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
   - Proton – Proton elastic scattering
5. Summary

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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Proton–antiproton elastic scattering was measured at the CERN SPS Collider at the centre-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 $\rho = 0.24 \pm 0.04$

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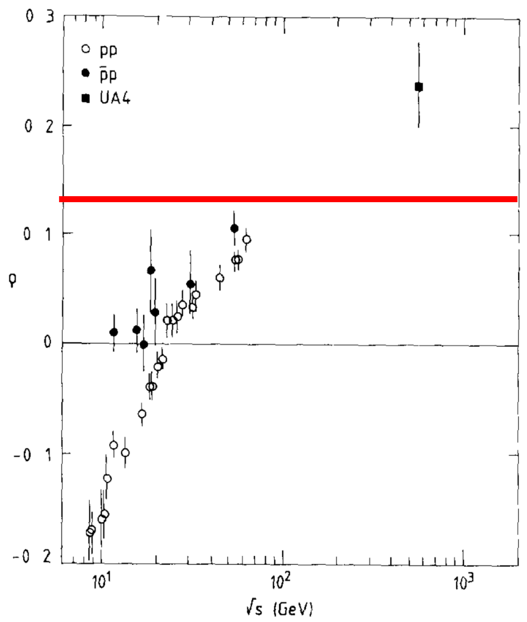


Fig 4 The present result on the parameter ρ is shown together with lower energy data for pp and p̄p elastic scattering

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

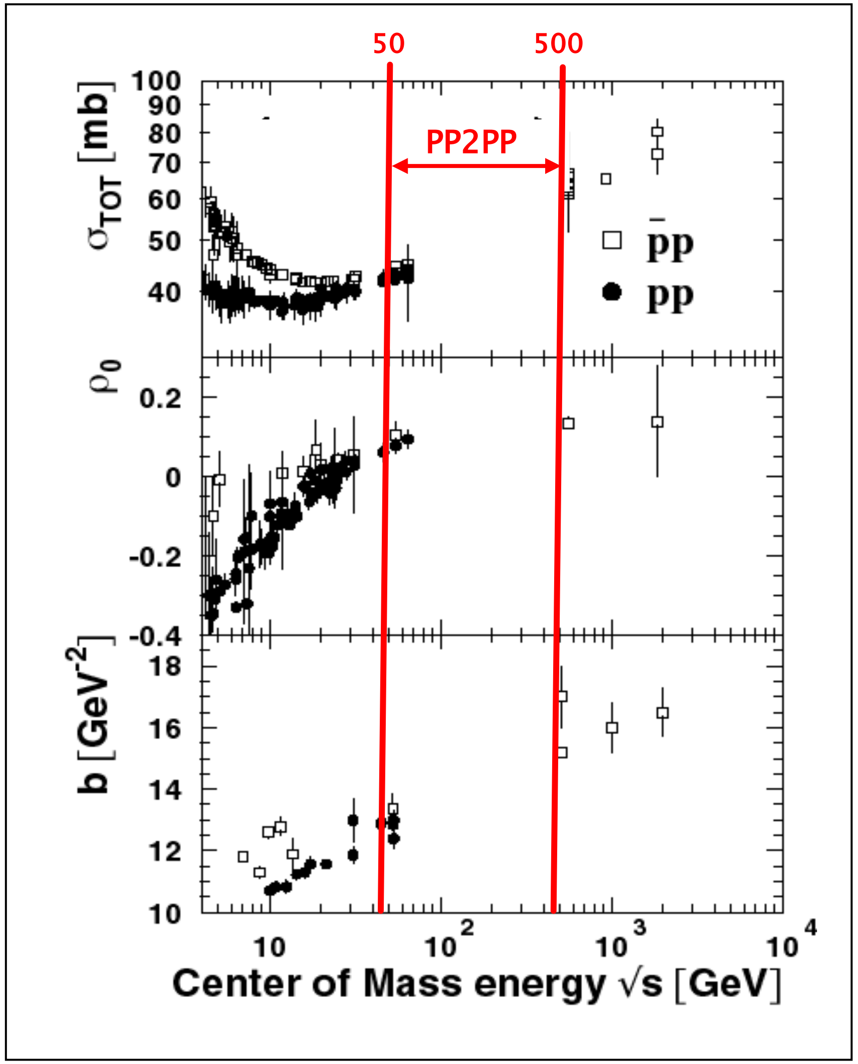
pp2pp energy range:

50 GeV ≤ $\sqrt{s}$ ≤ 500 GeV

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

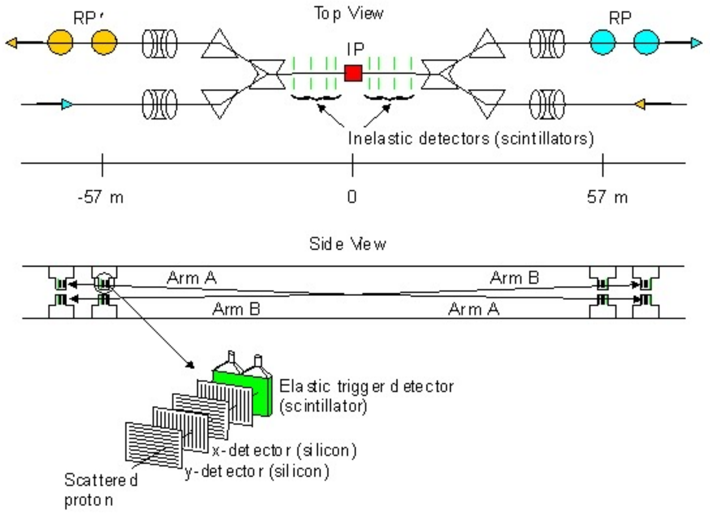
$$\sigma_{tot}^2 = \left(\frac{16\pi\,(\hbar c)^2}{1+\rho^2}\right)\left.\frac{d\sigma_{el}^h}{dt}\right|_{t=0}$$

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

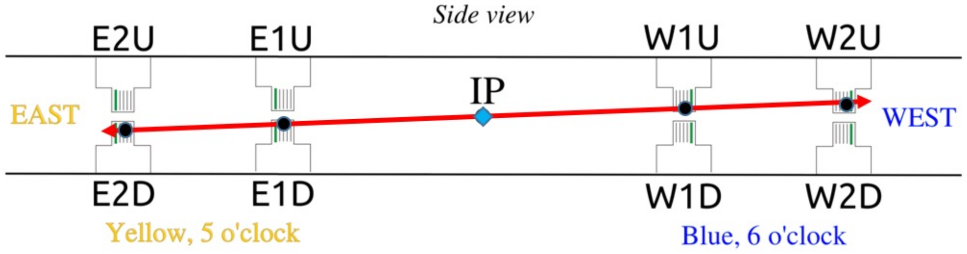


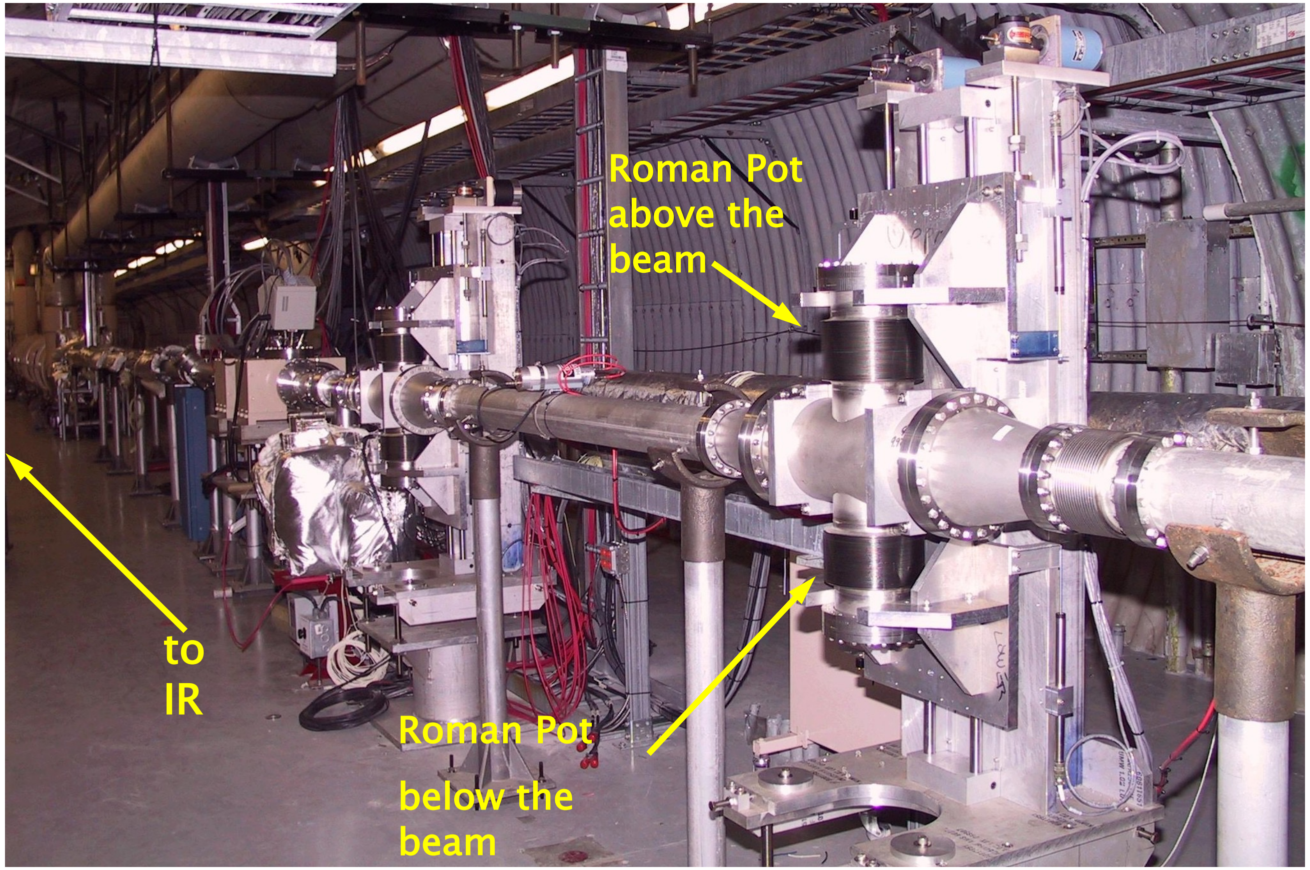
RHIC: Heavy Ion and Polarized Proton – Proton Collider

The Setup



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





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

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

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

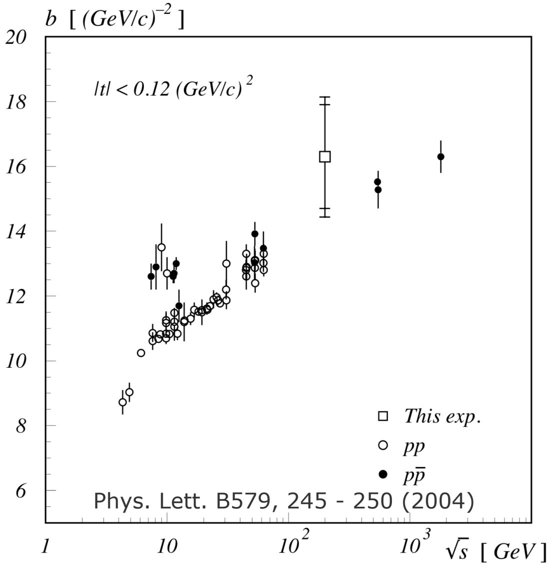
$$A_N(s,t)\frac{d\sigma}{dt} = \frac{-4\pi}{s^2}\mathrm{Im}\left\{\phi_5^*(\phi_1 + \phi_2 + \phi_3 - \phi_4)\right\}$$

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

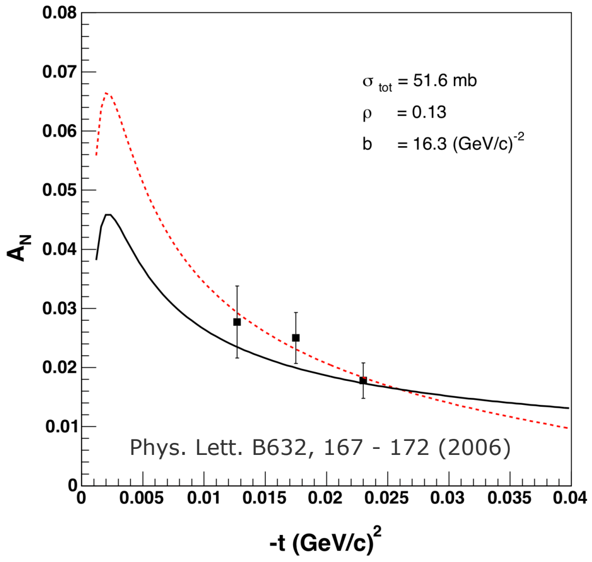
Results from PP2PP: $\sqrt{s} = 200$ GeV

Three papers in PLB

B-slope



A_N



r_5

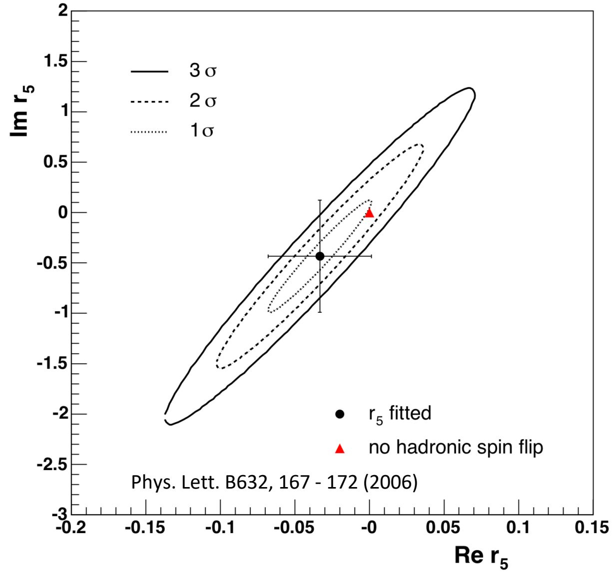


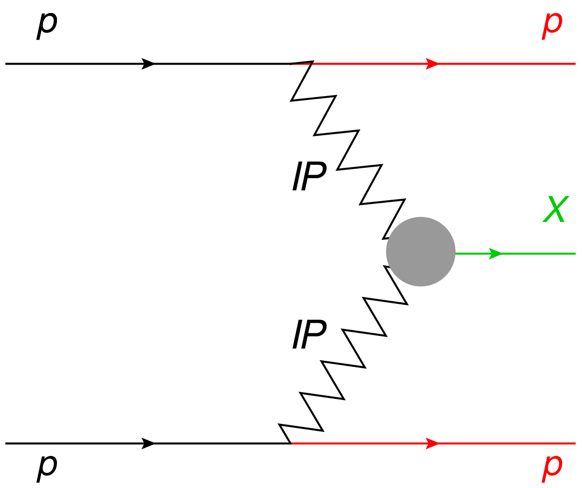
TABLE I: Double spin asymmetries A_{NN}, A_{SS}, $(A_{NN} + A_{SS})/2$ and $(A_{NN} - A_{SS})/2$ for the t-interval $0.010 \le -t \le 0.030$ (GeV/c)^2 at $< -t >= 0.0185$ (GeV/c)^2.

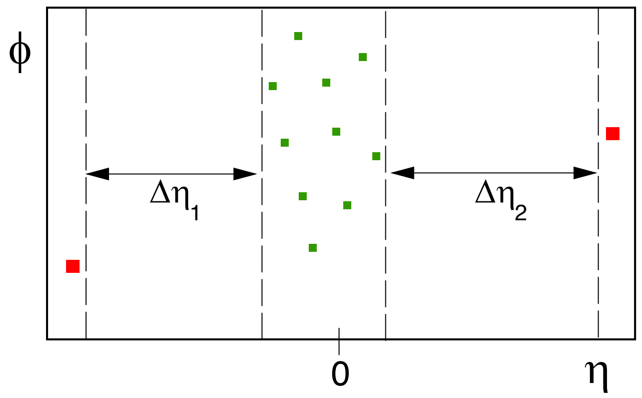
	A_{NN}	A_{SS}	$(A_{NN} + A_{SS})/2$	$(A_{NN} - A_{SS})/2$
$Asym$	0.0298	0.0035	0.0167	0.0131
$\Delta Asym$ (stat.+norm.)	±0.0166	±0.0081	±0.0091	±0.0096
$\Delta Asym$ (syst.)	±0.0045	±0.0031	±0.0034	±0.0072
$\Delta Asym$ due to $\Delta(P_Y \cdot P_B)$	±32.3 %			

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.





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

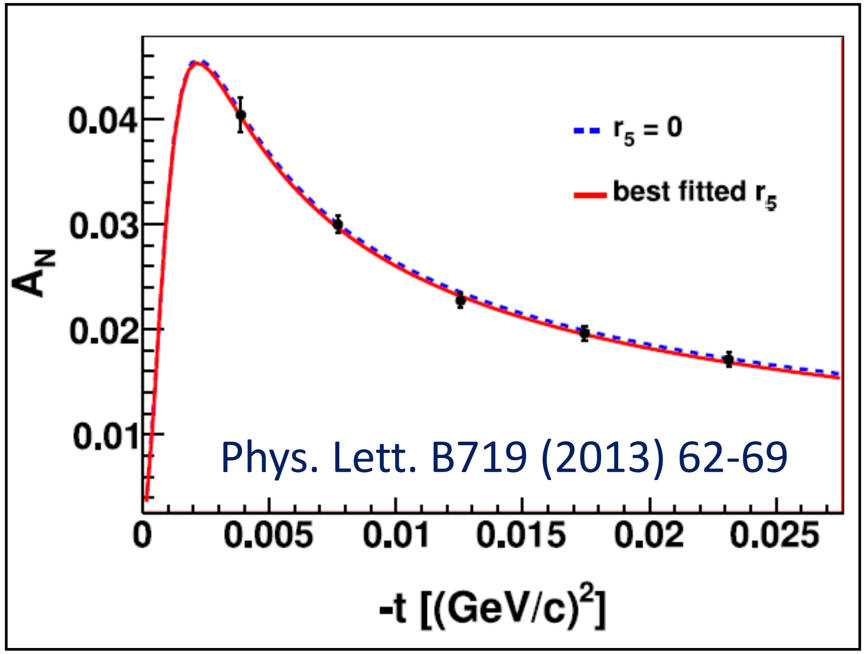
$\phi_4(s,t) = \langle +- | M | -+ \rangle$ double spin flip

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

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

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

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

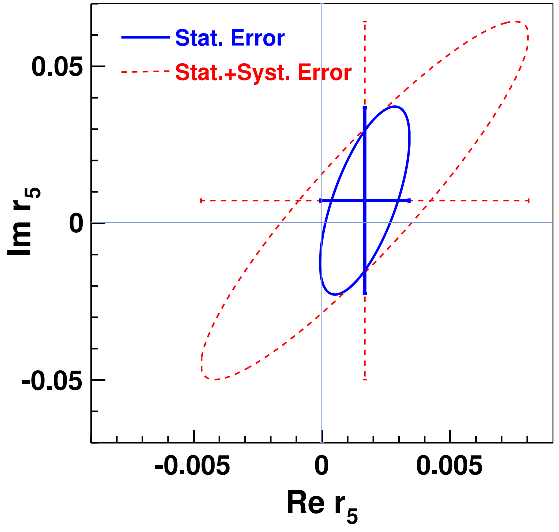


Re r_5 = 0.0017 +-0.0017 (stat.) +-0.061 (syst.)
Im r_5 = 0.007 +-0.03 (stat.) +- 0.049 (syst.)

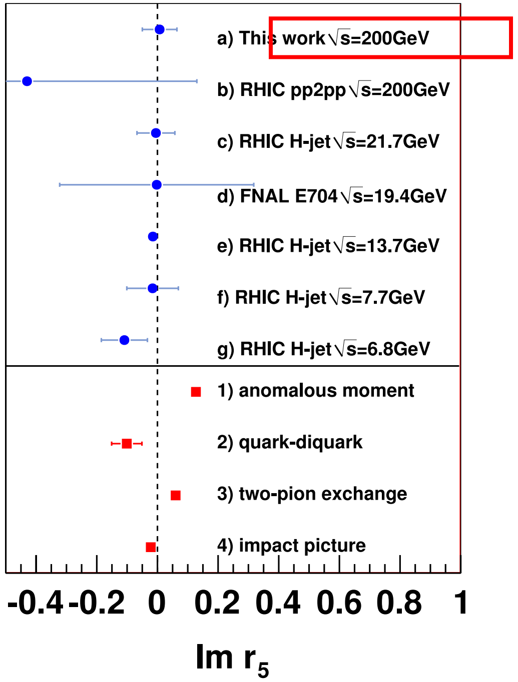
Pomeron spin-flip is consistent with zero

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.)



Phys. Lett. B719 (2013) 62-69

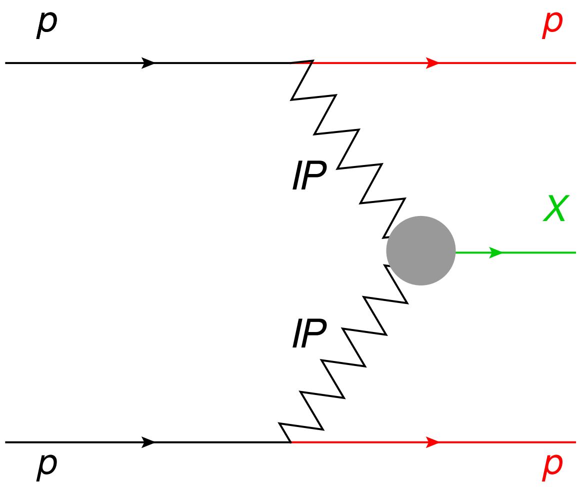


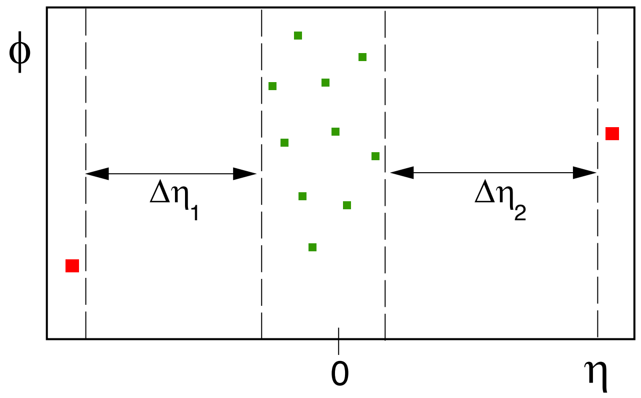
Pomeron spin-flip is consistent with zero

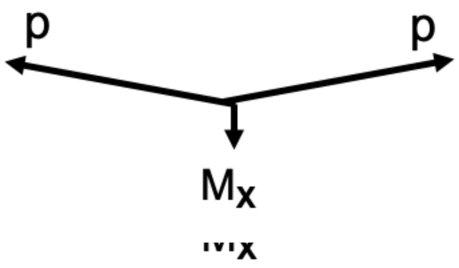
Central Exclusive Production (CEP)

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

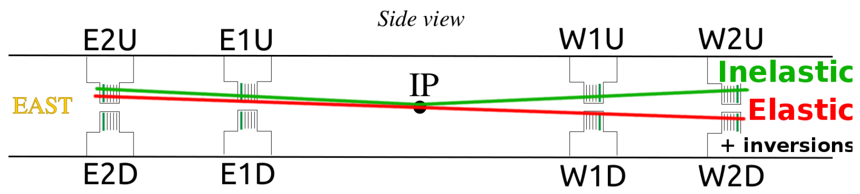
$\xi = \Delta p/p$

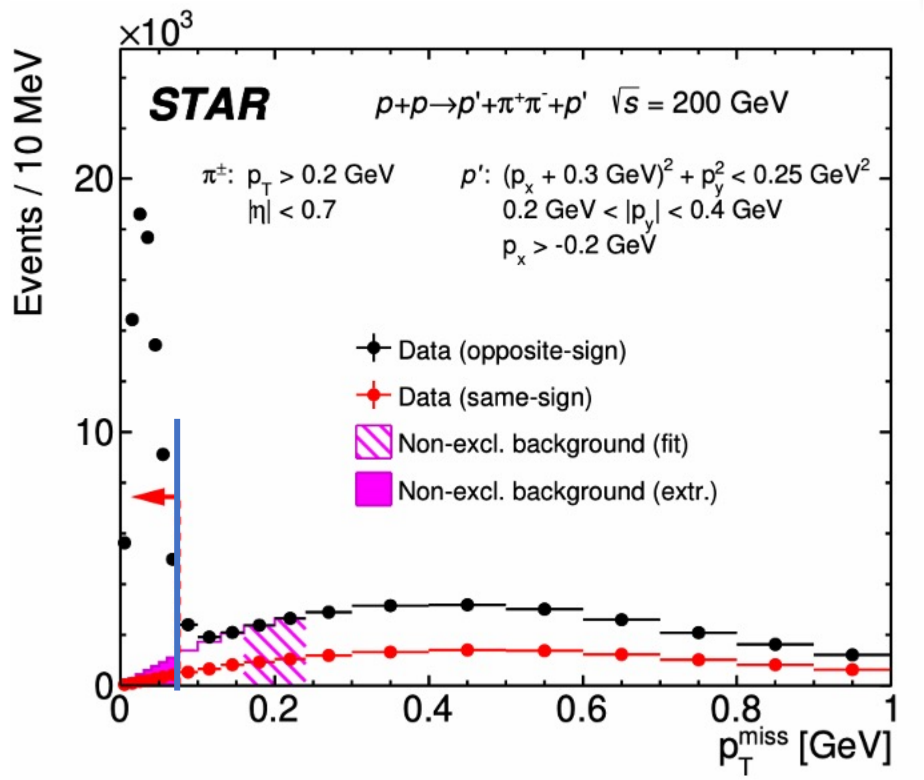
M_X invariant mass

- 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

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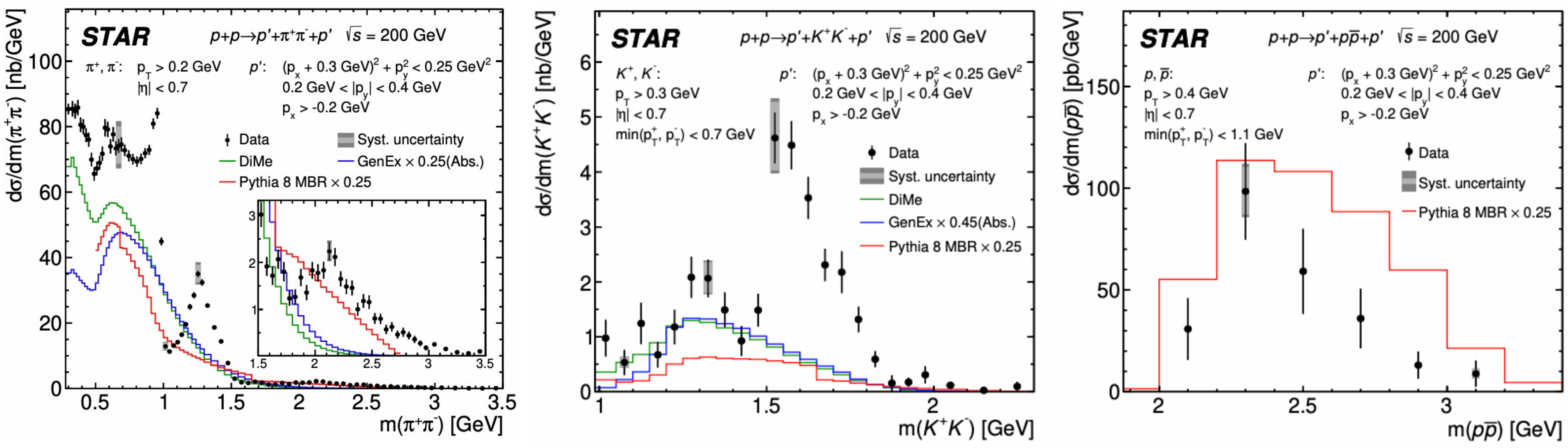
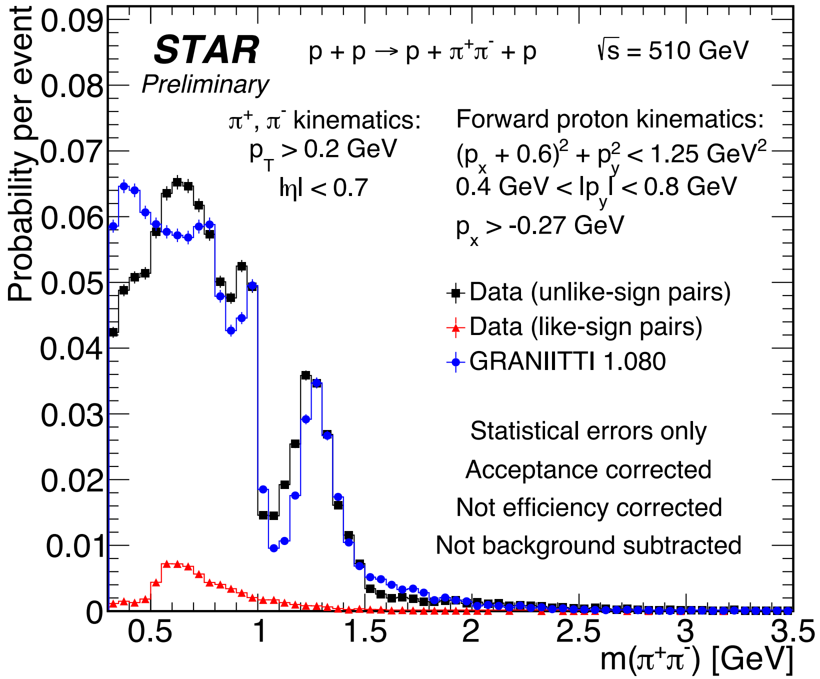
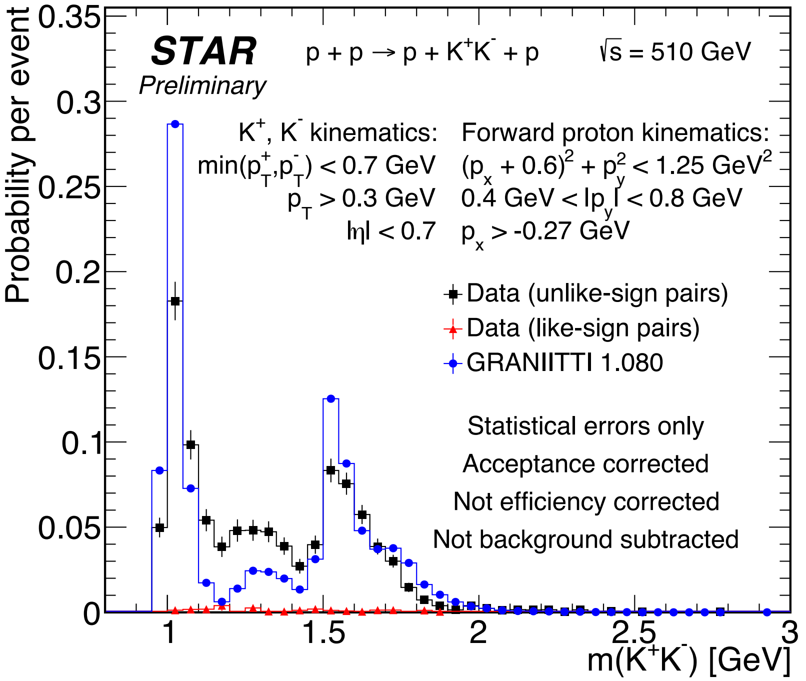


1. In $\pi^+\pi^-$ spectrum drop at f0(980), a peak at f2(1270) MeV and structure at about 2200 MeV , are observed.
2. Comparison with various continuum production models will help fine tune those models .

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

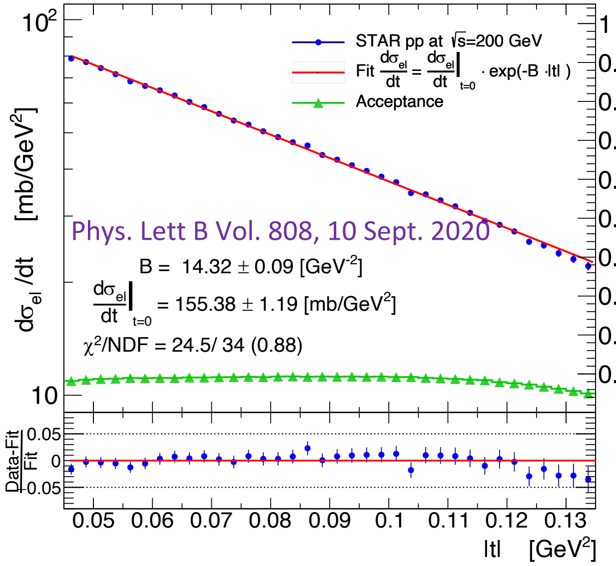
Tomas Truhlar, PhD student at CTU Prague work in progress

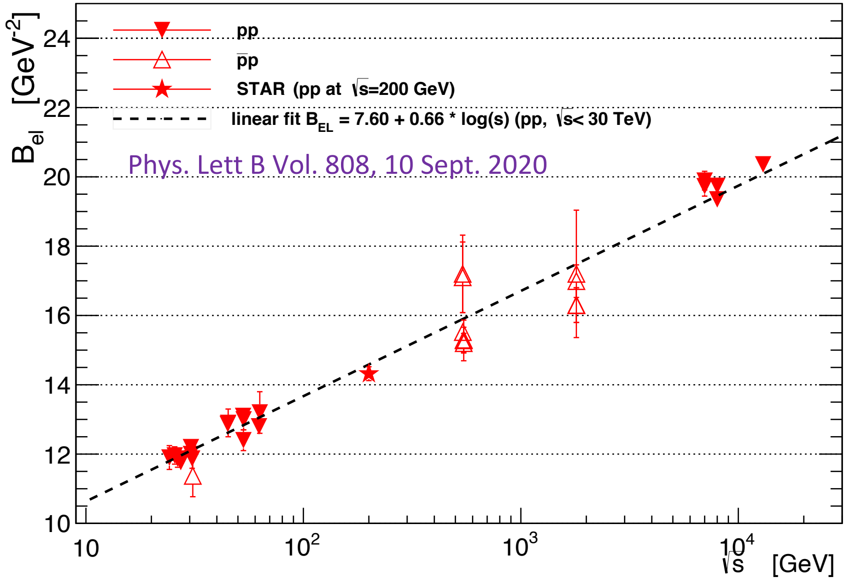




1. Features like those at $\sqrt{s}$ = 200 GeV are observed
2. Increased statistics for K^+K^- channel
3. Both compare well with the Graniitti simulator

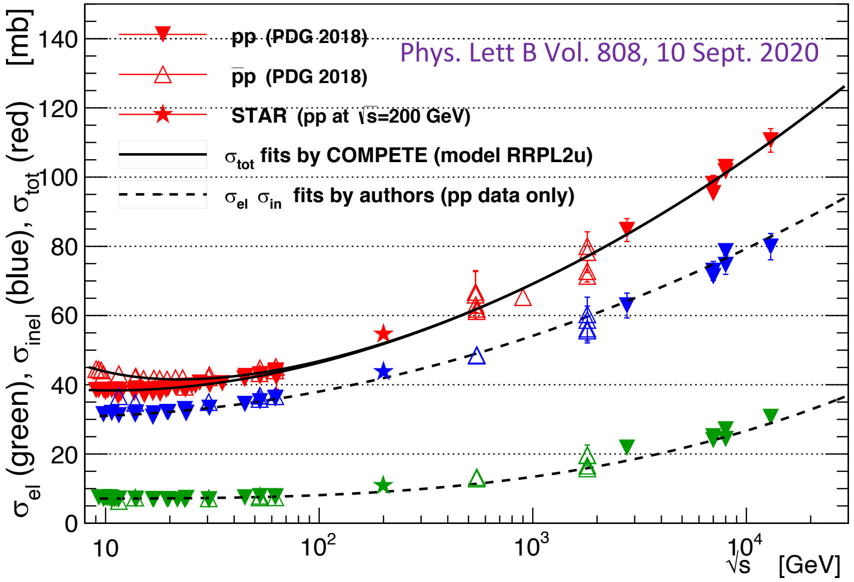
Results on Elastic scattering: $\sqrt{s} = 200$ GeV B-slope and σ_{tot}





Use optical theorem to obtain σ_{tot}

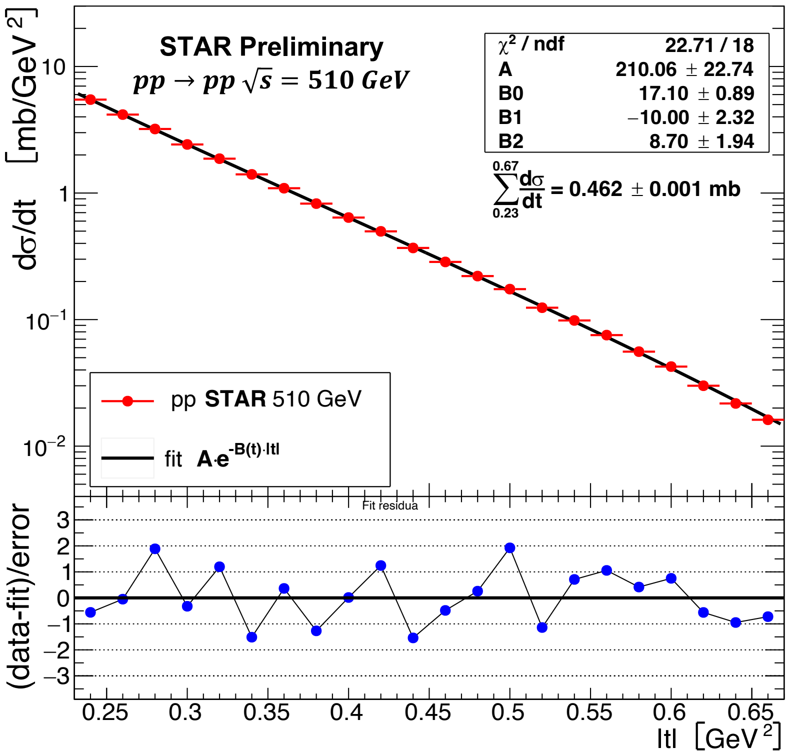
$$\sigma^2_{tot} = \left(\frac{16\pi\,(\hbar c)^2}{1+\rho^2}\right) \frac{d\sigma^h_{el}}{dt}\bigg|_{t=0}$$

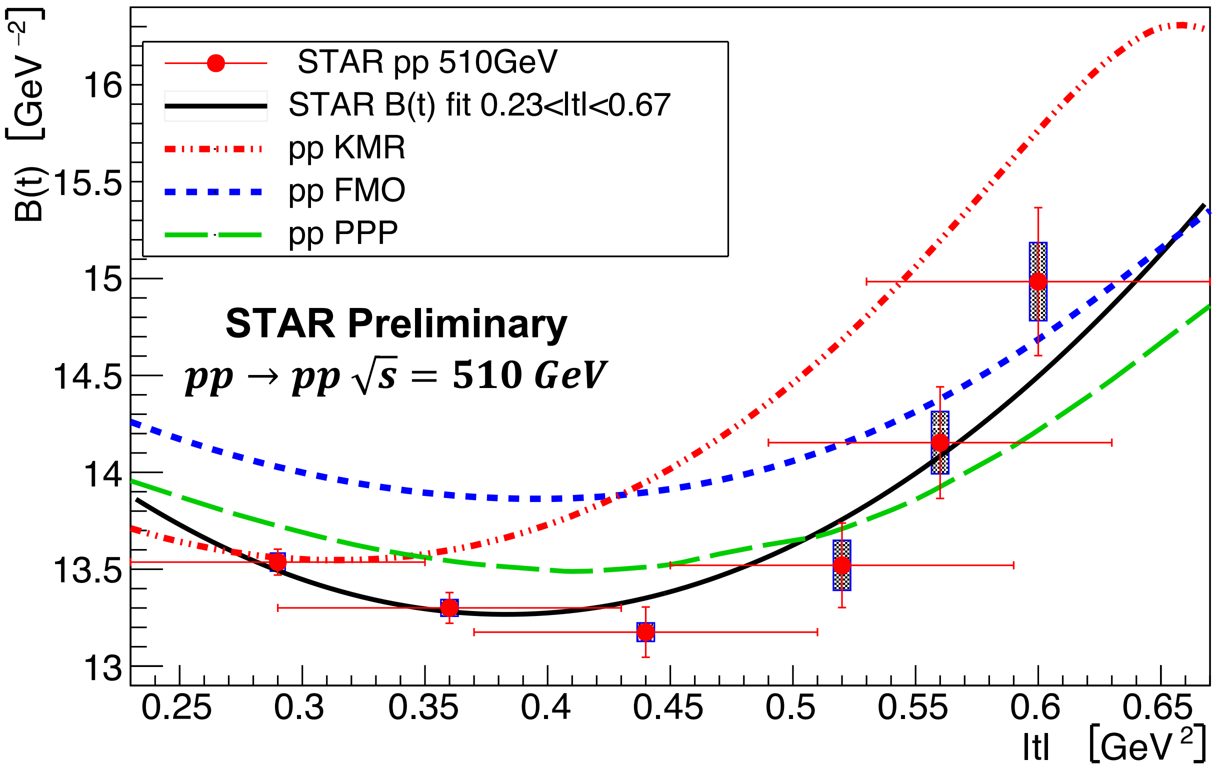


1. STAR obtained results on total, elastic and inelastic cross section in proton-proton collisions at √s = 200 GeV.
2. The results are within 2σ of the World data – fits do not include STAR data points.
3. This measurement "fills" the gap between results from CERN ISR (62 GeV) and TeV energies at the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

Results at 510 GeV: shape of dσ/dt

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





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

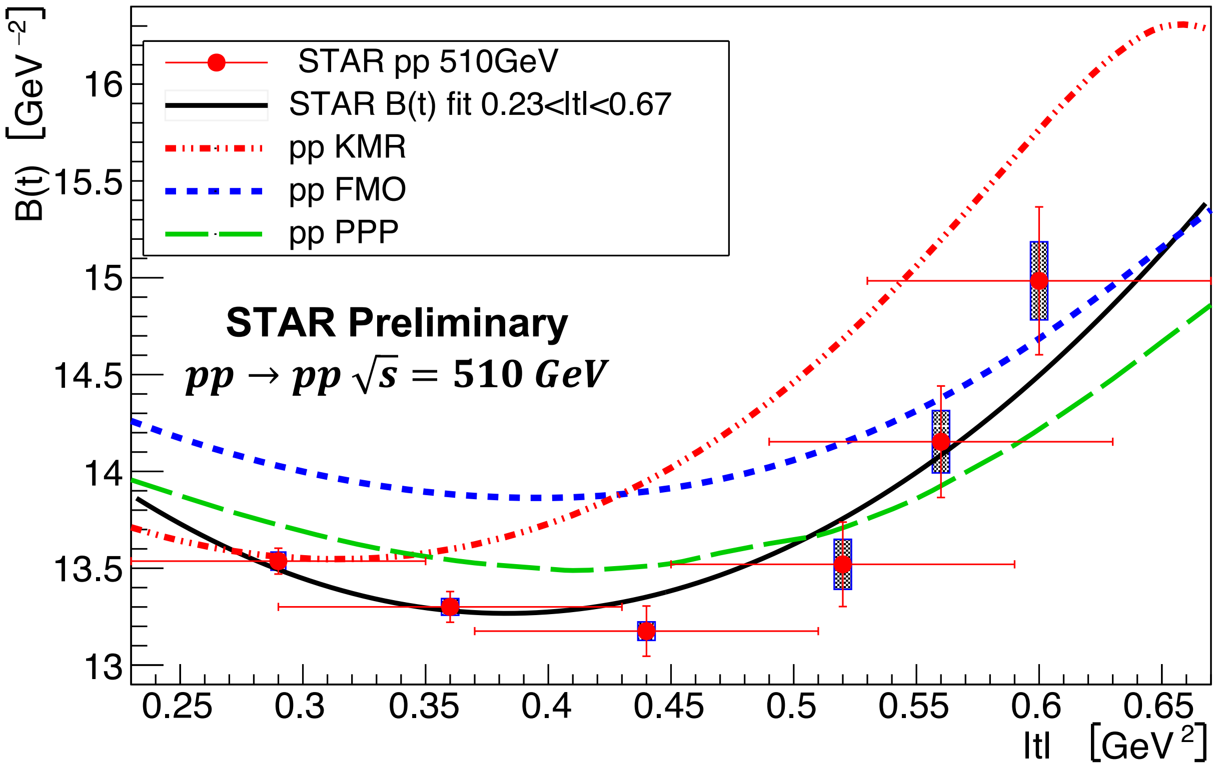
Summary

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
4. Total cross section measurement at $\sqrt{s}$ = 200 GeV
5. Measurement of pp elastic cross section at $\sqrt{s}$ = 510 GeV
6. Measurement od double spin asymmetry A_{NN} in pp at $\sqrt{s}$ = 200 GeV
7. Differential cross section measurement at $\sqrt{s}$ = 510 GeV
8. Study of CEP at $\sqrt{s}$ = 510 GeV

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

BACKUP

Results at 510 GeV: comparison with models



All models predict B(t) dependence in the t range of this experiment