Novel directions in UPC QCD studies at the LHC

QCD UPC studies after VM (quasi) elastic measurements

Mark Strikman, PSU

Workshop on photon-induced collisions at the LHC, CERN, June 2-4, 2014

Nonlinear effects: AA UPC at LHC vs HERA

The parameter to compare is:
(gluon density/area) x (strength of interaction)

$$\frac{C\alpha_s(Q^2)xG(x,Q^2)}{Q^2\,\text{"}area\text{"}} \quad where\ C_g \approx 9/4C_q$$ **Areas:** $\pi R_A^2 \,\&\, \pi r_N^2 (r_N \sim 0.8\, fm)$

LHC vs ep HERA $$\frac{(9/4)A^{1/3}\alpha_S(p_T^2)xG_N(x\sim 5\cdot 10^{-5},p_T^2)/p_T^2}{\alpha_S(Q^2)xG_N(x\sim 10^{-4},Q^2)/Q^2} \sim \mathbf{3}$$

for central γA collisions (with no centrality trigger the gain is a factor of 1.5 smaller). *A factor of 3 gain = change in x by a factor ~100.*

Will be possible to study energy dependence of the dijet cross section in the x range between 10^{-2} and 10^{-4} and check whether taming of the increase is happening at the smallest x.

Question 1: *What is dynamics of leading particle production in the hadron - nucleus interactions?*

Small p_t - key uncertainty in modeling high energy cosmic ray propagation through atmosphere. Most of cascade is due to pions - photons is the closest we can get to pions for these energies. Interpretation of the AUGER experiment.

Is *A-dependence / dependence on centrality* of $\sigma^{-1}_{inel} d\sigma(\gamma + A \to h + X)/dx_F$ stays the same when $\sigma(\rho N)$ grows from 25 mb to 40 mb? How does it depend on p_t starting from very low p_t(ALICE) ?

Transition to hard regime: $p_t \sim 2$ GeV/c and above.

RHIC experiments observe forward pion production in Deuteron-Gold at y=4, p_t <2.5 GeV/c(a) pQCD found to work in pp for p_t >1.5 GeV/c; (b) Strong suppression (factor of 3) in dAu and much larger suppression at small impact parameters (*potential pitfall - definition of centrality*)

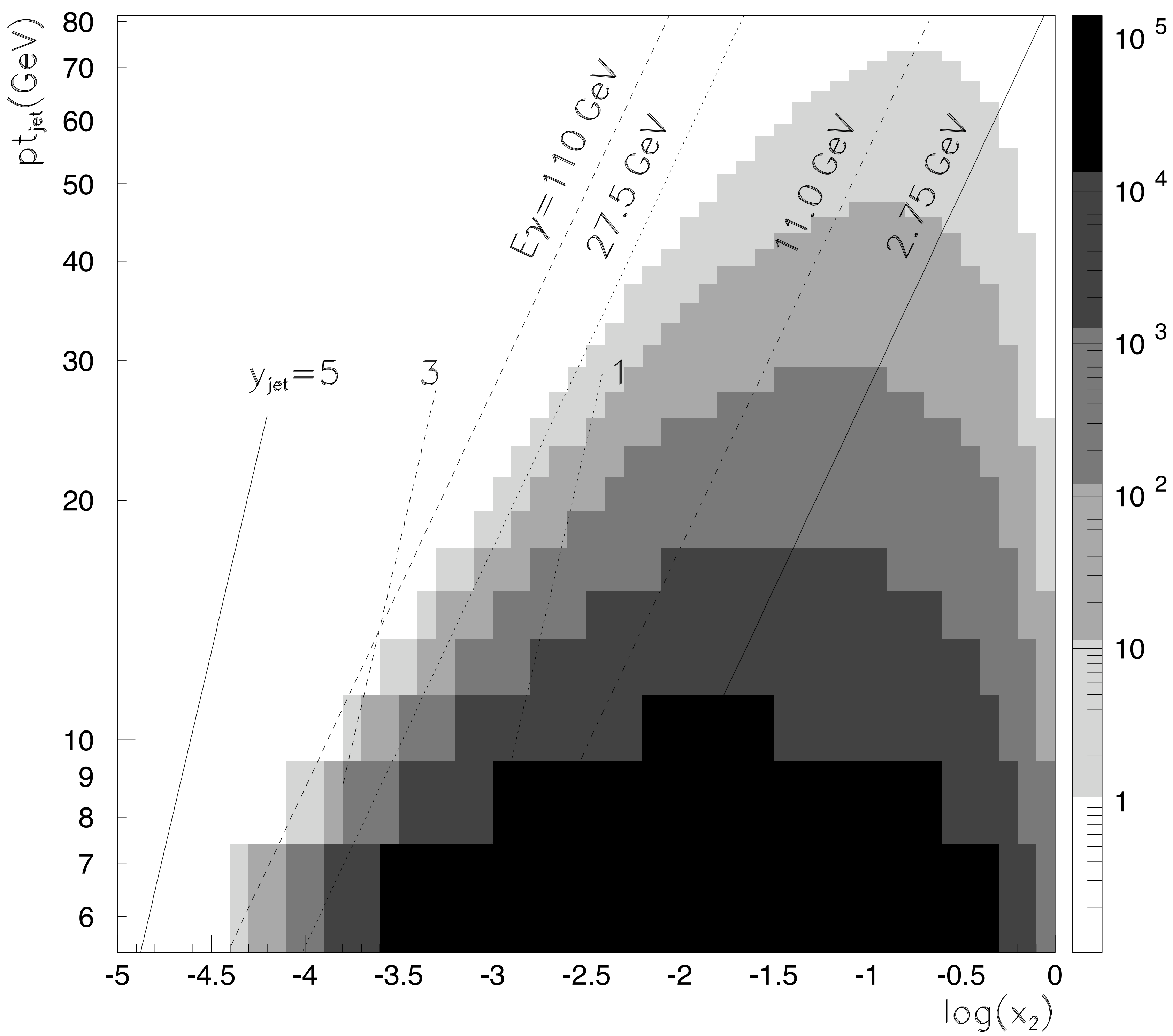
Interpretations - effect is due to strong gluon fields in nuclei a x $\sim 10^{-4}$

- *color glass condensate - eikonal rescattering + gluon suppression*
- *fractional energy losses for propagation of partons through strong gluon fields*

Major Impact on energy flow from large to central rapidities in AA collisions at RHIC and LHC

Question 11: *What are parton densities in nuclei at small x - is there significant deviation from the sum of nucleon pdfs (LT nuclear shadowing)?*

M.Klasen & R.Vogt talks



R.Vogt, S.White, MS, 2005

Expected rate of dijet photoproduction for a 1 month LHC Pb+Pb run at 0.4×10^{27} $cm^{-2}s^{-1}$. Rates are counts per bin of ±0.25 x_2 and 2 GeV/c in p_T. Large rates for b-meson jets as well.

Many more important handles to study dynamics, for example associated multiplicity at different rapidities,...

Are significant nuclear effects expected in the UPC AA kinematics at LHC?

The leading twist theory FS 98 based on AGK cutting rules and Collins factorization theorem for diffraction indicates that effects are likely to be significant (Guzey's talk)

Question III:

Where color coherence of pA interactions shows up. The pattern of the correlation of the jet production and centrality in γ A collisions - new probe of inelastic photon - nucleus interaction dynamics

Two key features of high energy scattering relevant for pA scattering at the LHC

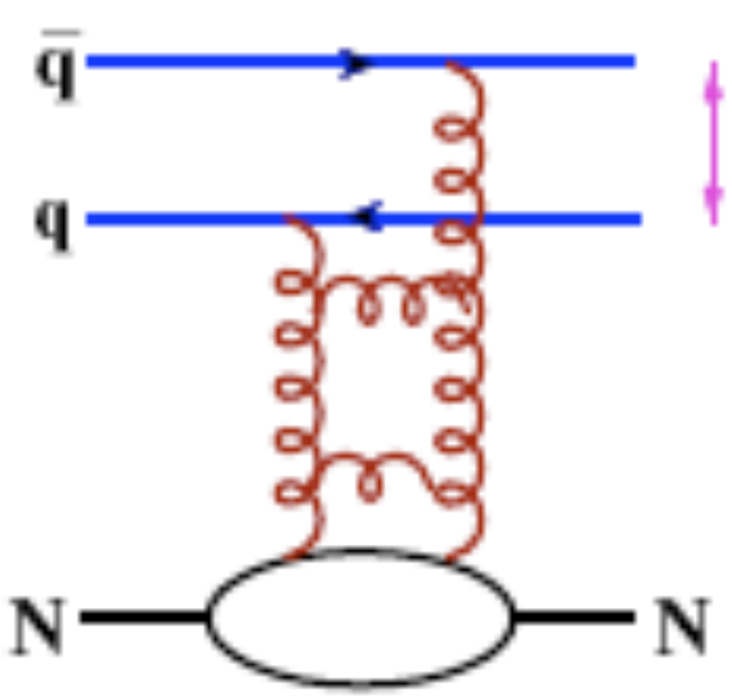
- High energy projectile stays in a frozen configuration distance $l_{coh} = c\Delta t$

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

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

- Strength of interaction of white system is proportional to the area occupies by color.

OCD factorization theorem for the <u>interaction of small size color singlet wave package of quarks and gluons.</u>

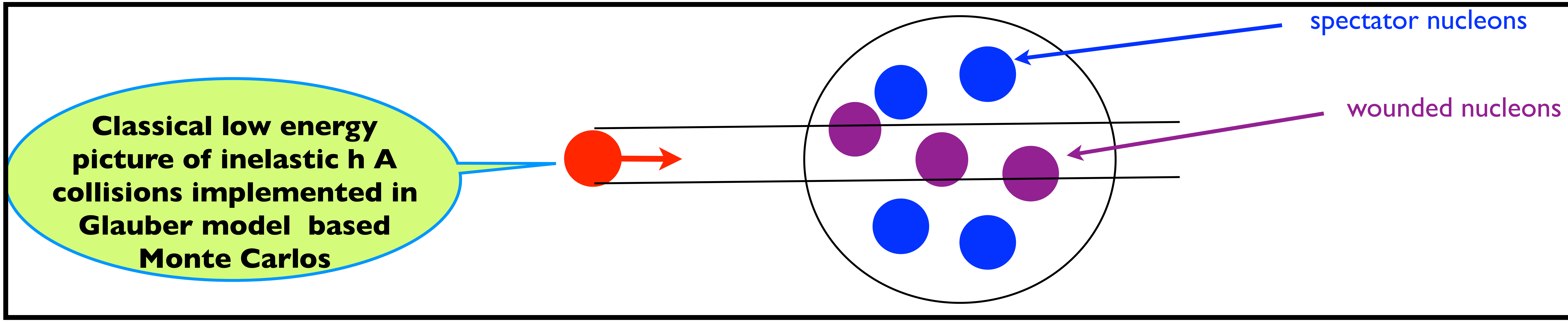


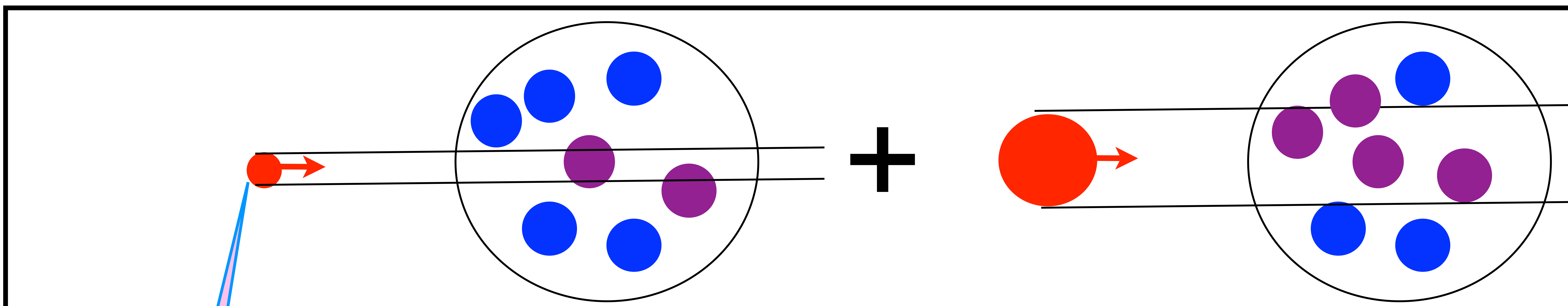
$$\sigma(d,x) = \frac{\pi^2}{3}\alpha_s(Q_{eff}^2)d^2\left[xG_N(x,Q_{eff}^2) + \frac{2}{3}xS_N(x,Q_{eff}^2)\right]$$

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

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

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





High energy picture of inelastic h A collisions consistent with the Gribov - Glauber model

Frozen configuration - same strength of interaction with different nucleons along the path *essentially semiclassical picture!!!* Large size is enhanced in high multiplicity events.

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

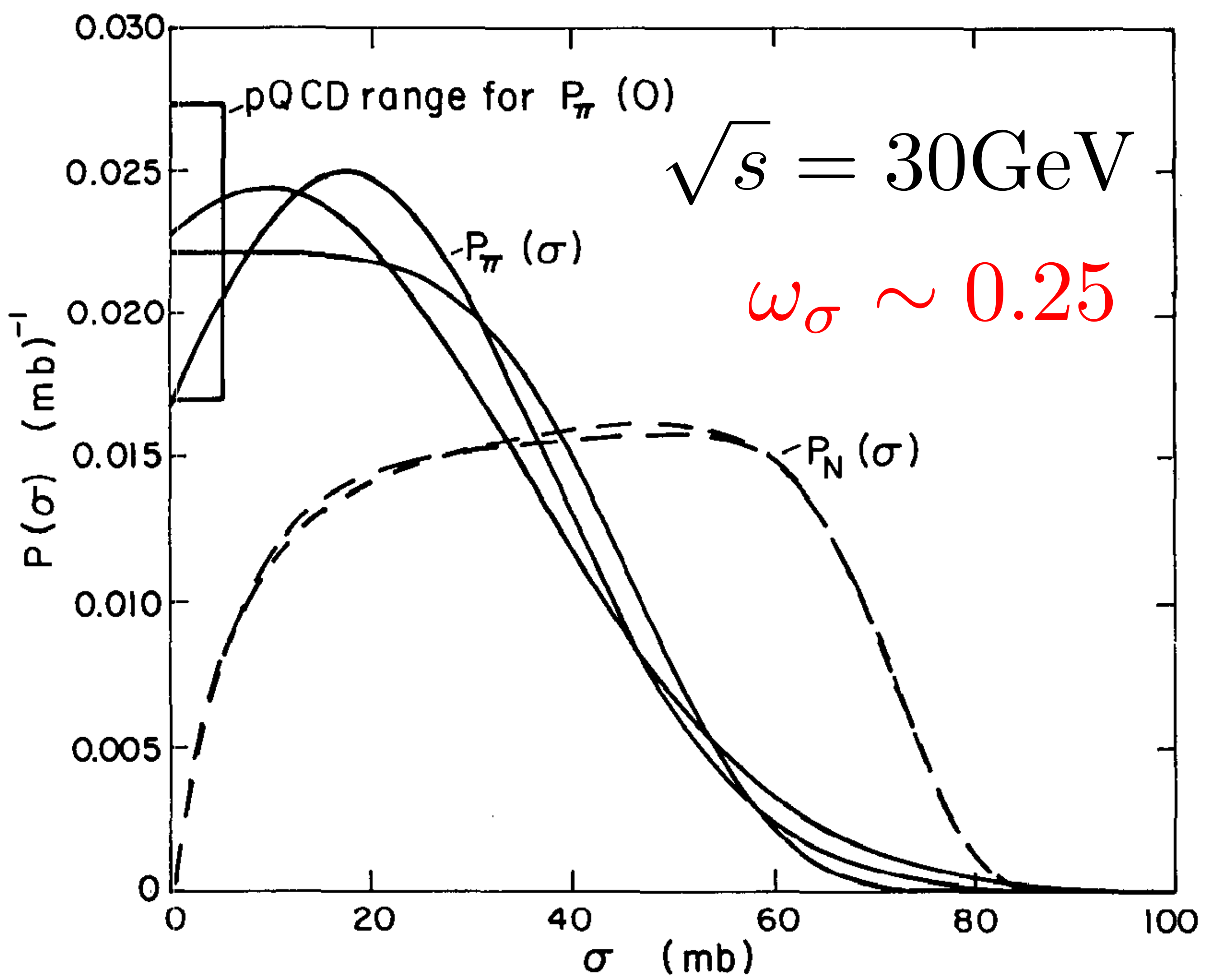
$$P(\sigma)_{|\sigma\to 0} \propto \sigma^{n_q-2}$$

Baym et al 1993 analog of QCD counting rules

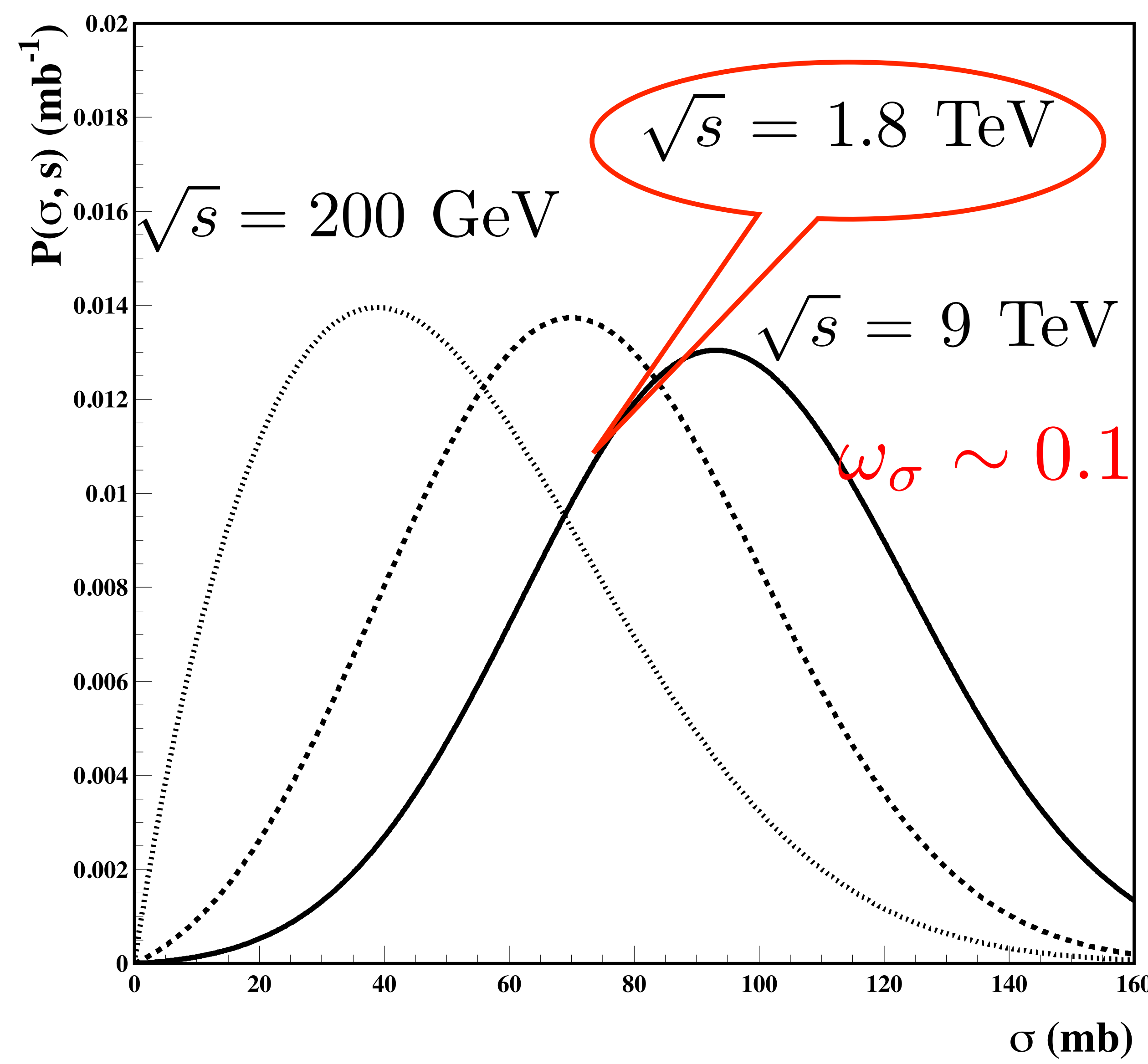
+ additional consideration that for a many particle system fluctuations near average value should be Gaussian

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

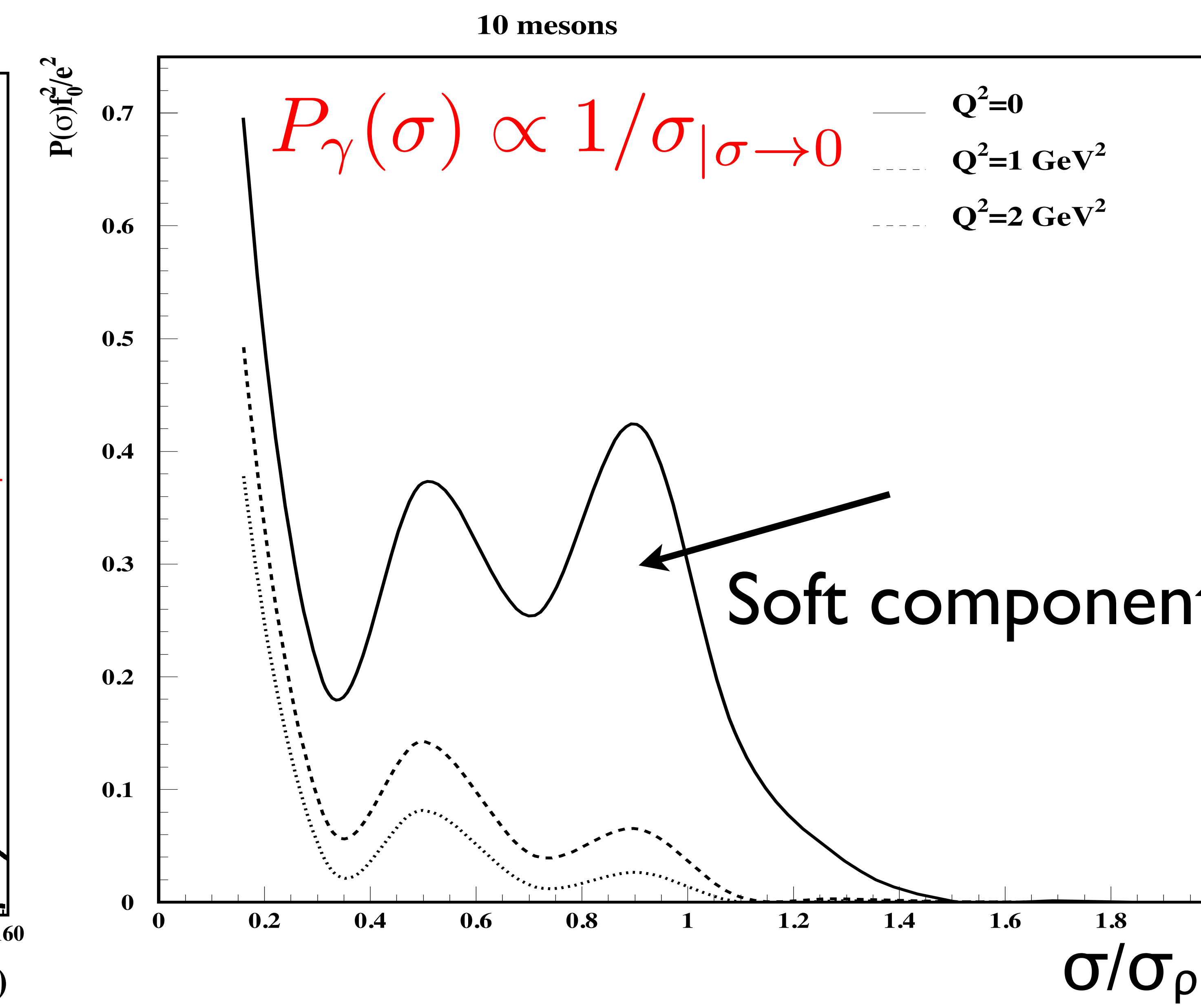
$P_N(\sigma)$



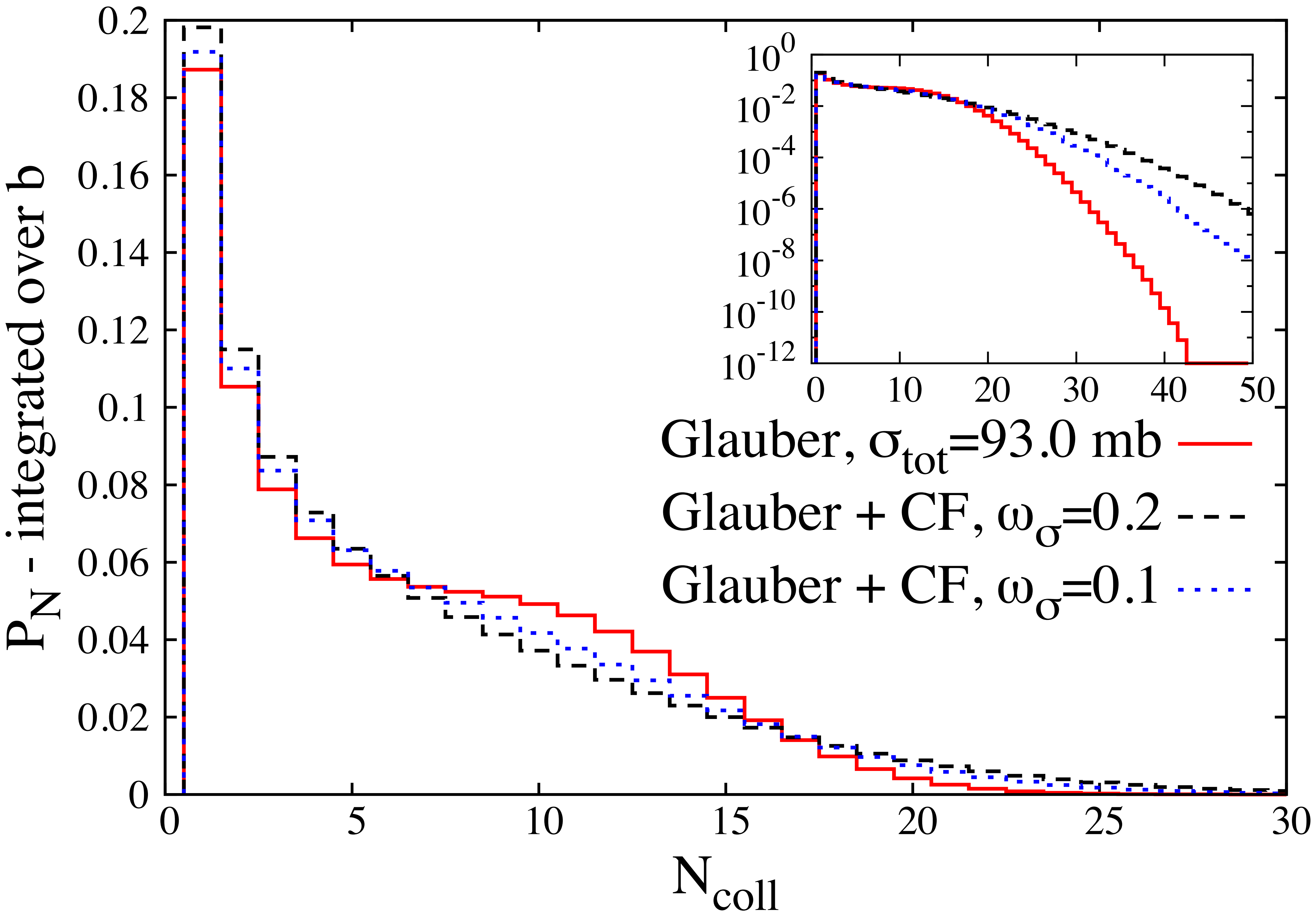
$P_N(\sigma)$ extracted from pp,pd diffraction Baym et al 93. $P_\pi(\sigma)$ is also shown

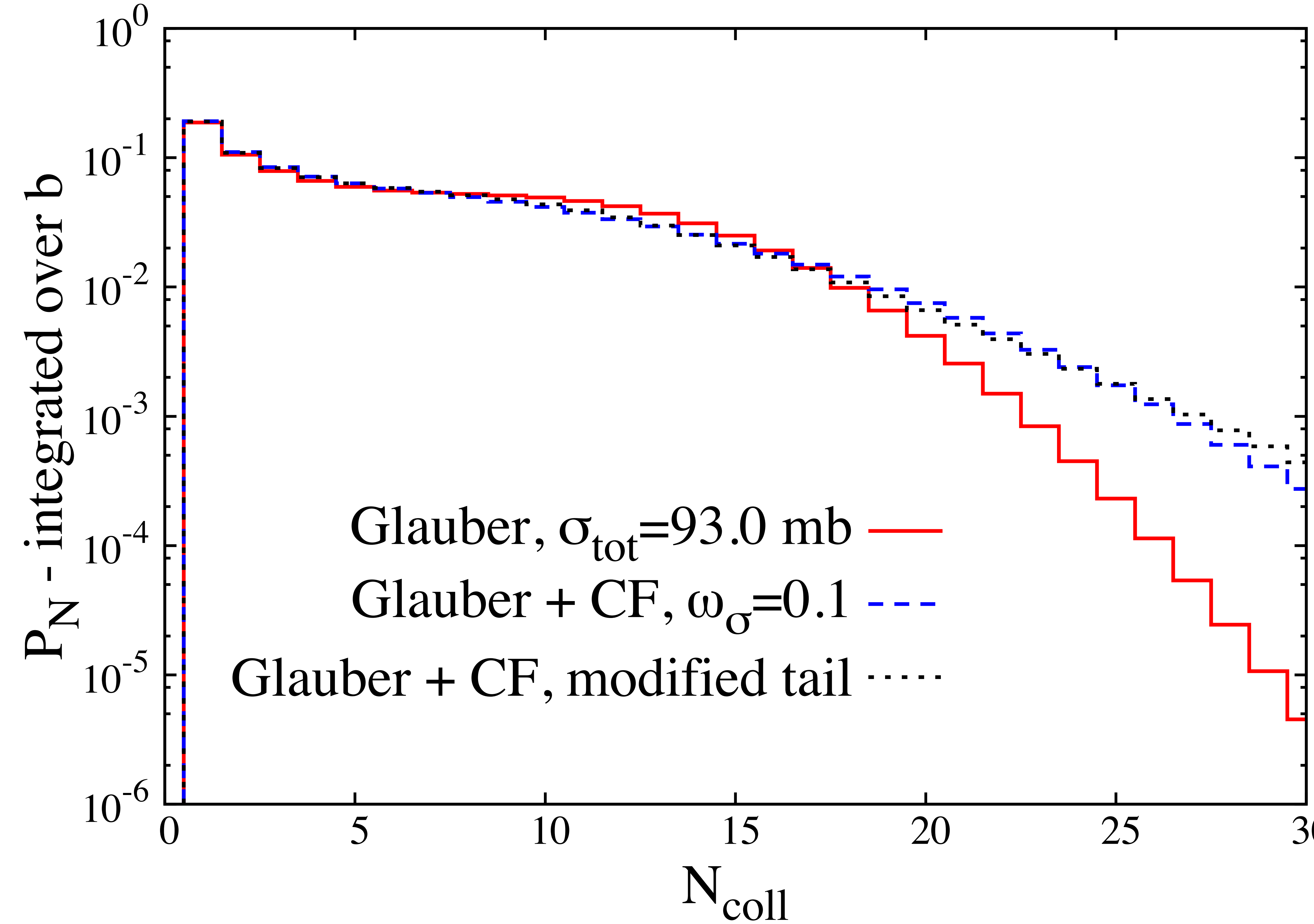


Extrapolation of Guzey & MS before the LHC data



L. Frankfurt, V. Guzey, MS
Phys.Rev. D58 (1998) 094039



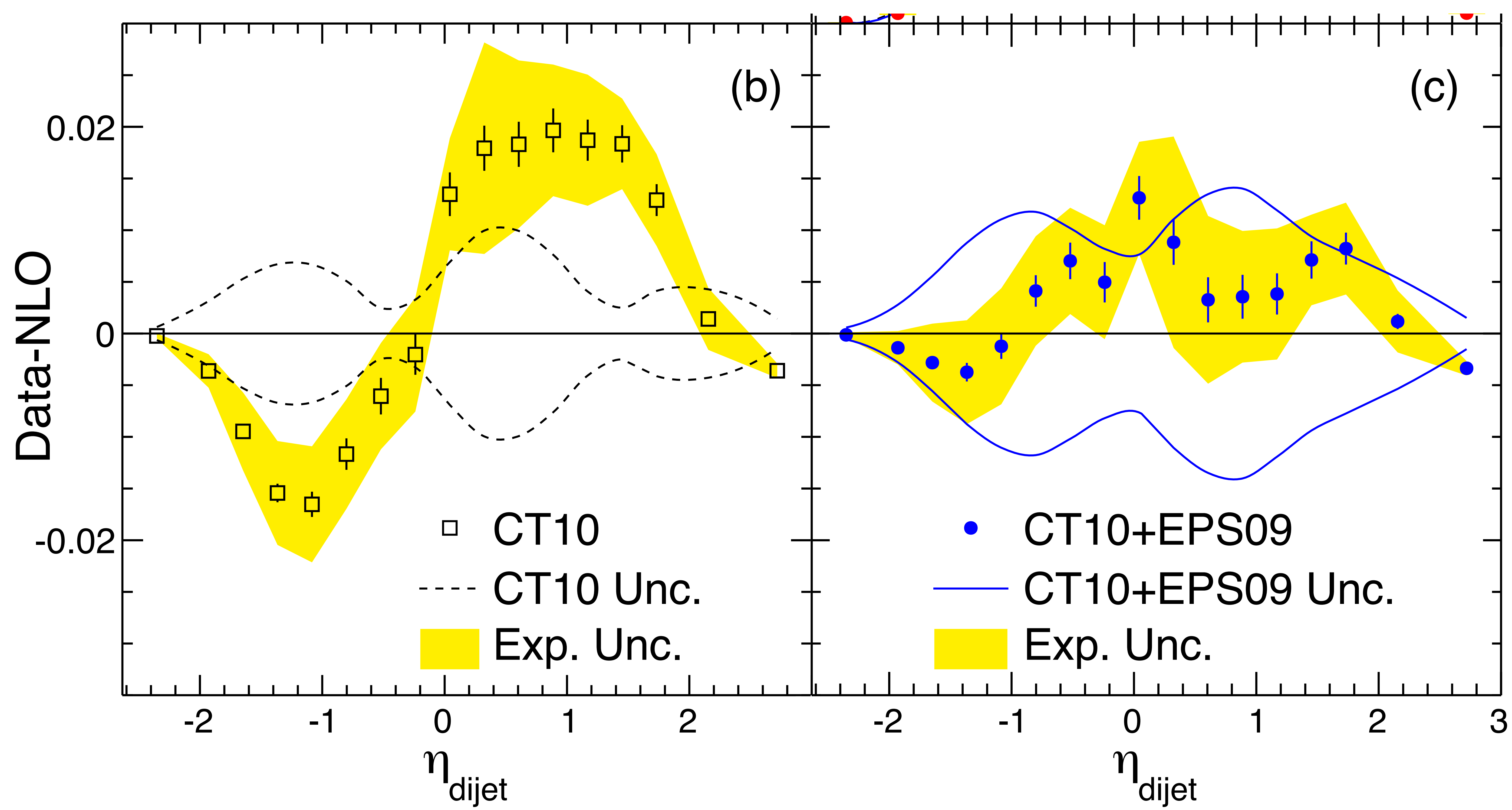


Color fluctuations lead to broadening of the distribution over N_{coll}. Effect is mostly sensitive primarily to the value of variance ω_σ. Explains deviations from the Glauber model observed by ATLAS and ALICE. For γA fluctuations are much stronger -- expect much larger effect which would be different for charm component.

An effective way to address these questions is to study correlation between dijet production and accompanying soft multiplicity in

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

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



❖ Dependence of jet rate on E_T in the nucleus fragmentation $3 < |\eta| < 5$ (ATLAS); sum of E_T in nucleus and proton ranges $4 < |\eta|$ (CMS)

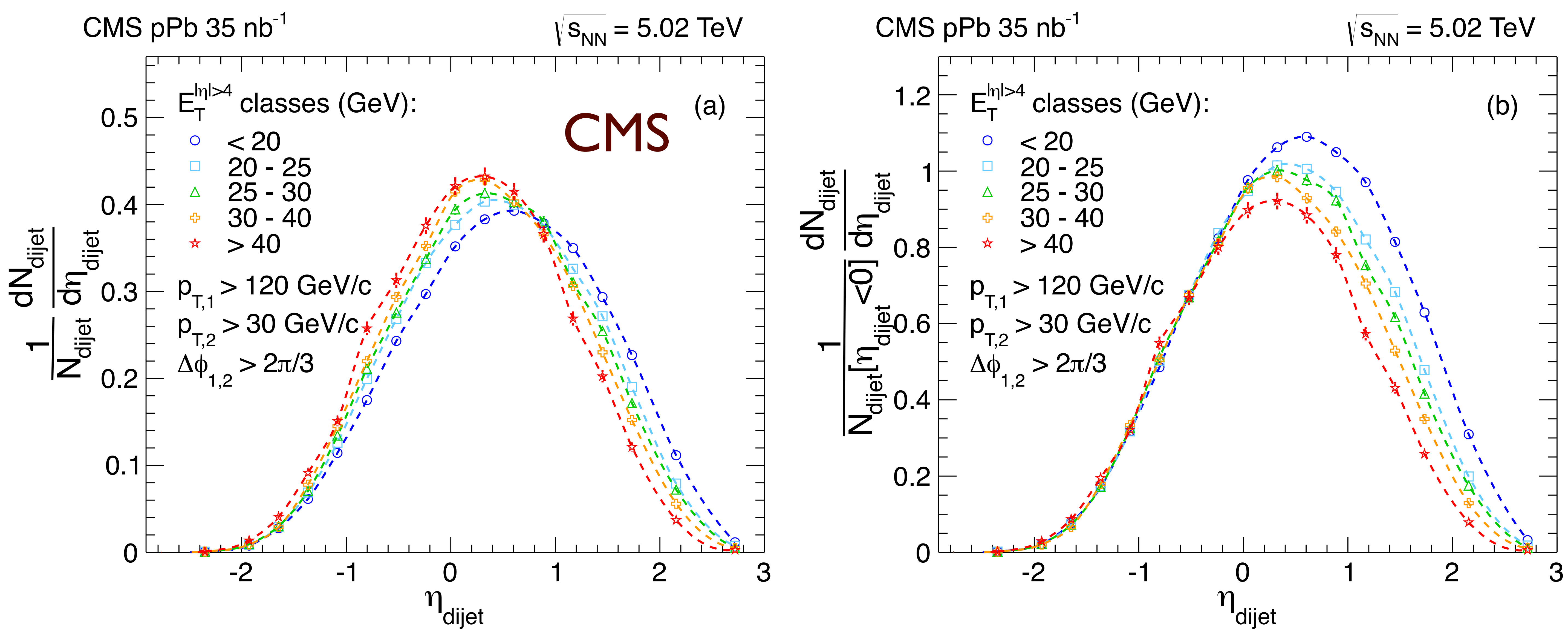
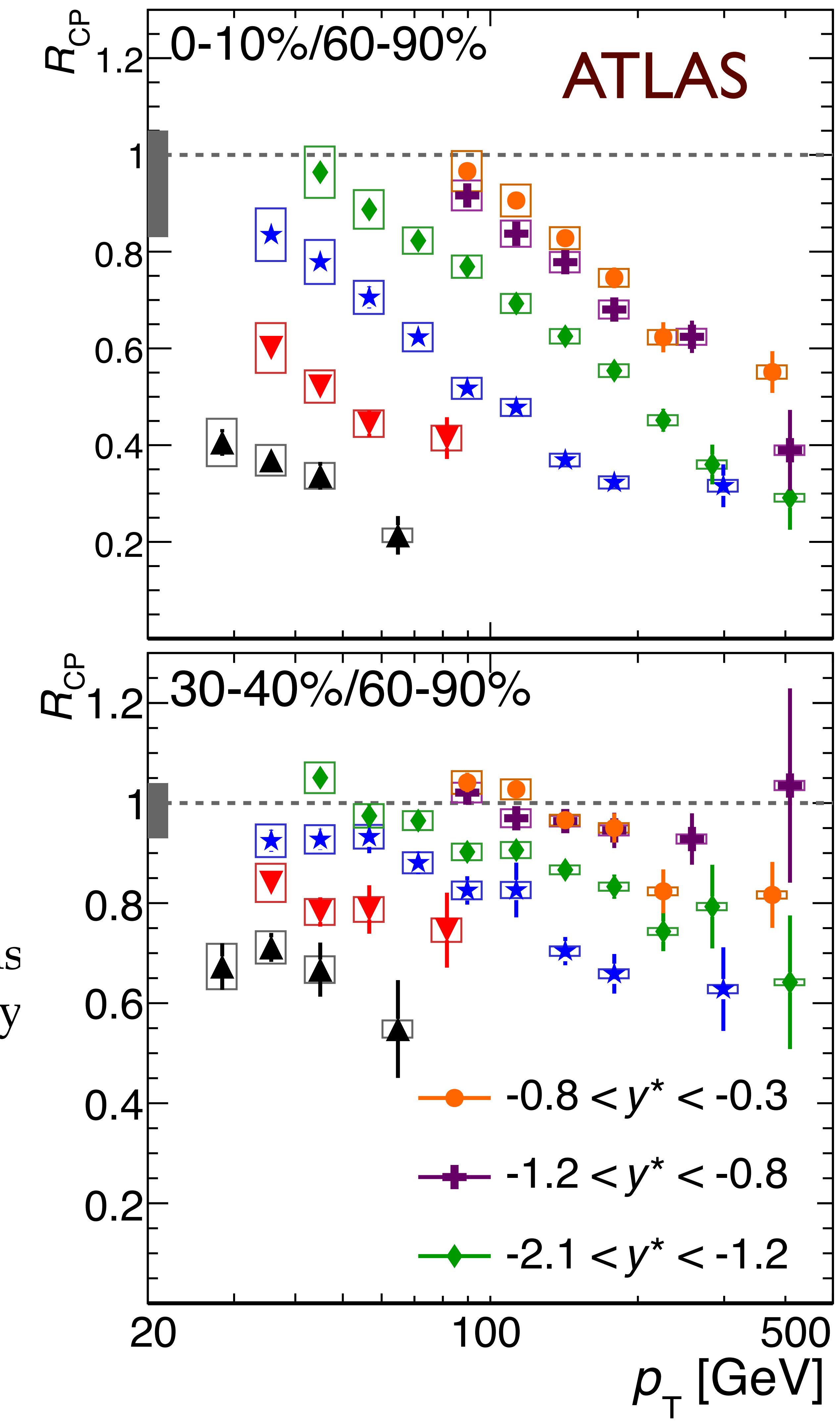
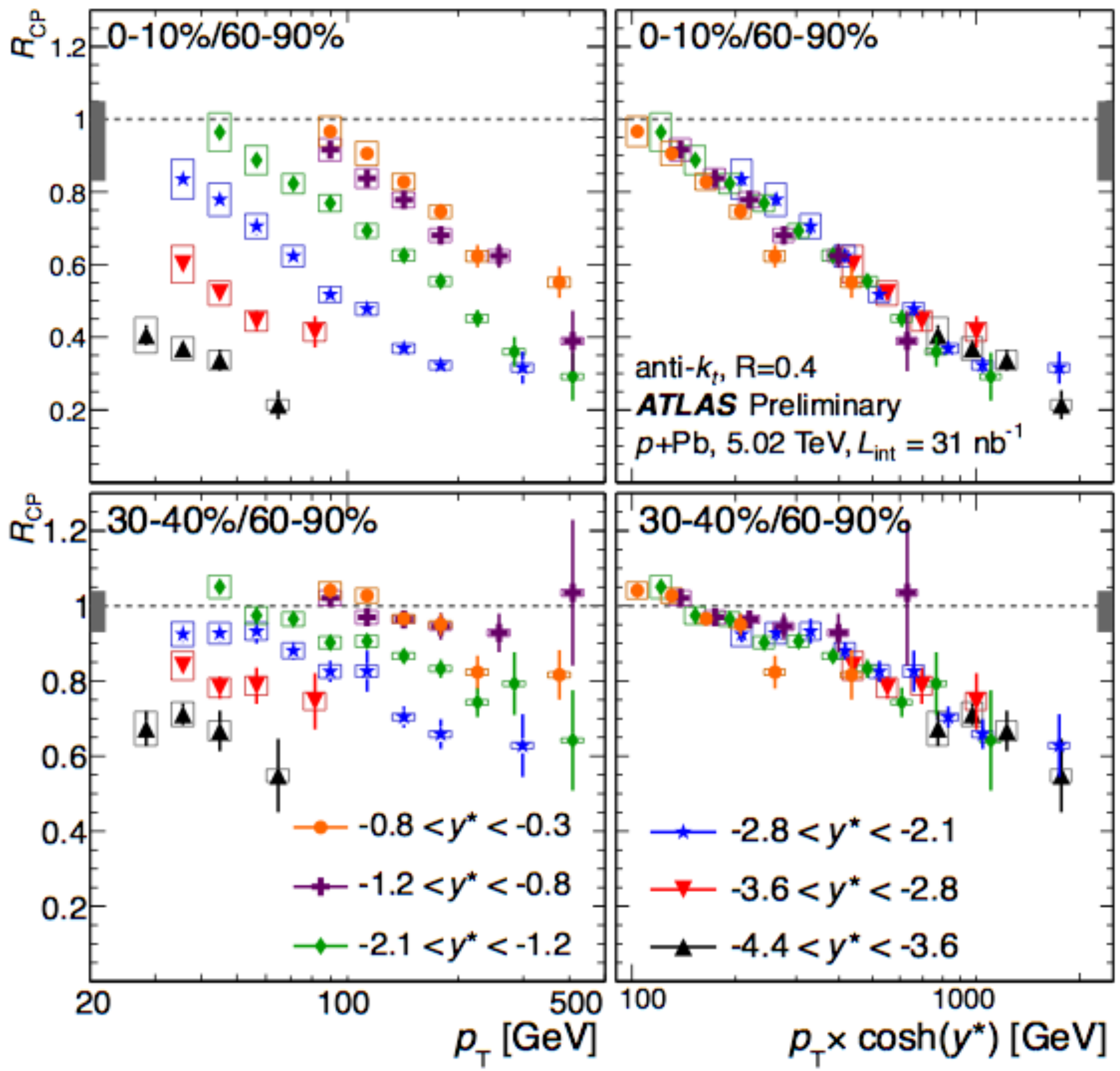


Figure 8: Dijet pseudorapidity distributions in the five HF activity classes. (a) The distributions are normalized by the number of selected dijet events. (b) The distributions are normalized by the number of dijet events with $\eta_{\text{dijet}} < 0$.



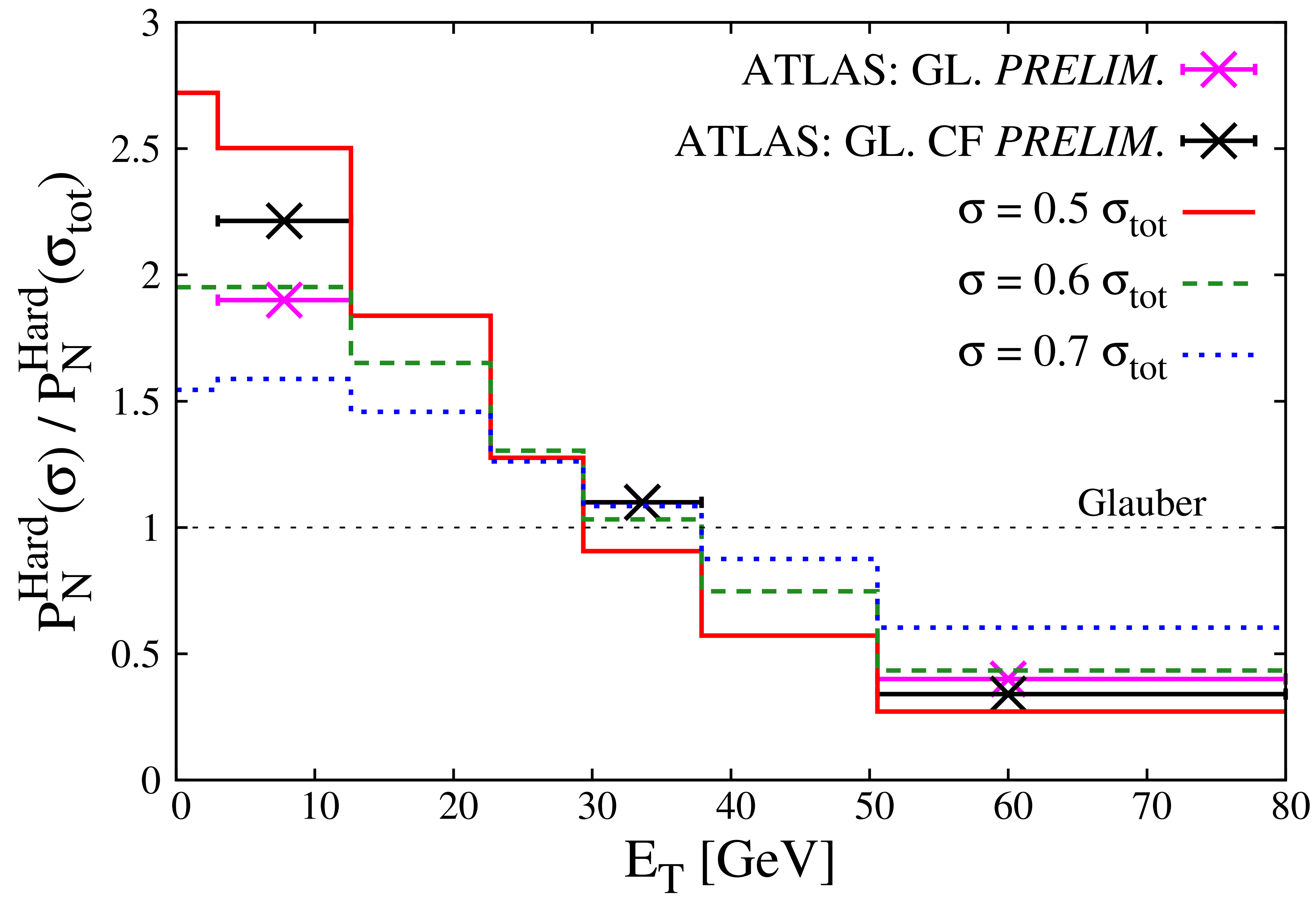
❖ x_p scaling (ATLAS) - suppression effect scales with

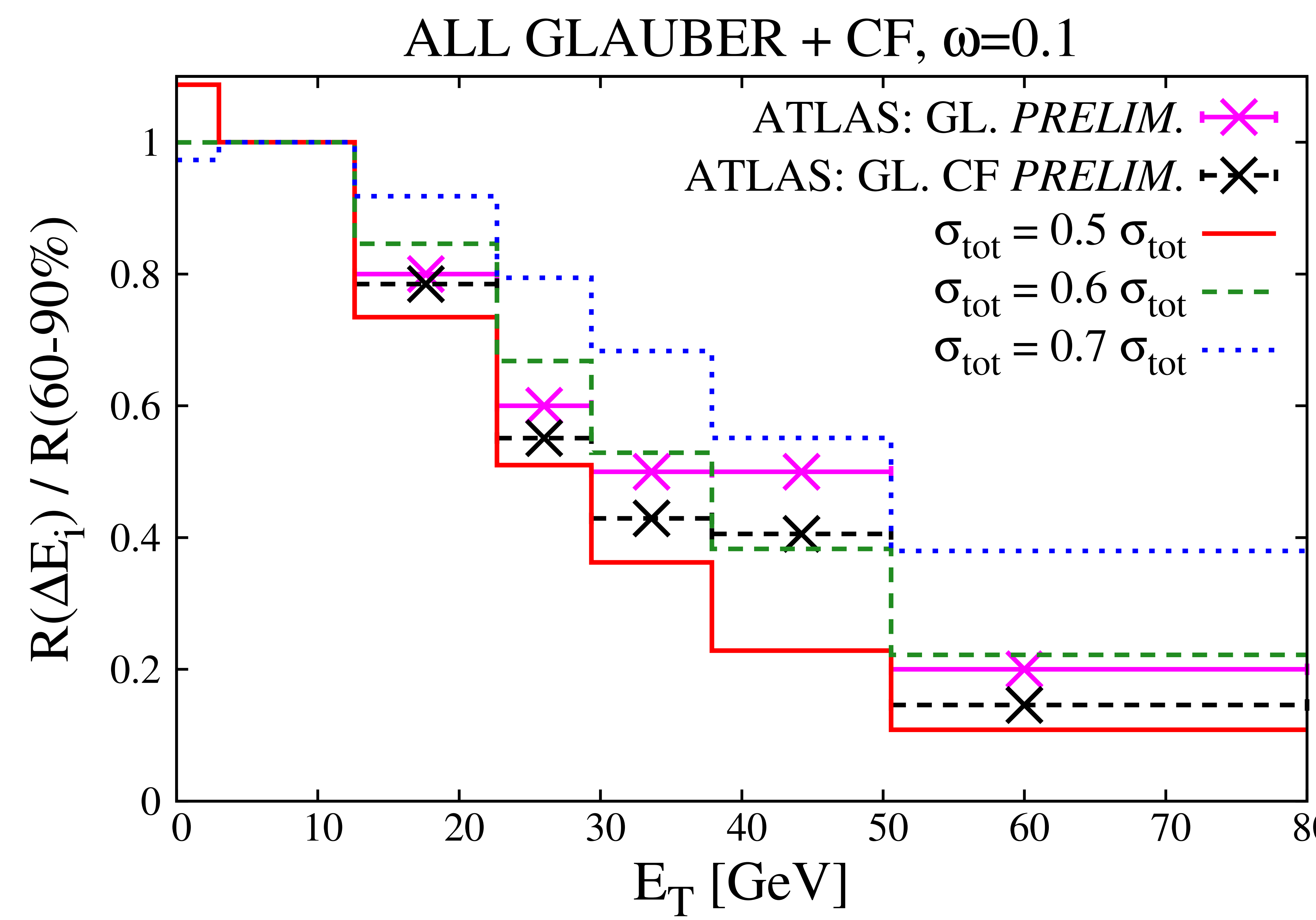


$x_p = p_T \times \cosh(y^*) / E_N$

$x_p = 0.5$

Theoretical expectation - configurations with large x partons are smaller and hence interact with a smaller cross section. Our analysis indicates that σ(x=0.5) ~ $\sigma_{tot}/2$ gives a reasonable description of the data





× *corrects ATLAS data for difference of N_{coll} in Glauber and CF models*

We can estimate σ(x=0.5)/σ_{tot}[fixed target]=1/4

from probability conservation relation:

$$\int_0^{\sigma(s_1)} P(\sigma, s_1) d\sigma = \int_0^{\sigma(s_2)} P(\sigma, s_2) d\sigma$$

Question IV: *How to discover in unambiguous way onset of the regime of of maximal strength interaction in hard processes - black disk regime / saturation?*

Inclusive signals: gross deviations from LT approximation

$F_{2A}(x,Q^2) = \sum_q e_q^2/12\pi^2 Q^2 2\pi R_A^2[1/3\ln A + \lambda \ln(x_0/x)]\theta(0.05/A^{1/3} - x),\ \lambda \sim 0.2 \div 0.3$

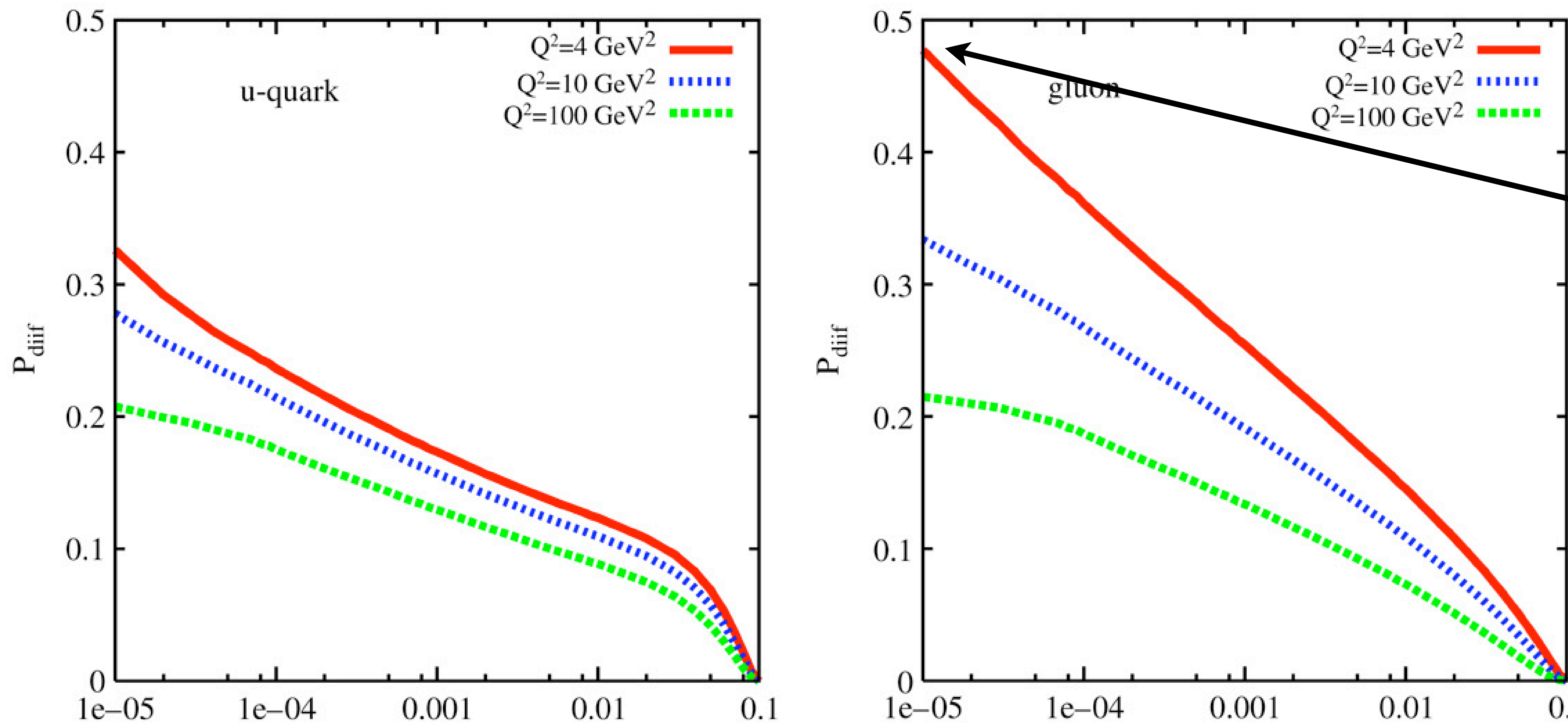
UPC allows another critical measurement is hard diffraction:

$$\gamma A \to jet_1 + jet_2 + X + A$$ for direct photon: $\beta_\gamma \approx 1$

In the black disk regime
$$\frac{\sigma(\gamma A \to jet_1 + jet_2 + X + A)}{\sigma(\gamma A \to jet_1 + jet_2 + X)} \approx 0.5$$

$$\frac{d\sigma_{(\gamma + A \to ``M'' + A)}}{dt dM^2} = \frac{\alpha_{em}}{3\pi} \frac{(2\pi R_A^2)^2}{16\pi} \frac{\rho(M^2)}{M^2} \frac{4\left|J_1(\sqrt{-t}R_A)\right|^2}{-tR_A^2}$$

$$where\ \rho(M^2) = \sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu^+\mu^-).$$

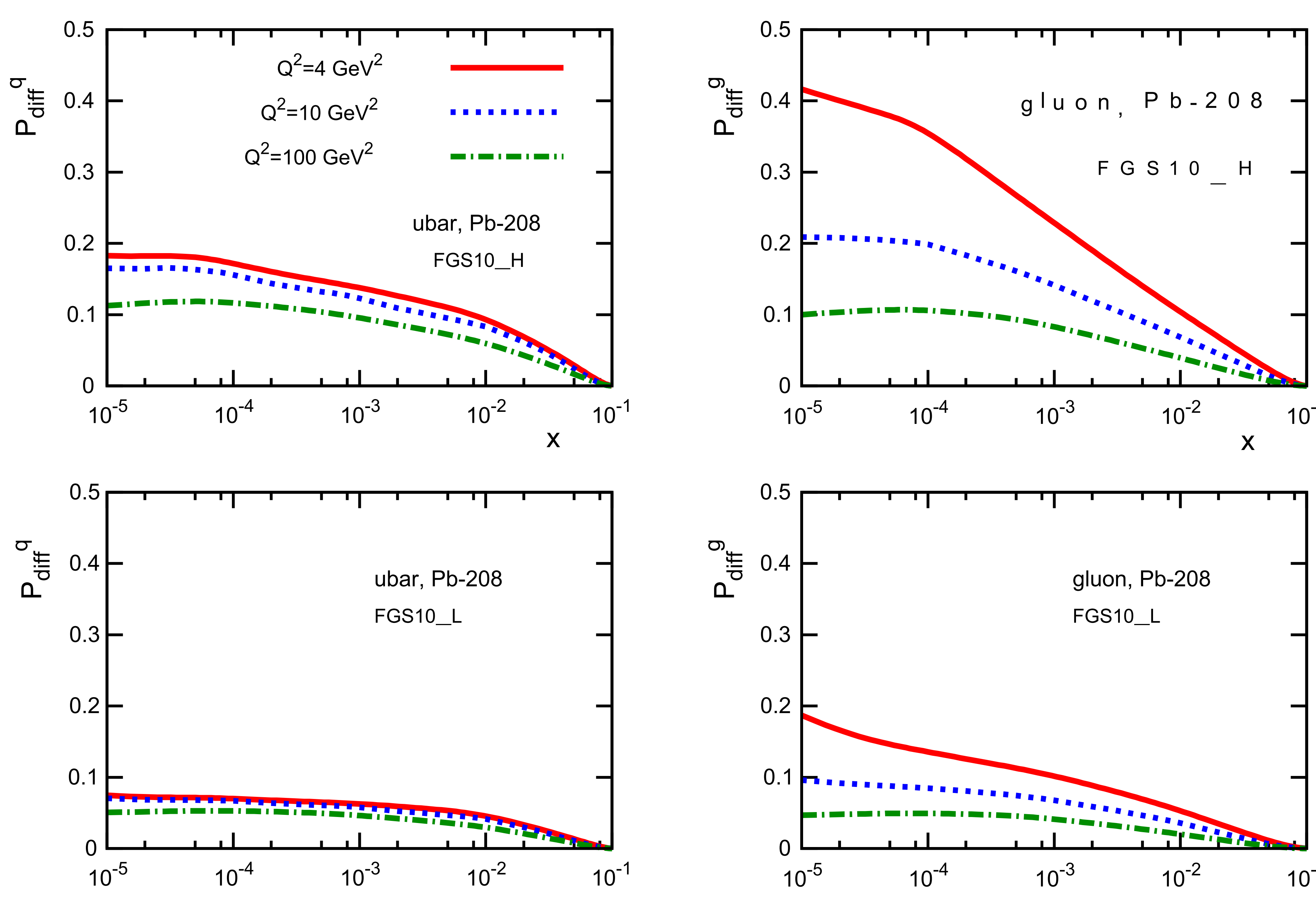


Black limit

Evidence for onset of BDR at HERA for gluons at Q=2 GeV

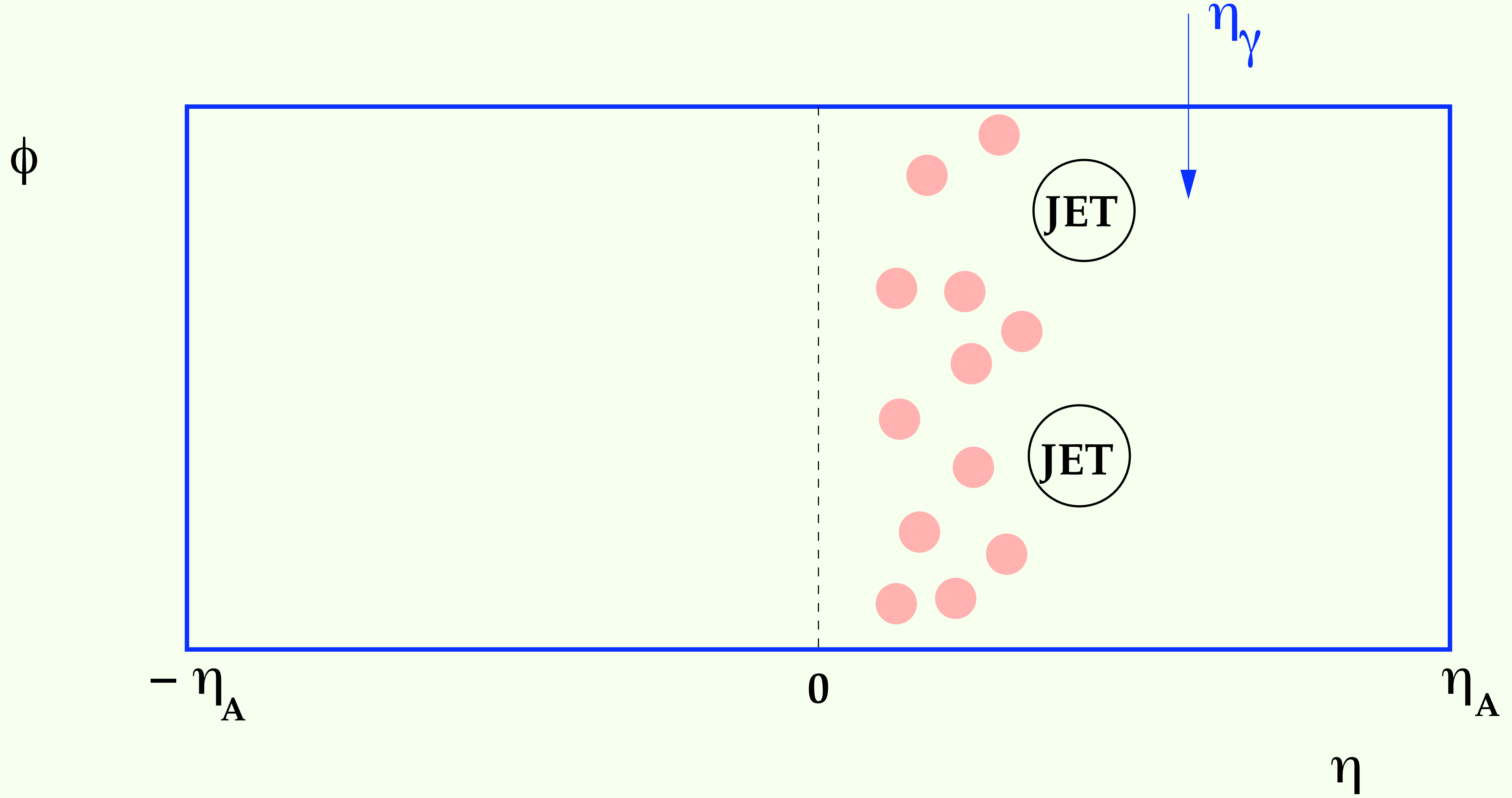
The probability of hard diffraction on the nucleon, $P_{j\ diff}$ as a function of x and Q^2 for u quarks (left) and gluons (right) based on the HERA data.

L. Frankfurt et al. / Physics Reports 512 (2012) 255–393



The probability of hard diffraction for scattering off Pb, $P_{j\ diff}$ as a function of x and Q^2 for u quarks (left) and gluons (right) for Q^2=4, 10, 100 GeV^2 calculated by Guzey et al 12 in the same approximations as LT nuclear pdf's. diff/total ratio is sensitive to the strength of fluctuations in the interaction strength - contribution of large x to small x via DGLAP evolution

In AA scattering it will be possible to measure gluon nuclear diffractive pdfs (or at least rapidity gap probabilities) in most of the small x kinematic range where measurements of nuclear gluon pdfs will be feasible . The key element is the possibility to use the direct photon mechanism to determine which of the nuclei has emitted the photon - - **10% of the dijet production for direct photon contribution is diffractive**



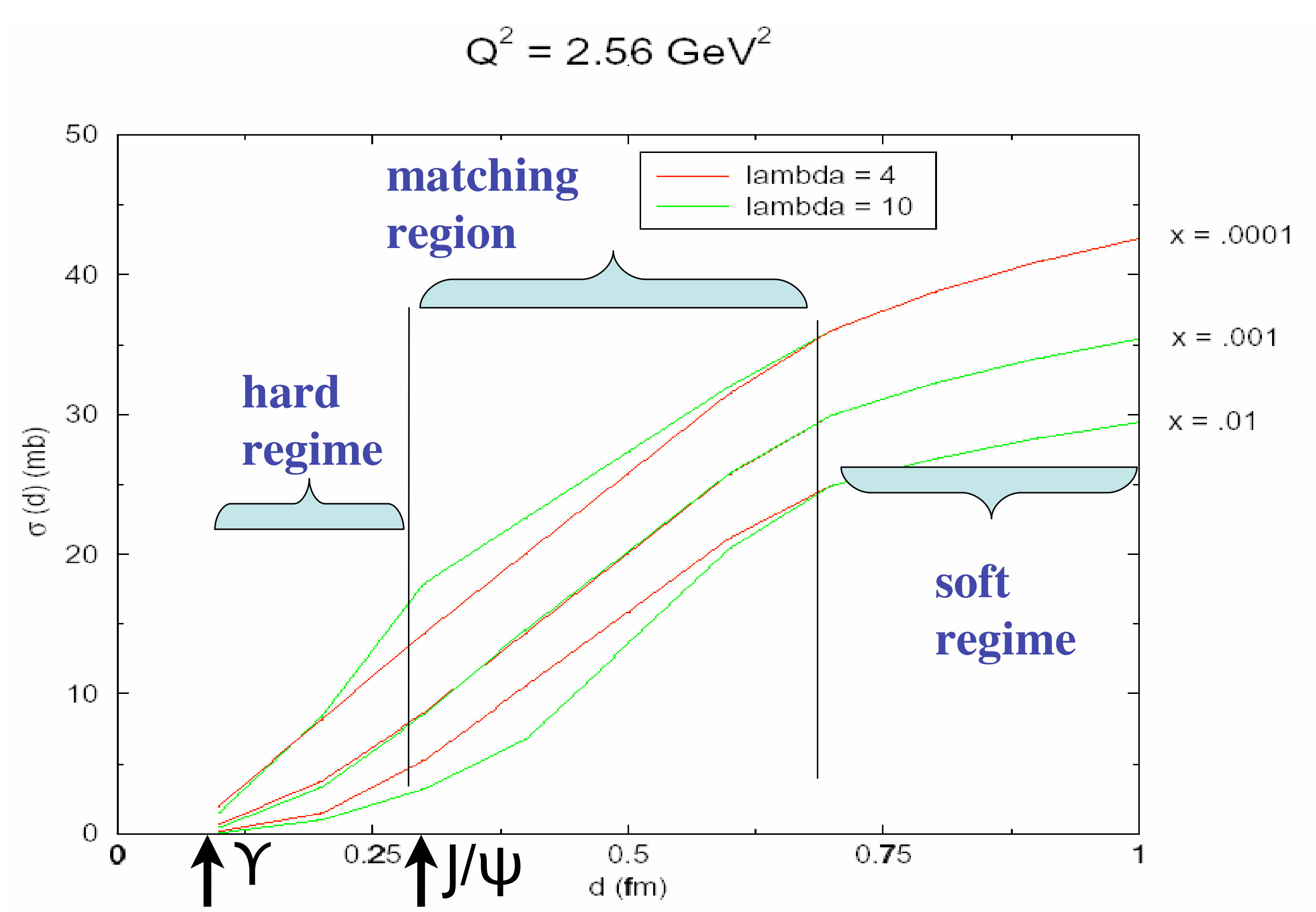
UPC induced direct photon hard diffraction: AA––> AA + 2jets +X

Question V: *How small dipoles interact with nuclear media?*

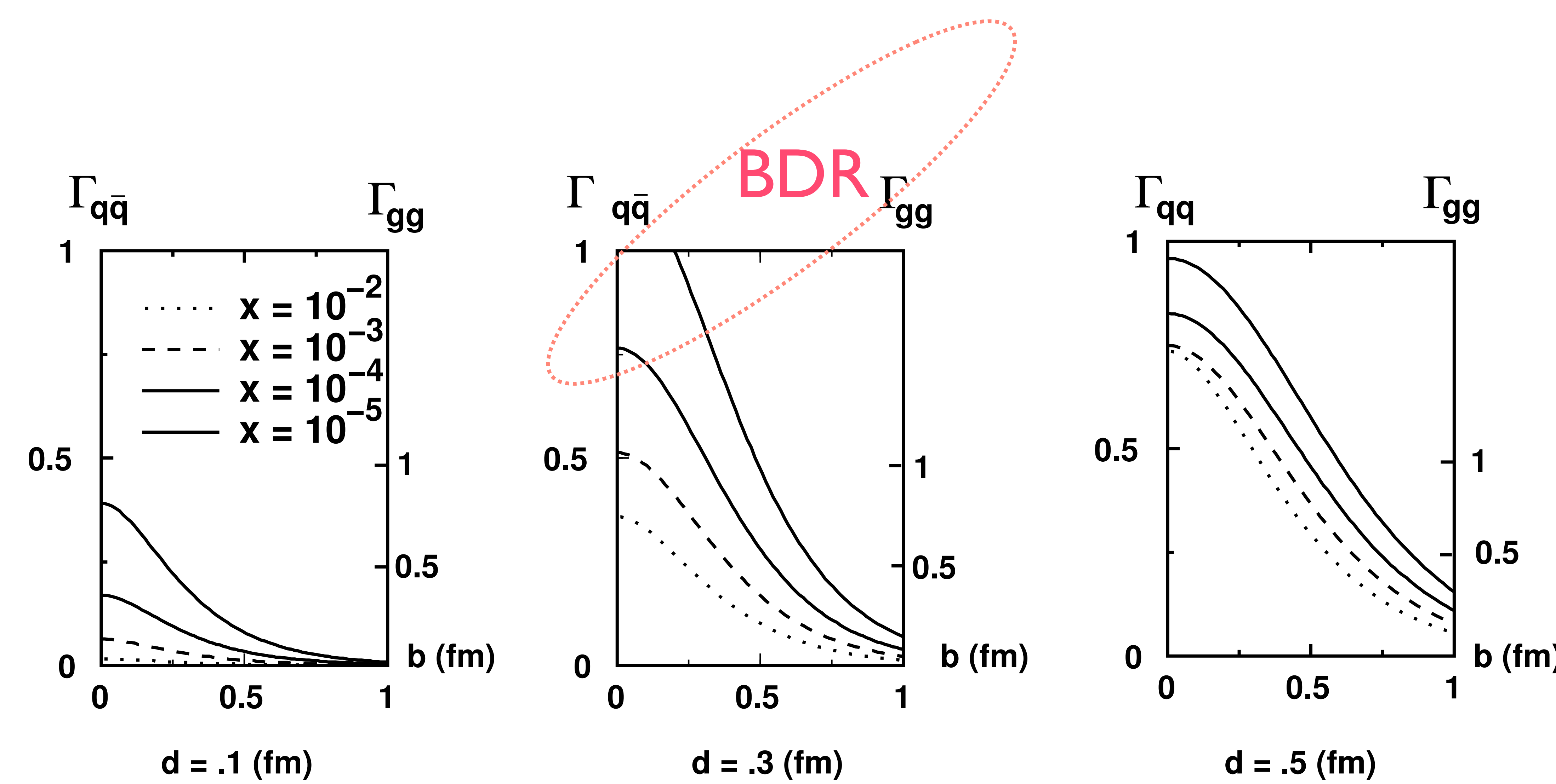
Expectations: *small size, low energies (relatively large $x \sim 10^{-2} \div 10^{-3}$)*

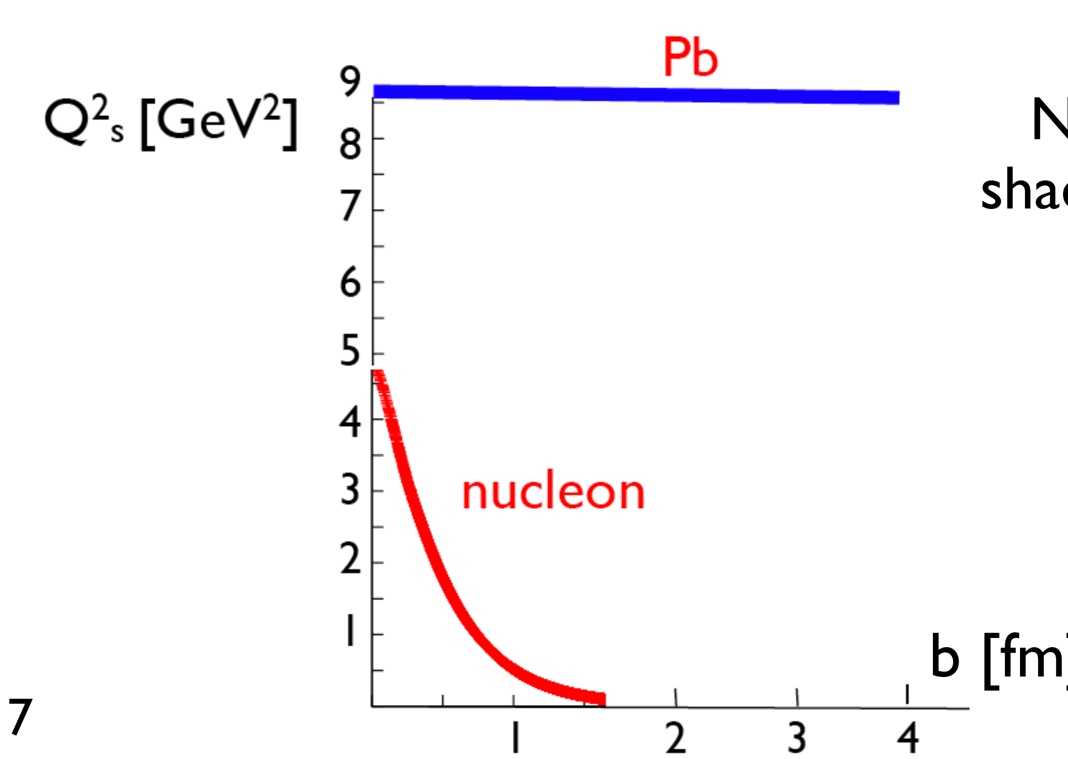
$$\sigma_{inel} = \frac{\pi^2}{3} F^2 d^2 \alpha_s(\lambda/d^2) x G_T(x.\lambda/d^2)$$

cross section is small, but onset of LT nuclear shadowing



studies of the "quark-antiquark dipole"(transverse size d) - nucleon cross section based pQCD and HERA data





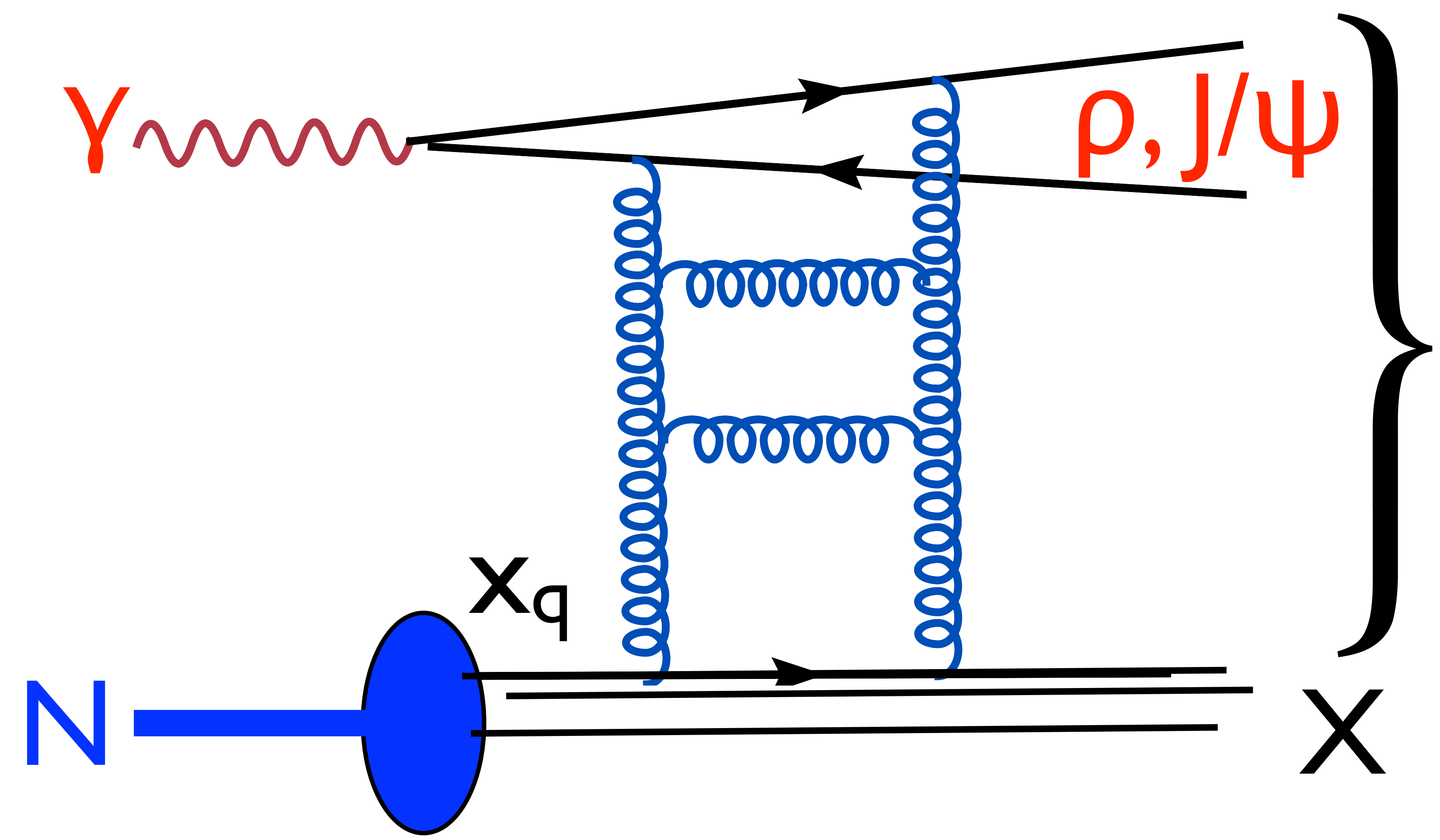
No LT shadowing

Gluon densities in nuclei and proton at b=0 are very similar!!!!

Difference is in a very different spread in b

Question VI: *What is Asymptotic behavior of the amplitude of the elastic scattering of small dipoles in QCD at large t ? Does BFKL approximation works?*

Both questions can be addressed by studying rapidity gap processes at large $t=(p_\rho-p_\gamma)^2$ which were first studied at HERA



$$s' = xW^2_{\gamma p},$$

Elementary reaction - scattering of a hadron (γ, γ*) off a parton of the target at large $t=(p_\gamma-p_V)^2$

FS 89 (large t pp→p +gap + jet), FS95

Mueller & Tung 91

Forshaw & Ryskin 95

$$x = \frac{-t}{(-t + M_X^2 - m_N^2)}$$

The rapidity gap between the produced vector meson and knocked out parton (roughly corresponding to the leading edge of the rapidity range filled by the hadronic system X) is related to $W_{\gamma p}$ and t (for large t, $W_{\gamma p}$ as

$$y_r = \ln \frac{x W_{\gamma p}^2}{\sqrt{(-t)(m_V^2 - t)}}$$

The choice of large t ensures two important simplifications. First, *the parton ladder mediating quasielastic scattering is attached to the projectile via two gluons*. Second is that *attachment of the ladder to two partons of the target is strongly suppressed*. Also the transverse size $d_{q\bar{q}} \propto 1/\sqrt{-t}$

$$\frac{d\sigma_{\gamma+p\to V+X}}{dtdx} = \frac{d\sigma_{\gamma+quark\to V+quark}}{dt}\left[\frac{81}{16}g_p(x,t) + \sum_i (q_p^i(x,t) + \bar{q}_p^i(x,t))\right]$$

Analyses with z cut, M^2_X/s < const cuts are good for study of the dominance of the mechanism of scattering off single partons. However they correspond to rapidity interval between VM and jet which are typically of the order $\Delta y = 2 - 3$.

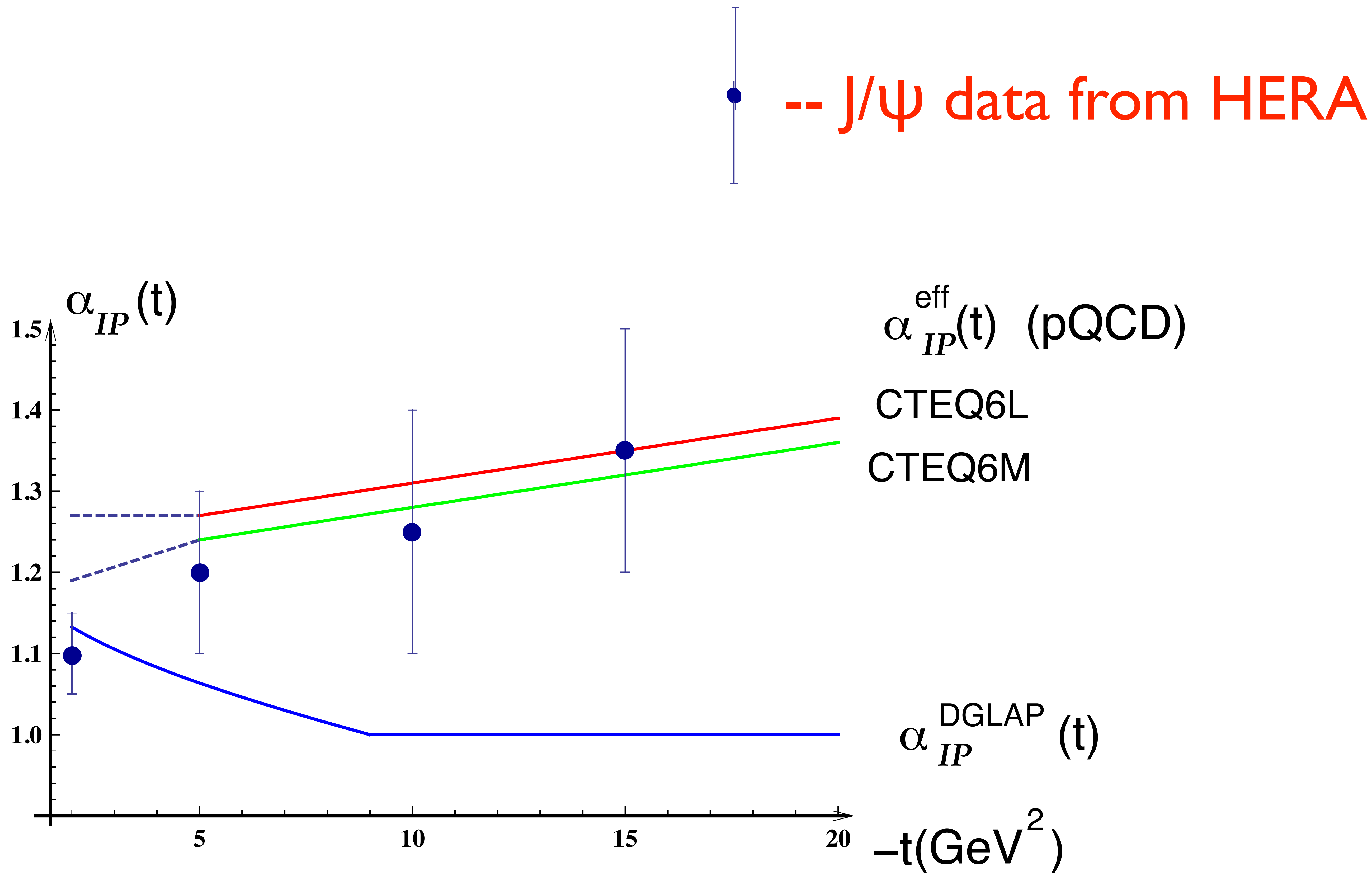
Optimal way to study BFKL dynamics is to keep M^2_X < const and vary W

Difficult but not impossible at HERA natural at LHC

At LHC one can study energy dependence of elastic $q\bar{q}$ - parton scattering at W'=20 GeV - 400 GeV

$$\sigma_{el}(q\bar{q} - q(g)(W' = 400GeV)/\sigma_{el}(q\bar{q} - q(g)(W' = 20GeV) \sim 10\,!!!$$ if δ=0.2 -- NLO BFKL

$$W' = W(q\bar{q} - parton) \propto \exp(y_r)$$



Large experimental value of $\alpha_{I\!P}^{eff}(t)$ is due to the dependence of x cut on t in the HERA data.
DGLAPS with $\alpha_{I\!P}^{eff}(-t \gg \text{few GeV}^2) = 1$ gives a good description of the data.

Blok, Frankfurt, MS, Phys.Lett. B690 (2010) 159-163

PRL **102,** 232001 (2009) PHYSICAL REVIEW LETTERS

Tracking Fast Small Color Dipoles through Strong Gluon Fields at the LHC

L. Frankfurt,[1] M. Strikman,[2] and M. Zhalov[3]

$$\gamma + A \to J/\psi(\rho, 2\pi) + \text{"gap"} + X$$ at large t

Complementary to $\gamma + A \to J/\psi + A$ and has several advantages:

(i) larger W range (due to ability to determine which of nuclei generated photon

(ii) Regulating x of the parton in nucleus - shadowing vs linear regime

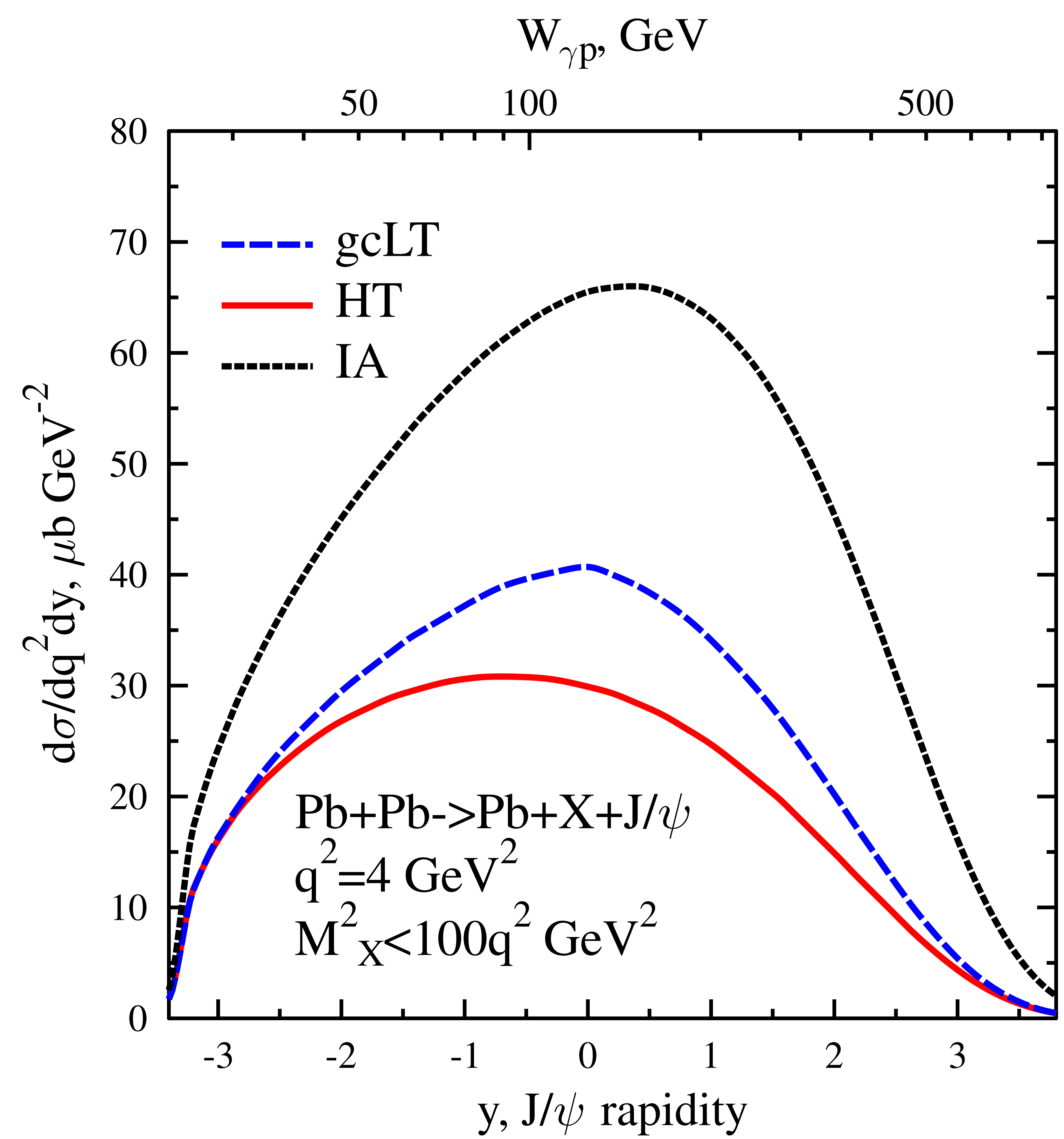
(iii) More central collisions - larger local gluon density

Qualitative Predictions:

- A_{eff}/A should increase with t at fixed W - smaller dipoles

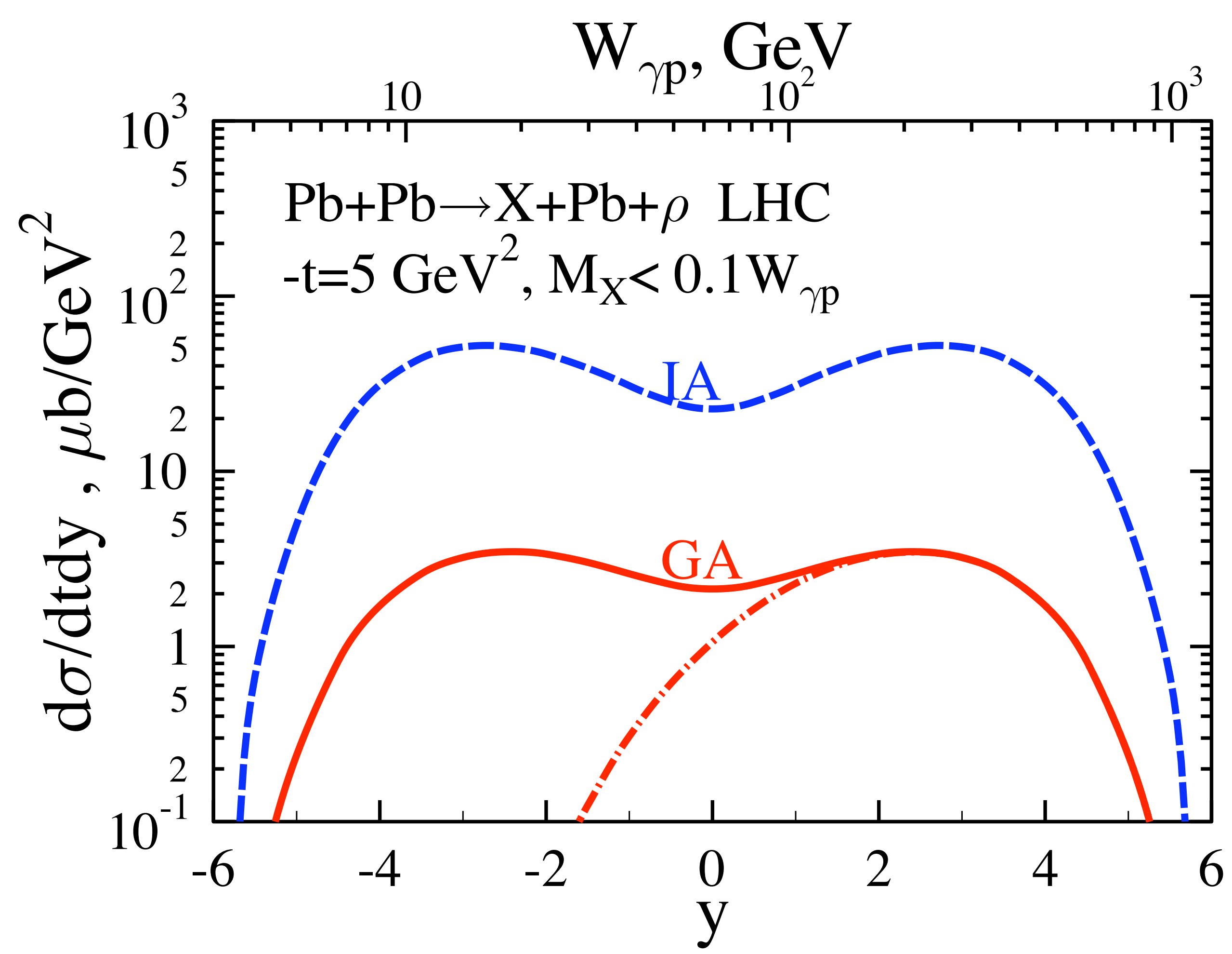
- A_{eff}/A should decrease with increase of W at fixed t - onset of black disk regime.
  Larger shadowing for small x (regulated by the rapidity covered by X-system)

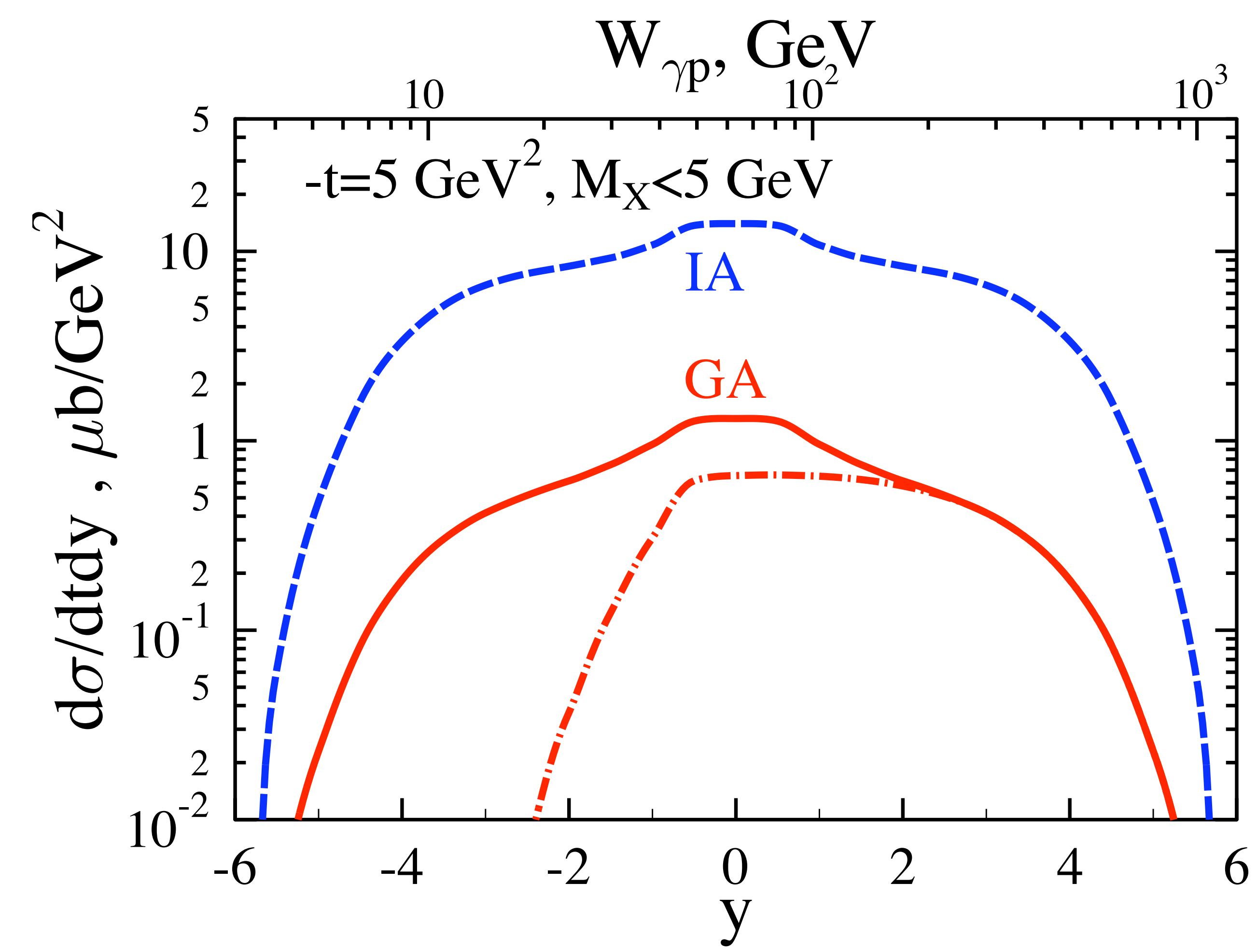
$$P_A^{\mathrm{gap}} = \frac{1}{A}\int d^2 b T(\vec{b})\left[1 - \sigma_{\mathrm{dip}-N}(x,d)\frac{g_A(x,Q^2,\vec{b})}{g_N(x,Q^2)}\right],$$



The rapidity distribution for the J/ψ photoproduction in the UPC

Pb+Pb→Pb+ J/ψ + gap + X (for one nucleus emitting photons)





Integrated over mass of produced system cross section of the nucleon dissociative ρ meson photoproduction at $-t=5\ \mathrm{GeV}^2$ in the ultraperipheral lead-lead collisions at LHC. The upper figure - the limit of the mass of produced system M_X is proportional to the photon-nucleon center of mass energy $M_X < 0.1 W_{\gamma p}$, in the right figure for central rapidities the limit of M_X is fixed by restriction $M_X < 5\mathrm{GeV}$. Solid line - calculations with Glauber-Gribov screening, dashed line calculations in the leading twist approximation neglecting nuclear shadowing correction which is very small for discussed kinematics, dot-dashed line - one-side contribution when ρ meson is produced by photons emitted by only one nucleus: large positive rapidities correspond to vector mesons produced by high energy photons. The counting rate can be estimated using expected luminosity for PbPb collisions $L=10^{-3}\ \mu b^{-1}\ \mathrm{sec}^{-1}$.

Feasible to reach $W_{\gamma N}= 1$ TeV - where BDR should hold down to dipole sizes 0.15 - 0.2 fm

Conclusions

- *Small x physics with protons and nuclei in* ***a factor of ten*** *larger energy range than at HERA though at higher virtualities both in inclusive and diffractive channels. As compared to pp at the LHC the x range is more narrow but virtualities where data can be meaningfully interpreted is smaller.*

- Interaction of small dipoles at ultrahigh energies - approach to black body regime, color opacity

- Color fluctuations in inelastic γA (especially with a dijet trigger) and rapidity gaps - new frontiers of studying high energy QCD