Single diffraction and elastic scattering in proton-proton collisions with the STAR detector at RHIC

Mariusz Przybycień

AGH University of Krakow, Poland

(on behalf of the STAR Collaboration)

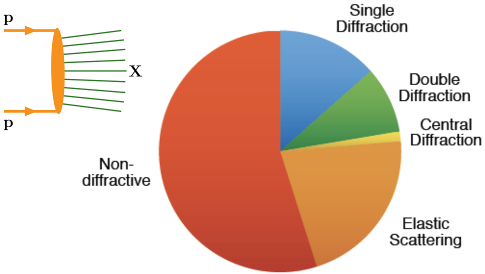
STAR

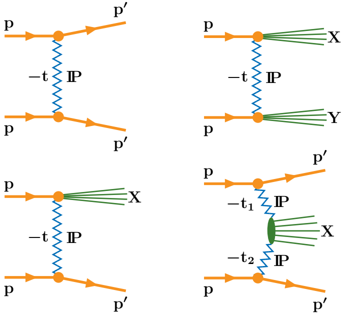
Diffraction and Low-x

Sicily, September 8 - 14, 2024

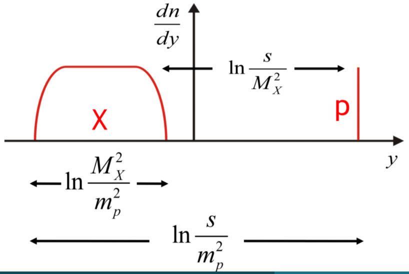
Diffraction in proton-proton scattering

- Decomposing the total pp cross section:





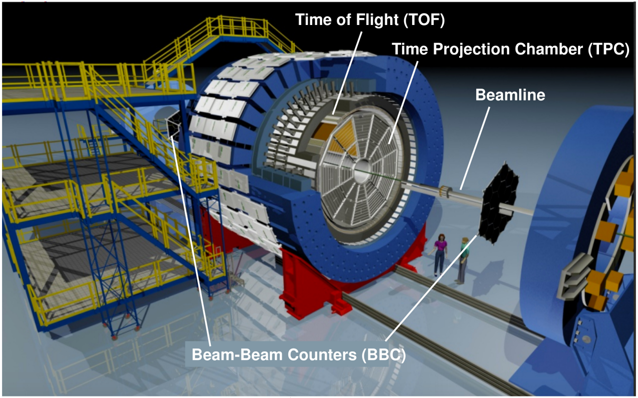
- Rapidity gaps in single diffraction (SD):

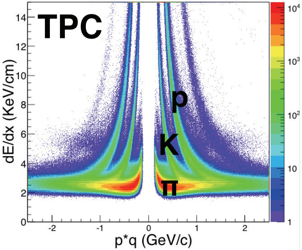


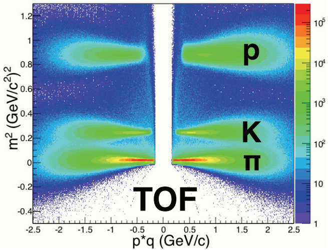
Presence of a large rapidity gap (LRG) ensures a large diffractive contribution, but does not distinguish fully between the SD process, its double dissociation (DD) analogue, and the tail of non-diffractive (ND) contributions in which LRPs occur due to random fluctuations in the hadronisation process.

Tagging of the forward-scattered proton enables to precisely select the SD process.

Solenoidal Tracker At RHIC experiment

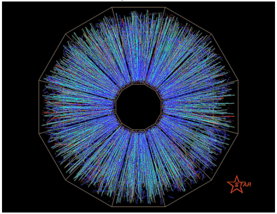






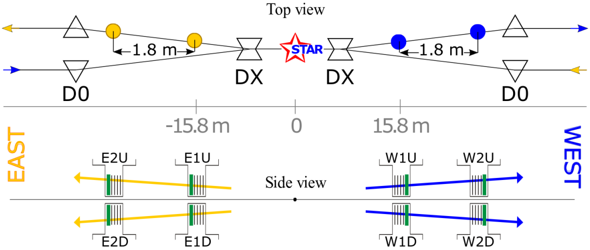
STAR detector

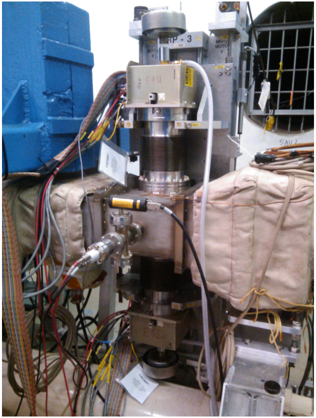
- TPC: dE/dx, L



- ToF: measures $\beta = \frac{L}{ct}$, $m^2c^2 = p^2\left(1/\beta^2 - 1\right)$
- TPC and ToF coverage: $|\eta| < 1,\ 0 < \phi < 2\pi$
- BBC: Scintilator tiles located at $3.3 < |\eta| < 5$
- ZDC-SMD: Calorimeters located at $z = \pm 18$ m from IP, with position detectors inserted between the modules.

STAR Roman Pot system





- Only vertical RP stations due to space constraints.
- Each RP vessel contains four Si strip detectors, with strips arranged alternately horizonthally and vertically. Scintillation detectors, used for trigger, are placed in each RP station behind Si planes.
- Scattering angles at IP and momentum losses of protons are reconstructed from local positions and angles measured in RP stations, based on the known geometry of the setup and magnetic field of the DX dipols (bending only in x-z plane).
- No special beam optics is required - RPs can participate in all physics pp runs.
- Continuous excellent detector performance in Run 15 and Run 17.

Single diffraction in proton-proton scattering at STAR

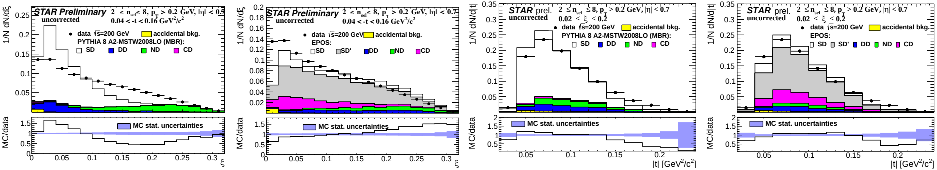
- Events selection and fiducial region in the SD measurement at $\sqrt{s} = 200$ GeV:
  - Exactly one proton candidate in the RP system with:

    $0.02 < \xi < 0.2$ where $\xi = 1 - E_{\text{p}}/E_{\text{beam}} \approx \frac{M_X^2}{s}$, and M_X is the invariant mass of the diffractive system,

    $0.04 < -t < 0.16$ GeV^2 where $-t = p_{\mathrm{T}}^2$, and p_{T} is related to the intact proton.
  - Charged particles, identified with help of TPC and ToF, were required to have $p_{\mathrm{T}} > 0.2$ GeV$/c$ and $|\eta| < 0.7$.
  - The fiducial region is further restricted to events with the number of charged particles within $2 \leqslant n_{\text{ch}} \leqslant 8$.
  - Background sources:

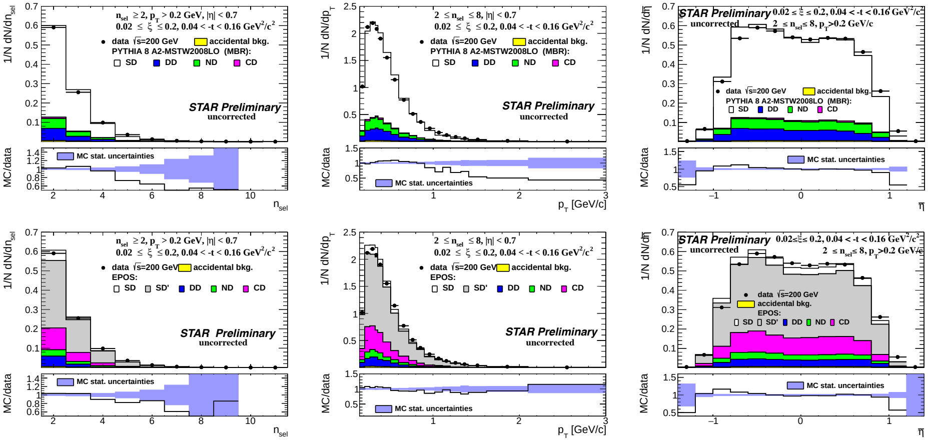
    Accidental background: random overlap of signals from two different collisions - estimated using randomly triggered data: $<1\%$ for $\xi > 0.02$, and $>10\%$ for $\xi < 0.02$.

    Single source background: originating from DD, CD and ND events - determined using PYTHIA 8 (MBR) and EPOS-LHC predictions (excluding SD$'$).



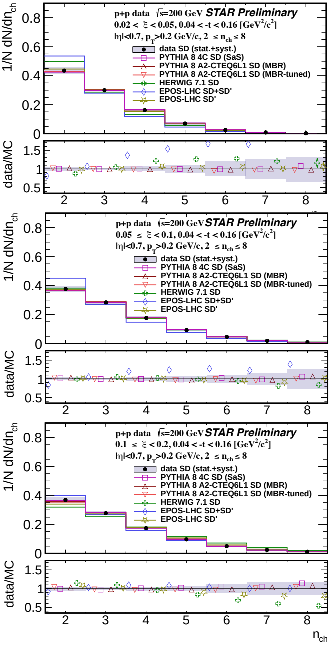
Charged particle production in SD at STAR

- EPOS-LHC describes the data very well.
- PYTHIA 8 predicts too soft p_{T} spectra and too small charged particle multiplicity.

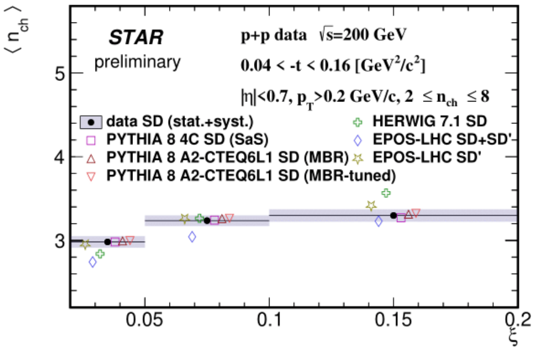


- In EPOS we distinguish the following event categories:
  - EPOS SD: with SD diffractive flag from generator
  - EPOS SD′: with ND flag but with only proton produced from beam remnant
  - EPOS ND: other events with non-diffractive flag

Single diffraction in proton-proton scattering in STAR

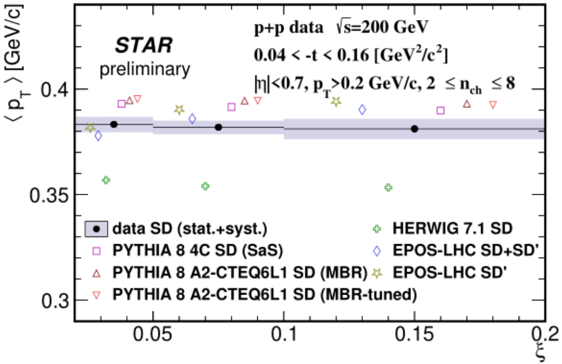


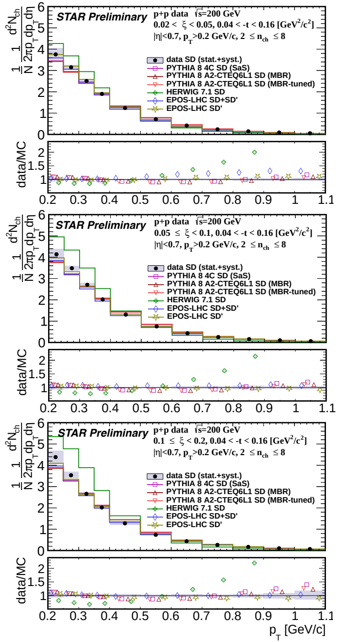
- Charged particle multiplicities in ξ intervals:
  - Data exhibit an expected increase of $\langle n_{\text{ch}} \rangle$ with ξ due to larger diffractive masses probed at larger ξ.
  - Shapes of the measured distributions are reproduced reasonably well by all PYTHIA 8 variants.
  - HERWIG predicts steeper, than observed in the data, increase of the $\langle n_{\text{ch}} \rangle$ with ξ.
  - EPOS SD+SD$'$ underestimates the data, while EPOS SD$'$ is consistent with the data.



Transverse momenta yields and dependence of $\langle p_T \rangle$ on ξ

- Densities of charged particles as a function of their p_T in intervals of ξ:
  - Data are consistent with no $\langle p_T \rangle$ dependence on ξ.
  - All PYTHIA 8 variants describe the data well.
  - HERWIG predicts much steeper rise towards lower p_T in all ξ intervals, resulting in significant underestimation of the measured $\langle p_T \rangle$.
  - EPOS models describe data better at lower ξ.

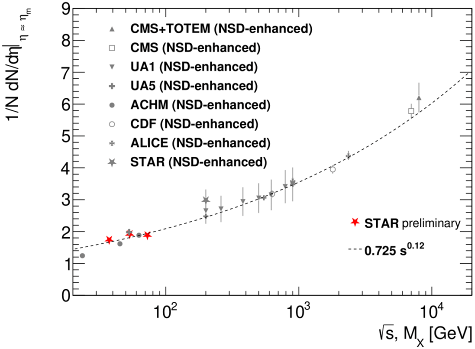




Comparison of signle with non-single diffraction

- Testing similarity between the diffractively dissociated system of mass M_X and hadronization of a system resulting from non-diffractive pp collisions at $\sqrt{s} = M_X$
- Particle densities should be comparable at mid-rapidity:

$$\eta_{\text{m}} = -\ln(\sqrt{s}/M_X) \text{ (for SD)} \quad \text{and} \quad \eta_{\text{m}} = 0 \text{ (for NSD)}$$



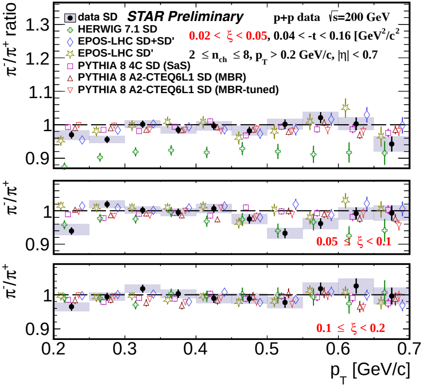
PYTHIA 8 used to extrapolate particle density from fiducial η-region to η_{m} and to accout for $n_{\text{ch}} = 1$ events.

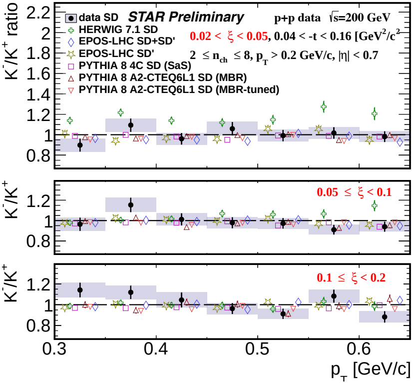
ξ-range	$\langle M_X \rangle$ [GeV]	η_{m}	f_{extr}
$0.02 - 0.05$	37.53	-1.67	0.80
$0.05 - 0.10$	53.52	-1.31	0.84
$0.10 - 0.20$	72.71	-1.01	0.83

- Preliminary STAR SD data show similarity of charged particle densities at midrapidity between SD and NSD enhanced measurements.

STAR results on particle production $\pi^{\pm}$, $K^{\pm}$, $\bar{p}$, p in SD

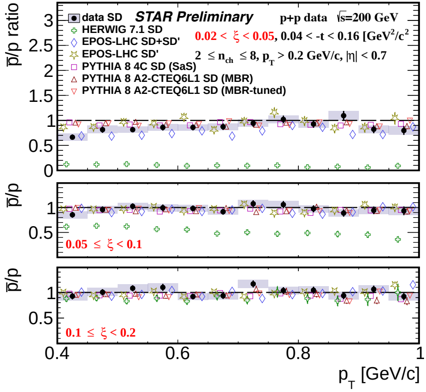
- Charge, isospin and baryon number conservation rules require that antiparticle to particle ratios tend to unity in mid-rapidity if fragmentation is the dominant source of particle production.
- Ratios in all three ξ ranges are consistent with unity with no p_T dependence.
- MC models agree with data, except HERWIG SD, which in the lowest ξ range predicts 10% excess of π^+ over π^- and 15% excess of K^- over K^+. Also large excess of $\bar{p}$ over p is predicted (see next slide).

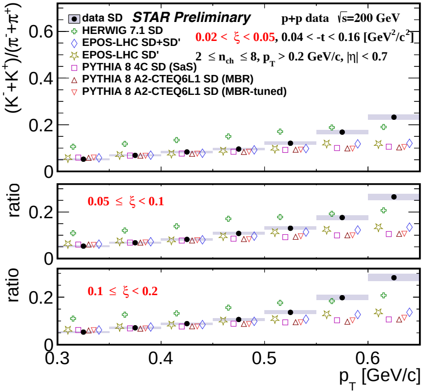




STAR results on particle production $\pi^{\pm}$, $K^{\pm}$, $\bar{p}$, p in SD

- The $\bar{p}/p$ ratio is sensitive to the baryon number transfer from forward to central rapidities: values below unity in $0.02 < \xi < 0.05$ indicate a non-negligible transfer of the baryon number.
- The $(K^+ + K^-)/(\pi^+ + \pi^-)$ ratio is sensitive to strangeness production in the fragmentation process: significant increase with increasing p_T suggests stronger p_T kicks during string breaking when producing $\bar{s}s$ than in case of $\bar{u}u$ or $\bar{d}d$.





Measuremnet of elastic proton-proton scattering in STAR

- Due to momentum conservation, the elastically scattered protons should be collinear:

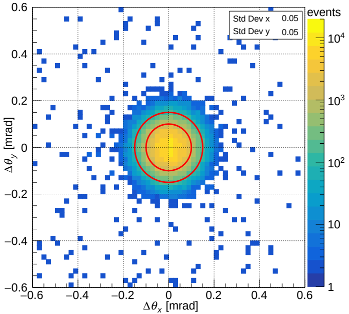
$$\Delta\theta = \theta^{\mathsf{W}} - \theta^{\mathsf{E}} < 3\,\sigma_{\Delta\theta}, \qquad \sigma_{\Delta\theta} = 50\ \mu\text{rad}$$

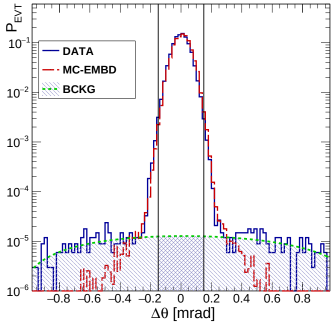
- The four momentum transfer at the protons' verticies is calculated as:

$$t = (p_{\text{in}} - p_{\text{out}})^2 \approx -p^2\theta^2$$

where p is the beam momentum and θ is the polar angle of the scattered protons.

- To stay away from the beam halo, a minimum $|t|$ corresponding to 12σ of the beam size is required, so that a coincidence arising from the beams' halos is not expected. To stay away from the apertures, additional cuts on the maximum $|t|$ and on the ϕ-range are also applied.
- The remaining background from central diffraction and from accidental overlap of single diffraction events is estimated using the $\Delta\theta$ distribution, and is found to be below 0.1%.





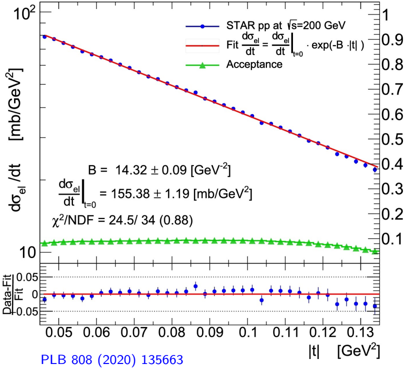
Elastic, inelastic and total proton-proton cross sections

- Measurements of elastic scattering at hadron colliders provides access to non-perturbative dynamics, which cannot be calculated from first principles:
  - $\sigma_{\text{tot}} = 4\pi\, \text{Im}[f_{\text{el}}(t)]|_{t=0}$ - the total hadronic cross section,
  - $\rho = \left. \frac{\text{Re}[f_{\text{el}}(t)]}{\text{Im}[f_{\text{el}}(t)]} \right|_{t=0}$, which probes Coulomb-nuclear interference (CNI).
- σ_{tot} and ρ are related by dispersion relations, which connect the ρ-parameter at a certain energy to the energy evolution of σ_{tot} both below and above this energy.
- STAR: p+p at $\sqrt{s} = 200$ GeV
  - Elastic cross section was measured in the range: $0.045 < -t < 0.135$ GeV^2 and fitted with: $\frac{d\sigma_{\text{el}}}{dt} = A \cdot e^{-B\cdot|t|}$

    $$B = 14.32 \pm 0.09(\text{stat})^{+0.13}_{-0.28}(\text{syst})\ \text{GeV}^{-2}$$
  - σ_{tot} was obtained from the ralation (assuming $\rho = 0.12 \pm 0.05$):

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

    $$\sigma_{\text{tot}} = 54.67 \pm 0.21(\text{stat})^{+1.28}_{-1.38}(\text{syst})\ \text{mb}$$



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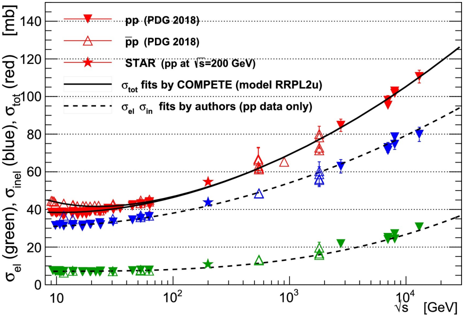
Elastic, inelastic and total proton-proton cross sections

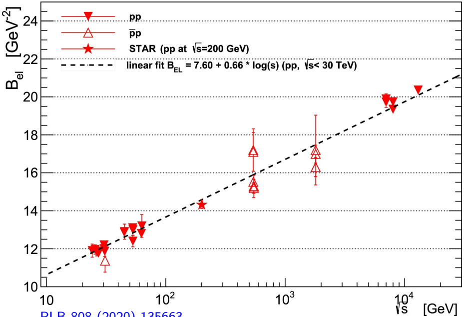
- Total measured fiducial elastic cross section:

  $\sigma_{\text{el}}^{\text{fid}} = 4.05 \pm 0.01(\text{stat})^{+0.18}_{-0.17}(\text{syst})$ mb
- Total measured extrapolated elastic cross section:

  $\sigma_{\text{el}}^{\text{extr}} = 10.85 \pm 0.03(\text{stat})^{+0.49}_{-0.41}(\text{syst})$ mb
- Total measured inelastic cross section:

  $\sigma_{\text{inel}} = 43.82 \pm 0.21(\text{stat})^{+1.37}_{-1.44}(\text{syst})$ mb
- The measured integrated cross sections follow the trend observed in measurements at other energies.
- The σ_{tot} agrees with the COMPETE prediction (51.79 mb) within 2σ of the total uncertainty.
- The measured nuclear slope parameter B also follow the logarithmic dependence on $\sqrt{s}$ obsrved in other measurements.





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Elastic scattering in proton-proton collisions

- STAR: p+p at $\sqrt{s} = 510$ GeV
  - Elastic cross section was measured in the range $0.23 < -t < 0.67$ GeV^2 and fitted with:

$$\frac{d\sigma_{\text{el}}}{dt} = A \cdot e^{-B(t)|t|}$$

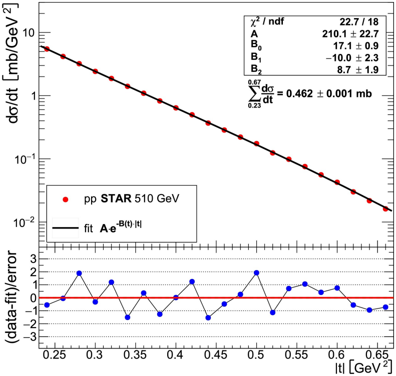
  - Two approaches were used for the form of the nuclear slope parameter B:

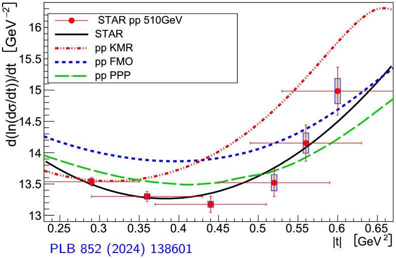
    $B(t) = B_0 + B_1 \cdot |t| + B_2 \cdot |t|^2$ - describes well the cross section in the whole t range,

    $B = \text{const}$ in six overlapping t-intervals - a minimum around $|t| = 0.4$ GeV^2 is observed, and overall shape of the measured values of B is followed by phenomenological models.

  - Total measured fiducial elastic cross section:

    $\sigma_{\text{el}}^{\text{fid}} =$
    $462.1 \pm 0.9(\text{stat}) \pm 1.1(\text{syst}) \pm 11.6(\text{scale})$ μb





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Summary

- In diffractive-like analyses at STAR uses the Roman Pot detectors to measure the forward-scattered intact protons.
- Charged-particle production spectra have been measured in SD process at $\sqrt{s} = 200$ GeV.
- Significant differences are observed between the measured and predicted by MC models distributions of ξ. EPOS-LHC and PYTHIA (MBR) without suppression of diffractive cross sections at large ξ provide the best description of the data.
- Similarity between the dissociation of diffractively produced system of mass M_X and hadronization of the system resulting from non-diffractive pp collisions at $\sqrt{s} \approx M_X$ reported for the first time by the UA4, was confirmed with much better precision.
- π^-/π^+ and $\mathrm{K}^-/\mathrm{K}^+$ production ratios are close to unity and consistent with most of model predictions except for HERWIG 7.1 SD.
- $\bar{\mathrm{p}}/\mathrm{p}$ production ratio shows a significant deviation from unity in $0.02 < \xi < 0.05$ range indicating a non-negligible baryon number transfer from forward to central region.
- $(\mathrm{K}^+ + \mathrm{K}^-)/(\pi^+ + \pi^-)$ ratio suggests that $s\bar{s}$ suppression in fragmentation process (factor 0.2 in PYTHIA 8) is too strong in diffractive system and p_{T} kicks during string(cluster) breaking producing $s\bar{s}$ is larger compared to $d\bar{d}$ or $u\bar{u}$.
- STAR measured also the differential cross section for elastic proton-proton collisions at $\sqrt{s} = 510$ GeV in the range $0.23 < -t < 0.67$ GeV^2 and studied its t-dependence.

Thank you for your attention!

Backup slides

Monte Carlo generators used in SD analysis

- PYTHIA 8: Diffractive cross sections are parameterized based on the exchange of Pomeron trajectory, $\alpha(t) = \alpha(0) + \alpha' t$, assuming Regge theory formalism:

$$\frac{d^2\sigma}{d\xi\, dt} \propto \left(\frac{1}{\xi}\right)^{\alpha(0)} \exp\left[Bt\right], \qquad B(\xi) = B_0 - 2\alpha' \ln \xi$$

  - Diffractive cross sections are arbitrarily suppressed at large values of $\xi > 0.1$.
  - Lund string model used for hadronization.
  - Main smples: C4 tune embedded in collision data:
    - $\alpha(0) = 1.0, \ \ \alpha' = 0.25$ GeV^{-2} (SaS model)
    - SD for unfolding, CD, DD, ND for background estimation.

- Additional samples for comparison with the measurements:
  - PYTHIA 8 A2 tune: $\alpha(0) = 1.104, \ \alpha' = 0.25$ GeV^{-2} (MBR model).
  - As above but without suppression at large values of $\xi > 0.1$ (MBR-tuned).
  - HERWIG 7.1 (soft tune) with alternative cluster hadronization model.
  - EPOS (LHC tune) with alternative (color exchange) string model.

    EPOS predicts a very large contribution of forward protons in ND events, that are well separated in rapidity from other final state particles. Therefore we distinguish the following categories:
    - EPOS SD: with SD diffractive flag from generator
    - EPOS SD': with non-diffractive flag but with only proton produced from beam remnant
    - EPOS ND: other events with non-diffractive flag