# Physics with Forward Protons at RHIC

**Tomáš Truhlář**

Faculty of Nuclear Sciences and Physical Engineering
Czech Technical University in Prague

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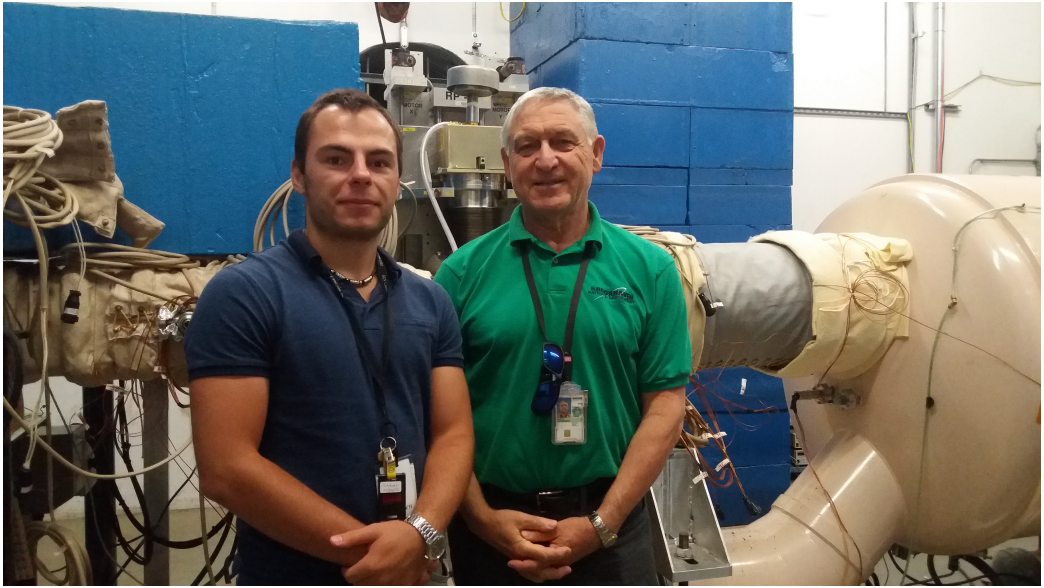
Supervisor: Włodzimierz Guryn, Ph.D,
Supervisor: doc. Mgr. Jaroslav Bielčík, Ph.D.


FACULTY OF
NUCLEAR SCIENCES
AND PHYSICAL
ENGINEERING
CTU IN PRAGUE

# Father of forward program at RHIC: Wlodek Guryn



- Summer 1990, seminar at FNAL: $\rho$ measurement at $Sp\bar{p}S$
- Discrepancy between measured $\rho = 0.24 \pm 0.04$ and expected $\rho = 0.12$ at $\sqrt{s} = 546$ GeV
- RHIC program was being formulated at that time $\Rightarrow$ a good thing to check

Volume 198, number 4 PHYSICS LETTERS B

**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

D BERNARD [a 1], M BOZZO [b], P L BRACCINI [c], F CARBONARA [d], R. CASTALDI [c], F CERVELLI [c], G CHIEFARI [d], E DRAGO [d], M HAGUENAUER [e], V INNOCENTE [e 2], P KLUIT [1], S LANZANO [d], G MATTHIAE [d 3], L MEROLA [d], M. NAPOLITANO [d], V. PALLADINO [d], G. SANGUINETTI [c], P. SCAMPOLI [c], S SCAPELLATO [c 4], G SCIACCA [d], G SETTE [b], J. TIMMERMANS [1], C VANNINI [c], J VELASCO [a 5], P G VERDINI [c] and F VISCO [d]

[a] *CERN, European Organization for Nuclear Research, CH-1211 Geneva 23, Switzerland*
[b] *Department of Physics and Sezione INFN, I-16146 Genoa, Italy*
[c] *Department of Physics and Sezione INFN, I-56100 Pisa, Italy*
[d] *Department of Physics and Sezione INFN, I-80125 Naples, Italy*
[e] *LPNHE/IN2P3-CNRS Ecole Polytechnique, F-91128 Palaiseau, France*
[f] *NIKHEF-H, NL-1009 DB Amsterdam, The Netherlands*

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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 $\rho$ of the real to the imaginary part of the hadronic amplitude the result $\rho = 0.24 \pm 0.04$

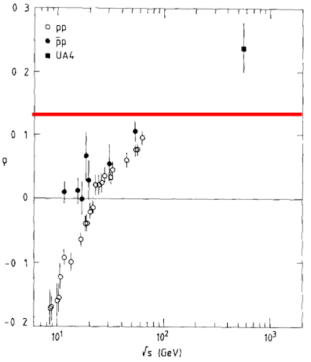
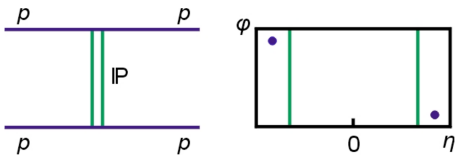



Fig. 4 The present result on the parameter $\rho$ is shown together with lower energy data for pp and p̄p elastic scattering



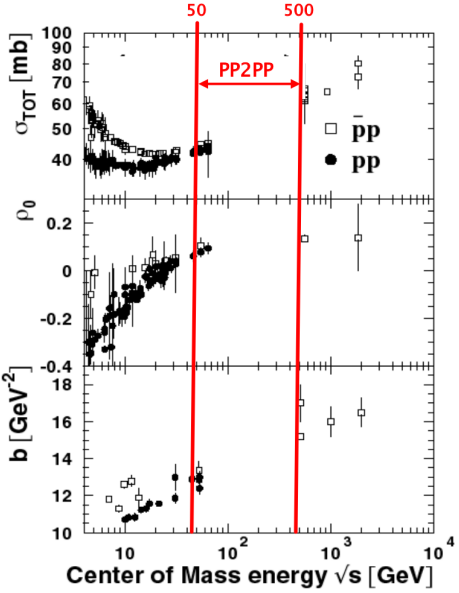

$$t = (p_1 - p_3)^2 \approx p^2\theta^2 \tag{1}$$

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

$$\rho = \left.\frac{Re\ f_h}{Im\ f_h}\right|_{t=0} \tag{3}$$

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

$$\sigma_{tot}^2 = \left(\frac{16\pi(\hbar c)^2}{1+\rho^2}\right)\left.\frac{d\sigma_{el}^h}{dt}\right|_{t=0} \tag{5}$$



**TOTAL and ELASTIC $pp$ CROSS SECTIONS AT RHIC**

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

**J. Bourotte, M. Haguenauer**
*Ecole Polytechnique/IN2P3-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*

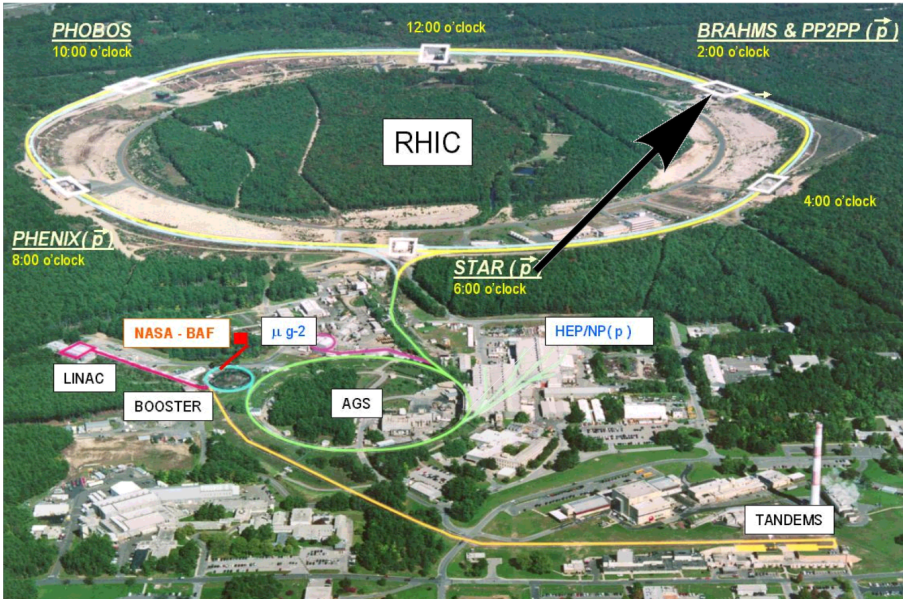
**G. Matthiae**
*University of Rome, Italy*

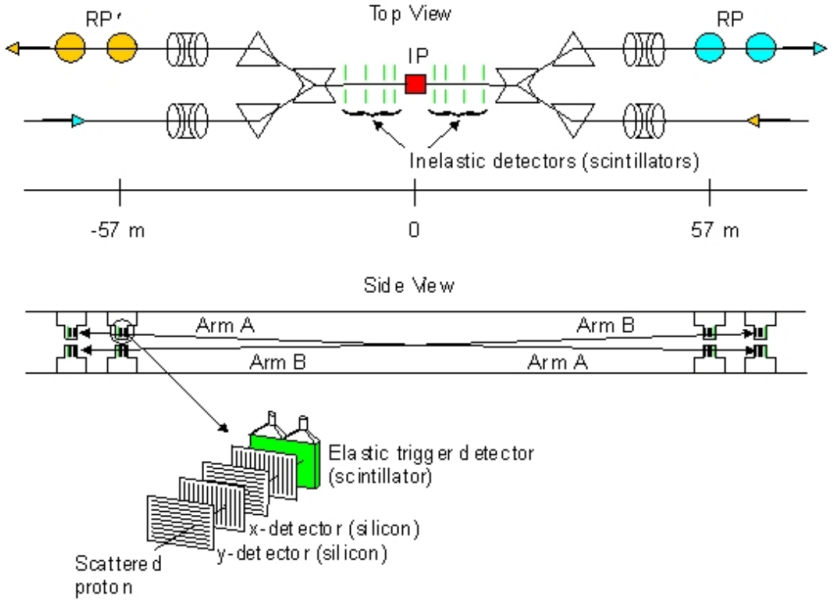
**A. Penzo, P. Schiavon**
*INFN-Trieste, Italy*

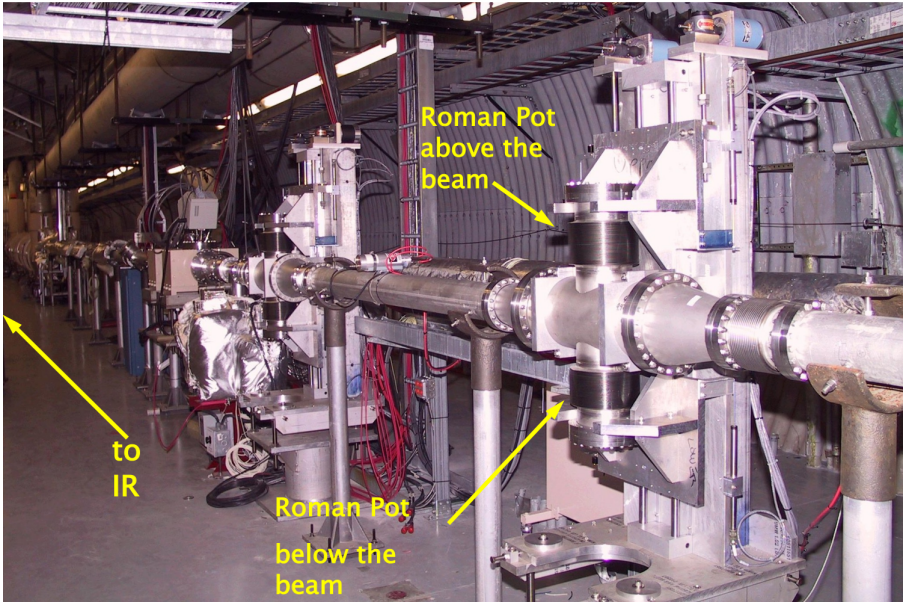
*spokesperson

**Abstract**

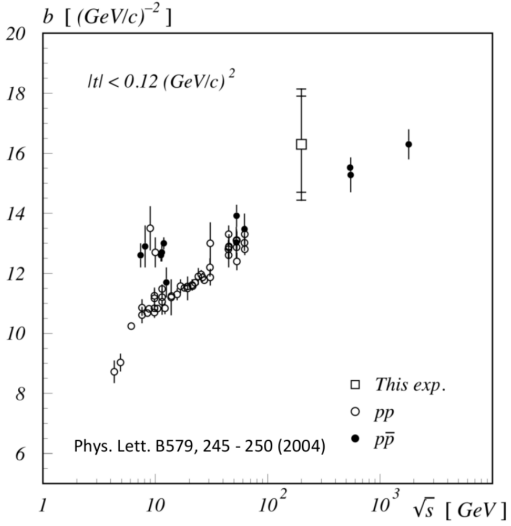
We are proposing to study proton-proton ($pp$) elastic scattering scattering at $\sqrt{s} = 500$ GeV. The lattice configuration and the angular coverage of the detector will allow the simultaneous study of all three regions that characterize elastic scattering, namely the Coulomb dominated region, the 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.


PHOBOS
10:00 o'clock
12:00 o'clock
BRAHMS & PP2PP ( p )
2:00 o'clock
RHIC
4:00 o'clock
PHENIX ( p )
8:00 o'clock
STAR ( p )
6:00 o'clock
NASA - BAF
μ g-2
HEP/NP ( p )
LINAC
BOOSTER
AGS
TANDEMS


Top View
RP'
RP
IP
Inelastic detectors (scintillators)
-57 m
0
57 m
Side View
Arm A
Arm B
Arm B
Arm A
Elastic trigger detector
(scintillator)
x-detector (silicon)
y-detector (silicon)
Scattered
proton


Roman Pot
above the
beam
to
IR
Roman Pot
below the
beam

- Less than 8 hours of beam time
- Three ongoing publication
- B-slope, Single and Double Spin asymmetries
- In 2005 funding crisis came
- PP2PP was cancelled by the BNL ALD
- The importance of this cartoon was learned



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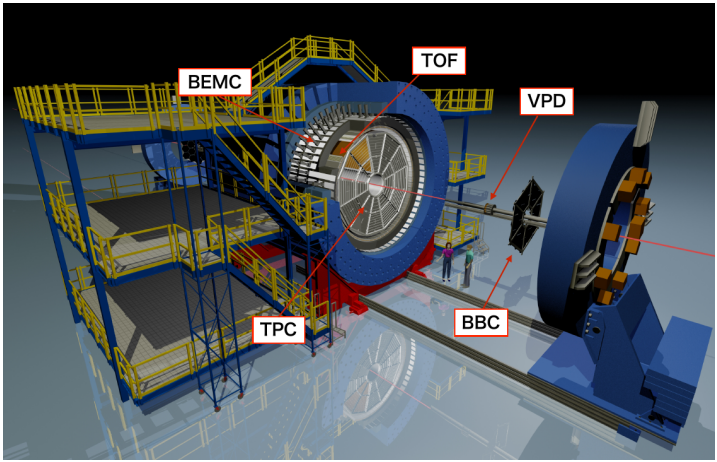
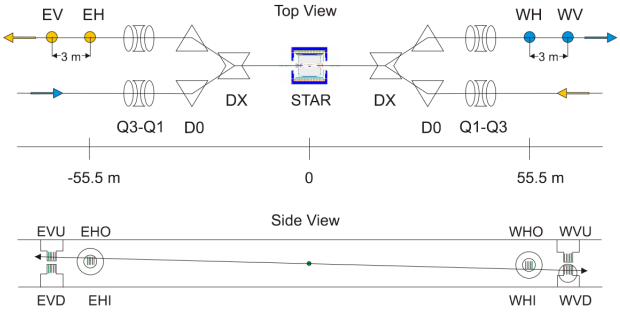
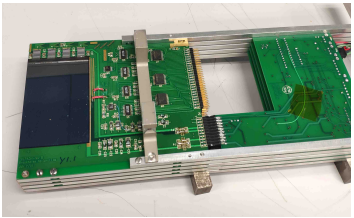
- Tracking of charged particles in the TPC covering $|\eta| < 1$ and full azimuthal angle
- Precise particle identification through the measurement of dE/dx and TOF
- Forward rapidity Beam-Beam Counters ($2.1 < |\eta| < 5.0$) used to ensure rapidity gaps
- Silicon Strip Detectors (SSD) in RP allow full reconstruction of the forward proton momentum and verification of interaction's exclusivity

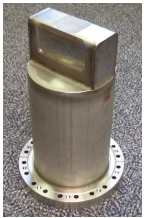


- Roman Pot Phase I*
- Roman Pot Phase II* setup has been used since 2015

  S. Bültmann et al., Nucl. Instr. Meth. A535, 415 (2004)
- Detectors are mounted in 4 stations, 2 stations on each side of STAR
- Each station holds one RP above and one RP below the beamline
- Each RP vessel contains a SSD package with active area of $\sim 8 \times 5$ cm$^2$
- Each package consists of a scintillation trigger counter and 4 SSDs with spatial resolution of $\approx$ 30 $\mu$m





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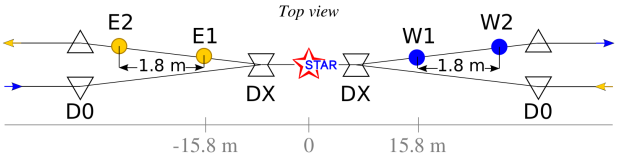
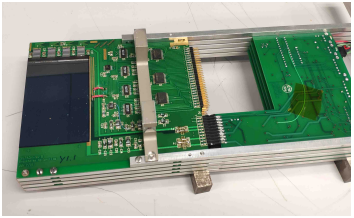
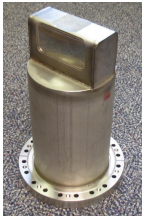
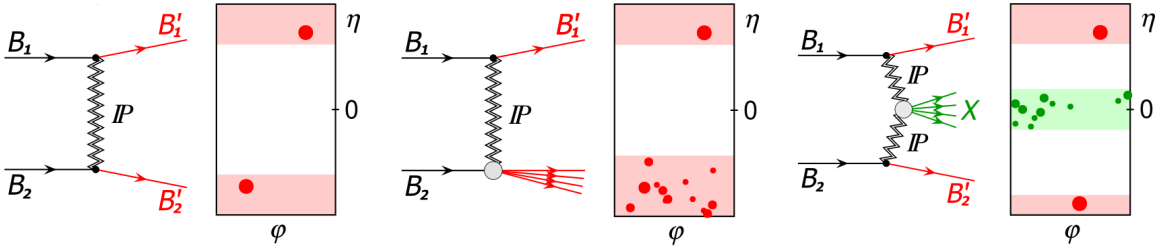


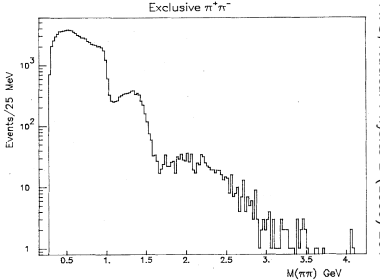





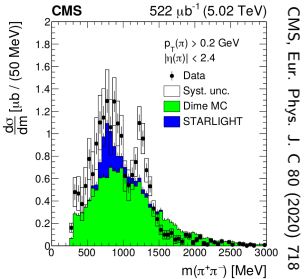
- Spin asymmetry results
- Elastic scattering: B-slope and $\sigma_{tot}$, $\sigma_{el}$
- Charged particle production at midrapidity in SDD and CP
- Central (inclusive/exclusive) production
- ...



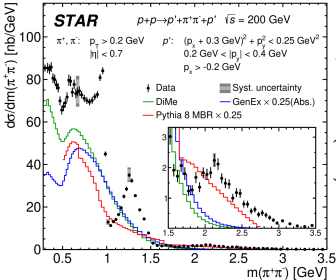
- Central Exclusive Production (CEP) through Double Pomeron Exchange (DPE) provides a gluon-rich environment for particle production
- CEP is considered to be a potential source of glueballs
- Glueballs are bound states consisting of only gluons and are predicted by the QCD theory
- Despite its theoretical predictions, the existence of a glueball has not been confirmed yet
- The first CEP through DPE was measured at Intersecting Storage Rings (ISR) and since then it has been studied at numerous experiments (AFS, NA22, CDF, UA8, STAR, CMS, ATLAS...)
- Although only at ISR, UA8 and STAR measured CEP (only them meassured forward protons)




AFS, Nuclear Physics B (1986) 264



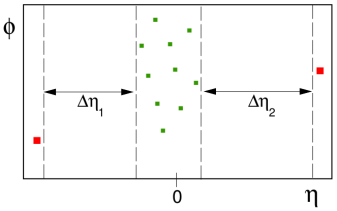

CMS, Eur. Phys. J. C 80 (2020) 718




STAR, JHEP 07 (2020) 178

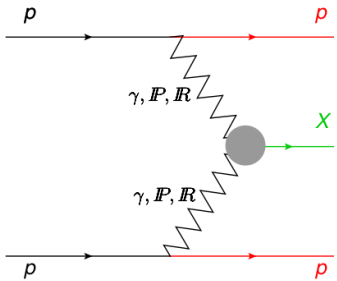
- Colliding protons stay intact and are measured in the Roman Pots (RP)
- Produced **central** system $X$ is well separated by rapidity gaps $\Delta\eta_{1,2}$ from the outgoing protons $p$
- **Central** system $X$ is fully measured in the Time Projection Chamber (TPC) and in the Time-of-Flight (TOF) systems

$$p + p \to p \overset{\Delta\eta_1}{\oplus} X \overset{\Delta\eta_2}{\oplus} p$$



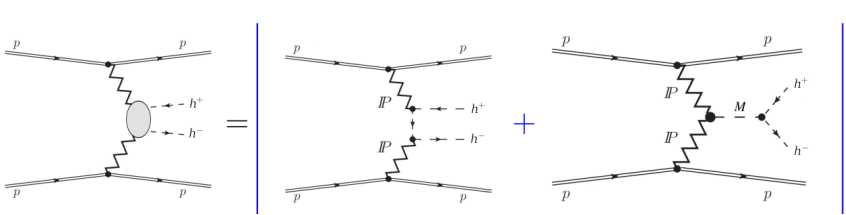

**Possible mechanisms of CEP:**

- Double Photon Exchange
  $\gamma + \gamma \to \gamma\gamma, l^+l^-, W^+W^-$
- Photon − IPomeron/ IRegeon fusion (photoproduction)
  $\gamma + \mathbb{P}/\mathbb{R} \to$ (pseudo)vector mesons, continuum
- Double IPomeron Exchange
  $\mathbb{P} + \mathbb{P} \to$ continuum, scalar/tensor mesons, glueballs




**DIPE is expected to be dominant at the RHIC energies**

- CEP of $h^+h^-$ is the simplest four(three) body QCD process: $p + p \to p + M(h^+h^-) + p$
- Topologically simple, theoretically complex and rich in phenomena
- Pomeron in QCD at lowest order is represnted by a pair of gluons
  $\Rightarrow$ DIPE is suitable for glueball production
- Dominantly low masses produced ($\lesssim 2$ GeV), lack of hard scale and pQCD not applicable
- Significant rescattering (absorption) effects via additional interaction between the protons
- Significant interference effects between resonance and continuum production

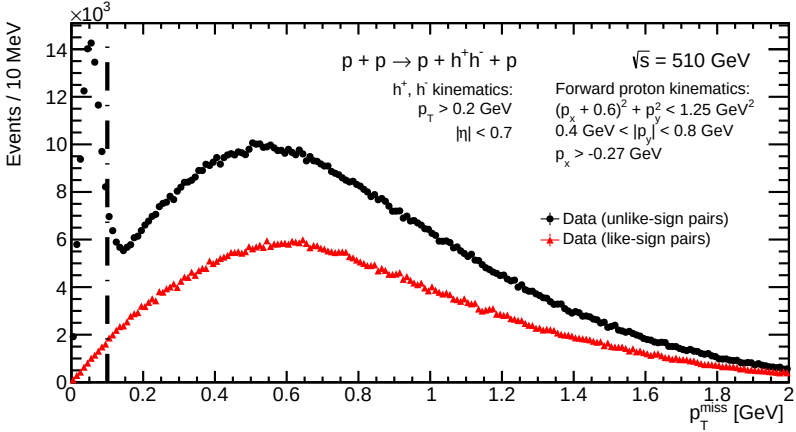


- Two phenomenological models based on Regge theory implemented in the form of MC generator:
  - **DiMe**: L.A. Harland-Lang et al., Eur. Phys. J. C72 (2012) 2110
    The phenomenology of CEP at hadron collider (dynamical treatment of absorption effects)
  - **GenEx**: P. Lebiedowicz and A. Szczurek, Phys. Rev. D81(2010)036003
    Exclusive $pp \to pp\pi\pi$ from the threshold to LHC (without absorptive corrections)
- Models can generate **only continuum** production
- Continuum also generated in Pythia8, with MBR model - R. Ciesielski, K. Goulianos, arXiv:1205.1446

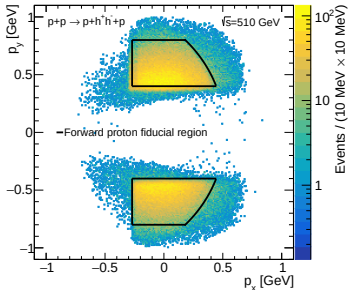
- **GRANIITTI**, a MC generator for high energy diffraction - M. Mieskolainen, arXiv:1910.06300
- GRANIITTI calculates inv. mass spectra assuming continuum and resonances contributions
  $M = f_0(500),\ \rho(770),\ f_0(980),\ \phi(1020),\ f_2(1270),\ f_0(1500),\ f_2(1525),\ f_0(1710)$
- Added CEP resonance couplings also tuned to STAR results at $\sqrt{s} = 200$ GeV

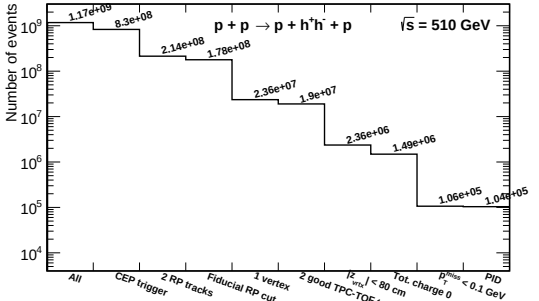
- Outgoing protons $pp$ and cental system $h^+h^-$ are fully measured
- The momentum conservation is used to verify **exclusivity** of the process

$$p_{\mathrm{T}}^{miss} := \left(\vec{p}_1 + \vec{p}_2 + \vec{h}_+ + \vec{h}_-\right)_{\mathrm{T}} = 0$$



- 830M events with CEP triggers were analyzed
- Exactly two tracks in Roman Pots inside the $p_x, p_y$ fiducial region with 3/4 silicon planes used in reconstruction
- Exactly one vertex in $\pm 80$ cm
- Exactly two primary TPC tracks matched with valid TOF hits satisfying good TPC track quality cuts:
  - $N_{hits}^{fit} \geq 25$
  - $N_{hits}^{dE/dx} \geq 15$
  - $|DCA(z)| < 1$ cm
  - $DCA(XY) < 1.5$ cm
- Cut on pseudorapidity of central tracks: $|\eta| < 0.7$
- Total charge equals 0 (looking for $h^+h^-$)
- Exclusivity cut: $p_{\mathrm{T}}^{miss} < 100$ MeV
- Particles were identified using the dE/dx and TOF
- After all the above selection criteria:
  101026 $\pi^+\pi^-$, 2558 $K^+K^-$ and 216 $p\bar{p}$



- Particles were identified using combined information from the TPC ($\chi^2_{dE/dx}$) and TOF ($m^2_{\mathrm{TOF}}$)

$$\chi^2_{dE/dx}(h^+h^-) = (n\sigma_{h^+})^2 + (n\sigma_{h^-})^2 \tag{6}$$

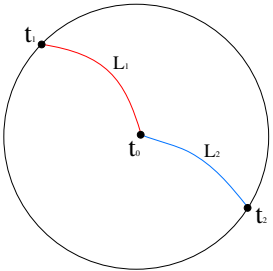
- $m^2_{\mathrm{TOF}}$ is derived from the assumption that both particles are of the same type ($m_1^2 = m_2^2 = m^2_{\mathrm{TOF}}$)

$$t_1 - t_0 = L_1\sqrt{1 + \frac{m_1^2}{p_1^2}} \tag{7}$$

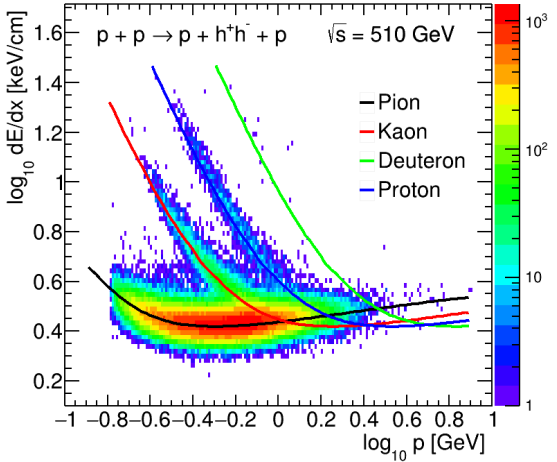
$$t_2 - t_0 = L_2\sqrt{1 + \frac{m_2^2}{p_2^2}} \tag{8}$$

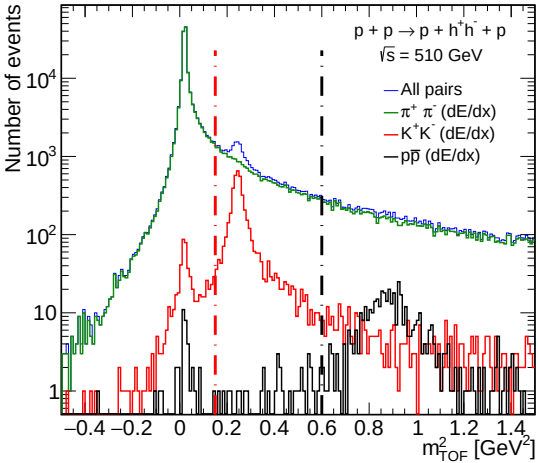
$$t_1 - t_2 = L_1\sqrt{1 + \frac{m_1^2}{p_1^2}} - L_2\sqrt{1 + \frac{m_2^2}{p_2^2}} \tag{9}$$

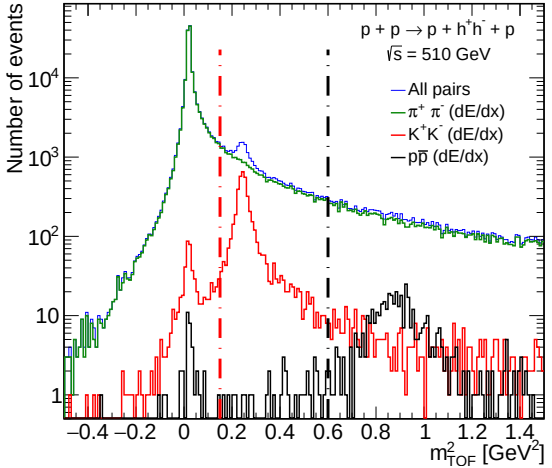
$$A \cdot (m^2_{\mathrm{TOF}})^2 + B \cdot m^2_{\mathrm{TOF}} + C = 0, \tag{10}$$



- $\pi^+\pi^-$ pairs production is dominant, as expected in DPE process at RHIC energies
- Peaks of pions, kaons and protons about their real mass squared can be seen
- Pions misidentified as kaons, using only the dE/dx information, can be seen as well





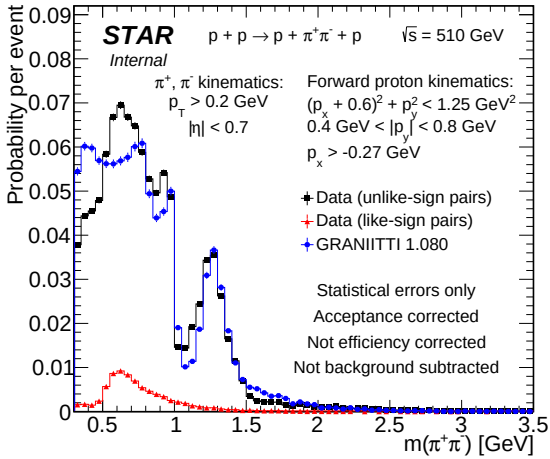

**if** $\chi^2_{dE/dx}(\pi\pi) > 9$ and
$\chi^2_{dE/dx}(KK) > 9$ and
$\chi^2_{dE/dx}(pp) < 9$ and
$m^2_{\mathrm{TOF}} > 0.6$ GeV
} **Protons**

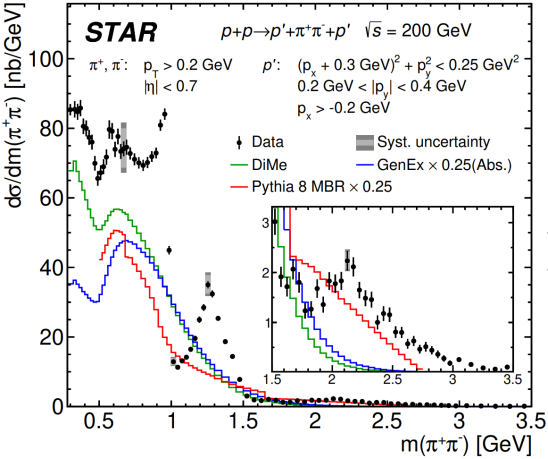
**else if** $\chi^2_{dE/dx}(\pi\pi) > 9$ and
$\chi^2_{dE/dx}(KK) < 9$ and
$\chi^2_{dE/dx}(pp) > 9$ and
$m^2_{\mathrm{TOF}} > 0.15$ GeV
} **Kaons**

**else if** $\chi^2_{dE/dx}(\pi\pi) < 12$ } **Pions**

**if** $\pi^+\pi^-$: $p_T > 0.2$ GeV
**if** $K^+K^-$: $p_T > 0.3$ GeV, $min(p_T^+, p_T^-) < 0.7$ GeV
**if** $p\bar{p}$: $p_T > 0.4$ GeV, $min(p_T^+, p_T^-) < 1.1$ GeV
} Estimated restricting fiducial cuts (from run15)

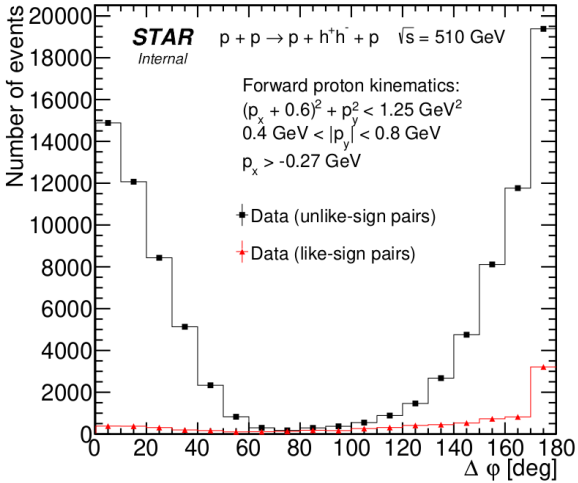
# Invariant mass of exclusively produced $\pi^+\pi^-$




- Four times better precision of the cross section compared to previous DPE measurement with forward proton tagging

- Spectra were divided into two $\Delta\varphi$ regions, the difference of azimuthal angles of the forward protons $\Rightarrow$ different Pomeron dynamics



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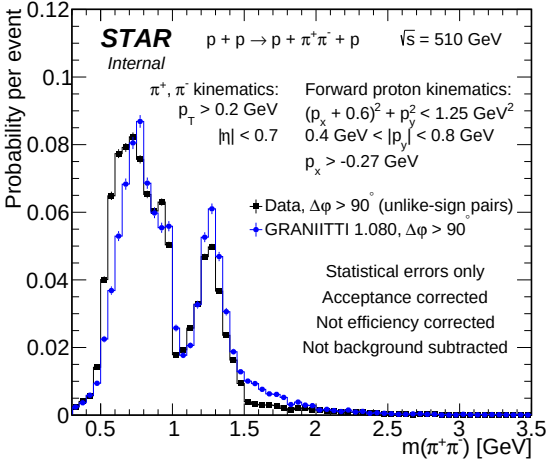
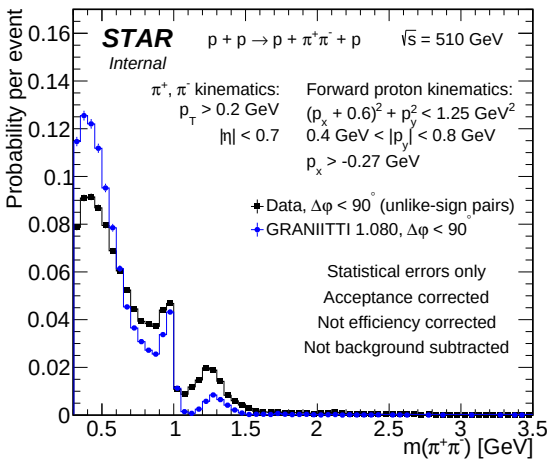
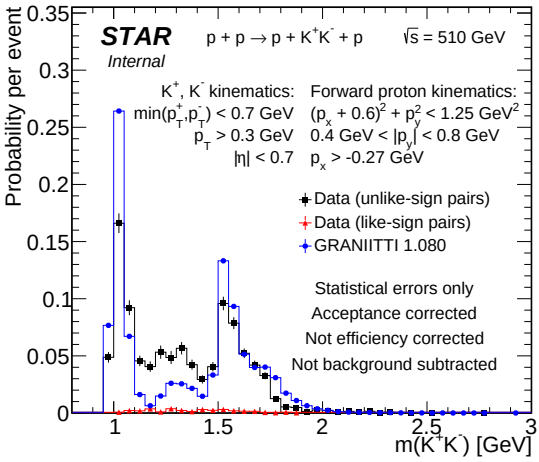
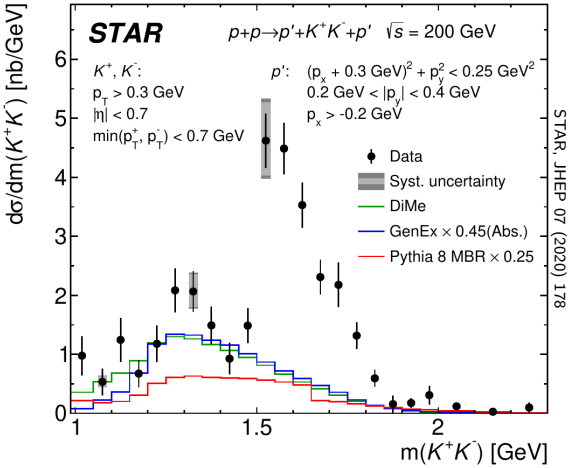


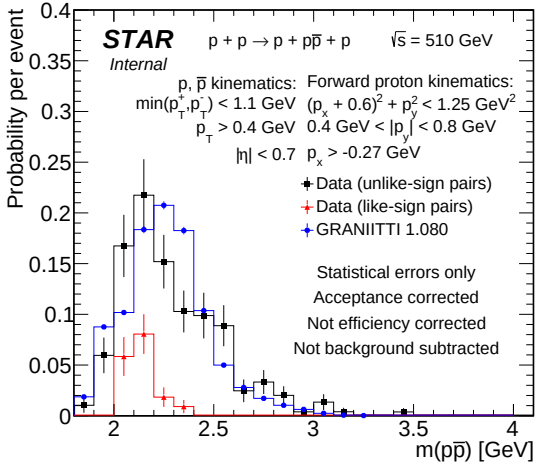



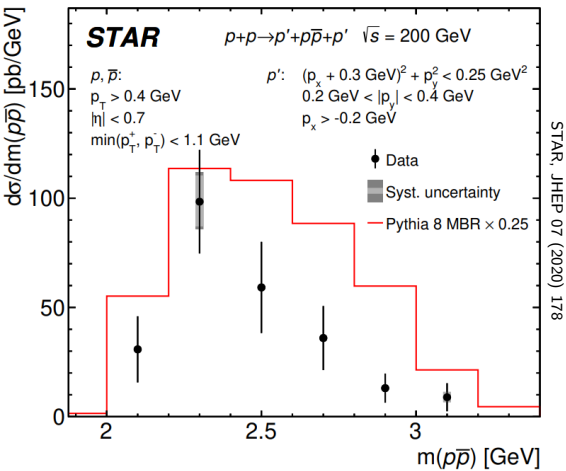



- A peak at 1 GeV (possible $\phi(1020)$ or $f_0(980)$) is close to the $K^+K^-$ mass threshold
  $\Rightarrow$ more studies have to be done

# Invariant mass of exclusively produced $p\bar{p}$



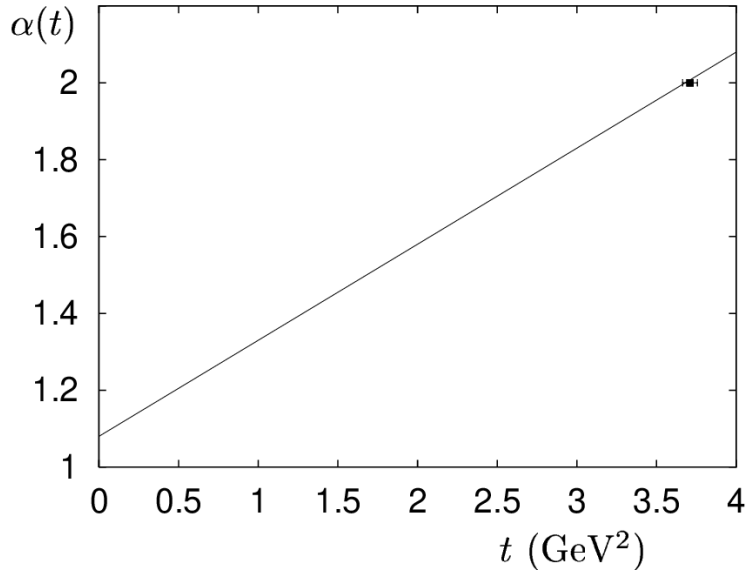




- The invariant mass spectrum of $p\bar{p}$ pairs does not show any resonances

- Attending Friday seminar could lead into a stand alone experiment
- The program with forward protons at RHIC delivered many important results
- CEP results are currently the highest center-of-mass energies at which the Double IPomeron Exchange has been measured with the detection of the forward-scattered protons
- Measurement of the diffractively scattered protons allowed full control of the interaction's kinematics and verification of its exclusivity
- High precision of this measurement, should help to constrain free parameters of the models
- The new MC generator, GRANIITTI, was compared to the data at $\sqrt{s} = 510$ GeV giving promising results
- The invariant mass spectra of $\pi^+\pi^-$, $K^+K^-$ and $p\overline{p}$ pairs confirmed features seen in previous measurements
- Interesting features are seen, like the peak at about 1 GeV in $K^+K^-$ at $\sqrt{s} = 510$ GeV

**Thank you!**

# Backup


$\alpha(t)$
2
1.8
1.6
1.4
1.2
1
0
0.5
1
1.5
2
2.5
3
3.5
4
$t$ (GeV$^2$)