Ultra-Peripheral Collisions at STAR

W. Schmidke, BNL
For the STAR Collaboration

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Northeastern Univ., Boston

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

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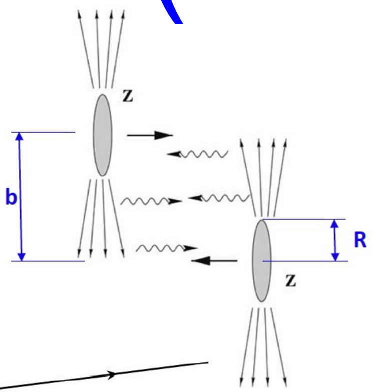
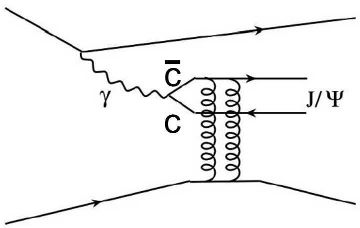
U.S. DEPARTMENT OF ENERGY

Ultra-Peripheral Collisions (UPC)

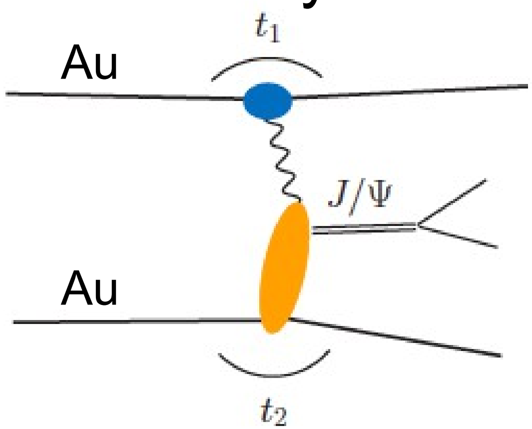
- UPC: b > 2R, hadronic interactions suppressed

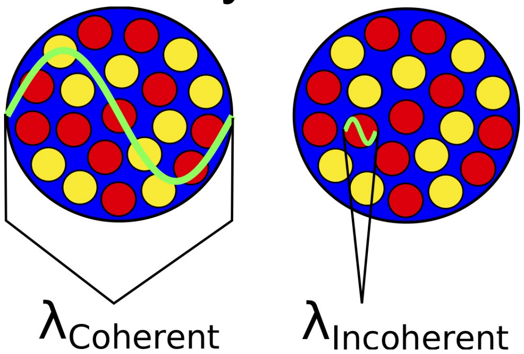


- Large flux of photons coming from Weizsaecker-Williams:
- WW photon from one beam particle
  → photoproduction on other beam particle
  e.g. J/ψ production, sensitive to gluons:

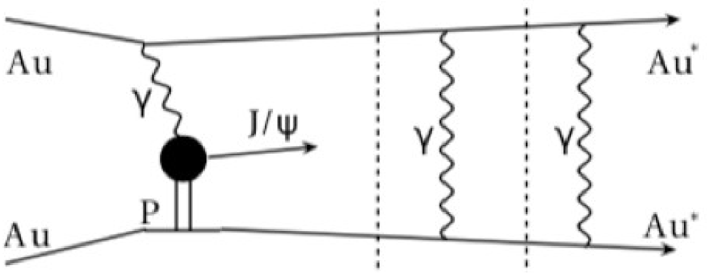


- Photon may interact: coherently, with whole nucleus
  incoherently, with individual nucleons





- 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

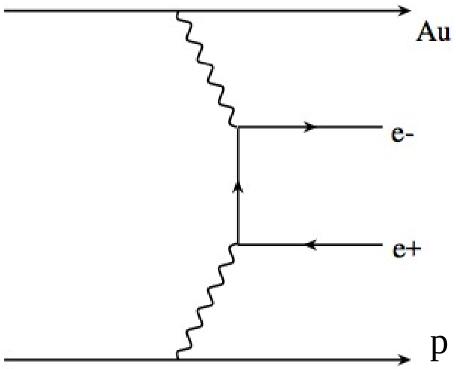


UPC processes in AuAu

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

High statistics

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

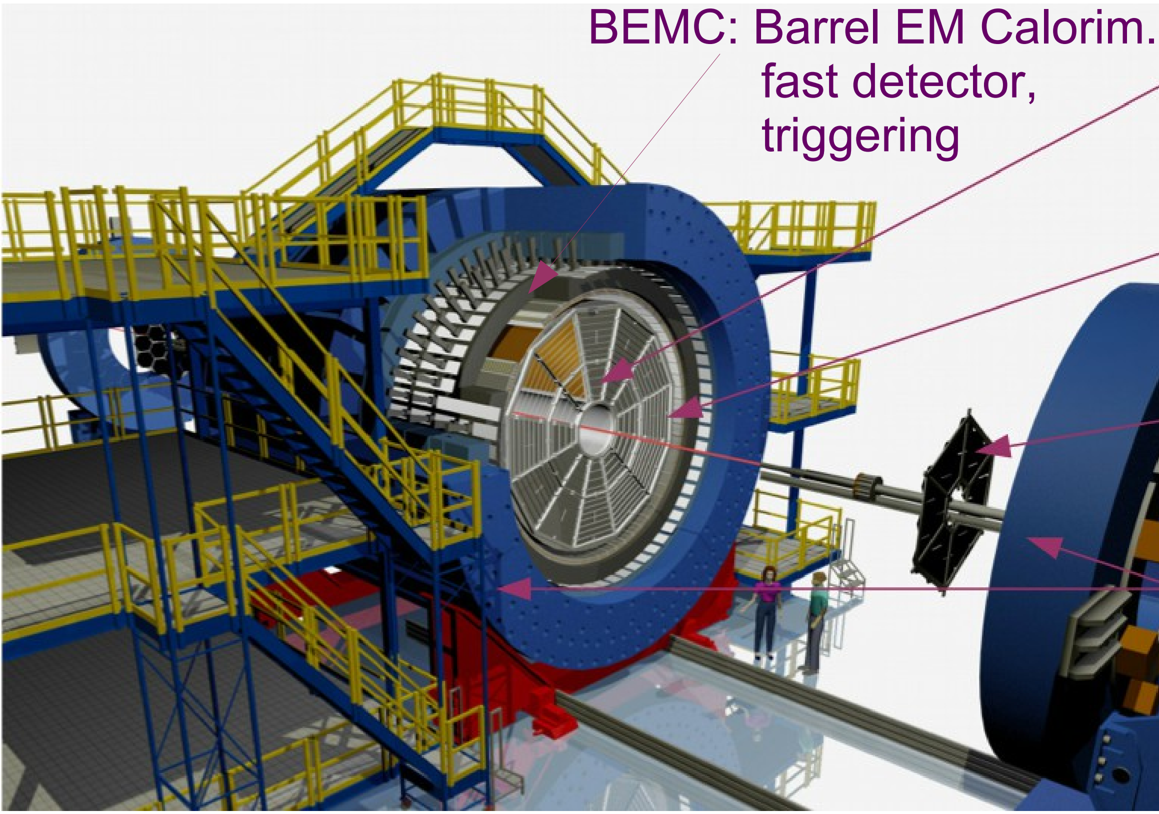


- QED $2\gamma \rightarrow e^+e^-$, m_{ee} continuum:
  low p_T

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



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
  $p\uparrow$+Au: reject nuclear breakup, veto ZDCs

Data sets: 2015 $p\uparrow$Au, L = 140 nb^{-1}
2016 AuAu, L = 13 nb^{-1}

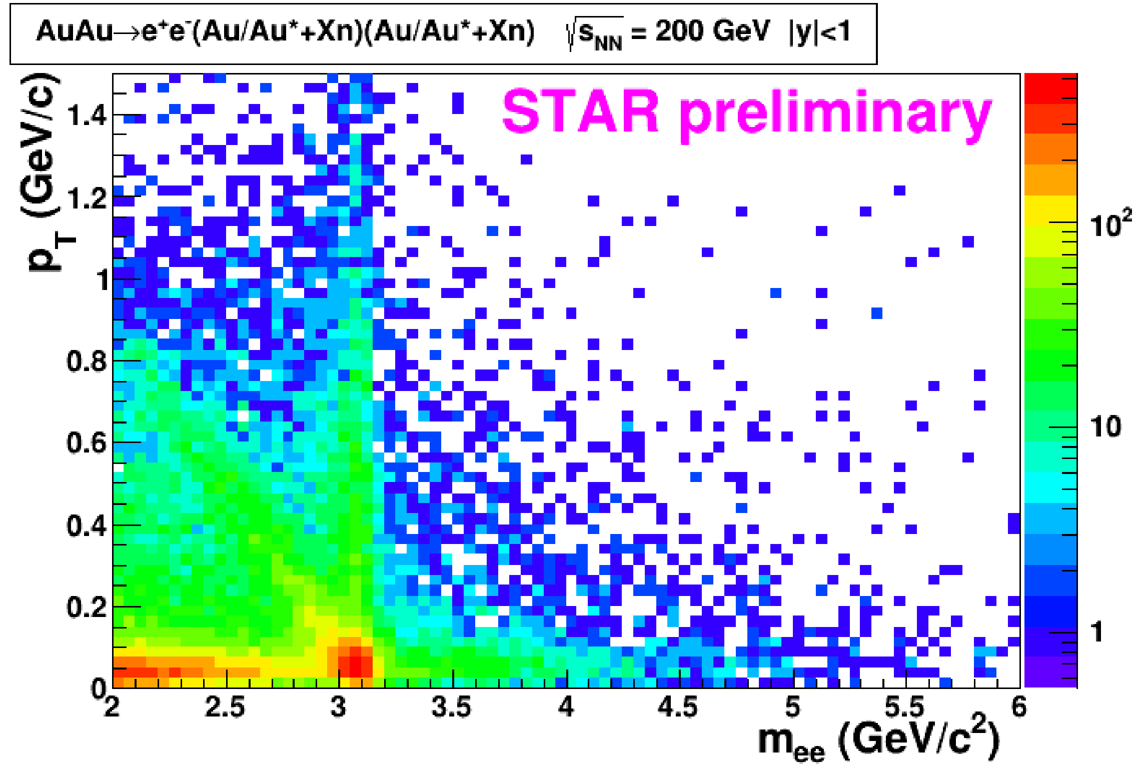
Offline selection:

- 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

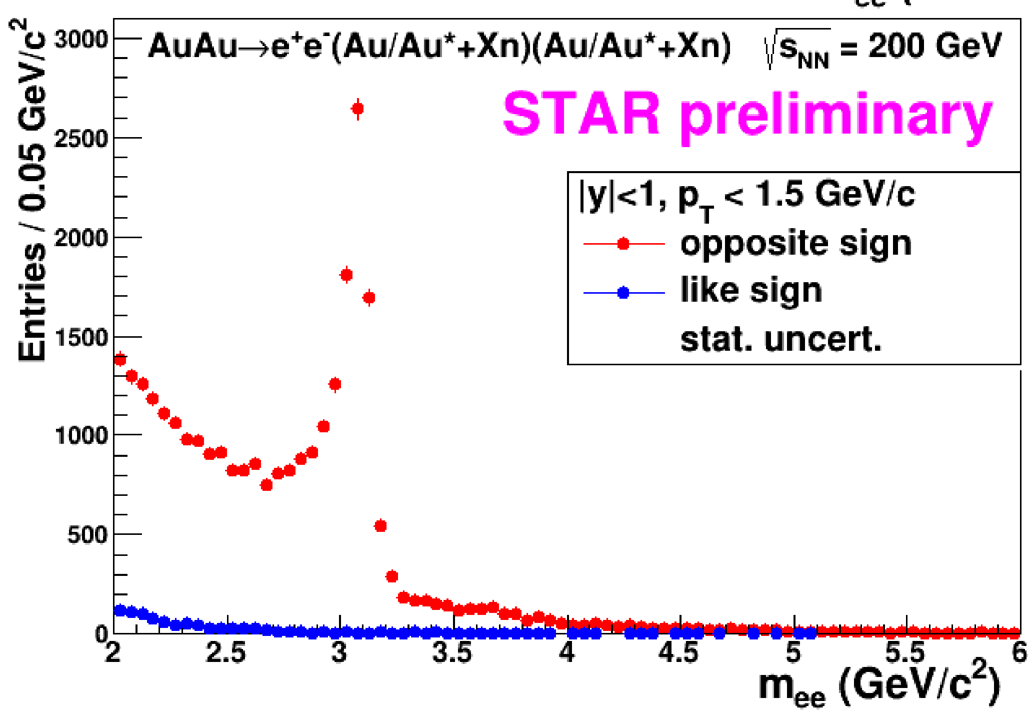
- p_T vs. m_{ee} for opp. sign pairs:

- High stat. features clear:
  - coh. J/ψ @ low p_T
    & rad. tail lower m_{ee}, higher p_T
  - inc. J/ψ @ high p_T
  - QED 2γ continuum @ low p_T



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

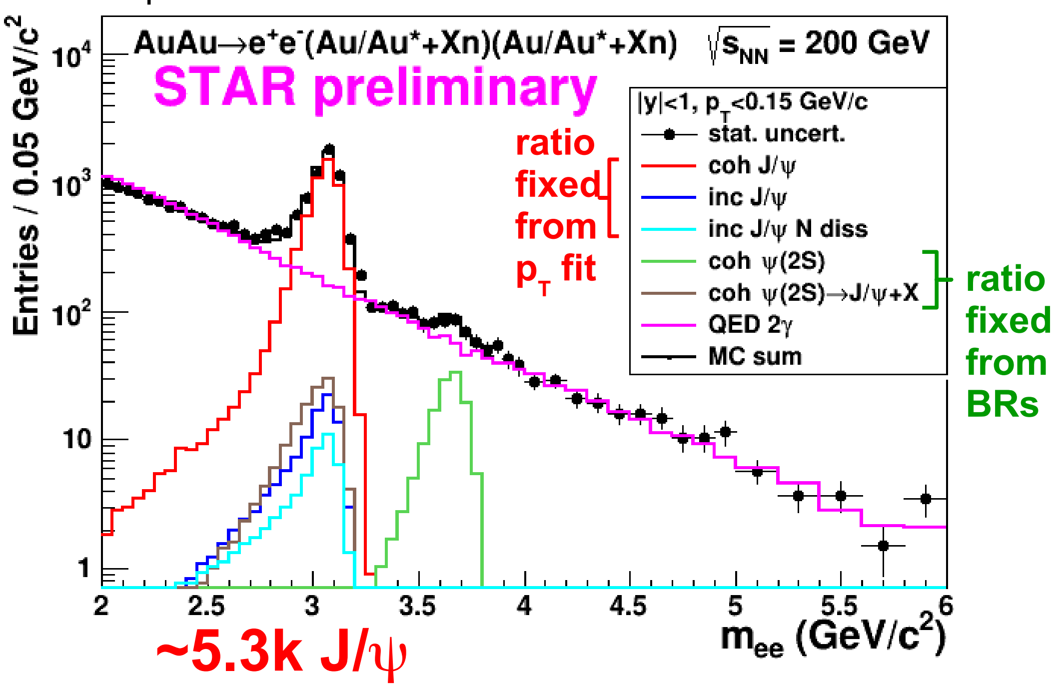
- Small like sign contamination @ low m_{ee}
  (& high p_T, not shown)
- Take as combinatoric bkg.: for final distributions take (opposite-like) sign



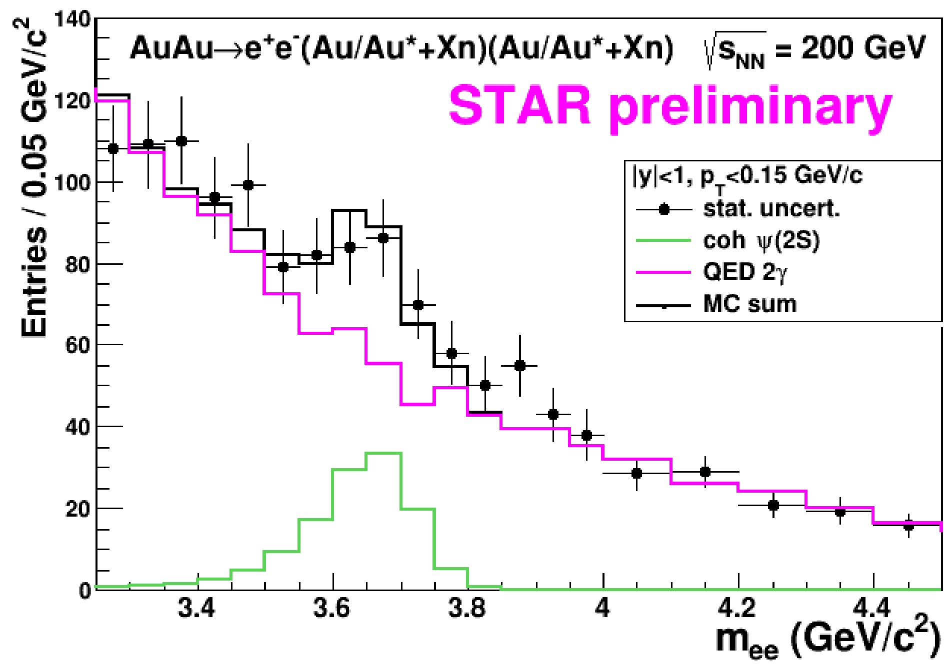
UPC procs→data comparison: m_{ee}

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

- p_T < 0.15 GeV/c:



- Zoom ψ(2S) region:

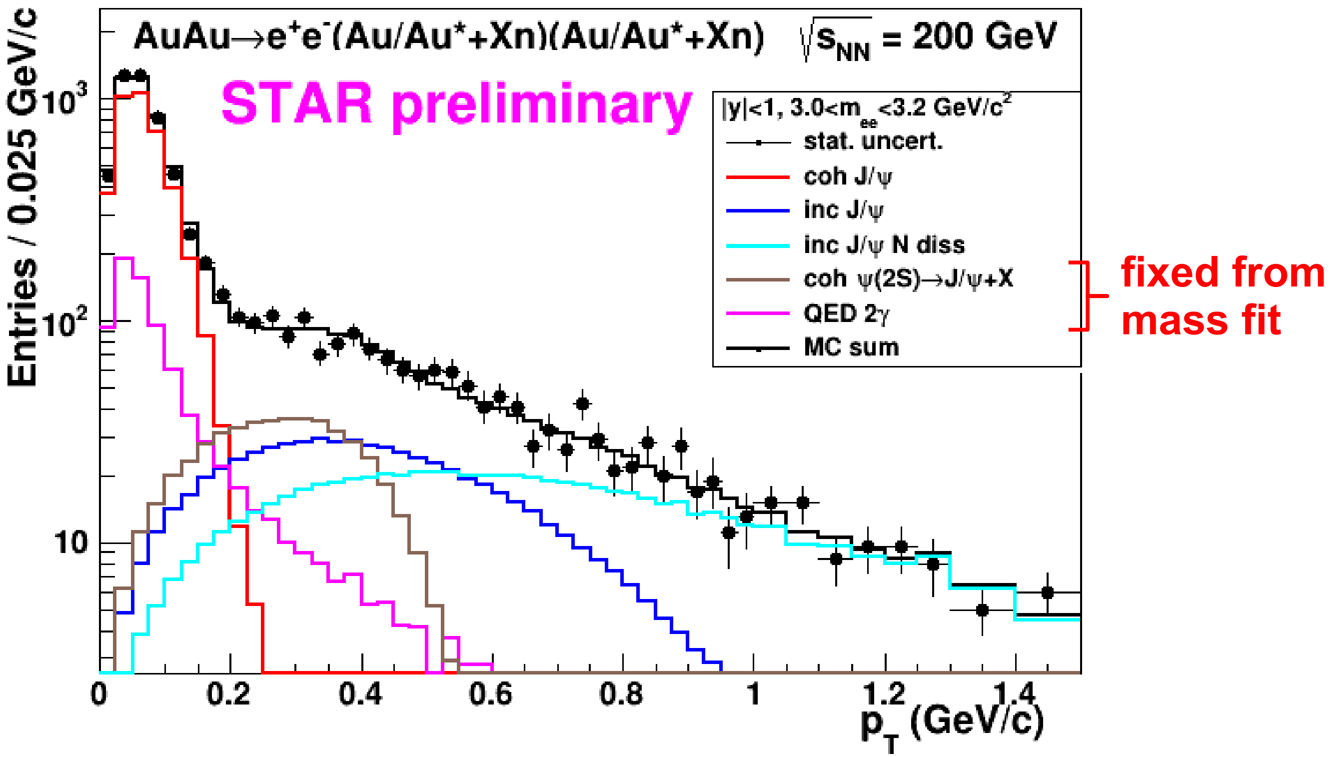


- Fit sum of: J/ψ, ψ(2S), QED 2γ
- Fit describes data: peaks & rad. tails & 2γ shape over ~3 orders mag. in σ

- ψ(2S): $N_{\psi(2S)}$ = 130 ± 23
  5.7 σ from zero
- Not stat. sensitive to inc. ψ(2S), buried by 2γ

UPC procs→data comparison: p_T

- Fix QED 2γ & $\psi(2S)$ from m_{ee} fit, fit sum others to data
- $3.0 < m_{ee} < 3.2$ GeV/c^2:

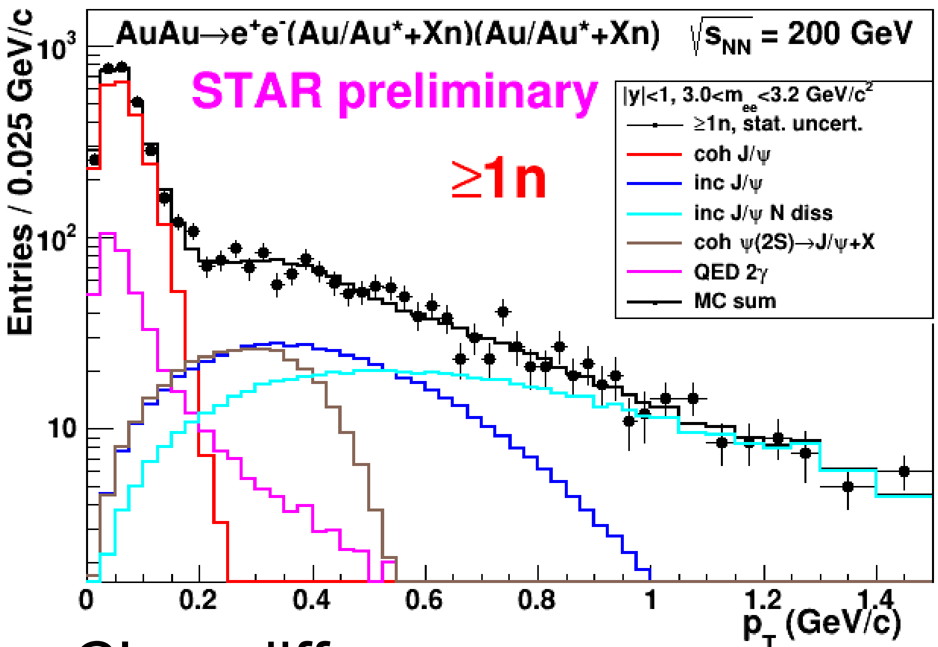


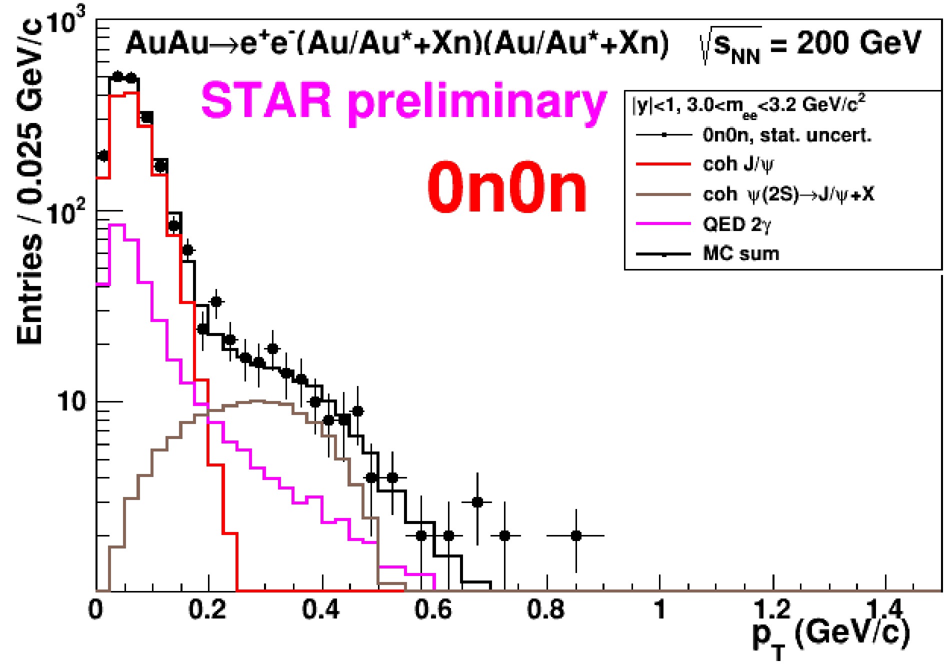
<u>Good description of data, need all processes:</u>

- coherent J/ψ & QED @ low p_T
- feed-down from $\psi(2S)$ & incoherent J/ψ @ mid p_T
- incoherent J/ψ w/ nucleon dissociation for high p_T tail

Nuclear dissociation ↔ J/ψ p_T

- 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)



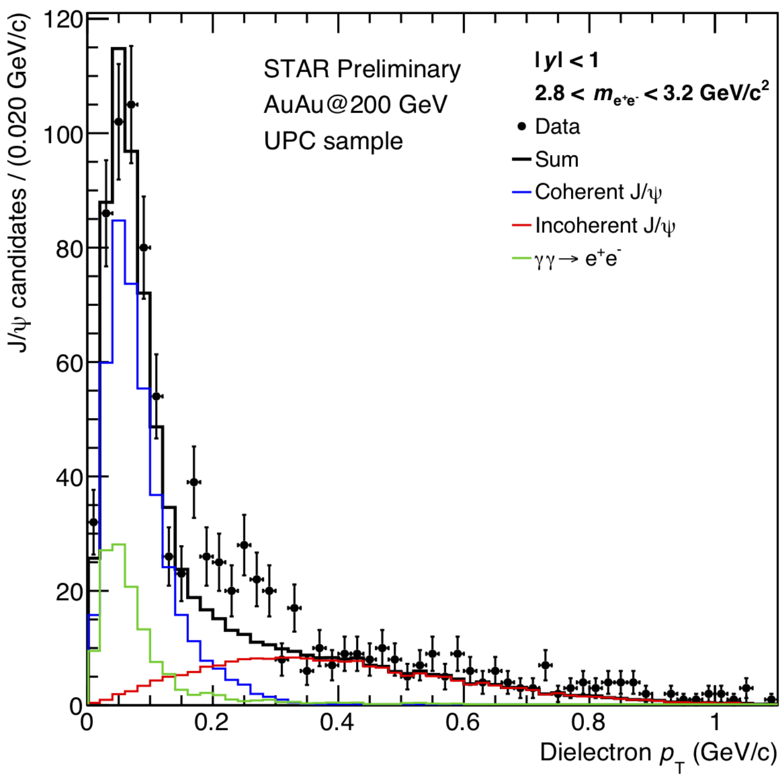


Clear difference:

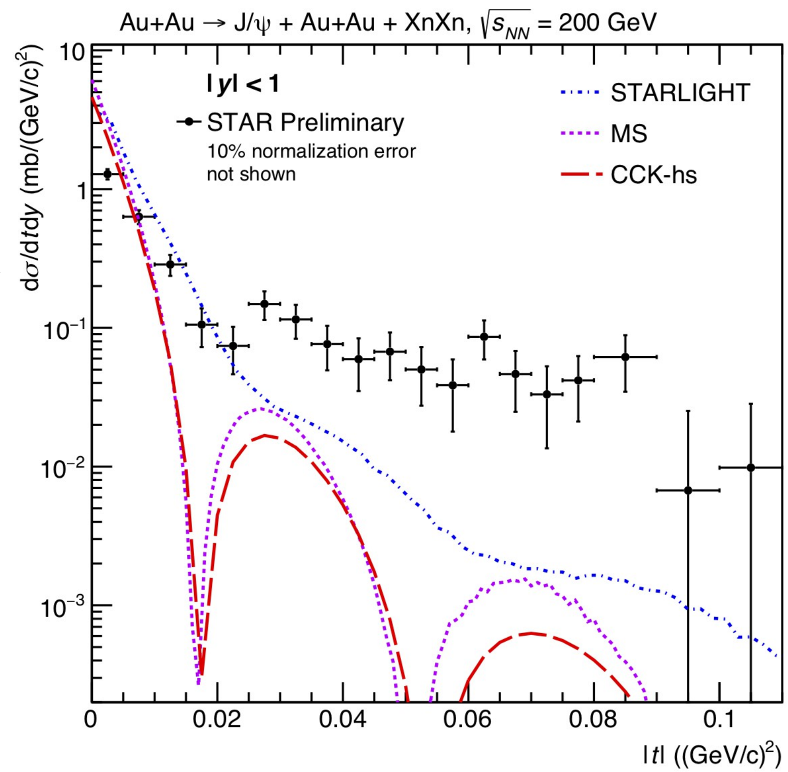
- Incoherent processes ~always produce a neutron
- Coherent processes also produce neutrons: Coulomb dissociation
- 0n0n fully described by coherent components & QED 2γ
  incoherent processes fit consistent w/ 0
- Vetoing on neutrons ⇒ clean sample of coherent processes
- Good starting point study of 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 2γ & J/ψ incoherent (exponential fit)
- Diff. cross section dσ/d|t|, $|t| \propto p_T^2$
- Compare to some models:



Can start model comparisons:

- Dip/ankle @ expected |t|?
- Dips washed out by γ p_T?

- STARLIGHT: Klein, Nystrand
  CPC 212 (2017) 258-268
- includes effects of photon p_T
- MS: Mäntysaari, Schenke
  Phys.Lett. B772 (2017) 832-838
- CCK: Cepila, Contreras, Krelina
  Phys.Rev. C97 (2018) no.2, 024901

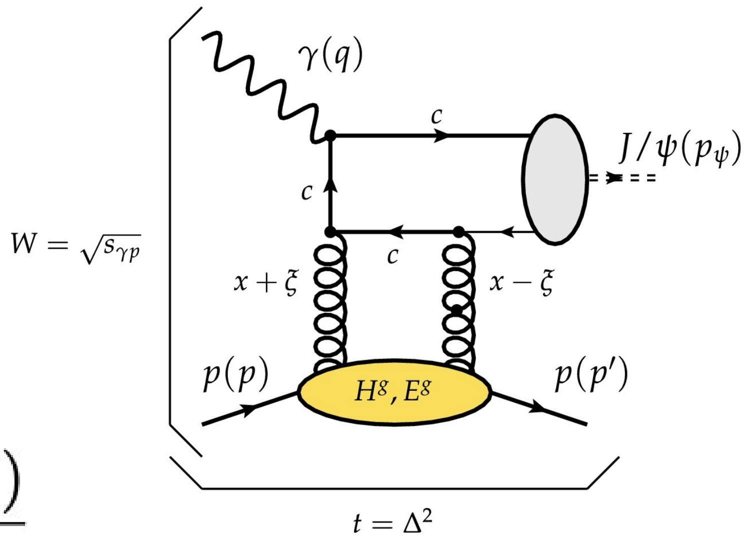
Generalized Parton Distributions

- 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 $E^{q,g}$ responsible for orbital angular momentum

Photoproduction w/ polarized protons

- Target particle 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*:

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

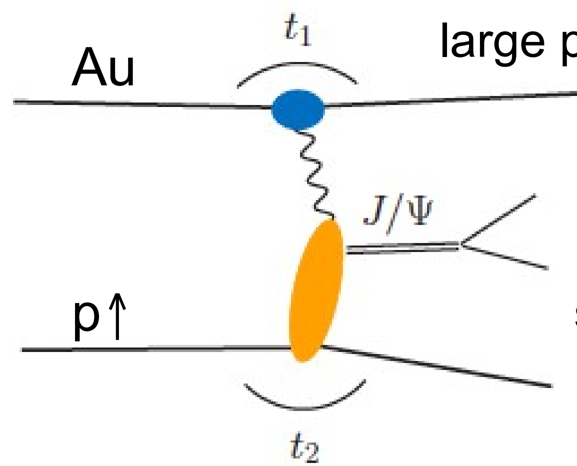
- $A^{\gamma}_{N} \propto E^g \Rightarrow$ sensitive to gluon orbital angular momentum L_g
- Unique RHIC capability: polarized protons, p↑Au run in 2015

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

UPC processes in p↑+Au

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

- Au photon source, p↑ target



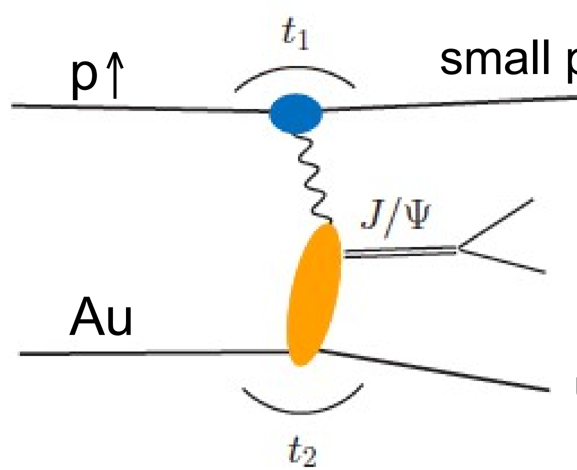
large photon flux $\propto Z_{Au}^{2}$

small nucleon target, high p_T

polarized target, $A_N^{\gamma} \propto E_g$

γAu J/ψ photoproduction:

- p↑ photon source, Au target



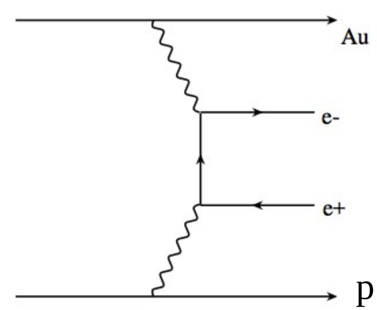
small photon flux $\propto Z_p^{2}=1$, small σ

large nuclear target, low p_T

unpolarized target, no asymmetry

Also:

- Continuum e^+e^- QED 2-γ process

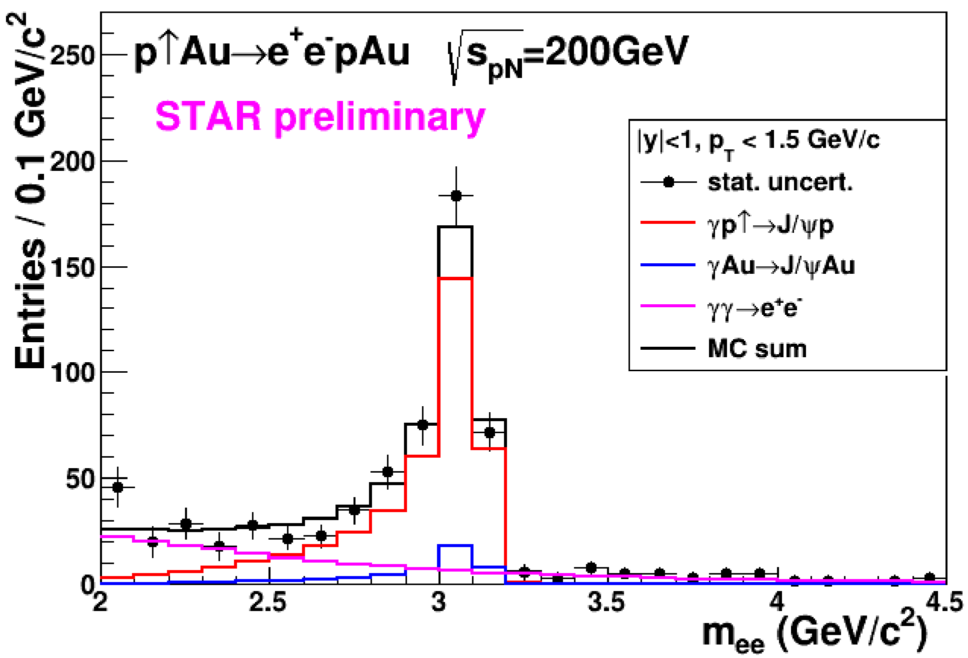


<u>Other processes seen in Au+Au:</u>

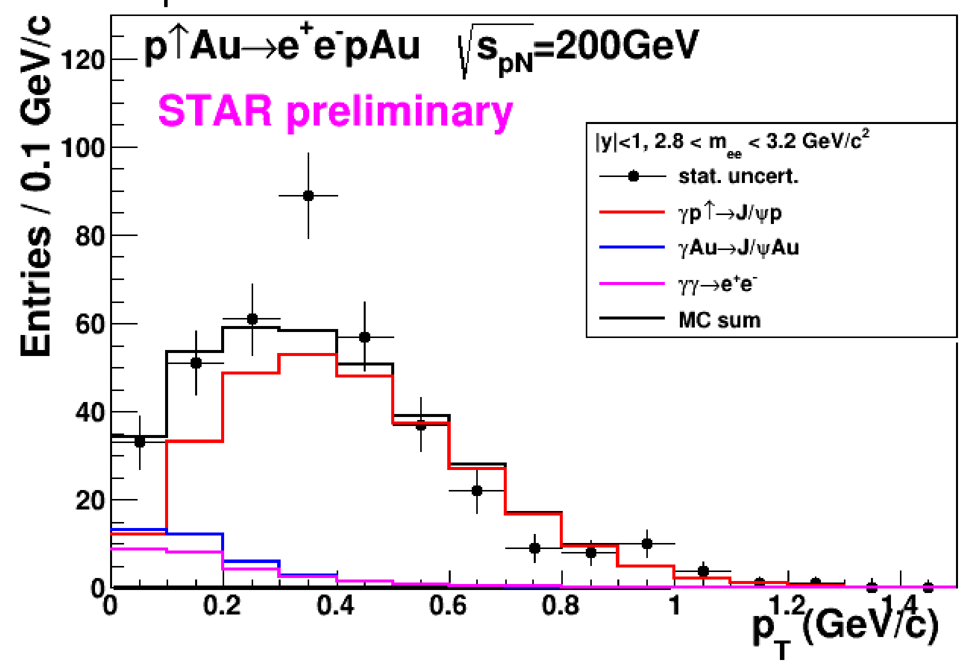
not discernible w/ statistics this data sample

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:



- 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 ↗

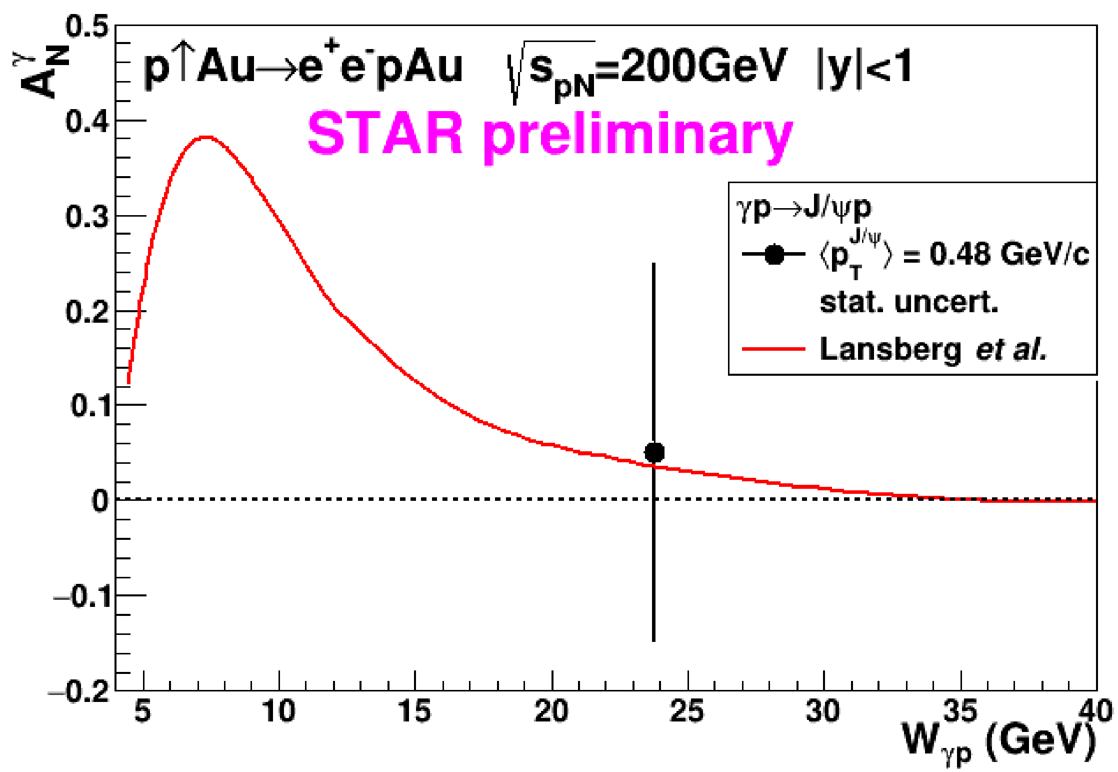
- γp↑ @ high p_T ~ AuAu incoherent γAu @ low p_T ~ AuAu coherent
- Want A_N^γ for γp↑ process, @ low p_T γAu & 2γ bkg., cut out
- For A_N^γ: $0.2 < p_T < 1.5$ GeV/c
- Purity = 92%

UPC J/ψ A^{γ}_{N}

- Count events $2.8 < m_{ee} < 3.2$ GeV/c^2, $0.2 < p_T < 1.5$ GeV/c for:
  p↑ beam spin up/down, J/ψ cos(φ)>0 / cos(φ)<0 (total 231 events)
- Correct for:
  purity = 92%, p↑ beam polarization P = 61.3%
- Result:
  $A^{\gamma}_{N} = 0.05 \pm 0.20$ @ $\langle W_{\gamma p} \rangle = 23.8$ GeV, $\langle p_T \rangle = 0.48$ GeV/c

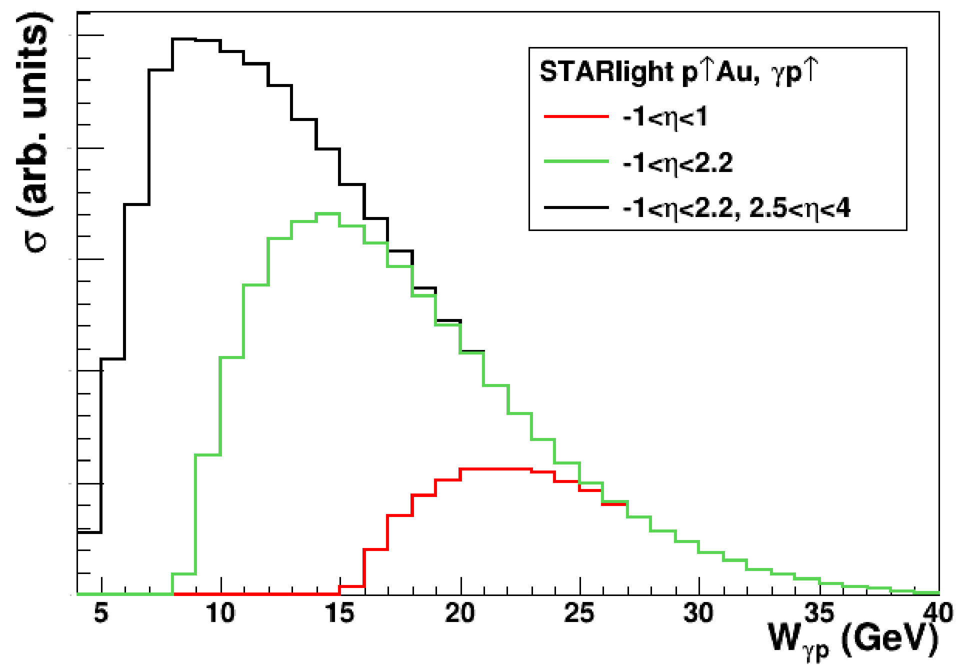
$W_{\gamma p}$ = γp c.m. energy

- Null result, but proof of principle this measurement
- Lansberg *et al.* have curve $\langle p_T \rangle = 0.7$ 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?

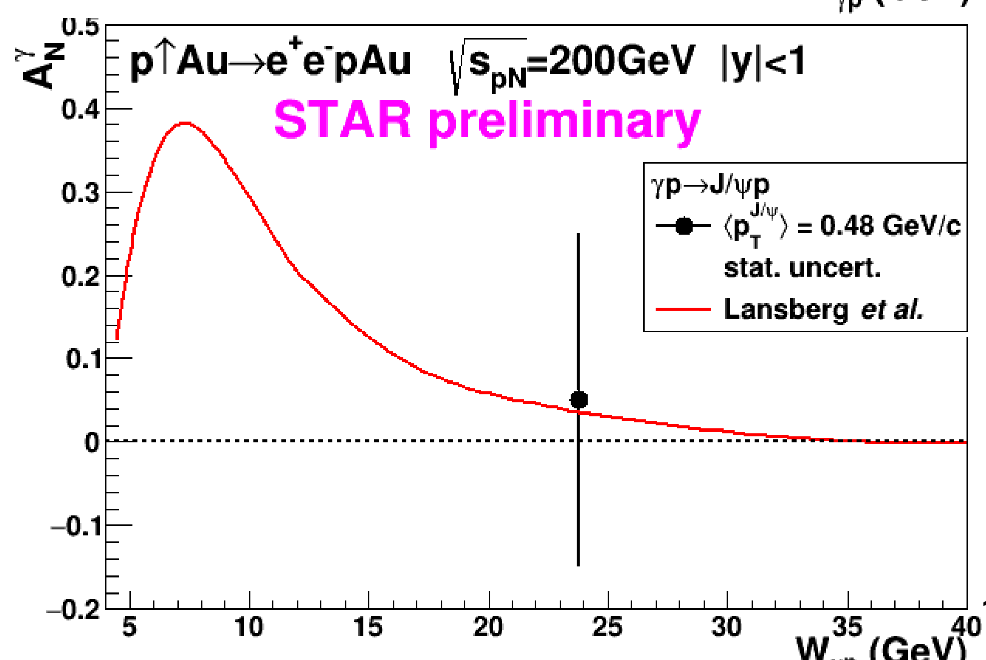


Future: UPC J/ψ A^{γ}_{N}

- 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

UPC in 200 GeV Au+Au

- Large statistics, processes observed:
  - J/ψ: coherent, incoherent, incoherent w/ nucleon dissociation
  - $\psi(2S)$: 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:

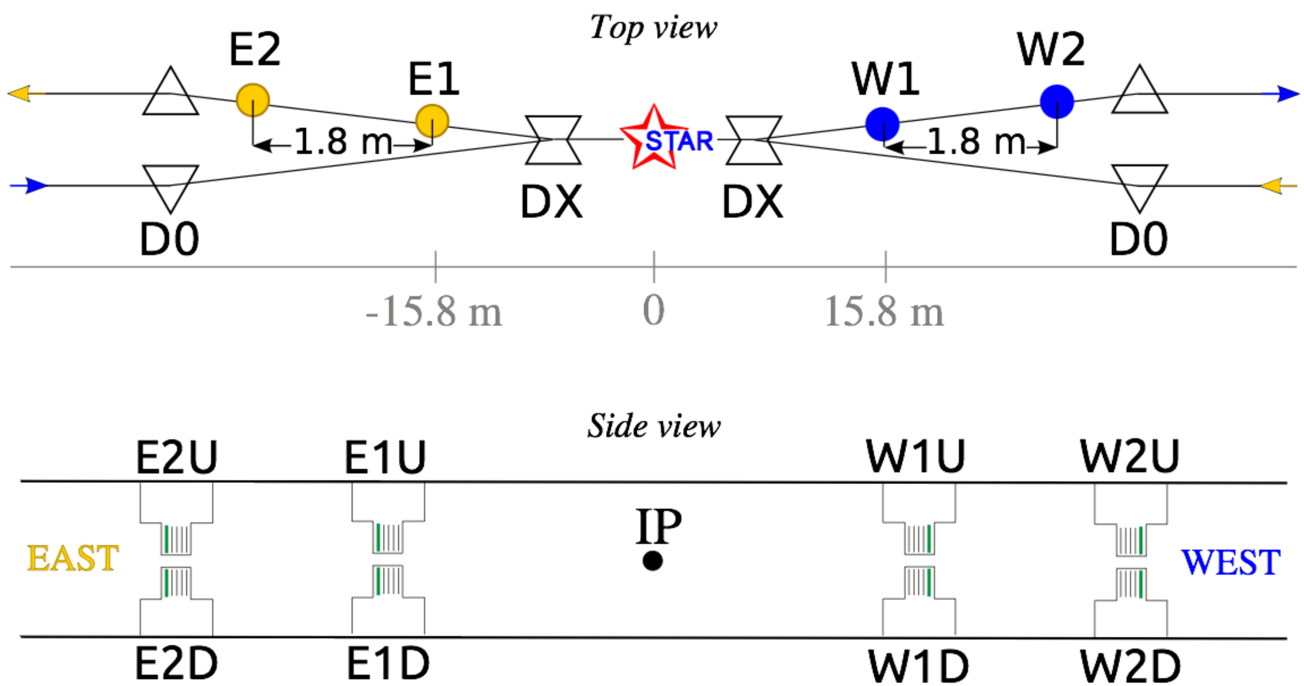
- Observed J/ψ in $\gamma p\uparrow$ & γAu, QED 2γ
- Proof of principle: measurement of $A^{\gamma}_{N} \propto E^{g} \sim$ gluon L_{g}

  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

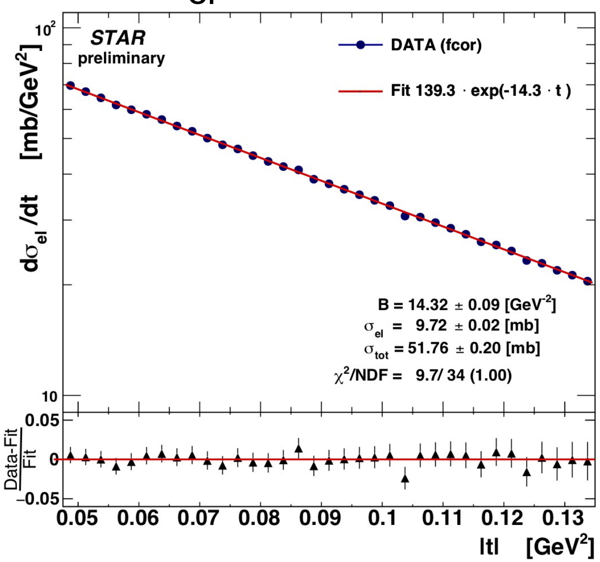


- Recent data w/ *pp*, *pAu*, *pAl* @ √s=200 GeV, *pp* @ 510 GeV
- First results from *pp* 200:
  - elastic *pp* scattering ⇒ total *pp* cross section
  - single diffractive dissociation
  - central exclusive production

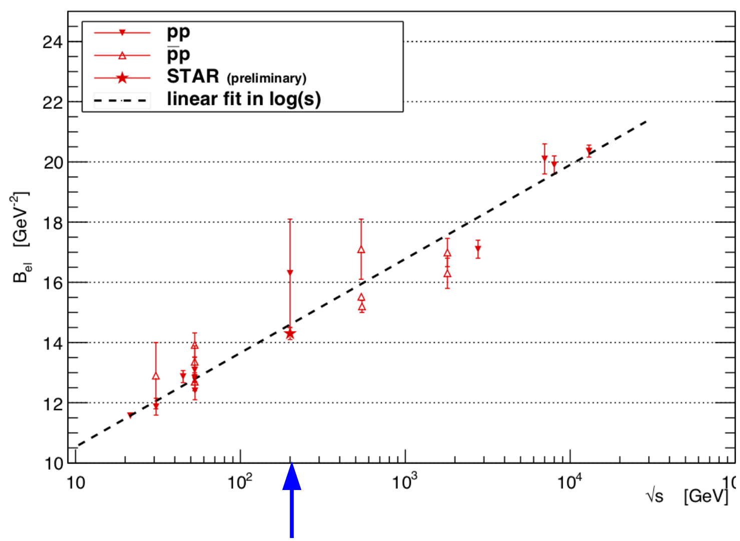
pp elastic scattering

- Fundamental *pp* physics measurement
- Measure back-to-back protons both beam directions, scattering angle $\Rightarrow$ momentum transfer t:

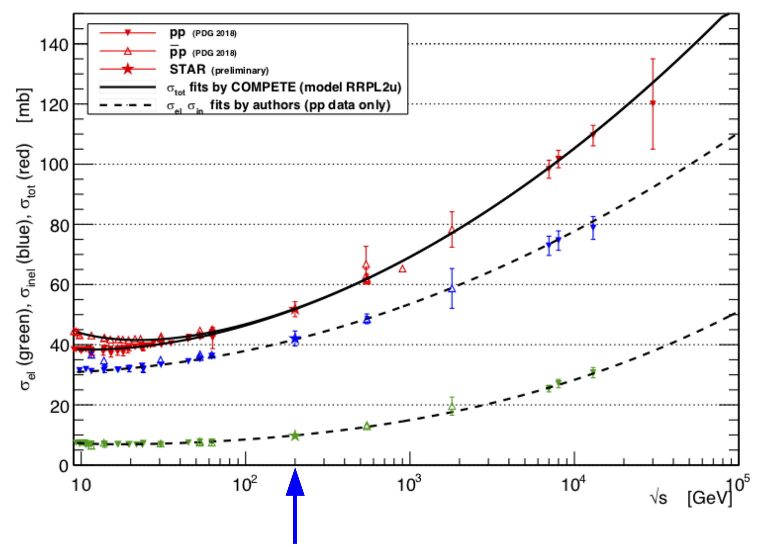
- $d\sigma_{el}/d|t|$:



- slope B_{el} & world data:



- $\sigma_{el,tot}$ & world data:



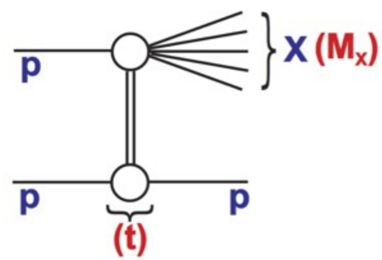
- $d\sigma_{el}/d|t|$ well described by $e^{-B|t|}$
- B_{el} = 14.32±0.09 @ $\sqrt{s}$=200 GeV consistent w/ world data $B_{el} \propto \log(s)$

- $\int e^{-B|t|} \Rightarrow \sigma_{el}$
- $d\sigma_{el}/d|t|\,\big|_{t=0}$, optical theorem $\Rightarrow \sigma_{tot}$, $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$
- consistent w/ fit world data

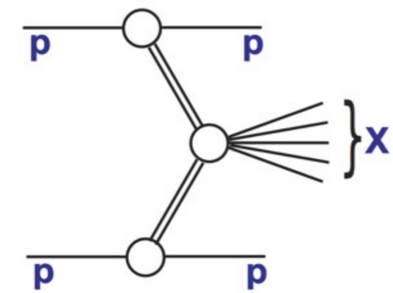
Diffractive final states

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

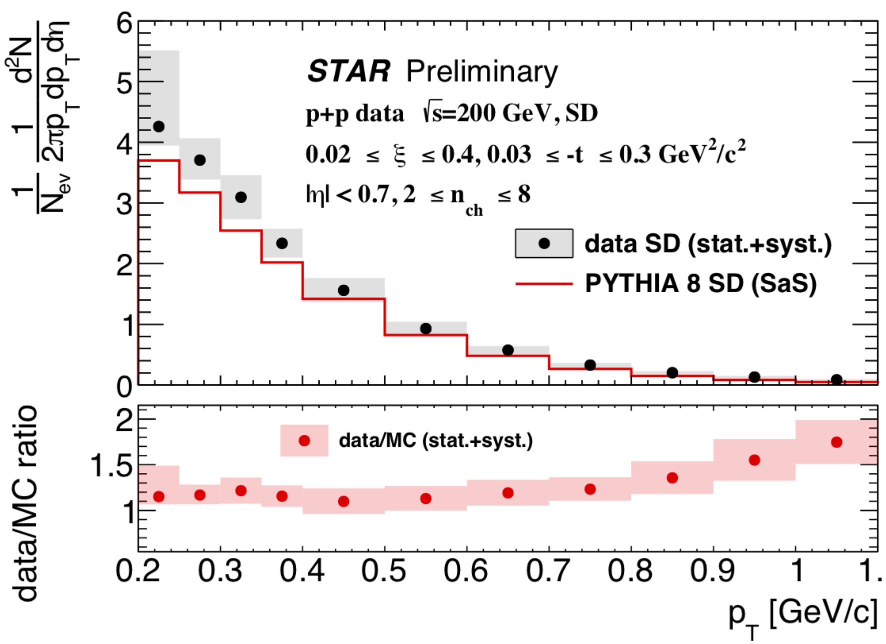
- Proton 1 side: single diffractive dissociation (SDD)

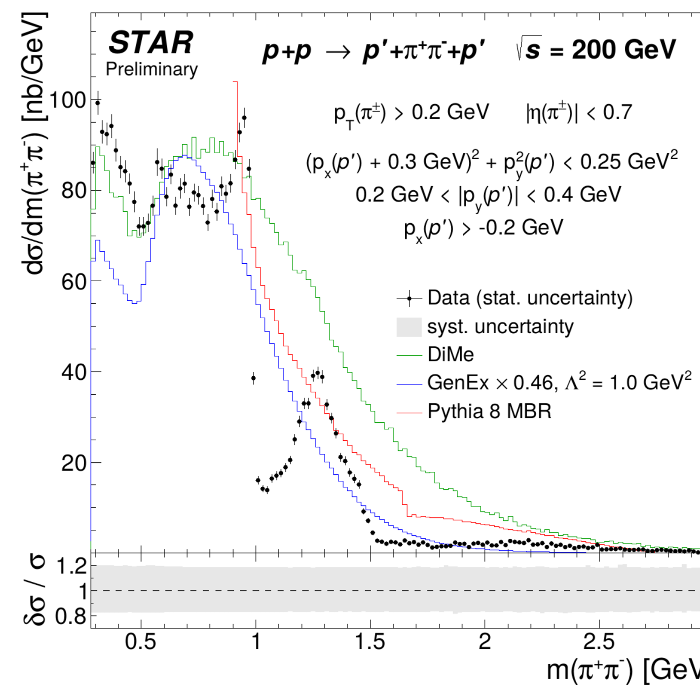


- Proton 2 sides: central exclusive production (CEP), 2 Pomeron fusion



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



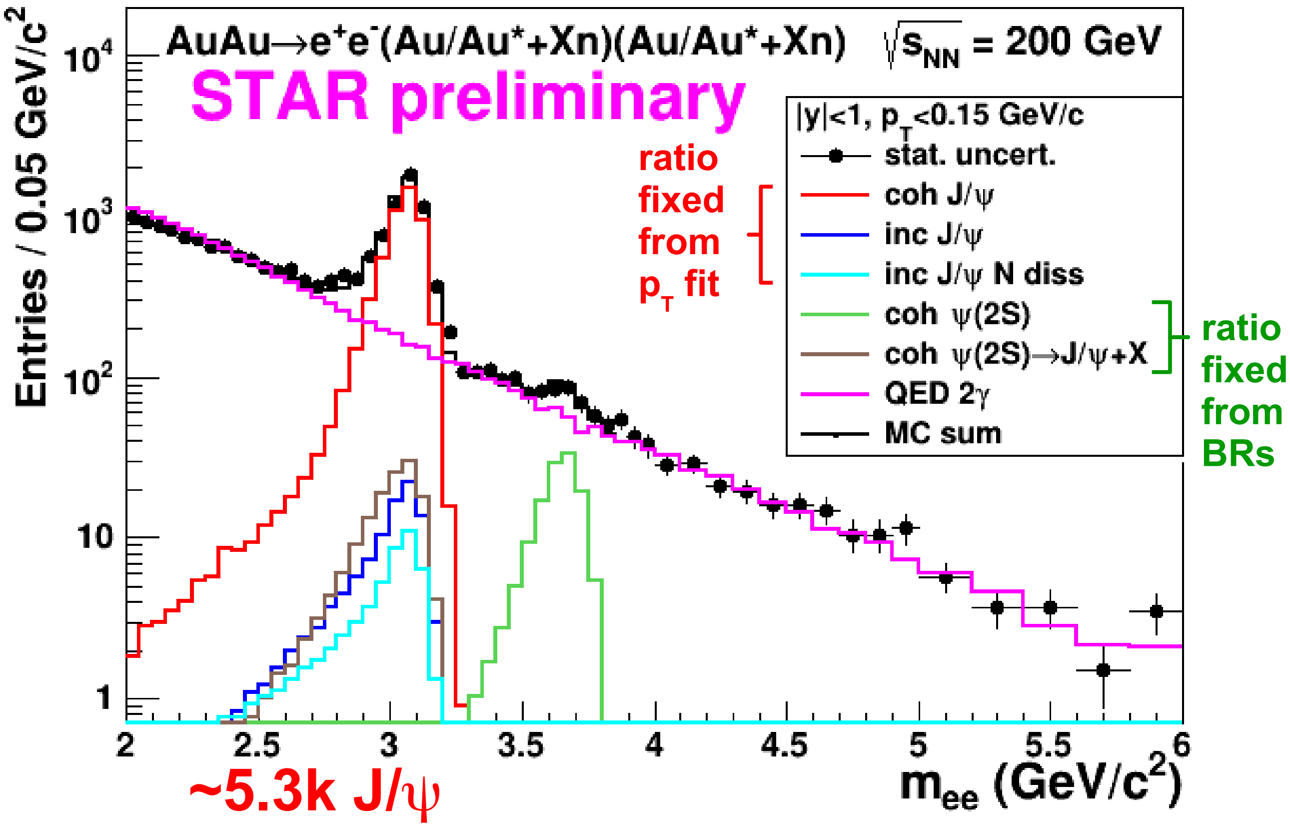


- SDD single particle p_T spectrum ~described by Pythia

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

Au+Au: m_{ee} fit

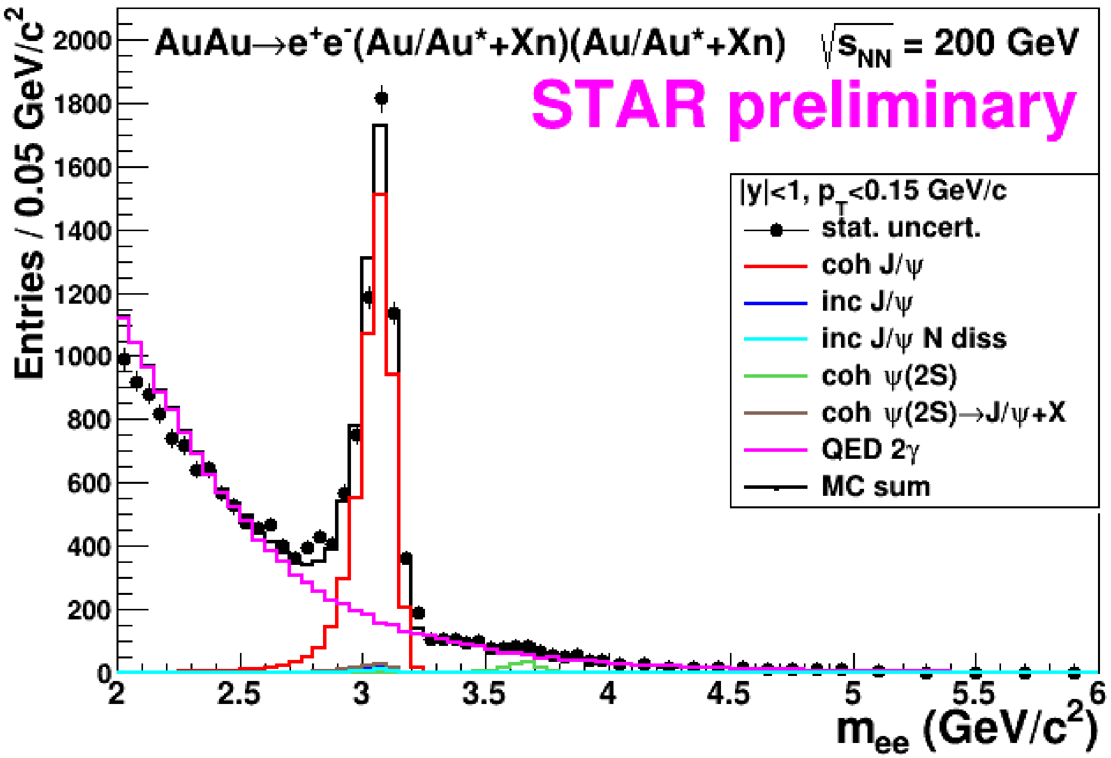
- m_{ee} fit not sensitive to different J/ψ components:



- Fix ratio ψ(2S)→J/ψ+X / ψ(2S)→e^+e^- by BRs
- Fix ratio (inc.:coh.) J/ψ from p_T fit (next step, iterated)
- Fit sum of: J/ψ, ψ(2S), QED 2γ

Au+Au: m_{ee} fit

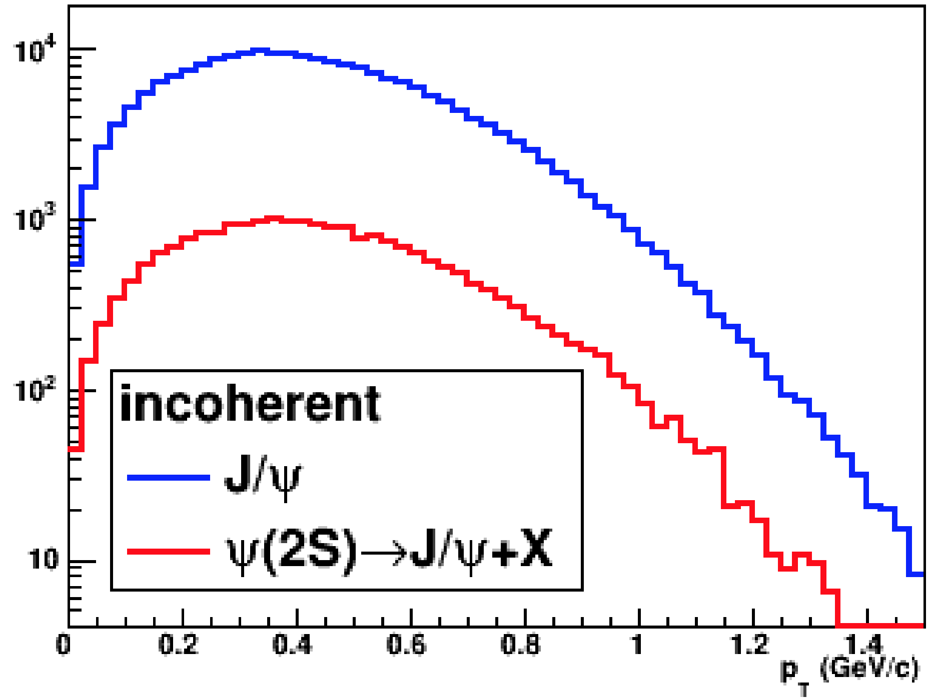
- On a linear Y scale:



- Deviation @ lowest m_{ee}: trigger threshold uncertainty
- Fit performed $2.2<m_{ee}<6$ GeV/c^2

Au+Au: p_T fit

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

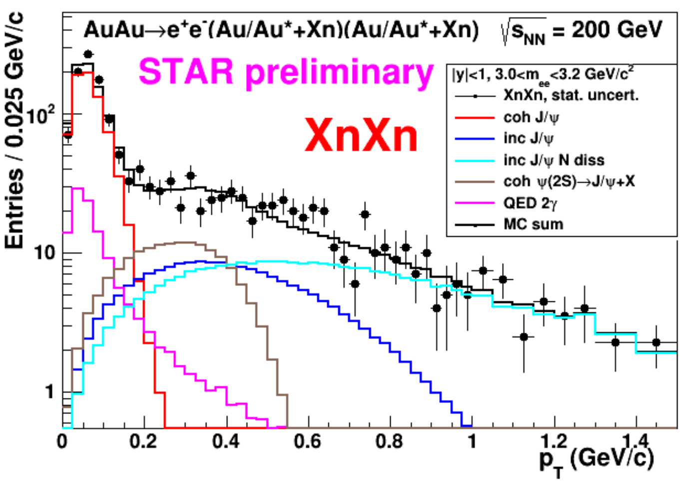


- ~indistinguishable
- treated as one component for comparison/fit to data

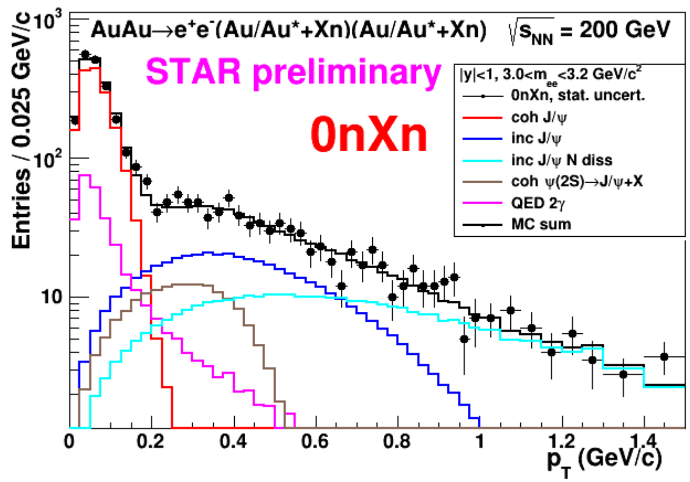
Au+Au: p_T for 3 ZDC categories

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

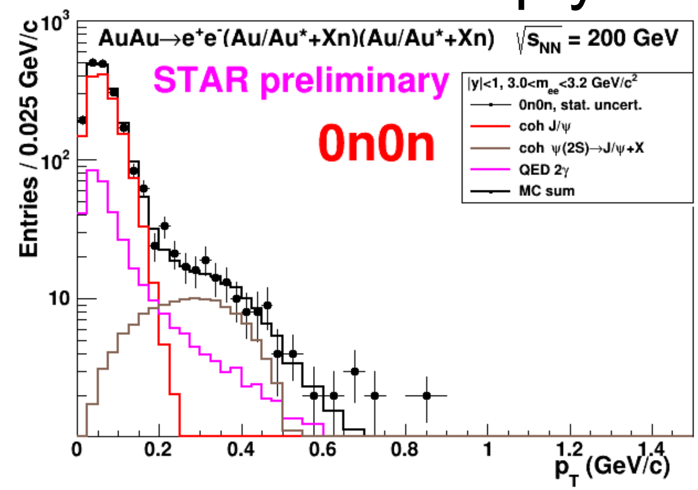
- ≥1n both ZDCs:



- ≥1n one ZDC,
  other ZDC empty:

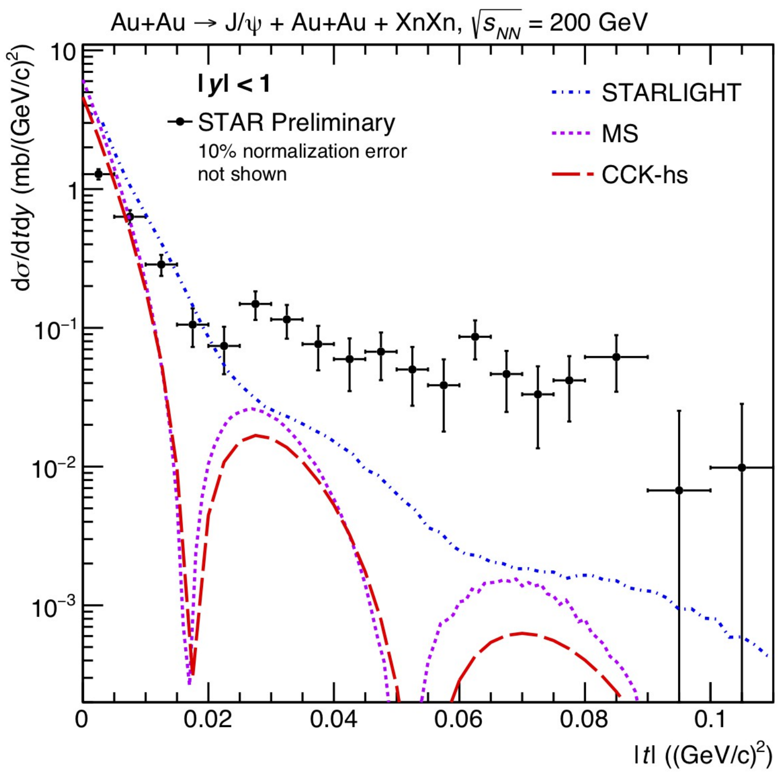


- both ZDCs empty:



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

Coherent J/ψ |t| 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

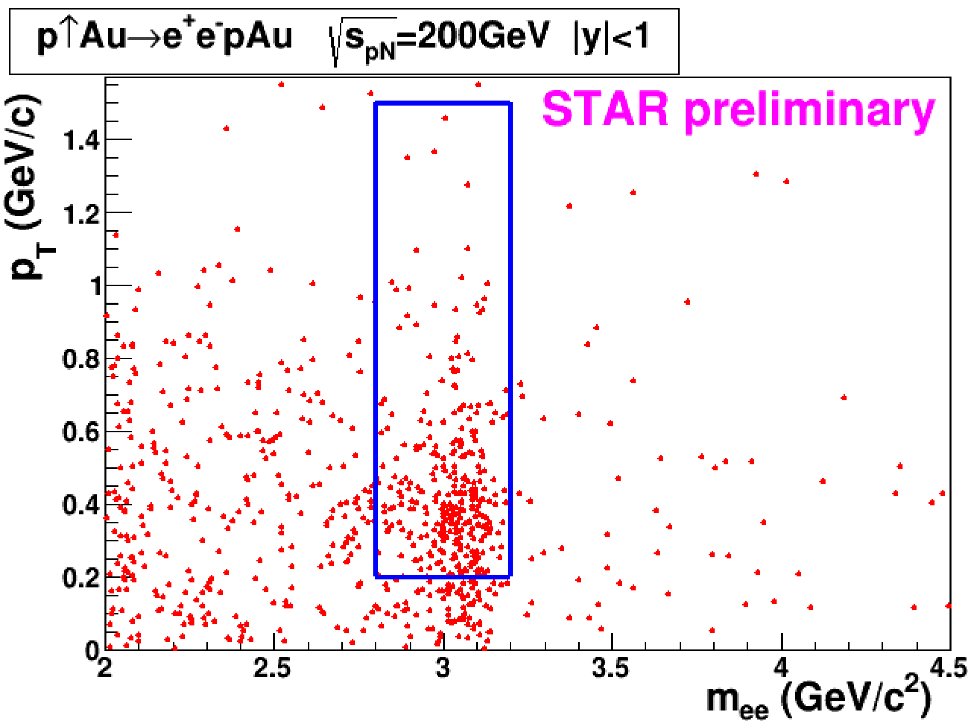
- CCK: Cepila, Contreras, Krelina, Phys.Rev. C97 (2018) no.2, 024901

- Hot spot model for nucleons, dipole approach-

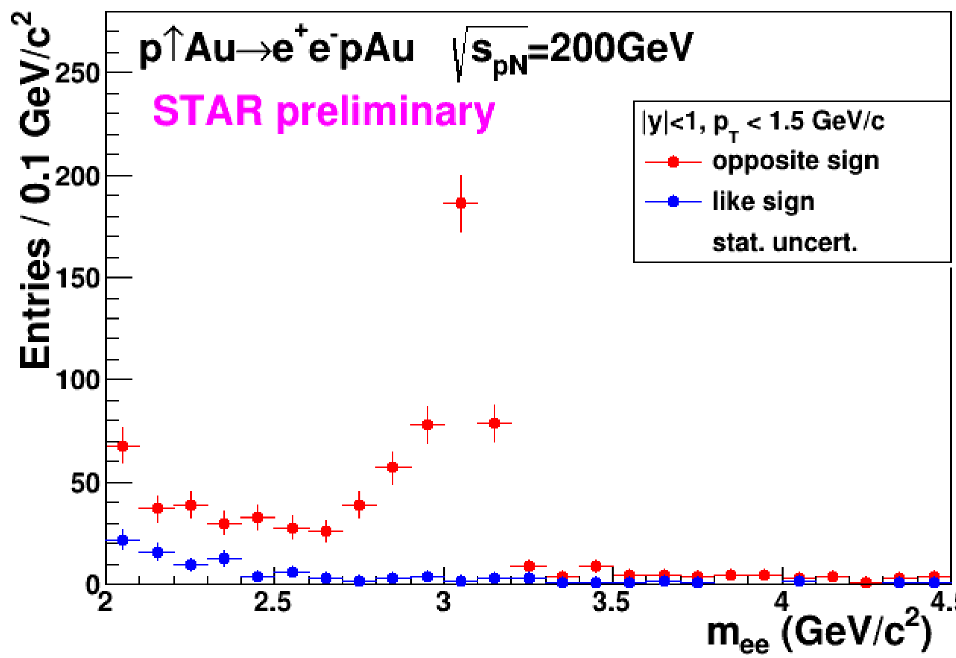
- MS & CCK scaled to XnXn using STARLIGHT

p↑+Au: p_T, m_{ee} distributions

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



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

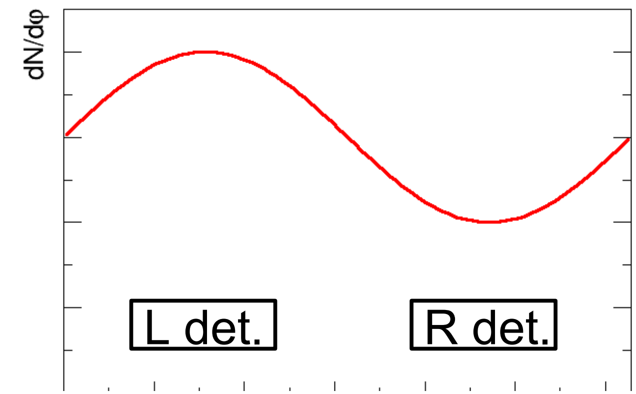


- Box shows fiducial region for A^{γ}_{N} measurement:
  $2.8<m_{ee}<3.2$ GeV/c^2,
  $0.2<p_T<1.5$ GeV/c

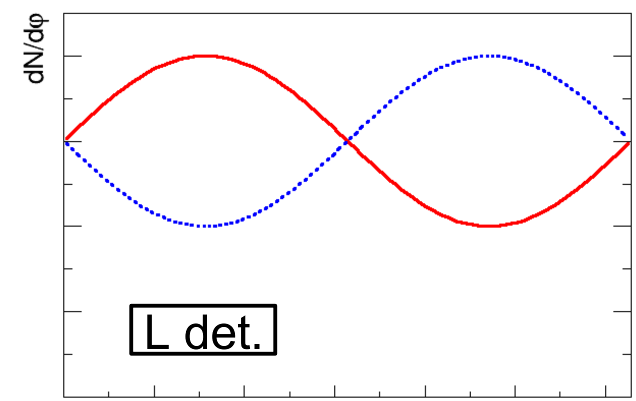
- For final distributions take (opposite-like) sign

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

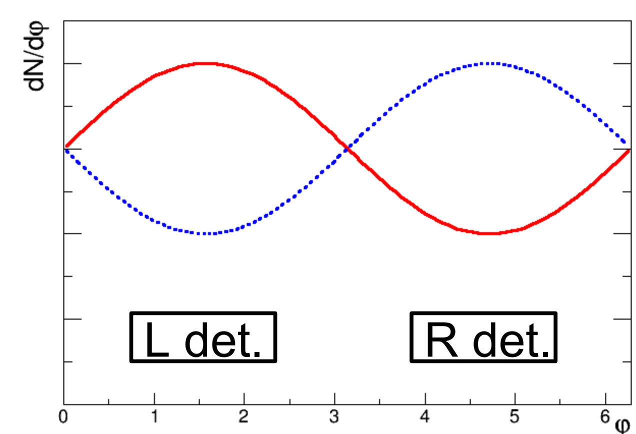


- If have one detector left of beam, and beam bunches w/ spin up (+) and down (-), can measure asym., but would need to know relative luminosities of +/- beams



- 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