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Probing small x QCD in ultraperipheral collisions at LHC

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HERA III at LHC

Mark Strikman, PSU

Based on the analyses performed together with

L.Frankfurt, V.Guzey, R.Vogt, C.Weiss, S.White, M.Zhalov

Trieste, May 23, 2006

Outline

- Introduction: What is UPC, why it is doable and why small x are interesting
- Lessons & questions from HERA
- Lesson from dA at RHIC
- What can be measured/discovered at LHC in UPC

Our study group is finishing work on the CERN Yellow report on UPC

Main thrusts of the HERA small x QCD physics:

- Small x parton densities
- Inclusive hard diffractive processes
- Hard exclusive processes: vector meson production, dijets, ...

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

• Crucial for understanding the structure of the underlying events in *central* pp collisions at LHC (the only collisions contributing to the new particle production) F & S & Weiss 03:

A parton with a given x_1 *and resolution* p_t *is sensitive to partons in another nucleon with*

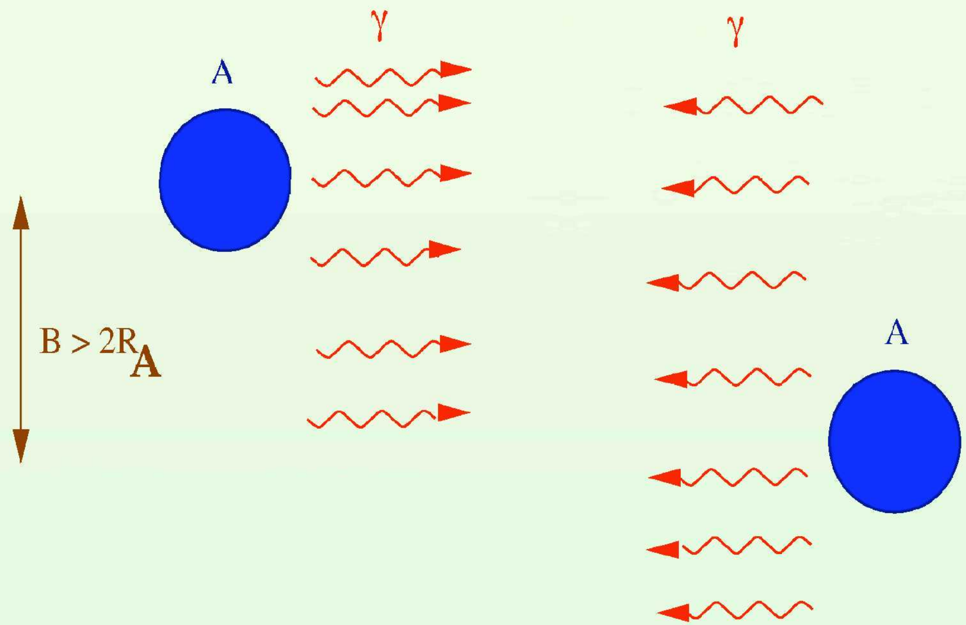
$$x_2 = \frac{4p_t^2}{s_{NN}x_1}$$

At LHC for $x_1 = 0.01, p_t = 2\text{GeV/c}$, $x_2 \sim 10^{-5}$!!.

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

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



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 - $pA, \& AA$

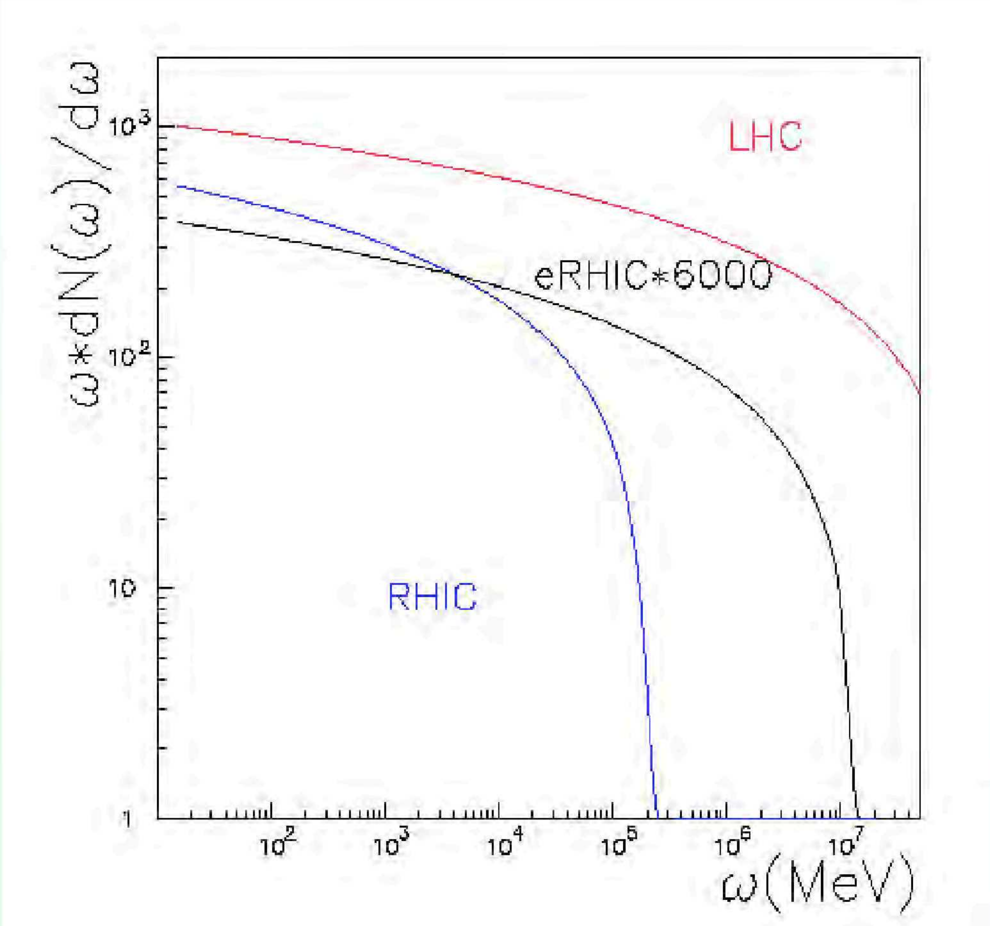
Counting rates are large up to

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

Note - for exclusive coherent exclusive diffraction in AA (but not in pA) cannot move beyond y=0 as cannot distinguish which of two nuclei emitted a photon.

Feasibility for ρ and J/ψ exclusive production was demonstrated at RHIC - see David d'Enterria's talk.

Equivalent Photon spectrum in target nucleus frame



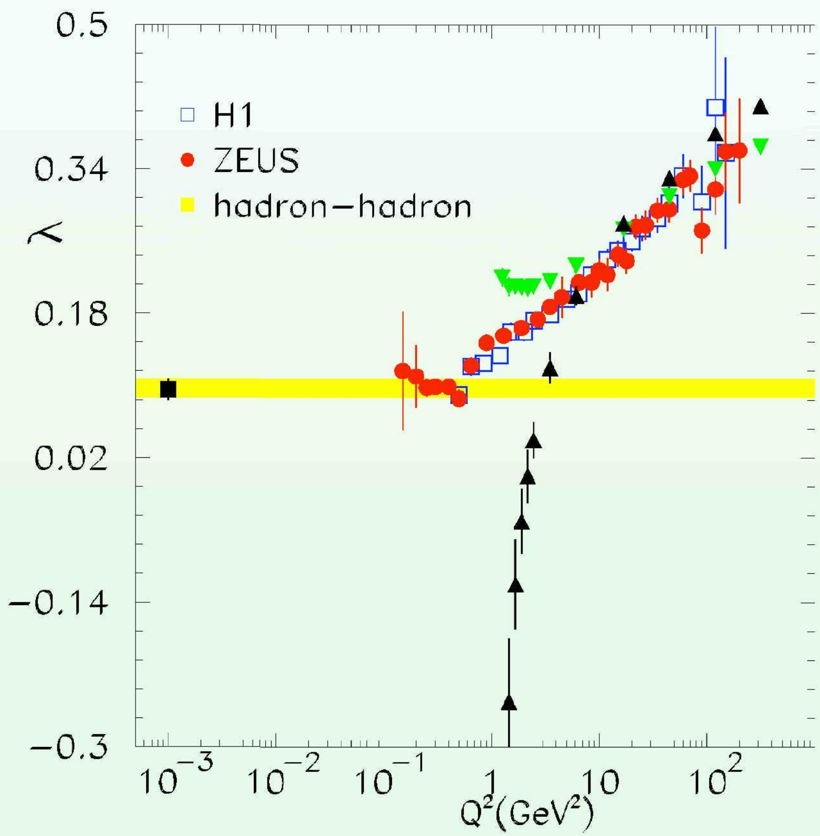
“Quasi-real” γ spectra compared to an e-hadron collider

->100 TeV @ LHC

Lessons from HERA

Something beyond DGLAP is happening at HERA

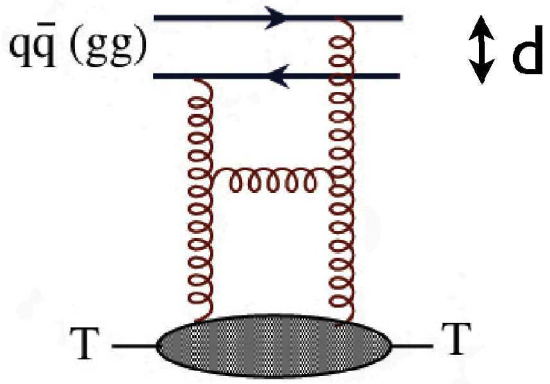
we find three pieces of evidence that interaction reach maximal strength for the gluon sector:



NLO Fits by ZEUS:

- ▼ $x\bar{q}(x,Q^2) \propto x^{-\lambda}$
- □ ● $F_{2p}(x,Q^2) \propto x^{-\lambda}$
- ▲ $xg(x,Q^2) \propto x^{-\lambda}$

Strength of interaction for a small color dipole with hadron



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

Baym et al 93

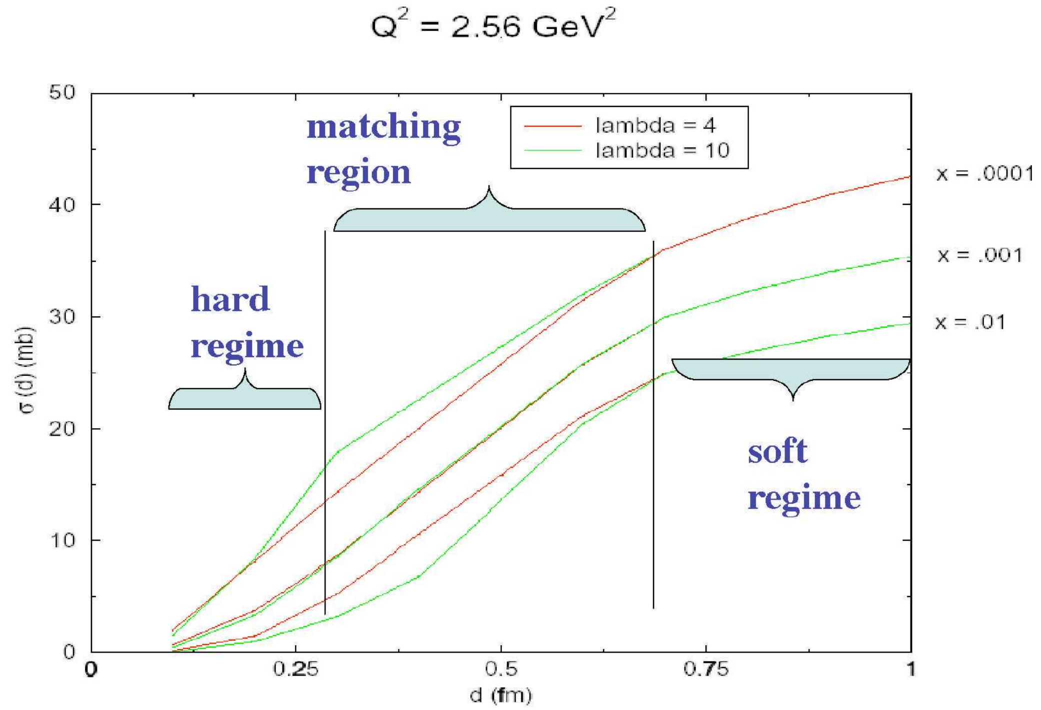
F^2 Casimir operator of color SU(3)

F^2 (quark) =4/3 F^2 (gluon)=3

Comment: This simple picture is valid only in LO. NLO would require introducing mixing of different components.

Combine:

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

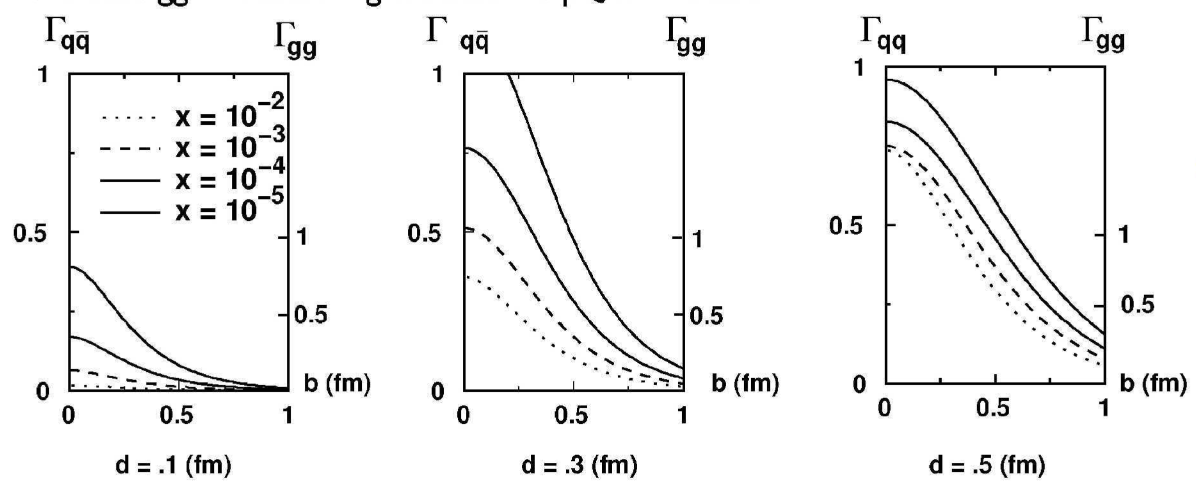


and the exclusive hard processes we can also estimate t-dependence of the elastic dipole-nucleon scattering and hence

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

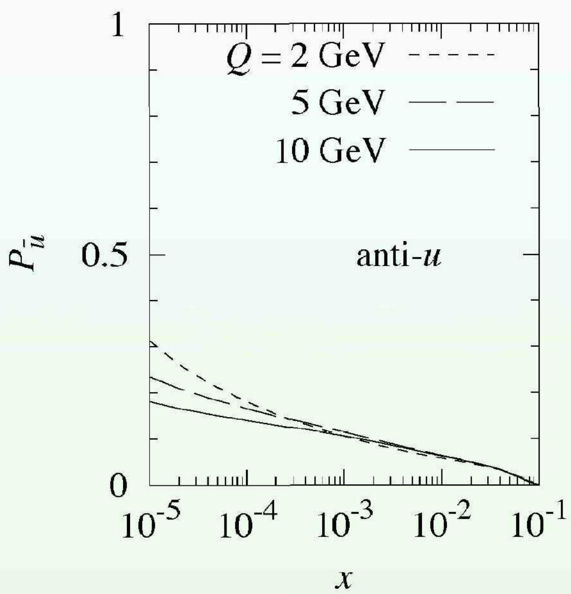
$\Gamma = 1$ *corresponds to the black disk limit = BDL -complete absorption* $\Gamma_{gg} = \frac{9}{4}\Gamma_{q\bar{q}}$

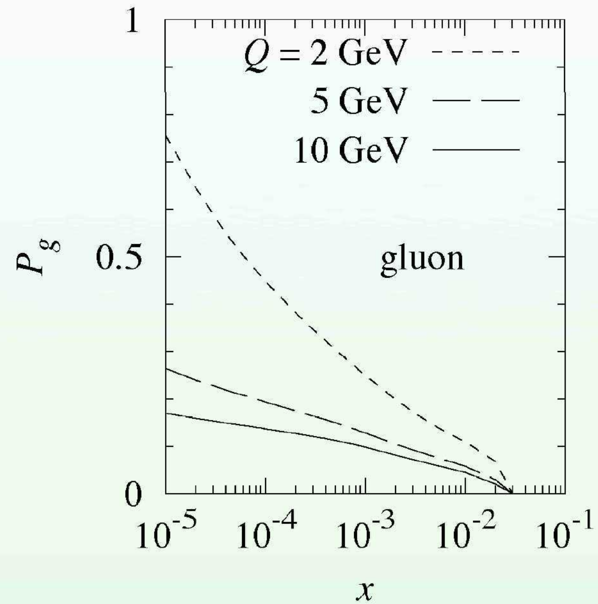
In the case gg-N scattering we assume pQCD relation



gg -N interaction seems close to BDL for $Q^2 \sim 4$ GeV², $x \sim 10^{-4}$

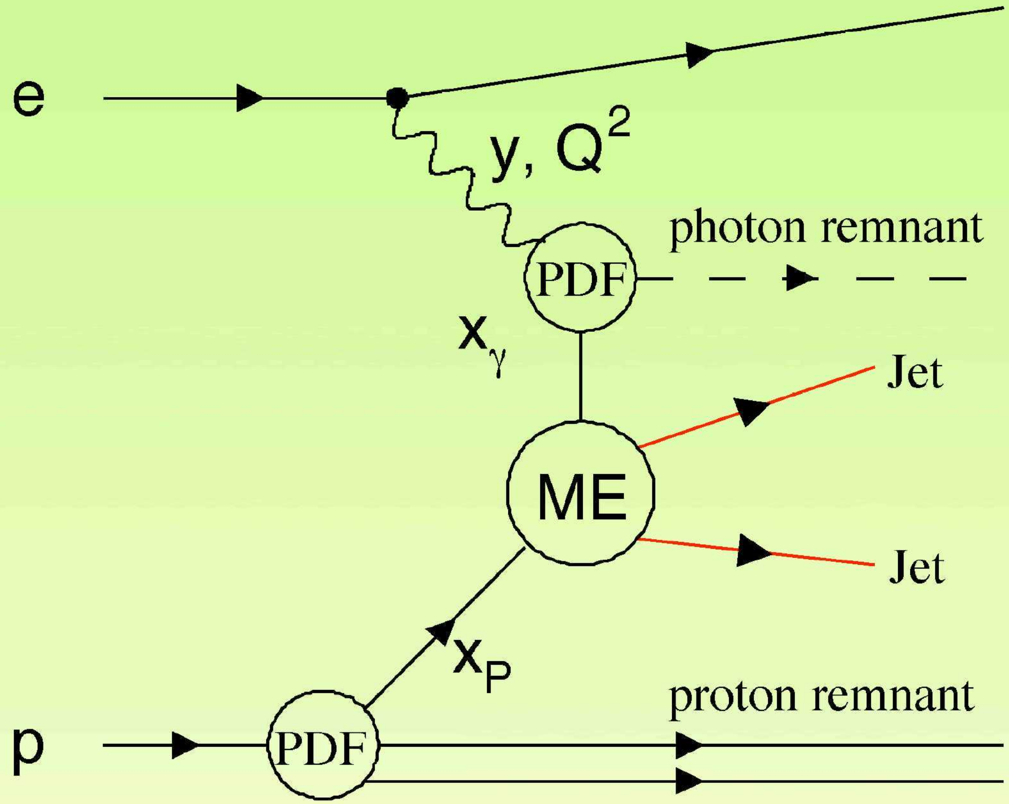
- Interactions where a hard probe directly couples to gluons at $Q^2 \sim 4\ GeV^2, x \sim 10^{-4}$ lead to diffractive final states with a probability, P_g close to 1/2- that is strength close to the unitarity limit (FS89)





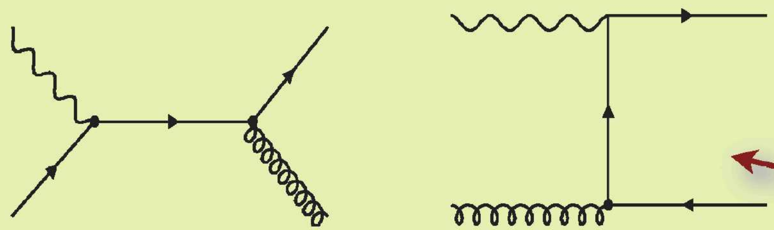
Second lesson

Real photon was effectively used for the QCD studies



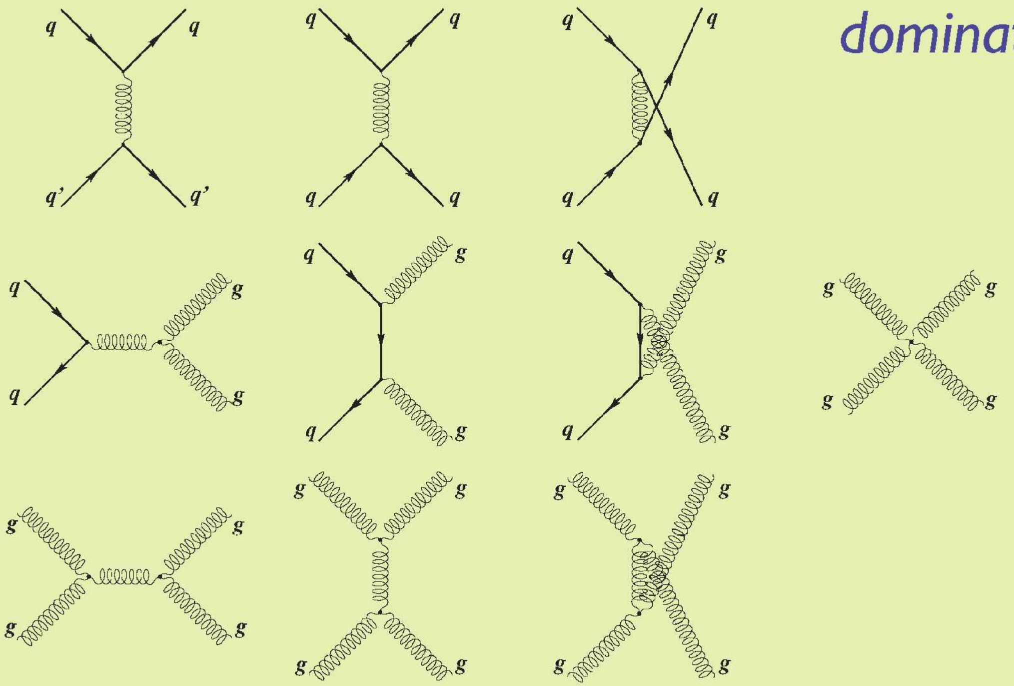
Schematic view of dijet production in ep *scattering studied at HERA*

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: $x_\gamma < 1$

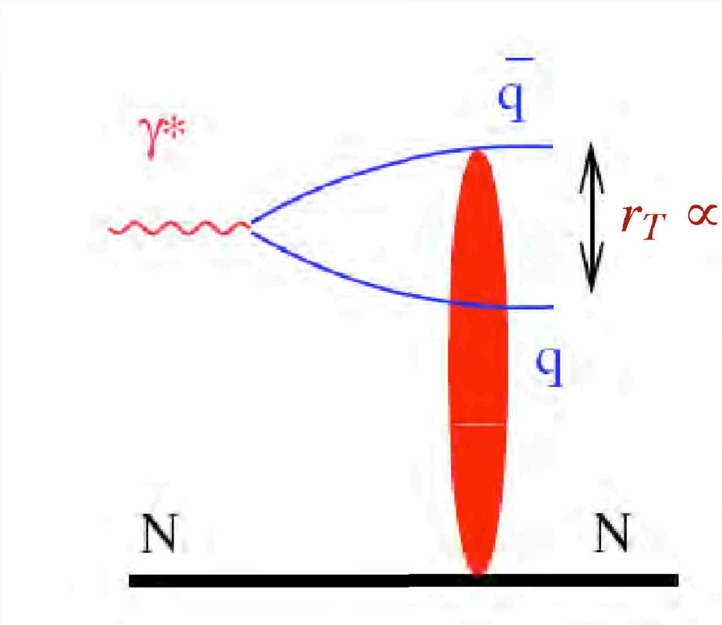
NLO is important - no separation between direct and resolved mechanisms - recently important theoretical progress - new MC codes are expected to be available soon.

Third lesson

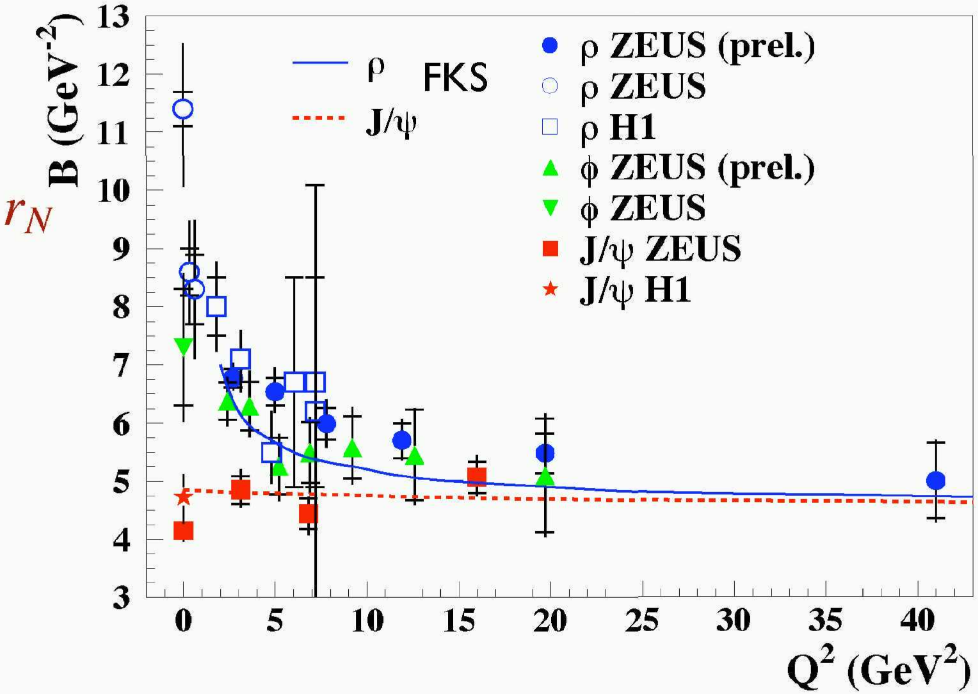
Universal t-slope: process is dominated by the scattering of quark-antiquark pair in a small size configuration - t-dependence is predominantly due to the transverse spread of the gluons in the nucleon - two gluon nucleon form factor,

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

$F_g(x,t)$. $d\sigma/dt \propto F_g^2(x,t)$.



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



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

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

Lesson from the forward pion production at RHIC:

Observation: the pion yield in the process $d + A \rightarrow \pi + X$ is strongly suppressed at forward rapidities as compared to the impulse approximation - a factor 0.3 for $y=4$.

Analysis of Guzey et al 04 - need to find a mechanism for suppression of the scattering of fast partons at $x>0.01$ partons which is not present in the Color Glass Condensate (CGC) model

Data of STAR 06 on correlations between forward and central production

Analysis of Frankfurt and MS - data require dominance of peripheral production - qualitative contradiction to the CGC prediction of dominance of central impact parameters.

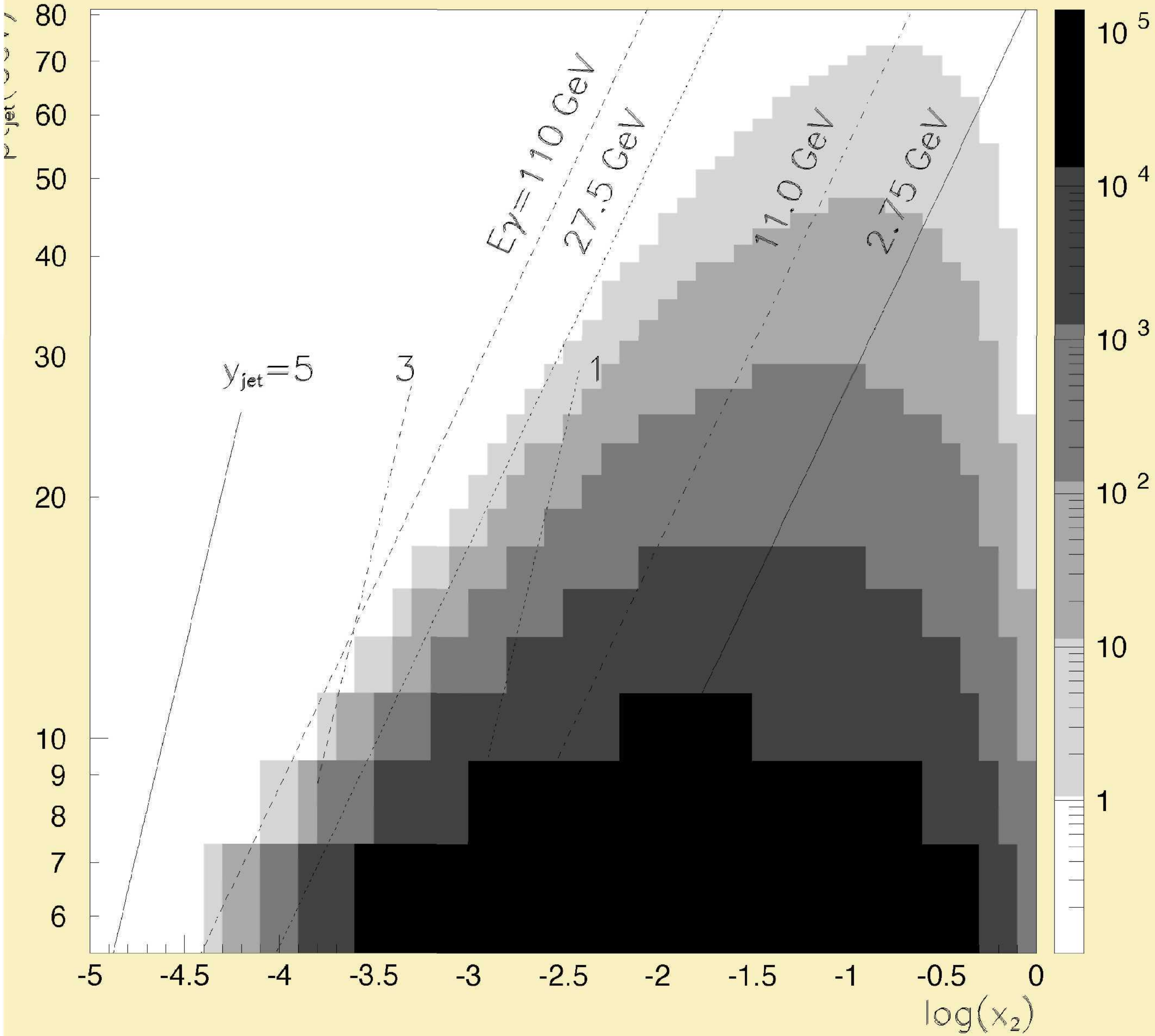
$\Rightarrow$ Large energy losses for scattering at high energies - natural when strength of interaction of small dipoles approach black disk limit

McDermott et al 01

What can be measured/discovered at LHC in UPC to follow up on HERA

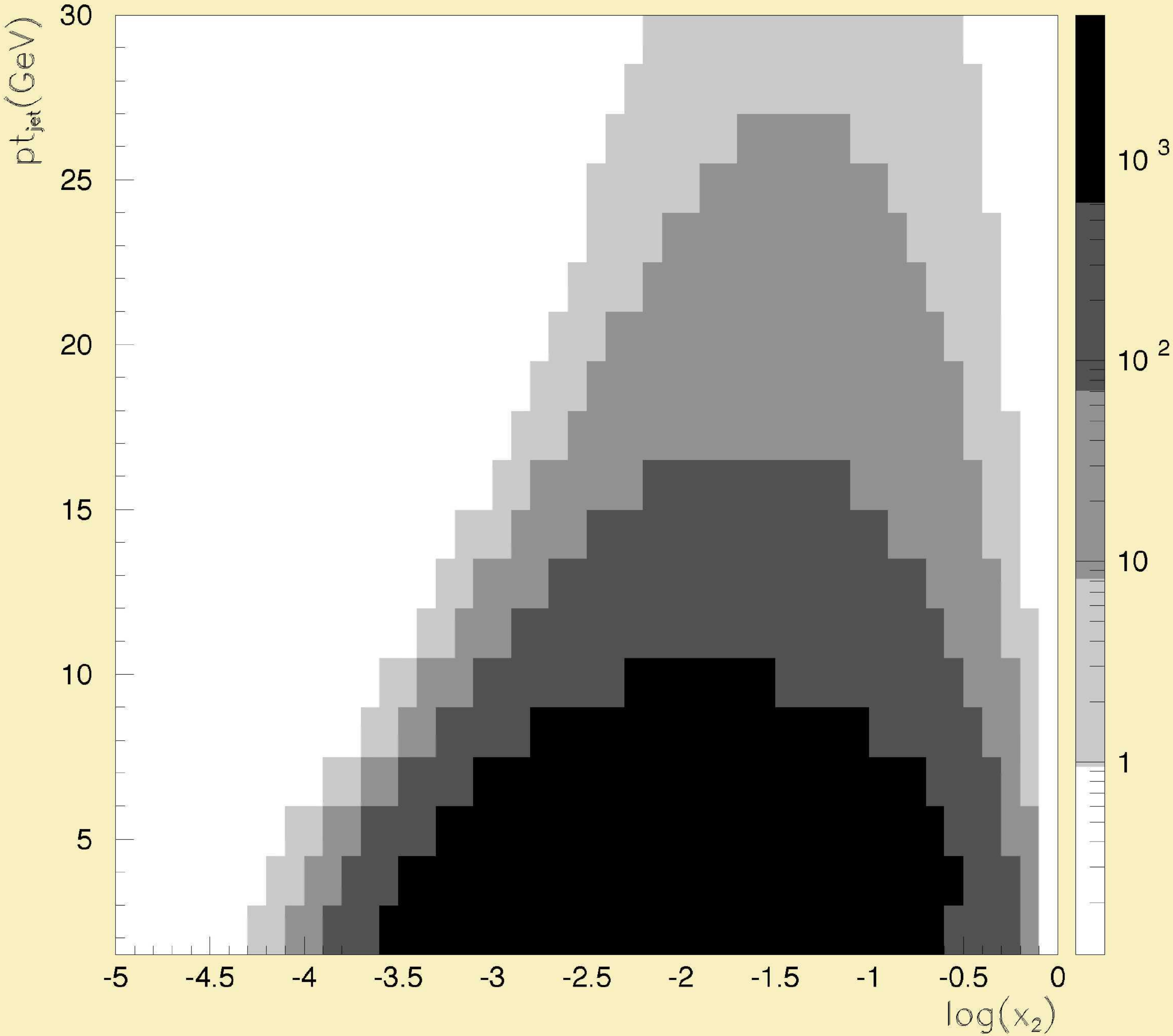
First results of the UPC study
for the CERN Yellow report on UPC

Study using triggering and acceptance of ATLAS

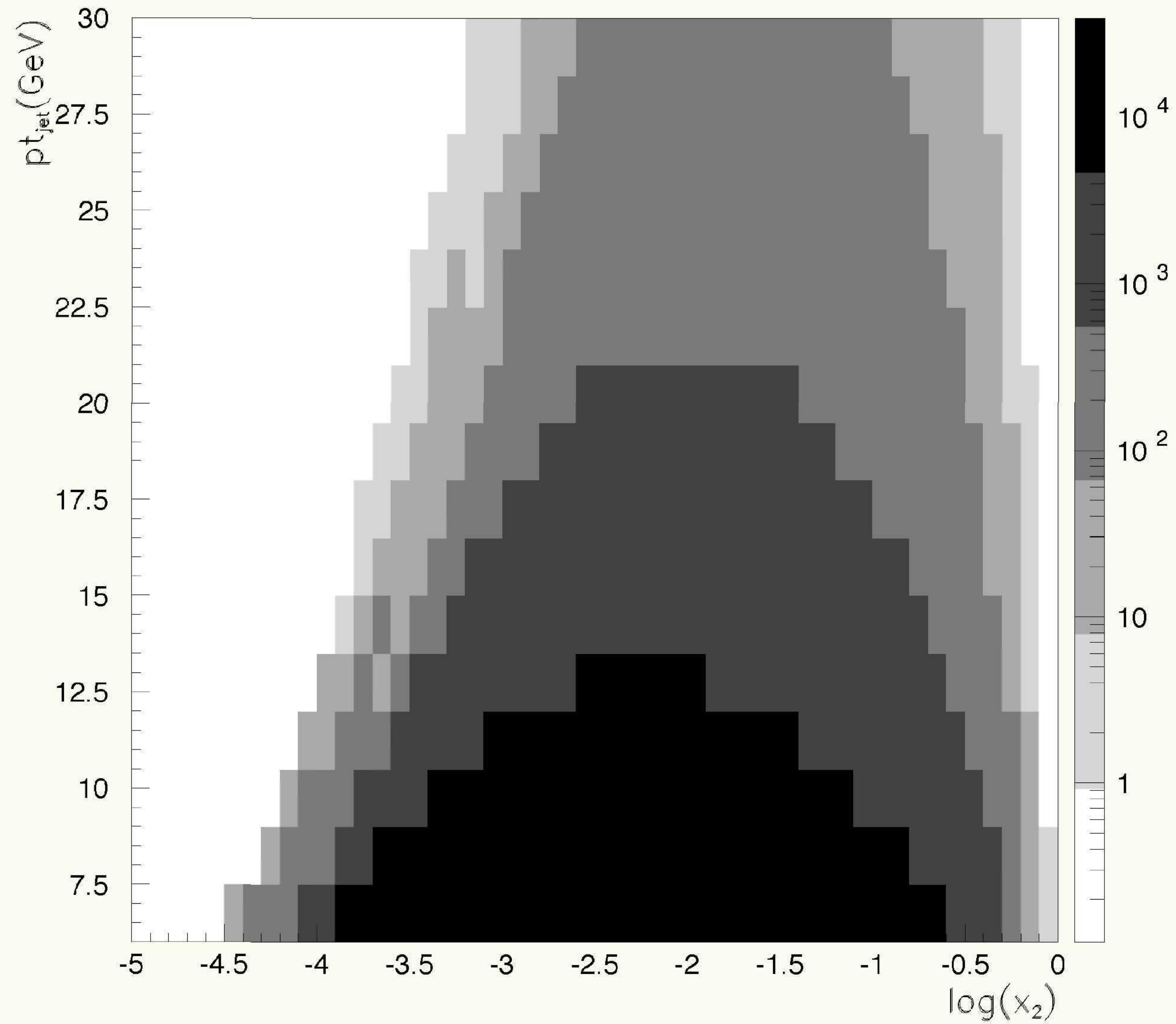


R.Vogt, S.White, MS

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.



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

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

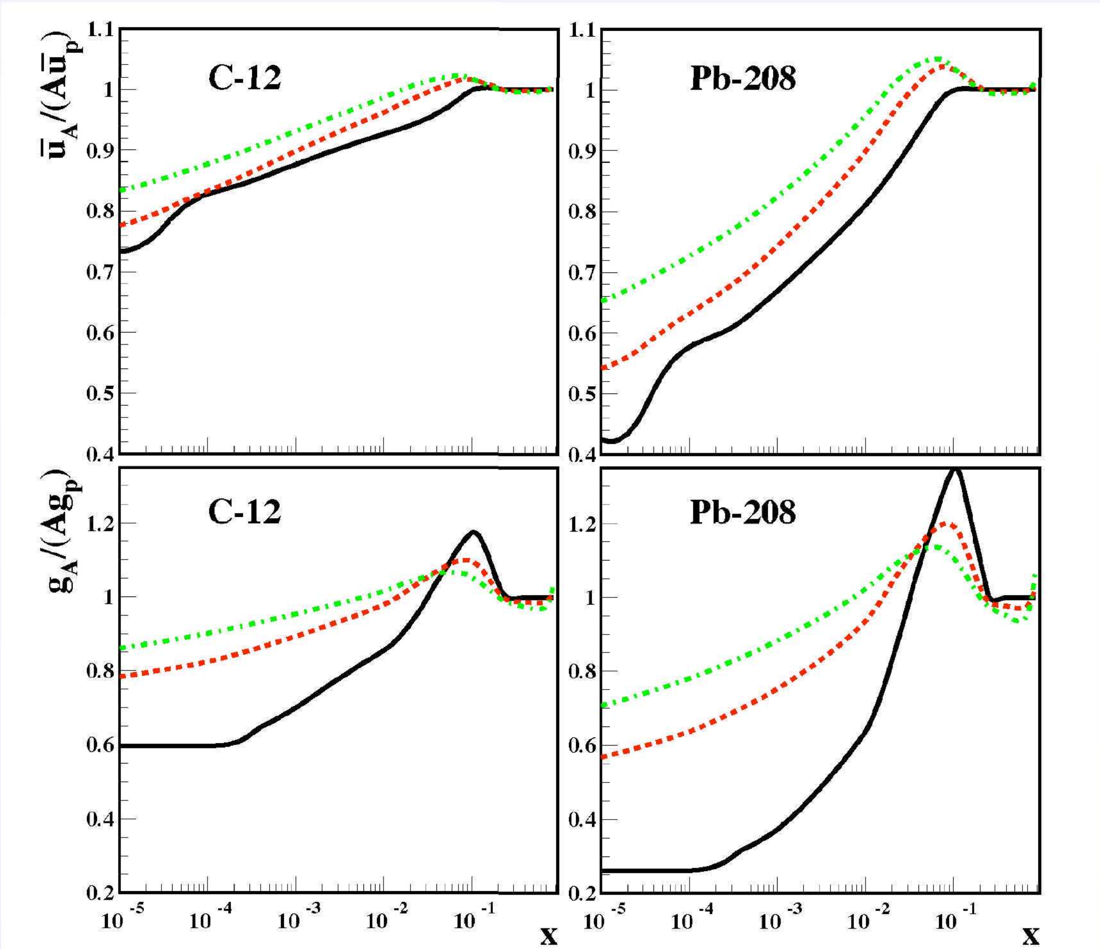
LHC vs ep HERA $$\frac{(9/4)A^{1/3}\alpha_S(p_T^2)xG_N(x\sim 5\cdot 10^{-5},p_T^2)/p_T^2}{\alpha_S(Q^2)xG_N(x\sim 10^{-4},Q^2)/Q^2}\sim 6$$

for central γA collisions (with no centrality trigger the gain is a factor of two 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 is a factor of 2

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.

Are significant nuclear effects expected in the UPC AA kinematics at LHC, say $p_t > 10$ GeV $\rightarrow x \geq 2 \cdot 10^{-4}$? Can estimate based on the theory of the nuclear leading twist shadowing Frankfurt and MS 98) which combines Gribov theory of inelastic nuclear shadowing, QCD factorization theorem for diffraction of Collins and input on diffractive pdfs from HERA. Expected suppression ~ a factor of 2 - would be doable.



Dependence of G_A/AG_N and $\bar{q}_A/Aq_N$ on x for Q=2(solid), 10(dashed), 100GeV (dot-dashed)curves calculated usingdi extracted from the HERA data, the quasieikonal model for N> 2 rescatterings assuming validity of theDGLAP evolution.

Frankfurt, Guzey, MS 03

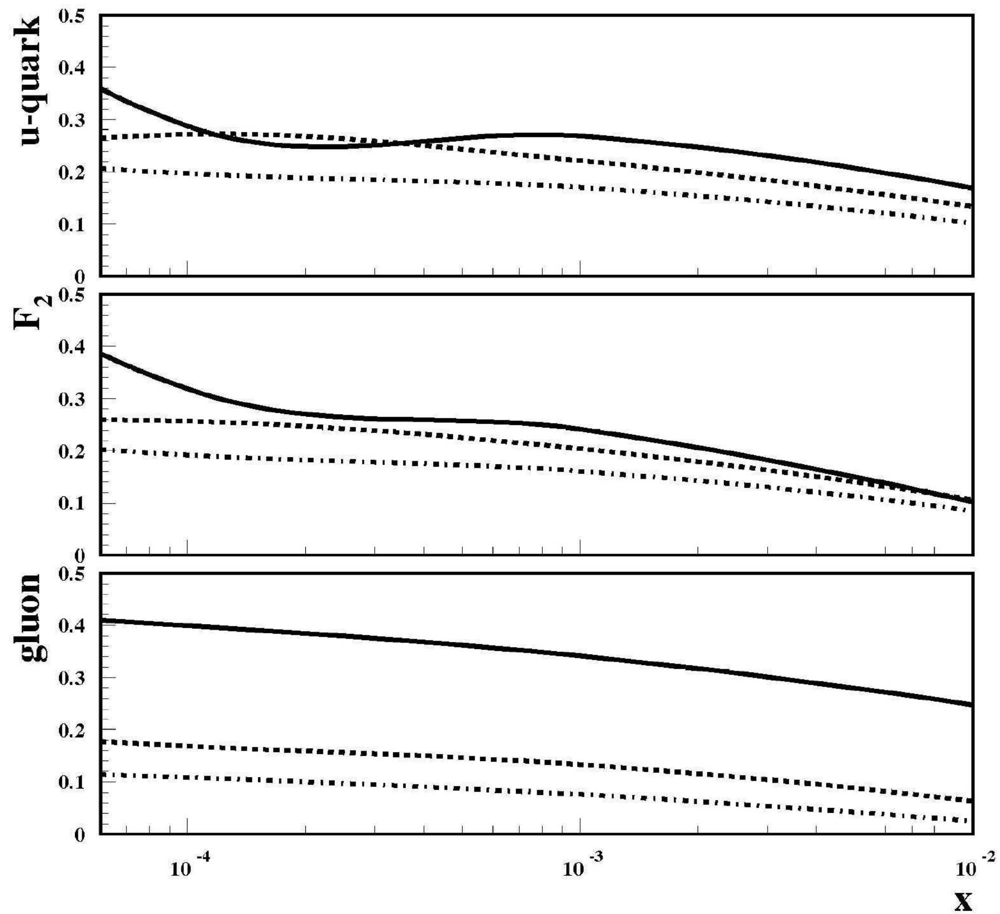
Another critical measurement is hard diffraction:

$\gamma A \to\ jet_1 + jet_2\ +\ X\ +\ A$ for direct photon: β≈ 1

In the black disk limit

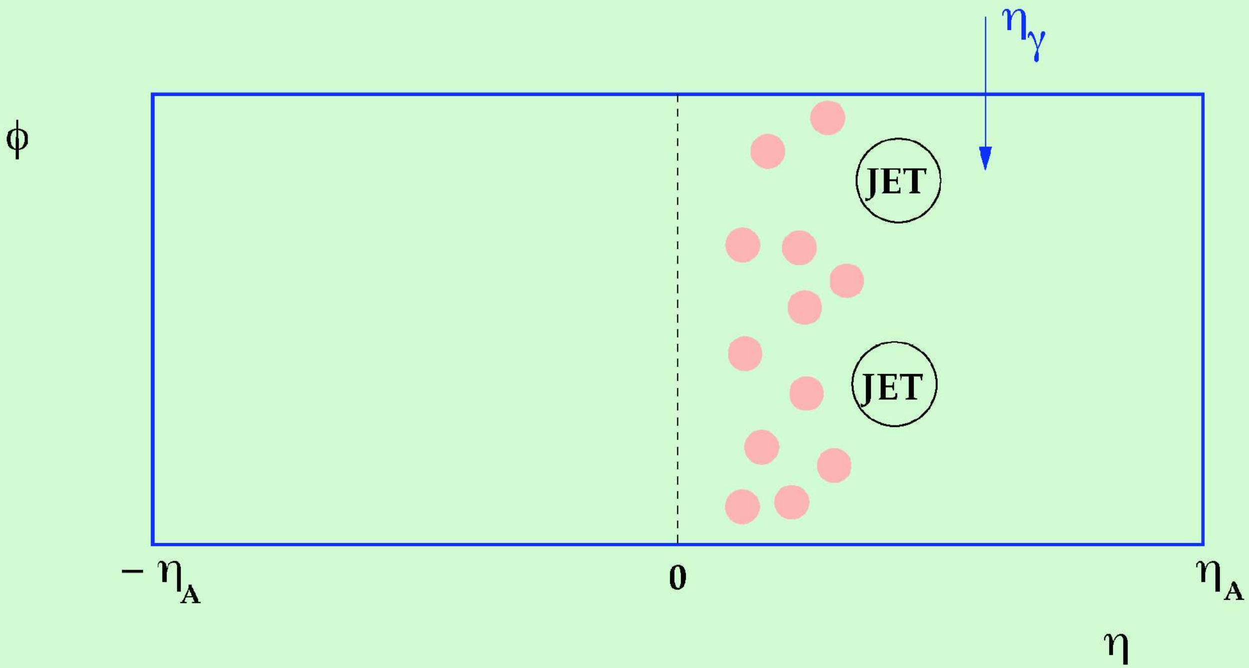
$$\frac{\sigma(\gamma A \to\ jet_1 + jet_2\ +\ X\ +\ A)}{\sigma(\gamma A \to\ jet_1 + jet_2\ +\ X)} \approx 0.5$$

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)



Proximity of the hard interactions with nuclei to BBL leads also to a large probability of diffractive events in nuclei (larger than in the proton). Results of the calculation within the leading twist model (Guzey, et al, 03) are shown the ratios $f_{j/A}^{D(2)}/f_{j/A}$ for the u-quarks and gluons and NLO $F_{2A}^{D(2)}/F_{2A}$ for ^{208}Pb at Q=2,10, 100 GeV.

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
- Diffraction into two, three jets

Soft (Pomeron) physics:

- Energy dependence of production of ρ,φ-mesons

Study of the onium production off nuclei is a good way to understand how close is interaction of a small dipole to the black disk limit in which

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

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

Dramatic enhancement of the process $\gamma + A \to 2jets + A$

as compared to the LT expectations (FGMS 02)

$$\sigma_{elastic}(\gamma + A \to J/\psi + A) \propto A^{2/3} \quad \sigma_{quasielastic}(\gamma + A \to J/\psi + A') \propto A^{1/3}$$

as compared to impulse approximation (naive color transparency)

$$\sigma_{elastic} \propto A^{4/3}, \ \sigma_{quasielastic} \propto A^{2/3}$$

❑ *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 of the nuclei emitted the photon.

The leading twist prediction is

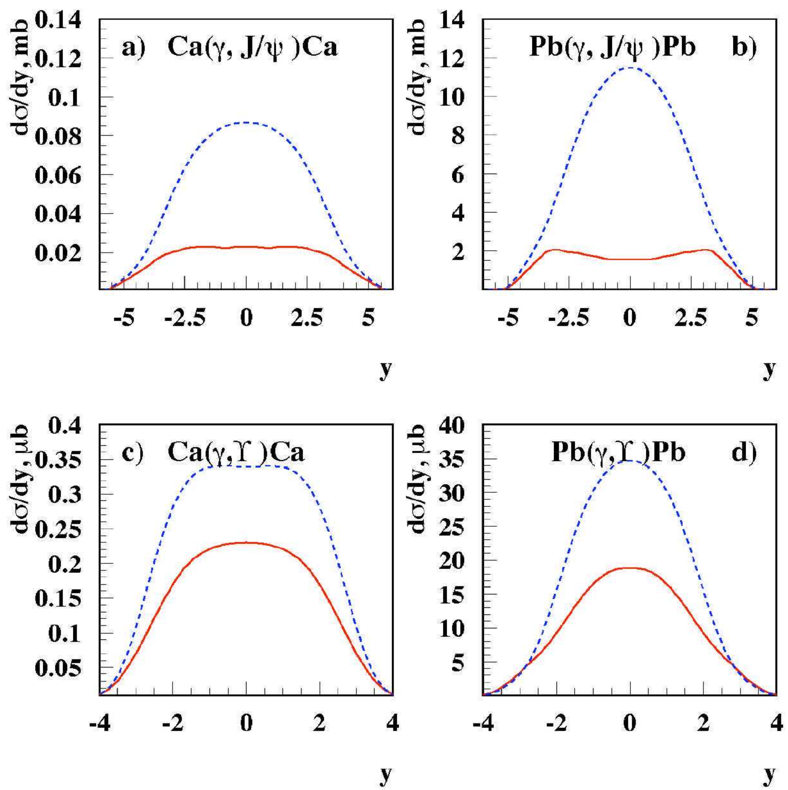
$$\sigma_{\gamma A \to VA}(s) = \frac{d\sigma_{\gamma N \to VN}(s, t_{min})}{dt} \left[\frac{G_A(x_1, x_2, Q^2_{eff}, t=0)}{AG_N(x_x, x_2, Q^2_{eff}, t=0)} \right]^2 .$$

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

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).

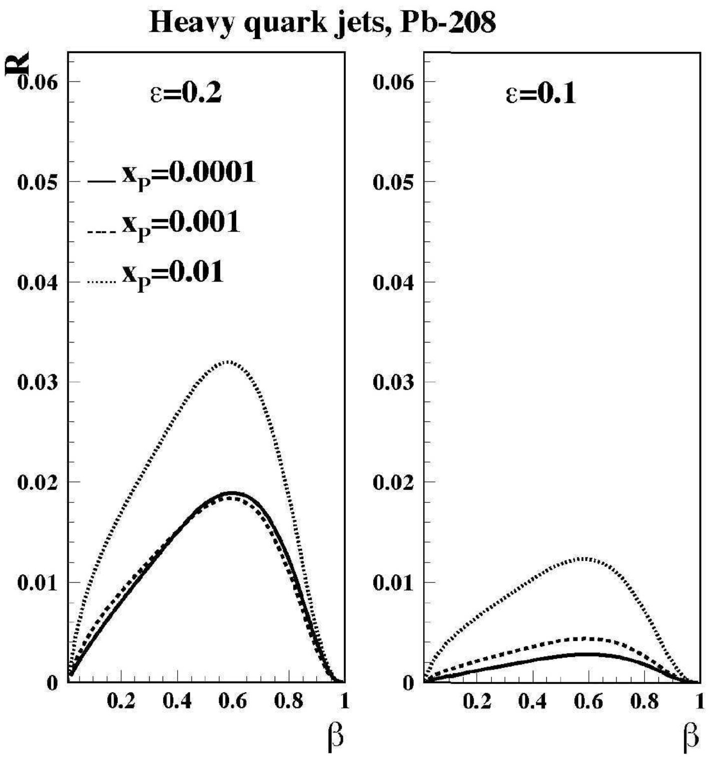
Experimental challenges: Trigger on relatively low transverse momentum leptons. Problem for J/ψ 's for $y=0$, for $y=2$-4 the ALICE study finds good rates. Acceptance for Upsilons is good in a wide rapidity range. Preliminary studies for CMS suggest that it would be possible to trigger at $y \sim 0$ with a large efficiency (P.Yeppes).

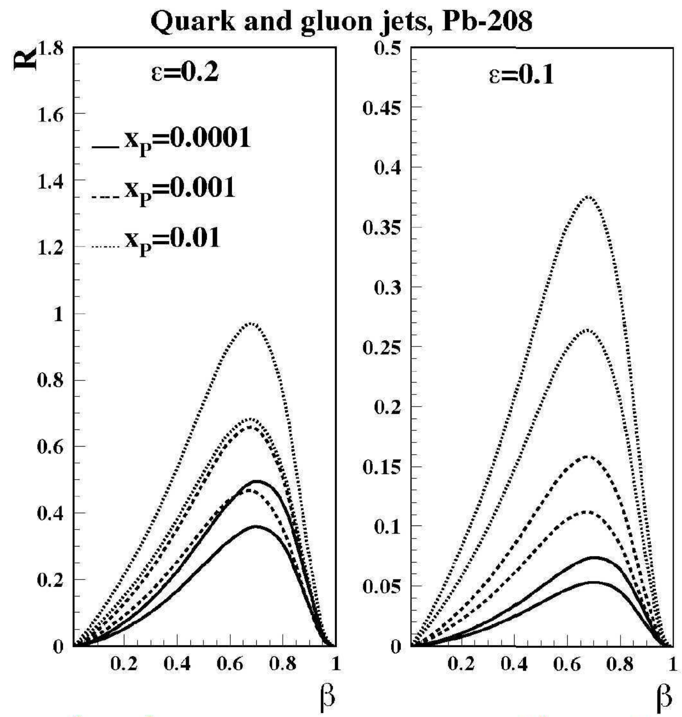
UPC in *p*A

*p*A ultraperipheral will play dual role -

- extend studies of the nucleon structure
- serve as a reference point to nuclear studies using UPC in AA collisions
- extend studies of the onium exclusive production to higher energies

Measurement of nucleon gluon pdfs. Situation is more complicated than in AA case (measurement of the nuclear pdfs) as we need to study jet production in the direct photon proton interactions $x_\gamma \sim 1$, and compare it to contribution due to nuclear diffractive pdf's at $\beta \sim 1$. Photon couples well to quarks (in particular heavy quarks), while in the inclusive dijet production gluon- gluon mechanism is strongly enhanced. Net result (Guzey and MS 05) - for heavy quarks photons win, for dijet production "nuclear Pomeron" contribution may win. Rates for heavy quarks are high enough - a slide in the beginning of the talk.





R is the ratio of "nuclear Pomeron" and photon contributions

Measurement of nucleon diffractive gluon pdfs.

Situation is likely to be better than for inclusive case as the probability of diffraction in γp is much higher (~10%) than in pp. Further theoretical analysis is necessary of the pp background for dijets (for heavy quarks definitely no problems) - but the counting rates are high.

Note that the 420 m Roman pots stations which are currently proposed for the Higgs searches will allow to detect protons for $x_{I\!P}$ between 10^{-2} and 10^{-3}. This would allow

a) To remove the processes

$$\gamma + p \rightarrow jet_1 + jet_2 + X + N^*(small\, diffractive\, mass)$$

b) Measure diffractive proton transverse momentum (even better $x_{I\!P}$ as well)

- Allow much more reliable comparison between the planned LHC hard diffraction data and and theory without absorption - no HERA data in most of the kinematics to be probed at LHC.

- Comparison with hard diffraction in AA UPC - which correspond to t~0

- Check of the leading twist theory of gluon shadowing - answer is expressed through the gluon diffractive pdf's at t~0

pPb run will allow measurements of diffractive gluon nucleon pdf's at $x \sim 10^{-2} \div 10^{-4}, Q \geq 7 \div 10\, GeV/c$

Studies of exclusive photoproduction processes in pA UPC:

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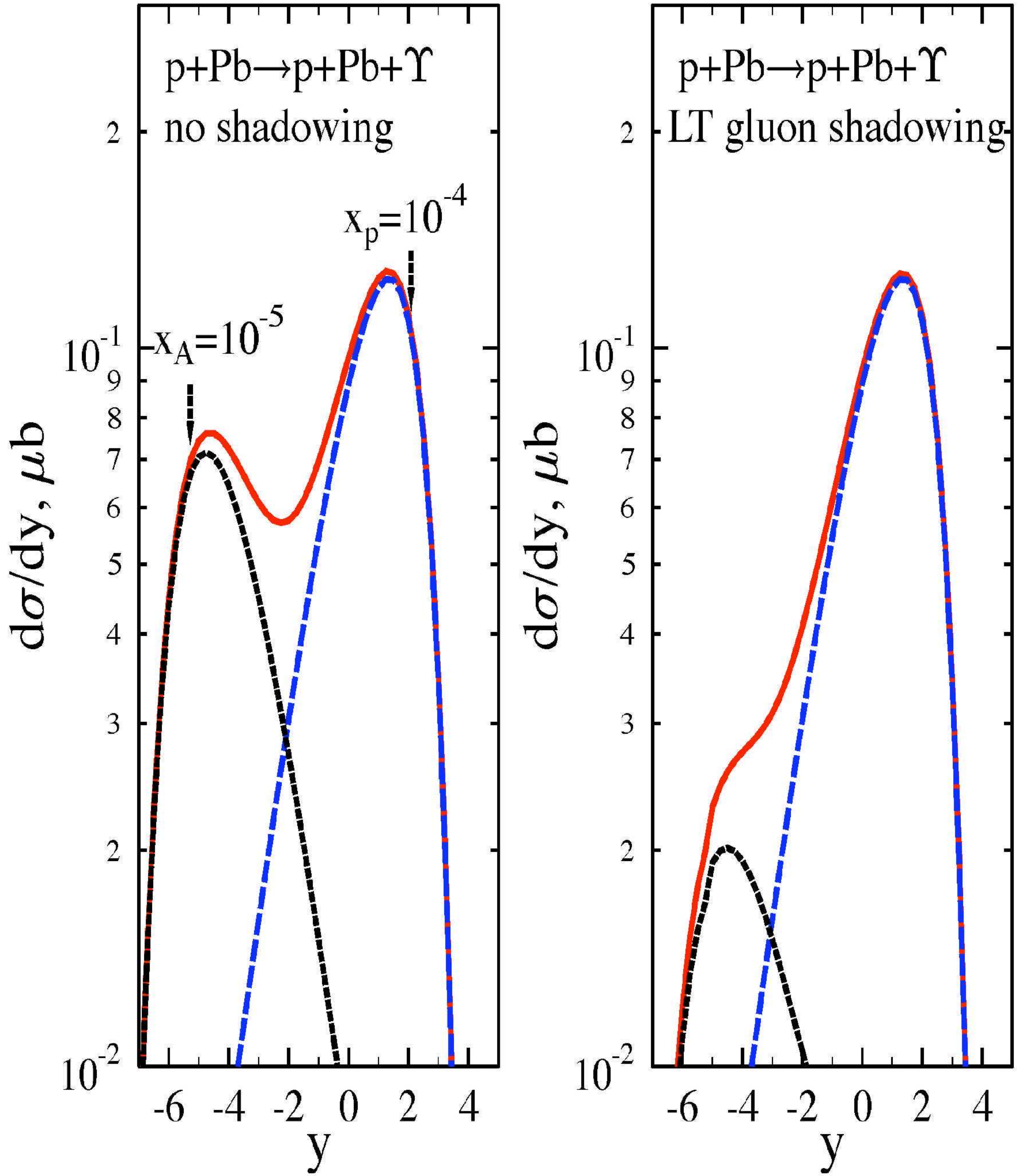
- Diffraction into two, three jets

Soft (Pomeron) physics:

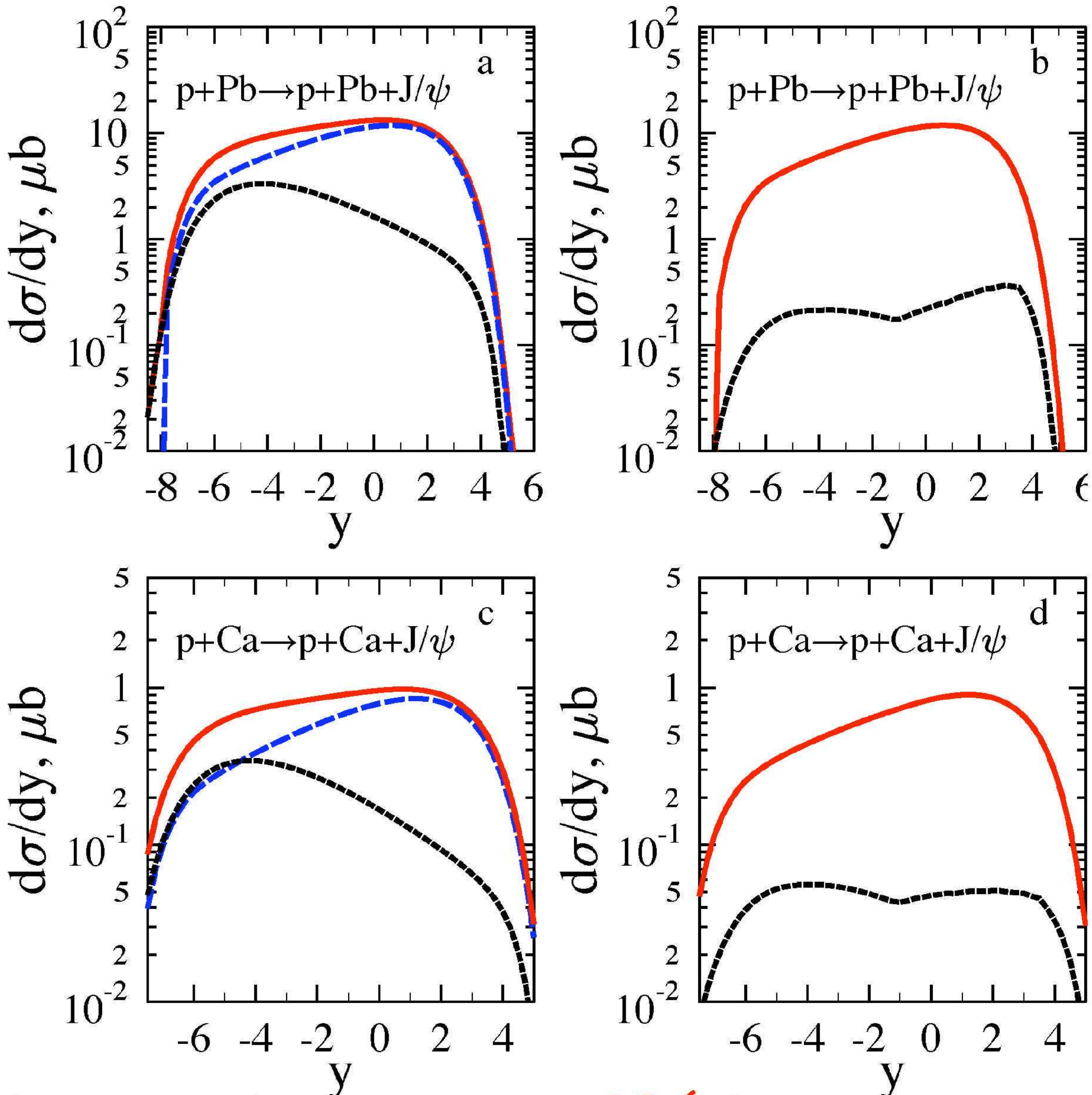
- Energy dependence of production of ρ,φ-mesons



Zhalov & MS 05

Sufficient to check pQCD prediction of $\sigma \sim W^{1.6}$ for Upsilon production, determination of the t-slope provided protons could be detected (420 m proposal) and measure nuclear shadowing at Q^2=40 GeV^2

Production of ϒ's in pA collisions : coherent γ+A →V+A is shown by black lines, and γ+p →V+p by blue lines.



High enough rates down to $x \sim 10^{-6}$, however extracting nuclear contribution would be a challenge if indeed the nuclear shadowing is as high as in FGS05. Would require resolution in transverse momentum of J/ψ of ~150 MeV/c.

Other directions:

Study of BRAHMS (RHIC) effect in gamma -A - energies are comparable

Vector meson with rapidity gaps - Pomeron structure and parton densities

Conclusions

Studies of UPC at LHC will address many (though not all) of the benchmark issues of HERA III proposal including

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 disk limit, color opacity

Low Q will be missed - will require studies at eRHIC

Several of the discussed measurements though doable from the angle of luminosity and kinematics are a challenge for detector design (β^*), triggering, systematics, etc. Need for joint studies by theorists, experimentalists, accelerator experts.

UPC Workshop at Trento - January 2007