Measurement of charged-particle production in single diffractive proton-proton collisions with the STAR detector

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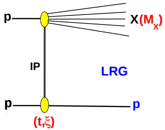
Single diffractive (SD) dissociation

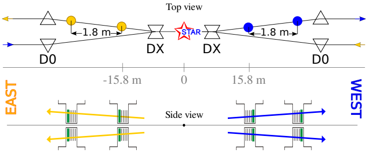


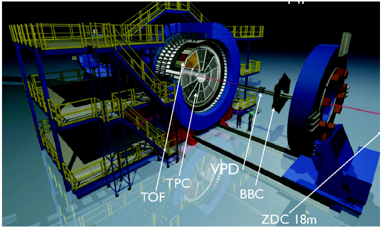
- The total $p+p \to p+X$ cross section is large and not well experimentally and theoretically separated from other processes.
- Previous analyses mainly based on rapidity gaps:
  - Not able to fully distinguish between the SD process, double dissociation (DD: $p+p \to X+Y$) and central diffraction (CD: $p+p \to p+X+p$) partners and the tail of non-diffractive (ND) contributions
  - No direct access to the underlying dynamics:
    - $-t$ - squared four momentum transfer
    - ξ - fractional energy loss of the intact proton ($\xi = M_X^2/s$)
- Only few measurements with proton tagging at ISR, SPS and LHC
  - Suppression of DD,CD and ND processes.
  - Direct access to t and ξ.
  - Only UA4 at $\sqrt{s} = 546$ GeV provides information on the fragmentation of the system X.

Motivations for SD measurement with STAR at $\sqrt{s} = 200$ GeV

- Better understand a significant part of total inelastic pp cross section
- Improve understanding of the low Bjorken-x region of proton structure
- Measure fragmentation and hadronization properties of proton diffractive excitation
- Better interpretation of cosmic ray air showers

Experimental setup





- Intact final state proton is scattered through a small angle of typically 2 - 5 *m*rad. Proton is measured in the Roman Pot (RP) detector at 16 m from the IP, the RP was placed at 35 mm from the beam in standard RHIC run of $\beta^* = 10$ m optics
- Other proton dissociates to produce a multi-particle hadronic system X. Charged particles with $p_T > 0.2$ GeV and $|\eta| < 1.0$ are measured in Time Projection Chamber (TPC) allowing determination of the primary vertex position and Particle Identification (PID) through dE/dx measurement.
- Trigger: Coincidence of the signal in RP with Time of Flight (TOF) activity and veto on inner part of Beam-Beam Counter (BBC) and Zero Degree Calorimeter (ZDC) on the scattered proton side. Inner part of BBC covers pseudorapidity range of $3.3 < |\eta| < 5.2$

Principles of the measurement

- Measure tracks with $p_T > 0.2$ GeV and $|\eta| < 0.7$ in TPC to get:
  - Charged particle distributions:

$$\frac{1}{N}\frac{dN}{dn_{\rm ch}}, \qquad \frac{1}{N}\frac{1}{2\pi p_{\rm T}}\frac{d^2N_{\rm ch}}{d\bar{\eta}dp_{\rm T}}, \qquad \frac{1}{N}\frac{dN_{\rm ch}}{d\bar{\eta}}$$

    in $2 \le n_{\rm ch} \le 8$ fiducial region. $\bar{\eta}$ defined with respect to intact proton direction.
  - Identified particle ratios (based on dE/dx):

$$\pi^+/\pi^-, \quad K^+/K^-, \quad p/\bar{p}, \quad (K^+ + K^-)/(\pi^+ + \pi^-)$$

  - Primary vertex position.
  - Matching with ToF hits to ensure selection of only in-time TPC tracks
- Measure track position and local angle at RP to get the proton momentum and thereby:
  - $-t = p_T^2$ $\quad 0.04 < -t < 0.16$ GeV^2
  - $\xi = 1 - E_p/E_{beam}$ $\quad 0.02 < \xi < 0.2$
- RP alignment based on elastic scattering events:
  - Physics Letters B 808 (2020) 135663
- TPC/TOF reconstruction efficiency obtained through embedding of single particle MC events into randomly triggered collision data:
  - Journal of High Energy Physics 7 (2020) 178

Monte Carlo Generators

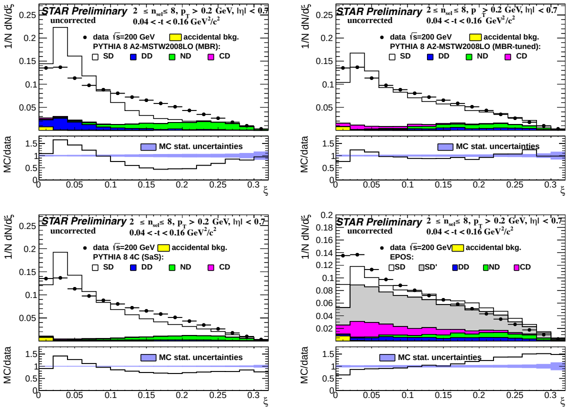
- PYTHIA 8
  - Diffractive cross sections parameterized based on the exchange of the Pomeron with trajectory $\alpha(t) = \alpha(0) + \alpha' t$, assuming Regge theory formalism.

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

  - Diffractive cross sections arbitrarily suppressed at large values of $\xi > 0.1$
  - Lund (longitudinal excitation) string model for hadronization
  - Main samples: C4 tune embedded into collision data:
    - $\alpha(0) = 1.0$, $\alpha' = 0.25$ GeV^{-2} (Schuler and Sjöstrand model)
    - SD for unfolding; CD, DD, ND for background subtraction
- Additional samples for results comparison:
  - PYTHIA8 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 the forward protons well separated in rapidity from other final state particles from non-diffractive events. Therefore EPOS prediction is separated into:
      EPOS-SD : with SD diffractive flag from generator
      EPOS-SD$'$: non-diffractive flag but only proton produced from beam remnant
      EPOS-ND : other events with non-diffractive flag

Background

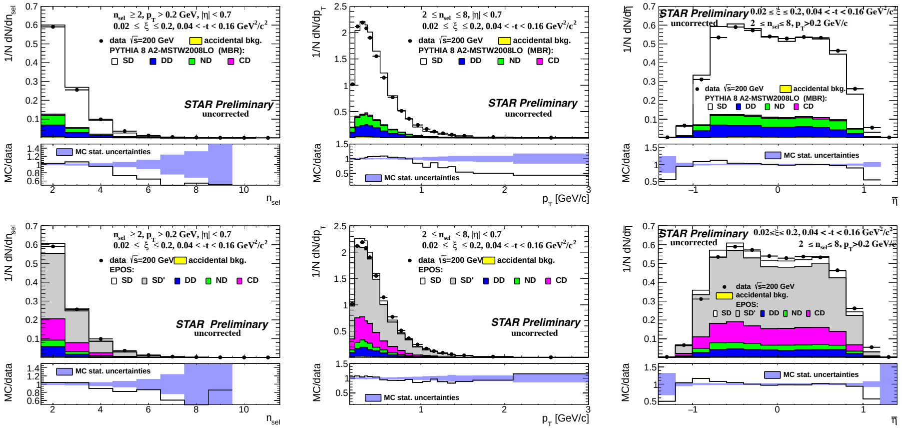
- Accidental background
  random overlap of signals from two different collisions estimated using the randomly triggered collision data: below 1% for $\xi > 0.02$ but above 10% at $\xi < 0.02$
- Single source background
  originating from DD, CD and ND events determined using PYTHIA 8 (MBR) and EPOS-LHC expectation (excluding SD′)



- PYTHIA 8 A2 (MBR)
  fails to describe the shape of ξ
- PYTHIA 8 A2 (MBR-tuned)
  agrees better with the data
- PYTHIA 8 C4 (SaS)
  predicts much smaller DD contribution vs. MBR
- EPOS-LHC
  shows a dominant contribution of non-diffractive (SD′)

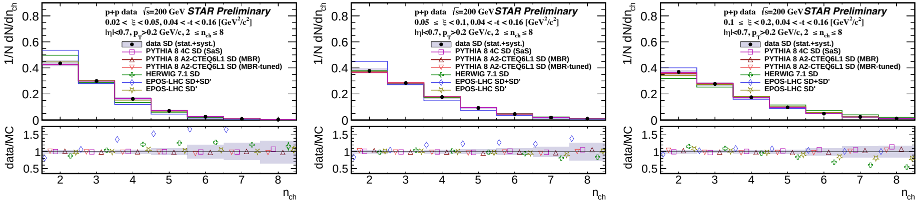
Final results limited to $0.02 < \xi < 0.2$ and provided in three ξ ranges.

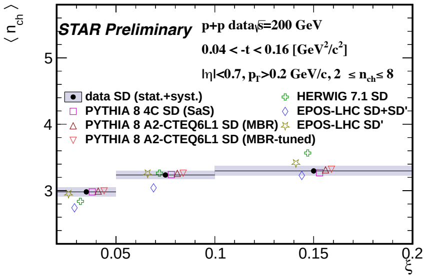
Detector level control plots



- EPOS-LHC very well describes the data
- All PYTHIA 8 models predict too soft p_T spectra and too small charged particle multiplicities

Data corrected using iterative Bayesian unfolding

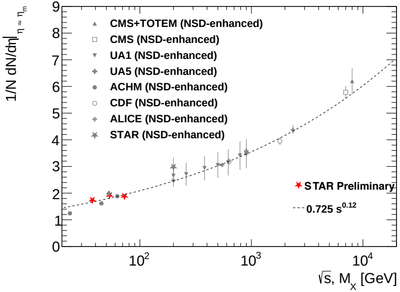


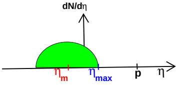


- Data exhibit an expected increase of the $\langle n_{ch} \rangle$ with ξ due to the larger diffractive masses probed at increasing ξ in SD process
- The shapes of the measured distributions are reproduced reasonably well by all PYTHIA 8 models

Results: Comparison to non-single diffraction

Test similarity between the dissociation of a diffractively produced system of mass M_X and the hadronization of the system resulting from non-diffractive *pp* collisions at $\sqrt{s} \approx M_X$





ξ range	$\langle M_X \rangle$	η_m	f_{extr}
$0.02 < \xi < 0.05$	37.53 GeV	-1.67	0.80
$0.05 < \xi < 0.1$	53.52 GeV	-1.31	0.84
$0.1 < \xi < 0.2$	72.71 GeV	-1.01	0.83

Particle density should be compared at mid-rapidity (η_m)

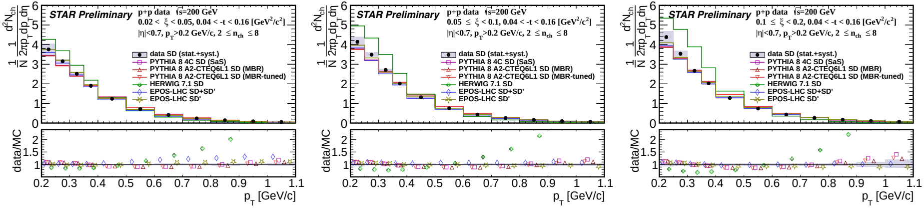
- $\eta_m = -\ln\left(\sqrt{s}/M_X\right)$ (SD) and $\eta_m = 0$ for non-single diffractive (NSD)
- Use PYTHIA 8 model to extrapolate particle density from η fiducial region to η_m a to account for $n_{ch} = 1$ events.

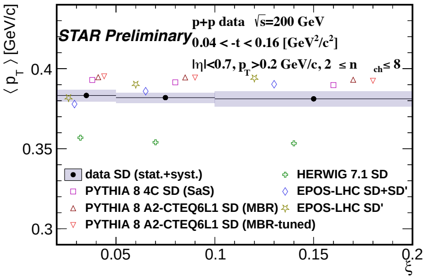
Preliminary STAR SD measurements show similarity of charged particle densities at midrapidity between SD and NSD enhanced measurements

Other measurements: see Eur. Phys. J.C74(2014) 3053 and references therein.

Results: Charged p_T momenta in three ξ regions

Observable sensitive to p_T kicks during string(cluster) breaking in fragmentation process

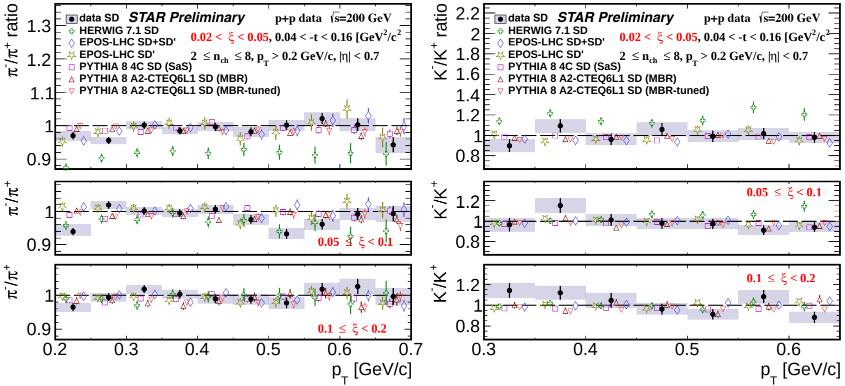




- Data show almost no $\langle p_T \rangle$ dependence on ξ.
- All PYTHIA 8 models describe data fairly well
- EPOS model describes data better at $\xi < 0.1$
- HERWIG SD predicts much steeper dependence of particle density on p_T in all three ξ ranges.

Results: π^-/π^+ and K^-/K^+ ratios

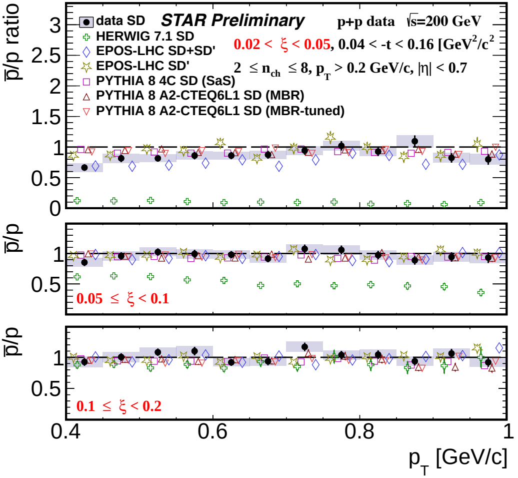
Charge, isospin and baryon number conservation predicts that anti-particle to particle ratios tend to unity in mid-rapidity if fragmentation is the dominant source of particle production

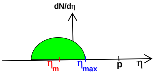


- Ratios in all three ξ ranges are consistent with unity with no p_T dependence
- MC models agree with data (except HERWIG SD)
- HERWIG SD, in the first ξ range predicts 10% excess of π^+ over π^- and predicts 15% excess of K^- over K^+. Also large excess of p over $\bar{p}$ is predicted (see next slide).

Results: $\bar{p}/p$ ratio

- Observable sensitive to the baryon number transfer from forward to mid-rapidities in *pp* scattering
- At RHIC ($\sqrt{s} = 200$ GeV) $\bar{p}/p$ is measured to be 0.8 (in good agreement with PYTHIA 8 prediction) for ND



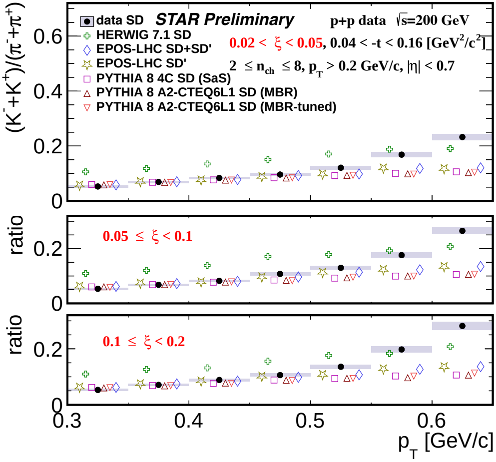


- Naively baryon number transfer in SD should be twice smaller compared to ND ($\bar{p}/p > 0.9$)
- PYTHIA 8 prediction for SD at $\sqrt{s} = 200$ GeV is 0.95 independently on ξ and p_T
- Data shows small ξ and p_T dependance.
  In first ξ range $\langle \bar{p}/p \rangle = 0.75$
  3 σ below PYTHIA 8 prediction.
- HERWIG SD shows large ξ dependance with large disagreement with data.
  Net baryon appears always close to rapidity edge (η_{max}) (backward baryon transfer).

Preliminary STAR results for SD $\bar{p}/p$ ratio suggest that some contribution from backward(beyond mid-rapidity) baryon transfer might be necessary to explain the data

Results: $(K^+ + K^-)/(\pi^+ + \pi^-)$ ratio

Observable sensitive to the strangeness production in fragmentation process



- The ratio increases from 0.05 at $p_{\mathrm{T}} = 0.3$ GeV to 0.22 – 0.25 at $p_{\mathrm{T}} = 0.65$ GeV. The slope of the p_{T} dependence significantly increases at $p_T = 0.5$ GeV in all three ξ intervals.
- PYTHIA 8 and EPOS-LHC agree very well with data at $0.3 < p_T < 0.5$ GeV but do not expect a change of the slope of p_{T} dependence at $p_T > 0.5$
- HERWIG SD predicts almost twice larger value independently from p_{T}

Preliminary STAR results for $(K^+ + K^-)/(\pi^+ + \pi^-)$ ratio in SD suggest that $s\bar{s}$ suppression in fragmentation process (factor 0.2 in PYTHIA 8) is too strong in diffractive system. Significant p_{T} dependence suggests that p_{T} kicks during string(cluster) breaking producing $s\bar{s}$ is larger compared to $u\bar{u}$ or $d\bar{d}$ production.

Summary

- STAR performed a measurement of the inclusive single diffractive dissociation process $p + p \to X + p$ at $\sqrt{s} = 200$ GeV
- The final state protons are directly reconstructed greatly reducing backgrounds from Non-Diffraction and Double Diffraction compared to previous analyses based on rapidity gaps.
- Inclusive and identified charged-particle production in Single Diffractive process has been measured.
- Significant differences are observed between the measured distributions of ξ and Monte Carlo model predictions. Among the models considered, 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 a diffractively produced system of mass M_X and the hadronization of the system resulting from non-diffractive pp collisions at $\sqrt{s} \approx M_X$ reported for the first time by the UA4 Collaboration, was confirmed with much better precision.
- π^-/π^+ and K^-/K^+ production ratios are close to unity and consistent with most of model predictions except for HERWIG 7.1 SD.
- $\bar{p}/p$ production ratio shows a significant deviation from unity in the $0.02 < \xi < 0.05$ range indicating a non-negligible transfer of the baryon number from the forward to the central region.
- $\bar{p}/p$ ratio suggests that some contribution from backward(beyond mid-rapidity) baryon transfer might be necessary to explain the data
- $(K^+ + K^-)/(\pi^+ + \pi^-)$ 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 $u\bar{u}$ or $d\bar{d}$ production.

Additional material

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