Heavy quark production at low $\sqrt{s}$ as a probe of high μ_B matter

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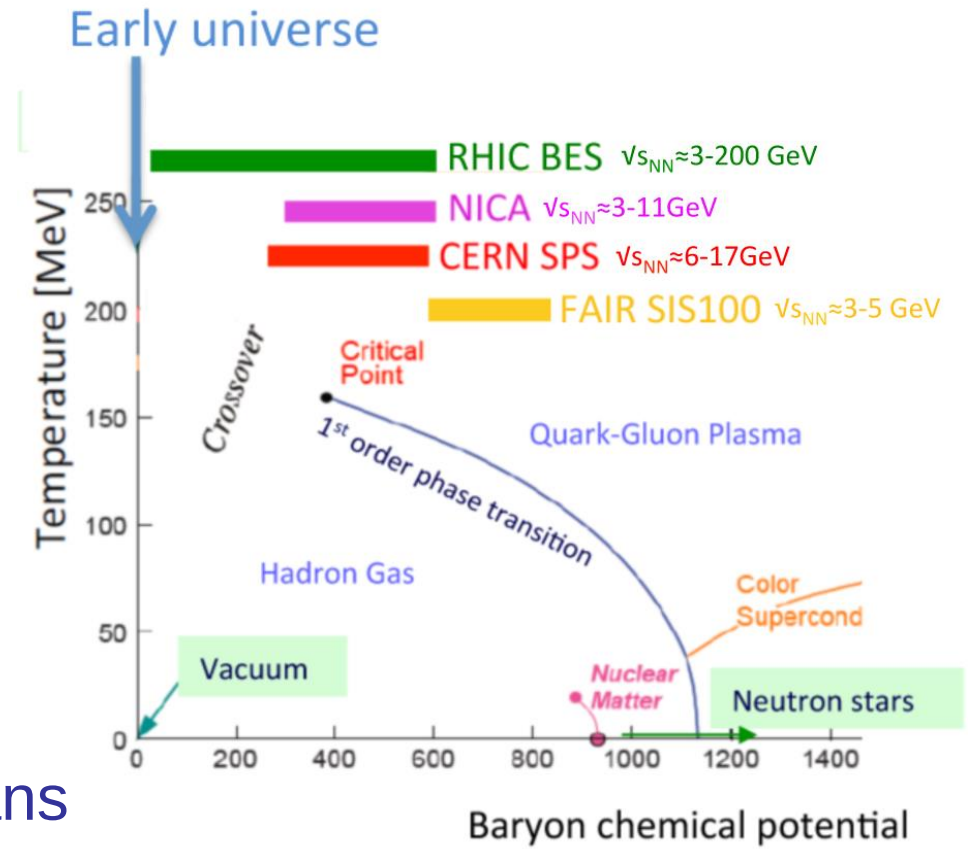
Heavy-ions: the low √s frontier

- **Goal**: explore the QCD phase diagram at large μ_B

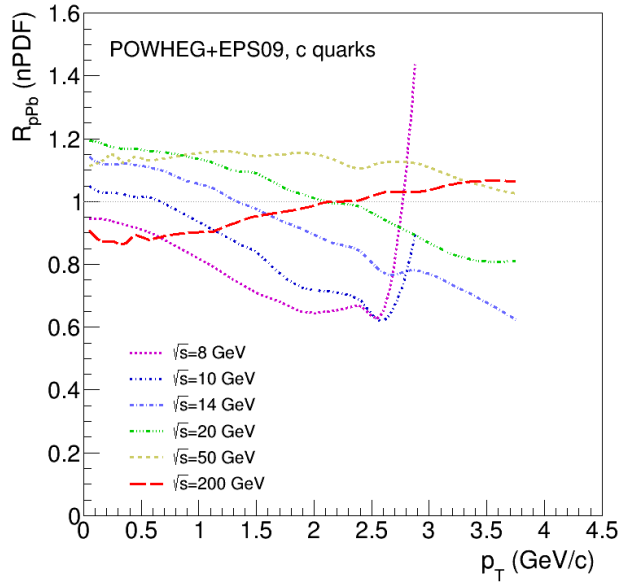
- Main questions:
  - ⇨ Presence of a **critical point**?
  - ⇨ First **order phase transition** at large μ_B?
  - ⇨ **Chiral symmetry** restoration?
  - ⇨ Onset of **deconfinement**
  - ⇨ Properties of the **QGP at large μ_B**

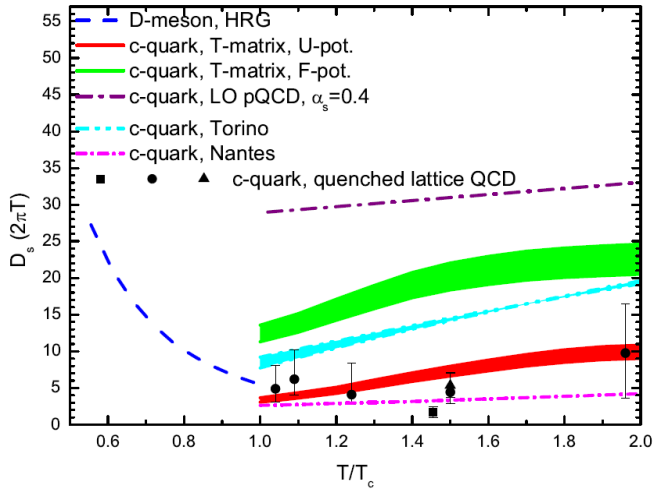
- Being studied at RHIC with Beam Energy Scans and at the SPS by NA61/SHINE experiment
  - ⇨ Up to now results mostly on soft hadronic processes



Charm at low √s: what can we learn?

- Almost unexplored energy domain
  - ⇨ No results available below top SPS energy
- Charm and charmonium production in p-A collisions
  - ⇨ Sensitive to **nuclear PDFs**
    - ✓ Q^2~10–40 GeV^2 and $0.1<x_{Bj}<0.3$ (anti-shadowing and EMC)
  - ⇨ Possible sensitivity to **intrinsic charm**
- Charm and charmonium yield and v_2 in A-A collisions
  - ⇨ **Onset of deconfinement**
  - ⇨ Constrain estimates of the **charm diffusion coefficient**
  - ⇨ Charm quark **thermalization** in a short-lived QGP
  - ⇨ Insight into **hadronization mechanism**
    - ✓ Enhanced D_s/D and Λ_c/D ratios in case of quark recombination
  - ⇨ Charm cross section sensitive to **chiral symmetry restoration**:
    - ✓ Enhancement of charm production at chiral restoration where the threshold for production of a $D\bar{D}$ pair may be reduced

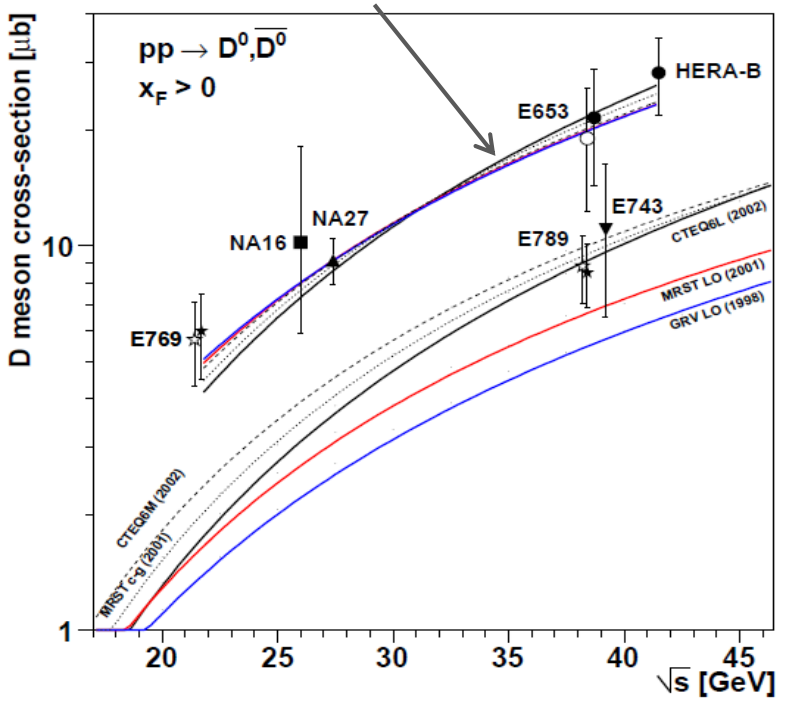




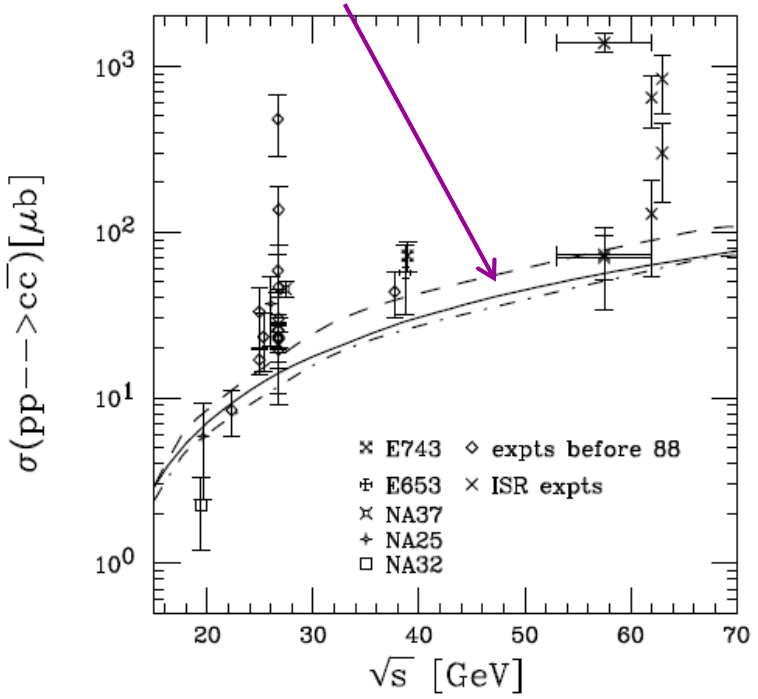
Charm cross section in p-A

- Unexplored energy domain
- Comparison of existing data to PYTHIA event generator and pQCD calculations

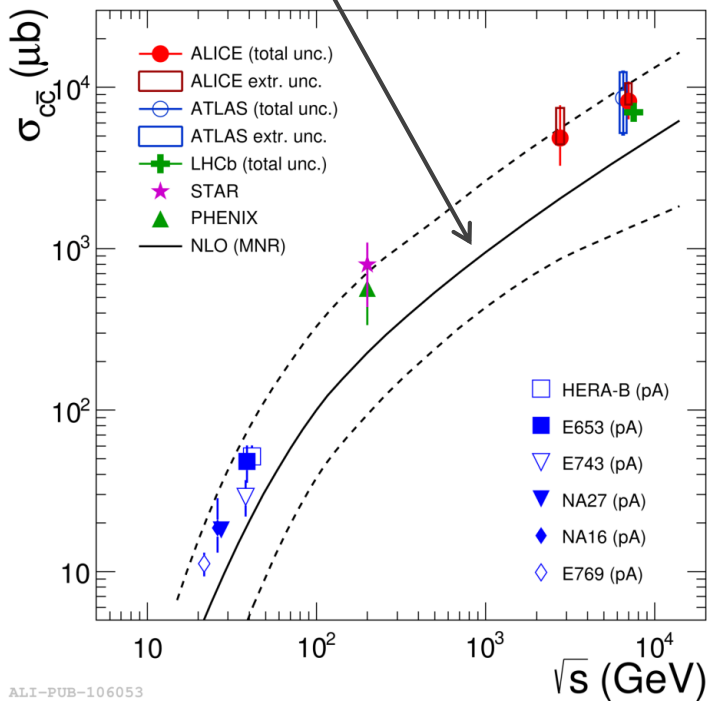
PYTHIA LO cross sections scaled with appropriate K-factor



MNR, m_c=1.2 GeV , μ=2m_c



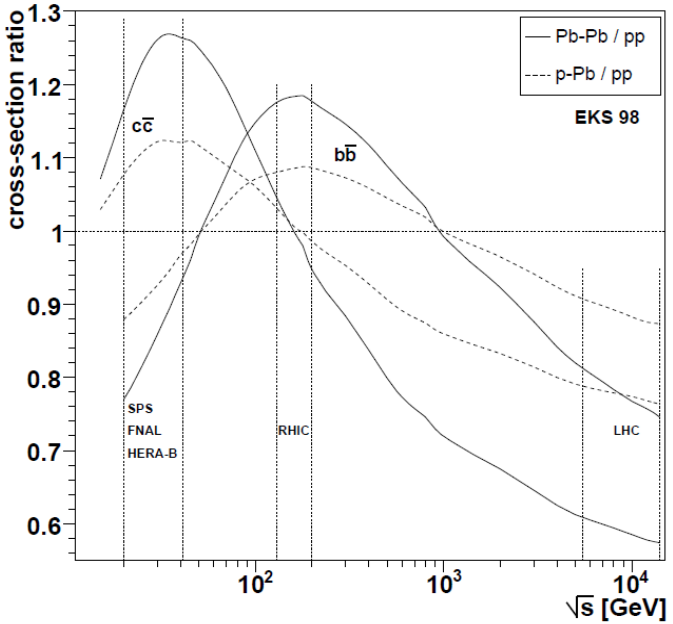
MNR, m_c=1.5 GeV, μ_F=μ_R=m_T

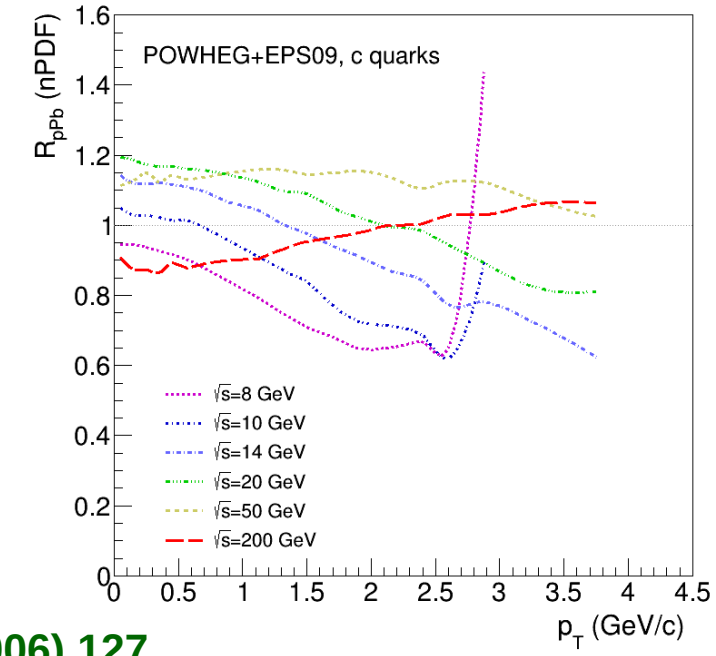


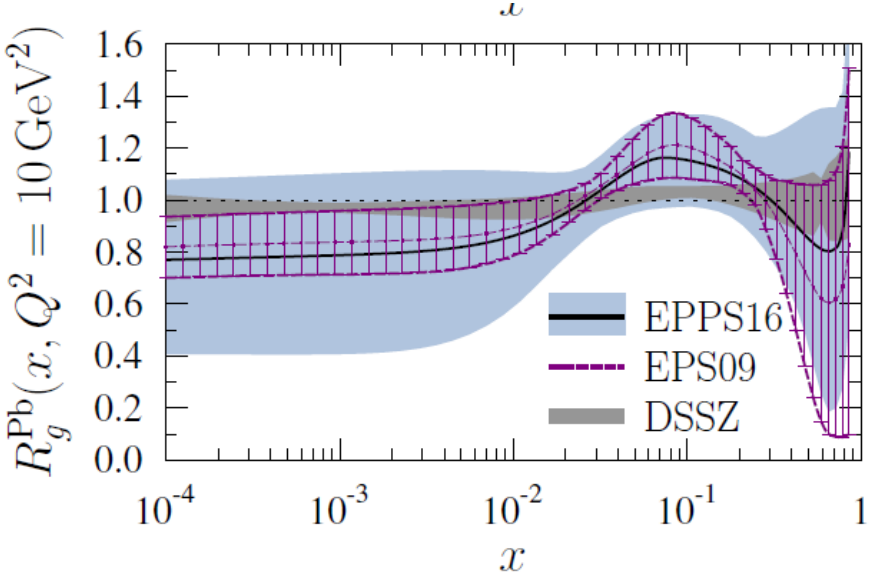
📖 Lourenco, Wohri, Phys.Rept.433 (2006) 127 📖 Vogt, Int.J.Mod.Phys.E12 (2003) 211 📖 ALICE, PRC94 (2016) 054908

Nuclear PDFs

- Sensitivity to **nuclear PDFs in p-A** collisions
  - ⇨ Probe EMC and anti-shadowing for $\sqrt{s_{NN}}$ ~ 10-20 GeV
  - ⇨ Perform measurements with various nuclear targets to access the A-dependence of nPDF
- p-A collisions at SPS offer a unique opportunity to investigate the large x_{Bj} region
  - ⇨ $0.1<x_{Bj}<0.3$ at Q^2~10-40 GeV^2





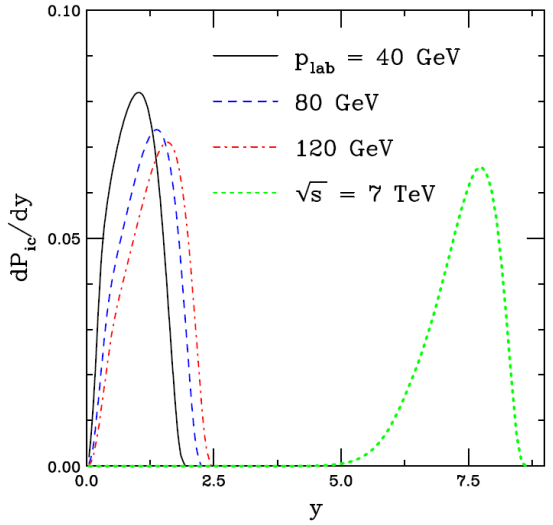


📖 Lourenco, Wohri, Phys.Rept.433 (2006) 127

📖 Eskola et al. , EPJ C77 (2017) 13

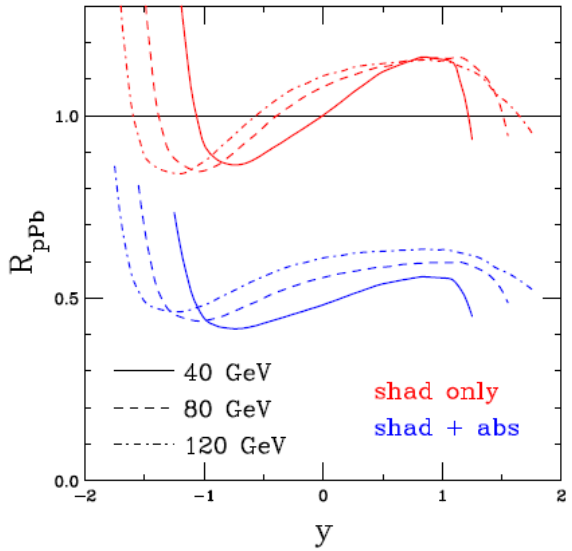
Intrinsic charm?

- Existence of a nonperturbative intrinsic heavy quark component in the nucleon wave function is a rigorous QCD prediction
  - ⇨ Intrinsic charm: e.g. 5-quark Fock state $|uudc\bar{c}\rangle$
- Unambiguous experimental confirmation still missing
- Intrinsic charm (IC) contribution dominant at large x_F and high p_T
  - ⇨ At colliders, large x_F pushed to very high rapidity -> difficult detection
  - ⇨ Low energy, fixed-target setups, may be better suited for discovery

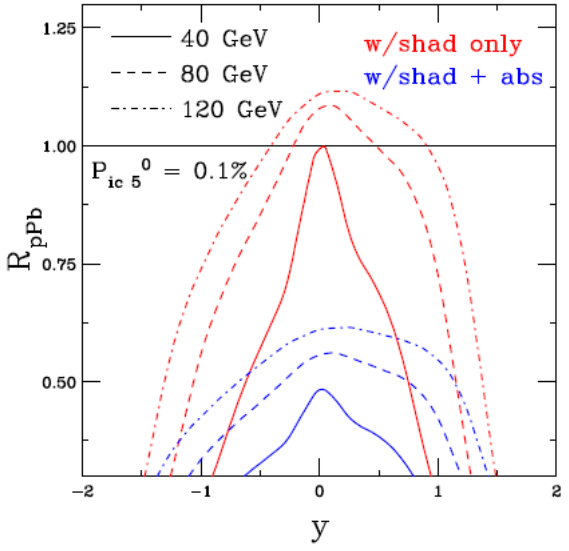


- J/ψ R_{pPb} at SPS energies expected to be overwhelmed by intrinsic charm, even at midrapidity with P_{ic}=0.1%

📖 **R. Vogt, PRC 103 (2021) 035204**
📖 **R. Vogt, preliminary studies**



w/o intrinsic charm



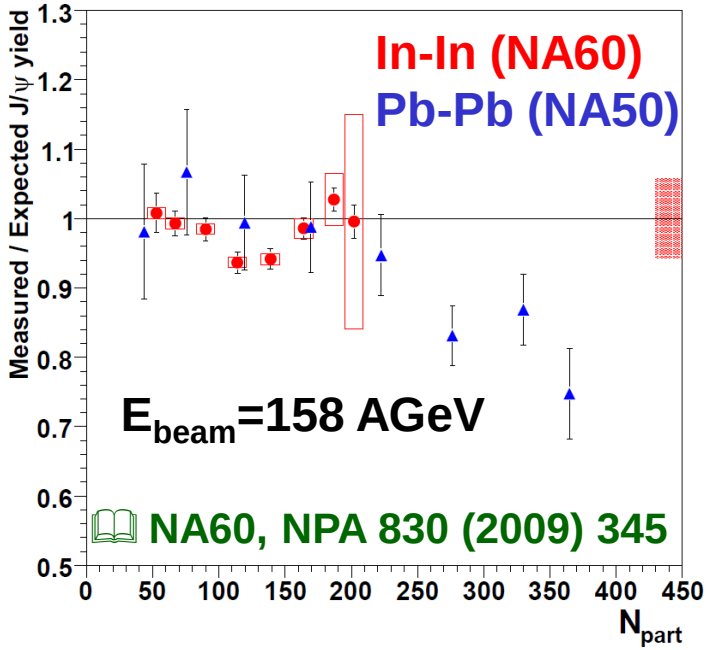
with intrinsic charm (P_{IC}=0.1%)

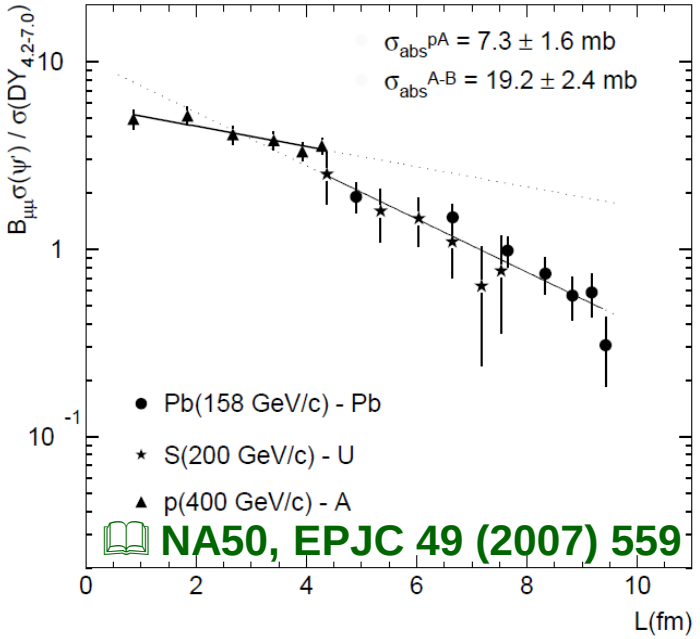
Charmonium yield in Pb-Pb collisions

- **J/ψ**: ~30% suppression in central Pb-Pb collisions at top SPS energy relative to expectation from cold nuclear matter effects
  - ⇨ Qualitatively consistent with melting of ψ(2S) and χ_c in the QGP
  - ⇨ Quarkonium dissociation in the QGP due to colour screening of the $c\bar{c}$ potential

📖 **Matsui, Satz, PLB178 (1986) 416**

- **ψ(2S)**: strong suppression also in peripheral Pb-Pb
  - ⇨ Sensitivity to dissociation in the hadronic phase?

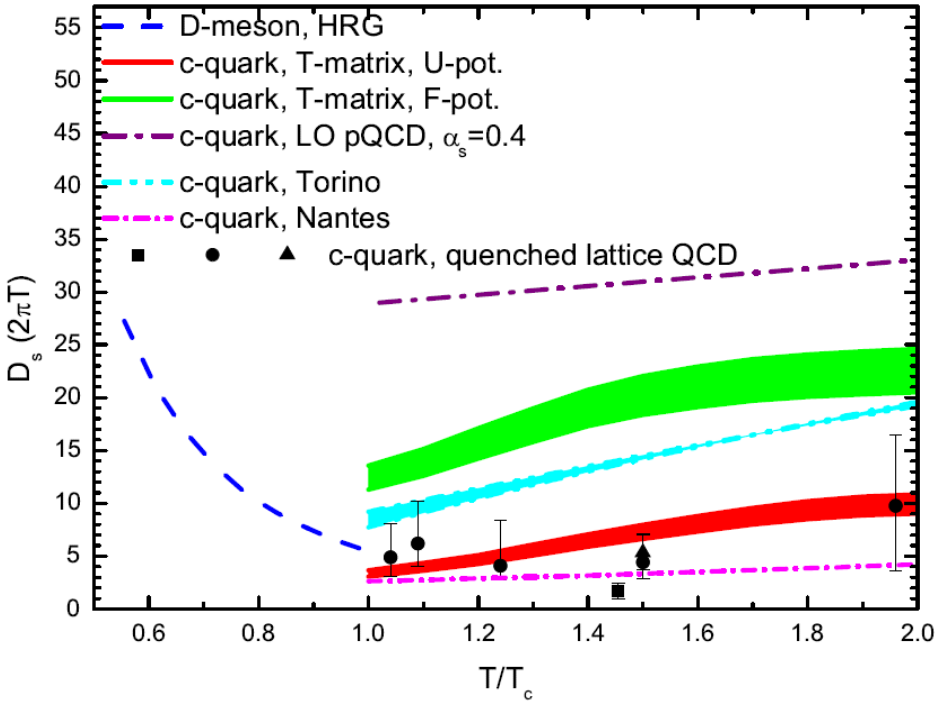




- Next goals:
  - ⇨ Improve accuracy at top SPS energy
    - ✓ Current results limited by DY statistics
  - ⇨ Extend the measurements to lower SPS energies and look for the **onset of the suppression**
  - ⇨ Correlate J/ψ suppression pattern with temperature from thermal dimuons
  - ⇨ Extend measurements to **other quarkonium states**: ψ(2S), χ_c

Open charm in Pb-Pb: dN/dp_T and R_{AA}

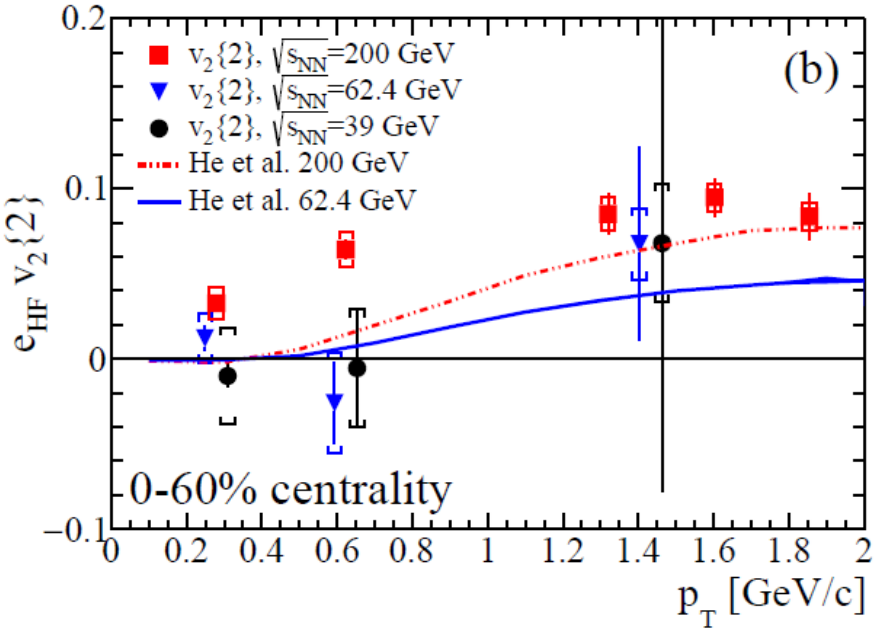
- Insight into **QGP transport properties**
  - ⇨ Charm diffusion coefficient larger in the hadronic phase than in the QGP around T_C
  - ⇨ Hadronic phase represents a large part of the collision evolution at SPS energies
    - ✓ Sensitivity to hadronic interactions
    - ✓ Test models which predict strongest in-medium interactions in the vicinity of the quark-hadron transition
  - ⇨ Measurement also important for precision estimates of diffusion coefficients at the LHC



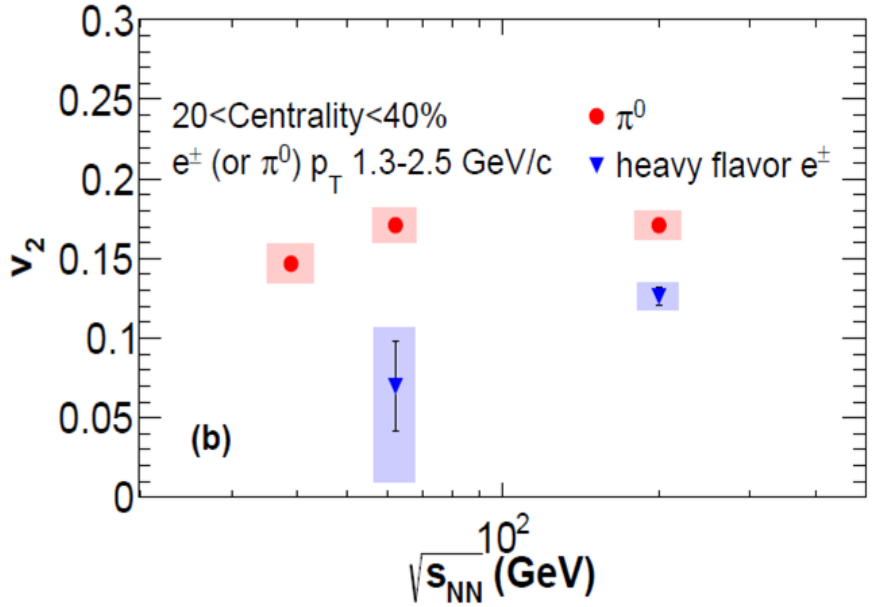
📖 **Prino, Rapp, JPG43 (2016) 093002**

Charm in Pb-Pb: elliptic flow

- Study **charm thermalization** (hydrodynamization…) at low $\sqrt{s_{NN}}$
  - ⇨ Current measurements of HF-decay electron v_2 at $\sqrt{s_{NN}}$=39 and 62 GeV/c from RHIC BES show:
    - ✓ Smaller v_2 than at $\sqrt{s}$=200 GeV
    - ✓ Not conclusive on v_2>0



📖 STAR, PRC 95 (2017) 034907

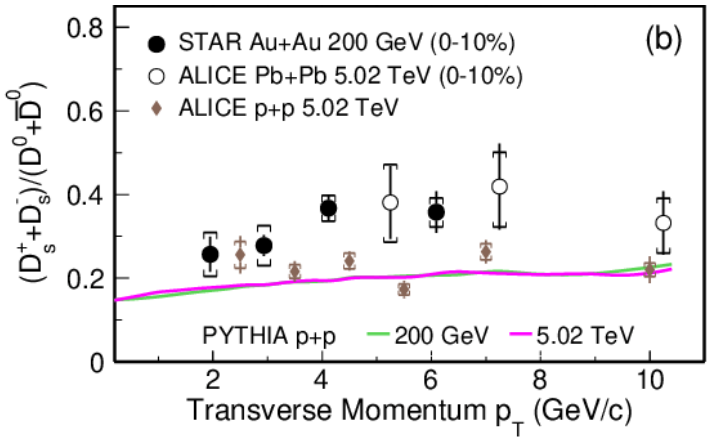


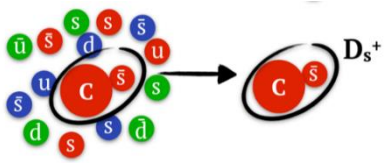
📖 PHENIX, PRC 91 (2015) 044907

Open charm hadrochemistry

- Yield of different charm hadron species to get insight into **hadronization mechanism**

- **Strange/non-strange** meson ratio (D_s/D):
  - ⇨ D_s/D enhancement expected in A-A collisions due to hadronisation via **recombination** in the strangeness rich QGP
  - ⇨ Complement studies of strangeness production by NA49 and NA61

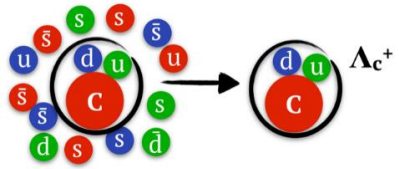


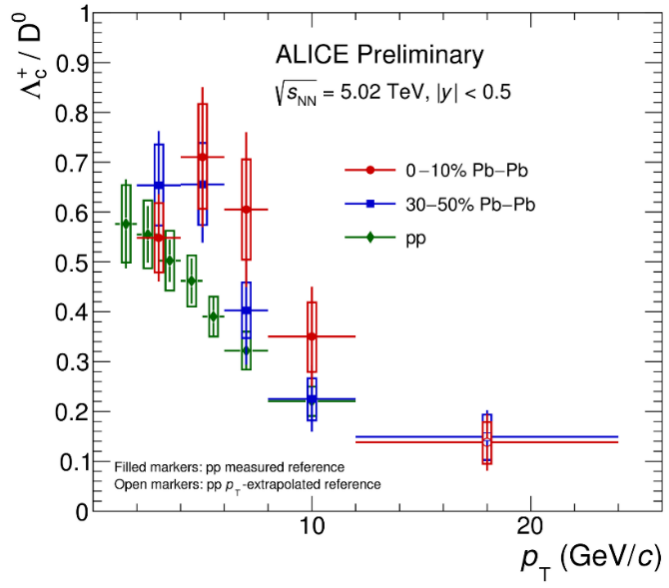


📖 **STAR, PRL 127 (2021) 092301**

📖 **ALICE, arXiv:2110.10006**

- **Baryon/meson** ratios (Λ_c/D):
  - ⇨ Expected to be enhanced in A-A in case of hadronisation via coalescence
  - ⇨ Interesting also in p-A since Λ_c/D^0 in pp (p-Pb) at LHC is higher than in e^+e^-





Charm cross section in Pb-Pb

- Total charm cross section in A-A collisions
  - ⇨ Measured so far by NA60 in In-In collisions from intermediate-mass dimuons with 20% precision
    📖 **NA60, EPJ C59 (2009) 607**
  - ⇨ Upper limit from NA49 measurements of D^0 mesons
    📖 **NA49, PRC73 (2006) 034910**

- Precise measurement requires to reconstruct all meson and baryon ground states (D^0, D^+, D_s^+ and Λ_c^+ and their antiparticles)

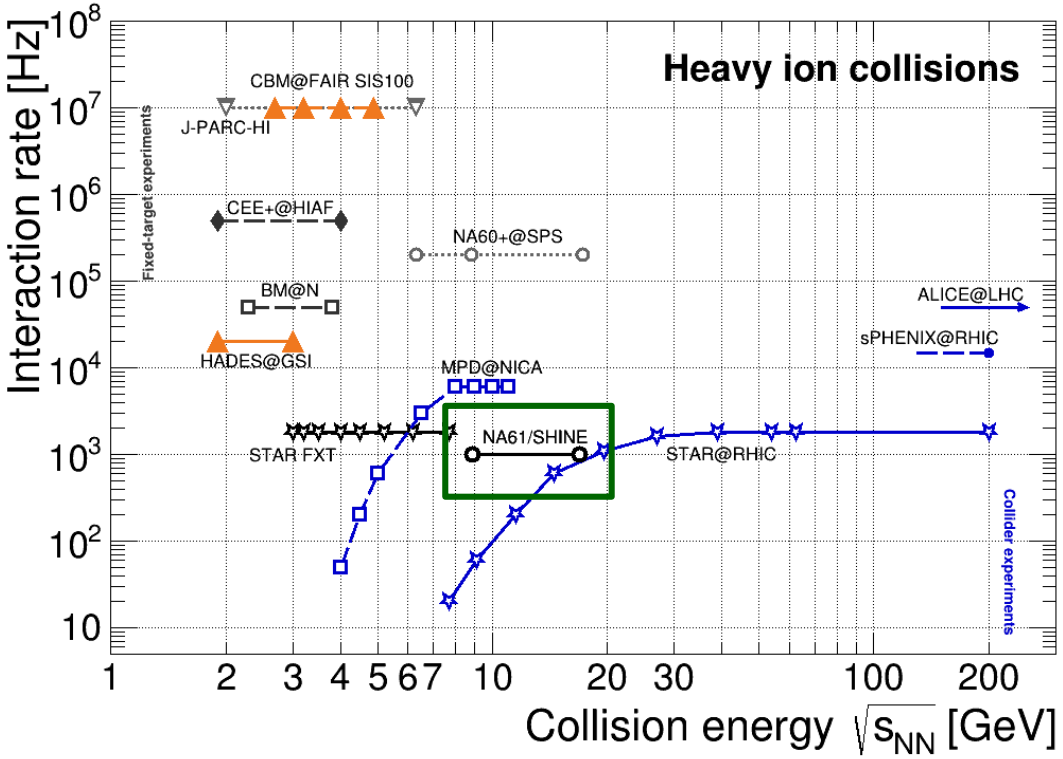
- Charm cross section **directly sensitive to chiral symmetry restoration**:
  - ⇨ Enhancement of charm production at chiral restoration where the threshold for production of a $D\bar{D}$ pair may be reduced
    📖 **Friman et al., Lect. Notes Phys. 814 (2011), 1**

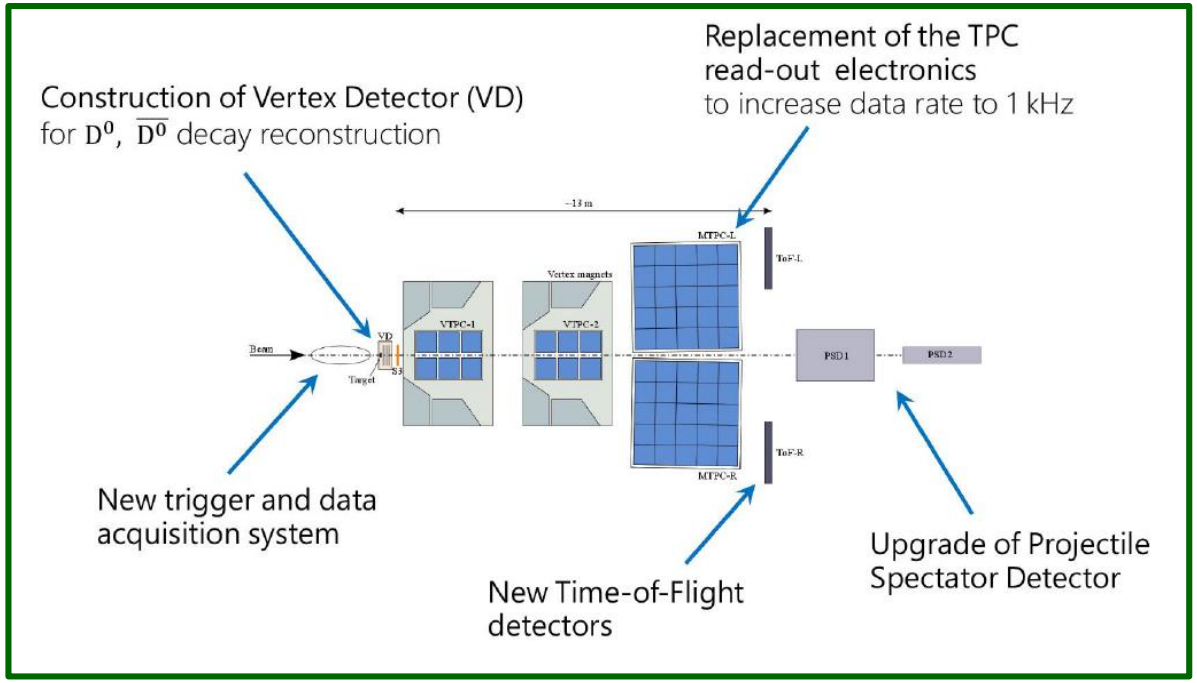
- Charm cross section **ideal reference for charmonia**

Prospects for measuring charm and charmonium at low $\sqrt{s_{NN}}$

Charm @ SPS: NA61/SHINE

- Data taking from 2022 with new vertex detector and other upgrades
- First systematic study of D^0 and D^+ yields vs collision energy and centrality

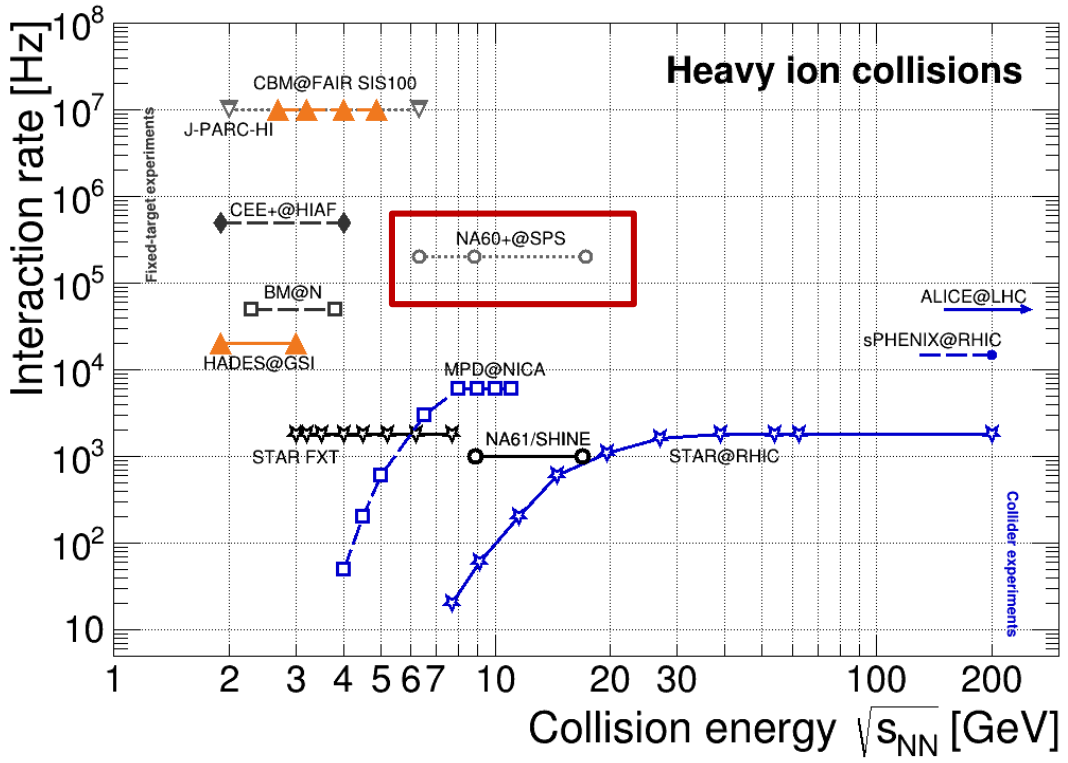




Year	Beam	#days	#events	#(D^0 + $\overline{D^0}$)	#(D^+ + D^-)
2022	Pb at 150A GeV/c	42	250M	38k	23k
2023	Pb at 150A GeV/c	42	250M	38k	23k
2024	Pb at 40A GeV/c	42	250M	3.6k	2.1k

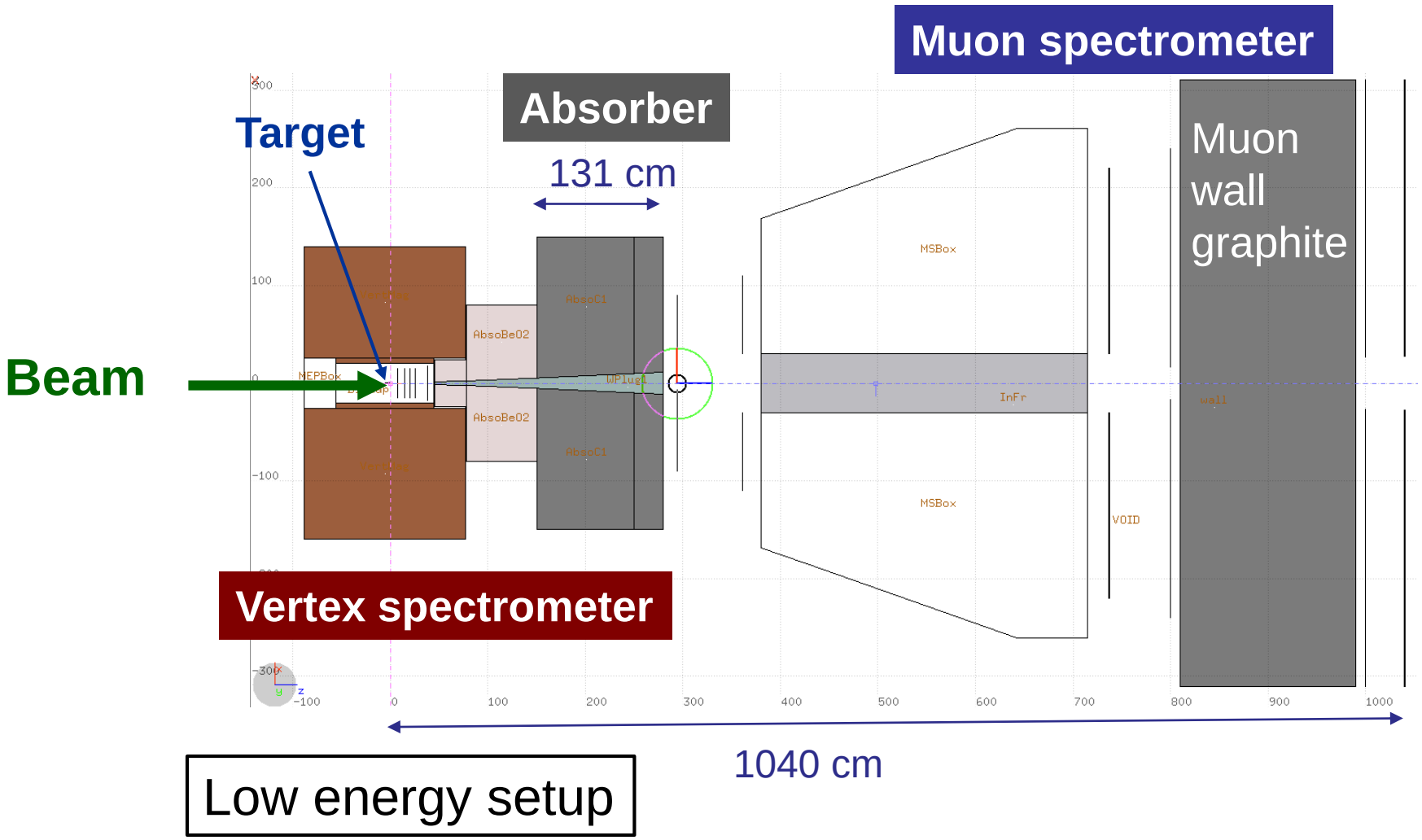
Charm and charmonium @ SPS: NA60+

- NA60+ proposed experiment at CERN
- Beam energy scan (BES) at the CERN SPS in the interval $\sqrt{s_{NN}}$≈6-17 GeV
- **Goal**: study of hard and electromagnetic processes at CERN-SPS energies and investigation of the high-μ_B region of the QCD phase diagram



- **Hard** processes:
  - ⇨ Probe the Quark-Gluon Plasma and study its transport properties
- **Electromagnetic** processes
  - ⇨ Information on the temperature of the system (QGP and/or hadronic)
  - ⇨ Information on the nature of the phase transition
  - ⇨ Insight into the approach to chiral symmetry restoration

NA60+ detector concept



Low energy setup

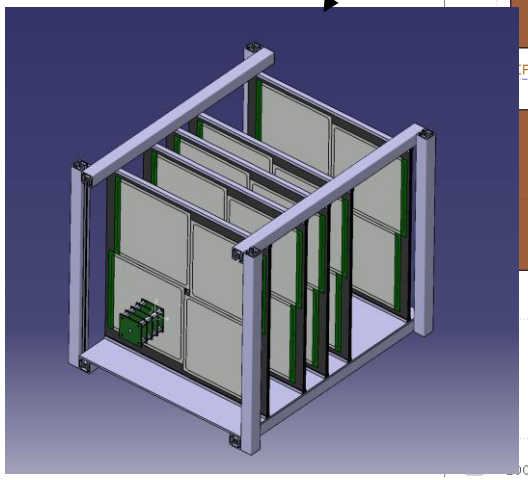
- **Muon spectrometer** to measure dimuons downstream of absorber
  - ⇨ Muon spectrometer length needs to be varied, to cover mid-rapidity at different $\sqrt{s}$
- **Vertex spectrometer** for precise tracking close to the interaction point

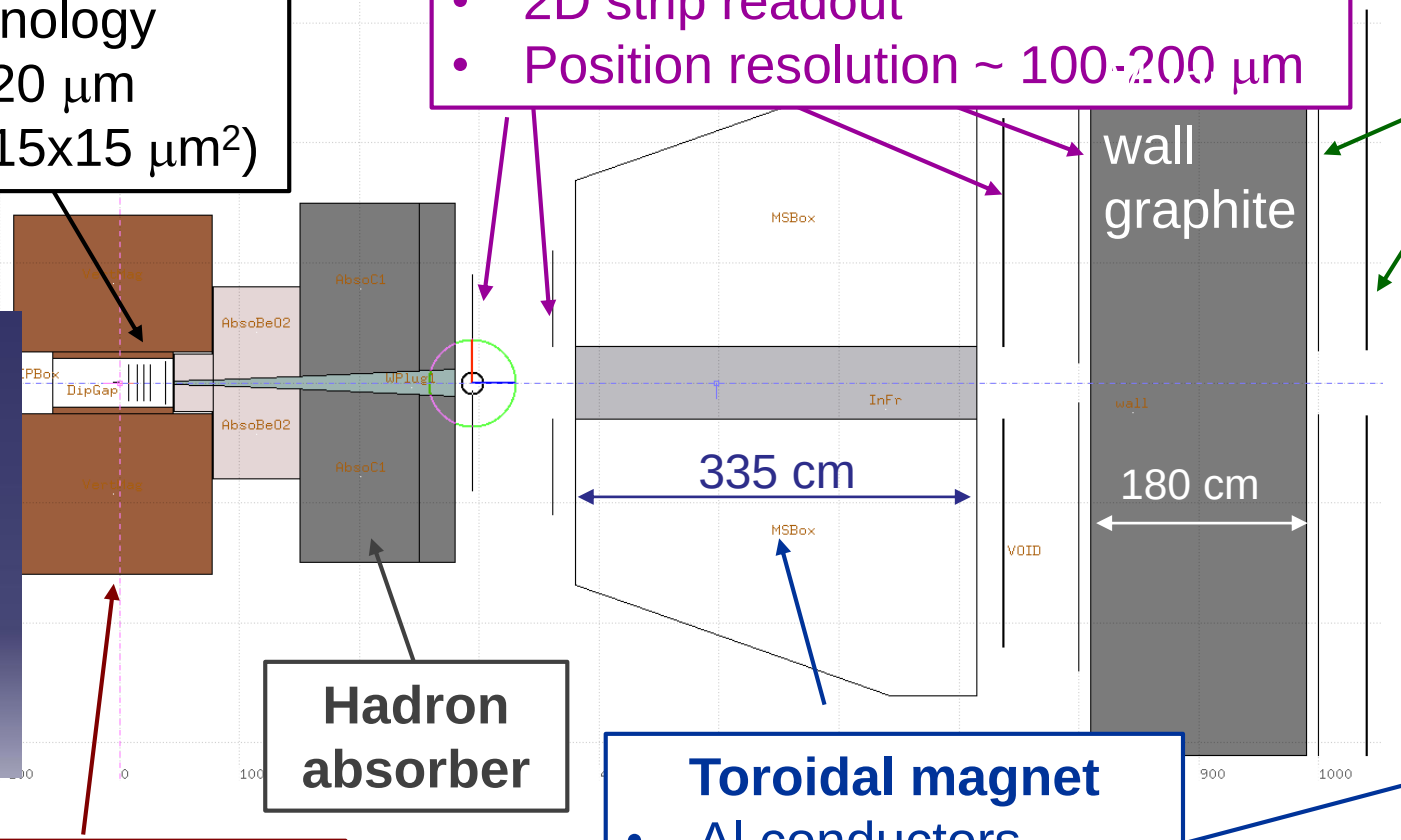
NA60+ detector: R&D in progress

Vertex telescope
- Large area MAPS with stitching technology
- Si thickness 20 μm
- Pixel size O(15x15 μm²)

Tracking stations
- GEM or MWPC
- 2D strip readout
- Position resolution ~ 100-200 μm

Trigger/ID stations





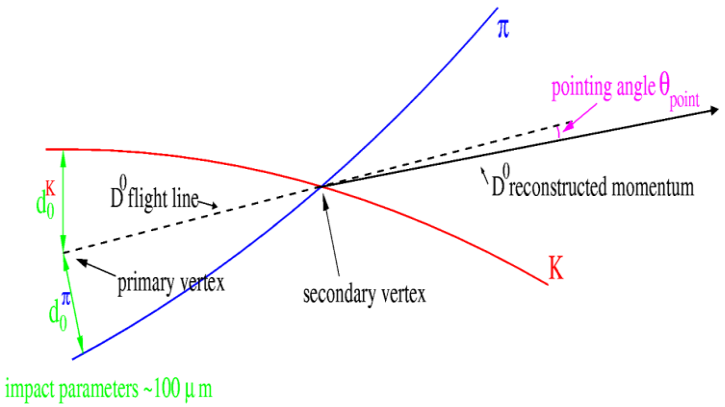
Hadron absorber

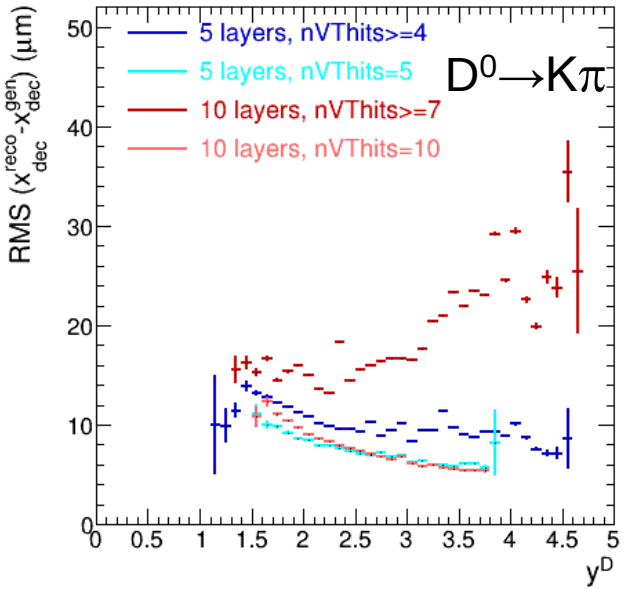
Dipole magnet

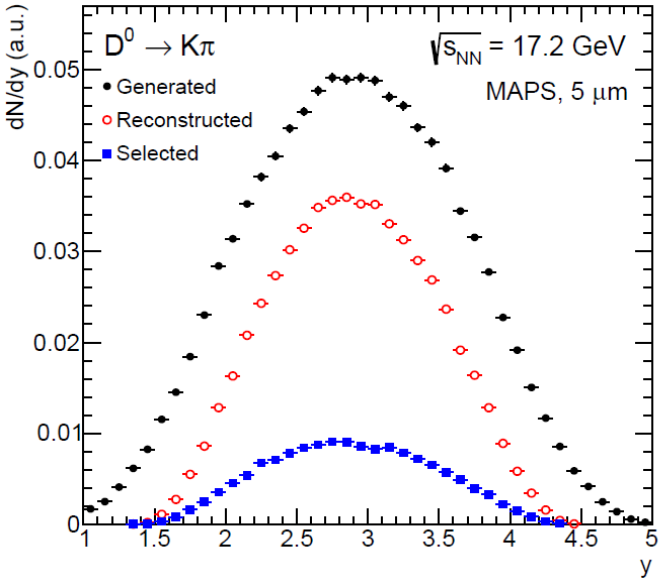
Toroidal magnet
- Al conductors
- B·R ~ 0.2-0.25 Tm

D-meson performance studies

- **Fast simulations** for central Pb-Pb collisions:
  - ⇨ D-meson signal simulation: p_T and y distributions from POWHEG-BOX+PYTHIA
  - ⇨ Combinatorial background: dN/dp_T and dN/dy of π, K and p from NA49
  - ⇨ Parametrized simulation of VT detector resolution + track reconstruction with Kalman filter
  - ⇨ Reconstruct D-meson decay vertex from decay tracks
  - ⇨ Geometrical selections based on displaced decay vertex topology
    - ✓ For D^0 in central Pb-Pb:
      initial S/B ~10^{-7}
      → after selections S/B ~0.5

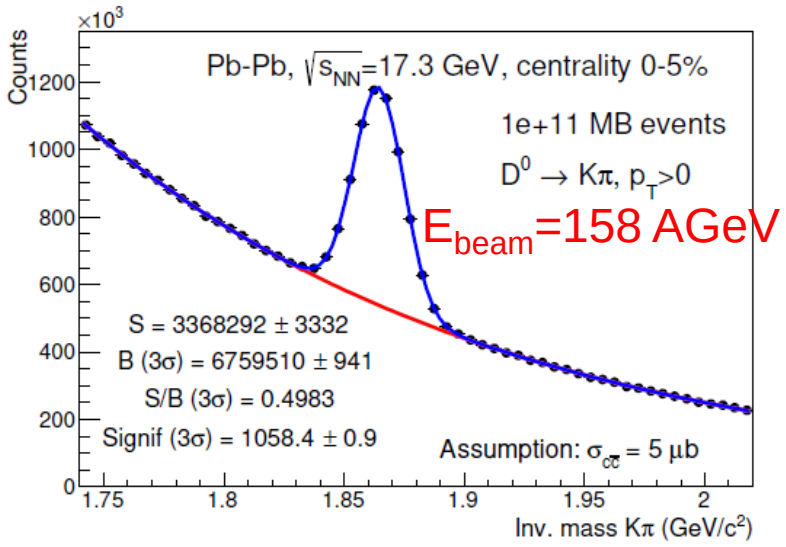




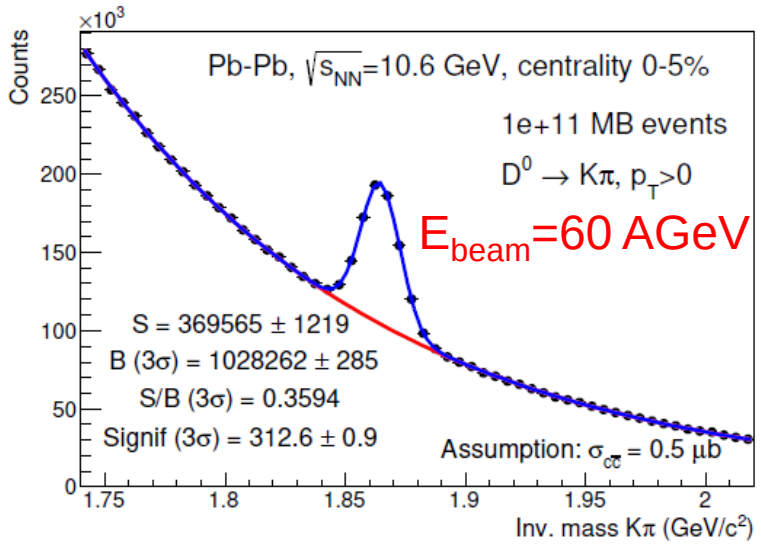


NA60+ physics performance : D mesons

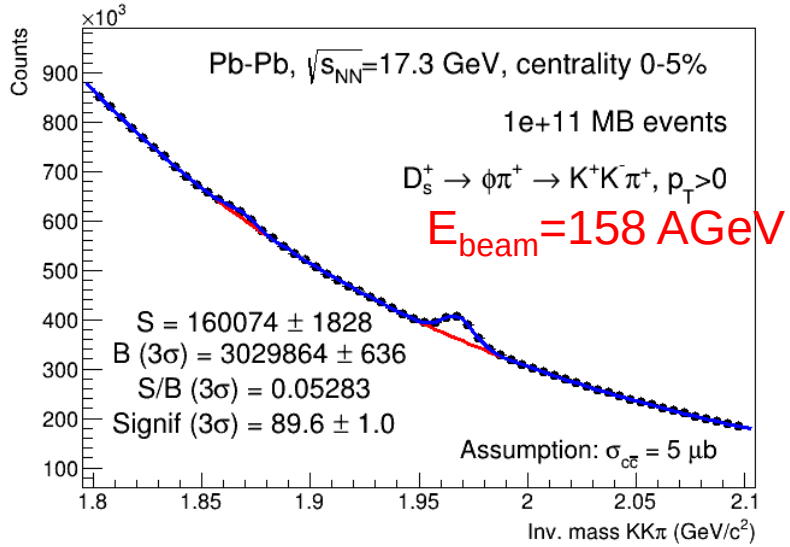
- With 10^{11} minimum bias Pb-Pb collisions (1 month of data taking)
  - ⇨ More than $3 \cdot 10^6$ reconstructed D^0 in central Pb-Pb collisions at $\sqrt{s_{NN}}$=17.3 GeV
    - ✓ Allows for differential studies of yield and v_2 vs. p_T, y and centrality
  - ⇨ D^0 accessible also at lower collision energies with statistical precision at the percent level
  - ⇨ Measurement of D_s yield feasible with statistical precision of few percent
  - ⇨ Performance studies ongoing for D^+ mesons and Λ_c baryons



$D^0 \rightarrow K\pi$

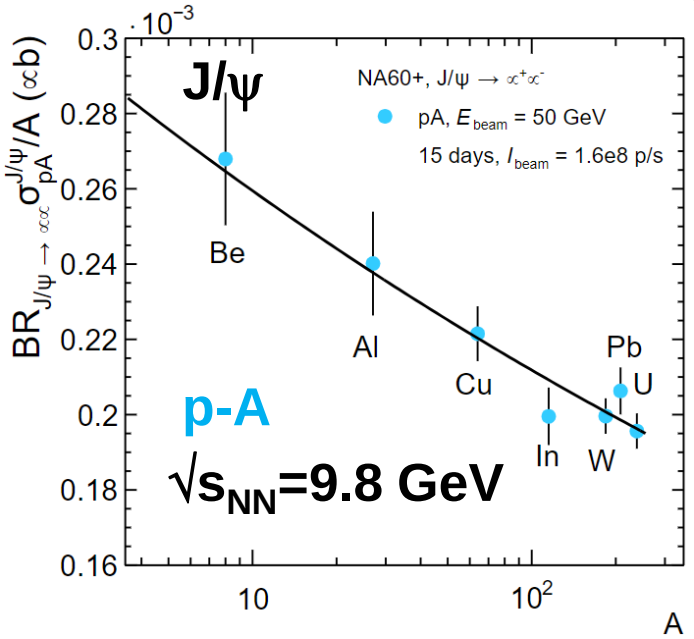


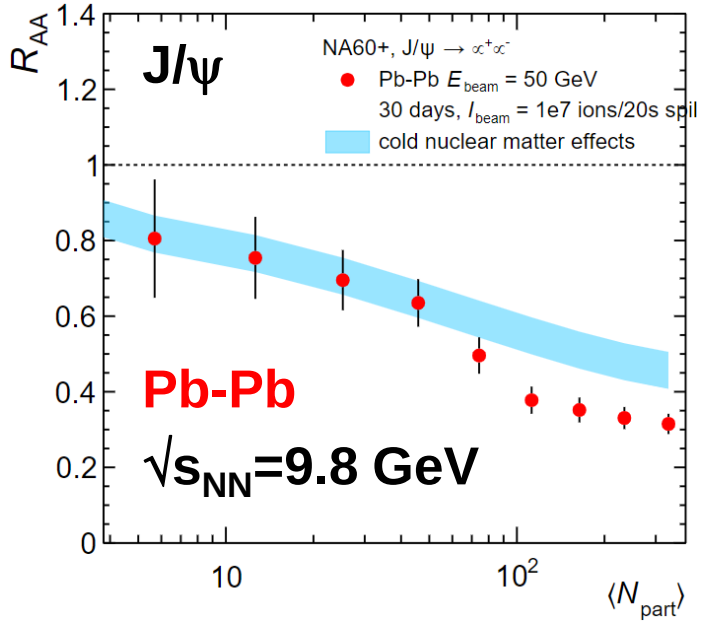
$D^0 \rightarrow K\pi$

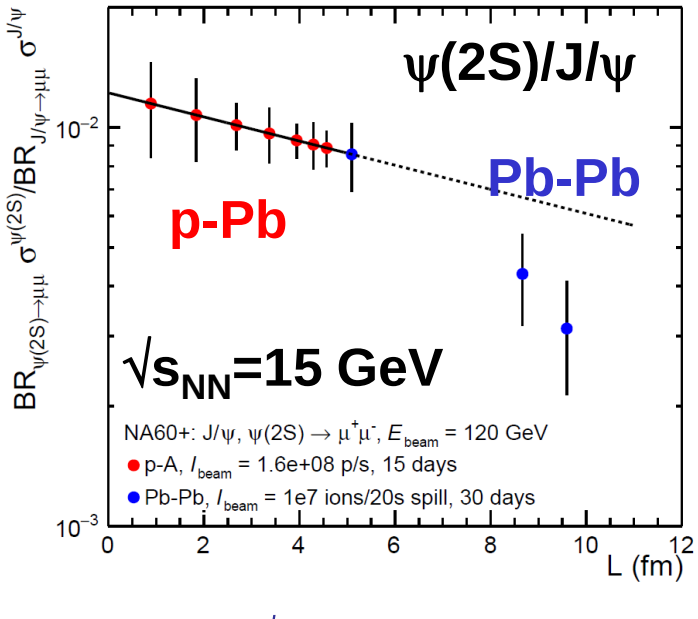


$D_s^+ \rightarrow \Phi\pi \rightarrow KK\pi$

NA60+ physics performance : J/ψ and ψ'







- In 30 days of Pb beam at $5 \cdot 10^5$ ions/s: **~10^4–10^5** (depending on $\sqrt{s_{NN}}$) reconstructed **J/ψ** in NA60+ acceptance
- Collect p-A data with different targets to calibrate cold nuclear matter effects
  - ⇨ Extrapolate the J/ψ cross section in pp collisions, needed for R_{AA}
  - ⇨ Extrapolate break-up effects to Pb-Pb collisions
- Strong potential for getting new insights into charmonium dissociation in the QGP

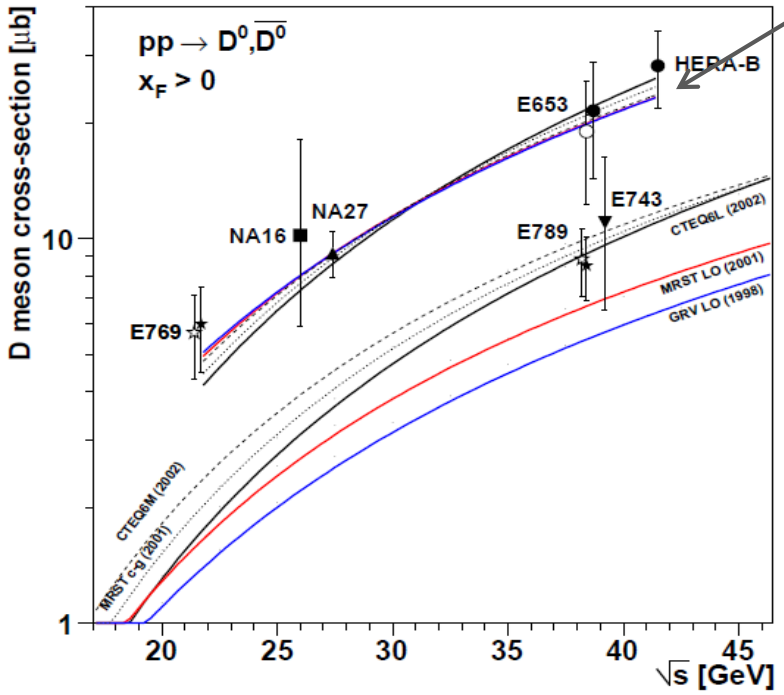
Summary and perspectives

- **Strong physics case** for a beam energy scan at the SPS with high intensity beams to measure **dimuons** at low and intermediate mass, **open charm and charmonium** in p-A and Pb-Pb collisions
- The proposed **experiment NA60+** can carry out these measurements with high precision
  - ⇨ More precise open charm measurements with respect to NA61/SHINE
  - ⇨ Additional and unique insight from measurements of charmonium and low-mass dimuons
  - ⇨ Complementary to CBM program at SIS, which will investigate lower $\sqrt{s}$
- More details on the project
  - ⇨ Webpage: https://na60plus.ca.infn.it/
  - ⇨ Expression of Interest: https://cds.cern.ch/record/2673280

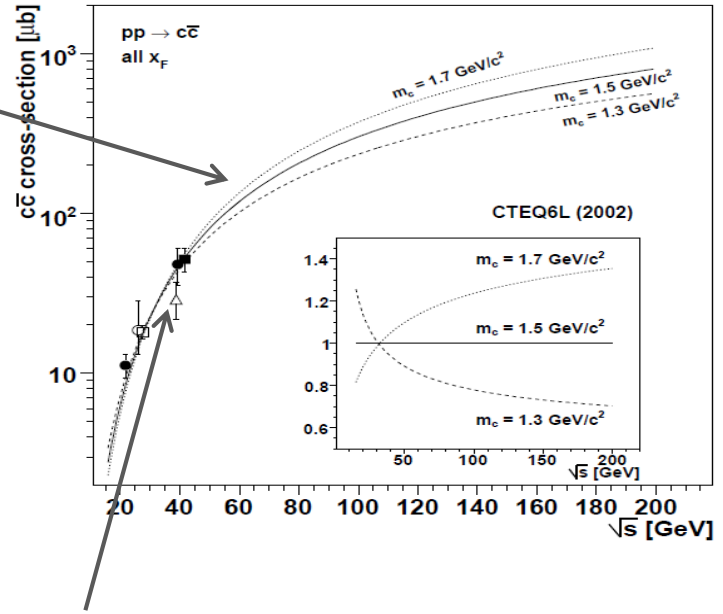
Backup

Charm cross section in p-A

- Unexplored energy domain
- Comparison of existing data to PYTHIA (LO) event generator



PYTHIA LO cross sections scaled with appropriate K-factor



Total charm cross section from:

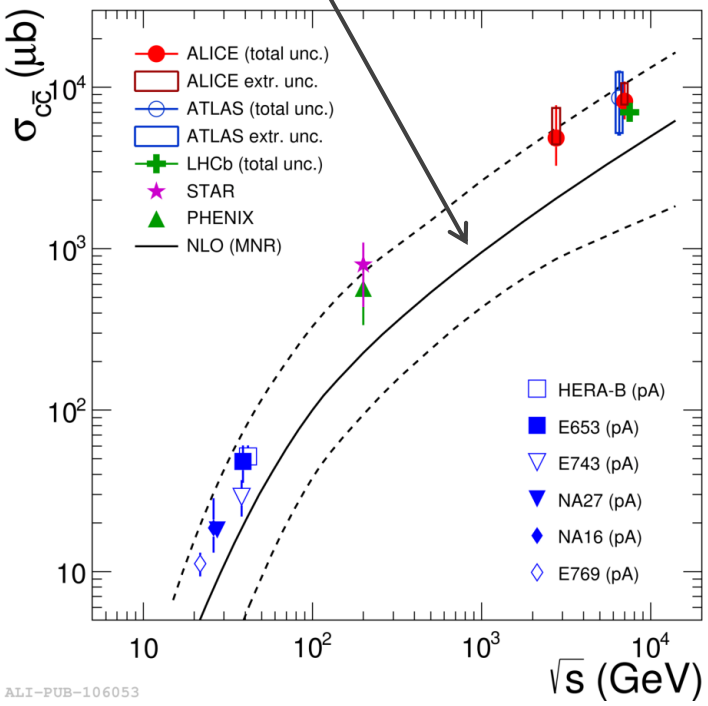
- Measured D^0 (D^+) cross sections
- Fragmentation fractions from e^+e^-

📖 **Lourenco, Wohri, Phys.Rept.433 (2006) 127**

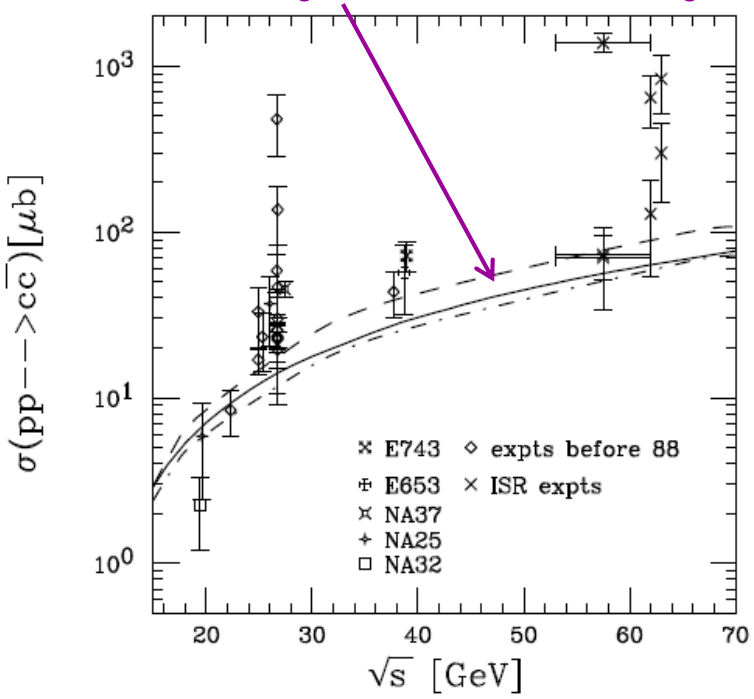
Charm cross section in p-A

- Unexplored energy domain
- Comparison of existing data to pQCD calculations (MNR) at NLO, NLL and NNLO

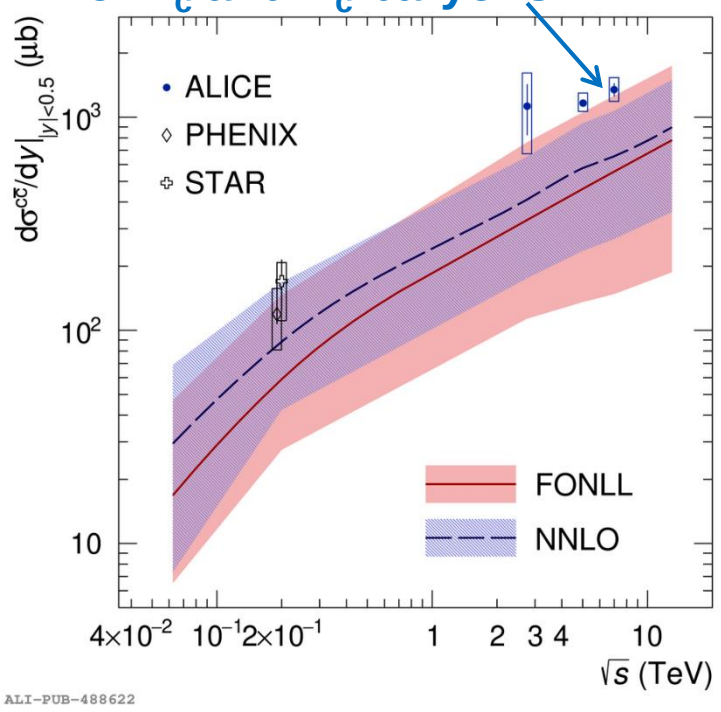
MNR, m_c=1.5 GeV, $\mu_F=\mu_R=m_T$



MNR, m_c=1.2 GeV , $\mu=2m_c$



Including measurements of Λ_c and Ξ_c baryons



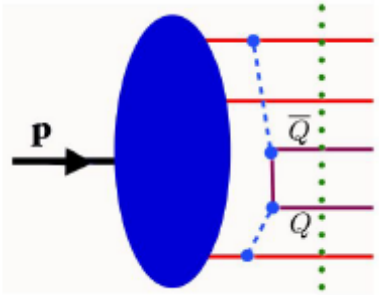
📖 ALICE, PRC94 (2016) 054908

📖 Vogt, Int.J.Mod.Phys.E12 (2003) 211

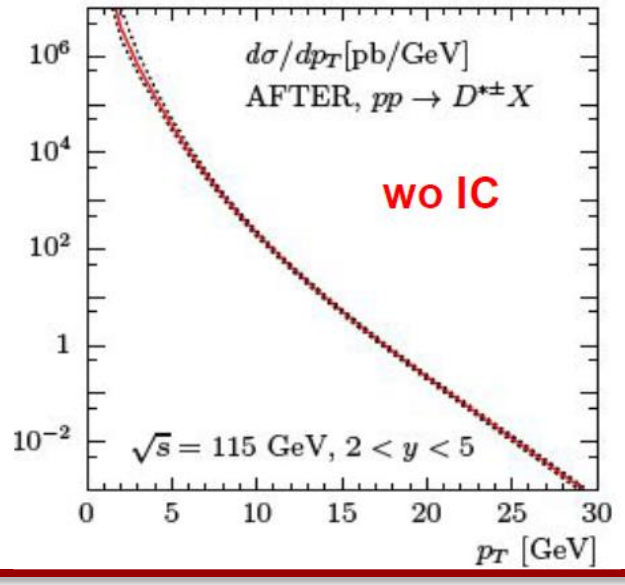
📖 ALICE, arXiv:2105.06335

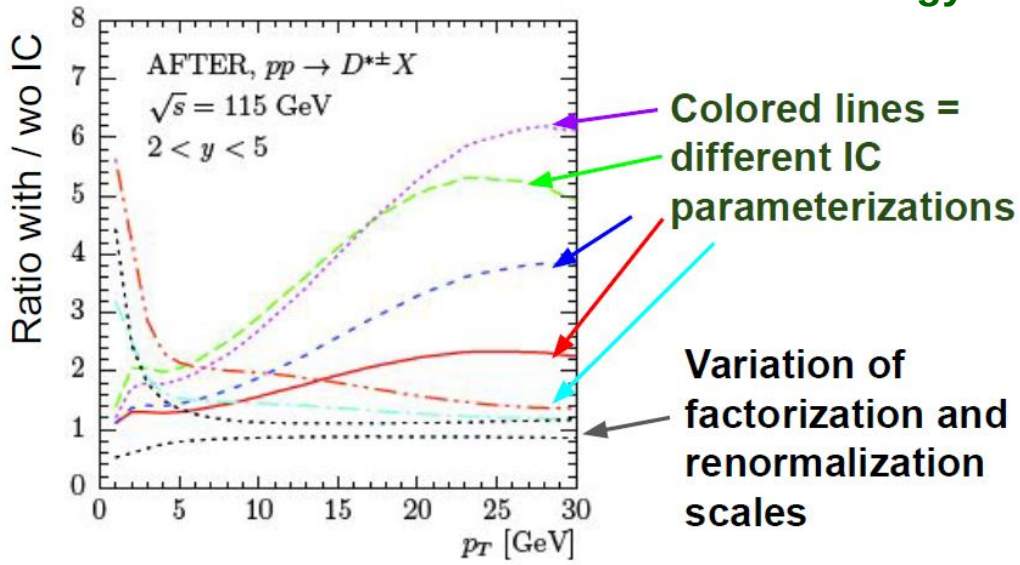
Intrinsic charm?

- Existence of a nonperturbative intrinsic heavy quark component in the nucleon is a rigorous QCD prediction
  - ⇨ Extrinsic contributions arise from gluon splitting in pQCD
  - ⇨ Intrinsic charm: nonperturbative component in proton wave function
    - ✓ E.g. 5-quark Fock state |uudcc>
- Unambiguous experimental confirmation still missing
  - ⇨ Intrinsic charm (IC) contribution dominant at large x and high p_T



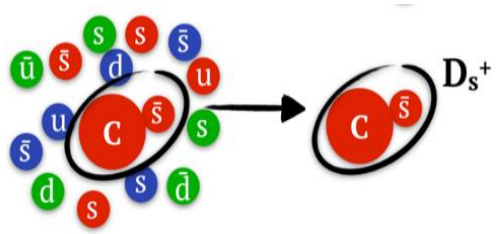
📖 S. J. Brodsky, Adv.High Energy Phys. (2015) 231547

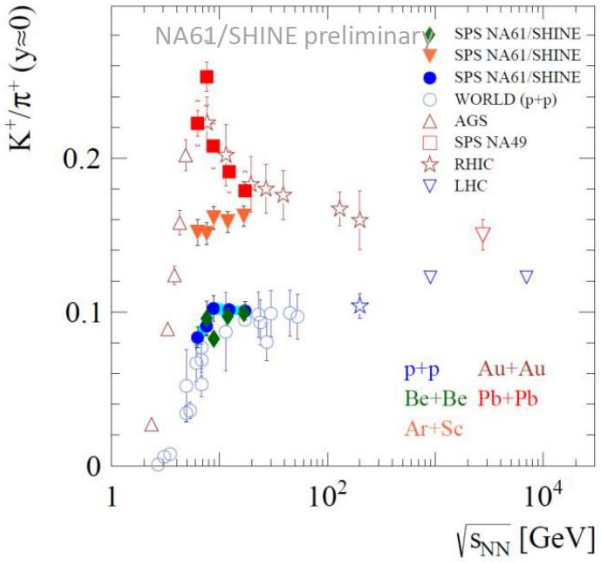


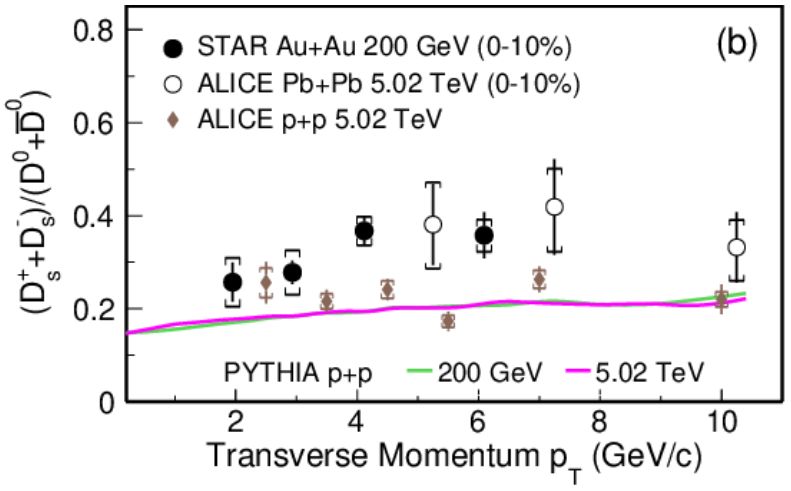


Open charm hadrochemistry

- Reconstruct different charm hadron species to get insight into **hadronization mechanism**
- **Strange/non-strange** meson ratio (D_s/D):
  - ⇨ D_s/D enhancement expected in A-A collisions due to hadronisation via **recombination** in the strangeness rich QGP
  - ⇨ Complement studies of strangeness production by NA61

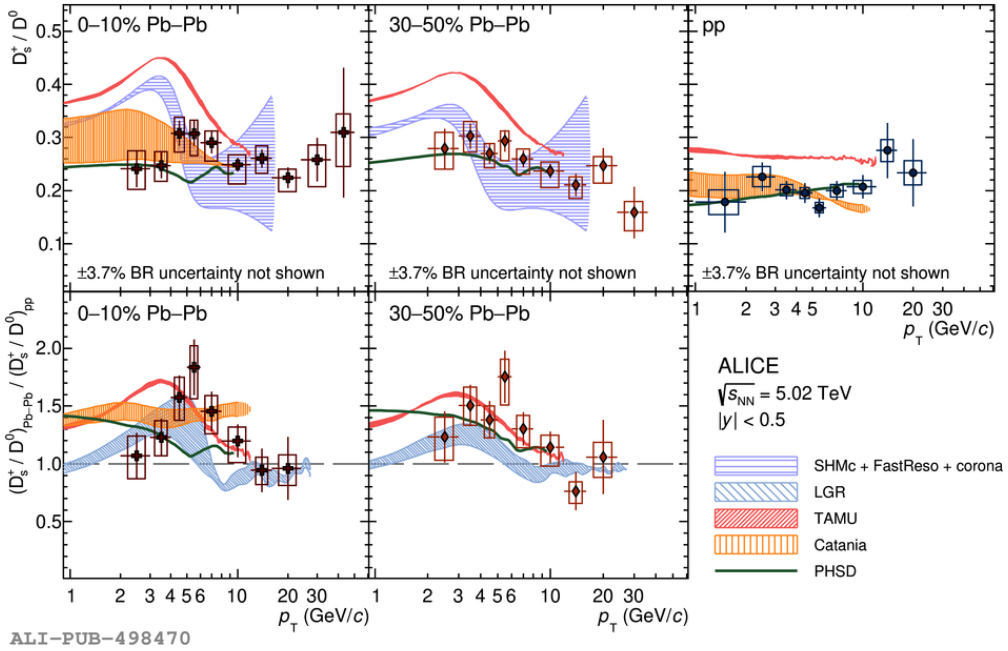






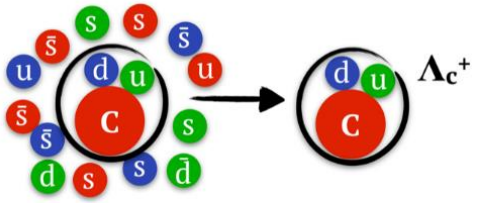
📖 **STAR, PRL 127 (2021) 092301**

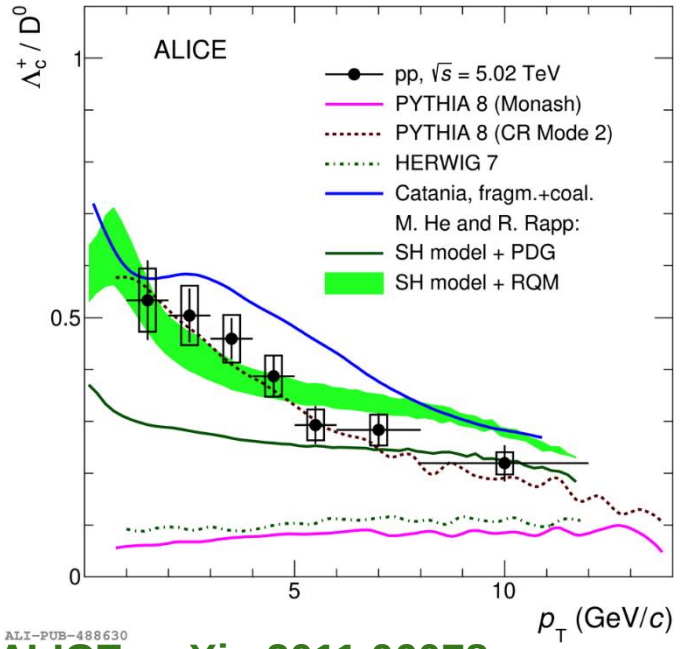
📖 **ALICE, arXiv:2110.10006**



Open charm hadrochemistry

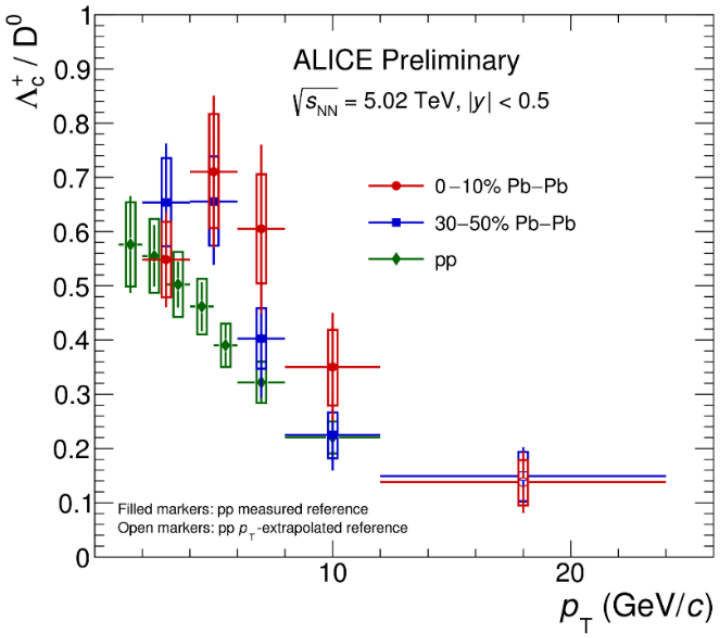
- Reconstruct different charm hadron species to get insight into **hadronization mechanism**
- **Baryon/meson** ratios (Λ_c/D):
  - ⇨ Expected to be enhanced in A-A in case of hadronisation via coalescence
  - ⇨ Interesting also in p-A since Λ_c/D^0 in pp (p-Pb) at LHC is higher than in e^+e^-



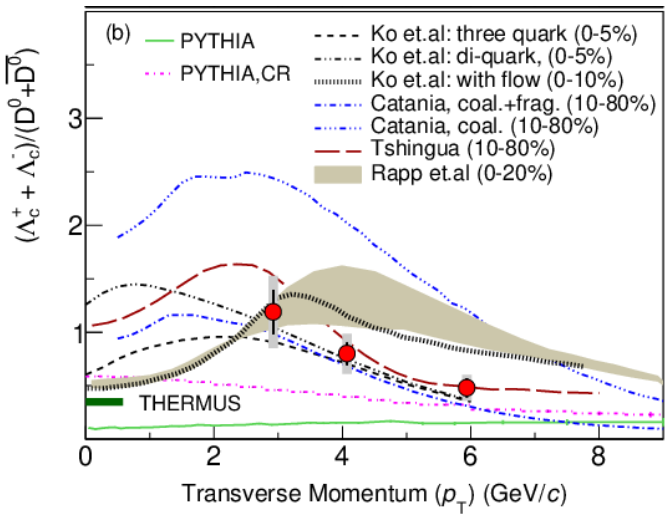


ALI-PUB-488630

📖 ALICE, arXiv:2011.06078



ALI-PREL-321702

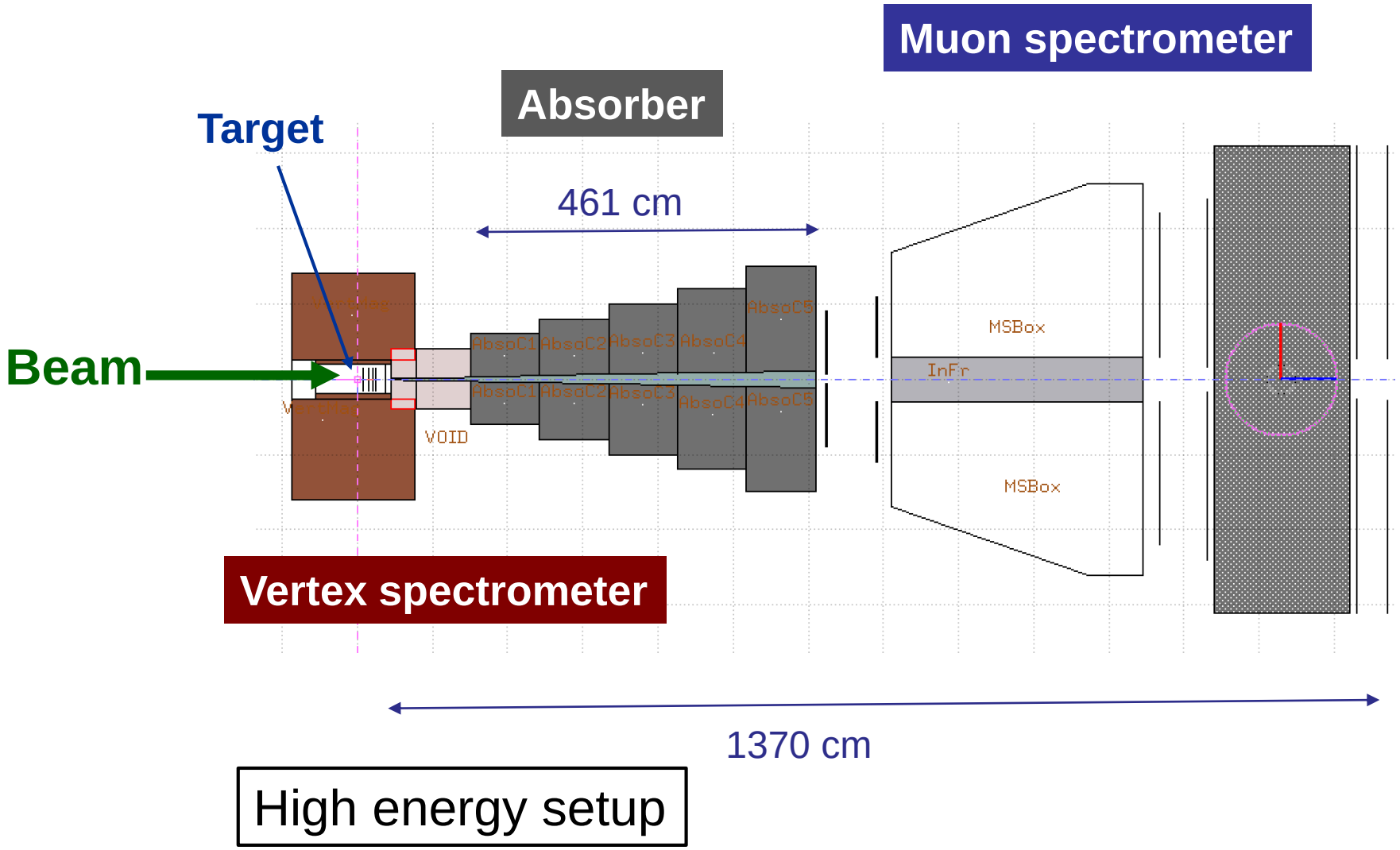


📖 STAR, PRL 124 (2020) 172301

NA60+ proposed program

- Beam energy scan (BES) at the CERN SPS in the interval $\sqrt{s_{NN}}$≈6-17 GeV
  - ⇨ ~4 week periods/year with Pb beams → **Pb-Pb collisions**
  - ⇨ Corresponding periods with proton beams: **p-A reference**, with different nuclear targets
  - ⇨ BES example: E_{beam} = 20, 30, 40, 80, 120, 160 GeV/nucleon
- High precision measurements of rare probes:
  - ⇨ Comprehensive measurement of full **dilepton** spectrum
    - ✓ **Thermal dimuons** from threshold up to 3 GeV
    - ✓ **Charmonium**: J/ψ, ψ(2S), χ_c
  - ⇨ **Hadronic** measurements:
    - ✓ Charmed mesons and baryons (D^0, $D^{\pm}$, D_s, Λ_c)
- Statistics goal at each energy of BES:
  - ⇨ ~$4 \cdot 10^6$ reconstructed $\mu^+\mu^-$ pairs from thermal dimuons
    - ✓ Factor ≈20 over NA60, >10^4 over RHIC/LHC experiments
  - ⇨ >~ $1.5 \cdot 10^4$ reconstructed J/ψ → $\mu^+\mu^-$
  - ⇨ ~10^7 reconstructed D^0 mesons

NA60+ detector concept

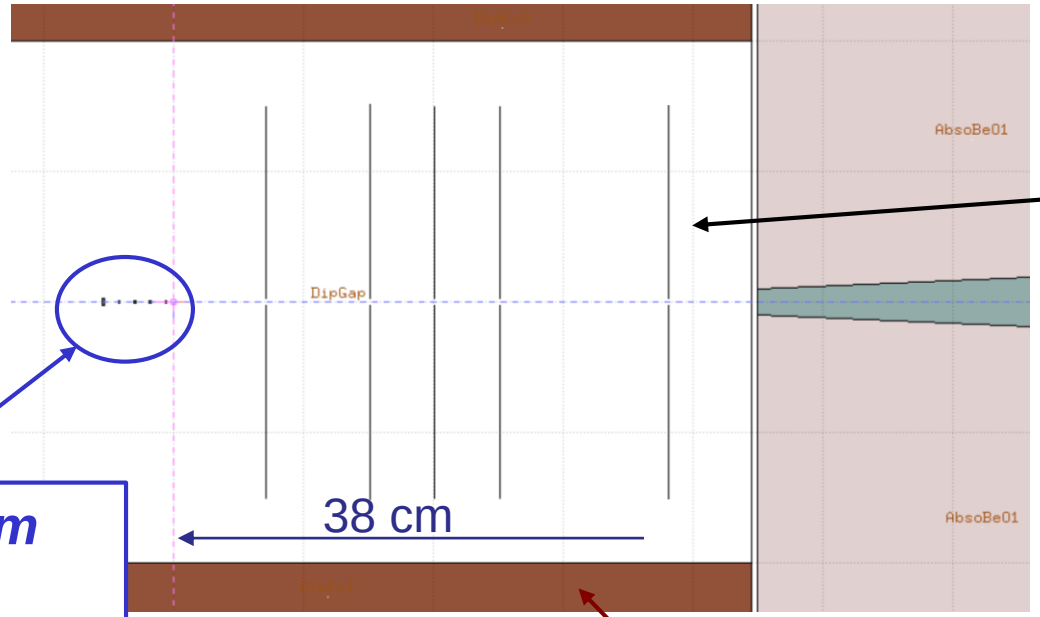


High energy setup

- **Muon spectrometer** to measure dimuons downstream of absorber
  - ⇨ Muon spectrometer length needs to be varied, to cover mid-rapidity at different $\sqrt{s}$
- **Vertex spectrometer** for precise tracking close to the interaction point

D-meson performance studies

- **Fast simulations** for central Pb-Pb collisions:
  - ⇨ D-meson signal simulation: p_T and y distributions from POWHEG-BOX+PYTHIA
  - ⇨ Combinatorial background: dN/dp_T and dN/dy of π, K and p from NA49
  - ⇨ Parametrized simulation of VT detector resolution + track reconstruction with Kalman filter

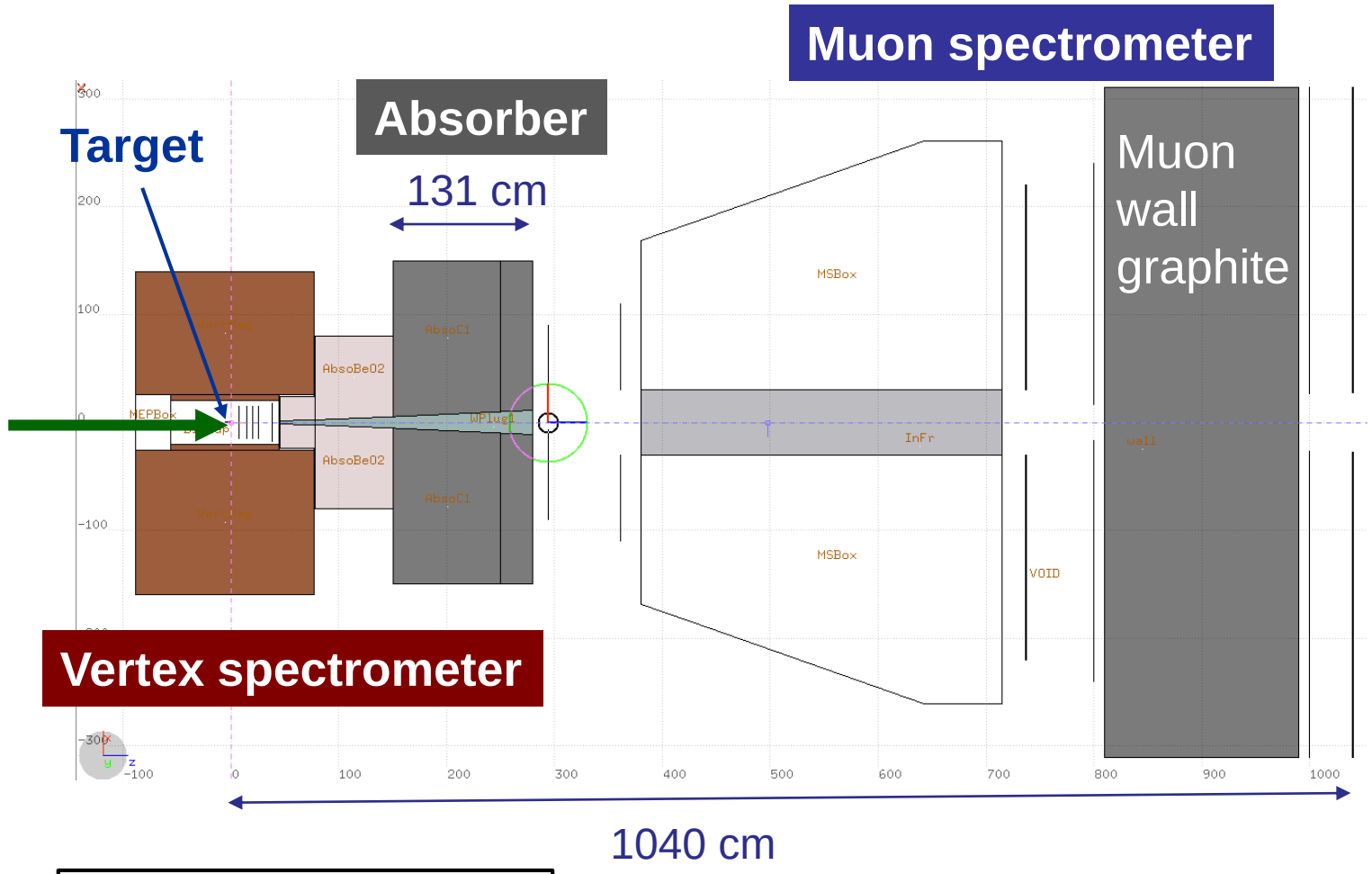


Vertex telescope
- Large area MAPS with stitching technology
- 5 to 10 planes
- Si thickness 20 μm
- Pixel size O(15x15 μm^2)
- Mechanical support and cooling on the borders

Target system
- 5 Pb disks
- 1.5 mm thick
- ≈15% inter. prob.

Dipole magnet
Wide gap dipole (MEP48)

NA60+ detector concept

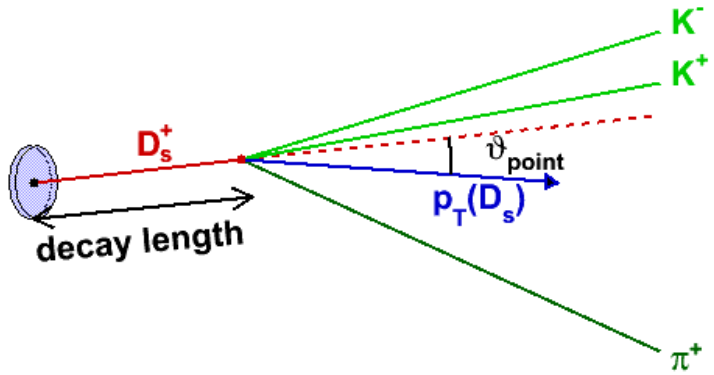


Low energy setup

- **Muon spectrometer** to measure dimuons downstream of absorber
  - ⇨ Muon spectrometer length needs to be varied, to cover mid-rapidity at different $\sqrt{s}$
- **Vertex spectrometer** for precise tracking close to the interaction point

Charm hadron reconstruction

- Charmed mesons and baryons can be reconstructed from their decays into 2 or 3 charged hadrons
- Small production cross section + small(ish) BRs
  - ⇨ Require large samples of minimum-bias collisions
- Mean proper decay lengths $c\tau$ ~60-300 μm
  - ⇨ High precision on tracking and vertexing required to discriminate the charm-hadron decay vertex from the interaction point

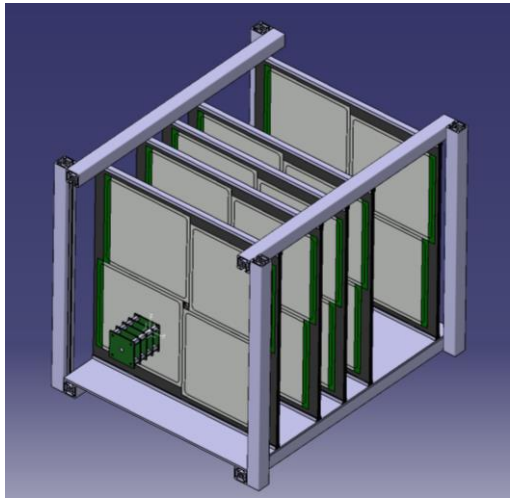


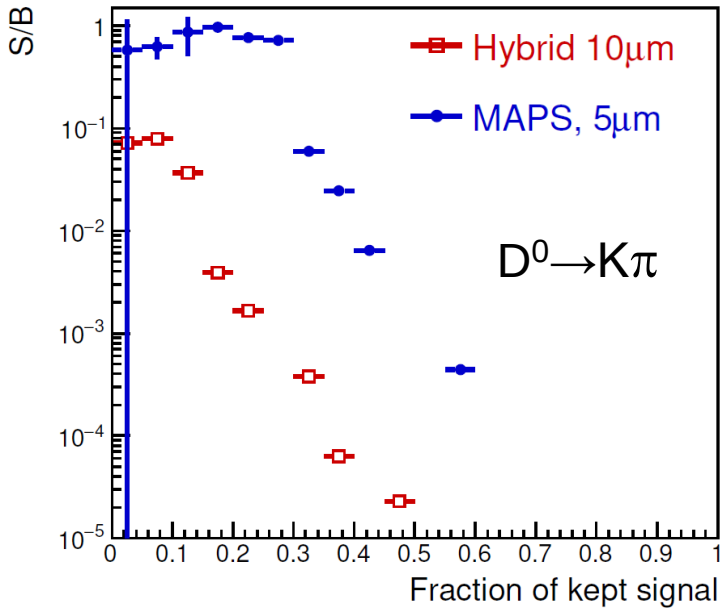
Hadron	Mass (MeV/c^2)	$c\tau$ (μm)	Decay	BR
D^0	1865	123	$\rightarrow K^-\pi^+$	3.95%
D^+	1869	312	$\rightarrow K^-\pi^+\pi^+$	9.38%
D_s^+	1968	147	$\rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$	2.24%
Λ_c^+	2285	60	$\rightarrow pK^-\pi^+$ $\rightarrow pK^0_s$ $\rightarrow \Lambda\pi^+$	6.28% 1.59% 1.30%

Charm hadron reconstruction

- Charmed mesons and baryons can be reconstructed from their decays into 2 or 3 charged hadrons
- Invariant mass analysis of fully reconstructed displaced decay-vertex topologies
  - ⇨ Decay products reconstructed in the vertex spectrometer
  - ⇨ Background reduction via geometrical selections based on displaced decay vertex topology ($c\tau$ ~60-300 μm)
- Detector requirements:
  - ⇨ Need high precision on track and vertex reconstruction
  - ⇨ Substantially better performance with state-of-the-art Monolithic Active Pixel Sensors

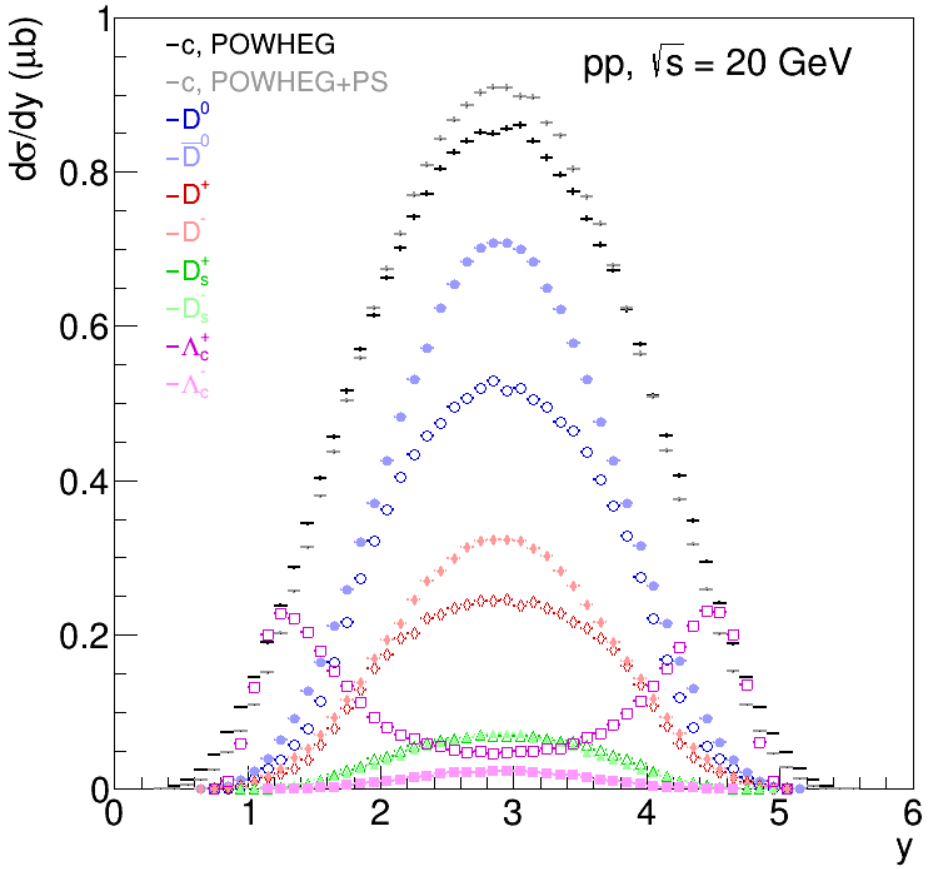
📖 **NA60+, https://cds.cern.ch/record/2673280**





D-meson performance studies

- **Fast simulations** for central Pb-Pb collisions:
  - ⇨ D-meson signal simulation: p_T and y distributions from POWHEG-BOX + PYTHIA



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- **Fast simulations** for central Pb-Pb collisions:
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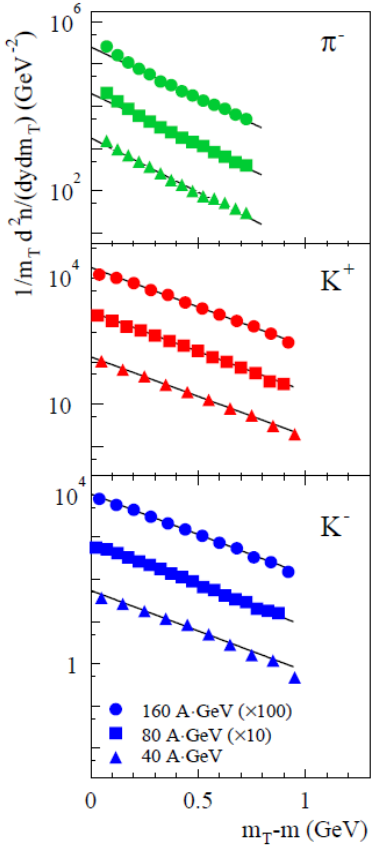
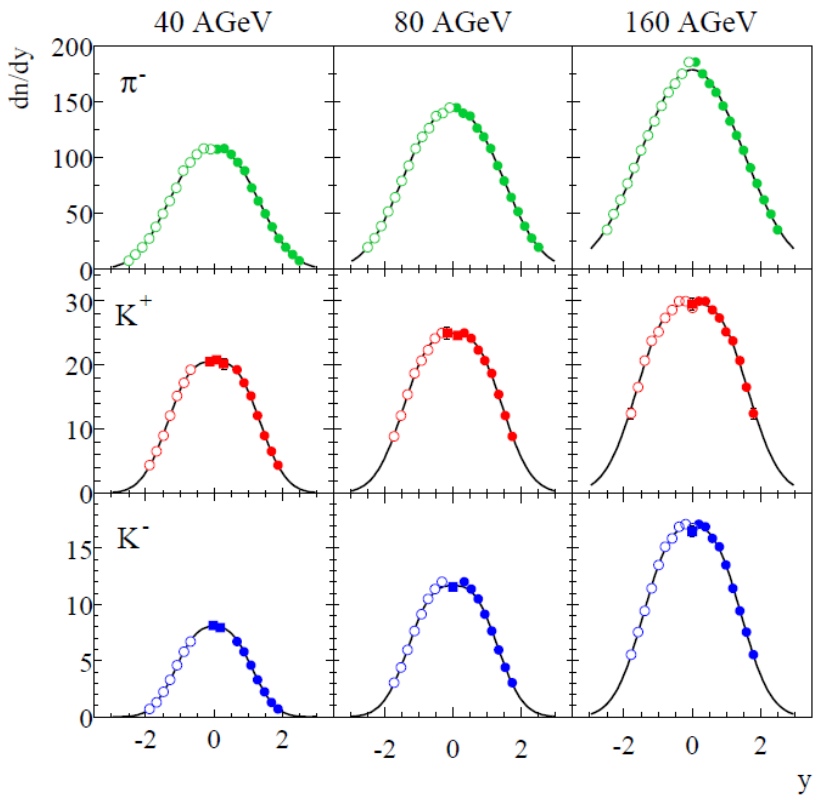
  - ⇨ Combinatorial background: dN/dp_T and dN/dy of π, K and p from NA49

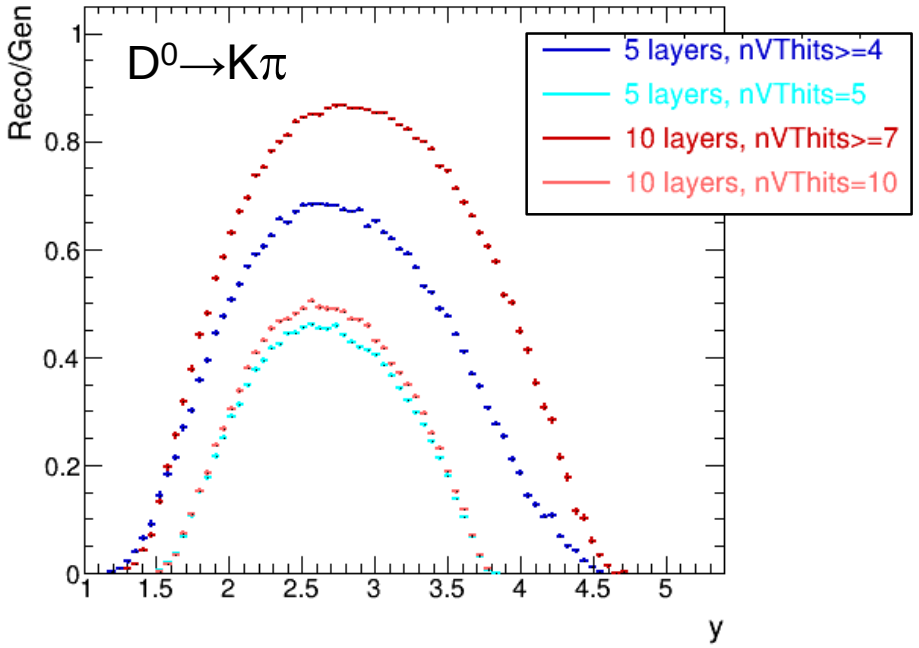


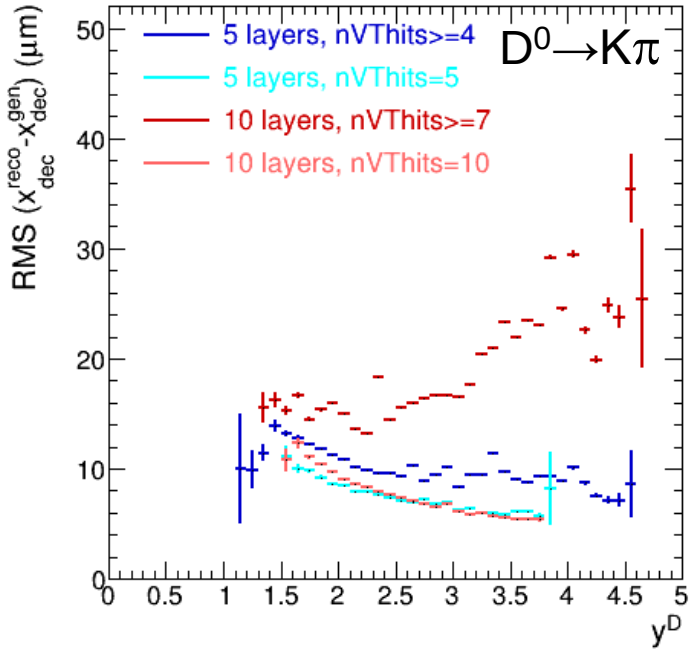


📖 **NA49, PRC 66 (2002) 054902**

D-meson performance studies

- **Fast simulations** for central Pb-Pb collisions:
  - ⇨ D-meson signal simulation: p_T and y distributions from POWHEG-BOX+PYTHIA
  - ⇨ Combinatorial background: dN/dp_T and dN/dy of π, K and p from NA49
  - ⇨ Parametrized simulation of VT detector resolution + track reconstruction with Kalman filter
  - ⇨ Reconstruct D-meson decay vertex from decay tracks





D-meson performance studies

- **Fast simulations** for central Pb-Pb collisions:
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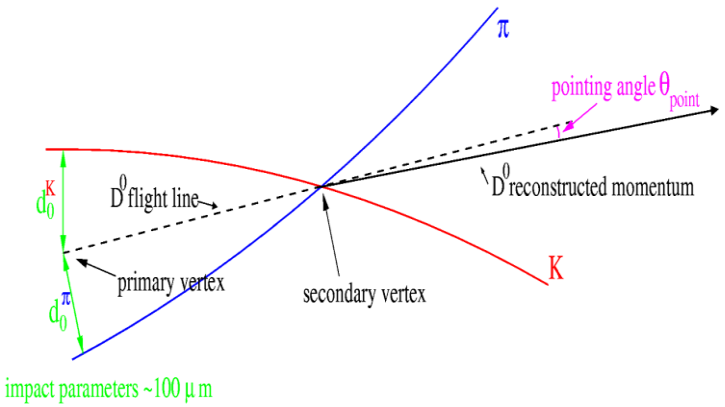
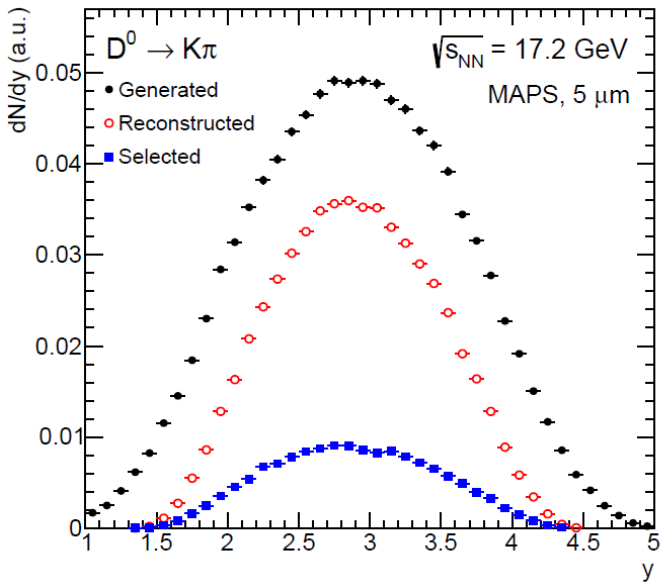
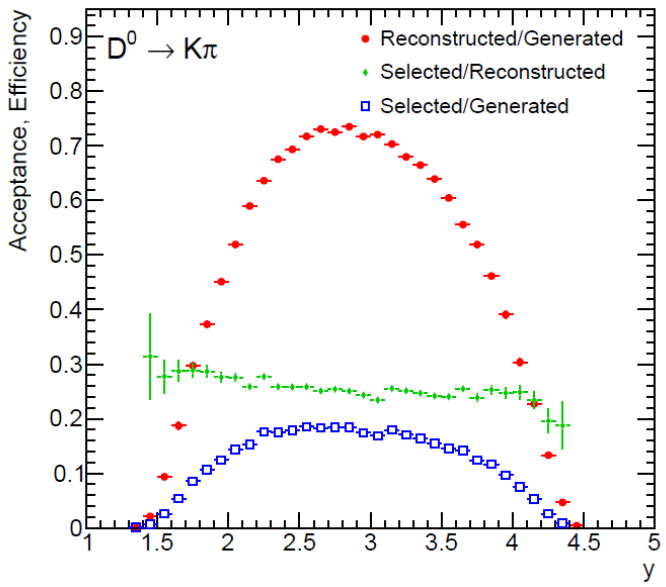
  - ⇨ Parametrized simulation of VT detector resolution + track reconstruction with Kalman filter
  - ⇨ Reconstruct D-meson decay vertex from decay tracks
  - ⇨ Geometrical selections based on displaced decay vertex topology
    - ✓ For D^0 in central Pb-Pb:
      initial S/B ~10^{-7}
      → after selections S/B ~0.5

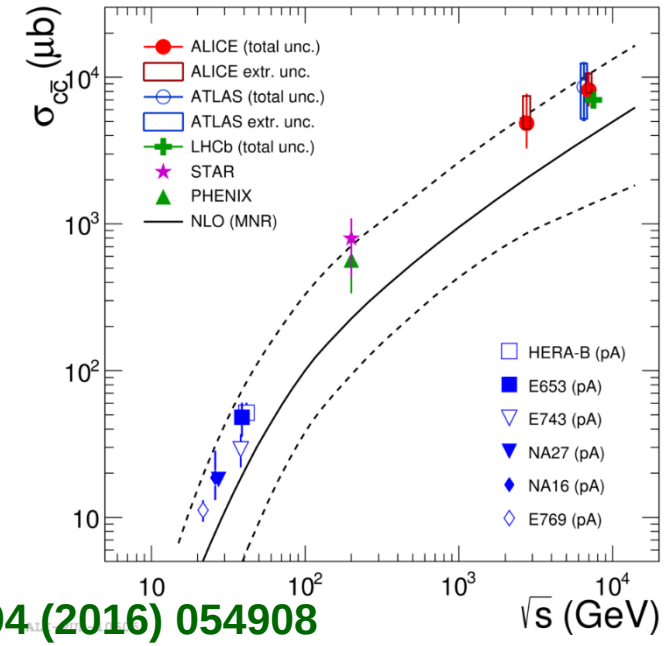




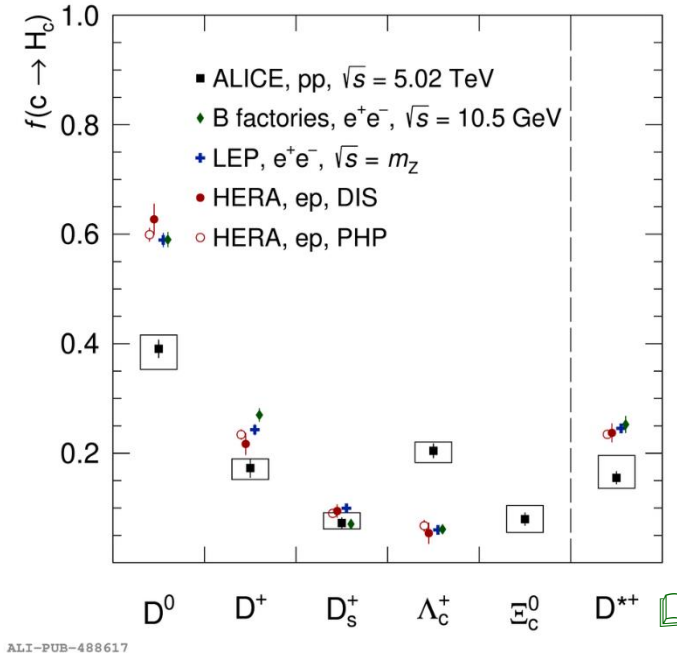


Normalization of signal

- Normalization of **signal yield per event** based on:
  - ⇨ (Assumption on) charm production cross section
    - ✓ Not measured at SPS energies
  - ⇨ Nuclear overlap function T_{AA} (Glauber)
  - ⇨ Fragmentation fractions of charm quarks in different charm hadron species, $f(c \rightarrow H_c)$
    - ✓ Not universal: different in pp at LHC and e^+e^- (ep) collisions



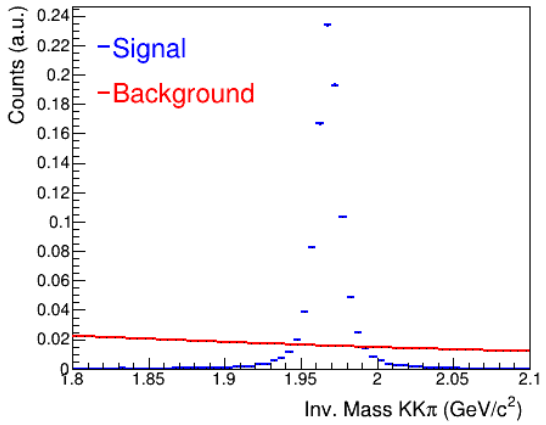
📖 **ALICE, PRC94 (2016) 054908**

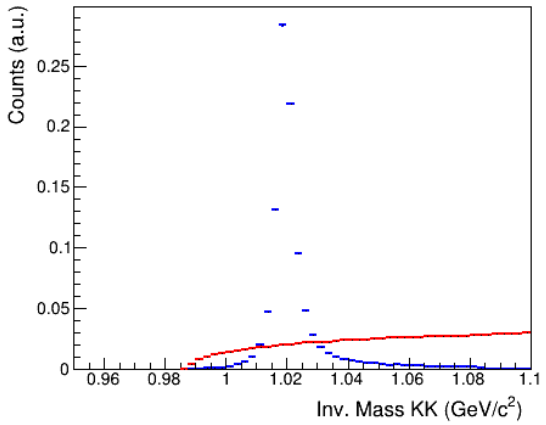


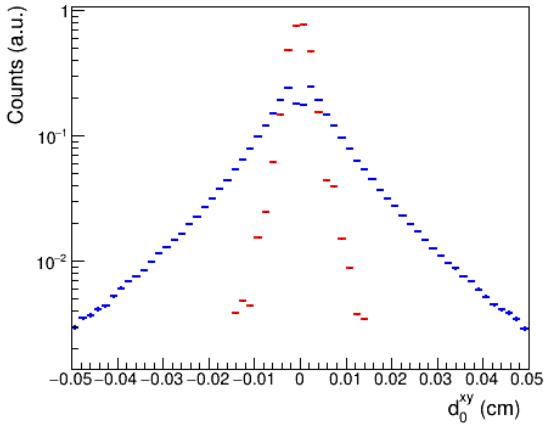
📖 **ALICE, arXiv:2105.06335**

NA60+ physics performance : D_s^+

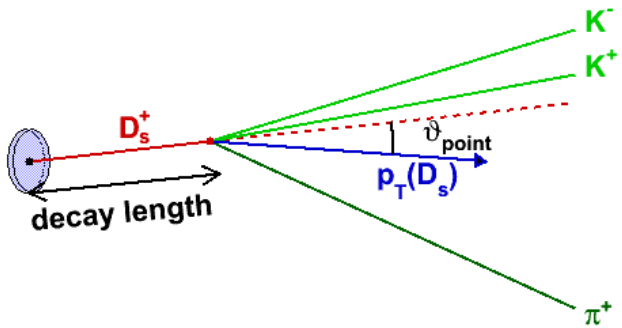
- Selections on **displaced decay vertex topology** and **K^+K^- invariant mass**

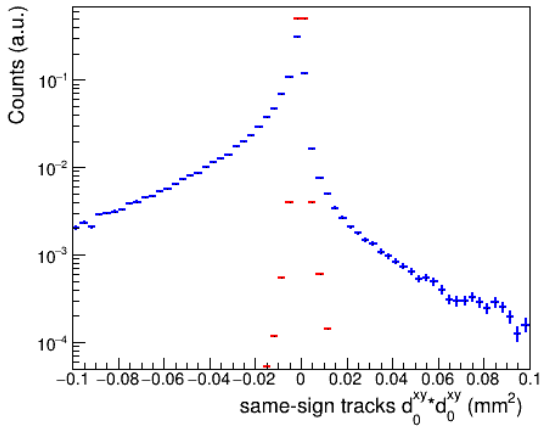


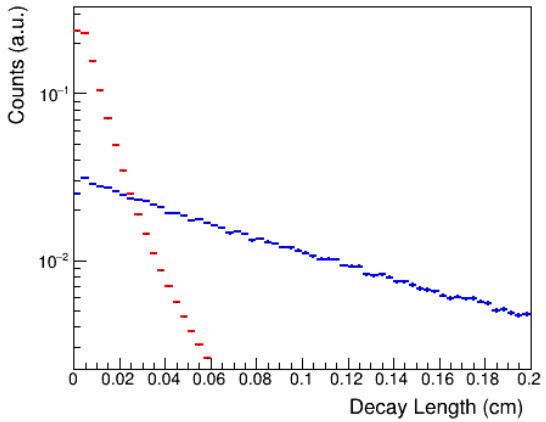


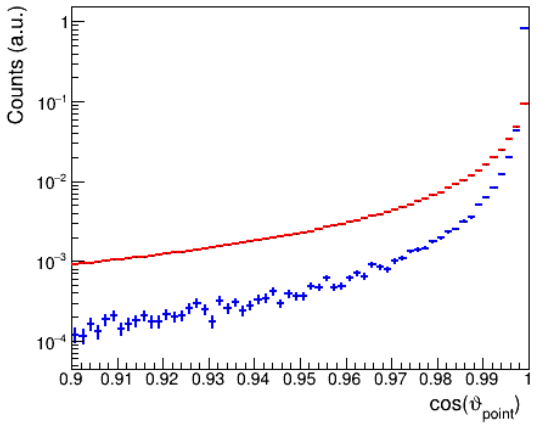


$D_s^+ \rightarrow \phi\pi \rightarrow KK\pi$





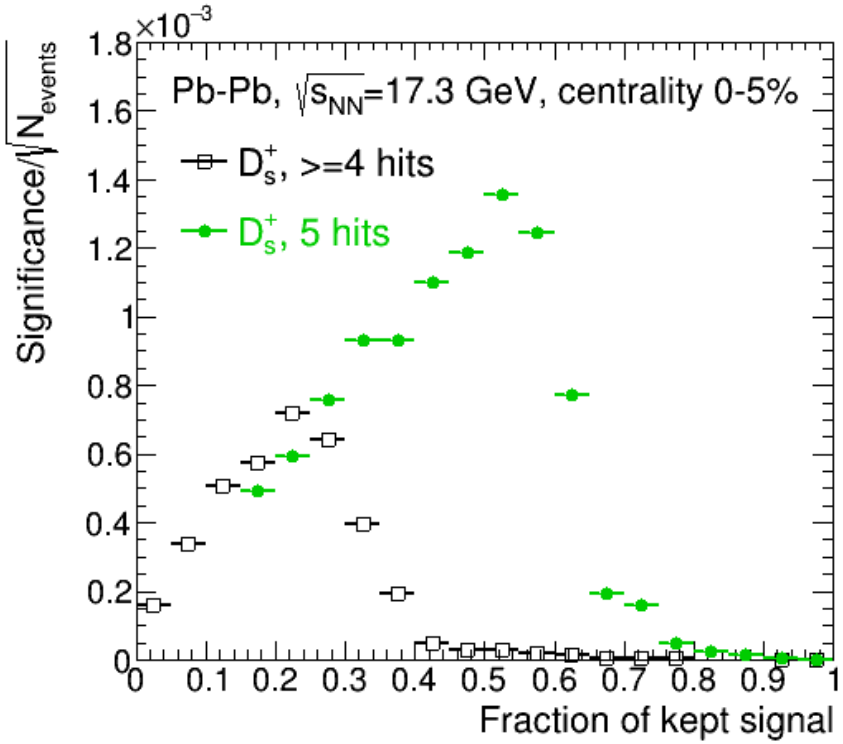


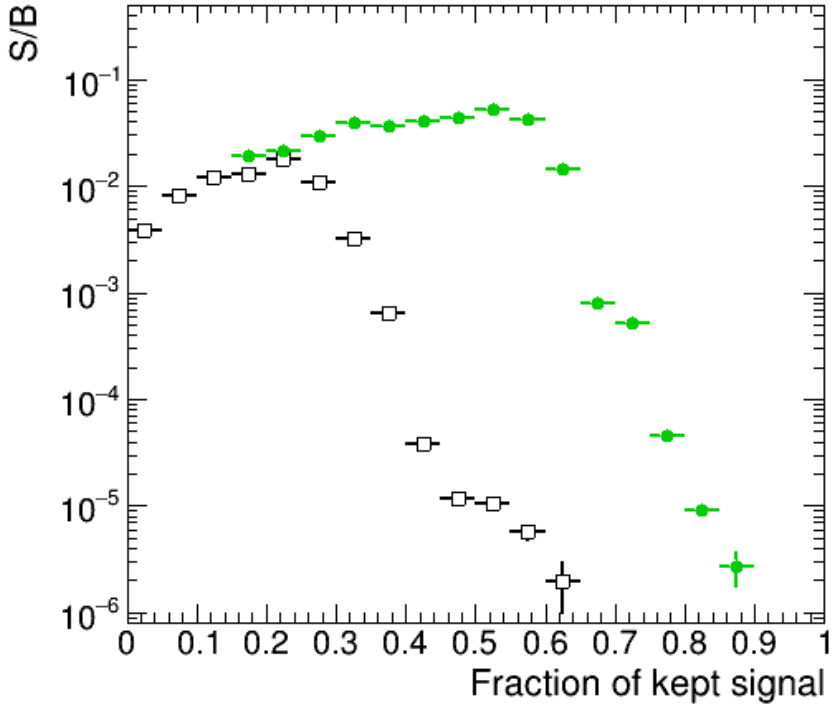


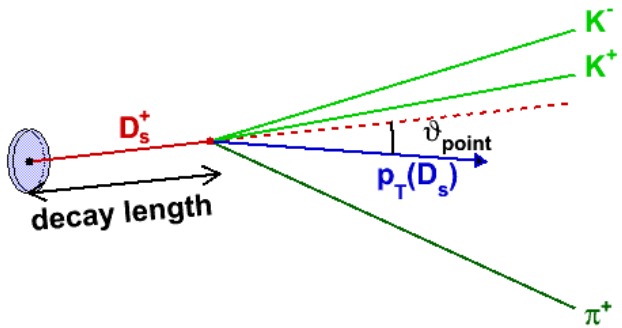
NA60+ physics performance : D_s^+

- Geometrical selections on displaced decay vertex topology
  - ⇨ Signal to background in central Pb-Pb:
    - ✓ Initial S/B ~$3 \cdot 10^{-10}$ → after selections (not optimized) S/B >~ 10^{-2}

$D_s^+ \rightarrow \phi\pi \rightarrow KK\pi$







Open charm hadrons

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D_s^+	**1968**	**147**	**$\rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$**	**2.24%**
Λ_c^+	2285	60	$\rightarrow pK^-\pi^+$ $\rightarrow pK^0_s$ $\rightarrow \Lambda\pi^+$	6.28% 1.59% 1.30%

- Fast simulations demonstrate feasibility of measuring of **D^0** and **D_s** mesons with very good statistical precision
- Measurements of **D^+** meson expected to be within reach
  - ⇨ Longer lifetime (-> larger displacement) and higher abundance than D_s meson
- Studies ongoing for **Λ_c** performance
  - ⇨ Short lifetime, more challenging separation of decay vertex
  - ⇨ Study also reconstruction of decays with a neutral strange hadron in the decay products

Summary and prospects

- First fast simulation studies demonstrate great perspectives for **open charm reconstruction** with NA60+
  - ⇨ Measure production in an (almost) unexplored energy domain
  - ⇨ Characterize **transport properties of QGP** by measuring yield, v_2 and hadrochemistry
- High resolution of monolithic active pixel sensors crucial for these analyses
- Further studies ongoing to extract the performance for **charm baryons** and to consolidate the estimates for **charm mesons** and **strange hadrons**