Low-x QCD via electromagnetic PbPb collisions at 5.5 TeV in CMS

ECT* Workshop on Photoproduction
Trento, 18th January 2007

David d'Enterria, Aurelien Hees*

CERN PH-EP

* [CERN summer student, currently at U.C. Louvain]
Overview

➢ Introduction:
  – Low-x QCD (gluon saturation, non-linear evolution)
  – Experimental probes of small-x PDFs, ”evidences” for gluon sat. ?
  – $\Upsilon$ photoproduction in UPC PbPb at LHC

➢ CMS experimental setup

➢ Quarkonia measurement in CMS:
  – Theoretical cross-sections for signal ($\Upsilon$) & background ($\gamma\gamma\rightarrow e^+e^-, \mu^+\mu^-$)
  – Trigger considerations: L1, background rates, HLT strategy
  – Input MC distributions: $\text{PbPb} \rightarrow (\gamma\text{Pb}) \rightarrow \Upsilon \text{Pb}^*, \text{PbPb} \rightarrow (\gamma\gamma \text{Pb}) \rightarrow \ell^+\ell^- \text{Pb}^*$
  – $\Upsilon \rightarrow e^+e^-, \mu^+\mu^-$ acceptances & (trigger, reco) efficiencies
  – Inv. mass distributions for $\Upsilon$ signal + $\ell^+\ell^-$ background. Yield extraction.
  – Results: Expected $dN/dp_T$, $dN/dy$, $dN/dm_{\text{inv}}$ for $\int \mathcal{L} dt = 0.5 \text{ nb}^{-1}$ PbPb

➢ Summary
Parton structure at low-x

➢ DIS ep collisions probe partonic distributions in the proton:

\[ Q^2 = \text{“resolving power”} \]

\[ Bjorken \; x = \text{momentum fraction carried by parton} \]

\[
\frac{d^2 \sigma}{dx \, dQ^2} = \frac{2\pi \alpha^2}{x \, Q^4} \left[ 2xy^2 F_1 + 2(1-y)F_2 \right]
\]

\[ F_1, F_2 = \text{proton structure functions.} \]

➢ HERA: strong rise at low-x of \( F_2(x,Q^2) \sim \text{sea-quarks}, \frac{\partial \ln F_2}{\partial \ln Q^2} \sim \text{gluons} \]
Parton \((x, Q^2)\) evolution at low-\(x\)

- **Q² - DGLAP** (parton branch.): \(F_2(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n\), \(Q_0^2 \sim 1\ \text{GeV}^2\)
- **x - BFKL** (parton emission ordered in \(p_L\)): \(F_2(x) \sim \alpha_s \ln(1/x)^n\)
- Linear equations (single parton radiation/splitting): cannot work at low-\(x\)

(i) High gluon density: nonlinear g-g fusion will balance parton branchings
(ii) pQCD (collinear & \(k_T\)) factorization should break (no incoherent parton scattering)
(iii) Violation of unitarity even for \(Q^2 \gg \Lambda^2\) (too large perturbative cross-sections)

- **BDR: Black-disk regime**
  [talks by Frankfurt, Strikman et al]
- **CGC = effective-field theory for low-\(x\) QCD**
  - Hadrons = classical fields below
  "saturation scale" \(Q_s\) (enhanced in nucleus)
  \(Q_s^2 \sim \alpha_s \frac{xG_A(x, Q_s^2)}{\pi R_A^2} \sim A^{1/3} \sim 6\)
  Gluons overlap for momenta \(\sim Q_s\)
  - Non-linear JIMWLK, BK evolution eqs.
Experimental probes of low-\(x\) PDFs (\(\gamma p, pp, \gamma A, AA\))

- **Perturbative** processes in pp, gp, AA, gA:
  - Drell-Yan, prompt \(\gamma\), (di)jets, heavy-Q:
    - Diffractive \(Q\bar{Q}\) (\(\gamma p, \gamma A\)):
      - Forward production \(\Rightarrow\) lower \(x\)

\[
x_{2\min} \sim \frac{p_T}{\sqrt{s}} \cdot e^{-y} = x_T \cdot e^{-y}
\]

Every 2-units of \(y\), \(x_{min}\) decreases by \(\sim 10\)
Example: Quarkonia $\gamma$-production @ HERA

$\gamma+p\rightarrow VM+p$ ($VM=J/\Psi,\Upsilon$) sensitive to gluon distribution squared:

$$\left. \frac{d\sigma(\gamma p \rightarrow V p)}{dt} \right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 \left[ xG(x, Q^2) \right]^2, \text{ with } Q^2 = M_V^2/4$$

$x = M_V^2/W_{\gamma p}^2$

Ryskin et al. ZPC 76 (1997)231

Discriminates different Ansätze & evolutions of $G(x, Q^2)$

Frankfurt, McDermont, Strikman, hep-ph/0009086
Teubner, DIS05
PDF \((x,Q^2)\) experimental maps: proton, nucleus

- Kinematical \((x,Q^2)\) domains covered experimentally:

much less nuclear PDF data available:

Note: most existing low-\(x\) nPDFs measurements in the non-perturbative regime
LHC PbPb: low-x nuclear PDF studies

- PbPb @ 5.5 TeV, pPb @ 8.8 TeV:

  (i) Very high $\sqrt{s}$ ⇒ $x_T = 2p_T/\sqrt{s} \sim 10^{-3} \sim 30-45$ times lower than AuAu,dAu @ RHIC!

  (ii) Sat. momentum ($A^{1/3} \sim 6$ enhancement factor): $Q_s^2 \sim [5 \text{ GeV}^2] \cdot e^{(0.3 \gamma)}$

  (iii) Very large perturbative cross-sections.


Ratio of gluon densities in Pb to p:

"Evidences" of $xG_A(x,Q^2)$ saturation in the nucleus?
AuAu (200 GeV) 0-5% central collisions:

- Reduced multiplicity predicted by saturation models (gluon “fusion” reduces incoming parton flux).

~ 700 charged particles per unit rapidity at y=0

Predicted multiplicities:

- HIJING (dN_{ch}/d\eta, b<3fm)
- HIJING+ZPC+ART (b=0)
- RQMD (b=3fm)
- UrQMD (b<3fm)
- VNI+UrQMD (b<1fm)
- HSD, VNI+HSD (b<2fm)
- NEXUS (b<2fm)
- DPM (Pb+Pb)
- DPMJET (Pb+Pb, 3%)
- SFM (5%)
- LEXUS (5%)
- EKRT saturation (b=0)
- Hydro+UrQMD (b=0)
- Fireball (~5%)
- McLV (dN_{ch}/d\eta, b=0)
RHIC: Total AA hadron multiplicity

- Final hadron multiplicity $\propto$ Initial multiplicity of released gluons $\propto Q_s$

$$\frac{dN}{d^2b d\eta} \propto \frac{1}{\alpha_s(Q_s^2)} Q_s^2 \propto xG(x, Q_s^2) \cdot A^{1/3}$$

+ "local parton-hadron duality" (1 gluon = 1 final hadron)

- Centrality & $\sqrt{s_{NN}}$ dependence well described:

Collision of 2 classical (saturated) fields

Armesto, Salgado, Wiedemann
PRL94 (2005) 022002

KLN, PLB507 (2001) 121
RHIC: Suppressed forward dAu $p_T$ spectra

- Hard hadrons at $y=0$ well described by coll. factoriz. + mild LT shadow:

- Suppressed fwd hadron spectra:
  $p_T \sim 2 - 4$ GeV/c not described by standard pQCD but by CGC:
  reduced # of partonic scattering centers in Au at $x \sim 10^{-3}$

- But RHIC & HERA saturation “evidences” too close to non-perturbative range ($Q_s^2 \sim 1$ GeV$^2$). Much better conditions @ LHC ($Q_s^2 \sim 5$ GeV$^2$, lower $x$, larger $y$)
Photon beams at the LHC

- High energy heavy-ions produce strong E.M. fields due to coherent action of $Z = 82$ protons:

- Equivalent flux of photons in EM (aka. Ultra-Peripheral, $b_{min} \sim 2R_A \sim 20$ fm) AA colls.:

$$\frac{dN_{\gamma}}{dz}(b > b_{min}) = \frac{\alpha_{em} Z^2}{\pi} \frac{1}{z} \left[ 2xK_0(x)K_1(x) - x^2 \left( K_1^2(x) - K_0^2(x) \right) \right]$$

- Photon beams:
  - Flux $\sim (Z^2)(\sim 7 \cdot 10^3$ for Pb). $\sigma(\gamma\gamma) \sim Z^4$ (i.e. $\sim 4 \cdot 10^7$) times larger than $e^\pm$ beams!
  - "Coherence condition" : $\gamma$ wavelength $>\text{nucleus size} \Rightarrow$ very low $\gamma$ virtuality

$$Q^2 = (\omega^2 / \gamma^2 + q_{\perp}^2) \lesssim 1 / R_A^2$$ (where $\gamma$ is the beam Lorentz factor),

$$\omega < \omega_{max} \approx \left( \frac{\gamma}{R} \right), \text{ and } q_{\perp} \lesssim \frac{1}{R} \approx 30 \text{ MeV}. \quad \text{Max. } \gamma \text{ energy: } E_{\gamma_{max}} \sim 80 \text{ GeV (PbPb-LHC)}$$

- Center-of-mass energies: $\gamma A$: max. $\sqrt{s}_{\gamma A} \approx 1.$ TeV $\approx 3. - 4. \times \sqrt{s}_{\gamma p}$ (HERA)
  
  $\gamma\gamma$: max. $\sqrt{s}_{\gamma\gamma} \approx 160 \text{ GeV} \approx \sqrt{s}_{\gamma\gamma}$ (LEP)
Low-x nuclear via UPC QQbar photoproduction

- QQbar (and in general, hard) diffractive photoproduction sensitive to the gluon density squared in the nucleus:

\[
\frac{d\sigma_{\gamma p,A \to V p A}}{dt}\bigg|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 \left[xG(x, Q^2)\right]^2
\]

\[Q^2 = \frac{M_V^2}{4}\quad \text{and} \quad x = \frac{M_V^2}{W_{\gamma p,A}^2}\]

Small-x probed in γA collisions at LHC:

- \(y=0: x(\Upsilon) = 2 \cdot 10^{-3}\)
- \(y \sim 2: x(\Upsilon) \sim [x(y=0)] \cdot e^{-y} \sim 10^{-4}\)

- Unexplored \((x, Q^2)\) regime of the nucleus wave function. Gluon saturation expected at low-x around \(Q_s^2 \sim 5-8\text{ GeV}^2\) ⇒ Suppressed hard photoproduction.
Cross-section predictions: UPC $\gamma$ Pb $\rightarrow$ $\Upsilon$

- Model predictions:

- Note: ~50% of UPC interactions have soft EM interactions leading to nuclear breakup w/ fwd. neutron ($X_n$) emission (important for triggering)

| Process                                    | $\sigma_{tot}$ | $\sigma_{X_n}$ | $\sigma_{X_n|X_n}$ |
|--------------------------------------------|----------------|----------------|--------------------|
| $PbPb \rightarrow \gamma Pb \rightarrow J/\psi + X$ | 32 mb          | 8.7 mb         | 2.5 mb             |
| $PbPb \rightarrow \gamma Pb \rightarrow \Upsilon(1S) + X$ | 173 $\mu$b     | 78 $\mu$b     | 25 $\mu$b         |

[Starlight: J. Nystrand, S.Klein, NPA752(2005)470]

[Frankfurt, Guzey, Strikman]

Impulse: $\sigma = 133$ mb

LT shadowing: $\sigma = 78$ mb

[similar calculations by Machado-Goncalves et al.]
Experimental setup
Compact Muon Solenoid (|\eta|<5)

SUPERCONDUCTING COIL

CALORIMETERS

ECAL Scintillating PbWO₄ Crystals

HCAL Plastic scintillator copper sandwich

IRON YOKE

TRACKERs

Silicon Microstrips Pixels

Drift Tube Chambers (DT)

Resistive Plate Chambers (RPC)

Cathode Strip Chambers (CSC)

Resistive Plate Chambers (RPC)

MUON ENDCAPS

Total weight: 12,500 t
Overall diameter: 15 m
Overall length: 21.6 m
Magnetic field: 4 Tesla
CMS-TOTEM acceptance

- HF, CASTOR, ZDC + TOTEM: Quasi-full acceptance at LHC

- Detection capabilities within $\eta \leq 6.7$ (and $\eta \geq 8.1$, neutral).
- Strong AA-UPC and rapidity-gap physics possible
- Hard scatt. measurements (jets, DY) possible at $x \sim 10^{-4}$-$10^{-6}$ in pp,pA
e± and μ± measurement in CMS (|η|<2.4)

Si TRACKER
Silicon Microstrips and Pixels

CALORIMETERS
ECAL PbWO₄ Plastic Sci/Steel sandwich
HCAL

MUON BARREL
Drift Tube Chambers (DT) Resistive Plate Chambers (RPC)

Tracking + ECAL + muon-chambers

Key:
- Muon
- Electron
- Charged Hadron (e.g. Pion)
- Neutral Hadron (e.g. Neutron)
- Photon

γ → e⁺e⁻
γ → μ⁺μ⁻
CMS Muon system

- 3 types of gaseous particle detectors for muon identification:
  - Drift Tubes (DT) in central barrel region
  - Cathode Strip Chambers (CSC) in endcap region
  - Resistive Plate Chambers (RPC) in barrel & endcaps

precise measurement of muon position (momentum)
fast info for LVL-1 trigger
CMS Muon system

- Drift Tubes (DT) in central barrel
- Resistive Plate Chambers (RPC) in barrel and endcaps
- Cathode Strip Chambers (CSC) in endcap region
Forward neutron detection in ZDC ($|\eta| \geq 8.3$)

- **ZDC** = tungsten+quartz-fibre sampling Cerenkov calorimeter with HAD and EM sections:

![Diagram](image1)

- **ZDC**: forward neutral energy ($n,\gamma$) detection:

![Diagram](image2)

Acceptance (neutral):

$\theta \approx (5.\text{cm})/140.\text{m} \approx 400 \mu\text{rad}$

$|\eta| \geq 8.3$, $p_T < O(2.\text{ GeV/c})$
UPC full CMS simulation analysis
**ϒ and ℓ⁺ℓ⁻ cross-sections in UPC (γ Pb and γ γ)**

- **Input MC: STARLIGHT** [J. Nystrand, S.Klein, NPA752(2005)470]

### Signal

| Process                  | σ_{tot} | σ_{Xn} | σ_{Xn|Xn} |
|--------------------------|---------|--------|-----------|
| PbPb → γ Pb → J/ψ + X   | 32 mb   | 8.7 mb | 2.5 mb    |
| PbPb → γ Pb → ϒ(1S) + X | 173 μb  | 78 μb  | 25 μb     |

### Background

<table>
<thead>
<tr>
<th>Process</th>
<th>γ γ → e⁺e⁻</th>
<th>γ γ → μ⁺μ⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ(m_{inv} &gt; 1.5 GeV/c²)</td>
<td>139 mb</td>
<td>45 mb</td>
</tr>
<tr>
<td>σ(m_{inv} &gt; 6.0 GeV/c²)</td>
<td>2.8 mb</td>
<td>1.2 mb</td>
</tr>
</tbody>
</table>

- We'll consider only ~50% of UPC interactions with nuclear breakup and fwd. neutron (Xn) emission (trigger)
Input MC distributions (ϒ signal)

➢ STARLIGHT Upsilon $p_T$, rapidity distributions:

- Peaked at very low $p_T$
  - $p_T \sim 2\hbar c/R \sim 50$ MeV/c
  - ("coherence condition")

- $\Upsilon$ centered at midrapidity
  - (narrow $d\sigma/dy$)

- Decay leptons also well within CMS acceptance

CMS $e^\pm$, $\mu^\pm$ acceptance

\[ \text{CMS } e^\pm, \mu^\pm \text{ acceptance} \]
Input MC distributions (continuum backgd.)

- STARLIGHT dilepton continuum mass, $p_T$, rapidity distributions:

  - Power-law like mass spectrum
  - Lepton pairs centered at midrapidity (narrow $d\sigma/dy$)
  - But most single leptons fwd peaked.
  - Outside CMS acceptance!
 UPC Level-1 trigger: signature & rates

➢ Use of following L1 primitives:

- Veto ('OR') on simultaneous activity in HF+/− (3<|η|<5): 1 or 2 rap-gaps
- Neutron signal in ZDC+ or ZDC- (|η|>8.3): nuclear breakup tagging
- Isolated ECAL tower above 3 GeV: γ decay electron
- Signal in muon RPCs (|η|<2.1) or CSCs (0.8<|η|<2.4): γ decay muon (>4 GeV)

➢ 2 UPC-L1 triggers:

- UPC-mu-L1 = (ZDC+ OR ZDC−) AND (HF+ OR HF−) AND (muonRPC OR muonCSC)
- UPC-elec-L1 = (ZDC+ OR ZDC−) AND (HF+ OR HF−) AND ECALtower(E>2.5 GeV)

➢ L1 trigger (background) rates ($\mathcal{L} = 0.5$ mb$^{-1}$s$^{-1}$) $\sim 2 – 4$ Hz

$$N_{UPC-\gamma} = \langle \mathcal{L} \rangle \times \sigma_{PbPb \rightarrow \gamma Pb \rightarrow \gamma} \times BR(\gamma \rightarrow l^+ l^-) = 0.5 \text{ mb}^{-1}\text{s}^{-1} \times 0.078 \text{ mb} \times 0.024 = 0.001 \text{ Hz}$$

$$N_{PbPb-ED+cosmic-backgd} = 2 \times N_{PbPb-ED} \times N_{\mu-cosmic} \times \Delta t_{\text{trig}} \approx 10^5 \text{ Hz} \times 180 \text{ Hz} \times 10^{-8} \text{ s} \approx 0.2 \text{ Hz}$$

$$N_{PbPb-periph-backgd} = \langle \mathcal{L} \rangle \times \sigma_{tot \ PbPb} \times \epsilon_{\text{periph}} \times \epsilon_{\text{high-}$p_T$ \mu/e} = 0.5 \text{ mb}^{-1}\text{s}^{-1} \times 8000 \text{ mb} \times 0.05 \times 2 \cdot 10^{-3} \approx 0.4 \text{ Hz}$$

$$N_{\gamma\gamma-em-backgd} = \langle \mathcal{L} \rangle \times \sigma_{\gamma\gamma \rightarrow e^+e^-} \times \epsilon_{\text{high-}$p_T$ e} = 5 \cdot 10^{26} \text{ cm}^{-2}\text{s}^{-1} \times 10^{-27} \text{ cm}^2 \text{ mb}^{-1} \times 139 \text{ mb} \times 0.01 = 0.7 \text{ Hz}$$

$$N_{\text{other}} \sim \text{(other diffractive } \gamma-Pb, \text{ IP-Pb, } \gamma\gamma \rightarrow X \text{ hard processes)} \sim 2 \text{ Hz}$$
UPC HLT trigger strategy

➢ Allocated UPC bandwidth in HLT:
  \[ 2.25 \text{ Mb/s (1\% total)} = 1 - 2 \text{ Hz for UPC evt. size 1 - 2 Mb.} \]

➢ Required L1\( \rightarrow \) HLT reduction factor: \( \sim 1 - 4 \)

➢ Application of one (or more of the) following HLT algorithms:
  (i) Verification of L1 elect./muon candidates (clean hadronic background)
  (ii) Evt. vertex within \( z<15 \text{ cm} \) (remove cosmic bckgd.)
  (iii) Low total transverse momentum \( (p_T<1 \text{ GeV/c removes most non-coh. prod.}) \)
  (iv) Back-to-back dielec./dimuons (HLT GlobalCalo and GlobalMu objects)

➢ If just condition (ii) is enough to reduce rates, one will be able to analyse offline other interesting diffractive processes too.
Results
Fully reconstructed $\Upsilon$ distributions

- Input & output $\Upsilon$ rapidity and $p_T$ distributions:

  **Electrons**

  - Input & output $\Upsilon$ rapidity distributions:
    - Better acceptance at $y=0$
    - Dip at $y=0$ (lowest total muon momentum)

  **Muons**

  - Input & output $\Upsilon$ rapidity distributions:
    - Better acceptance at $|y|\sim 2$

  - Very similar $p_T$ responses

  - Reco momentum slightly boosted.
Acceptance x Efficiencies $\Upsilon$

- Efficiencies-acceptances versus $y$ and $p_T$:
- Total Acc. × Effic. : $\sim 21\%$ ($\mu^+\mu^-$), $30\%$ ($e^+e^-$)

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

$\text{Acc} \times \text{Effic}(p_T) \sim \text{flat vs } p_T$

Better for electrons (higher yield at $y=0$ where EMCAL is more efficient)

Electron and muon analyses have complementary rapidity acc. × effic:
- $\mu^+\mu^-$: $\sim 60\%$ at $|y|\sim 1.5-2.5$
- $e^+e^-$: $\sim 60\%$ at $|y|<0.5$
Signal+background mixing according to relative cross-sections & BR:

\[
\frac{N_{\text{signal}}}{N_{\text{continuum}}} = \frac{\sigma_{PbPb \to \gamma Pb \to \gamma \gamma \to l^+ l^-} \times BR(\gamma \to l^+ l^-)}{\sigma_{PbPb \to \gamma Pb \to \gamma \gamma \to l^+ l^-} (m_{\text{inv}} = 6. - 12 \text{ GeV}/c^2)} \approx 0.35\% \ (0.15\%) \text{ for } \mu^+ \mu^- (e^+ e^-),
\]

Full CMS simulation+digi+hit+reconstruction:

- \( \Upsilon \to e^+ e^- \)
  - Peak position: \( \sim 9.35 \text{ GeV}/c^2 \)
  - Mass resolution: \( \sim 150 \text{ MeV}/c^2 \)

- \( \Upsilon \to \mu^+ \mu^- \)
  - S/B ~ 1
  - Peak position: \( \sim 9.52 \text{ GeV}/c^2 \)
  - Mass resolution: \( \sim 90 \text{ MeV}/c^2 \)

Excellent \( m_{\mu \mu} \) resol.: higher mass \( b \bar{b} \) states (\( \Upsilon', \Upsilon'' \) not yet in MC) can be resolved.
Expected $\Upsilon$ yields (PbPb 1-“year” luminosity)

- Backgd. subtracted $dN/dm^\text{inv}$ for $\int \mathcal{L} \, dt = 0.5 \text{ nb}^{-1}$ PbPb-5.5 TeV ($t=10^6$ s)
  (error bars = stat. uncertainties for integrated luminosity)

$\Upsilon \rightarrow e^+e^-$

$\Upsilon \rightarrow \mu^+\mu^-$

- Syst. uncertainties (dominated by backgd. subtraction, 5% lumin.): $\sim 10\%$

- Final total rates:
  \[N(\Upsilon \rightarrow e^+e^-) \sim 220\pm15\text{(stat)}\pm10\%(\text{syst})\]
  \[N(\Upsilon \rightarrow \mu^+\mu^-) \sim 180\pm13\text{(stat)}\pm10\%(\text{syst})\]

- Enough stats. for detailed studies (including $\gamma$-dependence) of gluon PDF
Summary

➢ Study of PbPb→(γ Pb)→ϒPb* at 5.5 TeV with γ→e⁺e⁻, μ⁺μ⁻ in CMS as a tool to study low-x gluon density & evolution in the nucleus.

➢ Trigger considerations: ZDC neutron-tagging, L1 primitives, background rates, HLT strategy.

➢ Full CMS sim+digi+hit+reco chain. Input MC (STARLIGHT) for expected signal (ϒ) and dilepton continuum background PbPb→(γγ Pb)→l⁺l⁻Pb*

➢ ϒ→e⁺e⁻, μ⁺μ⁻ acceptances & reco efficiencies. Inv. mass distributions for ϒ signal + l⁺l⁻ background. Yield extraction.

➢ Final full yield correction factors (includ trigger effic. and yield extraction):

\[ C(\Upsilon\rightarrow e^+e^-, \mu^+\mu^-) \approx 1/0.2 \]

➢ Expected rates for \( \int \mathcal{L} \ dt = 0.5 \text{ nb}^{-1} \) PbPb: \( N(\Upsilon\rightarrow e^+e^-, \mu^+\mu^-) \approx 400 \)

Enough statistics for detailed studies of gluon PDF.
Backup slides
Trigger efficiencies $\Upsilon$

- Momentum threshold cut >3 GeV/c at $|\eta|<2.5$ for $e^\pm$ (and also effectively $\mu^\pm$) removes significantly the continuum pair background without $\Upsilon$ loss:

\[
\Upsilon\rightarrow e^+e^- \quad \text{and} \quad \gamma\gamma\rightarrow e^+e^-
\]

$\varepsilon_{\text{loss}} \sim 3.5\%$ of Upsilon

$\sim 80\%$ of lepton pairs removed
**$\gamma A :$ Hard central production**

- **Quarkonia:** $\gamma+A \rightarrow J/\Psi, \gamma+A$ very sensitive to nuclear gluon density at small-$x$:
  
  Perturbative process:
  
  $\sigma(J/\Psi, \gamma) \sim |xG(x, Q^2)|^2$
  
  $\sim 30\%$ reduction of $G(x, Q^2) \Rightarrow 0.5 \cdot \sigma_{J/\Psi, \gamma}$
  
  Even stronger suppression expected if gluon saturation (CGC)

- **Dijet:** via gluon exchange (well described in QCD & tested @ HERA)
  
  Wider range of $Q^2$ than $QQ\bar{b}$.
  
  Photon-jet ($\sim 1\%$ of dijet rate) has clear signature
  
  $tt\bar{b}$ possible in $pA$ collisions (measure charge of top quark)

- Triggering in UPC processes only possible w/ ZDC neutron-tagging.
Muon reconstruction

- Best muon spectrometer at LHC (CMS)
- Excellent coverage:
  \(~5\) units of rapidity, \(2\pi\)
- Strongest magnetic field:
  \(4\) T, \(2\) T (return yoke)
- Tag from mu-chambers, momentum resolution from Silicon tracker
- Ecal + Hcal + Magnet
  - Iron absorbs hadrons
  - Barrel: \(p_T^\mu > 3.5\) GeV/c
  - Endcap: \(p_L^\mu > 4.0\) GeV/c
HERA: $F_2(x,Q^2)$ at moderate $Q^2$

- Saturation models describe well $F_2(x,Q^2)$ in “transition region” of moderate/low $Q^2$ (Note: also DGLAP, though at limit of applicability)

J. Forshaw, G. Shaw
JHEP 0412 (2004) 052
HERA: “Geometric scaling” of low-x $F_2(x,Q^2)$

- Saturation predicts low-x structure dependence on a single scale $Q_s^2$
  - DIS inclusive cross-section shows geo. scaling $\forall x < 0.01, 0.045 < Q^2 < 450 \text{ GeV}^2$

Described by dipole model:

$$
\sigma_{\gamma^*p}(\tau, Q^2) = \int_0^1 dz \int d^2r_\perp |\Psi(z, r_\perp; Q^2)|^2 \sigma_{\text{dipole}}(\tau, r_\perp)
$$

$$
\sigma_{q\bar{q}p}(r_\perp, x) = \sigma_0 \left[ 1 - \exp \left( -\frac{r^2 Q_s^2(x)}{4} \right) \right]
$$

$Q_s^2 < Q^2 < Q_s^4/\Lambda^2$

up to relatively large $Q^2$ (“extended scaling” region): BK/JIMWLK evolution
Saturation models can describe consistently total $\gamma p$ x-section ($F_2$) and DDIS ($x_{\text{IP}}F_2^{D(3)}$, Pomeron structure) and DVCS forward amplitudes:

- $x_{\text{IP}} = \text{fraction of p momentum carried by Pomeron}$
- $\beta = \text{fraction of IP momentum carried by struck parton}$

J. Forshaw, G. Shaw
JHEP 0412 (2004) 052
HERA: Geometric scaling in diffractive DIS

- Geometric scaling also observed in diffractive observables: DVCS, exclusive vector-meson:

C. Marquet, L. Schoeffel
PLB639 (2006) 471