Evidence for double parton interaction in dipion forward production in pp and d-Au collisions at RHIC

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Outline

Introduction I: Why hadroproduction in the forward (fragmentation) kinematics is promising way to look for non-linear effects.

Reminder: Suppression of the forward single pion production in d-Au - direct evidence for breaking of LT pQCD. Suggested mechanisms of suppression.

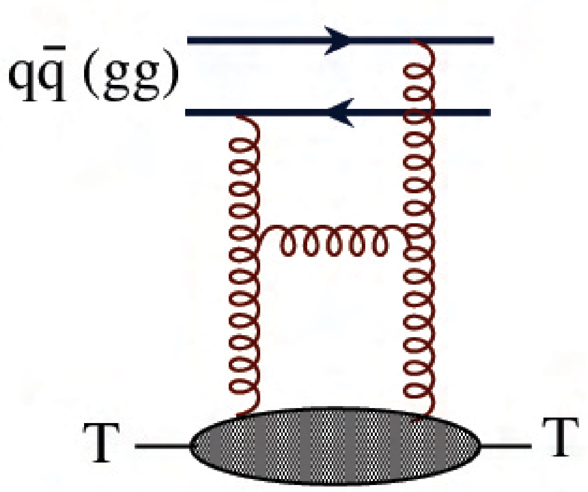
Double parton interaction mechanism of forward dipion production in pp and d-Au + mechanisms of suppression in dipion production.

Implications for LHC, LHeC, EIC

Fragmentation region for a given collision energy is most sensitive to nonlinear effects - breakdown of LT pQCD

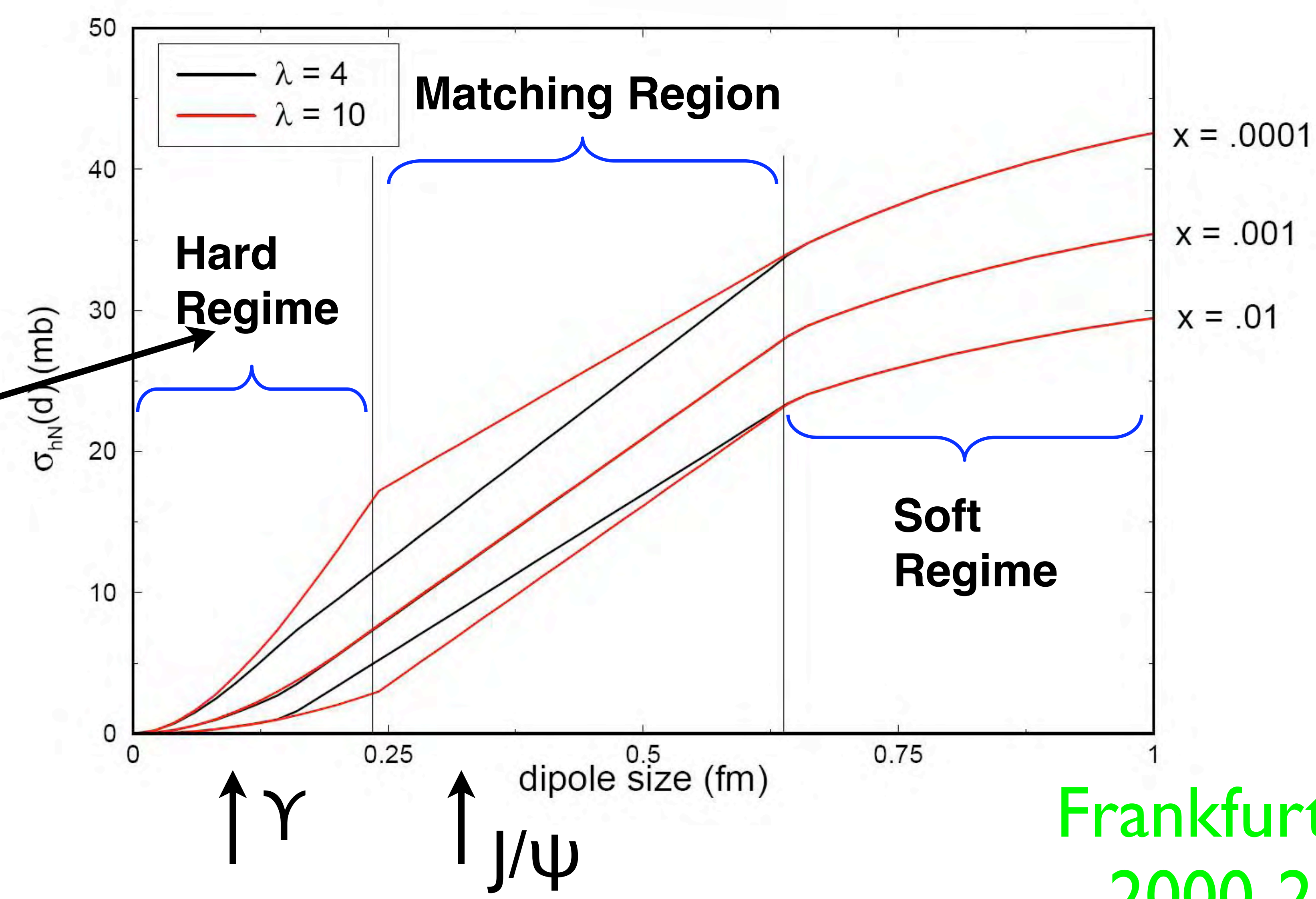
Reason: pQCD strength of parton interaction with a target rapidly grows with E_{inc}

The simplest example - small dipole, d, - nucleon interaction (for example J/ψ - N).



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

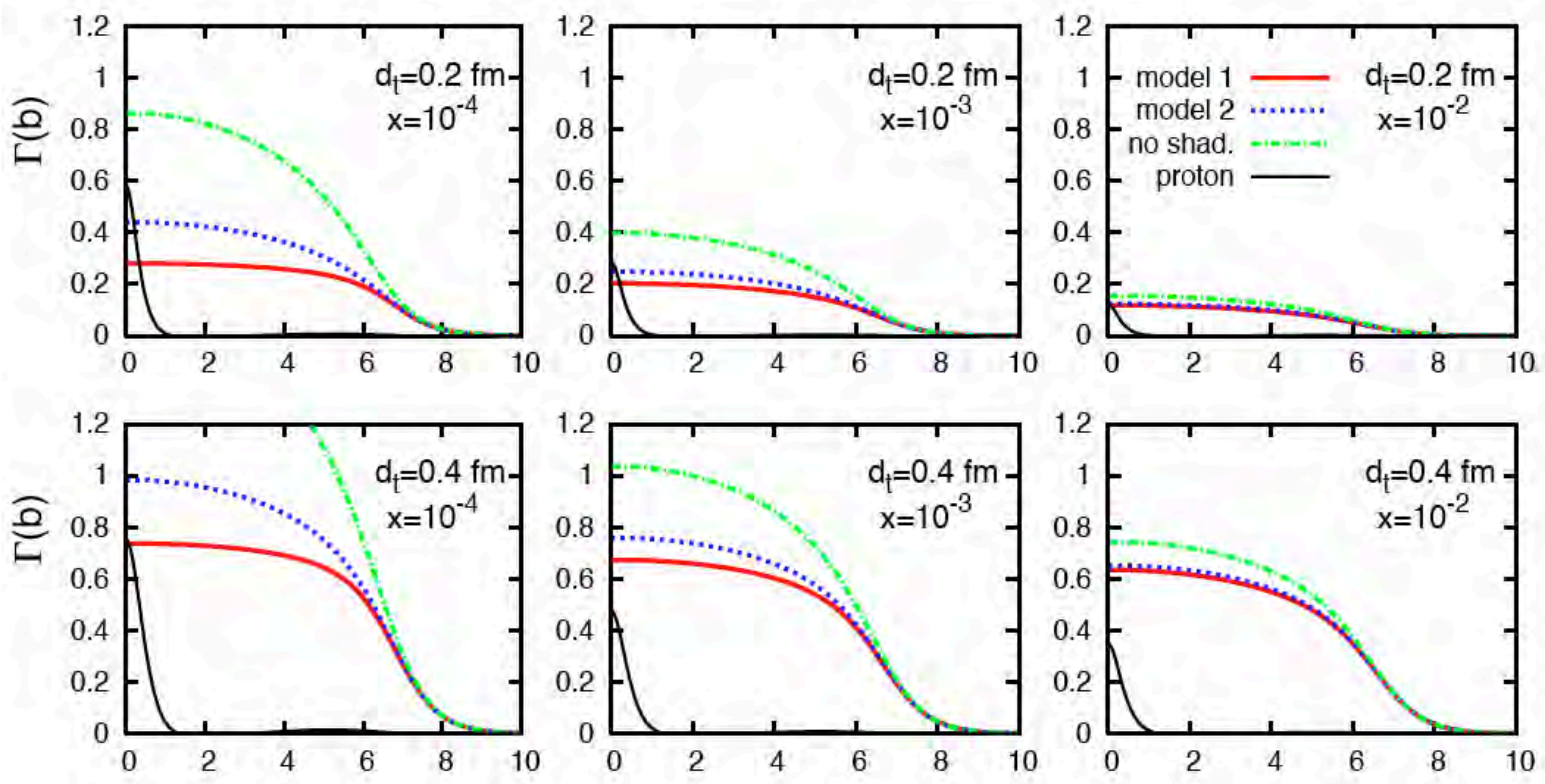
F^2 Casimir operator of color SU(3)



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

Frankfurt et al 2000-2001

Impact factor Γ(b) for quark - antiquark dipole p and dipole -Pb scattering



Update of Rogers et al 03

$p_t \approx 1.5\, GeV/c$

$p_t \approx \frac{\pi}{2d}$

$p_t \approx 0.75\, GeV/c$

Probability of inelastic interaction is
$P_{inel} = 1 - |1-\Gamma(b)|^2 \rightarrow P_{in} = 3/4$ for $\Gamma(b) = 1/2$

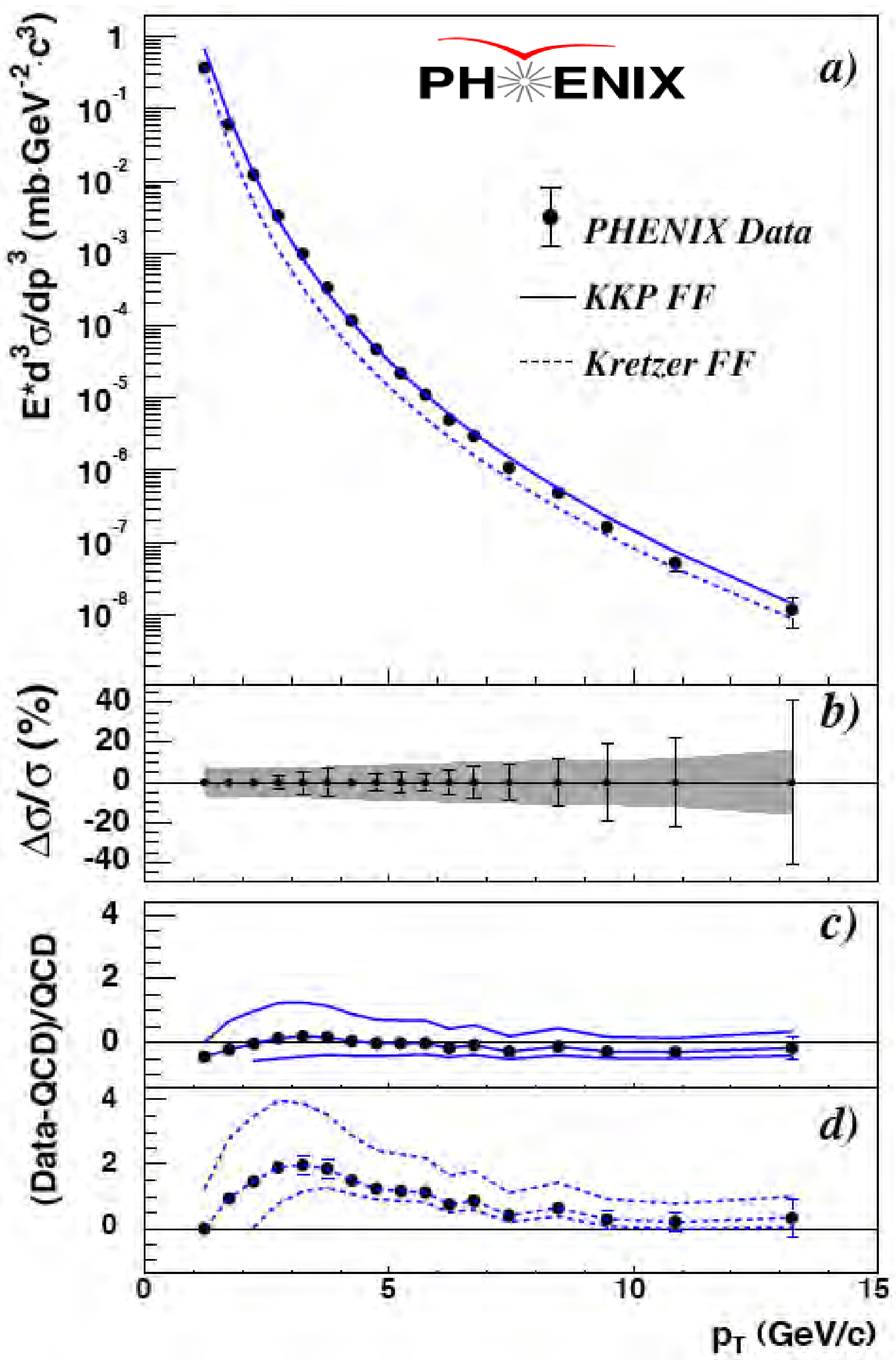
Gluon densities in nuclei and proton at b=0 are rather similar. Difference at <b> is ~30% larger

Main advantage of nuclei - easier to regulate impact parameters

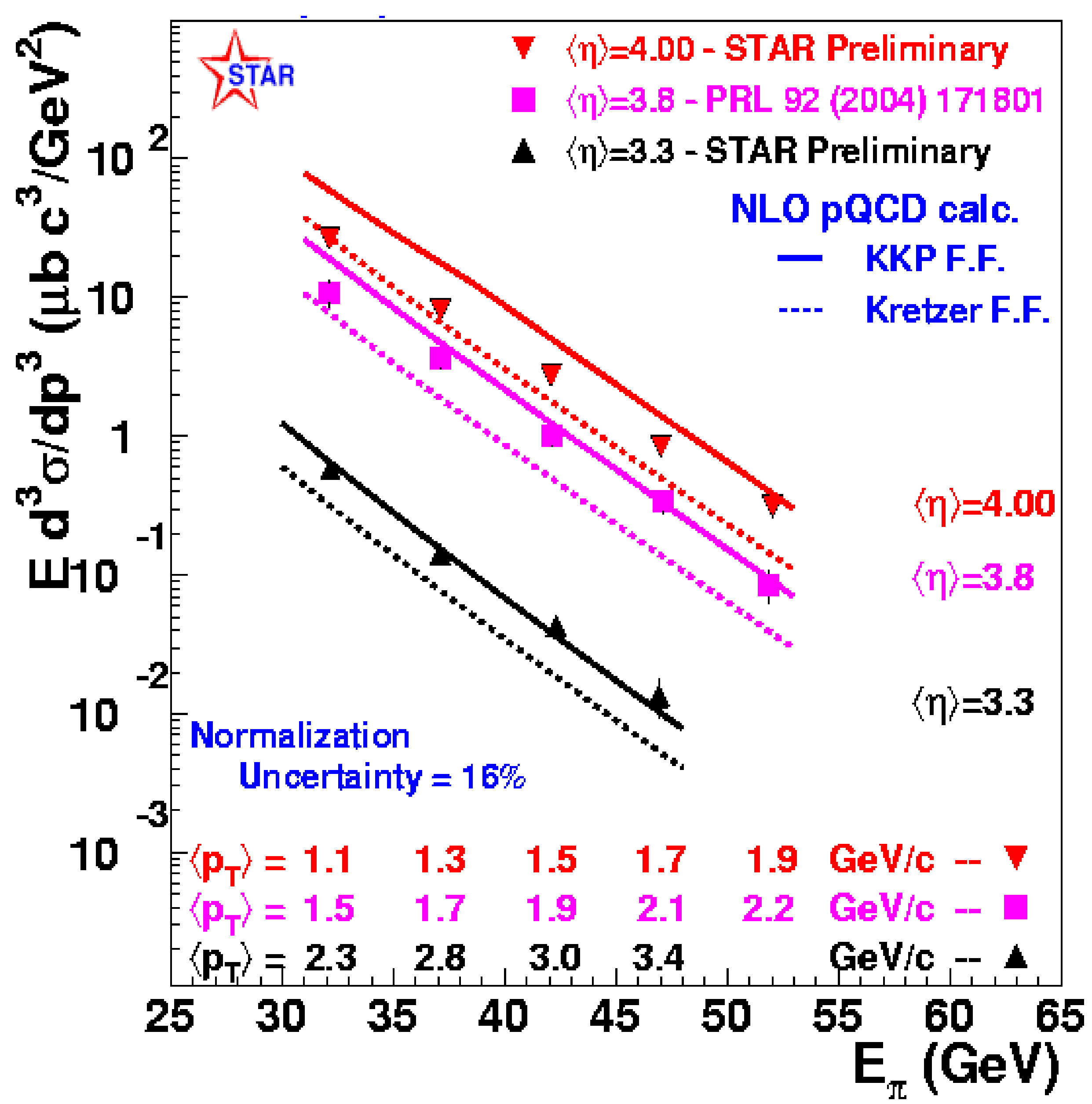
Expect large effects for $s_{dipole\text{-}A} \sim 10^4\, GeV^2$ - within the reach for forward kinematics at RHIC

Measurements of forward production of pions at pp and dAu collisions at RHIC (He's talk)

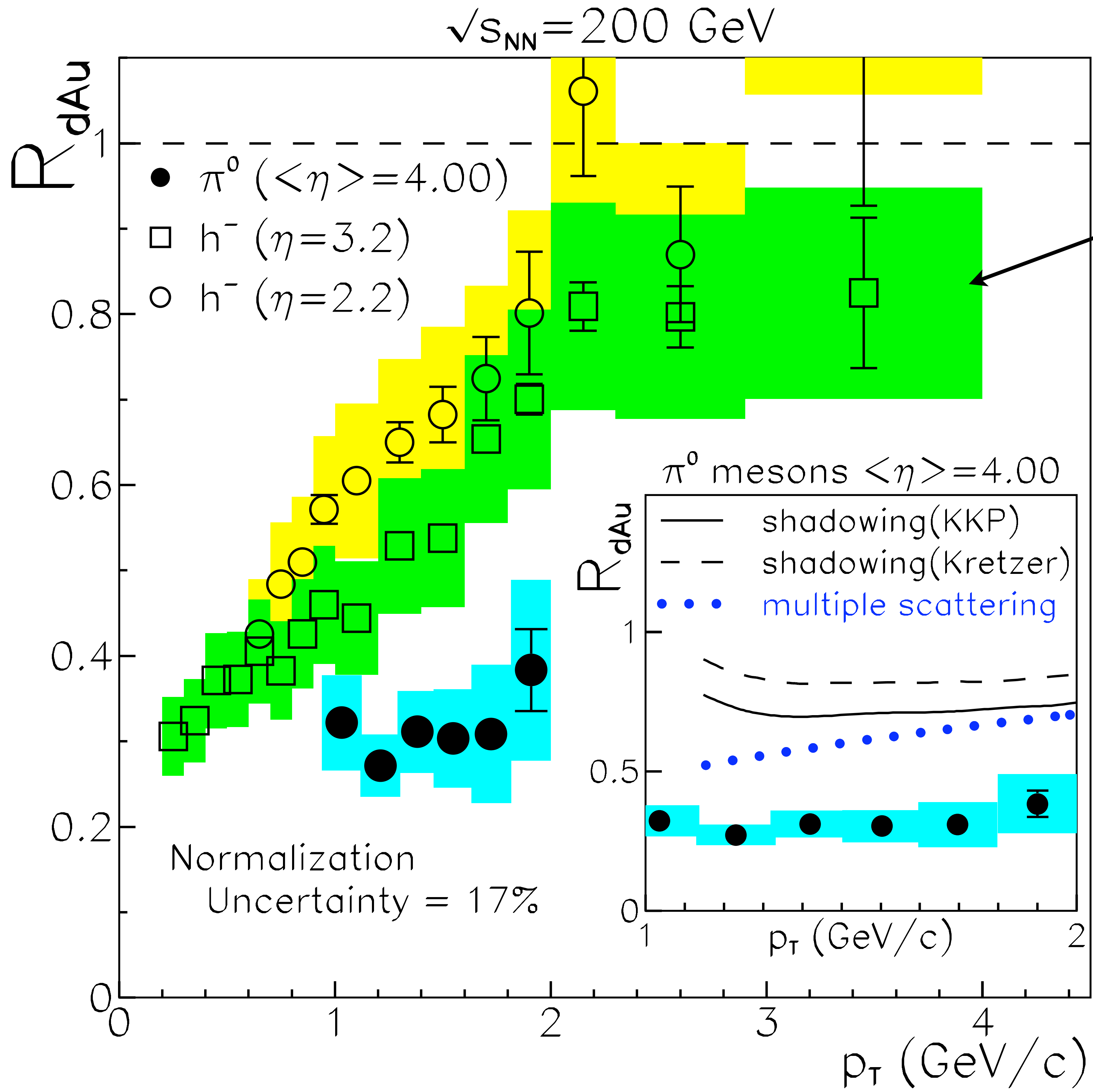
Key early observations.



$pp \to \pi^0 X$ **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

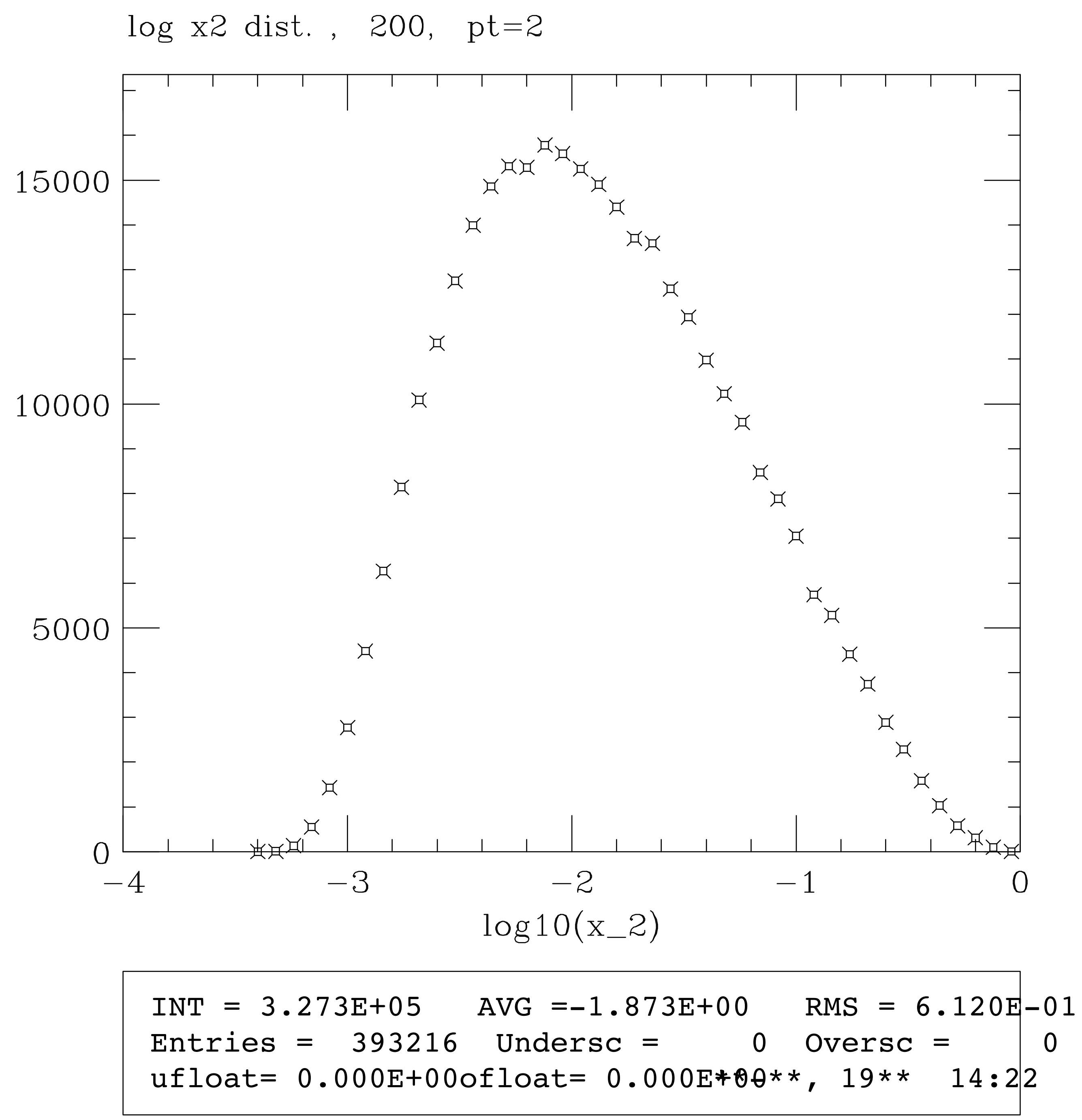
FIG. 3: Nuclear modification factor ($R_{\rm dAu}$) for minimum-bias d+Au collisions versus transverse momentum (p_T). The solid circles are for π^0 mesons. The open circles and boxes are for negative hadrons (h^-) at smaller η [10]. The error bars are statistical, while the shaded boxes are point-to-point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

Can the suppression be due to LT nuclear shadowing?

Guzey, MS, Vogelsang 04

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

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



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

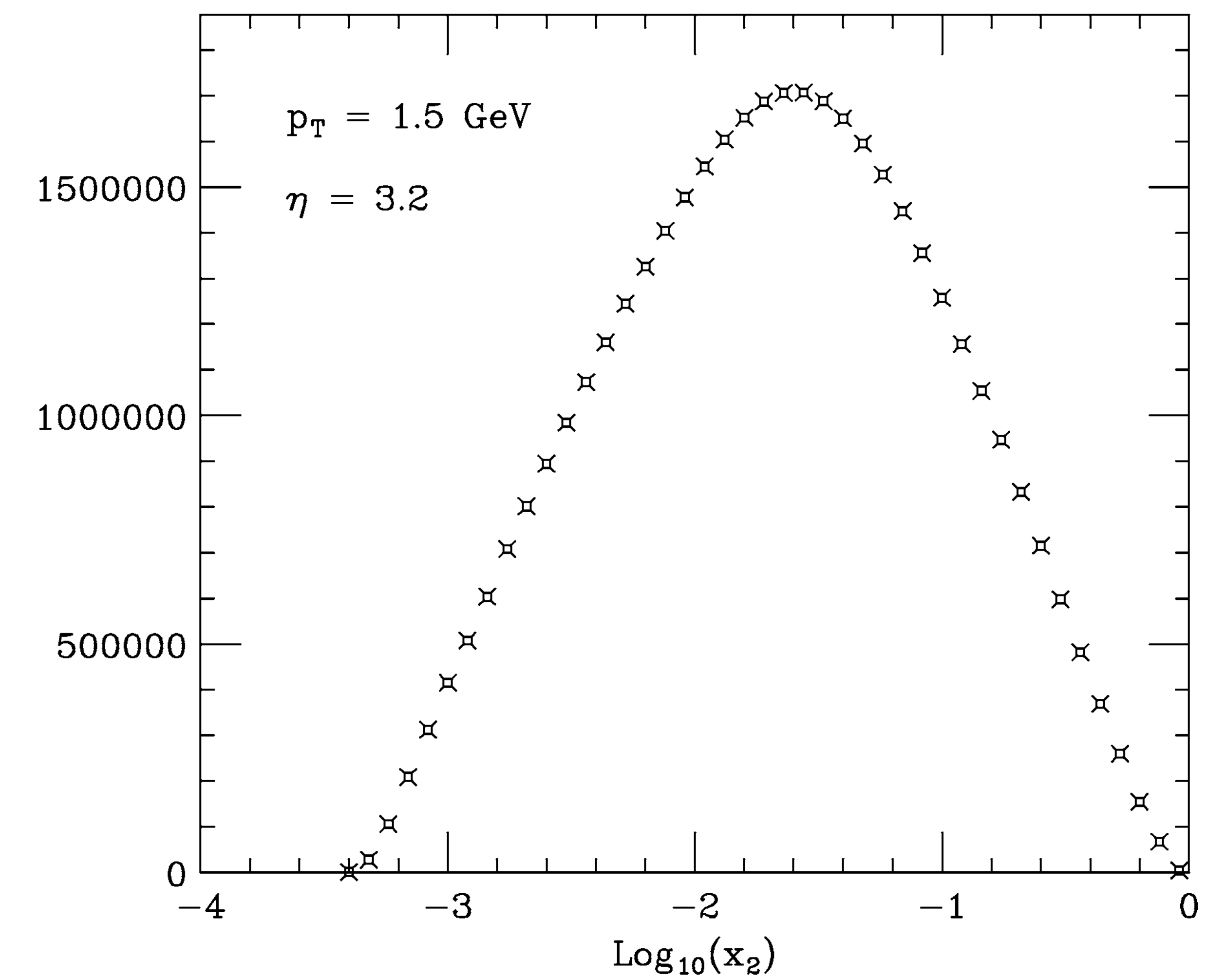


Fig. 1. Distribution in $\log_{10}(x_2)$ of the NLO invariant cross section $E\,d^3\sigma/dp^3$ at $\sqrt{s} = 200$ GeV, $p_T = 1.5$ GeV and $\eta = 3.2$.

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%. Overall effect of gluon shadowing is ~15%.

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

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.

Summary of the challenge

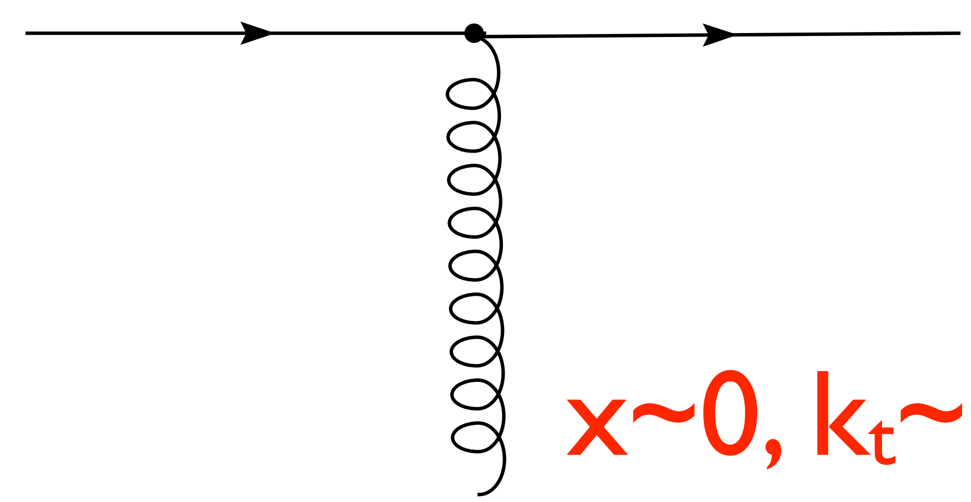
☞ For pp - pQCD works both for inclusive pion spectra and for correlations (will discuss later)

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

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.

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

✔ Color Glass Condensate inspired models



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 both for nucleus and nucleon targets by the scattering of partons with minimal x allowed by the kinematics: $x \sim 10^{-4}$ in a 2→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,

⇓

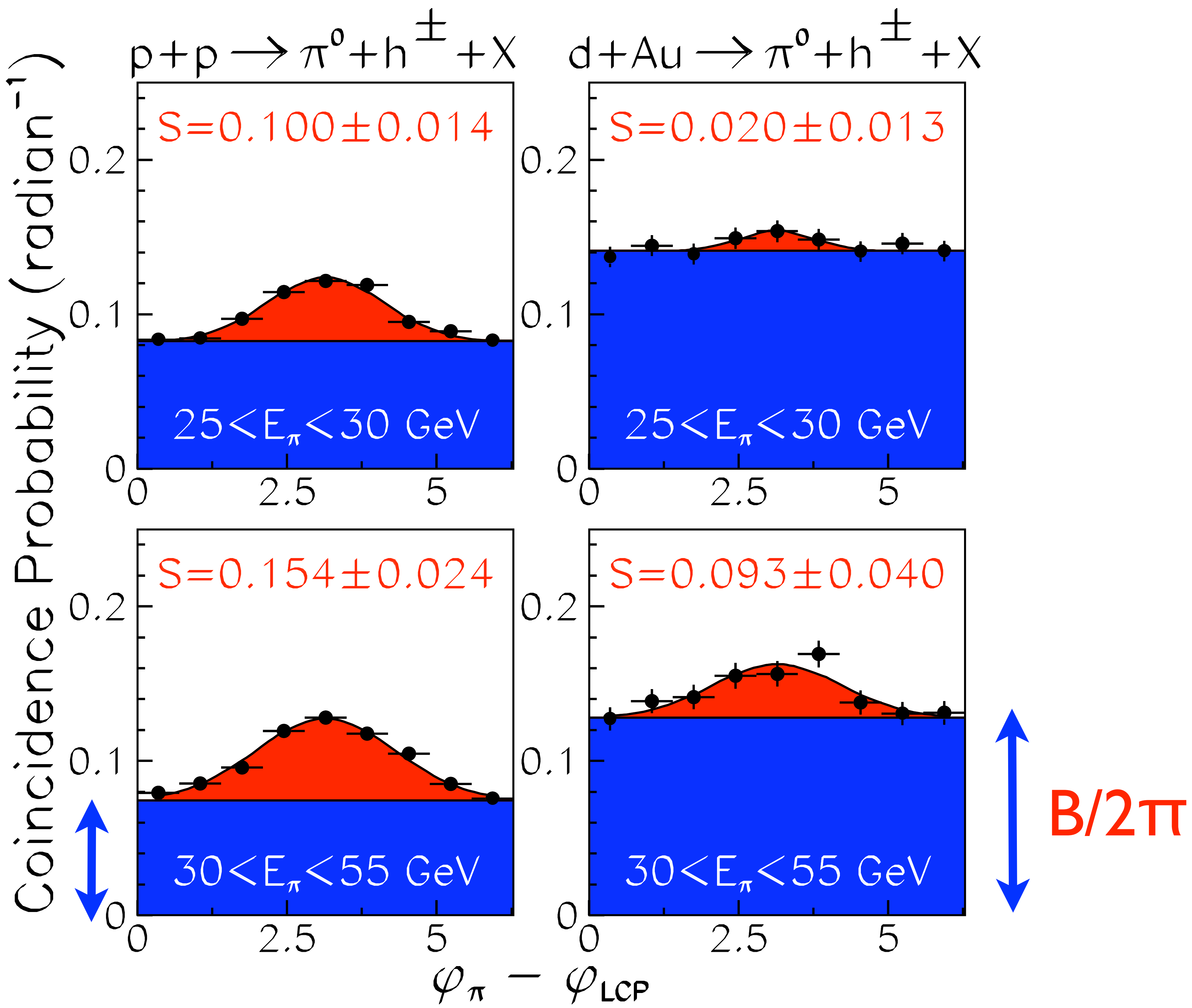
dominant yield from scattering at peripheral impact parameters

Analysis of the STAR correlation data of 2006

Forward central correlations - kinematics corresponding to x_A ~ 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 η=0 region (blue), in pp and in dAu - (while for b=0, N_{coll} ~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 $N_{coll} \sim 15$. 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.

To single out scattering of small x_A gluons GSV05 suggested to measure two forward pion production as a way to understand single pion forward production at sufficiently large p_t.

a dedicated run to measure forward $\pi^0+\pi^0$ production:

$pp \rightarrow \pi^0+\pi^0+ X$

$\eta_{1,2} \le 4$ ($x_F \le 0.5$), $p_T > 1.5$ GeV/c

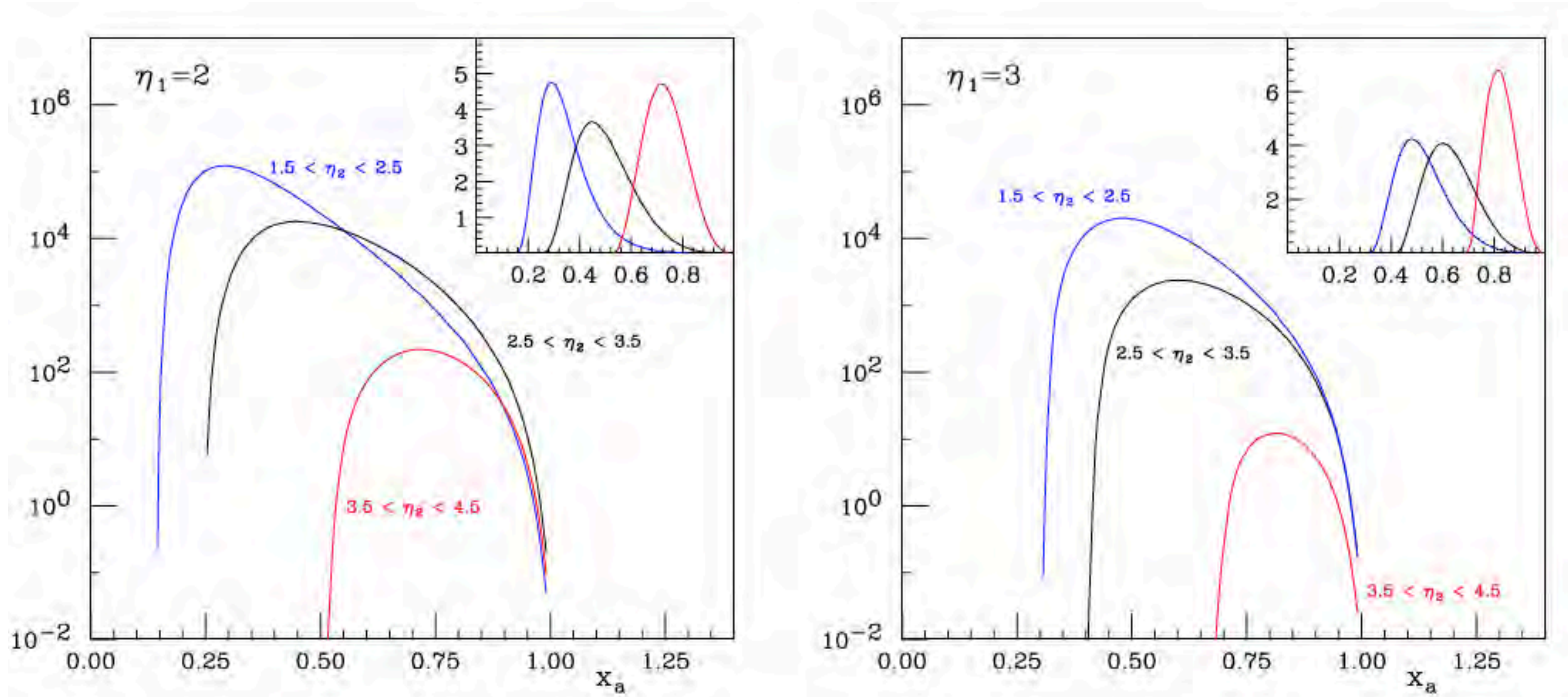
2009-2010

$d\text{-}Au \rightarrow \pi^0+\pi^0 + X$

analysis of MS + W.Vogelsang 2010

Evidence for double parton interaction mechanism in the forward production of two pions in pp and d-Au collisions at RHIC

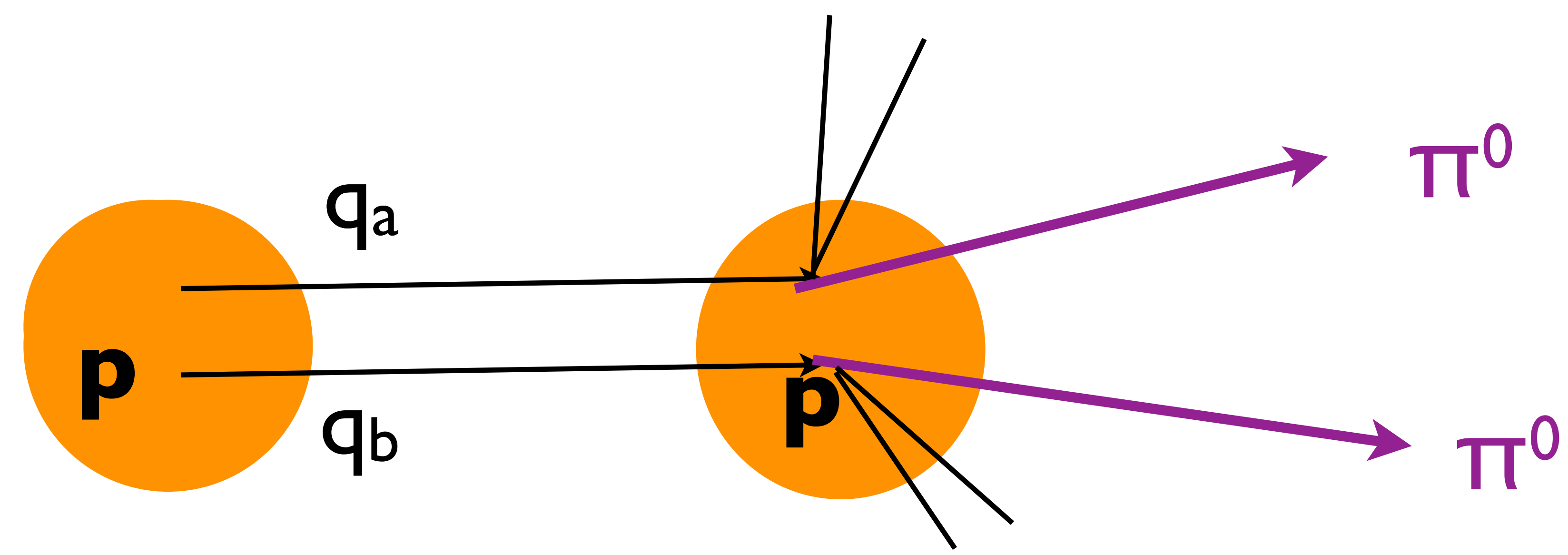
Trigger for two forward pions selects even larger x_q than the single pion trigger



fraction of cross section due to given x_a (x of the quark of the proton)

Large enhancement of double parton interactions in pp and especially d-Au:

(i) more likely for two quarks to share large x, (b) small gluon density is large - square of g(x).



$$\frac{d^4\sigma_{\rm double}}{dp_{T,1}d\eta_1 dp_{T,2}d\eta_2} = \frac{1}{\pi R^2_{\rm int}} \sum_{abc\,a'b'c'} \int dx_a dx_b dz_c dx_{a'} dx_{b'} dz_{c'}\; f^p_{aa'}(x_a, x_{a'}) f^p_b(x_b) f^p_{b'}(x_{b'})$$

$$\times \quad \frac{d^2\hat{\sigma}^{ab\to cX}}{dp_{T,1}d\eta_1} \frac{d^2\hat{\sigma}^{a'b'\to c'X'}}{dp_{T,2}d\eta_2} D^{\pi^0}_c(z_c)\, D^{\pi^0}_{c'}(z_{c'})\,.$$

$$f^p_{qq'}(x_q, x_{q'}) = \frac{1}{2}\left[f^p_q(x_q) \times \phi\left(\frac{x_{q'}}{1-x_q}\right) + (q \leftrightarrow q')\right]$$

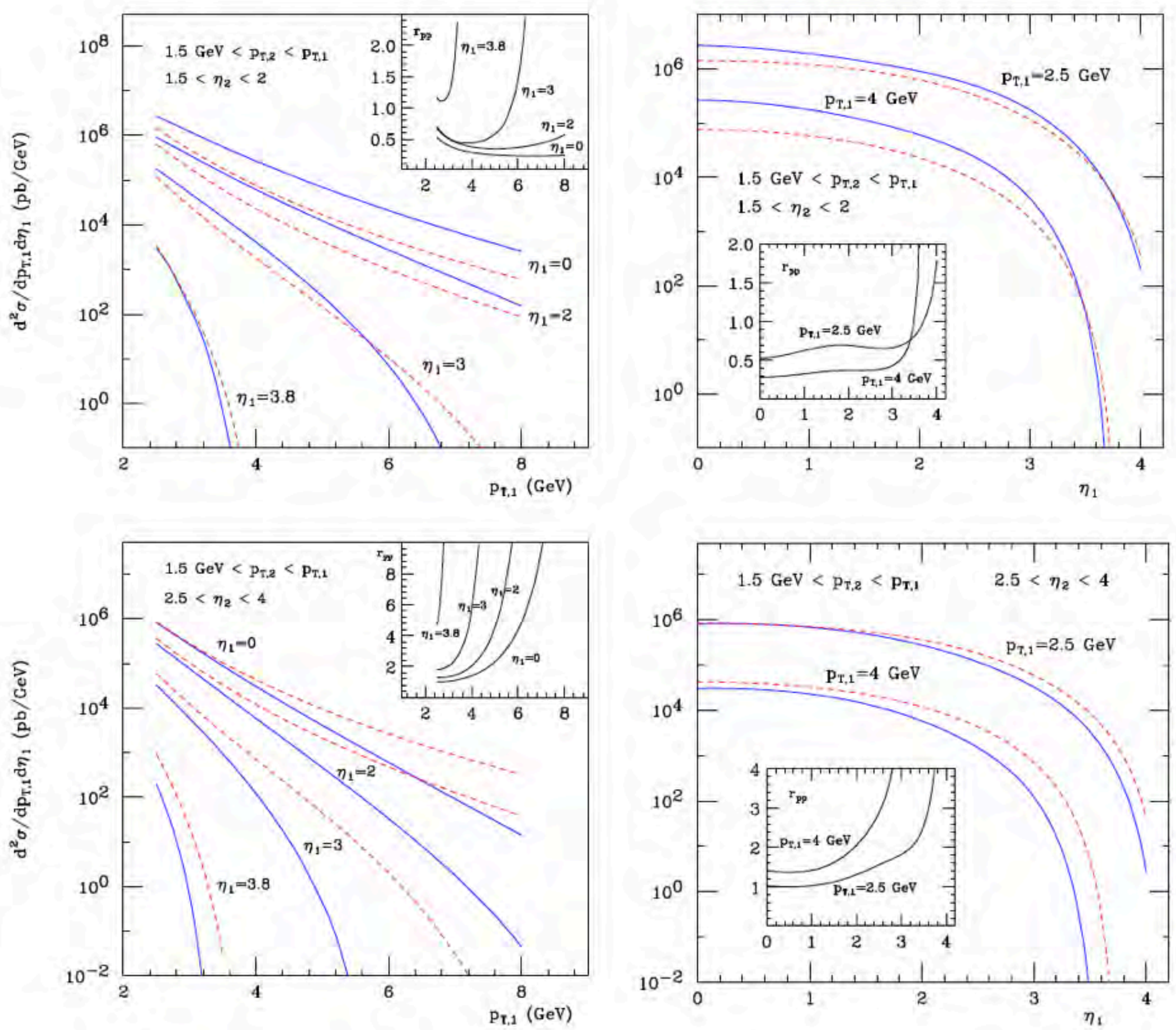
$$\phi(\xi) = \frac{c}{\sqrt{\xi}}(1-\xi)^n$$

In numerical calculations we used experimental value of $\pi R^2_{int} = 15$ mb

Note that if the typical distances between large x quarks are smaller than typical distances between small x gluons we get

$$\pi R^2_{\rm int} = \left[\int \frac{d^2\Delta}{(2\pi)^2} F^2_{2g}(\Delta) \right]^{-1} = \frac{12\pi}{m_g^2} \approx 14 \text{ mb}$$

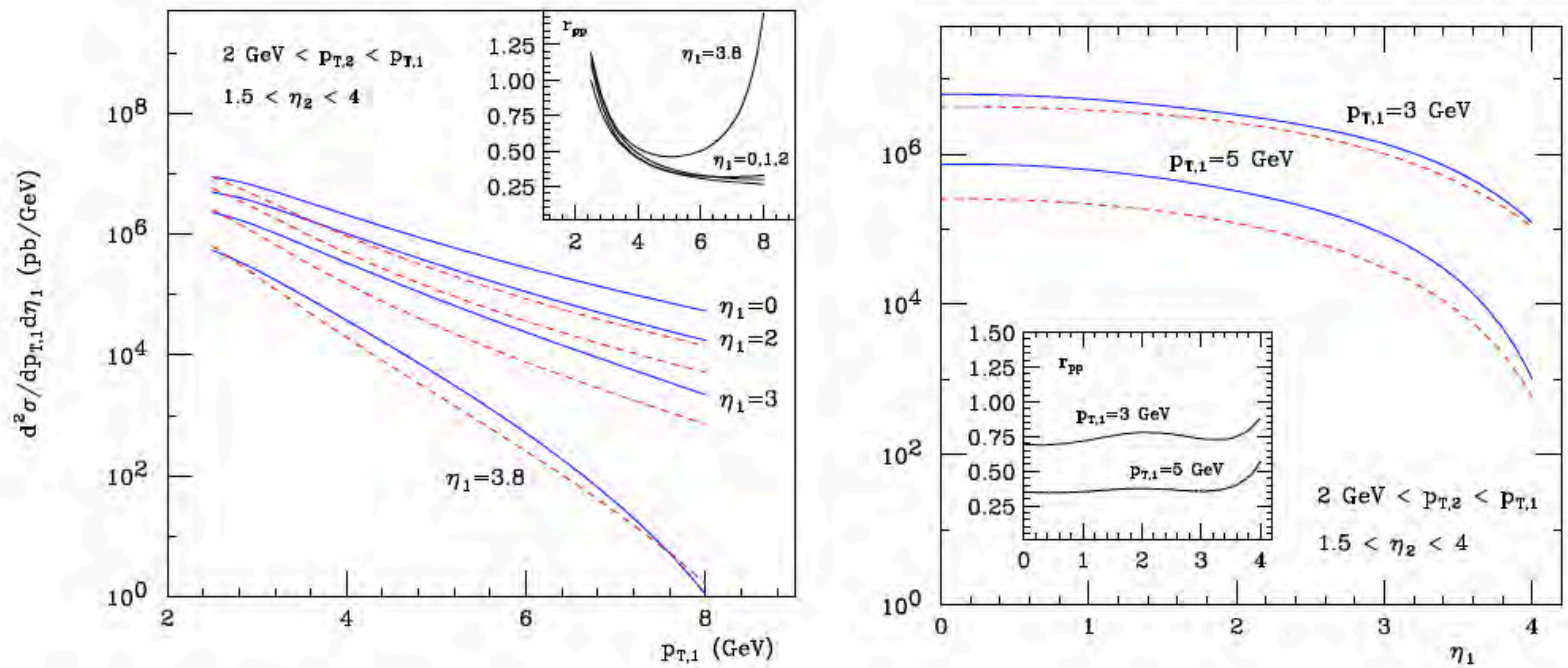
Two gluon form factor



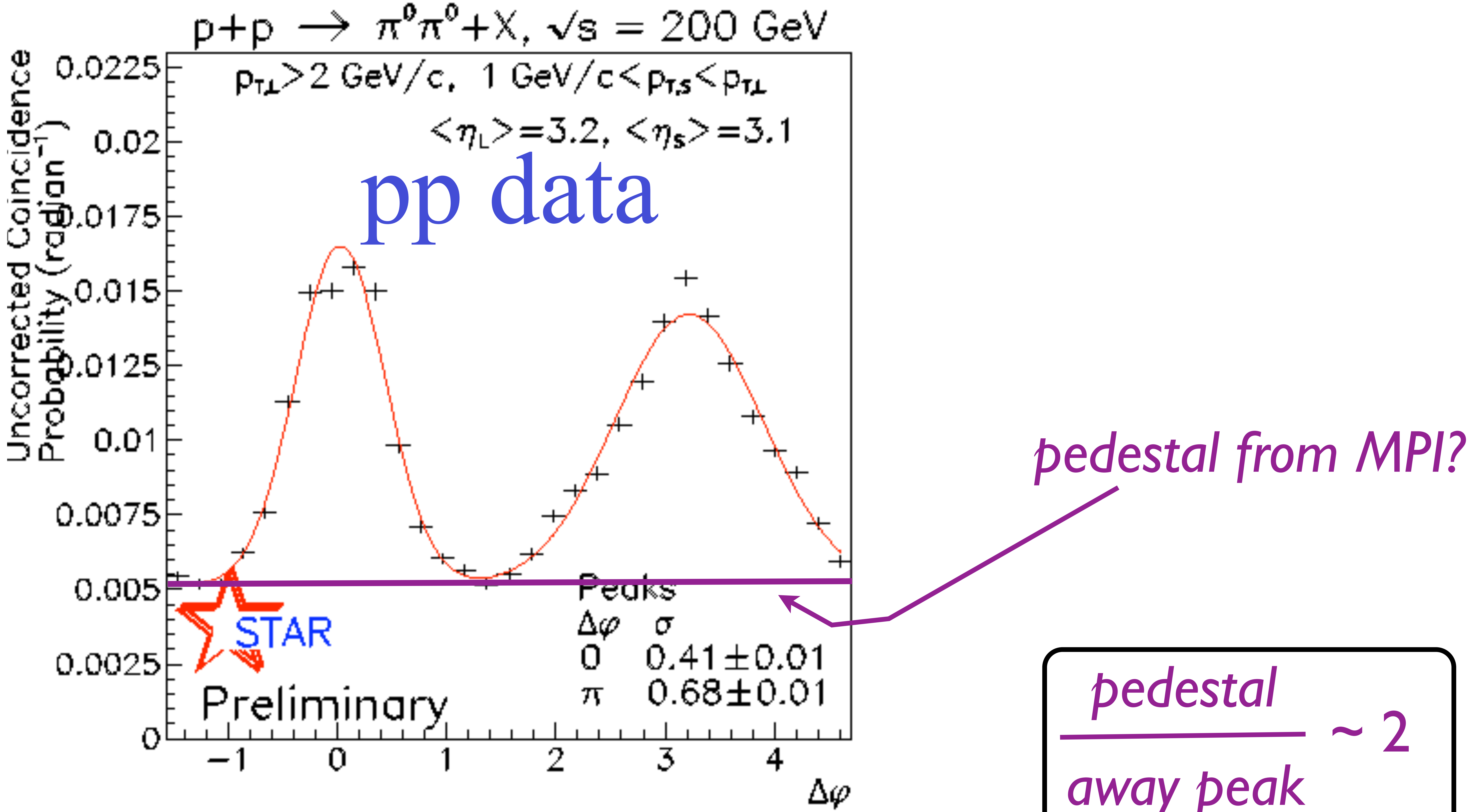
Comparison of the leading-twist cross section for $pp\to\pi^0+\pi^0+X$ (blue) and the double-interaction contribution (red) as functions of $p_{T,1}$ (left) and η_1. Insert the ratio of double and single cross sections.

We used LO cross sections; NLO most likely leads to a larger double/single ratio

Large effects also for √s =500 GeV



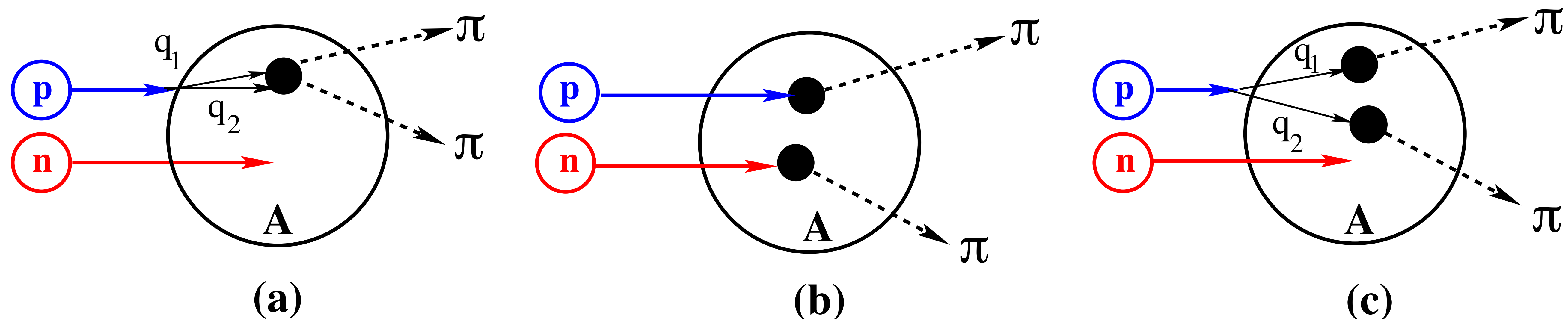
$$2\ \text{GeV} < p_{T,2} < p_{T,1}\ \ and\ 1.5 < \eta_2 < 4.$$



$$\frac{\textit{pedestal}}{\textit{away peak}} \sim 2$$

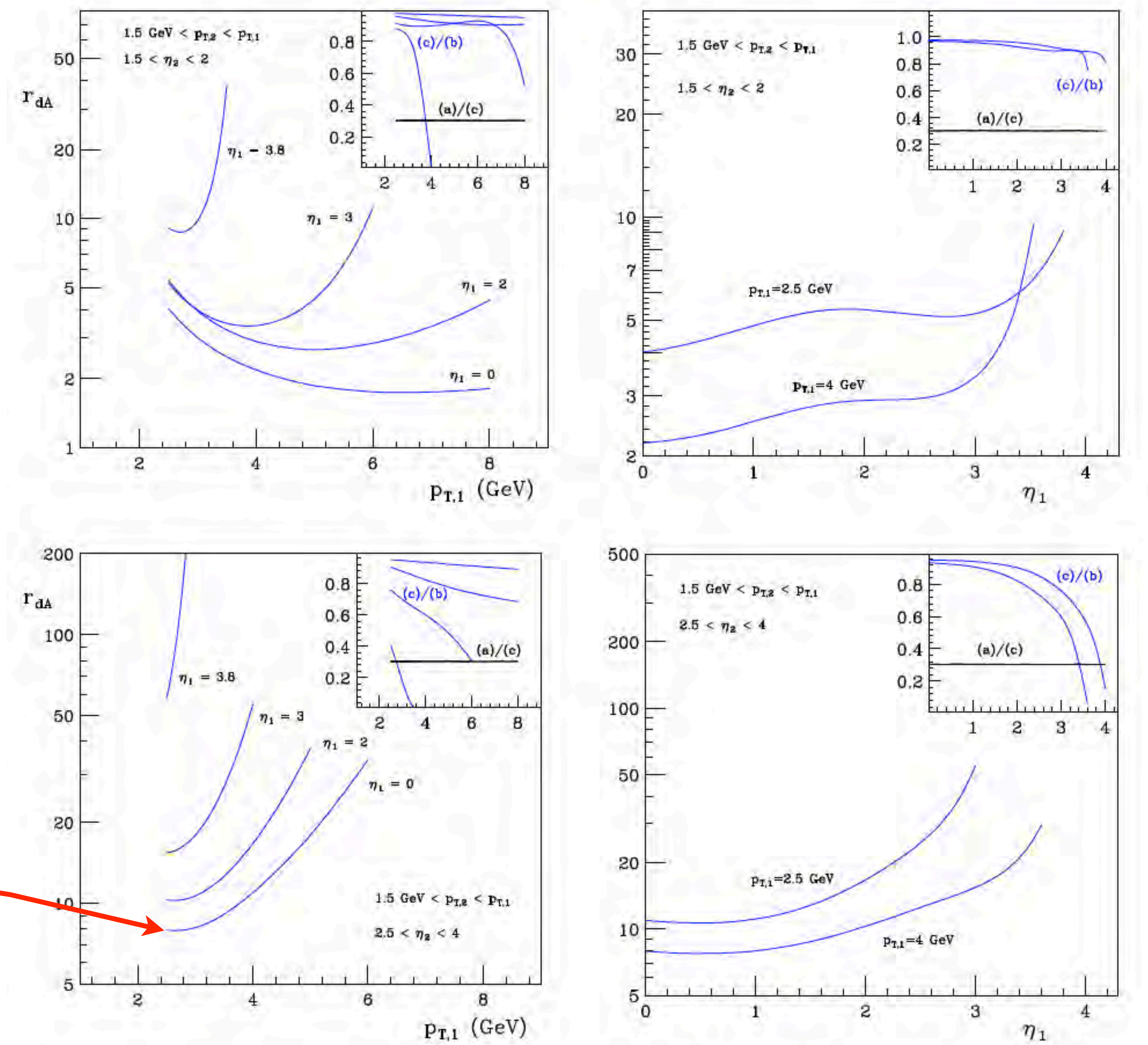
Thursday, December 2, 2010

Check - look at d-Au should see a large enhancement of the pedestal - two nucleons can hit many nucleons - (MS +Treleani 02)

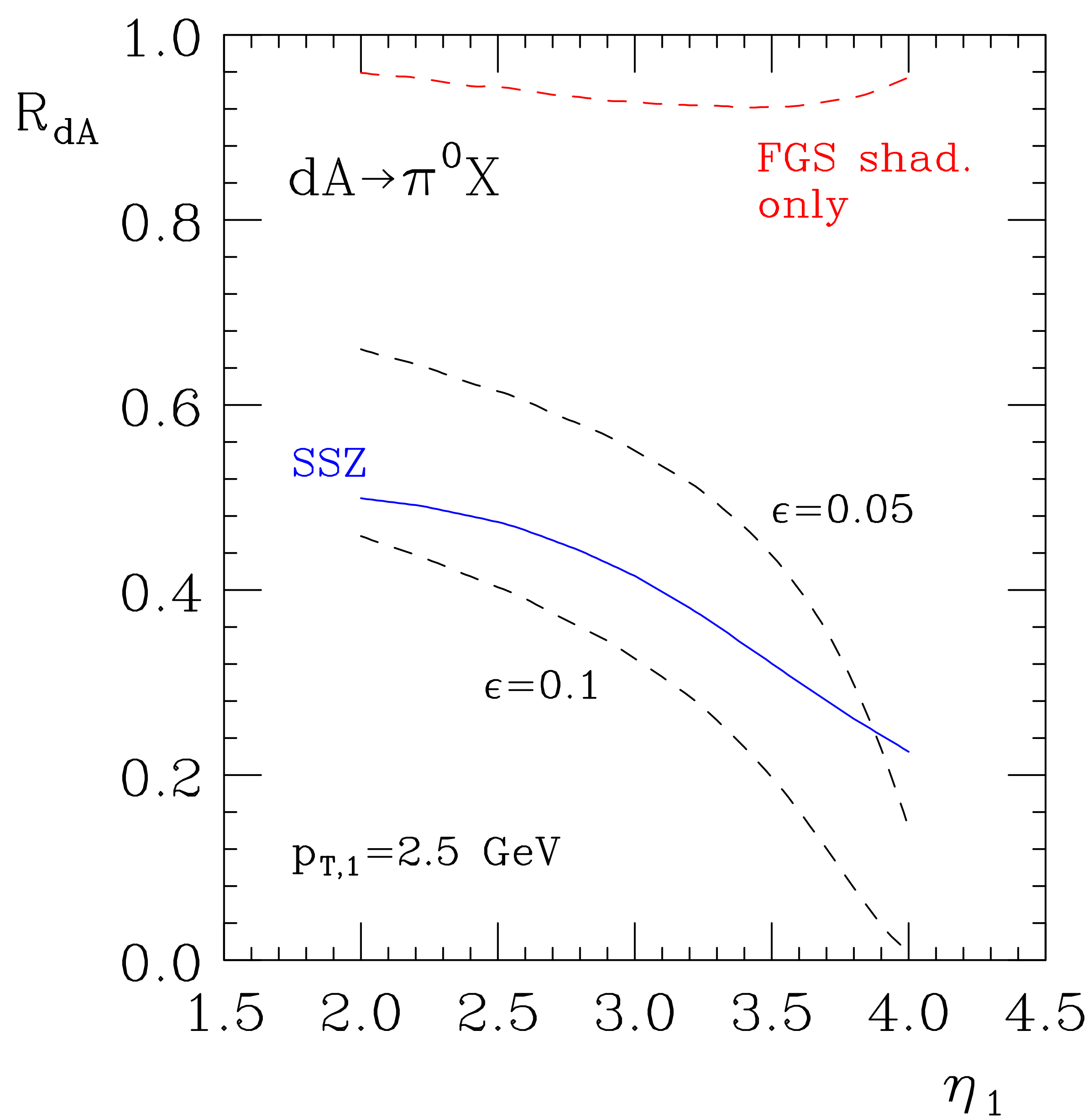


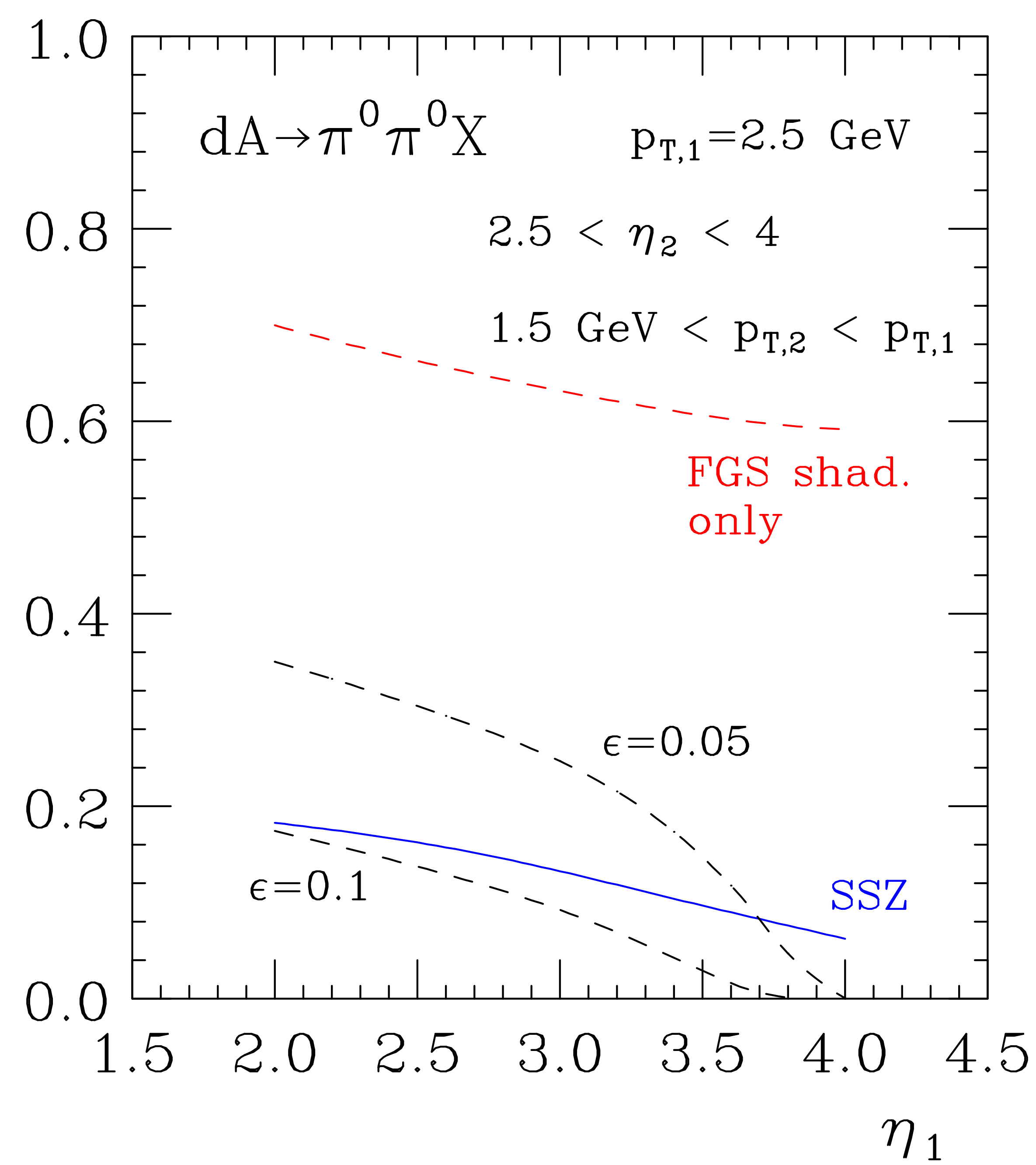
$$\frac{d^4\sigma^{NA}_{\mathrm{double,(b)}}}{dp_{T,1}d\eta_1 dp_{T,2}d\eta_2} = \int d^2b\, \frac{A-1}{A}\, T^2(b) \times \frac{1}{2}\left[\frac{d^2\tilde{\sigma}^{pN}_{\mathrm{LT}}}{dp_{T,1}d\eta_1}\frac{d^2\tilde{\sigma}^{nN}_{\mathrm{LT}}}{dp_{T,2}d\eta_2} + (p_{T,1},\eta_1 \leftrightarrow p_{T,2},\eta_2)\right]$$

Ratio r_{dA} of double-parton and leading-twist contributions in central dA → $\pi^0\pi^0X$ with no suppression effects included



Close to forward - central kinematics



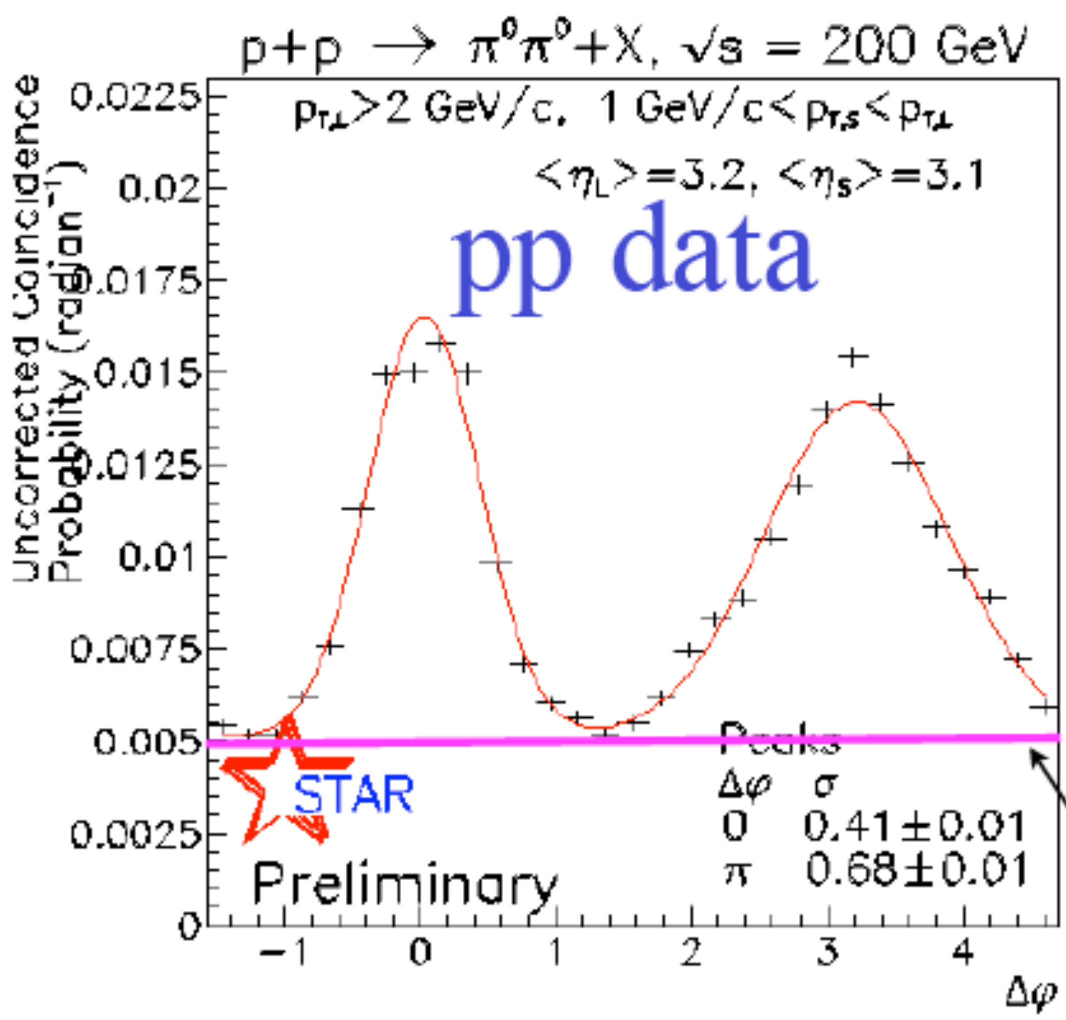


Nuclear modification factor R_{dA} for single-inclusive leading-twist pion production as a function of rapidity η_1 at $p_{T,1}$ = 2.5 GeV for fractional loss ε =0.05 & 0.1.The upper dashed line shows the effect of leading-twist shadowing for the Frankfurt-Guzey-Strikman (FGS) nuclear parton distributions. 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.

Right: Same for double-inclusive pion production - much larger suppression effect

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 than in pp
- ✶ Suppression of Δϕ =180° peak by a factor ~ four



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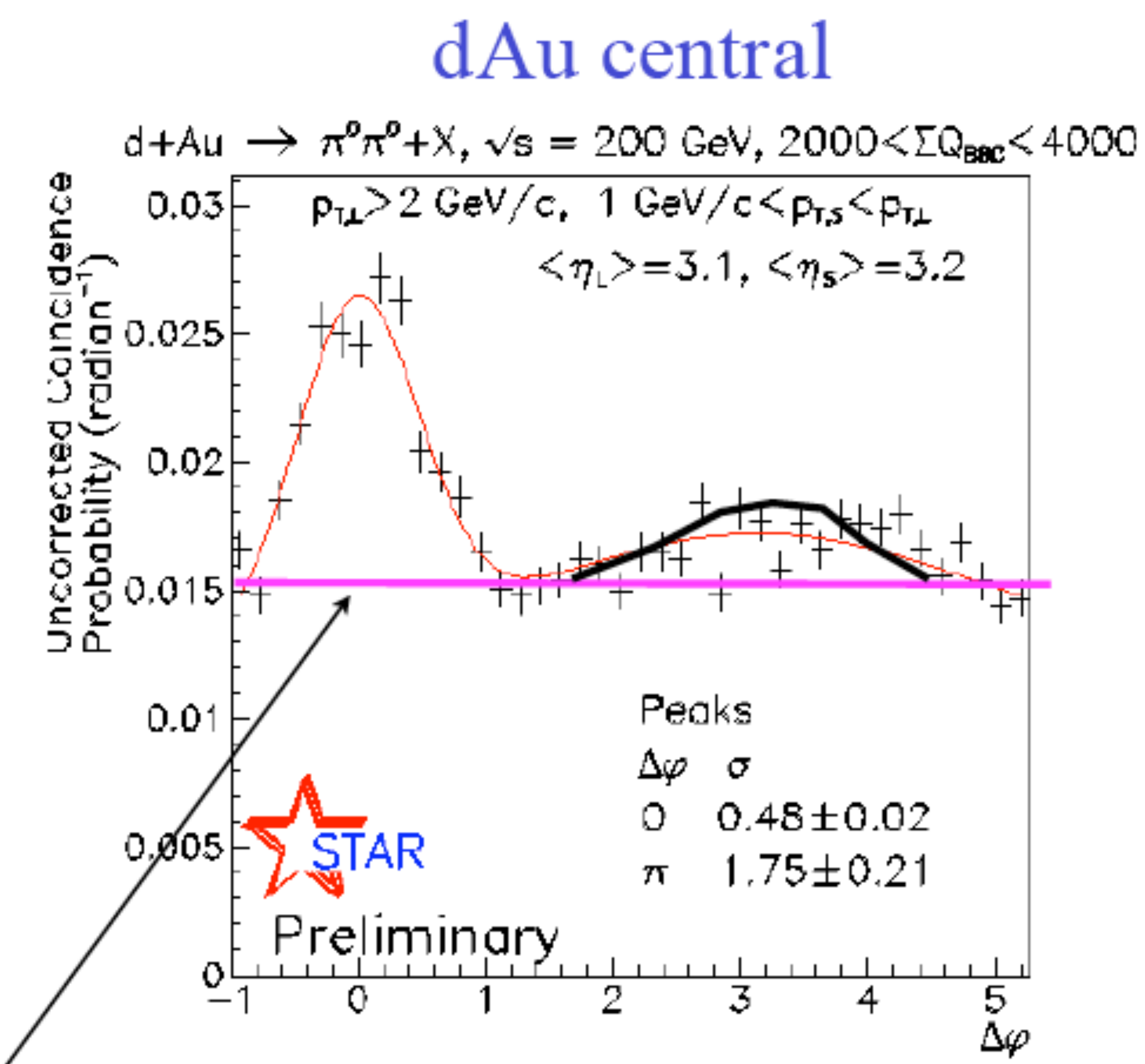
pedestal



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).

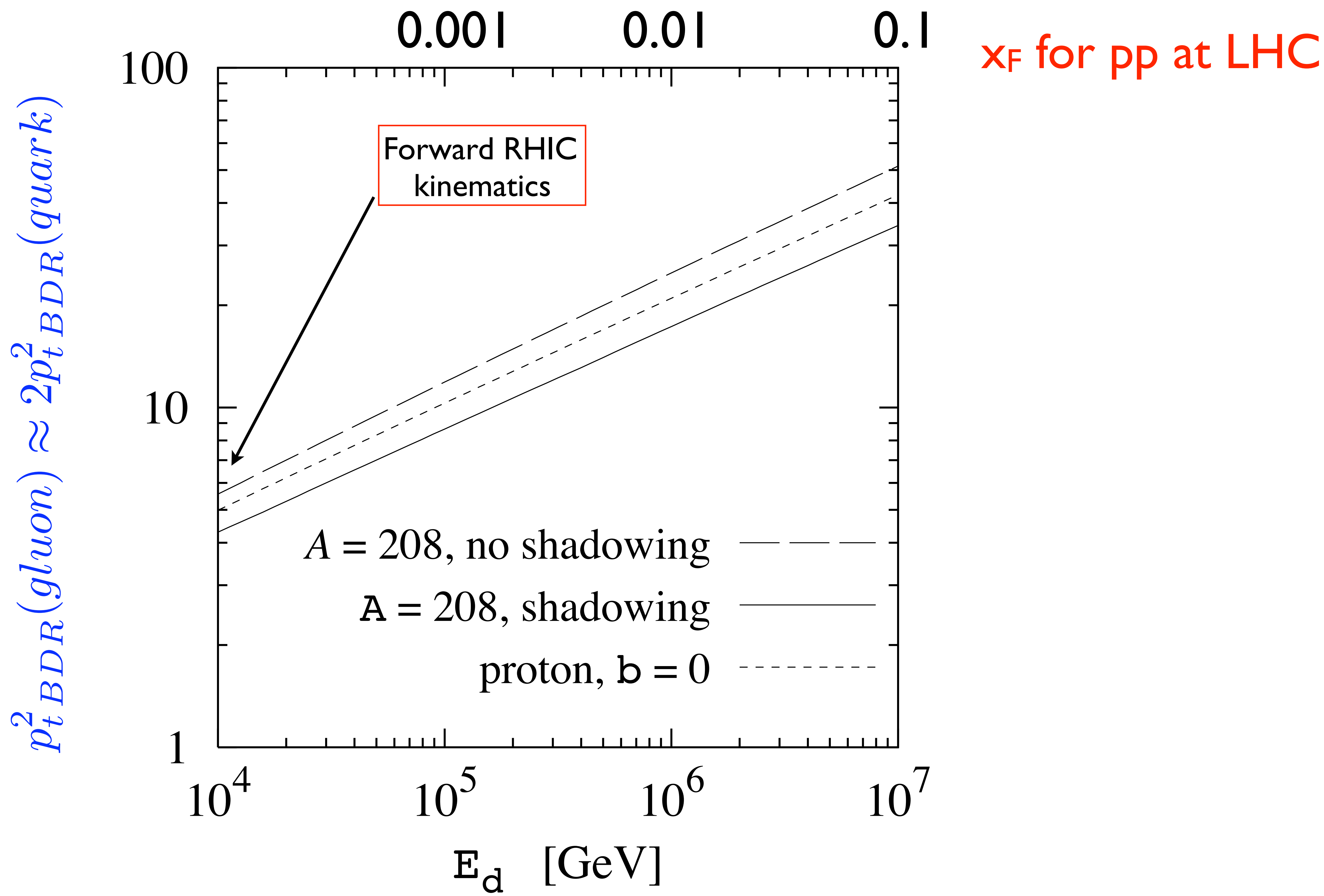
Large nonlinear effects at the LHC in wide range of rapidities.

in proton (A) - proton (A) collisions a parton with given x_R resolves partons in another nucleon with $x_2 = 4p_\perp^2/x_R s$

$$x_R = 0.01, p_\perp = 2GeV/c \;\Rightarrow\; x_2 \sim 8\times 10^{-6}$$

Onset of BDR for interaction of a small dipole - break down of LT pQCD approximation - natural definition of boundary: $\Gamma_{dip}(b) = 1/2$ - corresponds the probability for dipole to pass through the target at given b without interaction:

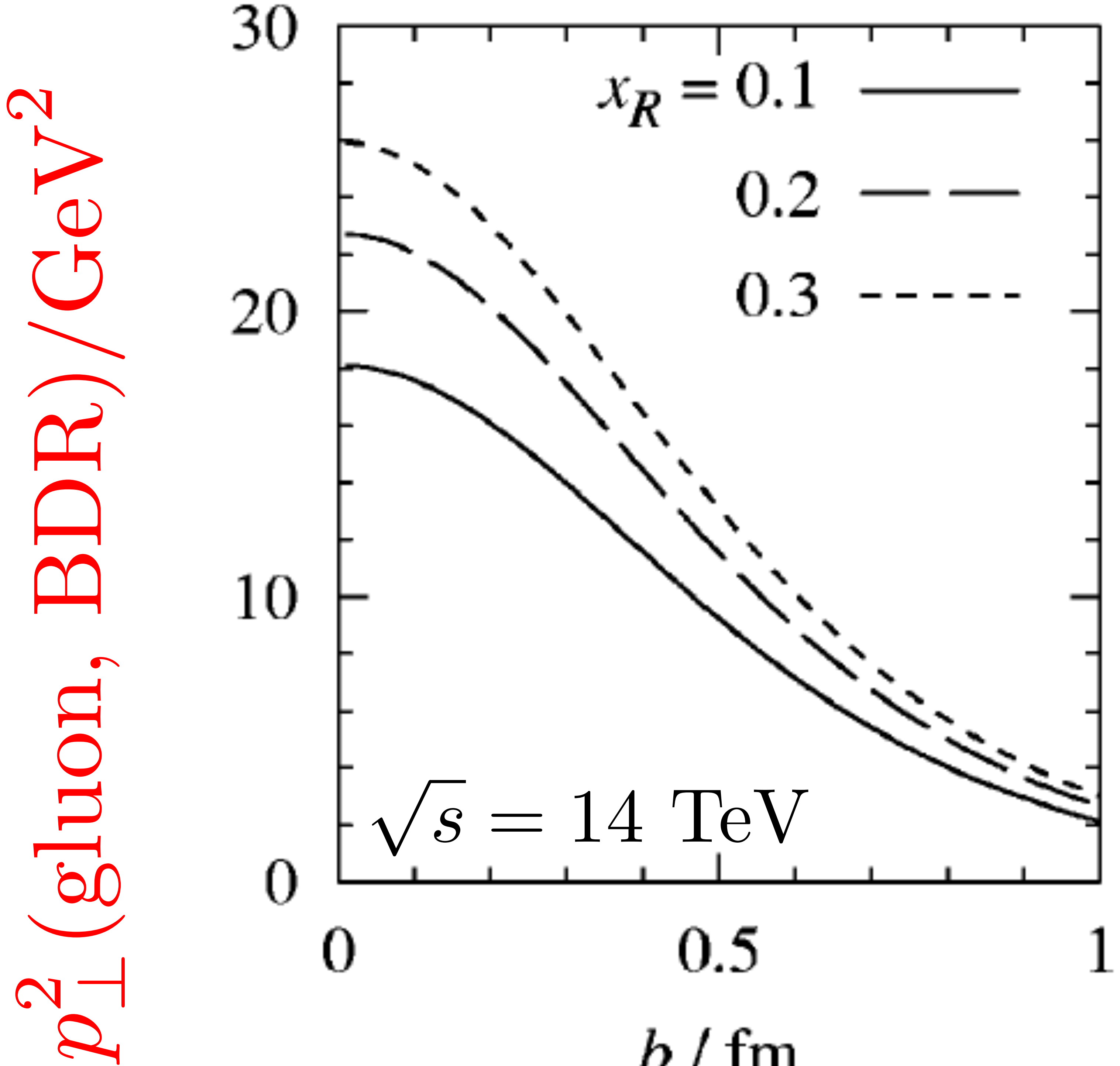
$|1-\Gamma_{dip}(b)|^2 < 1/4$ ⇒ $p_{t\,BDR} \sim \dfrac{\pi}{2d_{BDR}}$



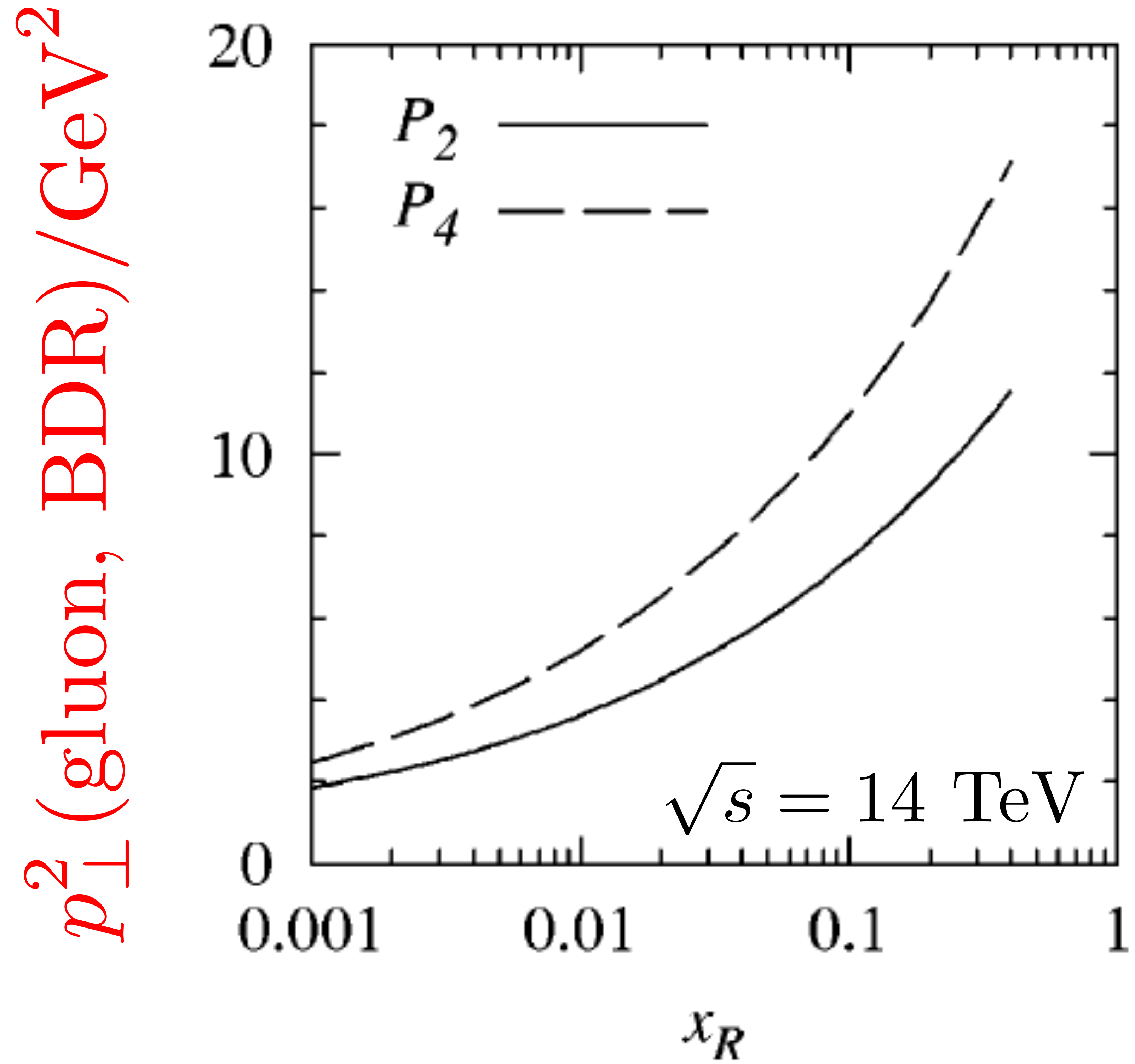
Warning - estimate assumes $x^{-\omega}$ regime for all x- may overestimate $p_{t\,BDR}$ for parton energies (in nucleus rest frame) $E_d > 10^5$ GeV - better to use double log approximation

At LHC largest effects are for

leading particles



events with centrality trigger - dijets (P_2);
four jets via double parton interactions (P_4)



Large flow of energy to central rapidities

Near future

Study of the structure of central collisions in pp at LHC: for example p_T < few GeV distribution of Z - boson in central and peripheral events; y -dependence of dijet production for moderate p_T disbalance,...

Ultraperipheral HI collisions at LHC = hard photon - nucleus scattering at $W \sim W_{HERA}$;
Production of leading dijets,...

If nonlinear effects are observed at expected p_t range

- *Need for high precision measurements to study onset of BDR at lower Q,W - ep/eA colliders*
- *Possibility to study high density quark rich systems produced in the nucleus fragmentation region in the central heavy ion collisions*
- *pA collisions at RHIC and LHC with emphasize on forward physics*

CONCLUSIONS

- RHIC data strongly indicate dominance of a peripheral mechanism of forward pion production. Interpretation of suppression of correlations in central collisions is very sensitive to the multiparton interactions.

- Consistent evidence from analysis of HERA data and leading pion production in d- Au for BDR up to transverse momenta 1 -- 1.5 GeV/c at $x \sim 10^{-4}$

- Multiparton mechanism + $2 \to 2$ with post selection suppression explain the bulk of the forward pion production regularities.

- Multiparton dominance making it very difficult to look for the contribution of $2 \to 1$ mechanism in forward - forward production.

Supplementary slides

A fast parton of the projectile cannot propagate through media in the BDR if it did not fluctuated into parton + gluon configuration with large transverse momenta.

Effectively this corresponds to fractional energy losses in BDR

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

Qualitatively different pattern than at finite x - finite energy losses since in the initial momen
no accompanying gluon field.

Inelastic cross section is calculable in terms of the probability of inelastic interaction, $P_{inel}(b)$ of a parton with a target at given impact parameter b

$$\sigma_{inel} = \int d^2b P_{inel}(b, s, Q^2)$$

σ_{inel} is calculable in QCD

$$P_{inel}(b,x,Q^2) = \frac{\pi^2}{3}\alpha_s(k_t^2)\frac{\Lambda}{k_t^2}xG_A(x,Q^2,b)$$

where $x \approx 4k_t^2/s_{qN}, Q^2 \approx 4k_t^2, \Lambda \sim 2$ (for the gluon case $P_{inel}(b)$ is 9/4 times larger)

If $P_{inel}(b,x,Q^2)$ approaches one or exceeds one it means that average number of inelastic interactions, N(b) becomes larger than one.

Denote as $G_{cr}(x,Q^2,b)$ value of G for which $P_{inel}(b,x,Q^2)=1$

$$N(b,x,Q^2) = G_A(x,Q^2,b)/G_{cr}(x,Q^2,b)$$