Paper Proposal on:
Results on Elastic Cross Sections in Proton--Proton Collisions at √s = 510 GeV

Wlodek Guryn

- **Title:**

  Results on Elastic Cross Sections in Proton--Proton Collisions at √s = 510 GeV

- **PAs:**

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Proposed Target Journal: Physics Letters B

Webpage: Only a framework at this time: ElasticScatteringGPC510GeV

Analysis Note: to be done

Analysis Information

- Data set: Run 17, RHICf period with special $\beta^{*} \approx 8\ m$
- Year: 2017
- Production tag: **P18ih,** st_rp stream ,upcDSTs from microDSTs
- Triggers used: RP_ET triggers
- Embedding: no embedding needed, background and efficiencies estimated from data driven method.

Technical Details

Analysis is very similar to the one published in the 200 GeV PLB paper

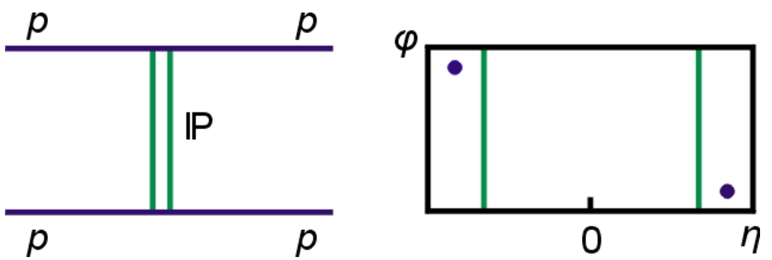
Elastic Scattering and Collinearity

$A = A(s,t)$ scattering amplitude is function of (s,t)

$A_+(s,t) = \frac{1}{2}(A_{pp}(s,t) + A_{p\bar{p}})$ symmetric under crossing

$A_-(s,t) = \frac{1}{2}(A_{pp}(s,t) - A_{p\bar{p}})$ asymmetric under crossing

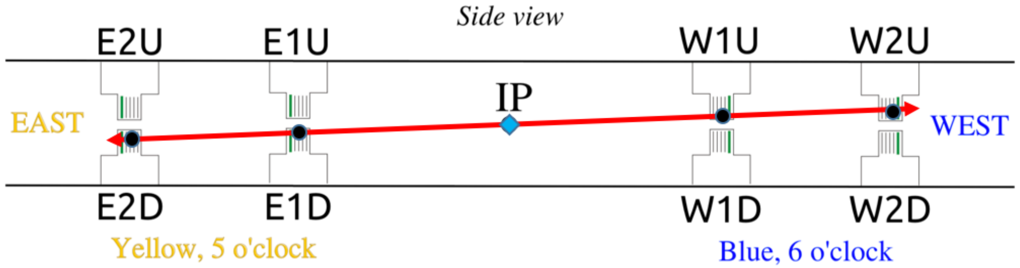
$$f_h = \left(\frac{\sigma_{tot}}{4\pi}\right)(\rho + i)\, e^{-\frac{1}{2}B|t|}$$



p + p → p + p

Four momentum transfer squared $t = (p_{in} - p_{out})^2 = -4p^2 \sin^2(\theta/2) \approx -p^2\theta^2$

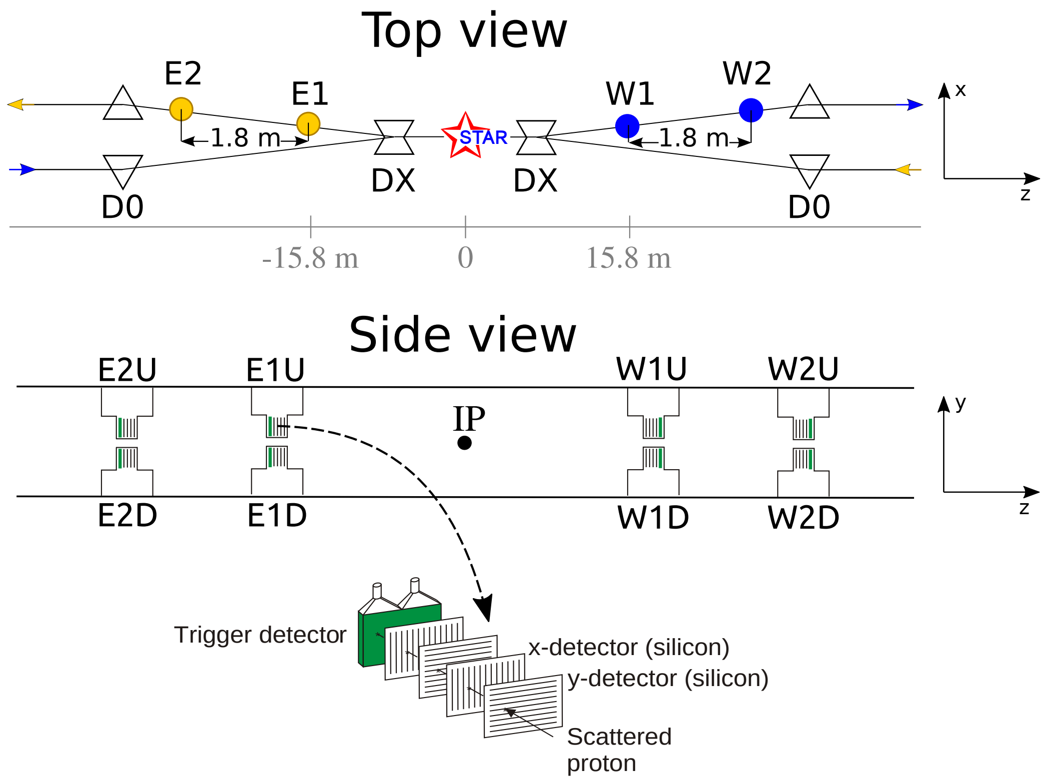
$$\vec{p_1} = -\vec{p_2} \Rightarrow (\Theta_{x1}, \Theta_{y1}) = (-\Theta_{x2}, -\Theta_{y2}) \Rightarrow \Delta\Theta_x = \Delta\Theta_y = 0$$



Two elastic combinations are possible: $(EU \wedge WD) \vee (ED \wedge WU)$

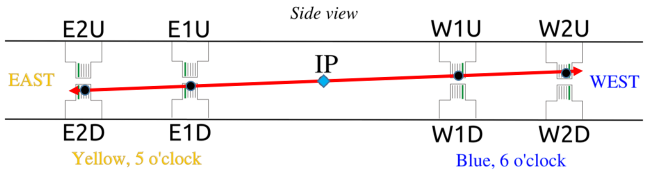
Minimum 3 points were required to fit the straight line in order to reconstruct θ => the final data sample consists of three point (3PT) and four point (4PT) events.

Experimental Setup

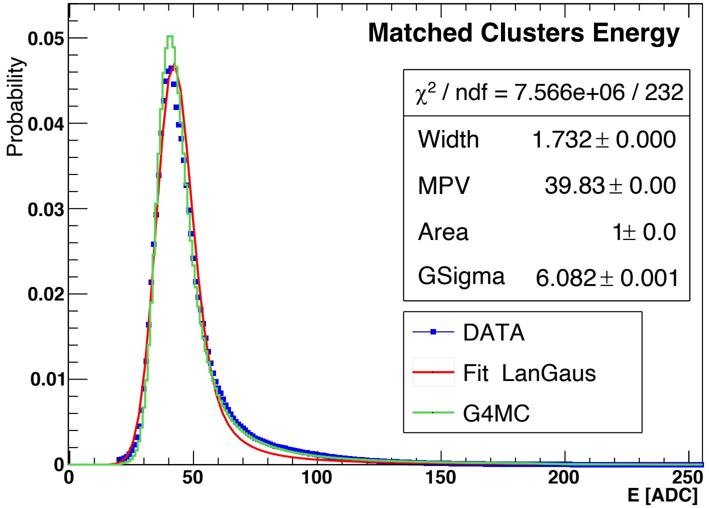


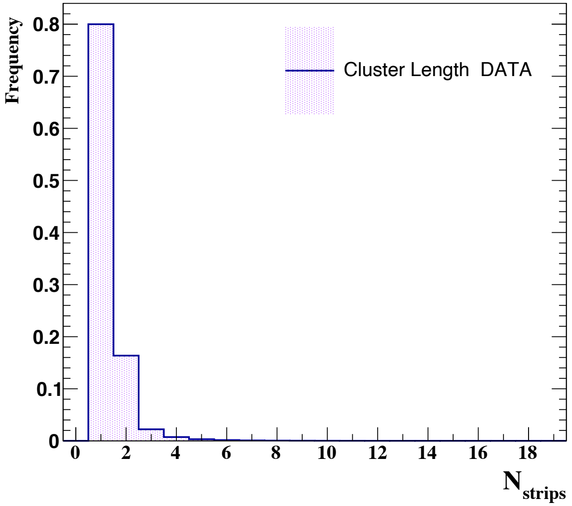
Caption: The layout of the RPs with the STAR detector (not to scale). The Roman Pot setup at STAR for measuring forward protons. Two sets of RPs are positioned between DX and D0 magnets, at 15.8 m and 17.6 m from the IP. Top and side view are shown.

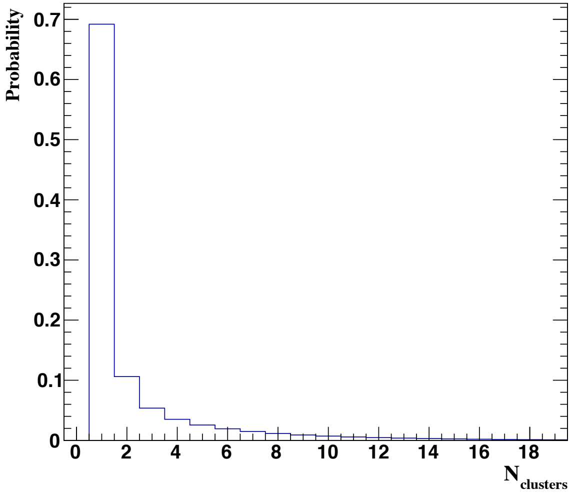
Technical details: SSD dE/dx and Clusters



1. Clusters are reconstructed from consecutive strips whose energy is > 5σ.
2. Accept clusters with energy > 20 ADC counts and length < 6 strips.







Event Reconstruction

Basically the same as in 200 GeV paper

- Use clusters reconstructed in μDSTs, with dE/dx cut and cluster length cut.
- Match clusters between two x-planes and y-planes to obtain (x, y) point in the RP.
- Perform corrections to survey alignment done using 4PT tracks.
- Scattering angle θ_x in (x,z) and θ_y in (y,z) planes separately was reconstructed using points reconstructed in the RPs and by fitting a straight line to those points.
- Event selection:
  1. Elastic event topology (ET): Only events with a combination of reconstructed points in the RPs consistent with elastic scattering were accepted.
  2. 4PT or 3PT data sample: Use only events with two-point tracks on one side and at least one point on the other side.
  3. Collinear (COL) events: Use events which satisfy 3σ cut in collinearity between East and West $\Delta\theta_{EW} \leq 3\sigma_\theta$.
  4. Fiducial volume GEO cut: Choose region in ($|t|$,ϕ) space to stay clear of apertures and the beam halo.
- Calculate the scattering angle $\theta^2 = \theta_x^2 + \theta_y^2$, ($|t|$, ϕ) values.
- Apply correction factors: efficiency, acceptance and beam tilt angle θ_x^B, θ_y^B.
- Make final distributions and fits.

Abstract

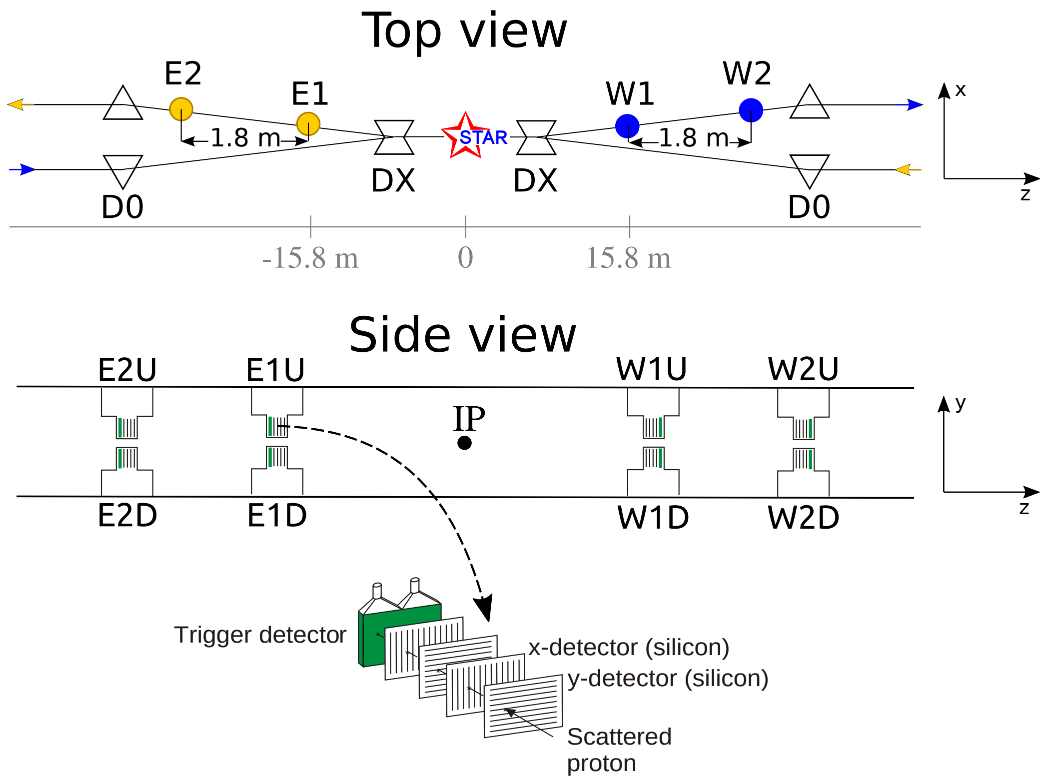
Results on Elastic Cross Sections in Proton–Proton Collisions at $\sqrt{s} = 510$ GeV

(Dated: January 28, 2021)

We report results on elastic cross sections in proton-proton collisions at $\sqrt{s} = 510$ GeV obtained with the Roman Pot setup of the STAR experiment at the Relativistic Heavy Ion Collider (RHIC). The elastic differential cross section was measured in the squared four-momentum transfer range $0.16 \leq -t \leq 1.06$ GeV^2. The value of the exponential slope parameter B of the elastic differential cross section $d\sigma/dt \sim e^{-Bt}$ in the measured $-t$ range $0.21 \leq -t \leq 0.60$ GeV^2 was found to be $B = 13.62 \pm 0.03(stat.) \pm 0.03(syst.)$ GeV^{-2} We also present the elastic cross section integrated within the STAR t-range $\sigma_{el}^{det} = 1.337 \pm 0.003(stat.) \pm 0.053(syst.)$ mb. We compare $d\sigma_{el}/dt$ in the t-range measured by STAR to the one obtained in $p\bar{p}$ collisions at $\sqrt{s} = 546$ GeV by the UA4 experiment at the S$p\bar{p}$S collider. The measured difference in the diffractive minimum region $-t$ range $0.75 \leq -t \leq 1.03$ GeV^2 is 0.353 ± 0.039 μb. Such difference is commonly explained by the C-odd amplitude in the pp and $p\bar{p}$ elastic scattering at $\sqrt{s} \approx 500$ GeV of the two experiments.

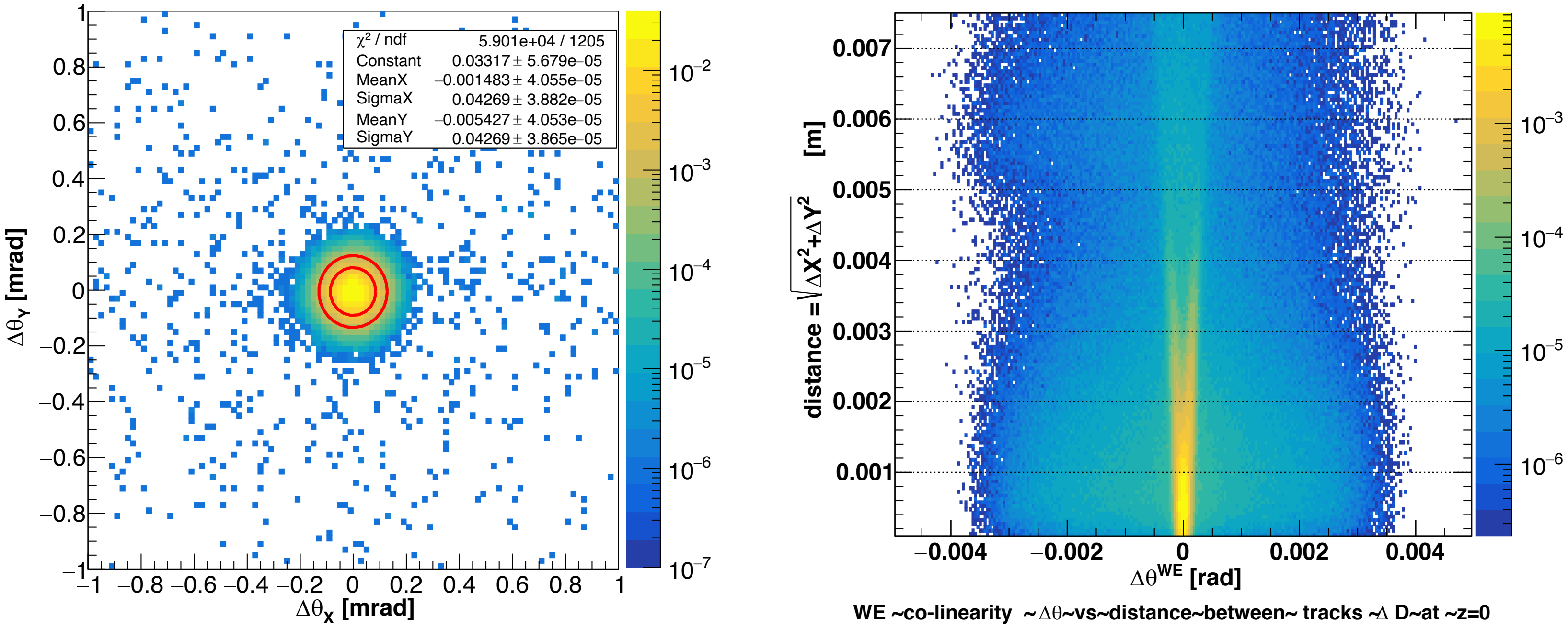
PACS numbers: 13.85.Dz, 13.85.Lg
Keywords: Elastic Scattering, Diffraction, Proton-Proton Collisions

Figure 1: ExperimentaL Setup



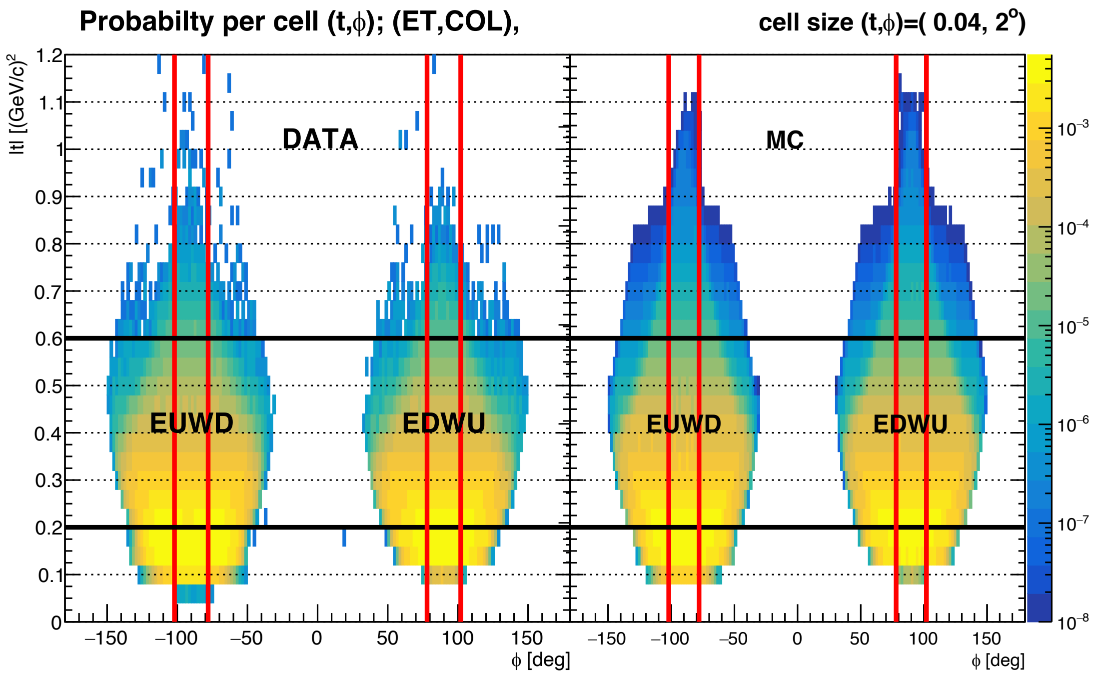
Caption: The layout of the RPs with the STAR detector (not to scale). The Roman Pot setup at STAR for measuring forward protons. Two sets of RPs are positioned between DX and D0 magnets, at 15.8 m and 17.6 m from the IP. Top and side view are shown.

Figure 2: Collinearity



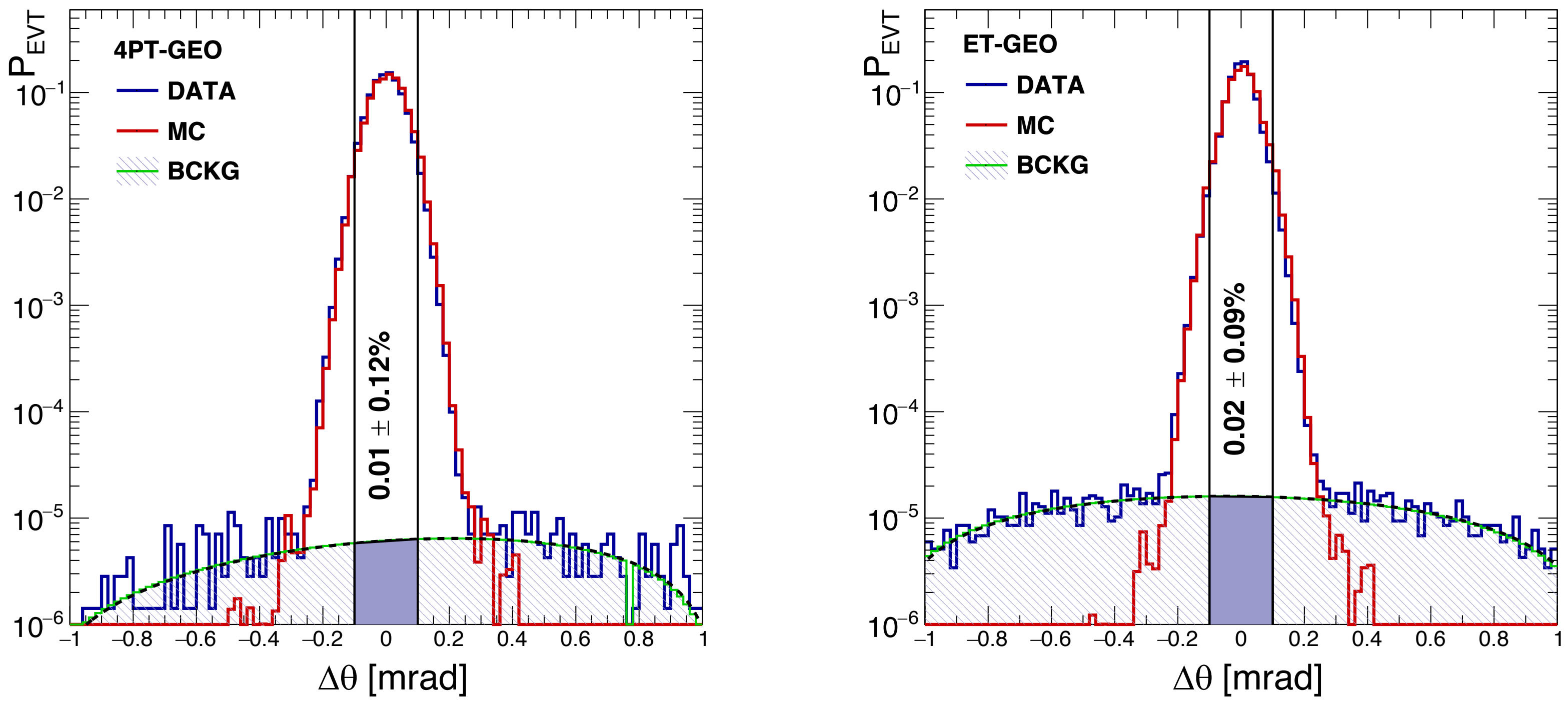
Caption: $\Delta\Theta_y$ vs $\Delta\Theta_x$ with the contours of 2σ and 3σ for 4 PT and 3Pt events. Cuts on Δ are at z=0.

Figure 3: Geometrical Acceptance – Choice of Fiducial Volume in (-t, ϕ) Space



Caption: |t| vs ϕ distributions from data for 3PT and 4PT events for two elastic arms. The boundaries of geometrical acceptance cuts for B-slope fit and for the full t-region are shown. Both data and Monte Carlo are shown.

Figure 4: Background and Collinearity in Δθ

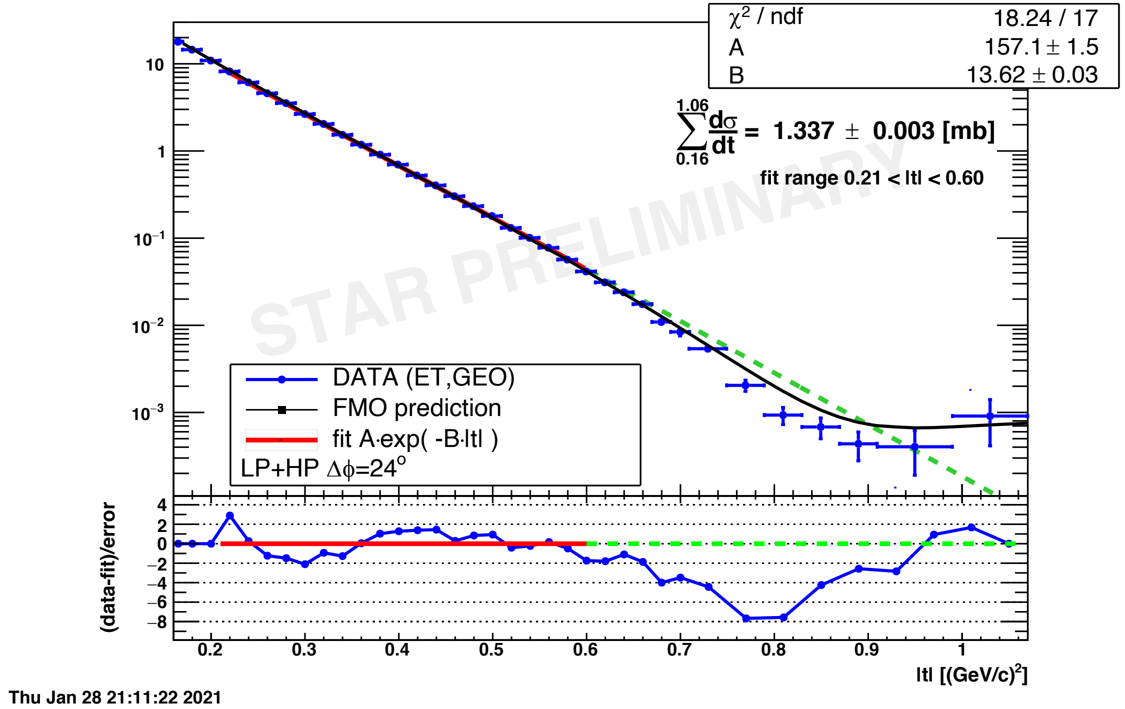


Caption: Collinearity in scattering angle Θ between the outgoing protons is shown. Background levels extrapolated from outside of $\pm 5\sigma_{\theta}$. They were small and therefore neglected.

Systematic Uncertainties

1. The main systematic uncertainty in the differential cross section $d\sigma/dt$ is luminosity calibration. It is estimated to be 4% at this time, which is what was achieved for the 200 GeV paper.
2. The main systematic uncertainty of comparison with UA4 is 10% normalization uncertainty of UA4 points.
3. To determine the systematic uncertainty in B-slope we varied the phase space of the fit ($\Delta\phi$, t) range , using 4PT and 3PT events), which yielded the uncertainty of 0.03.
4. The background was found to be small and was neglected.
5. The small values in 3 and 4 above are due to the fact that we chose the fiducial volume of the measurement away from the apertures and the beam halo.
6. Also small beam angular divergence allows relatively clean selection of the elastic events using collinearity.

Figure 5: Corrected $d\sigma_{el}/dt$ and B-slope

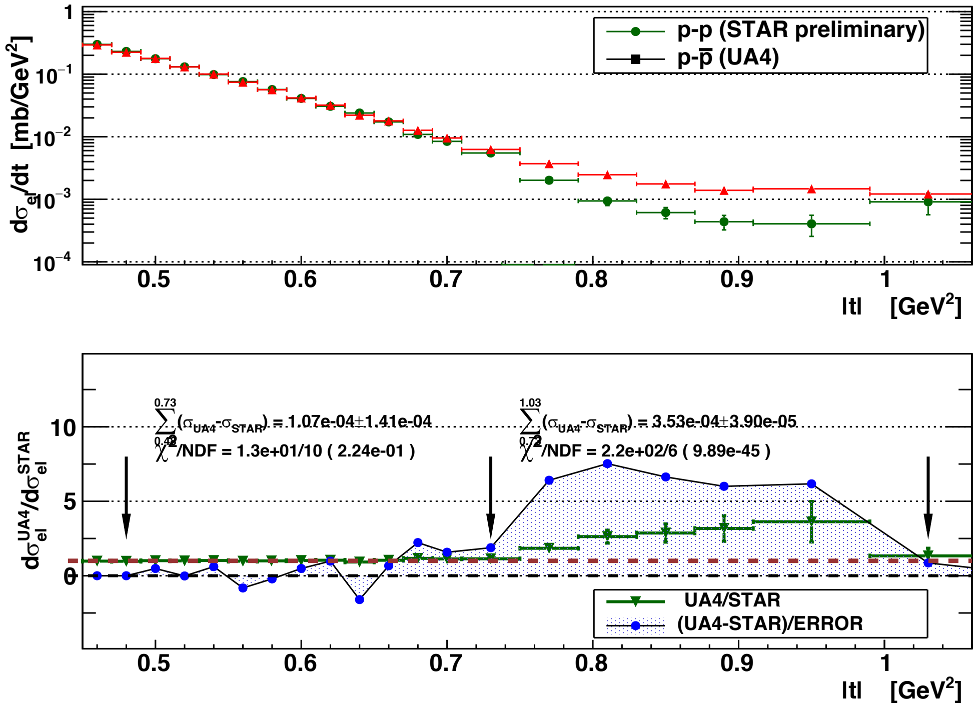


B = 13.62+-0.03(stat.)+-0.03(syst.)

Caption: Corrected differential cross-section $d\sigma/dt$ fitted with exponential $A \cdot e^{-Bt}$. The deviation from e^{-Bt} fit for $-t > 0.6$ GeV^2 is expected, due to the diffractive minimum at $-t \approx 0.9$ GeV^2 is also present.

Figure 6: The difference between pp and $p\bar{p}$ data in the dip region in order to test Odderon hypothesis in a model independent way

STAR $\sqrt{s}$ = 510 GeV is sufficient to compare with $\sqrt{s}$ =546 of the UA4 experiment.



Caption: Comparison of STAR data with UA4 data. The upper plot shows dσ/dt and the bottom plot shows the ratio of UA4 to STAR data with the differences scaled by the uncertainties. The comparison t- region range is indicated by the arrows, as is the range outside of the dip region. The binning is determined by UA4 data, with the last four bins combined into two bin in order to improve statistics of STAR data. The difference in the compared region is $\frac{0.353\mu b}{0.039\mu b} \approx 9\sigma$.

Conclusions

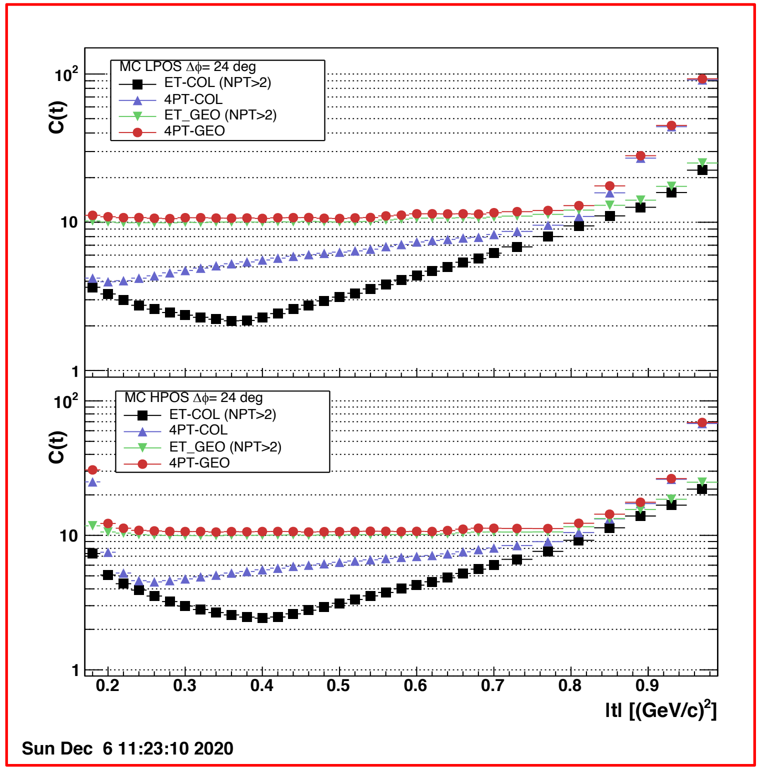
We report results on elastic cross sections in proton-proton collisions at $\sqrt{s} = 510$ GeV obtained with the Roman Pot setup of the STAR experiment at the Relativistic Heavy Ion Collider (RHIC). The elastic differential cross section was measured in the squared four-momentum transfer range $0.16 \le -t \le 1.06$ GeV^2. The value of the exponential slope parameter B of the elastic differential cross section $d\sigma/dt \sim e^{-Bt}$ in the measured $-t$ range $0.21 \le -t \le 0.60$ GeV^2 was found to be $B = 13.62 \pm 0.03(stat.) \pm 0.03(syst.)$ GeV^{-2} We also present the elastic cross section integrated within the STAR t-range $\sigma_{el}^{det} = 1.337 \pm 0.003(stat.) \pm 0.053(syst.)$ mb. We compare $d\sigma_{el}/dt$ in the t-range measured by STAR to the one obtained in $p\bar{p}$ collisions at $\sqrt{s} = 546$ GeV by the UA4 experiment at the S$p\bar{p}$S collider. The measured difference in the diffractive minimum region $-t$ range $0.75 \le -t \le 1.03$ GeV^2 is 0.353 ± 0.039 μb. Such difference is commonly explained by the C-odd amplitude in the pp and $p\bar{p}$ elastic scattering at $\sqrt{s} \approx 500$ GeV of the two experiments.

Conclusions

1. STAR measured elastic differential cross section in the |t|-range $0.16 < |t| < 1.06$ GeV^2.
2. The B-slope of dσ/dt in the $-t\ range\ 0.21 < -t < 0.60\ GeV^2$ is $B\ =\ 13.62 \pm 0.03(stat.) \pm 0.03(syst.)$.
3. The measured difference in $d\sigma/dt$ between pp and $\mathrm{p\bar{p}}$ is 0.353 ± 0.039 μb, with 10% normalization error in UA4 data.
4. The difference is consistent with existence of C-odd amplitude in pp and $\mathrm{p\bar{p}}$ elastic scattering, the t-region where the difference is measured. It shall undergo more cross checks to make sure.
5. Integrated elastic scattering cross section, dσ/dt, within the STAR |t|-acceptance of $0.16 < |t| < 1.06\ GeV^2$ is $1.337 \pm 0.003\ (stat.)$ mb with 4% luminosity systematic error.

BACKUP

Correction factors

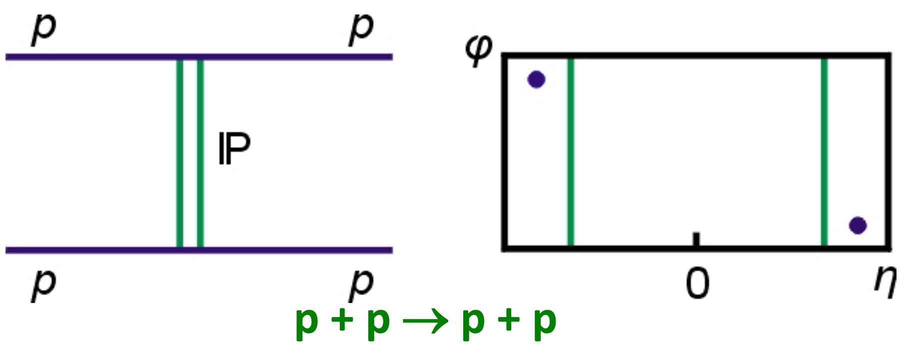


Two data samples: closer distance (LPOS) and farther (HPOS). Use $\pm 12°$ ϕ-cut around vertical.

Correction factors: track reconstruction efficiency from the data and geometrical acceptance obtained using GEANT4 MC with full beamline material simulation.

Motivation and some basics

Proton – Proton Elastic Scattering



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

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

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

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

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

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

Odderon Amplitude in Elastic Scattering

Scattering amplitudes:

PRL Vol 54 No 20, 2180 (1985)

$$A = A(s,t) \;\; \textbf{scattering amplitude is function of (s,t)}$$
$$A_+(s,t) = \frac{1}{2}(A_{pp}(s,t) + A_{p\bar{p}}) \;\; \textbf{symmetric under crossing}$$
$$A_-(s,t) = \frac{1}{2}(A_{pp}(s,t) - A_{p\bar{p}}) \;\; \textbf{asymmetric under crossing}$$

Note: Crossing symmetry changes particle to antiparticle.

The pp and $p\bar{p}$ amplitudes can be expressed as:

$$A_{pp}(s,t) = A_+(s,t) + A_-(s,t)$$
$$A_{p\bar{p}}(s,t) = A_+(s,t) - A_-(s,t)$$

The elastic differential cross section is expressed as:

$$\frac{d\sigma_{el}}{dt} = \frac{1}{64\pi ks(s-4m^2)}|A(s,t)|^2$$

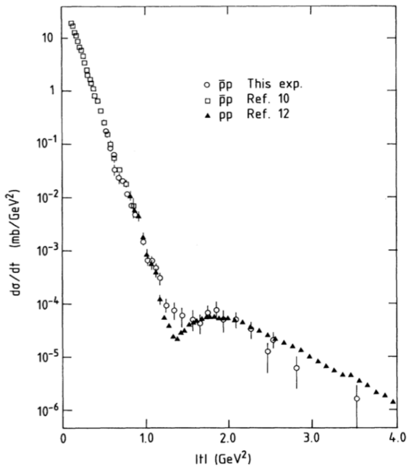


FIG. 2. Elastic differential $\bar{p}p$ cross section at $\sqrt{s} = 53$ GeV. Only t-dependent errors are shown. The systematic scale error is estimated at ±30%. Included are the low-t data from our previous experiment (Ref. 10) and the pp data of Ref. 12.

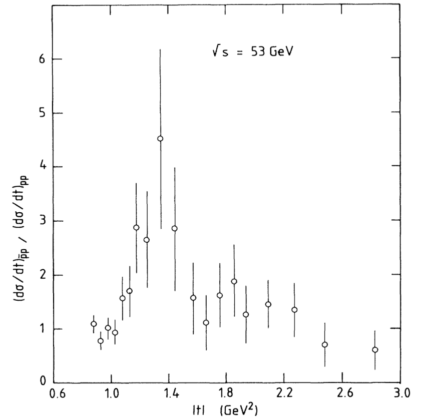
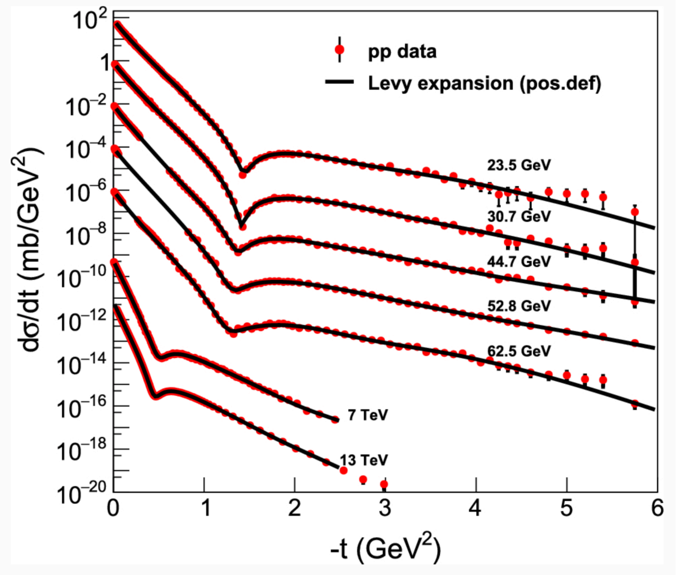
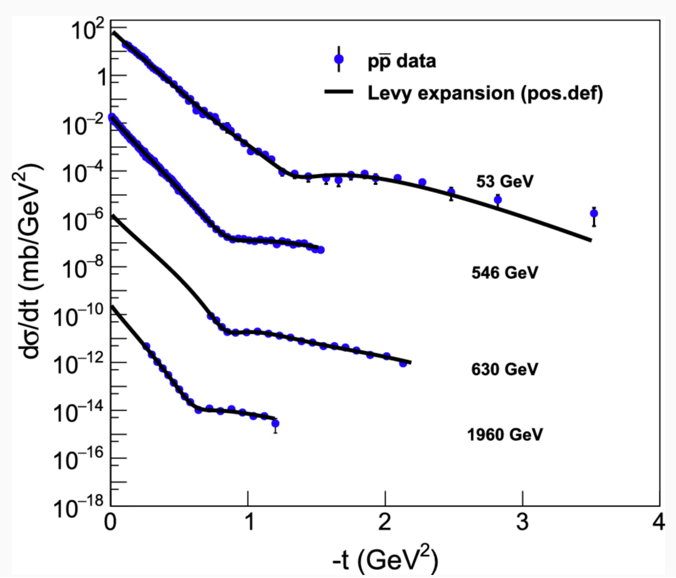


FIG. 3. The ratio of the $\bar{p}p$ differential cross section from this experiment to the pp differential cross section of Ref. 12 in the range $0.7 < |t| < 3.0$ (GeV/c)^2. The pp data of Ref. 12 have been multiplied by the factor 0.71 to take into account the normalization differences of the two experiments. Only t-dependent errors are shown. The ratio has an overall uncertainty of ±30% due to these normalization uncertainties.

- Odderon is a C=P=-1 partner of the Pomeron and is a solid part of QCD – three gluon exchange
- The first evidence of the Odderon amplitude in pp, $p\bar{p}$ scattering was observed at CERN's ISR.
- At the ISR in the diffractive minimum (dip) region $p\bar{p}$ is flat while pp has a dip.
- The best way to determine existence of the C-odd (Odderon) amplitude is to compare pp and $p\bar{p}$ in the diffractive minimum region at the same energy.

Current Status of dσ/dt at High Collider Energies

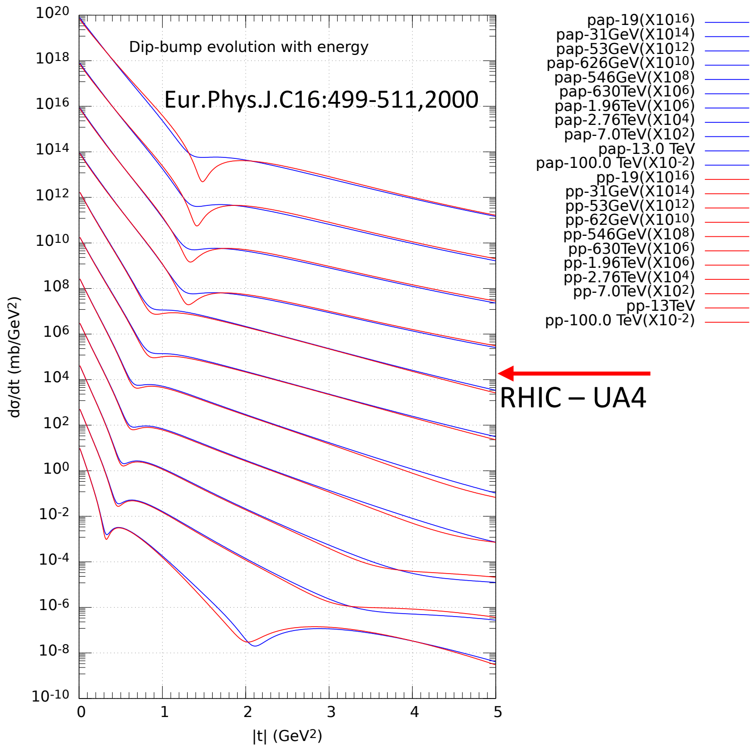




- Clearly there are diffractive minima (dips) in pp and no “dips” in $p\bar{p}$ at high energy.
- There exists direct comparison at 53 GeV, ISR measurement
- The only other direct comparison that could be done is 546 GeV $p\bar{p}$ UA4 and pp 510 GeV at RHIC (STAR).

Odderon – Current Status of Phenomenology

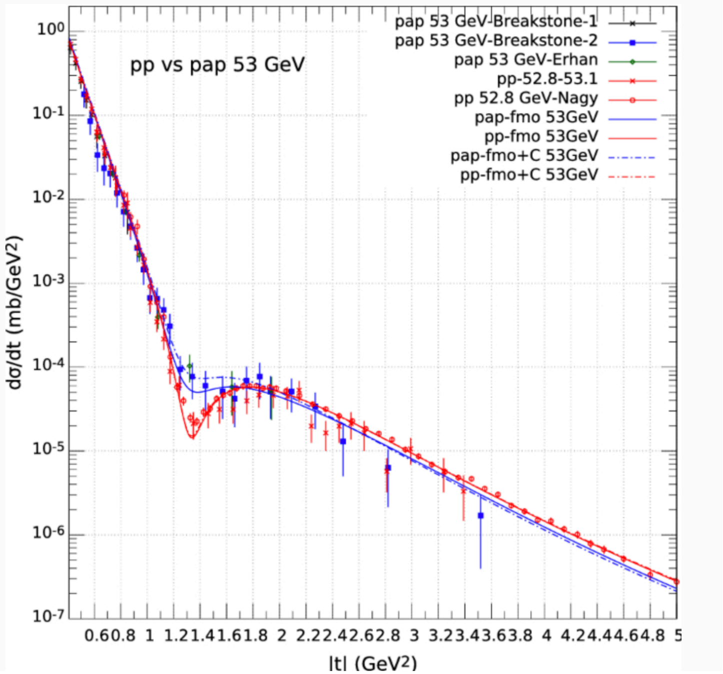
FMO = Froissart Maximal Odderon

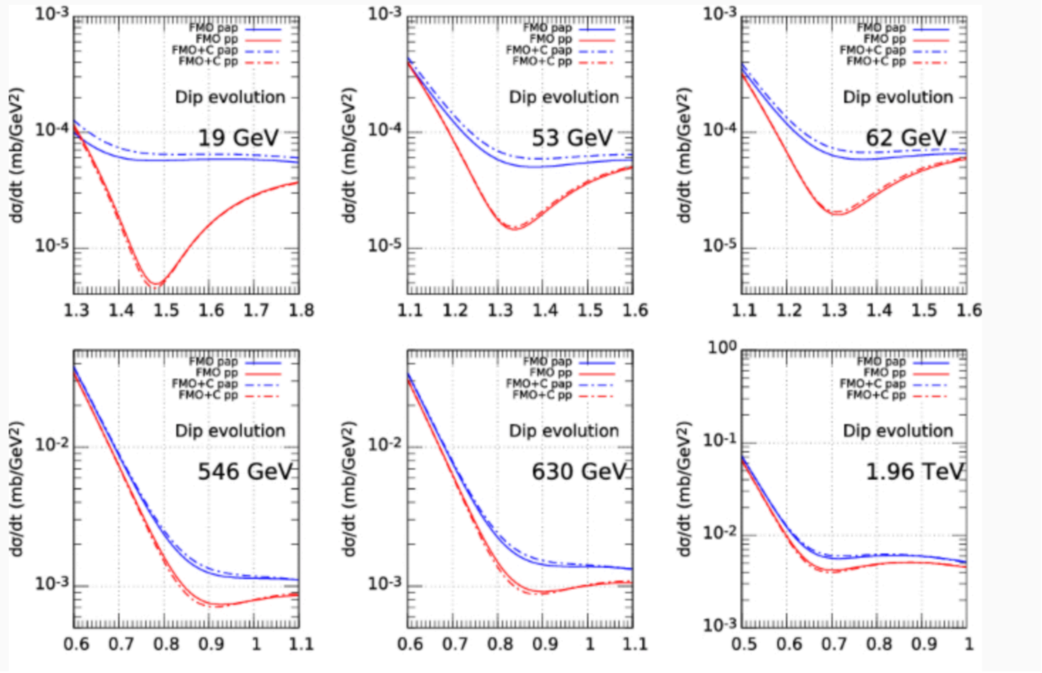


- The most recent model with the fit to world data on elastic scattering within the framework of Regge theory shows dips in pp and no dip in $p\bar{p}$. The model has an Odderon amplitude.
- Note that the “dip” is quite shallow, but still measurable at 510 GeV and also that at LHC $\sqrt{s}$ the difference between pp and $p\bar{p}$ is small => importance of RHIC data.
- This is not the only model with the Odderon, just the most recent one which includes LHC data.

Evolution of the Diffractive Minimum (dip) in pp and $p\bar{p}$

Eur.Phys.J.C16:499-511,2000

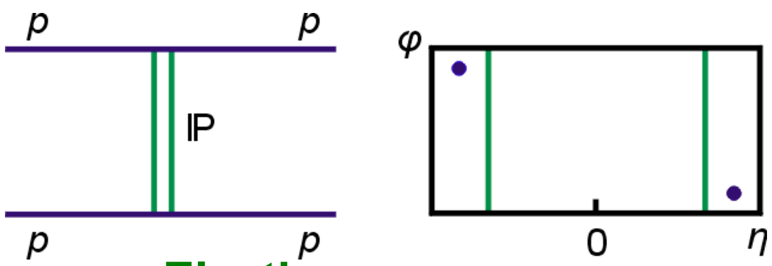




- A shallow diffractive minimum in $p\bar{p}$ is expected and seen in at $\sqrt{s}$ = 53 GeV at the ISR.
- The diffractive minimum is also shallower with increasing $\sqrt{s}$ for pp but a clear difference between pp and $p\bar{p}$ is seen.

Elastic Scattering

$J^{PC} = 0^{++}$ quantum numbers exchanged

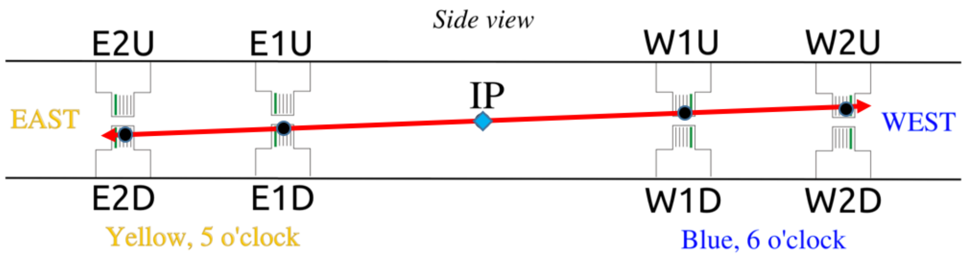


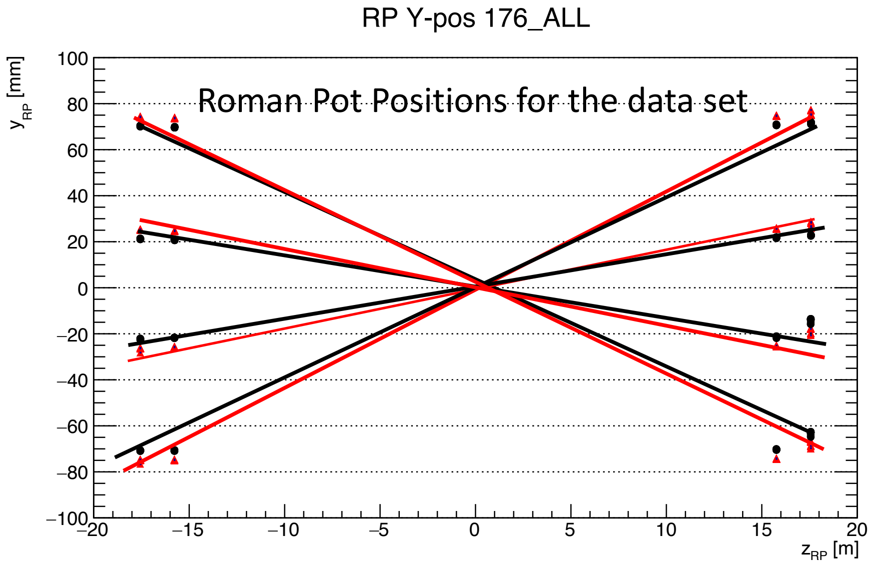
Elastic: p + p → p + p

1. proton-proton elastic scattering contributes about 20 % of the total cross section.
2. It provides crucial information about the Pomeron exchange in hadronic interactions in non-perturbative regime of QCD.
3. Study of the difference in the diffractive minimum region between pp and $p\bar{p}$ informs about C-odd amplitude in elastic scattering.
4. Mother of rapidity gaps ($\Delta\eta \approx 14$) and forward backward particle correlations.
5. Outgoing protons are collinear.
6. Scattering angles are small, of the order of few *mrad.*
7. Mandelstam variable -t is used to describe scattering: $t = (p_{in} - p_{out})^2 = -p^2\theta^2 = -p^2(\theta_x^2 + \theta_y^2)$.

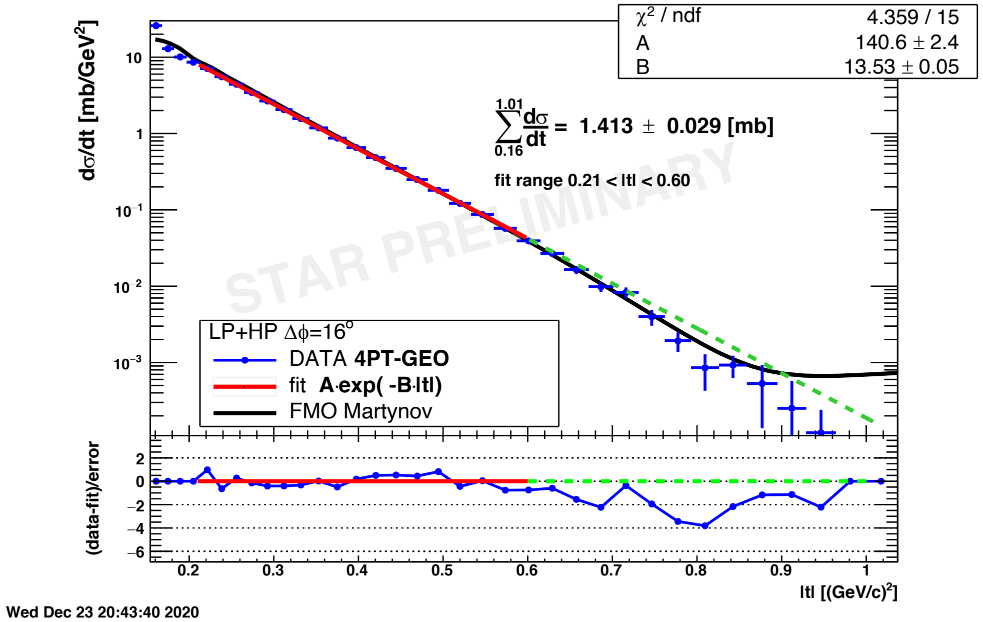
Analysis here is very similar to the published analysis in 200 GeV paper.

Technical Details: Roman Pot Positions





We use three point and four point data to reconstruct scattering angle θ, by fitting a straight line in (x,z) and (y,z) scattering planes.



χ² / ndf 4.359 / 15
A 140.6 ± 2.4
B 13.53 ± 0.05
$\sum_{0.16}^{1.01} \frac{d\sigma}{dt}$ = 1.413 ± 0.029 [mb]
fit range 0.21 < |t| < 0.60
STAR PRELIMINARY
LP+HP Δφ=16°
DATA 4PT-GEO
fit A·exp(-B·|t|)
FMO Martynov
dσ/dt [mb/GeV²]
(data-fit)/error
|t| [(GeV/c)²]
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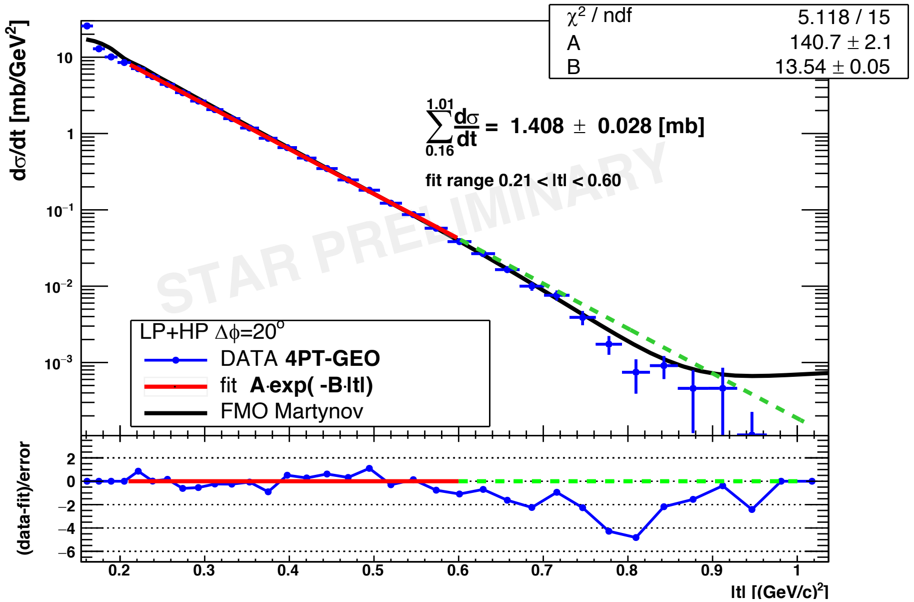
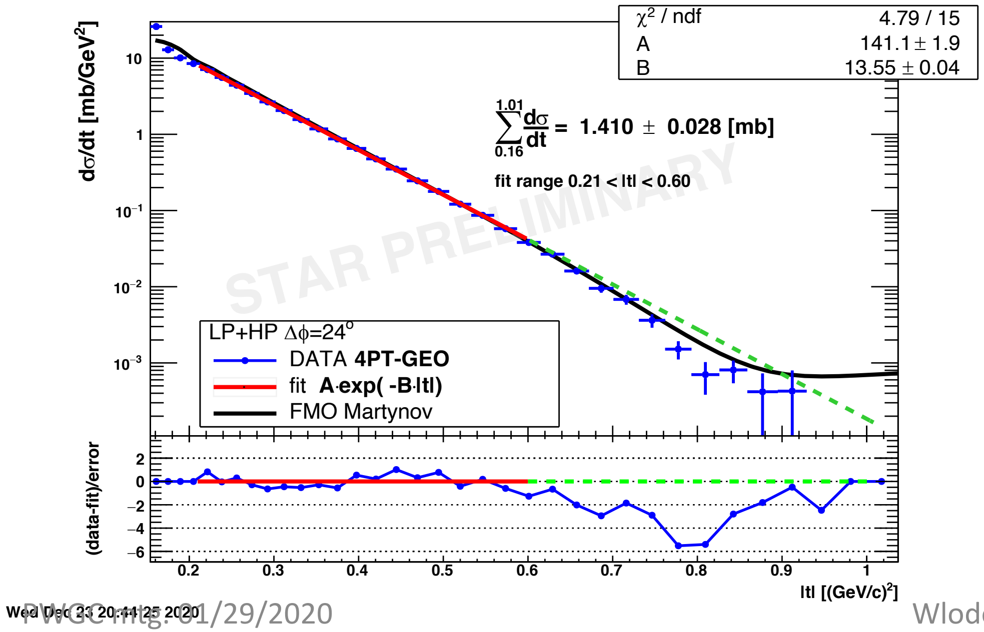
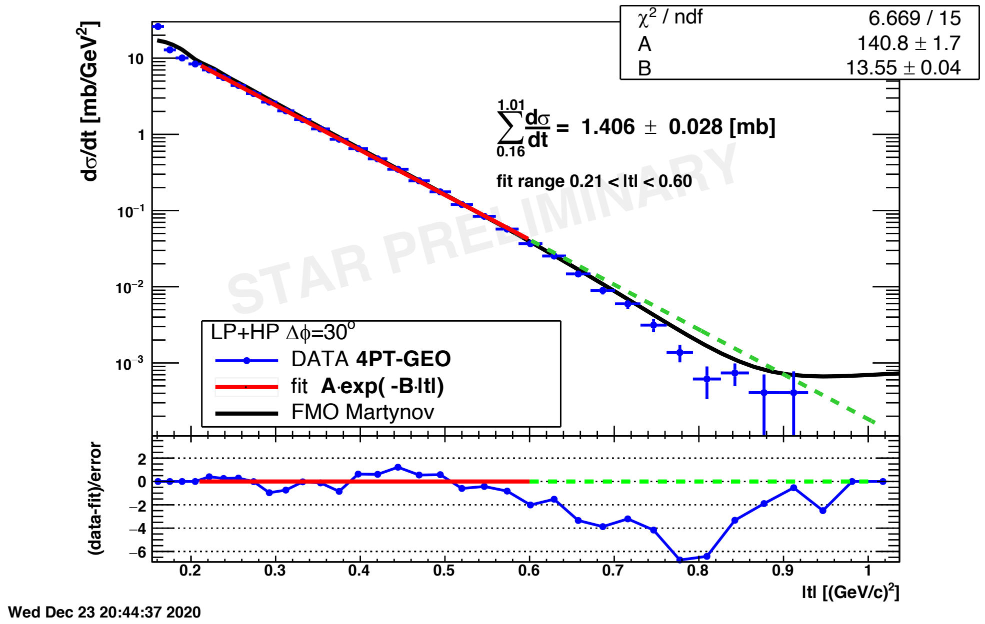


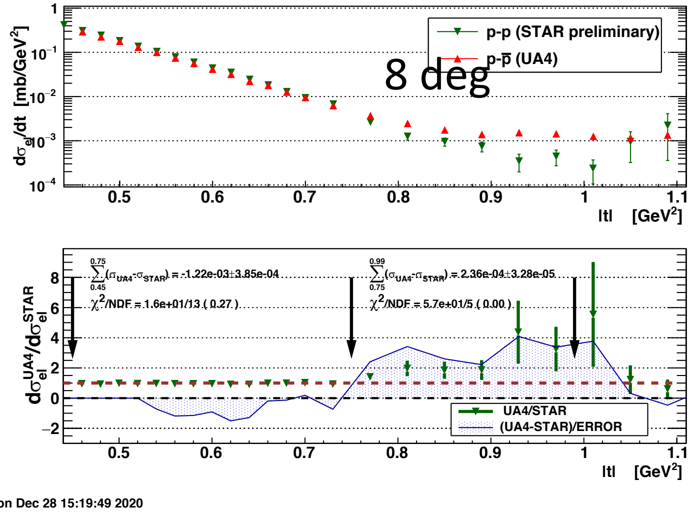
χ² / ndf 5.118 / 15
A 140.7 ± 2.1
B 13.54 ± 0.05
$\sum_{0.16}^{1.01} \frac{d\sigma}{dt}$ = 1.408 ± 0.028 [mb]
fit range 0.21 < |t| < 0.60
STAR PRELIMINARY
LP+HP Δφ=20°
DATA 4PT-GEO
fit A·exp(-B·|t|)
FMO Martynov
dσ/dt [mb/GeV²]
(data-fit)/error
|t| [(GeV/c)²]

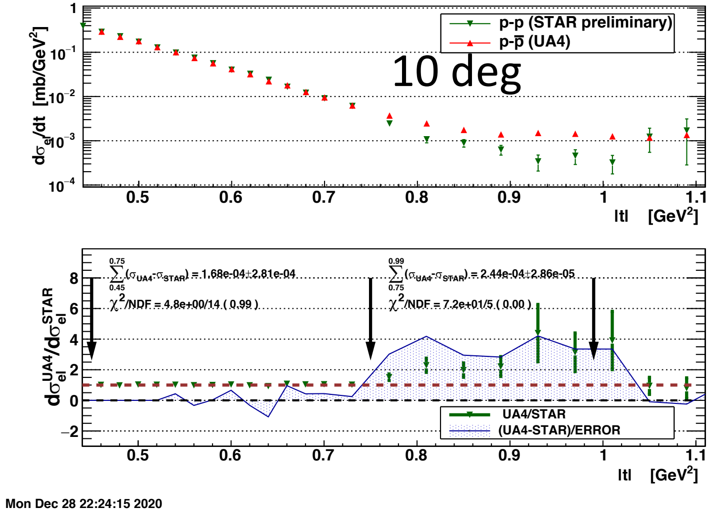


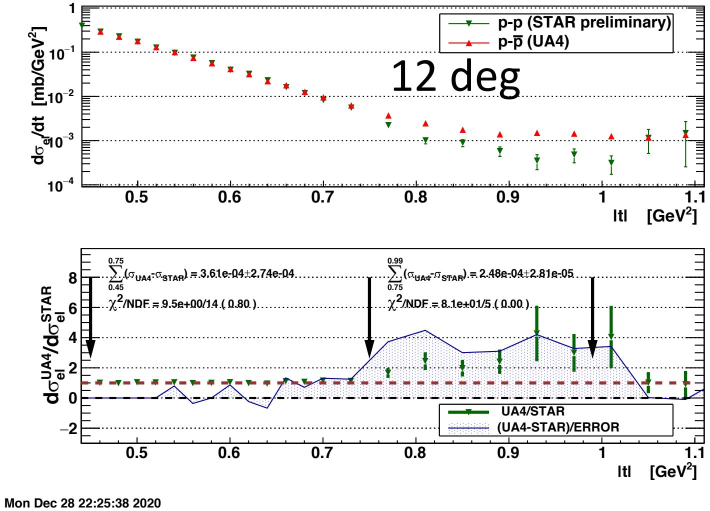
χ² / ndf 4.79 / 15
A 141.1 ± 1.9
B 13.55 ± 0.04
$\sum_{0.16}^{1.01} \frac{d\sigma}{dt}$ = 1.410 ± 0.028 [mb]
fit range 0.21 < |t| < 0.60
STAR PRELIMINARY
LP+HP Δφ=24°
DATA 4PT-GEO
fit A·exp(-B·|t|)
FMO Martynov
dσ/dt [mb/GeV²]
(data-fit)/error
|t| [(GeV/c)²]
Wed Dec 23 20:44:25 2020

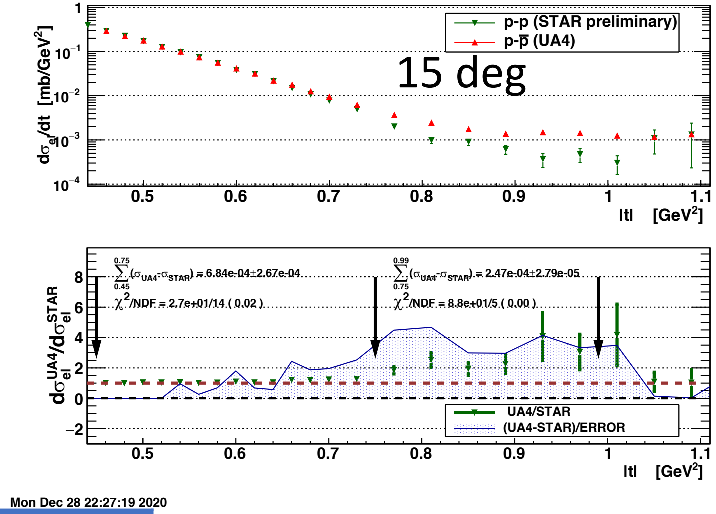


χ² / ndf 6.669 / 15
A 140.8 ± 1.7
B 13.55 ± 0.04
$\sum_{0.16}^{1.01} \frac{d\sigma}{dt}$ = 1.406 ± 0.028 [mb]
fit range 0.21 < |t| < 0.60
STAR PRELIMINARY
LP+HP Δφ=30°
DATA 4PT-GEO
fit A·exp(-B·|t|)
FMO Martynov
dσ/dt [mb/GeV²]
(data-fit)/error
|t| [(GeV/c)²]
Wed Dec 23 20:44:37 2020

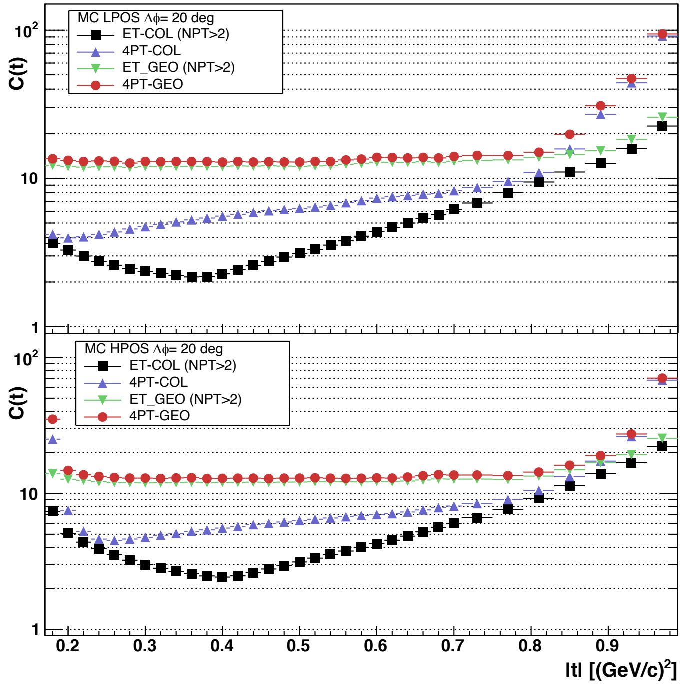




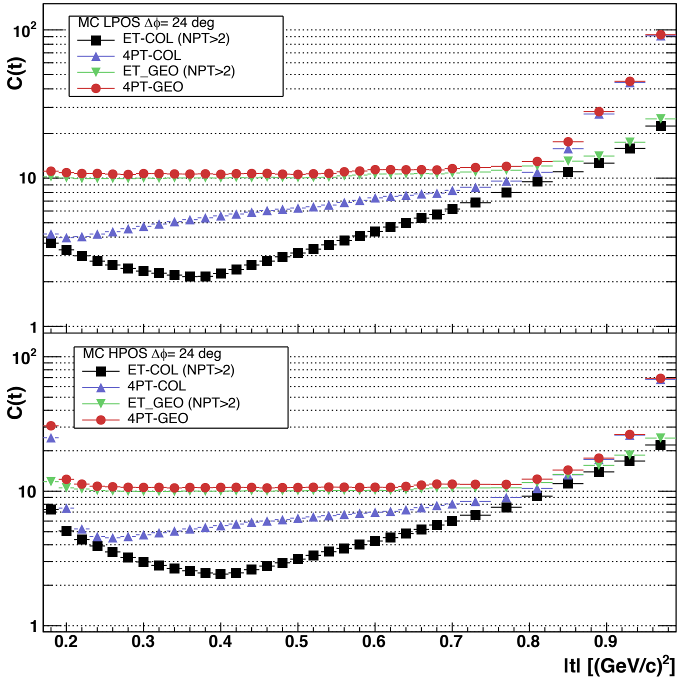




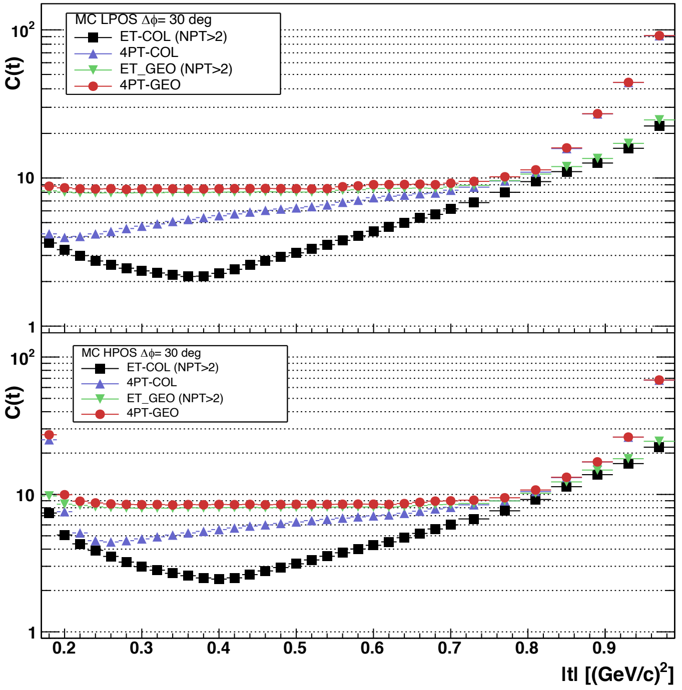
$\Delta\phi$ interval	$\Delta\sigma$ (mb)	#Dev	Chi2	Significance
+-8	2.36 +-0.328	7.2	57/5	
+-10	2.44+-0.286	8.5	72/5	
+-12	2.48+-0.281	8.8	81/5	
+-15	2.47+-0.279	8.8	88/5	



Sun Dec 6 11:21:28 2020

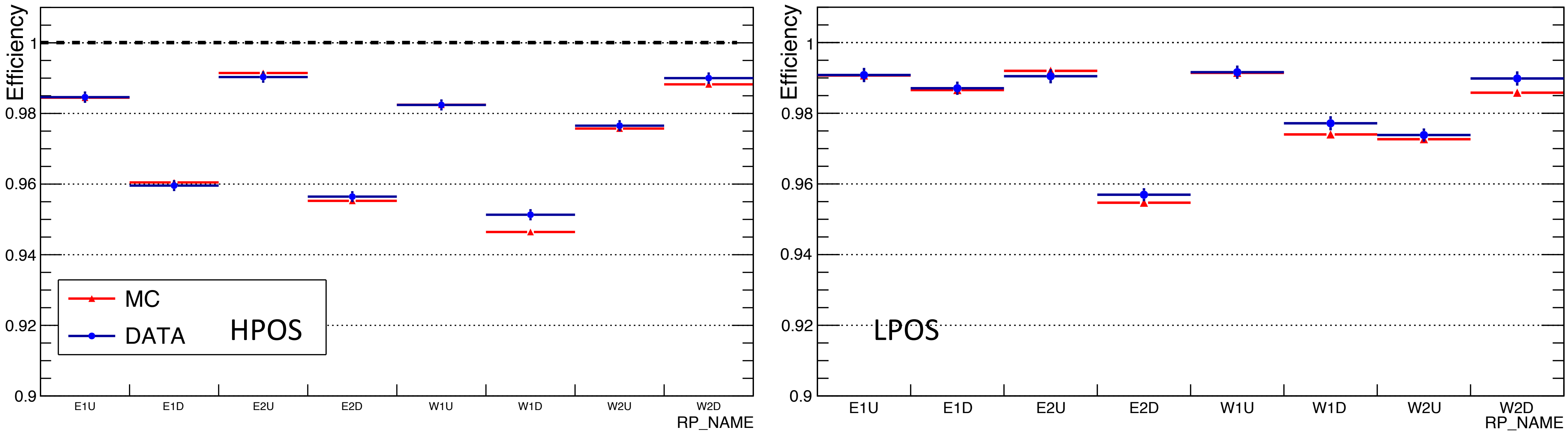


Sun Dec 6 11:23:10 2020



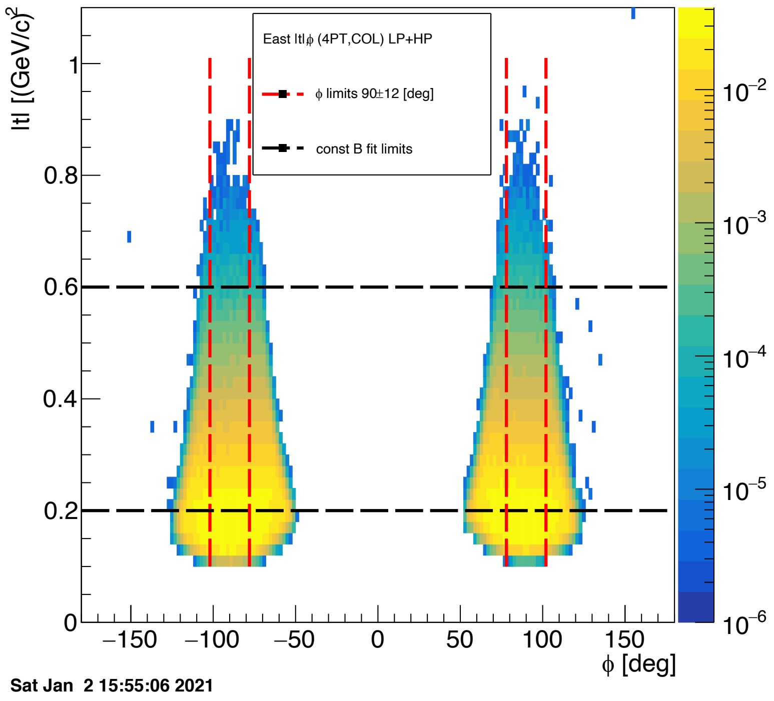
Sun Dec 6 11:25:17 2020

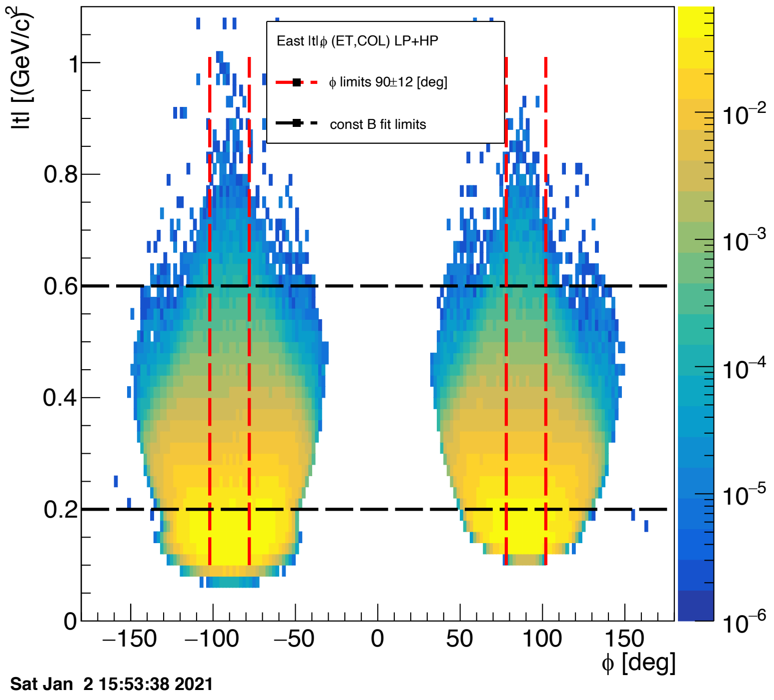
Point Reconstruction Rfficiency – Data and MC



Two data taking positions are shown

t vs ϕ for 3P and 4PT events





Results

1. B-slope of dσ/dt in the $|t| - range\ 0.21 < |t| < 0.60\ GeV^2$
2. C-odd hypothesis test
3. Integrated elastic scattering dσ/dt within STAR acceptance $0.16 < |t| < 1.01\ GeV^2$