Probing the small-x regime through photonuclear reactions at LHC

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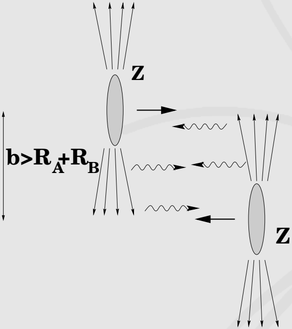
Outline

- Review of Ultraperipheral Collisions (UPC)
- Physics of UPC
- Vector meson production to probe small-x regime
- Diffractive parton distribution functions (DPDF)
- Summary

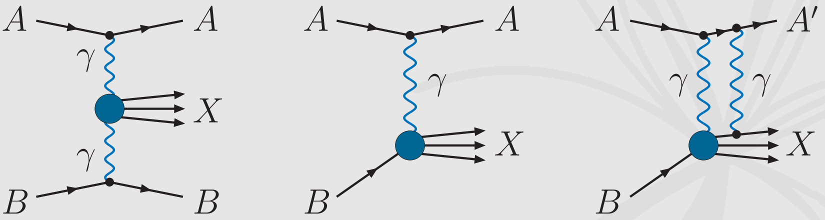
Ultraperipheral Collisions (UPC)

- Charged particles have a photon cloud around them proportional to Z^2;
- Usually, the production processes are studied with nuclei collisions;
- There are simultaneous hadronic and electromagnetic interactions;
  - It is not possible to separate both interactions;
  - Then, a cut in the impact parameter is required $|\vec{b}| > R_1 + R_2$;
- UPC's are investigated in large impact parameter processes.



Interactions

- There are two possible interacting processes
  - Electromagnetic processes by photon fusion;
  - Photonuclear reactions.
- There is the possibility to break up the nucleus by the exchange of an additional photon.



UPC kinematics

- The photons are radiated by the whole nucleus in a coherent emission;
- The photon virtuality is limited by the coherence condition

$$Q^2 \lesssim \frac{1}{R^2};$$

- As the Lorentz contraction does not affect the transverse plane, the uncertainty principle determines

$$p_T \lesssim \frac{1}{R} \approx \begin{cases} \text{28 MeV for Pb beams} \\ \text{330 MeV for p beams} \end{cases};$$

- In the longitudinal direction, the Lorentz factor increase the maximum momentum

$$k \lesssim \frac{\gamma}{R};$$

- The collision energy of $\gamma\gamma$ collisions is given by the photon momenta

$$W_{\gamma\gamma} = \sqrt{s_{\gamma\gamma}} = \sqrt{4k_1k_2}.$$

Photon flux

- When considering $\gamma\gamma$ collisions, the hadronic cross section is given by

$$\sigma_X = \int dk_1 dk_2 \frac{dL_{\gamma\gamma}}{dk_1 dk_2} \sigma_X^{\gamma\gamma}(k_1, k_2) \ ,$$

  where the $\sigma_X^{\gamma\gamma}$ is the partonic cross section;
- The two-photon luminosity is determined by the photon flux

$$\frac{dL_{\gamma\gamma}}{dk_1 dk_2} = \int_{b>R_A} \int_{r>R_A} d^2b \; d^2r \; \frac{d^3N_\gamma}{dk_1 d^2b} \frac{d^3N_\gamma}{dk_2 d^2r} \ ,$$

  where $dN/dkdr$ is the photon flux from a charge Z at a distance r;
- The constrain $b > R_i$ is not enough to consider a UPC: should be included the relation $b \gtrsim R_1 + R_2$
- It is useful to write the hadronic cross section in terms of the collisions energy

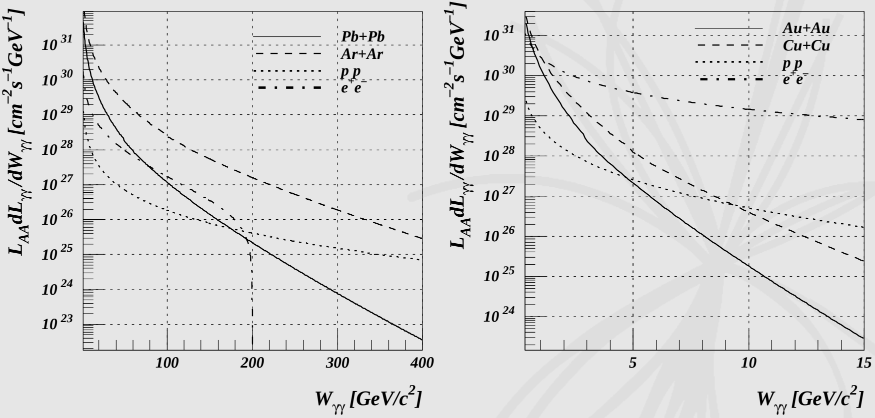
$$\sigma_X = \int \frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} W_{\gamma\gamma} \sigma_X^{\gamma\gamma}(W_{\gamma\gamma}) \ .$$

Photon collisions at Colliders

- Different kinematic regime can be compared through the relation

$$\frac{dL^{\mathrm{eff}}_{\gamma\gamma}}{dW_{\gamma\gamma}} = L_{AA}\frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}}$$

where L_{AA} is the AA luminosity.



Photonuclear cross section

- The hadronic cross section for γA collisions reads

$$\sigma_X = \int dk \, \frac{dN_\gamma}{dk} \, \sigma_X^\gamma(k) \, ,$$

  being the photon flux obtained by the Equivalent Photon Method;

- As appropriated in heavy-ion collisions, the photon flux is expressed in terms of the impact parameter

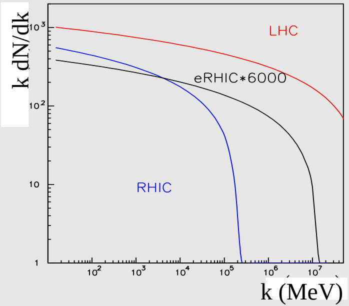
$$\frac{d^3N_\gamma}{dkd^2b} = \frac{Z^2\alpha w^2}{\pi^2 kb^2}\left[K_1^2(w) + \frac{1}{\gamma_L^2}K_0^2(w)\right] \, ,$$

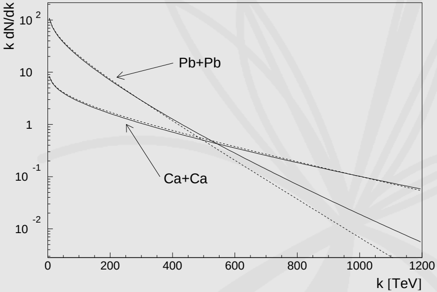
  where $\omega = kb/\gamma$;

- This photon flux decreases exponentially above a cutoff energy $1/R^2$;
  - Laboratory frame: $k_{\rm max} \approx \gamma/R_A$;
  - Target frame: $E_{\rm max} = (2\gamma^2 - 1)/R = \begin{cases} \text{500 GeV, RHIC} \\ \text{1 PeV, LHC} \end{cases}$

Photon flux: experimental data

- The photon flux at LHC will overcome any similar estimation from other colliders;
- For different energies, the flux has a dominance in distinct ranges.





Physical aspects

- The cloud around the nuclei are composed by quasi-real photons;
- Electromagnetic interactions have a long range action;
    - The photons can interact with the partons of the second nucleus;
    - These photons have smaller energy than partons, then

$$\sqrt{s_{\gamma N}} < \sqrt{s_{NN}}$$

- However, the coherent flux is proportional to Z^2, and then the photoproduction rate is enhanced;
- In photonuclear processes, many final states, such that

$$J/\psi, \Upsilon, Q\bar{Q}, jj$$

can be produced with high rates in UPC's.

Kinematics

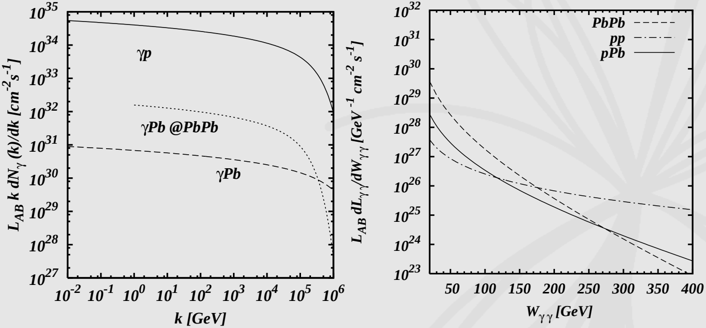
AB	L_{AB} (mb^{-1}s^{-1})	$\sqrt{s_{NN}}$ (TeV)	E_{beam} (TeV)	γ_L	k_{max} (GeV)	E_{max} (TeV)	$\sqrt{s_{\gamma N}^{\mathrm{max}}}$ (GeV)	$\sqrt{s_{\gamma\gamma}^{\mathrm{max}}}$ (GeV)
SPS								
In+In	-	0.017	0.16	168	0.30	5.71×10^{-3}	3.4	0.7
Pb+Pb	-	0.017	0.16	168	0.25	4.66×10^{-3}	2.96	0.5
RHIC								
Au+Au	0.4	0.2	0.1	106	3.0	0.64	34.7	6.0
pp	6000	0.5	0.25	266	87	46.6	296	196
LHC								
O+O	160	7	3.5	3730	243	1820	1850	486
Ar+Ar	43	6.3	3.15	3360	161	1080	1430	322
Pb+Pb	0.42	5.5	2.75	2930	81	480	950	162
pO	10000	9.9	4.95	5270	343	3620	2610	686
pAr	5800	9.39	4.7	5000	240	2400	2130	480
pPb	420	8.8	4.4	4690	130	1220	1500	260
pp	10^7	14	7	7455	**2452**	36500	**8390**	**4504**

pA vs. AA collisions

- The rate of ultraperipheral collisions have the form

$$rate = \frac{dN_\gamma}{dk}(\propto Z^2, Z^4) \times L_{AB}$$

- Ions with smaller Z are favored since they have larger luminosity than larger Z ions;
- It can be seen in the comparison of the effective luminosity among different collisions



Small-x regime seen through UPC

- As known from HERA data, gluon and sea-quark densities rise very quickly as x decreases;
- At small enough x, this growth may decrease proportional to $\ln(1/x)$;
- The increasing of the parton densities is regulated by
  - Shadowing;
  - Recombination effects
$$gg \to g;$$
  - Tunneling between different QCD vacua (suppressed at large x).
- These effects are significant in the core of the nucleon (large t);
- In its periphery the small-x physics will dominate;
  - The parton densities will increase asymptotically as $\ln^3(1/x)$.
- In LHC, these effects wil be seen with large-x in pA and AA collisions.

HERA small-x data

- As well-known, HERA observed the growth of the parton densities at small-x for wide Q^2 range;
- To study this regime, the vector meson production had been investigated:
  - light mesons at large Q^2
    $$\gamma g \to \phi, \rho^0;$$
  - heavy meson for all Q^2
    $$\gamma g \to J/\psi, \Upsilon.$$
- These processes have been calculated by the QCD factorization theorem for $t = 0$;
- It shows the interaction of small dipoles with the hadrons;
- Dependence on t: probe the gluon distribution as function of x.
  - Extend the range where the nonlinear effects show up ($Q^2 > 4$ GeV^2).

Black disc regime

- Combined analyses of data from inclusive DIS and hard vector meson production suggests that the interactions have the maximum strength for

$$Q^2 \leq 4 \text{ GeV}^2;$$

- This maximum-strength limit is called Black Disc Regime

$$a_{el}(t=0) = a_{inel} = 1$$

- This limit can be seen in process which hard probes (photons) couples to small-x partons;
- However, the limit is observed in a small Q^2 range, and then perturbative and nonperturbative effects are possible.
- It is expected to probe high gluon densities in LHC with large objects (nuclei) coupling to large-x partons.

Nonlinear QCD dynamics

- In the HERA data, nonlinear effects were seen in large diffractive gluon densities for $Q^2 \sim 4$ GeV^2 at $x_{\mathrm{max}} = 10^{-4}$;
- In LHC, the probability will increase for processes which hard probes will couple to small target x;
  - In other words, probe the high gluon densities.
- These effects will be observed using small dipoles to interact with the target (nuclei)

$$\sigma_{dip-h}(s_{dip-h}, r^2) = \frac{\pi^2}{4} C_F^2 r^2 \alpha_s(Q_{eff}^2)\, xg(x, Q_{eff}^2)$$

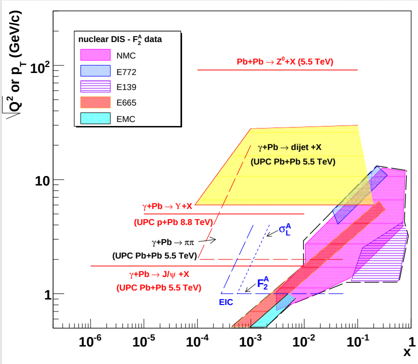
with $x = Q_{eff}^2/s_{dip-h}$, $C_F^2 = 4/3$ for $q\bar{q}$ and 3 for gg, and $Q_{eff}^2 \propto r^{-2}$;

- At high energies, the small-x gluons field become strong and the dipoles can not propagate in nuclei without absorption.
  - It shows the breakdown of the linear regime.

Color transparency → Color opacity

UPC at LHC

- Some of the approaches implemented in HERA can be used to study the small-x regime in pA and AA at LHC;
  - Gluon density mesurements;
  - Gluon-induced hard diffraction; and
  - Exclusive J/ψ and Υ production.
- The Q^2 and x range convered in LHC with UPC will be extended in comparison to the HERA data (understand the small-x dynamics);



PDF mesurements

- The main process investigated to mesure the gluon density is the γg fusion process

$$\gamma + g \longrightarrow jet + jet$$

- Jets of b or c quarks will probe the gluon distribution at

$$x \sim 5 \times 10^{-5}\ ,\ p_T \geq 6 \text{ GeV}$$

- Going down to $p_T \sim 5$ GeV: nonlinear effects will be a factor **six** higher than at HERA and **two** than at eRHIC;
- Dipole absorption in vector meson production:

$$x_{\text{eff}} = \frac{m_V}{2E_N} = \begin{cases} 2.5 \times 10^{-3} \text{ for } \Upsilon \\ 7.5 \times 10^{-4} \text{ for } J/\psi \end{cases}$$

- Considering the break up of the nucleus: factor **10** higher than coherent processes.

J/ψ production I

- The amplitude for J/ψ production in $\gamma A \rightarrow VA$ process is given by

$$\mathcal{M}(\gamma A \rightarrow VA) = \mathcal{M}(\gamma N \rightarrow VN)\,\frac{g_A(x, Q^2_{\rm eff})}{A g_N(x, Q^2_{\rm eff})}\,F_A(t_{\rm min});$$

- The J/ψ cross section can be mesured in the range

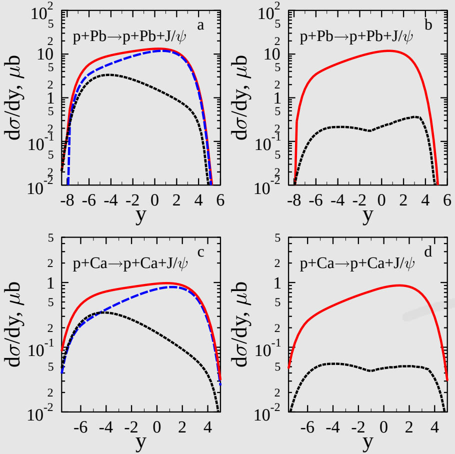
$$20 < W_{\gamma p} < 2000 \text{ GeV};$$

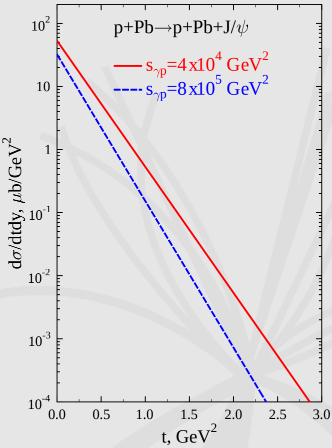
- The maximum energy corresponds to a momentum fraction of

$$x_{\rm eff} \sim 2 \times 10^{-6};$$

- At this scale, the small dipoles contribution domain is reached.
    - It is important to take into account this contributions.

J/ψ production II





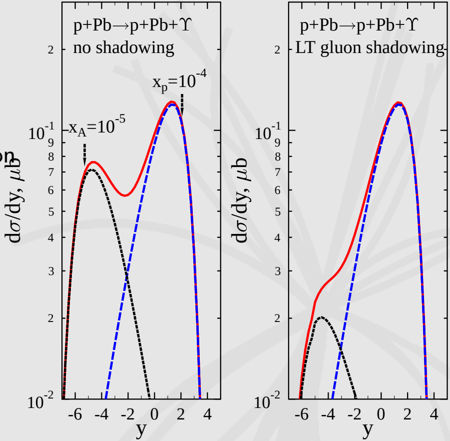
Υ production

- The nuclear contribution for the Υ production is much larger in γA processes;

- As can be seen in the figure, the dominate x region corresponds to $x \sim 10^{-5}$;

- In pA scattering, the Υ production can probe dipoles with 0.1 fm at very small x;

- Such interaction is not expected to be observed in other colliders.

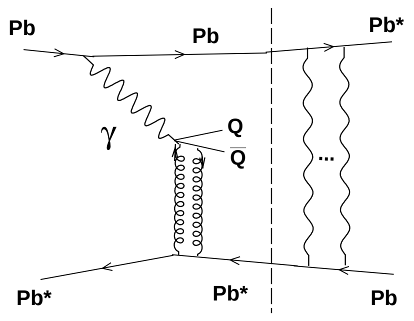


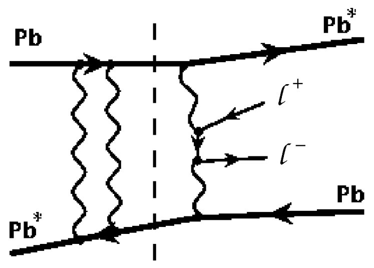
nPDF I

- The diffractive production of J/ψ and Υ by Pomeron exchange is important since the cross section depends on the gluon density

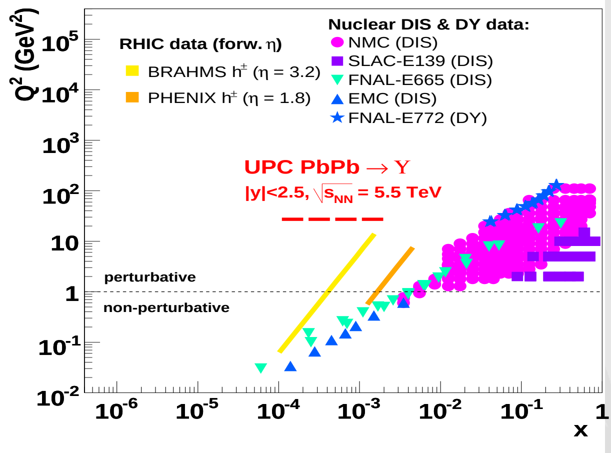
$$(d\sigma_{\gamma p,A \to V\, p,A}/dt)|_{t=0} \propto [xg(x, Q^2)]^2$$

where $Q^2 \approx M_V^2/4$ and $x = M_V^2/W_{\gamma p,A}^2$.





nPDF II



- These mesurements will help to constrain the low-x behavior of the nPDF in a range where saturation effects takes places due to the nonlinear evolution of the PDF.

nDPDF I

- The diffractive parton densities in the nucleus is obtained by

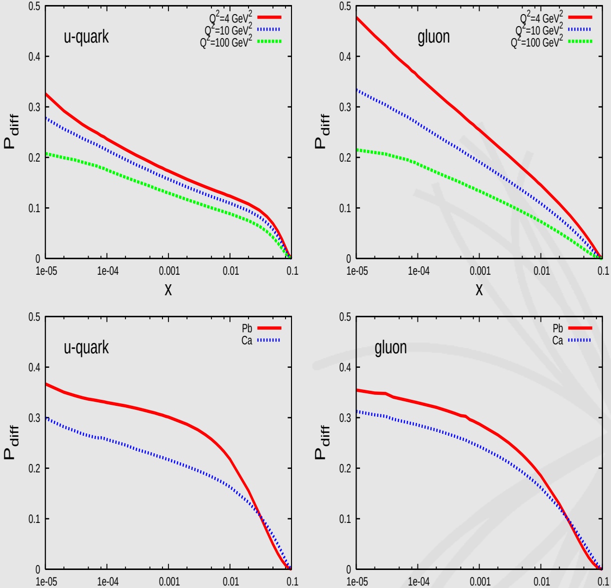
$$x f_{j/A}^{D(3)}(x, Q_0^2, x_{IP}) = 4\pi\beta\, f_{j/N}^{D(4)}(x, Q_0^2, x_{IP}, t_{\min}) \int d^2 b$$

$$\times \left| \int_{-\infty}^{\infty} dz\, \rho_A(b,z)\, e^{i x_{IP} m_N z}\, e^{-\frac{1-i\eta}{2}\sigma^j_{\mathrm{eff}}(x,Q_0^2)\int_z^\infty dz'\,\rho_A(b,z')} \right|^2 .$$

- This equation is valid for nucleon DPDF, but not for nDPDF since the factorization is broken due to the nuclear shadowing and the A dependence of the cross section.
  - The resulting nDPDF is evolved in Q^2 using the NLO DGLAP equation with leading-twist corrections.
- Then it is useful to analyse the probability of diffraction of a given parton j

$$P^j_{\mathrm{diff}} = \frac{\int_x^{x_{IP}^0} dx_{IP}\, x f_j^{D(3)}(x, Q^2, x_{IP})}{x f_j(x, Q^2)} .$$

nDPDF II


u-quark
gluon
Q^2=4 GeV^2
Q^2=10 GeV^2
Q^2=100 GeV^2
Pb
Ca
P_{diff}
X
0
0.1
0.2
0.3
0.4
0.5
1e-05
1e-04
0.001
0.01
0.1

Summary

- The UPC's will be mesured for the first time in the high energy regime;
- Since the γ interactions can be studied in UPC, the mesurements of DIS and lepton-proton can be extended with UPC;
- The small-x regime will be investigated in an extended range if compared to HERA data;
- Diffractive production of heavy meson will probe the small-x regime;
- UPC are a clean processes to study nonlinear effects and saturation physics.