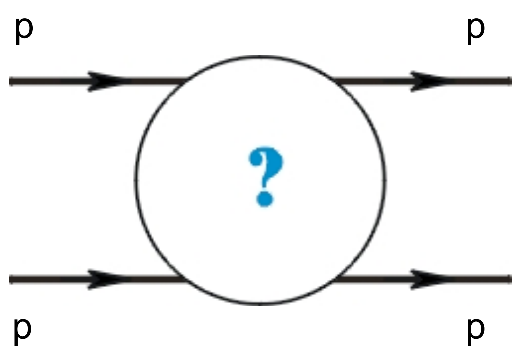
Glueball Searches with the STAR Detector at RHIC

Włodek Guryn BNL (for the STAR Collaboration)

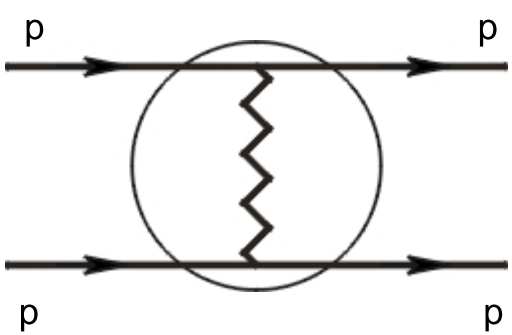
- Process of central production - physics program at STAR with forward protons
- The present: 2009 run preliminary results of Phase I program
- The near future: Phase I program continued
- The future: Phase II program, large data samples for Central Production
- Ultra peripheral AuAu collisions at STAR
- Other QCD topics of interest in Central Exclusive Production (Odderon, χ_c, glueball production and QCD scale invariance…)
- Summary

Physics Processes I

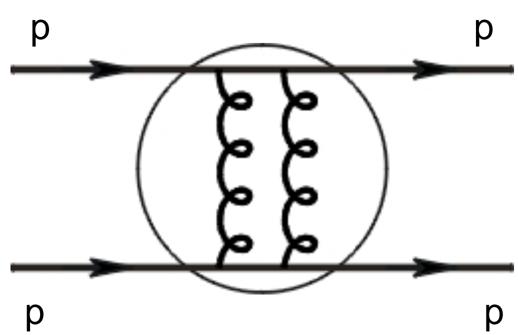


C=+1, C=−1

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



Non Pert. QCD

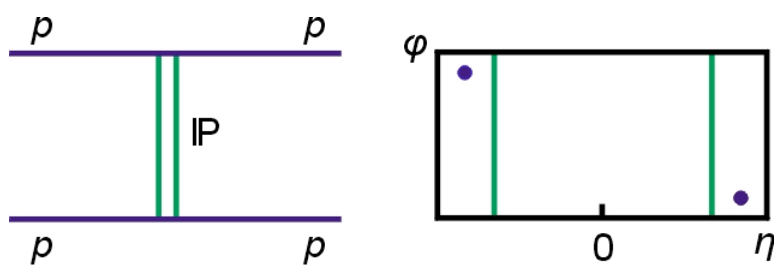


PQCD picture

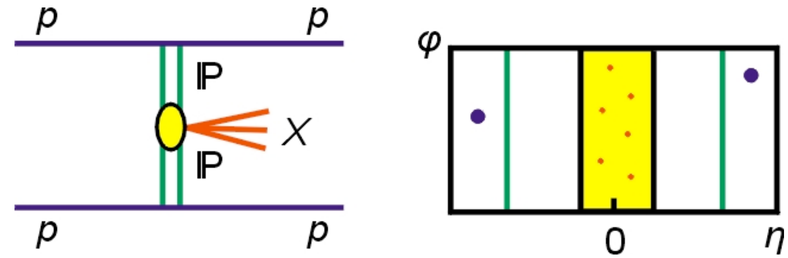
Processes with Tagged Forward Protons

QCD color singlet exchange: C=+1(IP), C=-1(O)

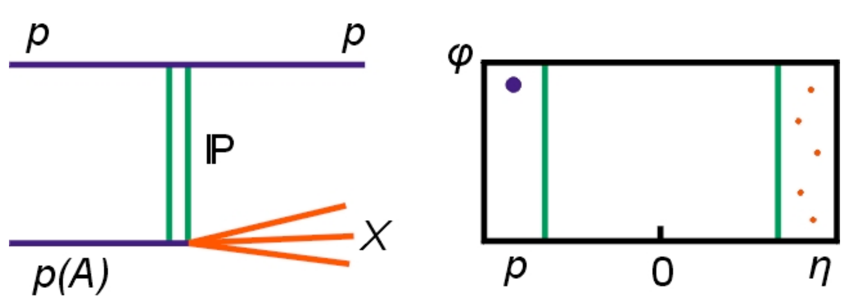
Discovery Physics



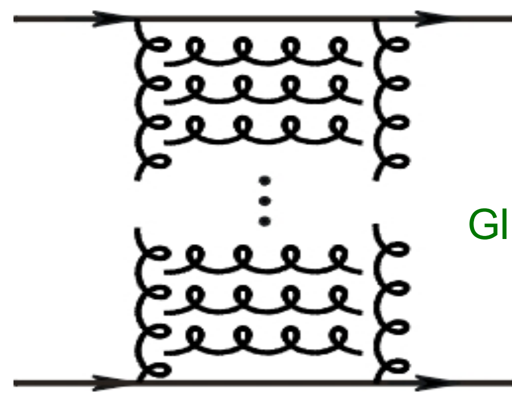
p + p → p + p elastic



p + p → p + X + p
diffractive X= particles, glueballs



p + p → p + X SDD



pQCD Picture
Gluonic exchanges

This Topic Has a Long History

B6 (1975) *ACTA PHYSICA POLONICA* No 1

CENTRAL DIFFRACTIVE PRODUCTION

BY G. BIAŁKOWSKI AND J. KALINOWSKI

Institute of Theoretical Physics, Warsaw University*

(Received April 1, 1974; Revised version received June 1, 1974)

The topological cross sections and some characteristics of the multiplicity distribution for central diffractive production via double pomeron exchange are discussed.

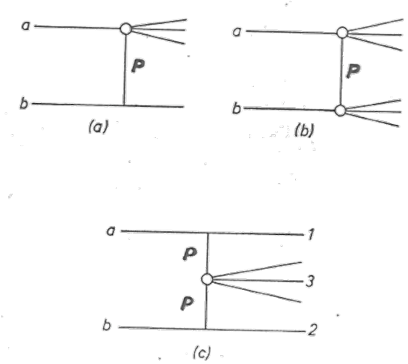
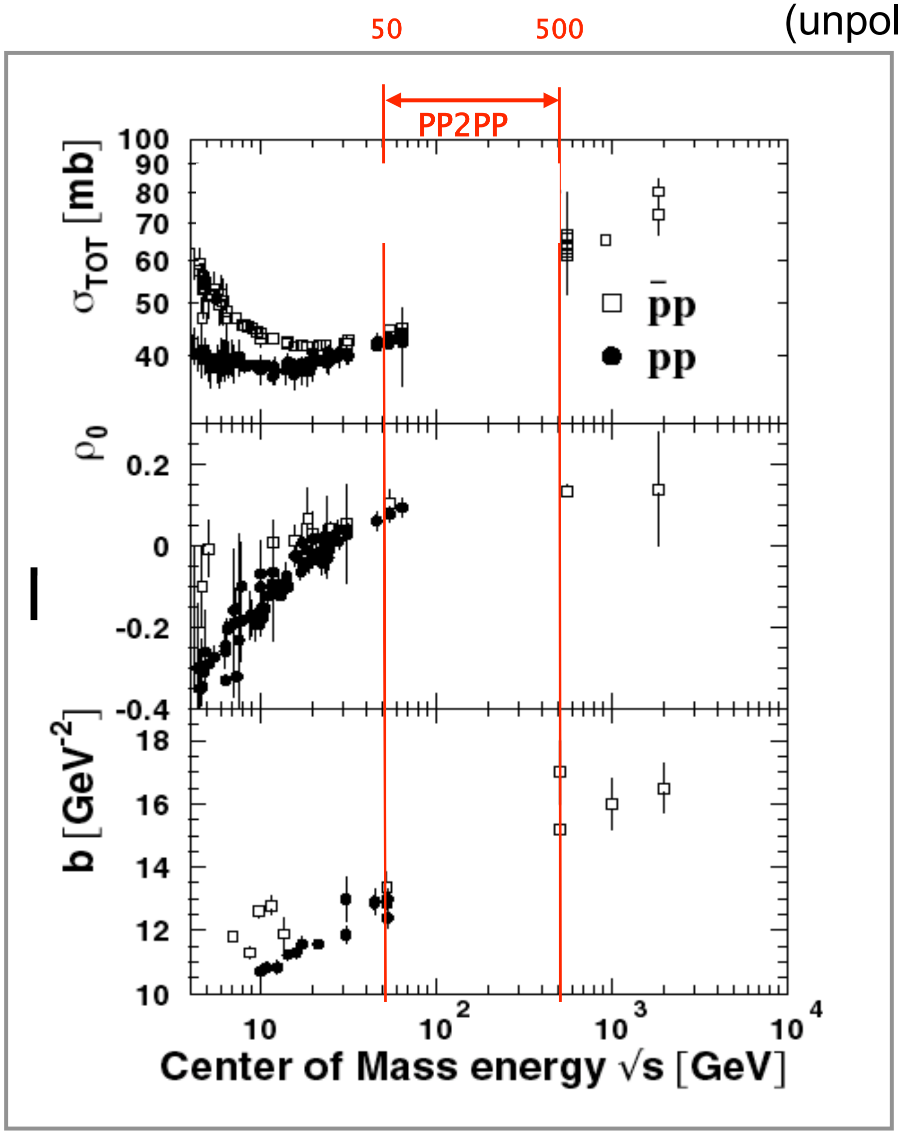


Fig. 1 a) Single diffractive excitation, b) double diffractive excitation,c) central diffractive production diagrams

Summary of the Existing Data

(unpolarized)



Highest energy so far:

pp: 63 GeV (ISR)

p$\bar{p}$: 1.8 TeV (Tevatron)

pp2pp energy range:

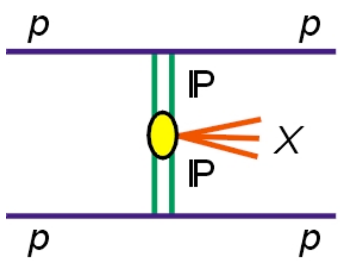
50 GeV ≤ $\sqrt{s}$ ≤ 500 GeV

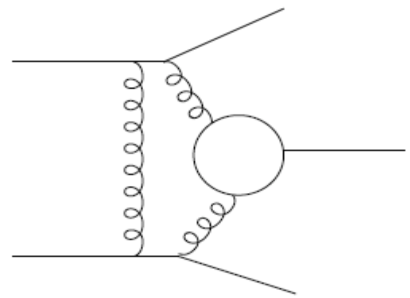
pp2pp |t|-range:

(at $\sqrt{s}$ = 500 GeV)

$4 \cdot 10^{-4}$ GeV^2 ≤ |t| ≤ 1.3 GeV^2

Central Exclusive Production in Double Pomeron Exchange (DPE)

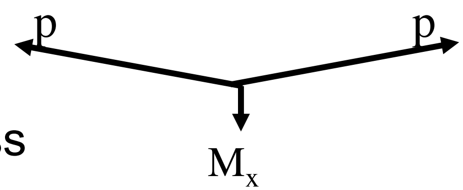




Method is complementary to:
- **GLUEX experiment (2015)**
- **PANDA experiment (>2015)**
- **COMPASS experiment (taking data)**
- **BESIII**

In the Double Pomeron Exchange (DPE) process each proton "emits" a Pomeron and the two Pomerons interact producing a massive system M_X

$M_X=\sqrt{\xi_1\xi_2 s}$ invariant mass



For each proton vertex one has
t four-momentum transfer
$\xi = \Delta p/p$

where $M_X = \pi^+\pi^-, \chi_c(\chi_b)$, qq(jets), H(Higgs boson), gg(glueballs)

The massive system could form resonances. We expect that because of the constraints provided by the double Pomeron interaction, glueballs, hybrids, and other states coupling preferentially to gluons, will be produced with much reduced backgrounds compared to standard hadronic production processes.

Glueball Spectrum

Sparse spectrum!

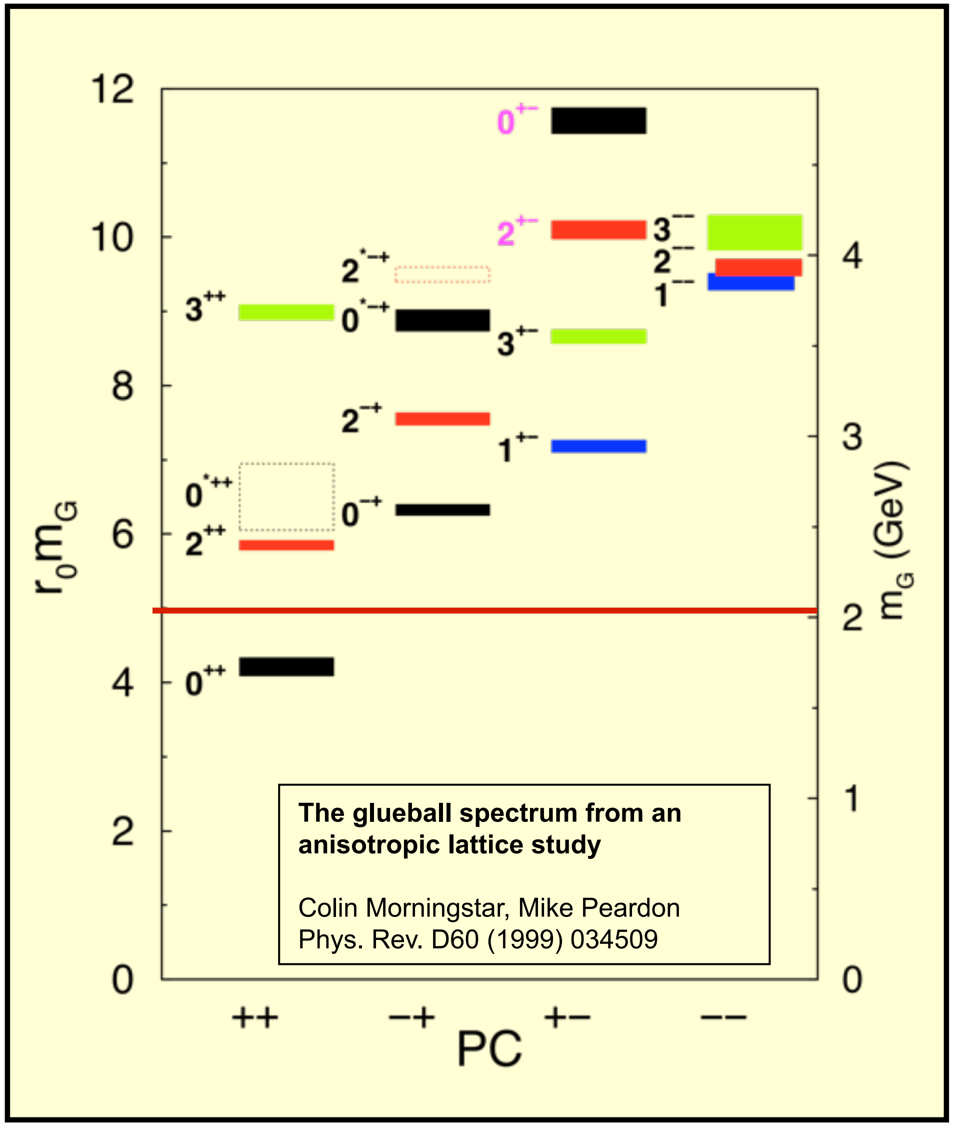
New I=0 mesons starting with

0^{++} 1.6 GeV

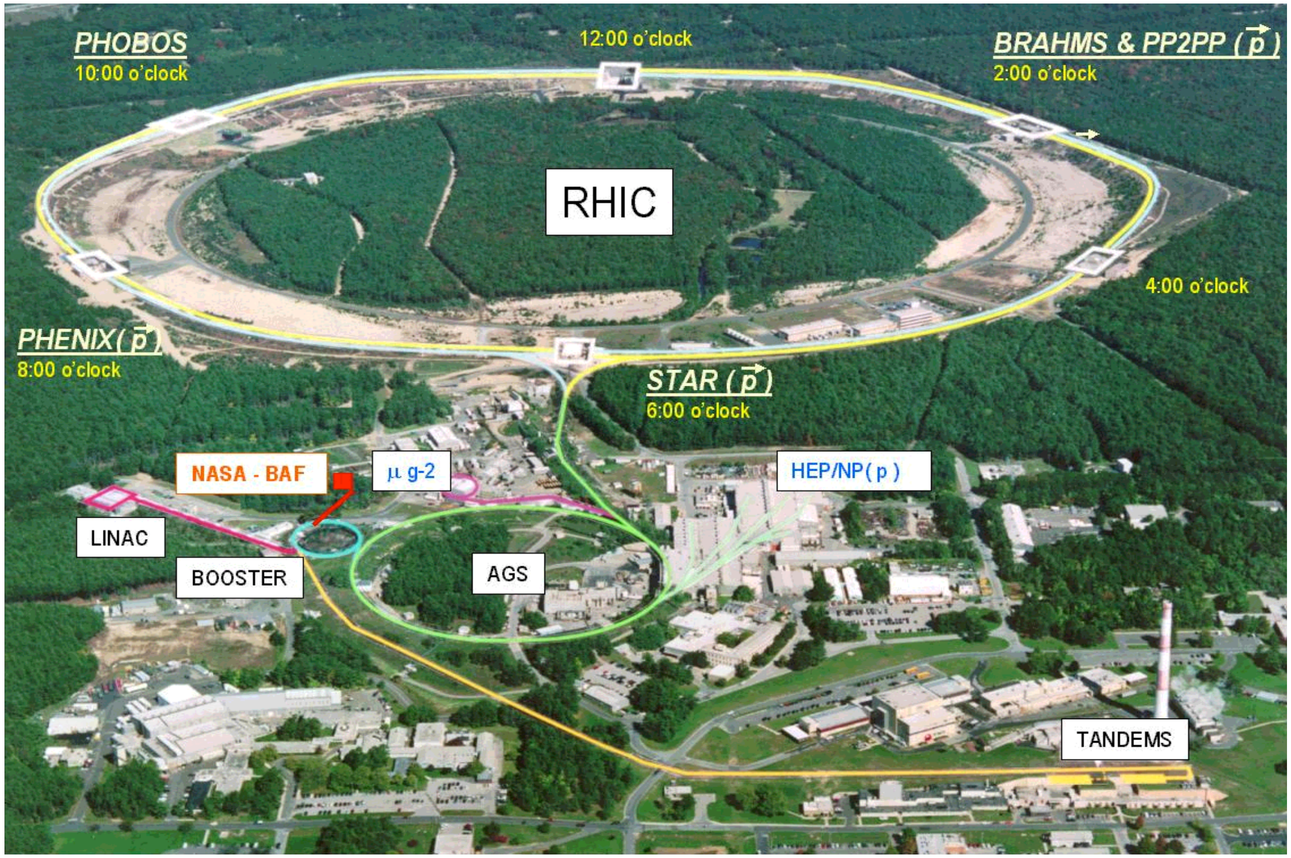
0^{-+} , 2^{++} 2.3 - 2.5 GeV

No **J^{PC}-exotic** glueballs until

2^{+-} at 4 GeV



The Relativistic Heavy Ion Collider

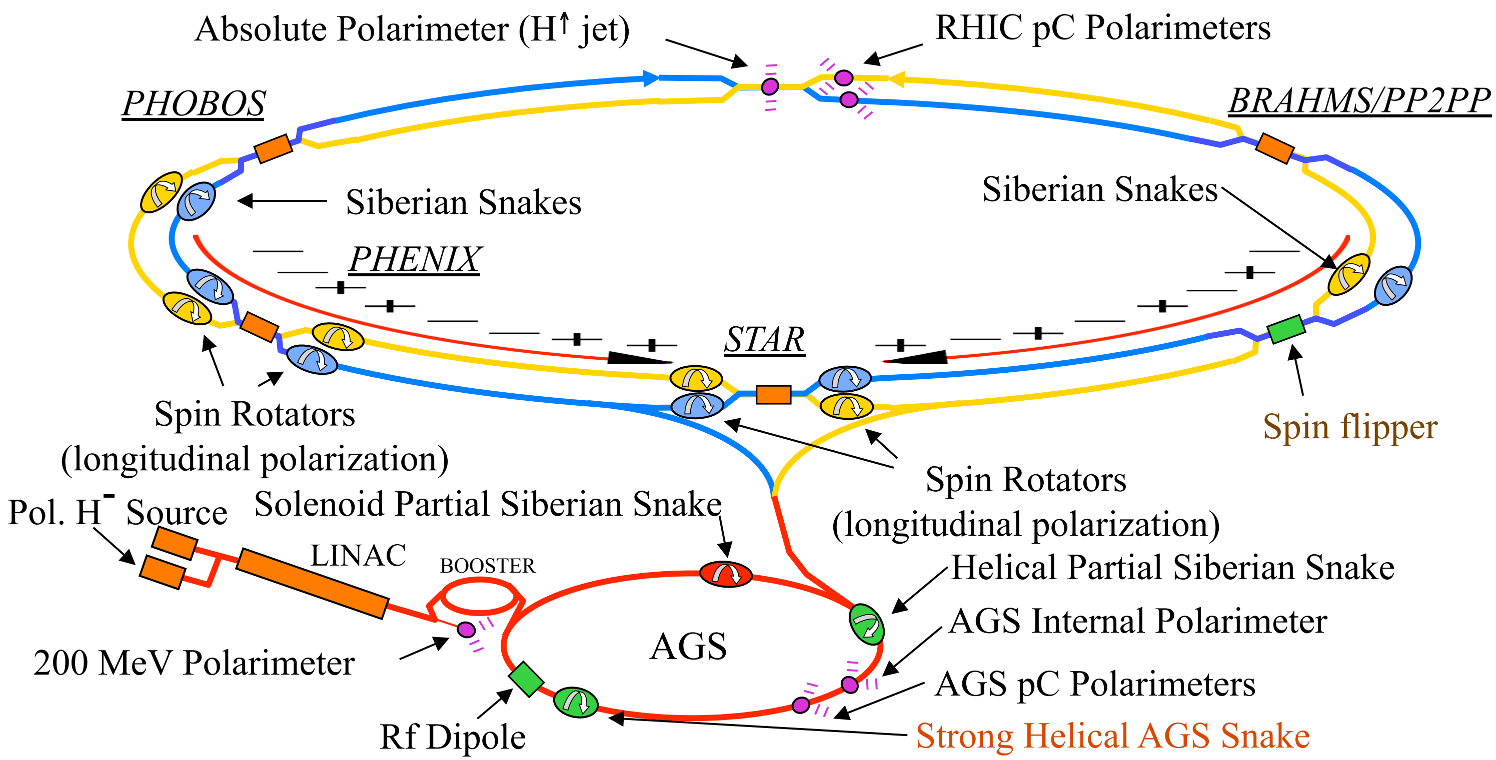


RHIC is a QCD Laboratory:

Nucleus- Nucleus collisions (AuAu, CuCu…); Asym. Nucl. (dAu);

Polarized proton-proton; eRHIC - Future

RHIC: the world's first polarized pp collider

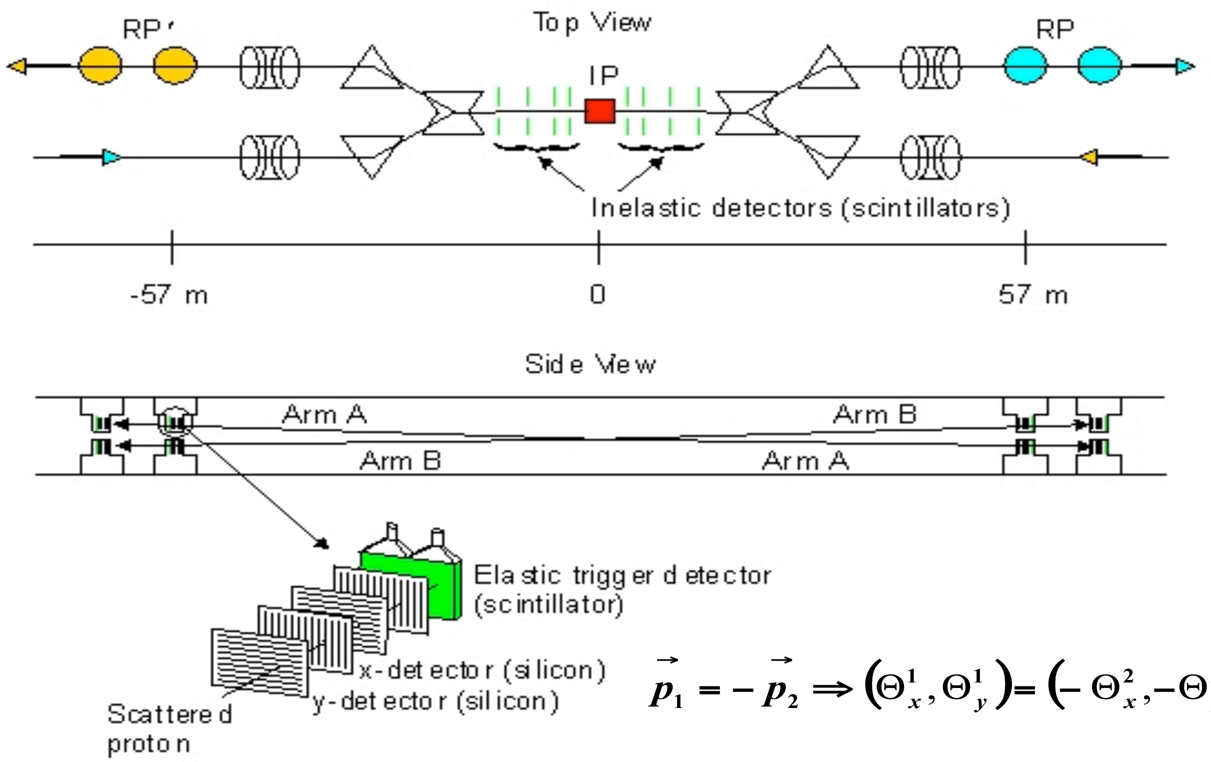


- Spin orientation varies bunch by bunch
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- "Billions" of spin reversals during a fill with little if any depolarization

Implementation at RHIC - tag forward protons

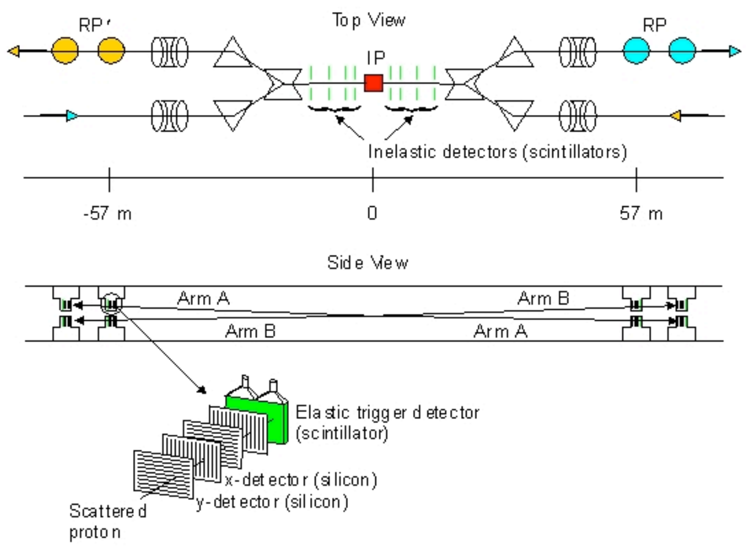
PP2PP Setup

Phys. Lett. B 579 (2004) 245-250, Phys. Lett. B 632 (2006) 167-172, Phys. Lett. B 647 (2007) 98-103
(Polish coauthors Chwastowski, Pawlik, Sandacz)



$$\vec{p}_1 = -\vec{p}_2 \Rightarrow \left(\Theta_x^1, \Theta_y^1\right) = \left(-\Theta_x^2, -\Theta_y^2\right)$$

Principle of the Measurement



- (Elastically) scattered protons have very small scattering angle θ^*, hence beam transport magnets determine trajectory scattered protons
- The optimal position for the detectors is where scattered protons are well separated from beam protons
- Need Roman Pot to measure scattered protons close to the beam without breaking accelerator vacuum

Beam transport equations relate measured position at the detector to scattering angle

$$\begin{pmatrix} x_D \\ \Theta_D^x \\ y_D \\ \Theta_D^y \end{pmatrix} = \begin{pmatrix} a_{11} & L_{eff}^x & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & L_{eff}^y \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix} \begin{pmatrix} x_0 \\ \Theta_x^* \\ y_0 \\ \Theta_y^* \end{pmatrix}$$

x_0, y_0: Position at Interaction Point
Θ^*_x Θ^*_y : Scattering Angle at IP
x_D, y_D : Position at Detector
Θ^x_D, Θ^y_D : Angle at Detector

Reconstruction of the Momentum Loss ξ

For inelastic forward protons there is an additional momentum loss term

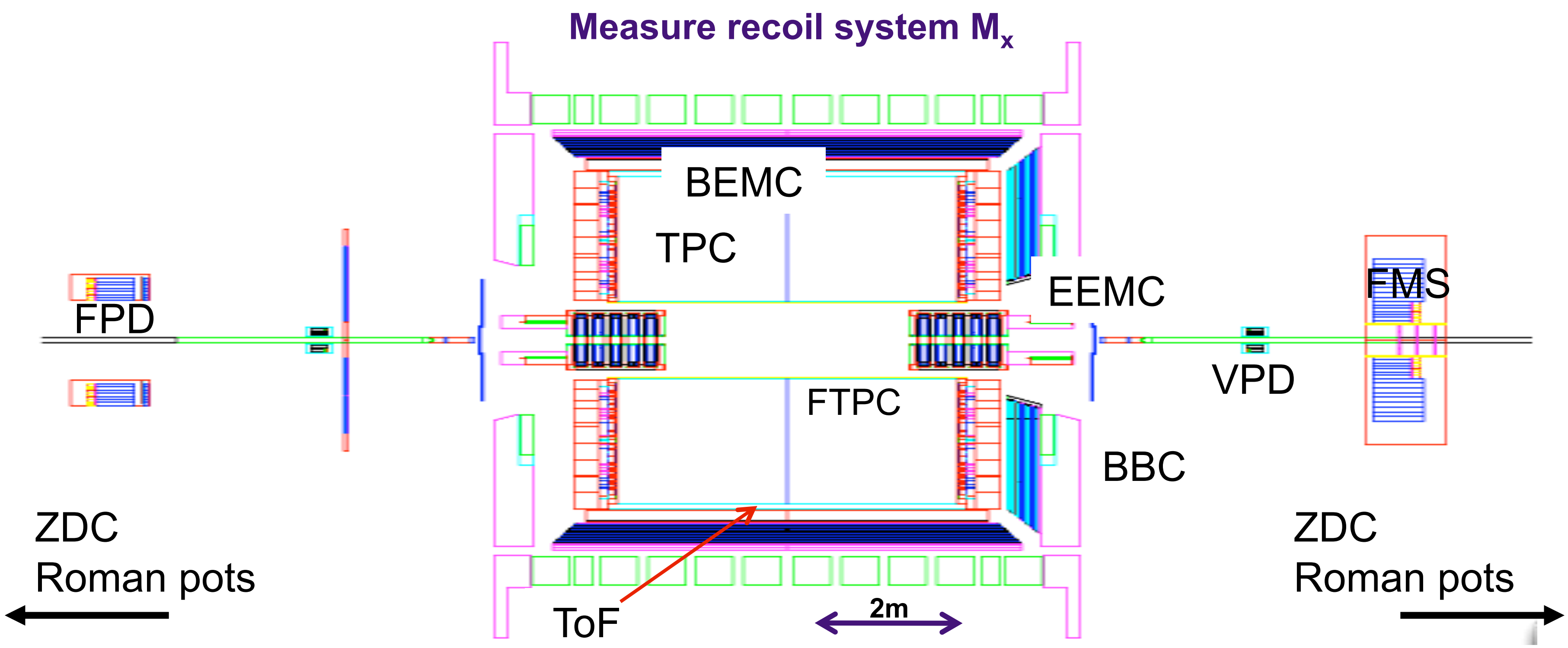
1. Need to measure vector at the detection point, hence two RPs are needed on each side of STAR.
2. For a proton, which scatters with Θ and ξ we have:

$$x_1 = a_1 x_0 + L_1 \Theta_x + \eta_1 \xi \,; \quad \textbf{detection point 1}$$
$$x_2 = a_2 x_0 + L_2 \Theta_x + \eta_2 \xi \,; \quad \textbf{detection point 2}$$

⇐ Accelerator transport

$$\begin{pmatrix} \Theta_x \\ \xi \end{pmatrix} = \frac{1}{Det} \begin{pmatrix} \eta_2; & -\eta_1 \\ -L_2; & -\mathrm{L}_1 \end{pmatrix} \begin{pmatrix} x_1 - a_1 x_0 \\ x_2 - a_2 x_0 \end{pmatrix}$$

Current *STAR* detector in cross section



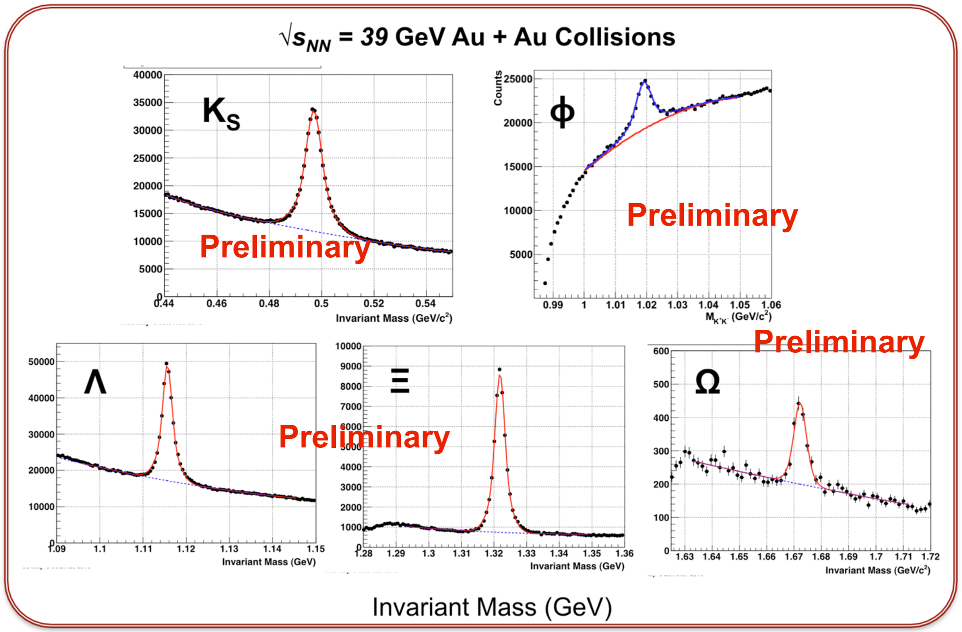
Large acceptance detector running since 2000

- High resolution tracking device: TPC in $-1<\eta<1$, $-\pi<\varphi<\pi$
- Forward rapidity gap veto
- FTPC: $2.5<|\eta|<4.2$, BBC: $3.8<|\eta|<5.2$

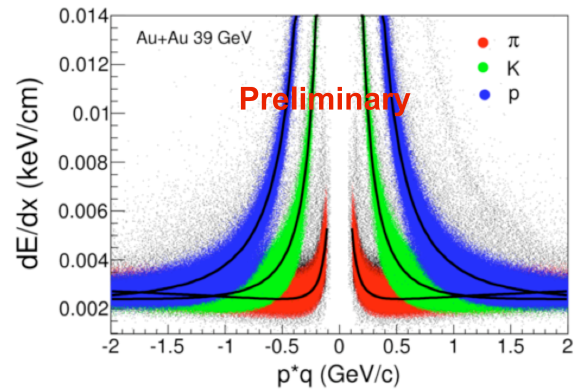
Great Charged Particle ID in the STAR TPC

- High resolution tracking device: TPC in $-1<\eta<1$, $-\pi<\varphi<\pi$
- Excellent particle identification capability: TPC dE/dx, ToF

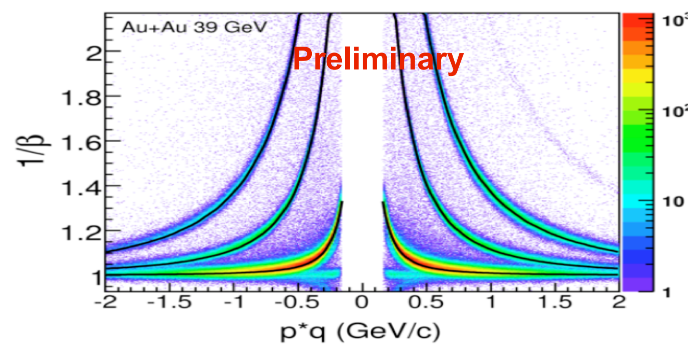
Particle Identification at STAR



Reconstructed hadrons: K_S, φ, Λ, Ξ, and Ω in Au+Au collisions at $\sqrt{s_{NN}}$ = 39 GeV



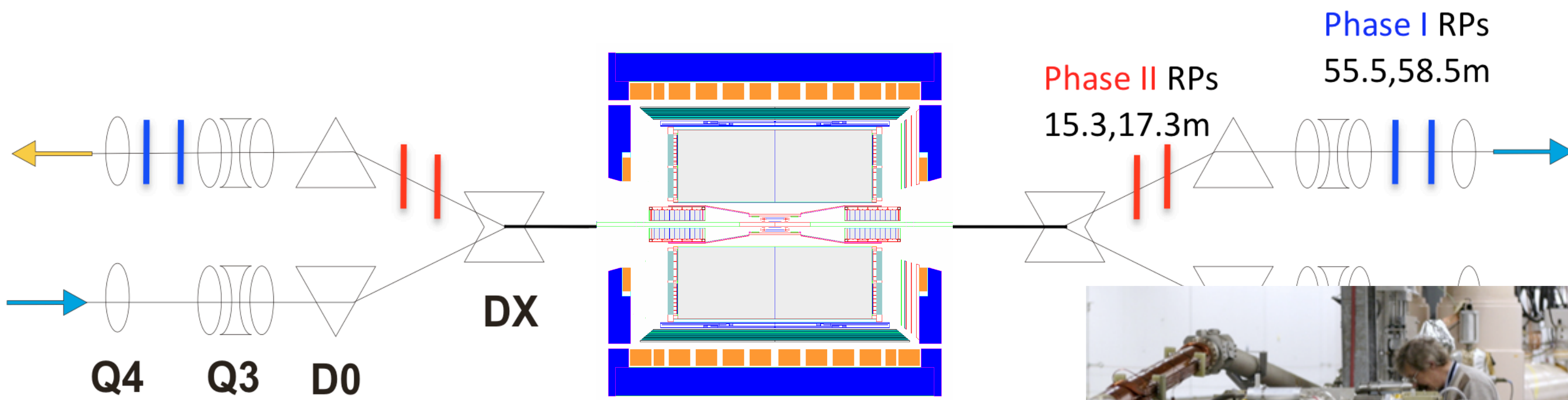
dE/dx vs. rigidity compared with theoretical expectations



Particle identification with new barrel Time-of-Flight system.

Implementation: STAR + pp2pp

1. Need detectors to measure forward protons: $\mathbf{t}$ - four-momentum transfer, $\xi = \Delta p/p$, M_X invariant mass and;
2. Detector with good acceptance and particle ID to measure central system



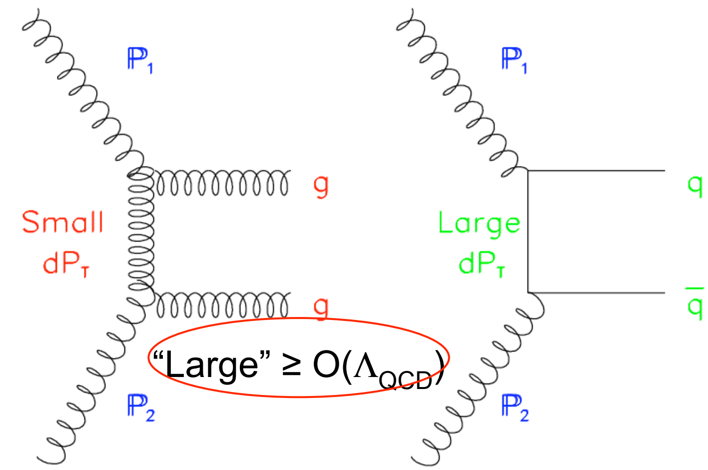
1. Roman Pot (RP) detectors to measure forward protons
2. Staged implementation for wide kinematic coverage
   - Phase I, present- low-t coverage
   - Phase II, future- higher-t coverage, large data samples

Kinematic “filter” (dp_T) for “gg”

(F. Close et al./W102)

PLB 397 339 (1997)

- Coupling of the exchange particles to the final state mesons for gluon exchange (small dp_T) and quark exchange (large dp_T)
- Spin-dependence of the coupling can be studied at RHIC

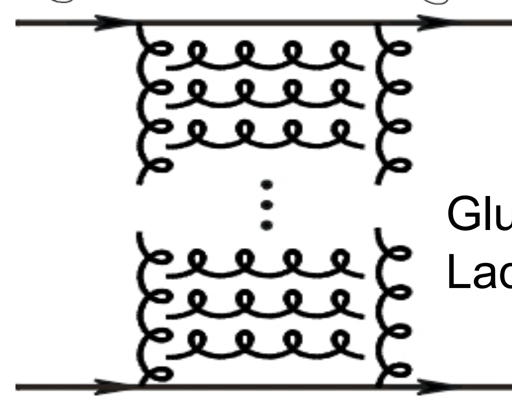


As predicted by Regge theory the diffractive cross section at RHIC is dominated by the Pomeron (gluonic) exchange, :

$\sigma_{RR} \sim s^{-2}$

$\sigma_{RP} \sim s^{-1}$

$\sigma_{PP} \sim$ const. or s^{α} where $\alpha \sim (0.1)$



Gluon Ladders

WA102 $f_0(1500)$ $\pi^+\pi^-\pi^+\pi^-$

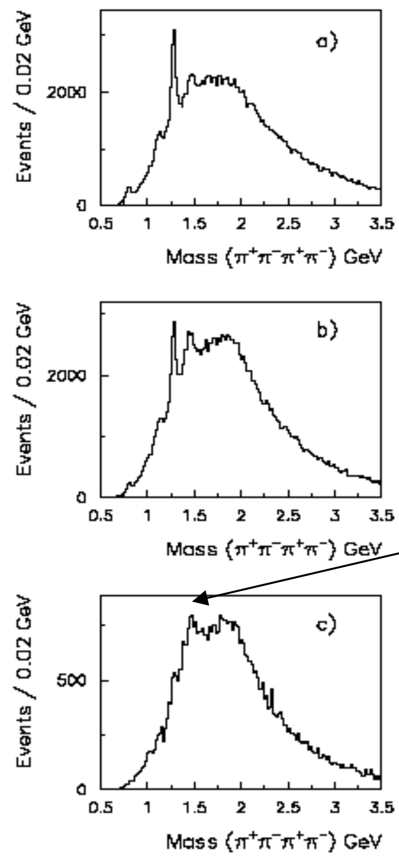
$\sigma(f_1)$= 7 μbarn

We are sensitive to this level of cross section

$\sigma(f_0)$= 3 μbarn

$f_1(1285)$

F.E.Close and A.Kirk, PLB397, 333 (1997).



dP_T > 0.5 GeV/c

0.2 GeV < dP_T < 0.5 GeV/c

$f_0(1500)$

dP_T < 0.2 GeV/c

Figure 3: The 4π mass spectra (i) With $dP_T > 0.5$ GeV exhibiting a clear $f_1(1285)$; (ii) $0.2 < dP_T < 0.5$ GeV (iii) $dP_T < 0.2$ GeV where the $f_1(1285)$ has disappeared while the $f_0(1500)$ is seen more clearly.

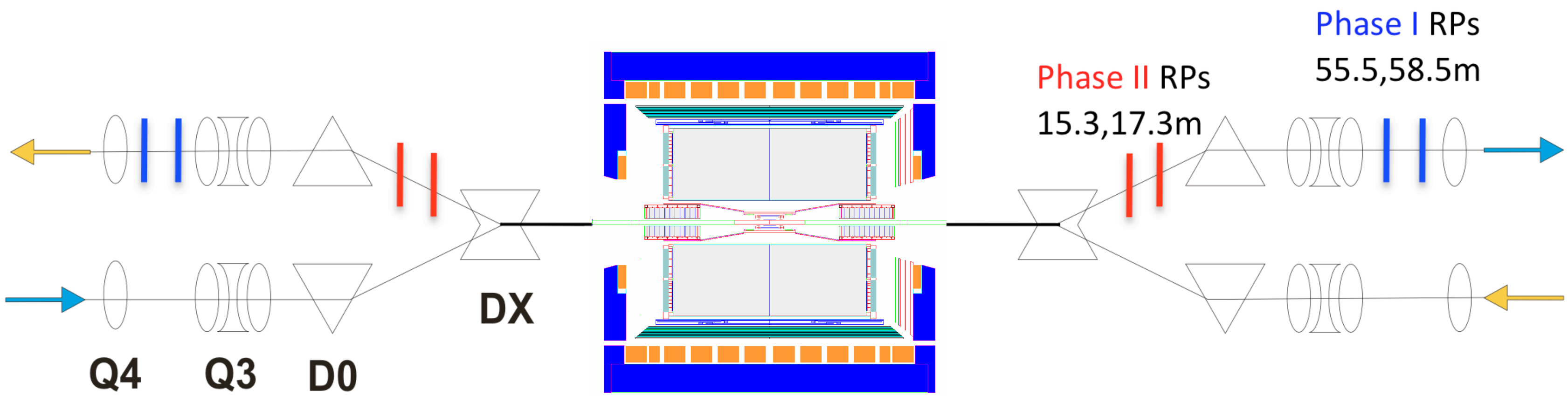
Central Exclusive Production Process in DPE

$p_1 p_2 \rightarrow p_{1'} M_X p_{2'}$

- Exclusive process with "small" momentum transfer:

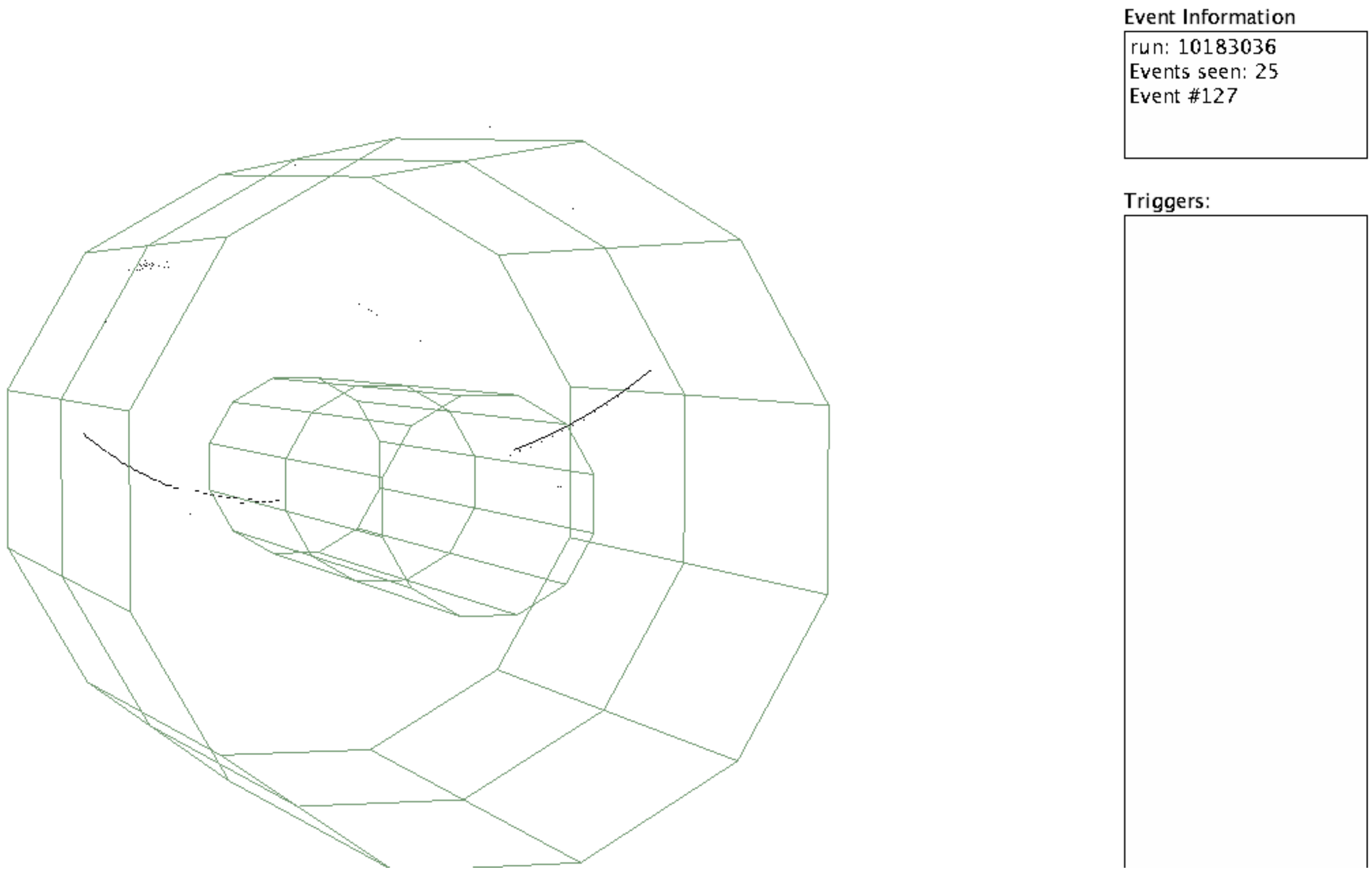
  $-t_1(p_1 \rightarrow p_1')$ and $-t_2(p_2 \rightarrow p_2')$
- M_X is centrally produced, nearly at rest, through DPE process
- In pQCD, Pomeron is considered to be made of two gluons: natural place to look for gluon bound state
- $M_X(\sim 1 - 3\ GeV/c^2) \rightarrow \pi^+\pi^-, \pi^+\pi^-\pi^+\pi^-, K^+K^-, \ldots$
- Lattice calculation: Lightest glueball $M(0^{++})=1.5\text{-}1.7\ GeV/c^2$ (PRD73 2006)
- Search for glueball (gg) candidates in M_x
- Candidates with conventional quantum numbers: need to be studied in a wide kinematical range

Phase I: 2009 data



- Data taken with RP and ToF multiplicity triggers for the central process
- Tracks reconstructed off line in TPC
- Require two reconstructed tracks in opposite direction in the RPs
- Work in progress for identifying exclusive DPE events: rapidity gaps, PID, p_T-balance, missing-mass…

Run 2009 Candidate Central Production Event

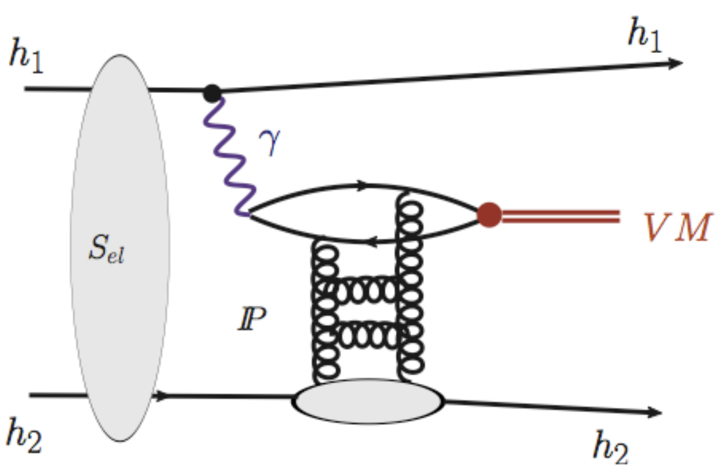


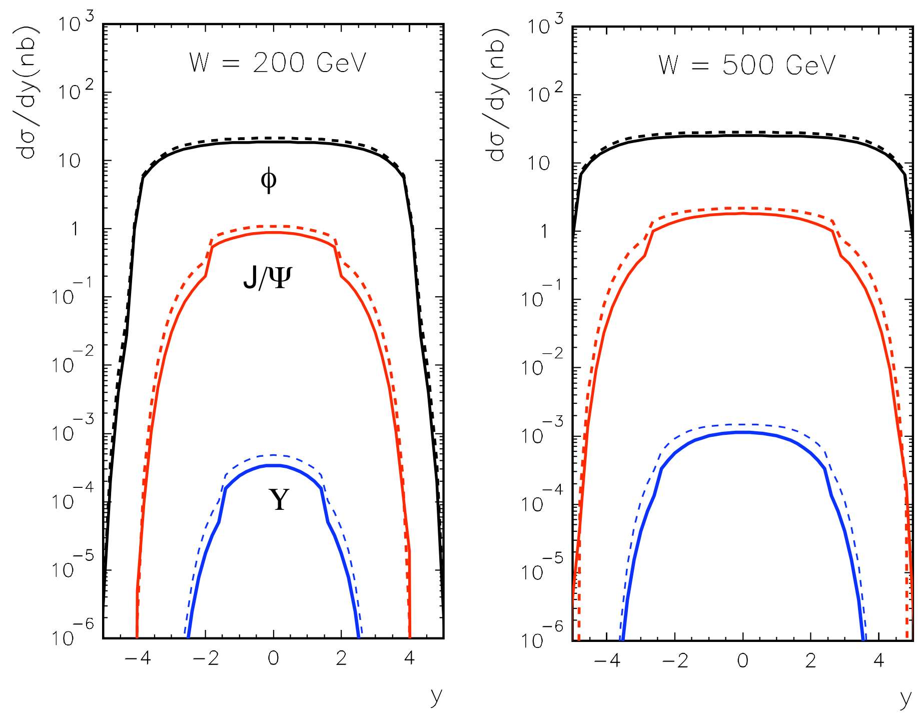
Phase I: First Look at Central Production

(Vector Meson Production)

Exclusive production of vectors meson in *pp and pbarp* collisions

A.Cisek, W. Schäfer and A. Szczurek, Meson 2010

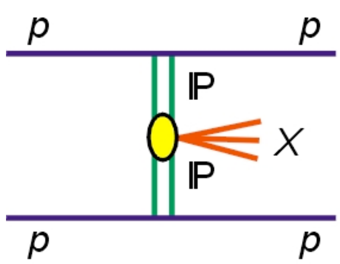


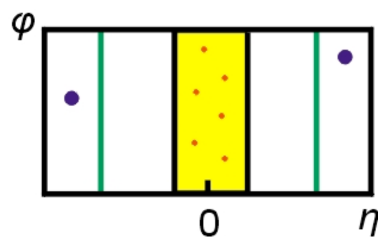


The ρ^0 cross section ~ few hundred nb

Phase I: First Look at Central Production

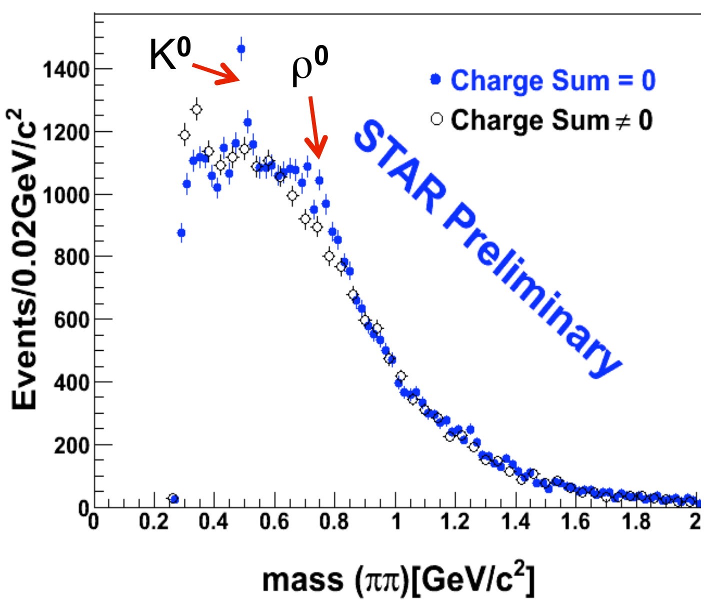
(non exclusive channels)

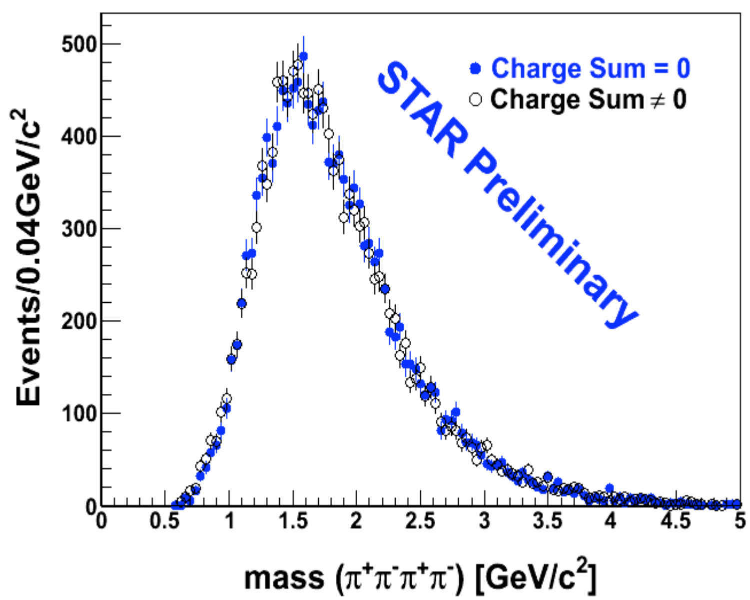




Double Pomeron Exchange

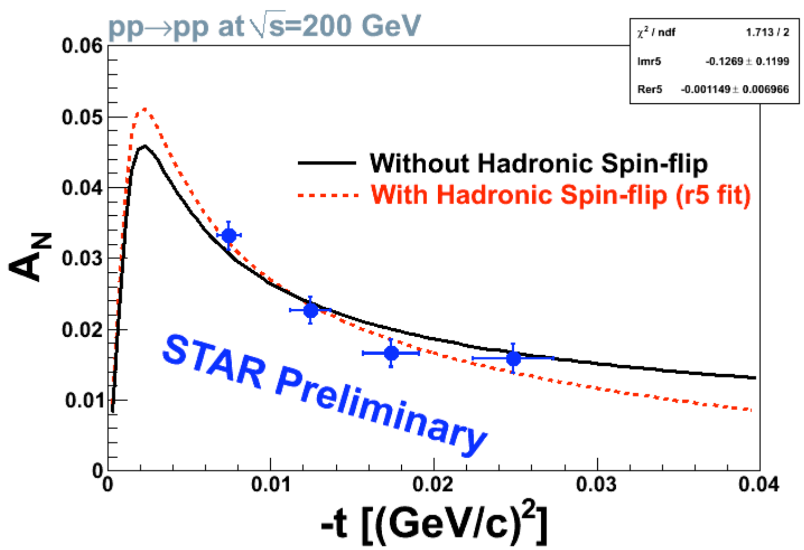
- Use RP and ToF multiplicity trigger online
- Reconstruct TPC tracks off line
- Confirm two tracks in the Roman Pots
- Reconstruct M_x using TPC tracks assuming all pions





Phase I Elastic Scattering: First high-statistics measurement of A_N at HE ($\sqrt{s}$=200 GeV)

$$A_N(t) = \frac{\sigma^{\uparrow}(t) - \sigma^{\downarrow}(t)}{\sigma^{\uparrow}(t) + \sigma^{\downarrow}(t)} = C_1 \phi_{flip}^{em*} \phi_{non-flip}^{had} + C_2 \phi_{flip}^{had*} \phi_{non-flip}^{em}$$



- Statistical errors + systematic *t*-scale uncertainty (10%) in the fit
- Higher-*t* reach planned from the upcoming $\sqrt{s}$=500 GeV (and with Phase II set-up) at RHIC

Phase II - Simulation Performance Plots

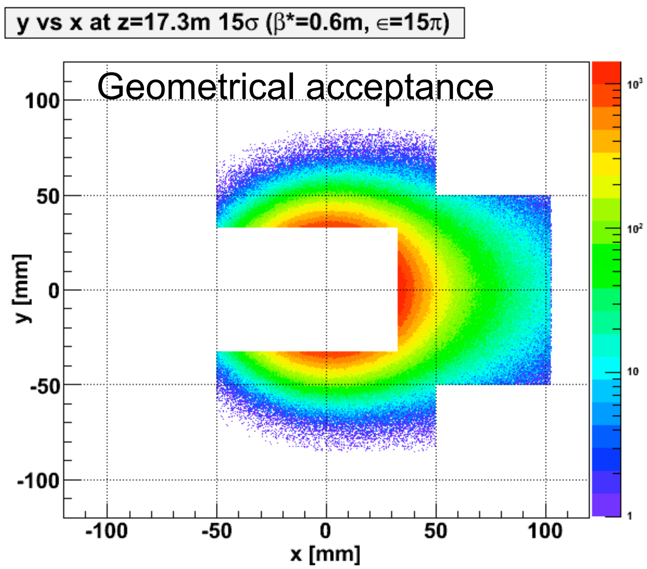
We assume the DPE cross section 140 μbarn, and branching ratios as measured at the ISR

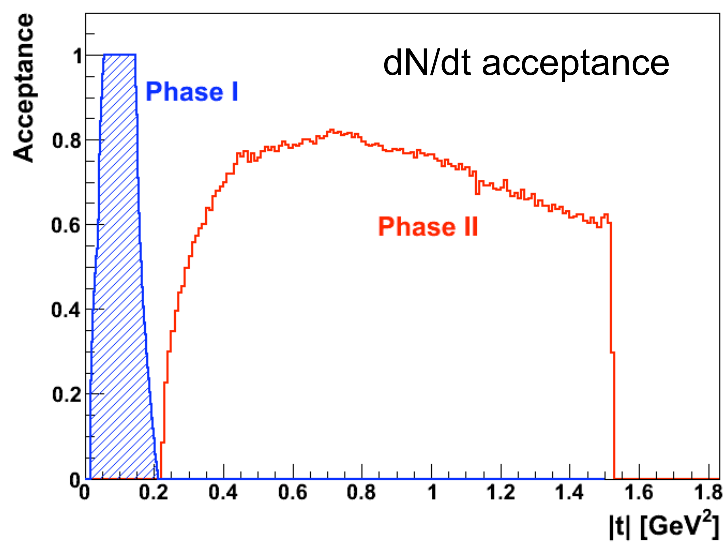
A. Breakstone *et al.*, Z. Phys. **C42**, (1989) 387

Reaction	Number of events	Cross section [μb]
(1) $pp \to pp(\pi^+\pi^-)$	16400	79.0 ± 13.0
(2) $pp \to pp(2\pi^+ 2\pi^-)$	5800	46.0 ± 10.0
(3) $pp \to pp(3\pi^+ 3\pi^-)$	1900	32.0 ± 9.0
(4) $pp \to pp(K^+K^-)$	560	6.5 ± 1.7
(5) $pp \to pp(K^+K^-\pi^+\pi^-)$	150	10.0 ± 3.3
(6) $pp \to pp(p\bar{p})$	120	0.8 ± 0.17
(7) $pp \to pp(p\bar{p}\pi^+\pi^-)$	65	1.3 ± 0.36

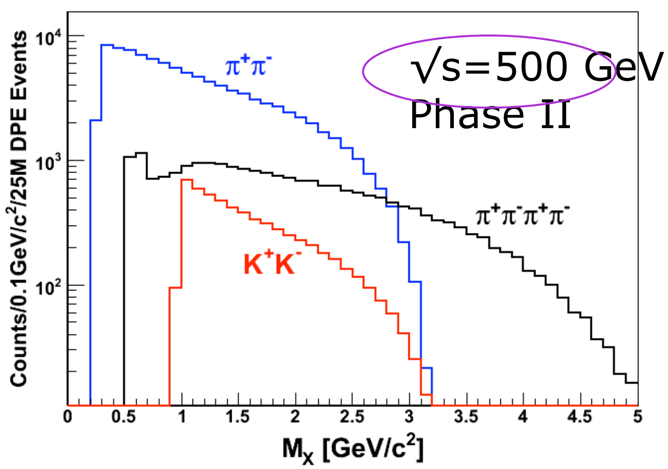
Phase II - Simulation Performance Plots

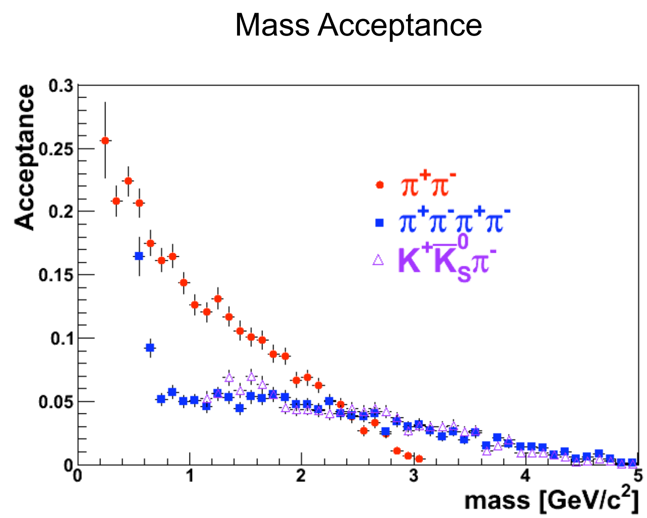
- Mass M_X calculated from the proton kinematics
- Use phase space to determine the decay of mass M_X in a particular channel
- Use STAR TPC acceptance to make sure that all decay products are measured.
- High-M_x reconstruction is limited by PID (π/K separation up to ~ 1.6 GeV/c)





Acceptance and expected yields in M_X





Event yields for 20 week run at 500 GeV

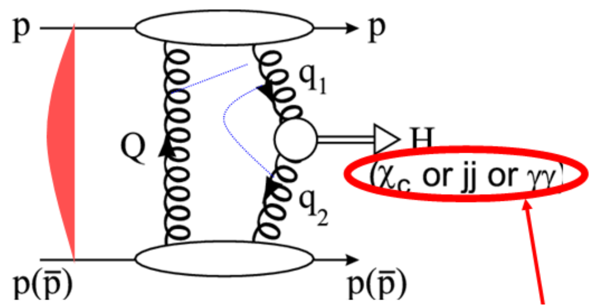
$\pi^+\pi^-\pi^+\pi^-$ - 2.7×10^6 events

$\pi^+\pi^-$ - 10.4×10^6 events

K^+K^- - 0.8×10^6 events

Other QCD Processes: χ_c Production

arXiv:1005.0695 L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin, W.J. Stirling



RHIC

$\sqrt{s}$ (TeV)	0.5	1.96	7	10	14
$\frac{d\sigma}{dy_{\chi_c}}(pp \to pp(J/\psi + \gamma))$	0.57	0.73	0.89	0.94	1.0
$\frac{d\sigma(1^+)}{d\sigma(0^+)}$	0.59	0.61	0.69	0.69	0.71
$\frac{d\sigma(2^+)}{d\sigma(0^+)}$	0.21	0.22	0.23	0.23	0.23

Table 3: Differential cross section (in nb) at rapidity $y_\chi = 0$ for central exclusive χ_{cJ} production via the $\chi_{cJ} \to J/\psi\gamma$ decay chain, summed over the $J = 0, 1, 2$ contributions, at RHIC, Tevatron and LHC energies, and calculated using GRV94HO partons, as explained in the text.

BR(χ_c => J /ψ+ γ)= 1.14 ± 0.08 %

CDF: σ (χ_c) = 76±10 ±10 nb
PRL 102, 242001 (2009)

Other QCD Processes: χ_c Production

Szczurek and collaborators

1. $\chi_c(0+)$ production:
R. S. Pasechnik, A. Szczurek and O. V. Teryaev, Phys. Rev. D **78**, 014007 (2008) [arXiv:0709.0857 [hep-ph]];

2. $\chi_c(1+)$ production:
R. S. Pasechnik, A. Szczurek and O. V. Teryaev, Phys. Lett. B **680**, 62 (2009) [arXiv:0901.4187 [hep-ph]];

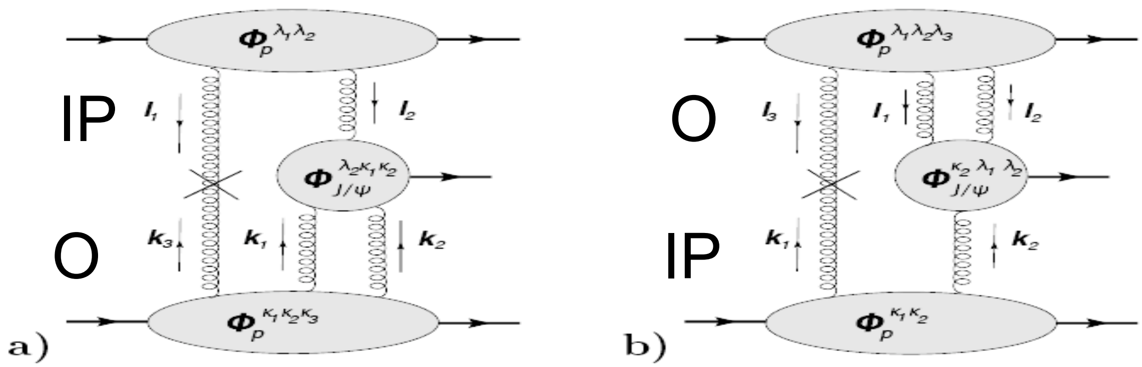
3. $\chi_c(2+)$ production:
R. S. Pasechnik, A. Szczurek and O. V. Teryaev, Phys. Rev. D **81**, 034024 (2010) [arXiv:0912.4251 [hep-ph]].

TABLE I: Integrated over full phase space cross sections (in nb) for the central exclusive $\chi_c(0^+, 1^+, 2^+)$ production at RHIC energy $W = 200$ GeV. Absorption effects and NLO QCD corrections to the $gg \to \chi_c$ vertex are included here. Gap survival factor for all χ_c states is taken here to be equal 0.1. Branching ratio to the channel of interest should be included in addition.

χ_c	without absorption	with absorption
$\chi_c(0^+)$	45	4.5
$\chi_c(1^+)$	2	0.2
$\chi_c(2^+)$	2	0.2

Odderon Contribution to J/ψ production

A. Bzdak et. al Phys. Rev.D 75.094023, also S. Klein, et. al PRL 92, 142003 (2004) for γIP



Calculation assumes:
- IP = 2 gluons, O = 3 gluons
- Soft Pomeron for small masses and hard Pomeron assumed for higher masses
- $E(s,m_V) \sim (\sqrt{s}/m_V)^{\lambda}$, where λ=0.2 (0.35)

$$E(s, m_V) = (x_0\sqrt{s}/m_V)^{2\lambda}.$$

$d\sigma^{corr}/dy$	J/ψ		Υ	
	odderon	photon	odderon	photon
Tevatron	0.3–1.3–5 nb	0.8–5–9 nb	0.7–4–15 pb	0.8–5–9 pb
LHC	0.3–0.9–4 nb	2.4–15–27 nb	1.7–5–21 pb	5–31–55 pb

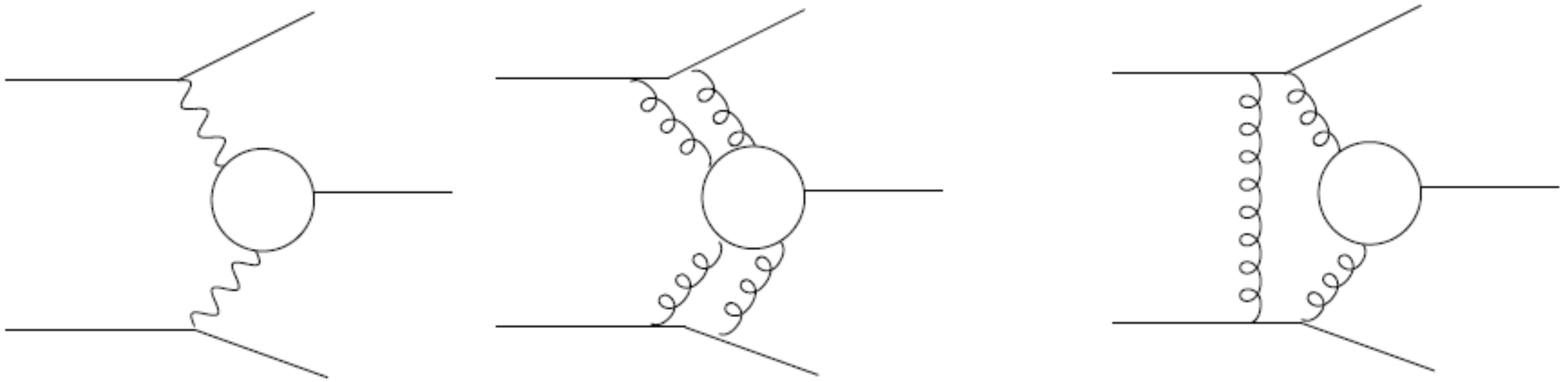
Use scaling from HERA to calculate cross sections from Tevatron to RHIC

J/ψ $(500/2000)^{0.4} \sim 0.4$ and for ϒ $(500/2000)^{0.7} \sim 5$

$d\sigma^{corr}/dy$ => J/ψ ~ 0.5 nb and ϒ ~ 0.8 pb

The Glueball Filter in Central Production and Broken Scale Invariance

John Ellis and Dmitri Kharzeev arXiv:hep-ph/9811222



Abstract

We propose a possible explanation of the kinematical dependence of the central production of the scalar glueball candidate observed recently by the WA91 and WA102 Collaborations, and discussed by Close and Kirk, in the context of the broken scale invariance of QCD. The dependences of glueball production on the transverse momenta and azimuthal angles of the final-state protons may be related to the structure of the trace anomaly in QCD.

The φ Correlations and Broken Scale Invariance

John Ellis and Dmitri Kharzeev arXiv:hep-ph/9811222

The azimuthal angle correlation between outgoing protons are an alternative filter to identify glueball states

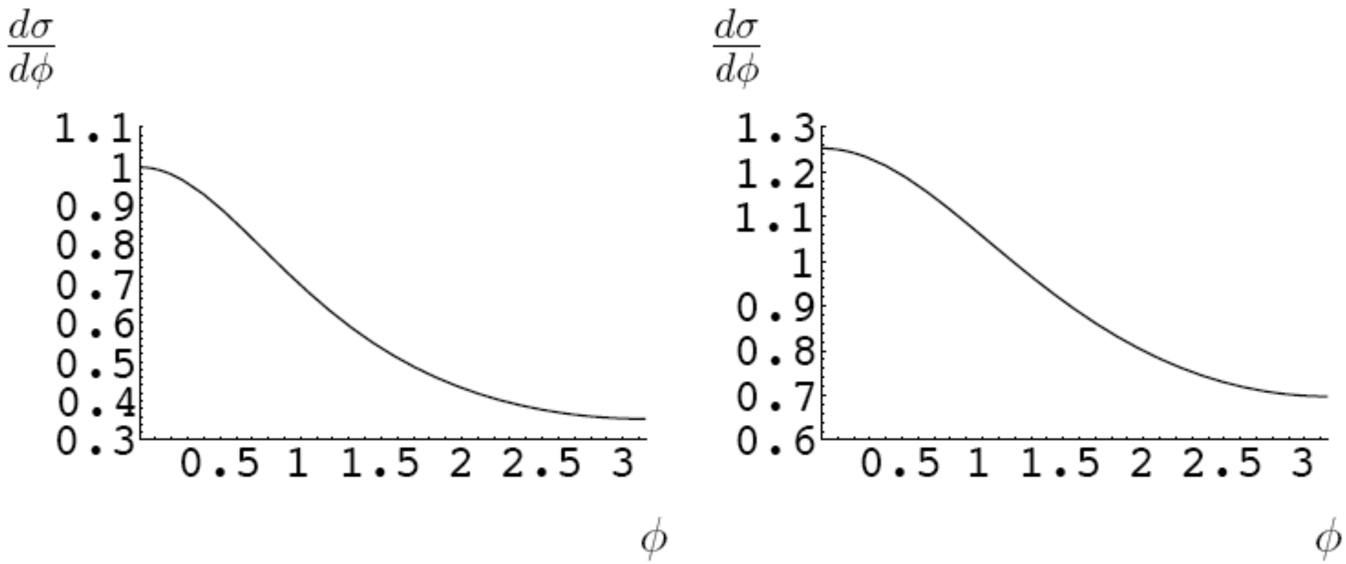


Figure 2: Distribution in the azimuthal angle ϕ (in radians) between the final-state protons in double-diffractive production of the $f_0(980)$ (left panel) and $f_0(1500)$ (right panel) states, calculated for the center-of-mass energy of the WA91 and WA102 experiments, and with $t = -0.5$ GeV^2 for both final-state protons.

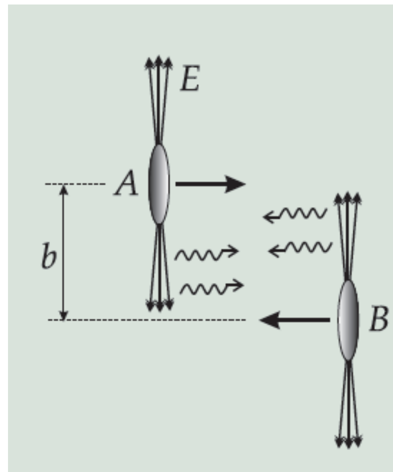
J/ψ Production in DPE and Photoproduction

1. In many cases J/ψ is produced.
2. The experimental challenge is to distinguish between production channels

Are ϕ correlations and dP_T distributions of the forward protons different for different reactions?

Need $d^2\sigma/dtd\xi$ for each process

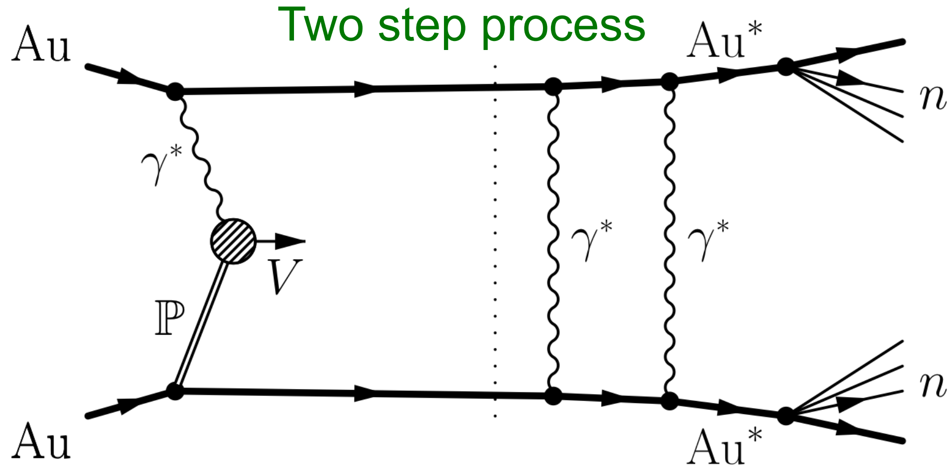
Ultra Peripheral Collisions (UPC) of Heavy Ions



Phys.Rept.458:1-171,2008 (arXiv:0706.3356)

- Ultra Peripheral Collisions: nuclei miss each other ($\gamma\gamma$ and γP interactions)
- Requires: $b > R_A + R_B$
- Weizsacker-Williams approach: a field of almost real photons

Particle Production in UPC

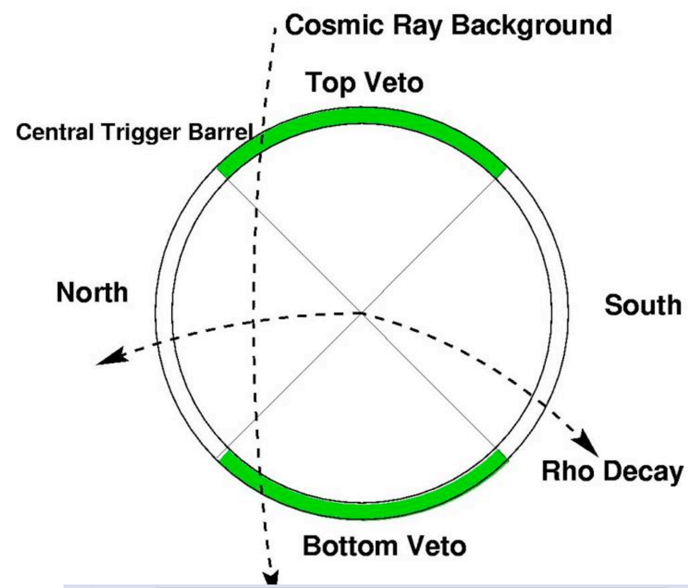


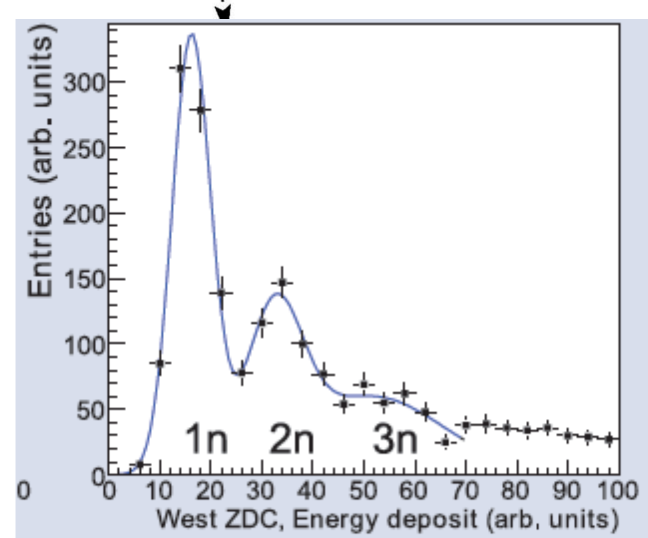
MAIN PHYSICS TOPICS

- Meson spectroscopy: ρ, ω, φ, ρ' = mix of ρ(1450) and ρ(1700);
- Transition from soft physics (ρ,ω,φ) to pQCD (J/Ψ, Y);
- e^+e^- pair production;
- Fundamental tests of Quantum Mechanics: interference between non overlapping particles

Signature and Triggering

- Signatures:
  - Coherent production dominates
  - Low transverse momentum ($p_T \leq 2h/RA \approx 60$ MeV)
  - Low multiplicity events with vertex
  - Events with nuclear breakup accompanied by forward neutrons
- Trigger:
  - Minimum bias
    - Low multiplicity
    - Neutrons in both ZDCs
  - Topology ToF and TPC:
    - Low multiplicity events
    - Coincidence of North and South
    - Top and Bottom veto cosmics

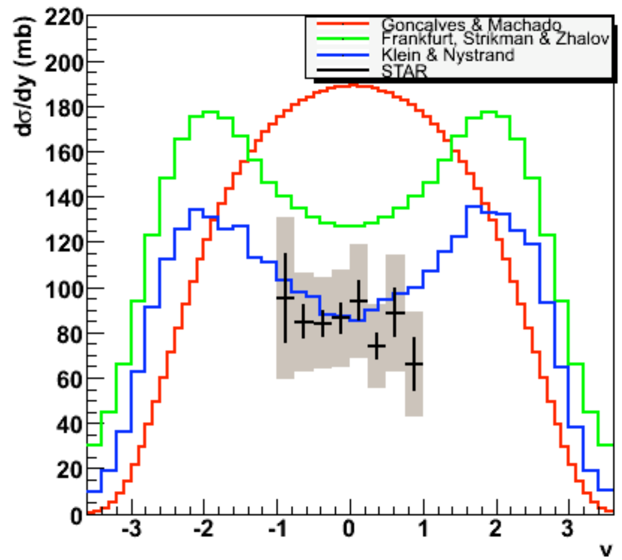


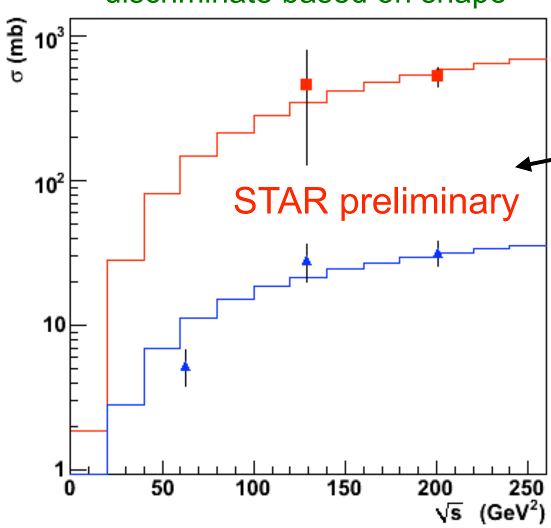


The ρ^0 photoproduction cross section

- Goncalves & Machado (EPJ C29,2003)
  - QCD color dipole approach
  - Nuclear effects and parton saturation phenomena
- Frankfurt, Strikman & Zhalov (PRC67 034901,2003)
  - Generalized vector dominance (VDM)
  - QCD – Gribov-Glauber approach
- Klein & Nystrand (PR C60 014903, 1999)
  - VDM
  - Classical mechanical approach for scattering

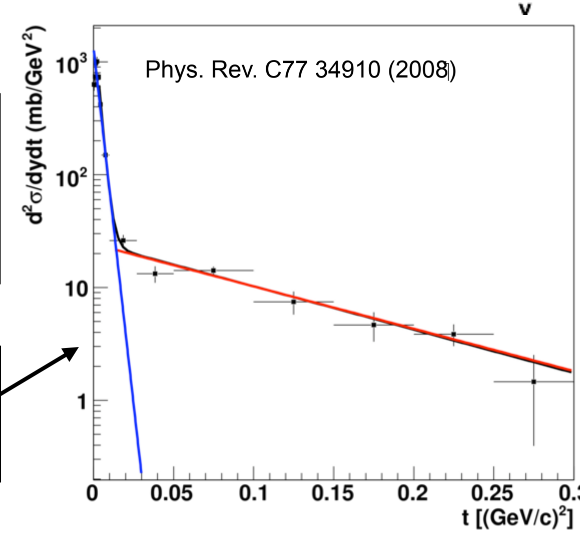
Klein & Nystrand model agrees well with the data, $|y|<1$ does not allow to discriminate based on shape





Red total cross section
Blue cross section with mutual excitation.
Simulation based on Klein & Nystrand

Coherent and incoherent form factors
Double exponential fit function
σ(incoh)/σ(coh)~ 0.29 ±0.03

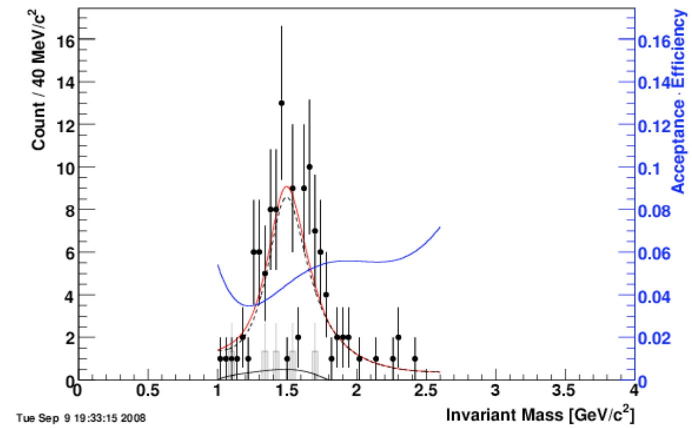


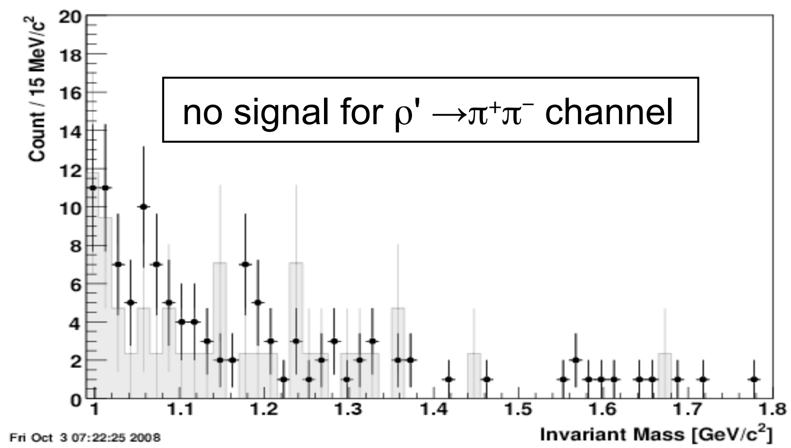
Photoproduction of $\pi^+\pi^-\pi^+\pi^-$

(arXiv:0912.0604) Phys.Rev.C81:044901,2010

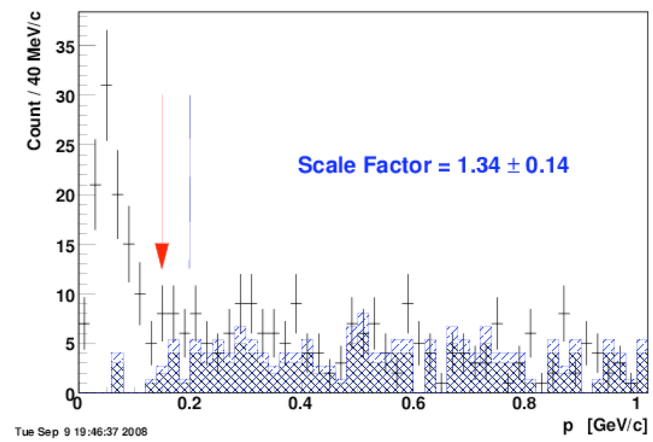
- Expected to be largely through a radially excited
  - Could be $\rho(1450)$ and/or $\rho(1700)$
- Studies of the substructure showed low mass pion pairs accompanied by $\rho(770)$

$\sigma_{coh}(\pi^+\pi^-\pi^+\pi^-)/\sigma_{coh}(\rho[770])=13.4 \pm 0.8$ %





Peak at low p_T is due to the coherent production



Summary

1. A new rich diffractive physics program with tagged forward protons in polarized proton-proton scattering at RHIC, has been launched and its significant expansion has been proposed.

2. It will search for new physics, including glueballs, Odderon and sphalerons (particle correlations in DPE process).

3. It will search for diffractive production of light and massive systems in double Pomeron exchange process. Possible Pomeron - Odderon interaction => J/ψ production, C−odd glueball.

4. Other QCD processes will be studied a) breaking of the scale invariance as a glueball filter; and b) χ_c central production.

5. Not discussed here - systematic study of the spin dependence of elastic scattering, of unpolarized quantities σ_{tot}, ρ, $d\sigma/dt$ in unexplored ranges of t and $\sqrt{s}$.

6. STAR has had a reach program with many common topics in heavy ion UPC collisions.

RHIC is an exciting, and complementary to other hadron colliders, place to do diffractive physics