High parton densities and low-$x$ QCD at LHC

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Overview

➢ Introduction:
  - Parton structure & evolution at low-x
  - Gluon saturation / non-linear evolution = Colour Glass Condensate (CGC)
  - HERA (proton) – RHIC (nucleus) – LHC (p,A) connection

➢ Experimental status:
  - Measuring parton distributions: processes, kin. domains, ...
  - Results at HERA (proton) and RHIC (nucleus)

➢ Low-x perspectives at LHC (p,A):
  - ALICE, ATLAS, CMS, LHCb capabilities
  - Examples: “Mueller-Navelet” jets, DY, γA in UPC AA, ...

➢ Summary
Parton structure at low-x

- DIS ep collisions probe partonic distributions in the proton:

  \[ Q^2 = \text{“resolving power”} \]

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

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

  \[ F_1, F_2 = \text{proton structure functions} \, , \, (y = \text{inelasticity}) \]

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

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(x, Q^2) evolution of PDFs

- **Q^2 - DGLAP** (parton branch.): \( F_2(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n, \ Q_0^2 \sim 1 \text{ GeV}^2 \) [LT, coll. factoriz.]
- **x - BFKL** (parton emission ordered in p_L): \( F_2(x) \sim \alpha_s \ln(1/x)^n \) [uPDFs, k_T-factoriz.]
- Linear equations (single parton radiation/split). **Cannot work** at low-x (esp. nucleus):
  
  (i) Too high gluon density: nonlinear multi-gluon fusion balances splittings
  (ii) pQCD (collinear & k_T) factorization should break (HT, no incoherent parton scatt.)
  (iii) Violation of unitarity even for \( Q^2 \gg \Lambda^2 \) (too large perturbative cross-sections)

\[ xG(x) = dN_g/dy \]
**Colour Glass Condensate (CGC)**

- **CGC = EFT in high-energy (small-x) QCD limit:**
  - Hadrons = classical fields below “saturation scale” $Q_s$:
    - "saturated gluon wave function"
    - $Q_s$ hard enough $\Rightarrow$ perturbative calc. (strong $F_{\mu\nu}$, weak coupling): $\alpha_s(Q_s^2) \ll 1$
    - $p, A+A = \text{Collision of gluon wave function(s): "resums" all multiple scatts.}$
    - **Color Glass** (quarks $\sim$ “static” color sources) **Condensate** (high gluon occupation)

- **Gluons overlap for momenta below:**
  
- **Saturation enhanced in nucleus:**

\[
Q_s^2 \sim \alpha_s \frac{x G_A(x, Q_s^2)}{\pi R_A^2}
\]

\[
Q_s^2 \sim A^{1/3} \sim 6
\]

[McLerran, Venugopalan, Kharzeev, Kovchegov, Jalilian-Marian, Mueller, Iancu, Gelis, Tuchin, Ikatura, Dumitru, ...]
Non-linear QCD evolution equations

➢ Quantum evolution of classical fields governed by JIMWLK eqs.
  • Non-linear, all-twist equations in saturation regime
  • Generalized Fokker-Planck eq. (diffusion of wave-function)
  • Large $N_c$ limit $\rightarrow$ BK $\rightarrow$ Weak-field limit $\rightarrow$ BFKL.

Additional quantum corrections: lead to anomalous dimension in "extended scaling" region:

\[
\frac{1}{Q^2} \rightarrow \left( \frac{1}{Q^2} \right)^\gamma \quad \gamma \simeq 1/2
\]

extended window of “applicability” outside CGC!

\[
Q_s^2 < Q^2 < \frac{Q_s^4}{\Lambda^2}
\]

[Jalilian-Marian, Iancu, McLerran, Kovner, Leonidov, Weigert ]
Low-x QCD: experimental methods
Measuring parton distributions (p,A)

➢ High-\( p_T \), heavy-Q (ep,eA):

➢ “Diffractive” QQbar (ep, γp, γA):

➢ Prompt γ, DY, dijets, Q (pp,pA,AA):
PDF \((x, Q^2)\) domains: proton, nucleus

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

- Note: most existing low-\(x\) nPDFs measurements in the non-perturbative regime

much less nuclear PDF data available:

e-A, p-A

e-p, p-p

PDF (\(x, Q^2\)) domains: proton, nucleus

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

- Note: most existing low-\(x\) nPDFs measurements in the non-perturbative regime
Small-$x \rightarrow$ Forward rapidities

- $2 \rightarrow 2$ parton kinematics:
  \[
  y = 0: \quad x_1 \sim x_2 \sim x_T = \frac{2p_T}{\sqrt{s}}
  \]

- $2 \rightarrow 1$ (gluon fusion) kinematics: even much lower $x$ allowed in CGC
  \[
  x_{1,2}^{2\rightarrow1} = \frac{p_T}{\sqrt{s}} (e^{\pm y})
  \]

CGC: $x(y=4) \sim 10^{-4}$

pQCD: $x(y=4) \sim 10^{-2}$

Momentum balanced by the "medium" ("gluon ladder")

(RHIC) Accardi, nucl-th/0405046
Photoproduction ($\gamma A$) in UPC AA collisions

- Heavy-ions (charge $Z$) produce strong EM fields (coherent action of all protons):

- Equivalent flux of photons in electromagnetic (aka. Ultra-Peripheral, $b_{\text{min}} \sim 2R_A$) $A+A$:

  $$\frac{dN_{\gamma}}{dE}(b > b_{\text{min}}) \propto \frac{\alpha_{\text{em}} Z^2}{\pi} \frac{1}{E}$$

  (soft bremsstrahlung $\gamma$ spectrum)

- Photon beams:
  - **Flux** $\sim Z^2$ ($\sim 7 \cdot 10^3$ for Pb).
  - "Coherence condition": $\gamma$ wavelength $>$ nucleus size

  Maximum $\gamma$ energy: $\omega < \omega_{\text{max}} \approx \frac{\gamma}{R} \sim 80 – 160$ GeV (Pb,Ca)

- Center of mass-energies (LHC): $\sqrt{s_{\gamma A}} \approx 0.7 – 2. \text{TeV} \approx (3 – 10) \times \sqrt{s_{\gamma p}}$ (HERA)

- Bjorken $x$ range in nucleus:

  - (y=0): $x(J/\Psi) \sim 3 \cdot 10^{-3}$, $x(\Upsilon) \sim 10^{-2}$
  - (y=3): $x(J/\Psi) \sim 2 \cdot 10^{-5}$, $x(\Upsilon) \sim 10^{-4}$

- Forward neutron-tagging (ZDC): $\sim 50\%$ UPC colls. lead to nuclear breakup.
Saturation effects at HERA (ep) and RHIC (dA,AA)
Saturation models describe well $F_2(x, Q^2)$ in “transition region” of moderate/low $Q^2$ (also DGLAP, though at limit of applicability)

Forshaw, Shaw
hep-ph/0411337
HERA: “Geometric scaling” of low-x $F_2(x,Q^2)$

➢ Saturation predicts low-x structure dependence on single scale $Q^2_s$
   DIS inclusive cross-section shows scaling for all $x < 0.01, 0.045 < Q^2 < 450 \text{ GeV}^2$

\[ Q_s^2(x) = Q_0^2 \left( \frac{x_0}{x} \right)^\lambda \]

, $Q_0 = 1 \text{ GeV}, \lambda = 0.3$

described by “dipole cross-section” model (derivable within CGC):

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

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

up to relatively large $Q^2$ (“extended scaling” region):

\[ Q_s^2 < Q^2 < Q_s^4/\Lambda^2 \]
Saturation models can describe consistently total $\gamma p$ x-section ($F_2$) and DDIS (\(x_{IP} F_2^{D(3)}\), Pomeron structure) and DVCS forward amplitudes:

\[ x_{IP} = \text{fraction of } p \text{ momentum carried by Pomeron} \]

\[ \beta = \text{fraction of IP momentum carried by struck parton} \]

Forshaw, Shaw

hep-ph/0411337
HERA: Geometric scaling in diffractive DIS

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

C. Marquet, L. Schoeffel
hep-ph/0606079
RHIC: Total AA hadron multiplicity (I)

- **AuAu (200 GeV) 0-5% central collisions:**
  - "Reduced" multiplicity predicted by saturation models.

- \( \sim 700 \) charged particles per unit rapidity at \( y=0 \)

- "Reduced" multiplicity predicted by saturation models.

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Final multiplicity $\propto$ Initial multiplicity of released gluons $\propto Q_s$:

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

+ “local parton-hadron duality” assumption
(1 gluon = 1 final hadron)

Centrality (and $\sqrt{s}$) dependence of hadron multiplicities described:

Armesto et al., hep-ph/0407018

AuAu – 200 GeV
RHIC: forward dAu $p_T$ spectra

- Suppression of hadron spectra: $p_T \sim 2 - 4$ GeV/c at forward rapidities (reduced number of partonic scattering centers at low-$x$):

- Plus, CGC can explain other pA phenomenology ...
  
  (1) Leading-twist “shadowing”: extended scaling region
  
  (2) Cronin-enhancement at $y=0$: gluons redistributed from low- to higher $x$

- However: RHIC/HERA saturation “evidences” at moderate $p_T$
  
  $Q_s \sim 1 - 2$ GeV/c too close to non-perturbative regime.
Low-x QCD at LHC
LHC: low-x proton PDF

- pp @ 14 TeV:
  (i) Very high $\sqrt{s}$ ⇒ Bjorken $x=2p_T/\sqrt{s}$ ~ 70 times lower than pp @ RHIC
  (ii) Saturation momentum: $Q_s \sim 0.2 (\sqrt{s})^{0.2-0.3} \sim 2$ GeV
  (iii) Very large perturbative cross-sections.

Processes:

- $p(p_1) + p(p_2) \rightarrow \text{jet} + \gamma + X$ Prompt $\gamma$
- $p(p_1) + p(p_2) \rightarrow \ell\ell + X$ Drell-Yan
- $p(p_1) + p(p_2) \rightarrow \text{jet}_1 + \text{jet}_2 + X$ Jets
- $p(p_1) + p(p_2) \rightarrow Q + \bar{Q} + X$ Heavy Flavours
- $p(p_1) + p(p_2) \rightarrow W/Z + X$ W,Z production

For $y > 5$, $M < 10$ GeV

⇒ $x$ down to $10^{-6}$-$10^{-7}$!
LHC: low-$x$ nuclear PDF

- PbPb @ 5.5 TeV, pPb @ 8.8 TeV:
  
  (i) Very high $\sqrt{s} \Rightarrow$ Bjorken $x=2p_T/\sqrt{s} \approx 30-45$ times lower than AuAu, dAu @ RHIC
  
  (ii) Saturation momentum: $Q_s \approx 0.2 A^{1/6} (\sqrt{s})^{0.2-0.3} \approx 3$ GeV
  
  (iii) Very large perturbative cross-sections.

Nuclear $xG(x, Q^2)$ basically unknown for $x<10^{-3}$!

Ratio of gluon densities in Pb to p:

$Q^2 = 3$ GeV$^2$
Forward Detectors in CMS/ATLAS

- CMS + TOTEM:
  - HF (Iron-Q-fiber calo): $3 < \eta < 5$
  - TOTEM-T1: $3.1 < \eta < 4.7$
  - TOTEM-T2 (GEM telescope): $5.3 < \eta < 6.7$
  - CASTOR (W/-Q-fiber calo): $5.25 < \eta < 6.5$
  - ZDC (W/Q-fiber calo): $\eta > 8.5$ (neutral)

- ATLAS:
  - Forw. Cal.: $3 < \eta < 5$
  - LUCID (Cerenkov Counter): $5.4 < \eta < 6.1$
  - ZDC (W/Q-fiber calo): $\eta > 8.5$ (neutral)
CMS + TOTEM forward detectors

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

- Detection capabilities within $\eta \leq 6.7$ (and $\eta \geq 8.1$, neutral).

- Hard scattering measurements (jets, high-$p_T$ hadrons, DY) down to $x \sim 10^{-6}$ in pp, pA, AA at LHC.
Forward Detectors in ALICE/LHCb

ALICE, LHCb forward muon spectrometers:

- Good capabilities for heavy-Q, QQbar measurements at low-x:
  - $2.5 < \eta < 4$
  - $2 < \eta < 5$
Example I: Forward jets

➢ Forward jet production ("Mueller-Navelet" jets):

- Hadron-hadron:
  - Jets separated by several $\Delta \eta$ very sensitive to non-DGLAP evolution (BFKL, gluon saturation):
    - Suppressed ratio sat./BFKL for forward jets at LHC
    - Marquet, Royon, hep-ph/0510266

➢ Measurement feasible in ATLAS/CMS forward calorimeters ($3 < \eta < 5$)
Example II: Forward Drell-Yan

- **Drell-Yan feasibility studies with CMS (CASTOR) + TOTEM (T2):**
  
  \[ pp, \; \sqrt{s} = 14 \text{ TeV} \]

- **T2 tracker+ CASTOR calo needed to deal w/ large QCD (and QED) bckgd.**
  
  Van Mechelen, Ochesanu, Sarkysian, CMS PTDR2 (see also M.Grothe talk)
Example III: Quarkonia photoproduction

- Exclusive QQbar: $\gamma p \rightarrow Vp$ ($V=J/\Psi, \Upsilon$) very sensitive to small-$x$ gluon:

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

Ryskin et al. ZPC 76 (1997)231

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

- $J/\Psi, \Upsilon$ photoproduction in UPC AA: access to nuclear $xG$

RHIC – 200 GeV

LHC – 5.5 TeV

Dd'E, nucl-ex/0601001

Strikman, Vogt, White hep-ph/0508296

No shadowing
Summary

➢ Gluon saturation and non-linear evolution must set-in at (some) low-x in hadronic wave-functions → Fundamental info on high-energy limit of QCD

➢ Hints of non-linear QCD dynamics in ep (HERA) and dA,AA (RHIC)

➢ LHC: provides a unique lab to study high parton density/evolution down to $x \sim 10^{-6}$ (and $Q_s \sim 2$-3 GeV) with forward detectors using perturbative probes in pp, pA, AA collisions
Backup slides
ZDC-tagged (hard) photoproduction

- Quarkonia: $\gamma + A \rightarrow J/\Psi, \Upsilon + A$ very sensitive to nuclear gluon density:

$$\sigma(J/\Psi, \Upsilon) \sim |xG(x, Q^2)|^2$$

$\sim 30\%$ reduction of $G(x, Q^2)$ $\Rightarrow 0.5 \cdot \sigma_{J/\Psi, \Upsilon}$

- Dijet: via gluon exchange (well described in QCD & tested @ HERA)

  Wider range of $Q^2$ than QQbar.
  Photon-jet ($\sim 1\%$ of dijet rate) has clear signature
  ttbar possible in pA collisions (measure charge of top quark)

- $\sim 50\%$ of gA events accompanied w/ nuclear breakup (forw. n emission): ZDC- tag needed for triggering
\gamma p \text{ interactions at the LHC}

\begin{itemize}
  \item \gamma g \text{ luminosity spectra:}
    \begin{itemize}
      \item 0.01 < x < 0.1, \gamma \text{ tagging range}
      \item 0.005 < x < 0.3, Bjorken-x range
    \end{itemize}
\end{itemize}

\gamma p \text{ physics Menu:}

\begin{itemize}
  \item anomalous \text{ \ W and \ Z production at } W_{\gamma q} \geq 1 \text{ TeV}
  \item top pair production – top charge + threshold scanning?
  \item single top production and anomalous Wtb vertex
  \item SM BEH – for example, \gamma b \rightarrow H b, \gamma q \rightarrow H W q
  \item SUSY studies (complementary to the nominal ones) - 
    \begin{itemize}
      \item \text{ \ H}^+ \text{ \ t \ production (and } \text{ \ H}^{++}\text{), b and t spairs, } t\chi \text{ pair, ...}
    \end{itemize}
  \item Exotics: compositness, excited quarks, ...
\end{itemize}
Saturation predictions @ LHC (nucleus)
Hadronic Forward Calorimeter (2.5 < η < 5)

- 11.2 m from IP5.
- Steel+quartz-fibre Cherenkov (EM+HAD) calorimeter
- 1.65 m absorber depth
- 900 towers (1200 channels): Δη x ΔΦ ~ 0.18 x 0.18
- Hamamatsu R7525 rad-hard PMTs
T2 and CASTOR (5.1 < \eta < 6.7)
CASTOR forward calorimeter ($5.1 < \eta < 6.6$)

- Tungsten plates + quartz fibres
- Cherenkov sampling calorimeter
- Light-guides + APDs readout
- Azimuth segmented (8 octants)
- EM section: $11.2 \text{ cm} \sim 19 \chi_0$
- HAD+EM sections: $136 \text{ cm} \sim 10 \lambda_I$
- 192 channels
TOTEM T2 Tracker (5.3 < \eta < 6.7)

- TOTEM GEM ("Gas Electron Multiplier") charged particle telescope detector:

- TOTEM GEM half telescope
- Shielding envelope
- ~ 500 mm
- GEM half telescope
- APV
- VFAT
- HV
Zero Degree Calorimeter ($|\eta| > 8.1$ neutral)

- **ZDC** = Tungsten-plates+Quartz-fibres sampling Cerenkov calorimeter with HAD and EM sections:

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

  - (Follows closely RHIC experience).
  - EM section: $x33$ 2mm-W cells ($\sim 19X_0$)
  - HAD sect: $x24$ 15mm-W cells ($\sim 5.6\lambda_0$)
  - PMTs: R7525 (as HF)
  - Rad hard to $\sim 20$ Grad (AA, pp low lum.)
  - Energy resolution $(n,\gamma)$: $\sigma/E \sim 10\%$
  - Position resolution: $\sim 2$ mm (EM sect.)
  - Signals available for L1
Low-x at the LHC (nucleus)

TOTEM:
- Approved July 2004 (TDR of TOTEM web page http://totem.web.cern.ch/Totem/)
- TOTEM stand alone
  - Elastic scattering, total pp cross section and soft diffraction.

CMS:
  - Diffraction with TOTEM Roman Pots and/or rapidity gaps
- Technical Proposal in preparation for new forward detectors (CASTOR, ZDC, +…)
  - Diffractive and low-x physics part of CMS physics program (low + high)

CMS+TOTEM:
- Prepare common LOI due in Summer 2006 (M. Grothe/V. Avati organizing)
  - Full diffractive program with central activity. TOTEM will be included as a subdetector in CMS (trigger/data stream)

ATLAS:
- LOI submitted (March 04) for RP detectors to measure elastic scattering/ total cross sections/luminosity. Diffraction will be looked at later

ALICE, LHCb: no direct forward projects plans but keeping eyes open.
Effective action describes a weakly coupled albeit non-perturbative system

\[ Q_S^2 \approx \alpha_S N_c \mu_A^2 \ln \left( \frac{\mu_A^2}{\Lambda^2} \right) \approx A^{1/3} \text{ for } A \gg 1 \]

\[ W_{\Lambda+} = \exp \left( - \int d^2 x_\perp \left[ \frac{\rho^a \rho^a}{2 \mu_A^2} - \frac{d_{abc} \rho^a \rho^b \rho^c}{\kappa_A} \right] \right) \]

\[ \mu_A^2 = \frac{g^2 A}{2\pi R^2} \propto A^{1/3} \]

\[ \kappa_A = \frac{g^3 A^2 N_c}{\pi^2 R^4} \propto A^{2/3} \]
Mechanism for parton saturation

- Competition between “attractive” bremsstrahlung and “repulsive” recombination effects.

Maximal phase space density =>

\[
\frac{1}{2(N_c^2 - 1)} \frac{x \, G(x, Q^2)}{\pi R^2 Q^2} = \frac{1}{\alpha_s(Q^2)}
\]

Saturated for

\[Q = Q_s(x) \gg \Lambda_{QCD} \approx 0.2 \text{ GeV}\]

Valence partons

“wee” parton cloud

\[P_z \rightarrow \infty\]

In infinite momentum frame (IMF),

\[|h> = |qqq> + |qqqqg> + \cdots |qqqqggg\cdots q\bar{g}g>\]

Construct “effective” theory of wee parton modes
Hadron at high energies is a Color Glass Condensate.

Gluons are colored

Random sources evolving on time scales much larger than natural time scales—very similar to spin glasses

Bosons with large occupation \( \# \sim \frac{1}{\alpha_s} \) - form a condensate

Typical momentum of gluons is \( Q_s \)
Low-$x$ at the LHC (nucleus)

LO CEM calculation

Gluon distribution functions at the scale of the charmonium calculation.
Rapidity distributions with different PDFs

Approximations:
- Calculation LO
- \( gg \) contr. dominant

\[
\hat{\sigma}_{ij}(\hat{S}) = \hat{\sigma}_{gg}
\]

\[
\frac{d\sigma_{CEM}^C}{dy} = K \int_{4m_Q^2}^{4m_H^2} d\hat{S} \hat{\sigma}_{gg} f_{i/A}(\sqrt{\frac{\hat{S}}{s}} e^y, \mu^2) f_{j/B}(\sqrt{\frac{\hat{S}}{s}} e^{-y}, \mu^2)
\]
CMS-TOTEM forward detectors ($|\eta| \sim 3-6.7$)

140 m

ZDC

CASTOR (Cal)

T2 (Track)

HF (Cal)

T1 (Track)

140 m

TOTEM T2

HF

TOTEM T1

IP
HF, TOTEM (T1,T2), CASTOR
Backup slides
Diffractive pp collisions

➢ No ZDC activity = large rapidity gap. **Complements** (trigger & offline) leading proton detectors e.g. in dijet **single diffraction**:

roman pots
p

\[ \text{p} \rightarrow \text{p} \ 2j \ X \]

[from A.Sobol CMS, Feb'06]

➢ ZDC (even w/o leading p detection) can help “calibrate” DPE Higgs prod.:

1\text{st} process measurable w/ ZDC. Both closely related (QCD part identical). Measurement of one constrains the other.

[from M.Albrow CMS, Feb'06]

➢ Bottom line: ZDC reduces to “zero” holes & cracks in CMS (full 4\pi). Helps all diffractive (Ip-, \gamma-mediated) analysis in pp,pA,AA.
\[ \gamma \gamma, \gamma A : \text{physics topics} \]

- **Typical diagrams** for \( \gamma \gamma \) and \( \gamma A \) collisions:

- **Physics:** QED, precision QCD
- **Measurements:** \( \ell^+ \ell^-, \text{C-even c\bar{c} b\bar{b}}, W^+W^- \ldots \)
- **Topics:** QED in strong regime \( (Z\alpha_{em} \sim 1) \), heavy-Q spectroscopy, [quartic GC \( (WW\gamma\gamma), \ldots \)]

- **Precision QCD**
  (low bckgd, simpler initial state than \( p,A+A \))

- **Quarkonia, heavy-Q, jets ...**

- **Nuclear \( G_A(x,Q^2) \), low-x physics, QQbar in cold nuclear matter**

- **All UPC measurements at RHIC:** ZDC-triggered (neutron tagging)!
\(\gamma\gamma\): Discovery physics & others

- \(\gamma\gamma \rightarrow \text{Higgs} (\rightarrow \bar{b}b)\)
  - Rate is very low (better w/ lighter ions, pA or pp)
  - Establishes the nature of Higgs (\(J^{PC}\), SM vs. MSSM)

- \(\gamma\gamma \rightarrow W^+W^- \& \text{photoproduction of } W^+W^-\):
  - Study quartic/triple \(\gamma\gamma WW, \gamma WW\) vertices
  - Anomalous coupling sensitive to new physics

- Other “discovery” channels:
  - \(\gamma\gamma\) production of magnetic monopoles, SUSY, ...

- Others:
  - \(e^+e^-\) pair production
    Tests QED in very strong fields (grazing \(b=2R\) colls ~ 5 \(e^+e^-\) pairs produced). Huge rates: \(\sigma\sim13,000\) b in ALICE inner Si
  - Quantum correlations in multiple Vector Meson Production
  - QQbar spectroscopy: \(\gamma\gamma \rightarrow 0^+2^+\) states (\(\eta_b, \chi_{b0}, \chi_{b2}, \ldots\)).