UPC overview at the LHC
UPC physics is shedding light on a given target (p, A or \( \gamma \)): to tame hadronic cross section you’ve to go ultra peripheral

\[
\text{Photon flux } \propto Z^2
\]

\( \rho, \Phi, J/\Psi, \Psi(2S), \bar{\gamma} \)

\( \rho, \rho, \rho, \rho, Pb \)

\( \rho, Pb \)

\( Pb, Pb \)

\( Pb, Pb \)

Two (or four) tracks in an otherwise empty detector...

...and may be neutrons

ZDC (\( d_{IP} \sim 100 \text{ m} \)) may detect these neutrons

\[\alpha \to Z\alpha : \text{QED test} \]
General comment: UPC triggering not trivial:
- **hw:**
  - Few tracks (2 to 4) \(\rightarrow\) requires low noise detectors;
  - Low \(p_{T}\) decay products *(below threshold)*;
  - relatively small cross section \(\rightarrow\) background rejection;
  - soft QED \(e^+e^-\) pairs have large cross section

Measurements at different rapidity (different Bjprken-x) important

\(\rightarrow\) barrel: - silicon detector (low intrinsic background), but background from the huge \(e^+e^-\) cross section at low
  - gas detectors far from IP (noise to be tamed for «few hits»- trigger, physics background from late particles)
  - hadronic background, easier to reject by forward scintillators

Workaround: triggering with the Zero Degree Calorimeters. But can we really rely on that ?
Coherent interactions: $\lambda \sim R_N \sim 6 \text{ fm} \sim \hbar c/p_T \rightarrow p_T \sim 197 \text{ MeV/fm} / 6 \text{ fm} \sim 33 \text{ MeV/c}$

Does the nucleus stay **always** intact after the collision? No, it’s just a 70% probability!

J/$\Psi$ coherent production with neutrons $\geq 1$:

- Starlight (Klein, Nystrand): 68%;
- Rebyakova, Strikman and M. Zhalov: 78%;

→ ALICE data: 0.70± 0.05

Comments on ZDC triggering:
- Only a part of the cross section can be taken. Rescale required to compare to the full $\sigma$ (adding a 10% sys error)
- Event generator do not include neutron production in the final state. Bias?
The LHC Run1 grape harvest:
- Exclusive two-photon production of lepton pairs, 40 pb\(^{-1}\)

\[ \sigma(p \rightarrow p\mu^+\mu^-p) = 3.38^{+0.58}_{-0.55} \text{ (stat.)} \pm 0.16 \text{ (syst.)} \pm 0.14 \text{ (lumi.) pb} \]

- Central exclusive \(\gamma\gamma\) production
  \(\rightarrow\) no candidates

CMS calorimetry (em + hadronic) at work. Powerful search for \(\gamma\) (\(E_T > 5\) GeV).
Exclusive $J/\Psi$ and $\Psi(2S)$ vector meson production has been studied in the dimuon channel using the LHCb detector.

$$
\sigma_{pp \rightarrow J/\Psi \rightarrow \mu^+\mu^-} (2.0 < \eta_{\mu^\pm} < 4.5) = 291 \pm 7 \pm 19 \text{ pb},
$$

$$
\sigma_{pp \rightarrow \psi(2S) \rightarrow \mu^+\mu^-} (2.0 < \eta_{\mu^\pm} < 4.5) = 6.5 \pm 0.9 \pm 0.4 \text{ pb},
$$

Data agree well with models including saturation...but with models not including saturation too.
Hunting for proton gluon saturation

Hera data up to $W_{\gamma p} \sim 300$ GeV

Growth of the cross section interpreted by pQCD model as an increase of gluon density approaching smaller Bjorken-$x$

Main issues: in pp you cannot tag the proton that radiated the photon.

$W_{\gamma p}^2 = 2E_p M_{J/\psi} e^{\pm y}$

A model dependent result can be obtained assuming a power law, and extracting $\sigma(W+) \text{ by using HERA fit for } \sigma(W+)$ and vice versa

a) You have a $W_{\gamma p}^+$ and $W_{\gamma p}^-$ solution for each event: power low assumption required “a priori”

b) The background from inelastic events is $W$ dependent (quite different for $W_{\gamma p}^+$ and $W_{\gamma p}^-$)

...the average has large uncertainties

In p-Pb event the photon is radiated by the Pb nucleus in 96% of the events
p-Pb
- $J/\Psi$ study in p-Pb collisions in two different interval of $\gamma p$ centre of mass energies $W$; at the moment results available at forward rapidities.
Hunting for proton gluon saturation

Hera data fit by a Power low \( \sigma \propto W_{\gamma p}^{\alpha} \)

\[ \alpha = (0.69 \pm 0.02 \text{(stat)} \pm 0.03 \text{ (syst)}) \]

Zeuss

\[ \alpha = (0.67 \pm 0.03 \text{ (stat + syst)}) \]

H1

ALICE data up to ~ 700 GeV
\[ \alpha = (0.68 \pm 0.06 \text{ (stat + syst)}) \]

→ No smoking guns of a change of gluon PDF behavior from HERA to LHC (within the errors)

Next pPb run: go to higher energies would be important for this measurement

arXiv:1406.7819 , accepted by PRL
- $\gamma \gamma \rightarrow l^+l^-$ study in p-Pb collisions, L=35 nb$^{-1}$,  
  (I. Katkov, at PhotonLHC2014)  
  $\rightarrow$ good agreement to LO QED.
Pb-Pb
ALICE provided the first **direct** experimental evidence for nuclear gluon **shadowing** *(Talk by D. De Gruttola)*

Few caveats:
- ALICE results (and predictions) include $\Upsilon(2s)$ feed-down subtraction (~ 10%)
- CMS result rescaled (triggered by ZDC, requiring neutron production)

Both experiment support gluon shadowing at Bjorken-$x \sim 10^{-2}$ – $10^{-3}$
In the past years we built-up UPC presentations showing the uncertainties in the plot below as a motivation to study $J/\Psi$ photoproduction in A-A systems (given $\sigma_{J/\Psi} \propto |G(x,q^2)|^2$ at LO).

$$R_{gPb}(x,Q^2) = \frac{G_{Pb}(x,Q^2)}{AG_p(x,Q^2)}$$

It’s time to use these results to constrain the $G(x,q^2)$.

First attempt by Kryshen, Strikman and Zhalov:

PLB 726 (2013) 270

Divide the $J/\Psi$ cross section by the photon flux $\gamma + $Pb $\rightarrow J/\Psi + $Pb
and by the IA (Impulse Approximation) cross section (nucleus treated as the superposition of A nucleons)

$$S(W_{\gamma P}) \equiv \left[ \frac{\sigma^{exp}_{\gamma Pb \rightarrow J/\Psi Pb}(W_{\gamma P})}{\sigma^{1A}_{\gamma Pb \rightarrow J/\Psi Pb}(W_{\gamma P})} \right]^{1/2}$$

$S$ can be interpreted as suppression due to the nuclear gluon shadowing.
Strong shadowing, consistent with LTA (NNPDF, CTEQ6L1) or EPS09, CMS data useful
and Run2 sowing
Bread and butter: deeper into saturation and gluon shadowing
Gluon shadowing at similar x but at a different mass scale!

→ ALICE (CMS): ~ 500 coherent J/Ψ using 22 μb⁻¹ (160 μb⁻¹)
  - $\sigma_{J/\Psi} / \sigma_\gamma \sim 180$ ;
  - $\Gamma_{J/\Psi} \sim 2*\Gamma_{\gamma}$
→ $1000 \mu b^{-1} / 22 \mu b^{-1} * 500/180 * 0.5 \sim 60 \gamma$

...a joint effort is required to keep statistical uncertainties at a reasonable level.

Caveat: HERA constrain to the $\gamma$-p cross section could really be poor

\( t = p T_2 \) distribution of differential cross sections of photo-production of vector mesons may discriminate among saturation and non-saturation models. → dip (or multiple dips) in the \( t \) distribution of diffractive photoproduction of vector mesons

\[ \gamma + p \rightarrow J/\psi + p \]

- At forward rapidity we have contributions both from \( x \sim 10^{-2} \) (95%) and \( 10^{-4} \) (5%), depending on the Pb nucleus emitting the photon. → tagging by using ZDC activity, see arXiv:1109.0737 → Gluon shadowing at \( 10^{-4} \) feasible!

→ Run2: 2,500 \( J/\psi \) * 5% * 30% ~ 40 tagged \( J/\psi \) at \( x \sim 10^{-4} \) (1 nb\(^{-1}\))
UPC hunting for new physics beyond the SM
So far, no direct observation of this process. In the SM the above box diagram involves quarks, W, etc, → Extra contributions from new heavy charged particles and/or super symmetric partners of SM particles? See PRL 111, 080405 (2013) σ depends on the $M_{\gamma\gamma}$ threshold. $M_{\gamma\gamma} > 5$ GeV → $\sigma \sim 30$–40 nb

With 1 nb$^{-1}$, $\sqrt{s_{NN}}$=5.5 TeV → N~30-40 events (threshold $M_{\gamma\gamma} > 5$ GeV)

→ In ALICE a lower threshold could be used (but larger background expected).
  a) $\gamma$ conversion in/before the TPC
  b) $\gamma$ conversion in ECAL/DCAL

CMS/ATLAS: 50% (Acc x eff)
ALICE: Acceptance, efficiency to be evaluated; assuming a conservative 20%
→ N~20 events in CMS/ATLAS, 5-10 events in ALICE (depending on the threshold).

Run3 is required for a large statistics, but we can start at Run2
Thanks also to the previous effort at RHIC (STAR, PHENIX) & theoreticians working at UPCs.

~15 experimental papers published/being submitted at the LHC by ALICE, LHCb, CMS; > 100 Proceedings.

But «they lived happily ever after» does not apply....Run2 will be exciting but challenging...
1) **Bump Hunting (BH)**
   Narrow $e^+e^-$-resonance over a QED background
   - good mass resolution: $\sigma_{A'\text{mass}} \sim 1$ MeV

2) **Secondary decay vertex (vertexing)**
   Detached vertex from few mm to tens cm
   - good spacial resolution: $\sigma_{\text{vertex}} \sim 1$ mm
At LHC nice preliminary results from ALICE in $\pi^0$ decay (but limited to $M < 100 \text{ MeV/c}^2$).

UPC can go up to few GeV:

- Collected 300 $ee$ events with $M < 2 \text{ GeV/c}^2$ (L=0.2 $\mu$b$^{-1}$). Factor 5000 larger statistics at Run 2
• Run2 will be a great step forward in UPC for pp, P-Pb and Pb-Pb collisions

• Luminosity is important but it is just a required ingredient: UPC results need a proper, sometimes not straightforward, interpretation (several processes at work): a tight collaboration with theoreticians is mandatory.

• Few analysis are at the statistical limit at Run2: a joint effort between LHC experiments would be a great help.

• Hope we will quote this workshop not as «the workshop on photon-induced collisions» but «the first workshop on photon-induced collisions»......
\( \gamma \gamma \to \text{ee} \)

\(~280\) events \((2.3 < M_{\gamma \gamma} < 10)\) GeV/c^2

\(~300\) events \((0.6 < M_{\gamma \gamma} < 2.0)\) GeV/c^2 (C. Mayer talk)

<table>
<thead>
<tr>
<th>Data</th>
<th>STARLIGHT</th>
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<tr>
<td>(\sigma(M_{e^+e^-} \in [0.6, 2.0] \text{ GeV/c}^2;</td>
<td>\eta_{1,2}</td>
</tr>
<tr>
<td>(\sigma(M_{e^+e^-} \in [2.2, 2.6] \text{ GeV/c}^2;</td>
<td>\eta_{1,2}</td>
</tr>
<tr>
<td>(\sigma(M_{e^+e^-} \in [3.7, 10.0] \text{ GeV/c}^2;</td>
<td>\eta_{1,2}</td>
</tr>
</tbody>
</table>
12,000 J/Ψ midrapidity dN/dy, dN/dt (see A. Stasto talk)
2,500 J/Ψ at forward rapidity
  → at forward rapidity we have contributions both from x \sim 10^{-2} and 10^{-5}.

How low in Bjorken x can we go at the moment?

- Barrel \rightarrow x \sim 10^{-3}
- At forward rapidity we have contributions both from x \sim 10^{-2} (95%) and 10^{-4} (5%), depending on the Pb nucleus emitting the photon.
  → tagging by using ZDC activity, see arXiv:1109.0737  → Gluon shadowing at 10^{-4} feasible!

Now: 5% of the UPC forward J/Ψ from low x. 30% of them with neutron emission.
With the present statistics (55 \mu b^{-1}) \rightarrow 80 \times 0.05 \times 0.2 \sim 1 \text{ event}

→ Run2: 2,500 J/Ψ \times 5\% \times 30\% \sim 40 \text{ tagged J/Ψ at x} \sim 10^{-4} \text{ (1 nb}^{-1})

Run 3 required for a good statistics, but results may come also at Run 2
Particles of light, photons, interact with visible matter and its building blocks—protons, neutrons and electrons. Perhaps the same is true for dark matter. In other words, does the visible photon have a counterpart, a dark photon, that interacts with the components of dark matter?

Search for heavy (dark) photon $A'$ (sometimes $U$) is an important part of the scientific program at JLAB: HPS dedicated experiment. $A'$ couples very weakly to electrons. Fine structure constants $\alpha = e^2/4\pi$; $\alpha' = g'^2/4\pi$; $e^2 = \alpha'/\alpha$
Central exclusive $\gamma\gamma$ production

No diphoton event found with

$$\sigma\left( E_T(\gamma) > 5.5 \text{ GeV}, \mid \eta(\gamma) \mid < 2.5 \right) < 1.18 \text{ pb} \text{ using } 37 \text{ pb}^{-1}$$

CDF observed 43 events: $\sigma(E_T > 2.5 \text{ GeV}, \mid \eta \mid < 1) = (2.48^{+0.4}_{-0.35} \text{ (stat)} +0.4_{-0.51} \text{ (sys)}) \text{ pb}$

**Run2**: $L \sim 100 \text{ fb}^{-1} \rightarrow$ factor 3000 higher statistics (if pileup under control)

Access to high statistics $\Upsilon$ production

CMS & TOTEM: PPS (Proton Precision Spectrometer)

Mainly diffraction but UPC can be studied too:
Central exclusive production $pp \rightarrow pp+X$ ($X= WW, ZZ, \gamma\gamma, \text{ di-jets, ...}$)

$W, Z, \gamma$ pair production search for anomalous coupling
Run 1 at the LHC:

<table>
<thead>
<tr>
<th>Year</th>
<th>system</th>
<th>energy $\sqrt{s}$ (TeV)</th>
<th>integrated luminosity</th>
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<tbody>
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<td>p-p</td>
<td>7</td>
<td>45 pb$^{-1}$</td>
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<tr>
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<tr>
<td>2012</td>
<td>p-p</td>
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<td>23 fb$^{-1}$</td>
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<tr>
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<td>~ 10 μb$^{-1}$</td>
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<td>p – Pb</td>
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<td>~ 30 nb$^{-1}$</td>
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