Ultra-Peripheral Collisions at STAR

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- Ultra-Peripheral Collisions (UPC) & $e^+e^-$ processes
- The STAR detector & UPC data selection
- UPC $J/\psi$ in Au+Au
- UPC $J/\psi$ in polarized $p^\uparrow$+Au
Ultra-Peripheral Collisions (UPC)

- UPC: $b > 2R$, hadronic interactions suppressed

- Large flux of photons coming from Weizsaecker-Williams:
  - WW photon from one beam particle
    $\rightarrow$ photoproduction on other beam particle
    e.g. $J/\psi$ production, sensitive to gluons:

  - Photon may interact: coherently, with whole nucleus
    incoherently, with individual nucleons

  - Coherent: nucleus may survive intact, or
    break up via mutual Coulomb dissociation
  - Incoherent: nucleus likely breaks up
    nucleon may emerge w/ full momentum, or
    dissociate into multiparticle final state
UPC processes in AuAu

- Observed here in low $p_T$ $e^+e^-$ pairs
- Not sensitive to all w/ present statistics, as noted later

**High statistics**
- $J/\psi$ photoproduction, $m_{ee} \sim m_{J/\psi}$: coherent, large nucleus $\leftrightarrow$ low $p_T$
  incoherent, small nucleon $\leftrightarrow$ high $p_T$
  incoherent w/ nucleon diss. $\leftrightarrow$ higher $p_T$

- QED $2\gamma \rightarrow e^+e^-$, $m_{ee}$ continuum:
  low $p_T$

**Low statistics**
- $\psi(2S) \rightarrow e^+e^-$, $m_{ee} \sim m_{\psi(2S)}$: coh. low $p_T$, inc. high $p_T$, nucl. diss. higher $p_T$
- Feed-down $\psi(2S) \rightarrow J/\psi + X$, $J/\psi \rightarrow e^+e^-$, $m_{ee} \sim m_{J/\psi}$: higher $p_T$ from 2S decay
  $BR(\psi(2S) \rightarrow J/\psi + X) \cdot BR(J/\psi \rightarrow e^+e^-) / BR(\psi(2S) \rightarrow e^+e^-) \sim 4.6$
The STAR detector, data selection

**Trigger:**
- Back-to-back showers in BEMC
- Veto BBC (reject hadronic central collisions)
- Au+Au: BEMC 'active', also require 2-6 hits in TOF
- p↑+Au: reject nuclear breakup, veto ZDCs

**Offline selection:**
- Reject high activity events (# TOF hits, # BEMC showers)
- 2 tracks match BEMC showers, vertex in the STAR center
- Tracks well reconstructed, dE/dx select ee, reject hadron pairs

**Data sets:**
- 2015 p↑Au, $L = 140$ nb$^{-1}$
- 2016 AuAu, $L = 13$ nb$^{-1}$
Au+Au: data features

- $p_T$ vs. $m_{ee}$ for opp. sign pairs:
  - High stat. features clear:
    - coh. $J/\psi$ @ low $p_T$
    - & rad. tail lower $m_{ee}$, higher $p_T$
    - inc. $J/\psi$ @ high $p_T$
    - QED $2\gamma$ continuum @ low $p_T$

- $m_{ee}$ for opp./like-sign pairs:
  - Small like sign contamination @ low $m_{ee}$
    - (& high $p_T$, not shown)
  - Take as combinatoric bkg.: for final distributions take (opposite-like) sign
UPC processes (slide 3) generated w/ STARlight, modifications:
- $p_T$ of coherent $J/\psi$ & $2\gamma$ too high, reweighted to match data
- incoherent $J/\psi$ w/ nucleon dissociation $p_T$ shape from HERA

Passed processes through simulation of the STAR detector: templates
Fit sum templates to data

$p_T < 0.15$ GeV/c:

**Zoom $\psi(2S)$ region:**

$\psi(2S)$: $N_{\psi(2S)} = 130 \pm 23$
5.7 $\sigma$ from zero
Not stat. sensitive to inc. $\psi(2S)$, buried by $2\gamma$

**UPC procs→data comparison: $m_{ee}$**

- Fit sum of: $J/\psi$, $\psi(2S)$, QED $2\gamma$
- Fit describes data: peaks & rad. tails & $2\gamma$ shape over ~3 orders mag. in $\sigma$
• Fix QED $2\gamma$ & $\psi(2S)$ from $m_{ee}$ fit, fit sum others to data
• $3.0 < m_{ee} < 3.2 \text{ GeV/c}^2$

Good description of data, need all processes:
• coherent $J/\psi$ & QED @ low $p_T$
• feed-down from $\psi(2S)$ & incoherent $J/\psi$ @ mid $p_T$
• incoherent $J/\psi$ w/ nucleon dissociation for high $p_T$ tail
Nuclear dissociation ↔ J/ψ p

- Zero Degree Calorimeters in each beam direction:
  - tag ≥1 neutron with ~ nucleon beam energy (100 GeV)
  - J/ψ p_T: at least 1 n one side vs. no neutrons either side (0n0n)

Clear difference:
- Incoherent processes ~always produce a neutron
- Coherent processes also produce neutrons: Coulomb dissociation
- 0n0n fully described by coherent components & QED 2γ
- Incoherent processes fit consistent w/ 0
- Vetoing on neutrons ⇒ clean sample of coherent processes
- Good starting point study of coherent p_T, analysis continuing...
Coherent J/ψ |t| distribution

- More developed STAR result: UPC J/ψ $p_T$ distributions from 2014
- Trigger required neutrons both sides: incoherent present, subtract

-subtract QED $2\gamma$ & J/ψ incoherent (exponential fit)
- Diff. cross section $d\sigma/d|t|$, $|t| \propto p_T^2$
- Compare to some models:

  - STARLIGHT: Klein, Nystrand
    CPC 212 (2017) 258-268
    - includes effects of photon $p_T$
  - MS: Mäntysaari, Schenke
  - CCK: Cepila, Contreras, Krelina

Can start model comparisons:
- Dip/ankle @ expected |t|?
- Dips washed out by $\gamma p_T$?
Generalized Parton Distributions

- GPDs: Correlated quark momentum and helicity distributions in transverse space
- Access to: 3D imaging of proton $q$ & $g$ orbital angular momentum $L_q$ & $L_g$
- GPDs for each $q,g$: $H_{q,g}^{\eta}/E_{q,g}^{\eta}(x,\xi,t)$ conserve/flip nucleon helicity
- The GPDs $E_{q,g}^{\eta}$ responsible for orbital angular momentum

Photoproduction w/ polarized protons
- Target particle polarized proton $p^{\uparrow}$:
  $J/\psi$ photoproduction $d\sigma/d\varphi \propto 1 + A_N^\gamma \cos(\varphi)$
  $\varphi = \text{azimuthal angle around beam axis}$
- $A_N^\gamma$ calculable with GPDs*:
  \[ A_N^\gamma \propto p_T \cdot \frac{\text{Im}(H^g \cdot E^g*)}{|H^g|^2} \]
- $A_N^\gamma \propto E^g \Rightarrow \text{sensitive to gluon orbital angular momentum } L_g$
- Unique RHIC capability: polarized protons, $p^{\uparrow}$Au run in 2015

**UPC processes in $p^{↑}+Au$**

$\gamma p^{↑} J/\psi$ photoproduction:
- Au photon source, $p^{↑}$ target

$\gamma Au J/\psi$ photoproduction:
- $p^{↑}$ photon source, Au target

Also:
- Continuum $e^+e^-$ QED 2-$\gamma$ process

Other processes seen in Au+Au:
- not discernible w/ statistics this data sample
As for Au+Au fit sum MC templates to data:

- Fix ratio J/Ψ components (γp↑:γAu)
  from p_T fit (next step, iterate)
- Fit data to sum J/Ψ and QED 2γ
- Good description all features:
  - J/Ψ peak location, width & rad. tail
  - QED 2γ continuum
- Fix 2γ for p_T fit, fit sum γp↑, γAu

γp↑ @ high p_T ~ AuAu incoherent
γAu @ low p_T ~ AuAu coherent

Want A_Nγ for γp↑ process, @ low p_T γAu & 2γ bkg., cut out
For A_Nγ: 0.2 < p_T < 1.5 GeV/c
Purity = 92%
Count events $2.8 < m_{ee} < 3.2$ GeV/$c^2$, $0.2 < p_T < 1.5$ GeV/$c$ for:

- $p^\uparrow$ beam spin up/down, $J/\psi \cos(\varphi) > 0 / \cos(\varphi) < 0$ (total 231 events)

Correct for:

- purity = 92%, $p^\uparrow$ beam polarization $P = 61.3$

Result:

$$A_N^\gamma = 0.05 \pm 0.20 \at \langle W_{\gamma p} \rangle = 23.8 \text{ GeV}, \langle p_T \rangle = 0.48 \text{ GeV/c}$$

$W_{\gamma p} = \gamma p$ c.m. energy

Null result, but proof of principle this measurement

Lansberg et al. have curve $\langle p_T \rangle = 0.7$ GeV/$c$, remade for 0.48 GeV:

(J. Wagner, private communication)

Can see what's needed to test such models:

- higher statistics
- lower $W_{\gamma p}$

Future @ RHIC?

STAR preliminary
These analyses used central STAR $-1<\eta<1$

Already in STAR:
iTPC tracking, endcap EMC triggering $1<\eta<2.2$

Coming soon 2021+ STAR Forward Upgrade w/ tracking & calorimetry $2.5<\eta<4$

Future RHIC $p^{\uparrow}Au$ runs 2022+:
- measure @ lower $W_{\gamma p}$
- higher cross section (stats.)
- larger $A_{N}^{\gamma}$

Should be sensitive to e.g. Lansberg et al. models
Summary UPC

UPC in 200 GeV Au+Au
- Large statistics, processes observed:
  - J/ψ: coherent, incoherent, incoherent w/ nucleon dissociation
  - ψ(2S): coherent in e⁺e⁻ & J/ψ+X channels
  - QED 2γ
- Nuclear dissociation tagged by neutrons in 0° calorimeters:
  - incoherent processes ~always produce neutron
  - veto neutrons → clean sample coherent processes

UPC in 200 GeV polarized p↑+Au:
- Observed J/ψ in γp↑ & γAu, QED 2γ
- Proof of principle: measurement of \( A_N^\gamma \propto E^g \sim \text{gluon } L_g \)
  null result here, but:
- Promising outlook for future RHIC runs
Extras
STAR Forward Diffraction

- STAR has a Roman Pot (RP) system: RHIC proton beams, tag/measure scattered $p$ w/ ~beam energy

![Top view diagram](image1)

![Side view diagram](image2)

- Recent data w/ $pp$, $pAu$, $pAl$ @ $\sqrt{s}=200$ GeV, $pp$ @ 510 GeV
- First results from $pp$ 200:
  - elastic $pp$ scattering $\Rightarrow$ total $pp$ cross section
  - single diffractive dissociation
  - central exclusive production
**pp elastic scattering**

- Fundamental *pp* physics measurement
- Measure back-to-back protons both beam directions, scattering angle $\Rightarrow$ momentum transfer $t$:
  - $d\sigma_{el}/d|t|$ well described by $e^{-B|t|}$
  - $B_{el} = 14.32 \pm 0.09$ @ $\sqrt{s}=200$ GeV
  - consistent w/ world data $B_{el} \propto \log(s)$

- **slope $B_{el}$ & world data:**
- **$\sigma_{el,tot}$ & world data:**
  - $\int e^{-B|t|} \Rightarrow \sigma_{el}$
  - $d\sigma_{el}/d|t| \big|_{t=0}$, optical theorem
  - $\Rightarrow \sigma_{tot}, \sigma_{inel} = \sigma_{tot} - \sigma_{el}$
  - consistent w/ fit world data
Diffractive final states

• Final states measured in central STAR, tag proton in RP:

  - Proton 1 side: single diffractive dissociation (SDD)

  - Proton 2 sides: central exclusive production (CEP), 2 Pomeron fusion

• Final state properties, input for models, e.g.:

  - CEP $m_{\pi\pi}$ spectrum many features, no model describes all features partial wave analysis?

• SDD single particle $p_T$ spectrum ~described by Pythia
Au+Au: $m_{ee}$ fit

- $m_{ee}$ fit not sensitive to different J/$\psi$ components:

- Fix ratio $\psi(2S) \rightarrow J/\psi + X / \psi(2S) \rightarrow e^+e^-$ by BRs
- Fix ratio (inc.:coh.) J/$\psi$ from $p_T$ fit (next step, iterated)
- Fit sum of: J/$\psi$, $\psi(2S)$, QED $2\gamma$
On a linear Y scale:

- Deviation @ lowest $m_{ee}$: trigger threshold uncertainty
- Fit performed $2.2 < m_{ee} < 6$ GeV/c$^2$
Au+Au: $p_\perp$ fit

- MC $p_\perp$ templates for two processes:
  - incoherent $J/\psi \rightarrow e^+e^-$
  - feed-down incoherent $\psi(2S) \rightarrow J/\psi + X$, $J/\psi \rightarrow e^+e^-$

- ~indistinguishable
- treated as one component for comparison/fit to data
Au+Au: $p_T$ for 3 ZDC categories

- Shown w/ vertical scale same range $10^3$:

  - $\geq 1n$ both ZDCs:
  - $\geq 1n$ one ZDC, other ZDC empty:
  - both ZDCs empty:

  Coherent peak always present & prominent regardless of neutrons: Coulomb dissociation
  Incoherent components only present when some neutrons
  \[ \rightarrow \text{fit consistent with zero for } 0n0n \]
Coherent $J/\psi \ |t|\text{ distribution}$

- **STARLIGHT:** Klein, Nystrand, CPC 212 (2017) 258-268
  - VMD and Glauber approach, includes effects of photon pT
- **MS:** Mäntysaari, Schenke, Phys.Lett. B772 (2017) 832-838
  - Dipole approach with IPsat amplitude
- **CCK:** Cepila, Contreras, Krelina, Phys.Rev. C97 (2018) no.2, 024901
  - Hot spot model for nucleons, dipole approach
- **MS & CCK** scaled to XnXn using STARLIGHT
**p↑+Au: p_T, m_{ee} distributions**

**p_T vs m_{ee} for opp. sign pairs:**

- Box shows fiducial region for $A_N^\gamma$ measurement:
  
  \[ 2.8 < m_{ee} < 3.2 \text{ GeV/c}^2, \]
  
  \[ 0.2 < p_T < 1.5 \text{ GeV/c} \]

**m_{ee} dist. or opp./like sign pairs:**

- For final distributions take (opposite-like) sign

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**STAR preliminary**

$p^{\uparrow}Au \rightarrow e^+e^-pAu \quad \sqrt{s_{NN}}=200\text{GeV} \quad |y|<1$
**Cross-ratio** (for non-spin experts)

- If have one beam w/ spin up, and detectors left (L) and right (R) of beam, can measure asym. but would need to know relative acceptances of L/R detectors

- If have one detector left of beam, and beam bunches w/ spin up (+) and down (-), can measure asym., but would need to know relative luminosities of +/- beams

- If have both L/R detectors and +/- bunches, acceptances and luminosities cancel out in the “cross-ratio”*:

$$\epsilon = \frac{\sqrt{N_{R+}N_{L-}} - \sqrt{N_{L+}N_{R-}}}{\sqrt{N_{R+}N_{L-}} + \sqrt{N_{L+}N_{R-}}}$$

* NIM 109 (1973) 41