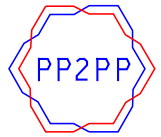
From Elastic Scattering to Central Exclusive Production: Physics with Froward Protons at RHIC

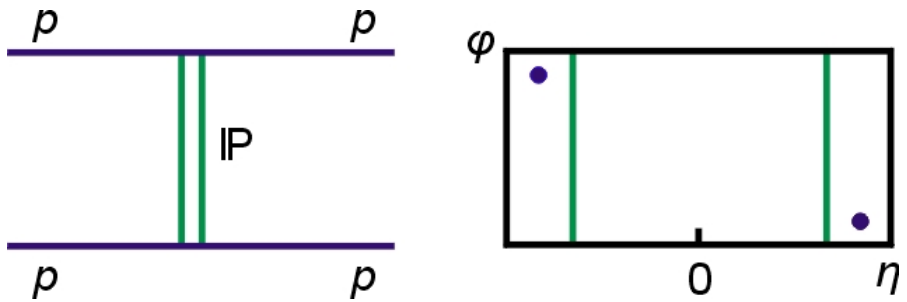
Włodek Guryn
Brookhaven National Laboratory

1. Elastic Scattering
2. PP2PP experiment – Roman Pots and first results
3. Move to STAR experiment
4. Results at STAR
5. Summary and future

Some of the earlier results have been shown at this conference, which has been a very welcoming venue for this physics – Thank You!



Proton – Proton Elastic Scattering



p + p → p + p

$$\frac{d\sigma}{dt} = \pi |f_c + f_h|^2$$

four-momentum transfer squared: $t = (p_1 - p_3)^2 \approx p^2\theta^2$

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

$$f_c = -\frac{2\alpha G_E^2(t)}{|t|} e^{i\alpha\phi}$$

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

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

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)

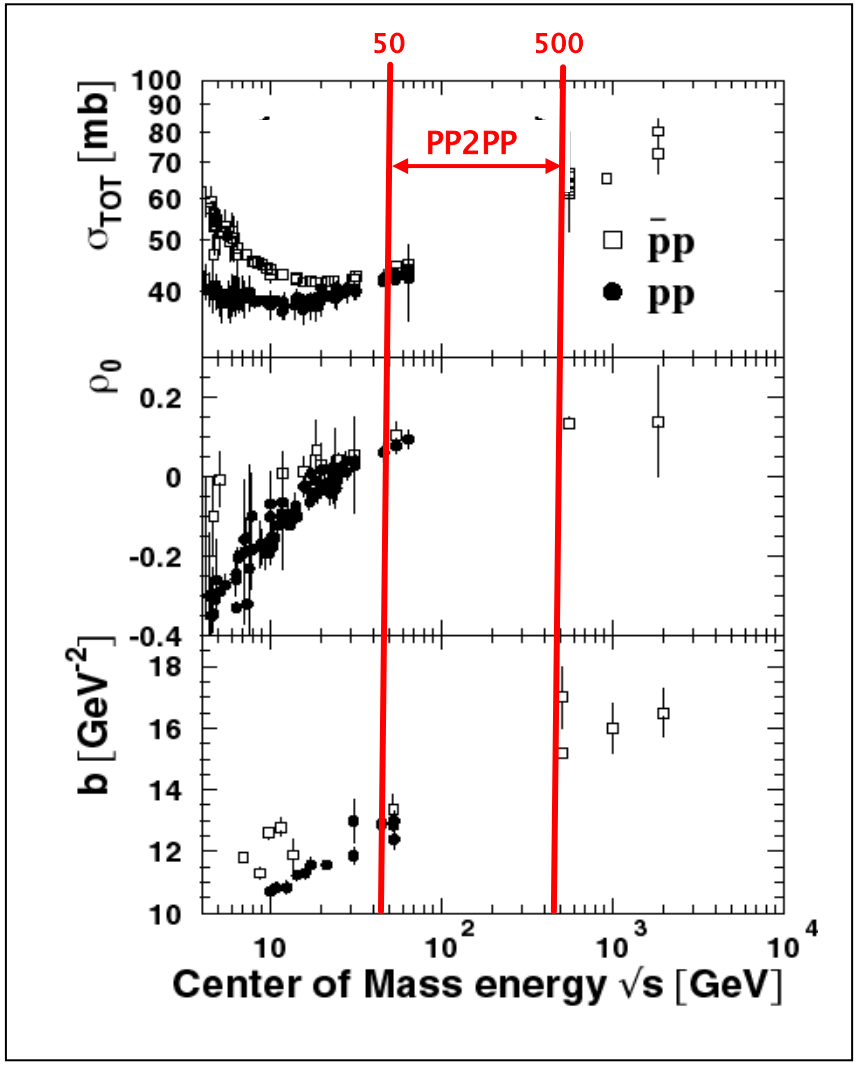
pp2pp energy range:

50 GeV $\leq \sqrt{s} \leq$ 500 GeV

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

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

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



RHIC: Heavy Ion and Polarized Proton – Proton Collider

The Collaboration: LOI #1 at RHIC

TOTAL and ELASTIC pp CROSS SECTIONS AT RHIC

W. Guryn*, M. Sakitt, S. Tepikian
Brookhaven National Laboratory, USA

J. Bourotte, M. Haguenauer
Ecole Polytechnique/IN3P3-CNRS, Palaiseau, France

M. Bozzo, M.Conte, G.Setteo
Universita di Genova and Sezione INFN, Genova, Italy

S. Majewski, C. Zorn
CEBAF, USA

N. Akchurin
University of Iowa, USA

G. Matthiae
University of Rome, Italy

A. Penzo, P. Schiavon
INFN-Trieste, Italy

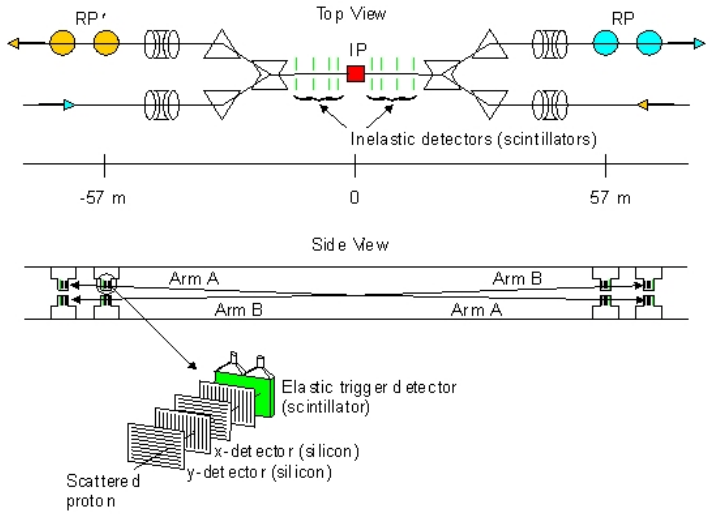
*spokesperson

Abstract

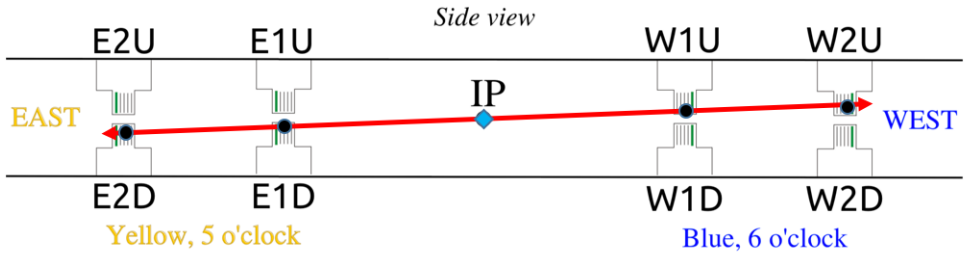
We are proposing to study proton-proton (pp) elastic scattering scattering at $\sqrt{s} = 500$ GeV. The lattice configuration and the angular coverage of the detector will allow the simultaneous study of all three regions that characterize elastic scattering, namely the Coulomb dominated region, the Coulomb-hadronic interference region and the hadronic dominated region, for four momentum transfer t in the range $0.0005 < t < 0.12 GeV/c^2$. The case for the large t up to $6 GeV/c^2$ is also presented. Application to the case of polarized beams is also discussed.

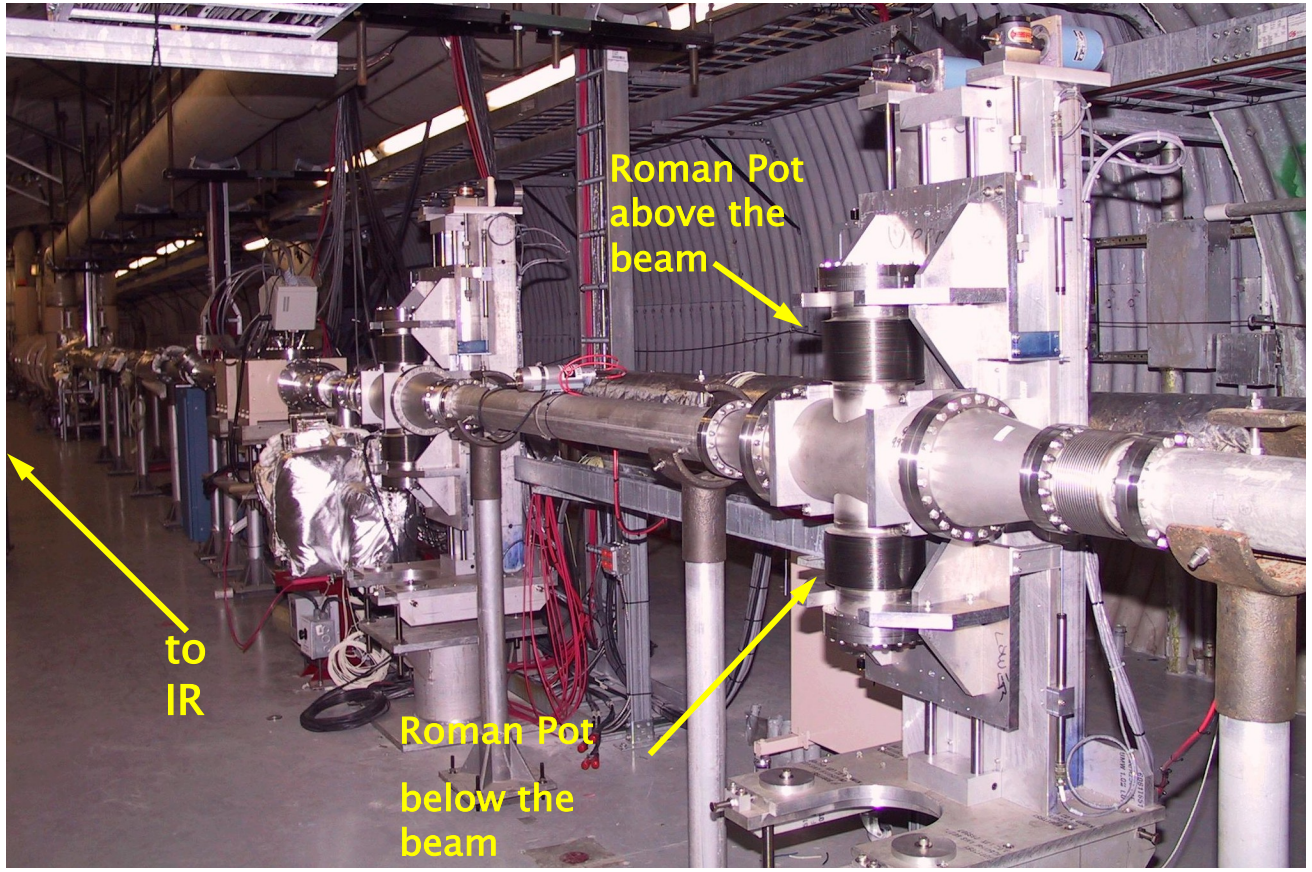
- We had very smart and competent people who were attracted to a small experiment at a world class facility – this was crucial. This included IFJ and AGH-UST from Krakow.
- We were also lucky to get support from many people not on PP2PP but who were interested enough to find time to solve many technical issues and participate in construction – also very crucial.

The Setup



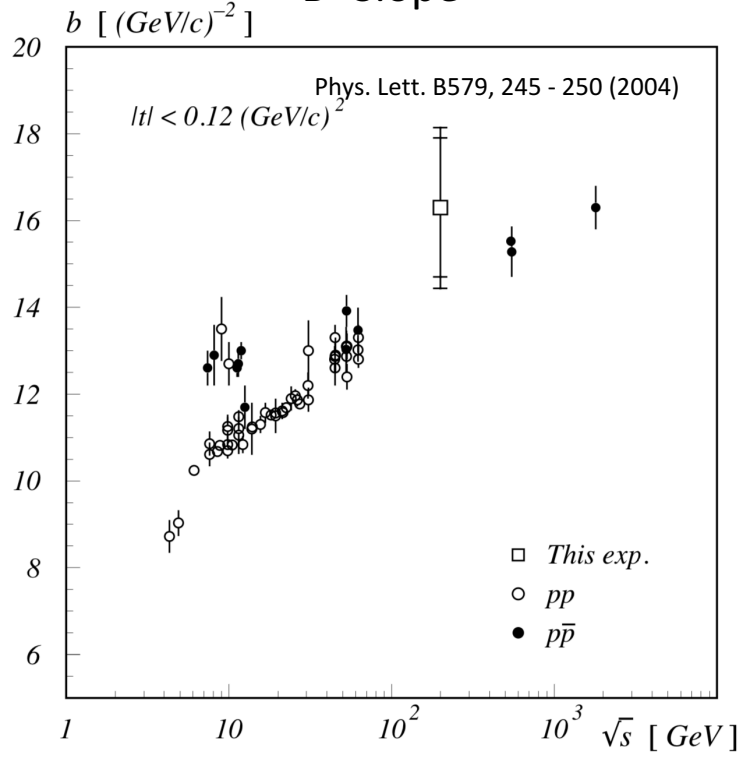
$$\vec{p}_1 = -\vec{p}_2 \Rightarrow (\Theta_x^1, \Theta_y^1) = (-\Theta_x^2, -\Theta_y^2)$$





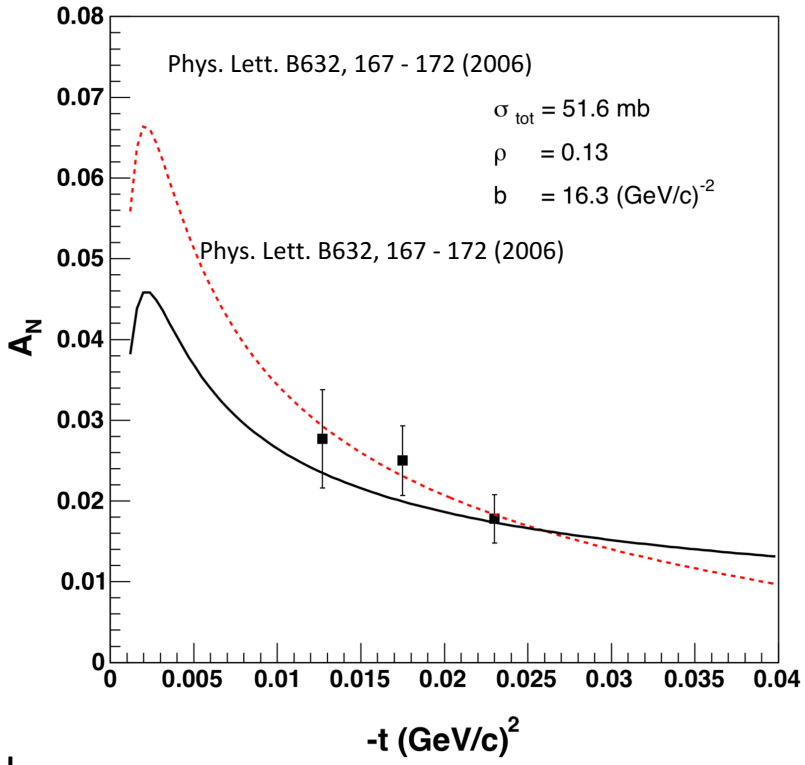
Results from PP2PP at small -t

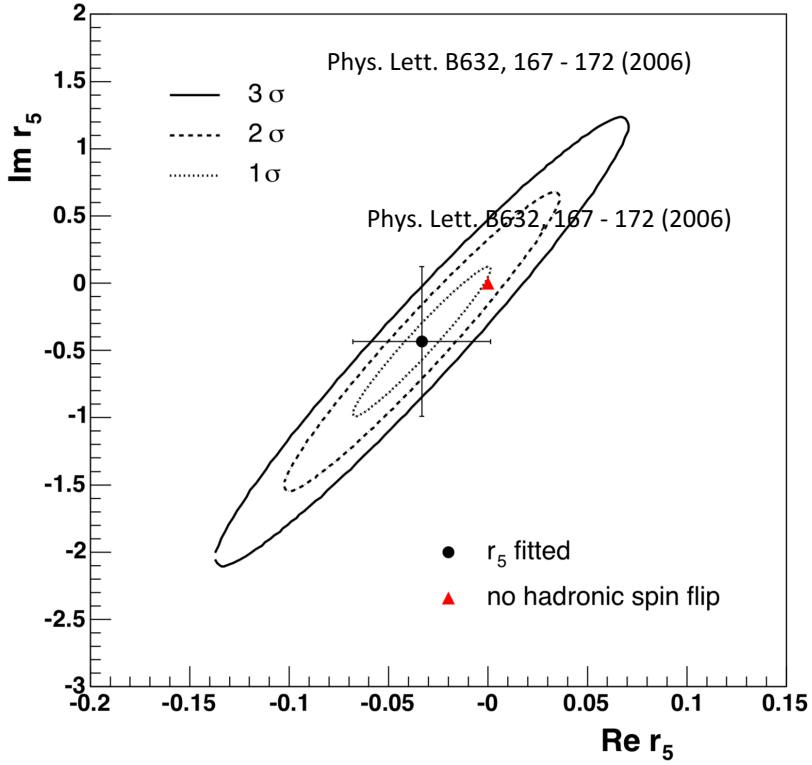
B- Slope



Nuclear Slope B – consistent with world data (relatively large uncertainty due to limited running time)

Single spin asymmetry A_N





Single spin analyzing power A_N => Hadronic spin-flip (r_5)
r_5 consistent with zero

Results from PP2PP ctnd.

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

	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.)	$\pm$0.0166	$\pm$0.0081	$\pm$0.0091	$\pm$0.0096
$\Delta Asym$ (syst.)	$\pm$0.0045	$\pm$0.0031	$\pm$0.0034	$\pm$0.0072
$\Delta Asym$ due to $\Delta(P_Y \cdot P_B)$	$\pm$32.3 %			

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

Double spin asymmetry A_{NN} consistent with zero

Three papers published in PLB

Then the 2006 RHIC funding crisis came

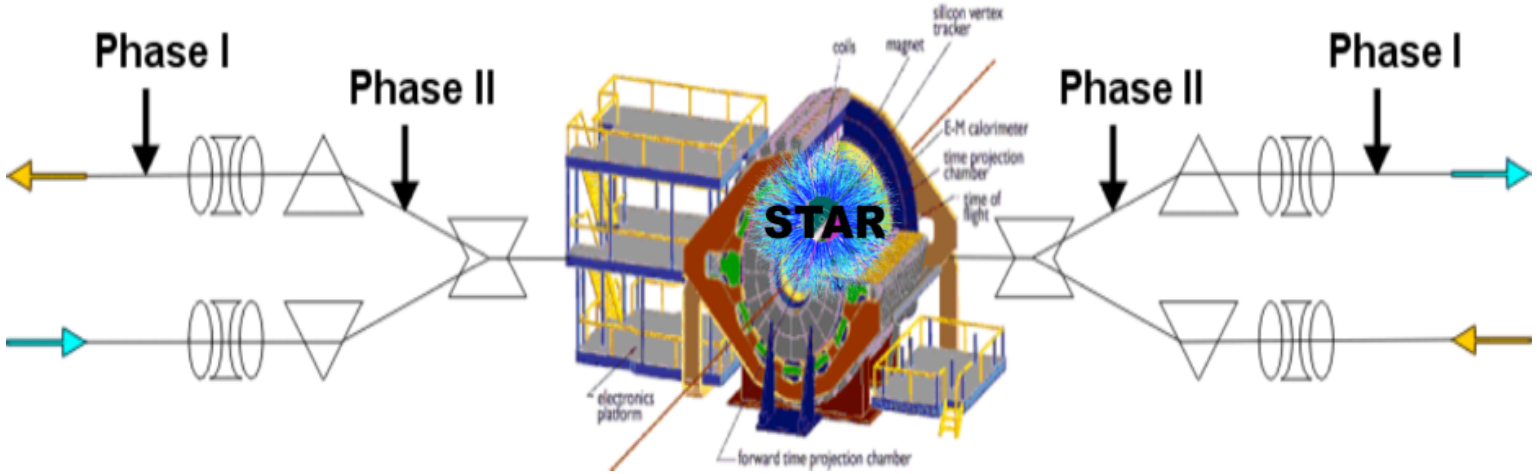
In 2005, despite very good progress and three publications being worked on at the time, the PP2PP experiment was cancelled by BNL ALD because of 2006 budget constraints, where there was no money to run RHIC. Let alone continue PP2PP.

This is when I learned the importance of this cartoon.

Joining STAR in 2006: Physics with Tagged Forward Protons

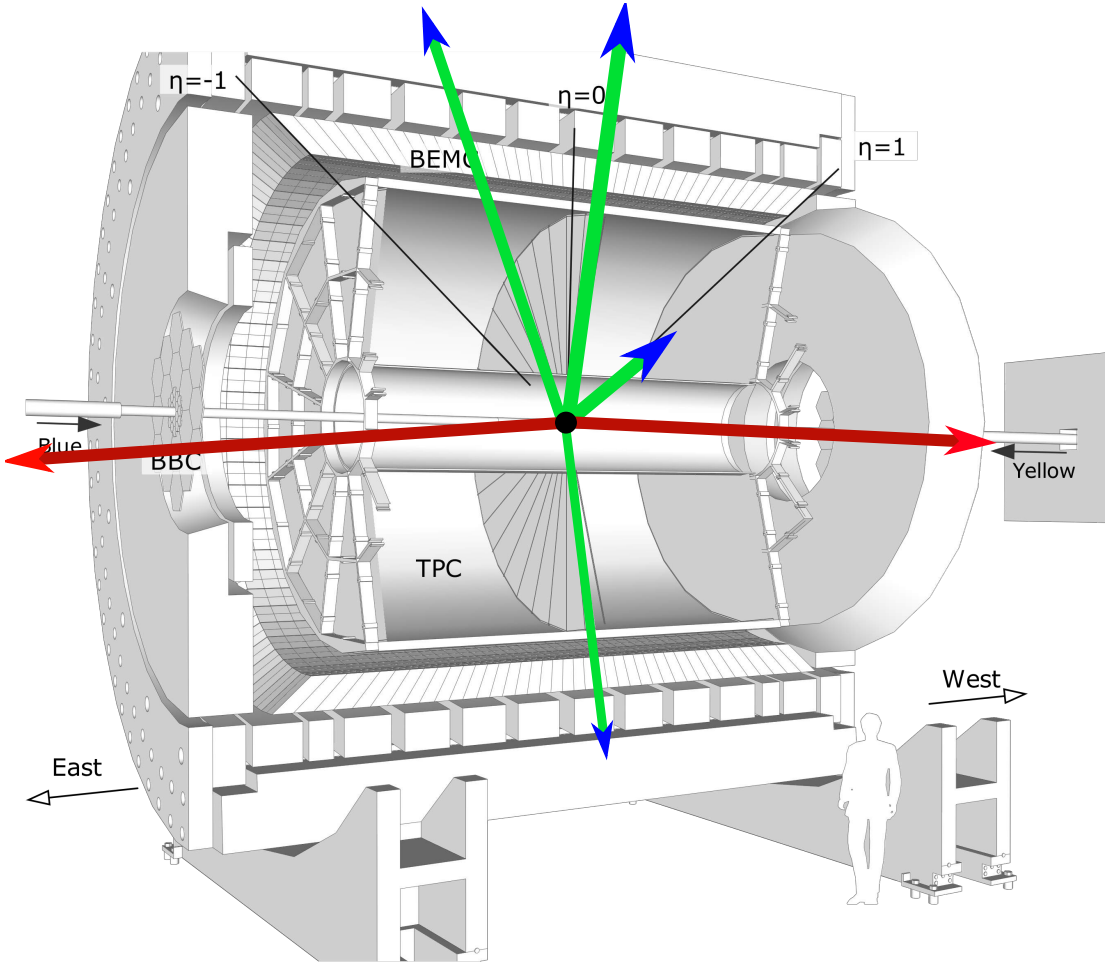
Need detectors to tag forward protons and detector with good acceptance and particle ID to measure central system

Roman Pots of PP2PP and STAR

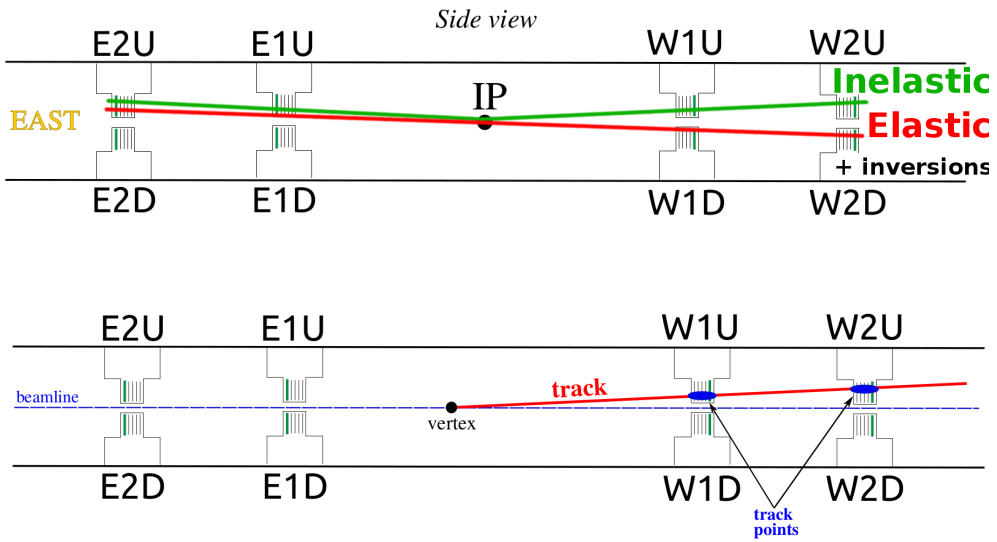


1. Elastic Scattering
2. Central Exclusive Production
3. Particle Production in SDD and CP

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.

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

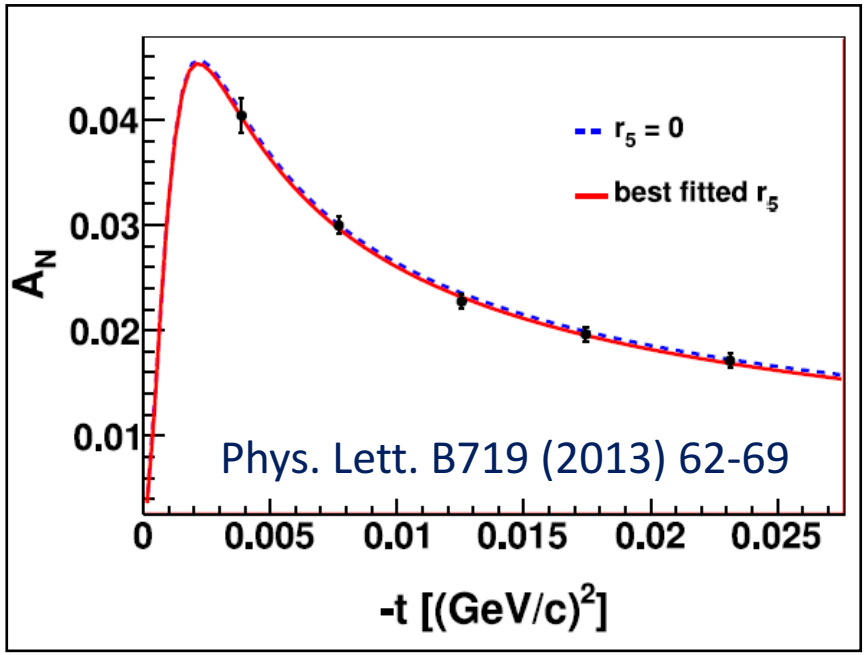
$\phi_4(s,t) = \langle +- | M | -+ \rangle$ double spin flip

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

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

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

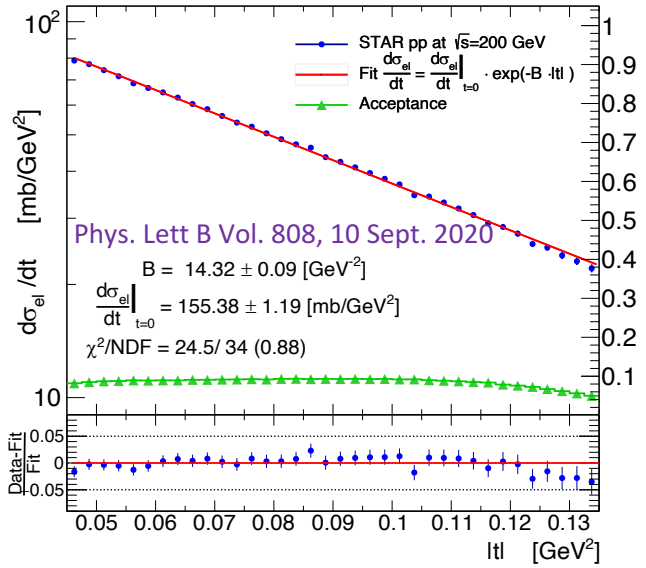
$$A_N(s,t)\frac{d\sigma}{dt} = \frac{-4\pi}{s^2}\,\mathrm{Im}\left\{ \phi_5^*(\phi_1 + \phi_2 + \phi_3 - \phi_4) \right\}$$

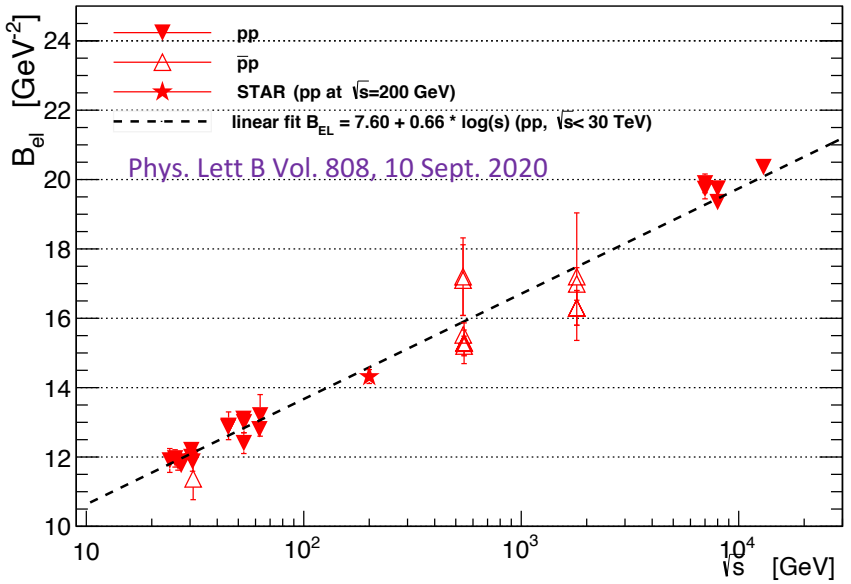


Re r_5 = 0.0017 +-0.0017 (stat.) +-0.061 (syst.)
Im r_5 = 0.007 +-0.03 (stat.) +- 0.049 (syst.)

Pomeron spin-flip is consistent with zero

Results on Elastic scattering: B-slope and σ_{tot}

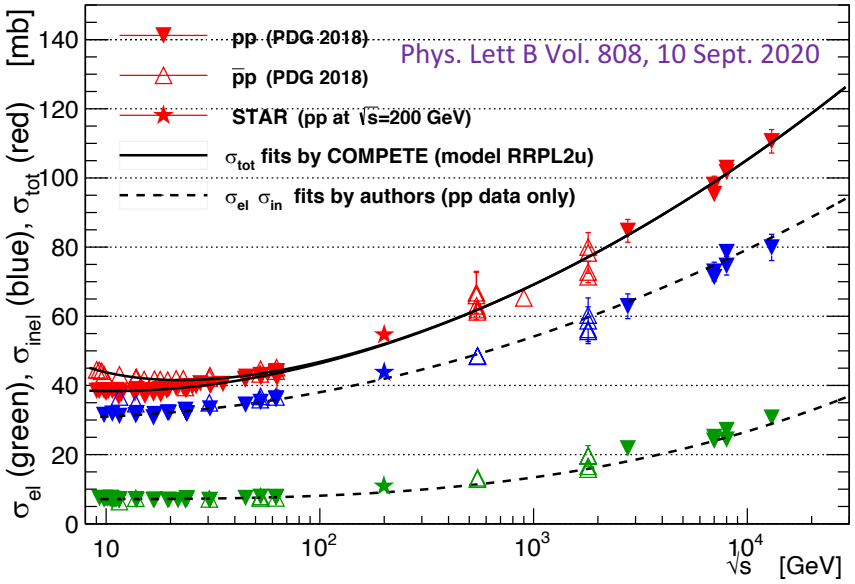




Use optical theorem to obtain σ_{tot}

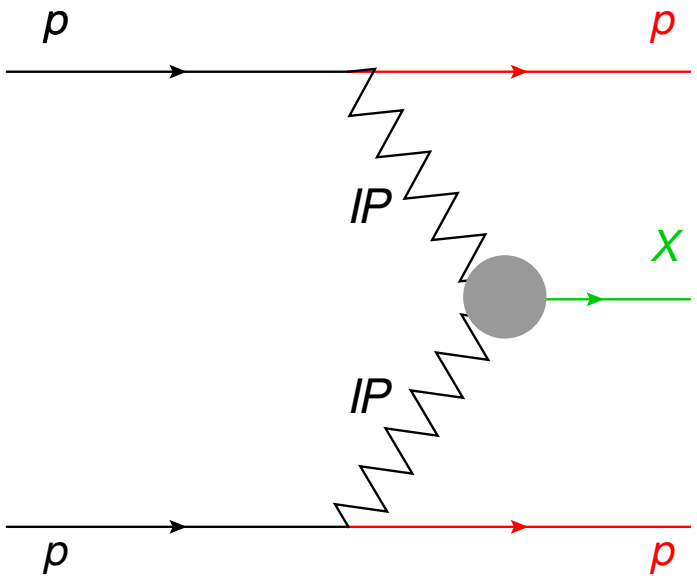
$$\sigma_{tot}^2 = \left(\frac{16\pi\,(\hbar c)^2}{1+\rho^2}\right)\left.\frac{d\sigma_{el}^h}{dt}\right|_{t=0}$$

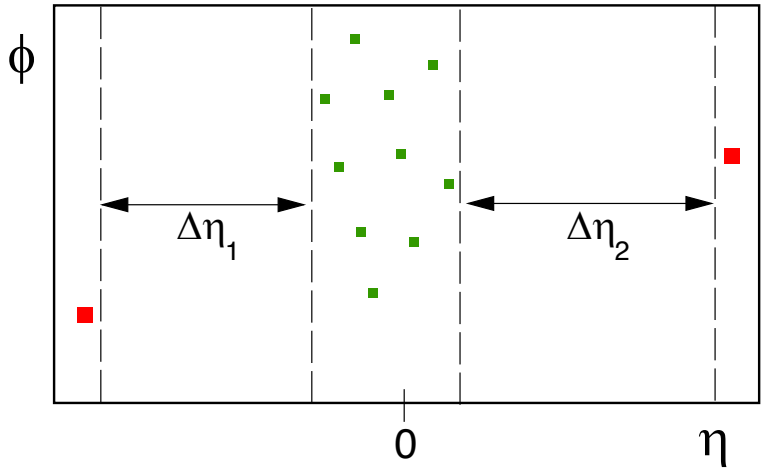
1. STAR obtained results on total, elastic and inelastic cross section in proton-proton collisions at √s = 200 GeV.
2. The results are within 2σ of the World data – fits do not include STAR data points.
3. This measurement ”fills” the gap between results from CERN ISR (62 GeV) and TeV energies at the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



Central Exclusive Production (CEP)

pp => p X p





Exclusive means that all particles in the final state are measured

$\pi^+\pi^-$, K^+K^-, $p\bar{p}$ production in CEP

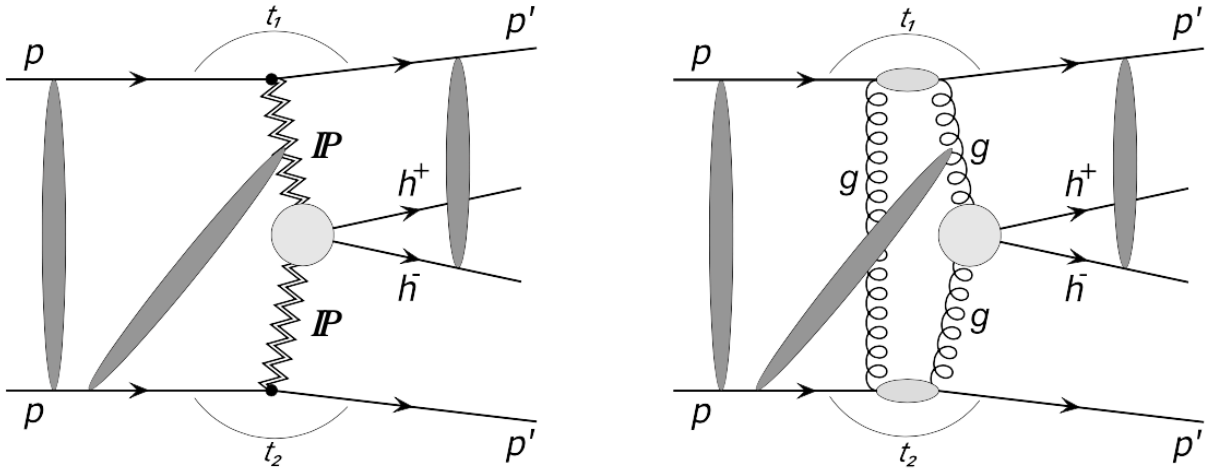
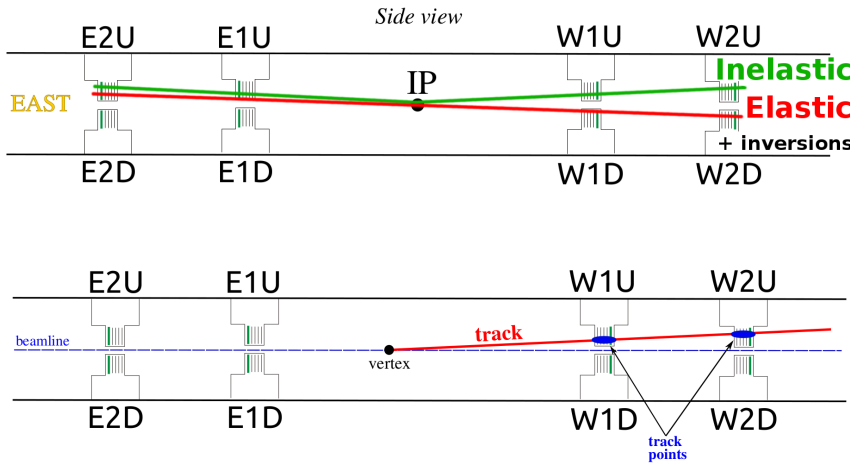


Figure 1. (left) Generic diagram of CEP of h^+h^- in DPE model. The scattered beam protons emerge intact from the collision and the charged particle pair is produced in the central rapidity region. (right) The two-gluon approximation of DPE in pQCD. The grey ovals represent some of the possible absorptive corrections.

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

Roman Pots

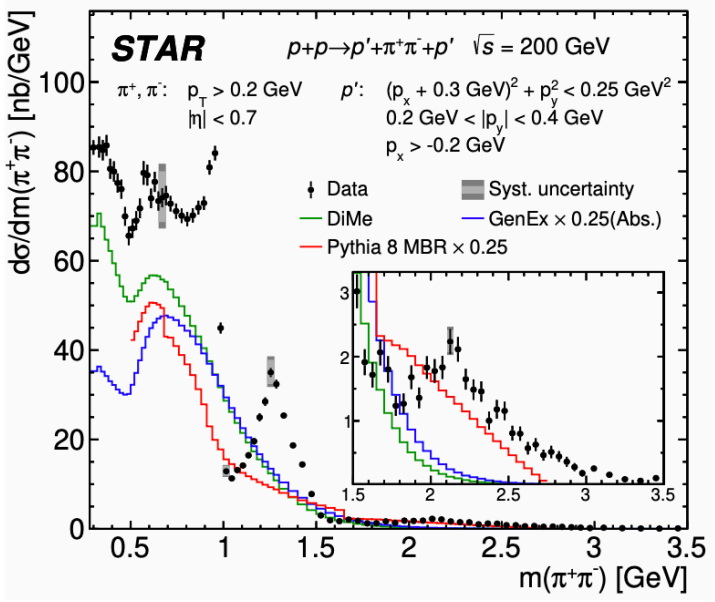


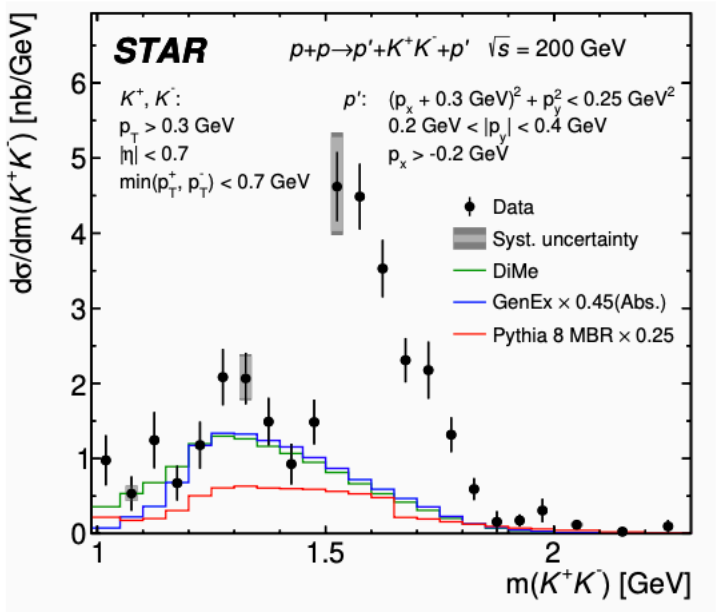
1. Only Elastic or Inelastic combination of protons in Roman Pots were accepted
2. Exactly 2 good quality tracks in Roman Pots (one per side, all 8 planes were used)
3. Exactly 2 primary TPC tracks from the same vertex
4. 2 TOF hits matched with tracks from TPC
5. Total charge of tracks = 0
6. No cuts on TPC/TOF track quality
7. Total missing transverse momentum of all measured particles $p_T^{miss} < 100$ MeV/c
8. PID for $\pi^+\pi^-$ based on dE/dx only at this time

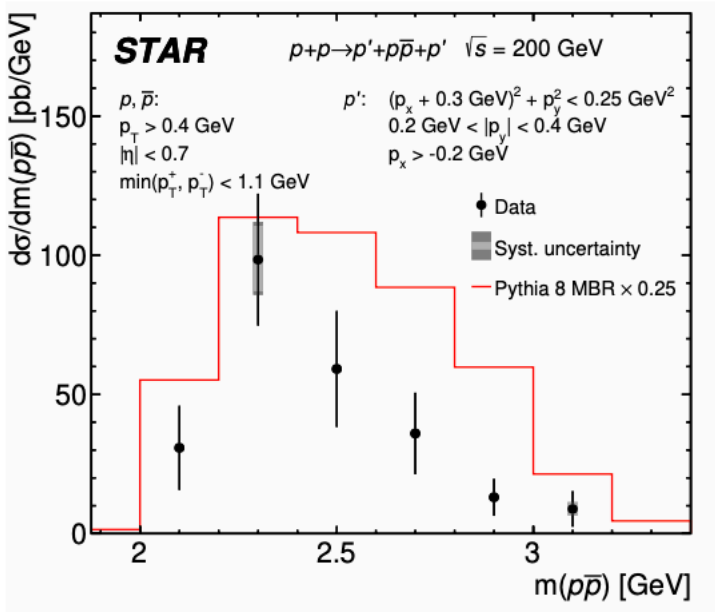
$$n\sigma_{\pi}^{pair} = \sqrt{\left(n\sigma_{\pi^+}^{trk}\right)^2 + \left(n\sigma_{\pi^-}^{trk}\right)^2} < 3$$

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

Rafal Sikora's PhD at AGH UST, *J. High Energy Phys.* **2020,** 178 (2020)



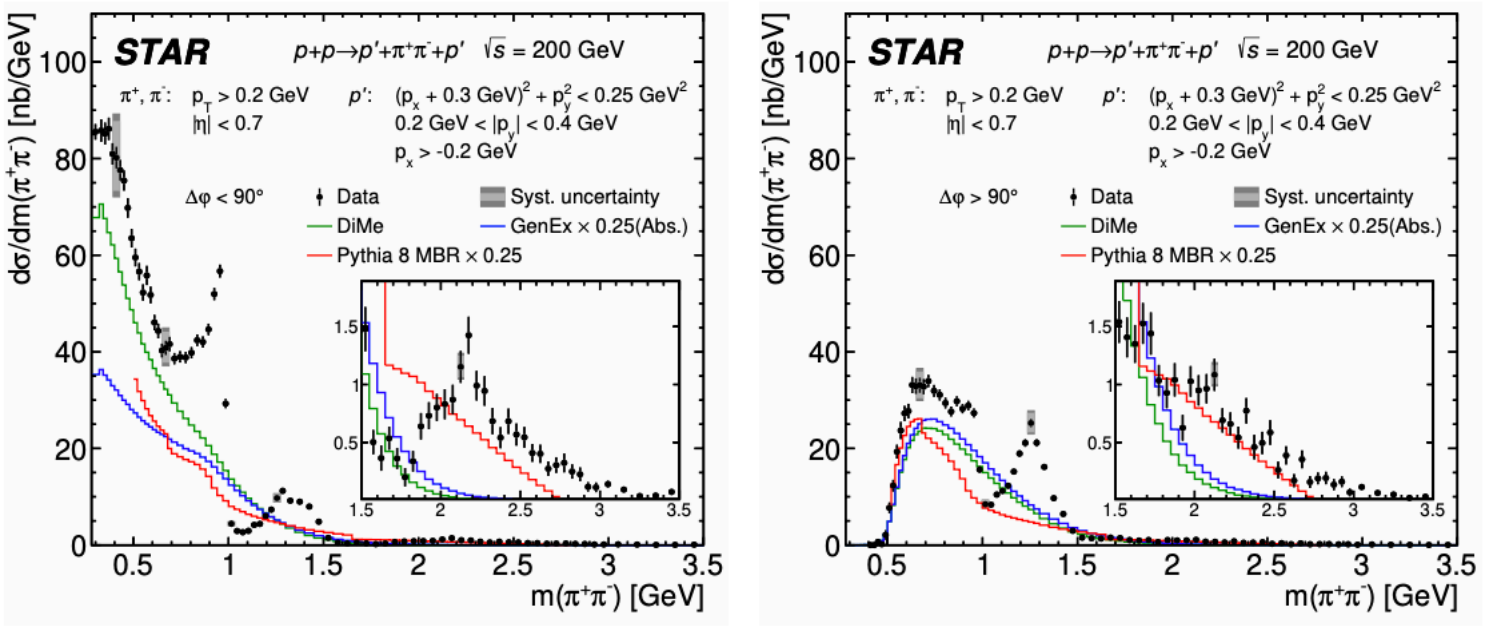




1. In $\pi^+\pi^-$ spectrum drop at f0(980), a peak at f2(1270) MeV and structure at about 2200 MeV , are observed.
2. Comparison with various continuum production models will help fine tune those models .

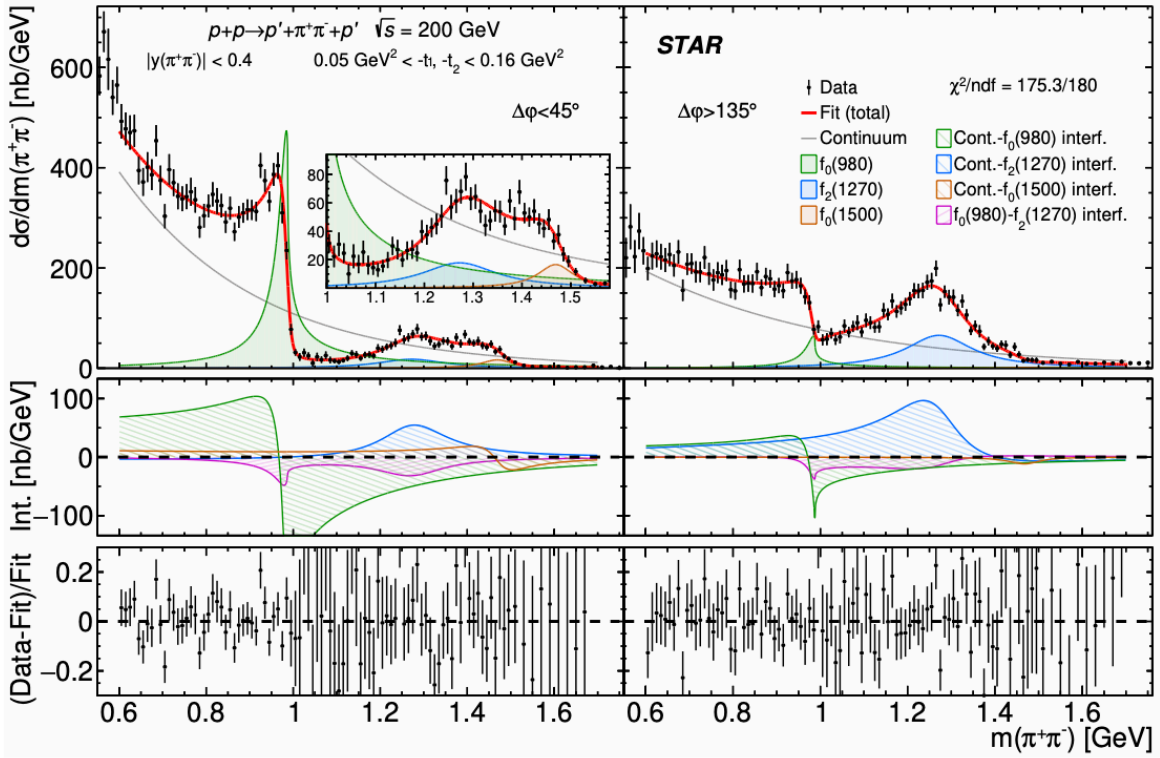
$\pi^+\pi^-$ at $\sqrt{s}$ = 200 GeV in more detail: $\Delta\phi$ dependence

Rafal Sikora's PhD at AGH UST, *J. High Energy Phys.* **2020,** 178 (2020)



1. In the $\Delta\phi < 90^\circ$ range, the peak around the f2(1270) resonance in data is significantly suppressed.
2. Peak at f0(980) as well as possible resonances in the mass ranges 1.3 − 1.5 GeV and 2.2 − 2.3 GeV, are enhanced compared to the $\Delta\phi > 90^\circ$ range.
3. In the range $\Delta\phi < 90^\circ$, the DiMe model describes well both the normalization and the shape of the mass spectrum at $m(\pi^+\pi^-) < 0.5$ GeV.

$\pi^+\pi^-$ in more detail: mass spectrum interpretation



Rafal Sikora's PhD at AGH UST,
J. High Energy Phys. **2020,** 178 (2020)

1. Two $\Delta\phi$ regions are examined.
2. The result of the fit is drawn with a solid red line. The squared amplitudes for the continuum and resonance production are drawn with lines of different colors.
3. The most significant interference terms are plotted in the middle panels, while the relative differences between each data point and the fitted model is shown in the bottom panels.

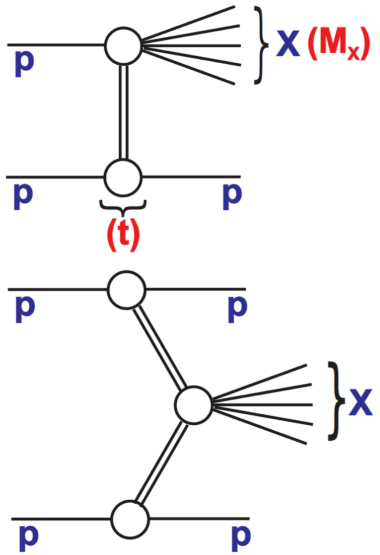
Charged Particle Production at Midrapidity in SDD and CP at $\sqrt{s}$ = 200 GeV

Lukasz Fulek, PhD thesis AGH UST

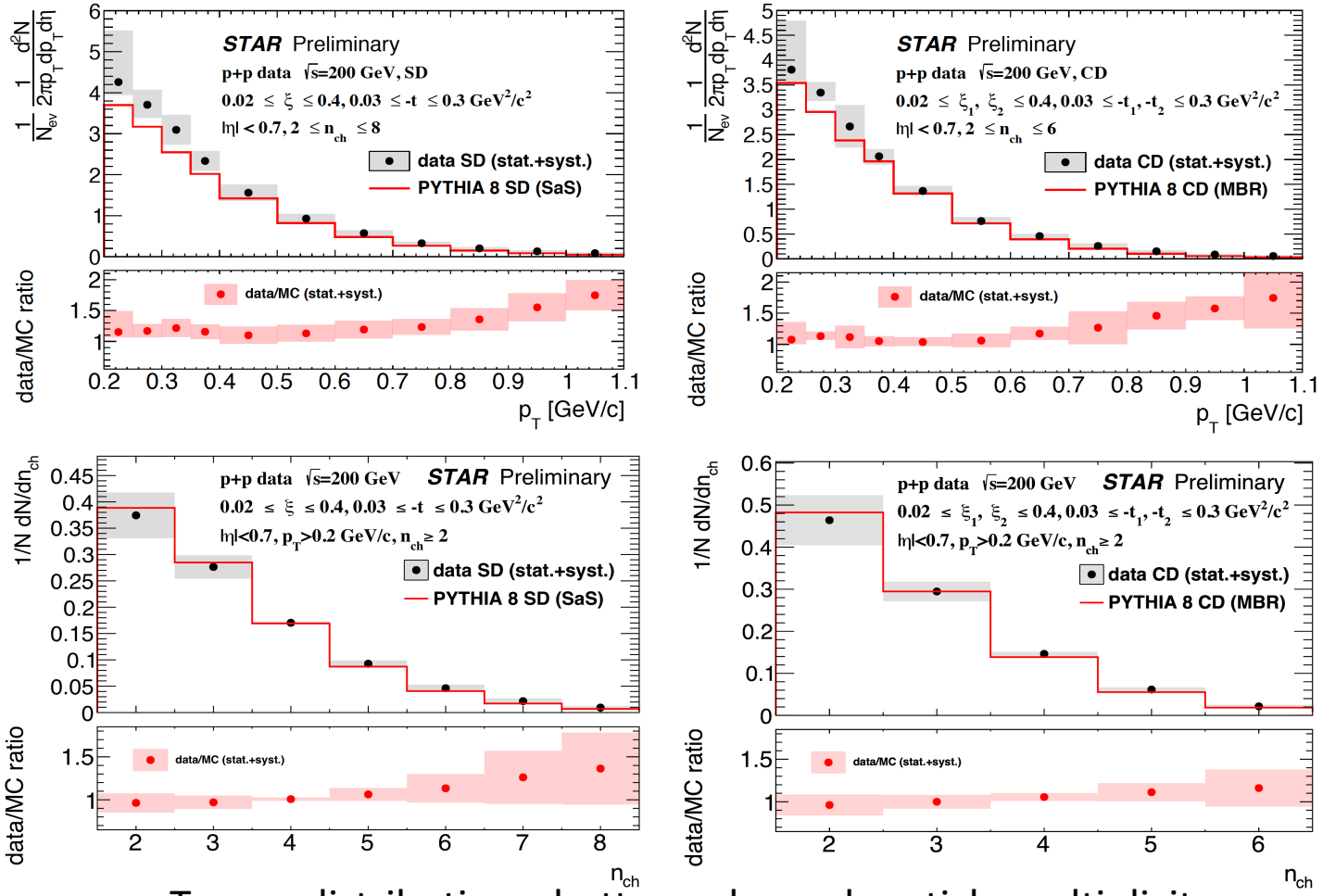
arXiv:1906.04963

$$p + p \rightarrow p + X$$

$$p + p \rightarrow p + X + p$$



Fairly good agreement between MC and data



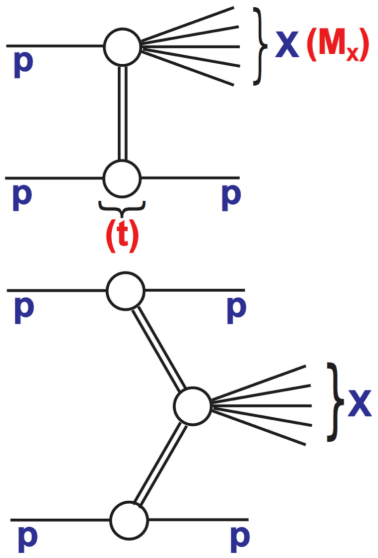
Top: p_T distributions, bottom: charged particle multiplicity

Charged Particle Production at Midrapidity in SDD and CP at $\sqrt{s}$ = 200 GeV

Lukasz Fulek, PhD thesis AGH UST, arXiv:1906.04963

$$p + p \rightarrow p + X$$

$$p + p \rightarrow p + X + p$$



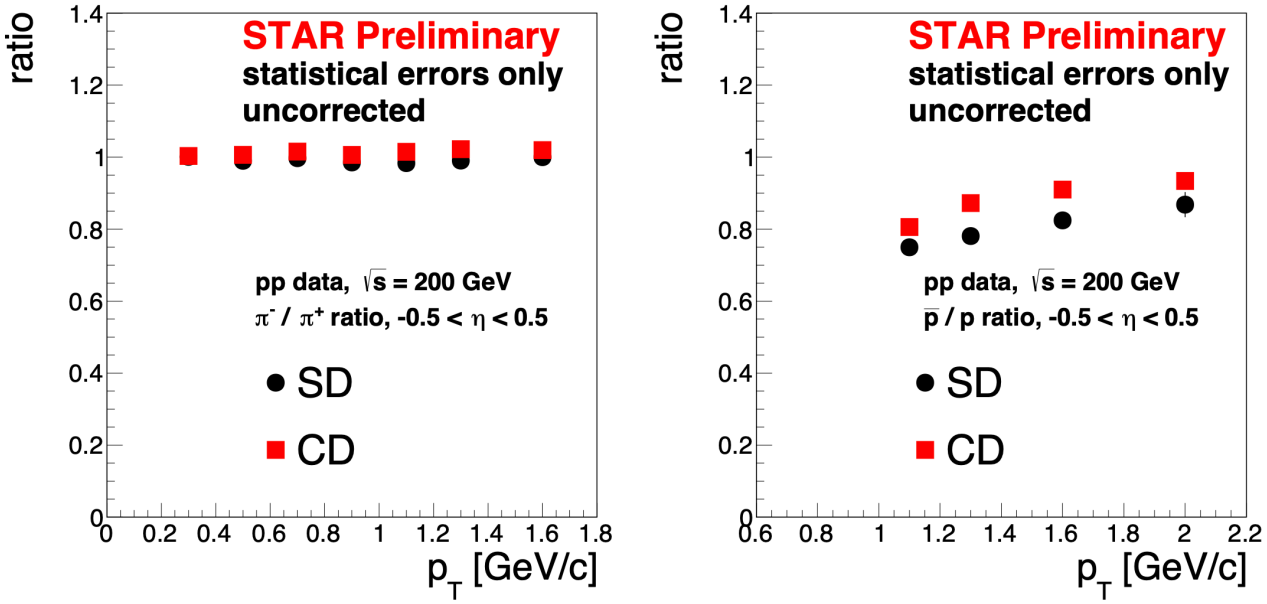
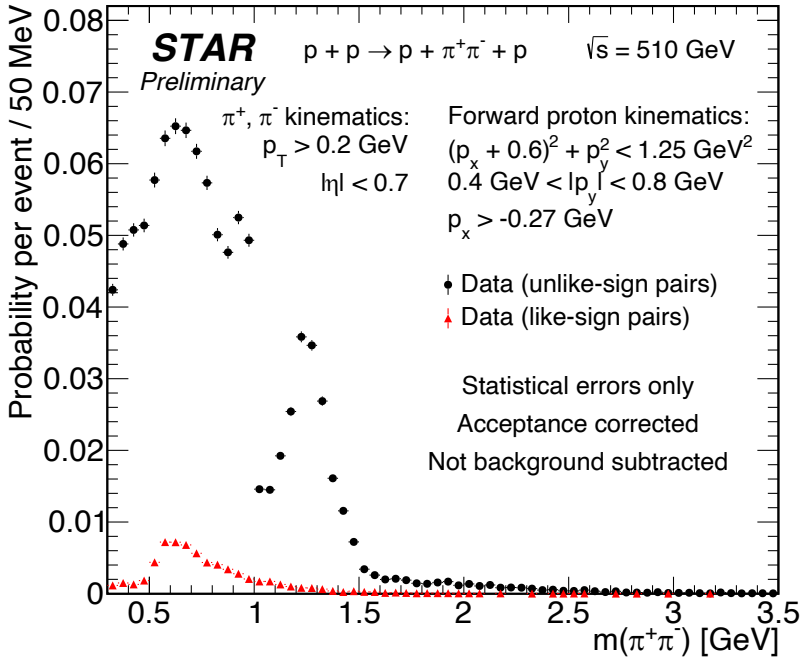
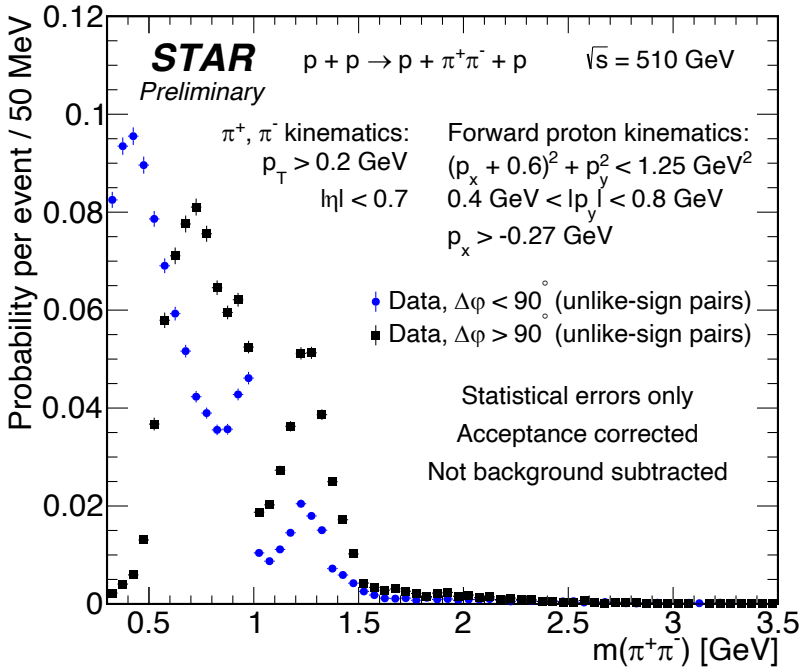


Fig. 5: Comparison of the π^-/π^+ (left) and $\bar{p}/p$ (right) ratios in $|\eta| < 0.5$ interval between CD and SD processes.

Results on CEP at $\sqrt{s} = 510$ GeV

Tomas Truhlar, PhD student at CTU Prague, ICHEP 2020





Features similar to those at $\sqrt{s}$ = 200 GeV are observed

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 $\sqrt{s}$ = 200 GeV
- A very comprehensive study of CEP at $\sqrt{s}$ = 200 GeV was performed, which will affect phenomenological models (R. Sikora PhD thesis)
- Also very comprehensive study particle production in CP and SDD at $\sqrt{s}$ = 200 GeV was performed, which will affect phenomenological models (L. Fulek PhD thesis)

Other physics topics under study

1. Measurement of pp elastic cross section at $\sqrt{s}$ = 510 GeV
2. Measurement od double spin asymmetry A_{NN} in pp at $\sqrt{s}$ = 200 GeV
3. Study of CEP at $\sqrt{s}$ = 510 GeV (T. Truhlar PhD thesis in progress)