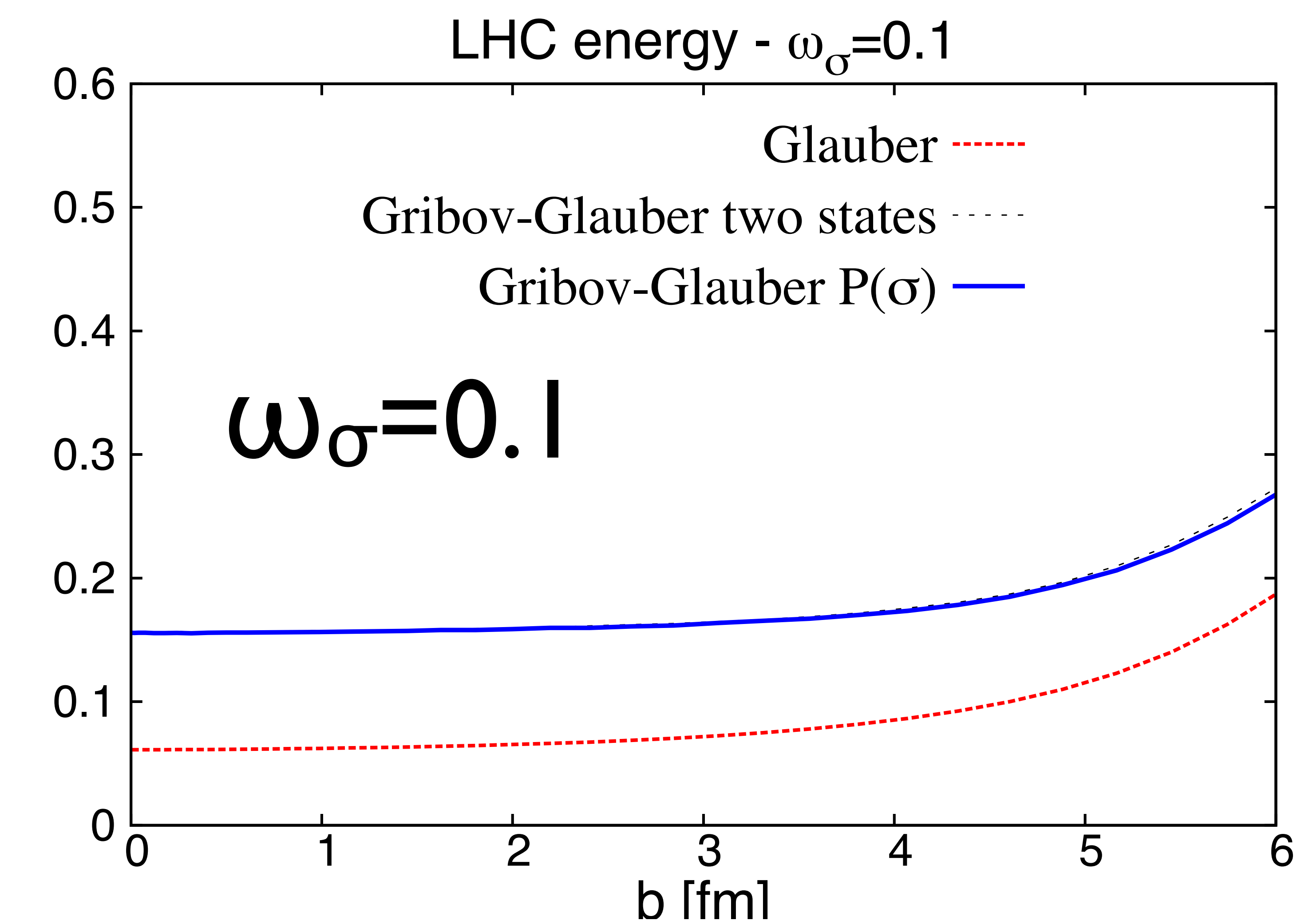
Large color fluctuation effect for dispersion even though in dispersion one integrates over impact parameters. Effect is much larger for fixed b - see below

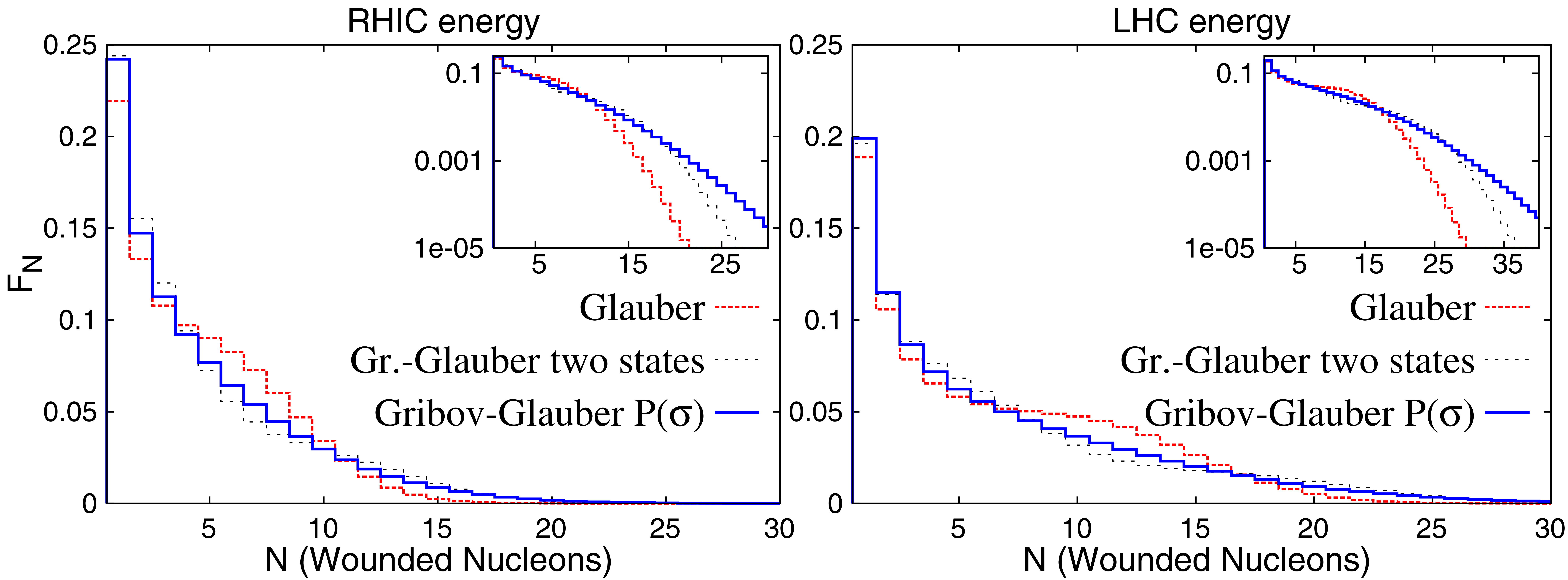


The probability P_N (b) of having N inelastically interacting (wounded) nucleons in a pA collision, vs. impact parameter b, when using simple Glauber (red curves) and a distribution P (σ) (green curves); We show the probabilities P_N (b) for N=1 (top row) for both energies and the curves for N corresponding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

Fluctuations give dominant contribution to fluctuations of N for fixed b

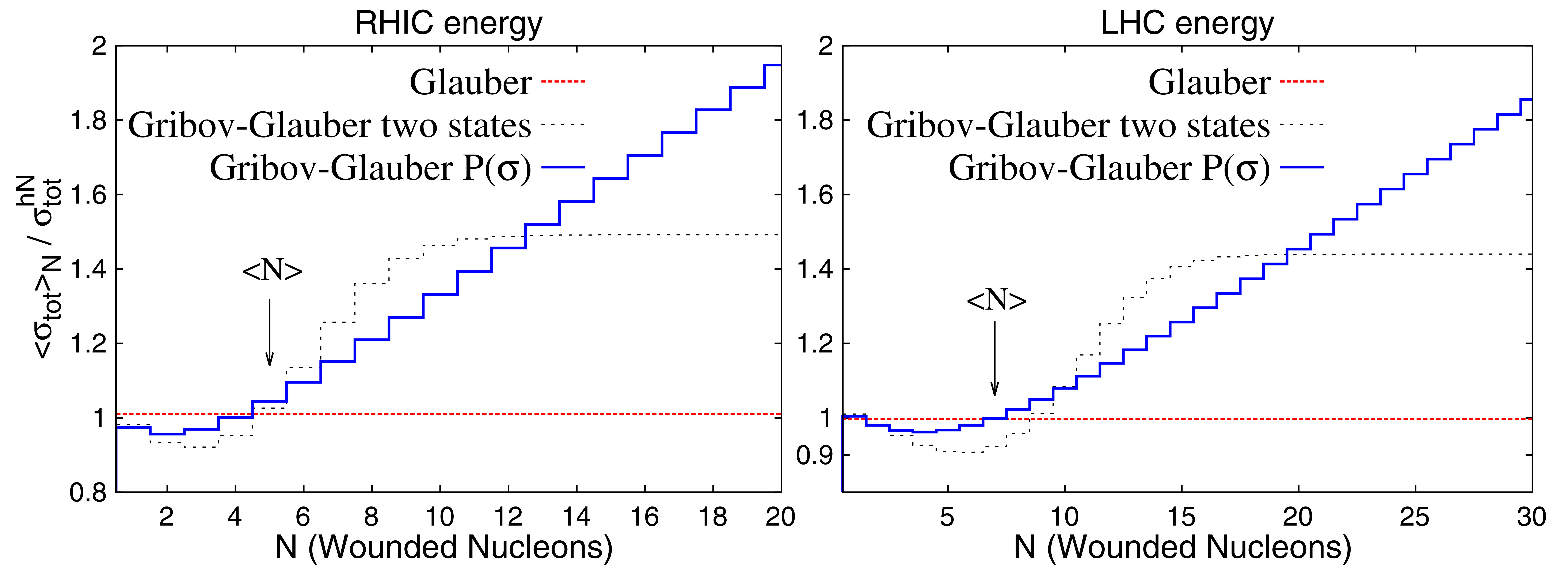






Effect of the event-by-event fluctuating values of σtot, for RHIC and LHC energies on the number of wounded nucleons,

A factor of ~10 enhancement for N~ 4 <N>

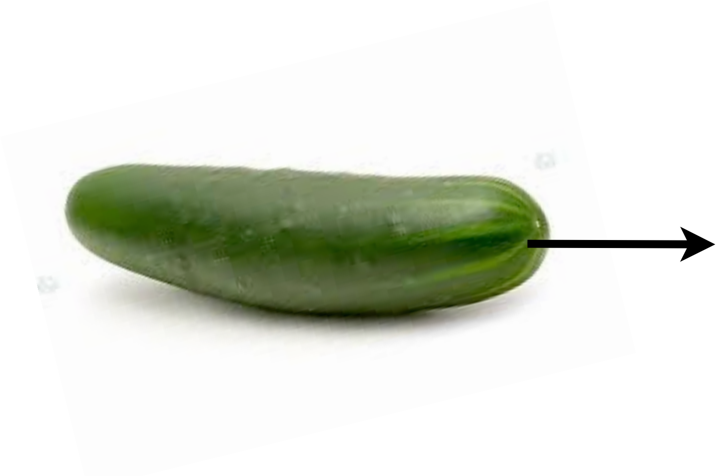


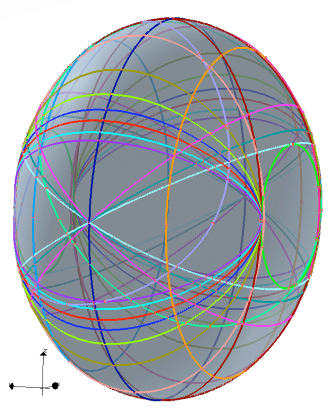
Effect of fluctuations on the event-by-event fluctuating values of cross section. Small number of wounded nucleons, M, selects σ's smaller than average - large M --- - $\sigma > \sigma_{tot}$

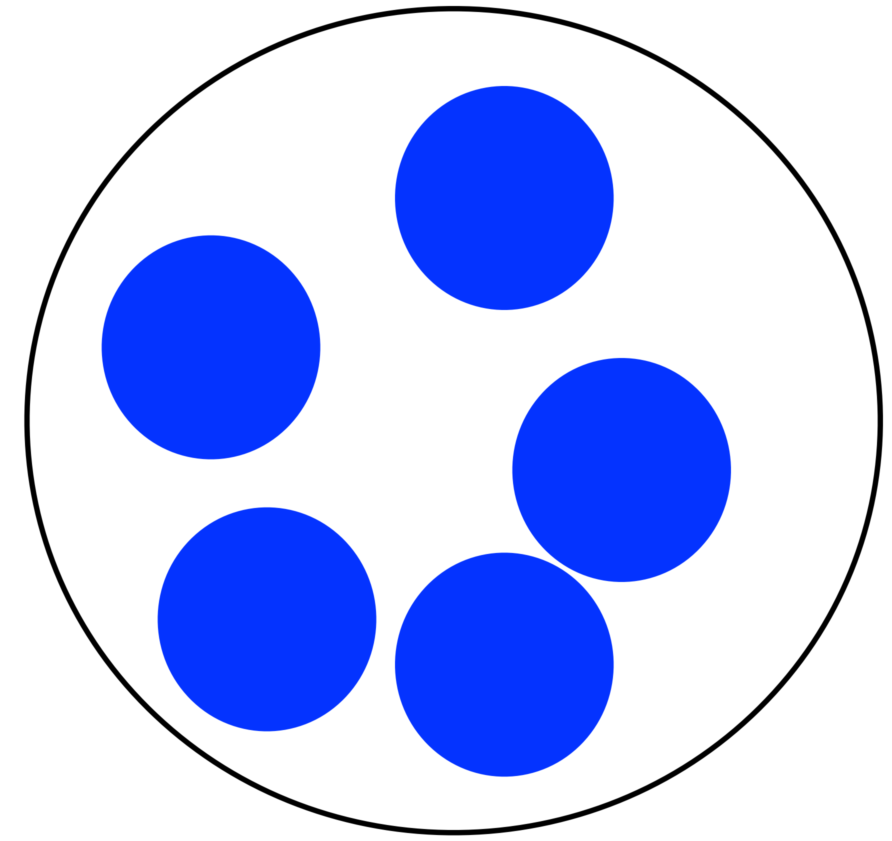
$$\frac{\langle \sigma_{tot} \rangle}{\sigma_{tot}^{hN}} \sim 2 \quad \text{for } N/\langle N\rangle = 4$$

Reminder: RHIC studied d-Au - smaller effect of fluctuations for hard trigger.

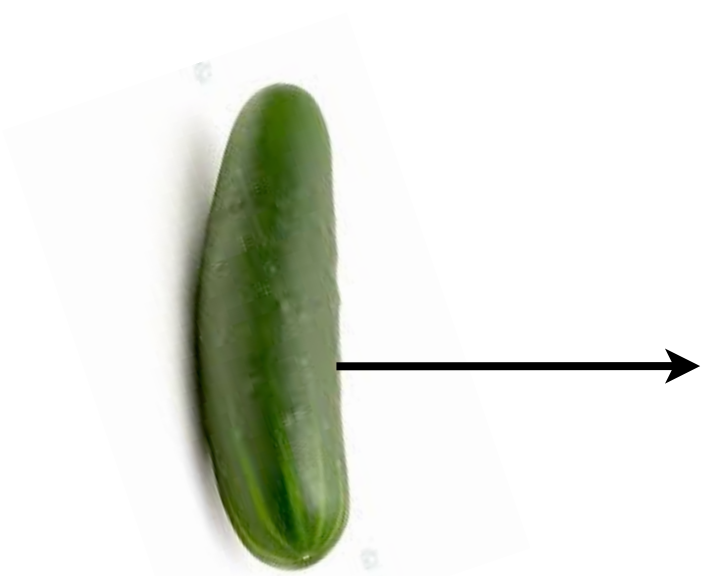
Different σ's --- different size, different shape, different parton densities

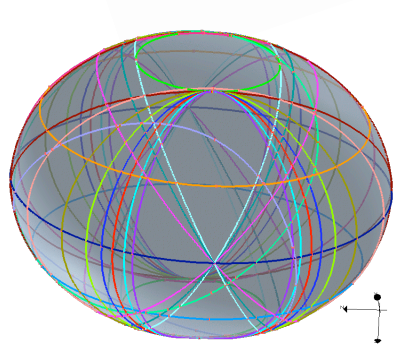




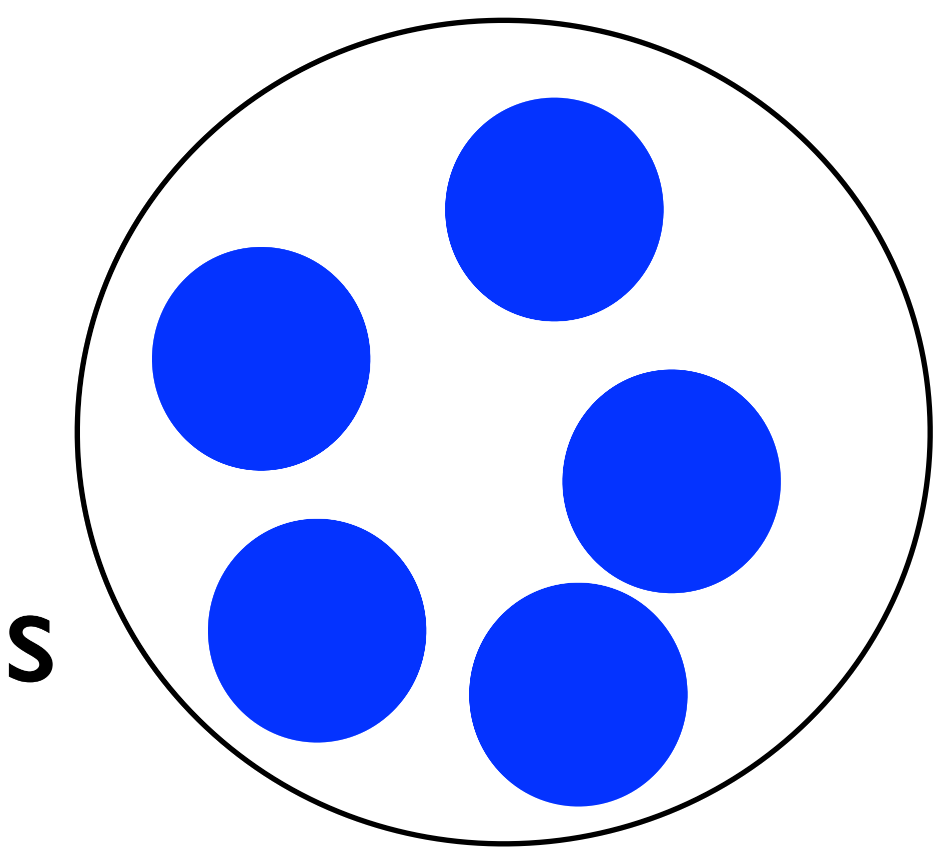


Conditional pdfs





would lead to ridges



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

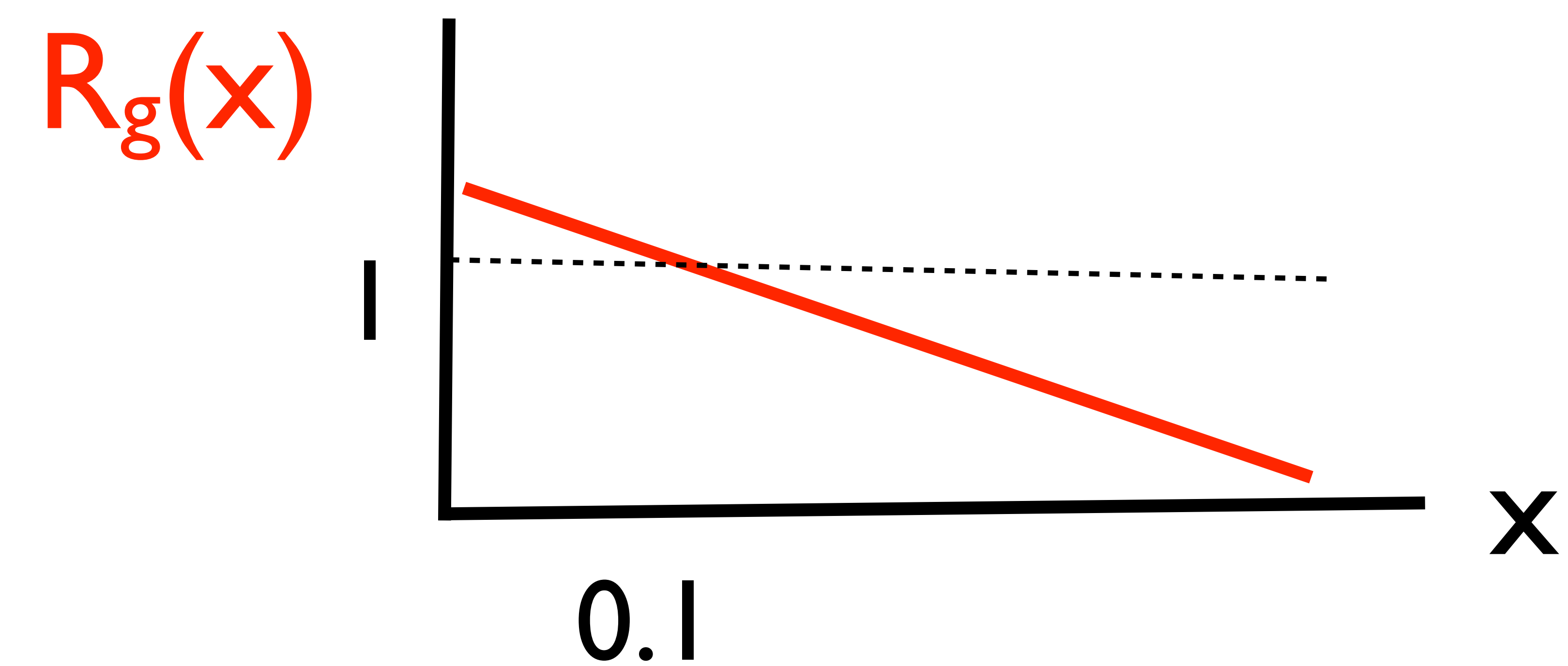
Idea:

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

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

Illustration



$$G(x, Q^2 \, |\sigma) \quad = \quad G(x, \xi Q^2)$$

$$\xi(Q^2) \quad \equiv \quad (\sigma / \langle\sigma\rangle)^{\alpha_s(Q_0^2)/\alpha_s(Q^2)} \qquad where\, Q_0^2 \sim 1\,\mathrm{GeV}^2$$

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 (large number of wounded nucleons?)

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.

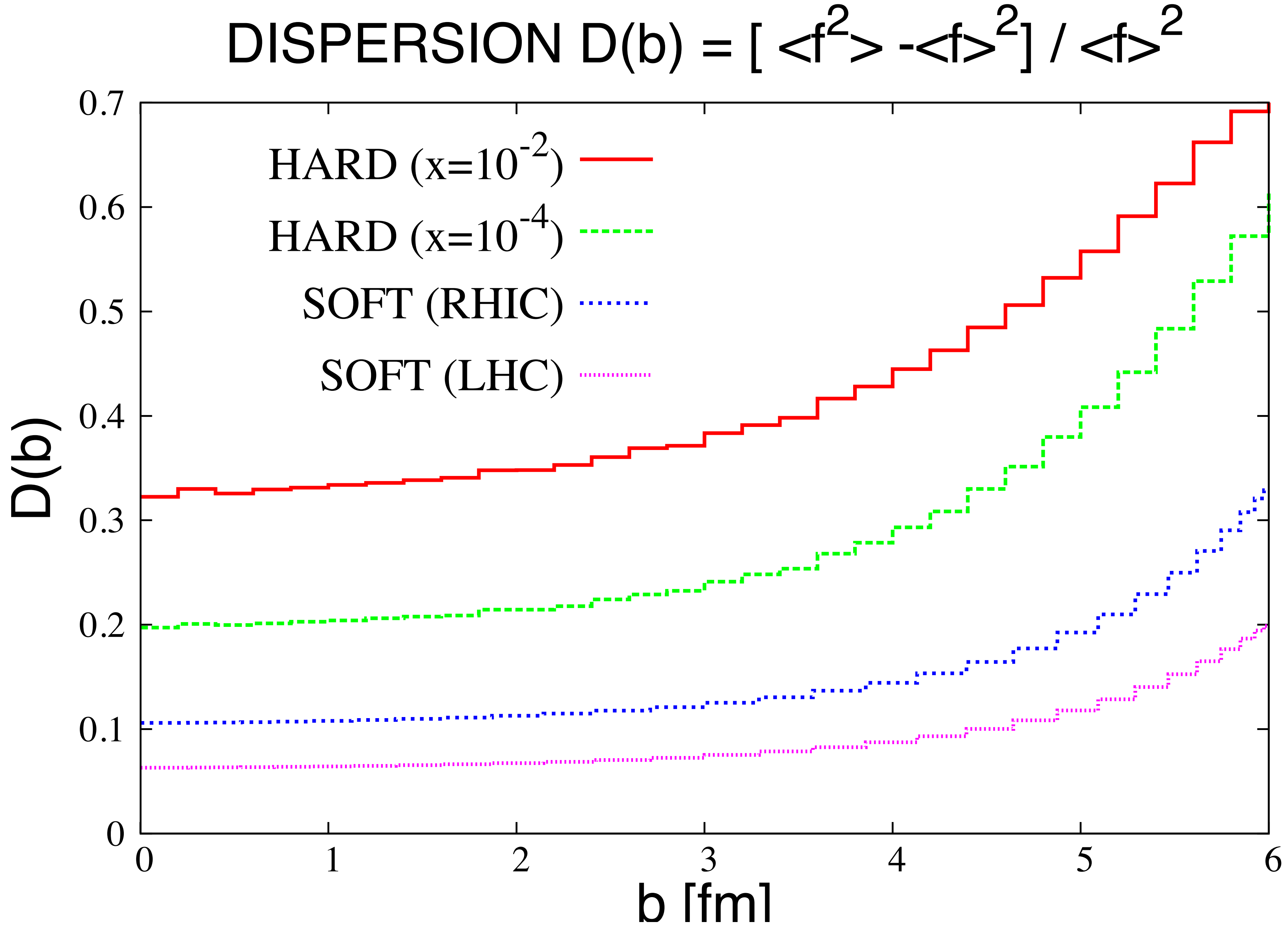
Conclusions

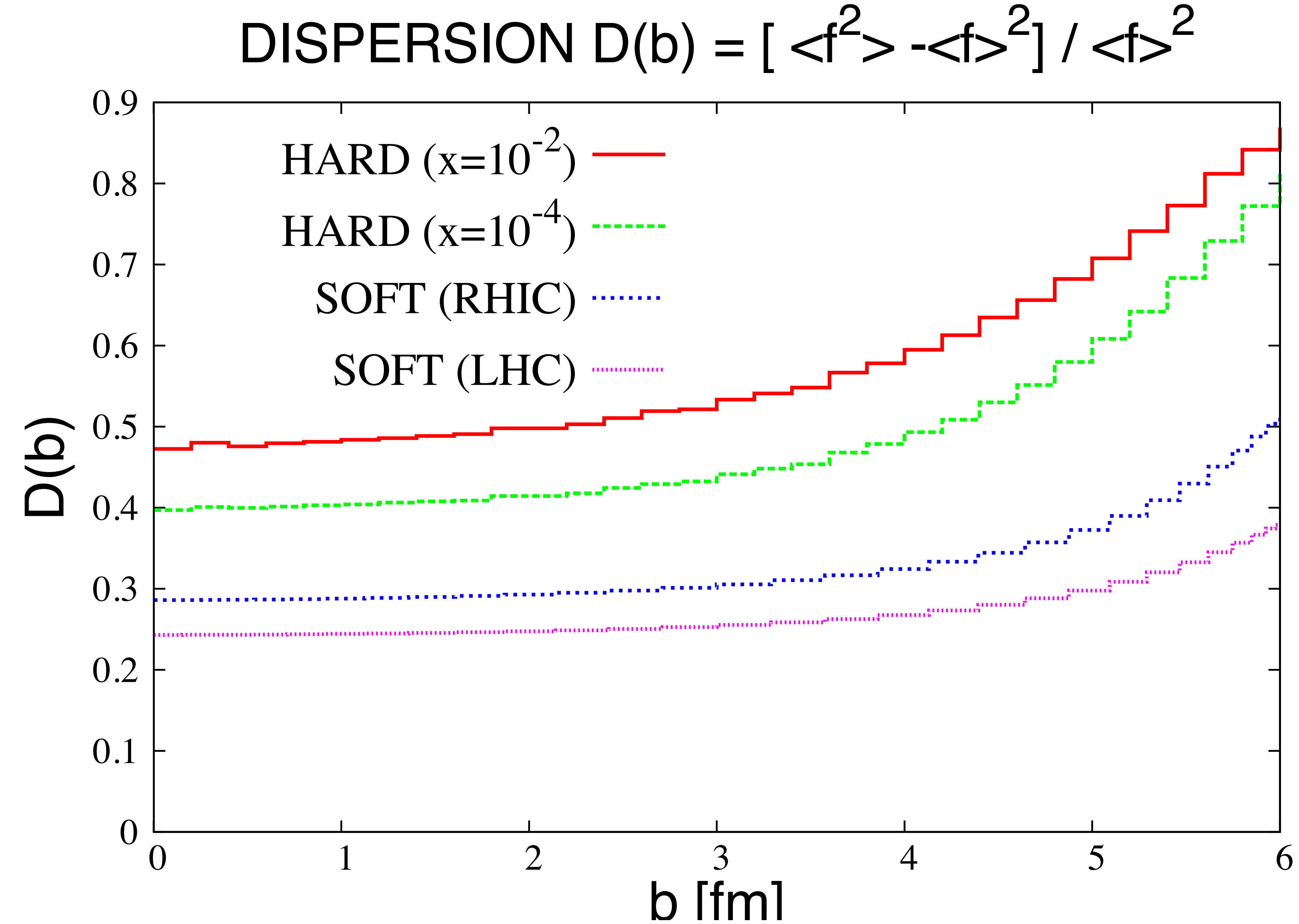
Color fluctuations in hadrons are well established both in hard and soft phenomena

Gribov-Glauber picture of hadron - nucleus scattering can be implemented for diffractive and inelastic processes using the color fluctuation formalism

Color fluctuations lead to nontrivial correlations of hard and soft components of pA interaction.

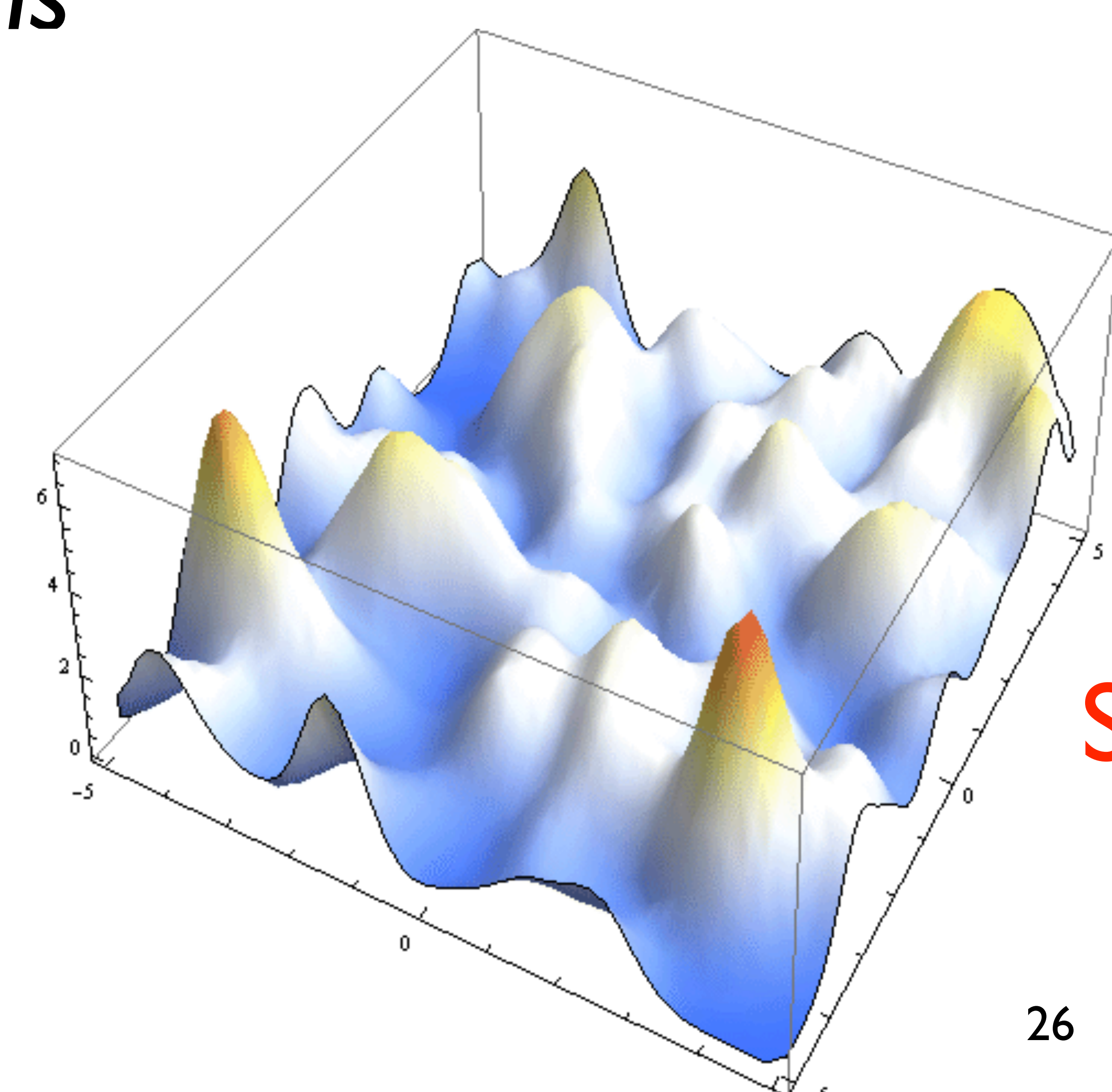
A promissing strategy to observe effects of color fluctuations would be to use a large x_p trigger





effect of fluctuations of the number of nucleons

nucleon color fluctuations + fluctuations of the number of nucleons



Alvioli & MS

Snapshot of transverse distribution of gluons

Making use of the completeness of partonic states, we find that the elastic($X = p$) and total diffractive (X arbitrary) cross sections are proportional to

$$(d\sigma_{\rm el}/dt)_{t=0} \quad \propto \quad \left[\sum_n |a_n|^2 G(x,Q^2|n)\right]^2 \equiv \langle G\rangle^2,$$

$$(d\sigma_{\rm diff}/dt)_{t=0} \quad \propto \quad \sum_n |a_n|^2 \left[G(x,Q^2|n)\right]^2 \equiv \langle G^2\rangle.$$

Hence cross section of inelastic diffraction is $\sigma_{\rm inel} = \sigma_{\rm diff} - \sigma_{\rm el}$

$\Rightarrow$

$$\boxed{\omega_g \equiv \frac{\langle G^2\rangle - \langle G\rangle^2}{\langle G\rangle^2} = \frac{d\sigma_{\gamma^*+p\to VM+X}}{dt} \Big/ \left.\frac{d\sigma_{\gamma^*+p\to VM+p}}{dt}\right|_{t=0}}$$

Strength of the gluon field should depend on the size of the quark configurations - for small configurations the field is strongly screened - gluon density much smaller than average.

Do we know anything about such fluctuations?

Yes - MS + LF + C.Weiss, D.Treliani PRL 08

Consider $\gamma_L^* + p \to V + X$ for Q^2 > few GeV^2

In this limit the QCD factorization theorem (BFGMS03, CFS07) for these processes is applicable

Expand initial proton state in a set of partonic states characterized by the number of partons and their transverse positions, summarily labeled as $|n\rangle$

$$|p\rangle = \sum_n a_n |n\rangle$$

Each configuration n has a definite gluon density $G(x, Q^2| n)$ given by the expectation valu the twist--2 gluon operator in the state $|n\rangle$

$$G(x,Q^2) \;=\; \sum_n |a_n|^2 G(x,Q^2|n) \;\equiv\; \langle G\rangle$$

Simple "scaling model" based on two assumptions

- At moderate energies $\sqrt{s}$ = 20 GeV the hadronic cross section of a configuration is proportional to the transverse area occupied by the color charges in that configuration,

$$\sigma \propto R^2_{\rm config}$$

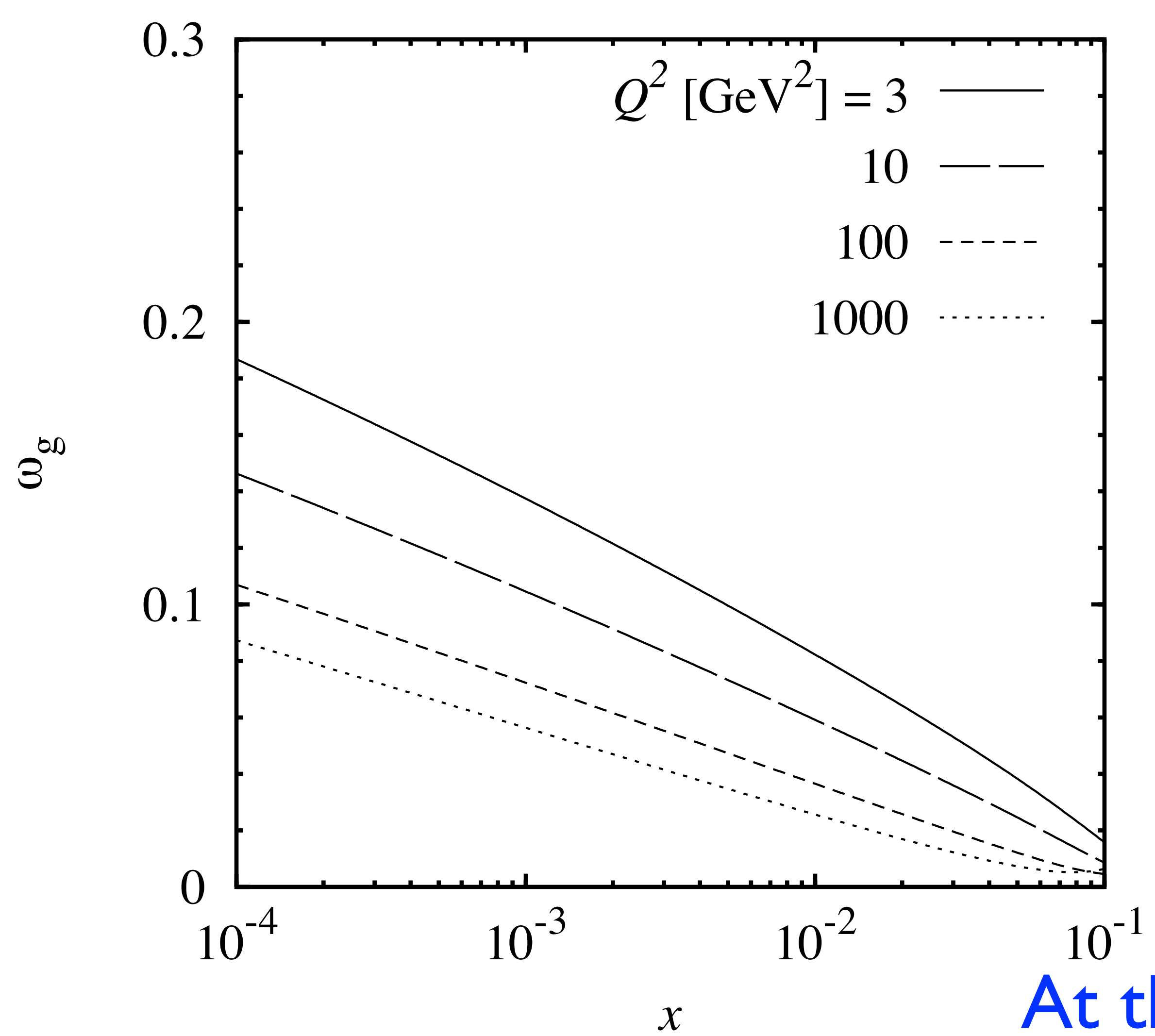
- the normalization scale of the parton density changes proportionally to the size of the configuration

$$\mu^2 \propto R^{-2}_{\rm config} \propto \sigma^{-1}$$

(in the spirit of Close et al 83 - EMC effect model)

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

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



The dispersion of fluctuations of the gluon density, ω_g, as a function of x for several values of Q^2, as obtained from the scaling model

Warning: the model designed for small x < 0.01. There maybe other effects which could contribute to ω_g for large x

At the same time decrease of ω_g with Q^2 at x=const - generic effect

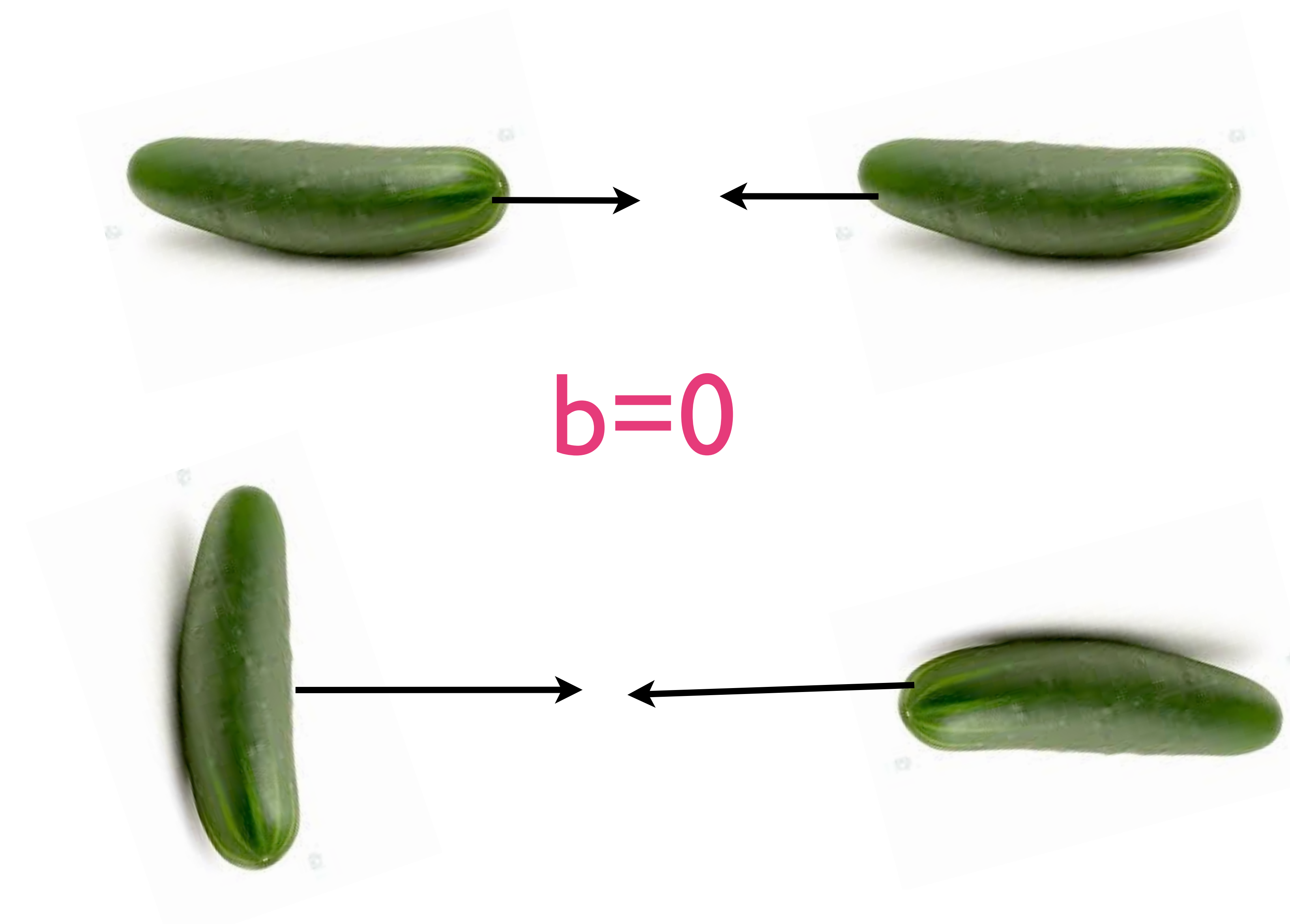
Gluon fluctuations have to be explored both theoretically and experimentally (ultraperipheral collisions at LHC) including implications for LHC final states

Enhancement due to fluctuations is expressed through fluctuations of GPDs
(*more complicated because of the shape fluctuations*)

$$R_{fl} = \frac{g_N(x_1, Q^2|\sigma) g_{1N}(x_2, Q^2|\sigma)}{g_N(x_1, Q^2) g_{1N}(x_2, Q^2)} \frac{\langle S \rangle}{S}$$

S- transverse area of overlap.

$$R = R_0 R_{fl}$$



Large fluctuations of S if nucleon (hard partons in the nucleon) form a pancake or a cucumber

> diquark model: $r_{string} / r_{tN} \sim 1/2 \div 1/3$ →
> $\langle S \rangle / S_{head\text{-}on} \sim 4 \div 9$

Measurement of R as a function N_{ch} for different x's of colliding partons and observing R exceeding ~4 for large N_{ch} would be unambiguous evidence for gluon fluctuations

Large R_{fl} may explain the large rate of dijets in the HM data