First $D^0 + \bar{D}^0$ measurement in nucleus-nucleus collisions at SPS energies with NA61/SHINE

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(for the NA61/SHINE Collaboration)

Hard Probes 2024
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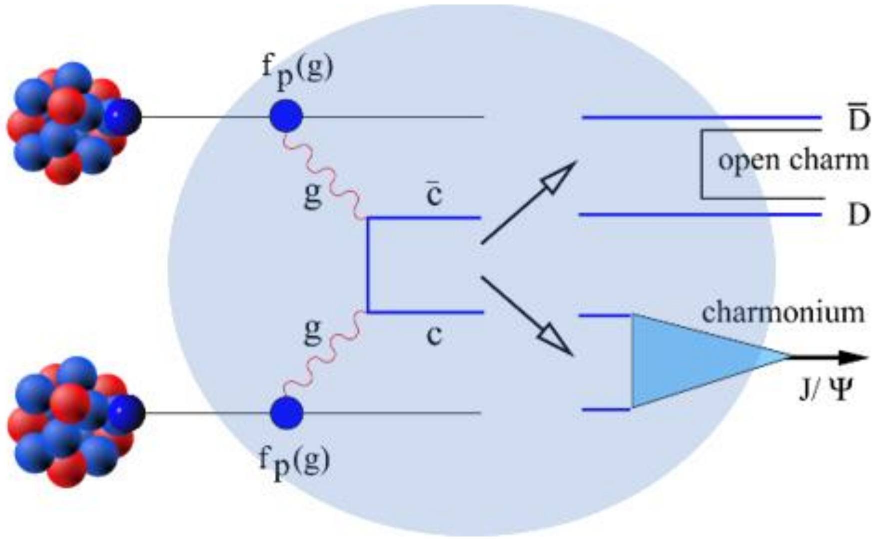
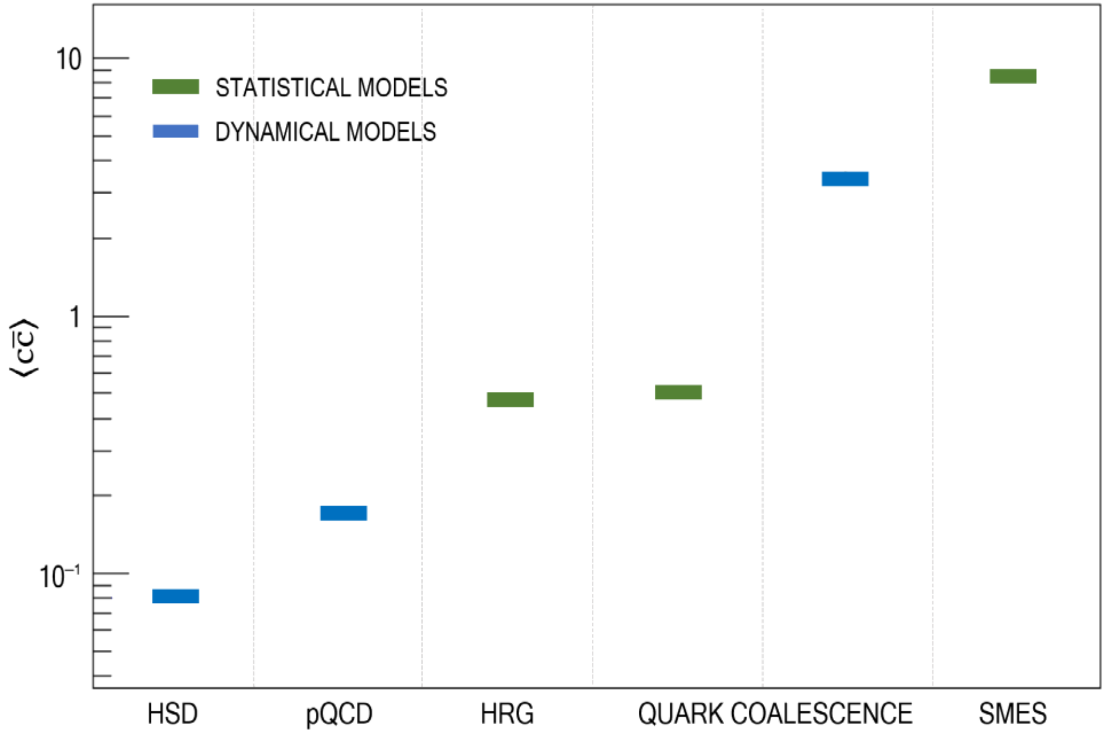
Motivation of open charm measurements



- Heavy quarks are produced in the hard scattering processes that occur in the early stage of the collision between partons of the incoming nuclei;
- By studying charm hadrons one can get insight into properties of the medium created in the collision;
- Such measurements can be in a big interest at the SPS energies, close to the threshold of QGP creation.
- There are no measurements of open charm in A+A collisions at SPS.

Models of charm production

- Predictions of charm yield differ by up to two orders of magnitude for central heavy-ion collisions at the top SPS energy (beam momentum 150*A* GeV/*c*, $\sqrt{s_{NN}}$ = 16.8 GeV);

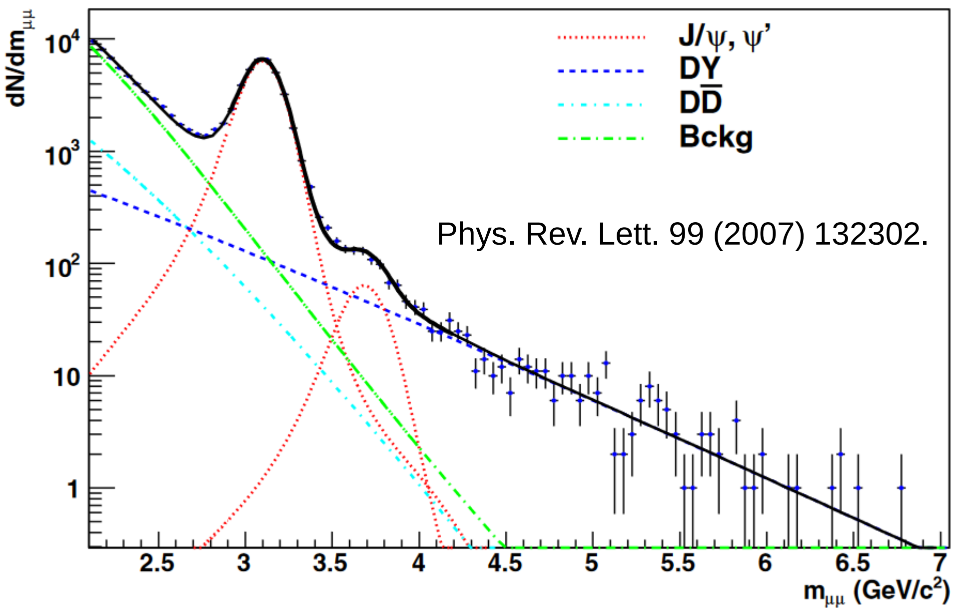


- Obtaining precise data on $D^0+\bar{D}^0$ is expected to narrow the spectrum of viable theoretical models and thus learn about the charm quark and hadron production mechanisms.

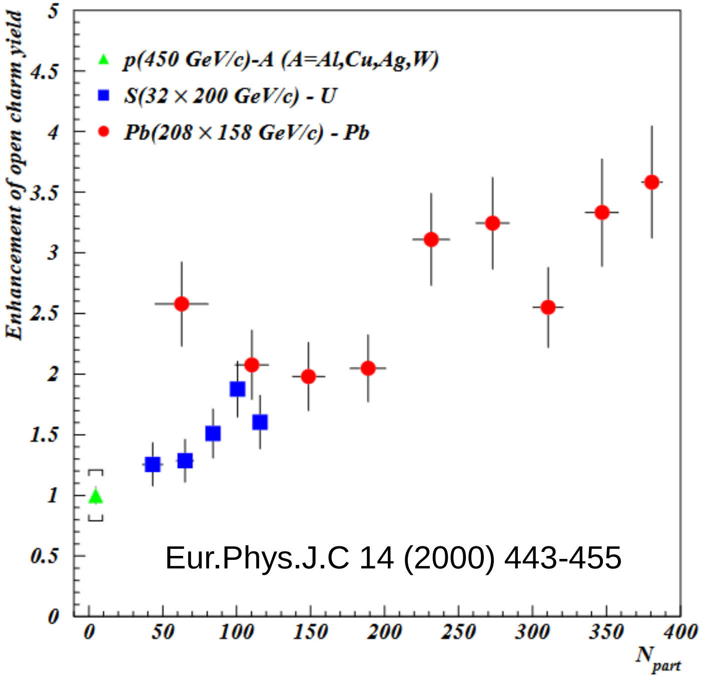
- **HSD:** Hadron-String Dynamics
  O. Linnyk et al. Int. J. Mod. Phys. E 17 (2008), 1367-1439
- **pQCD**: the scaled PYTHIA calculations
  P. Braun-Munzinger et al. Phys. Lett. B 490 (2000), 196-202
- **HRG**: Hadron Resonance Gas Model
  M. I. Gorenstein et al. J.Phys.G 27 (2001) L47-L52
- **Statistical Quark Coalescence**:
  M. I. Gorenstein et al. Phys.Lett.B 509 (2001) 277-282
- **Dynamical Quark Coalescence**: ALCOR and MICOR models extended to charm formation.
  P. Levai et al. J.Phys.G 27 (2001) 703-706
- **SMES**: A statistical model of the early stage
  M. Gazdzicki et al., Acta Phys. Polon. B 30 (1999), 2705

NA38/NA50 & NA60

- Indirect estimation of open charm yield using dimuons from semi-leptonic charm quark pair decays by NA50 and NA60;
- Open charm contribution was separated via the fit procedure from an inclusive dimuon distribution, which also contains charmonium and Drell-Yan components;
- Centrality-dependent scaling factor for open charm production in PYTHIA is needed to reproduce the di-muon background in the intermediate mass range.



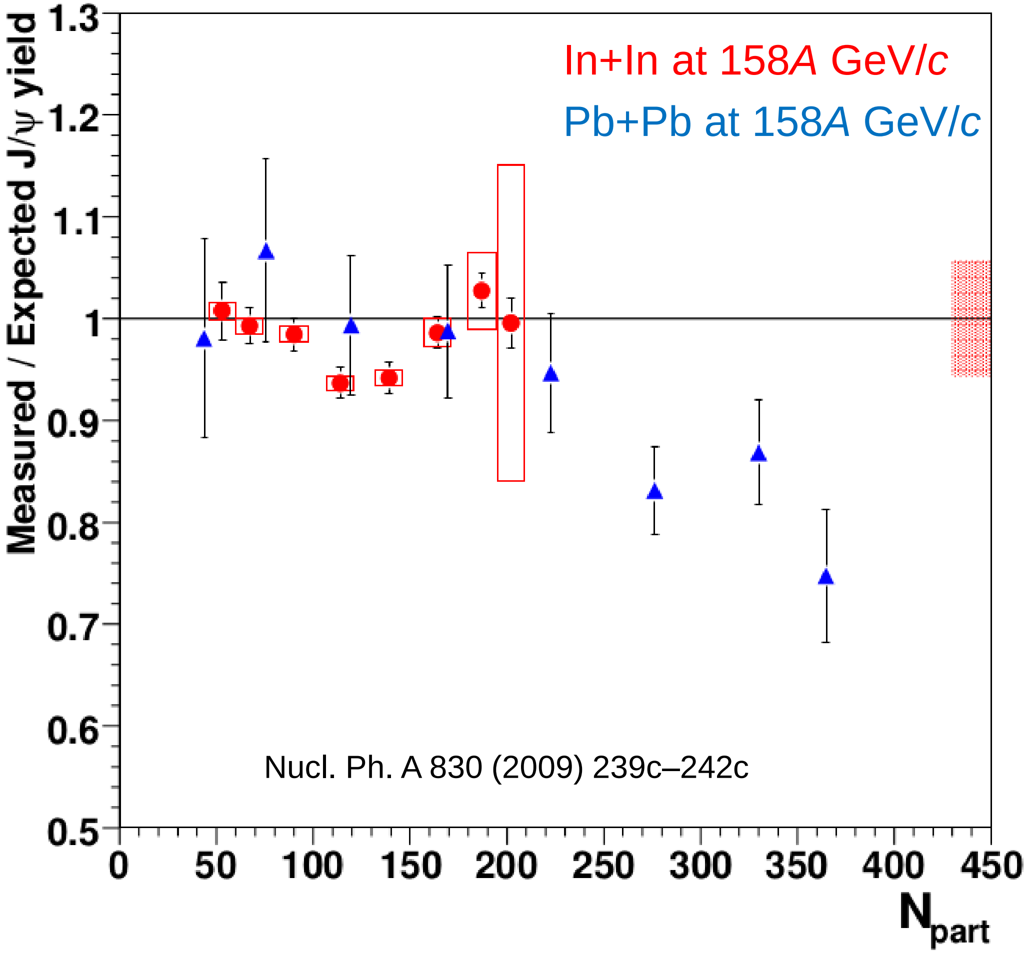
Phys. Rev. Lett. 99 (2007) 132302.



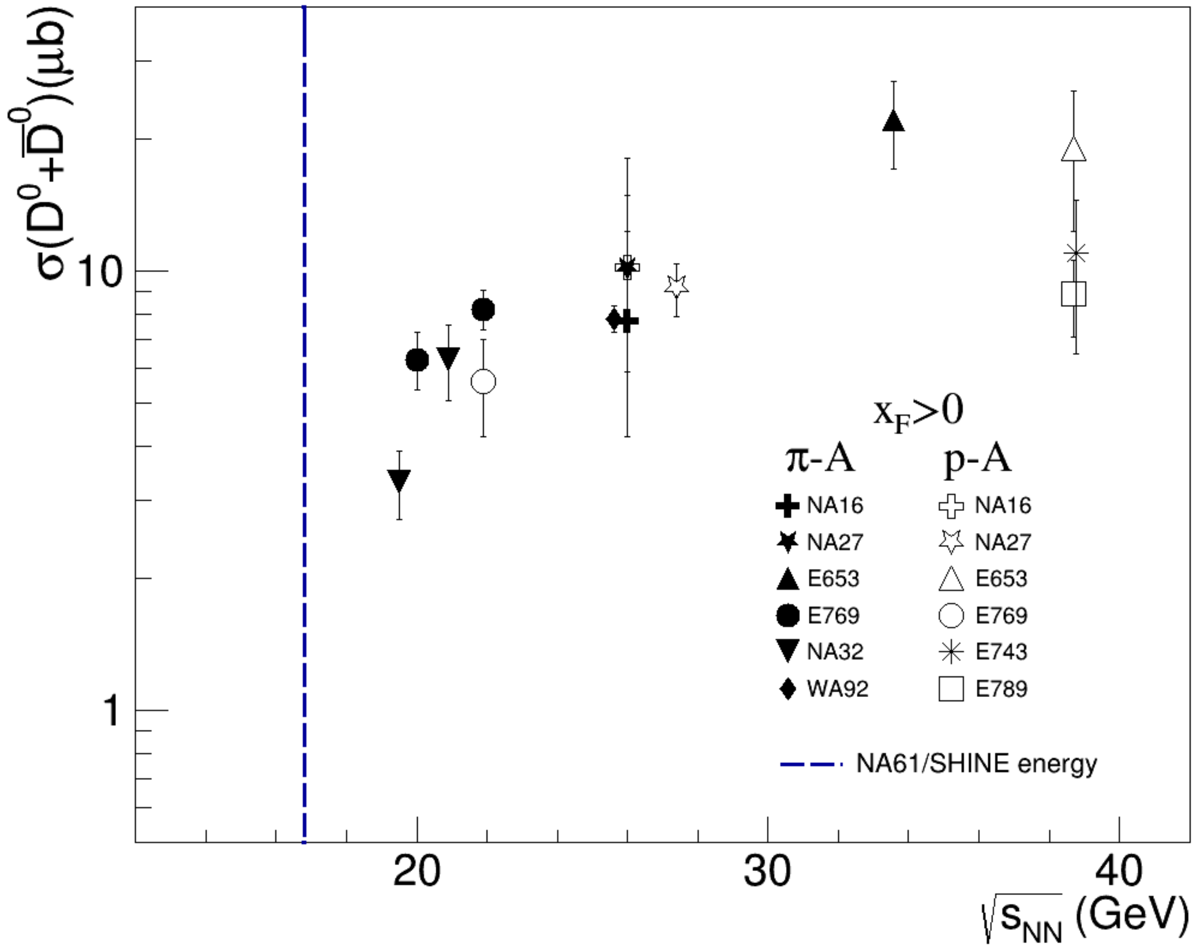
Eur.Phys.J.C 14 (2000) 443-455

Anomalous J/ψ suppression

- For central heavy-ion collisions (N_{part} ~ 200) anomalous J/ψ suppression is observed in In+In and Pb+Pb collisions by NA60;
- It was initially attributed to onset of QGP formation in nuclear collisions, however CNM explanations have been proposed:
  - Shadowing;
  - Nuclear absorption.
- Open charm measurements would provide another view to the anomalous J/ψ suppression observed by NA60.



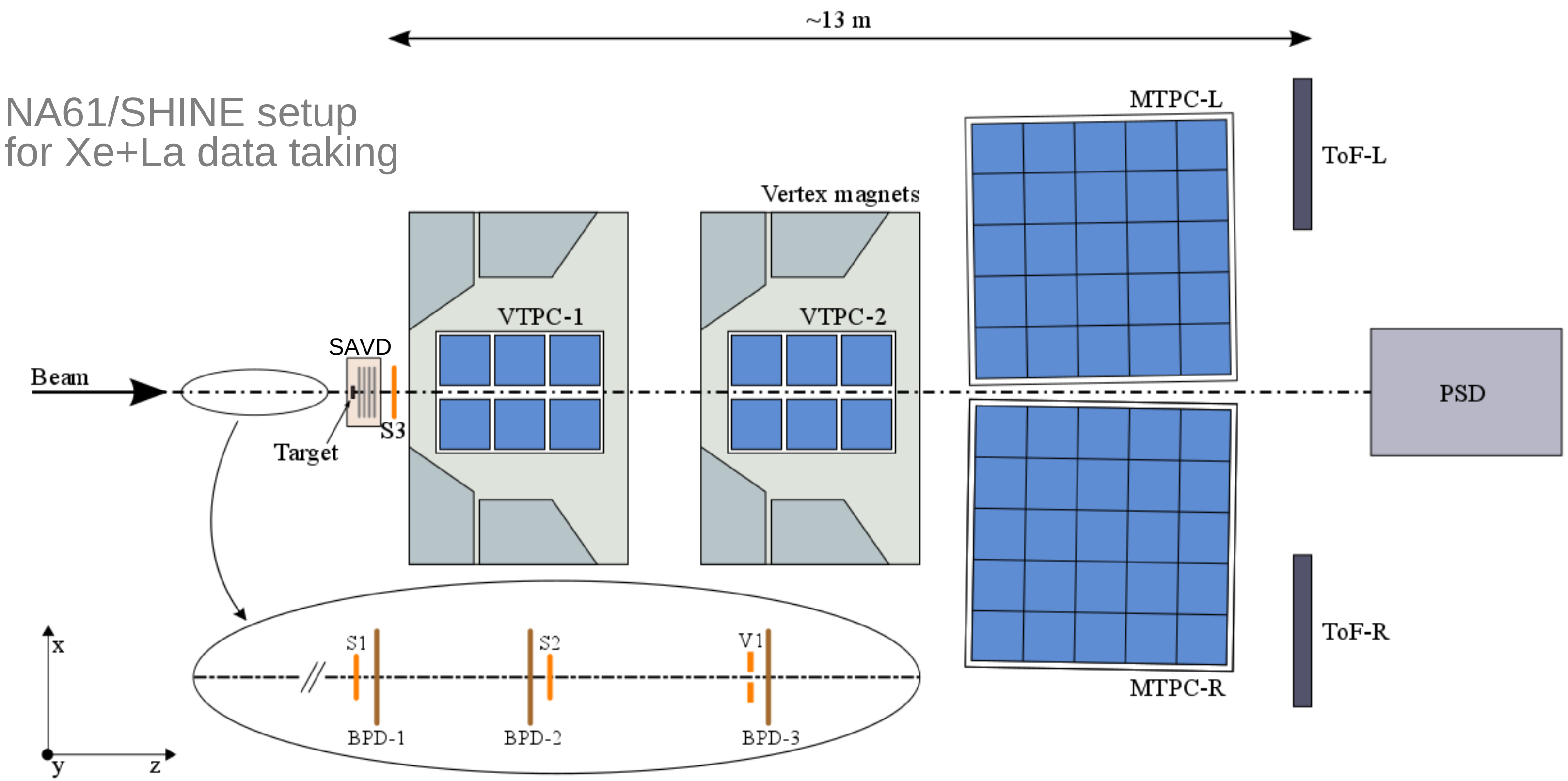
p+A measurements of charm at low $\sqrt{s_{NN}}$



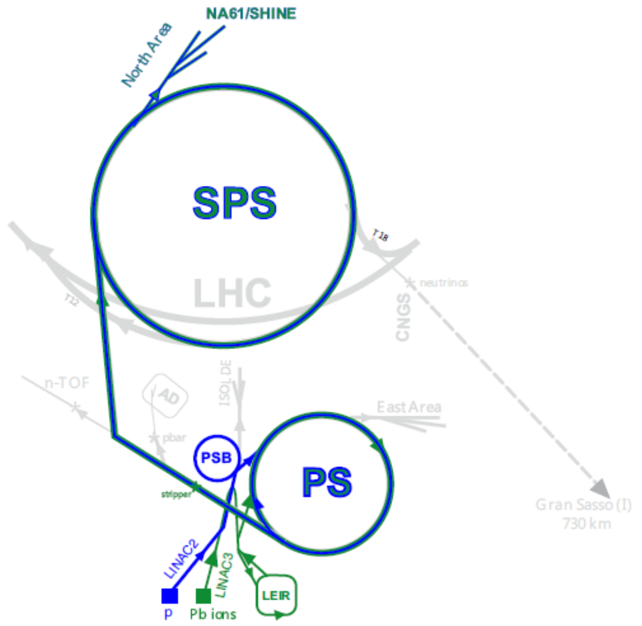
- Open charm measurements in *π*+A and *p*+A data from SPS and Fermilab experiments;
- No data at the top SPS energies (for A+A).

The NA61/SHINE experiment at CERN SPS

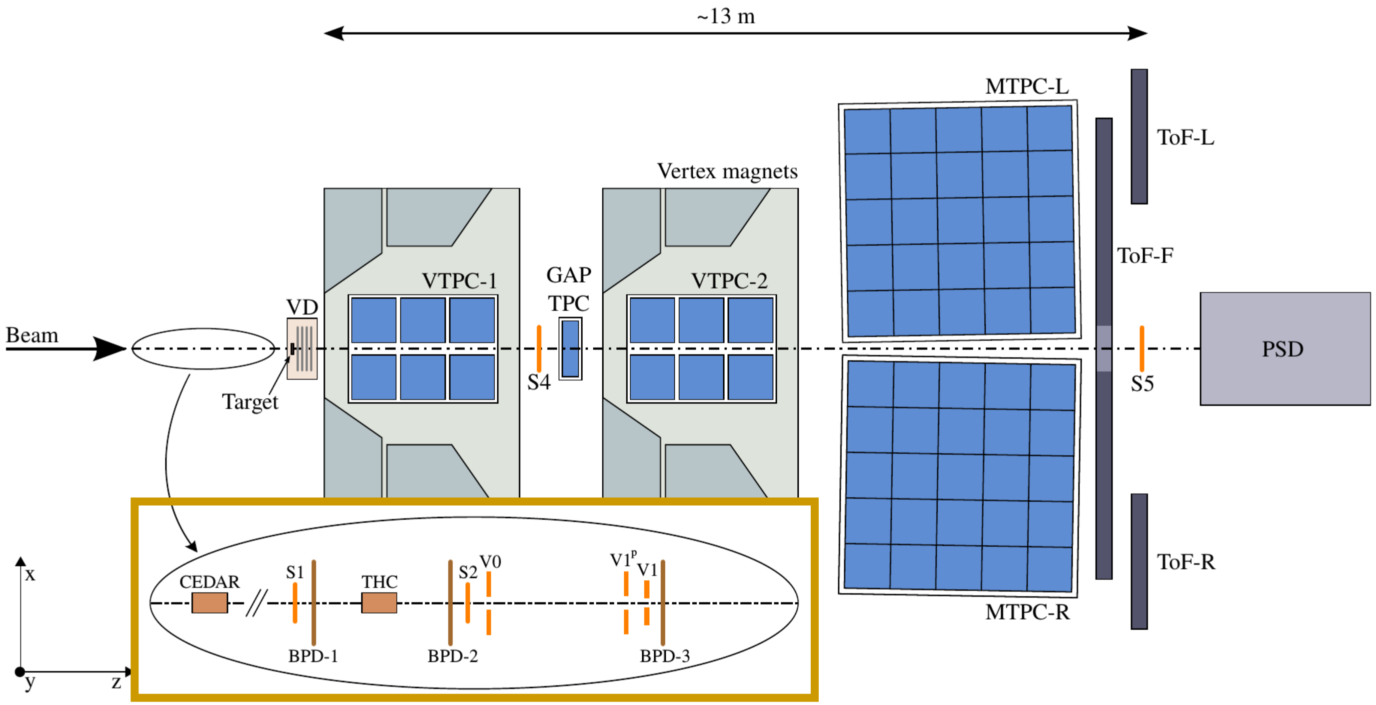
NA61/SHINE setup
for Xe+La data taking



- Beam types: π, K, p, Be, Ar, Xe, Pb
- p_{beam} =13A−158A(400) GeV/c
- $\sqrt{s_{NN}}$ = 5.1−17.3 (27.4) GeV



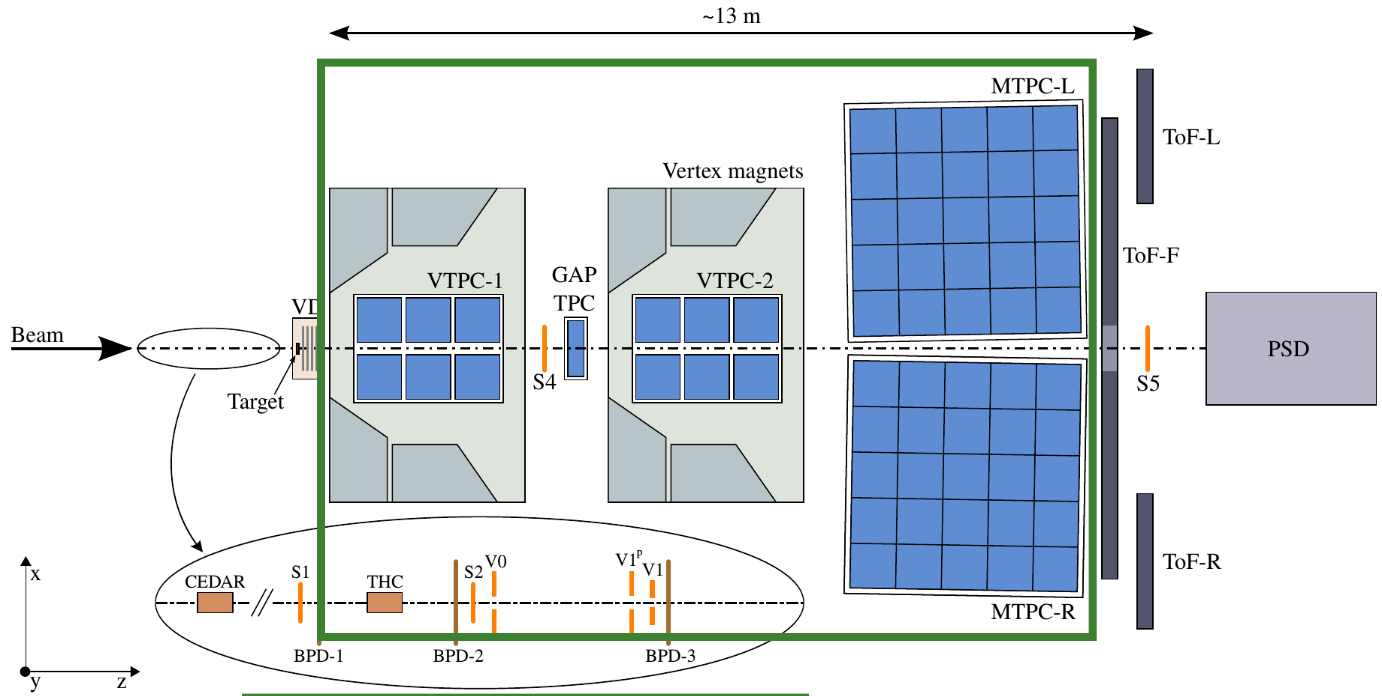
The NA61/SHINE experiment



- Beam detectors
  - Position
  - Charge
  - Time

of beam particles

The NA61/SHINE experiment



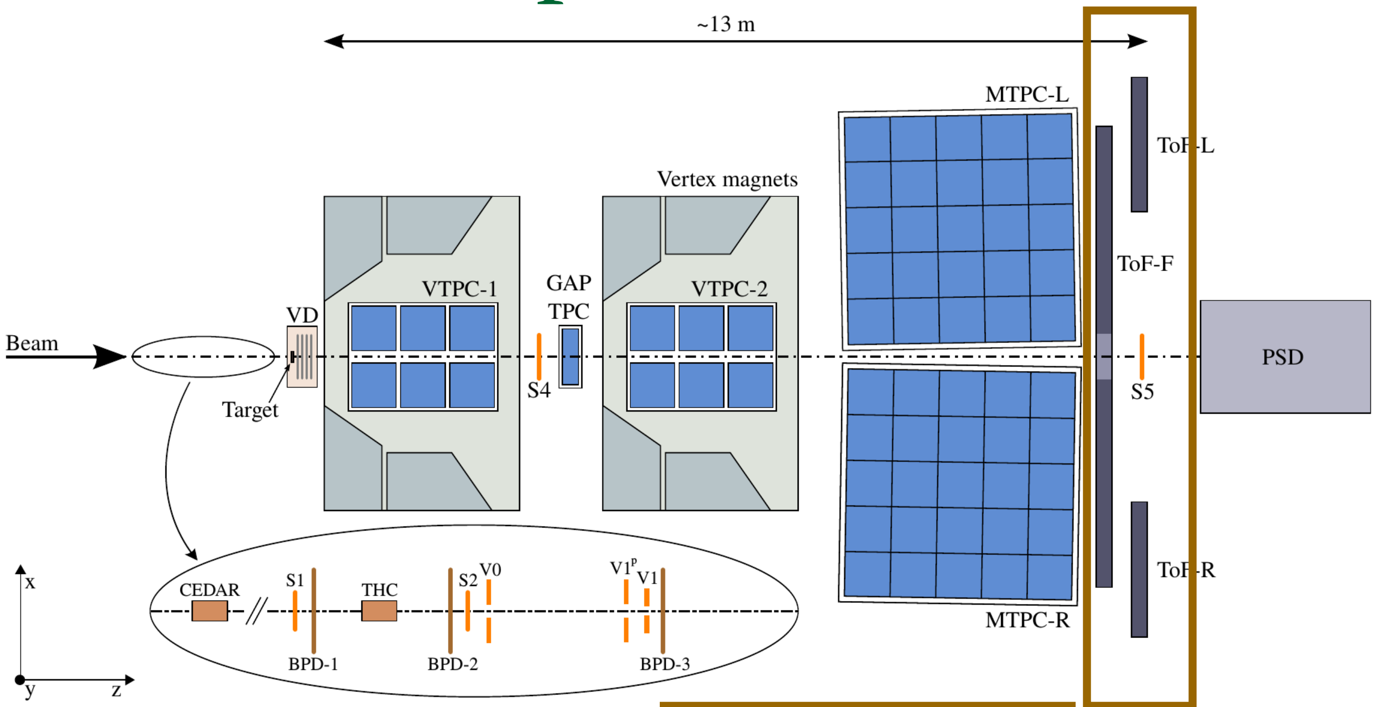
Beam detectors
- Position
- Charge
- Time

of beam particles

TPCs
- Momentum
- Charge
- PID (dE/dx)

of produced particles

The NA61/SHINE experiment



Beam detectors
- Position
- Charge
- Time

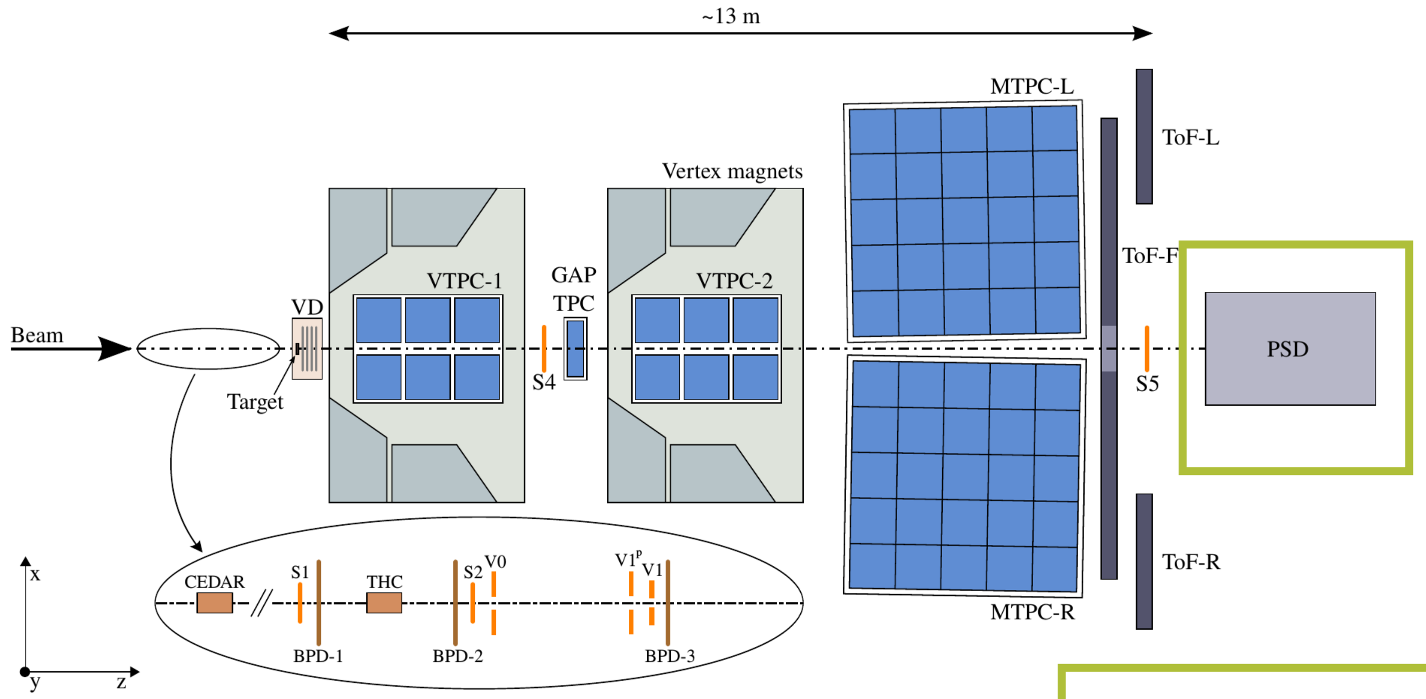
of beam particles

TPCs
- Momentum
- Charge
- PID (dE/dx)

ToF
- PID (mass)

of produced particles

The NA61/SHINE experiment



Beam detectors
- Position
- Charge
- Time

of beam particles

TPCs
- Momentum
- Charge
- PID (dE/dx)

ToF
- PID (mass)

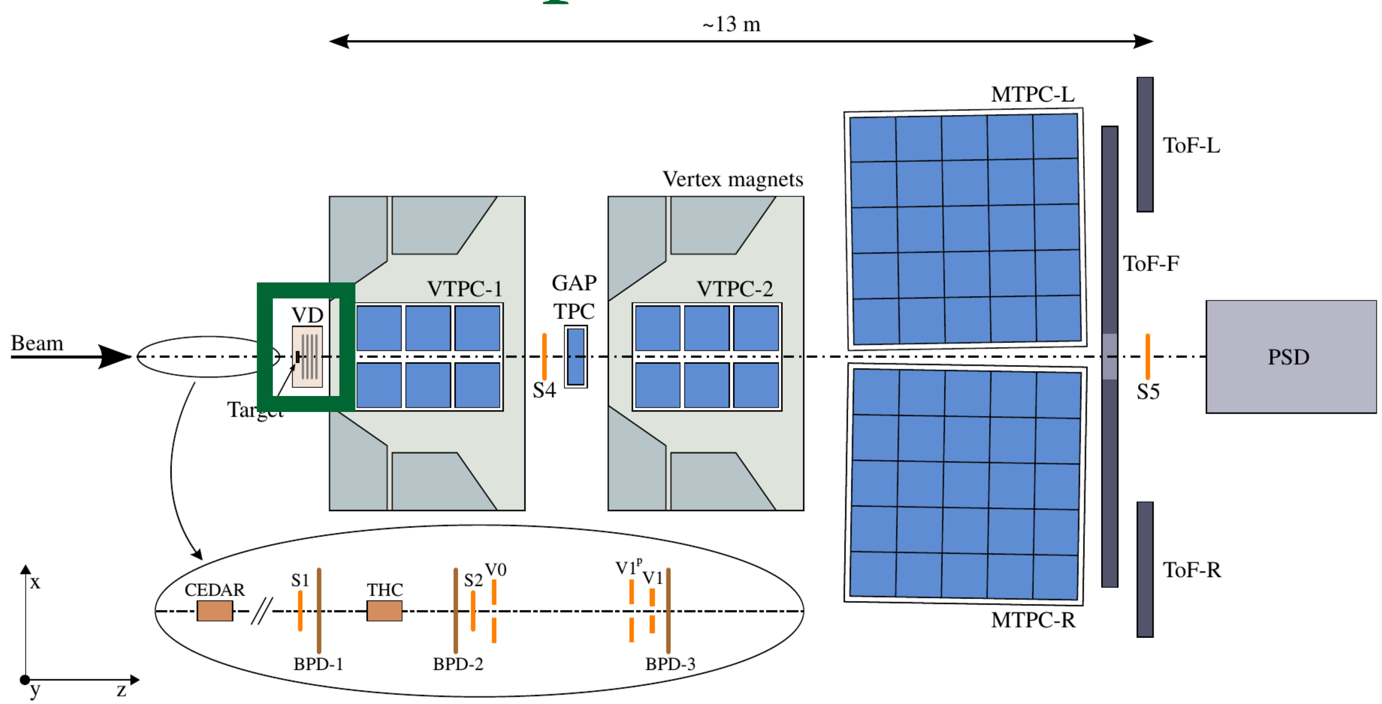
of produced particles

PSD calorimeter
- energy

of projectile spectators

The NA61/SHINE experiment

new Small Acceptance Vertex Detector



Beam detectors

- Position
- Charge
- Time

of beam particles

TPCs

- Momentum
- Charge
- PID (dE/dx)

ToF

- PID (mass)

of produced particles

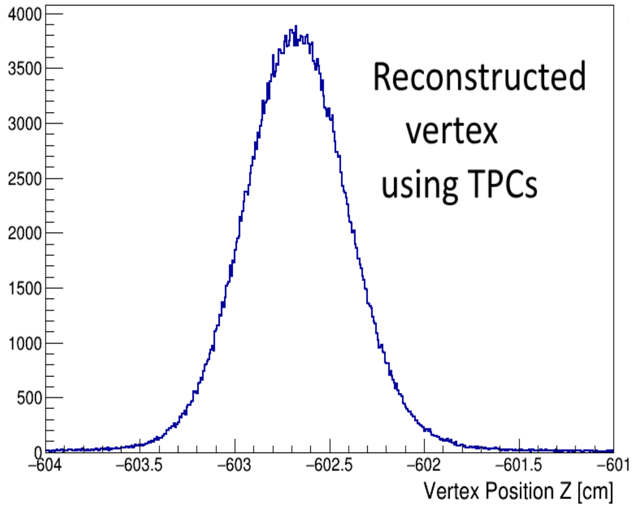
PSD calorimeter

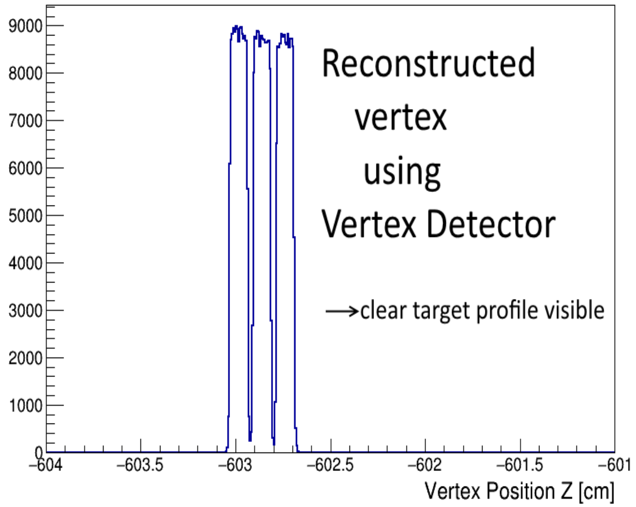
- energy

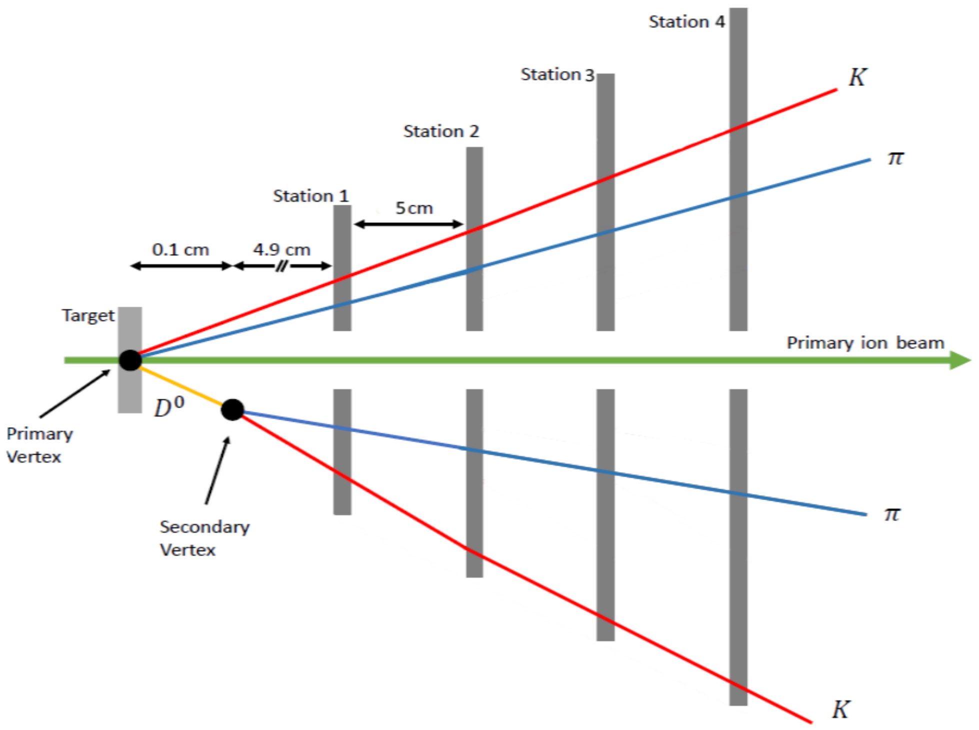
of projectile spectators

Small Acceptance Vertex Detector

- Four stations at z = 5, 10, 15 and 20 cm;
- 16 MIMOSA sensors with pixel size 18.4×18.4 μm^2;
- Primary vertex resolution $\sigma_{x,y} \approx$ 1 μm, σ_z = 15 μm;
- Secondary vertex resolution
  $\sigma_{x,y} \approx$ 10 μm, σ_z = 170 μm for D^0 and $\overline{D}^0$.







- The SAVD acceptance for $D^0 + \overline{D}^0$ is

$$-0.5 < y < 1.0$$
$$0.2 < p_T < 2.0 \text{ GeV}/c$$

(analysis is performed in this single bin)

Event and track selection

- Event selection:
  - Data taking of **Xe+La 150*A* GeV/*c*** in 2017 (before LS2)**;**
  - 1.93M **0-20%** central events;
- Track selection:
  - 3 or 4 SAVD hits (→ spatial resolution)
  - ≥10 TPC hits (→ momentum resolution)
  - No PID was applied.

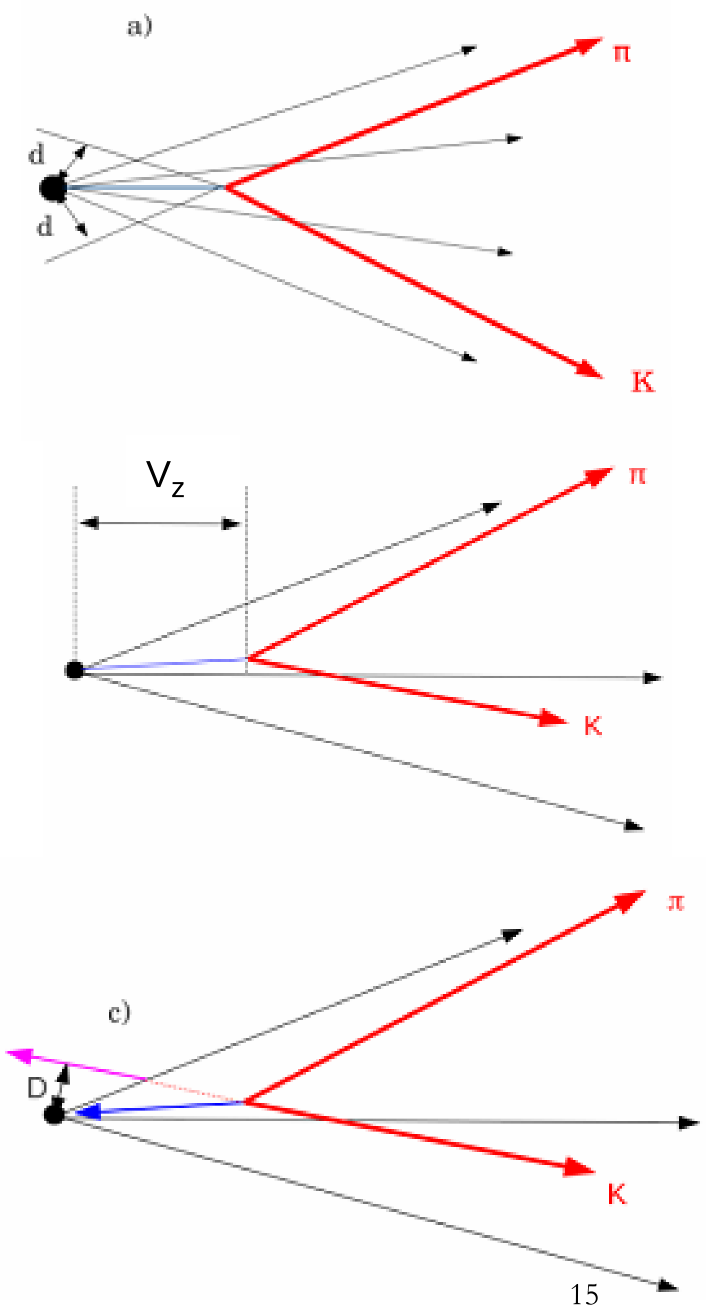
D^0+$\bar{D}^0$ reconstruction

$$D^0 \rightarrow K^- + \pi^+$$

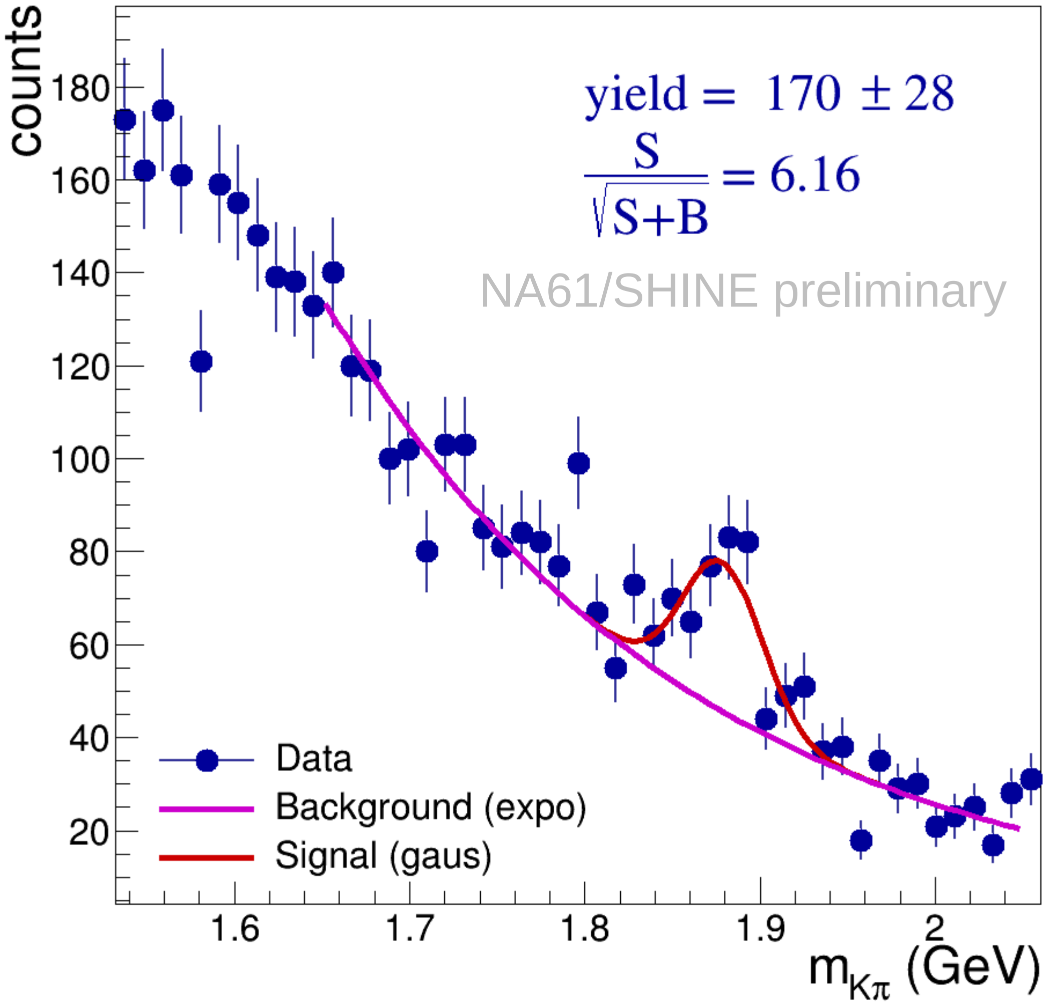
$$\bar{D}^0 \rightarrow K^+ + \pi^-$$

(BR=3.93%)

cut	value
(a) Impact parameter of daughter **d**	>36 μm
(b) Distance between primary and secondary vertices **V_z/γ**	>0.15 mm
(c) Impact parameter of parent **D**	<20 μm
Distance of closest approach **DCA**	<42 μm
Parent momentum (in lab frame) **p**	13<p<38 GeV/*c*

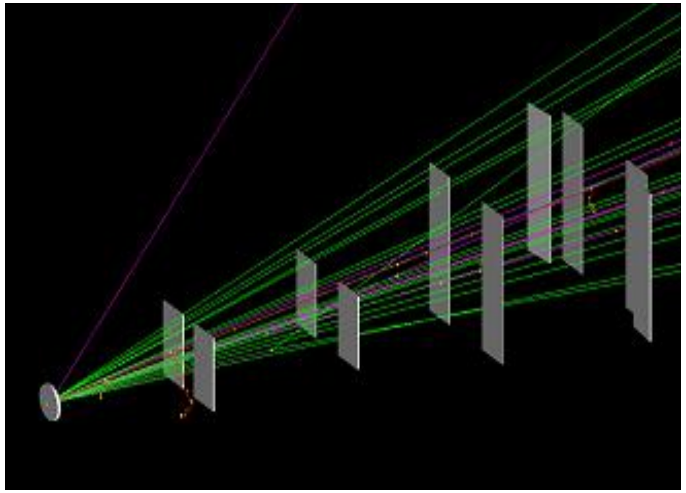


Inclusive $D^0 + \bar{D}^0$ signal in 0-20% Xe+La at 150*A* GeV/*c*

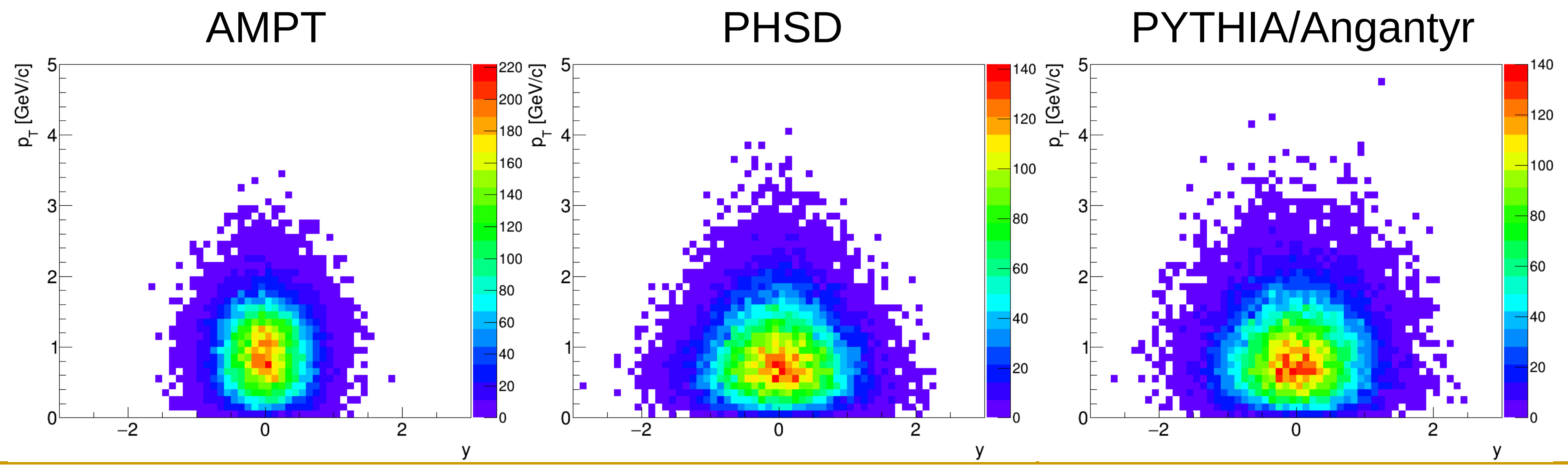


- $K\pi$-invariant mass distribution for 0-20% Xe+La at 150*A* GeV/*c*;
- This is the first direct observation of $D^0 + \bar{D}^0$ signal at the SPS energies with significance better than 5.

Simulations in GEANT4



- For obtaining the corrections the simulation in GEANT4 was performed:
  - The background was described using the EPOS model;
  - The signal phase space was parametrized using 3 models;
  - The yield of $D^0+\bar{D}^0$ from the models not used;
  - Parametrized signal is used to enrich background event.



Visible yield of $D^0 + \bar{D}^0$ in 0-20% Xe+La at 150A GeV/c

correction with:	$N_{visible}(D^0 + \bar{D}^0)$
AMPT	0.184±0.032 (stat)
PHSD	0.204±0.036 (stat)
PYTHIA/Angantyr	0.201±0.035 (stat)

$N_{visible}(D^0 + \bar{D}^0)$
0.196 ± 0.035 (stat) **± 0.051** (syst)

-0.5 < y < 1.0
0.2 < p_T< 2.0 GeV/c

Systematic uncertainties include:
- Model-dependent phase space;
- Track quality cut selection;
- Spatial cuts selection;
- Signal extraction procedure;
- Background fitting procedure.

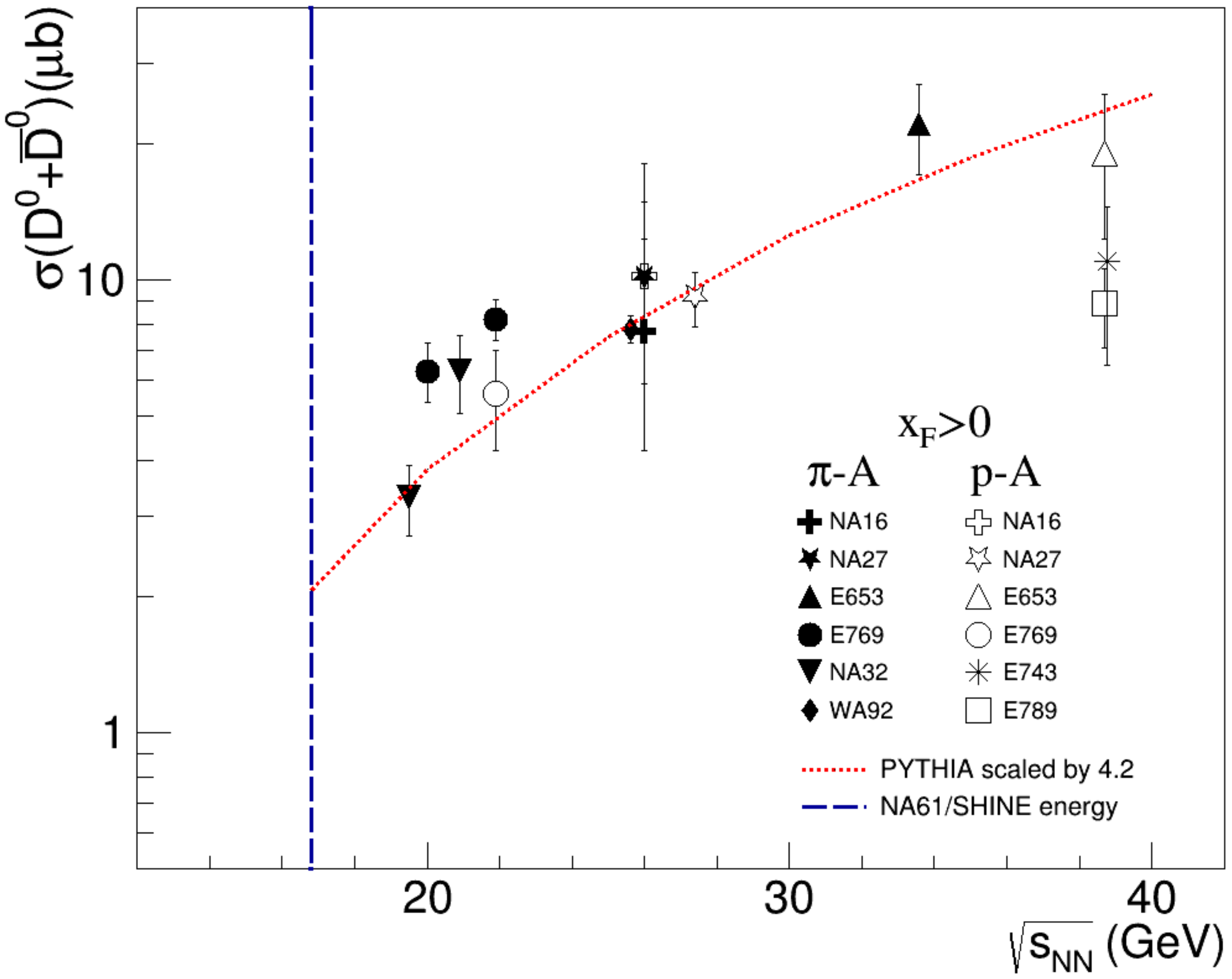
$\langle D^0 + \bar{D}^0 \rangle$ and dN/dy in 0-20% Xe+La at 150A GeV/c

correction with:	$\frac{dN\,(D^0+\bar{D}^0)}{dy}$ for **-0.5 < y < 1.0**	**Yield in 4π** $\langle D^0 + \bar{D}^0 \rangle$
AMPT	**0.129**±0.023(stat) ± 0.035(syst)	**0.218**±0.039(stat) ± 0.060(syst)
PHSD	**0.148**±0.026(stat) ± 0.036(syst)	**0.303**±0.054(stat) ± 0.074(syst)
PYTHIA/Angantyr	**0.147**±0.026(stat) ± 0.037(syst)	**0.300**±0.052(stat) ± 0.075(syst)

- Extrapolation factors for AMPT significantly differ from PHSD and PYTHIA/Angantyr due to different phase space distribution of $D^0+\bar{D}^0$:
  AMPT: 84.1% of all $D^0+\bar{D}^0$are in the selected $y - p_T$ bin
  PHSD: 67.4%
  PYTHIA/Angantyr: 66.9%

Syst. uncertainty doesn't include model dependence

Estimation of $\langle D^0 + \bar{D}^0 \rangle$ for Xe+La from p+A data



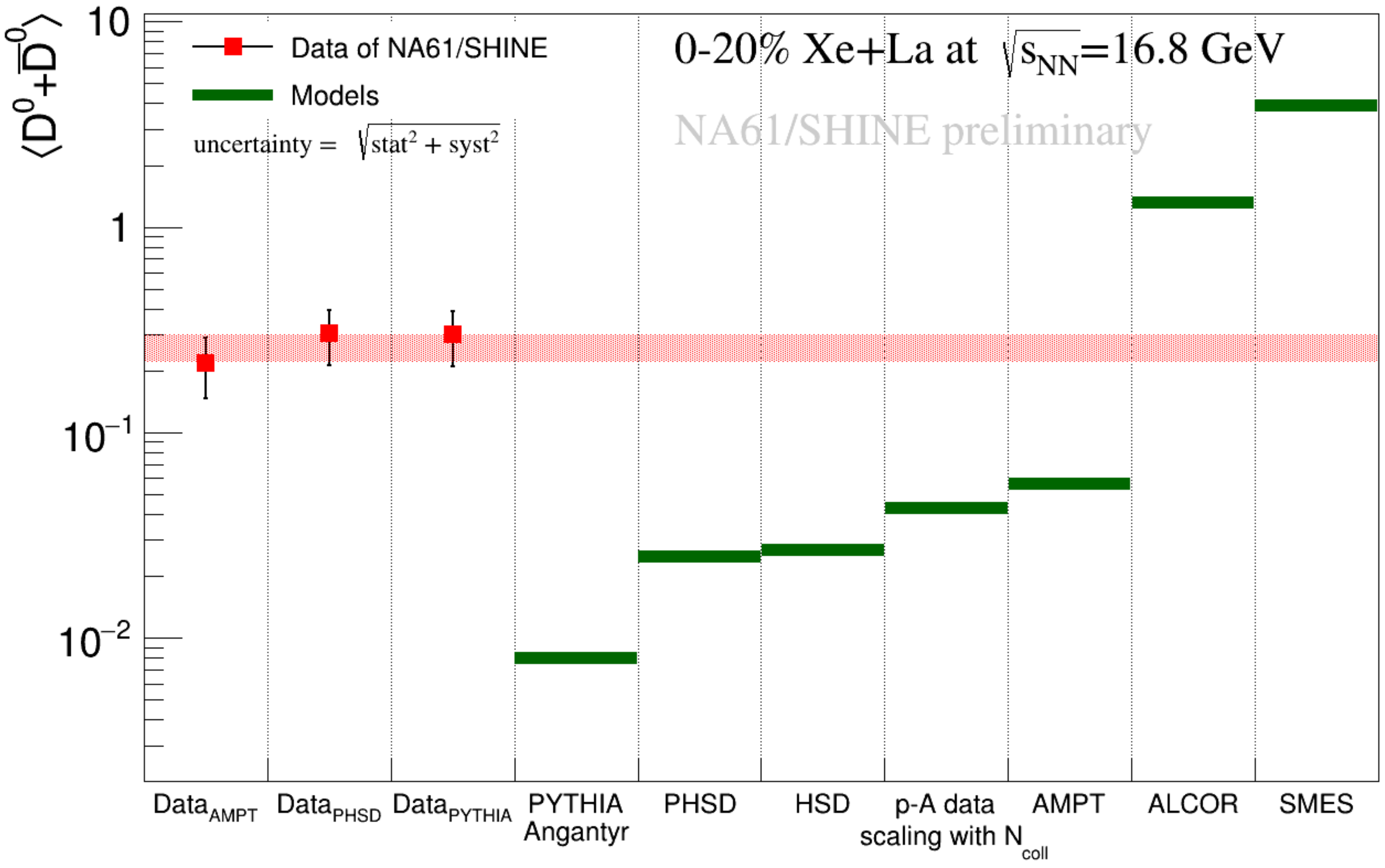
- Fit *p*+A data with PYTHIA:
  - PYTHIA reasonably describes energy dependence;
  - PYTHIA underestimates the $D^0+\bar{D}^0$ production cross-section by the factor 4.2.

- One can estimate $D^0+\bar{D}^0$ yield for Xe+La at $\sqrt{s_{NN}}$= 16.8 GeV from the extrapolation of *π*+A and *p*+A data:

$$\langle D^0 + \bar{D}^0 \rangle = 2 \times \frac{\sigma_{D^0+\bar{D}^0}}{\sigma_{inelastic\ for\ p+p}=32\text{mb}} \times N_{coll} = 0.043$$

Xe+La 0-20% N_{coll} = 331.1

Comparison of $\langle D^0 + \bar{D}^0 \rangle$ with models



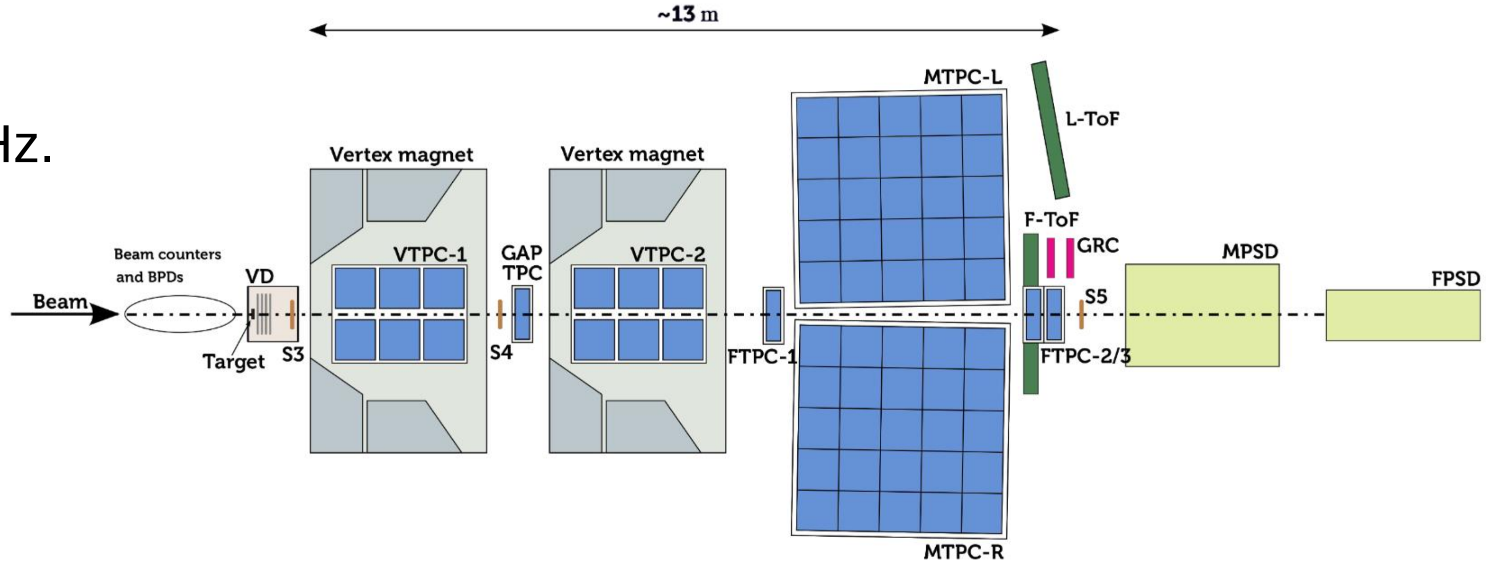
Red band indicates theoretical uncertainty of the obtained result.

- Precision of the data is sufficient to discriminate between extreme model predictions;
- The dynamical microscopic models (Pythia, PHSD, HSD) significantly underestimate $\langle D^0 + \bar{D}^0 \rangle$ while ALCOR and SMES overestimate it;
- AMPT predicts value slightly (~2σ) lower;
- The obtained results are above *p*+A extrapolation at the level of ~2-3σ:
  - Imprecision of the extrapolated *p*+A cross-section;
  - Imprecision of the obtained result due to unknown phase space;
  - Hadronization in A+A vs *p*+A?
  - Fermi-motion?
  - N_{coll} or N_{part} scaling?

SMES: scaled from 0-20% Pb+Pb using N_{part} = 173.7/272.5
ALCOR (Dynamical Quark Coalescence): scaled from *J.Phys.G 27 (2001) 703-706* using N_{coll} = 331.1/598.8

Outlook: LS2 upgrade

- Data taking rate from 80 Hz to 1.2 kHz.
- Upgraded Vertex Detector based on ALPIDE sensors;
- Upgraded TPC readout & DAQ.



- In 2022-2023 NA61/SHINE collected ~180M Pb+Pb events at 150*A* GeV/*c*. The data should allow:
  - the p_T and y differential measurements of D^0 and $\overline{D}^0$;
  - measurements of other charm hadrons;

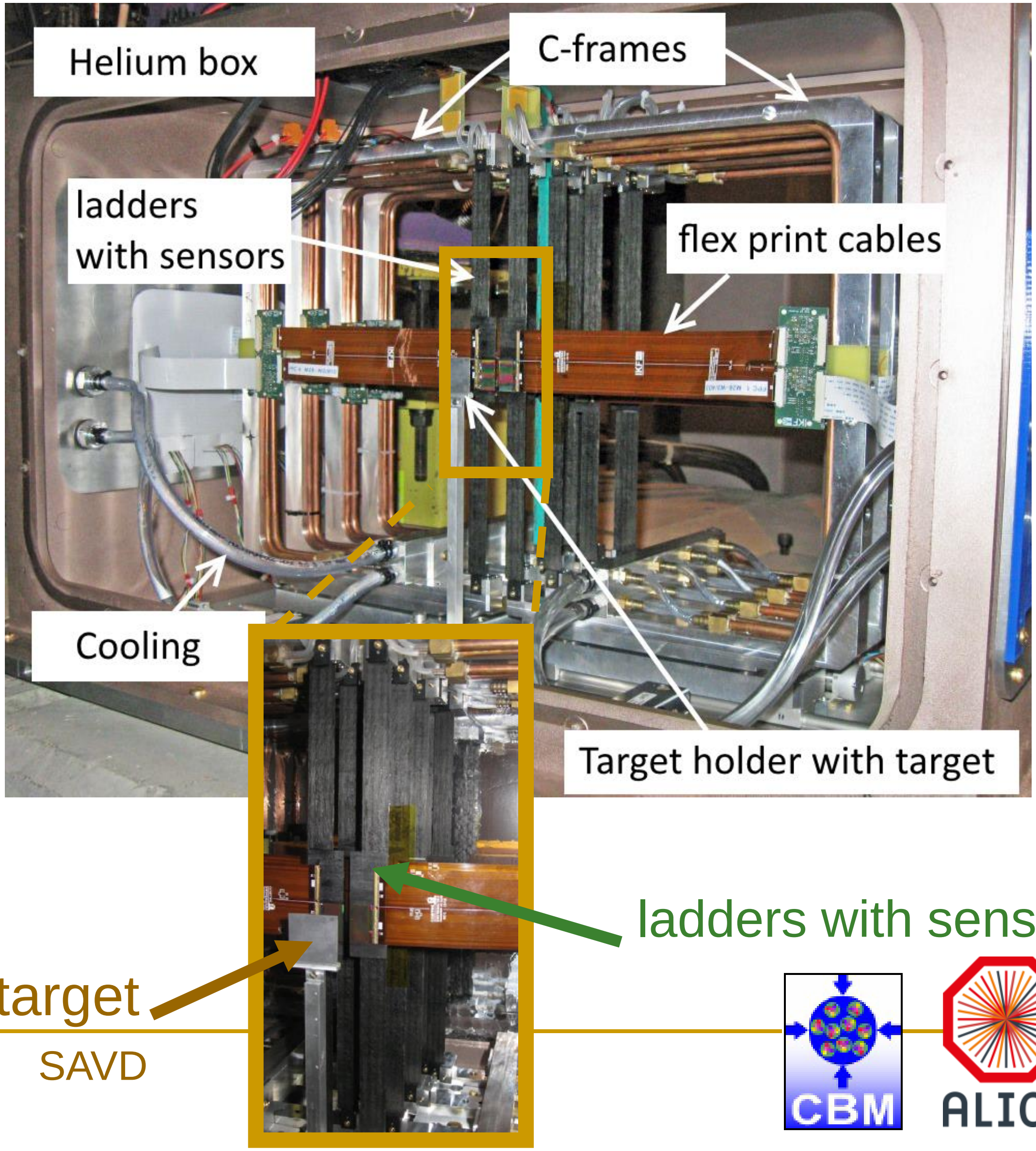
→ Better insight into charm production mechanisms at energies close to production threshold.

Summary & Outlook

- The first direct open charm observation in heavy-ion collisions at the SPS energies was done for Xe+La 0-20% central collisions at 150*A* GeV/*c*.
- Precision of the obtained result is sufficient to disentangle between theoretical models.
- Stay tuned for new results!

Thank you for your attention!

Vertex Detector



SAVD

- Main purpose of the Vertex Detector is the improvement of track resolution near the interaction point to allow reconstruction of secondary vertices;

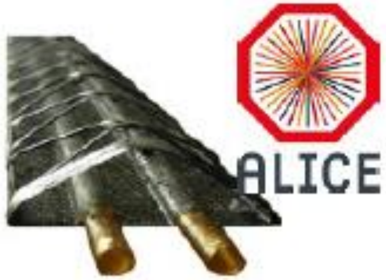
- SAVD is positioned between the target and the VTPC-1;
- Four planes of coordinate-sensitive detectors are located at 5, 10, 15 and 20 cm distance from the target.

25

Main Vertex Detector components

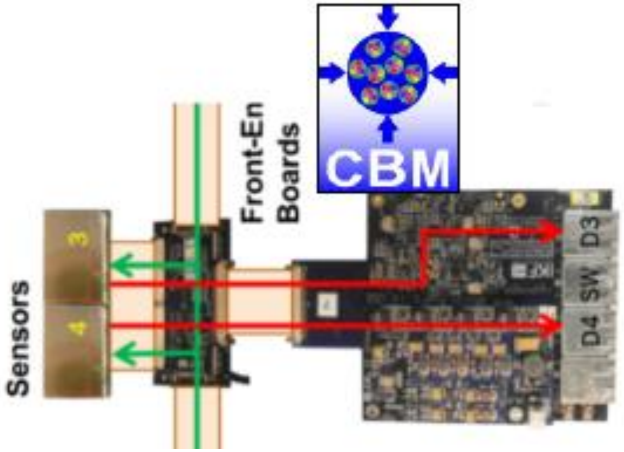
- MIMOSA-26AHR
  - 1152x576 pixels of 18.4x18.4µm2
  - 3.5 µm resolution, 0.05% X0
  - Readout time: 115.2 µs, 50µm thin

  PICSEL Group, IPHC Strasbourg



- ALICE ITS ladder
  - Ultra light carbon fibre
  - < 0.3% X0 including water cooling

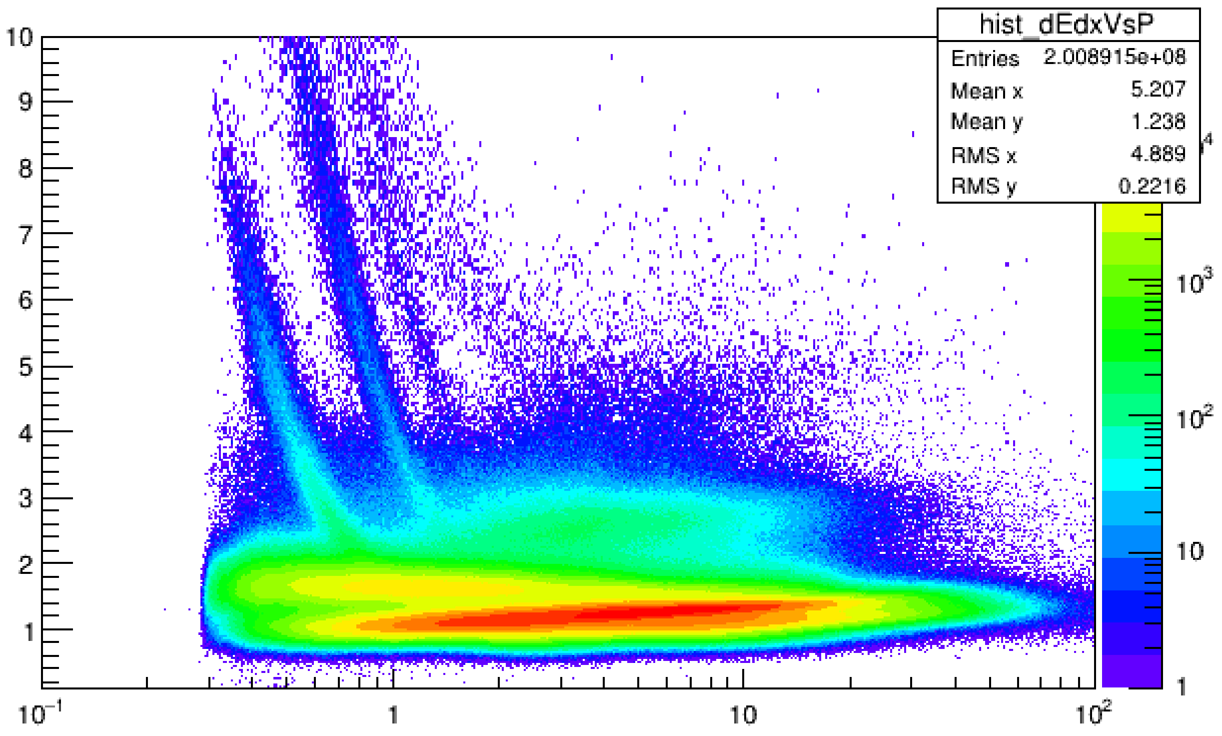
  St. Petersburg, CERN

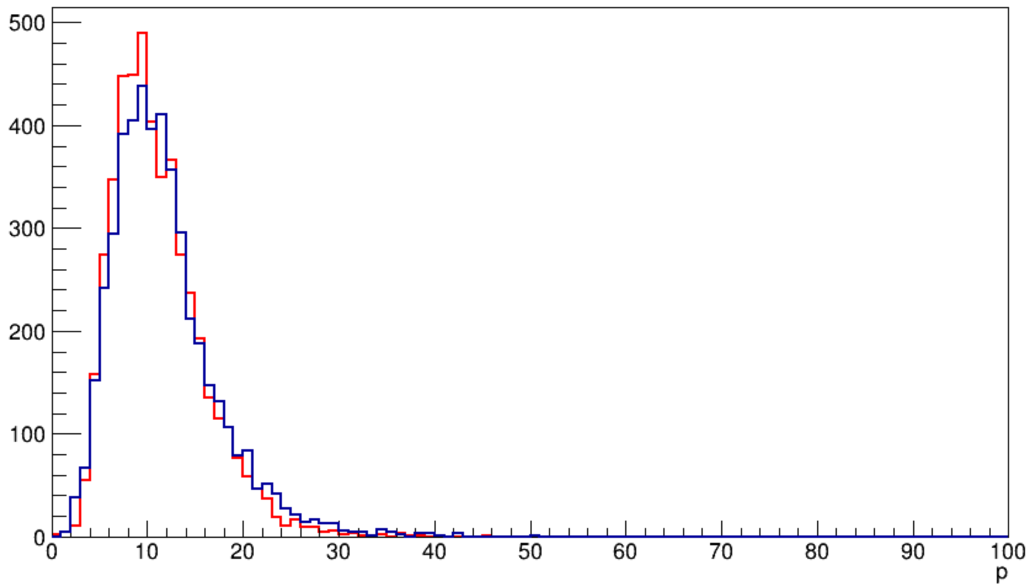


- CBM Micro Vertex Detector Prototype
  - Sensor integration
  - Flex print cables, Front-end boards
  - Read-out based on TRB3 FPGA Board

  Goethe Universitet Frankfurt am Main

dE/dx





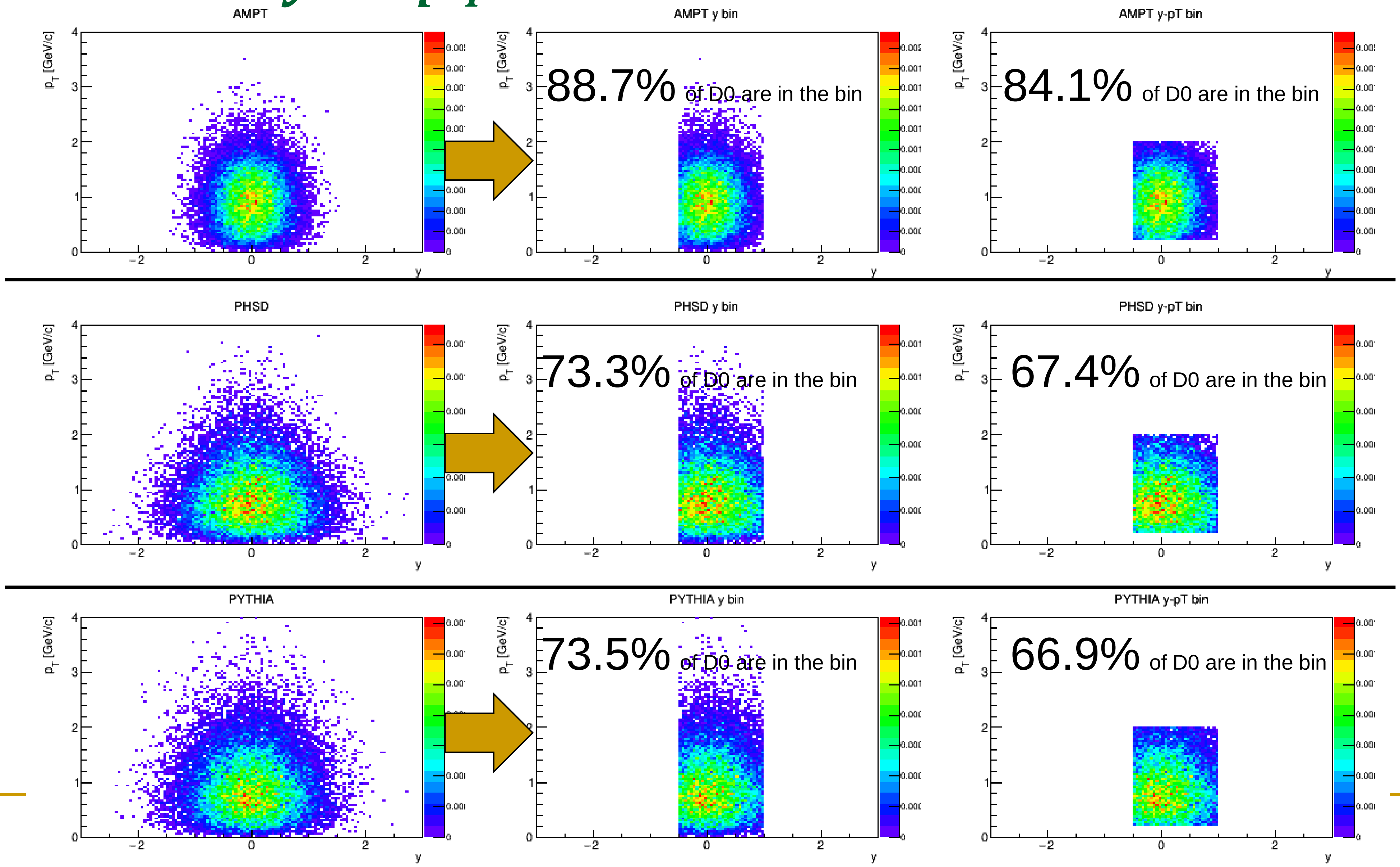
Daughters of $D^0 + \overline{D^0}$ are in the range of 5-30 GeV/*c*, where π and K dE/dx curves overlap.
So, no dE/dx used

$D^0 + \bar{D}^0$ in $y - p_T$ bin

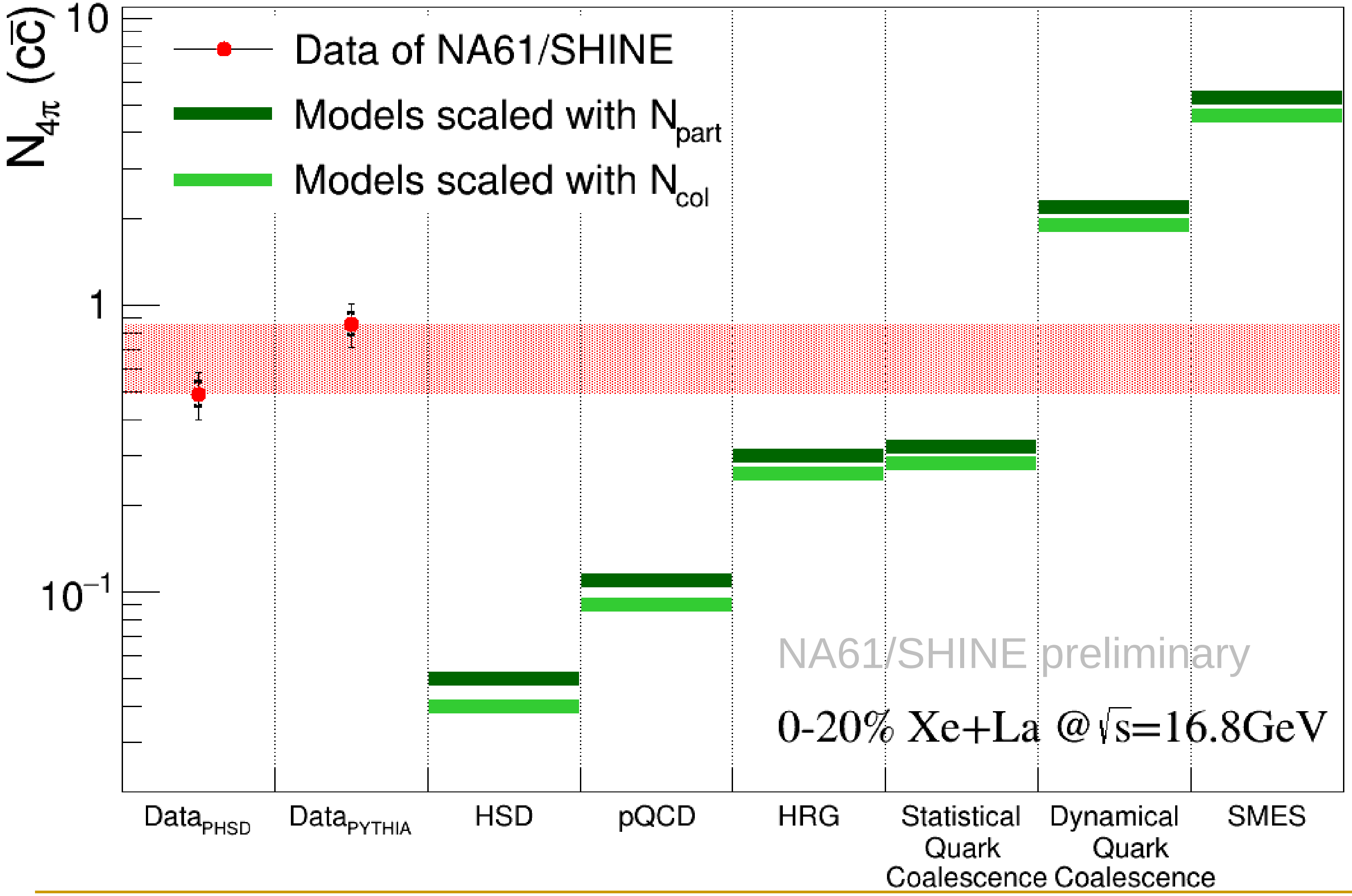
AMPT

PHSD

PYTHIA/ Angantyr



Comparison $N_{4\pi}(c\bar{c})$ with models



Scaling with N_{coll} = 331.1/598.8
Scaling with N_{part} = 173.7/272.5

- Values for the models are scaled from Pb+Pb 0-20%;
- Values for data scaled from $\langle D^0 + \bar{D}^0 \rangle$ using ratio provided by event generators:

	Ratio of $c\bar{c}$ decaying into $(D^0 + \overline{D^0})$
PHSD	62%
PYTHIA/Angantyr	35%

- Comparison of the data and models show significant discrepancy between them:
  while some models (SMES) is overestimating the charm yield, other (HSD) underestimating it.
- The closest model predictions to obtained result are HRG and Quark Coalescence.

|---| Stat uncertainty
[---] Syst uncertainty