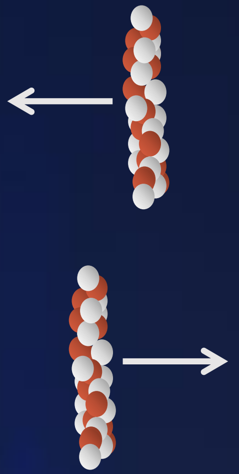
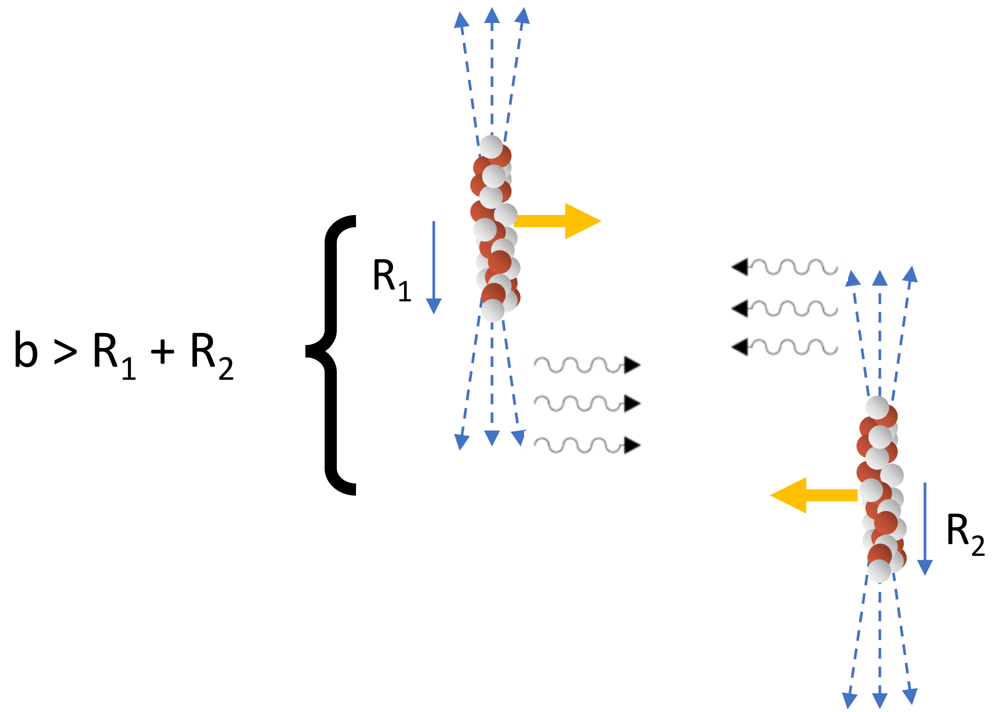
Ultra-peripheral Collisions at STAR



Janet Seger (for the STAR Collaboration)

Creighton University

Ultra-peripheral Collisions



- Large impact parameter($b > R_1 + R_2$) → no nuclear overlap → no "collision" → electromagnetic interactions dominate
- Relativistic heavy ions are intense source of quasi-real photons
  - Q ~ 1/R ~ 0.06 GeV (Au) or 0.28 GeV (p)
  - Photon flux ~ Z^2 from each nucleus
  - Experimentally: very low multiplicity events with small momentum transfer, rapidity gaps
- Photoproduction in γp and γA interactions
- QED processes in $\gamma\gamma$ interactions

Photoproduction of vector mesons

- Has been extensively studied at HERA, RHIC, LHC
- Factorize into
  - photon emission
  - interactions with nuclear target
- Allows one to probe the nucleus via QCD to learn about shadowing, saturation effects, nPDFs

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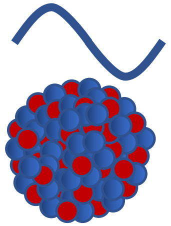
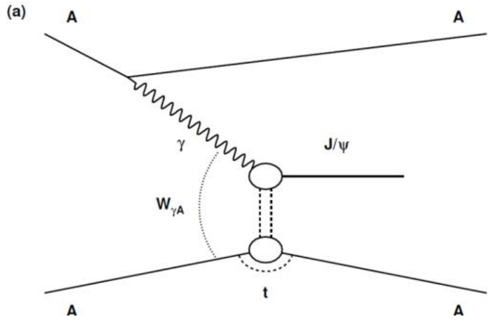
- Coherent interaction: Photon interacts with entire nucleus
  - Nucleus generally remains intact
  - Small momentum transfer: $p_T \sim \hbar/R_A \sim 15$ MeV
  - Max photon energy $\sim \gamma\hbar/R_A \sim 3$ GeV at RHIC





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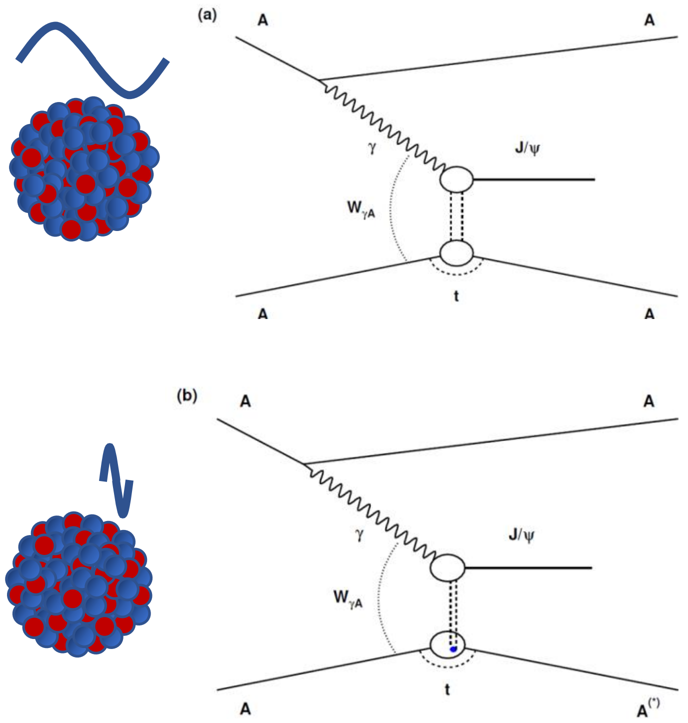
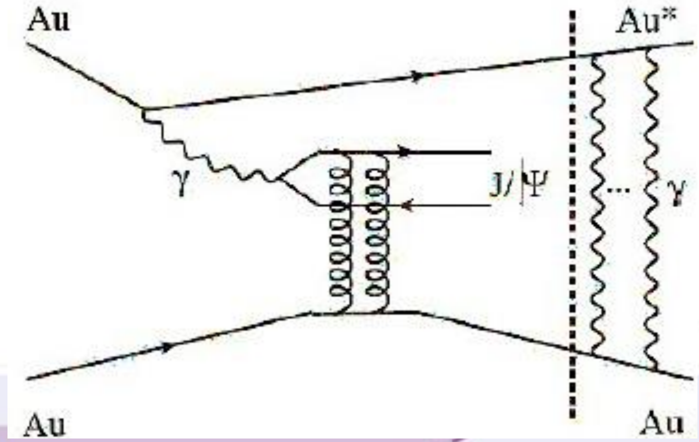
  - Small momentum transfer: $p_T \sim \hbar/R_A \sim 15$ MeV
  - Max photon energy $\sim \gamma\hbar/R_A \sim 3$ GeV at RHIC
- Incoherent interaction: Photon can interact with individual nucleons
  - Nucleus generally breaks
  - Momentum transfer is bigger: $p_T \sim \hbar/R_A \sim 100$ MeV
  - Max photon energy $\sim \gamma\hbar/R_A \sim 20$ GeV at RHIC



Diagrams from Cepila, Jan et al. , Phys. Rev. C97 (2018) no 2, 024901

Heavy Vector Mesons: J/ψ

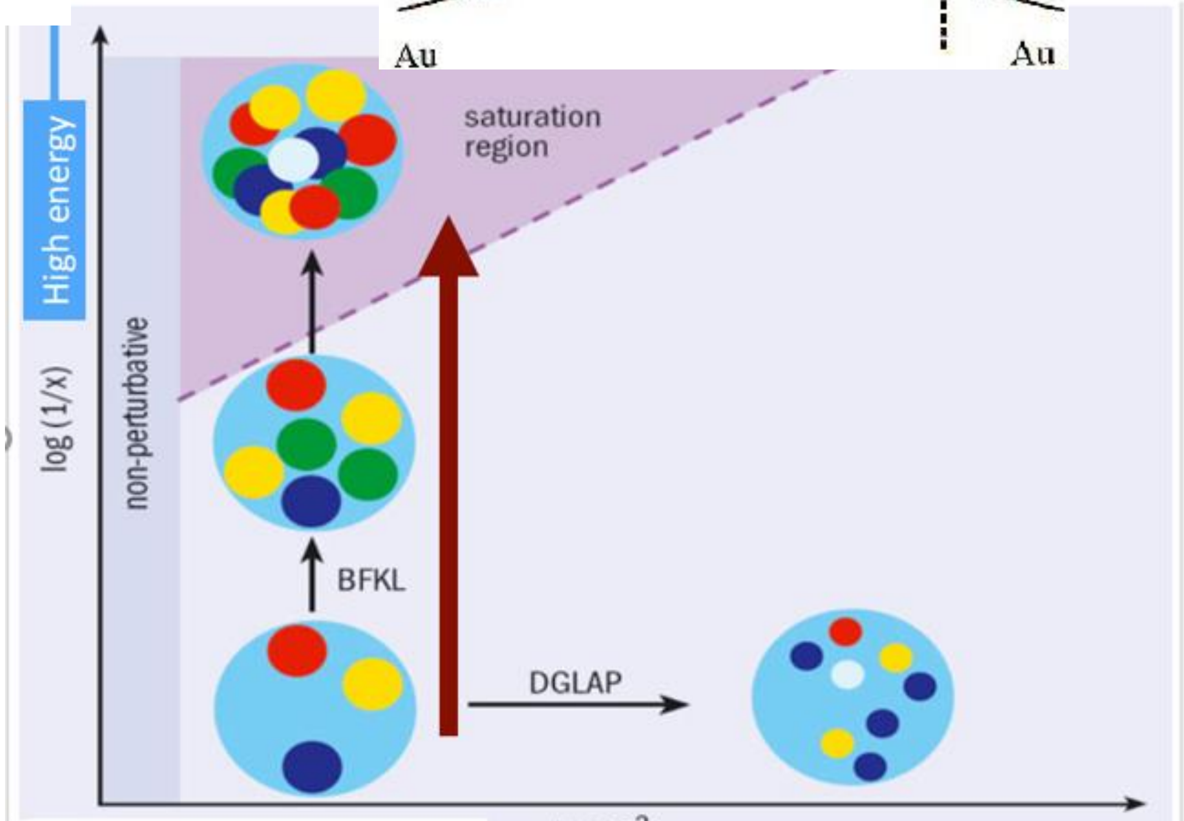
$$\frac{d\sigma^{\gamma^* A \to J/\psi\, A}}{dt} \propto \left(xG_A(x, Q^2)\right)^2$$



- 2-gluon exchange at the lowest order
- Probe of gluon distribution function
- For vector mesons:

$$x \simeq \frac{m_{J/\psi} e^{-y}}{\sqrt{s}} \qquad Q^2 = M^2_{J/\psi}/4$$

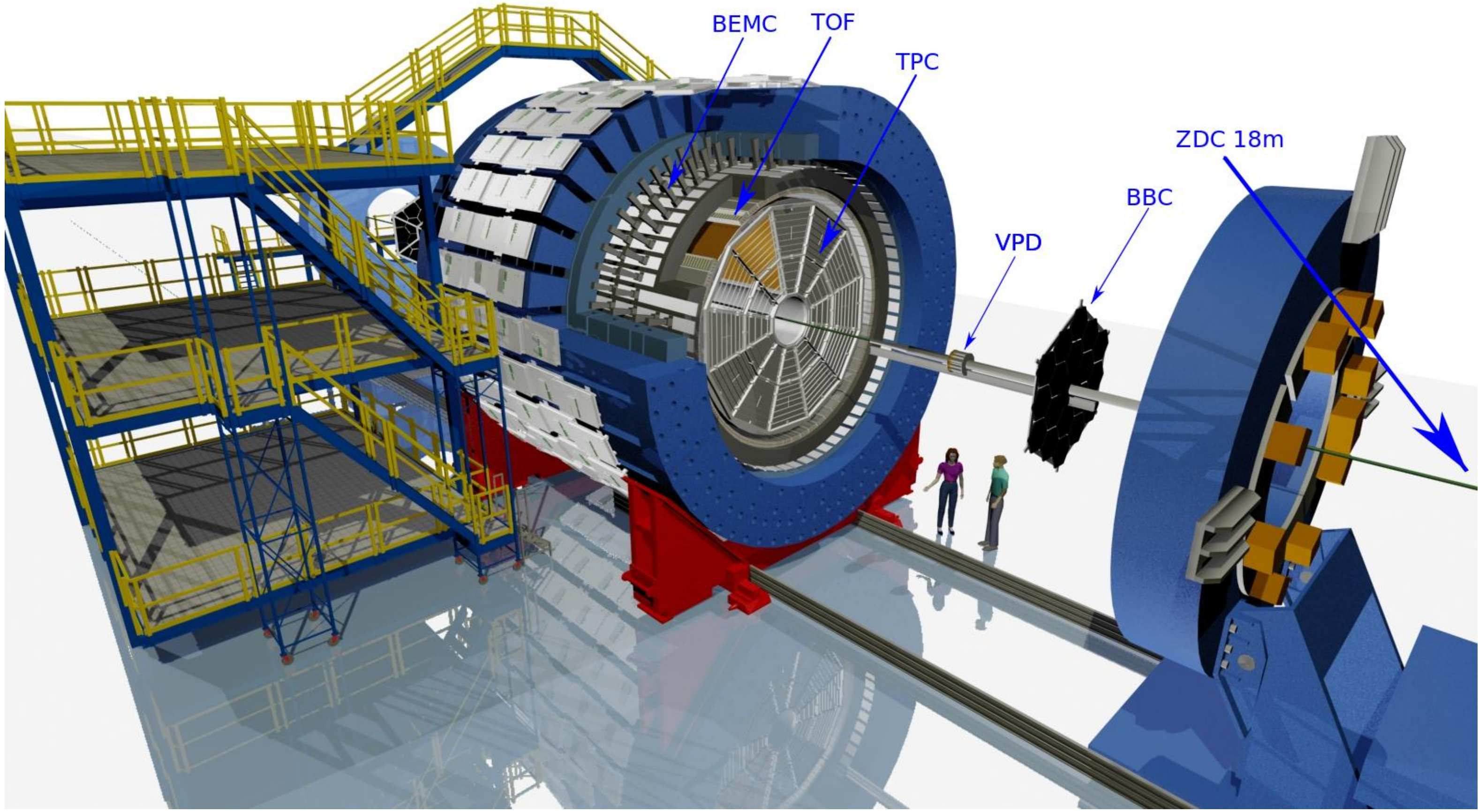
- Measurements at different rapidities sample different values of x



CERN Courier, July 20, 2010

The STAR detector

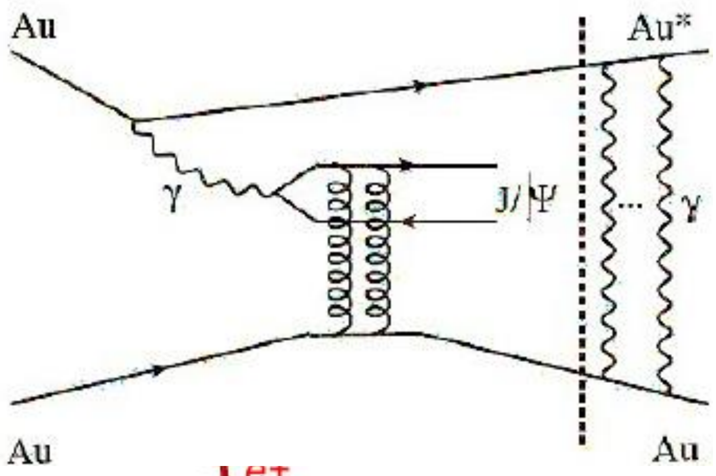
- Central tracking and particle identification, forward counters and neutron detection
- Time Projection Chamber: tracking and identification in $|\eta| < 1$
- Time-Of-Flight: multiplicity trigger, identification and pile-up track removal
- Barrel ElectroMagnetic Calorimeter: topology trigger and pile-up track removal
- Beam-Beam Counters: scintillator counters in $2.1 < |\eta| < 5.2$, forward veto
- Zero Degree Calorimeters: detection of very forward neutrons, $|\eta| > 6.6$

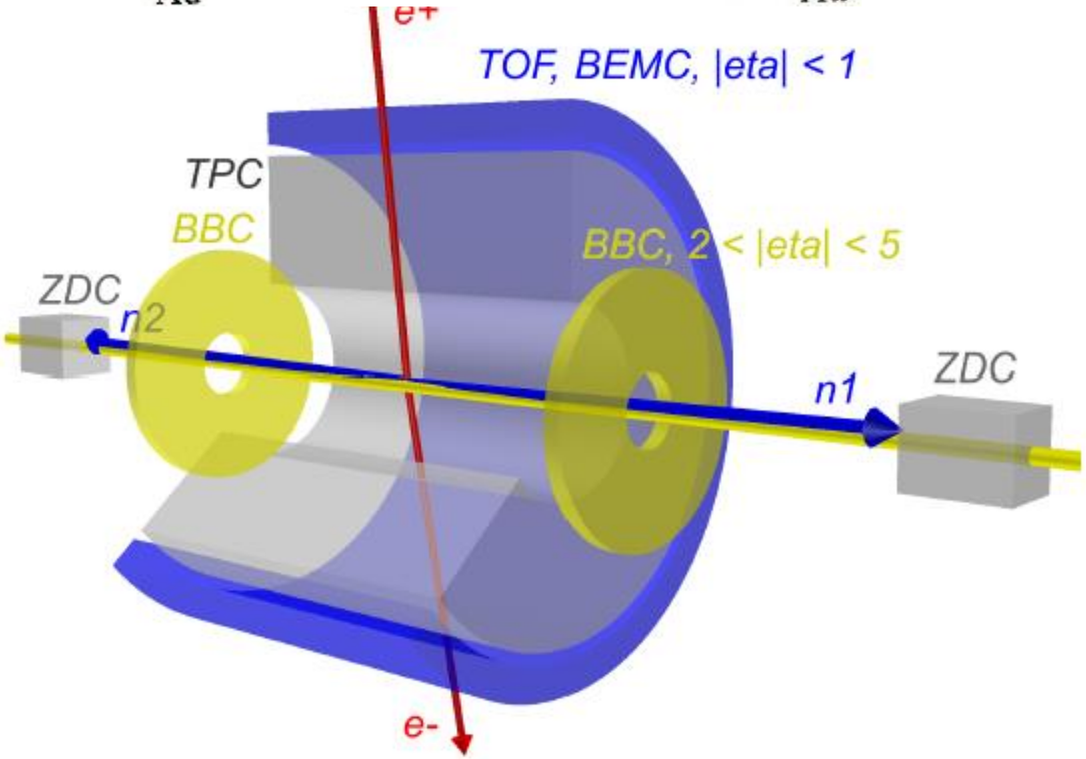


UPC trigger at STAR

Trigger requires:

- Back-to-back hits in BEMC
- Limited activity in TOF
- Veto from both BBCs
- Signal in both ZDCs (xnxn)
  - Energy deposition within 1/4 to 4 beam-energy neutrons
  - Full efficiency for single neutrons





J/ψ candidates observed in e^+e^- decay channel

200 GeV Au+Au data from 2014 run at STAR

Selection criteria:

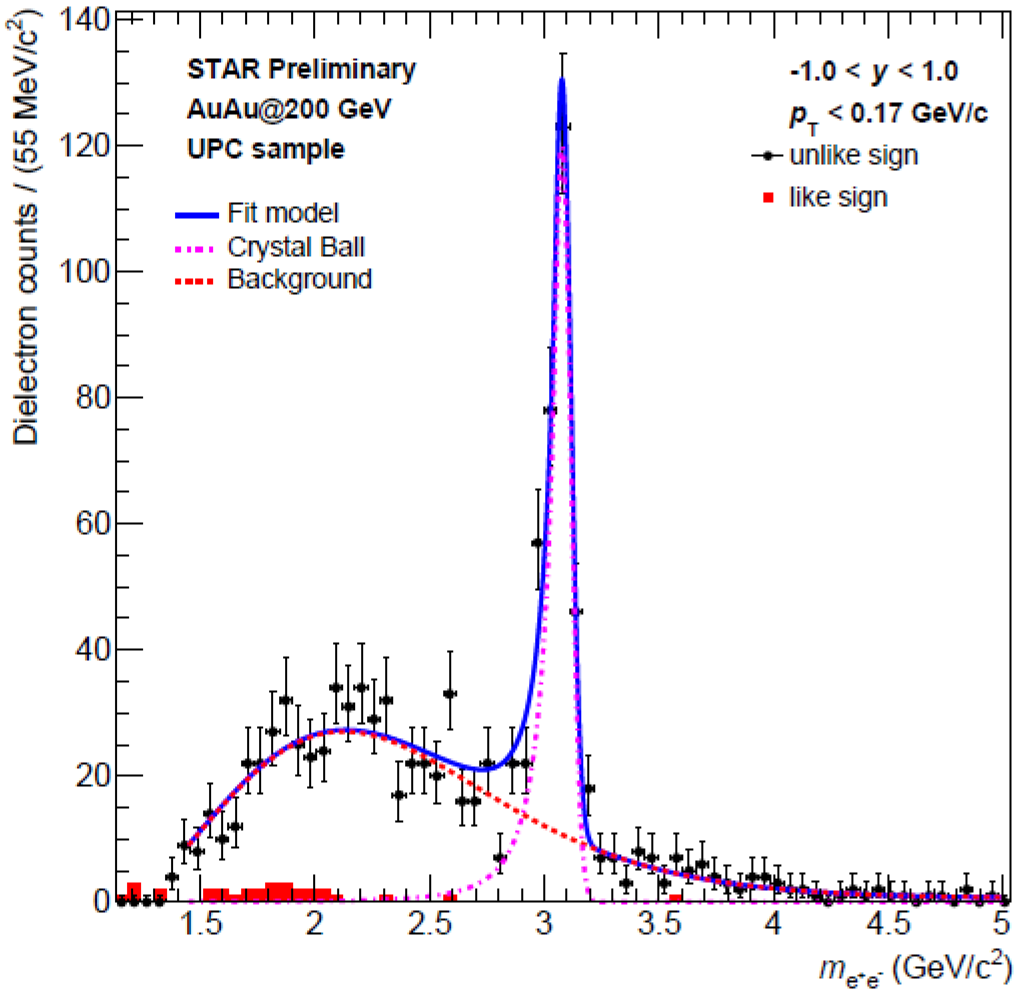
- Vertex with exactly two tracks of opposite sign
- $|y| < 1$
- $p_T < 0.17$ GeV/c

Like-sign background is minimal

Non-negligible background from e^+e^- continuum is parametrized with empirical formula

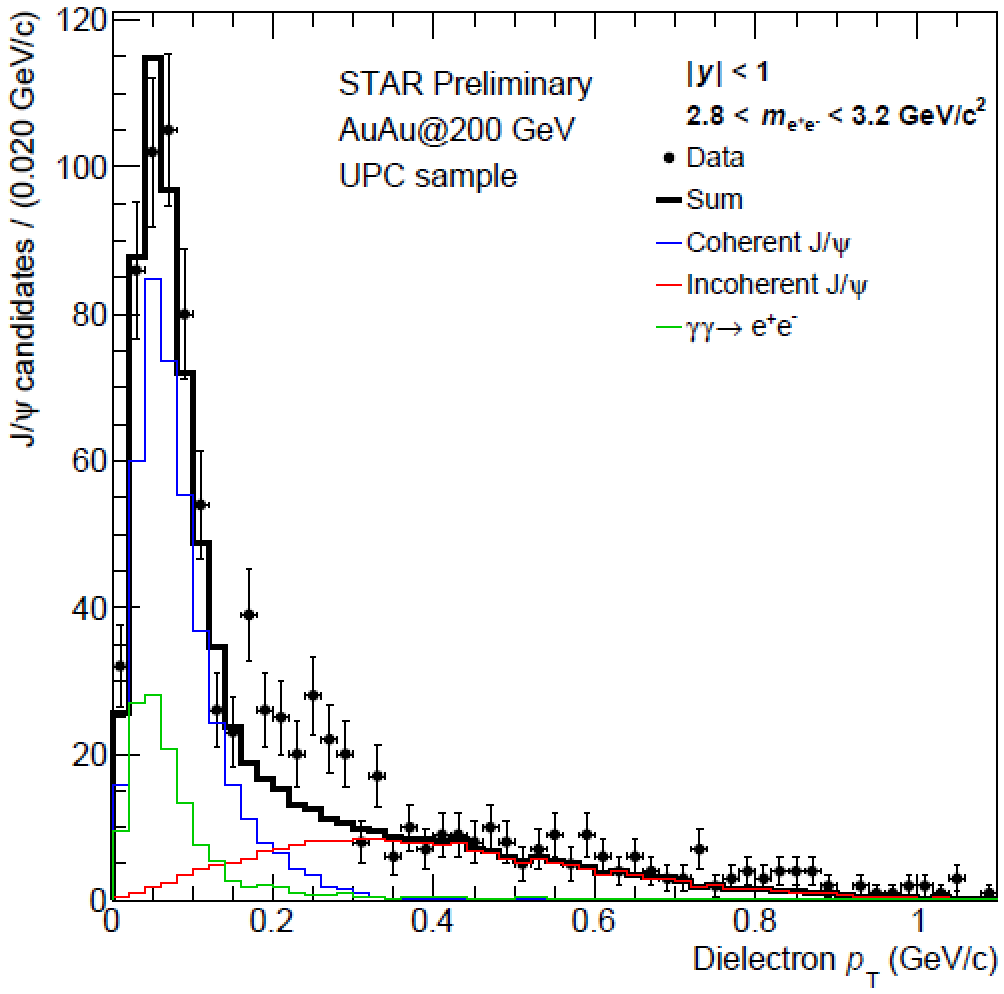
$$f_{\gamma\gamma\to e^+e^-} = (m - c_1)e^{\lambda(m-c_1)^2+c_2m^3}$$

- Effective convolution of $\gamma\gamma \rightarrow e^+e^-$ cross section and detector effects



Transverse momentum of J/ψ candidates

- Select candidates within J/ψ mass peak
- Distribution is mostly well reproduced by the template from STARLIGHT for different contributions
  - e^+e^- normalized using mass fit
  - Discrepancy in region $0.2\ \mathrm{GeV}/c < p_T < 0.4\ \mathrm{GeV}/c$

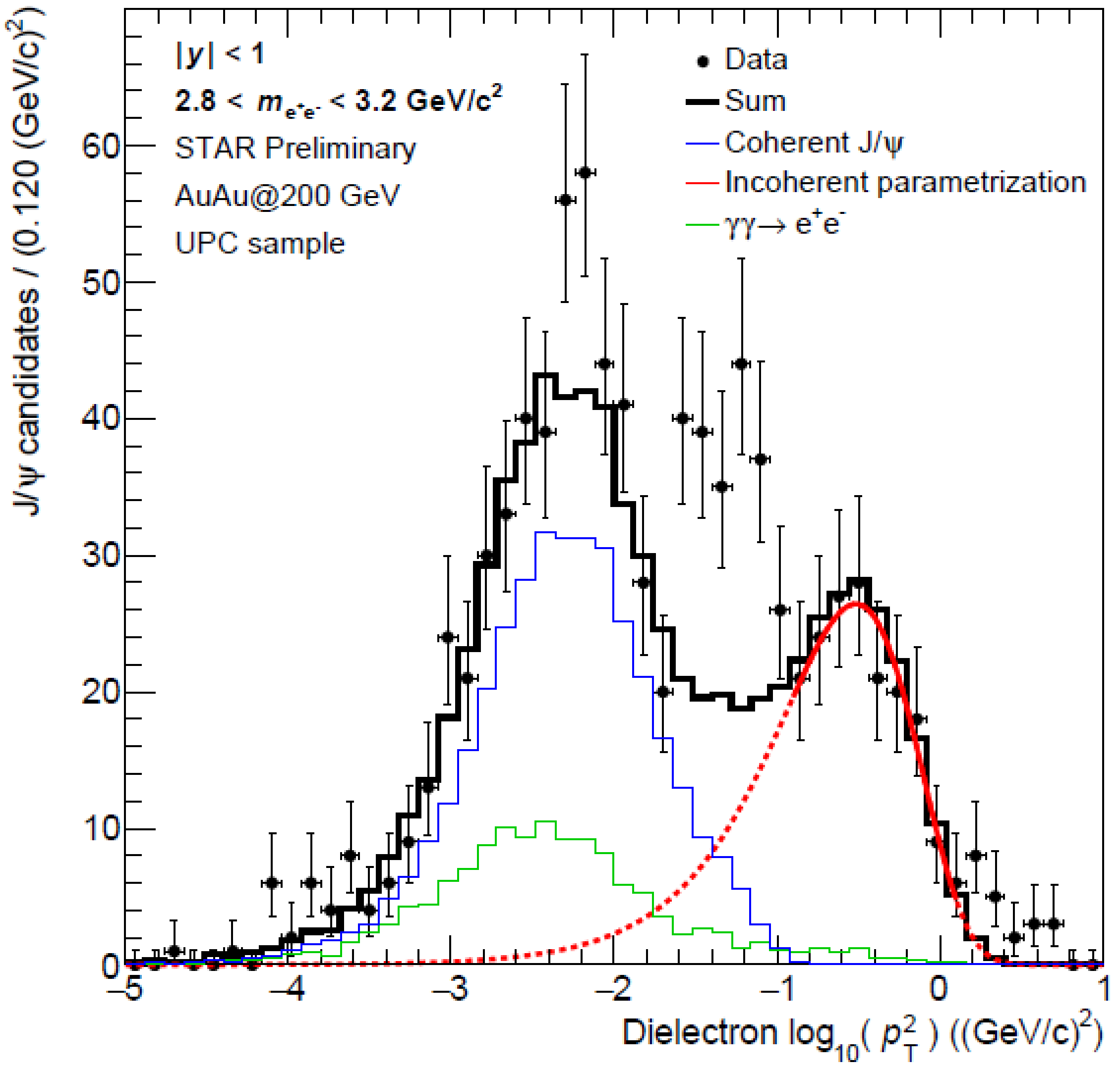


Separate incoherent from coherent

- Plot as a function of $\log_{10}(p_T^2)$
- Parametrize the incoherent contribution at high p_T (well above coherent peak)

$$f_{\text{incoherent}} = A \cdot e^{-bp_T^2}$$

- Extrapolate to lower p_T and subtract to get coherent sample



Diffractive dip seen in coherent $d^2\sigma/dtdy$

- After background subtraction
- $t \approx - p_T^2$

Model comparisons:

- **STARLIGHT:** Klein, Nystrand, CPC 212 (2017) 258-268
  - Vector meson dominance
  - Glauber approach
  - Includes photon p_T
- **MS:** Mäntysaari, Schenke, Phys.Lett. B772 (2017) 832-838
  - Dipole approach with IPsat amplitude
  - Scaled to XnXn using STARLIGHT
- **CCK:** Cepila, Contreras, Krelina, Phys.Rev. C97 (2018) no.2, 024901
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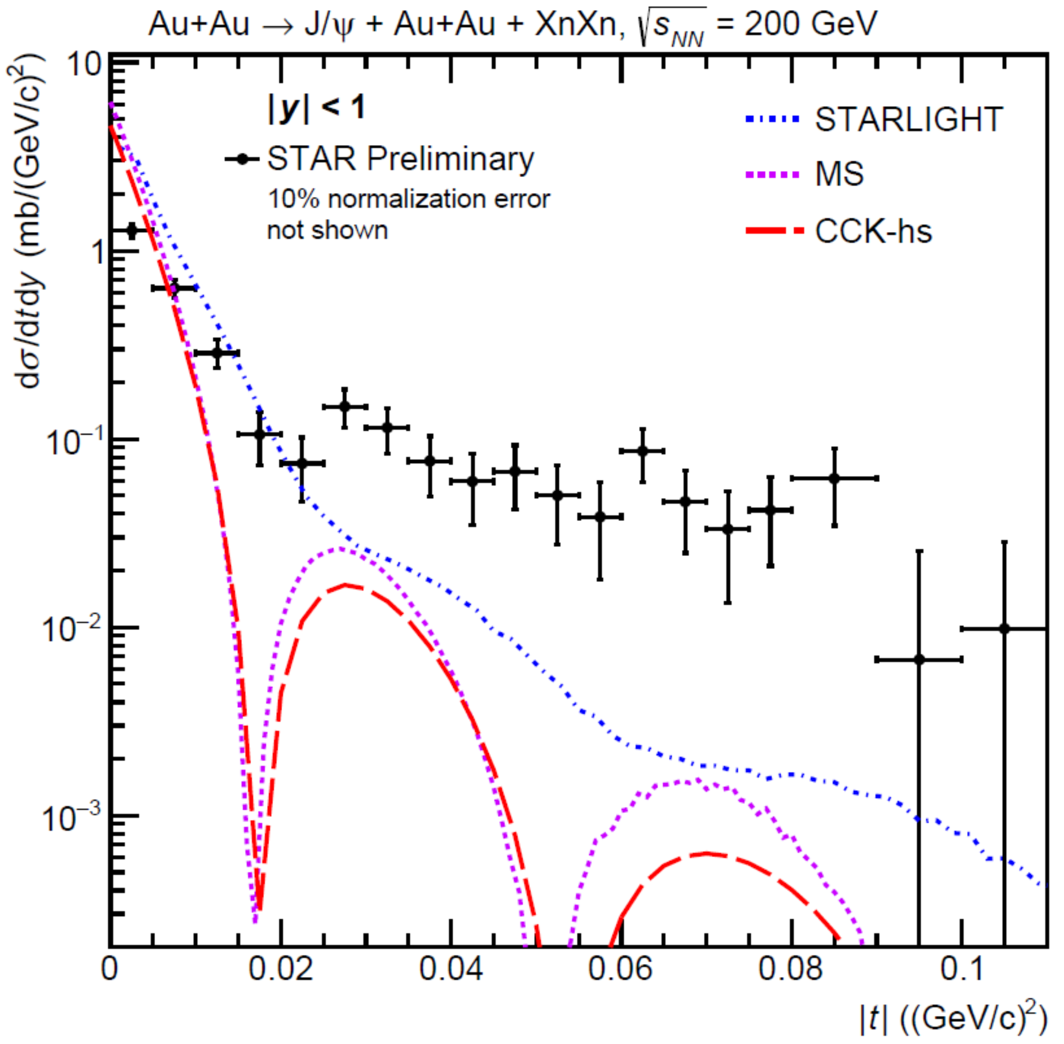

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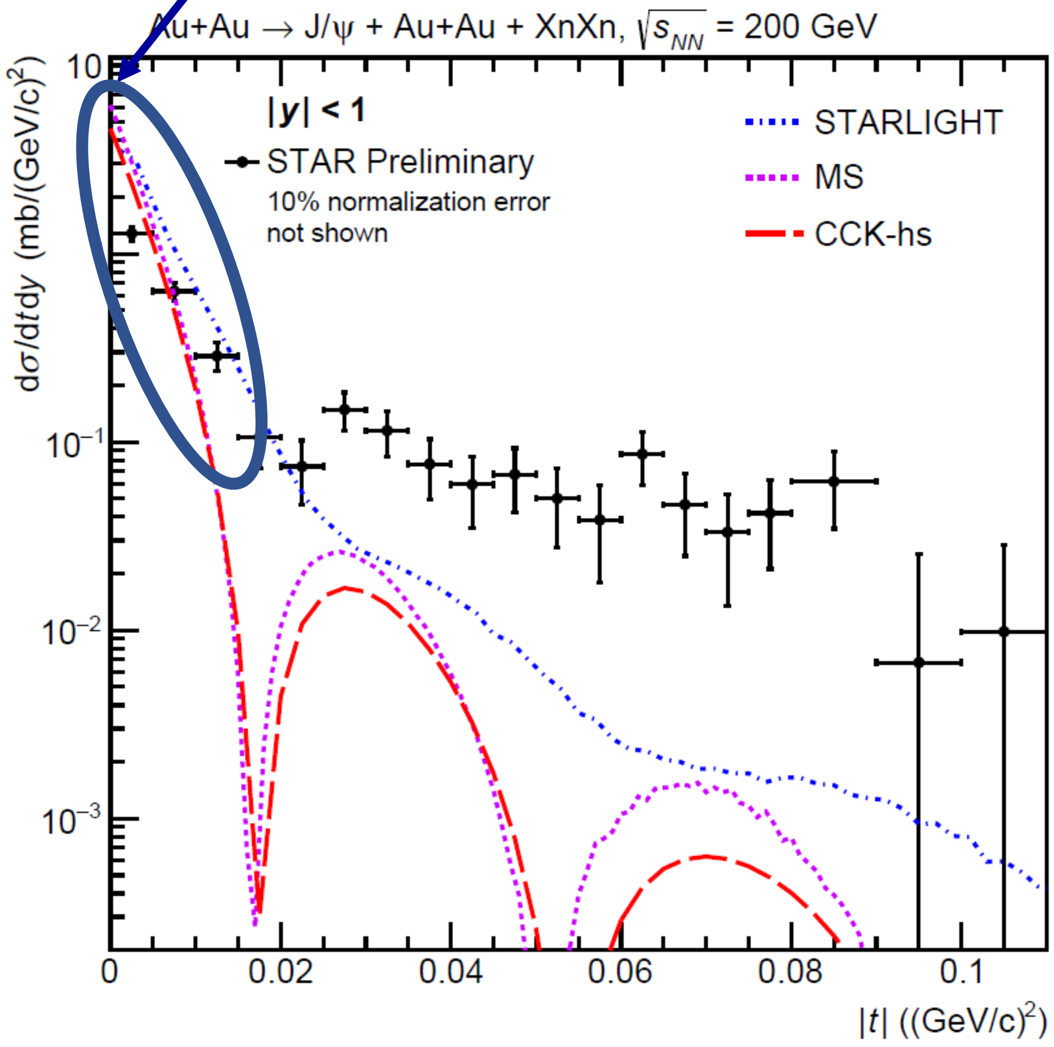
Slope below first diffractive minimum is consistent with the Glauber approach in STARLIGHT



Diffractive dip seen in coherent dσ/dt

- After background subtraction
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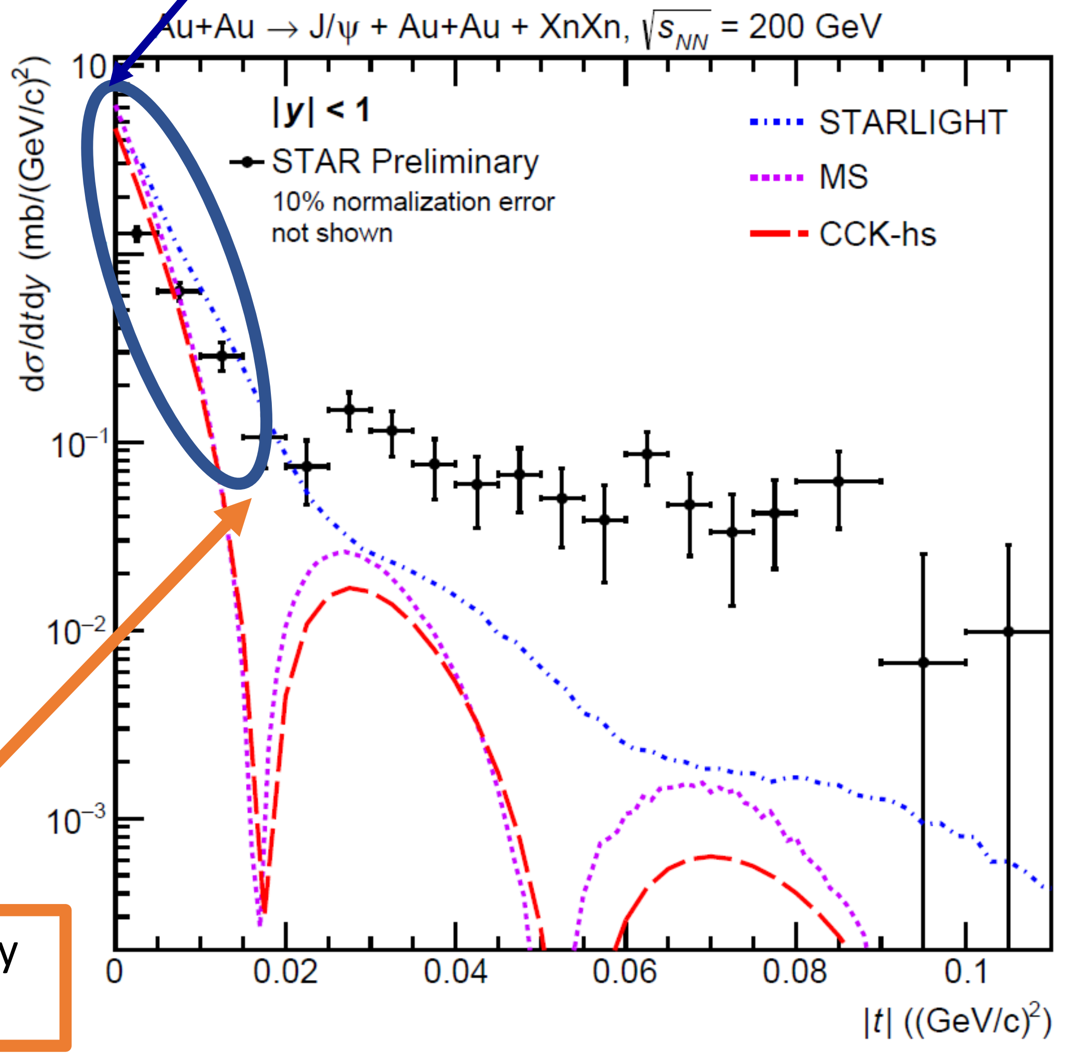
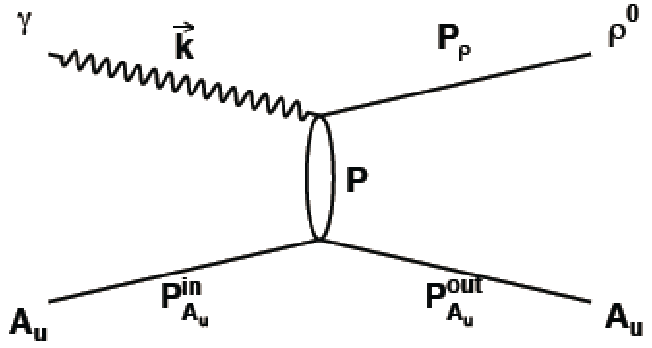


Diffractive dip around $|t| \approx 0.02$ GeV^2 is correctly predicted by the dipole MS and CCK models

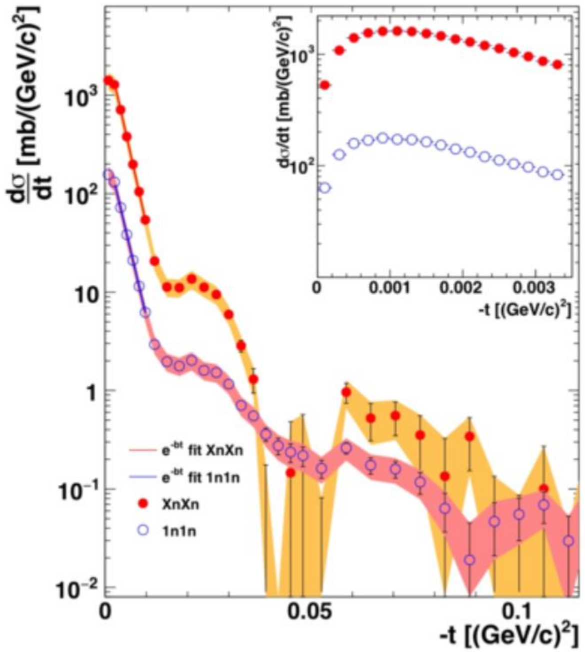
Coherent ρ photoproduction

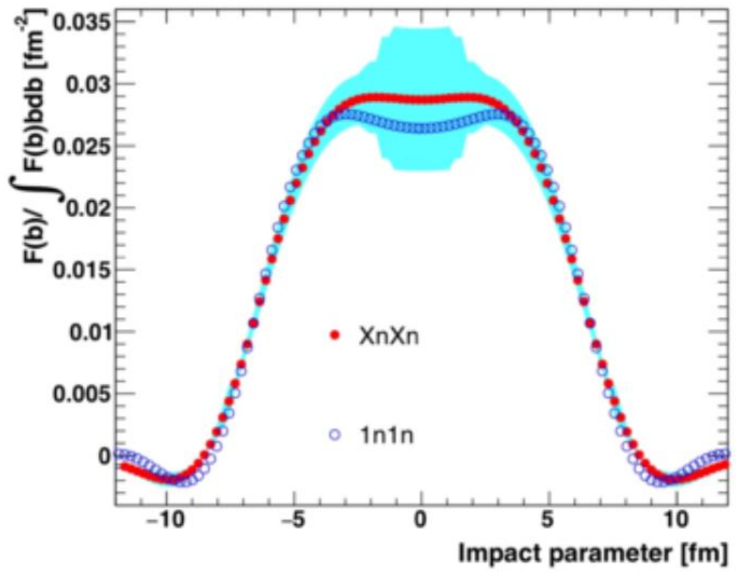
- High statistics 200 GeV Au+Au dataset
- Like-sign background has been subtracted
- Incoherent fit to dipole form factor at high t, extrapolated to lower t and subtracted to reveal coherent signal
- Diffractive dips evident
- Fourier-Bessel transform of dσ/dt gives nuclear density profile

$$F(b) \propto \frac{1}{2\pi}\int_0^\infty dp_T p_T J_0(bp_T)\sqrt{\frac{d\sigma}{dt}}$$



$Au + Au \rightarrow \rho + Au + Au + XnXn$, $\sqrt{s_{NN}}$=200 GeV





STAR: Phys. Rev. C **96** (2017) 54904

Shadowing changes effective shape of nucleus

- Photon fluctuates to $q\bar{q}$ dipole, scatters off nucleus to emerge as ρ
- Smaller mass → larger dipole → interacts on the front of the nucleus
  - "black disk"
- Higher mass → smaller dipole → penetrates further, sees internal nucleons
  - Woods-Saxon distribution

$$\sigma_c = \int d^3\vec{k} |\Sigma_i A_i exp(i\vec{k} \cdot \vec{x}_i)|^2$$

- Do we see a difference in shape for different dipole size (mass) ?

Data selection and mass binning

- Exactly 2 tracks from a common vertex
- $|Z_{vtx}| < 50$ cm
- $|y_{\pi\pi}| > 0.04$ (removes cosmic rays)
- Each track has > 25 space points
- $0.62\ \mathrm{GeV}/c^2 < M_{\pi\pi} < 0.95\ \mathrm{GeV}/c^2$
- Divide into three mass bins of ~ equal statistic

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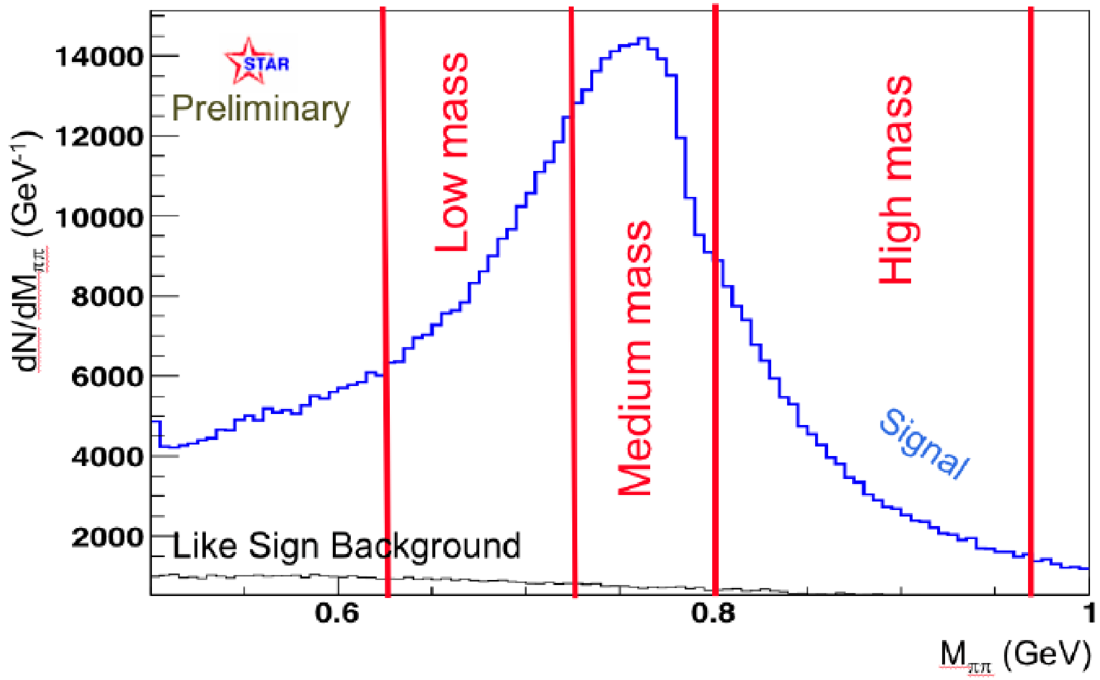
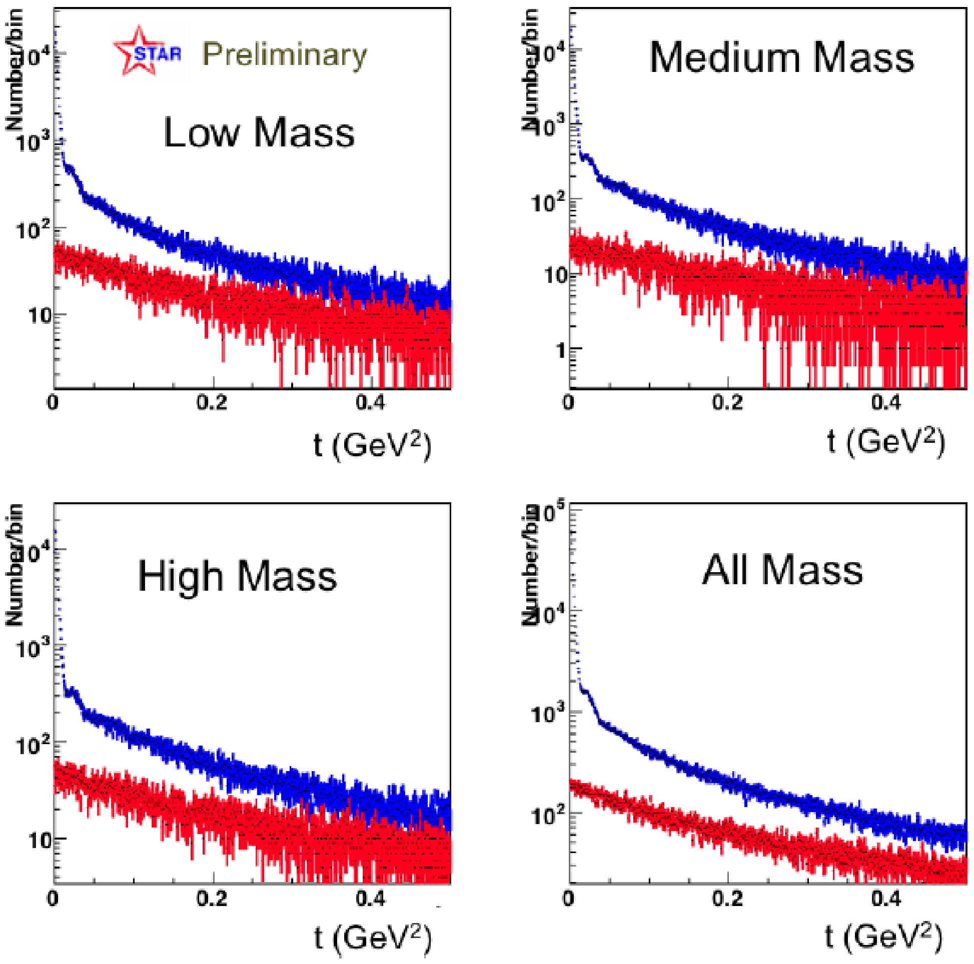


PoS(DIS2018)047

Subtract like-sign and incoherent backgrounds

Red: like-sign background
Blue: opposite sign pairs



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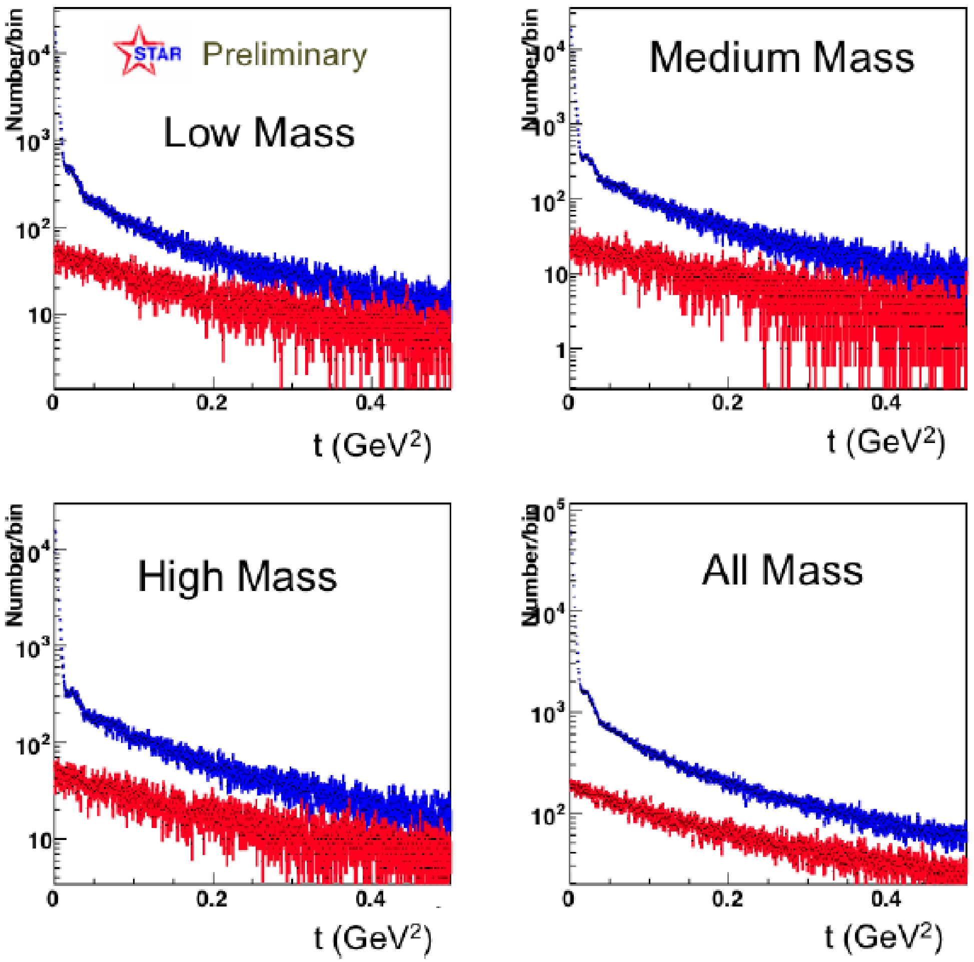
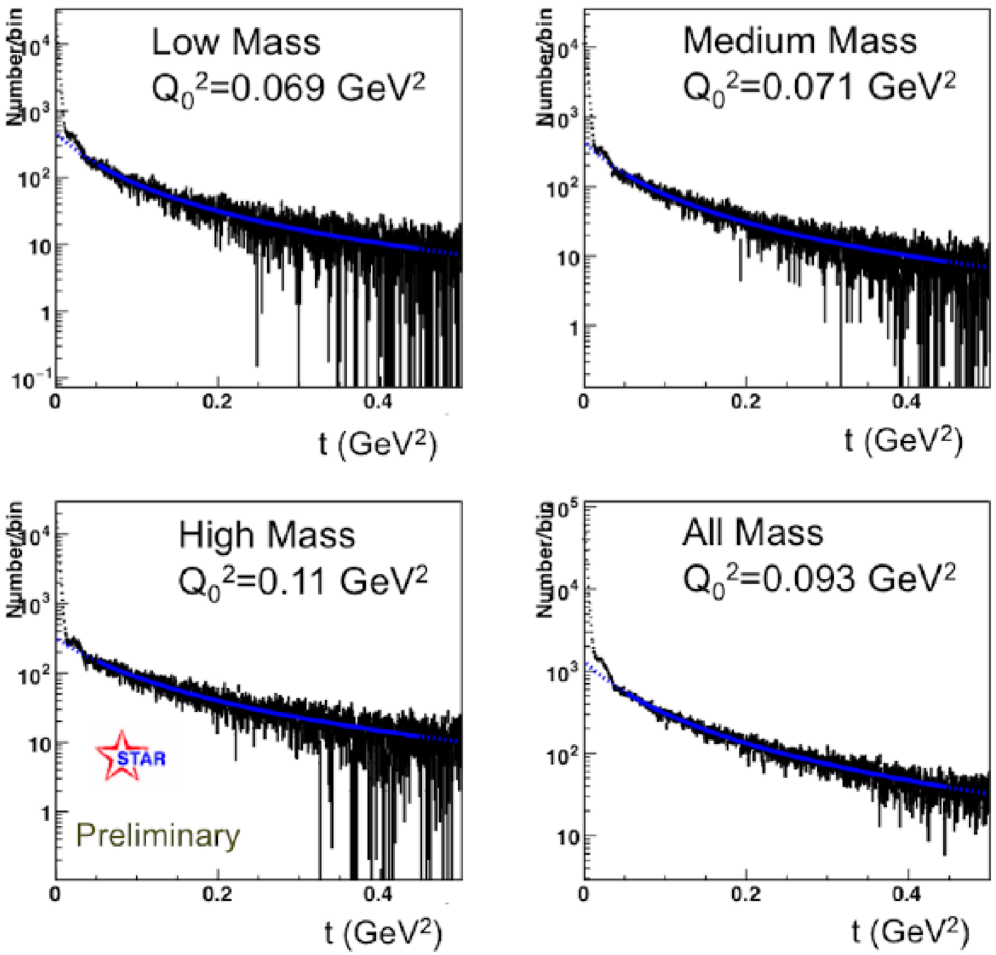


After subtraction of like-sign background
Fit with dipole form factor

$$\frac{dN}{dt} = \frac{A/Q_0^2}{(1+t/Q_0^2)^2}$$

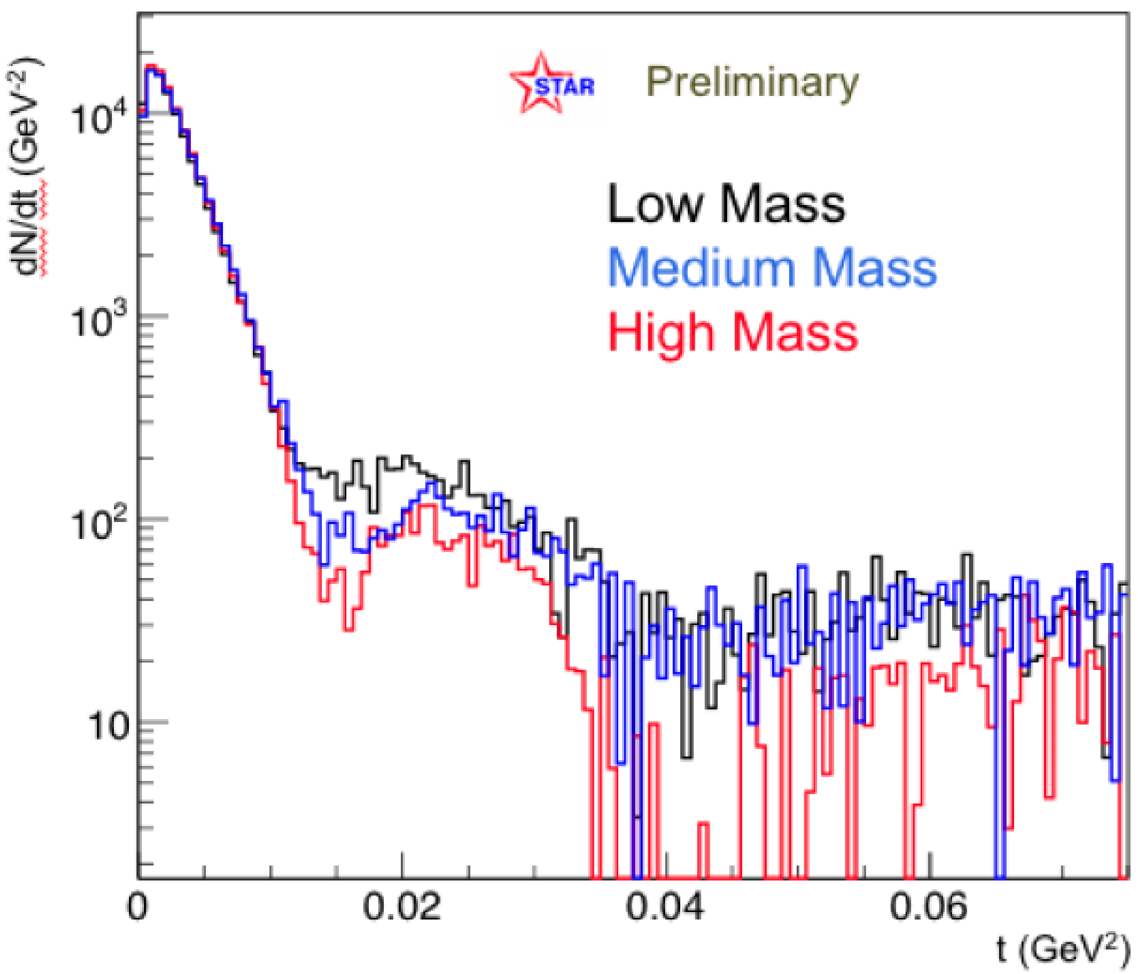


PoS(DIS2018)047

dσ/dt for Coherent ρ mesons

- After subtraction of incoherent contribution
- Normalized to same number of events/$M_{\pi\pi}$ bin
- Depth of diffractive dip varies with mass

$Au + Au \rightarrow \rho + Au + Au + XnXn,\ \sqrt{s_{NN}}$=200 GeV



PoS(DIS2018)047

Transform to F(b)

$$F(b) \propto \frac{1}{2\pi} \int_0^{\sqrt{t_{\max}}} dp_T p_T J_0(bp_T) \sqrt{\frac{d\sigma_c}{dt}}$$

- Use t_{max} = 0.006 GeV^2 for baseline
  - Below first dip
  - Vary as systematic

- Effects of shadowing would be to broaden the distribution
  - In the black disk limit, F(b) would be constant
  - Expect lower-mass to be broader, flatter

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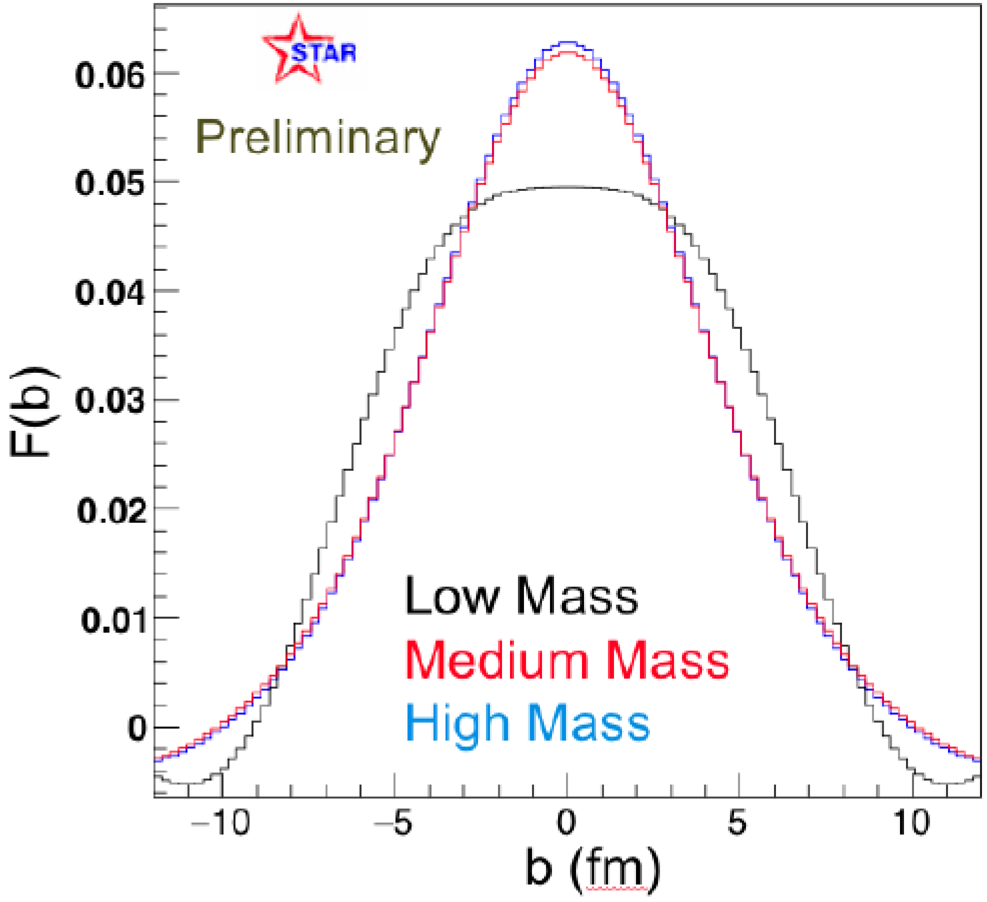

PoS(DIS2018)047

Windowing effect from choosing t_{max}

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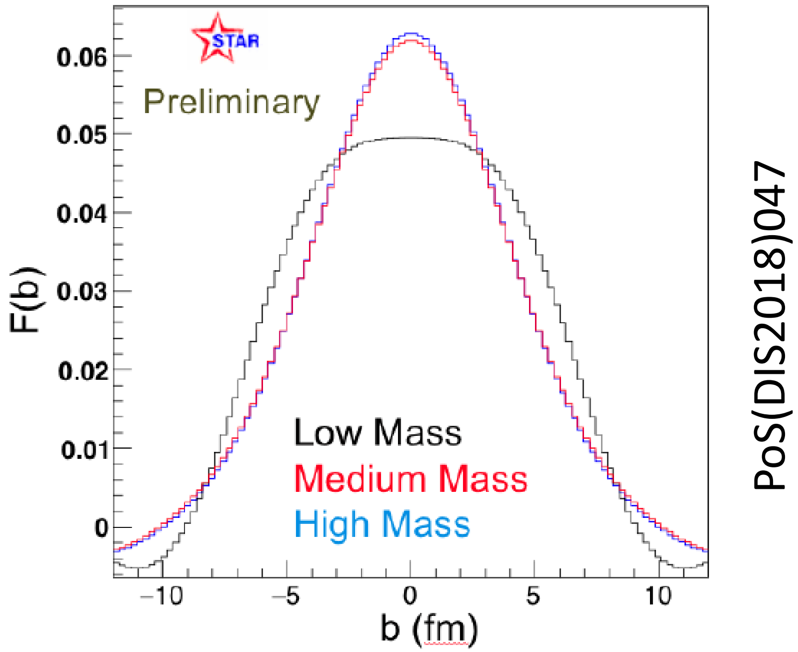
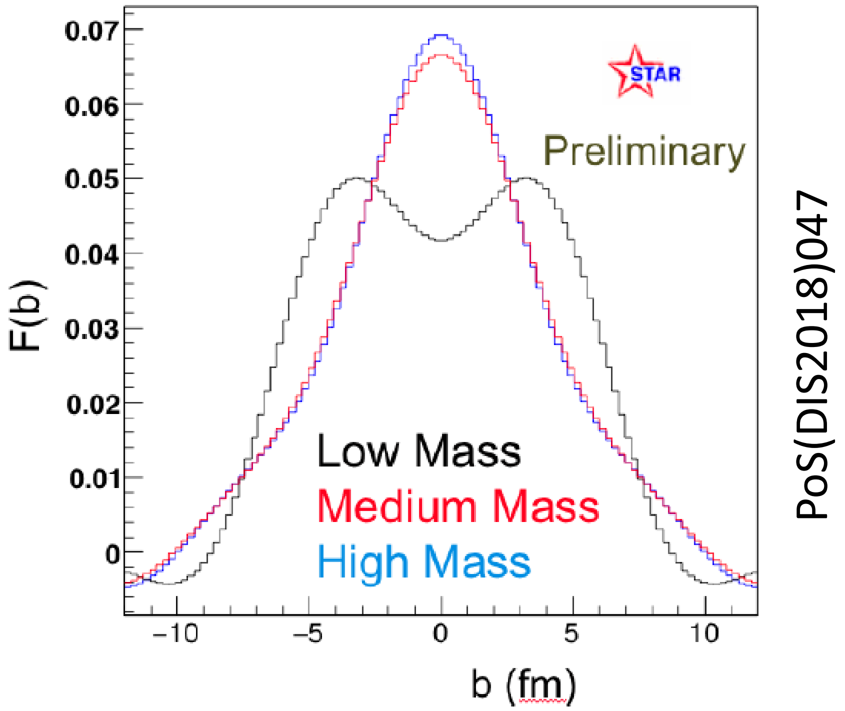
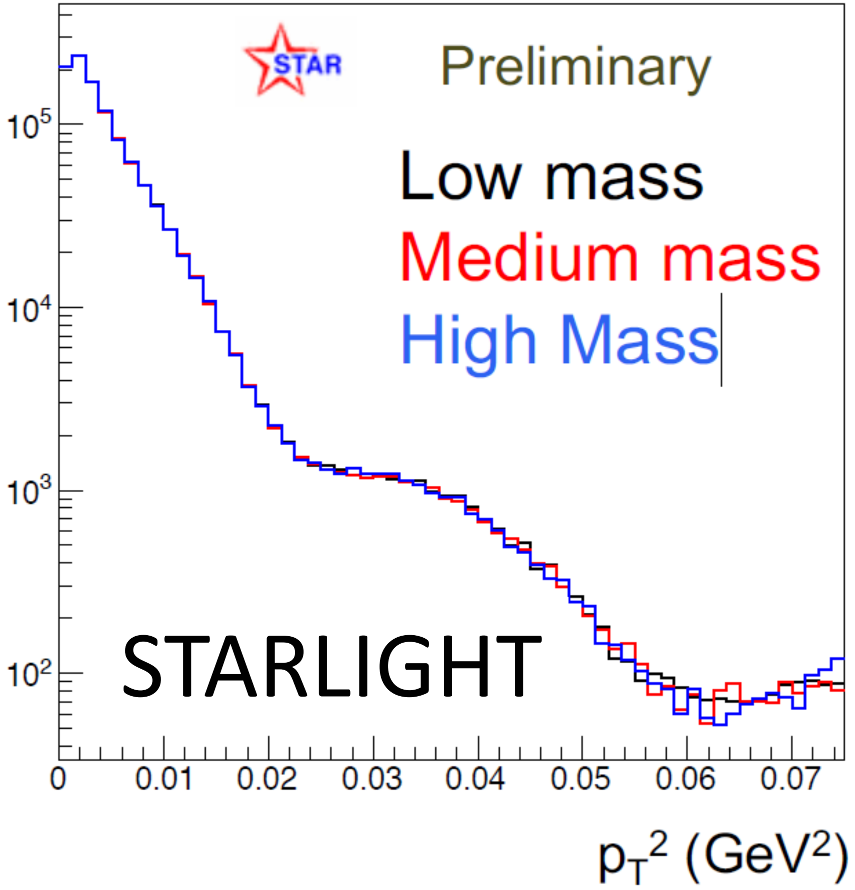




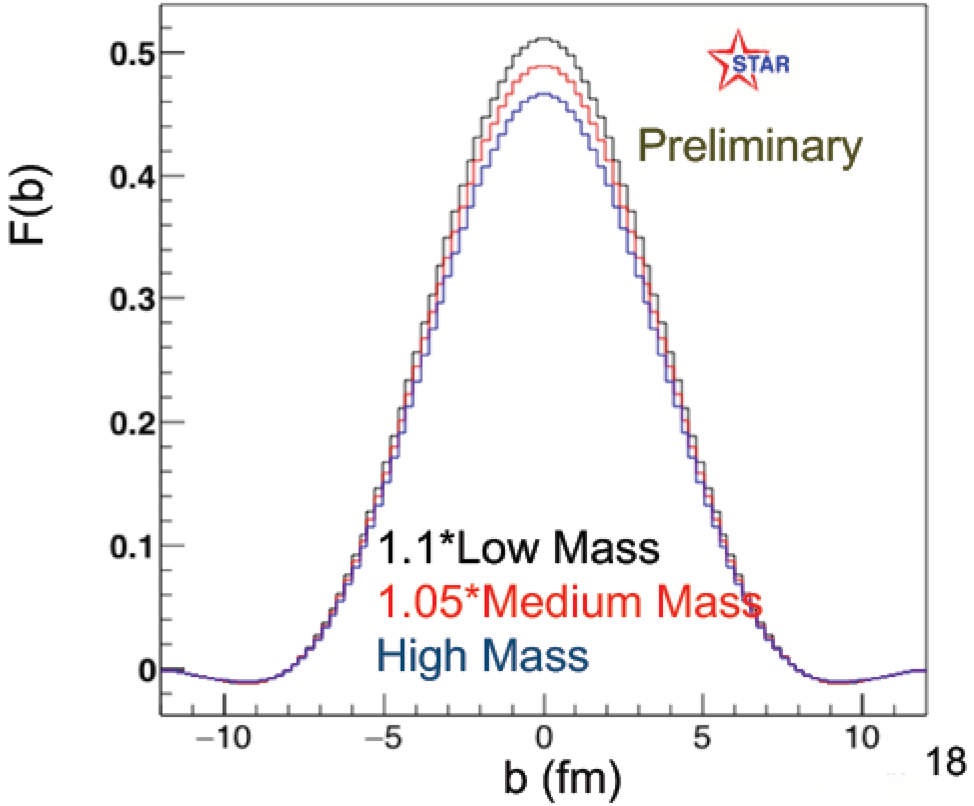
- Choice of t_{max} affects the shape, particularly at b = 0 fm
- Does not change the general trend that lower-mass → wider distribution

STARLIGHT, for comparison

- No shadowing effects included



STARLIGHT variation with $M_{\pi\pi}$



Conclusions

- STAR has a high statistics sample of coherently produced ρ mesons
  - Allows clear observation of diffractive dips
  - Shape of $d\sigma/dt$ sensitive to distribution of interaction sites
  - $M_{\pi\pi}$ serves as a proxy for dipole size
  - Pilot study shows shape difference with mass (dipole size)
    - Systematic effects due to choice of t_{max}
- Diffractive structure also seen in lower-statistics sample of coherently produced J/ψ
  - Location of diffractive dip in $d\sigma/dt$ consistent with dipole models
  - Slope of $d\sigma/dt$ at low t reproduced by Glauber model