Probing the Nucleus with Ultra-Peripheral Collisions

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Ultra-peripheral Collisions: What and Why

Photoproduction as a nuclear probe

STAR Results at 130 GeV/nucleon:

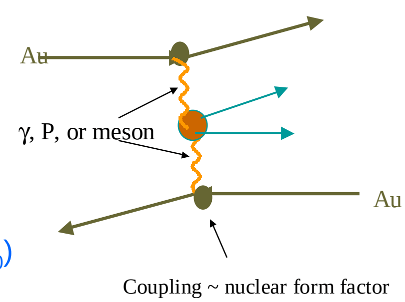
- Au + Au --> Au + Au + ρ^0
- ρ^0 production with nuclear excitation
- Direct $\pi^+\pi^-$ production & interference

A peek at 200 GeV/nucleon & beyond

Conclusions

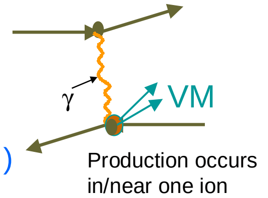
Coherent Interactions

- b > 2R$_{A;}$
  - no hadronic interactions
  - <b> ~ 25-50 fermi at RHIC
- Ions are sources of fields
  - photons
    - Z^2
  - Pomerons or mesons (mostly f_0)
    - A^2 (bulk) $A^{4/3}$ (surface)
  - Fields couple coherently to ions
    - Photon/Pomeron wavelength λ = h/p> R_A
    - amplitudes add with same phase
    - $P_\perp < h/R_A$, ~30 MeV/c for heavy ions
    - $P_{||} < \gamma h/R_A$ ~ 3 GeV/c at RHIC
- Strong couplings --> large cross sections

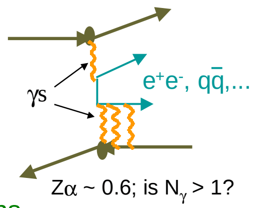


Specific Channels

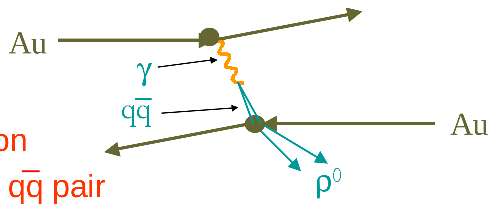
- Vector meson production
  - $\gamma A \rightarrow \rho^0, \omega, \phi, J/\psi, \ldots A$
  - Production cross sections --> $\sigma(VN)$
  - Vector meson spectroscopy ($\rho^*, \omega^*, \phi^*, \ldots$)
  - Wave function collapse



- Electromagnetic particle production
  - $\gamma\gamma \rightarrow$ leptons,mesons
  - Strong Field (nonperturbative?) QED
    - $Z\alpha \sim 0.6$
  - meson spectroscopy $\Gamma_{\gamma\gamma}$
    - $\Gamma_{\gamma\gamma}$ ~ charge content of scalar/tensor mesons
    - $\Gamma_{\gamma\gamma}$ is small for glueballs



Exclusive ρ^0 Production

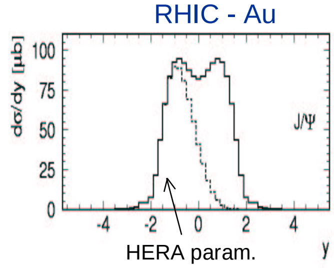


- One nucleus emits a photon
- The photon fluctuates to a $q\bar{q}$ pair
- The pair scatters elastically from the other nucleus
- $q\bar{q}$ pair emerges as a vector meson
- $\sigma(\rho)$ ~ 590 mb ~ 8 % of σ_{AuAu} at 200 GeV/nucleon
  - 120 Hz production rate at RHIC design luminosity
- $\rho, \omega, \phi, \rho^*$ rates at RHIC all > 5 Hz
- J/ψ , Ψ', ϕ^*, ω^*, copiously produced, Υ a challenge

Elastic Scattering with Soft Pomerons

- Glauber Calculation
  - parameterized HERA data
    - Pomeron + meson exchange
    - all nucleons are the same
  - $\sigma \sim A^2$ (weak scatter limit)
    - All nucleons participate
    - J/ψ
  - $\sigma \sim A^{4/3}$ (strong scatter limit)
    - Surface nucleons participate
    - Interior cancels (interferes) out
  - $\sigma \sim A^{5/3}$ (ρ^0)
- depends on σ(Vp)
  - sensitive to shadowing?

RHIC - Au



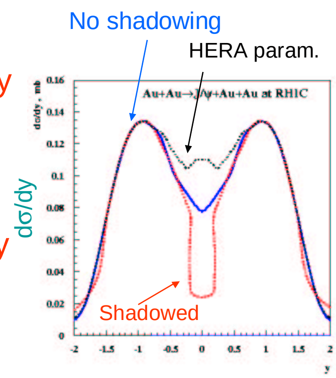
HERA data + Glauber
Klein & Nystrand, 1999

$Y = 1/2 \ln(2k/M_V)$

Elastic Scattering with Hard Pomerons

- Valid for $c\bar{c}$ or $b\bar{b}$
- dσ/dy & σ depend on gluon distributions
- shadowing reduces mid-rapidity dσ/dy
  - Effect grows with energy
  - σ reduced ~ 50% at the LHC
- colored glass condensates may have even bigger effect

RHIC - Au

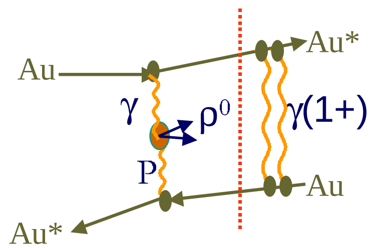


Leading Twist Calculation
Frankfurt, Strikman & Zhalov, 2001

$Y = 1/2 \ln(2k/M_V)$

Nuclear Excitation

- Nuclear excitation 'tag's small b
- Multiple photon exchange
  - Mutual excitation
- Au* decay via neutron emission
  - simple, unbiased trigger
- Multiple Interactions probable
  - P(ρ^0, b=2R) ~ 1% at RHIC
  - P(2EXC, b=2R) ~ 30%
- Non-factorizable diagrams are small for AA

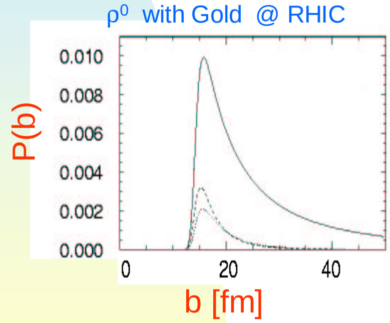


$$\sigma = \int d^2 b P_{2EXC}(b) P_{\rho^0}(b)$$

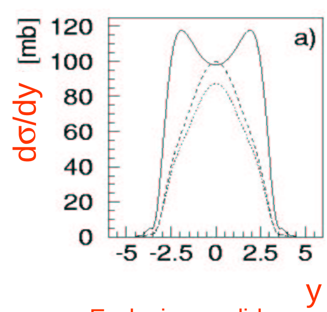
Interaction Probabilities & dσ/dy

- Excitation + ρ^0 changes b distribution
  - alters photon spectrum
    - low <b> --> high <k>

ρ^0 with Gold @ RHIC



ρ^0 with gold @ RHIC

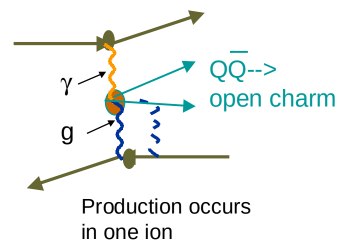


Exclusive - solid
X10 for XnXn - dashed
X100 for 1n1n - dotted

Baltz, Klein & Nystrand (2002)

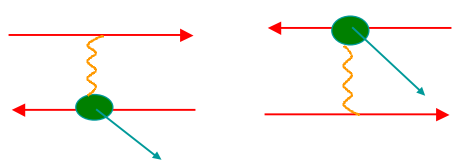
Photoproduction of Open Quarks

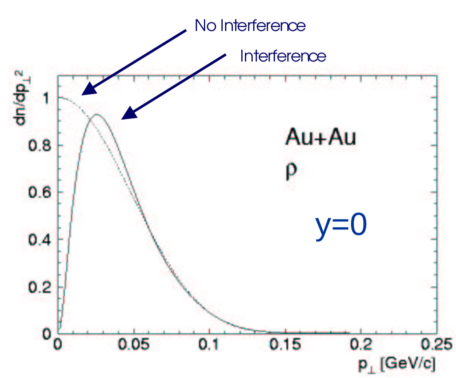
- $\gamma A \rightarrow c\bar{c}X, b\bar{b}X$
- sensitive to gluon structure function.
- Higher order corrections problematic
- Ratio $\sigma(\gamma A)/\sigma(\gamma p)$ --> shadowing
  - removes most QCD uncertainties
- Experimentally feasible (?)
  - high rates
  - known isolation techniques
- Physics backgrounds are gg--> $c\bar{c}$, $\gamma\gamma$ --> $c\bar{c}$
  - $\gamma\gamma$ cross section is small
  - gg background appears controllable by requiring a rapidity gap



Interference

- 2 indistinguishable possibilities
  - Interference!!
- Similar to pp bremsstrahlung
  - no dipole moment, so
  - no dipole radiation
- 2-source interferometer
  - separation b
- $\rho, \omega, \phi, J/\psi$ are $J^{PC} = 1^{--}$
- Amplitudes have opposite signs
- $\sigma \sim |A_1 - A_2 e^{ip\cdot b}|^2$
- b is unknown
  - For p_T << 1/<b>
    - destructive interference

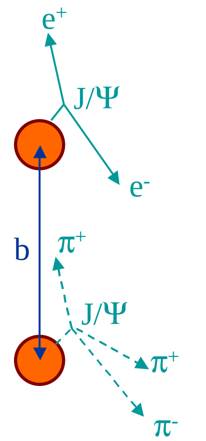




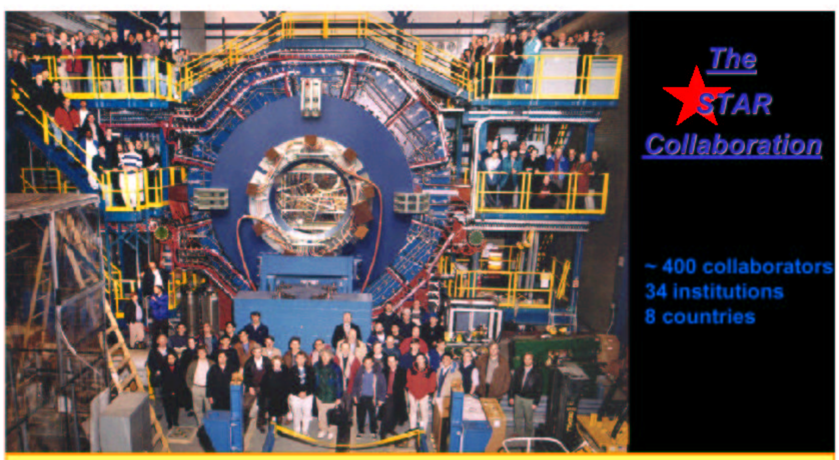
$\rho^0 \longrightarrow \pi^+\pi^-$ p_T (GeV/c)

Entangled Waveforms

- VM are short lived
  - decay before traveling distance b
- Decay points are separated in space-time
  - no interference
  - **OR**
  - the wave functions retain amplitudes for all possible decays, long after the decay occurs
- Non-local wave function
  - **non-factorizable**: $\Psi_{\pi+\pi-} \neq \Psi_{\pi+}\Psi_{\pi-}$
- Example of the Einstein-Podolsky-Rosen paradox



(transverse view)



Brazil: Sao Paolo
England: Birmingham
Germany: Frankfurt, MPI - Munich
China: IHEP - Beijing, IPP - Wuhan
France: IReS - Strasbourg, SUBATECH-Nantes
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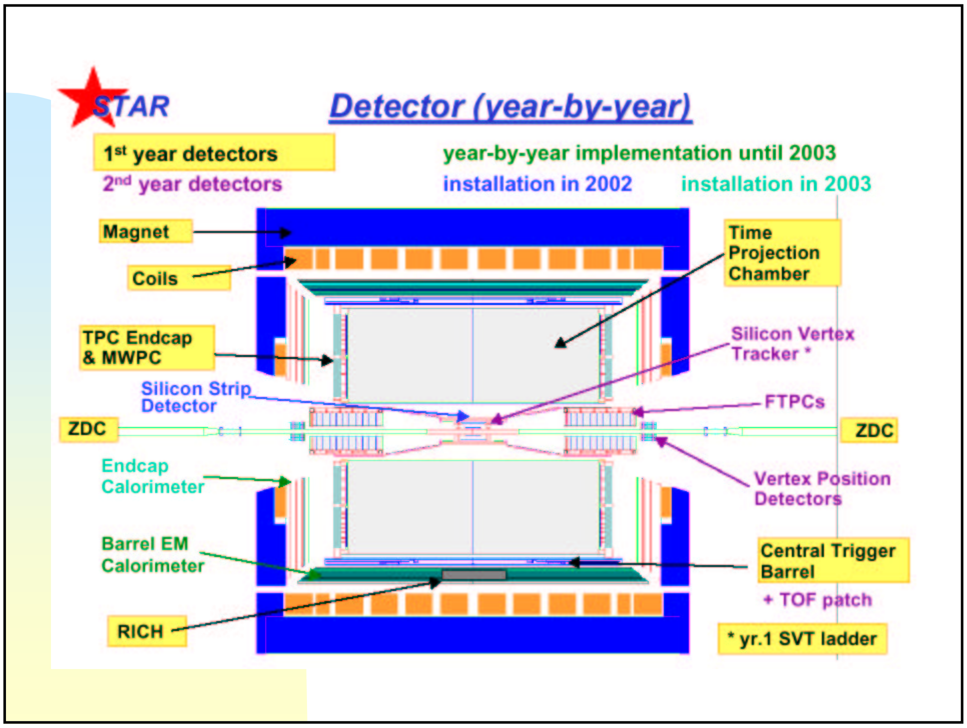
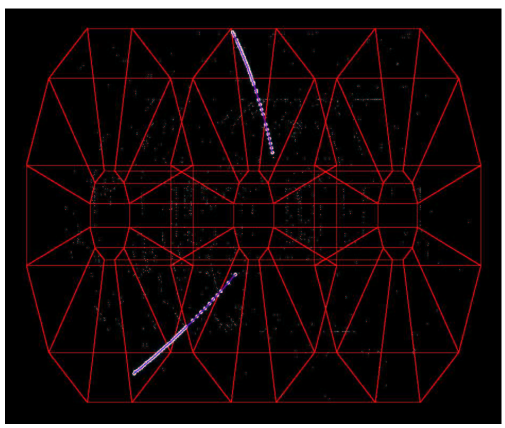


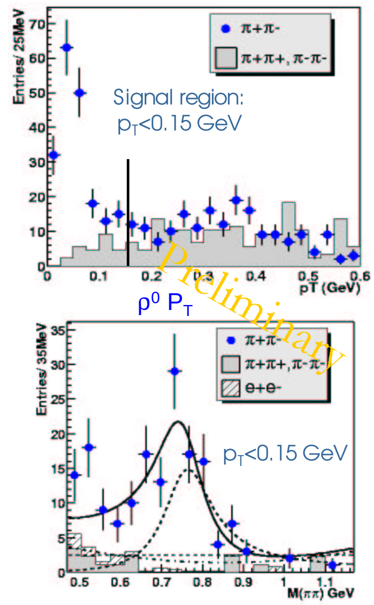
ρ^0 Analysis

- Exclusive Channels
  - ρ^0 and nothing else
    - 2 charged particles
    - net charge 0
- Coherent Coupling
  - $\Sigma p_T < 2h/R_A$ ~100 MeV/c
  - back to back in transverse plane
- Backgrounds:
  - incoherent photonuclear interactions
  - grazing nuclear collisions
  - beam gas interactions



Exclusive ρ^0

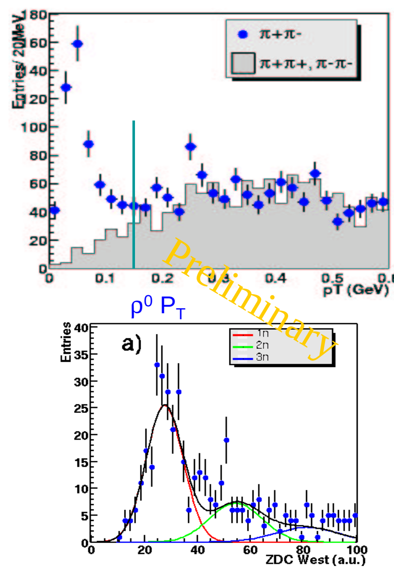
- (prototype) trigger on 2 roughly back-to-back tracks
  - 30,000 events in ~ 9 hours
- 2 tracks in interaction region
  - reject cosmic rays
- peak for p_T < 150 MeV/c
- $\pi^+\pi^+$ and $\pi^-\pi^-$ give background shape
  - $\pi^+\pi^-$ pairs from higher multiplic events have similar shape
  - scaled up by 2.1
    - high p_T ρ^0 ?
- asymmetric $M_{\pi\pi}$ peak



M($\pi^+\pi^-$)

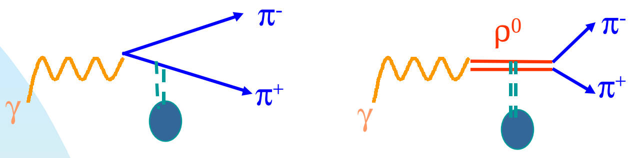
'Minimum Bias' Dataset

- Trigger on neutron signals in both ZDCs
- ~800,000 triggers
- Event selection same as peripheral
- $\pi^+\pi^+$ and $\pi^-\pi^-$ model background
- neutron spectrum has single (1n) and multiple (Xn) neutron components
  - Coulomb excitation
  - Xn may include hadronic interactions?
  - Measure σ(1n1n) & σ(XnXn)



ZDC Energy (arbitrary units)

Direct $\pi^+ \pi^-$ production

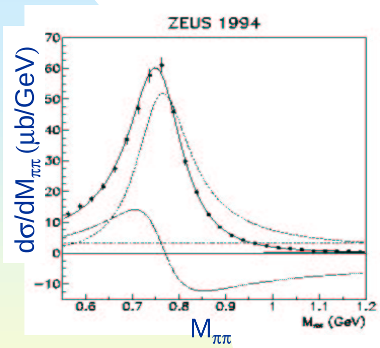


$\gamma A \to \pi^+ \pi^- A$ $\gamma A \to \rho^0 A \to \pi^+ \pi^- A$

- The two processes interfere
  - 180^0 phase shift at $M(\rho^0)$
    - changes $\pi^+ \pi^-$ lineshape
- good data with γp (HERA + fixed target)
- $\pi^+\pi^-$: ρ^0 ratio should depend on $\sigma(\pi A)$:$\sigma(\rho A)$
  - decrease as A rises?

ρ^0 lineshape

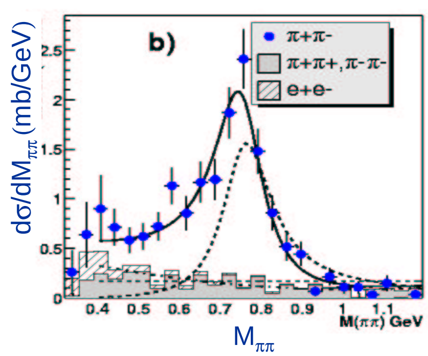
ZEUS $\gamma p \to (\rho^0 + \pi^+\pi^-)p$



$$\frac{d\sigma}{dM_{\pi\pi}} = \left| A \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + i M_\rho \Gamma_\rho} + B \right|^2 + f_{PS}$$

e^+e^- and hadronic backgrounds

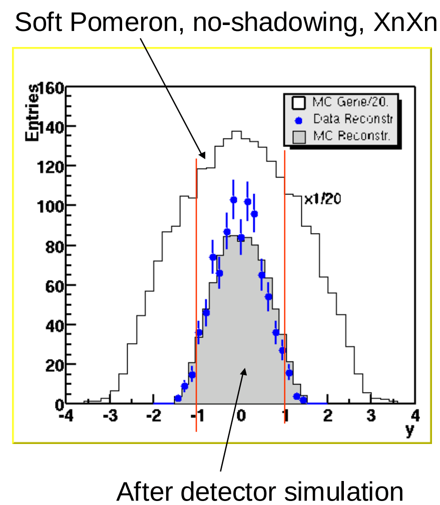
STAR $\gamma Au \to (\rho^0 + \pi^+\pi^-)Au^*$



Fit to ρ^0 Breit-Wigner + $\pi^+\pi^-$
Interference is significant
$\pi^+\pi^-$ fraction is comparable to ZEUS

dN/dy for ρ^0(XnXn)

- ρ $d\sigma/dy$ are different with and without breakup
- XnXn data matches simulation
- Extrapolate to insensitive region



Cross Section Comparison

	STAR	Theory
Exclusive ρ^0	~ 125-500 mb	350 mb
ρ^0 with XnXn	~ 30 +/- 7.5 mb	27 mb
ρ^0 with 1n1n	~ 2 +/-0.7 mb	3.25 mb

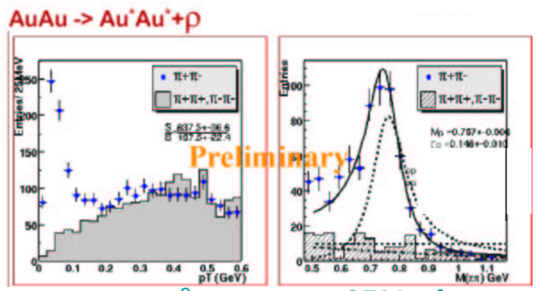
Preliminary

Baltz, Klein & Nystrand (2002)

- Normalized to 7.2 b hadronic cross section
- Systematic uncertainties: luminosity, overlapping events, vertex & tracking simulations, single neutron selection, etc.
- Exclusive ρ^0 bootstrapped from XnXn
- Good agreement
  - factorization works

A peek at the 2001 data

- 200 GeV/nucleon
  - higher σs
- higher luminosity
- 'Production' triggers
- Minimum Bias data:
  - 10X statistics
- Topology Data
  - 50X statistics
- Physics
  - precision ρ^0 σ and p_T spectra
  - $\sigma(e^+e^-)$ and theory comparison
  - 4-prong events (ρ*(1450/1700)???)



ρ^0 spectra - 25% of the min-bias data

Conclusions

- RHIC is a high luminosity γγ and γA collider
- Coherent events have distinctive kinematics
- Photonuclear Interactions probe the nucleus
  - σ(AA --> AAV) is sensitive to σ(VA)
    - probes gluon density (shadowing)
- STAR has observed three peripheral collisions processes
  - Au + Au -- > Au + Au + ρ^0
  - Au + Au -- > Au* + Au* + ρ^0
    - The ρ^0:direct $\pi^+\pi^-$ is similar to gA nteractions
- The ρ^0 cross sections agree with theoretical expectations