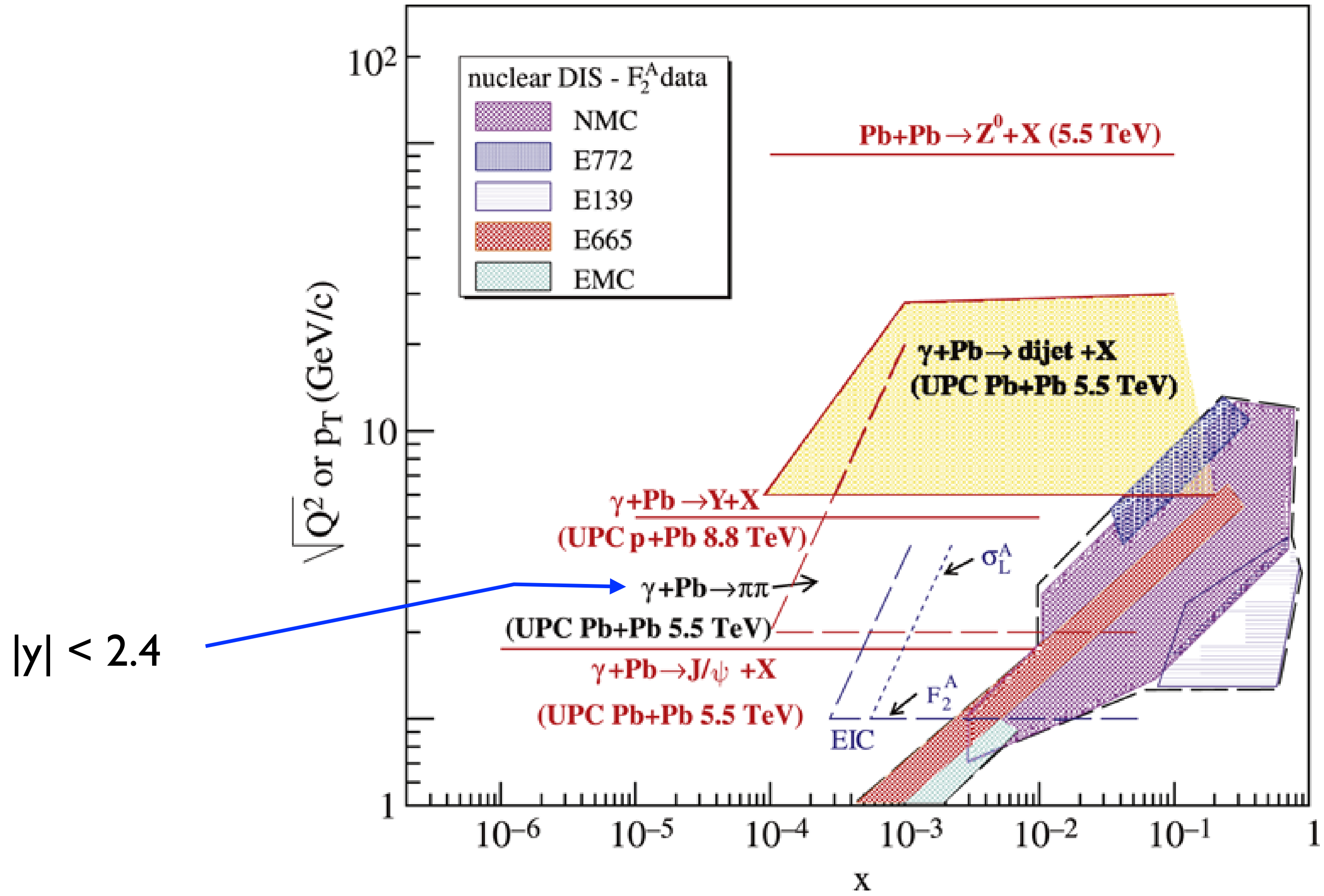
Topics in UPC

final states, signals of onset of black regime, rapidity gap at large t

Mark Strikman, PSU

Probing QCD in Photon-Nucleus Interactions at RHIC and LHC: the Path to EIC, Seattle, 2/15/17

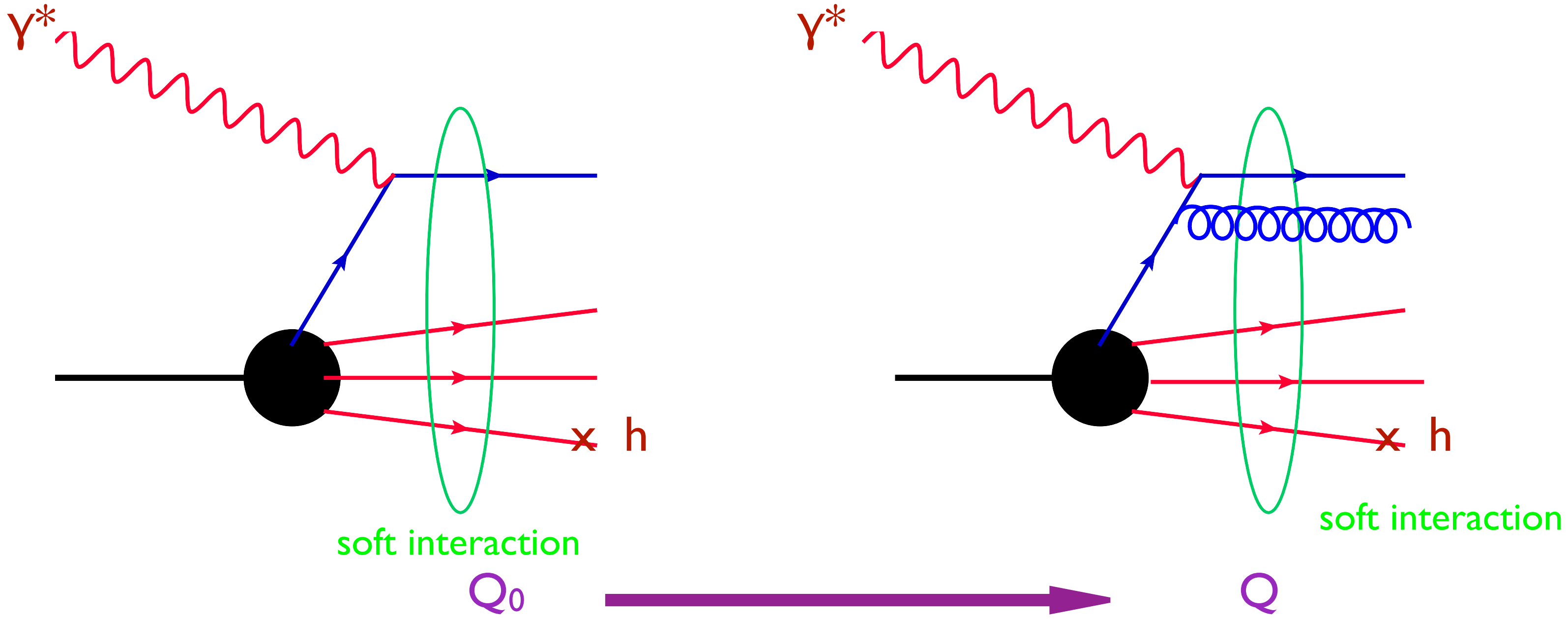
UPC - testing QCD dynamics in LT limit and looking for its breakdown at small x with current LHC detectors



From UPC Phys.Rep. 2008

Looking for onset of QCD Factorization for nuclear fragmentation in direct vs resolved photon vs DIS.

Physics of the factorization theorem for fragmentation: soft interactions between "h" and the partons emitted in the γ^* - parton interaction do not resolve the changes of the color distribution between the scale Q_0 >> soft scale and $Q > Q_0$.



Production of "h" at x, Q is the same as for Q_0 and x' been "ancestor of x

If target is long enough and the Lorentz factor gq system is not sufficiently large the final state interaction will be different from that of q slowing down the onset of factorization regime.

Probing formation time of produced hadrons and photon structure

Fast hadrons (along dijet) - within acceptance of LHC detectors.
Can be studied already with ATLAS first data including comparison direct vs resolved photon:

direct photon -- the factorization limit for integral over p_t of leading hadron

absent of correlation between neutron production (zero degree calorimeter - ZDC) and presence of a leading hadron
break down of the factorization for spectrum differential in p_t??.
Correlation with p_t of leading hadron - connection to TMD issues (dijet disbalance - P.Kotko talk)

Global probe of formation of hadrons including ones slow in the nucleus rest frame

Look for ZDC signal - via e.g. process π^+-(pn) → nn followed by cascade

Hadron activity in a wide range of rapidities will be non-trivial function of x_γ :

ZDC - signal should grow with decrease of x_γ

Data on soft neutrons so far only from E665 experiment at FNAL: Best are μPb data

$$\langle N(Pb)(E_n \leq 10\ \mathrm{MeV}\rangle = 5 \pm 1$$

with slight indication of a drop (for Pb not Ca)between ν= 70 GeV and 200 GeV

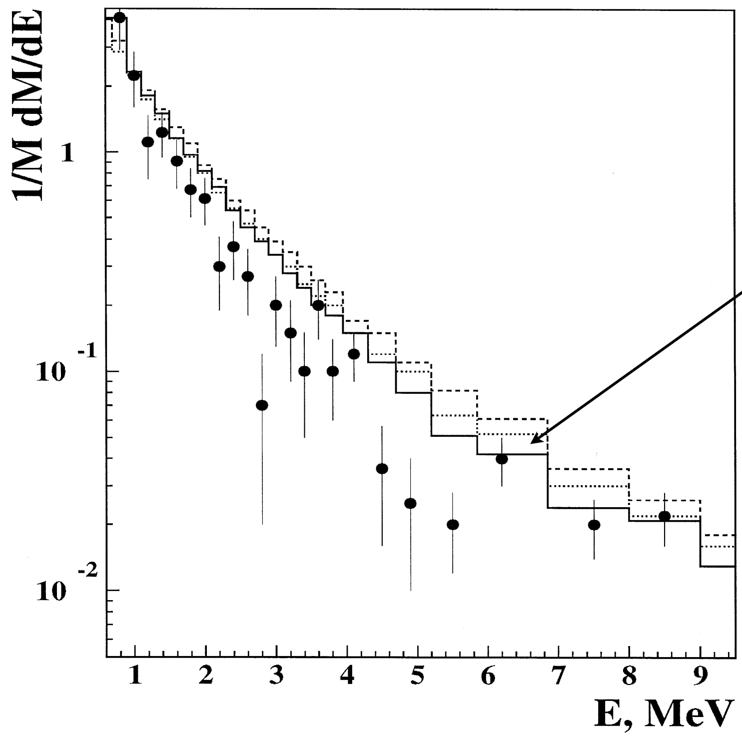


Fig. 3. Comparison of the results of the Monte Carlo cascade-evaporation calculation of the neutron spectra in $\mu + Pb \to n + X$ process with E-665 data [11].

Theoretical calculation - assuming only produced nucleons with T< 500 MeV can reinteract

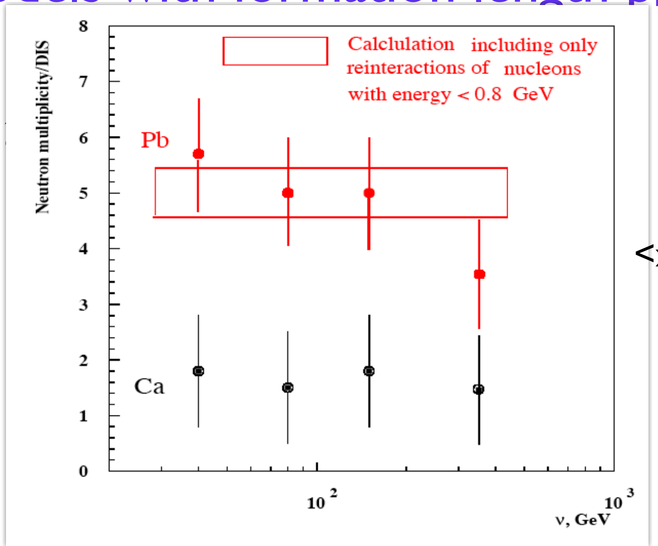
MS, Tverskoi, Zhalov 1999

$$\langle N(Pb)(E_n \leq 10\ \mathrm{MeV}\rangle_{lower\ limit} = 6 \pm 1.5$$

Much less than in the models with formation length p_h/μ^2

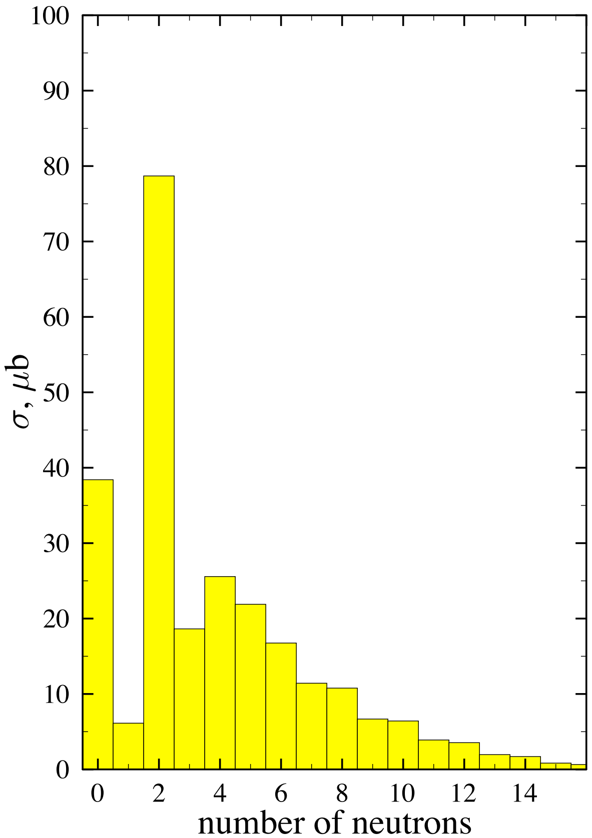
Evidence for amazingly small FSI at high energies?

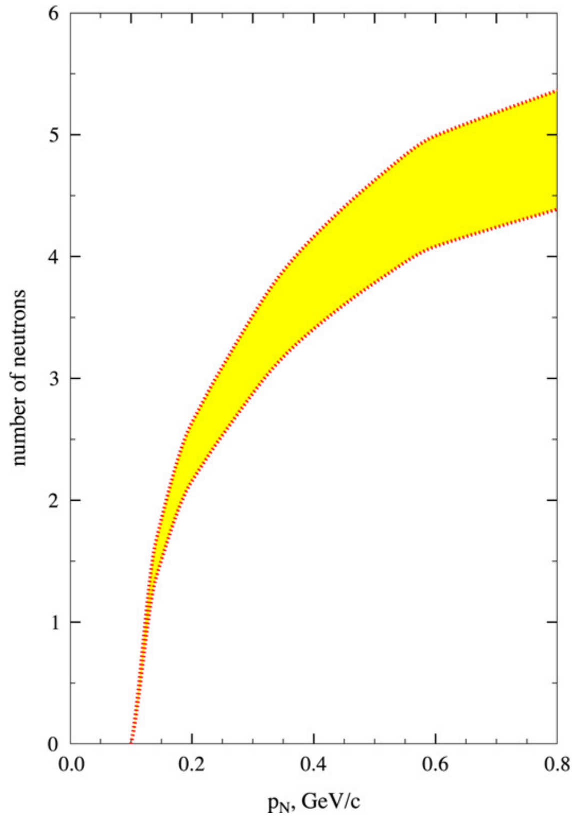
problem with data?



<x>=0.05

Another comment on ZDC - can try to analize / explore J/ψ quasielastic scattering



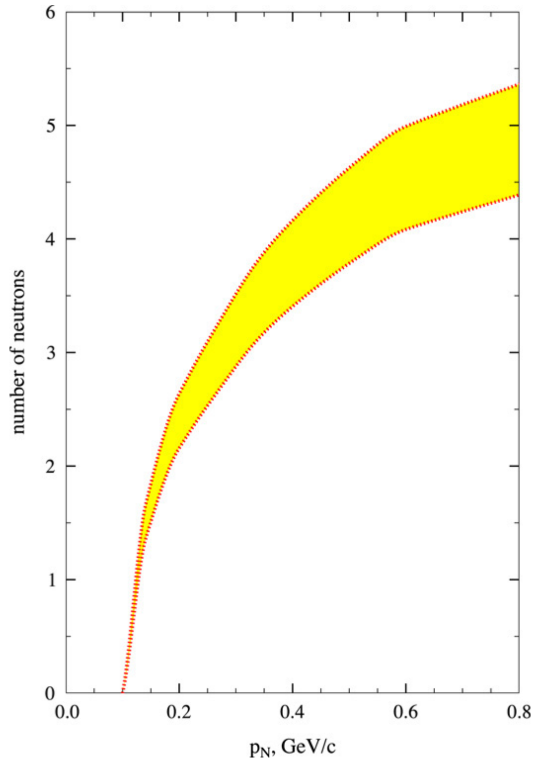


The incoherent cross section for the J/ψ production in UPC of Au ions at RHIC as a function of the number of accompanied neutrons.

Tverskoi, Zhalov & MS

The average number of neutrons emitted in incoherent J /ψ production in Au + Au UPCs at RHIC and ϒ production in Pb + Pb UPCs at the LHC as a function of the recoil nucleon momentum, $p_N = \sqrt{|t|}$.

What happens when one nucleon is removed from arbitrary point in the nucleus



The average number of neutrons emitted in incoherent J/ψ production in Au + Au UPCs at RHIC and Υ production in Pb + Pb UPCs at the LHC as a function of the recoil nucleon momentum, $p_N = \sqrt{|t|}$.

Tverskoi, Zhalov, MS

Glauber: For central impact parameters 10 wounded nucleons

$N_{neutrons} \sim 50$!!???

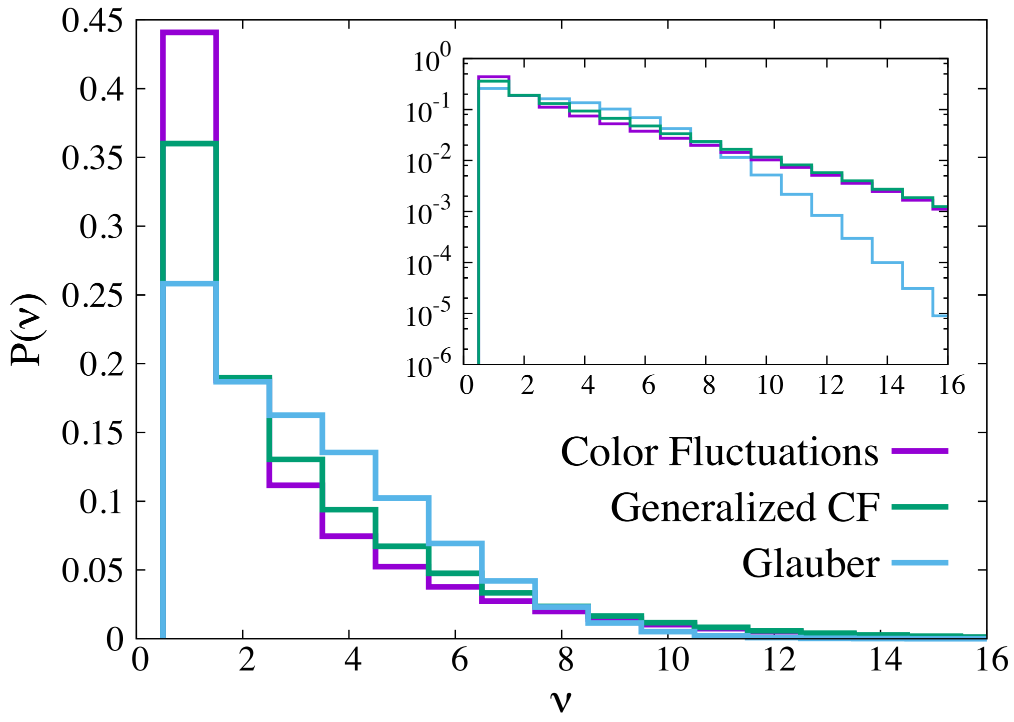
expect large fluctuations in particular due to difference between Gribov-Glauber and Glauber approximations. Dispersion from cross section fluctuations is ~ 0.1 leading to fluctuations of

$N_{neutrons} \sim 35 -- 55$

Plus cascade fluctuations

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

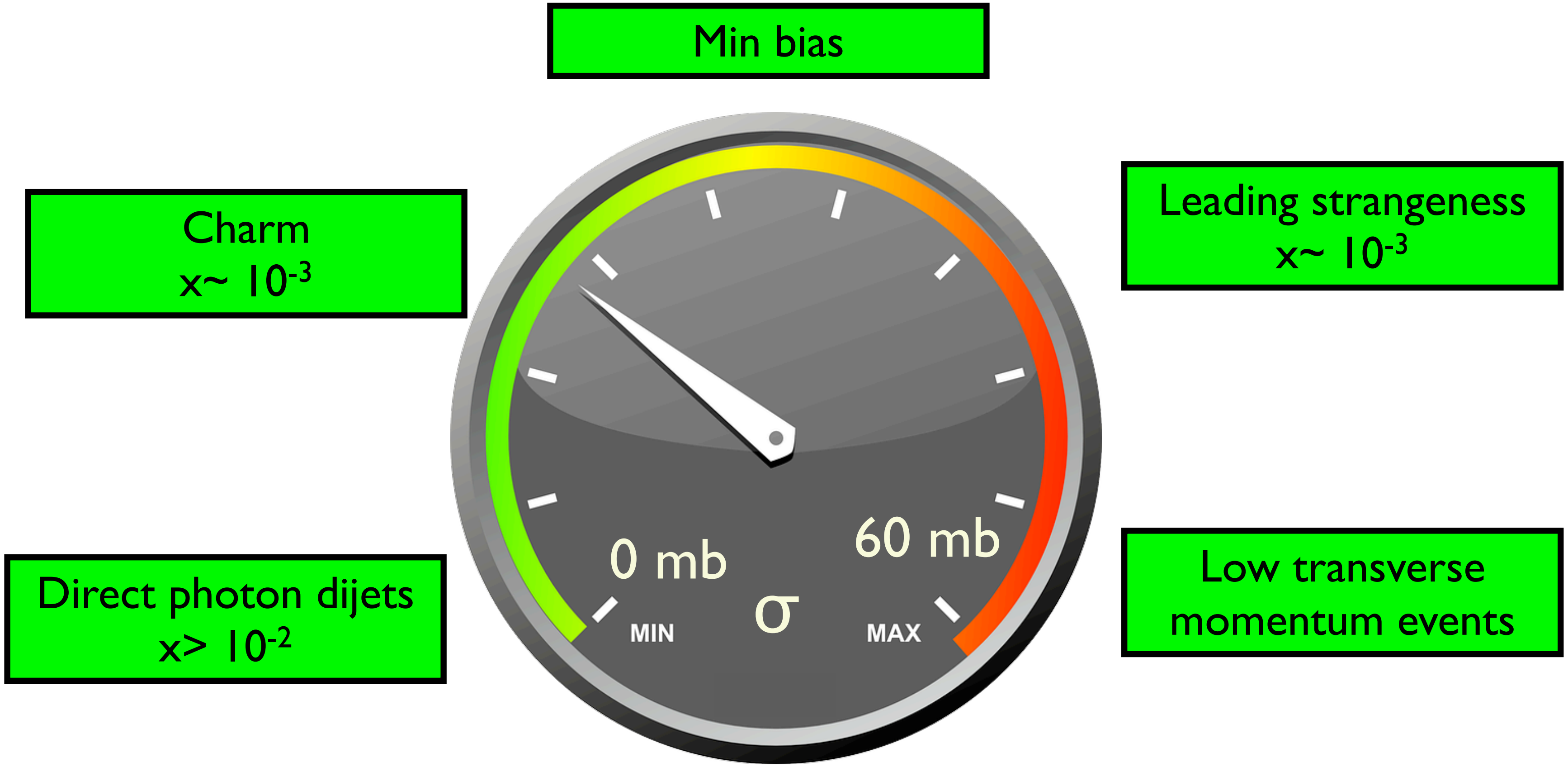
Huge fluctuations of the strength of γN interaction - soft and small dipoles,.. (Leonya Frankfurt's talk) → large fluctuations in the number of wounded nucleons in γA collisions



Alvioli, Guzey, Zhalov, LF, MS - Physs.Lett. in press

distribution over the number of wounded nucleons in γA scattering, W ~ 70 GeV

Tuning strength of interaction of configurations in photon using forward (along γ information). Novel way to study dynamics of γ & γ interactions with nuclei*



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

Conclusions for part 1

First UPC LHC data for jet production & minimal bias inelastic interactions - a door to understanding hadron formation at collider energies

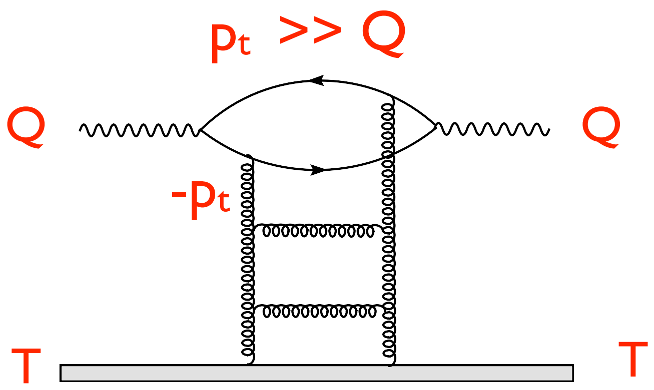
ZDC analysis important for future progress

Post selection effect in BDR - effective fractional energy losses

"Parton Propagation" for $p_t \leq p_t^{(BDR)}$

The simplest case example: *Inclusive production of leading hadrons in DIS for* $Q < 2p_t^{(BDR)}$

Frankfurt, Guzey, McDermott, MS 2000



The mechanism of fragmentation in BDR: presence of large gluon fields in the target selects quark and antiquark in the γ^* wave function with $p_t \propto Q_{BDR}$ and known z-distribution peaked at ~1/2

q and $\bar{q}$ fragment independently since in this case overlap between showers is small (as long as LC fractions are large). Photon energy is split before the collision

Post selection effect in BDR - effective fractional energy losses

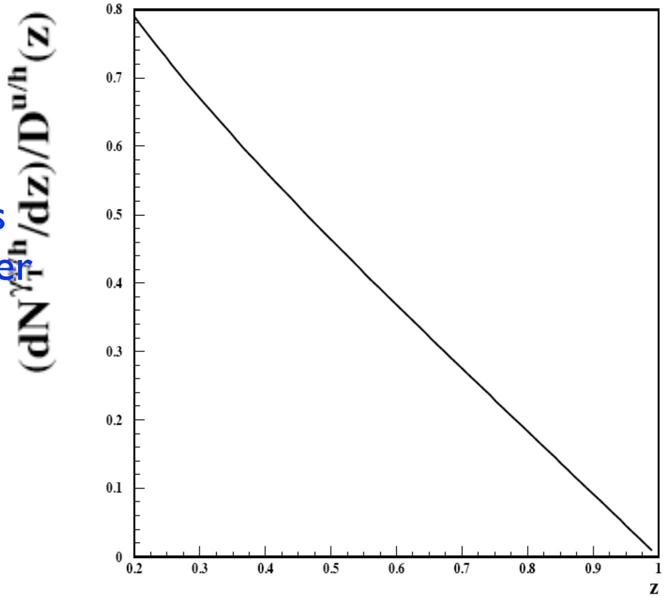
"Parton Propagation" for $p_t \leq p_t^{(BDR)}$

The simplest case example: *Inclusive production of leading hadrons in DIS for* $Q < 2p_t^{(BDR)}$

Hence to a first approximation

$$\bar{D}^{\gamma_T^* \to h}(z) = 2\int_z^1 dy D_q^h(z/y)\frac{3}{4}(1+(2y-1)^2)$$

Gross scaling violation in BDR as compared to DGLAP. The leading particle spectrum in BDR is strongly suppressed. The inclusion of the $q\bar{q}g$ states in the virtual photon wave function (due to the QCD evolution) further amplifies the effect. Effectively this corresponds to fractional energy losses in BDR: $\Delta E \propto E$. No such effect for large x DIS (finite energy losses) since in the initial moment no accompanying gluon field.



The total differential multiplicity normalized to the up quark fragmentation function as a function of z at $Q^2=2\ GeV^2$.

Will refer to this effect as post-selection

estimate: $$\Delta E = cE(L/3fm),\ c \approx 0.1$$

Technical remark

Leading parton fragmentation is much more sensitive to onset of BDR than the total cross section. Can be seen from the application of the AGK cutting rules.⇒

$$\sigma_{tot} = \sigma_1 - \sigma_2 + \sigma_3 + ...$$

$$\sigma_{leading} \propto \sigma_1 - 4\sigma_2 - 8\sigma_3 + ...$$

20% correction for total cross section ⇒

a factor ~ 5 reduction in the leading hadron spectrum

⇒ *the estimate of the previous slide may underestimate the suppression for inelastic cross section (though it should be reasonable for diffractive component)*

Post-selection effects in d -Au collisions at RHIC

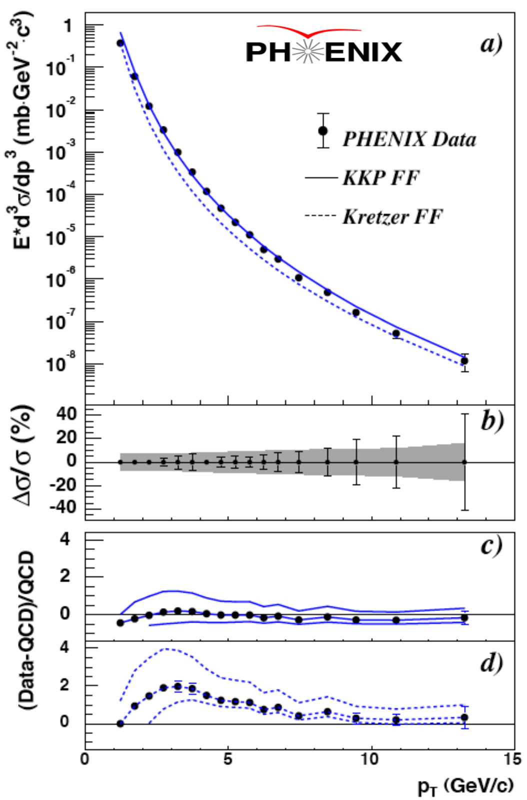
Semi quantitative estimates (FS07) :

- quarks near BDR effectively loose in average ~ 10 --15 % of their energy via qg splitting
- gluons effectively loose a larger fraction of their energy since gg splitting is more symmetric in z

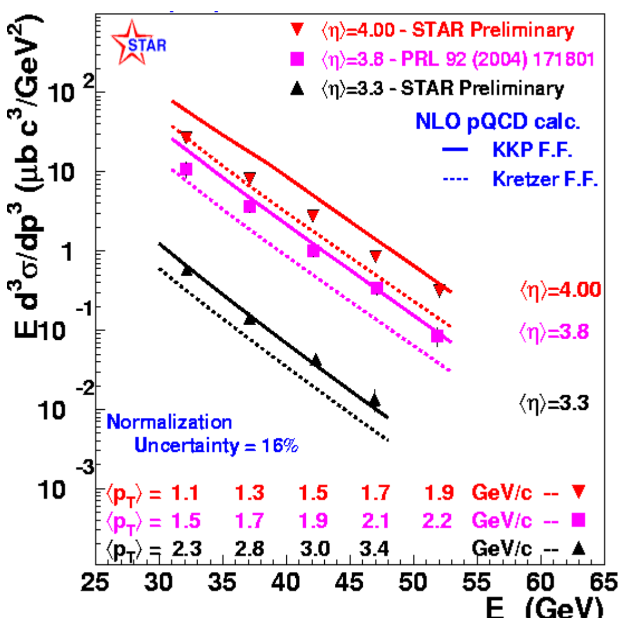
Much more for $p_t < p_t$ (BDR)

RHIC observed suppression of forward pion production in the d-Au collisions in the kinematics ($E_q > 20$ GeV) - can post-selection be relevant?

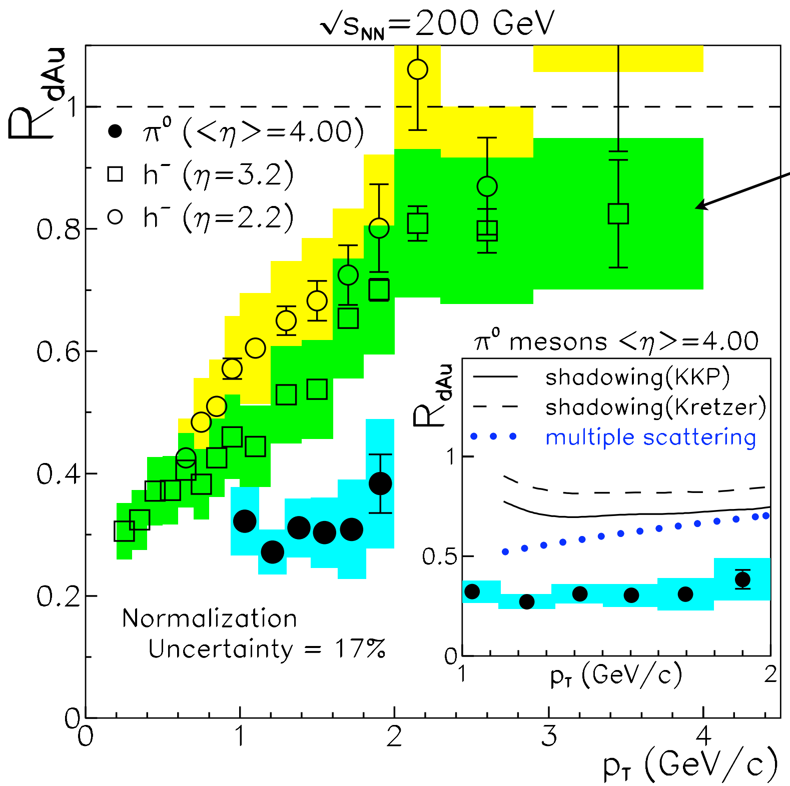
Summary of the first observations



$pp \to \pi^0 X$ **at RHIC - STAR**



The pp data are consistent with NLO pQCD calculations of Vogelsang et al. for $p_t > 1.3$ GeV/c. However they are sensitive to the gluon fragmentation which contributes !!! even at the highest pion energies



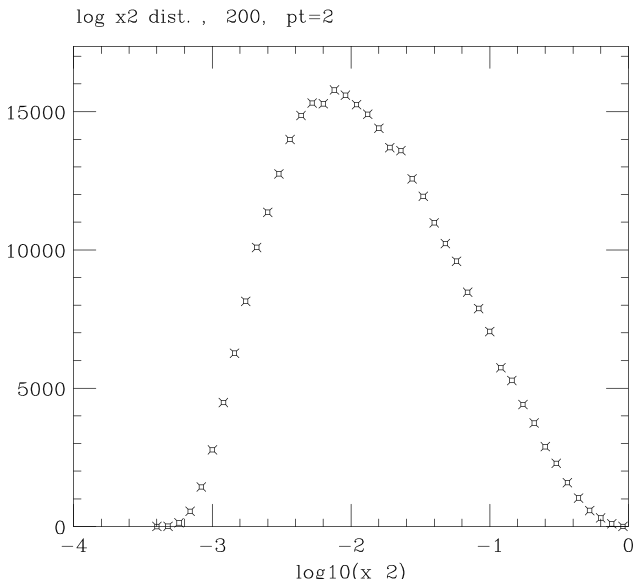
Significant nuclear suppression = $R_{dAu}/1.5$

BRAHMS and STAR are consistent when an isospin correction which reduces h^- ration measured by BRAHMS by a factor ~ 1.5 (Guzey, MS, Vogelsang 04 =GSV04) is introduced

FIG. 3: Nuclear modification factor (R_{dAu}) for minimum-bias d+Au collisions versus transverse momentum (p_T). The solid circles are for π^0 mesons. The open circles and boxes are for negative hadrons (h^-) at smaller η [10]. The error bars are statistical, while the shaded boxes are point-to-point systematic errors. (Inset) R_{dAu} for π^0 mesons at $\langle\eta\rangle = 4.00$ compared to the ratio of calculations shown in Figs. 2 and 1.

What values of x_2 (smaller of two x's) are important in pQCD calculations?

$\sqrt{s} = 200GeV, \langle\eta\rangle = 3.8, p_t = 2GeV/c$



$\sqrt{s} = 200GeV, \langle\eta\rangle = 3.2, p_t = 1.5GeV/c$

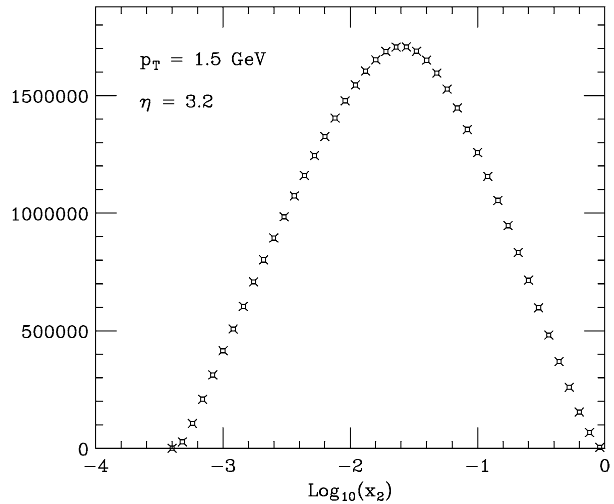


Fig. 1. Distribution in $\log_{10}(x_2)$ of the NLO invariant cross section $E\,d^3\sigma/dp^3$ at $\sqrt{s} = 200$ GeV, $p_T = 1.5$ GeV and $\eta = 3.2$.

Guzey, MS, Vogelsang 04

Area under the curve illustrates relative contribution of different regions of x_2. Median of the integral is $x_2 \sim 0.013$. The mean value of x_2 is substantially larger.

Shape is nearly the same for different pion channels. It is a also practically the same in LO and NLO. Median x for different inputs (fragmentation, LO vs NLO) for the same pion kinematics are the same within 20%

Scattering of small $x_2 < 10^{-3}$ partons gives a very small contribution to the total forward pion yield

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 - 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

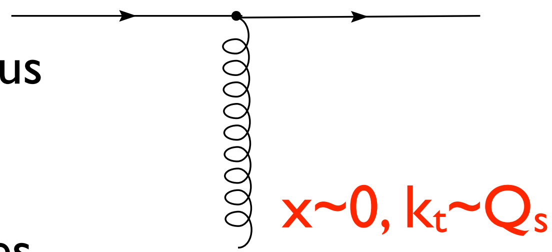
nuclear pdf = A nucleon pdf for such x (suppression of the LT mechanism should be >> than observed suppression of inclusive spectrum), ✌ 2 → 1 mechanism dominates

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

Two possible explanations of d-Au data both based on presence of strong small x gluon fields

✔ Color Glass Condensate inspired models

Assumes that the process is dominated both for a nucleus and nucleon target by the scattering of partons with minimal x allowed by the kinematics: $x \sim 10^{-4}$ in a $2 \to 1$ process. Plus NLO emissions from quark and gluon lines.



Two effects - (i) gluon density is smaller than for the incoherent sum of participant nucleons by a factor N_{part}, (ii) enhancement due to increase of k_t of the small x parton: $k_t \sim Q_s$. → Overall dependence on N_{part} is $(N_{part})^{0.5}$. Hence collisions with high p_t trigger are more central than the minimal bias events, no recoil jets in the kinematics where such jets are predicted in pQCD.

⇓

dominant yield from central impact parameters

✔ *Post-selection (effective energy losses) in proximity to black disk regime* - 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 BDR - post selection - energy splits before the collision - effectively 10- 15 % energy losses decreasing with increase of k_t. Large effect on the pion rate since x_q's, z's are large,

⇓

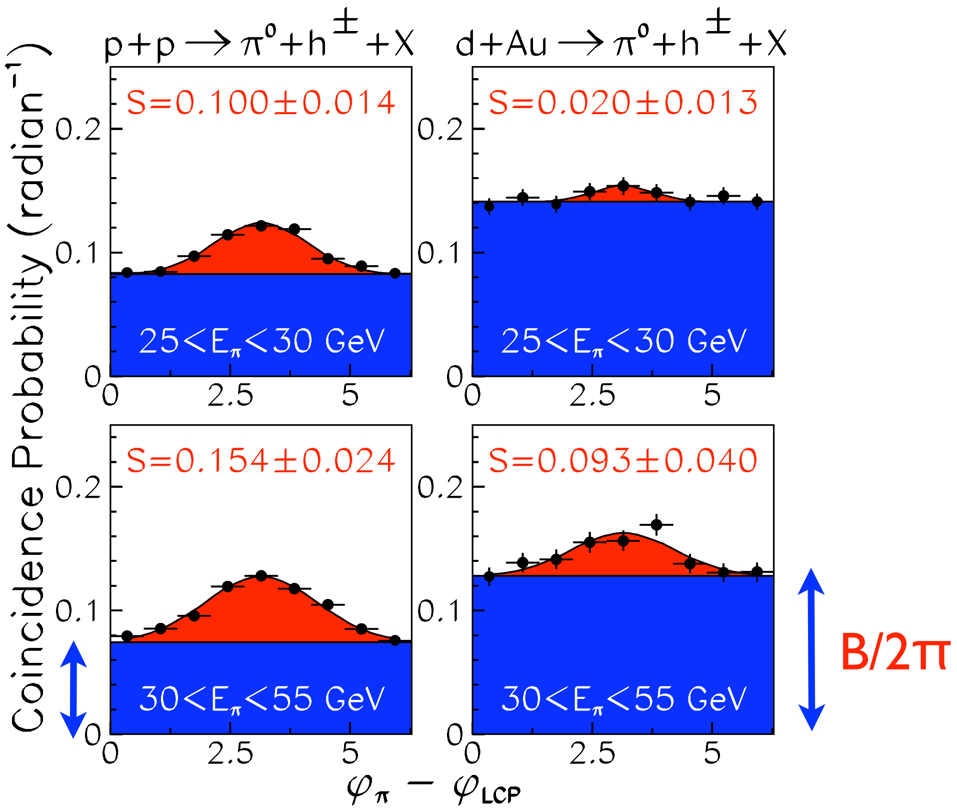
dominant yield from scattering at peripheral impact parameters

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 $(1\text{-}B\text{-}S) < 0.01$, $S < 0.01$ since for such collisions $N_{coll} \sim 13$. 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

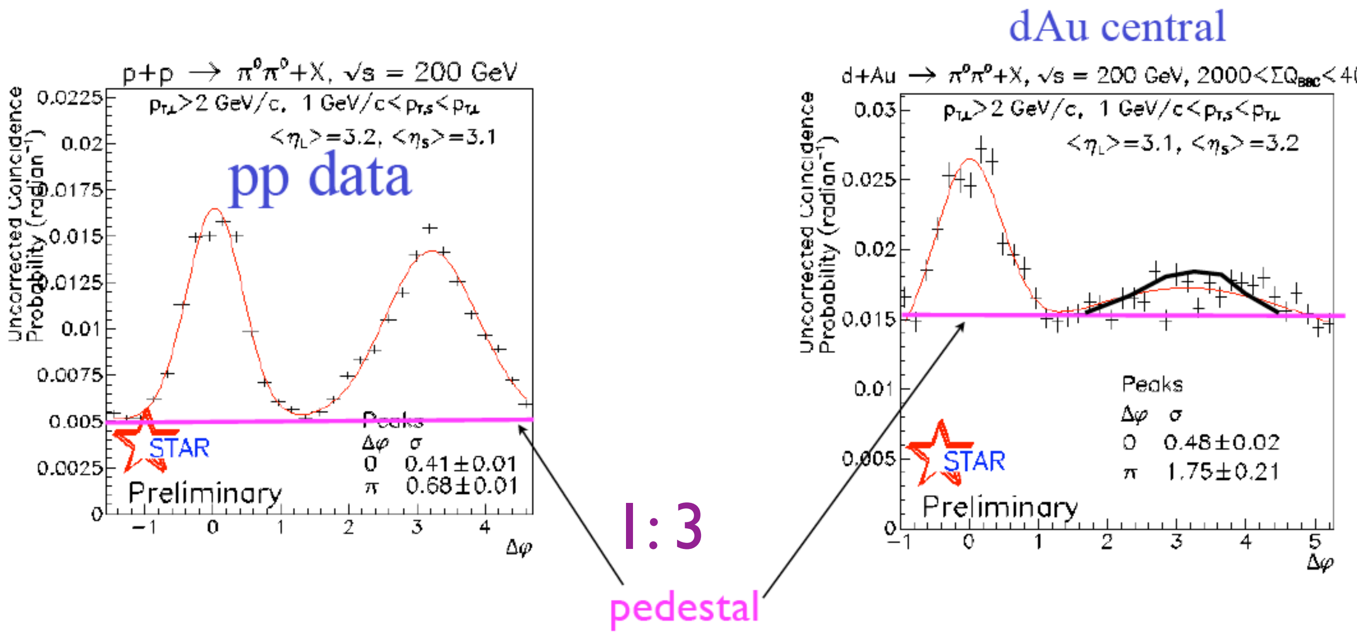
STAR - R ~0.5 Gregory Rakness - private communication

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

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

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 ~ four

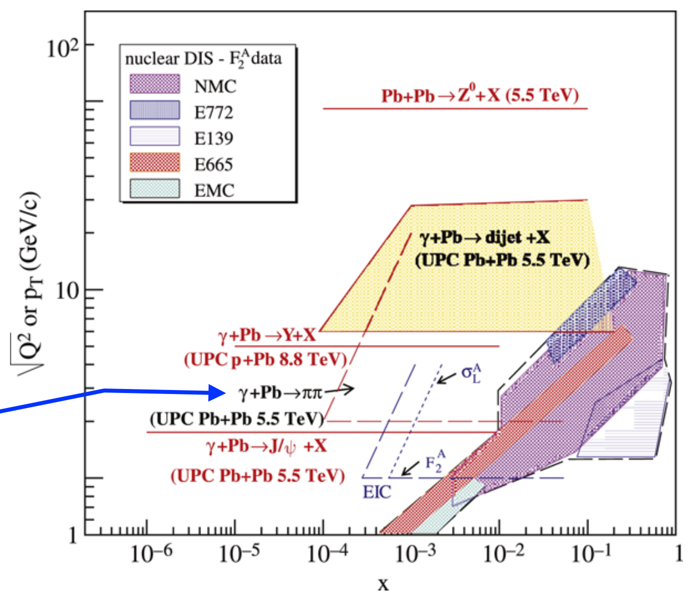


Black curve is the pp data peak above pedestal for φ ~π scaled down by a factor of 4

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).

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

UPC test: Post selection mechanism leads to suppression of pion production mostly at large x_F (use of |y| < 2.4 trackers)



|y| < 2.4

Suppression of the leading pions at p_T ~few GeV in UPC.

$$x_{eff} = 4p_t^2/W^2(\gamma N) \geq 10^{-4}$$

comparable / smaller than in D Au

Can explore various x_A kinematics detecting recoil minijet, two forward pions, centrality (neutrons).

Conclusions for part 2

There are good chances observe non - linear effects in photon fragmentation region via pion production, and perhaps minijets

Will focus on two questions which could be studied in process

$$\gamma(\gamma^*) + p(A) \to \text{"vector meson"} + \text{rapidity gap} + \text{X}$$

in ultraperipheral collisions pA/AA at LHC

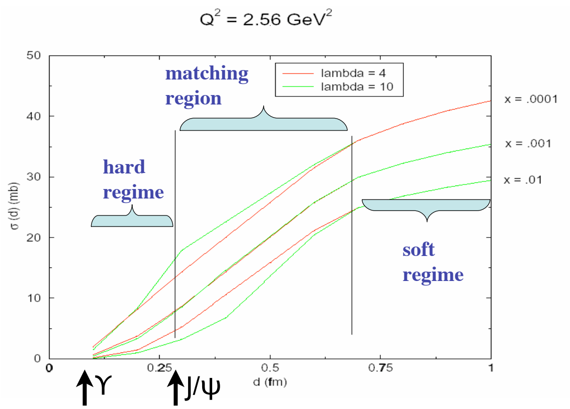
- *What is (pre)asymptotic behavior of the amplitude of the elastic scattering of small dipoles in QCD at large t ? At what energies BFKL approximation works?*

- *How small dipoles interact with nuclear media?*

Expectations for interaction of small size dipoles:

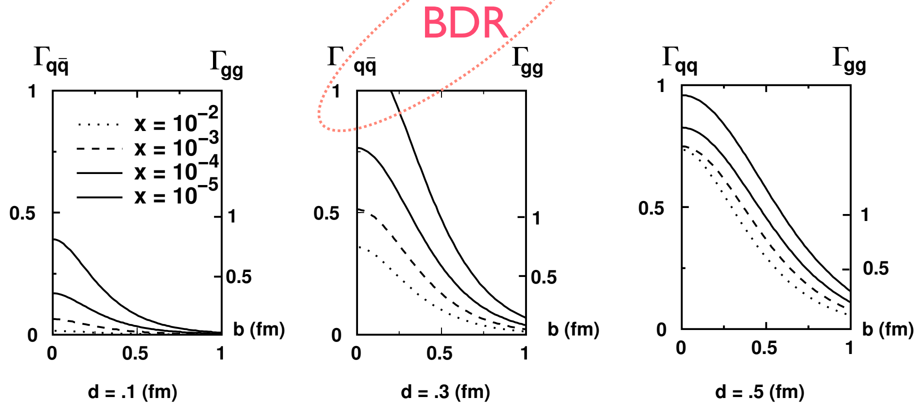
at low energies (relatively large $x \sim 10^{-2} \div 10^{-3}$) cross section is small, but rapidly grows with energy. LT shadowing slows growth.

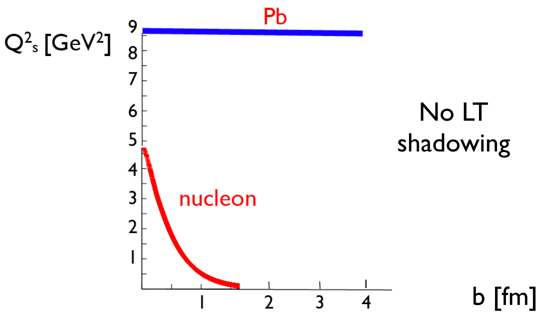
$$\sigma_{inel}^{dipole-T}(x,d) = \frac{\pi^2}{3} F^2 d^2 \alpha_s(\lambda/d^2) x G_T(x,\lambda/d^2), \lambda \sim 4 \div 8$$



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

black disk regime of complete absorption





Gluon densities in nuclei and proton at b=0 are very similar!!!! Especially if one takes into account LT nuclear shadowing (Takaki's talk)

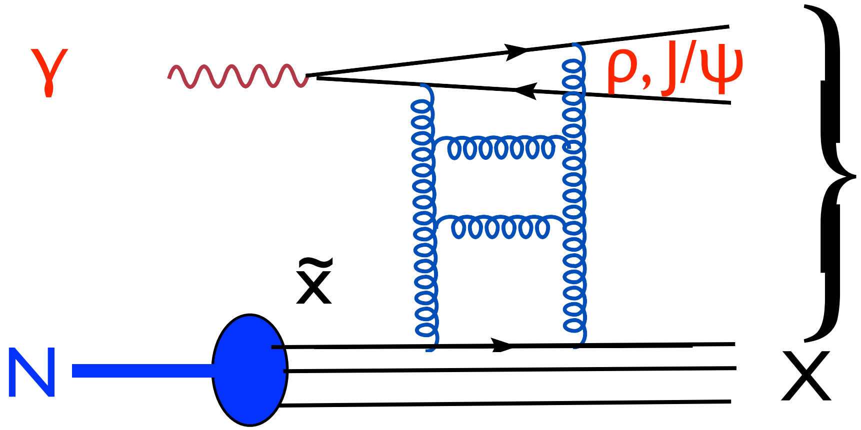
Difference is in a very different spread in b

b - transverse distance of parton from the target center

Problems for the study -

- Hard gap processes have two large scales Q^2 and 1/x (Stasto's talk)
- *How small size dipoles propagate through the nuclear media*

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



$$s' = \tilde{x} W^2_{\gamma p}$$

Elementary reaction - scattering of a hadron (γ, γ*)

off a parton of the target at large $t=(p_\gamma-p_V)^2$

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

FS 89 (large t pp→p +gap + jet),

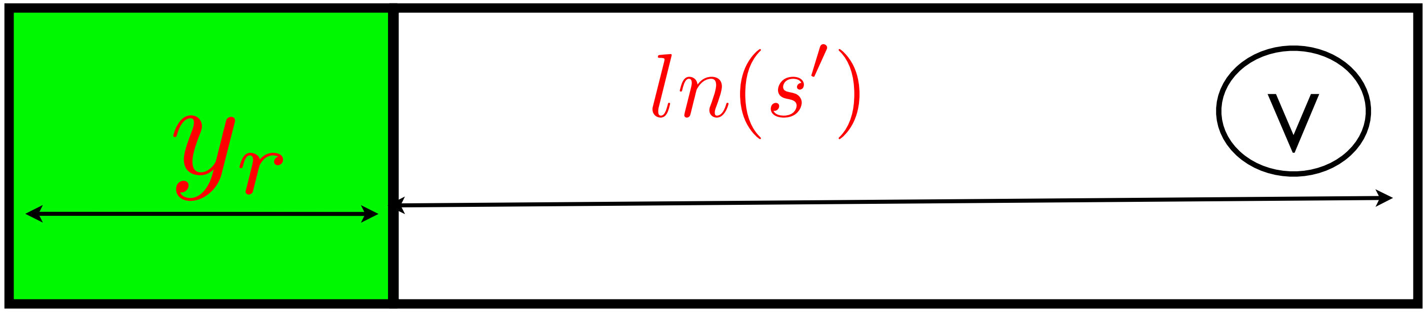
Mueller & Tung 91

FS95

Forshaw & Ryskin 95

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

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



The choice of large t ensures several important simplifications:

✳ *the parton ladder mediating quasielastic scattering is attached to the projectile via two gluons*.

✳✳ *attachment of the ladder to two partons of the target is strongly suppressed*.

✳✳✳ *the transverse size* $d_{q\bar{q}} \propto 1/\sqrt{-t} \sim 0.15\text{fm for } J/\psi \text{ for } -t \sim m_{J/\psi}^2$

$$\frac{d\sigma_{\gamma+p\to V+X}}{dt d\tilde{x}} =$$

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

t-range for sufficient squeezing -t ~ few GeV^2, For J/ψ -t ~ 4 -- 10 GeV^2,

Note - t-dependence is weak

$$\frac{d\sigma}{dt} \propto \frac{1}{(t+t_0)} \frac{1}{(-t+m^2_{J/\psi})^3}$$

Large rates up to large t

LF & MS & Zhalov 2008

HERA --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 Δy = 2 - 3.

Optimal way to study BFKL dynamics is different: keep M^2_X (in practice y_r)< const and study W- dependence.

Was difficult but not impossible at HERA, natural at LHC and LHeC

At LHC one can study energy dependence of elastic qq - parton scattering at W'=20 GeV - 400 GeV, higher W' at LHeC

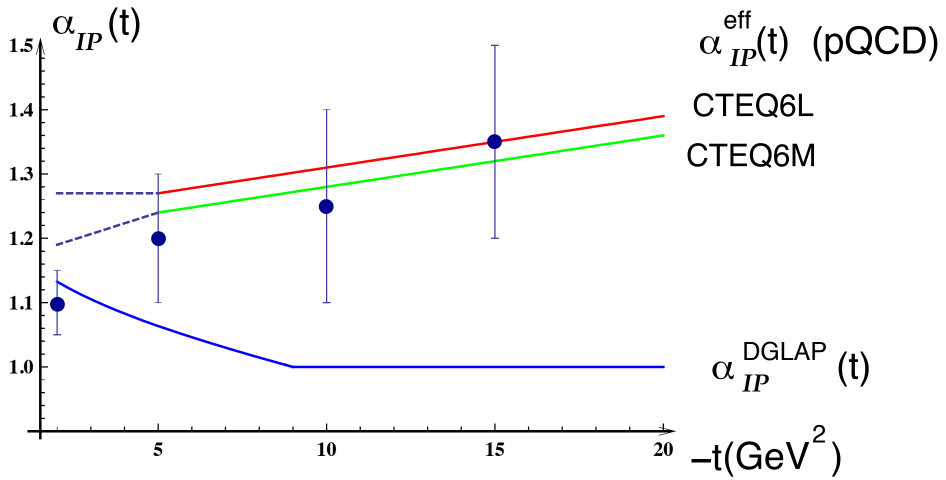
$$\sigma_{el}(q\bar{q}-q(g)(W'=400GeV)/\sigma_{el}(q\bar{q}-q(g)(W'=20GeV) \sim 10\,!!!$$

if Δ=0.2 -- NLO BFKL

$$W'^2 \equiv W^2(q\bar{q}-parton) = \tilde{x}W^2$$

better rapidity coverage of detector → larger W' range

 -- J/ψ data from HERA



Large experimental value of $\alpha_{I\!P}^{eff}(t)$ is due to the dependence of cut on t in $\tilde{x}$

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

W' too small?

LHC has a good coverage in rapidity:

Corresponds to a range of change of s‘ of 10^4 is -- further veto detector closer to proton fragmentation can further increase s’ range.

Guess - elastic cross section would remain constant till switching to BFKL growth at $\Delta y \sim 6$--8. *Onset of BFKL dynamics only at higher* Δy. (Anna’s talk)

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

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

at large t

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

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

Complementary to γ+ A →J/ψ +A and has several advantages:

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

(ii) Regulating of $\tilde{x}$ for the parton in nucleus - shadowing vs linear regime for $G_A(x,Q)$

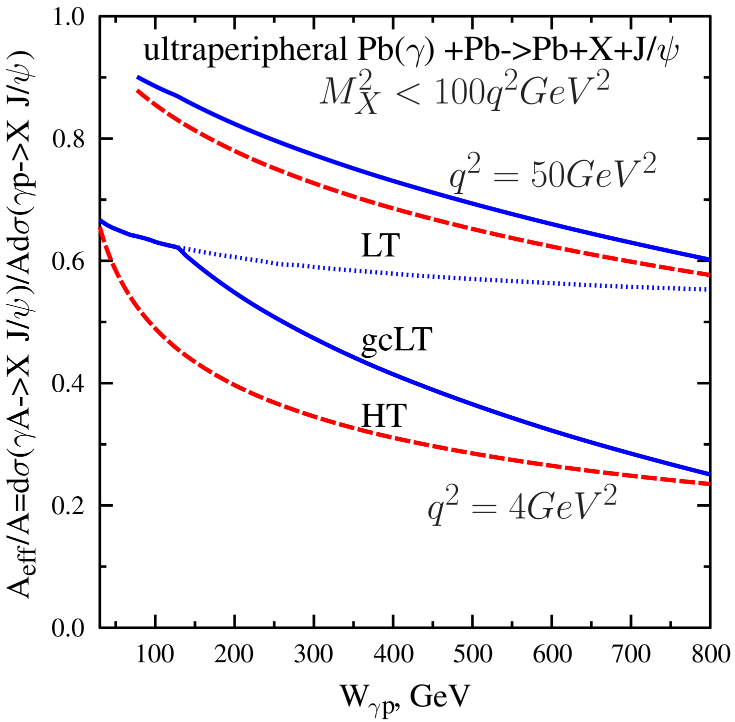
(iii) More central collisions - larger local gluon density

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)

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

$$q^2 \equiv -t = Q^2$$



The rapidity survival probability for the J/ψ photoproduction as a function of W

Conclusions for part 3

Large t semiexclusive rapidity gap processes represent one of the best if not the best tool for study of

Energy dependence of small dipole elastic scattering, testing one scale BFKL dynamics

Propagation of the small dipoles of different size through the nuclear media regulating the role of the leading twist shadowing, providing possibility to test onset of nonlinear (black disk ?) regime