Diffraction @ RHIC: pp & pA

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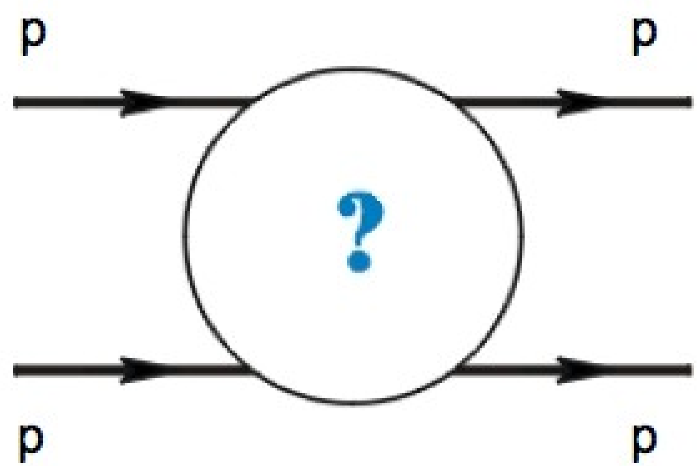
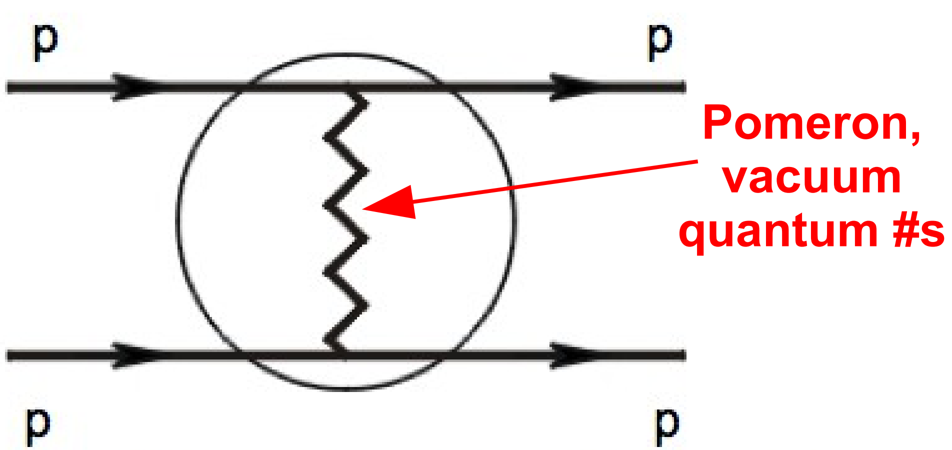
Riken BNL Workshop
Feb. 8-10, 2016 @ BNL

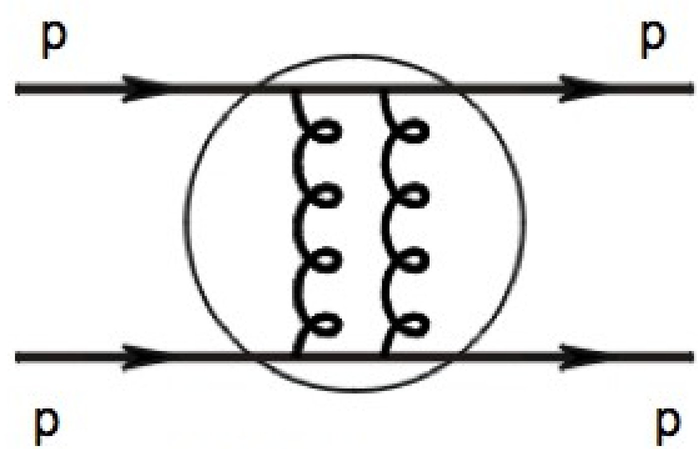
- Diffraction: scattering with colorless exchange, processes
- Experimental signatures: rapidity gap, proton detection
- Experimental capabilities: Roman Pots
- One RHIC diffraction result (among very few!):
  pp single diffraction, particle/antiparticle ratios
- New/future data
- Coming measurement:
  forward π^0 asymmetries in diffraction
- Future measurement:
  Ultra peripheral J/ψ production on $p\uparrow$, asymmetry $\propto E_g$
- Outlook

Scattering w/ colorless exchange



In t-channel it is an exchange with quantum numbers of vacuum





Non Pert. QCD – small mom. transf.

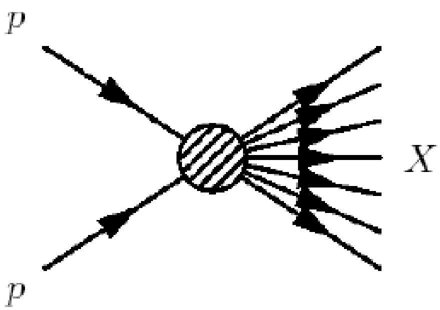
pQCD picture

Domain of Regge theory, where scattering amplitudes are parametrised as function of (s,t)

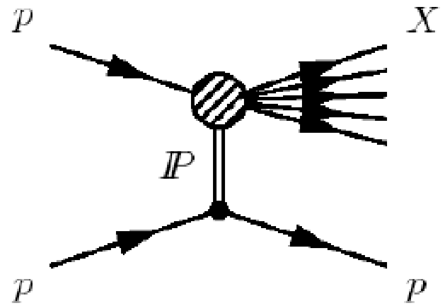
Domain of QCD Lagrangian, from which scattering amplitudes are calculated

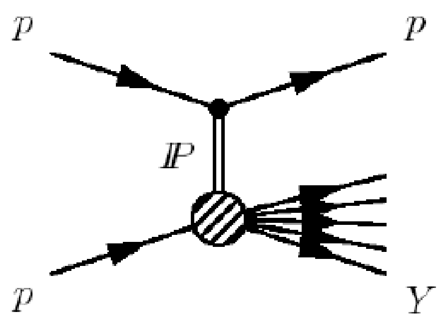
Processes

Colorless exchange represented as Pomeron IP

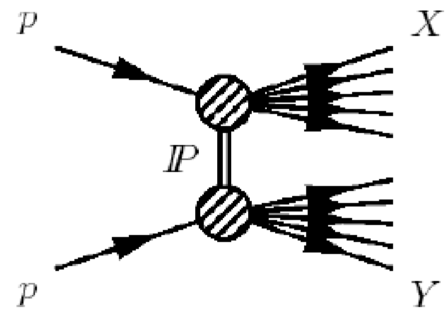


- Non-diffractive, hard central scattering

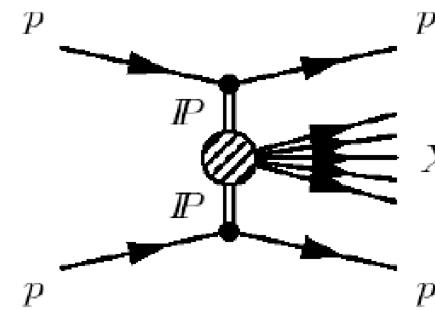




- Single Diff. Dissociation (SDD), one proton breaks up



- Double Dissociation (DD) diffraction, both protons break up

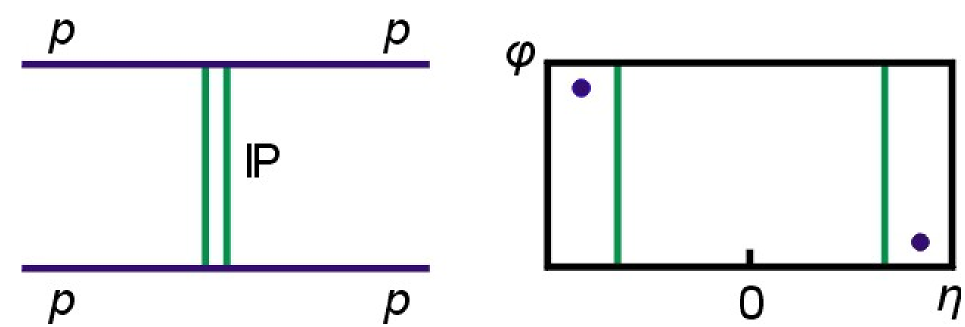


- Central Exclusive Production (CEP), double Pomeron exchange IPIP → X, both protons intact

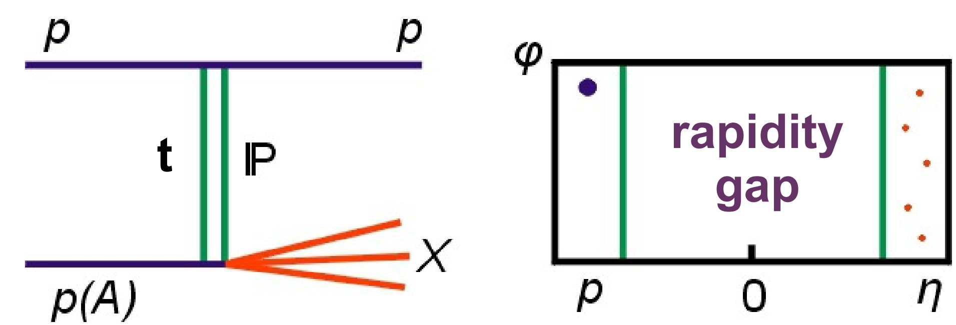
- Not shown: elastic scattering pp → pp both protons intact, full beam energy

Experimental signatures

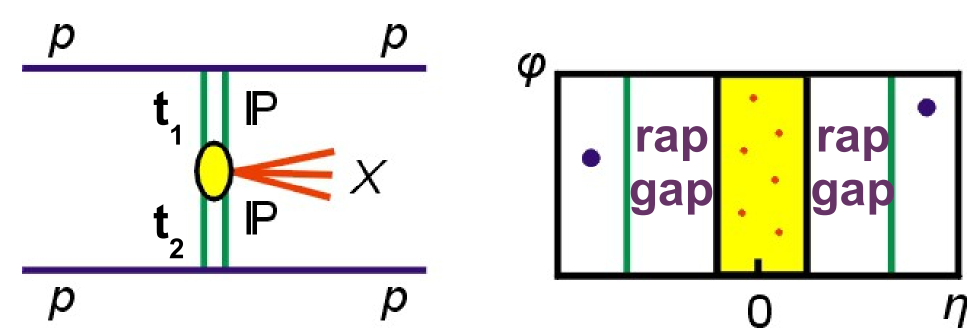
- Elastic: 2 forward protons ~E_{beam}



- SDD: 1 forward proton ~E_{beam}
  central activity, rapidity gap



- CEP: 2 forward protons ~E_{beam}
  central activity, rapidity gaps



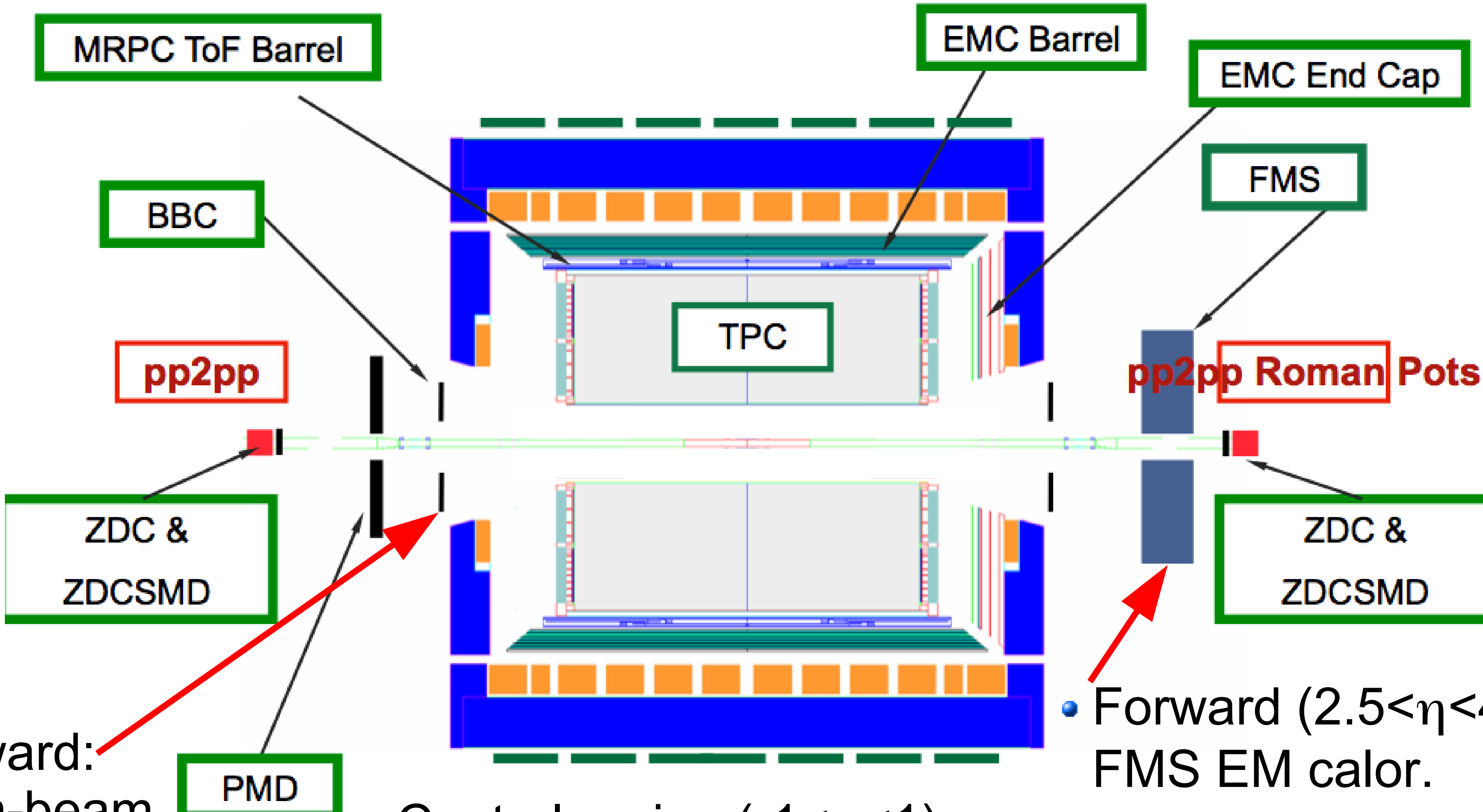
<u>Experimental requirements</u>

- detect forward rapidity gaps

- detect very forward protons,
measure momentum transfer ⇒ |t| of exchanged Pomeron(s)

Experimental measurements

e.g. STAR @ RHIC:

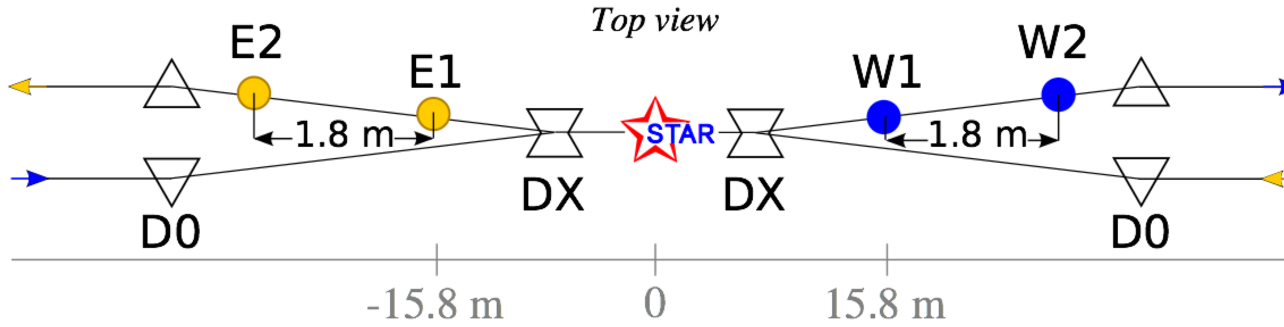


- Forward: beam-beam counter (BBC) veto activity
  $\Rightarrow$ rapidity gap
- Central region ($-1<\eta<1$): tracking, PID with TPC, TOF EM calorimetry
- Forward ($2.5<\eta<4$): FMS EM calor. (Forward Meson Spectrometer)
- Very forward: Roman Pots (RP)

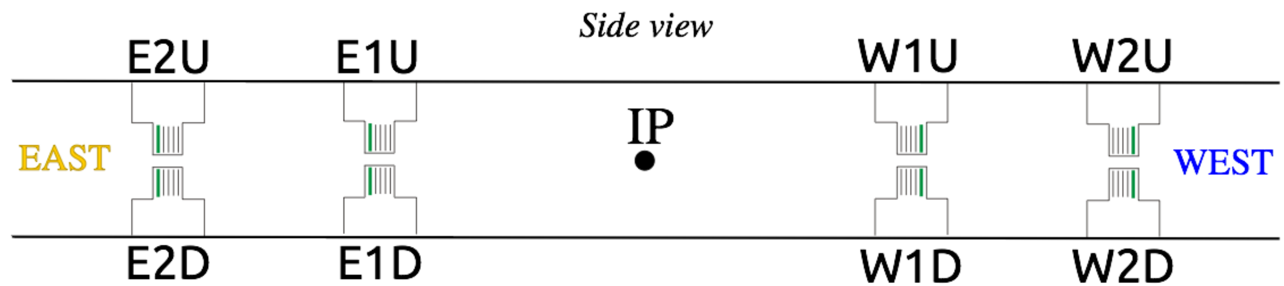
Roman Pots (@ STAR)

<u>2015 setup</u>

- Silicon strip detectors, x&y strips,~17m from IP

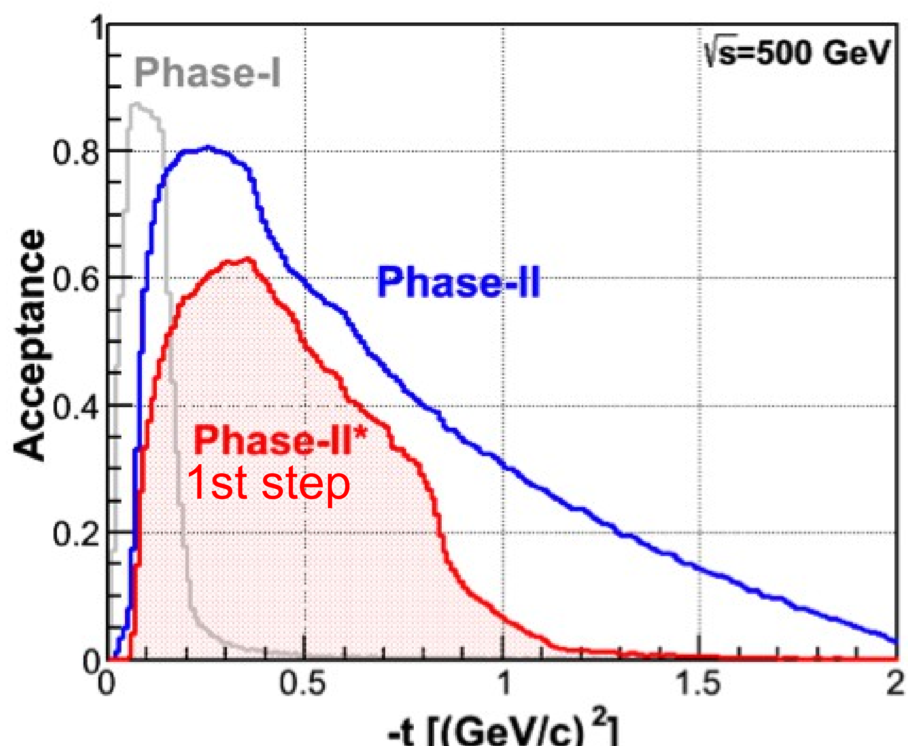


- Approach above/below beam to ~20mm ~50% azimuth acceptance



<u>Setup has evolved</u>

- 2009 Phase-I: detectors farther from IP, lower |t|
- 2015 Phase-II*: detectors closer, larger |t| range, increased acceptance
- 20?? Phase-II: increased acceptance



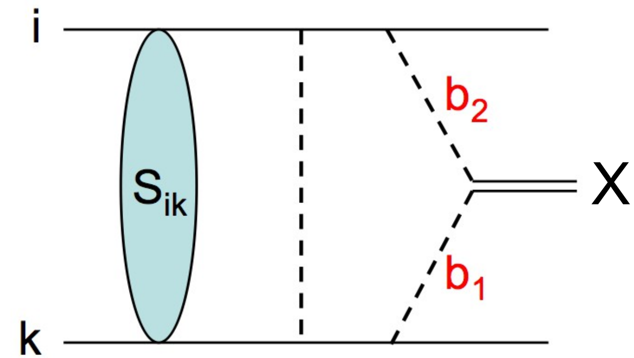
acceptance
@ s=√200 GeV
scale $(100/250)^2$

Diffractive tagging

<u>Rapidity gaps:</u>

- Detectors (BBC) relatively simple, have been in place many years
- But gaps can smear out, diffractive/non-diffractive ambiguity
- Serious: multiple Pomeron exchanges can destroy gaps, large corrections

e.g. M.G. Ryskin, A.D. Martin and V.A. Khoze, Eur. Phys. J. C60 (2009) 265



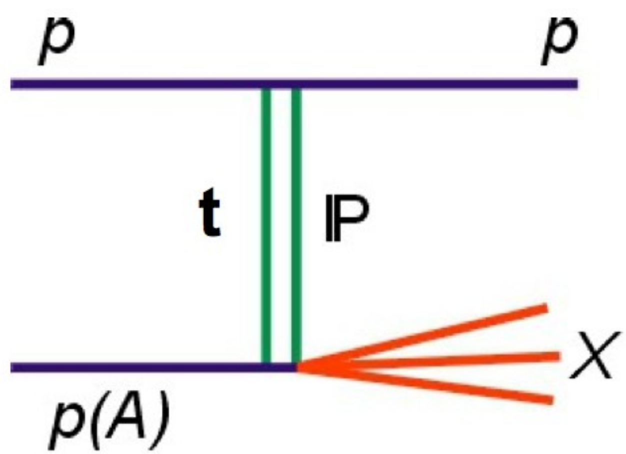
<u>Roman Pots</u>

- Detectors complex to build & operate, large resources, human & $$$
- Worth the effort: gold standard of diffractive tagging
- Unambiguous tagging of: elastic pp→pp (only way to measure)
  Single Diffractive pp→pX
  Central Exclusive Production pp→pXp

<u>STAR has invested in RP system</u>

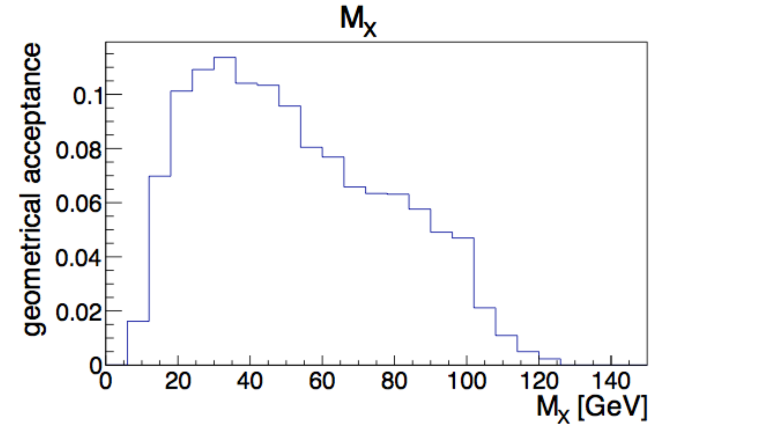
- First a quick look at some 2009 RP results

SDD in pp √s=200GeV

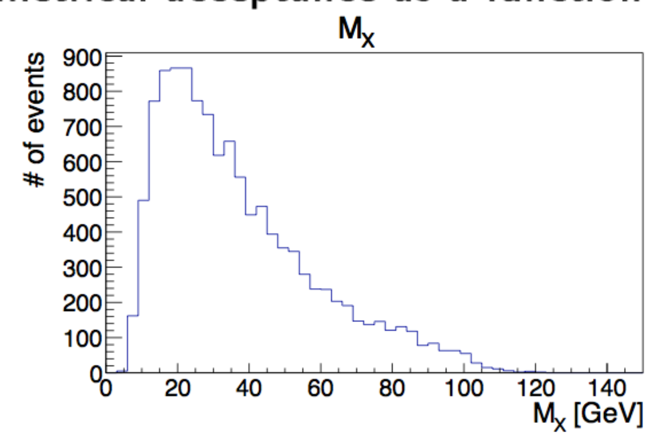


Select events:
- One proton in RP one side
- No BBC hit proton on side (gap)
- BBC hit on opposite side
- X: ≥ 2 tracks in TPC

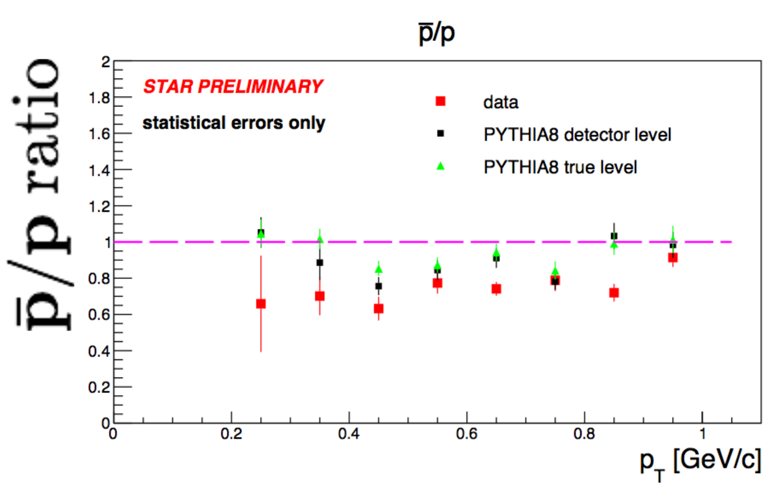
Measurements:
- Mass of system X $15<M_X<110$ GeV
- $\overline{p}$ / p ratio:
  - slight rise with track p_T
  - mean ~0.8 similar to PYTHIA8



Geometrical acceptance as a function of M_X



Mass of the diffractive system X



More data

That was just a small example;
other results 2009 data, pp 100×100 GeV

- Elastic pp→pp Single/Double Spin Asymmetries
- CEP mass spectra: $\pi^+\pi^2$, K^+K^-, $\overline{p}p$, …

Since then STAR has more RP data, 2015:

- pp 100×100 GeV
- pAu 100×100 GeV/nucleon
- pAl 100×100 GeV/nucleon

Analyses just beginning...

And more near/long term future:

- 2017 - pp 250×250 GeV
- 202? - pp, pAu...???

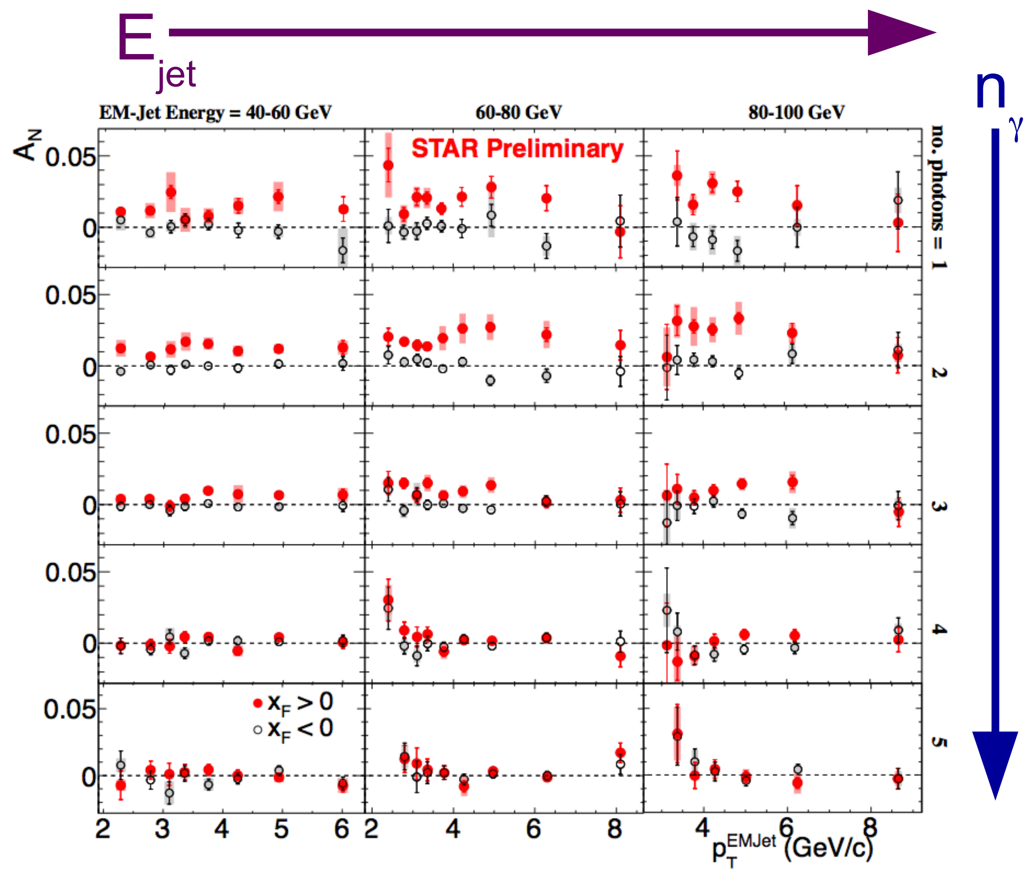
And most important:

- <u>RHIC protons are polarized</u>, transverse or longitudinal
- Numerous diffraction↔spin questions, to date unexplored
- A couple of topics

Forward π^0 asymmetries

- Inclusive events (no diff. tag): forward ($2.5<\eta<4$) FMS EM calor. STAR sees significant transverse asymmetry A_N

- Largest for n_γ=1,2: single π^0's
- Decreases w/ increasing n_γ ("jettiness")
- A_N flat vs. p_T, all n_γ & E_{jet}



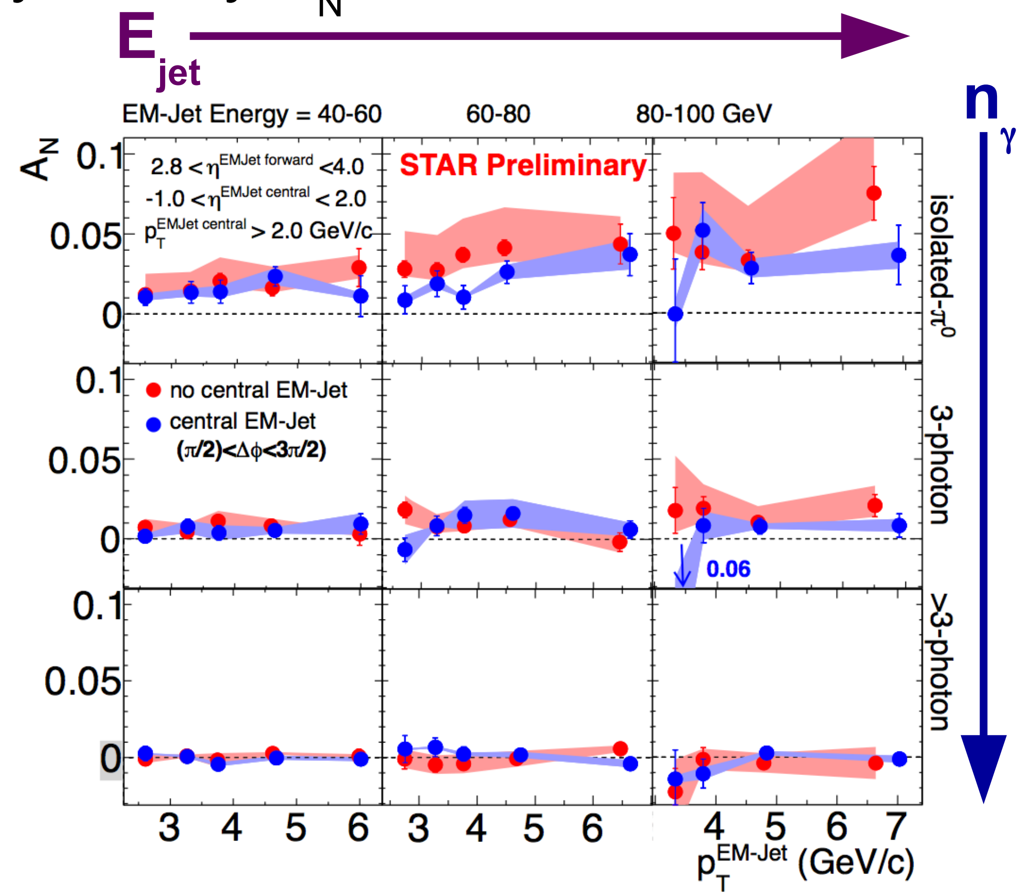
<u>For QCD 2→2 processes expect:</u>

- $A_N \propto 1/p_T$
- π^0 has equal *u,d* quark content
  Gamberg *et al.*: *u,d* quarks opposite asymmetries, should ~cancel

- Observations inconsistent w/ A_N from QCD 2→2 processes
- Transverse asymmetries may be of diffractive nature
- Investigate @ RHIC w/ diffraction tagging

Forward π^0 asymmetries

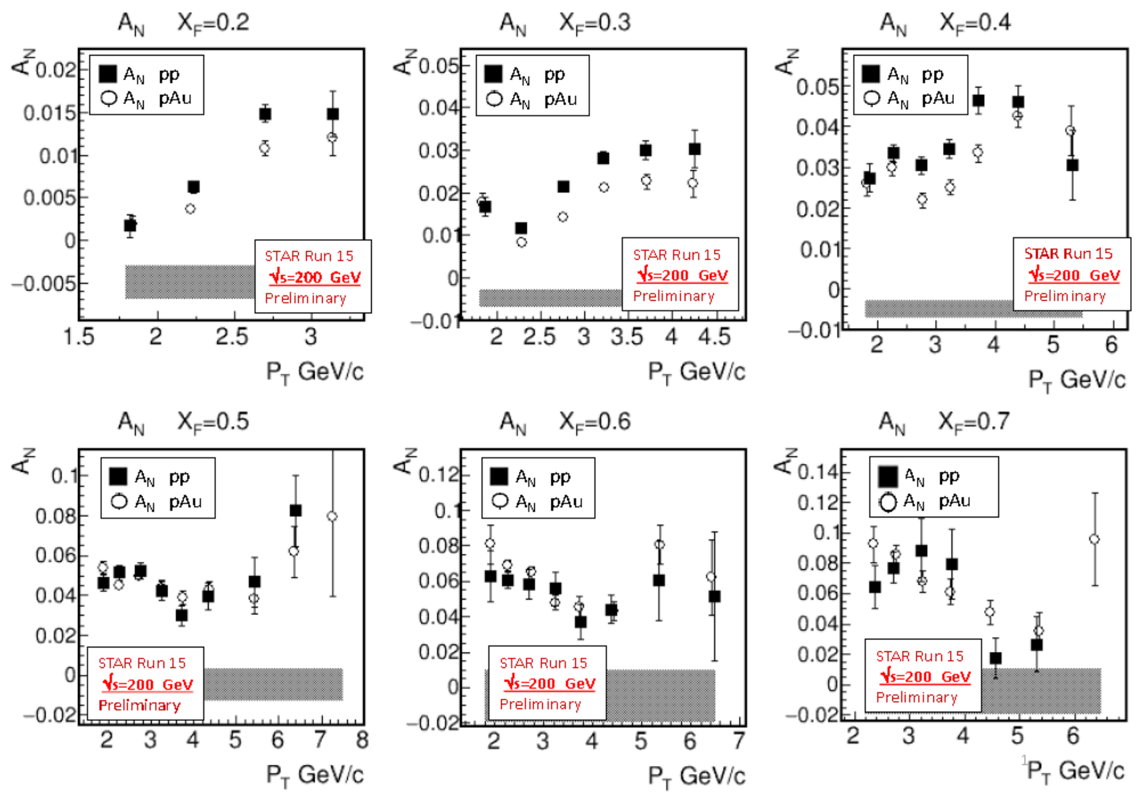
- Inclusive events (no diff. tag): forward ($2.5<\eta<4$) FMS EM calor. STAR sees significant transverse asymmetry A_N
- Largest for $n_\gamma=1,2$: single π^0's



- All inclusive events (red points)
- Additionally require a jet in central region $-1<\eta<2$ and opposite side $\pi/2<\Delta\phi<3\pi/2$
  $\Rightarrow$ **dijets** (blue points)
- Large A_N for small n_γ (π^0's) decreases w/ dijet requirement
- Dijets strongly select $2\rightarrow2$ processes
- Observations inconsistent w/ A_N from QCD $2\rightarrow2$ processes
- Transverse asymmetries may be of diffractive nature
- Investigate @ RHIC w/ diffraction tagging

Forward π^0 asymmetries

- Inclusive events (no diff. tag): forward ($2.5<\eta<4$) FMS EM calor.
- π^0 asymmetries in pp, pAu:
- Almost no change in A_N between p (solid squares) and Au (open circles):

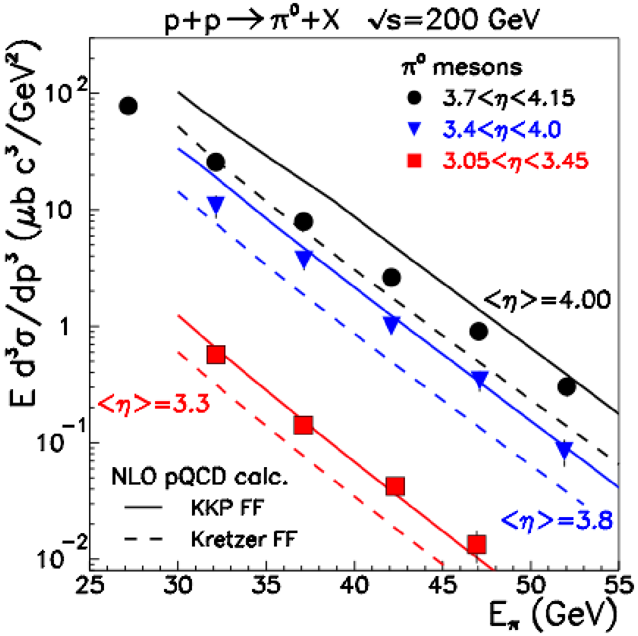


- Color Glass Condensate approach:
  - based on 2→2
  - expect A_N decrease going from p to Au
- Observations inconsistent w/ A_N from QCD 2→2 processes
- Transverse asymmetries may be of diffractive nature
- Investigate @ RHIC w/ diffraction tagging

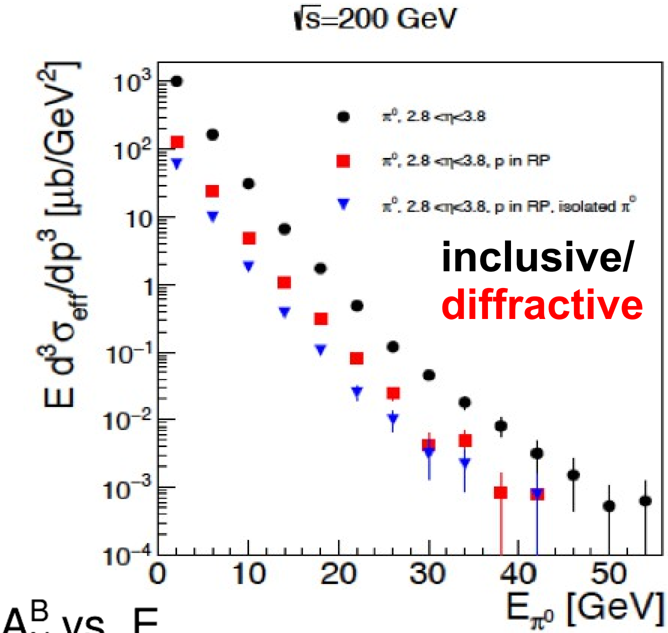
Forward π^0 asymmetries

<u>Can check soon in 2015 data w/ RP tag</u>

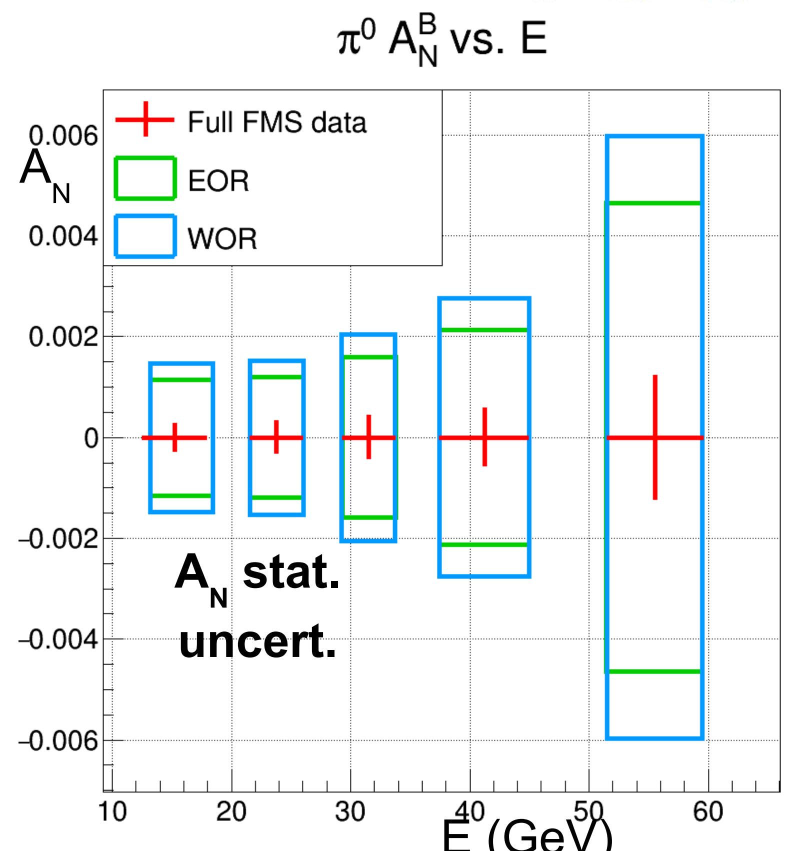
- Pythia-8 reproduces measured π^0 inclusive:



- Pythia-8 predicts $\sigma_{diff} \sim 20\% \; \sigma_{inclusive}$:



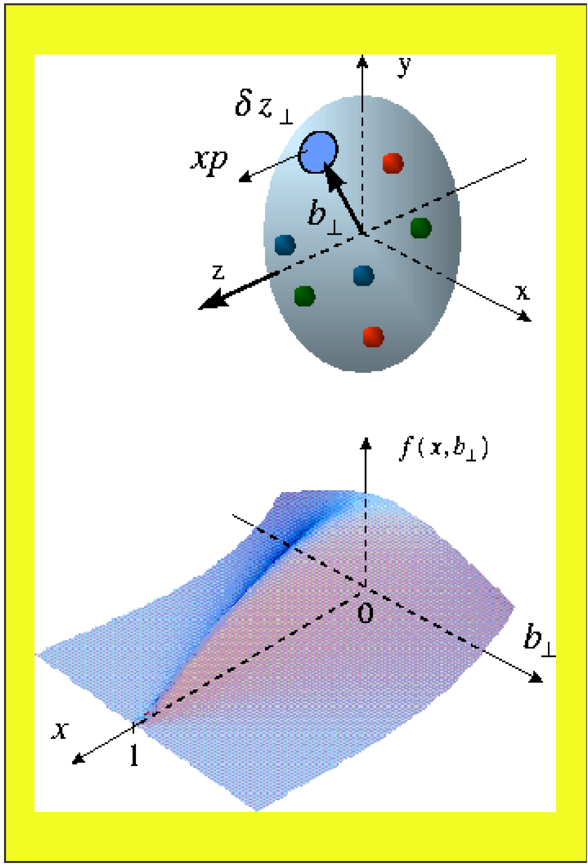
- A_N ~3-5% in this kinematic region
- Expected A_N stat. uncert. <1%
- **Should have clear answer to this question soon...**



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 characterized, for each *q*,*g*:

	unpolarized	polarized
conserve nucleon helicity →	$H^q(x,\xi,t)$	$\tilde{H}^q(x,\xi,t)$
flip nucleon helicity →	$E^q(x,\xi,t)$	$\tilde{E}^q(x,\xi,t)$



- Spin Sum Rule: $$\frac{1}{2} = J_q^z + J_g^z = \frac{1}{2}\Delta\Sigma + \sum_q \mathcal{L}_q^z + J_g^z$$

$$J_{q,g}^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx\left(H^{q,g} + E^{q,g}\right)\right)_{t\to 0}$$

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

Generalized Parton Distributions

Quantum #s final state → select different GPDs

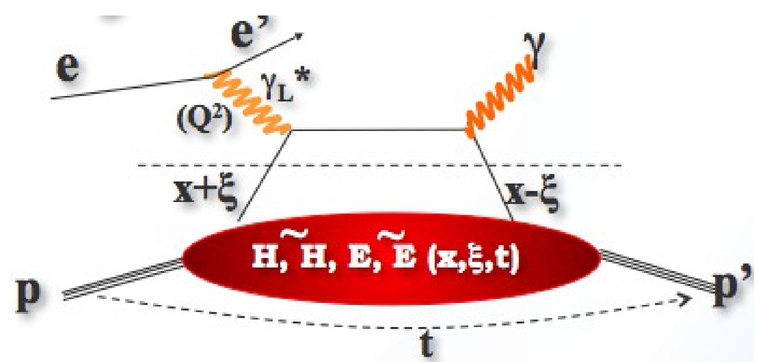
- DVCS ep → epγ: H^q E^q $\tilde{H}^q$ $\tilde{E}^q$
- Pseudo-scalar mesons: $\tilde{H}^q, \tilde{E}^q$

  π: 2Δu+Δd η: 2Δu-Δd
- Vector mesons: H^q, E^q

  ρ^0: 2u+d, 9g/4 ω: 2u-d, 3g/4 ϕ: s, g ρ^+: u-d ψ: g

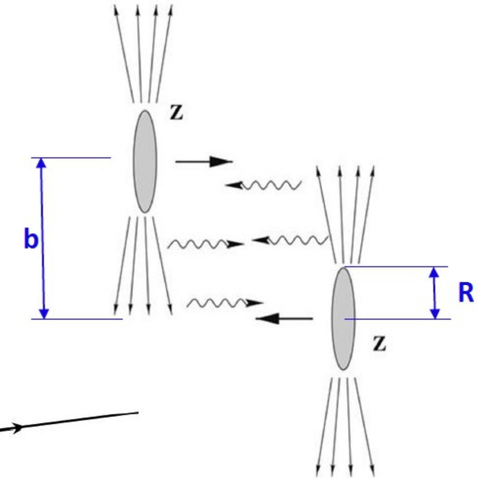
- Measure GPDs through exclusive reactions

- Golden Channel: DVCS ep → epγ
  access to all GPDs
  all kinematics measured

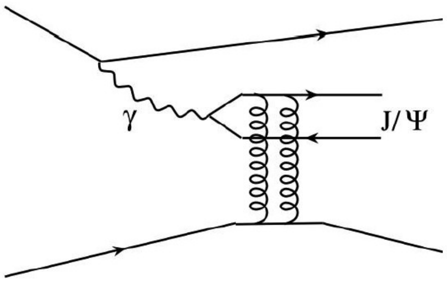


- We don't have an Electron Ion Collider yet
- But we can explore at RHIC:
  - VM production in Ultra Peripheral Collisions (UPC)
  - with polarized protons

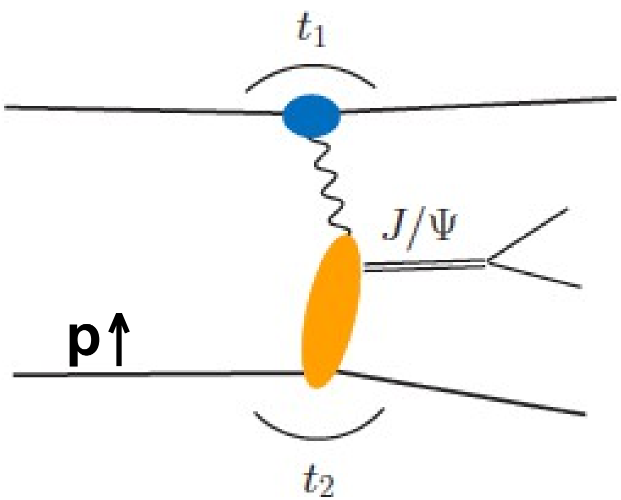
Ultra Peripheral Collisions



- UPC: b > 2R, hadronic interactions suppressed
- Large flux of Weizsaecker-Williams photons
- WW photon from one beam particle
  → photoproduction on other beam particle
  e.g. J/ψ production:



- Target particle polarized proton p↑:
  - measure J/ψ transverse asymmetry A_{UT}
  (Unpolarized beam γ, Transverse polarized target p↑)

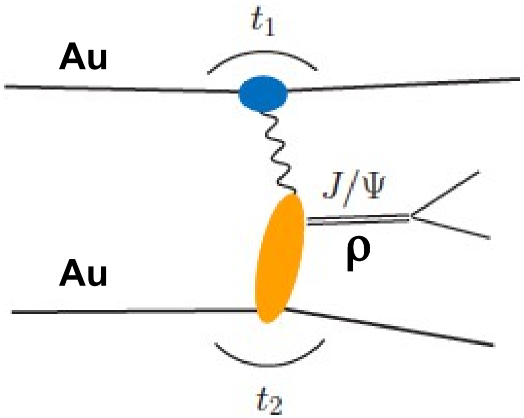


- A_{UT} calculable with GPDs:

$$A_{UT}(\Pi, t) \sim \frac{\sqrt{t_0 \, 2 \, t}}{m_p} \frac{\mathrm{Im}(E / \; H)}{|H|} \qquad t = \frac{M^2_{J/-}}{s}$$

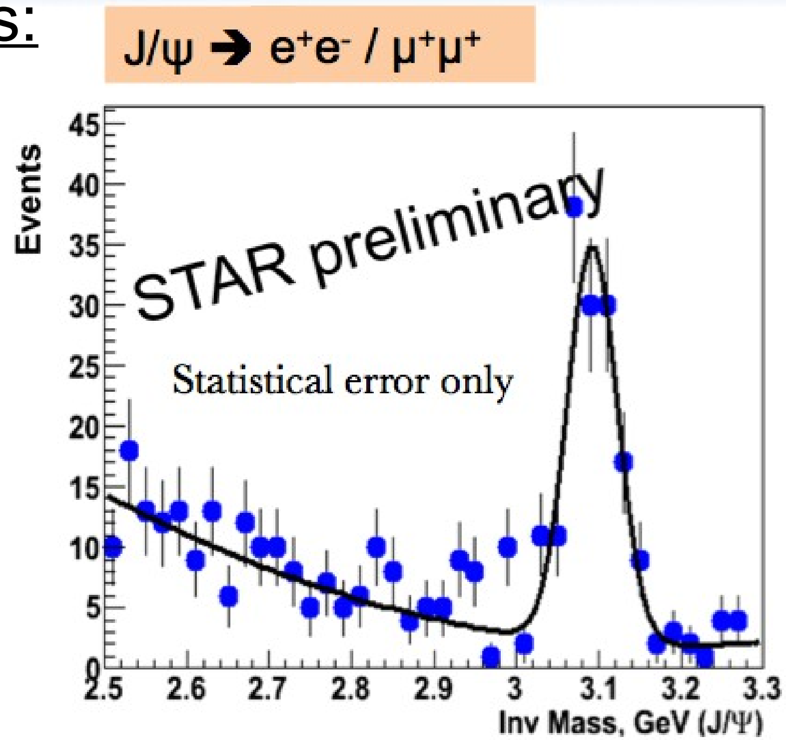
$A_{UT} \propto E_g \Rightarrow$ sensitive to gluon orbital angular momentum L_g

J/ψ in AuAu UPC

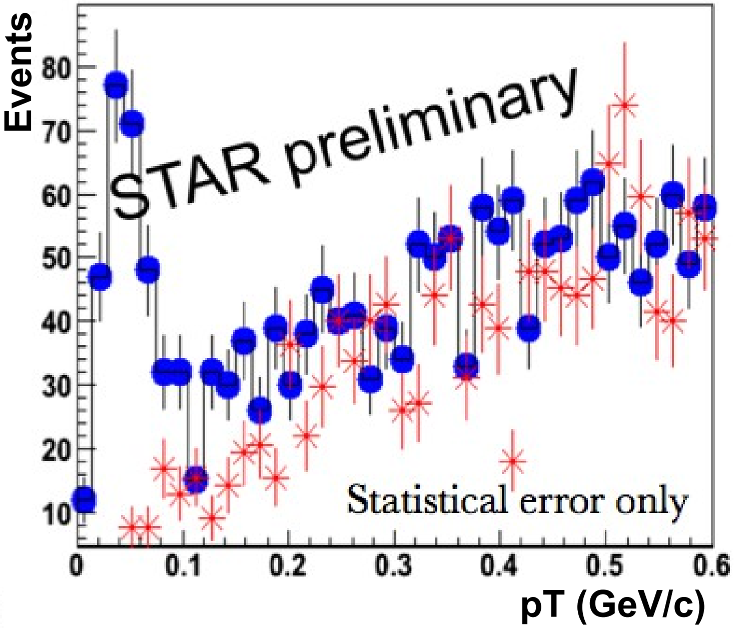


- STAR already has an AuAu UPC program:
  VM photoproduction: $\rho \rightarrow \pi^+\pi^-$, $J/\psi \rightarrow e^+e^-/\mu^+\mu^-$
- Triggered:
  - $\geq$2 hits in TOF system (decay daughters)
  - 1 neutron each Zero Degree Calorimeter (ensure good beam ×ing) (neutrons from Au photo-disintegration)
  - no BBC activity (ensure diffractive, non-central AuAu)

<u>Run 10 ~100 J/ψ's:</u>



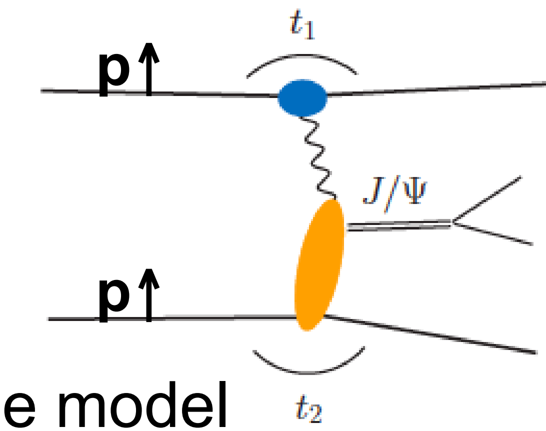
<u>At low pT<100 MeV/c:</u>



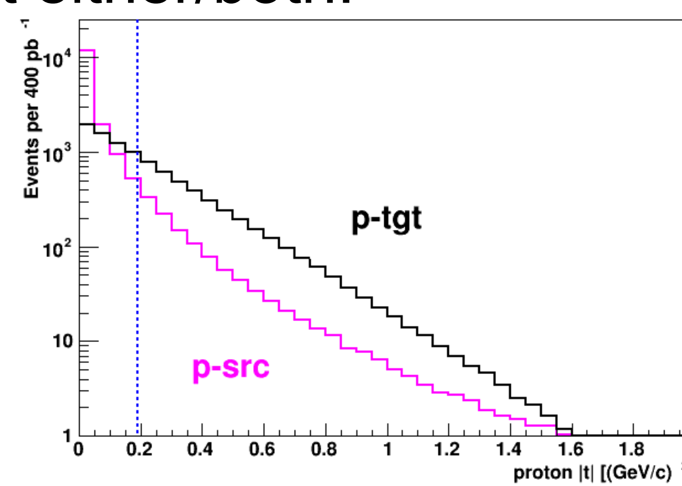
- STAR demonstrated measurement of UPC J/ψ's

J/ψ in p↑p↑ UPC

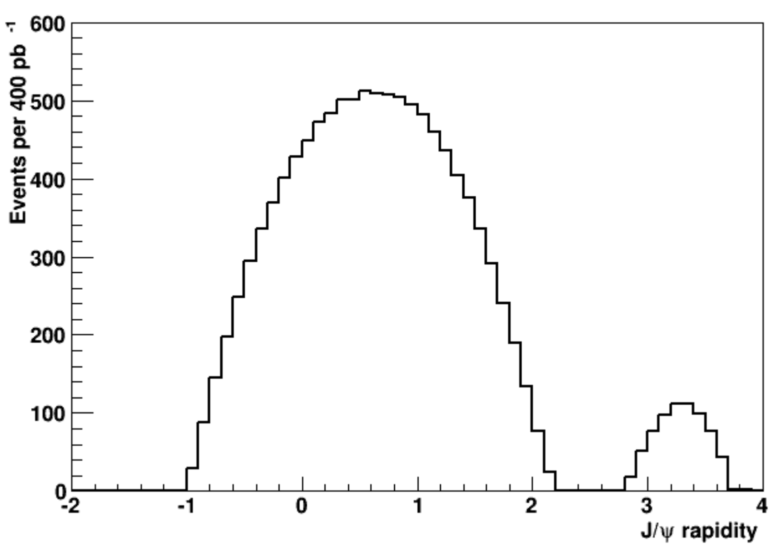
- Planned: √s=500 GeV p↑p↑ (transverse polar.) Run17 L~400 pb^{-1}
- Trigger on:
  - 2 EM showers STAR calorimeters (J/ψ→e$^+$e$^-$)
  - Hit in either Roman Pot
  - no BBC activity (ensure diffractive)



- Events rates estimated w/ Sartre:
  - VM production & DVCS based on bSat color dipole model
  - designed for ep, eA; extended w/ WW flux to pp, pA
- RP measures 0.19<|t|<1.9 (GeV/c)^2; may detect either/both:
  - proton from source of photon (lower |t|)
  - proton from target of photon (higher |t|)



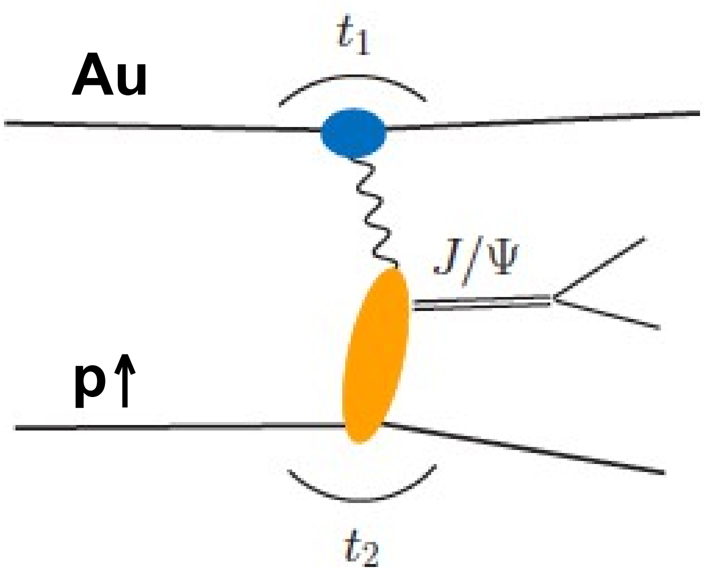
- J/ψ→e$^+$e$^-$ in central STAR EMC & FMS:

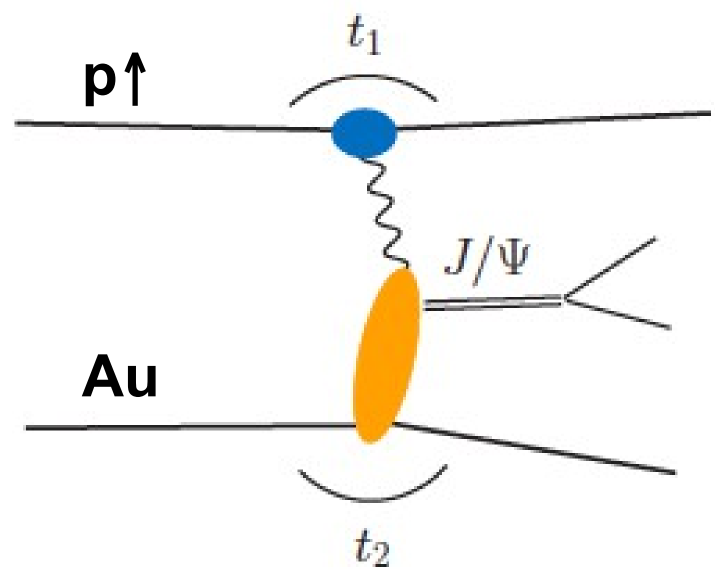


- Expect ~11k J/ψ's
- Good sample 1st look at $A_{UT} \propto E_g$

J/ψ in p↑Au UPC

- Considered: $\sqrt{s}$=200 GeV p↑Au Run 202? L~1.75 pb^{-1}
- Here 2 processes:



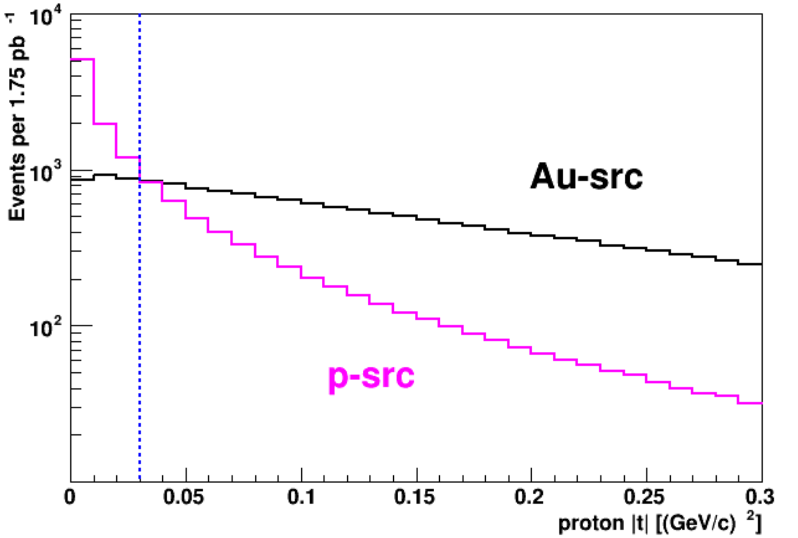


- Au photon source, p↑ target
- Boost in photon flux $\propto Z_{Au}^2$
- Polarized target:
  measure $A_{UT} \propto E_g$

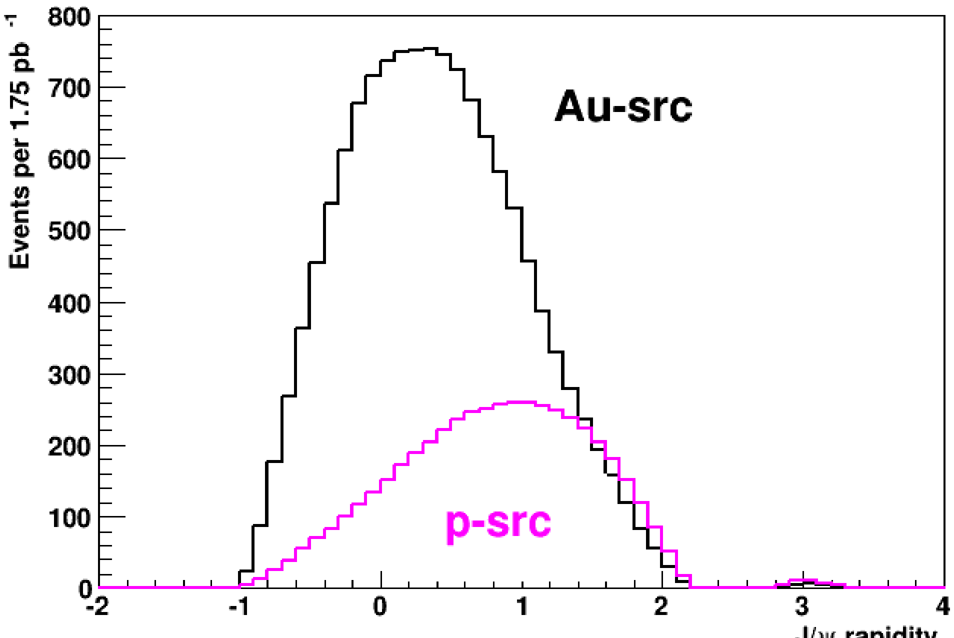
- p↑ photon source, Au target
- Boost in γA cross section $\propto A_{Au}^2$
  (coherent)
- Unpolarized target: no asymmetry

J/ψ in p↑Au UPC

- Trigger on:
  - 2 EM showers STAR calorimeters ($J/\psi \rightarrow e^+e^-$)
  - Hit in Roman Pot facing p↑ beam
  - no BBC activity (ensure diffractive)
- Events rates estimated w/ Sartre
- RP measures $0.03<|t|<0.3$ $(GeV/c)^2$; may detect either:
  - proton from source of photon, Au target suppressed, mostly below RP |t| range
  - proton from target of photon, Au source mostly in RP |t| range



- $J/\psi \rightarrow e^+e^-$ in central STAR EMC & FMS:



- Expect ~13k J/ψ's p↑-target background ~5k Au-target
- Adjust signal/ background: vary RP |t| , J/ψ rapidity
- Good sample for $A_{UT} \propto E_g$

note: RHIC P(100GeV)>P(250GeV)

Outlook

- That was just two soon or someday diffraction results
- More also underway, e.g. from 2015 data:
  - Central Exclusive Production $pp \rightarrow pXp$

    X low mass hadronic states, exotics?
  - Single Diffractive Dissociation (extending 2009 shown)
- And much more...

Until now:

- "Diffraction: A Neglected Child At RHIC" (E. Aschenauer)
- Powerful tool: Roman Pots

  $\Rightarrow$ nurture the child to full potential