Probing small x QCD in ultraperipheral collisions at LHC

and eA/ep physics at eRHIC

Mark Strikman, PSU

Based primely on the analyses performed together with
L.Frankfurt, V.Guzey, R.Vogt, C.Weiss, S.White, M.Zhalov

PANIC, Satellite workshop: New fronties at RHIC
OCTOBER 29, 2005

Main trusts of the HERA small x QCD physics:

- Small x parton densities
- Inclusive hard diffractive processes
- Hard exclusive processes: vector meson production, dijets, ...
- Looking for clean reactions to study "perturbative Pomeron"

Main issues:

- high gluon densities, violation of DGLAP,
- diffractive pdf's   - leading twist vs higher twist;
- generalized parton densities at small x

Theory - gluons are most interesting for small x:

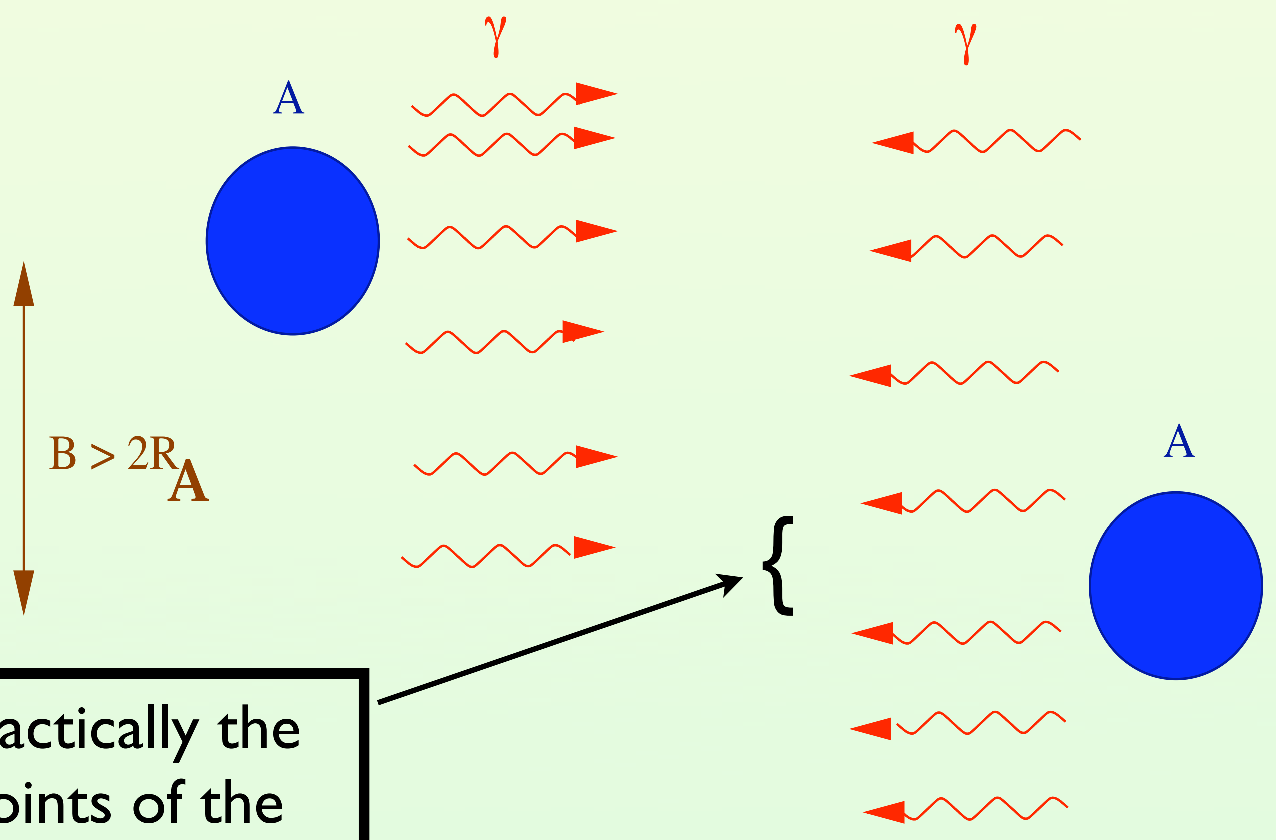
- they drive evolution and quark sea,
- interaction in the gluon sector is much stronger

Theory & HERA experience: photoproduction of dijets, heavy quarks, exclusive heavy meson production are good *"gluonometers"*

ZEUS
HERA
LHC
CMS
UPC
small
x

Ultraperipheral Collisions ≡ UPC

What is UPC? Collisions of nuclei (pA) at impact parameters $b \geq 2R_A$ where strong interaction between colliding particles is negligible



Flux of photons is practically the same for different points of the interacting nucleus

Ultraperipheral Nucleus–Nucleus Collision

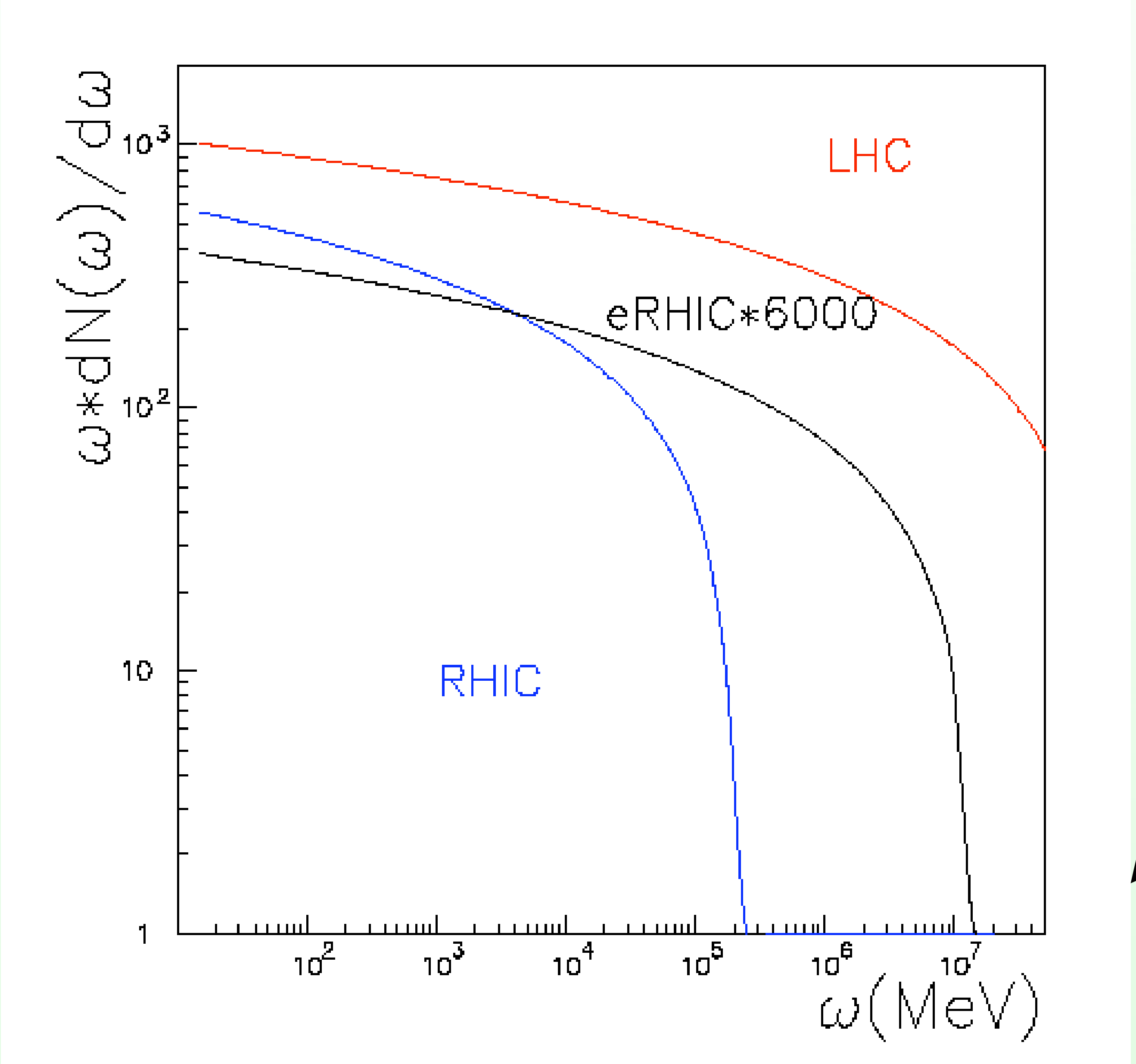
Trigger: One or both nuclei remain intact

Breakup of nuclei due to the Coulomb excitations are allowed (emission of few soft (in the nucleus rest frame) neutrons. Contribution of strong interactions due to nucleus-nucleus scattering at $b \sim 2R_A$ is a small correction (weak A-dependence & small probability of diffraction). One can also study asymmetric UPC - $pA, \& AA$

Counting rates are large up to

$$s_{eff}^{\gamma A}(LHC) \sim (1TeV)^2, \sim 10 s_{max,\ HERA}(\gamma p)$$

Equivalent Photon spectrum in target nucleus frame



"Quasi-real" γ spectra compared to an e-hadron collider

->100 TeV @ LHC

Example: exclusive vector meson production

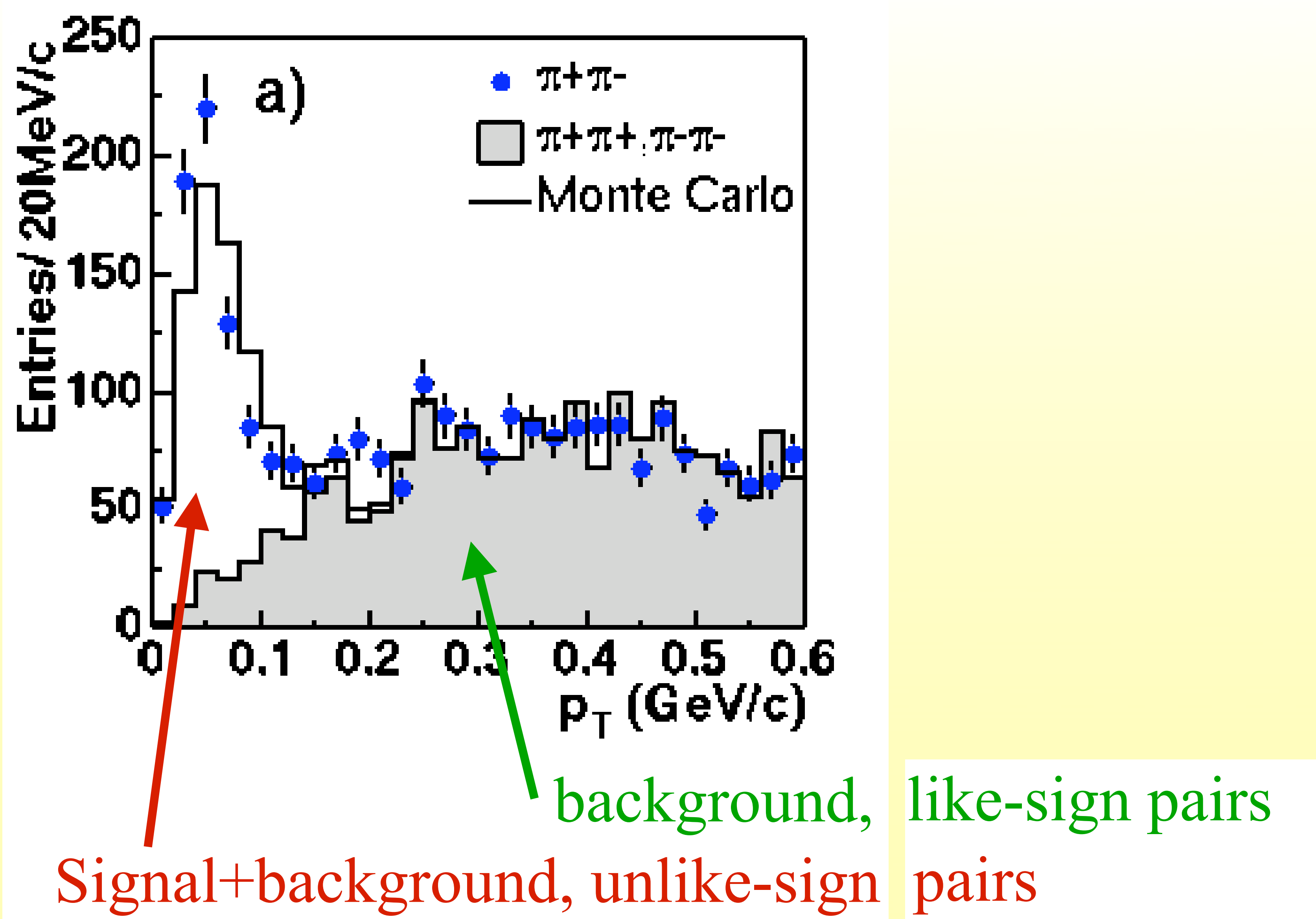
$$\frac{d\sigma(AA \to VAA)}{dy} = N_\gamma(y)\sigma_{\gamma A \to VA}(y) + N_\gamma(-y)\sigma_{\gamma A \to VA}(-y).$$

$$rapidity \quad y = \frac{1}{2}\ln\frac{E_V - p_3^V}{E_V + p_3^V} = \ln\frac{2k}{m_V}.$$

The flux of the equivalent photons $N_\gamma(y)$ is

$$N(y) = \frac{Z^2\alpha}{\pi^2}\int d^2b\Gamma_{AA}(\vec{b})\frac{1}{b^2}X^2[K_1^2(X) + \frac{1}{\gamma}K_0^2(X)].$$

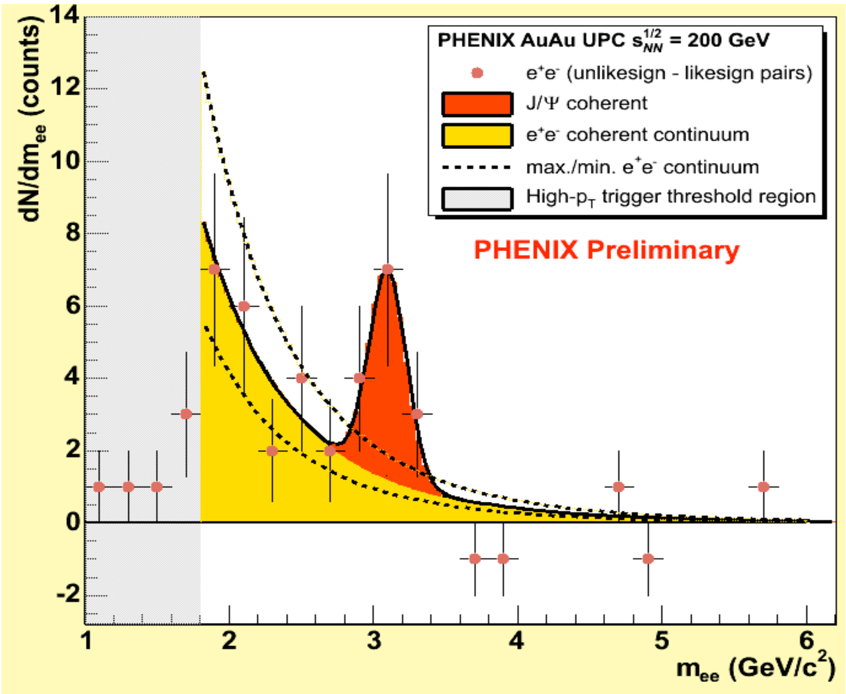
$K_0(X), K_1(X)$ – modified Bessel functions with argument $X = \frac{bm_V e^y}{2\gamma}$, γ is Lorentz factor and $\vec{b}$ is the impact parameter.



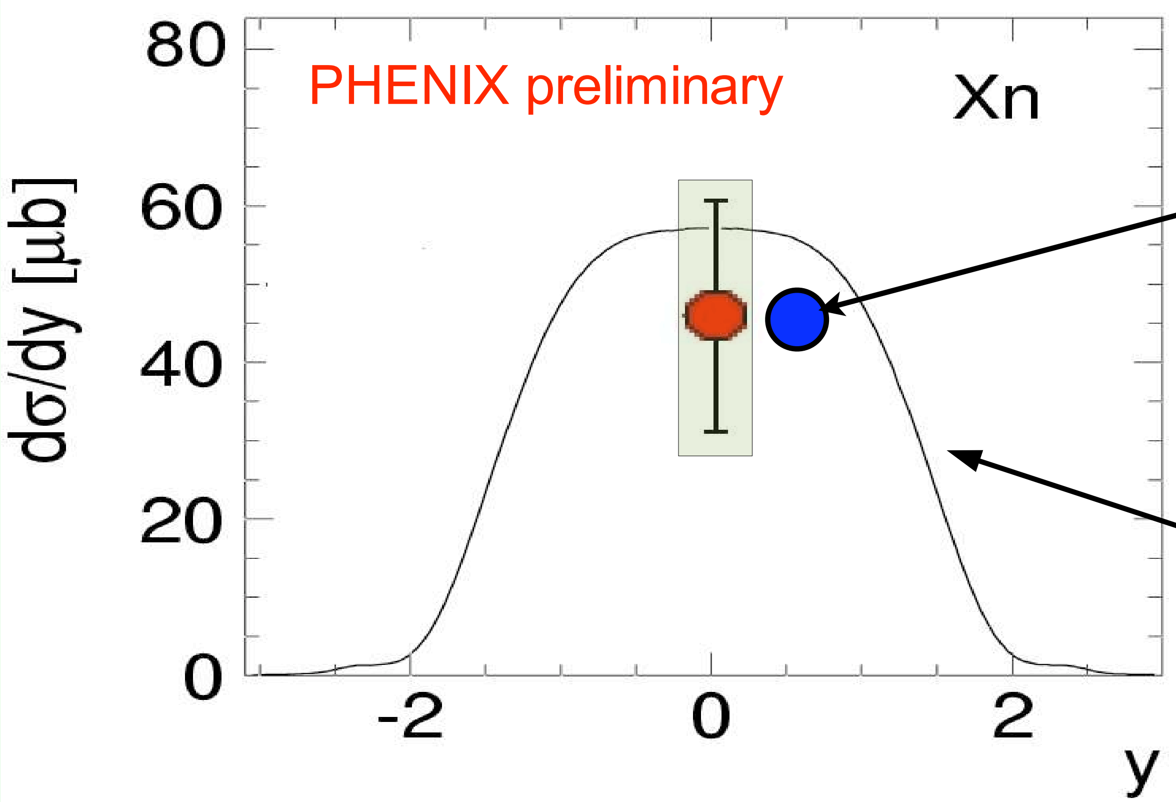
The first data from STAR (RHIC) (S.Klein group). Analysis can be done using vector dominance model coupled with the Glauber model (corrections are small for heavy nuclei)

$\longrightarrow$ reaction tests understanding of the UPC picture: $\sigma_{coh}^{th} = 490$ mb (Frankfurt, Zhalov, MS) to be compared to the STAR value $\sigma_{coh}^{exp} = 370 \pm 170 \pm 80$ mb.

dN/dm_{ee} (background subtracted) w/ fit to (MC) expected dielectron continuum and J/Ψ signals:



$d\sigma_{J/\psi}/dy|_{y=0}$ = 44 ± 16 (stat) ± 18 (syst) μb

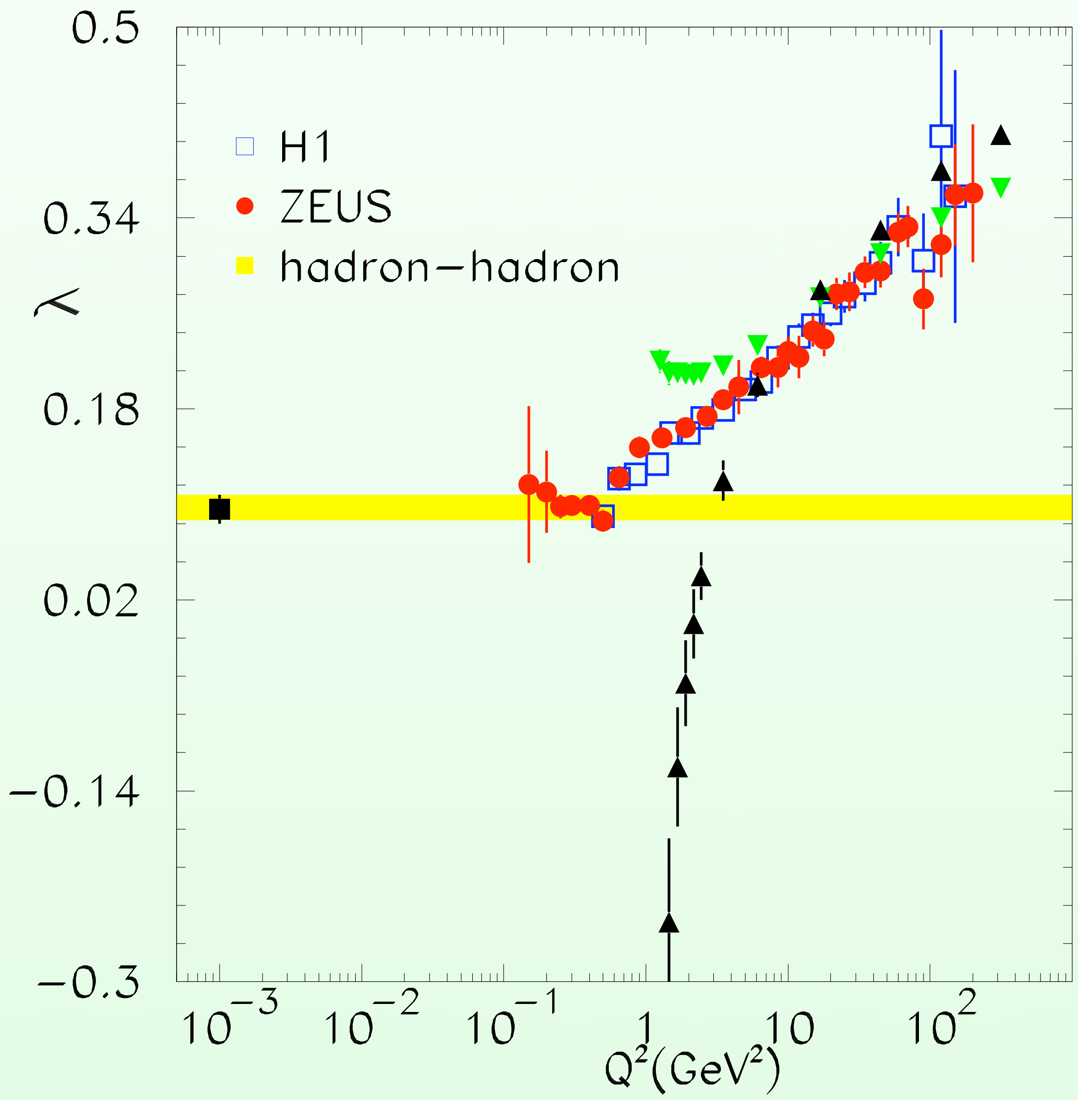


MS, Tverskoy, Zhalov - coherent + quasielastic, σ_{eff} (J/ψ N)=3 mb

Nystrand, coherent

Does something beyond DGLAP happens at HERA?

I see three pieces of evidence that interaction reach maximal strength for the gluon sector:



NLO Fits by ZEUS:

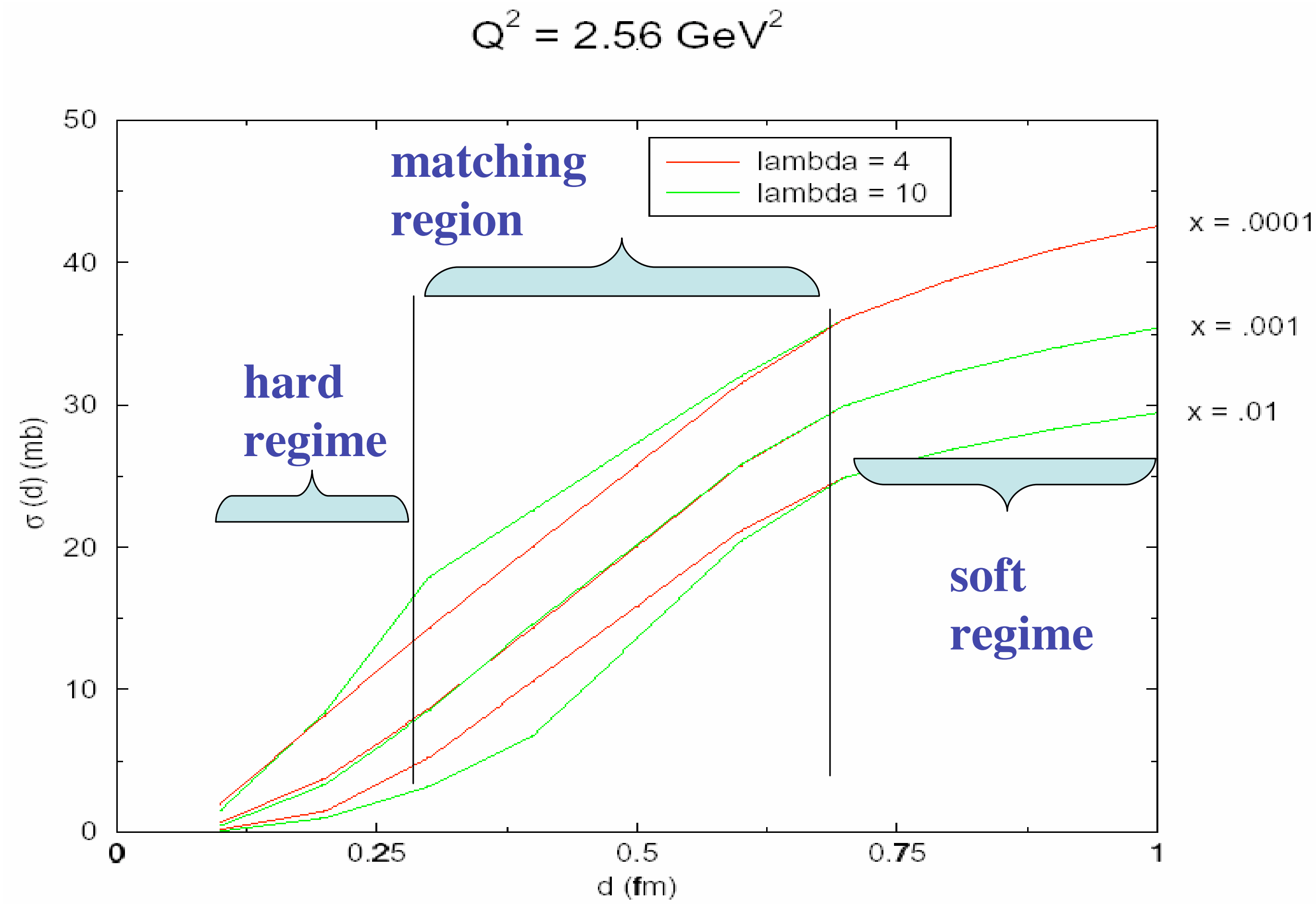
▼ $x\bar{q}(x,Q^2) \propto x^{-\lambda}$

□ ● $F_{2p}(x,Q^2) \propto x^{-\lambda}$

▲ $xg(x,Q^2) \propto x^{-\lambda}$

Combine:

studies of the dipole quark-antiquark-nucleon cross section based on HERA data

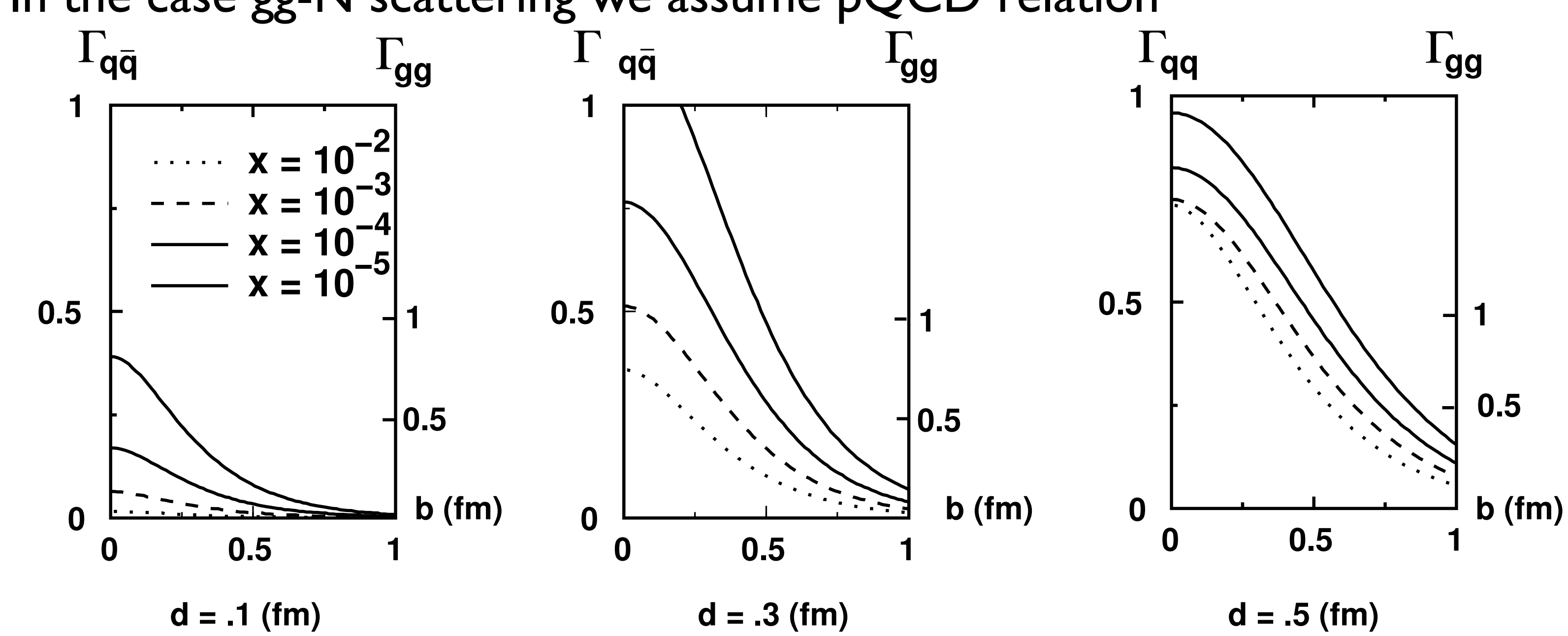


and the exclusive hard processes we can also estimate t-dependence of the elastic dipole-nucleon scattering and hence

estimate impact factors for $q\bar{q} - N\, scattering$ $\Gamma_h(s,b) = \frac{1}{2is}\frac{1}{(2\pi)^2}\int d^2\vec{q}e^{i\vec{q}\vec{b}}A_{hN}(s,t)\,;\;\; ImA = s\sigma_{tot}\exp(Bt/2)$

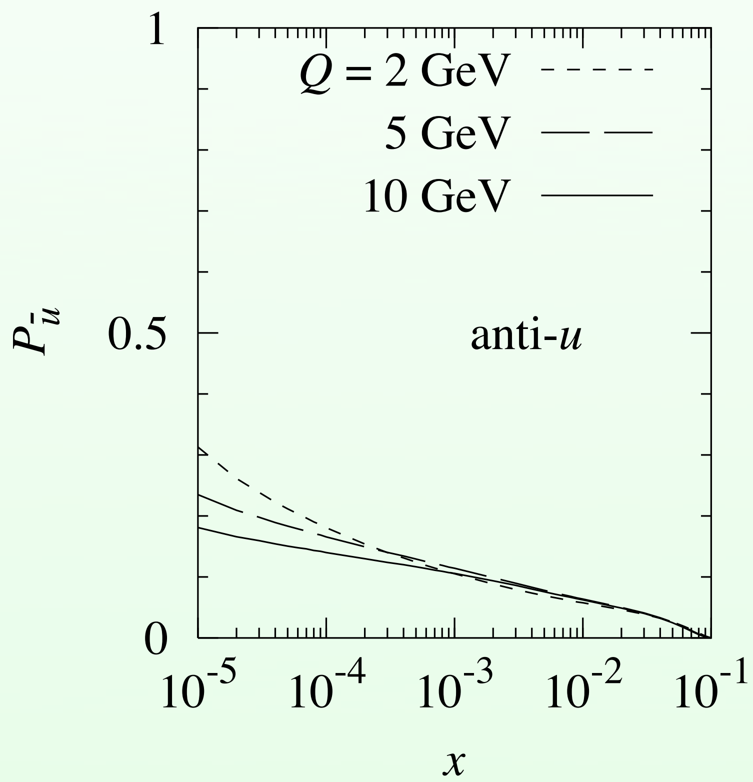
$\Gamma = 1$ *corresponds to the black disk limit = BDL -complete absorption* $\Gamma_{gg} = \frac{9}{4}\Gamma_{q\bar{q}}$

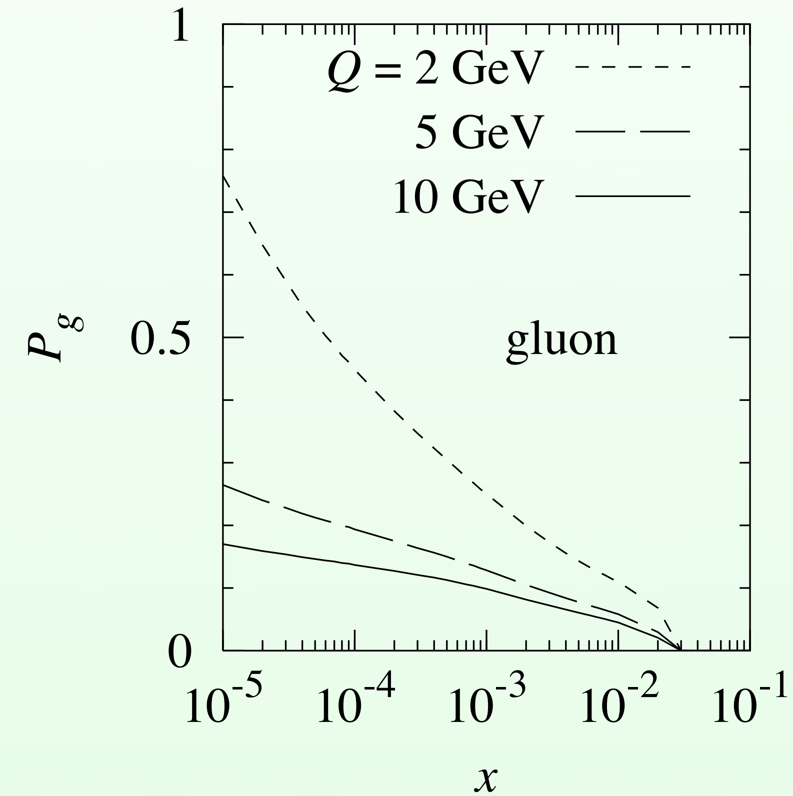
In the case gg-N scattering we assume pQCD relation



gg -N interaction seems close to BDL for Q^2~4 GeV^2, x~10^{-4}

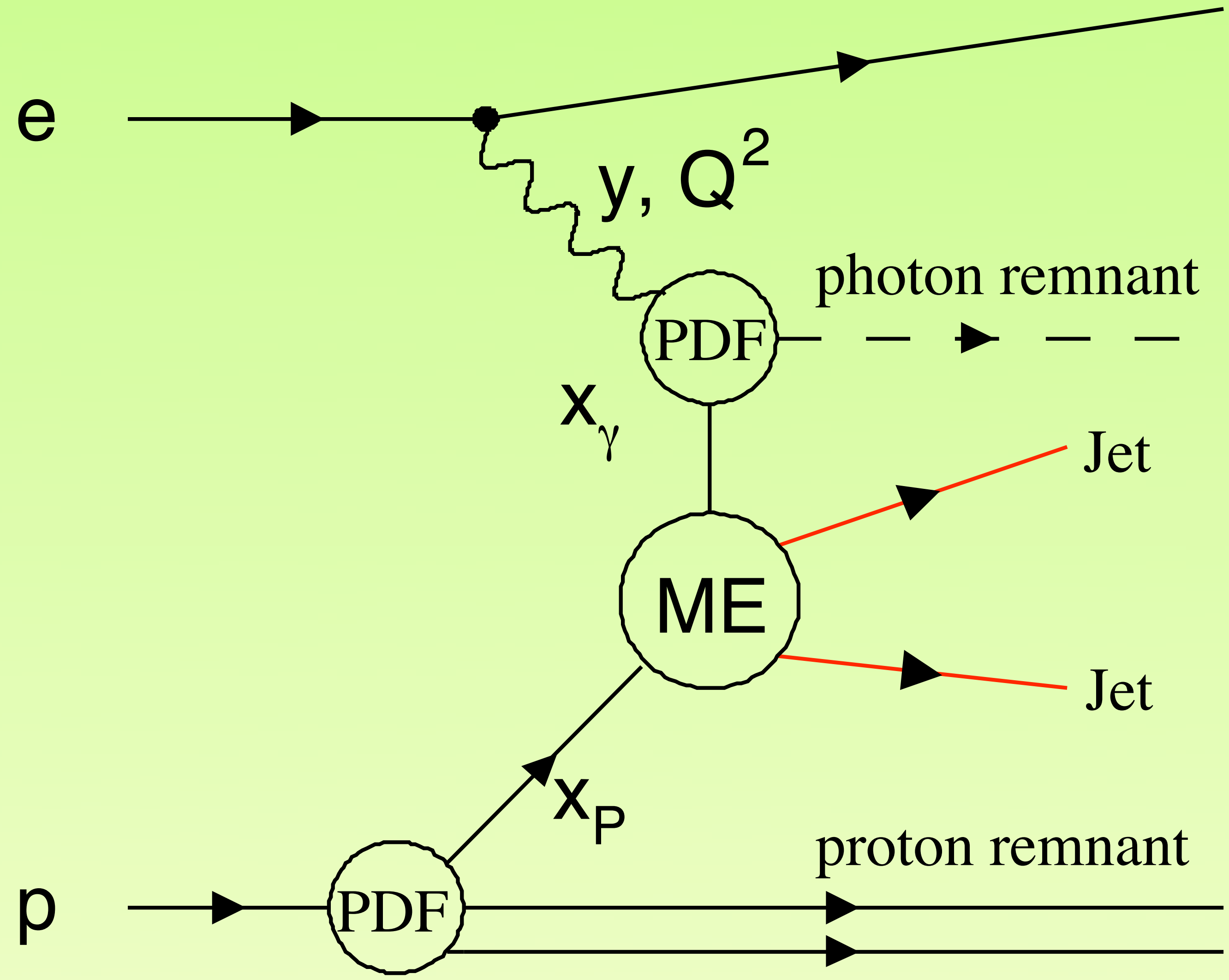
- Interactions where a hard probe directly couples to gluons at $Q^2 \sim 4\ GeV^2, x \sim 10^{-4}$ lead to diffractive final states with a probability, P_g close to 1/2- that is strength close to the unitarity limit (FS89)





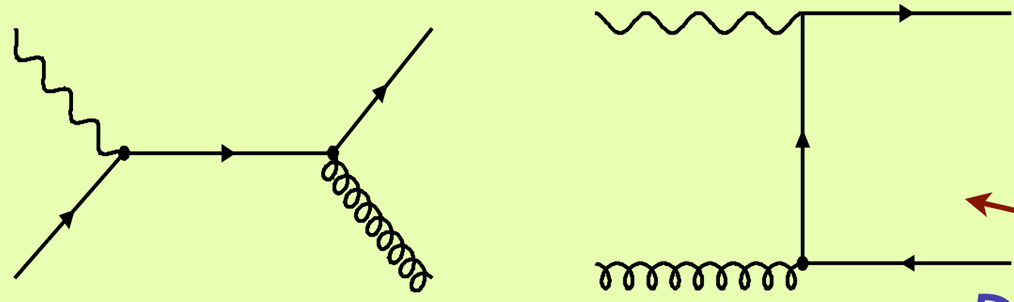
Another lesson from HERA

Real photon was effectively used for the QCD studies



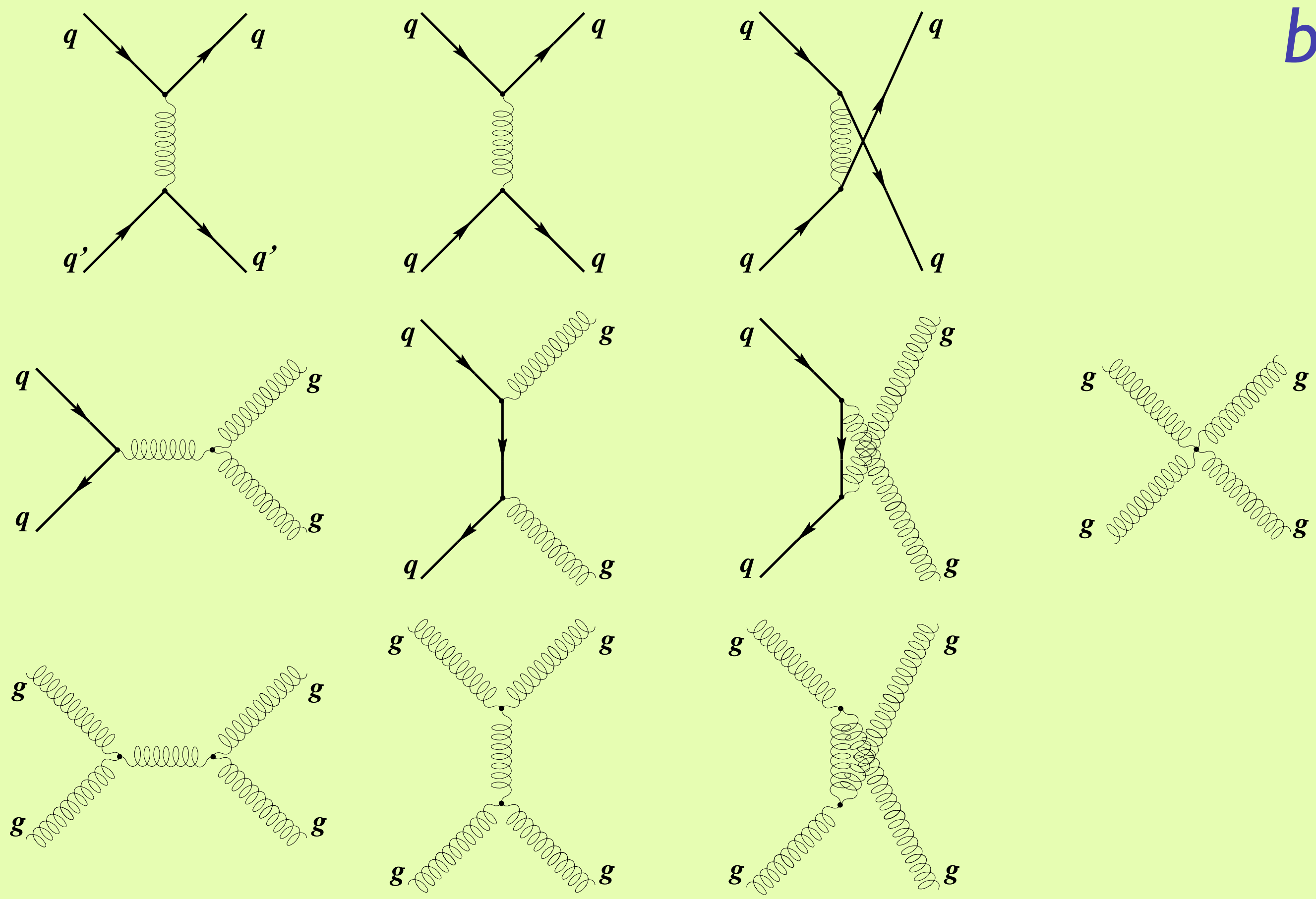
Schematic view of dijet production in ep *scattering studied at HERA*

x_γ *and* x_p *are light cone fractions of partons of photon and proton*



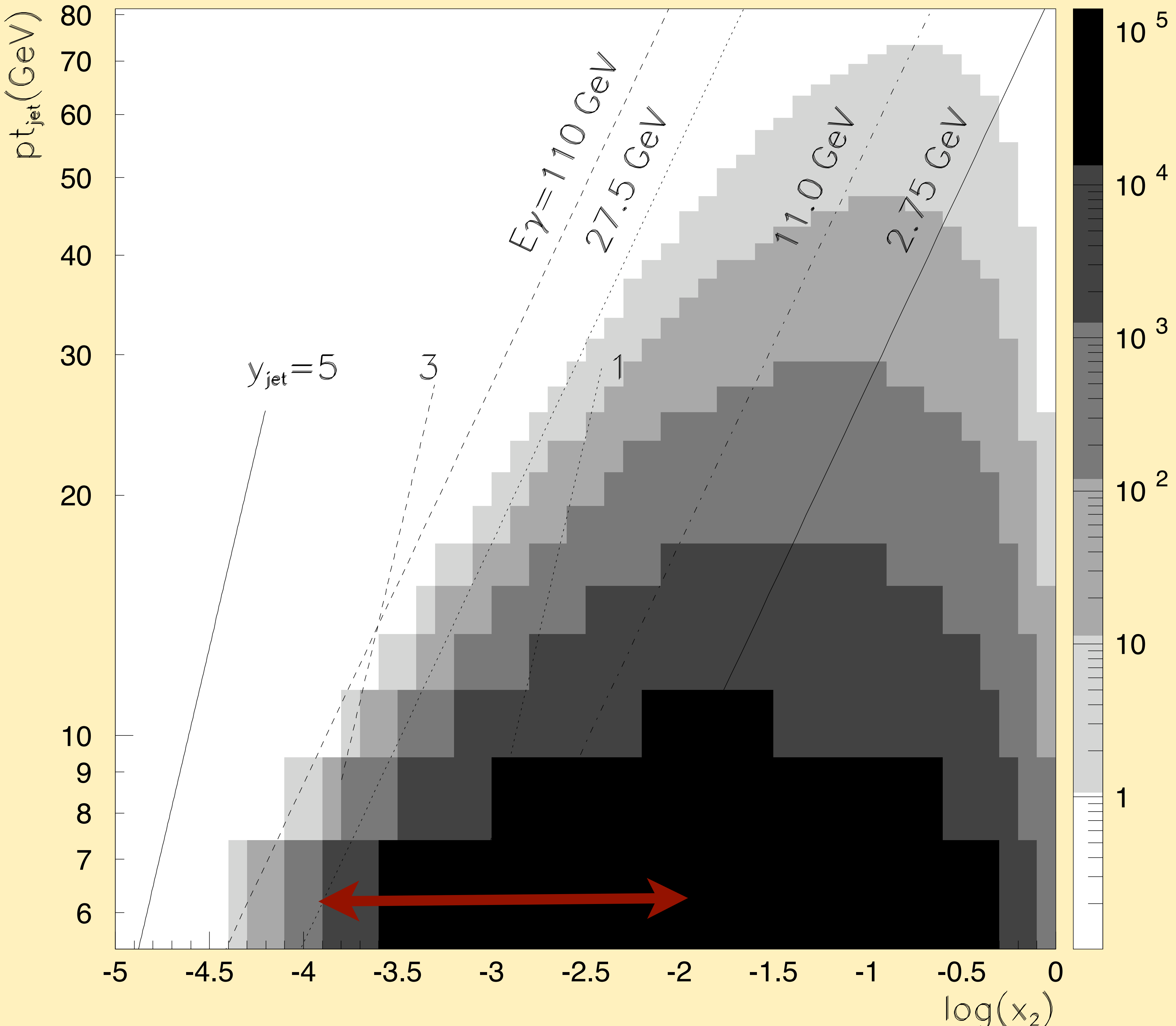
LO diagrams for direct photon: $x_\gamma = 1$

Dominant diagram for small x_p dominated by the nucleon gluon density



LO diagrams for resolved photon: $x_\gamma < 1$

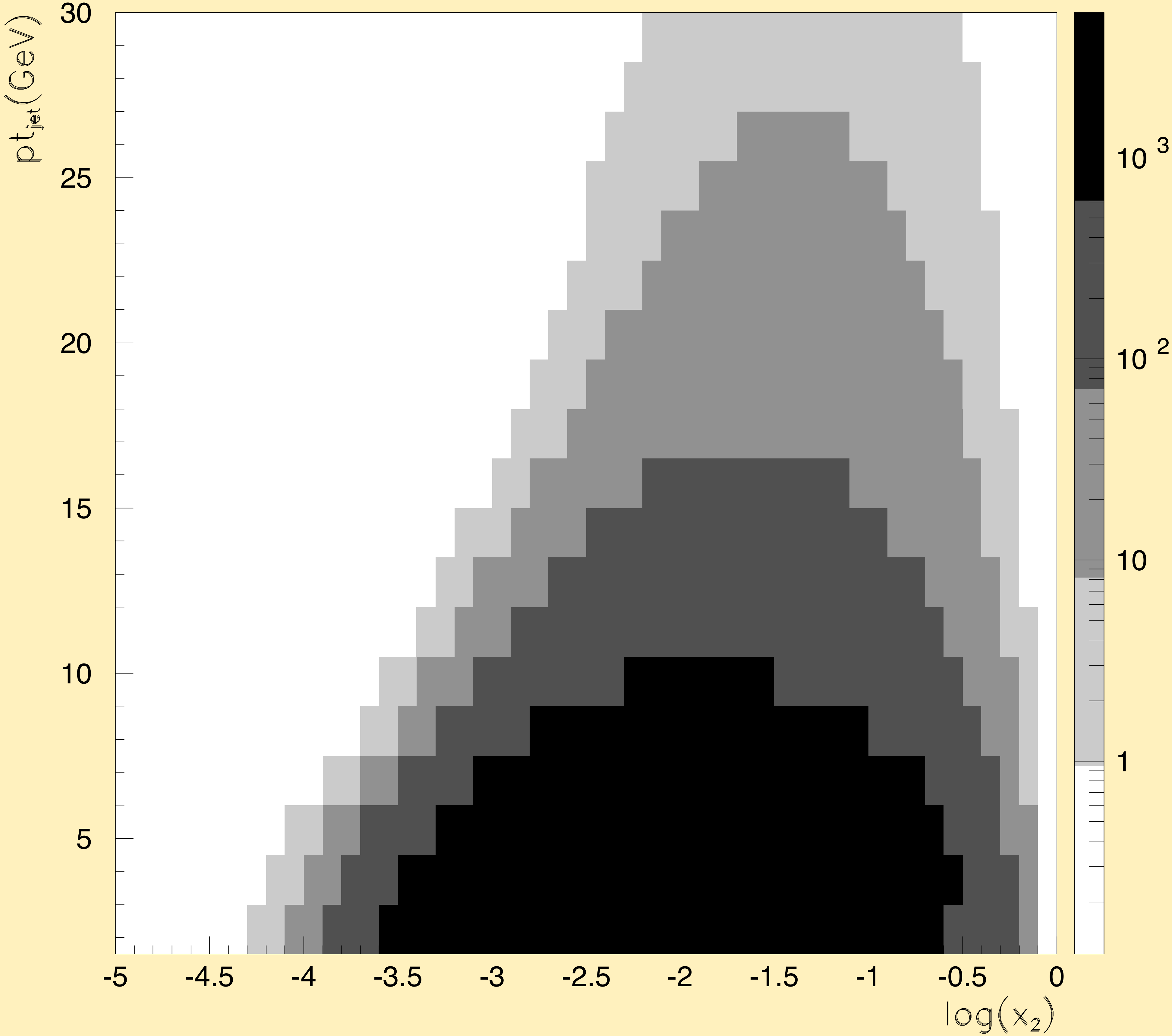
NLO is important - no separation between direct and resolved mechanisms - recently important theoretical progress - new MC codes are expected to be available soon.



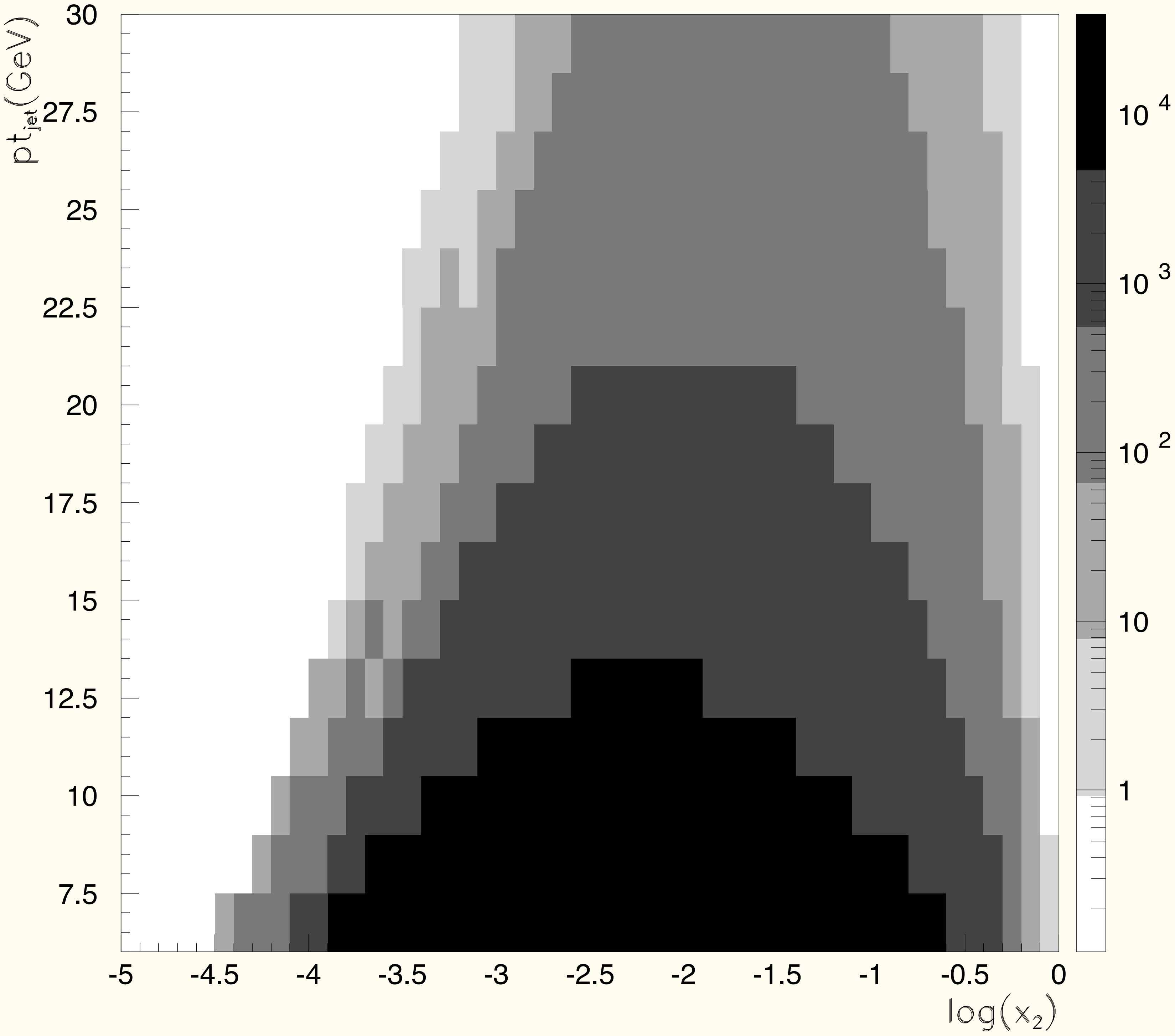
Expected rate of dijet photoproduction for a 1 month LHC Pb+Pb run at 0.4×10^{27} $cm^{-2}s^{-1}$. Rates are counts per bin of ±0.25 x_2 and 2 GeV/c in p_T.

R. Vogt, S. White, MS

Study of x_2 dependence of jets at moderate p_t over two decades in x - high gluon densities will be signaled by taming of the x-dependence.



Rate for b-quark photoproduction. The same as for dijets but p_T bins are 1.5 GeV/c



Expected rate for b-quark photoproduction in a one month LHC pPb run with at 7.4×10^{29} $cm^{-2}s^{-1}$.

Nonlinear effects: AA UPC at LHC vs HERA and eRHIC

The parameter to compare is:

(gluon density/unit area) $*$ (strength of interaction)

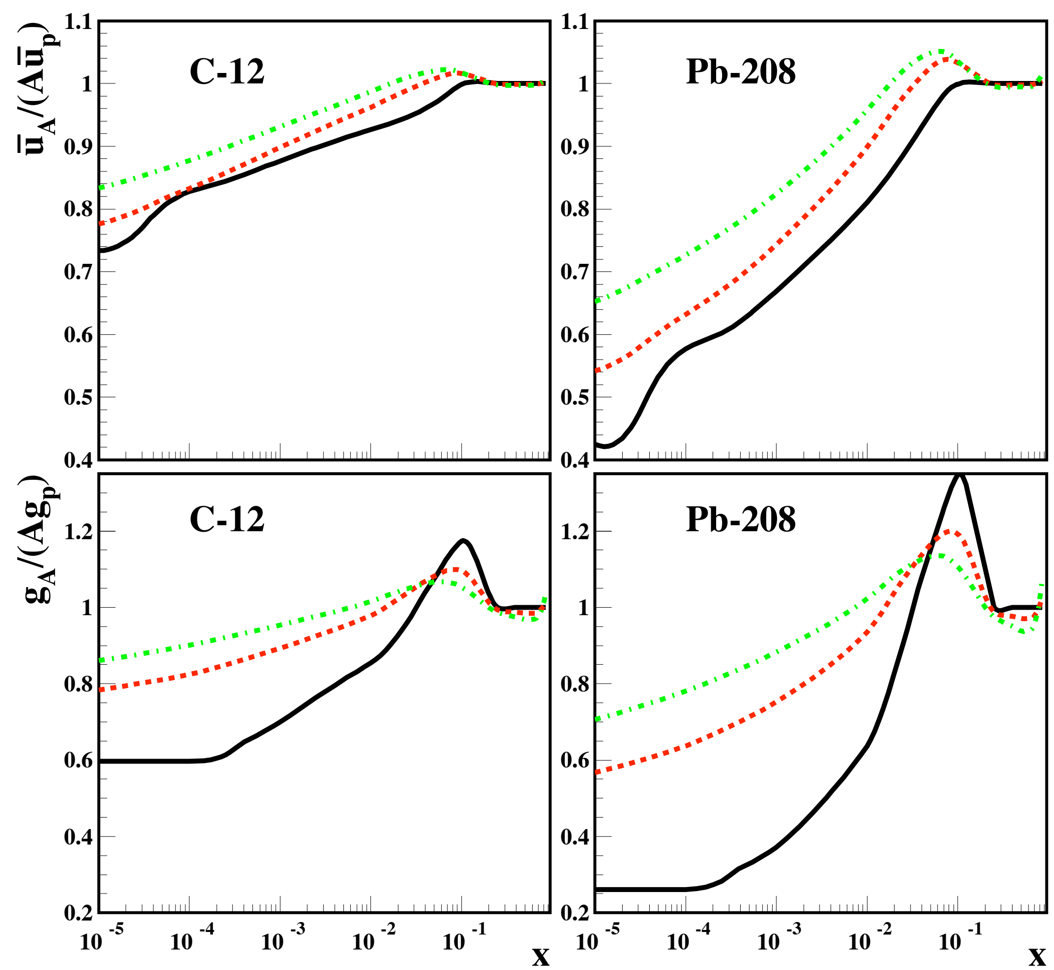
$$\frac{C\alpha_s(Q^2)xG(x,Q^2)}{Q^2 \, "area"} \qquad where\ C_g \approx 9/4C_q$$

LHC vs ep HERA $$\frac{(9/4)0.7\,A^{1/3}\alpha_s(p_T^2)xg(x\sim 5\times 10^{-5},p_T^2)/p_T^2}{\alpha_s(Q^2)xg(x\sim 10^{-4},Q^2)/Q^2} \sim 3\ .$$

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.*

LHC vs eRHIC: eA at Q=2, x=10^{-3} the gain: a factor of 1.5

In the region of transverse momenta where leading twist dominates (if we assume $p_t > 10$ GeV → $x \geq 2 \cdot 10^{-4}$) it will be possible to measure $G_A(x,p_t)$ in nuclei and hence check whether leading twist gluon shadowing is significant for large virtualities. If it is on the level expected in the leading twist calculations of Guzey et al (~ a factor of two suppression) measurements certainly will be doable. Effect can be further enhanced with centrality trigger.



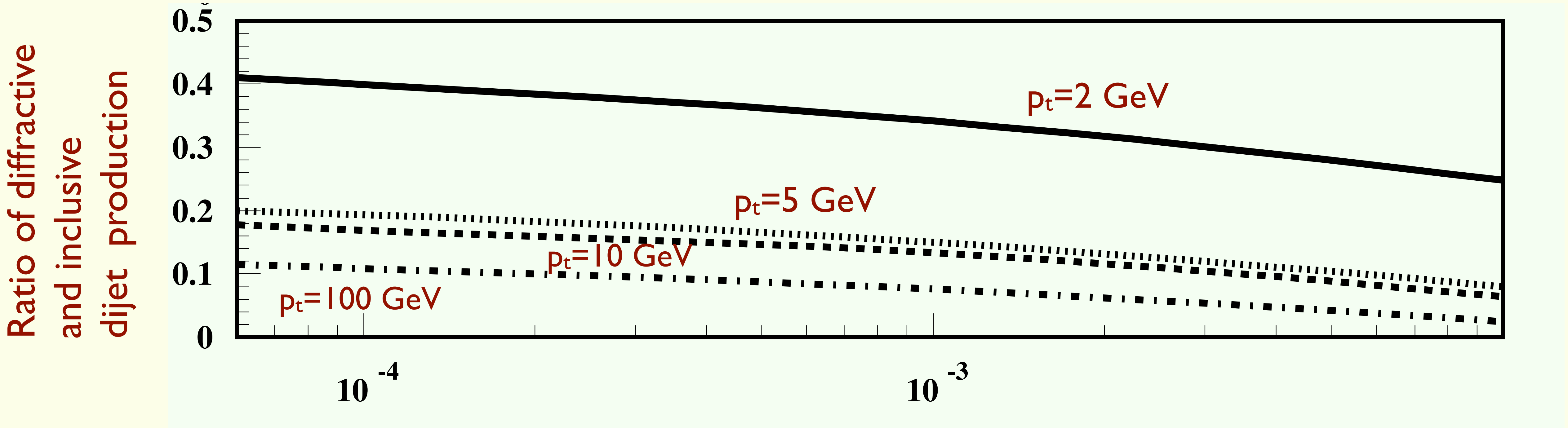
Dependence of G_A/AG_N and $\bar{q}_A/A\bar{q}_N$ on x for Q=2 (solid), 10 (dashed), 100 GeV (dot-dashed) curves calculated using diffractive parton densities extracted from the HERA data, the quasieikonal model for $N \geq 3$, and assuming validity of the DGLAP evolution.

Another critical measurement is hard diffraction:

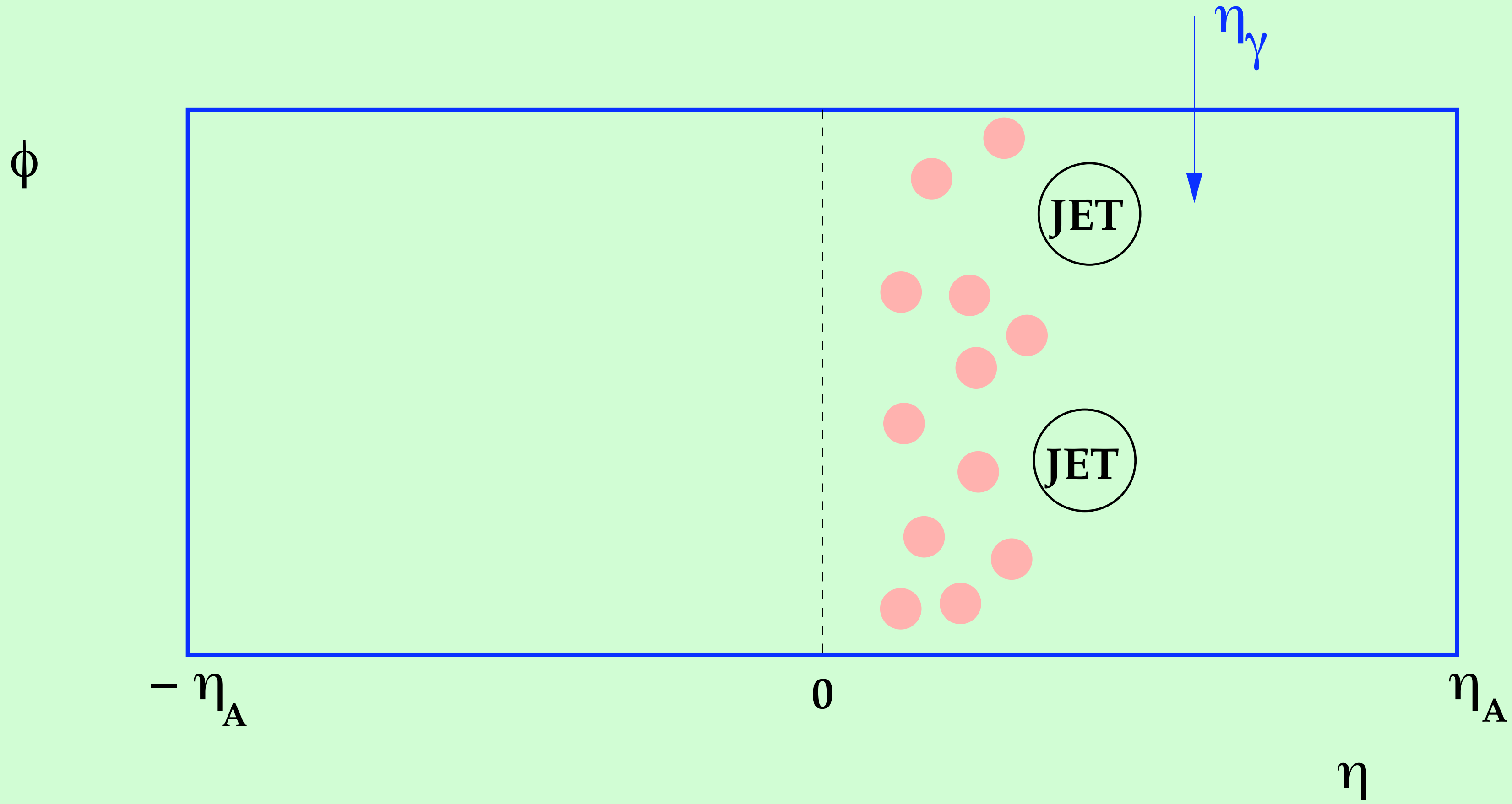
$\gamma A \rightarrow jet_1 + jet_2 + X + A$ for direct photon: $\beta \approx 1$

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

Nuclear diffractive pdfs were calculated by Guzey et al 03 in the same approximations as LT nuclear pdf's (no model necessary for double rescattering provided HERA diffraction data are used)



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



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

Studies of exclusive photoproduction processes:

Hard physics:

- Onium production (coherent A) and incoherent (nucleus break up)
- Diffraction into two, three jets
- Onium (ρ) production at large p_t with rapidity gaps

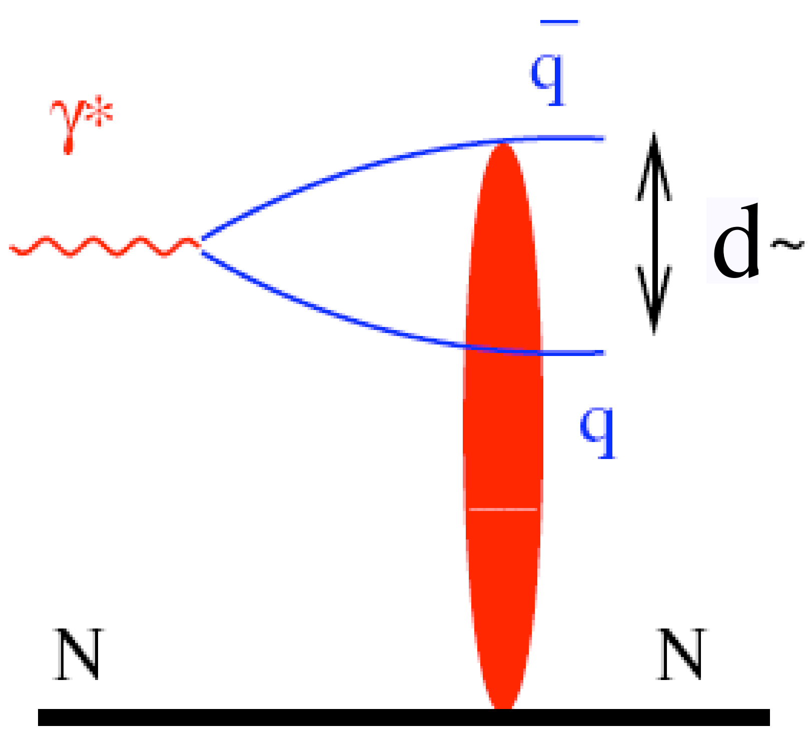
Soft (Pomeron) physics:

- Energy dependence of production of ρ,φ-mesons

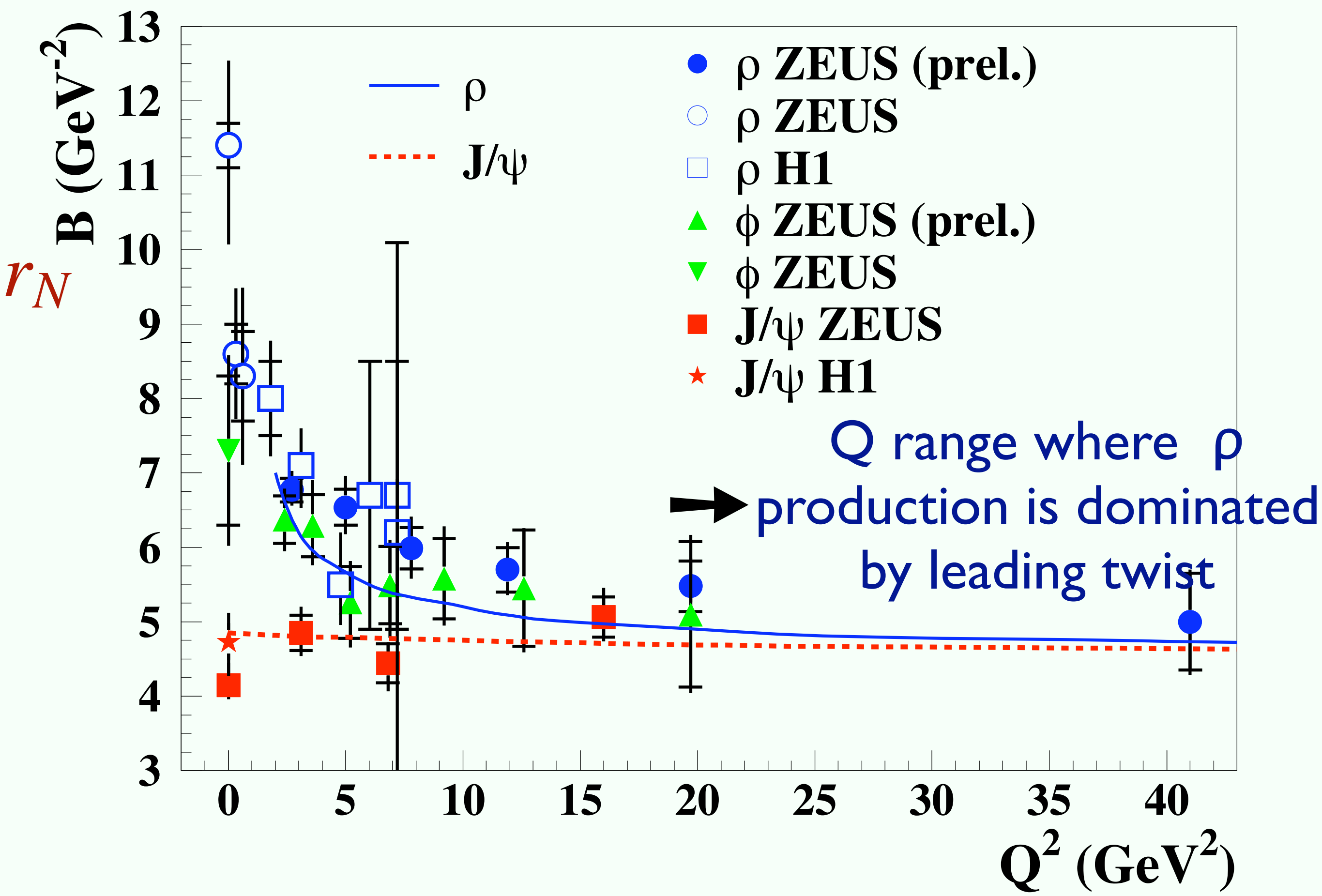
- General consensus - J/psi photoproduction is dominated by scattering of small dipoles - key test : universality of t-slopes

t-dependence is predominantly due to the transverse spread of the gluons in the nucleon - two gluon nucleon form factor,

Onset of universal regime FKS[Frankfurt,Koepf, MS] 97.

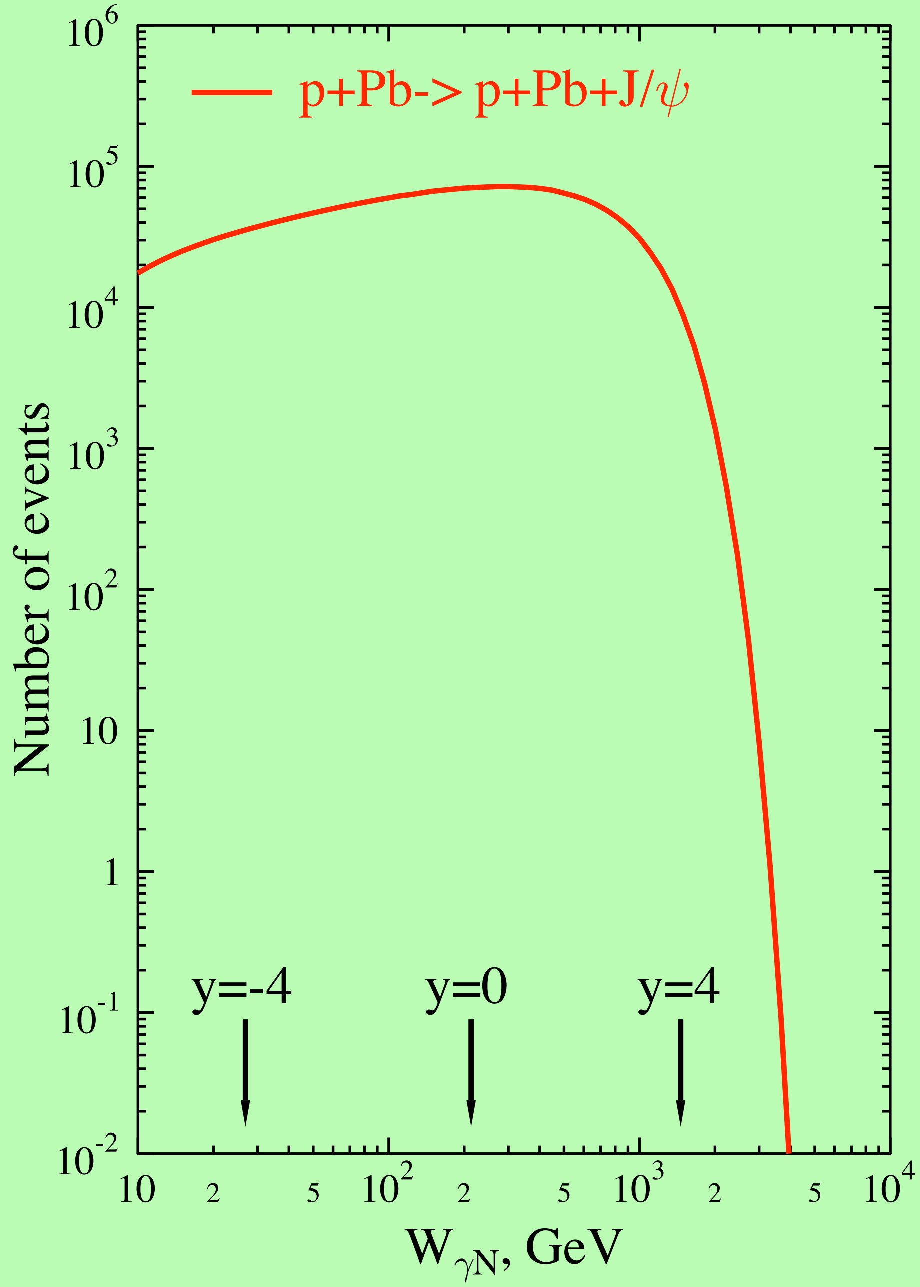


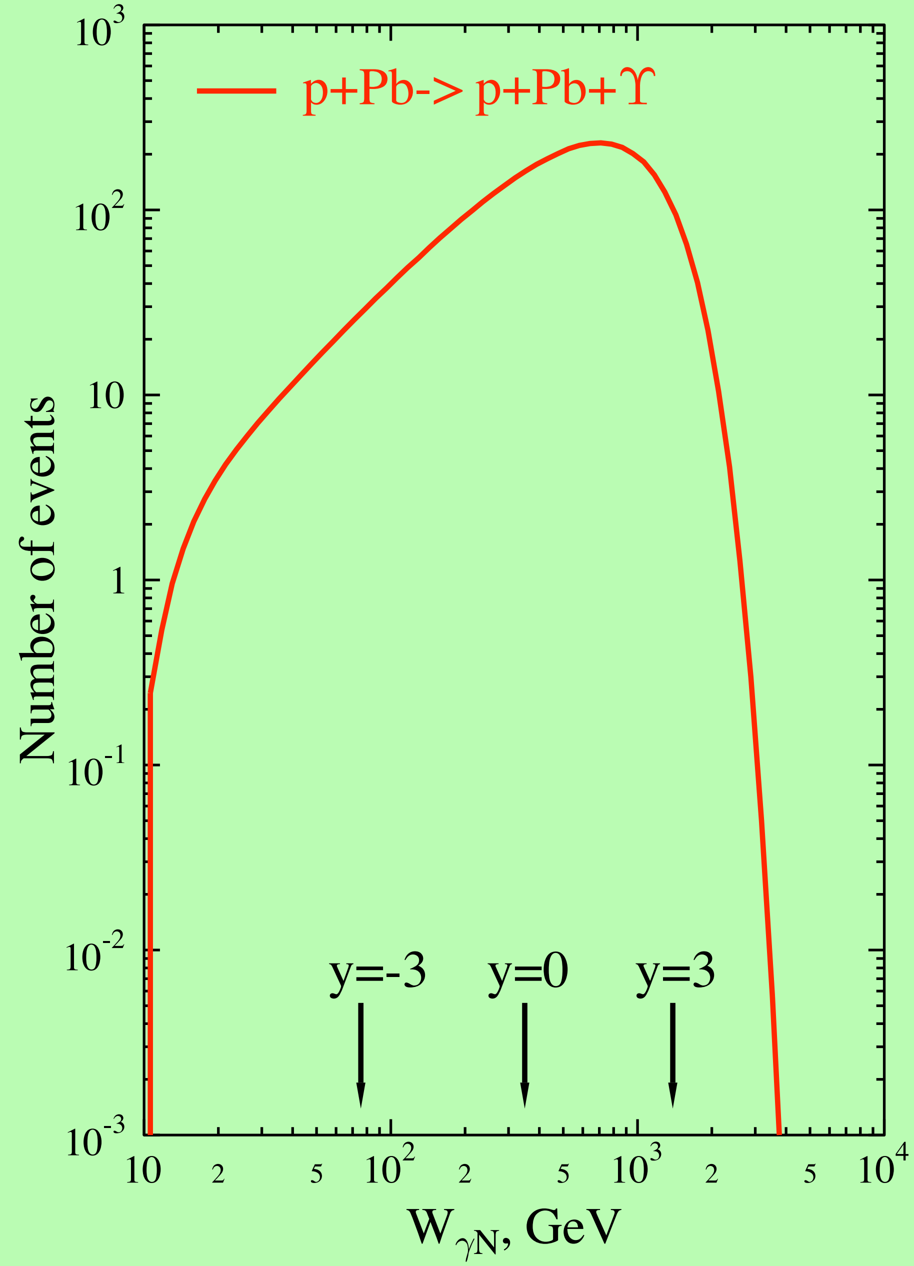
$$d \sim r_T \propto \frac{1}{Q}\left(\frac{1}{m_c}\right) \ll r_N$$



Convergence of the t-slopes, B ($\frac{d\sigma}{dt} = A\exp(Bt)$), of ρ-meson electroproduction to the slope of J/psi photo(electro)production.

⇒ Transverse distribution of gluons can be extracted from $\gamma + p \to J/\psi + N$





The rates per unit rapidity were calculated assuming Yellow report lumi . Number of events is for one dilepton mode.Sufficient to check pQCD prediction of $\sigma \sim W^{1.6}$ Upsilon production and determination of the t-slope provided protons could be detected.

❑ *Exclusive onium production*

AA collisions - one can reach $W_{\gamma N} = \sqrt{4E_N m_V}$ *due to the dominance of photons with smaller energy.* $\longrightarrow x_{min}(J/\psi) = 0.0005, x_{min}(\Upsilon) \sim 0.0015$.

The nuclear Coulomb induced dissociation occurs at small impact parameters. At the same time in such events the photon spectrum is harder. (Can be used enhanced contribution of hard photons)Baltz, Klein Nystrand, 02. (Price a factor of 10 reduction in counting rate). Allows to extend measurements for J/ψ *case to* $y \sim 2$, $\rightarrow x \sim 10^{-5}$.

Another approach - use of the break up channels - processes where nucleus emits few neutrons (Tverskoi, MS , Zhalov 05). Allows to determine which nucleus emitted the photon.

The leading twist prediction is

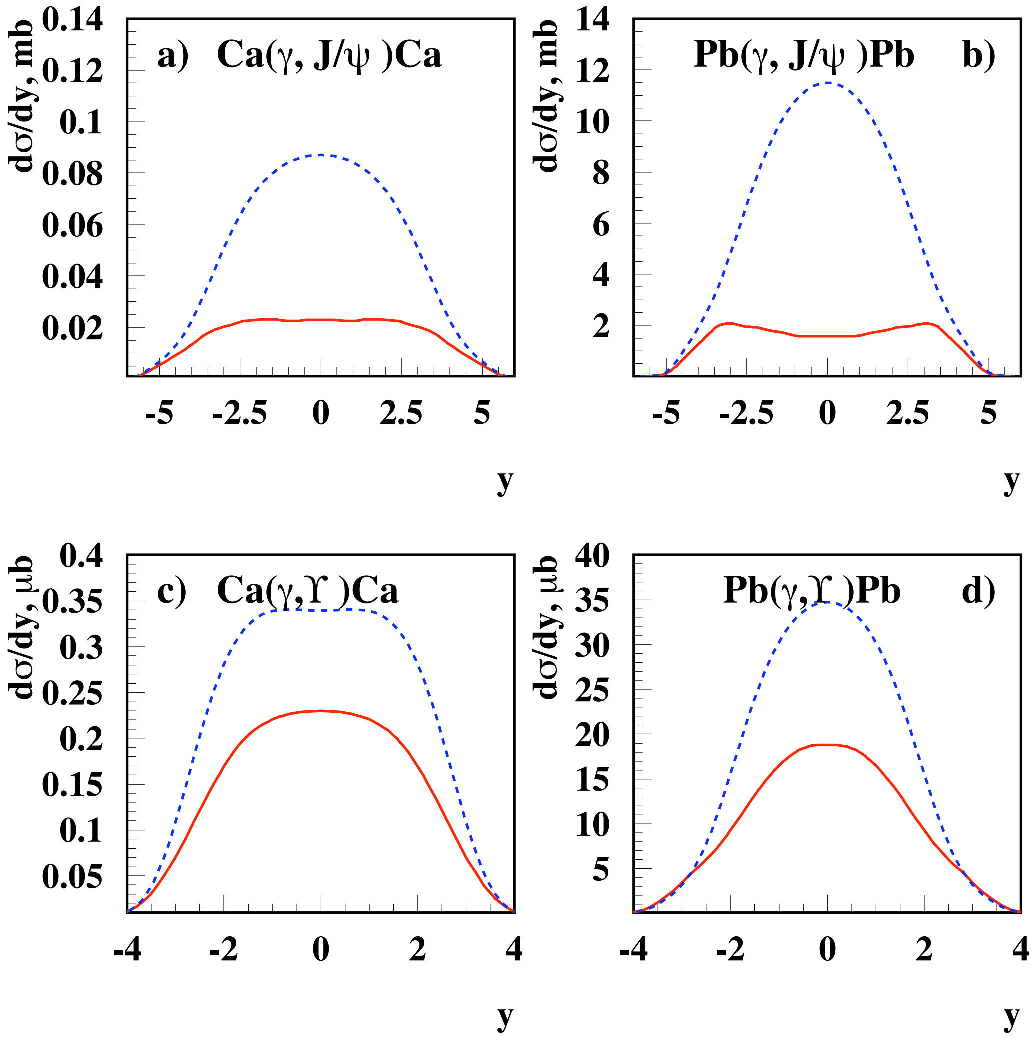
$$\sigma_{\gamma A \to VA}(s) = \frac{d\sigma_{\gamma N \to VN}(s, t_{min})}{dt} \left[\frac{G_A(x_1, x_2, Q^2_{eff}, t = 0)}{A G_N(x_x, x_2, Q^2_{eff}, t = 0)} \right]^2 .$$

$$\cdot \int_{-\infty}^{t_{min}} dt \left| \int d^2 b dz e^{i\vec{q}_t \cdot \vec{b}} e^{-q_l z} \rho(\vec{b}, z) \right|^2 ,$$

where $x_1 - x_2 = \frac{m_V^2}{s} \equiv x$.

The expectations for the BBL will be discussed later.

☛ *Onset of perturbative color opacity at small x and onium coherent photoproduction.*



The rapidity distributions for the J/ψ and Υ coherent production off Ca and Pb in UPC at LHC calculated with the leading twist shadowing based on H1 parameterization of gluon density(solid line) and in the Impulse Approximation(dashed line).

Experimental challenges: Trigger on relatively low transverse momentum leptons. Problem for J/ψ 's for $y=0$, for $y=2-4$ the ALICE study finds good rates. Acceptance for Υ is good in a wide rapidity range. No studies so far for other detectors. CMS seems more optimistic for $y=0$ coherent J/ψ.

Another important process to study Pomeron dynamics:

$$\gamma + A(p) \to \rho\ (J/\psi)(p_t > 1\ \text{GeV}) + \text{"rapidity gap"} + X$$

Issues:
- rapidity dependence - from soft to hard Pomeron,
- A-dependence - onset of color transparency

Conclusions

Studies of UPC at LHC will be able to use most of the probes of small x dynamics available at HERA

- ★ *Small x physics with protons and nuclei in* ***a factor of ten*** *larger energy range though at higher virtualities both in inclusive and diffractive channels*
- ★ Interaction of small dipoles at ultrahigh energies - approach to regime of black body limit, color opacity
- ★ Larger nonlinearity reach than eRHIC
- ★ Low Q< 4 GeV will be mostly missed (relevant for RHIC kinematics)- will require studies at eRHIC