J/ψ Production in Ultra-Peripheral Heavy-Ion Collisions at STAR

W. Schmidke, BNL
For the STAR Collaboration

DIS 2021
Stony Brook Univ. (virtual)

- Ultra-Peripheral Collisions (UPC) & e^+e^- processes
- The STAR detector & UPC data selection
- UPC J/ψ in Au+Au
- UPC J/ψ in polarized p↑+Au

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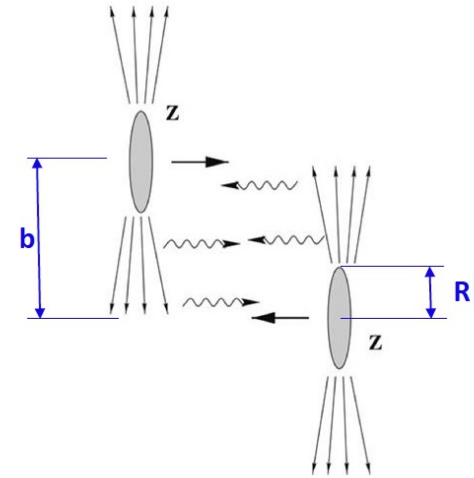
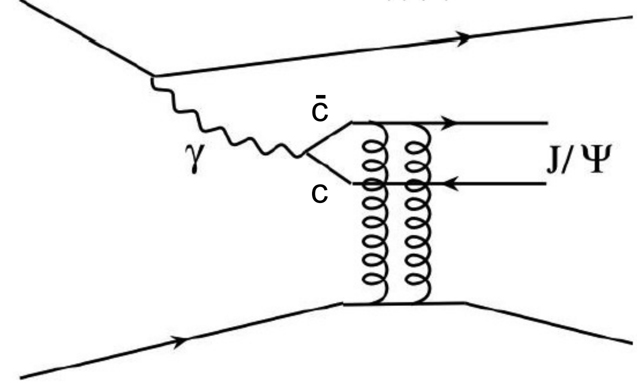
Ultra-Peripheral Collisions (UPC)



- UPC: b > 2R, hadronic interactions suppressed

- Large flux of photons coming from
  Weizsaecker-Williams:

- WW photon from one beam particle
  → photoproduction on other beam particle
- e.g. J/ψ production, sensitive to gluons:



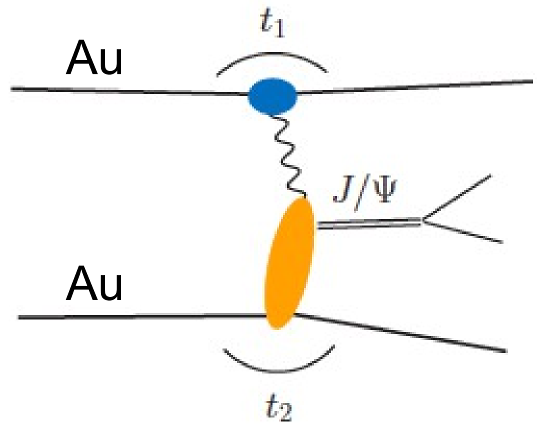
<u>AuAu:</u> gluon content of Au
models UPC photon flux from Au &:

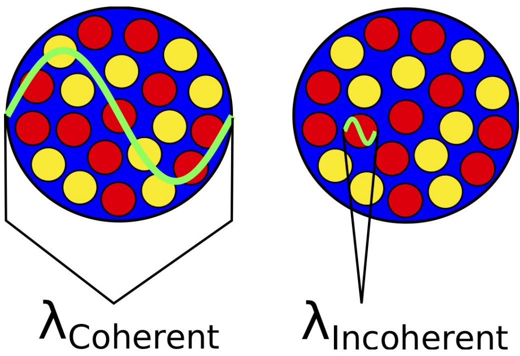
- STARlight: γ+p→J/ψ+p from HERA data
  ⇒ γ+Au→J/ψ+Au classical Glauber, some gluon shadowing
- Sartre: dipole model + bSat saturation
  see talk by T. Toll

<u>pAu</u>: gluon content of p
- J/ψ asymmetry ∝ gluon GPD E^g; compare E^g parameterization

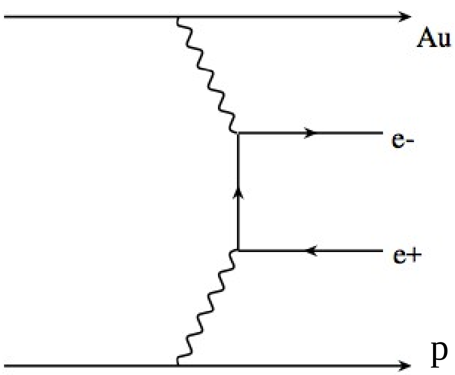
UPC processes in Au+Au

$J/\psi \to e^+ + e^-$



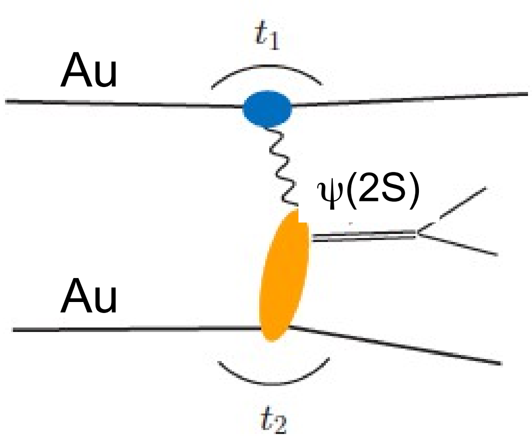


- Photoproduction J/ψ ($m_{ee} \sim m_{J/\psi}$):
  - coherent, off nucleus, low p_T
  - incoherent, off nucleus, high p_T
    elastic $\gamma + p \to J/\psi + p$
    inelastic $\gamma + p \to J/\psi + p + X$ (nucleon dissociation)

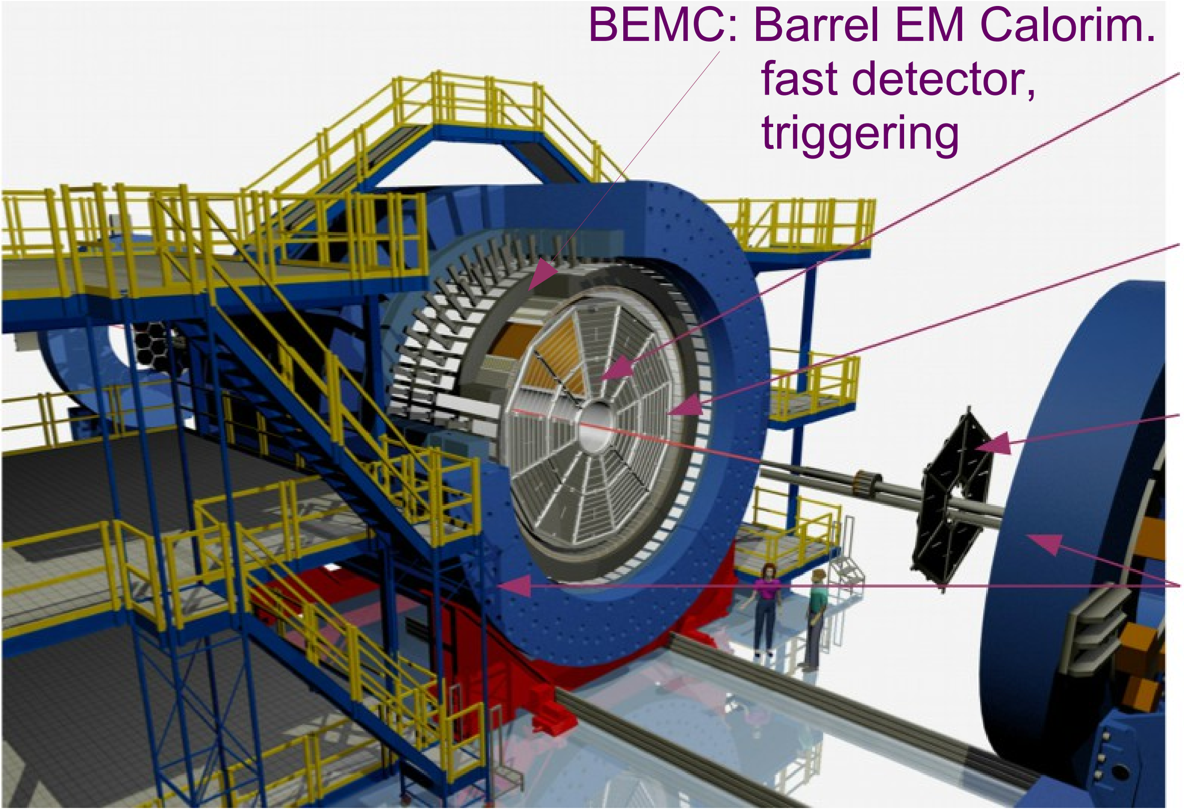


- QED 2γ (m_{ee} continuum):
  $\gamma + \gamma \to e^+ + e^-$

- Photoproduction $\psi(2S)$, decays:
  $\psi(2S) \to e^+ + e^-$ ($m_{ee} \sim m_{\psi(2S)}$)
  $\psi(2S) \to J/\psi + X$
  $J/\psi \to e^+ + e^-$ ($m_{ee} \sim m_{J/\psi}$) (feeddown)
  Statistics sensitive to only $\psi(2S)$ coherent



The STAR detector, data selection



ZDC: ±18m from IP
0° calorimeters, forward neutrons

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

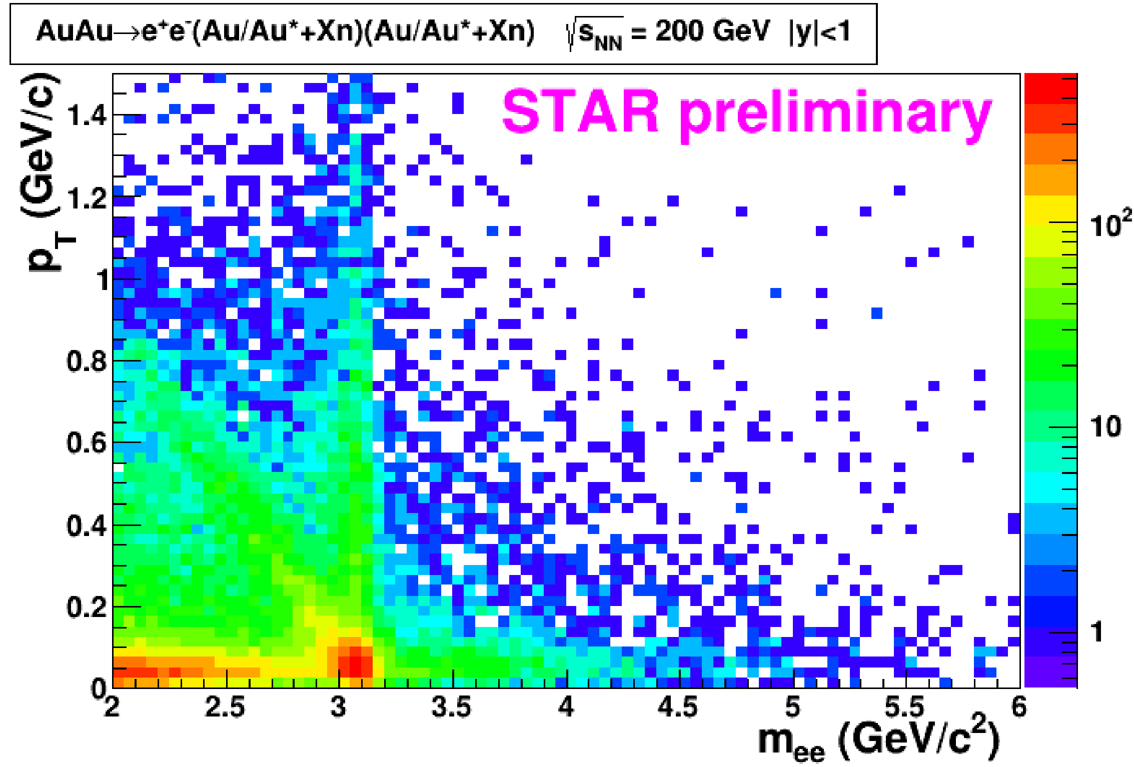
Data sets: 2015 p↑Au, L = 140 nb^{-1}
2016 AuAu, L = 12 nb^{-1}

Offline selection:

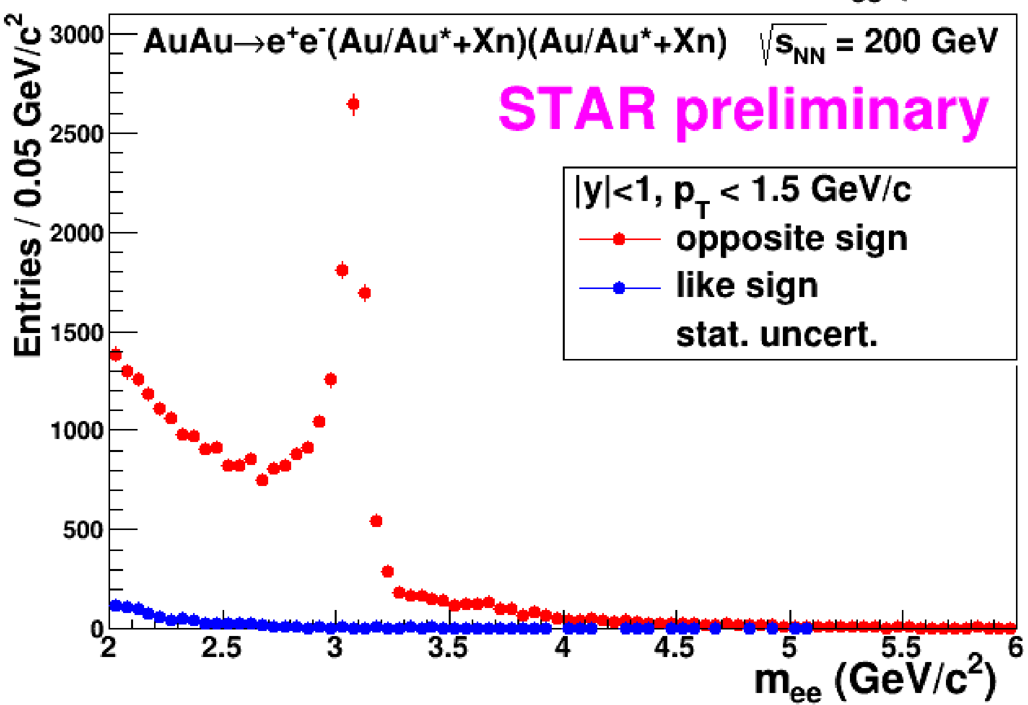
- Reject high activity events (# TOF hits, # BEMC showers)
- 2 tracks match BEMC showers, vertex in the STAR center
- Tracks well reconstructed, dE/dx select *ee*, reject hadron pairs

Au+Au: data features

- p_T vs. m_{ee} for opp. sign pairs:
- High stat. features clear:
  - coherent J/ψ @ low p_T
    & rad. tail lower m_{ee}, higher p_T
  - incoherent J/ψ @ high p_T
  - QED 2γ continuum @ low p_T



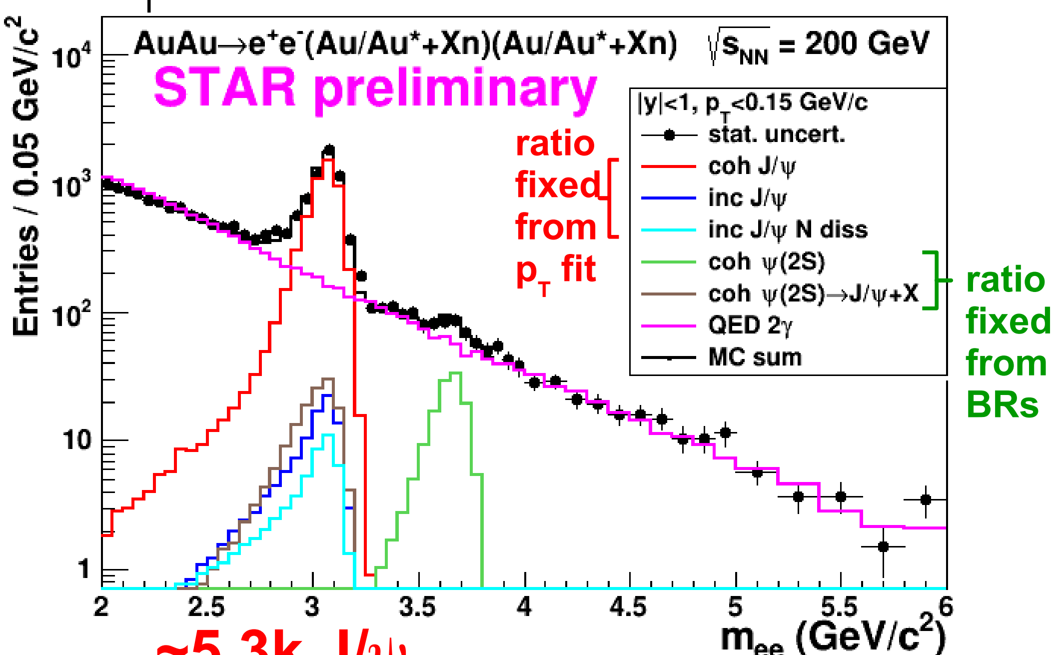
- m_{ee} for opp./like-sign pairs:
- Small like sign contamination, mostly @ low m_{ee}
- Take as combinatoric bkg.:
  final distributions =
  opposite sign - like sign



UPC procs→data comparison: m_{ee}

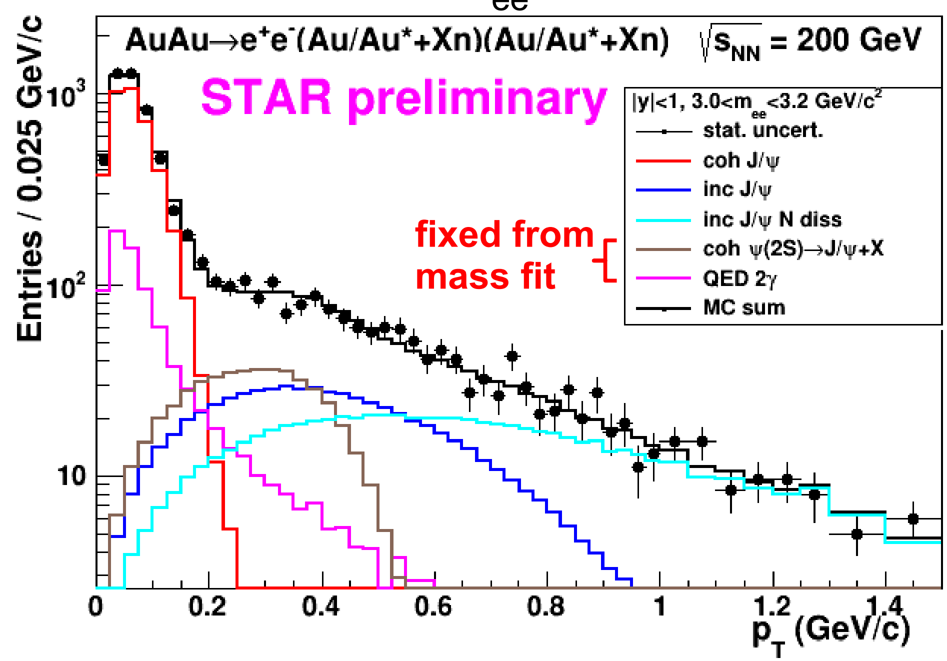
- UPC processes (slide 3) generated w/ STARlight, modifications:
  - p_T of coherent J/ψ & 2γ too high, reweighted to match data
  - incoherent J/ψ w/ nucleon dissociation p_T shape from HERA
- processes → STAR simulation → templates; fit sum to data

- p_T < 0.15 GeV/c:



~5.3k J/ψ

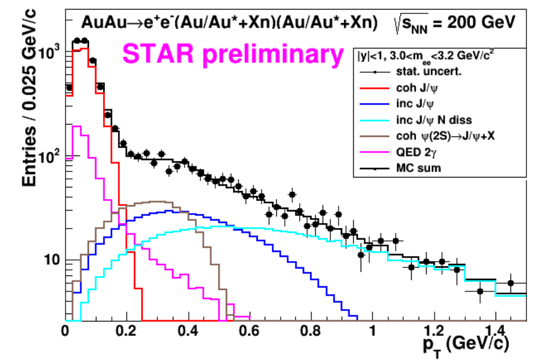
- J/ψ peak 3.0 < m_{ee} < 3.2 GeV/c^2:

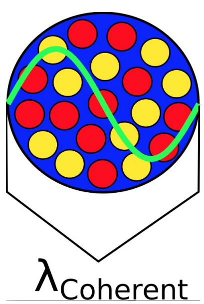


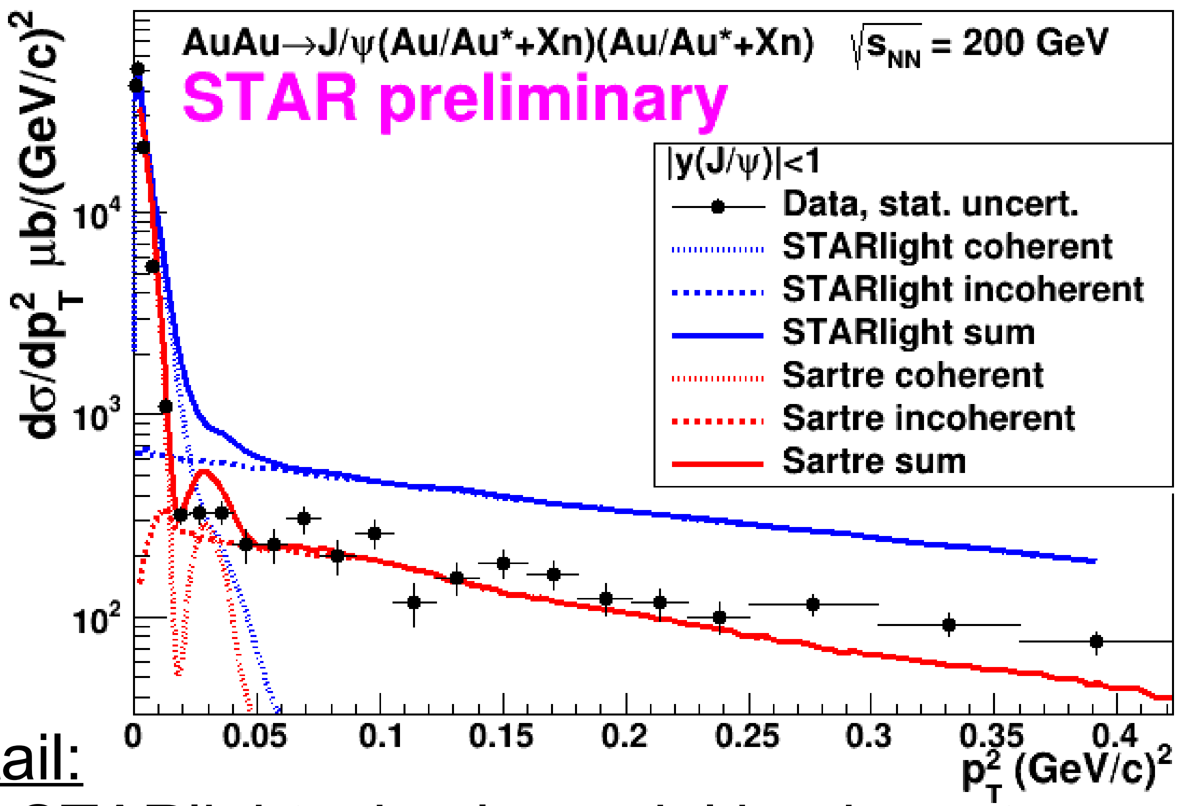
- Good description of data: VM peaks & rad. tails; 2γ shape ~3 orders mag. in σ
  J/ψ p_T coherent/incoherent components
- Use templates for: background subtractions, acceptance corrections

J/ψ p_T^2~|t| distribution

- Subtract non-direct J/ψ components (2γ , feeddown)
- Cross section: $d\sigma/dp_T^2$ (p_T^2~|t|)
- 2 components clear, data & models: coherent (low p_T^2) & incoherent (high p_T^2)

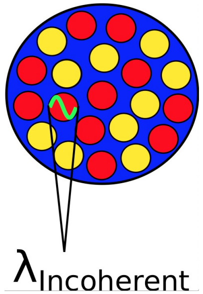






STARlight: Comput.Phys.Commun. 212 (2017) 258

Sartre: Comput.Phys.Commun. 185 (2014) 1835
Phys.Lett.B 803 (2020), 135277

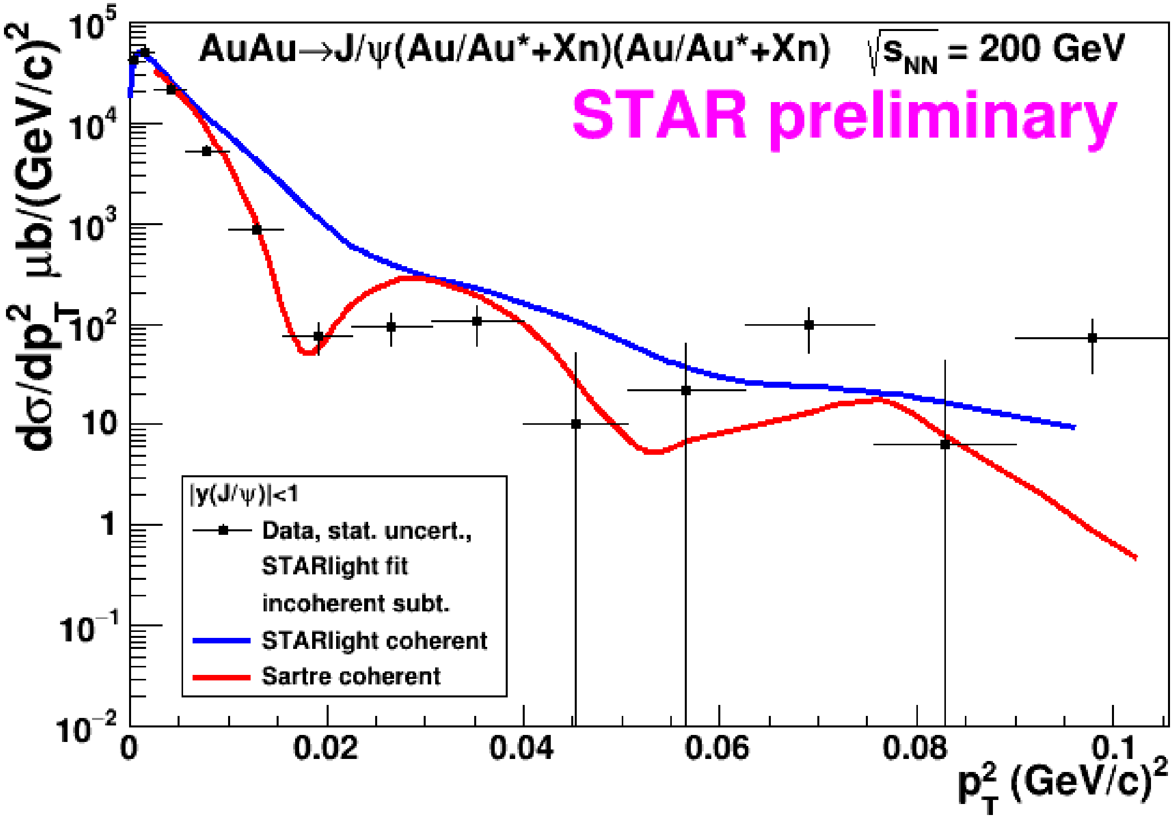


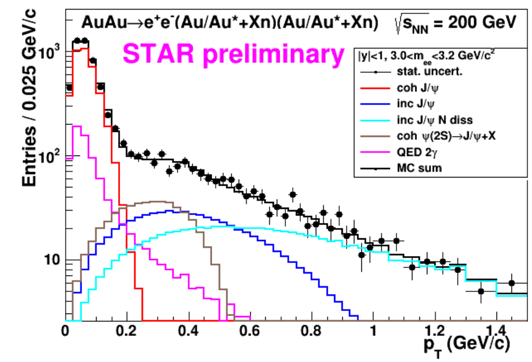
Incoherent tail:

- Data ~40% STARlight, simple model inadequate
- Sartre close in magnitude
- Highest p_T^2 data rise faster than models: inelastic γ+p→J/ψ+p+X ? or subnucleon fluctuations, see talk T. Toll

Coherent J/ψ p_T^2~|t| distribution

- Also subtract: STARlight incoherent fit to data





- $d\sigma/dp_T^2$~0 for p_T^2>0.1 (GeV/c)^2
- Total $\sigma = \int dp_T^2$

  data: 219 ± 5 (stat.) μb

  (scale uncert. ~10%)

  STARlight: 285 μb

  Sartre: 222 μb

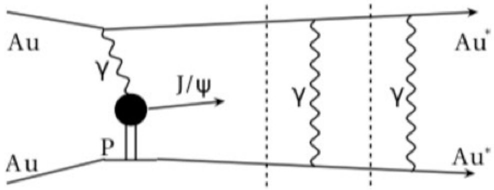
- Data/STARlight ~25%: shadowing; lowest p_T^2 data fall steeper
- Sartre: good description magnitude & shape @ lowest p_T^2
- Both models ~ data magnitude in higher p_T^2 tail
- Diffractive dips in Sartre → smeared by UPC γ p_T in STARlight

  data do not distinguish

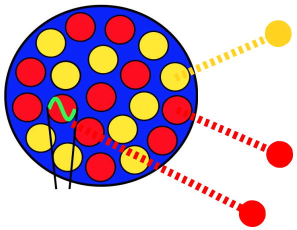
Nuclear dissociation ↔ J/ψ p_T

<u>2 mechanisms nuclear dissociation</u>

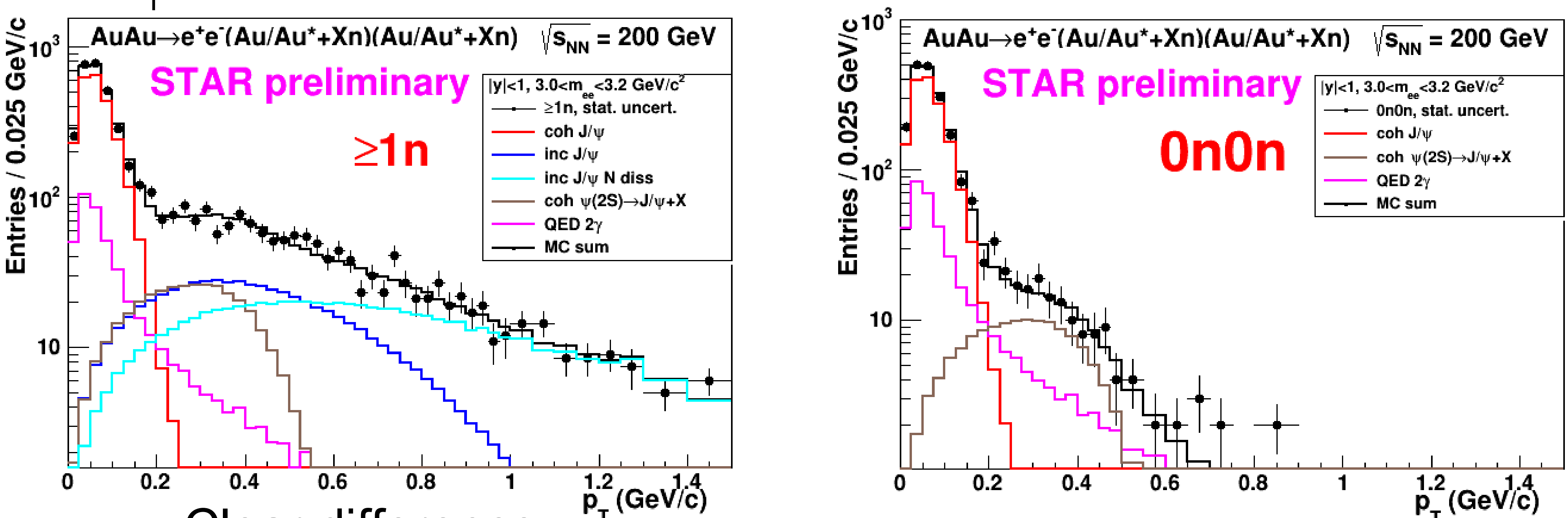
- Coulomb excitation: coherent & incoherent



- Incoherent w/ breakup:



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



<u>Clear difference:</u>

- High p_T incoherent usually produces neutron
- Relevant @ EIC: coherent/incoherent VM tagging
  compare models e.g. BeAGLE
  https://wiki.bnl.gov/eic/index.php/BeAGLE

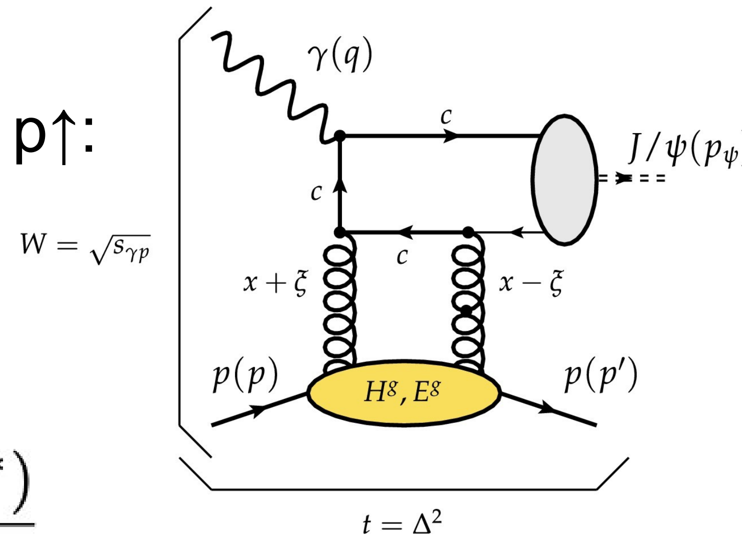
Generalized Parton Distributions

- 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*: $H^{q,g}/E^{q,g}(x,\xi,t)$ conserve/flip nucleon helicity
- The GPDs $E^{q,g}$ related to orbital angular momentum

<u>Photoproduction w/ polarized protons</u>

- Target particle transversely polarized proton p↑:
  J/ψ photoproduction $d\sigma/d\varphi \propto 1 + A^{\gamma}_{N}\cos(\varphi)$

  φ = azimuthal angle around beam axis



- A^{γ}_{N} calculable with GPDs*:

$$A_N^{\gamma} \propto p_T \cdot \frac{\mathrm{Im}(H^g \cdot E^{g*})}{|H^g|^2}$$

- $A^{\gamma}_{N} \propto E^{g} \Rightarrow$ sensitive to gluon orbital angular momentum L_g
- Unique RHIC capability: polarized protons, p↑Au run in 2015

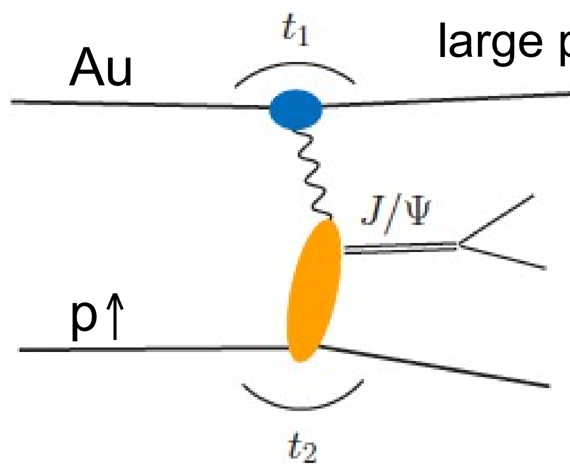
*J.P. Lansberg, L. Massacrier, L. Szymanowski, J. Wagner, Phys.Lett. B793 (2019) 33-40)

UPC processes in p↑+Au

$J/\psi \rightarrow e^{+}+e^{-}$

$\gamma p\uparrow$ J/ψ photoproduction:

- Au photon source, p↑ target dominant process



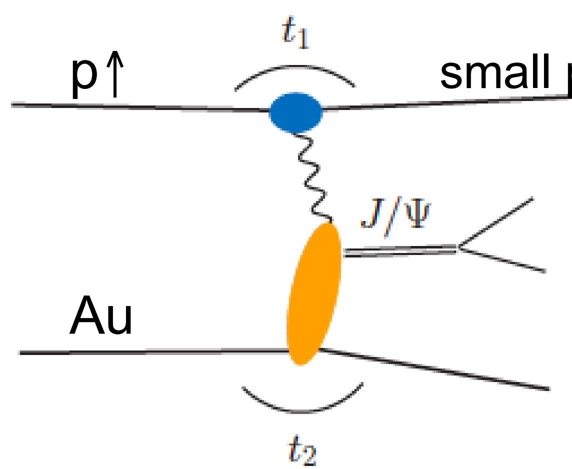
large photon flux $\propto Z_{Au}^{2}$

small nucleon target, high p_T

polarized target, $A^{\gamma}_{N} \propto E_g$

γAu J/ψ photoproduction:

- p↑ photon source, Au target



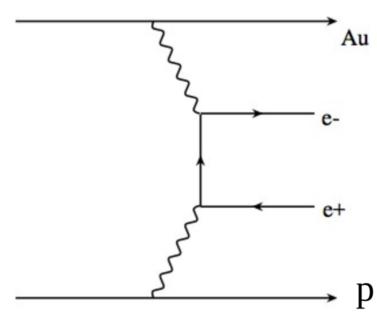
small photon flux $\propto Z_p^{2}=1$, small σ

large nuclear target, low p_T

unpolarized target, no asymmetry

Also:

- Continuum $e^{+}e^{-}$ QED 2-γ process

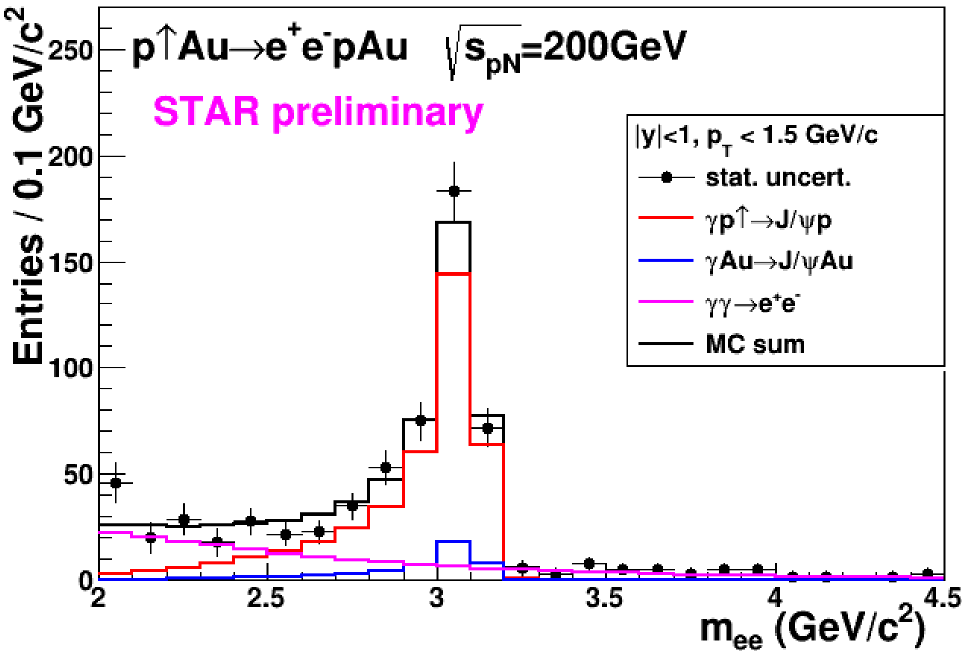


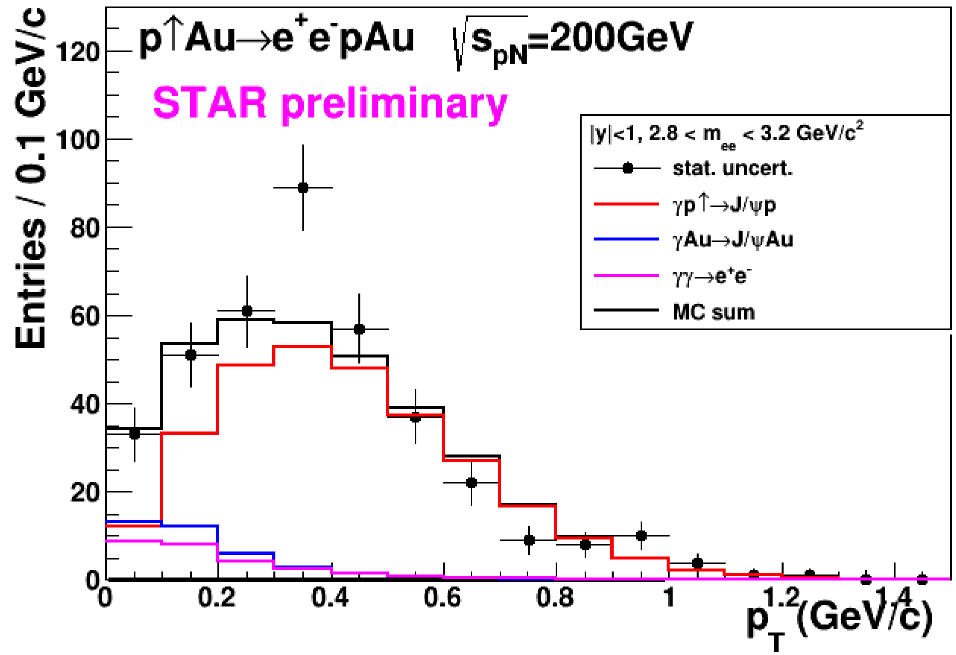
<u>ψ(2S) & inelastic incoherent processes seen in Au+Au:</u>

not discernible w/ statistics this data sample

UPC procs → p↑+Au data

- As for Au+Au fit sum MC templates to data:
- m_{ee}:
- p_T for $2.8 < m_{ee} < 3.2$ GeV/c²:





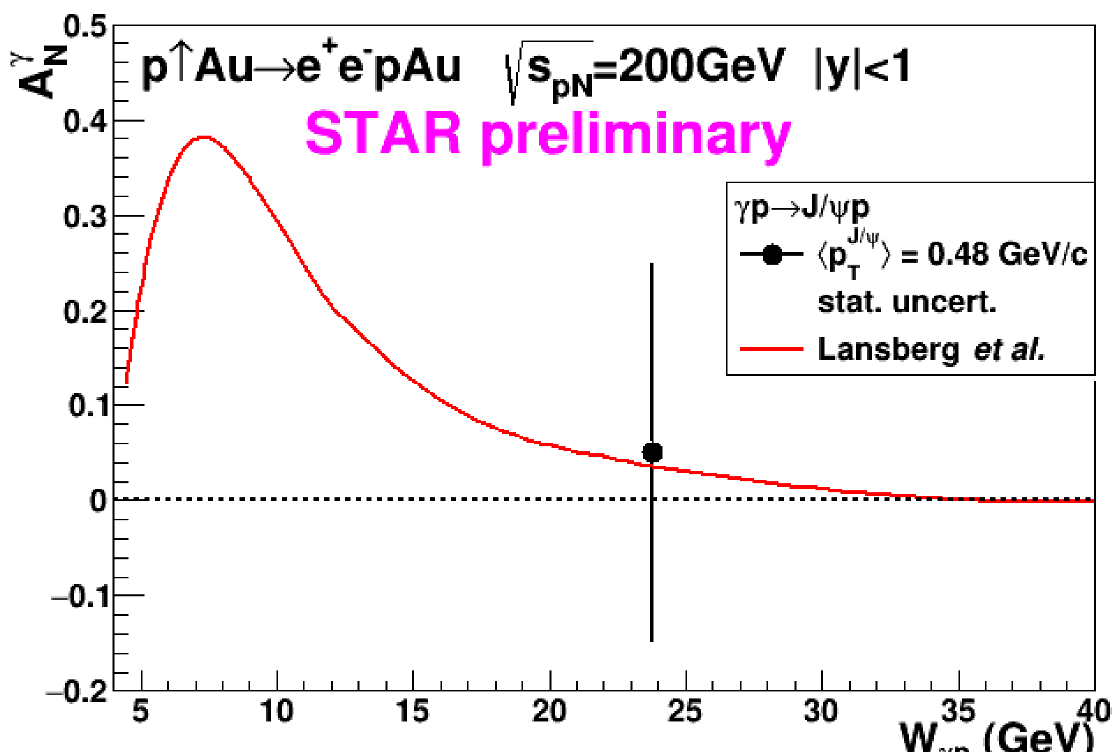
- Fit data to sum J/ψ (γp↑ & γAu) and QED 2γ
- m_{ee}: good description all features: J/ψ peak location, width & rad. tail
  QED 2γ continuum
- p_T: γp↑ @ high p_T ~ AuAu incoherent, γAu @ low p_T ~ AuAu coherent
- Want A_N^γ for γp↑ process; γAu & 2γ background @ low p_T, cut out
- For A_N^γ: $0.2 < p_T < 1.5$ GeV/c, purity = 92%

UPC J/ψ A_N^γ

- Signal range ($2.8<m_{ee}<3.2$ GeV/c^2, $0.2<p_T<1.5$ GeV/c), count events for: p↑ beam spin up/down, J/ψ cos(φ) >0 or <0 (total 231 events)
- Correct for: purity = 92%, p↑ beam polarization ⟨P⟩ = 61.3%
- Result:

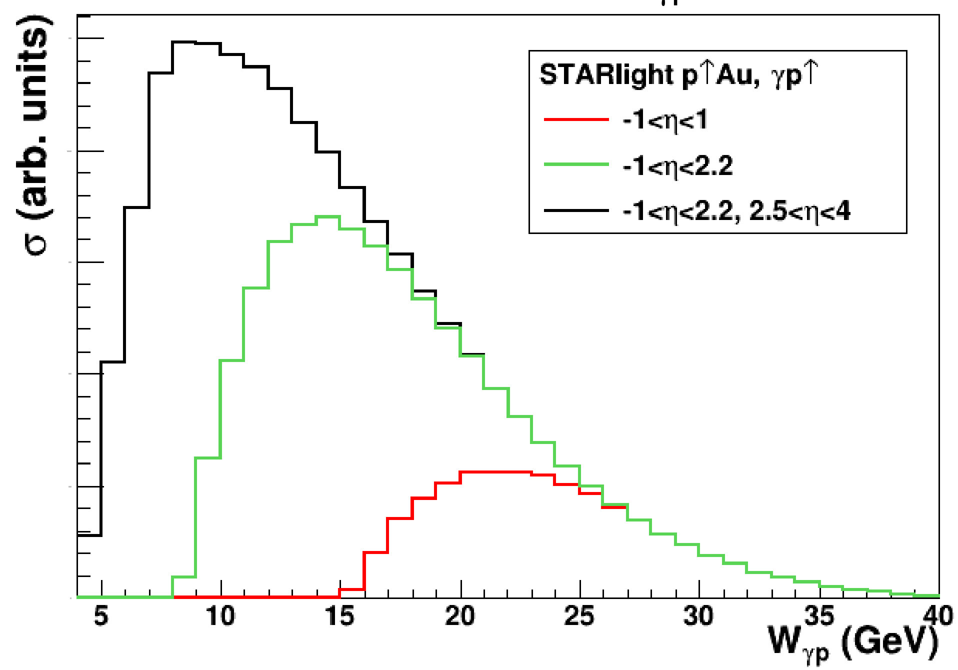
  $A_N^\gamma = 0.05 \pm 0.20$ @ $\langle W_{\gamma p}\rangle = 23.8$ GeV, $\langle p_T\rangle = 0.48$ GeV/c

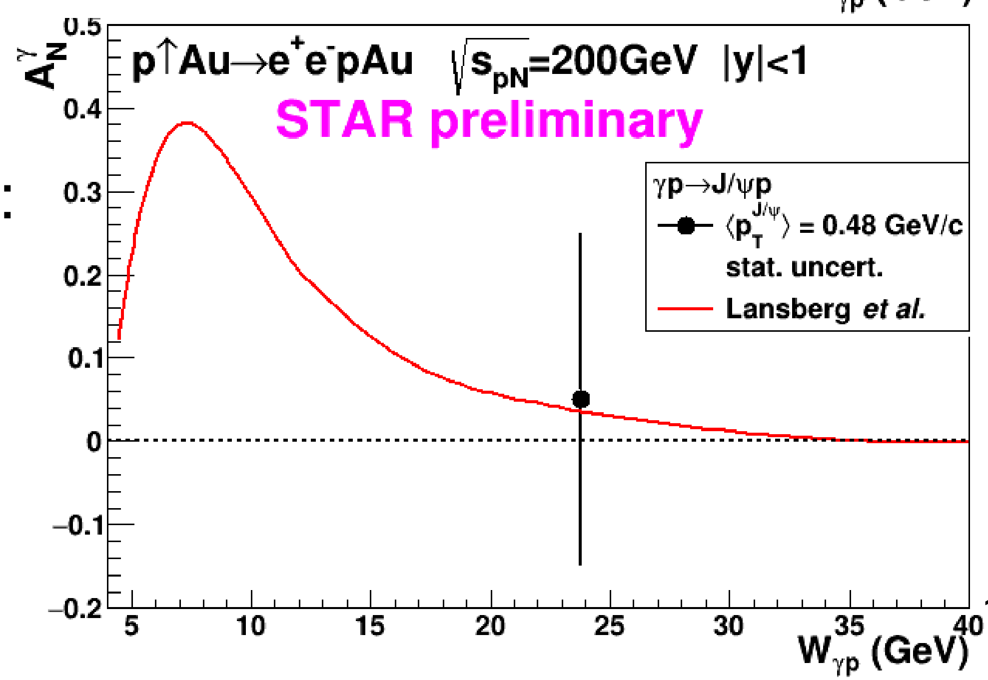
  $W_{\gamma p}$ = γp c.m. energy
- Null result, but proof of principle this measurement
- Lansberg *et al.* have curve ⟨p_T⟩ = 0.7 GeV/c, remade for 0.48 GeV:
  (J. Wagner, private communication)
- Can see what's needed to test such models:
  - higher statistics
  - lower $W_{\gamma p}$
- Future @ RHIC?



Future: UPC J/ψ A^{γ}_{N}

- Soon: 2017 $\sqrt{s}$=510 GeV p↑+p↑, analysis starting, but $W_{\gamma p}$~40 GeV
- 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↑+Au runs 2022+: measure @ lower $W_{\gamma p}$
  - higher cross section (stats.)
  - larger A^{γ}_{N}
- Should be sensitive to e.g. Lansberg *et al.* models





Summary UPC J/ψ

UPC in 200 GeV Au+Au

- Large statistics, J/ψ processes observed:
  coherent, incoherent elastic & inelastic; also QED 2γ
- Sartre model good description J/ψ coherent & incoherent elastic
- Incoherent processes ↔ neutron tag
- Future RHIC Au+Au runs 2023 & 2025:
  7× statistics & extended kinematic range

UPC in 200 GeV polarized p↑+Au:

- Observed J/ψ in γp↑ & γAu, QED 2γ
- Proof of principle: measurement of $A^{\gamma}_{N} \propto E^{g} \sim$ gluon L_{g}
  null result here, but:
- Future RHIC p↑+Au run 2024:
  9× statistics & extended kinematic range ⇒ sensitive to A^{γ}_{N}

Promising outlook for future RHIC runs

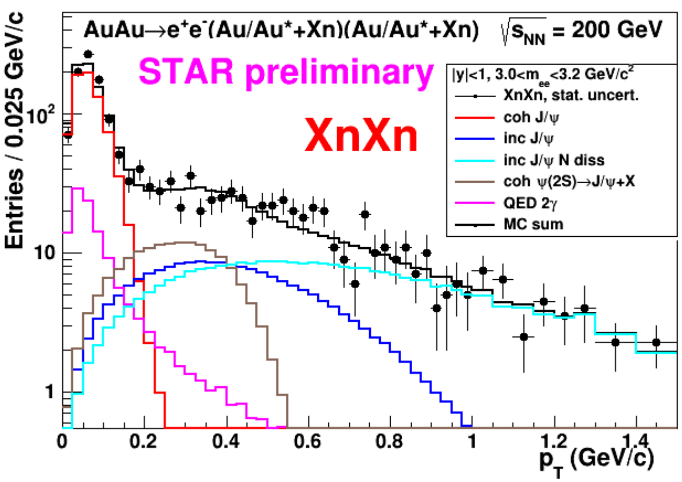
"The STAR Beam Use Request for Run-21, Run-22 and data taking in 2023-25",
- The STAR experiment. https://drupal.star.bnl.gov/STAR/starnotes/public/sn0755

Extras

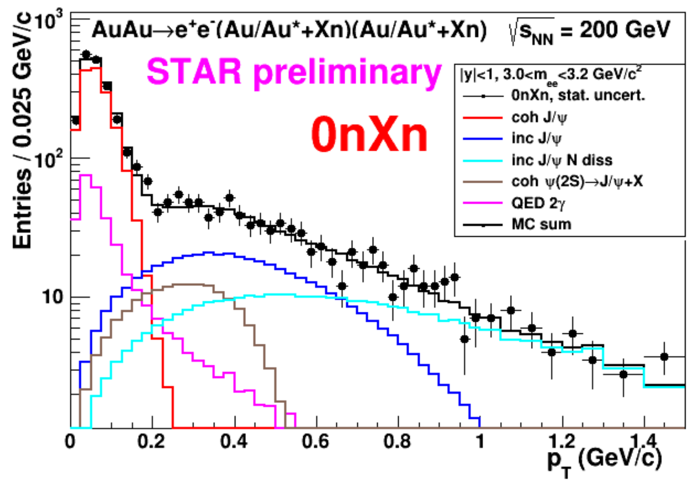
Au+Au: p_T for 3 ZDC categories

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

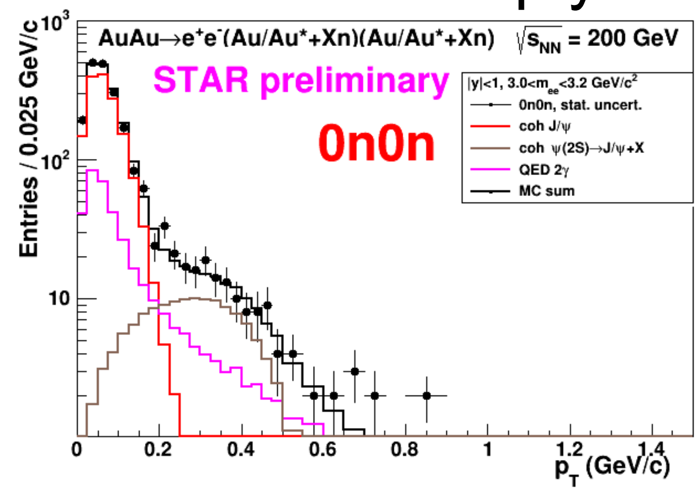
- ≥1n both ZDCs:



- ≥1n one ZDC,
  other ZDC empty:



- both ZDCs empty:



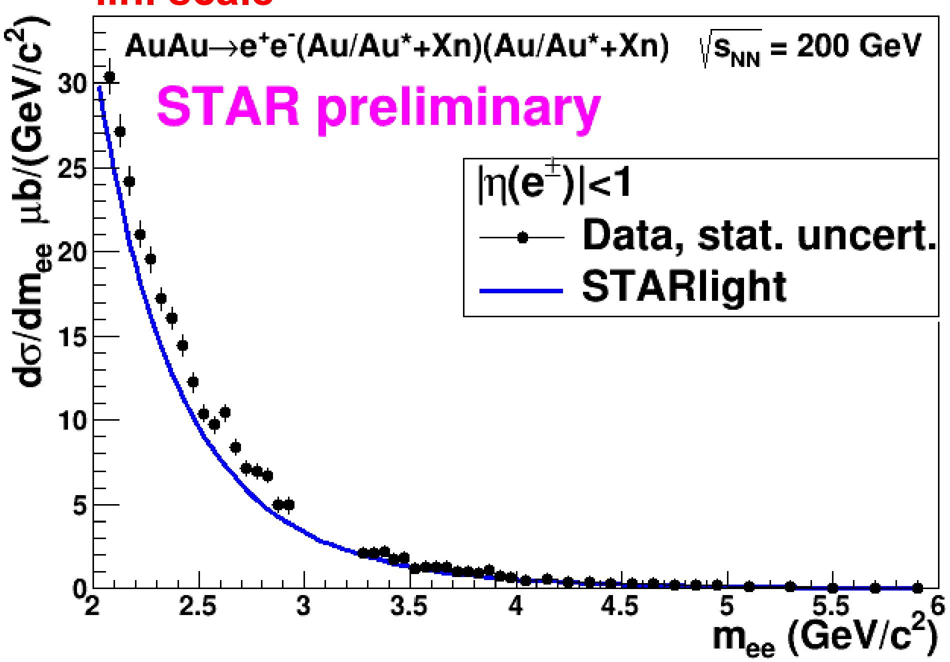
- Coherent peak always present & prominent regardless of neutrons: Coulomb dissociation
- Incoherent components only present when some neutrons → fit consistent with zero for 0n0n

$\gamma+\gamma\rightarrow e^{+}+e^{-}$

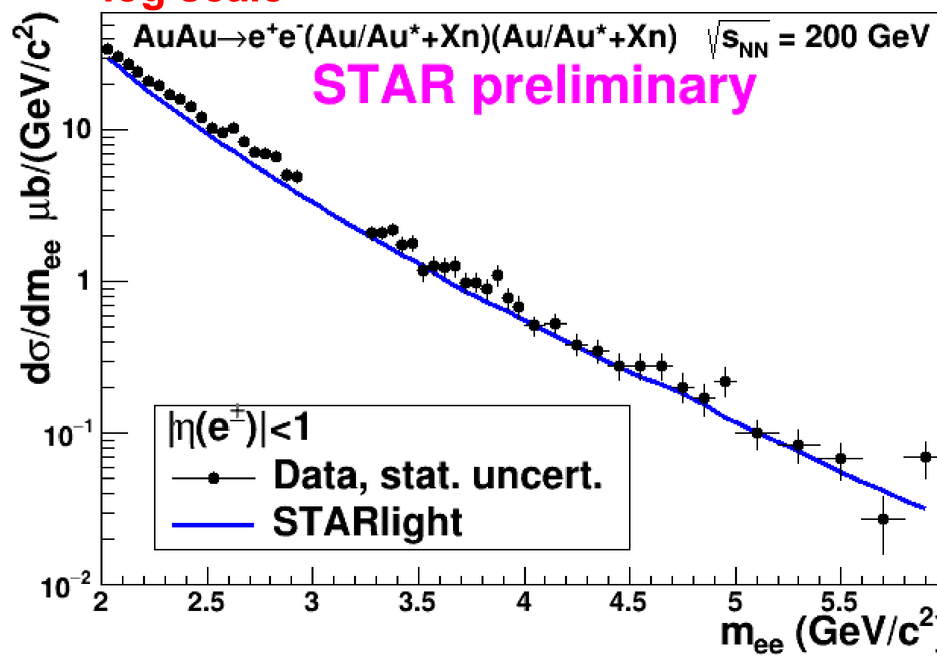
Free byproduct these data: $d\sigma/m_{ee}$ for $\gamma+\gamma\rightarrow e^{+}+e^{-}$

- STARlight: describes shape over 3 orders magnitude in σ
- Data σ ~15% > STARlight:
- STARlight: no $e^{+}e^{-}$ inside nucleus

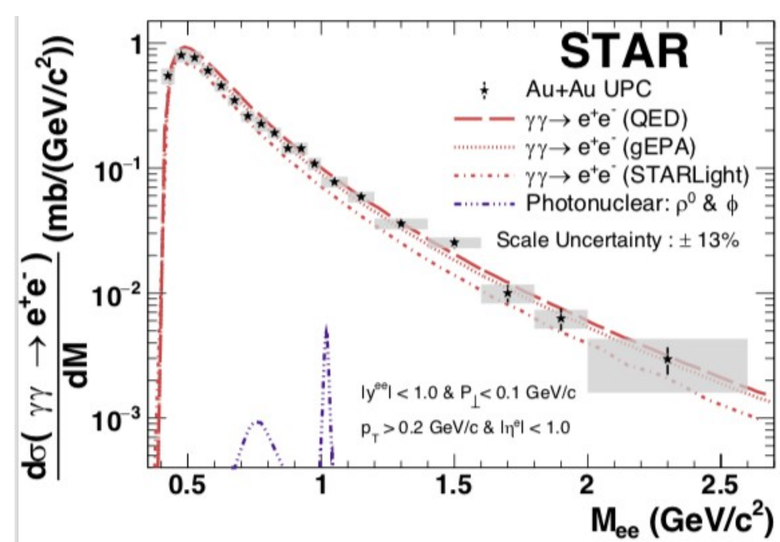
lin. scale



log scale

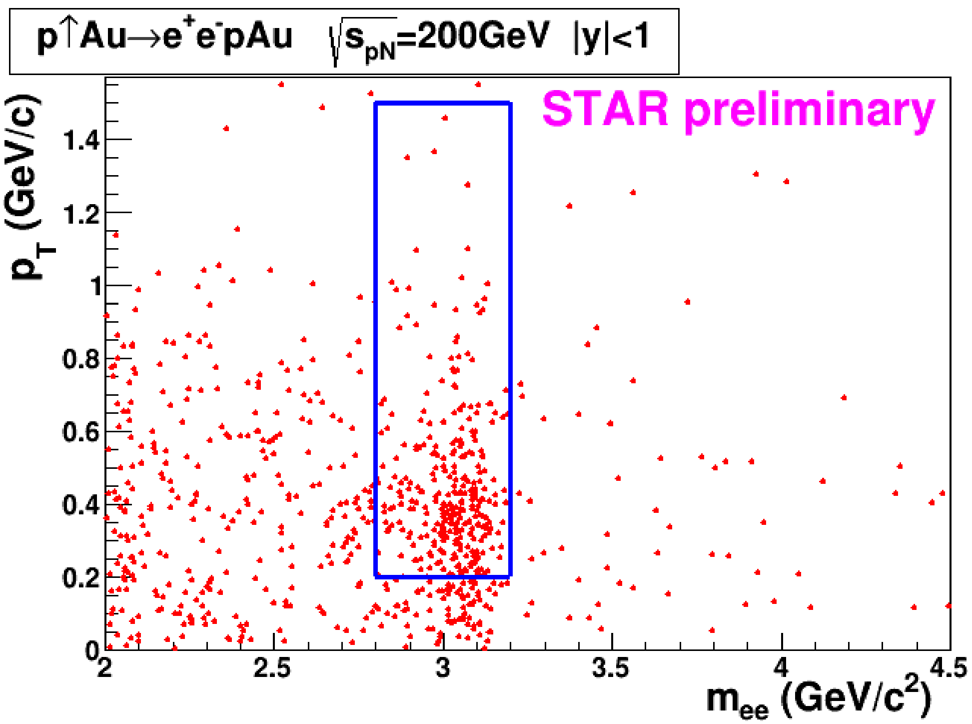


- Improved QED calculations agree better with data, here for lower m_{ee}:

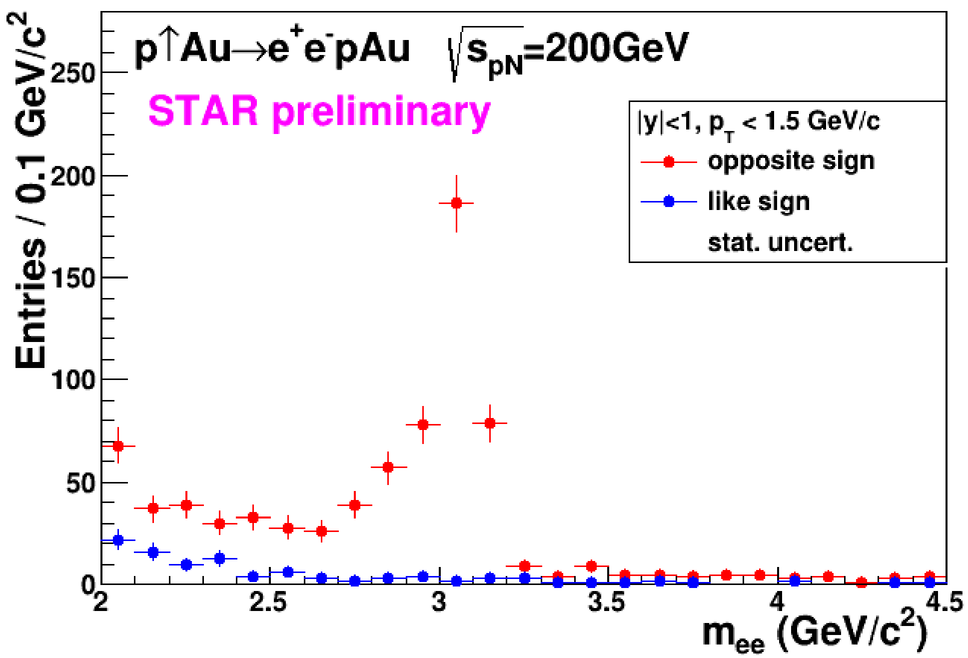


p↑+Au: p_T, m_{ee} distributions

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



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

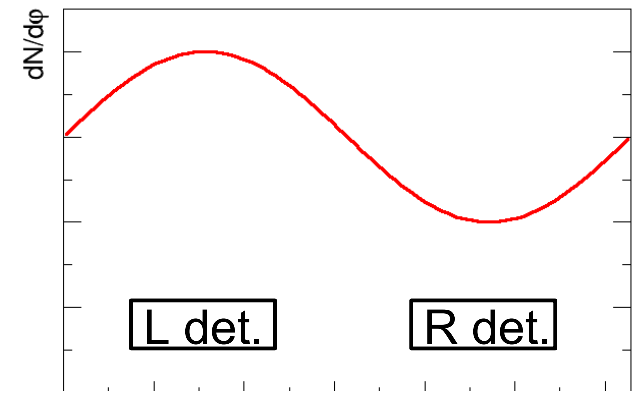


- Box shows fiducial region for A^{γ}_{N} measurement:
  $2.8<m_{ee}<3.2$ GeV/c^2,
  $0.2<p_T<1.5$ GeV/c

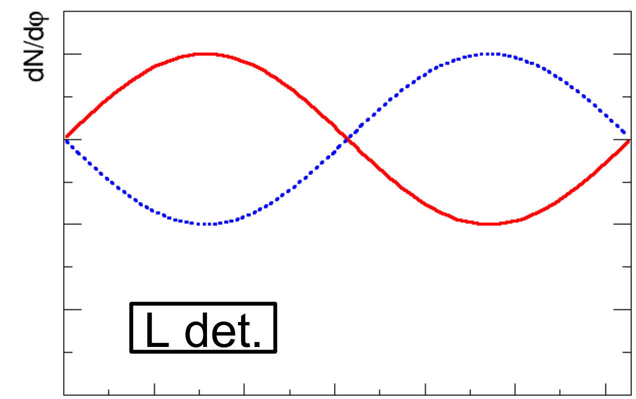
- For final distributions take (opposite-like) sign

Cross-ratio (for non-spin experts)

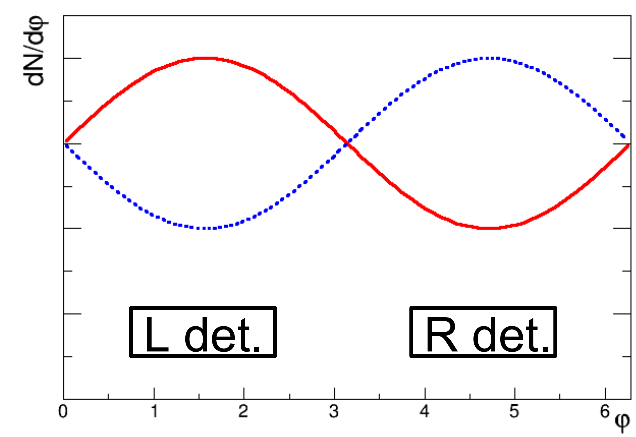
- If have one beam w/ spin up, and detectors left (L) and right (R) of beam, can measure asym. but would need to know relative acceptances of L/R detectors



- 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

*http://www4.rcf.bnl.gov/~cnipol/Documentations/Papers/TechniquesForMeasurementOfSpinHalfAndSpin1PolarizationAnalyzingTensors.pdf