Physics with Tagged Forward Protons in Proton-Proton Collisions at RHIC

The Journey from Elastic Scattering to Central Exclusive Production and Back

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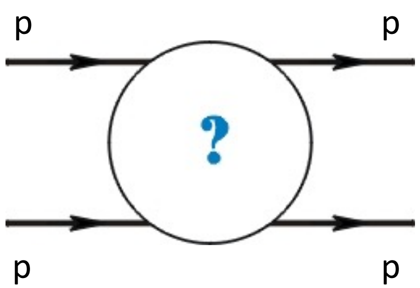
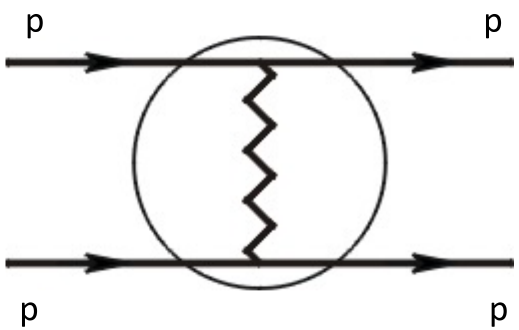
1. Elastic Scattering
2. PP2PP experiment – Roman Pots and first results
3. Move to STAR experiment
4. Results at STAR
   - Central Exclusive Production (CEP)
   - Proton – Proton elastic scattering
5. Summary

Tagged Forward Protons – Physics Processes I

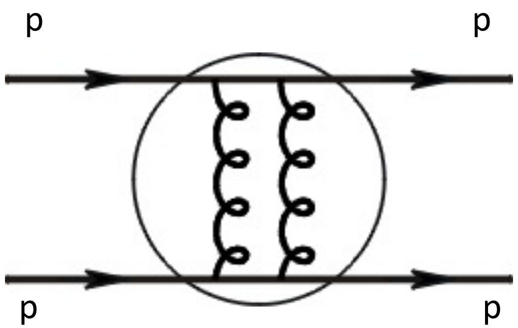


C=+1, C=−1

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



Non Pert. QCD – small mom. transf.



pQCD picture – large mom. transf.

Domain of Regge theory – scattering amplitudes A are parameterized as function of (s,t) => A(s,t)

Domain of QCD Lagrangian – scattering amplitudes are calculated using the QCD Lagrangian.

How it all started: The ρ-value from UA4

It was summer of 1992 or so when I attended a student/postdoc seminar at FNAL (I was working on D0 experiment at the time). I learned about the anomalous ρ–measurement at CERN.

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THE REAL PART OF THE PROTON–ANTIPROTON ELASTIC SCATTERING AMPLITUDE AT THE CENTRE OF MASS ENERGY OF 546 GeV

UA4 Collaboration

Amsterdam–CERN–Genova–Napoli–Palaiseau–Pisa

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Received 25 August 1987

Proton–antiproton elastic scattering was measured at the CERN SPS Collider at the centr-of-mass energy $\sqrt{s}=546$ GeV in the Coulomb interference region The data provide information on the phase of the hadronic amplitude in the forward direction The conventional analysis gives for the ratio ρ of the real to the imaginary part of the hadronic amplitude the result $\rho=0.24\pm0.04$

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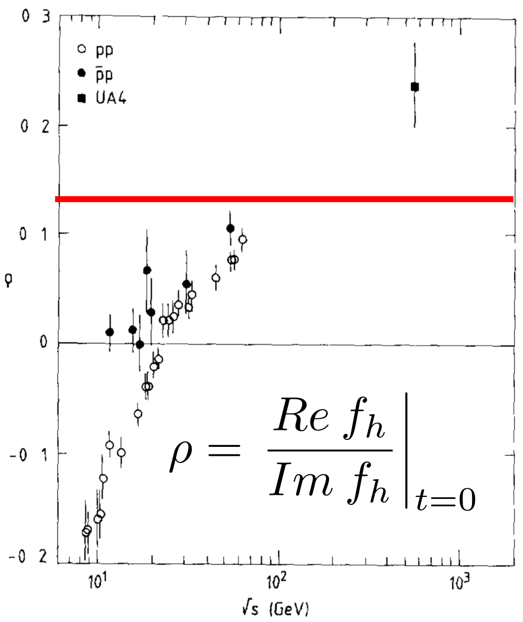


Fig 4 The present result on the parameter ρ is shown together with lower energy data for pp and p̄p elastic scattering

The expected value was $\rho = 0.12$

Knowing that RHIC program was being formulated I decided that this would be a good thing to check at RHIC.

The Gap – Status at the time of the proposal

Highest energy at that time:

pp: 63 GeV (ISR)

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

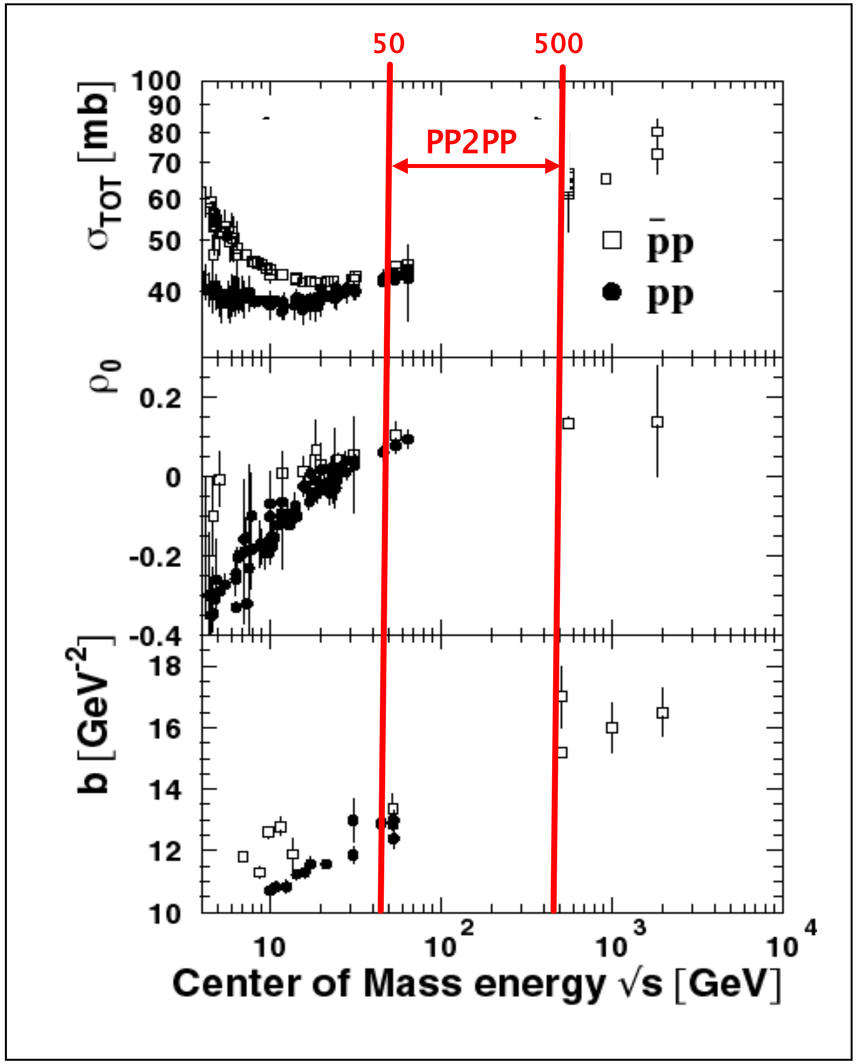
pp2pp energy range:

50 GeV ≤ $\sqrt{s}$ ≤ 500 GeV

$$\rho = \left.\frac{Re\ f_h}{Im\ f_h}\right|_{t=0}$$

$$\sigma_{tot}^2 = \left(\frac{16\pi\,(\hbar c)^2}{1+\rho^2}\right) \left.\frac{d\sigma_{el}^h}{dt}\right|_{t=0}$$

$$f_h = \left(\frac{\sigma_{tot}}{4\pi}\right)(\rho + i)\, e^{-\frac{1}{2}B|t|}$$



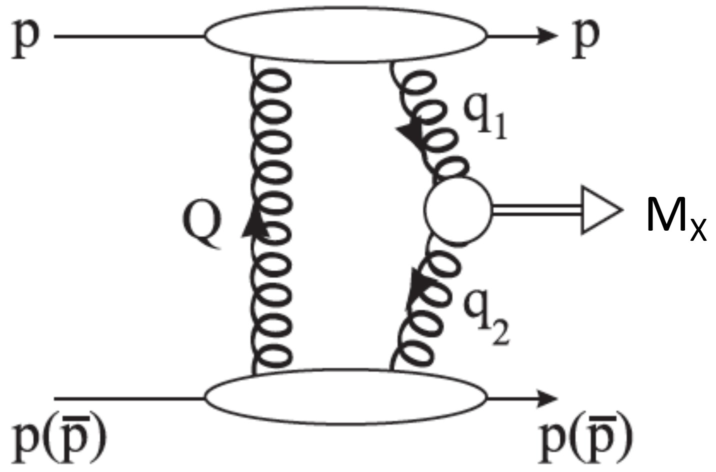
CEP at high energies

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

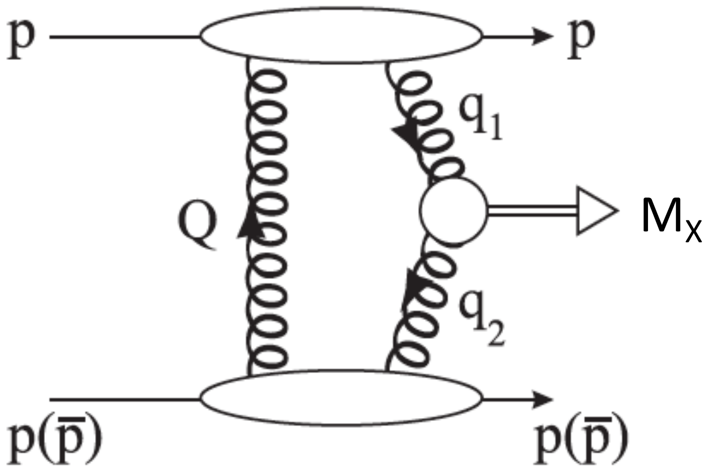
$\sigma_{RR} \sim s^2$

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

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



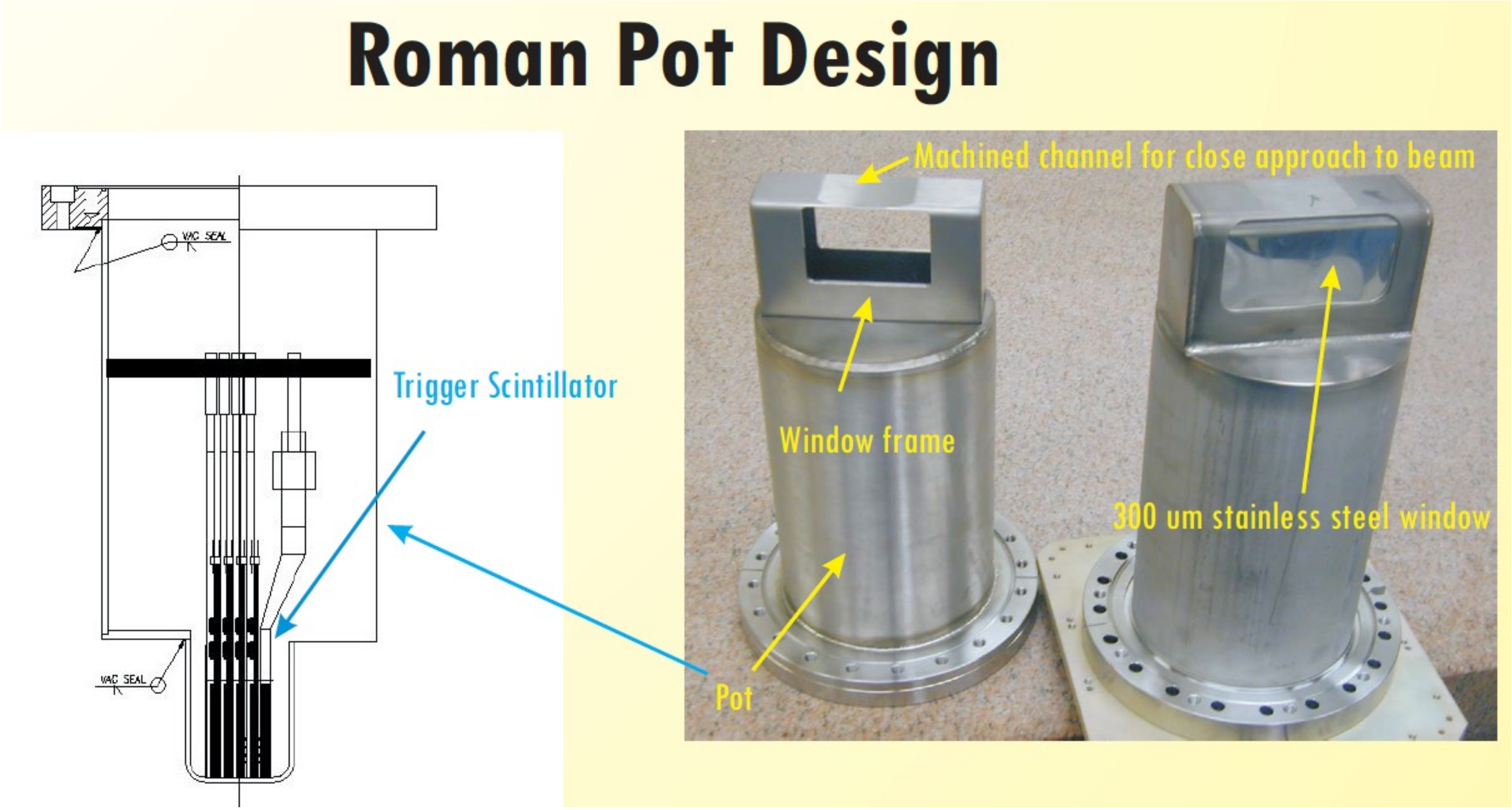
Central Production – Short Summary



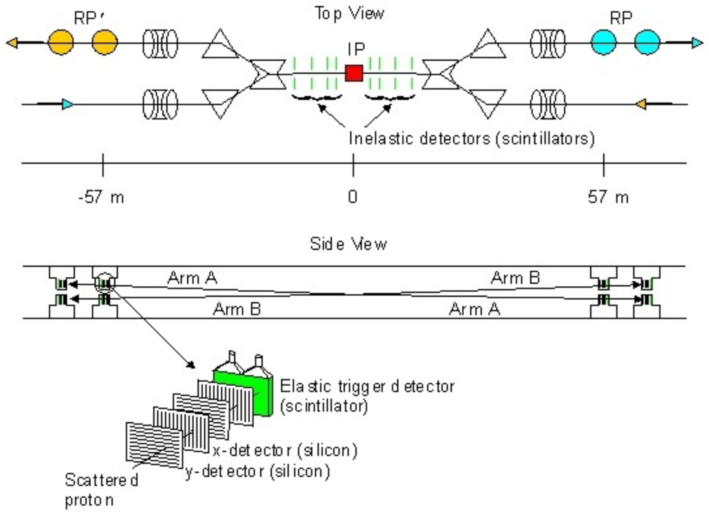
- Colliding protons interact via a colour singlet exchange and remain intact after the interaction.
- In the collider experiment those protons follow magnetic field of the accelerator and remain in the beam pipe.
- A system of mass M_X is produced, whose decay products are present in the central detector region.
- Tagging on forward protons assures rapidity gap (modulo) soft rescattering processes, which fill the gap. Such effect is quantified by gap survival probability factor.

RHIC: Heavy Ion and Polarized Proton – Proton Collider

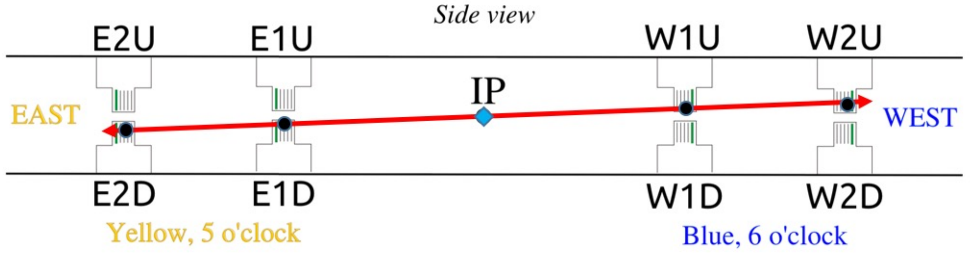
Roman Pot Design – Very Conservative

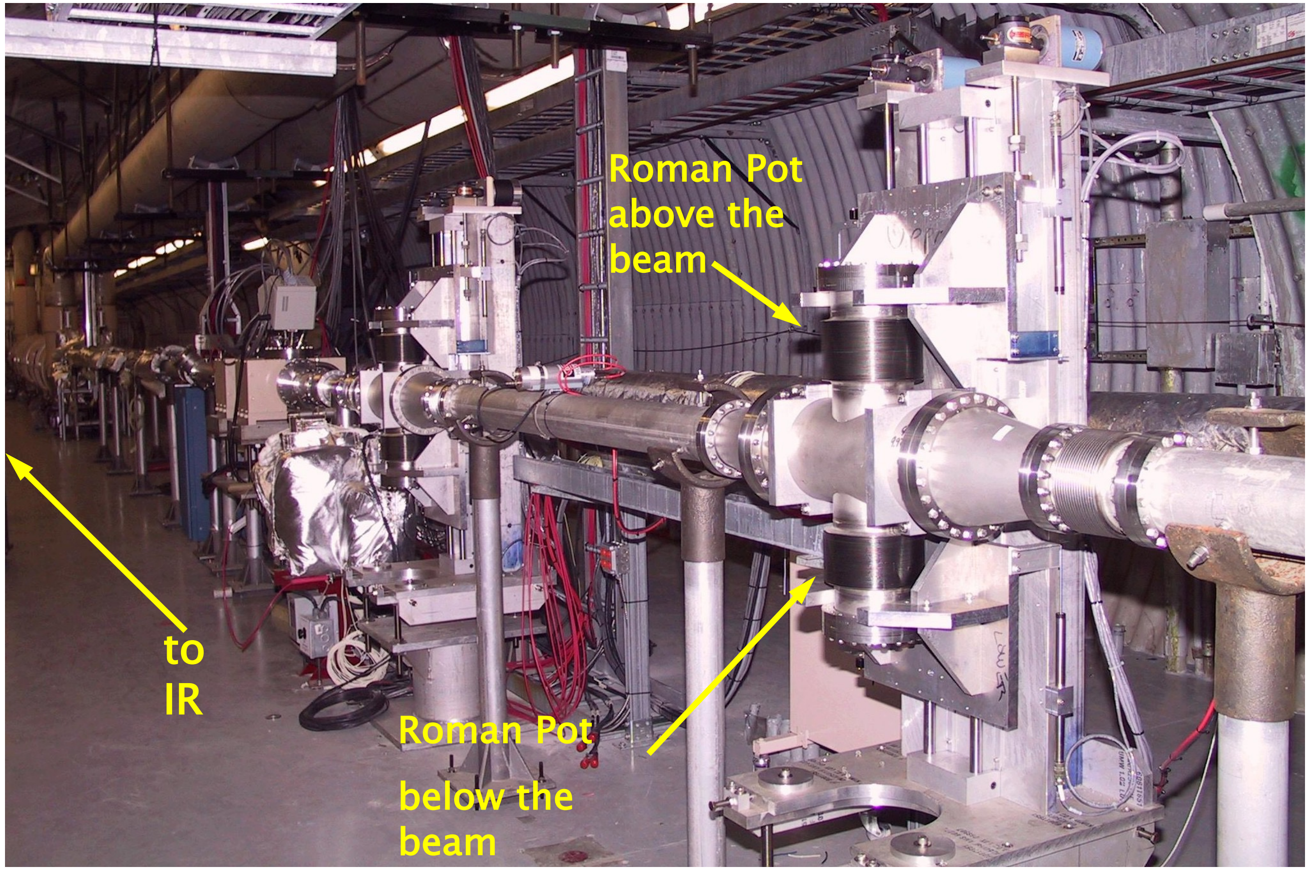


The Setup



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





Spin dependence in elastic scattering

Matrix elements

$\phi_1(s,t) = \langle ++|M|++\rangle$ non–flip

$\phi_2(s,t) = \langle ++|M|--\rangle$ double spin flip

$\phi_3(s,t) = \langle +-|M|+-\rangle$ non–flip

$\phi_4(s,t) = \langle +-|M|-+\rangle$ double spin flip

$\phi_5(s,t) = \langle ++|M|+-\rangle$ single spin flip

$\phi_i(s,t) = \phi_i^{EM}(s,t) + \phi_i^{HAD}(s,t)$

$$\frac{d\sigma}{dt} = \frac{2\pi}{s^2}\left\{|\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2\right\}$$

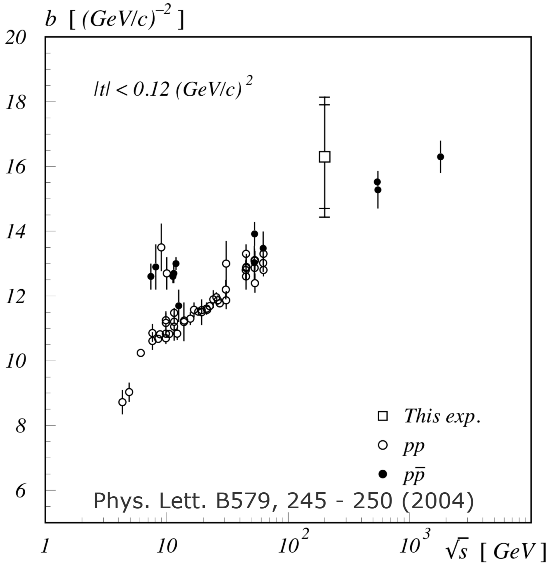
$$A_N(s,t)\frac{d\sigma}{dt} = \frac{-4\pi}{s^2}\mathrm{Im}\left\{\phi_5^*(\phi_1 + \phi_2 + \phi_3 - \phi_4)\right\}$$

$$r_5 = \mathrm{Re}\, r_5 + i\,\mathrm{Im}\, r_5 = \frac{m\phi_5}{\sqrt{-t}\,\mathrm{Im}\phi_+}$$

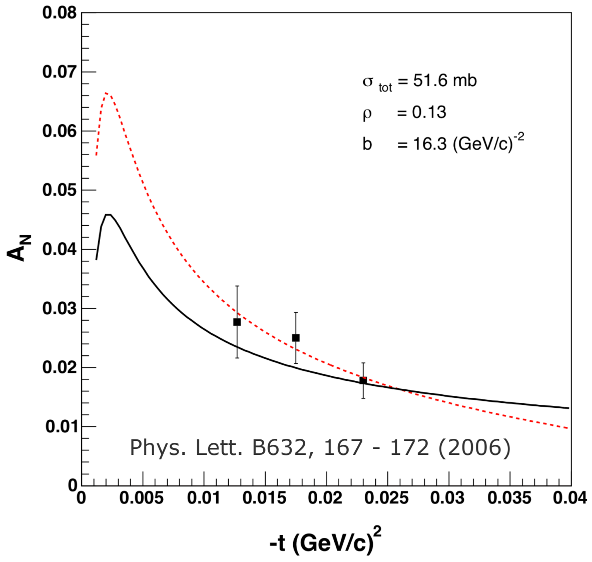
Results from PP2PP: $\sqrt{s} = 200$ GeV

Three papers in PLB

B-slope



A_N



r_5

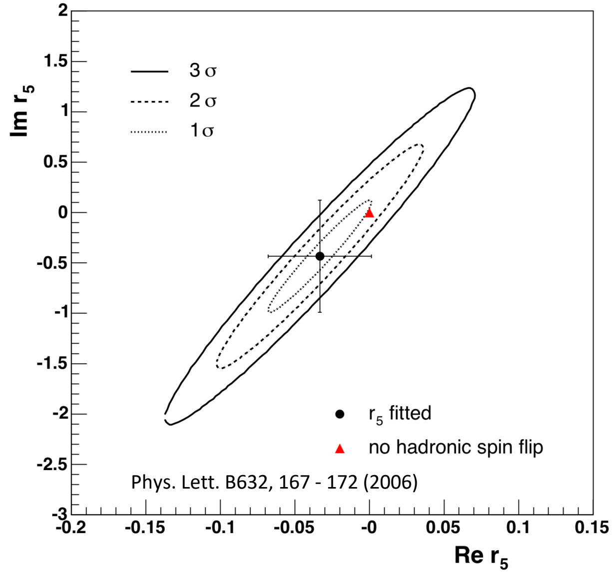


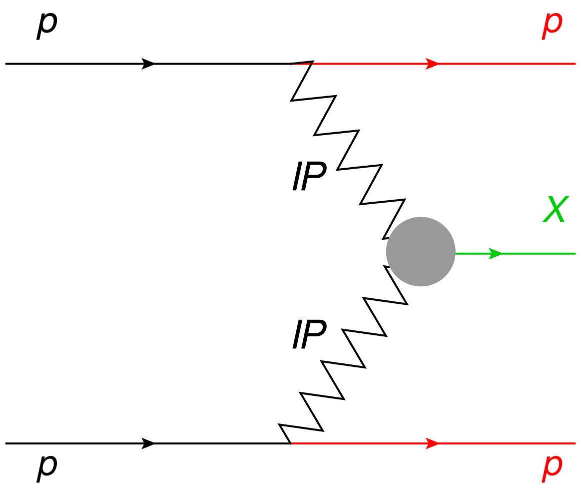
TABLE I: Double spin asymmetries A_{NN}, A_{SS}, $(A_{NN} + A_{SS})/2$ and $(A_{NN} - A_{SS})/2$ for the t-interval $0.010 \le -t \le 0.030$ (GeV/c)^2 at $< -t >= 0.0185$ (GeV/c)^2.

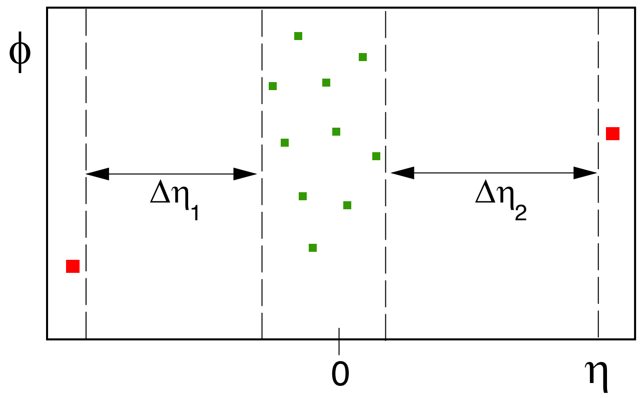
	A_{NN}	A_{SS}	$(A_{NN} + A_{SS})/2$	$(A_{NN} - A_{SS})/2$
$Asym$	0.0298	0.0035	0.0167	0.0131
$\Delta Asym$ (stat.+norm.)	±0.0166	±0.0081	±0.0091	±0.0096
$\Delta Asym$ (syst.)	±0.0045	±0.0031	±0.0034	±0.0072
$\Delta Asym$ due to $\Delta(P_Y \cdot P_B)$	±32.3 %			

Phys. Lett. B647, 98 - 103 (2007)

Move to the STAR experiment

- A big motivation was Central Exclusive Production (CEP) to take advantage of combining Roman Pots of the PP2PP experiment with the STAR's capabilities to measured central system.
- Elastic scattering program also continued.





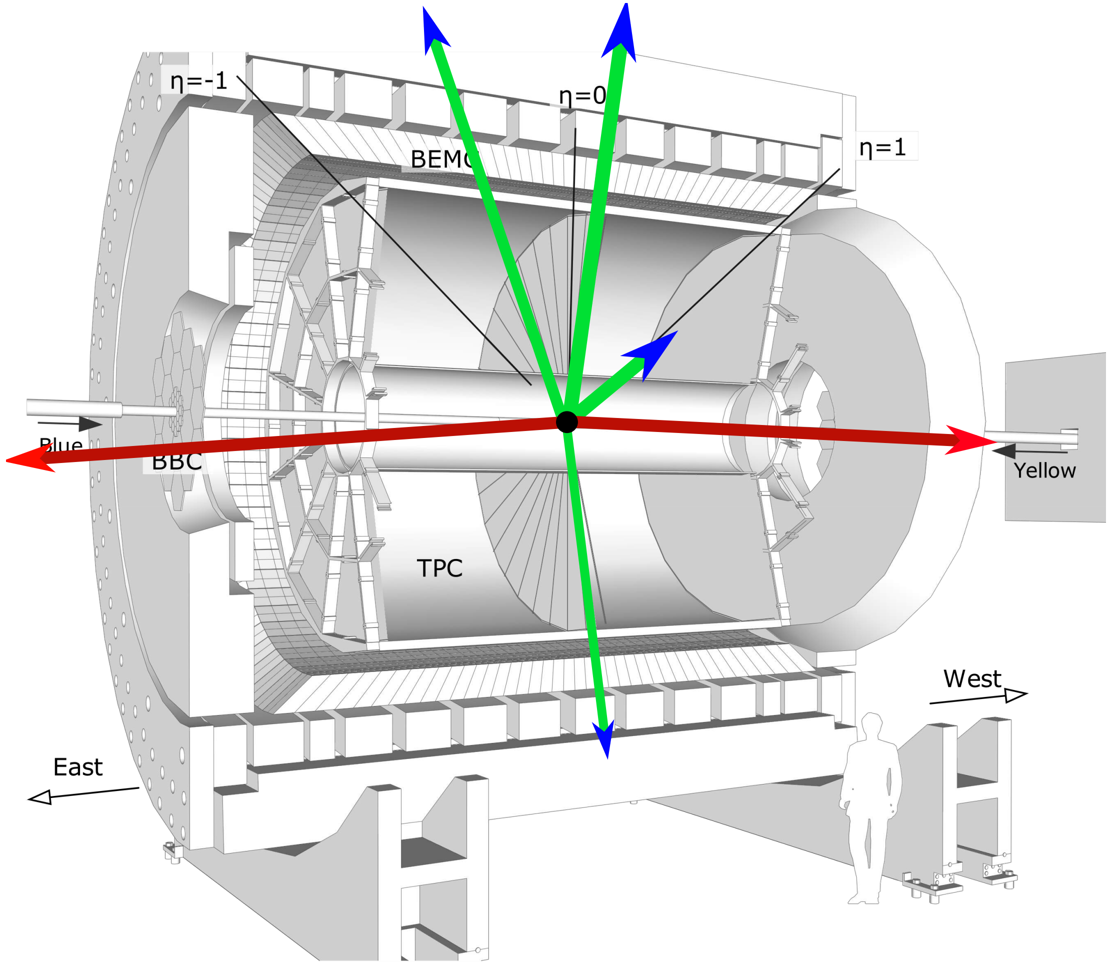
Need a detector with particle ID and good acceptance

Detector at RHIC, which has good acceptance and charged particle ID to measure central system: STAR

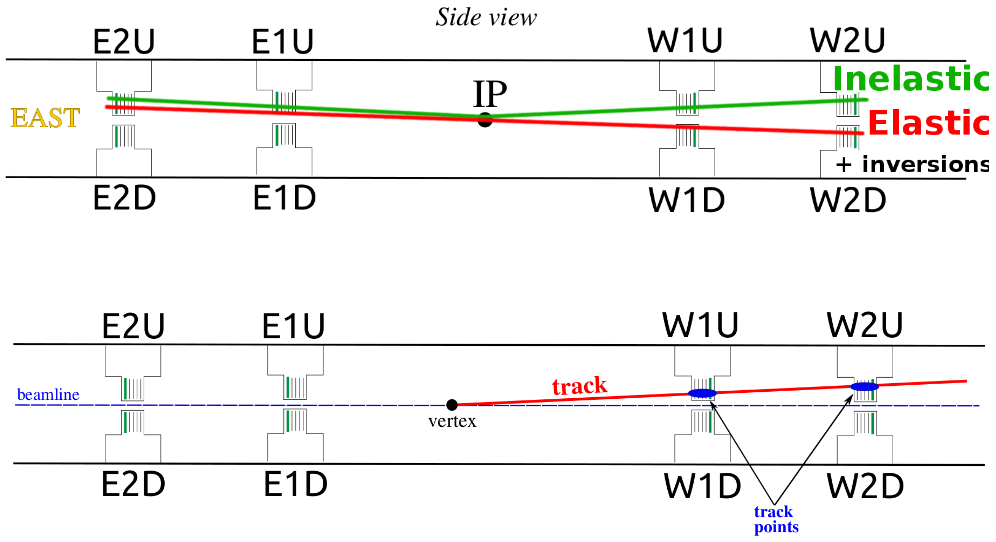
Large acceptance detector running since 2000

- High resolution tracking device with particel ID: TPC in $-1<\eta<1$, $-\pi<\varphi<\pi$;
- Highly segmented ToF sysytem;
- Forward rapidity gap veto;
- BBC: $3.8<|\eta|<5.2$

CEP at STAR: Combine Excellent PID of STAR with Forward Proton Measurement of PP2PP



Roman Pots

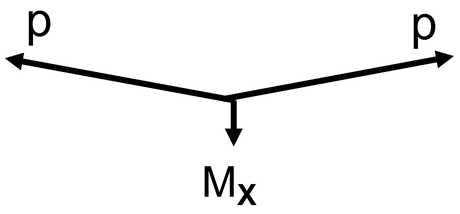


Roman Pot setup moved to STAR and PP2PP became part of the STAR experiment. Elastic scattering is also part of the physics program.

Central Exclusive Production in DPE

In the Central Exclusive Production process there is a momentum balance between the central system M_X and the outgoing protons.

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



For each proton vertex one has

t four-momentum transfer

$\xi = \Delta p/p$

The massive system could form resonances. We expected 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.

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Single spin A_N asymmetry result

Matrix elements

$\phi_1(s,t) = \langle ++ | M | ++ \rangle$ non–flip

$\phi_2(s,t) = \langle ++ | M | -- \rangle$ double spin flip

$\phi_3(s,t) = \langle +- | M | +- \rangle$ non–flip

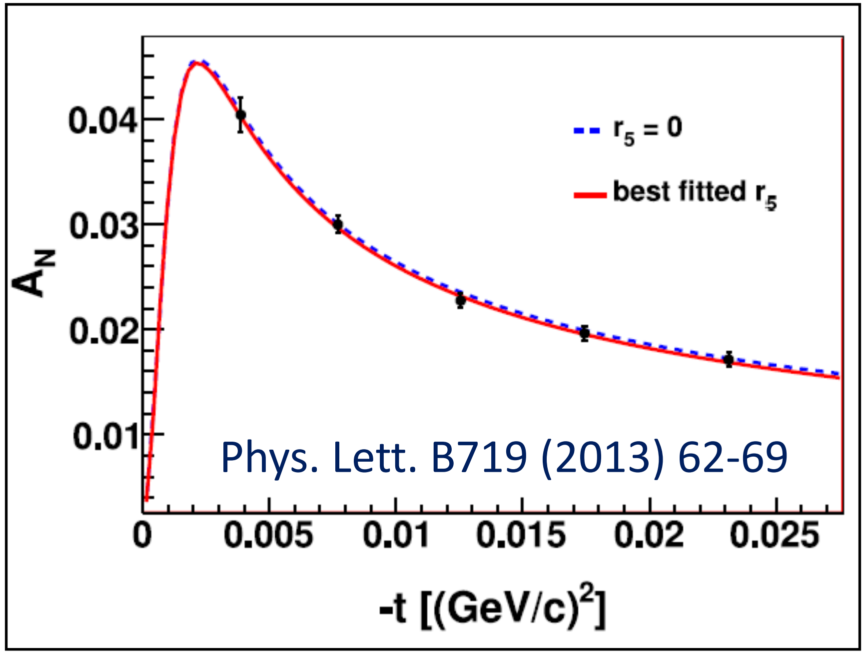
$\phi_4(s,t) = \langle +- | M | -+ \rangle$ double spin flip

$\phi_5(s,t) = \langle ++ | M | +- \rangle$ single spin flip

$$\phi_i(s,t) = \phi_i^{EM}(s,t) + \phi_i^{HAD}(s,t)$$

$$\frac{d\sigma}{dt} = \frac{2\pi}{s^2}\left\{|\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2\right\}$$

$$A_N(s,t)\frac{d\sigma}{dt} = \frac{-4\pi}{s^2}\mathrm{Im}\left\{\phi_5^*(\phi_1 + \phi_2 + \phi_3 - \phi_4)\right\}$$

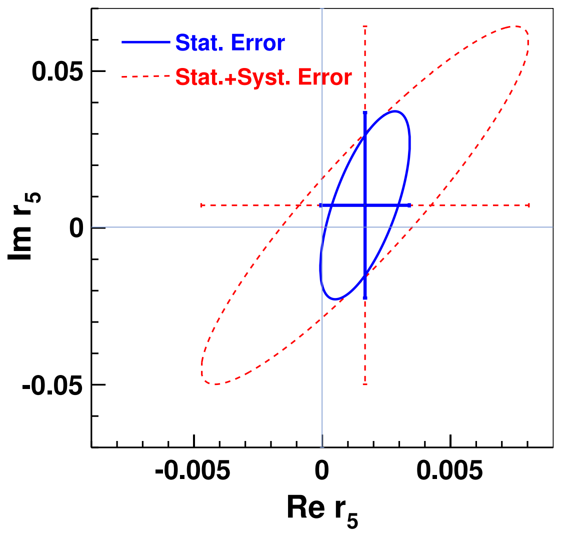


Re r_5 = 0.0017 +-0.0017 (stat.) +-0.061 (syst.)
Im r_5 = 0.007 +-0.03 (stat.) +- 0.049 (syst.)

Pomeron spin-flip is consistent with zero

Result on A_N – Comparison with Models and World Data

Re r_5 = 0.0017 +-0.0017 (stat.) +-0.061 (syst.)
Im r_5 = 0.007 +-0.03 (stat.) +- 0.049 (syst.)



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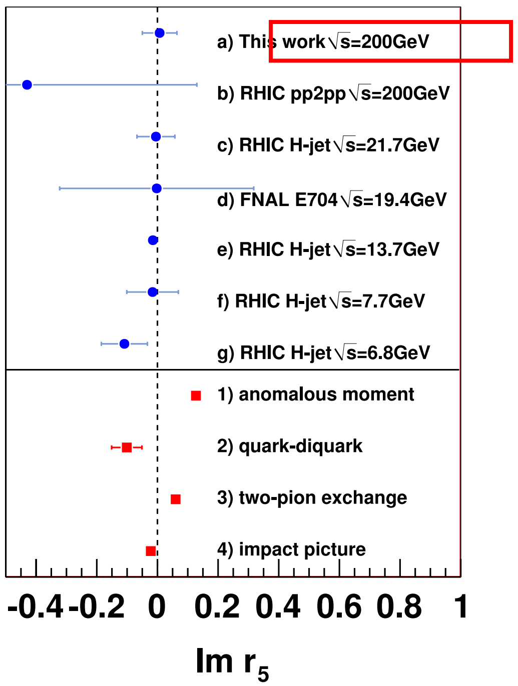
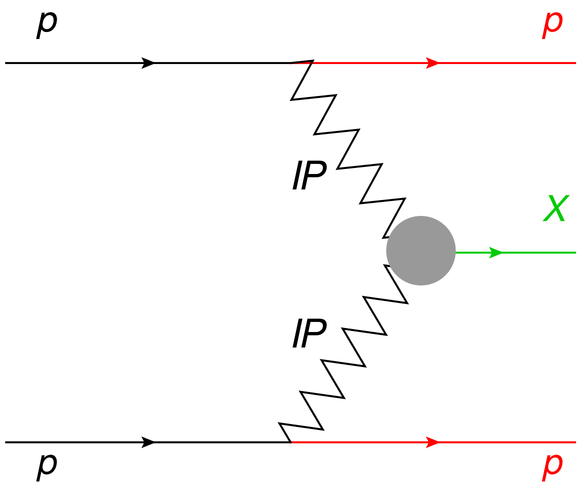


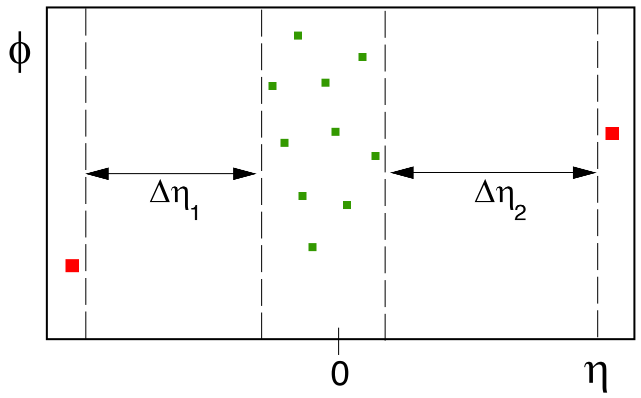
Pomeron spin-flip is consistent with zero

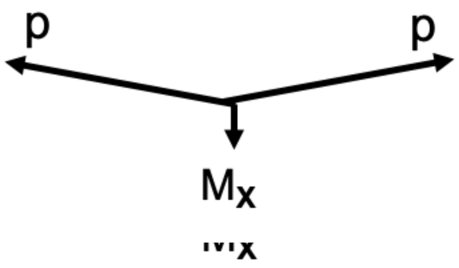
Central Exclusive Production (CEP)

Exclusive means that all particles in the final state are measured

pp => p X p







For each proton vertex one has

t four-momentum transfer

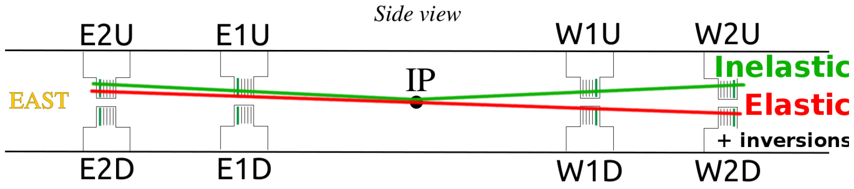
$\xi = \Delta p/p$

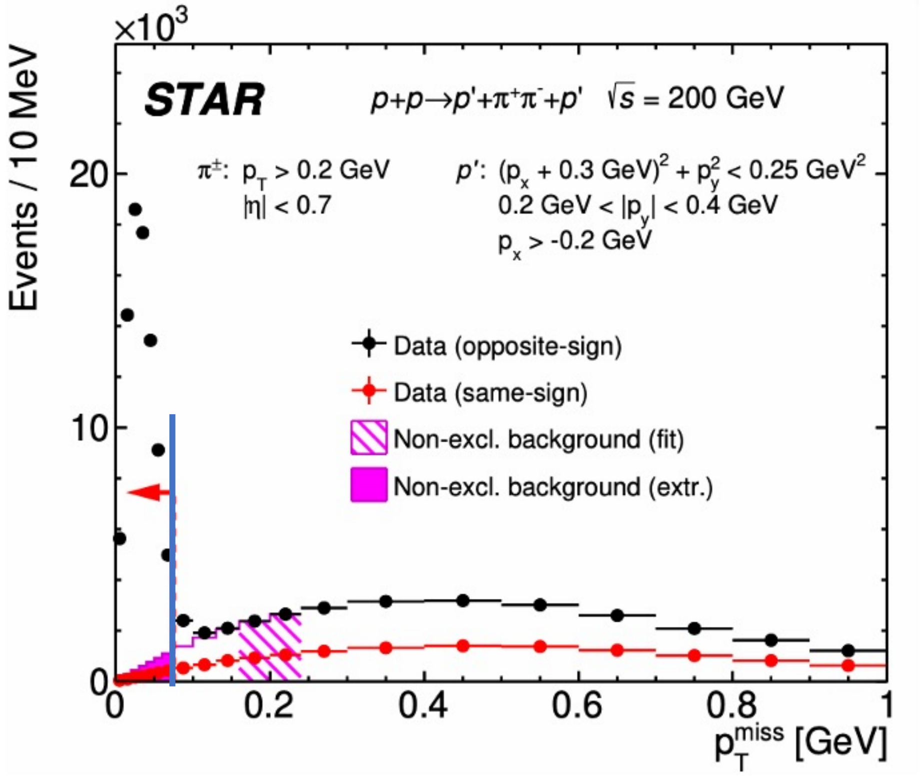
M_X invariant mass

- In terms of QCD, Pomeron exchange consists of the exchange of a color singlet combination of gluons.
- Hence, triggering on forward protons at high (RHIC) energies predominantly selects exchanges mediated by gluonic matter.

Event Cuts for pp => p $\pi^+\pi^-$ p

Roman Pots

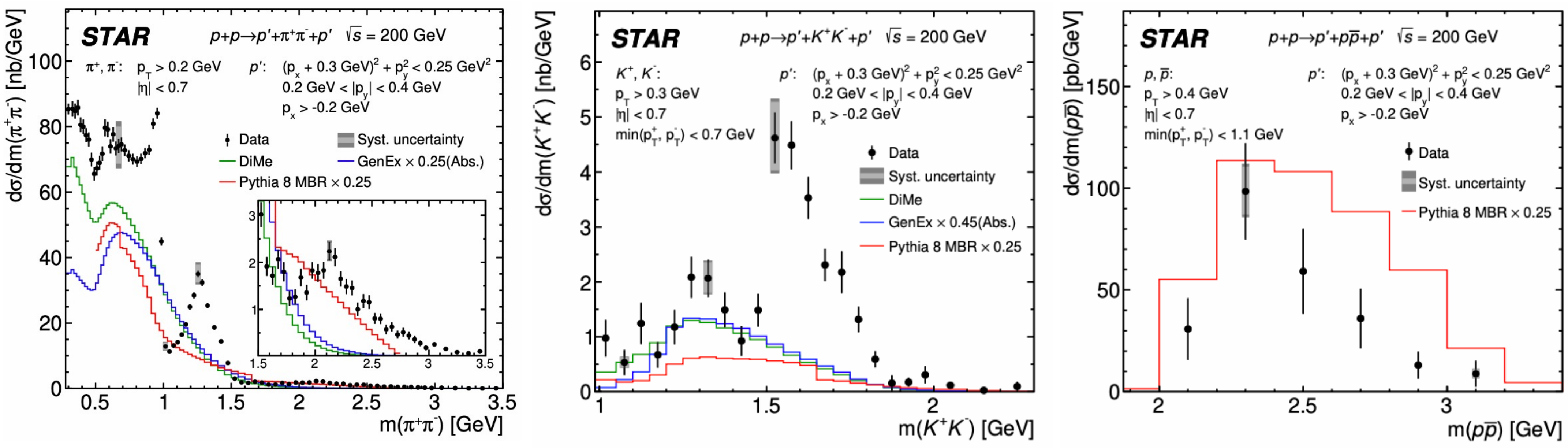




1. Only Elastic or Inelastic combination of protons in Roman Pots were accepted
2. Exactly 2 good quality tracks in Roman Pots (one per side, all 8 planes were used)
3. Exactly 2 primary TPC tracks from the same vertex
4. 2 TOF hits matched with tracks from TPC
5. Total charge of tracks = 0
6. No cuts on TPC/TOF track quality
7. Missing transverse momentum of all measured particles p_T^{miss} < 70 MeV/c to assure exclusivity
8. PID for $\pi^+\pi^-$ based on dE/dx and ToF

Results on CEP: $\pi^+\pi^-$, K^+K^-, $p\bar{p}$ production at $\sqrt{s}$ = 200 GeV

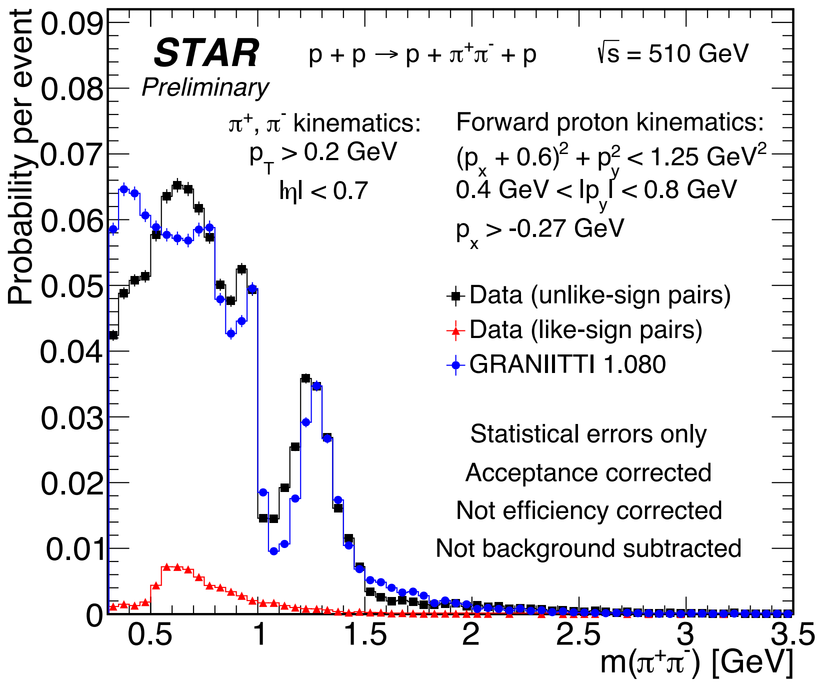
J. High Energy Phys. **2020,** 178 (2020)

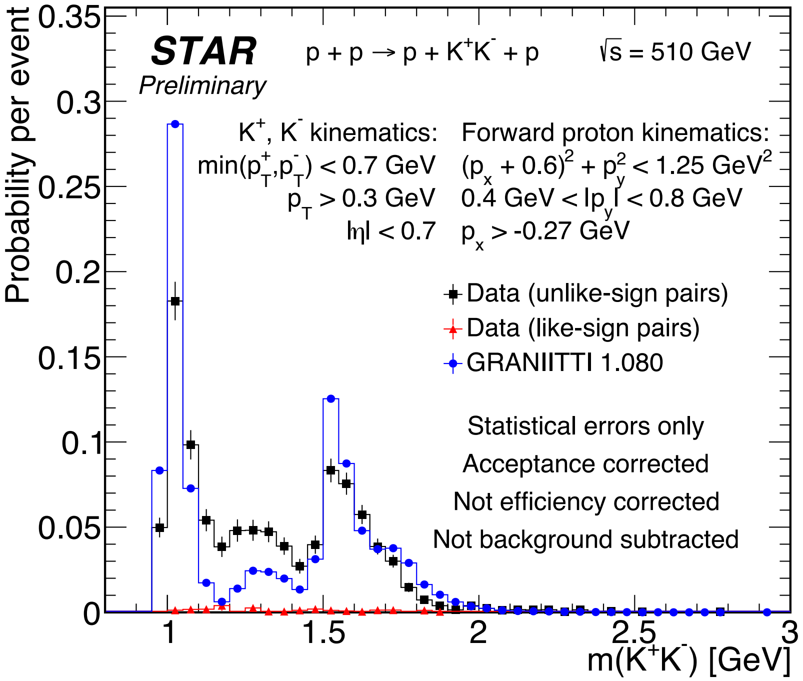


1. In $\pi^+\pi^-$ spectrum drop at f0(980), a peak at f2(1270) MeV and structure at about 2200 MeV , are observed.
2. Comparison with various continuum production models will help fine tune those models .

Results on CEP at $\sqrt{s} = 510$ GeV: $\pi^+\pi^-$ and K^+K^- spectra

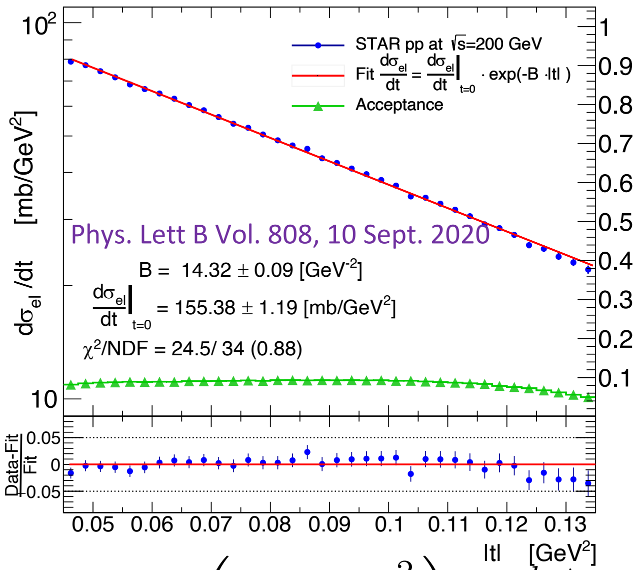
Tomas Truhlar, PhD student at CTU Prague work in progress

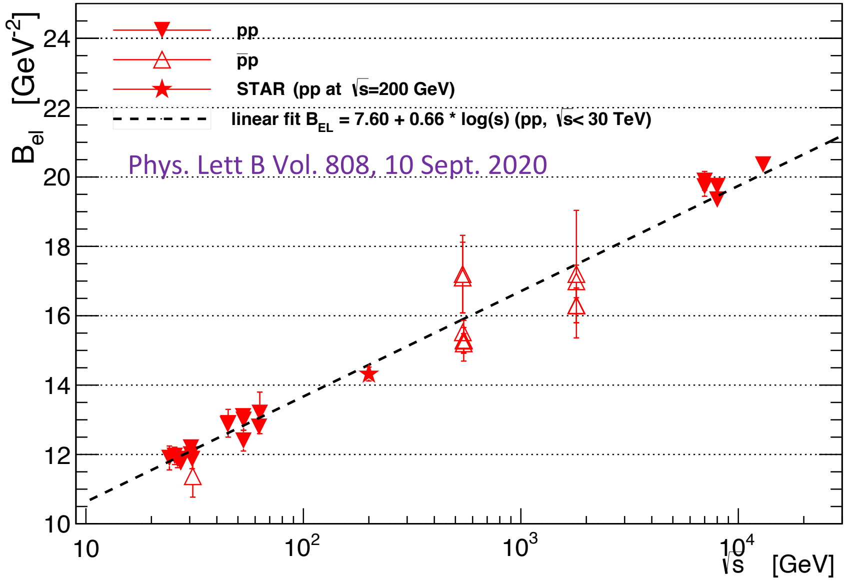




1. Features like those at $\sqrt{s}$ = 200 GeV are observed
2. Increased statistics for K^+K^- channel
3. Both compare well with the Graniitti simulator

Results on Elastic scattering: $\sqrt{s} = 200$ GeV B-slope and σ_{tot}

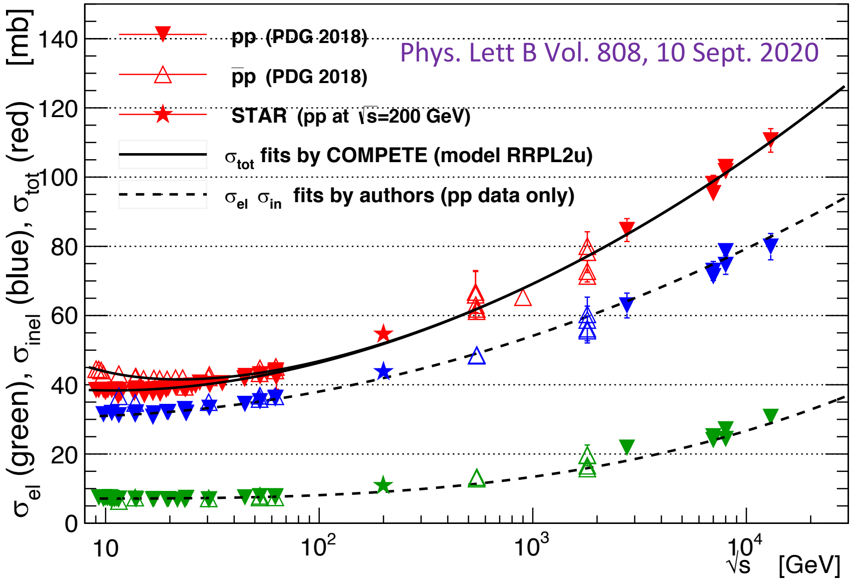




Use optical theorem to obtain σ_{tot}

$$\sigma_{tot}^2 = \left(\frac{16\pi\,(\hbar c)^2}{1+\rho^2}\right) \left.\frac{d\sigma_{el}^h}{dt}\right|_{t=0}$$

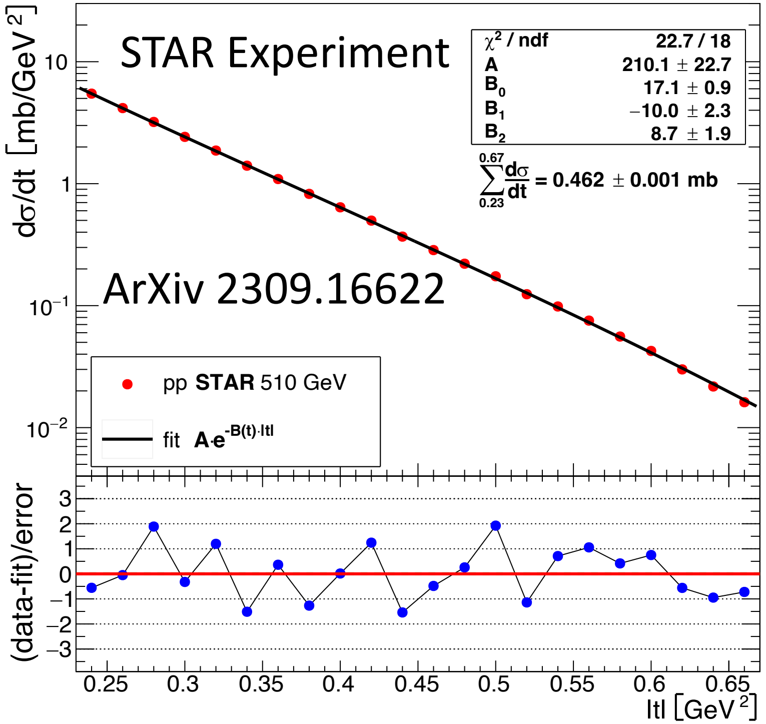
σ_{tot}=54.67±0.21(stat.)+1.28−1.38(syst.)



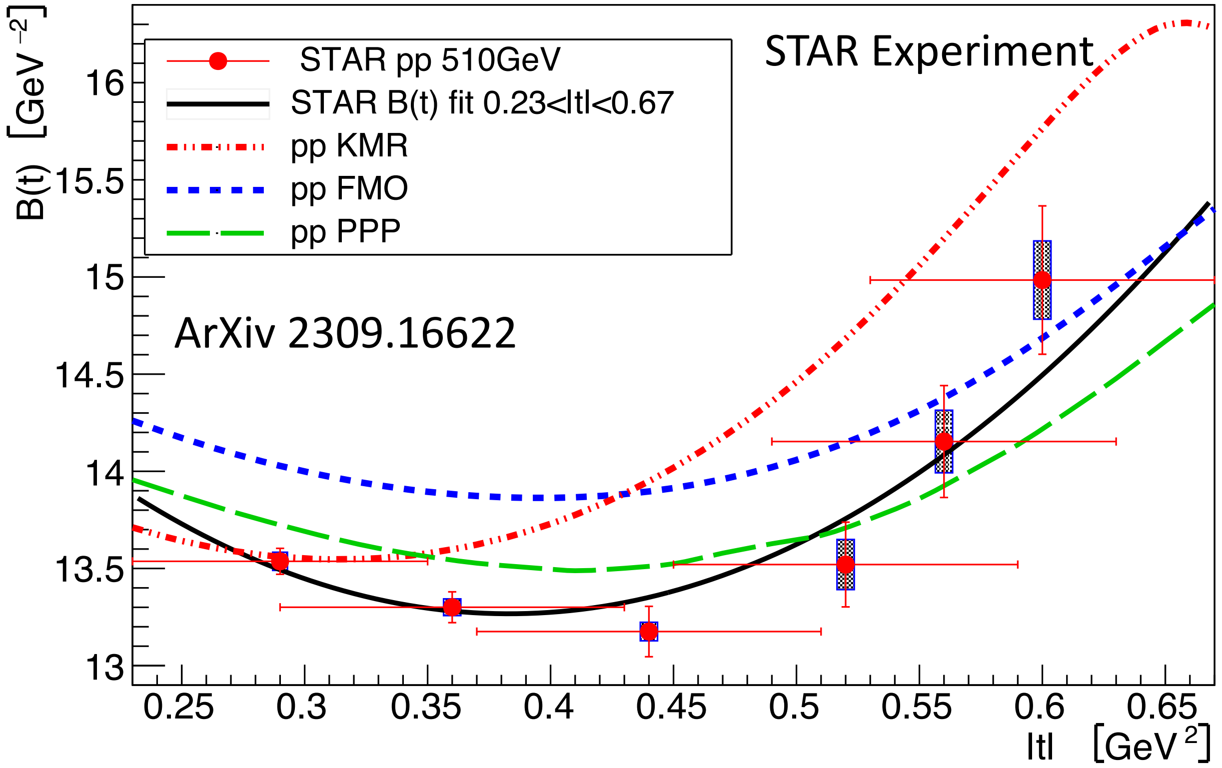
1. STAR obtained results on total, elastic and inelastic cross section in proton-proton collisions at √s = 200 GeV.
2. The results are within 2σ of the World data – fits do not include STAR data points.
3. This measurement "fills" the gap between results from CERN ISR (62 GeV) and TeV energies at the LHC.

Results at 510 GeV: shape of dσ/dt

$0.23 \leq -t \leq 0.67\ GeV^2$



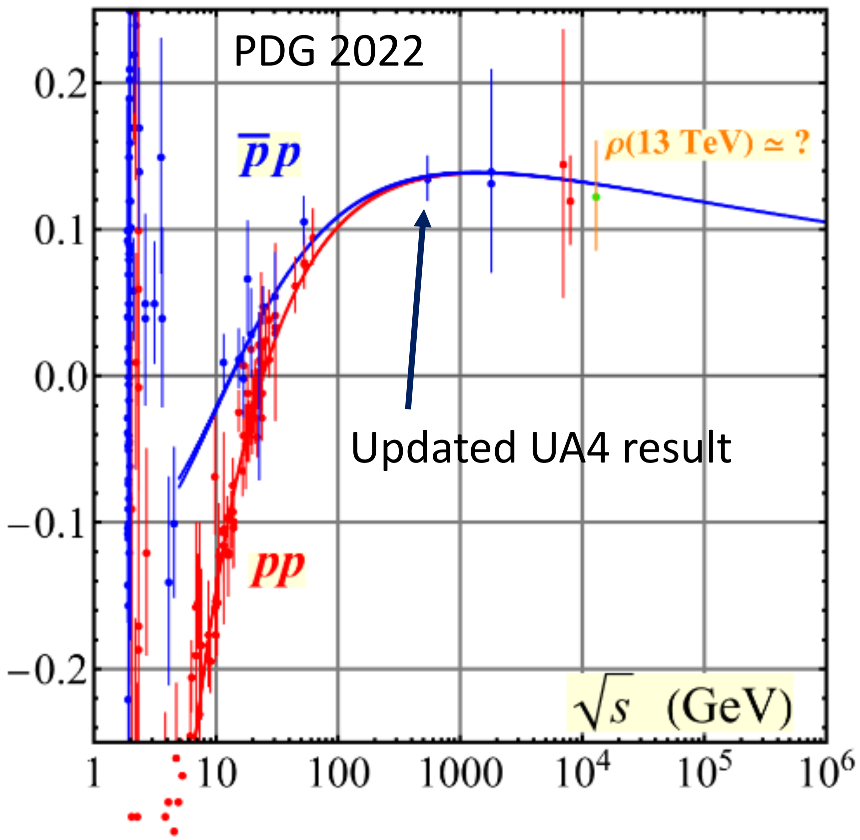
Top panel: The *pp* elastic differential cross section *dσ/dt* fitted with an exponential $Ae{-}B(t)|t|$ with $B(t)$ as in Eq. 12. Bottom panel: Residuals (Data4 - Fit)/Error. The uncertainties on the data points are smaller than the symbol size.



Comparison of the STAR *pp* result in six *t* sub-intervals with three models: FMO [24], KMR [27] and PPP [28]. The black line is fit to the full data set as described in Eq. 12. The horizontal size of the error bars indicates the *t* range where *B* = const. was fitted. The vertical size of the shaded rectangles indicate the systematic uncertainty of the STAR data points.

In the ***t*** range of this measurement the exponential slope B(t) has a quadratic dependence on ***t***

Back to the ρ measurements



The ρ puzzle was resolved before RHIC started.

Now at the LHC history repeats itself.

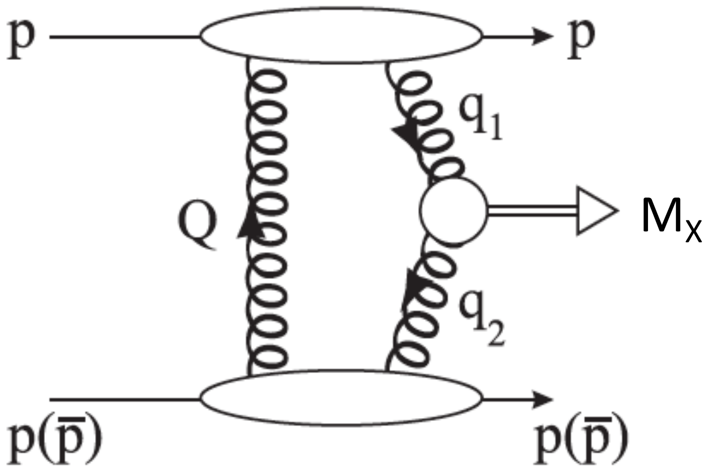
Summary

1. The program with forward protons at RHIC delivered many important results
2. What started as a stand-alone experiment evolved into a more comprehensive physics program with the STAR detector
3. Results included:
   - Elastic scattering and its spin dependence at √s = 200 GeV
   - A very comprehensive study of CEP at √s = 200 GeV was performed, which will affect phenomenological models
4. Total cross section measurement at √s = 200 GeV
5. Measurement of pp elastic cross section at √s = 510 GeV
6. Measurement od double spin asymmetry A_{NN} in pp at √s = 200 GeV
7. Differential cross section measurement at √s = 510 GeV
8. Study of CEP at √s = 510 GeV

This reach program would not happen if not for the ρ–measurement by UA4

BACKUP

Production Processes of Interest in CEP

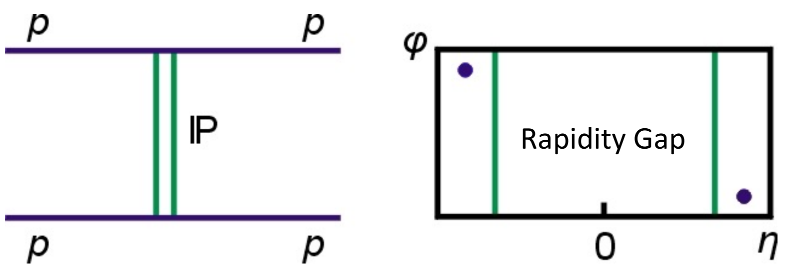


$M_X = \pi^+\pi^-, \chi_c(\chi_b)$, qq(jets), H(Higgs boson), gg(glueball)

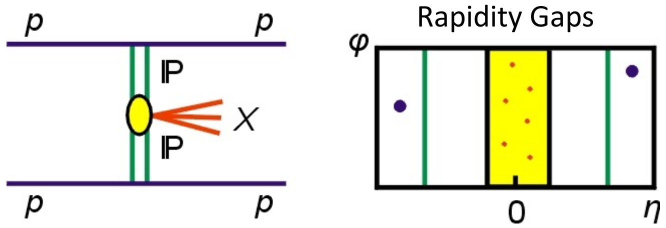
CEP is a promising way to study the physics of new particles (e.g. SM/SUSY Higgs, techniparticles...) at the LHC .

CEP is also a good tool to study lighter, better understood objects, e.g. χ_c, χ_b, $\gamma\gamma$ and jj production as well as expected gg systems (glueballs)

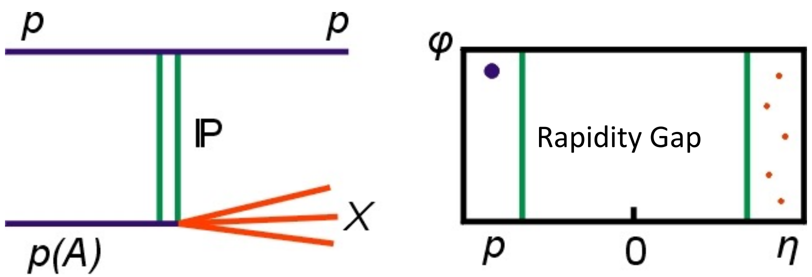
Few Examples – Elastic and Inelastic Processes



Elastic: p + p → p + p



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



SDD: p + p → p + X

For each proton vertex one has

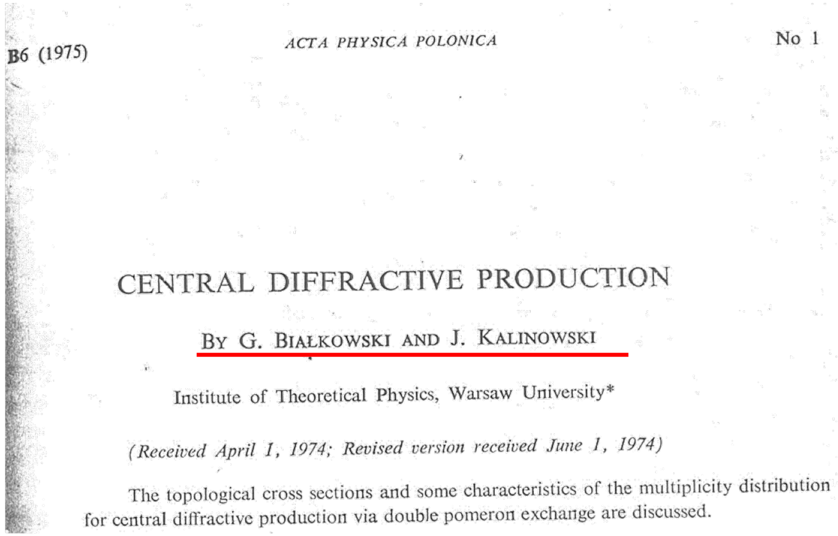
t four-momentum transfer

$\xi = \Delta$**p/p**

M_X invariant mass

In terms of QCD, Pomeron exchange consists of the exchange of a color singlet combination of gluons. Hence, triggering on forward protons at high (RHIC) energies predominantly selects exchanges mediated by gluonic matter.

This topic has a long history



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CENTRAL DIFFRACTIVE PRODUCTION

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

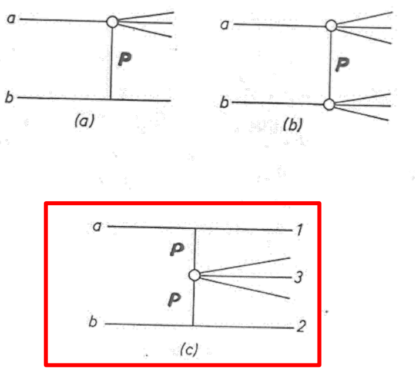
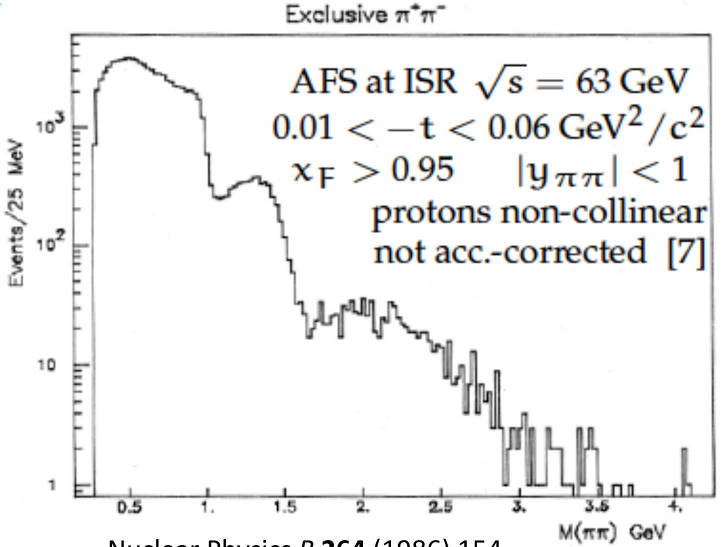


Fig. 1 a) Single diffractive excitation, b) double diffractive excitation,c) centr diagrams



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Recent summary and history of Central Exclusive Production (CEP) in:

International Journal of Modern Physics A, Volume: 29, Number: 28 (10 November 2014), Central Exclusive Production in Hadron–Hadron Collisions; Guest Editors: M. Albrow, V. Khoze and C. Royon