Open charm measurements at the NA61 experiment at CERN SPS

Dag Larsen
Anastasia Merzlaya

Valday
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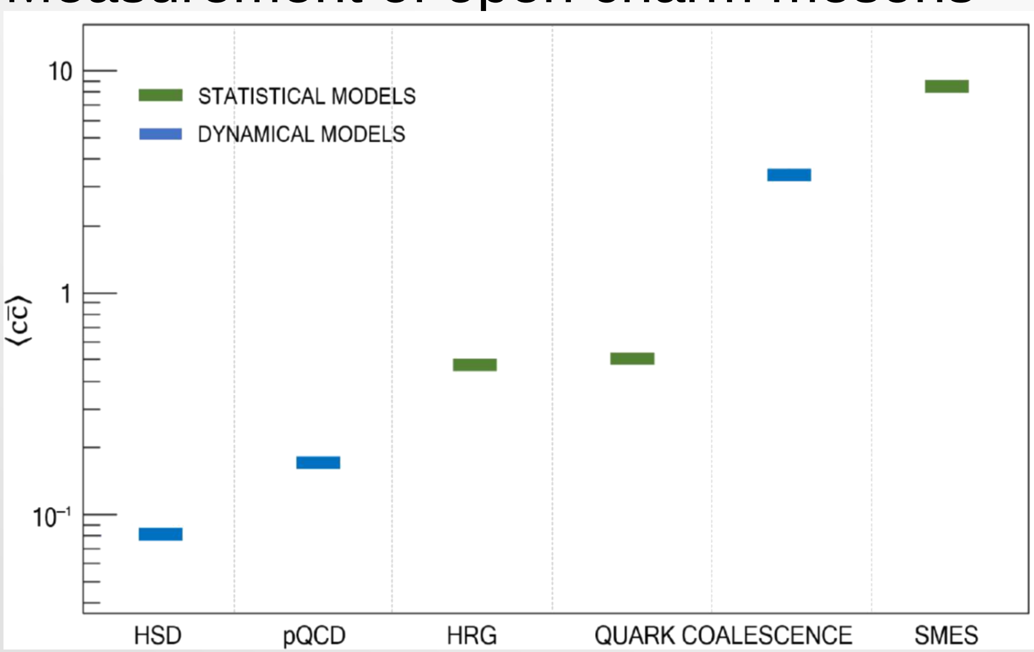
Outline

- Open charm measurement motivation
- NA61/SHINE experiment at CERN
- Vertex Detector (VD)
- VD event reconstruction
- Current results
- Upgrade of VD
- Summary & outlook

Model predictions

- Probability of cc pair converting into $J/\psi \rightarrow \langle c\bar{c} \rangle$
- Two main approaches: dynamical and statistical models
  - Predictions differ by factor upto 50 for PbPb at top SPS energy
- To discriminate models the $\langle c\bar{c} \rangle$ produced in full phase space is needed
  - Measurement of open charm mesons



HSD
Linnyk, Bratkovskaya, Cassing, IJMP E17 1367

pQCD
Gavai et al. IJMP A 10 2999
Braun-Munzinger, J. Stachel, PLB 490, 196

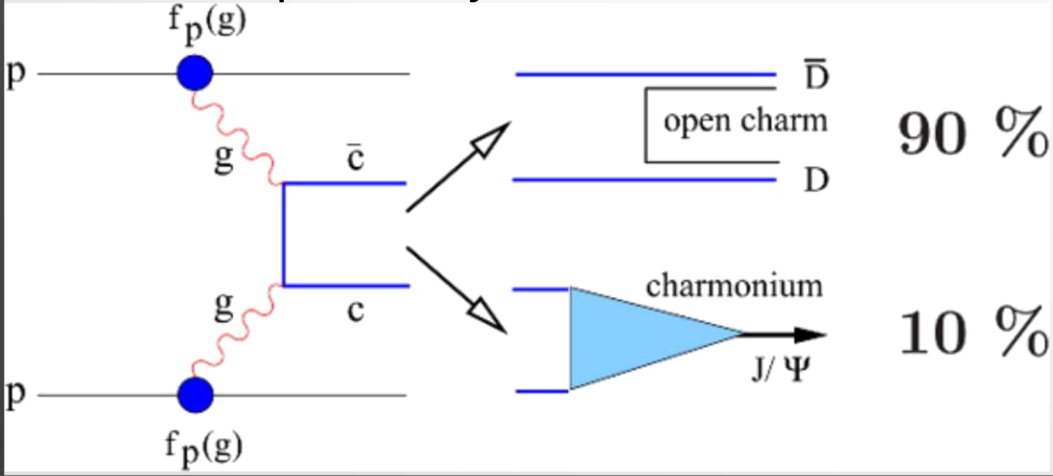
HRG, Quark Coalesc. Stat.
Gavai et al. IJMP A10 2999
Braun-Munzinger, J. Stachel, PLB 490, 196

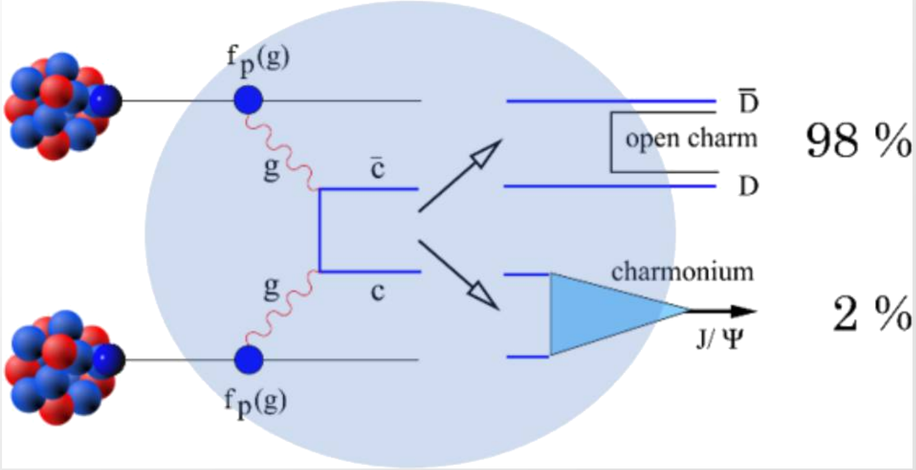
Quark Coalesc. Dyn.
Levai, Biro, Csizmadia, Csorgo, Zimanyi, JP G27, 703

SMES
Gazdzicki, Gorenstein, APP B30, 2705

D^0 as signal of deconfinement

- Production of D^0 is expected to be different in confined and deconfined matter
  - Confined matter: lightest charm carrier – D meson; production of $\langle D\bar{D}\rangle$ pair ~3.7 GeV
  - Deconfined matter: charm carrier – c quark; production of $\langle c\bar{c}\rangle$ pair ~2.6 GeV
  - More abundant charm production is expected in deconfined than in confined matter
- Probability of $\langle c\bar{c}\rangle$ pair hadronising to J/ψ: $P\left(c\bar{c} \rightarrow J/\psi\right) \equiv \frac{\langle J/\psi \rangle}{\langle c\bar{c} \rangle} \equiv \frac{\sigma_{J/\psi}}{\sigma_{c\bar{c}}}$
  - Measurements of on both J/ψ and $\langle c\bar{c}\rangle$ in full phase space need to calculate this probabilty



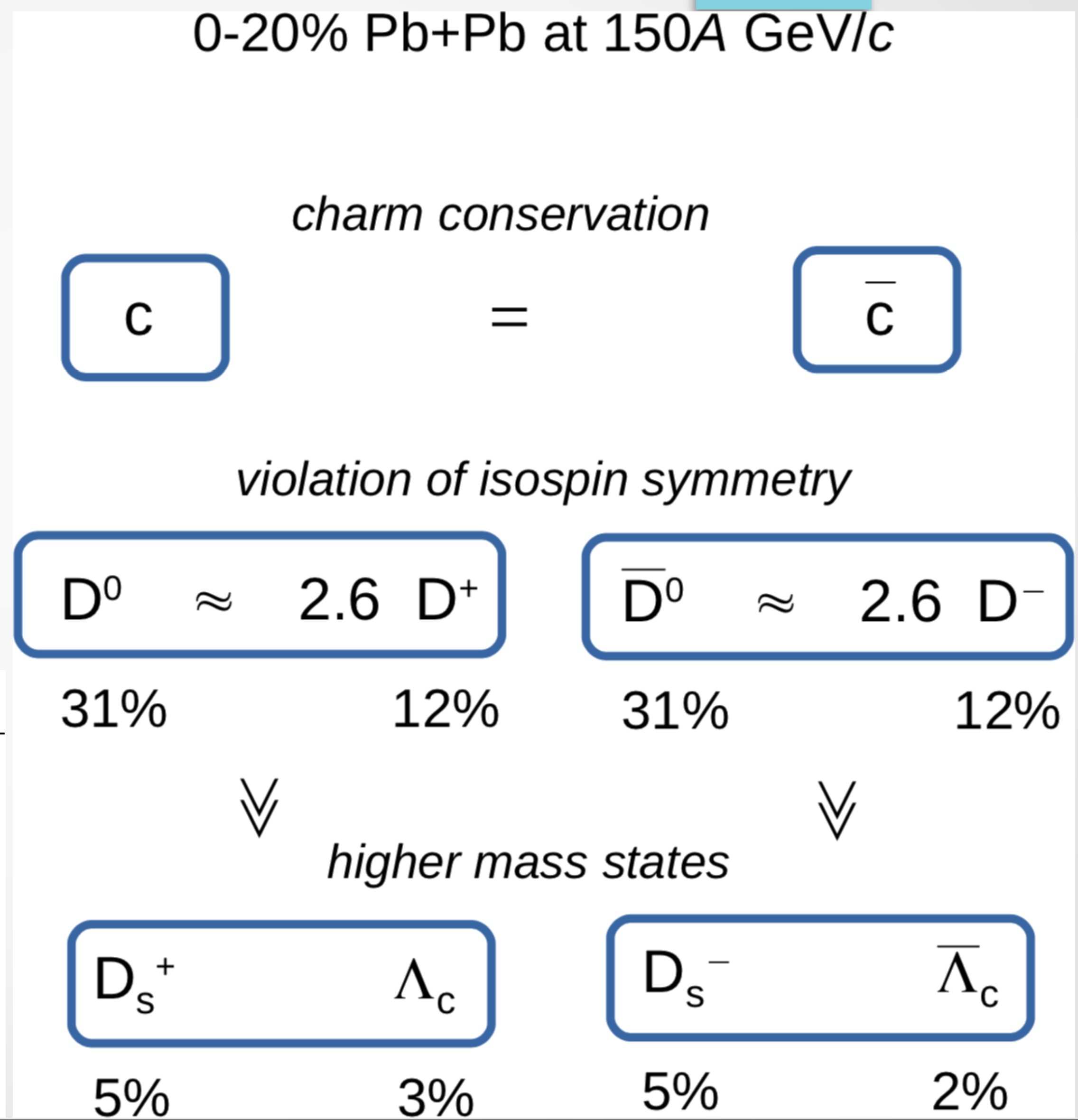


Measurment of $\langle c\bar{c} \rangle$

- Measuring D^0, $\bar{D}^0$, D^+, D^- will probably give good $\langle c\bar{c} \rangle$ estimate

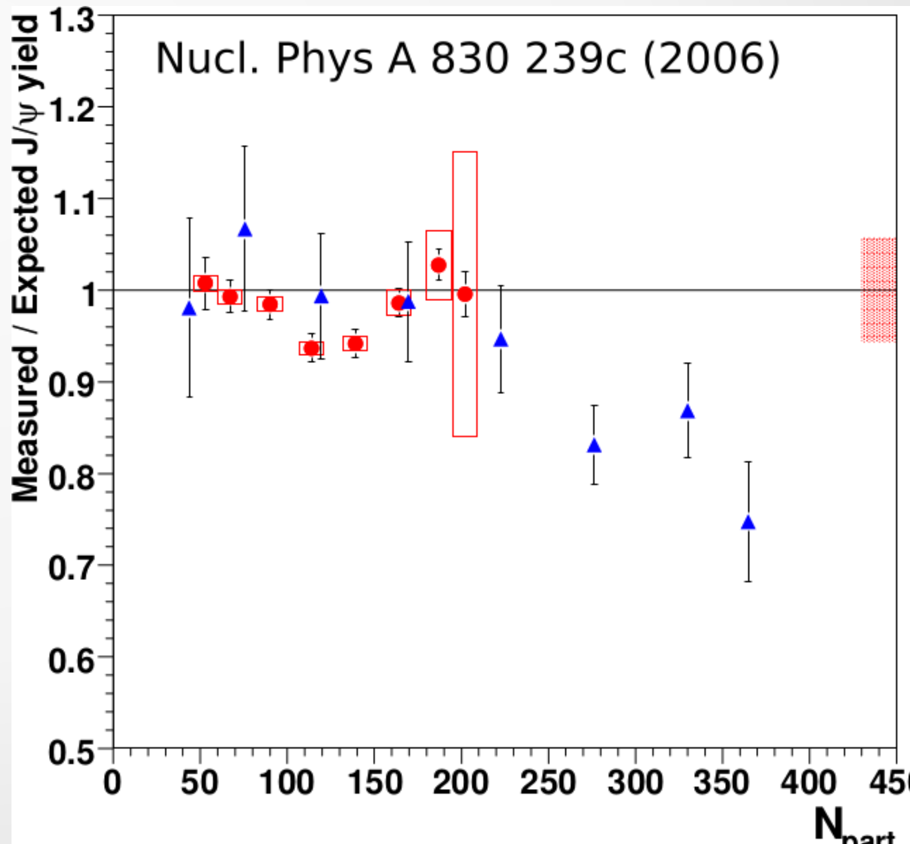
- Charm hadrons that may be measured with VD in NA61/SHINE experiment:

Hadron	Decay channel	$c\bar{\tau}$ [μm]	BR
D^0	$\pi^+ + K^-$	123	3.89%
D^+	$\pi^+ + \pi^+ + K^-$	312	9.22%
D_S^+	$\pi^+ + K^- + K^+$	150	5.50%
Λ_c	$p + \pi^+ + K^-$	60	5.00%

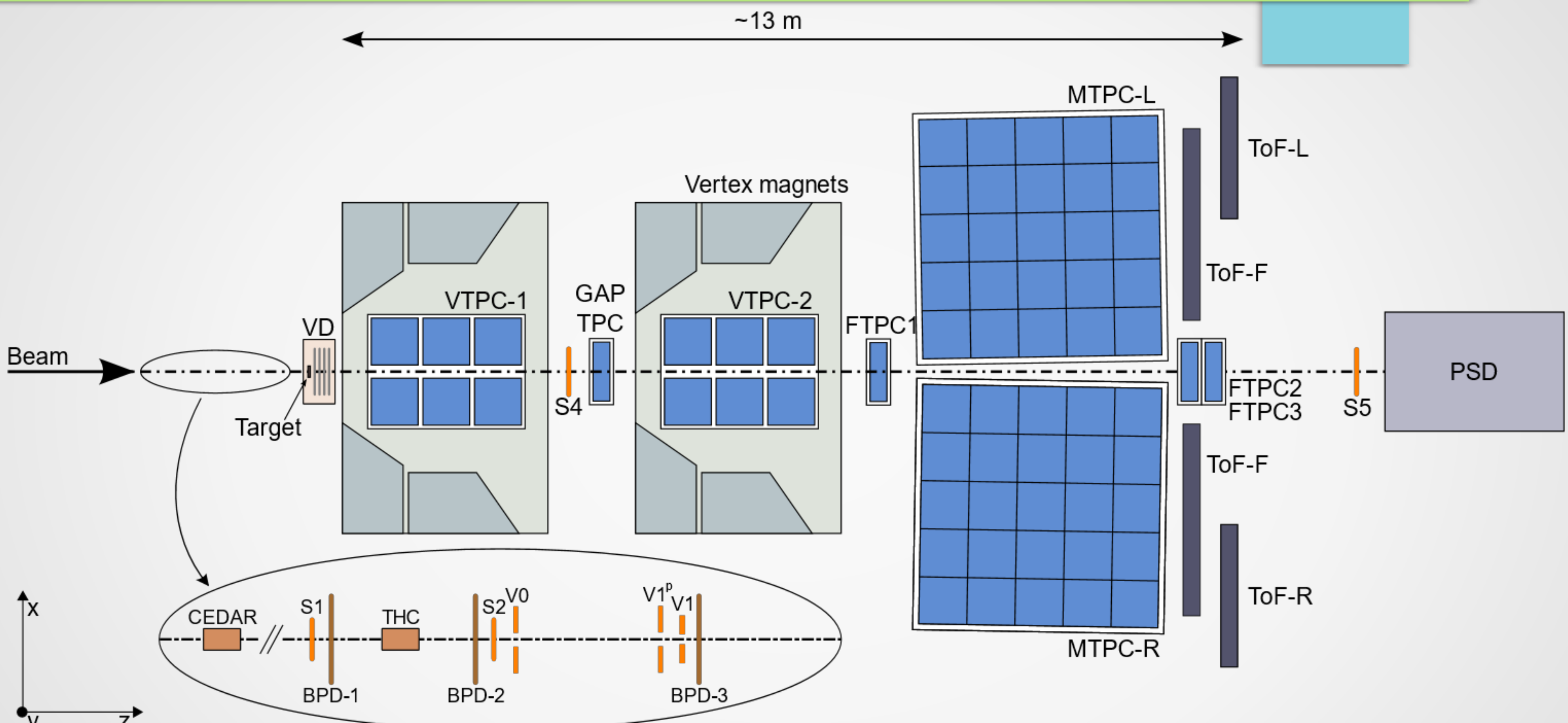


Anormalous J/ψ supression

- NA60 experiment measured the production of J/ψ in InIn and PbPb collisions
- For lower number of participants the yields are consistent with the theoretical pQCD estimations
- However, at N_{part}~200 the result shows significant drop, known as anomalous J/ψ suppression
  - It was attributed to onset of QGP formation in nuclear collisions, however other explanations have also been proposed.
- To verify observed signature of QGP formation one needs to measure total balance of charm
  - It can be done by measurement of open charm in all channels



The NA61/SHINE facility



- S1, S2, V1, V1: trigger system for event selection
- VD: high-precision determination of primary vertex
- VTPC: 1.5 T magnetic field, momentum measurement, resolution: 10^{-4}
- MTPC: dE/dx measurement, specific energy loss
- ToF: Time-of-flight measurements, improves particle identification
- PSD: zero-degree calorimeter, determine forward energy

Data taking capabilities

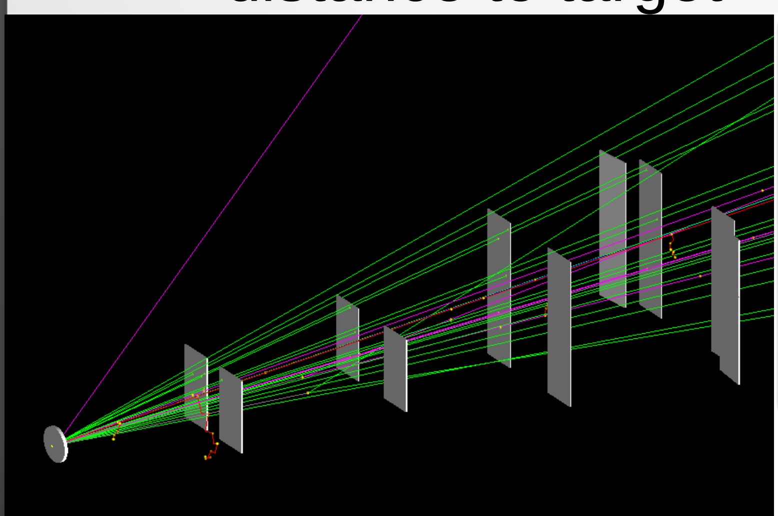
- Ion beams:
  - Primary: Ar, Xe, Pb 13*A* – 150/160*A* GeV/*c*
  - Secondary: Be from Pb fragmentation, 13*A* – 150/160*A* GeV/*c*
- Hadron beams:
  - Primary: proton 400 GeV/*c*
  - Secondary: hadron beams: pion, kaon, proton 13 – 400 GeV/*c*
- Targets:
  - Solid state from ~1 mm to ~1 m
  - Liquid hydrogen target 20 cm
- Data taking rate: 1 M events/day (currently)

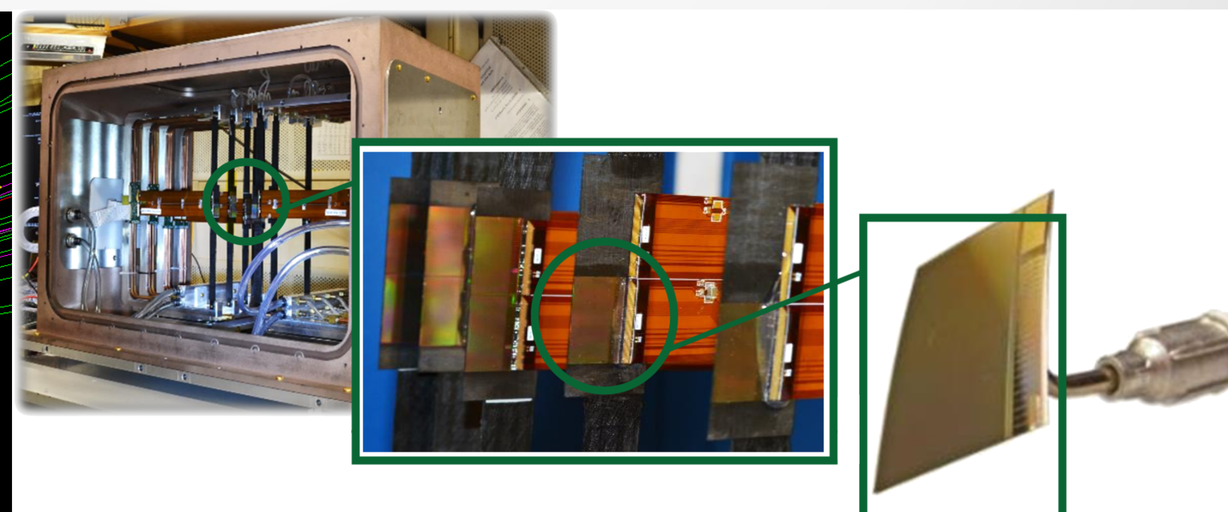
Physics programme – current

- SHINE – Sps Heavy Ion and Neutrino Experiment
- Strong interaction programme:
  - Search for critical point
  - Study of onset of deconfinement
- Cosmic ray programme:
  - Measurements for simulations of cosmic ray shower (Pierre Auger Observatory, CASCADE)
- Neutrino programme:
  - Measurement for simulations of initial neutrino flux (T2K, Fermilab)

Small acceptance Vertex Detector (SAVD)

- Measuring open charm requires very precise determination of secondary vertex
  - This is possible using detector based on silicon sensors
- The SAVD has 4 sensor layers (stations) 50mm apart
  - First station 50mm behind target
  - 16 sensors arranged so that covered area increases with distance to target



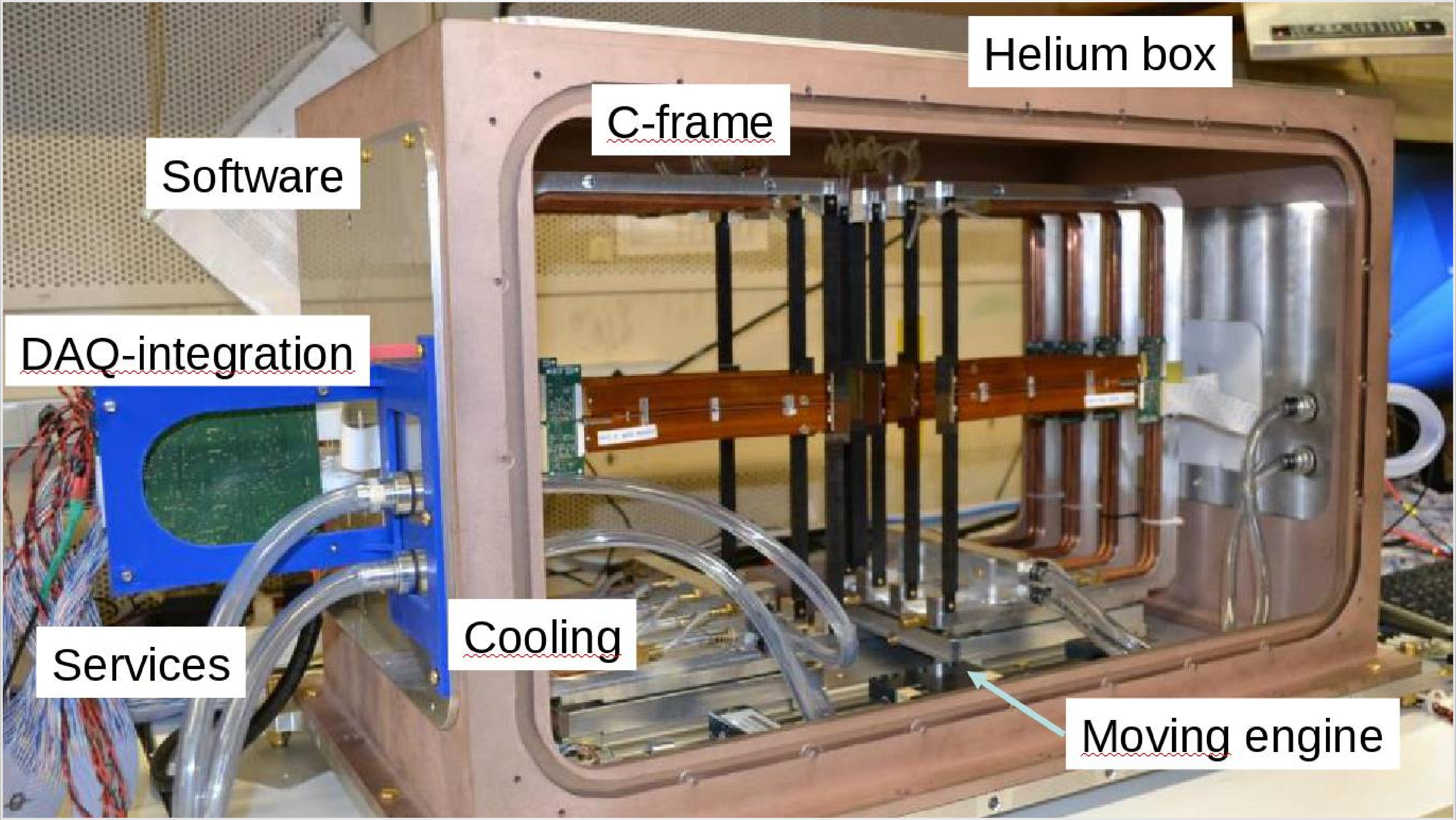


SAVD technology

- Sensors: MIMOSA26
  - Developed for CBM MVD prototype by IPHC Strasbourg
- Read-out: TRB board
  - Developed for CBM MVD prototype by IKF Frankfurt
- Mechanical support: light-weight carbon-fibre ladders
  - Developed for ALICE ITS upgrade by Saint-Petersburg State University
  - <0.3% X_0

Vertex Detecor components

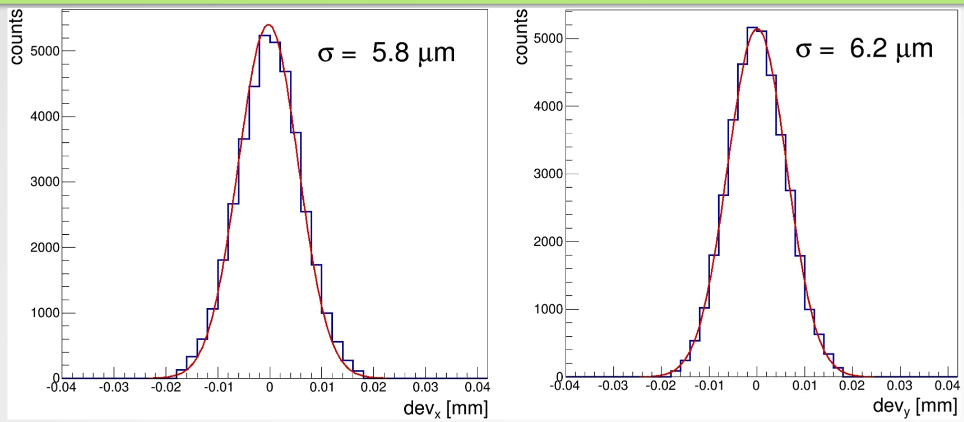
Integration by UJ Krakow

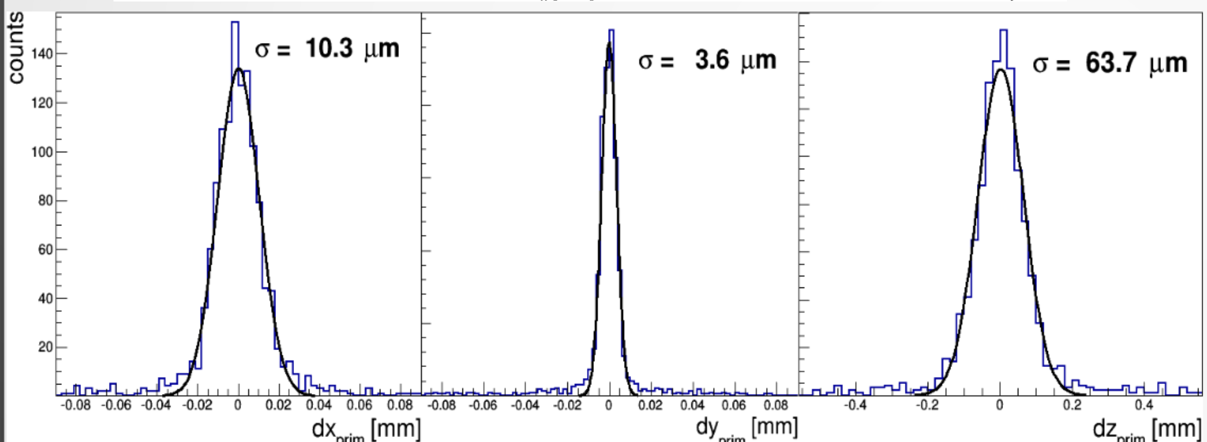


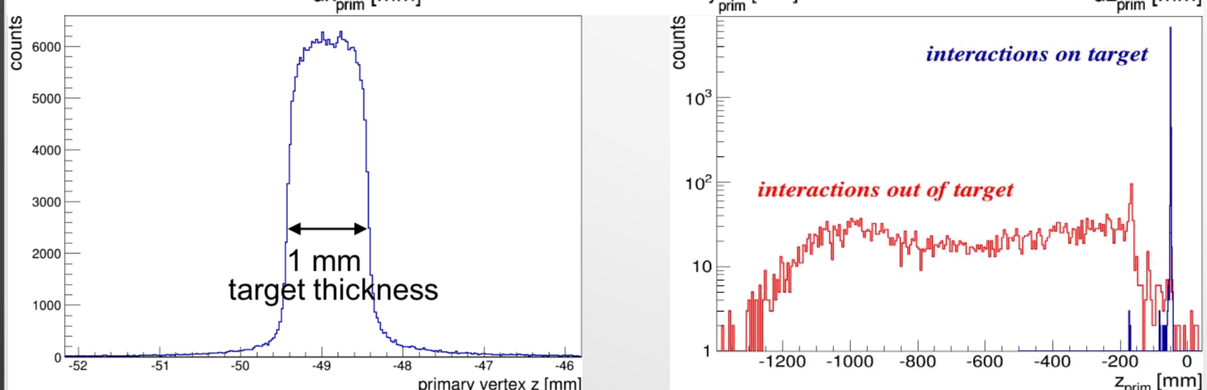
Event reconstruction

- Search for 4-hit tracks
  - Hits from each of 4 sensor layers are fitted with linear
  - Track candidates passing certain cuts are kept
- 4-hit tracks are fitted with parabola
  - Calculate preliminary primary vertex (point of closest approach)
  - Using primary vertex, search for 3-hit tracks
- 3-hit tracks are fitted with parabola
  - Calculate final primary vertex
- Extend TPC tracks to primary vertex
  - Pick up hits in VD along extended TPC tracks using Kalman filter

SAVD performance – PbPb at 150A GeV/c







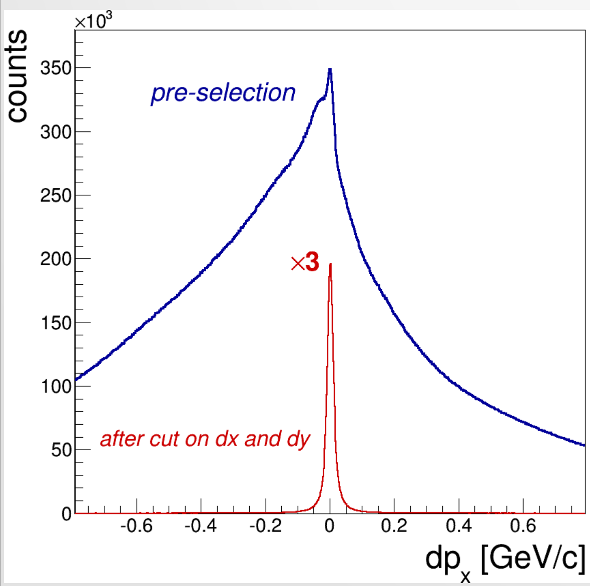
- Sensor position resolution:

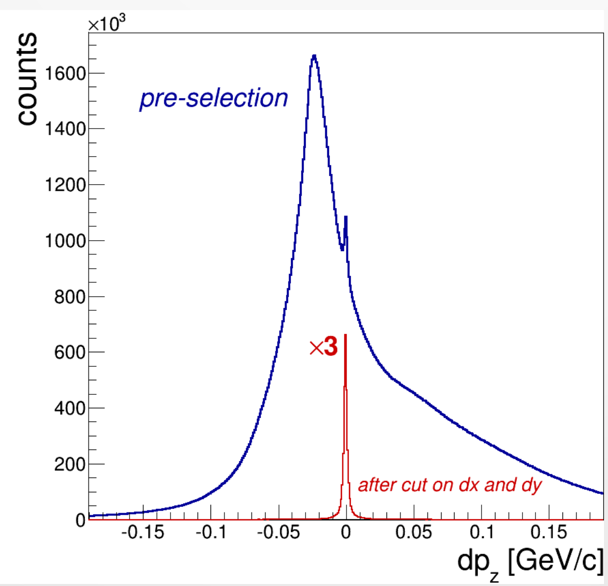
$$\sigma_{x/y} = \sqrt{\frac{2}{3}}\,\sigma_{dev_{x/y}}$$

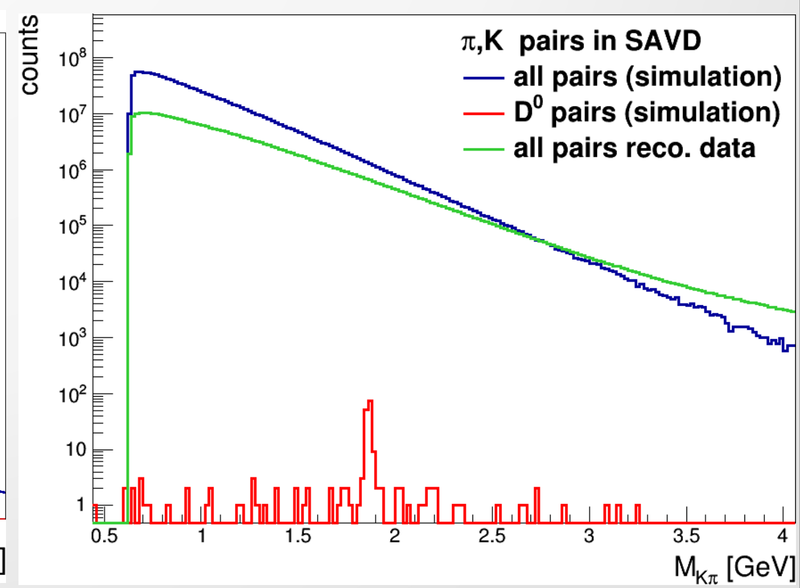
  - About 5µm as expected
- Primary vertex resolution: σ_x=5µm, σ_y=1.8µm, σ_z=30µm
  - Resolution less good in y because of magnetic field
  - Can discriminate in/out-of target events

Matching of tracks to TPCs

- VD tracks must be matched to correct TPC track
  - VD tracks extrapolated to TPC volume using TPC momentum
- Pre-selection: cut on y-slopes
- After further dx, dy cuts: clear correlation peaks for dp_x, dp_y
- VD track obtain momentum, PID from matched TPC track
- Offset from track matching used for callibrating VD—TPC position

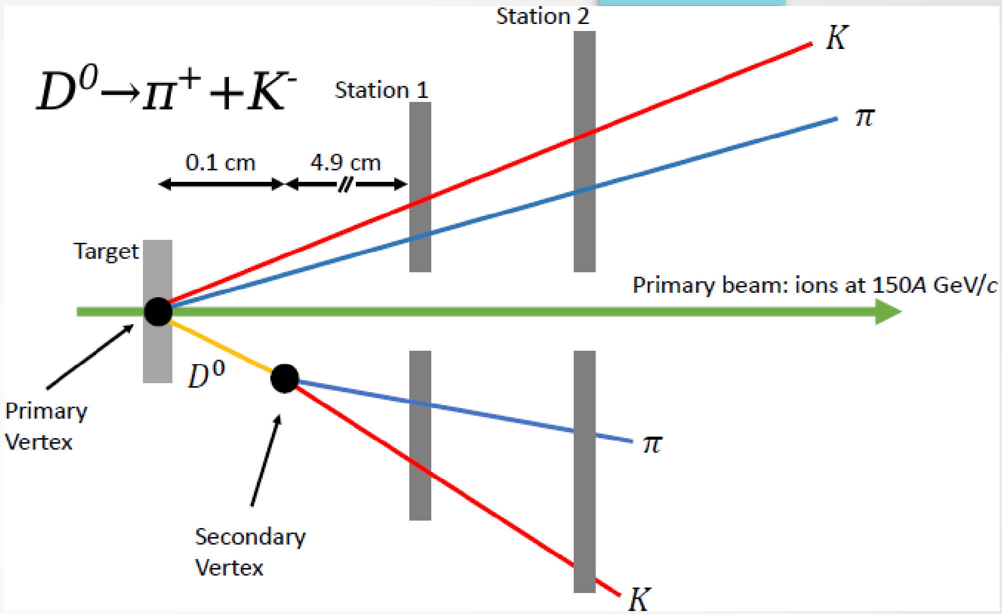






D^0 reconstruction

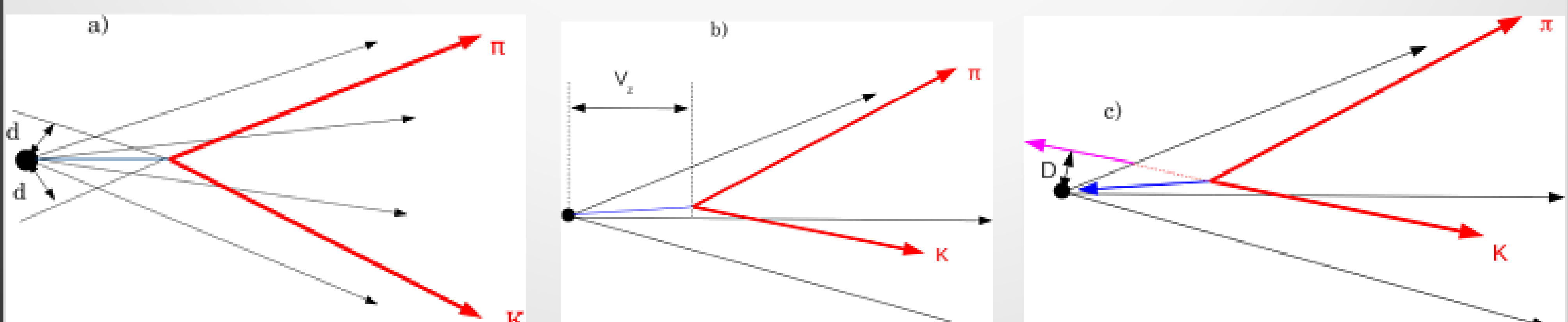
- VD needed to reconstruct primary/ secondary vertices with sufficient resolution
  - cτ(D^0)≃123μm, but with Lorentz boost (βγ≈10) the displacement is about 1mm
  - TPC vertex resolution about 1cm
- VD tracks matched to TPC tracks used
- Each VD track paired with another VD track
  - Assumed to be either kaon or pion
- Cuts applied (next slide)



Meson	Decay channel	$c\tau$	Branching ratio
D^0	$D^0 \rightarrow K^- + \pi^+$	122.9 μm	(3.91±0.05)%
D^0	$D^0 \rightarrow K^- + \pi^+ + \pi^+ + \pi^-$	122.9 μm	(8.14±0.20)%
D^+	$D^+ \rightarrow K^- + \pi^+ + \pi^+$	311.8 μm	(9.2±0.25)%
D_s^+	$D_s^+ \rightarrow K^+ + K^- \; \pi^+$	149.9 μm	(5.50±0.28)%
D^{*+}	$D^{*+} \rightarrow D^0 + \pi^+$	...	(61.9±2.9)%

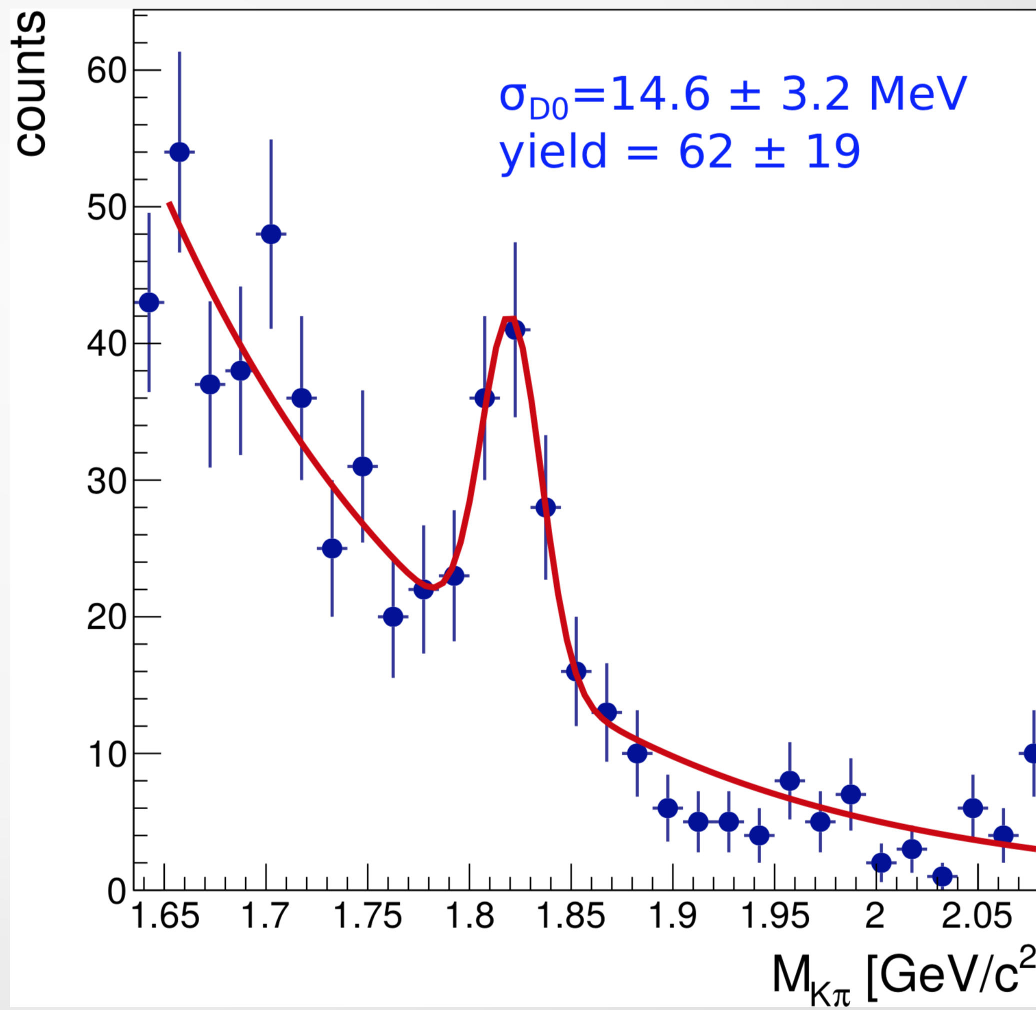
D^0 background selection cuts

- Transverse momentum p_T>0.34GeV/c
- (a) Track impact parameter d>34μm
- (b) Longitudinal distance of D^0 decay to interaction point V_z>475μm
- (c) Impact parameter for D^0 candidate momentum vector D<21μm

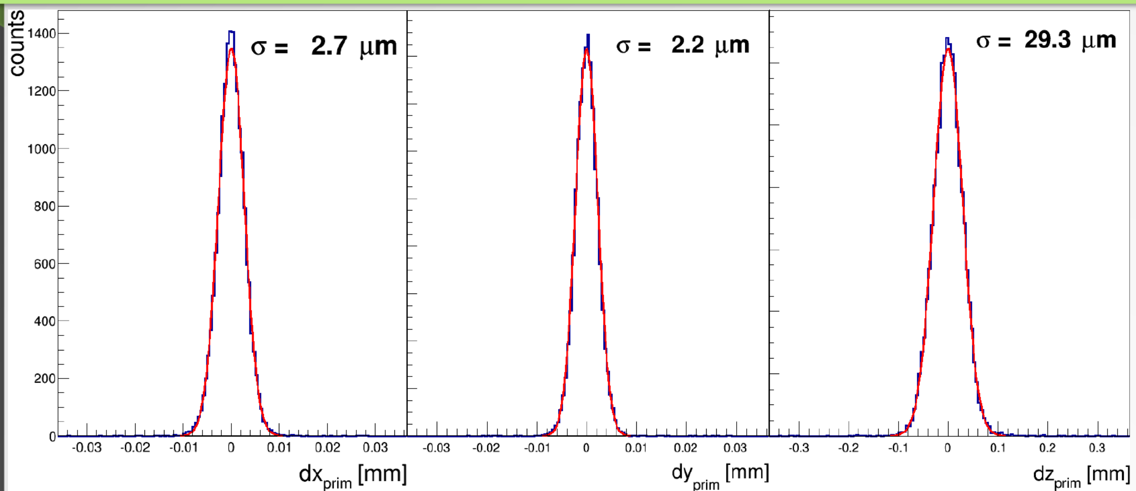


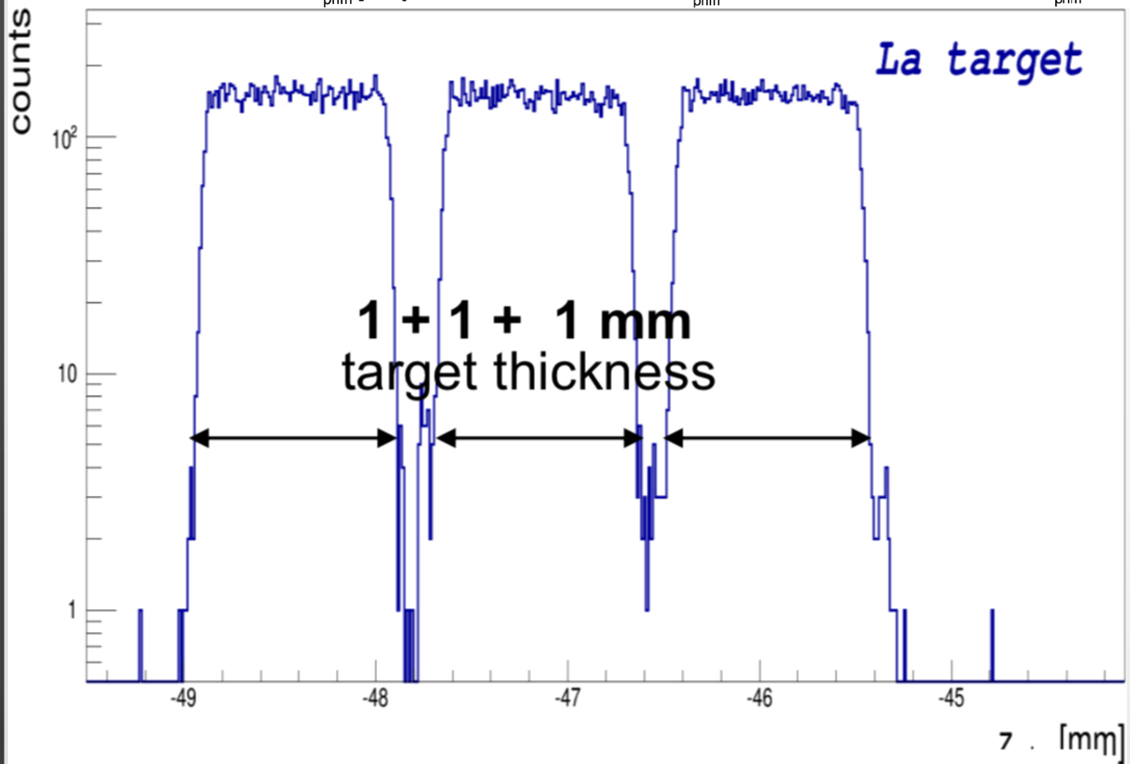
D^0 observation

- Result from about 140k central PbPb at 150A GeV/c events
  - However data was mainly for testing with several uncontrolled settings
  - Errors are only statistical
- HSD simulation gives about 100 D^0 for 200k events
- Not yet with PID selection since TPC drift velocity currently being calibrated
  - Should reduce background by factor 5

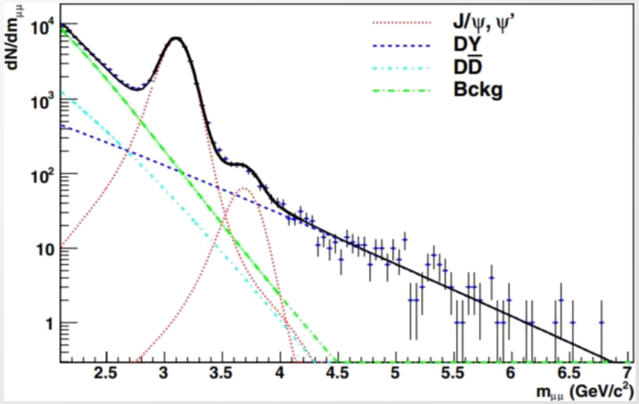


SAVD performance – XeLa at 150*A* GeV/c





- VD setup much better optimised during XeLa data taking than PbPb test
- Primary vertex resolution: σ_x=1.3μm, σ_y=1.0μm, σ_z=15μm
  - Structure of 3 layers of La target visible
- D^0 was measured indirectly by NA60 in InIn (similar size as XeLA) 160*A* GeV/c – VD will provide direct measurement

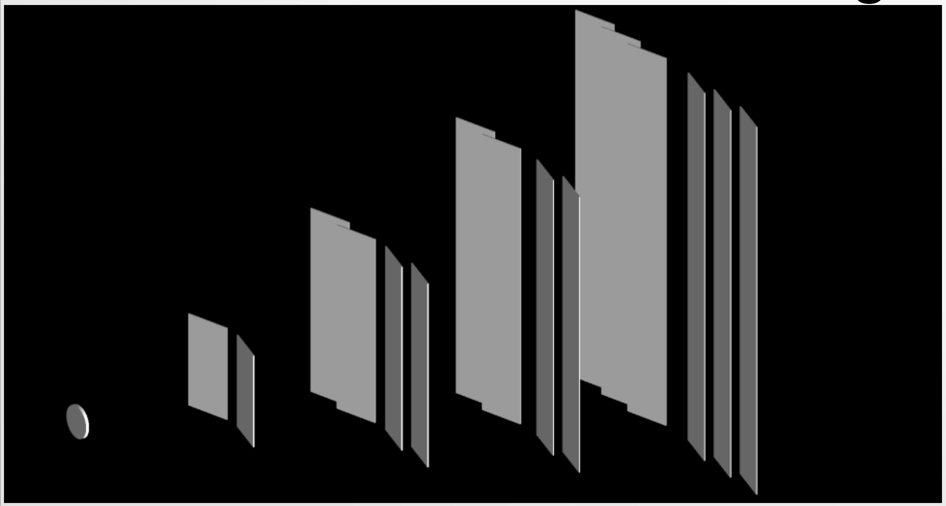


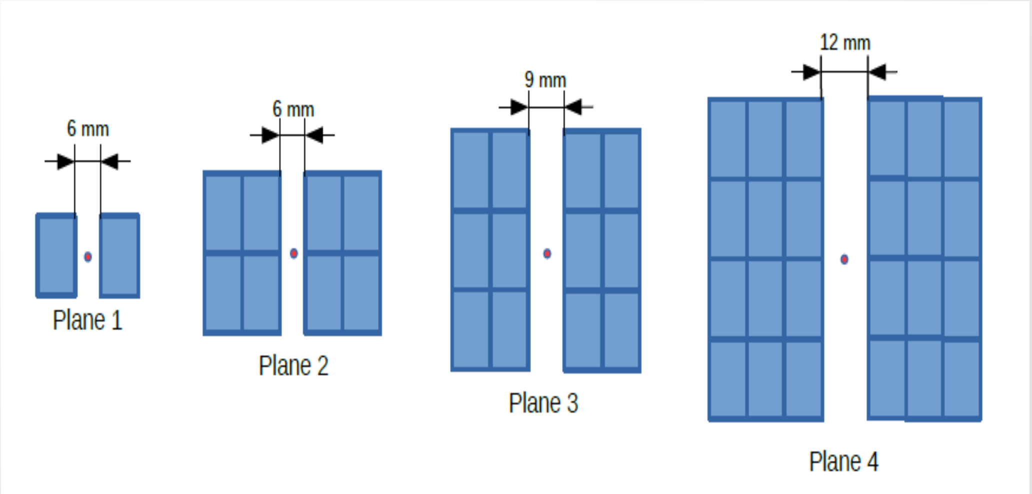
NA61/SHINE physics programme – update

- NA61/SHINE is submitting an addendum for further physics measurements using the NA61/SHINE facility
  - Strong interactions: open charm measurements
  - Cosmic rays: light ion fragmentation with intergalactic matter
  - Neutrino: further reference measurements for T2K, Hyper-K, Dune targets
- Open charm requires significantelly more statistics than current programmes
  - 80 Hz → 1 kHz
  - Also beneficial for other programmes
- An order of magnitude higer data taking rate must be accomodated by all detectors and sub-systems
  - In particular, the TPCs and Projectile-Spectator detectors must be upgraded as well
  - Also much higer radiation dose must be accounted for
  - Next slides will show upgrade of VD to accommodate this

Upgraded VD sensor layout

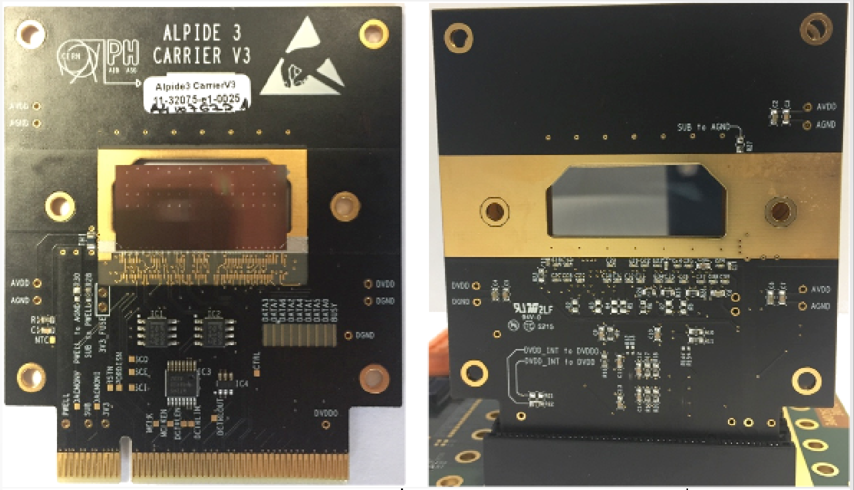
- Detailed Geant simulations were carried out to find optimal cost/performace design
  - Location of VD relative to TPCs, layer location with in VD, number of sensors, etc.
- Settled for design with 46 sensors (16 for SAVD), and 4 layers as in current SAVD
  - Will allow for re-using existing mechanical support





ALPIDE sensor

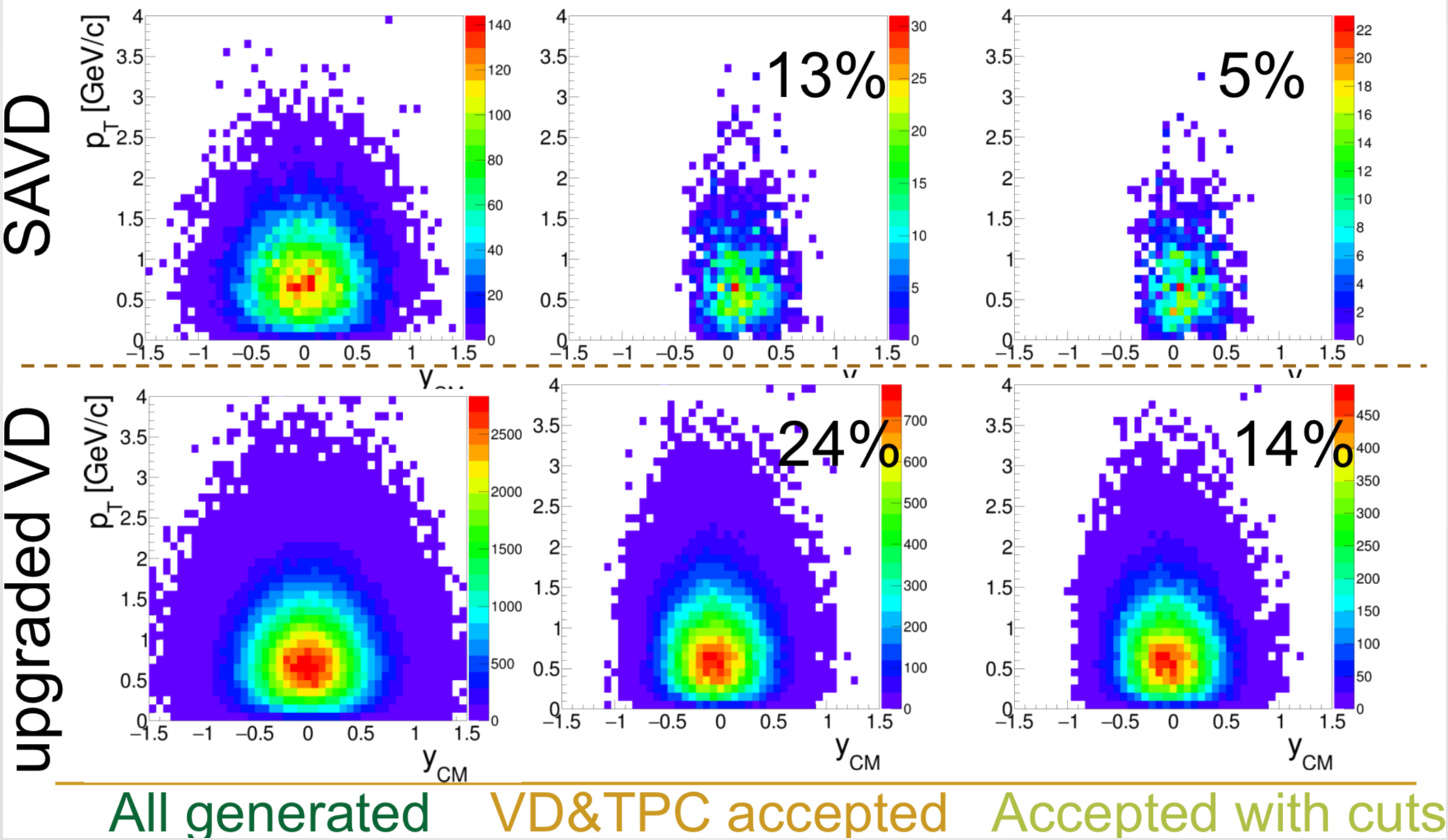
- Main motivation for changing to ALPIDE sensor is faster read-out
  - Additionally, it has 2 orders less noise than Mimosa26
  - Slightly larger
- It was tested last year in NA61/SHINE experiment to verify it can sustain required radiation doses
- Main down-side is less spatial resolution, but simulations show it is sufficient



	MIMOSA-26AHR	ALPIDE
Sensor thickness (μm)	50	50
Spatial resolution (μm)	3.5	5
Dimensions (mm^2)	10.6×21.2	13.8×30
Power density (mW/cm^2)	40	40
Time resolution (μs)	115.2	10
Detection efficiency (%)	>99	>99
Dark hit occupancy	$\lesssim 10^{-4}$	$\lesssim 10^{-6}$

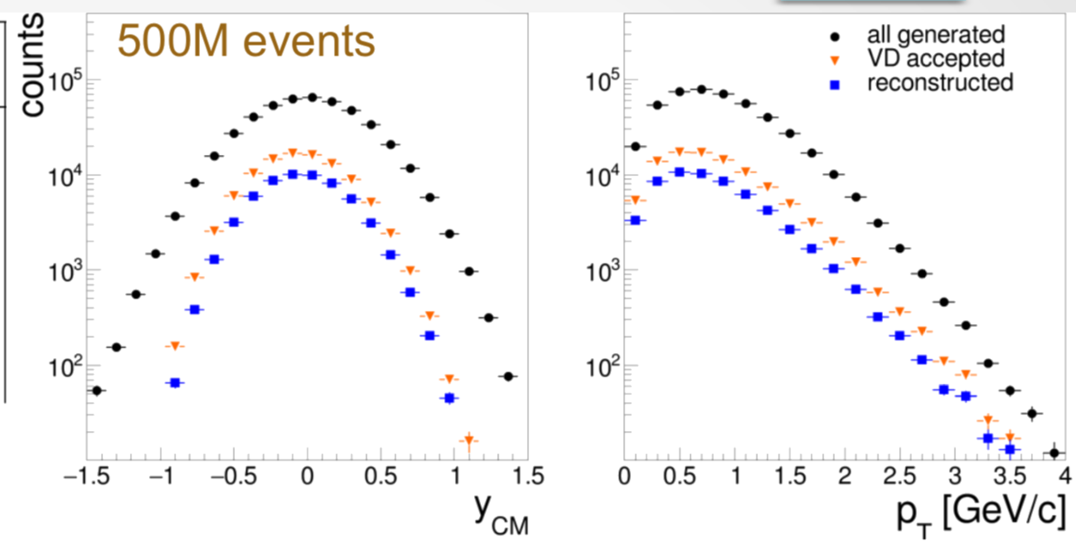
Comparison (AMPT) SAVD-LAVD

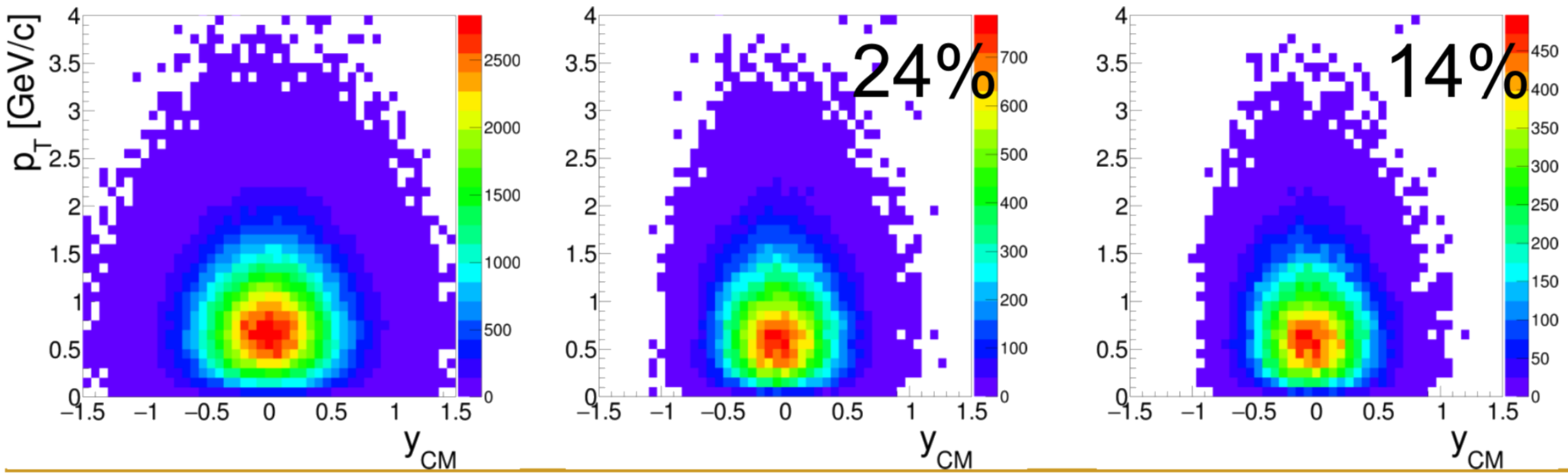
Increasing the VD acceptance: $32 cm^2 \rightarrow 190 cm^2$



Anticipated results (AMPT) – D^0 & $\overline{D}^0$

Meson	Decay channel
D^0	$D^0 \rightarrow K^- + \pi^+$
D^0	$D^0 \rightarrow K^- + \pi^+ + \pi^+ + \pi^-$
D^+	$D^+ \rightarrow K^- + \pi^+ + \pi^+$
D_s^+	$D_s^+ \rightarrow K^+ + K^- \pi^+$
D^{*+}	$D^{*+} \rightarrow D^0 + \pi^+$

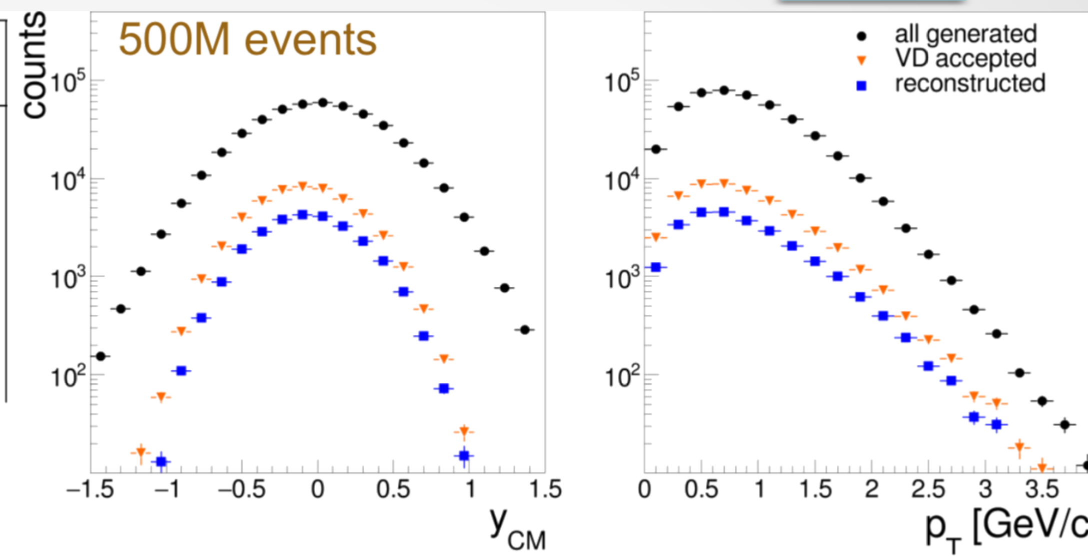


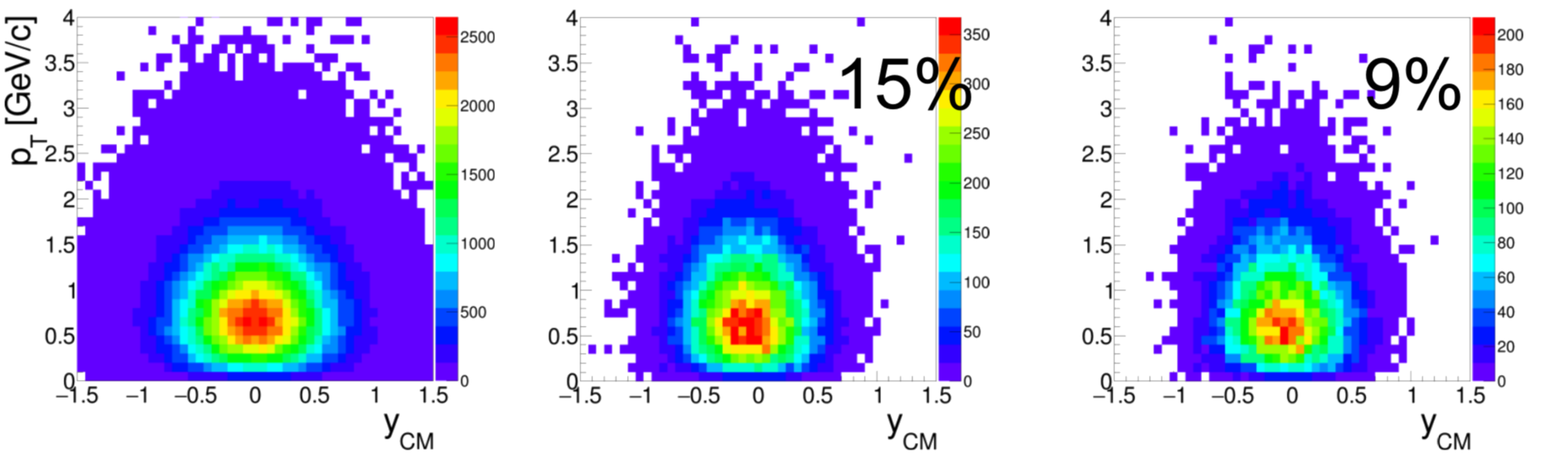


All generated VD&TPC accepted Accepted with cuts

Anticipated results (AMPT) – D^+ & D^-

Meson	Decay channel
D^0	$D^0 \rightarrow K^- + \pi^+$
D^0	$D^0 \rightarrow K^- + \pi^+ + \pi^+ + \pi^-$
D^+	$D^+ \rightarrow K^- + \pi^+ + \pi^+$
D_s^+	$D_s^+ \rightarrow K^+ + K^- \ \pi^+$
D^{*+}	$D^{*+} \rightarrow D^0 + \pi^+$





All generated VD&TPC accepted Accepted with cuts

Upgraded VD data taking plans

- The upgraded VD is planing to start data taking 2022
  - (Possibility of early start already 2021 being discussed)
- Topics:
  - Charm yield versus centrality
  - Charm yield as signal of deconfinement
  - Open charm production mechanism (dynamical versus statistical models)

Year	Reaction	Events	$D^0+\overline{D}^0$	$D^+ + D^-$
2022	Pb+Pb 150A GeV/c	250M	38k	23k
2023	Pb+Pb 150A GeV/c	250M	38k	23k
2024	Pb+Pb 40A GeV/c	250M	3.6k	2.1k

	0-10%	10-20%	20-30%	30-60%	60-90%
№ $D^0+\overline{D}^0$	31k	20k	11k	13k	1.3K
№ $D^+ + D^-$	19k	12k	7k	8k	0.8K
$\langle W \rangle$	327	226	156	70	11

500M minimum bias events in future VD.

Summary & outlook

- Small-acceptance vertex detector for NA61/SHINE experiment constructed
  - Open charm peak probably observed
  - Will take more Pb+Pb data later this year – may be sufficient for preliminary results
- Upgraded vertex detector with larger acceptance and faster readout being prepared
  - Will allow to disentangle predictions from different theoretical models
  - Allow for measuring charm yields versus centrality/spectra
  - Start of data taking 2021/2022

Thank you for your attention!