Review of Ultraperipheral Collisions

Lecture at the WE-Heraeus Summer School
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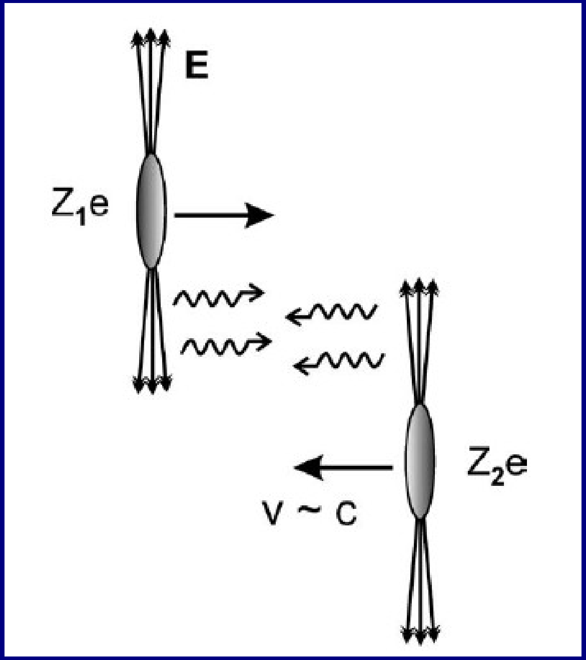
What are Ultra-peripheral Collisions?

Collisions between nuclei and protons with impact parameters larger than the sum of the radii.

Strong interactions suppressed. Interactions instead mediated by the electromagnetic field.



The EM fields correspond to an equivalent flux of photons (Fermi/ Weizsäcker-Williams).

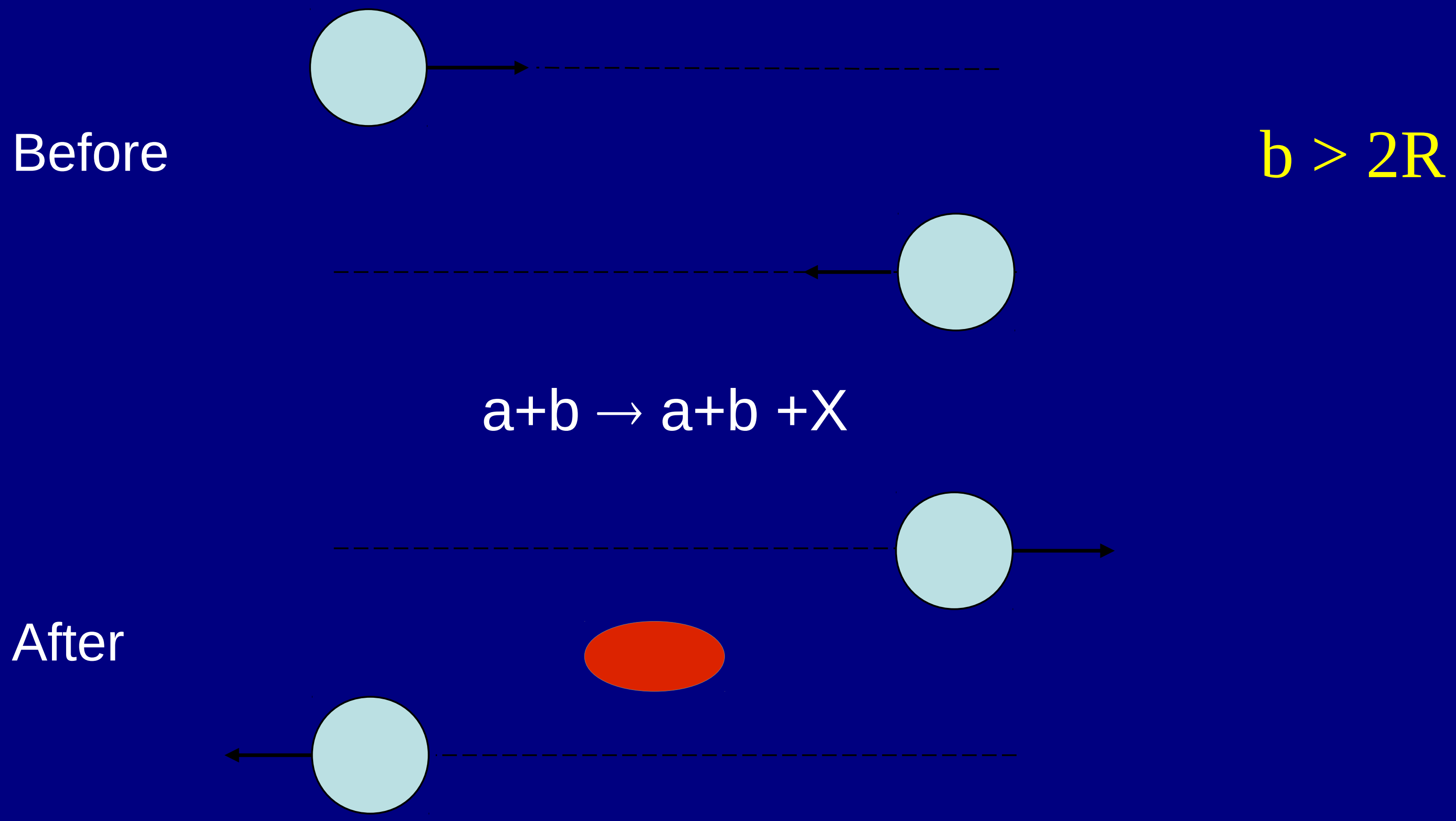
Two-photon and photonuclear/photon-proton interactions can be studied at unprecedented energies in UPC at the LHC.

Two “recent” review articles: C.A. Bertulani, S.R. Klein, J. Nystrand, Ann. Rev. Nucl. Part. Sci. 55 (2005) 271; A.J. Baltz et al., Phys. Rept. 458 (2008) 1.

Outline

- Introduction to ultraperipheral collisions
- Review of expectations and experimental results so far
- Outlook to the future

Suppose you collide two particles, which survive the collision, while some particles are produced in the middle.



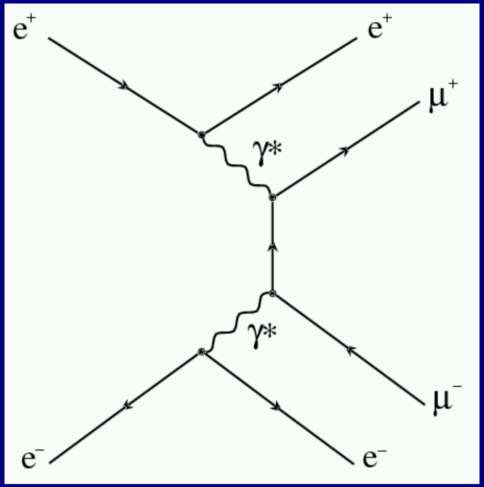
What is “X”? And what are the production mechanisms?

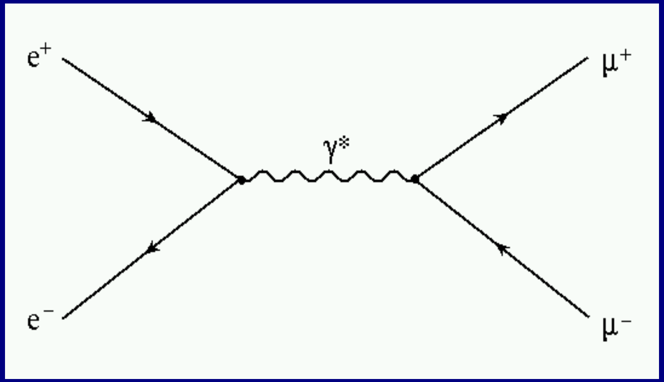
== > Will depend on the projectiles.

Consider an e+e- collision

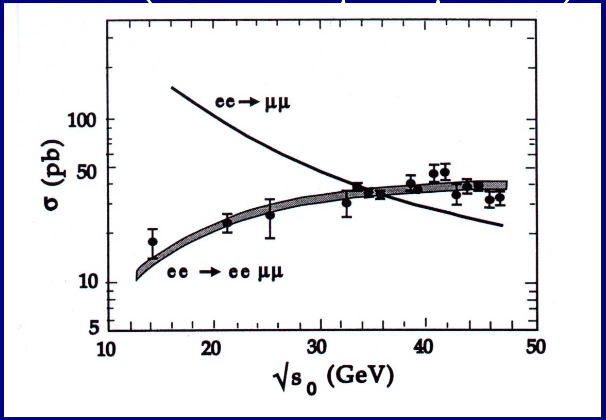
The quantum of the electromagnetic field is the photon ==>
two-photon interactions are possible, for example
$e^+ + e^- \rightarrow e+\ e- + \mu^+ + \mu^-$

At high energies this reaction will have a larger cross section than the "usual" leading order $e^+ + e^- \rightarrow \mu^+ + \mu^-$ reaction





$\sigma(e^+ + e^- \rightarrow \mu^+ + \mu^- +X)$



The asymptotic behavior of higher-order terms can be completely different from that of lower-order terms.

H. Cheng and T.T. Wu Phys Rev Lett 23(1969)1311
S.J. Brodsky, T. Kinoshita, H. Terazawa Phys Rev D 4(1971)1532

Consider a pp or AA collision

The protons/nuclei are charged objects, so two-photon interactions are possible.

However, the protons also interact strongly. The quantum of the strong force is the gluon. The gluon carries color ==> Emission of a single gluon not possible if the proton should remain intact.

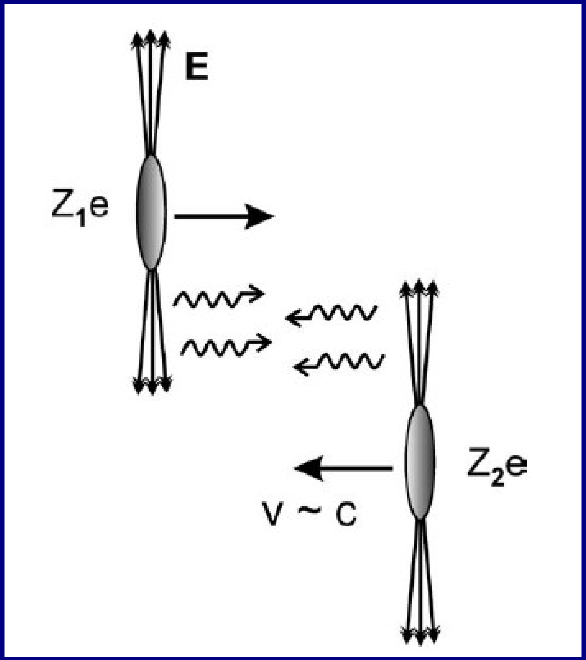
Emission of two (or more gluons) with an intact proton is possible. Such colorless exchange can be considered to mediated by a phenomenological particle, the "Pomeron".

$\gamma\gamma \rightarrow X$, $PP \rightarrow X$, and, in addition, $\gamma P \rightarrow X$ interactions are possible.

pp: Pomeron-Pomeron interactions dominate, $\gamma\gamma$ and γP can give significant contribution for certain final states (leptons, spin = 1).

AA: $\gamma\gamma$ and γA dominate. Can occur for impact parameters up to 100s of fm. Pomeron-Pomeron restricted to $b \approx 2R$ (A.J. Schramm, D.H. Reeves, Phys. Rev. D 55 (1997) 7312).

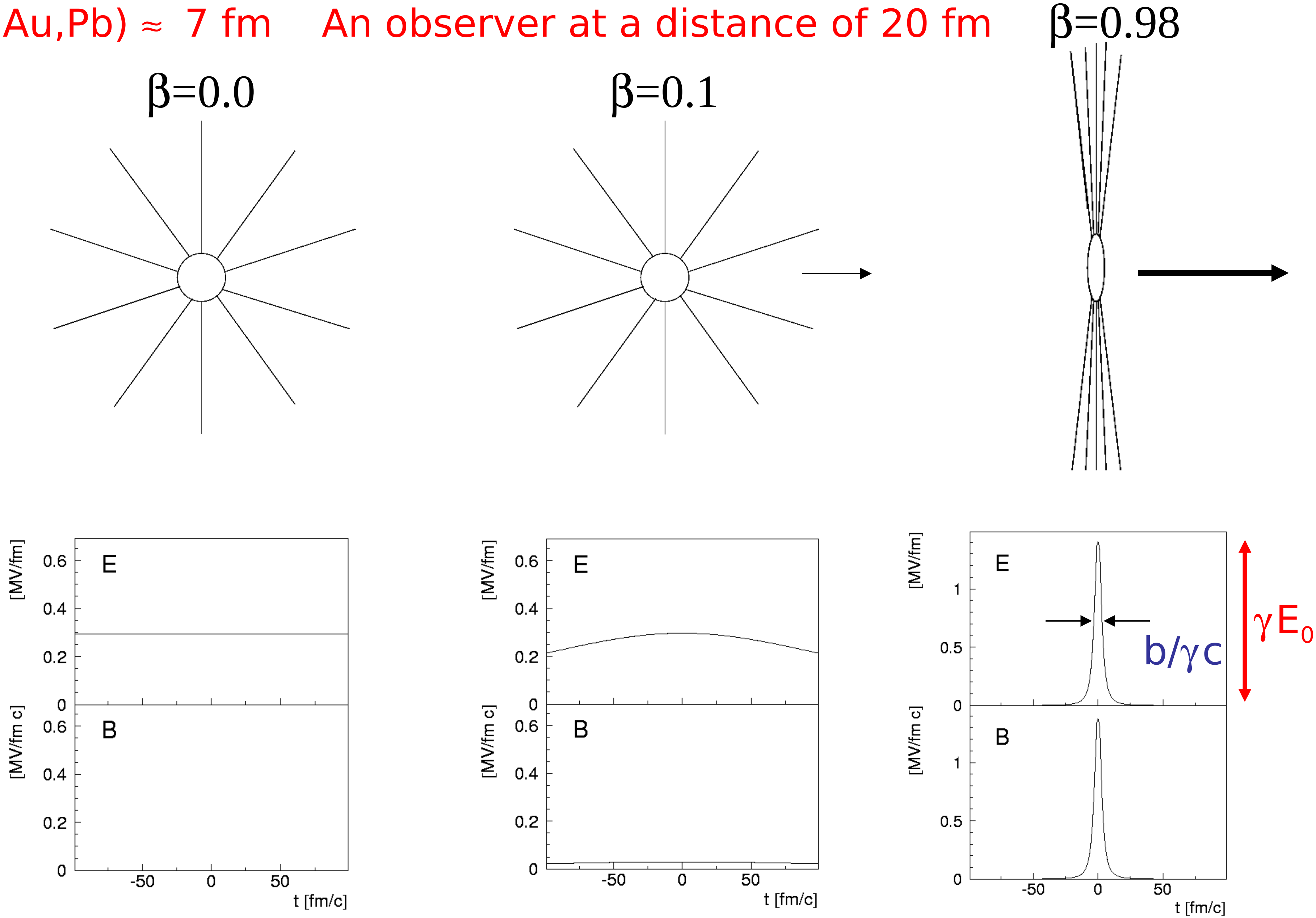
The electromagnetic field in an Ultra-peripheral Heavy-Ion Collision



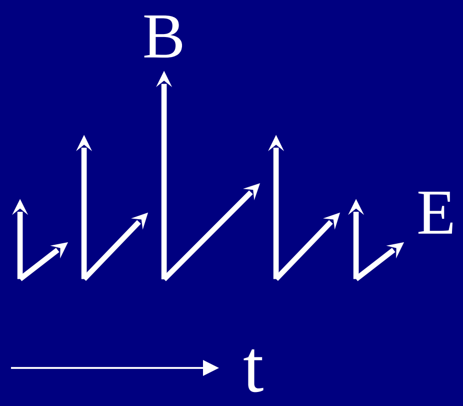
The EM fields correspond to an equivalent flux of photons (Fermi/ Weizsäcker-Williams).

Electromagnetic fields of a moving charged particle

R(Au,Pb) ≈ 7 fm   An observer at a distance of 20 fm

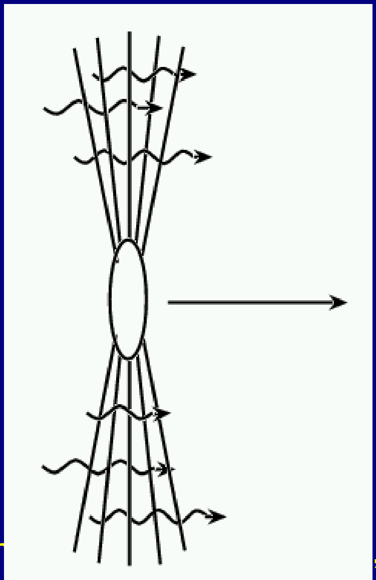


Electromagnetic fields of a moving charged particle



1) $|E| \approx |B|$ 2) $(E \perp B)$ 3) $\Delta t \sim b/\gamma c$

Fermi 1924: The effect of the fields is equivalent to a flux of of photons with a continous energy spectrum. (hep-th/0205086)



Pulse width $b/\gamma c \leftrightarrow$ the spectrum contains photons w/ $\omega < \gamma c/b$

Quantum Mechanical derivation 1935 by Weizsäcker,Williams. $\Rightarrow$ *Weizsäcker-Williams method*

We can calculate $n(\omega)$ through a Fourier transform.

Electromagnetic fields of a moving charged particle

When we Fourier transform the electromagnetic pulse, we get the photon flux at one point. To get the total photon spectrum, we have to integrate over all points, i.e. over all impact parameters $b > R$ (R is the radius of the projectile).

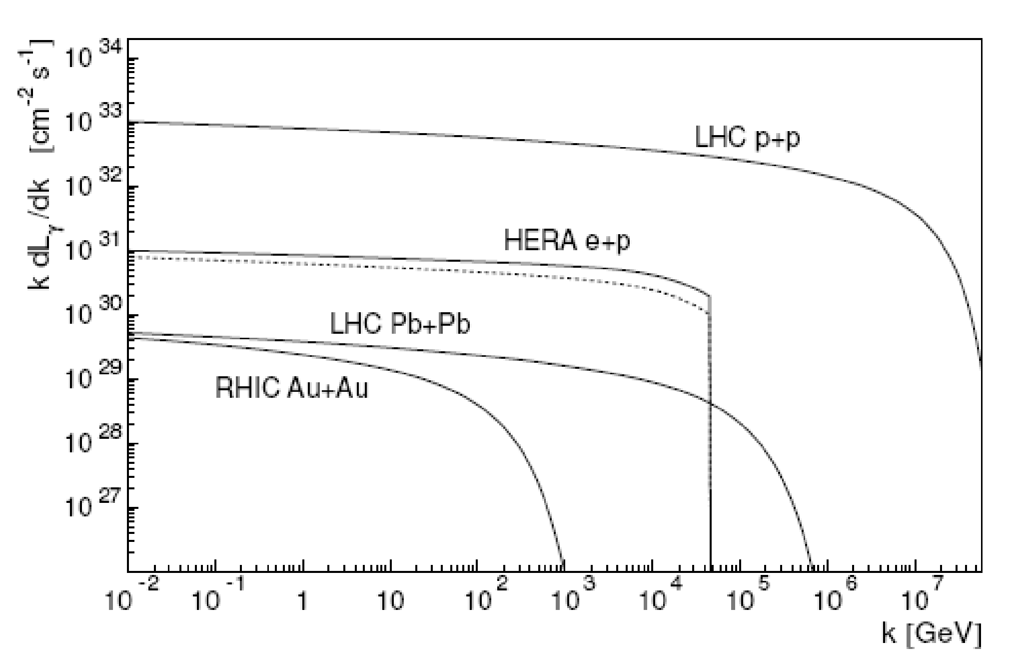
The Equivalent Photon Luminosity

The spectrum of photons with energy $E_\gamma = x \cdot E_{beam}$ and virtuality Q^2 in QED is given by

$$x\frac{dn_\gamma}{dx dQ^2} = \frac{\alpha Z^2}{\pi}\left(1 - x + 1/2x^2\right)\frac{Q^2 - Q^2_{min}}{Q^4}$$

Q^2_{min} is constrained by x and the mass of the projectile. For hadron beams, the maximum of Q^2 is given by a form factor. In configuration space, this corresponds to $Q^2_{max} = (1/R)^2$.

Integrating over all virtualities gives the following equivalent photon spectrum (energy in the rest frame of the target).



The Equivalent Photon Luminosity

The total photon spectrum is obtained by integrating over all possible virtualities Q^2 with a form factor taking into account the finite size of the projectile

$$k\frac{dn}{dk} = \int k \frac{dn}{dk dQ^2} \left| F(Q^2) \right|^2 dQ^2$$

In the semi-classical picture, this corresponds to integrating over all impact parameters b > R.

For a nucleus-nucleus collision, it's however more appropriate to work in impact parameter space with a cut-off at b>2R and use

$$k\frac{dn}{dk} = \int k \frac{dn}{dk db^2} db^2$$

with

$$k\frac{dn}{dk db^2} = \left| \int E(\bar{b}, t) e^{ikt} dt \right|^2$$

G Baur and L.G. Ferreira Filho: Nucl. Phys A 518 (1990) 786.
R.N. Cahn and J.D. Jackson: Phys. Rev. D 42 (1990) 3690.

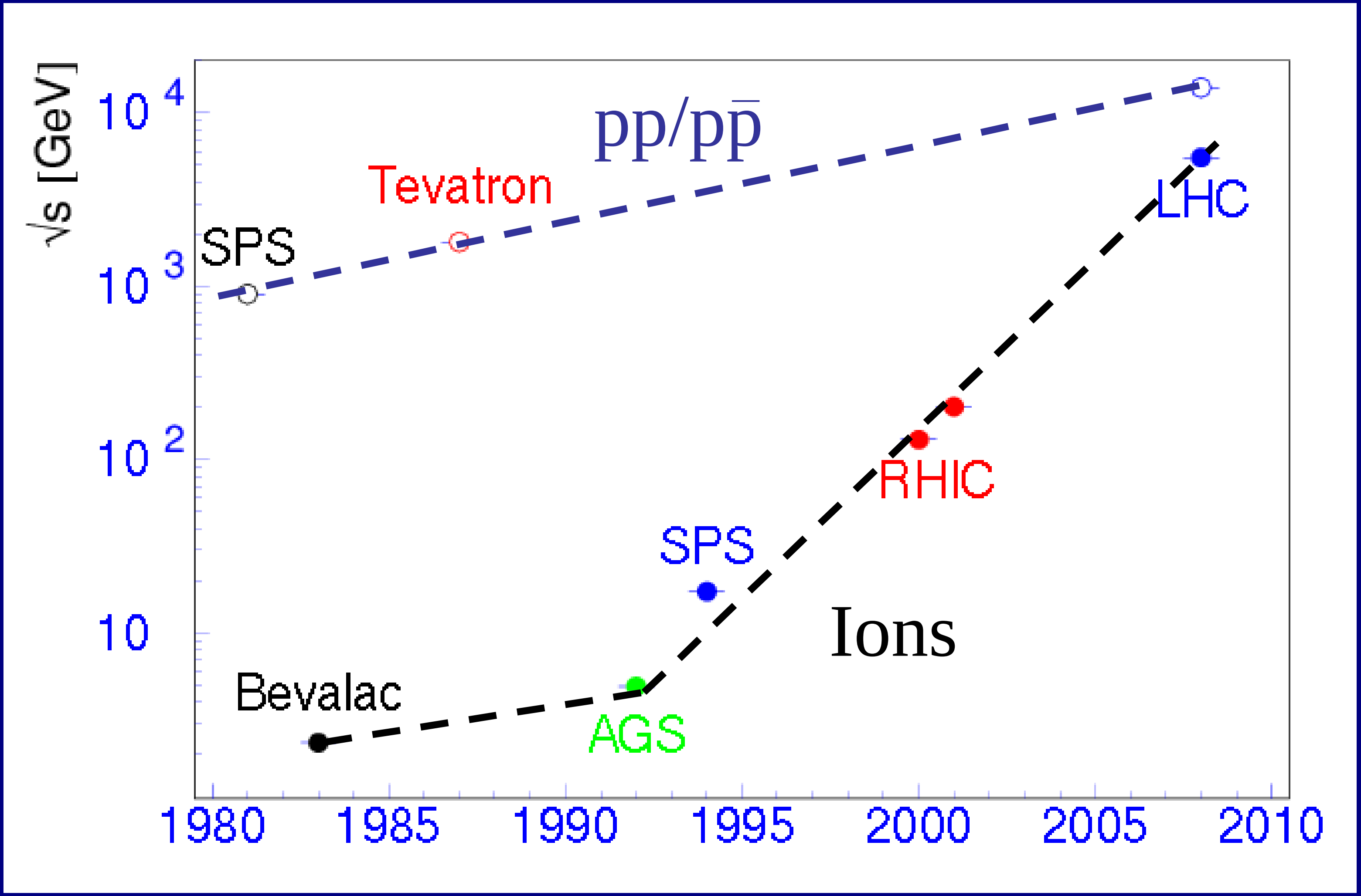
The idea to use heavy-ions to study electromagnetic interactions is of course not new

Charged particles are able to excite nuclei without penetrating into the nucleus by means of the action of the their electric field upon the nucleus when they pass nearby.
V.F. Weisskopf, Physical Review, 1938.

The novel feature is the extremely high photon energies available, higher even than with any existing or planned lepton beams, and that *particle production* can be studied!

This has earlier only been possible with lepton beams, for example in e^+e^-, e+p, e+nucleus interactions.

The maximum $\sqrt{s}_{nn}$ of truly heavy ions has increased dramatically during the last 25 years:



Electromagnetic Interactions in p+p and A+A vs. in e+p(A) and e+e Collisions

Traditionally, photon-induced interactions have been studied with electron beams:

Two-photon interactions at PEP, Petra, LEP.

Photon-proton interactions at HERA and in fixed target expts w/ electron beams.

Difference between leptons and protons/nuclei as γ sources:

- Leptons only interact electromagnetically (and weakly).
- With hadronic beams, also strong interactions can occur and these must be suppressed.
- The photon spectra are restricted by the form factor of the photon emitter.

Electromagnetic Interactions in p+p and A+A vs. in e+p(A) and e+e Collisions

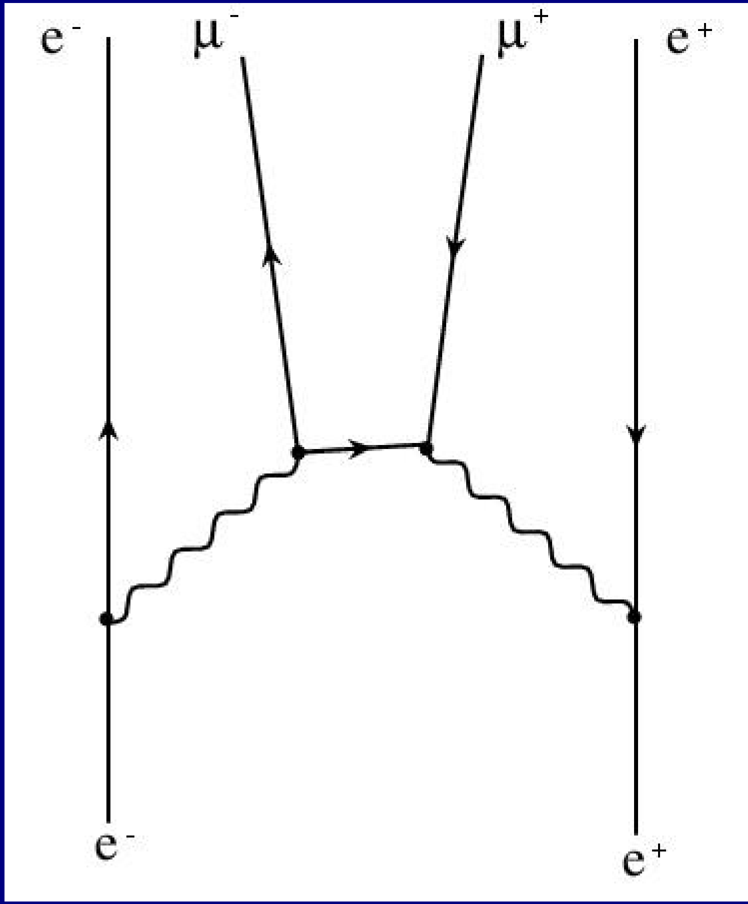
Why study electromagnetic interactions at hadron colliders?

- Higher photon energies than at any existing accelerator (LHC).
- Very little data on photonuclear interactions at high energies. Nuclear parton distributions poorly known.
- An opportunity to study strong electromagnetic fields (coupling $Z\sqrt{\alpha}$ rather than $\sqrt{\alpha}$ in heavy-ion collisions).
- Interference between the photon-emitter and target.
- An opportunity to search for the Odderon.

Suppose we want to calculate the process

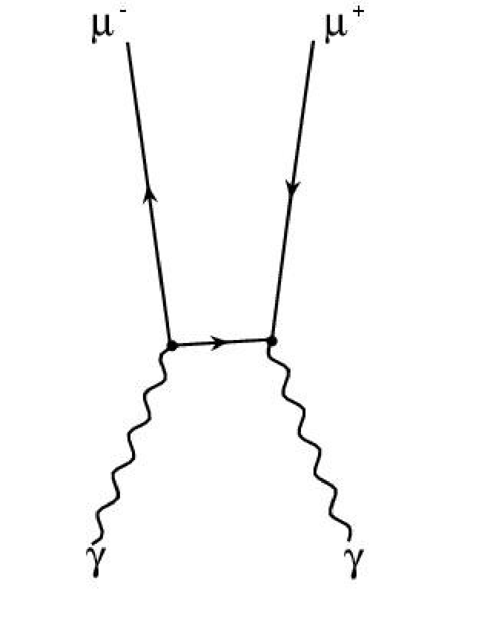
$e^+e^- \rightarrow e^+e^- + \mu^+\mu^-$

This would correspond to the following diagram:



4 vertices, 3 internal lines not easy …

Instead, calculate the cross Section for $\gamma\gamma \rightarrow \mu^+\mu^-$

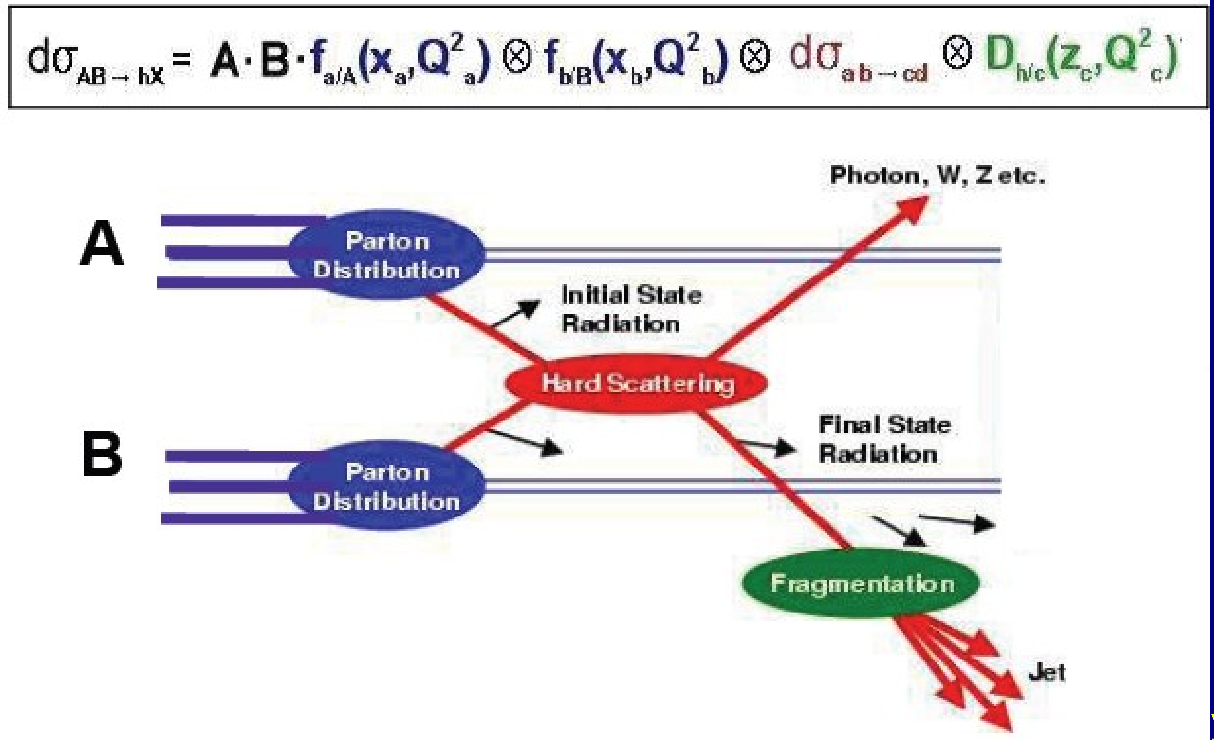


And use the method of equivalent photons:
Each electron has a photon-spectrum $n(\omega) = dn_\gamma/d\omega$

$$\sigma(e^+e^- \rightarrow e^+e^- + \mu^+\mu^-) = \int\int n(\omega_1)n(\omega_2)\sigma(\gamma\gamma \rightarrow \mu^+\mu^-)d\omega_1 d\omega_2$$

We can of course replace the e+ e– with nuclei,
Pb+Pb $\rightarrow$ Pb+Pb + $\mu^+\mu^-$; just leads to a different $n(\omega)$.

Note also the similarity with calc. of hard processes in pp/PbPb:



Method of equivalent photons for photonuclear interactions

To each source we associate a photon flux (i.e. a certain number of photons per energy interval, $dn_\gamma/d\omega$)

$$\sigma(A + A \rightarrow A + X) = 2\int n(\omega)\sigma_{\gamma A \rightarrow X}(\omega) d\omega$$

The “2” just takes into account that both nuclei can emit photons.

Integral between some ω_{min} and ω_{max}.

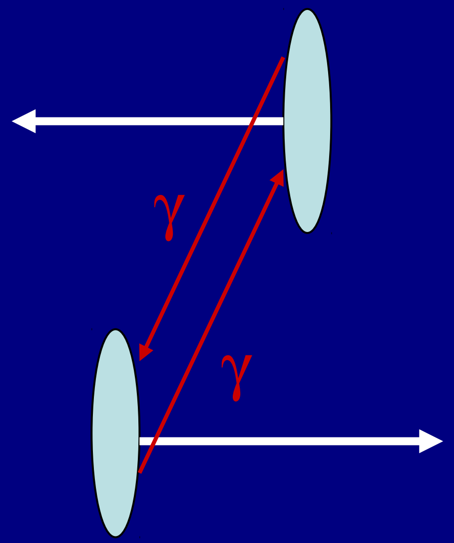
Natural cut-offs:

ω_{min} – threshold for the reaction $\gamma A \rightarrow X$.

ω_{max} – cut off by the photon spectrum; $\omega_{max} << E_{beam}$ for protons and nuclei.

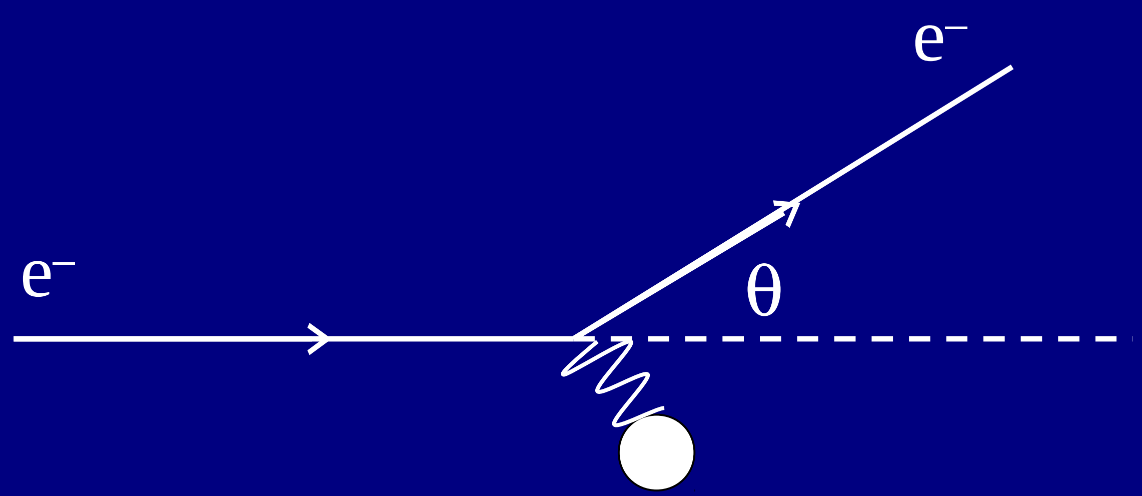
Electromagnetic interactions in heavy-ion interactions vs. in e^+e^- and ep (eA)

- Directional symmetry. Both beams (nuclei) and can act as photon emitter or target.
- Away from y=0, the different photon emitter/target combinations give different contributions.
- Strong fields lead to high probability for emission of multiple photons.



Energy and momentum of the photon

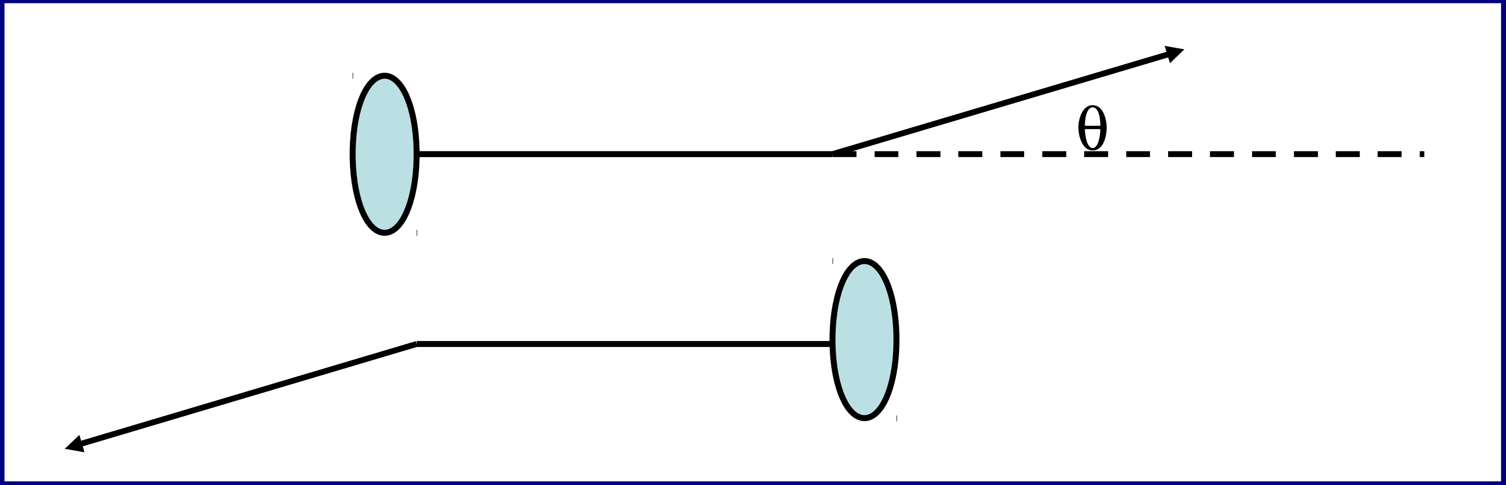
If we measure the scattered electron (E,**p**), we know the 4-momentum of the exchanged photon



“electroproduction” - the outgoing electron is detected, implies rather large Q^2.

“photoproduction” - the outgoing electron is not detected, Q^2 can be small.

No tagging of nuclei



The coherence requirement limits the angular deflection to

$$\theta \sim 0.175 / (\gamma \cdot A^{4/3})$$

At RHIC

Au	A=197	θ ~ 1 μrad
Si	A=28	θ ~ 17 μrad

At LHC

Pb	A=208	θ ~ 0.05 μrad
Ar	A=40	θ ~ 0.3 μrad

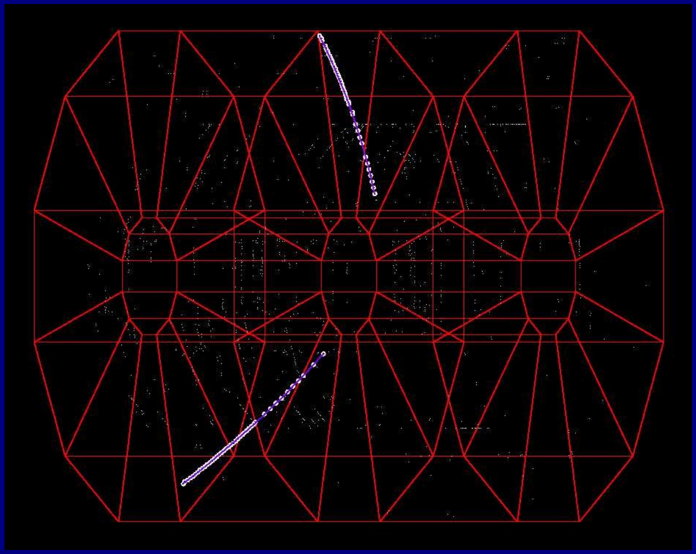
⇒Not possible to tag the outgoing nuclei. Might be possible with protons.

Experimental method: Rapidity gaps, reconstruct the entire event, signal of coherence from low p_T.

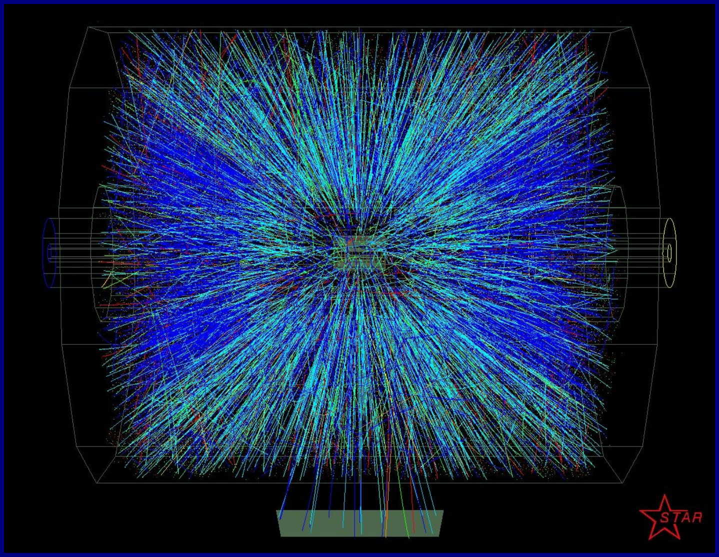
Experimental observation of UPC

Compare central and ultra-peripheral collision

2 tracks



> 1,000 tracks



Reconstructing an UPC event is usually not a problem.

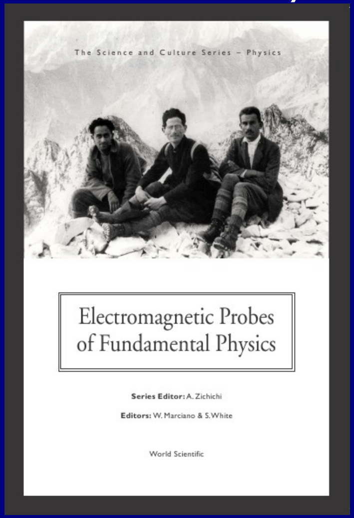
The main challenge is triggering:

Trigger on events with low multiplicity around mid-rapidity with veto (rapidity gaps) on either side.

Outlook from 12 years ago

Workshop on Electromagnetic Probes of Fundamental Physics, Erice, Sicily, 16 – 21 October 2001.

Results summarized in “Hot topics in ultra-peripheral ion collisions”, http://arxiv.org/abs/hep-ex/0201034.



Proceedings edited by S. White and W. Marciano.

- What was expected?
- What has been done?
- What was not expected?
- What can be done in the future?

Outlook from 12 years ago

What is the most interesting physics? (from "Hot topics in ultra-peripheral ion collisions", http://arxiv.org/abs/hep-ex/0201034):

1. Gluon shadowing in Nuclei.

2. Pomeron Couplings to Nuclei.

3. Interferometry with Short-Lived Particles.

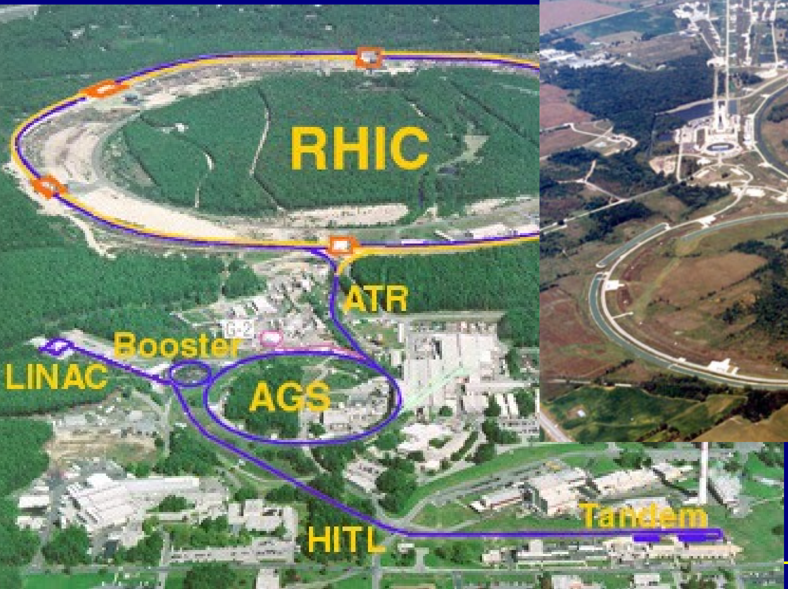
4. Searches for New Physics:
   - Triple gauge coupling γWW from $\gamma\gamma \rightarrow WW$ interactions.
   - Two-photon production of Higgs and Z-pairs.
   - Search for glueballs and other exotic bound states.

Experimental Results on Ultra-Peripheral Collisions
The Hadron Colliders RHIC, Tevatron and LHC

RHIC (1st collisions 2000):
Au+Au at $\sqrt{s_{nn}}$ = 200 GeV; p+p at $\sqrt{s}$ = 200 and 500 GeV.

Tevatron (1987 - 2011):
p+p at $\sqrt{s}$ = 1.8 and 1.96 TeV

LHC (2009 -):
Pb+Pb at $\sqrt{s_{nn}}$ = 2.76 (5.5) TeV; p+p at $\sqrt{s}$ = 7,8, (14) TeV.



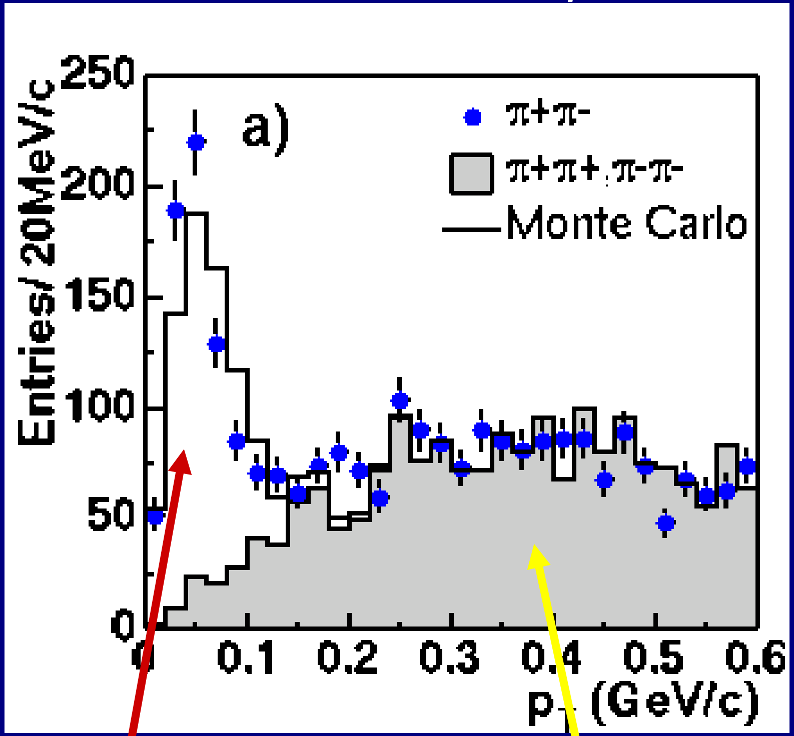
The first UPC result from RHIC

Exclusive ρ^0-production, Au+Au→Au+Au+ρ^0
(C. Adler et al. (STAR Collaboration) PRL 89(2002)272302).

"Two charged particles in an otherwise empty detector"

Clear signal for coherent production seen in p_T distribution.

Run 1 $\sqrt{s_{NN}}$ = 130 GeV –
Identification of coherent ρ^0.



Signal+background, unlike-sign pairs

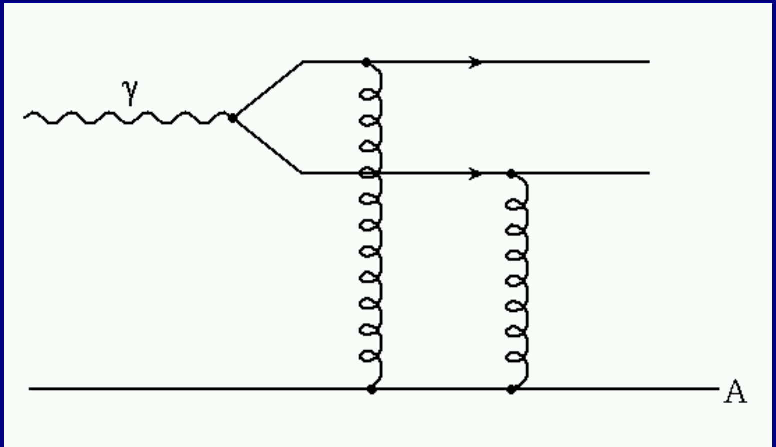
background, like-sign pairs

1. Gluon shadowing in Nuclei

Exclusive photoproduction of heavy vector mesons calculable from pQCD

$$\frac{d\sigma}{dt}\bigg|_{t=0} = \frac{\alpha_s^2\Gamma_{ee}}{3\alpha M_V^5}16\pi^3[xg(x,\frac{M_V^2}{4})]^2$$ Ryskin 1993

$\Rightarrow$ Sensitive probe of g(x), $[(g(x))^2]$

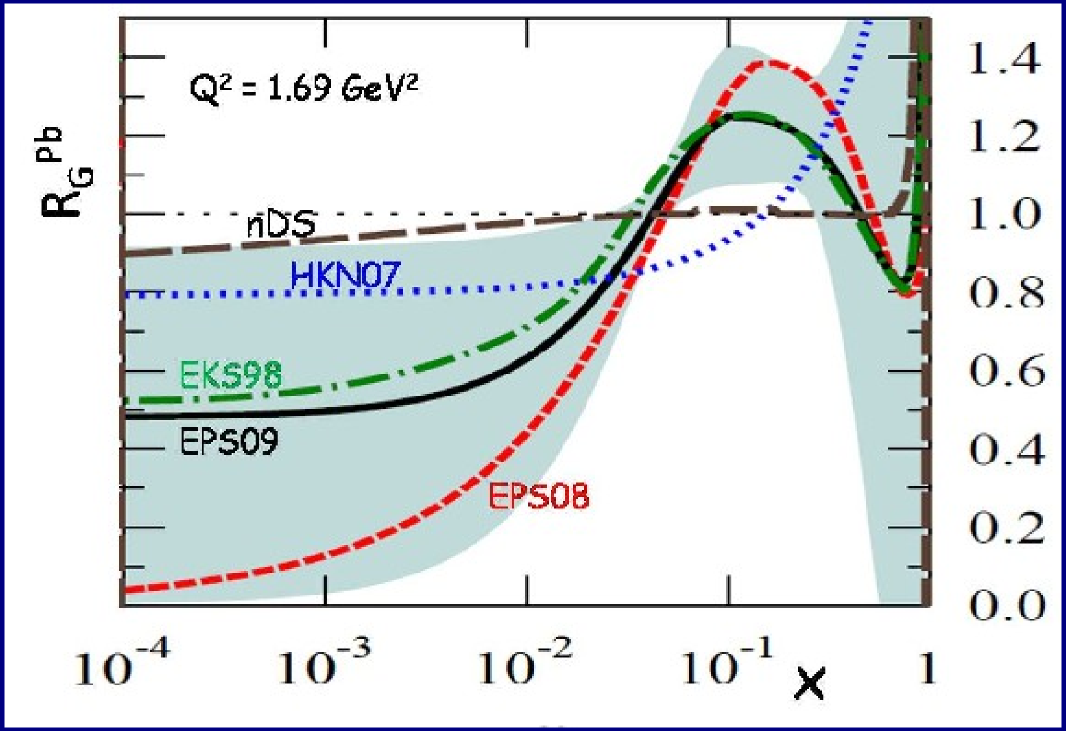


Two gluons can be exchanged without color transfer ↔ exchange of a Pomeron

Also studied by Frankfurt LL, McDermott MF, Strikman M, *J. High Energy Physics* 02:002 (1999) and
Martin AD, Ryskin MG, Teubner T *Phys.Lett.* B454:339 (1999)

1. Gluon shadowing in Nuclei

Big uncertainties in the nuclear gluon distribution. Different parameterizations available.



Measuring exclusive vector meson production at the LHC can Improve this for $Q^2 \sim M_V^2$ and $x \approx 10^{-2} - 10^{-4}$ (x range is rapidity dependent).

1. Gluon shadowing in Nuclei

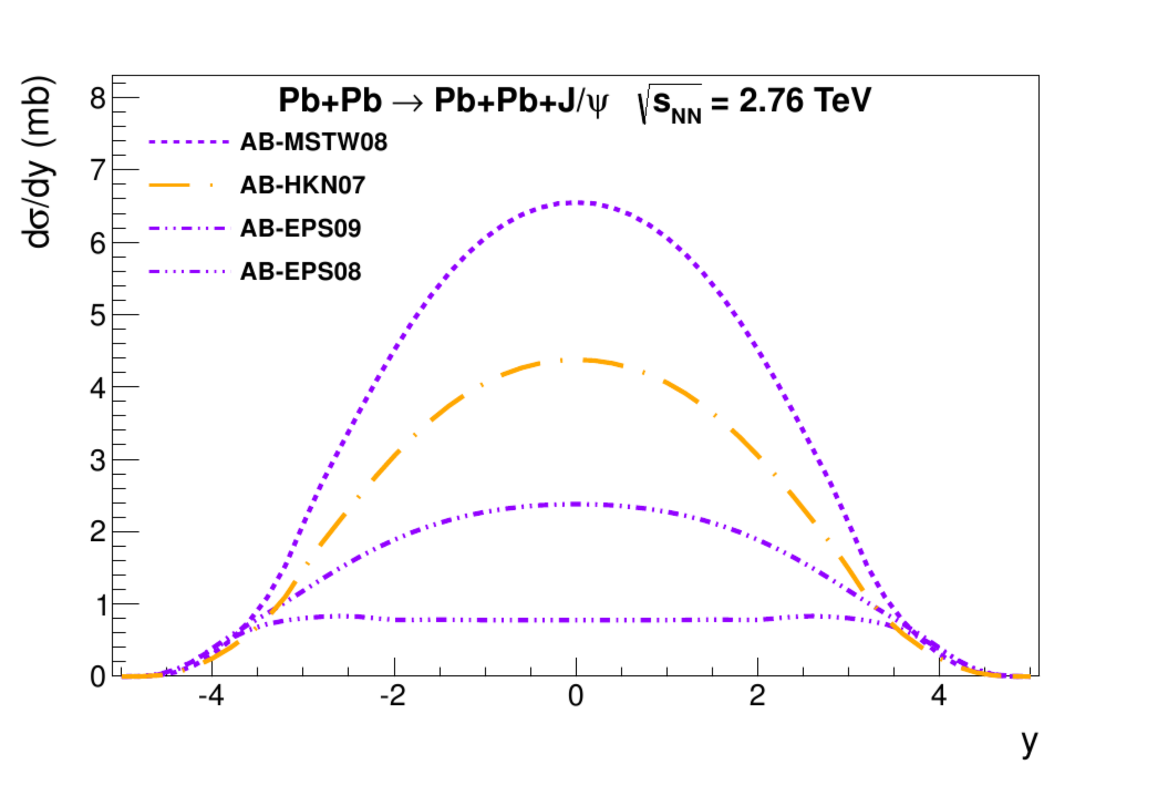
Calculation by Adeluyi and Bertulani assuming $\sigma \propto (g(x))^2$.
(Phys. Rev. C 85 (2012) 044904)

Normalizing to γp data from HERA.

MSTW08 – no nuclear effects (A^2 scaling)

HKN07, EPS09, EPS08 - different nuclear g(x).

Leads to very different cross sections for J/ψ, especially at midrapidity!



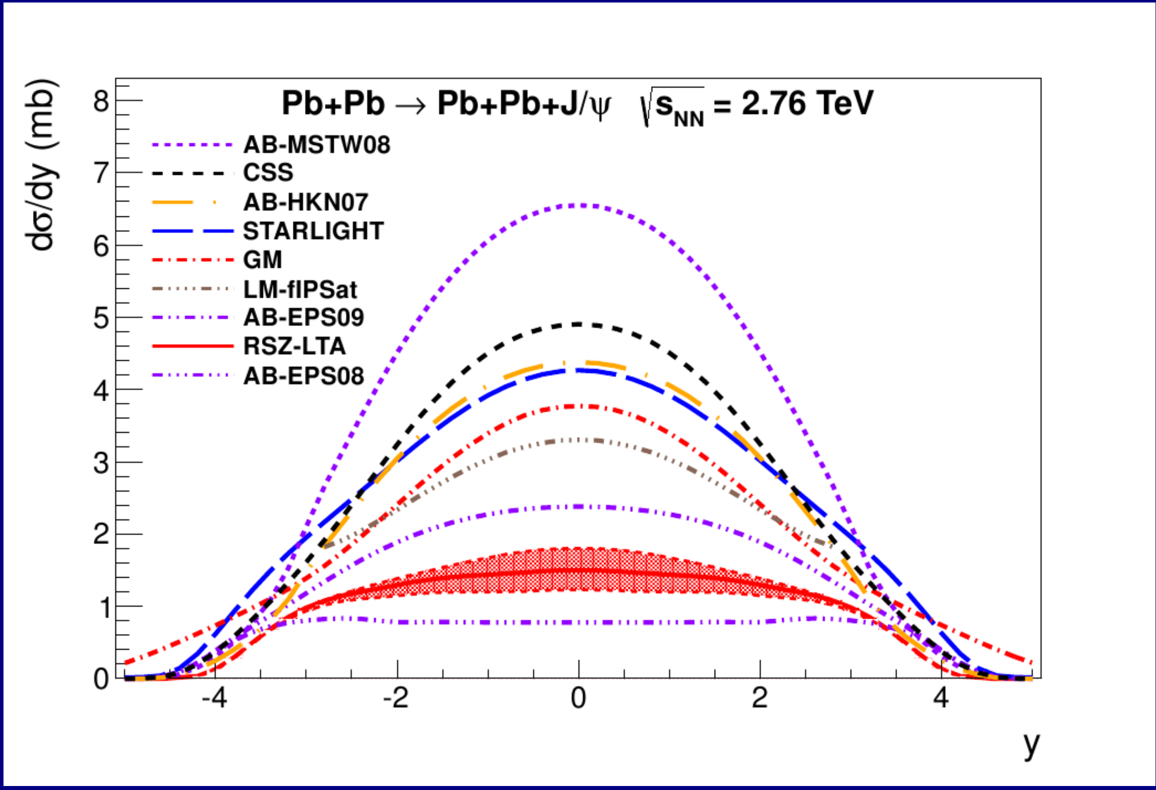
1. Gluon shadowing in Nuclei

Also other models on the market

Many based on the Color Dipole Model (CSS, GM, LM-fIPSat).

RSZ-LTA – calculates nuclear shadowing from Leading Twist Approximation

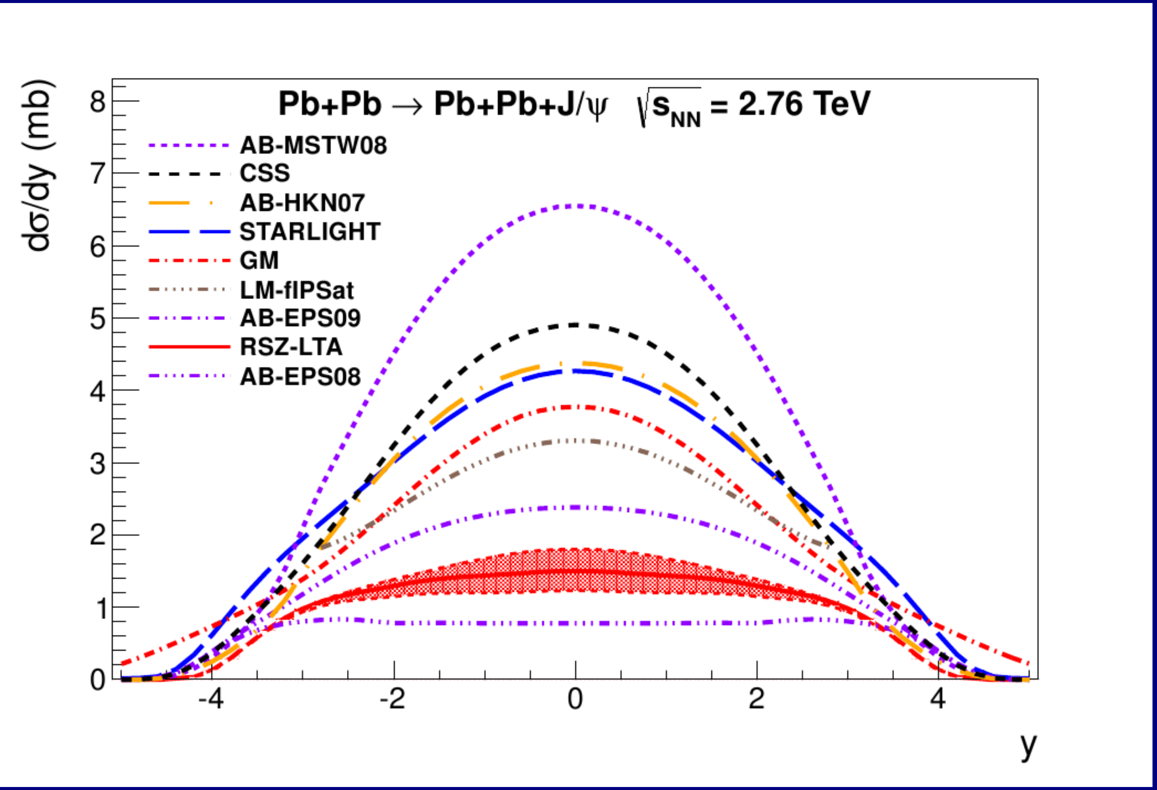
STARLIGHT – scales the measured p cross section using a Glauber Model.



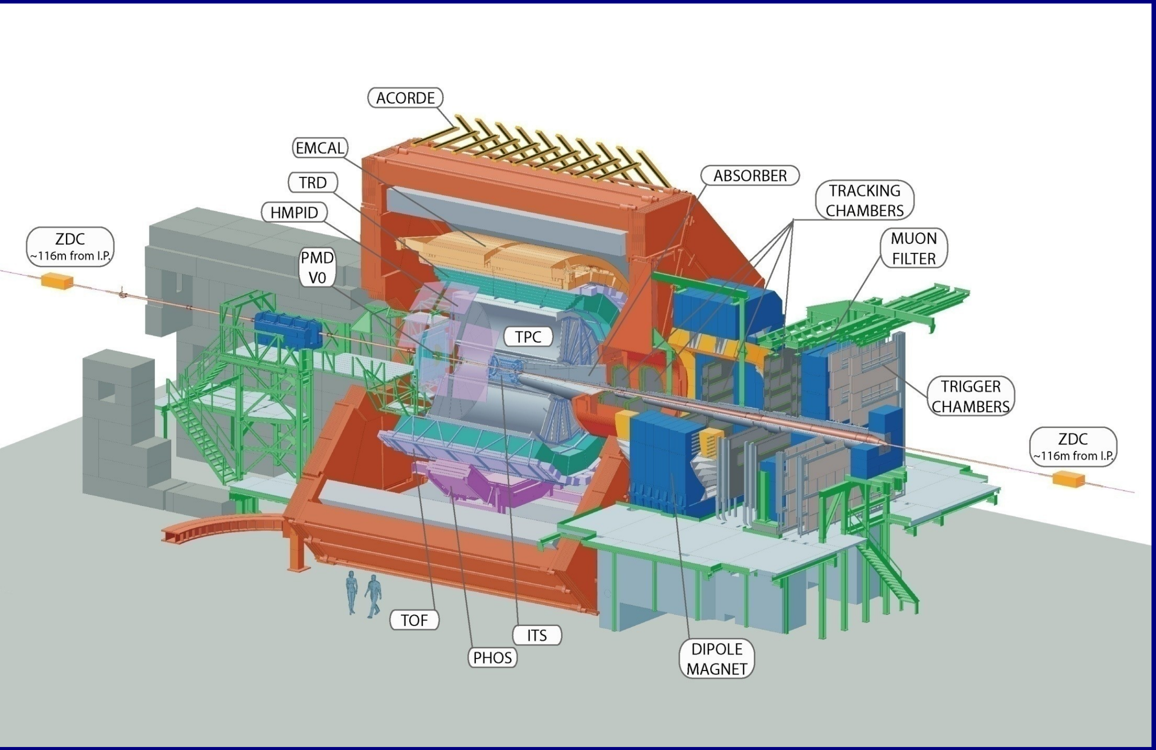
For exact references, see arxiv:1305.1467

1. Gluon shadowing in Nuclei

This was the situation ~1 year ago.



The ALICE Experiment at the LHC

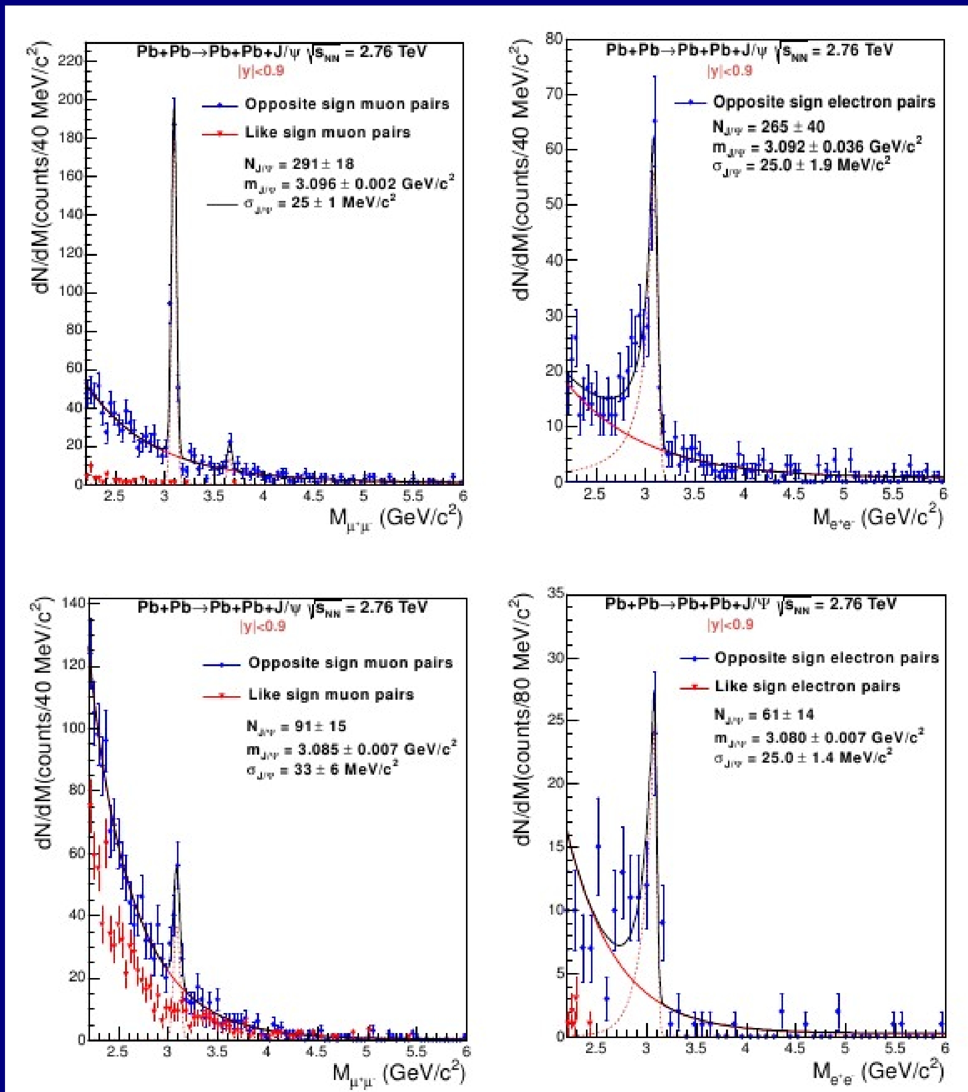


- A central tracking system (ITS + TPC) with particle identification.
- Acceptance |η| ≤ 0.9, p_T > 100 MeV/c
- Trigger from SPD and TOF

- A muon arm at forward rapidities -4.0 < η < -2.5.
- Triggering, tracking and identification of muons.
- VZERO counters for triggering and vertex determination; used here as veto detectors to define rapidity gaps (-3.7 < η < -1.7) and (2.8 < η < 5.1).
- Zero-Degree Calorimeters (ZDC) – 116 m from interaction point.

Exclusive J/ψ production in Pb-Pb collisions

Invariant mass distributions – midrapidity

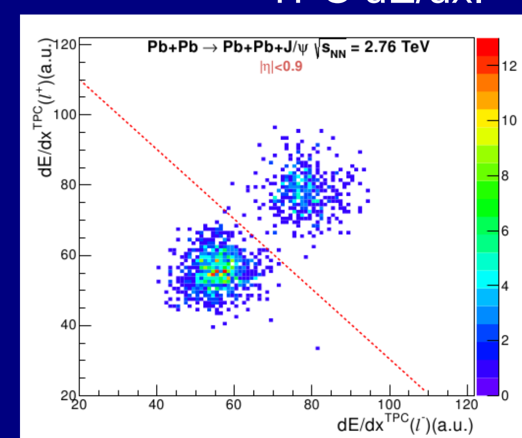


Coherent selection.
p_T < 0.2(μ) / 0.3 (e) GeV/c.

J/ψ and continuum $\gamma\gamma \rightarrow l^+l^-$ contribution.

Incoherent selection.
p_T > 0.2 (μ) / 0.3 (e) GeV/c.

e/μ separation
TPC dE/dx.

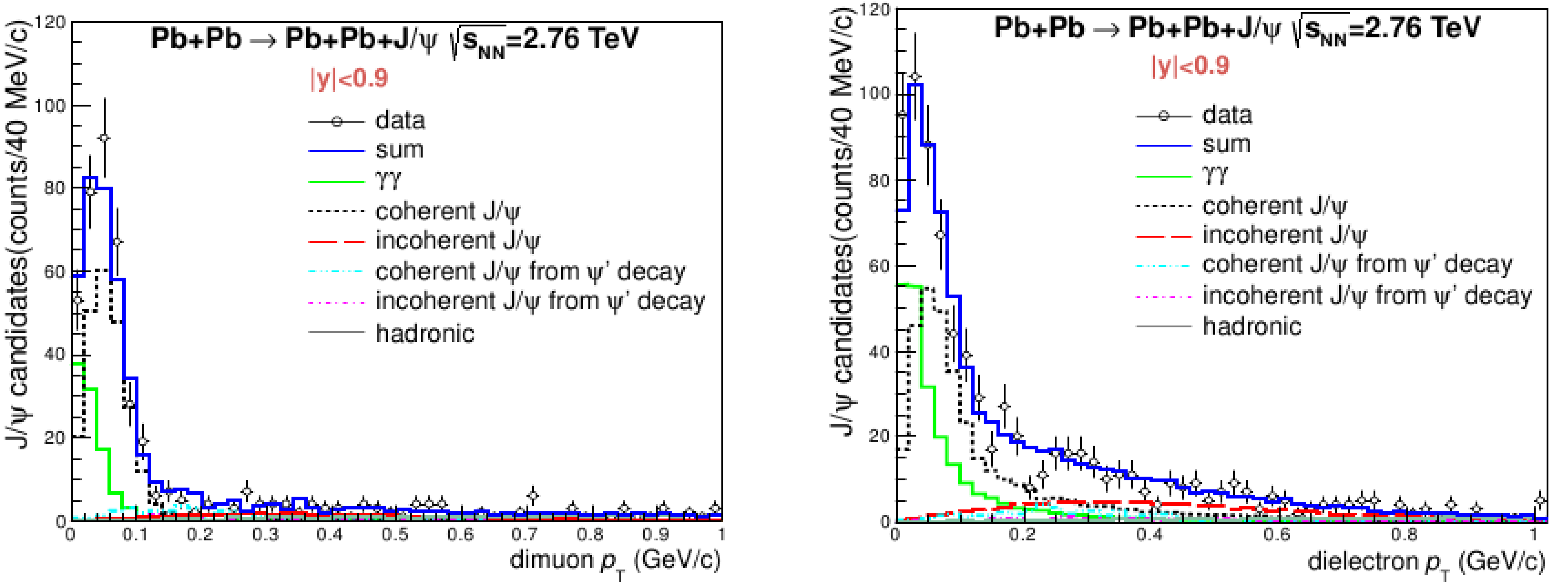


ALICE Collaboration, arxiv:1305.1467

Exclusive J/ψ production in Pb-Pb collisions

Transverse momentum distributions – midrapidity

ALICE Collaboration, arxiv:1305.1467



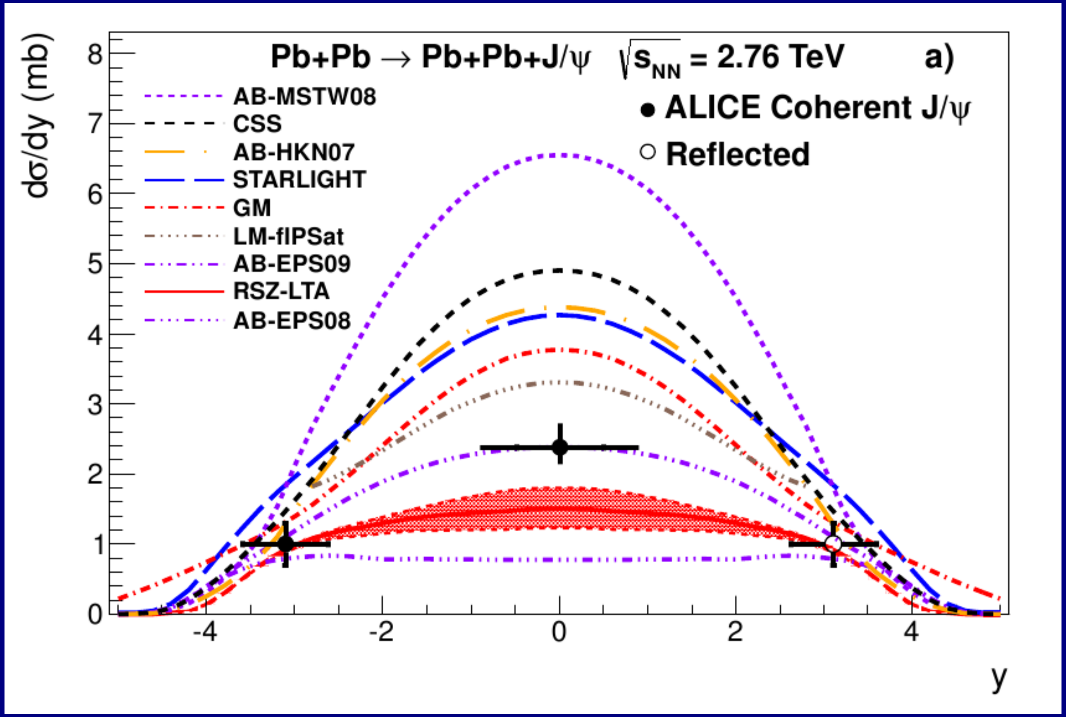
Clear coherent peak from J/ψ and continuum $\gamma\gamma \rightarrow l^+l^-$ observed at low p_T.

Full spectrum explained by, in addition, incoherent J/ψ, J/ψ from feed down from ψ', and some hadronic contribution at high p_T.

Templates from STARLIGHT Monte Carlo (photoproduction) and from data at higher centralities (hadronic).

1. Gluon shadowing in Nuclei

Result from ALICE on exclusive production of J/ψ.



ALICE Collaboration

Phys. Lett. B 718 (2013) 1273

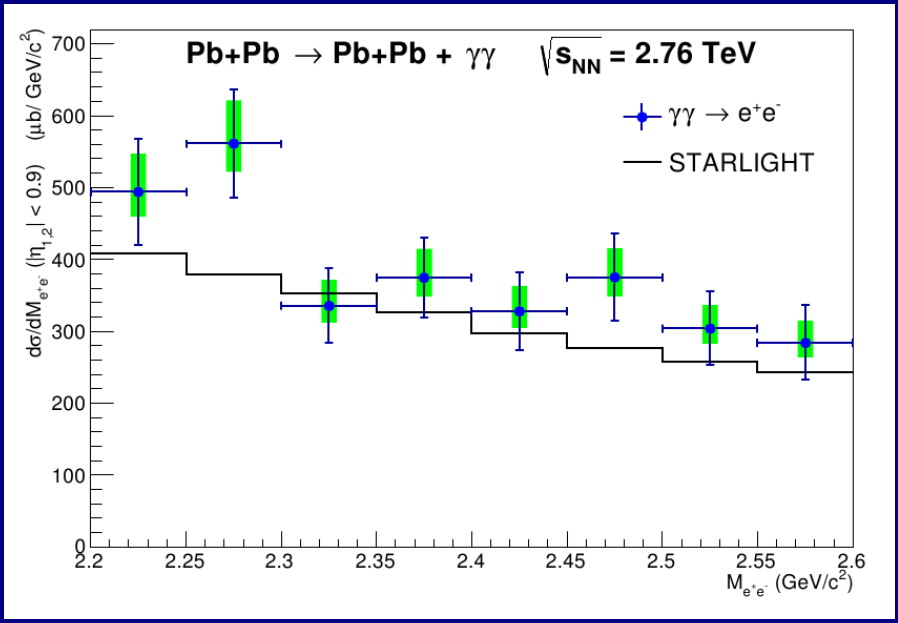
and

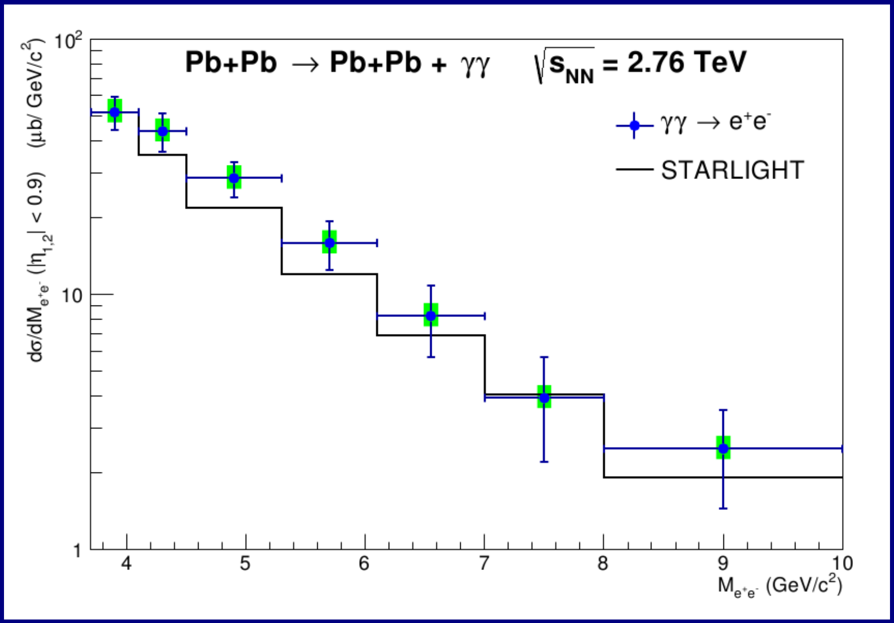
arxiv:1305.1467

This result from ALICE shows that the distribution in the $x \approx 10^{-2} - 10^{-3}$ range is consistent with the EPS09 parameterization.

ALICE has also measured the QED process $\gamma\gamma \rightarrow e+e-$

Measurement outside the J/ψ peak:
$2.2 < m_{inv} < 2.6$ GeV, $3.7 < m_{inv} < 10.0$ GeV

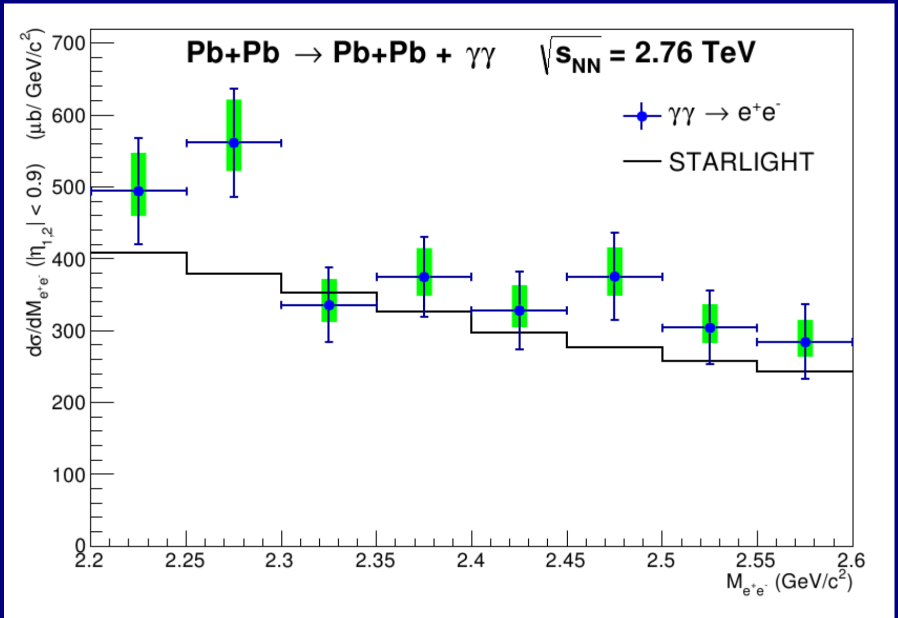


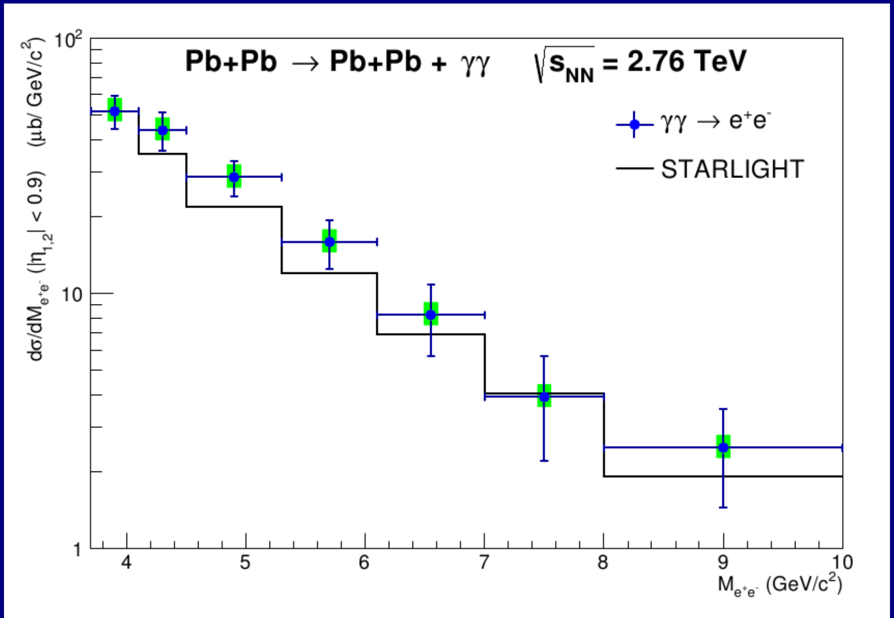


ALICE		STARLIGHT
$\sigma(2.2<m_{inv}<2.6$ GeV, $\lvert y\rvert<0.9$, $\lvert\eta_{1,2}\rvert<0.9)$	$= 154 \pm 11$ (stat.) +17/-11 (syst.) μb	128 μb
$\sigma(3.7<m_{inv}<10.0$ GeV, $\lvert y\rvert<0.9$, $\lvert\eta_{1,2}\rvert<0.9)$	$= 91 \pm 10$ (stat.) +11/-8 (syst.) μb	77 μb

Experimental uncertainty ≈15%. Most accurate heavy-ion measurement of $\gamma\gamma \rightarrow e+e-$ so far. (arxiv:1305.1467)

ALICE has also measured the QED process $\gamma\gamma \rightarrow e+e-$





ALICE		STARLIGHT
$\sigma(2.2<m_{inv}<2.6$ GeV, $\lvert y\rvert<0.9$, $\lvert\eta_{1,2}\rvert<0.9)$	$= 154 \pm 11$ (stat.) $+17/-11$ (syst.) μb	128 μb
$\sigma(3.7<m_{inv}<10.0$ GeV, $\lvert y\rvert<0.9$, $\lvert\eta_{1,2}\rvert<0.9)$	$= 91 \pm 10$ (stat.) $+11/-8$ (syst.) μb	77 μb

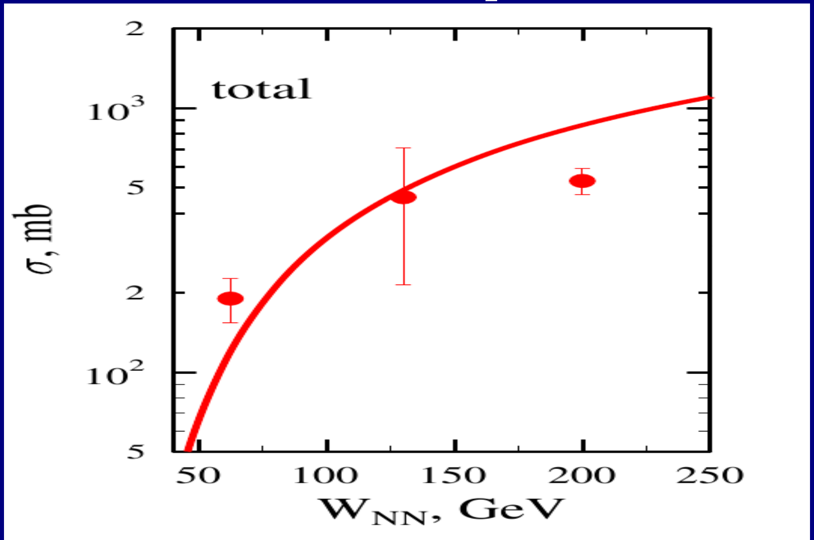
Shape and magnitude of cross section in agreement with STARLIGHT.

STARLIGHT includes the LO Born term and calculates the Weizsacker-Williams spectrum of equivalent photons in impact parameter space.
(A.J. Baltz, Y. Gorbunov, S.R. Klein, J. Nystrand, Phys. Rev. C 80 (2009) 044902).

2. Pomeron Couplings to Nuclei

Exclusive (light) vector meson photoproduction, γ+A $\rightarrow$ V+A.

Exclusive ρ^0 production measured by STAR at $\sqrt{s_{NN}}$ = 62.4, 130, and 200 GeV [STAR Collaboration, PRL 89(2002)272302, PRC 77(2008)034910, PRC 85(2012)014910]



A Glauber model calculation (Rebyakova, Strikman, Zhalov, PLB 710 (2012) 647) overpredicts the measured cross section at 200 GeV by nearly a factor of 2.

2. Pomeron Couplings to Nuclei

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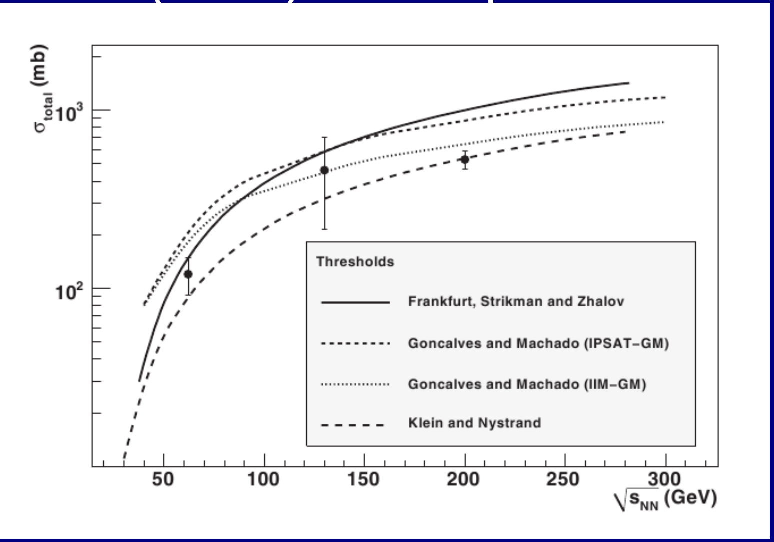
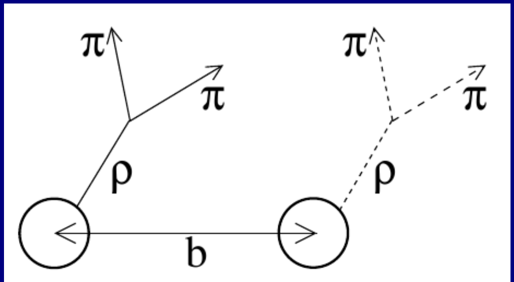


The cross section relatively well reproduced by STARLIGHT MC (based on Klein, Nystrand, PRC 60 (1999) 014903), which ignores the elastic part of the total cross section.

3. Interferometry with Short-Lived Particles

A vector meson can be produced on either nucleus in a A+A $\rightarrow$ A+A+V reaction.



The cross section is the sum of the two possibilities

$$\frac{d\sigma}{dydp_T} = \int_{b>2R} k_1 \frac{dN}{dk_1 d^2b} \sigma(\gamma A_2) f_{1,2}(p_T) + k_2 \frac{dN}{dk_2 d^2b} \sigma(\gamma A_1) f_{2,1}(p_T)\, d^2\vec{b}\,.$$

This can be written as the sum of two amplitudes squared

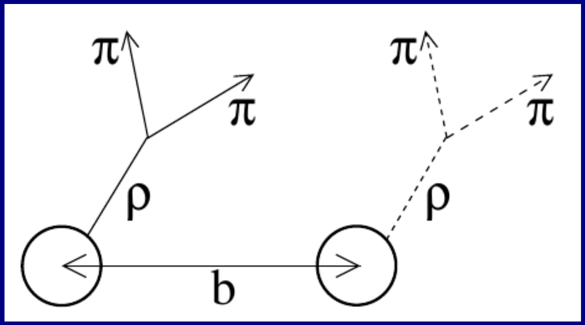
$$\frac{d\sigma}{dydp_T} = \int_{b>2R} \left(|A_1|^2 + |A_2|^2\right) d^2\vec{b}\,,$$

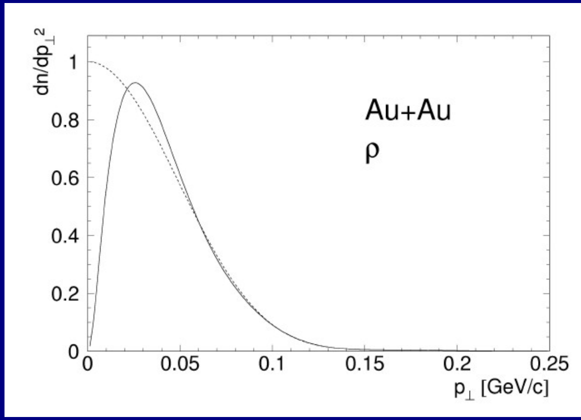
But when p_T << 1/b, interference becomes important and one must add the amplitudes:

$$\frac{d\sigma}{dydp_T} = \int_{b>2R} |A_1 + A_2|^2\, d^2\vec{b}\,.$$

3. Interferometry with Short-Lived Particles

A vector meson can be produced on either nucleus in A+A → A+A+V reactions.





S.R. Klein, J. Nystrand, Phys. Rev. Lett. 84 (2000) 2330;
K. Hencken, G. Baur, D. Trautmann, PRL 97 (2006) 012303.

Median separation between nuclei for light vector meson production typically ≈ 50 fm at RHIC.

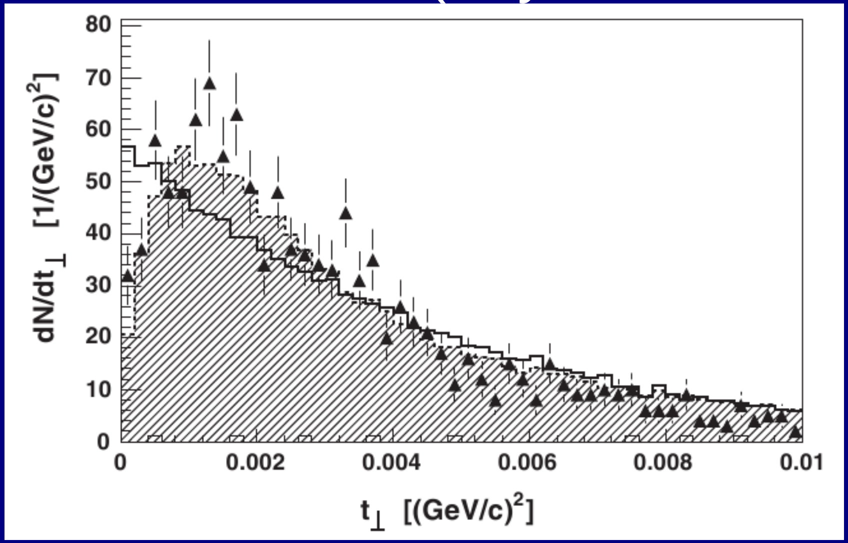
For $p_T < \approx 1/50$ fm ≈ 5 MeV/c, the interference will suppress the yield and modify the p_T spectrum.

But the life-time of the ρ^0 is only 1 fm/c, so it will have decayed long before information is propagated from one source two the other.

One thus has “interferometry with short-lived particles”.

3. Interferometry with Short-Lived Particles

Transverse momentum spectrum of exclusive ρ^0 studied in detail by STAR at RHIC (Phys. Rev. Lett. 102 (2009) 112301)



Solid histogram – no interference

Dashed histogram – with interference

Parameterize the p_T spectrum according to

$$\frac{dN}{dt} = A \exp(-kt)[1 + c(R(t) - 1)],$$

C = 0 – no interference

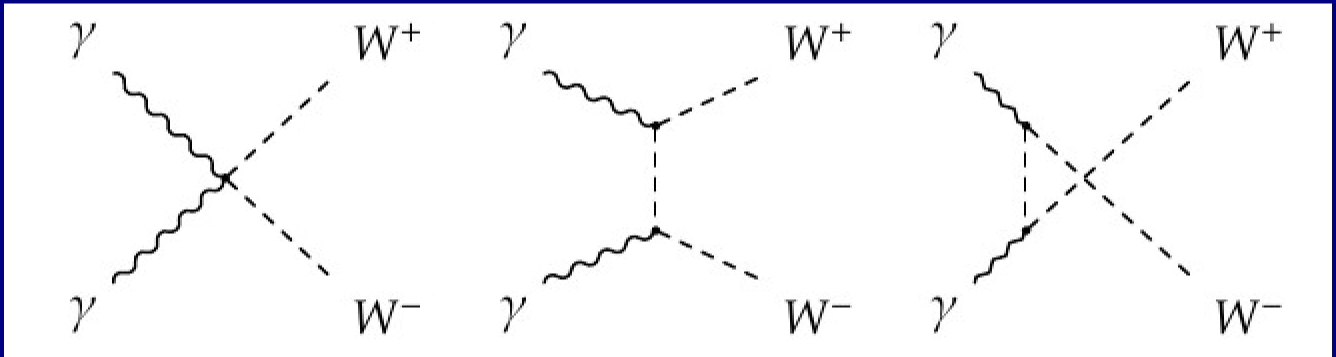
C = 1 – full interference

Obtain the result C = 0.87 ± 0.05(stat.) ± 0.08(syst.), consistent with full interference.

4. Searches for New Physics

- Triple gauge coupling γWW from $\gamma\gamma \rightarrow WW$ interactions.

LO diagrams for $\gamma\gamma \rightarrow WW$



Involves triple γWW and quartic $\gamma\gamma WW$ couplings

The *triple* couplings are better constrained from other measurements, but the *quartic* couplings are unique to two-photon interactions.

Recent first observation of $\gamma\gamma \rightarrow WW$ from CMS, arxiv:1305.5596. Finds 2 signal events to be compared with the SM prediction 2.2 ± 0.4 events. Sets best limits so far on anomalous $a^W_{0,C}$ couplings.

Recent constraints also from D0, Tevatron (observes no $\gamma\gamma \rightarrow WW$ events!), arxiv:1305.1258.

Outlook from 12 years ago

1. Gluon shadowing in Nuclei. ✓

2. Pomeron Couplings to Nuclei. ✓

3. Interferometry with Short-Lived Particles. ✓

4. Searches for New Physics:
   - Triple gauge coupling γWW from $\gamma\gamma \to WW$ interactions ✓
   - Two-photon production of Higgs and Z-pairs
   - Search for glueballs and other exotic bound states

But note that ✓ does not mean that the topic has been exhausted!

What was not expected?

(A personal and perhaps biased view)

"Ultra-peripheral collisions" can be studied also in pp collisions, for the certain final states. In addition to $\gamma\gamma \rightarrow WW$, results on

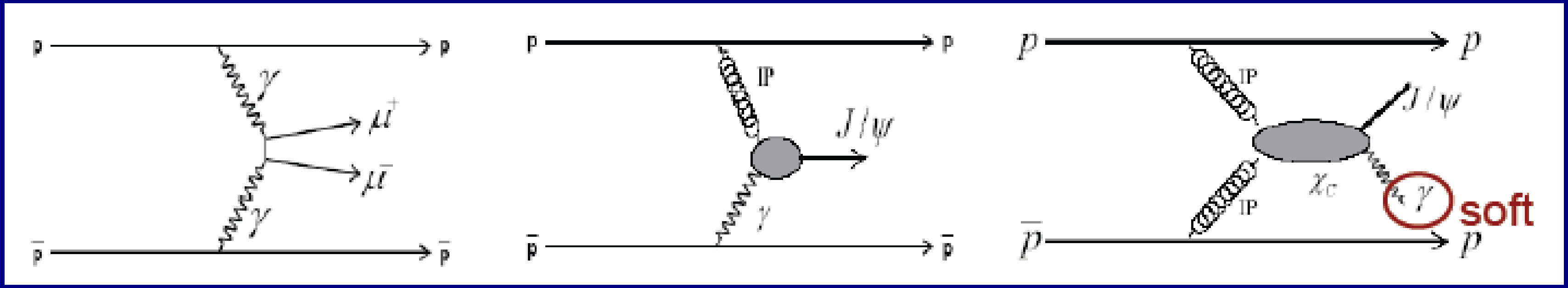
- Exclusive vector meson production, $\gamma + p \rightarrow J/\psi + p$. Predictions (S.R. Klein, J. Nystrand PRL 92 (2004) 142003) followed by data from CDF (PRL 102 (2009) 242001) and LHCb (J. Phys. G 40 (2013) 045001).

- Two-photon production of di-lepton pairs from CDF (PRL 102 (2009) 222002) and CMS (JHEP 01 (2012) 052).

Proton-Nucleus collisions provide an excellent opportunity to study certain γ+p interactions. Unlike in pp or AA collisions, the photon emitter (nucleus) and photon target (proton) can be separated.

”Ultra-peripheral” Collisions at the Tevatron

Three possible contributions to the process $p+\bar{p} \to p+\bar{p}+\mu^+\mu^-$:

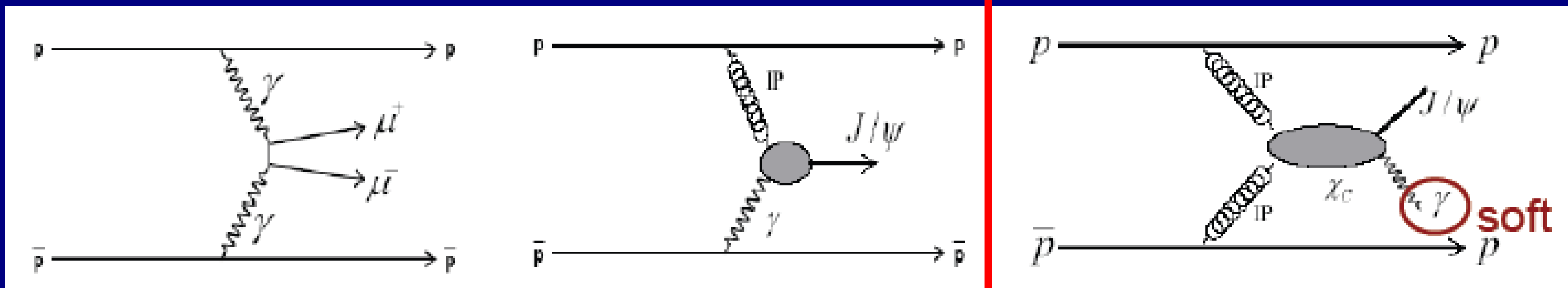


Note: no feed down from χ_c to Ψ’.

A contribution from Odderon+Pomeron also possible.

"Ultra-peripheral" Collisions at the Tevatron

Calculations for the first two ($\gamma\gamma$ and γP) – STARLIGHT MC:



$\sigma(pp \to pp + J/\Psi(1S))$: 19.6 nb $\sigma \cdot Br(\mu\mu)$: 1.16 nb

$\sigma(pp \to pp + \Psi'(2S))$: 3.2 nb $\sigma \cdot Br(\mu\mu)$: 23 pb

$\sigma(pp \to pp + \mu\mu)$: 2.4 nb ($m_{inv} > 1.5$ GeV/c^2)

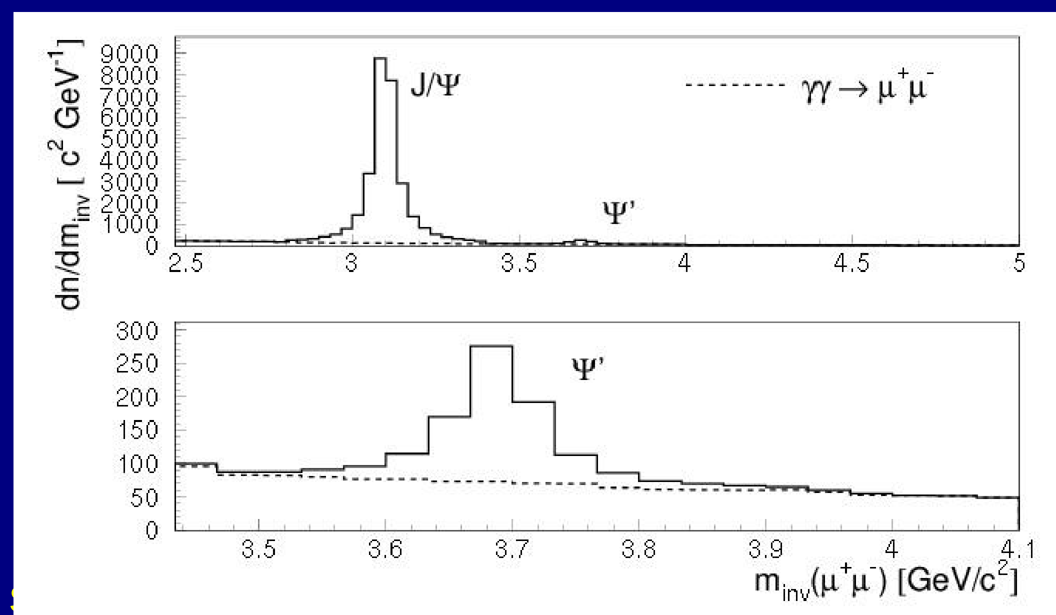
Applying cuts on the $\mu^+\mu^-$:

$p_T > 0.5$ GeV/c

$|\eta| < 2.0$ $\Rightarrow$

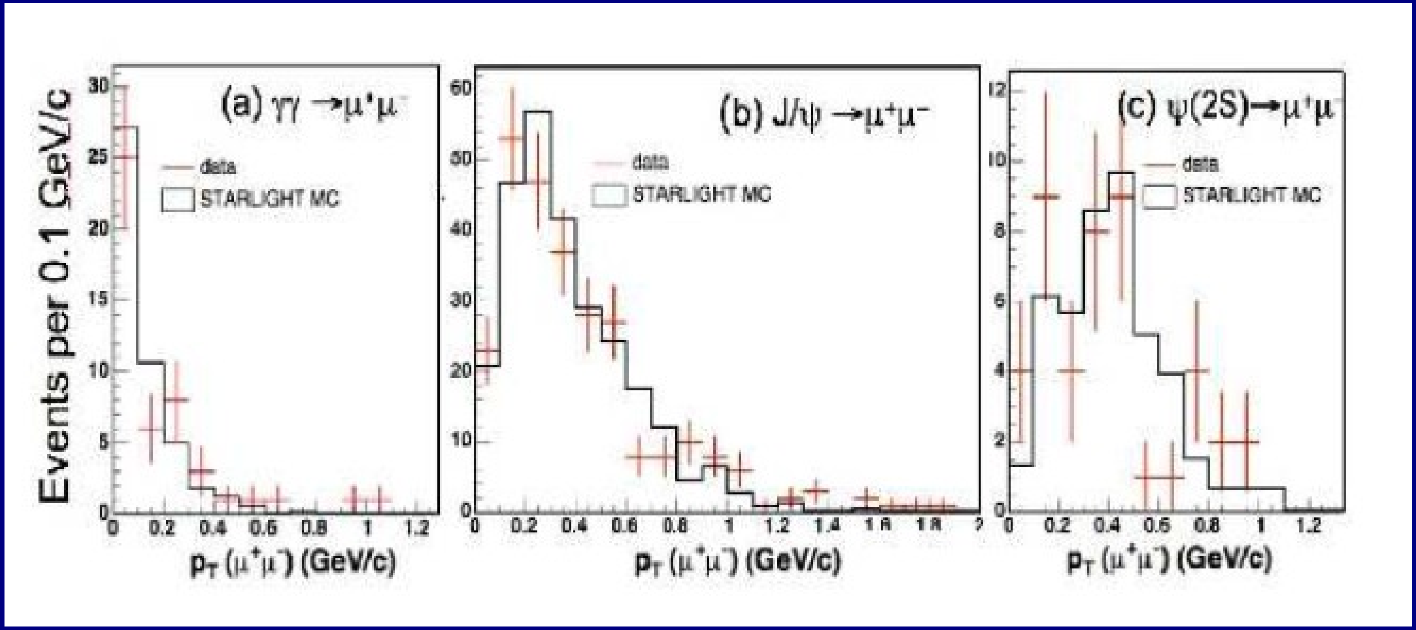
Yield(Ψ')/Yield(J/Ψ) ≈ 1:50

S.R.Klein, J.Nystrand, PRL 92 (2004) 142003 (J/Ψ only).



Ultra-Peripheral Collisions in CDF

p_T distributions in agreement with expectations.



(T.Aaltonen et al. (CDF Collaboration) arXiv:0902.1271)

Ultra-Peripheral Collisions in CDF

Comparison of cross sections:

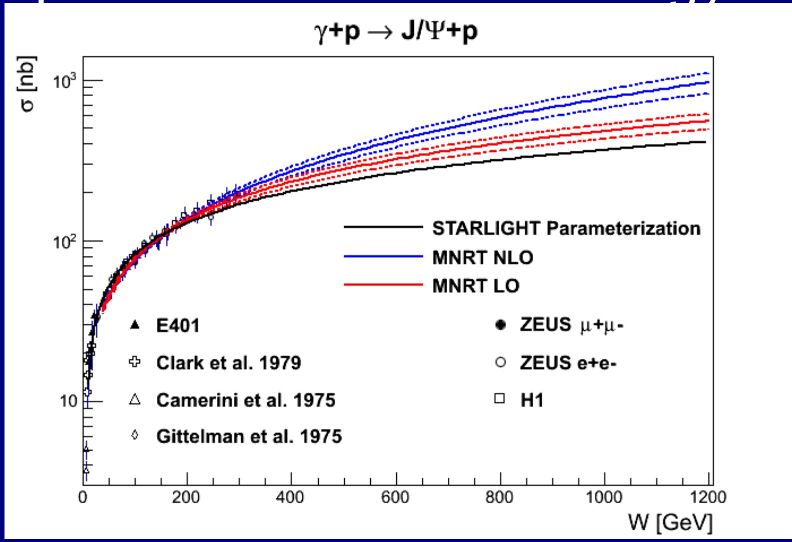
	Theory	CDF (PRL 102 (2009) 242001)
J/Ψ:	$\frac{d\sigma(y=0)}{dy} = 2.7^{+0.6}_{-0.2}\,\mathrm{nb}$	$\frac{d\sigma(y=0)}{dy} = 3.92 \pm 0.62\mathrm{nb}$
Ψ':	$\frac{d\sigma(y=0)}{dy} = 0.46^{+0.11}_{-0.04}\,\mathrm{nb}$	$\frac{d\sigma(y=0)}{dy} = 0.53 \pm 0.14\mathrm{nb}$

Sets a limit on the Odderon contribution to the J/Ψ (95% c.l.):

$$\frac{d\sigma(y=0)}{dy} < 2.3\mathrm{nb}$$

Exclusive vector meson production in p+Pb collisions at the LHC

Exclusive J/ψ photoproduction, γ+p → J/ψ+p, measured at HERA up to center of mass energy W = 300 GeV.



MNRT – Martin, Nockles, Ryskin, Teubner, PLB 662 (2008) 252, arxiv:1307.7099.

Also calculations in b-Sat model (Graeme Watt et al.), arxiv:1206.2913, 1211.4831.

In p+Pb, W given by rapidity of the J/ψ.

Examples: y = 4.0 (ALICE muon spectrometer) ==> W = 1200 GeV
y = 5 (LHCb) ==> W = 1900 GeV

A factor 4-6 higher than at HERA.

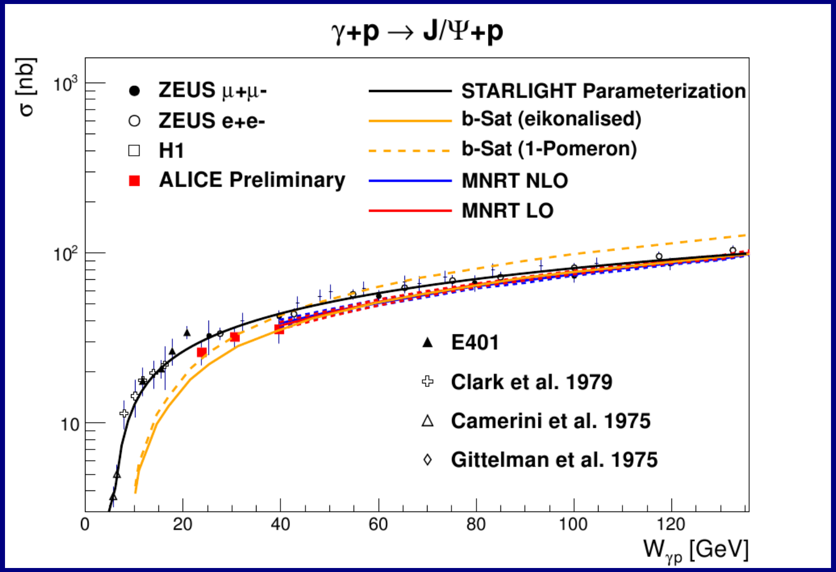
LHCb result in pp collisions (JPG 40 (2013) 045001) covers these energy ranges, but extracting σ(γ+p → J/ψ+p) ambiguous because of symmetry between photon target and emitter.

Exclusive J/ψ production in p-Pb collisions

Recent cross sections (ALICE Preliminary):
Presented by J. Nystrand at EPS HEP conference, Stockholm, July 2013, and by D. Tapia Takaki at SQM in Birmingham, July 2013.

Measurement with ALICE muon arm (2.5<y<4.0):

p-Pb : proton moves towards muon arm, $21 \leq W_{\gamma p} \leq 45$ GeV
Pb-p : Pb nucleus moves towards muon arm, $550 \leq W_{\gamma p} \leq 1160$ GeV



ALICE p-Pb result compared with data from fixed target experiments and model calculations.

b-Sat: arxiv:1206.2913; 1211.4831.
MNRT: PLB 662 (2008) 252.

What can be done in the future?

1) Exclusive vector mesons:

Higher collision energy; new species ψ', $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$; extended acceptance ==> Better constraints on gluon distribution, wider range of x and scale Q^2 ($\sim M_V^2$)probed.

2) Electroweak final states:

$\gamma\gamma \to WW$, $\gamma\gamma \to \gamma\gamma$, $\gamma\gamma \to ZZ$ $\gamma\gamma \to$ Higgs

3) Inclusive photoproduction of heavy quarks and jets.

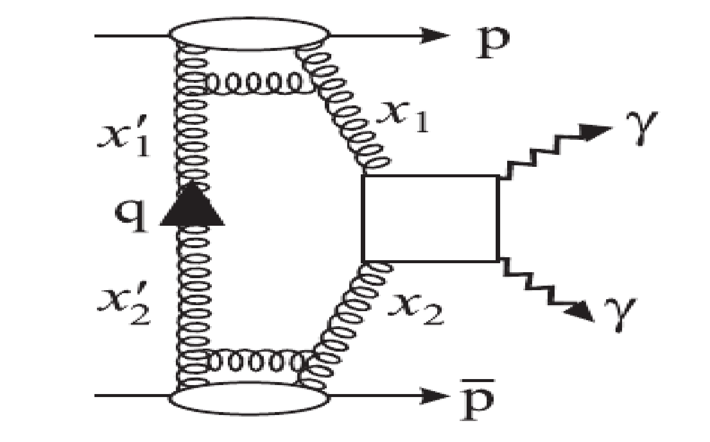
Photoproduction of ccbar through photo-gluon fusion, $\sigma \approx 1$ b in Pb+Pb collisions at the LHC (Klein, Nystrand, Vogt, Phys. Rev. C 66 (2002) 044906).
Photonuclear jet or dijet production, γ+parton $\to$ jet or dijet (Strikman, Vogt, White, PRL 96 (2006) 082001).

4) Meson spectroscopy (e.g. glueballs, excited vector meson states), high precision measurements of $\gamma\gamma \to e^+e^-$ to study QED with strong fields, using Roman pots to tag the outgoing protons might improve resolution and enable new final states to be studied ...

Exclusive production in pp vs. AA

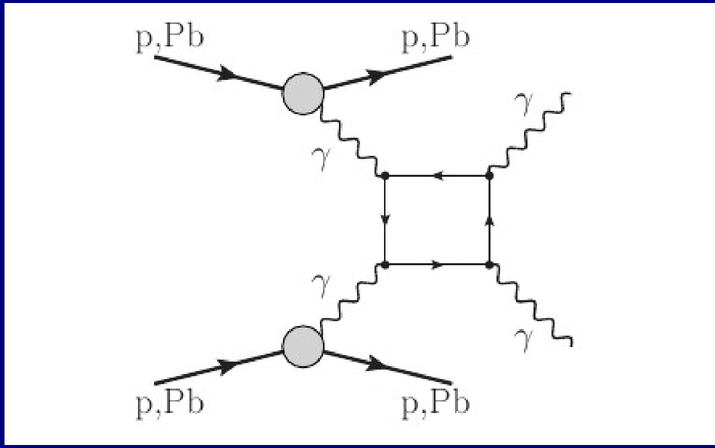
Different production mechanisms may dominate. Consider exclusive $\gamma\gamma$ (or Higgs) production:

p-p



V. A. Khoze, A.D. Martin, M.G. Ryskin, W.J. Stirling, Eur. Phys. J C 38 (2005) 475.

Pb-Pb



D. d'Enterria, G.G. Silveira, PRL 111 (2013) 080405.

In p-p collisions, 3 (or more) gluon exchange dominate, whereas for heavy-ion collisions, $\gamma\gamma\rightarrow\gamma\gamma$ dominate.

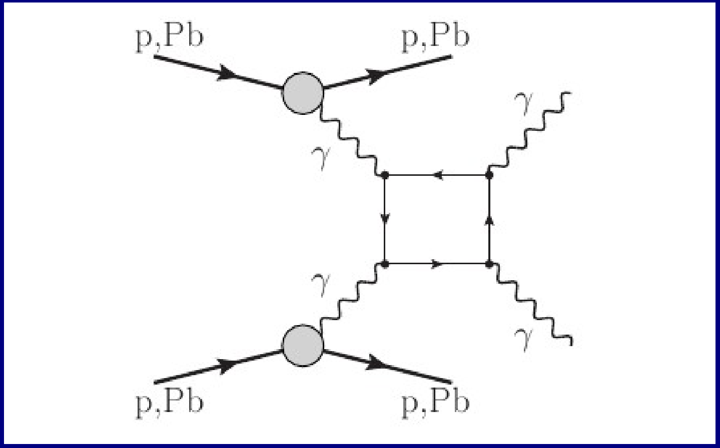
Exclusive $\gamma\gamma$ production

Light-by-light scattering, $\gamma\gamma\rightarrow\gamma\gamma$, has so far not been directly observed.

The reaction is of fundamental interest as deviations from SM prediction may be caused by anomalous gauge couplings, SUSY particle contributions in the loop etc.

According to the recent paper (d'Enterria, Silveira PRL 111 (2013) 080405), $\approx$200 signal events with m_{inv} > 5 GeV can be expected in the Atlas/CMS acceptance in a 10 nb^{-1} Pb-Pb run.

==> Pb-Pb collisions at the LHC might thus provide the first opportunity to study this process!



Summary

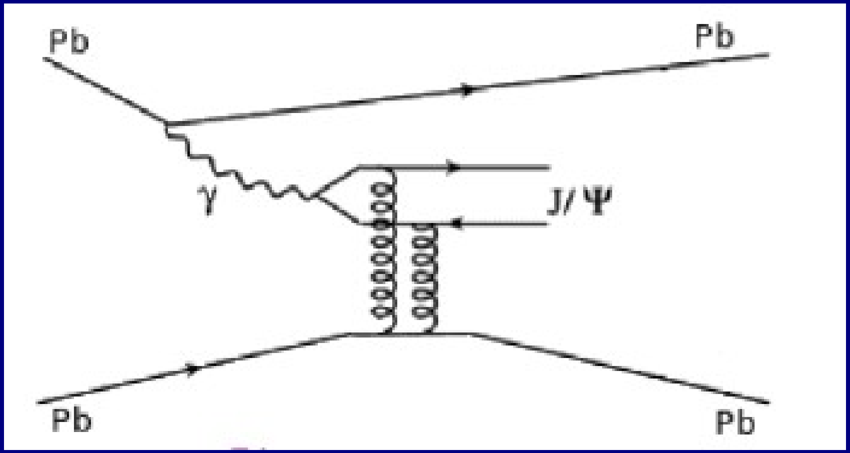
- Particles are produced in ultra-peripheral collisions at hadron colliders. The feasibility to study them with the existing detectors at RHIC, the Tevatron, and the LHC has been demonstrated.

- Many of the topics proposed as most interesting 12 years ago have actually been studied.

- Many topics remain as the LHC moves into the high energy/high luminosity phase.

Backup

Exclusive vector meson production



- Heavy vector mesons provide a hard scale.

- Exclusive production can be modelled through exchange of 2 gluons. (Ryskin 1993).

Several predictions for exclusive production Pb+Pb → Pb+Pb+J/Ψ at the LHC:

- S.R. Klein, J. Nystrand Phys. Rev. C 60 (1999) 014903.
- V. Rebyakova, M. Strikman, M. Zhalov Phys. Lett. B 710 (2012) 647.
- A. Adeluyi, C.A. Bertulani Phys. Rev. C 85 (2012) 044904.
- V.P. Goncalves, M.V.T. Machado Phys. Rev. C 84 (2011) 011902.
- A. Cisek, W. Schäfer, A. Szczurek Phys. Rev. C 86 (2012) 014905.
- T. Lappi, H. Mäntysaari, Phys. Rev. C 87 (2013) 032201.

Data on exclusive J/ψ production in γ-p collisions

E401: M. Binkley et al. Phys. Rev. Lett. 48 (1982) 73.

A.R. Clark et al.: Phys. Rev. Lett. 43 (1979) 187.

U. Camerini et al.: Phys. Rev. Lett. 35 (1975) 483.

B. Gittelman et al.: Phys. Rev. Lett. 35 (1975) 1616.

Zeus: Eur. Phys. J C24 (2002) 345.

H1: arxiv:1304.5162; Eur. Phys. J C46 (2006) 585.