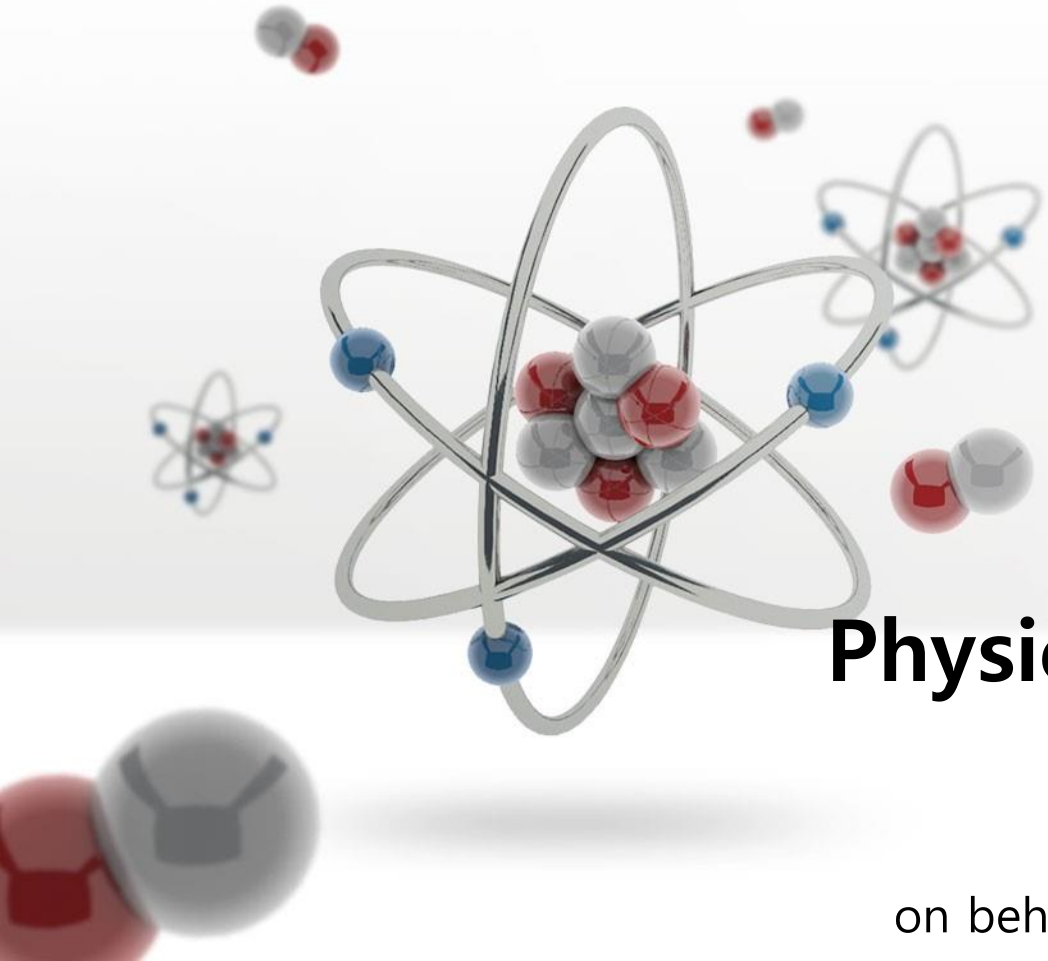


Physics beyond collider – future NA61

Szymon Puławski
on behalf of NA61/SHINE collaboration

Physics motivation

NA61 physics program beyond 2020

Strong interaction program		Cosmic ray program	Neutrino program
Open charm in heavy ion collisions	Multi-strange hyperons in heavy ion collisions	Fragmentation cross sections needed for interpretation of AMS-02 data	Accelerator and atmospheric neutrino experiments expressed interest in thin-target measurements

Cosmic ray program

1G$ (AMS) game-changing data 'cannot be' exploited because of GeV nuclear physics (XS uncertainties >> AMS-02 data uncertainties)

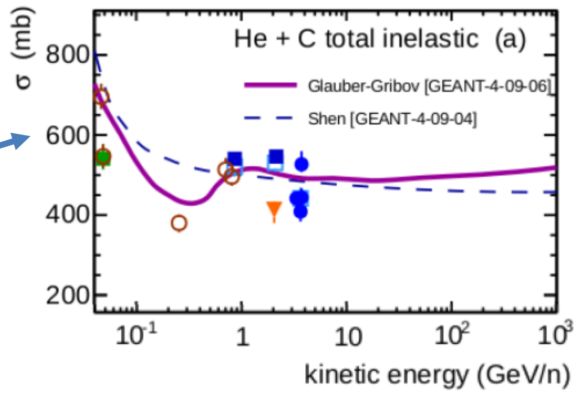
Cosmic Ray data modelling requires

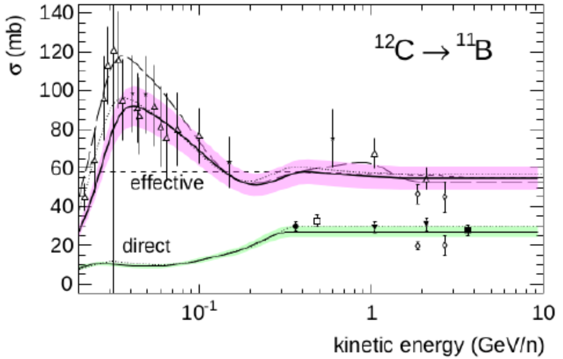
- Reaction cross-section (CR destruction)

- Production cross sections (secondary species)
- No data above 5 GeV/n

- Cross section uncertainties ~10-15%
- AMS-02 uncertainties ~3%

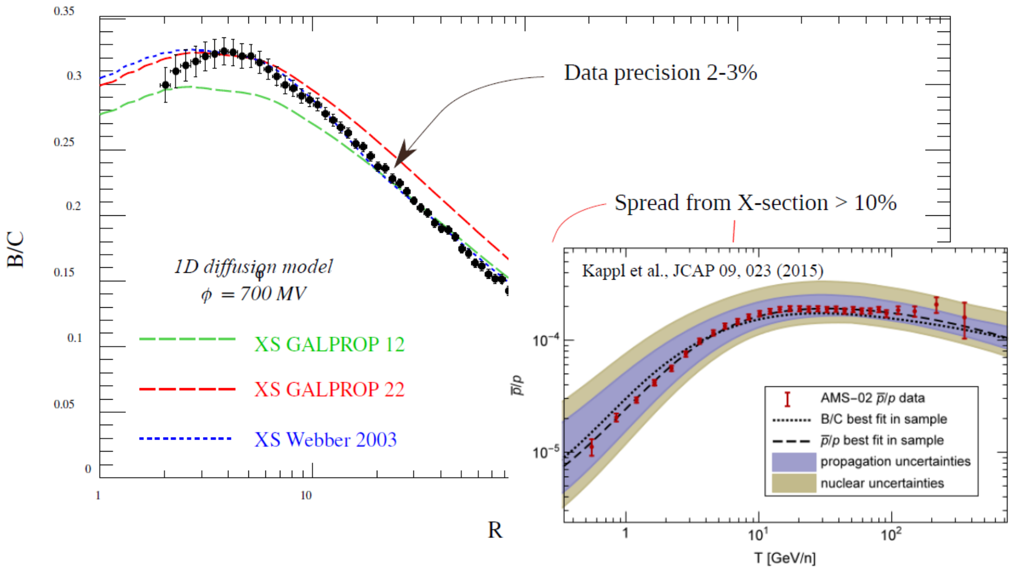
Tomassetti: arXiv1707.06917





Cosmic ray program

From Y. Genolini



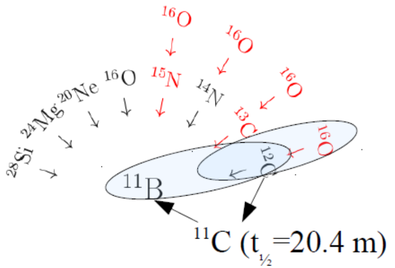
Nuclear cross section is dominant systematic uncertainty on transport parameters

Cosmic ray program

Ranking of individual XS (with short-lived nuclei)
[Set $\sigma_{(P+T\to F)} = 0$ one at a time, propagate, sort]

Separate short-lived (ghost) nuclei

$$\sigma_{CR}^{P+T\to X} = \sigma_{Direct}^{P+T\to X} + \sum_i Br_i\, \sigma_{Ghost}^{P+T\to Xi(\to X)}$$



→ Exactly what we need!

N.B.: flight time between target/detector determines which XS is measured (direct or cumulative of some sort)

Contributions (with ghosts) for B at 10 GeV/n

secondary	=	84.7%
primary	=	0%
radioactive	=	15.3%

Sorted XS	Involved	XS[mb]
$\sigma(^{12}C+H \to {}^{11}B)$	20.0%	30.0
$\sigma(^{12}C+H \to {}^{11}C^{[20.4m\to 11B]})$	17.9%	26.8
$\sigma(^{16}O+H \to {}^{11}B)$	19.9%	27.3
$\sigma(^{12}C+H \to {}^{10}B)$	8.3%	12.3
$\sigma(^{16}O+H \to {}^{10}B)$	8.1%	11.0
$\sigma(^{11}B+H \to {}^{10}B)$	4.4%	38.9
$\sigma(^{16}O+H \to {}^{12}C)$	3.0%	32.3
$\sigma(^{16}O+He \to {}^{11}B)$	3.0%	36.6
$\sigma(^{12}C+He \to {}^{11}B)$	2.9%	38.6
$\sigma(^{12}C+He \to {}^{11}C^{[20.4m\to 11B]})$	2.6%	34.6
$\sigma(^{14}N+H \to {}^{11}B)$	2.6%	29.2
$\sigma(^{12}C+H \to {}^{10}C^{[19.3s\to 10B]})$	2.1%	3.1
$\sigma(^{13}C+H \to {}^{11}B)$	1.5%	22.2
$\sigma(^{16}O+H \to {}^{13}O^{[8.6ms\to 13C]})$	1.4%	30.5
$\sigma(^{16}O+He \to {}^{10}B)$	1.2%	14.7
…		

Energy	10 GeV/nuc		
1 step	80.6%		
2 steps	15.9%		
>2 steps	3.5%		
>1%	$^{11}B \leftarrow {}^{12}C$	32.4%	87%
	$^{11}B \leftarrow {}^{16}O$	18.8%	
	$^{10}B \leftarrow {}^{12}C$	10.4%	
	$^{10}B \leftarrow {}^{16}O$	9.0%	
	$^{10}B \leftarrow {}^{11}B \leftarrow {}^{12}C$	2.3%	
	$^{11}B \leftarrow {}^{24}Mg$	1.8%	
	$^{11}B \leftarrow {}^{12}C \leftarrow {}^{16}O$	1.7%	
	$^{11}B \leftarrow {}^{15}N \leftarrow {}^{16}O$	1.6%	
	$^{11}B \leftarrow {}^{14}N$	1.5%	
	$^{11}B \leftarrow {}^{28}Si$	1.4%	
	$^{11}B \leftarrow {}^{20}Ne$	1.4%	
	$^{10}B \leftarrow {}^{11}B \leftarrow {}^{16}O$	1.3%	
	^{10}Be decay	3.4%	
	# of reactions	Total	
[0.1%, 1%]	28	8.8%	13%
[0.01%, 0.1%]	90	3.5%	
< 0.01%	277	0.7%	

To reach 3% precision on B flux @10 GeV

Need a 2% precision on ~ 10 reactions

and 10% precision on the rest

Energy dependent cross section measurement for all important reactions:

- parameterization
- compilation of data

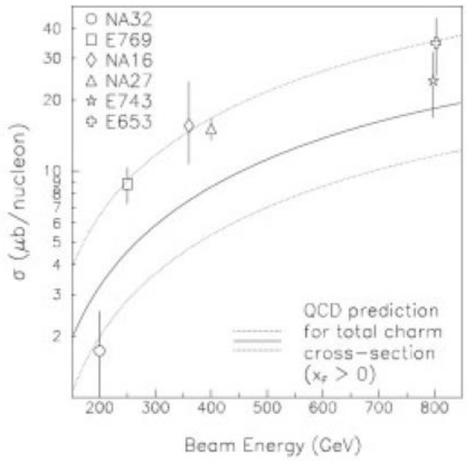
Maurin – NA61 beyond 2020 workshop

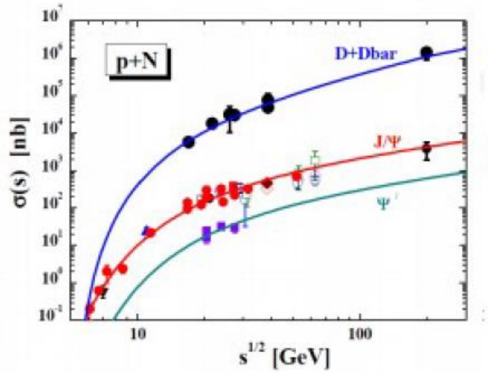
Strong interaction program

Open charm and multi-strange hadron production

Why open charm:

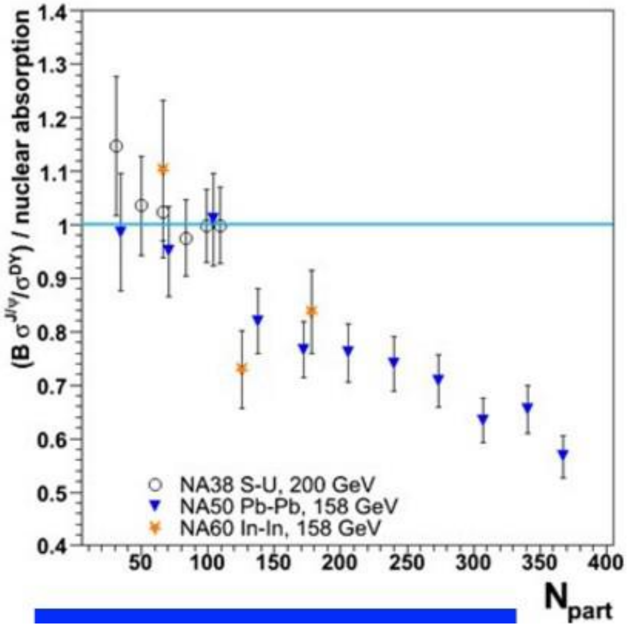
- No measurements for A+A at SPS energies
- Important for onset of deconfinament

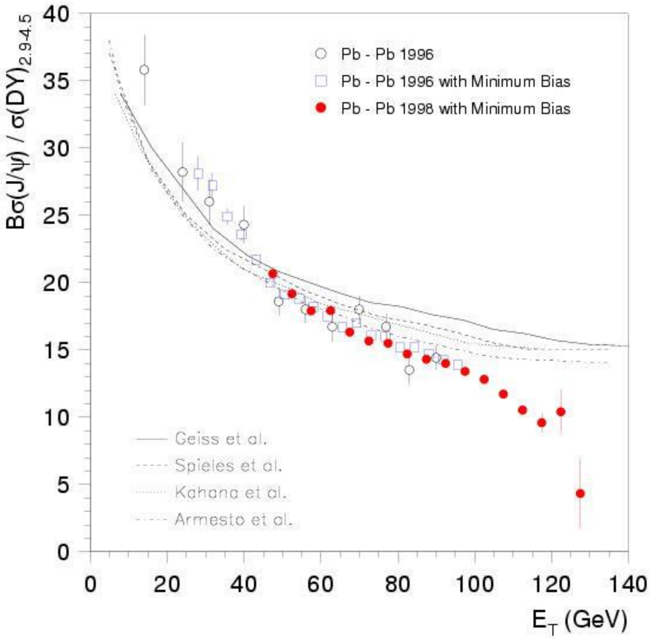




Strong interaction program

Extensive data on <J/Ψ> production at SPS

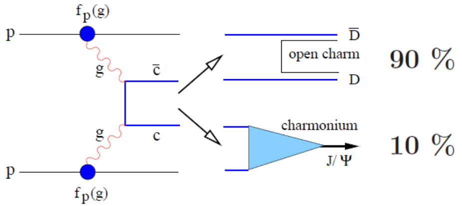




Strong interaction program

How to properly calibrate J/Ψ production
(Satz – NA61 beyond 2020 workshop)

charmonium production
in *pp* collisions



J/ψ measured in pp collisions is approximately

60 % direct $J/\psi(1S)$, 30 % $\chi_c(1P)$ & 10 % ψ' (2S)feed-down

narrow resonances → decay outside interaction region

medium sees traversal of higher resonances

- crucial question:

are these features

(hidden/open, relative quarkonium fractions)

changed in nuclear collisions?

Strong interaction program

modifications in nuclear collisions:

- initial state effects
  - pdf modification (shadowing, antishadowing)
  - energy loss of incident parton (gluon)
- final state effects
  - energy loss of primary $c\bar{c}$
  - cold nuclear matter effect on (nascent) charmonium
  - secondary matter effect on (nascent) charmonium

(Satz – NA61 beyond 2020 workshop)

Strong interaction program

previous analysis procedure:

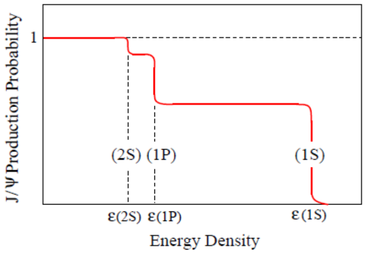
- measure production in pp and pA
  - determine pdf modification (shadowing, antishadowing)
  - determine parton energy loss
  - determine cold nuclear matter effect
- construct model for AA
  - scale pp by number of collisions
  - incorporate initial & cnm final state modifications
- compare to AA data: is there *anomalous behavior?*
  i.e., something not accounted for by model $\longrightarrow$ inconclusive

Strong interaction program

Theoretical Scenarios

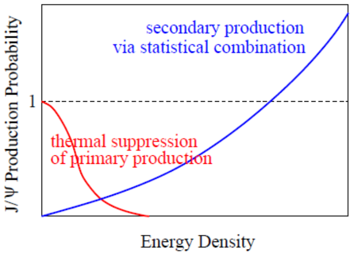
- sequential suppression

  color screening dissociates charmonium states in QGP first higher excited states (2S), (1P), then ground state (1S)



- statistical enhancement

  all primary charmonia dissociated at high collision energy, overabundance of charm quarks equilibration, $c\bar{c}$ excess survives hadronisation by statistical combination



- Both scenarios claim that presence of medium modifies the relative fraction of $c\bar{c}$ going into charmonia
- neither says anything about how many $c\bar{c}$ pairs are produced in AA relative to scaled pp

Conclusions

Only measurements of hidden/open heavy flavor production,

measurements of excited/ground state quarkonium production

in pp, pA, AA

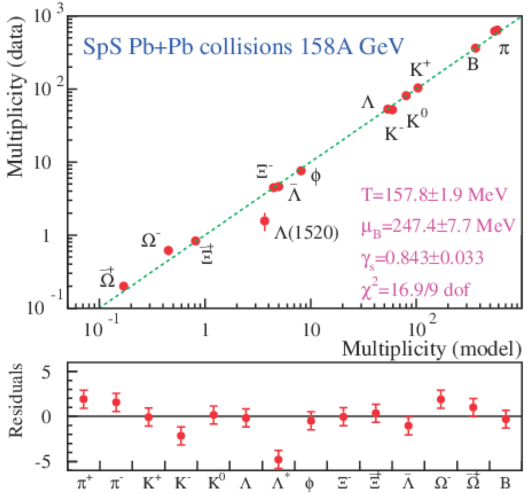
can provide model-independent answers

to model-independent questions.

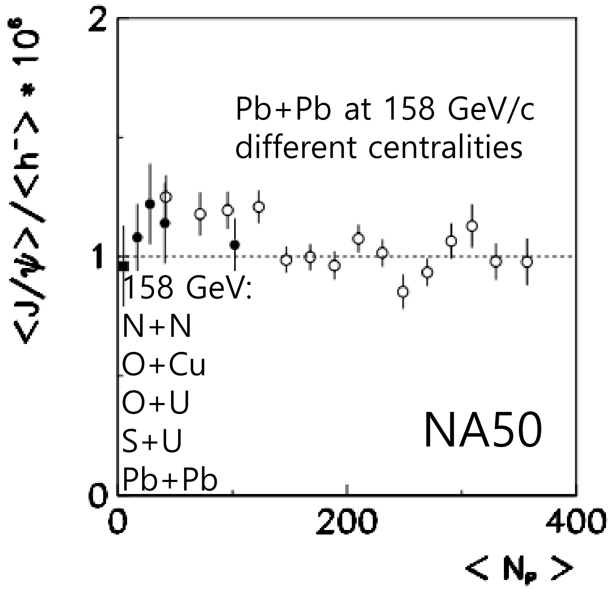
Strong interaction program

Alternative model – statistical hadronization model

Successfully describes strange and non-strange particle production



$\langle J/\Psi\rangle(\sim V)/\langle h^-\rangle(\sim V) = const(A)$



NA61/SHINE - beams and targets

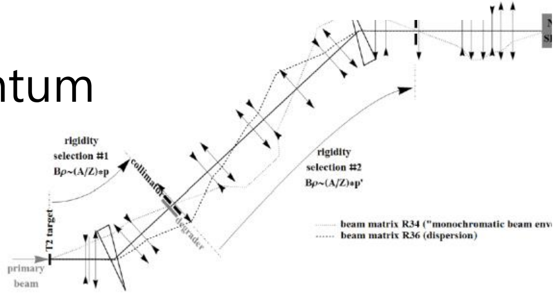
Possible beams:

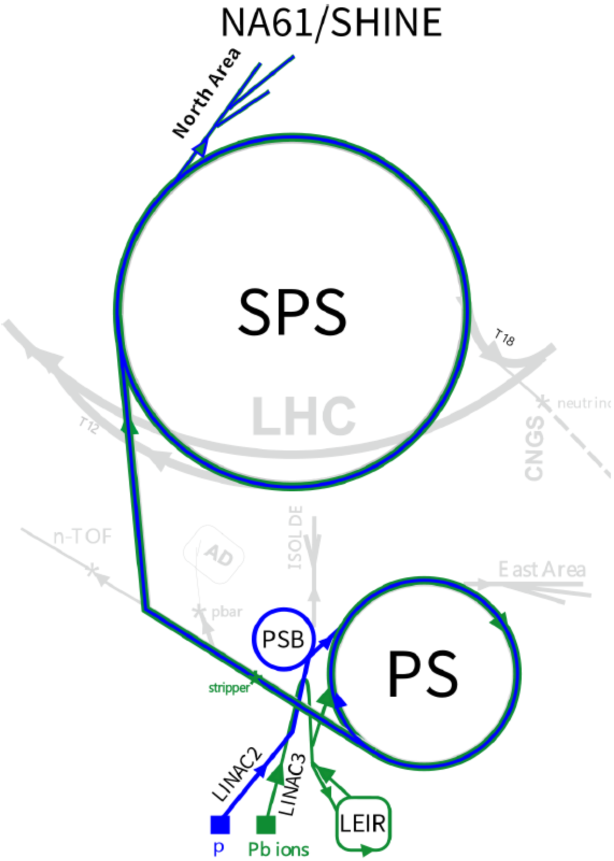
- Hadrons:
  - Primary protons at 400 GeV/c
  - Secondary (π, K, p) at 13–350 GeV/c
- Ions:
  - Primary: Ar, Xe, Pb at 13*A*–150*A* GeV/c
  - Secondary from Pb fragmentation (e.g. Be) at 13*A*–150*A* GeV/c

Targets:

- Almost any solid state (from 500 μm to 1 m)
- Liquid hydrogen (20 cm)

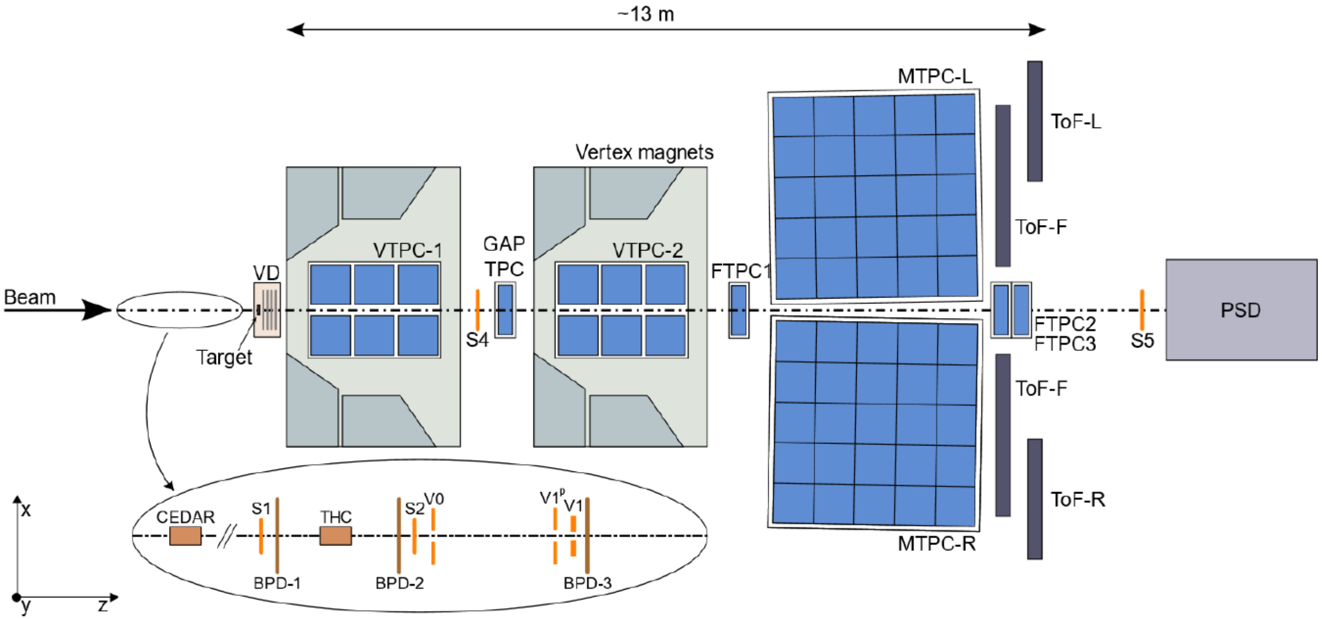
H2 beamline is used for momentum and chargé selection as well as nuclear fragments separation





NA61 spectrometer

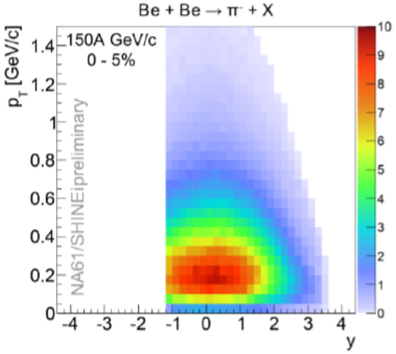
Large acceptance hadron spectrometer – coverage of the full forward hemisphere, down to $p_T = 0$



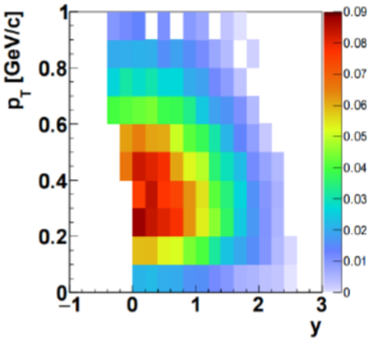
NA61 particle identification

- Particle identification methods
  - d*E*/dx — based on TPCs energy loss measurements
  - ToF-d*E*/dx — based on combined TPCs and ToFs measurements
  - h^- — used for π^- identification based on Monte-Carlo models
  - V0, Ξ, Ω, D^0 — based on decay topology
- Example phase space coverage of various identification methods:

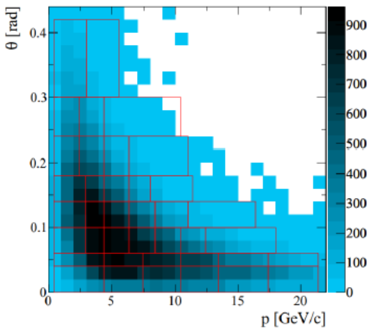
π^- from h^- method
Be + Be



K^- from ToF-d*E*/dx
p + p



Λ from V0
p + C



Facility upgrades

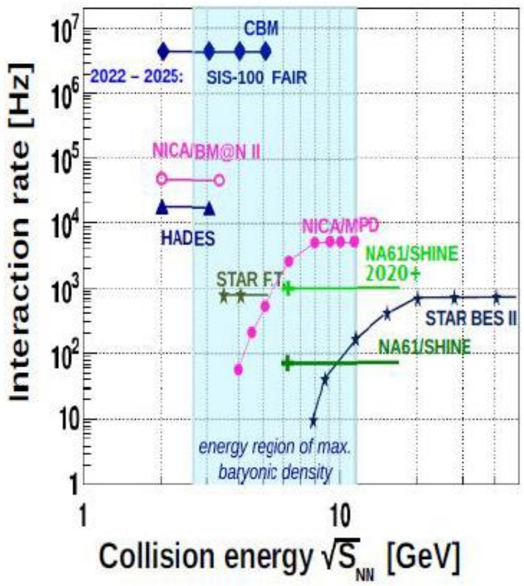
Increase readout rate to 1kHz:

New TPC readout electronics (from ALICE)

New Data Acquisition System

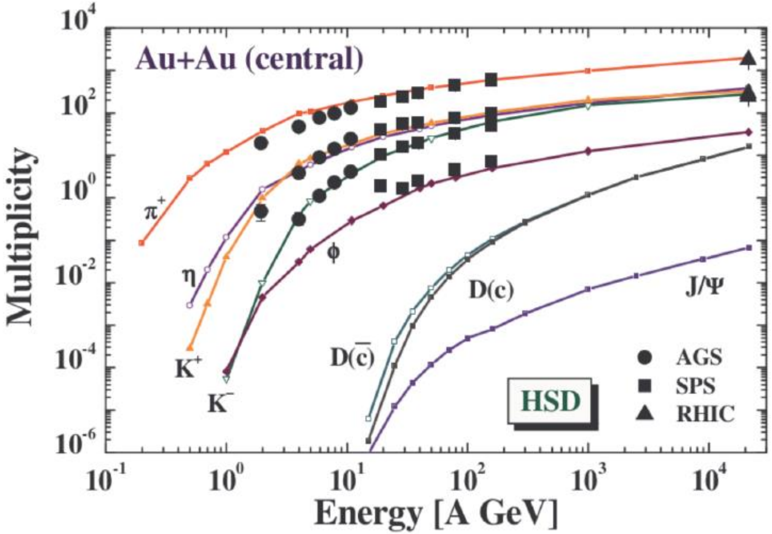
Detectors upgrades:

- Large acceptance Vertex Detector based on ALPIDE sensors
- New ToF walls based on mRPC technology
- New BPDs based on scintillating fibers
- Upgrade of the PSD to handle large beam intensities



Open charm simulations

200k of the 0-10% most central Pb+Pb collisions at 150AGeV/c were generated using the AMPT (A MultiPhase Transport) model



The model properly describes production of charged pions and kaons.

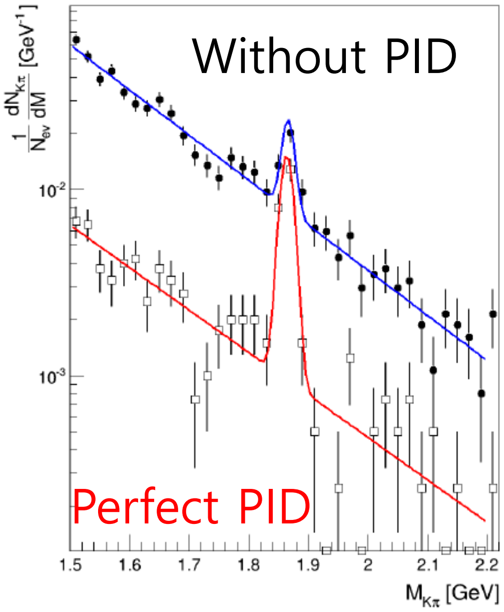
The AMPT model predicts an average multiplicity of about 0.01 for $D^0 + \overline{D}^0$ mesons produced in central Pb+Pb collisions at 150*A* GeV/c (significantly lower than the predictions of PYTHIA and HSD)

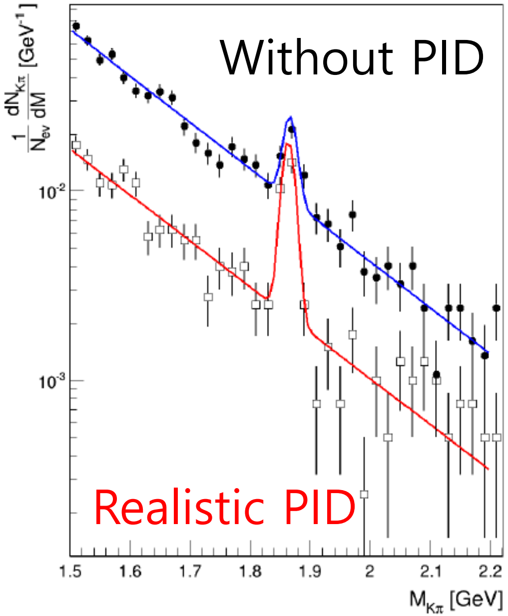
AMPT mean multiplicity for $D^0 + \overline{D}^0$ mesons was scaled to the HSD prediction.

L. Zi-Wei et al. Phys. Rev. **C72** (2005) 064901
E. Linnyk, Bratkovskaya and W. Cassing Int. J. Mod. Phys. **E17** (2008) 1367.

SAVD simulations results

The invariant mass of pion-kaon pair candidates after the cuts for the SAVD.

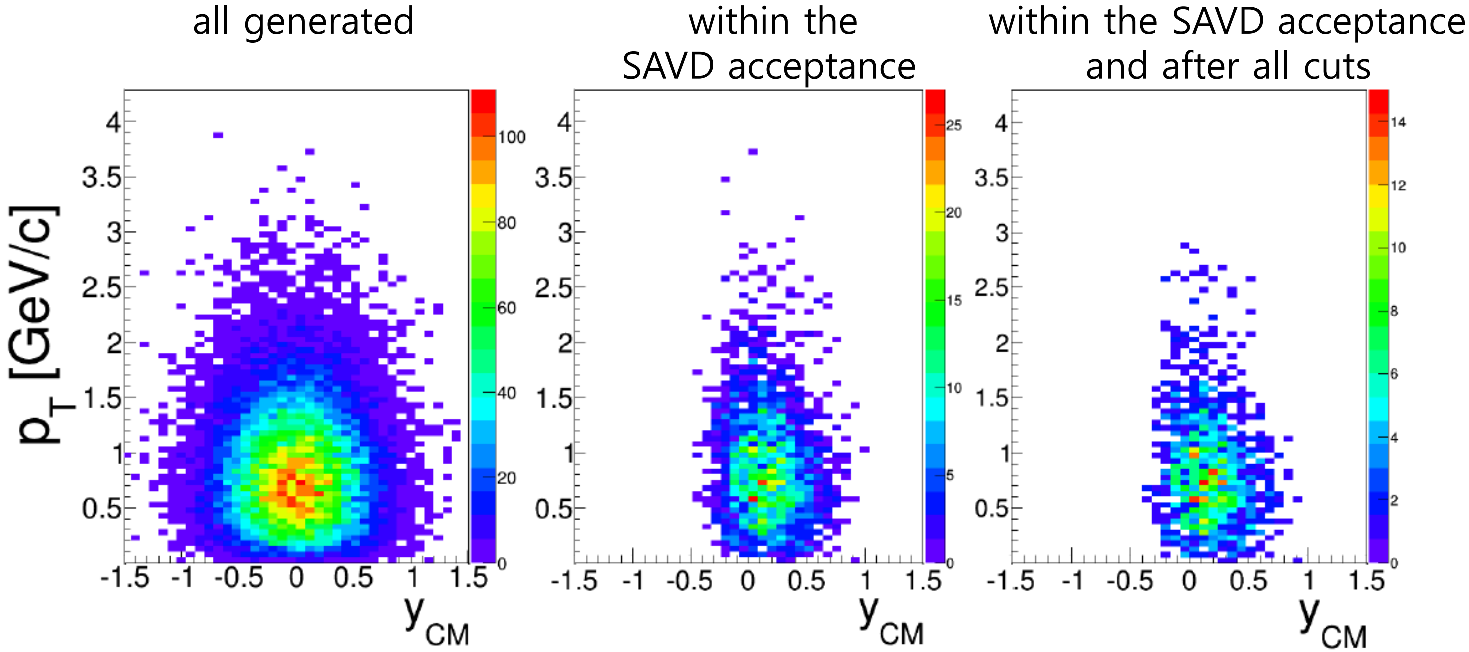




The total number of measured $D^0 + \overline{D}^0$ decays in 4 millions central **Pb+Pb collisions at 150*A* GeV/c** (statistics after 1 day of data taking beyond 2020) is estimated to be about **1500**

SAVD simulations results

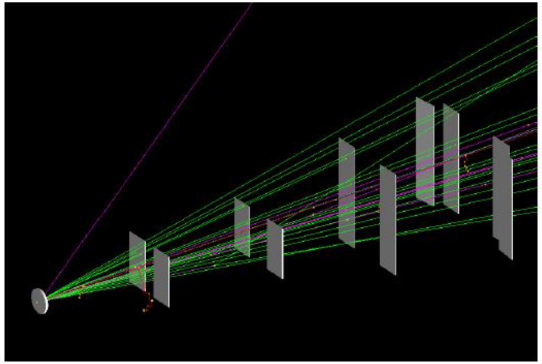
Population of D^0 mesons in transverse momentum p_T and rapidity y.

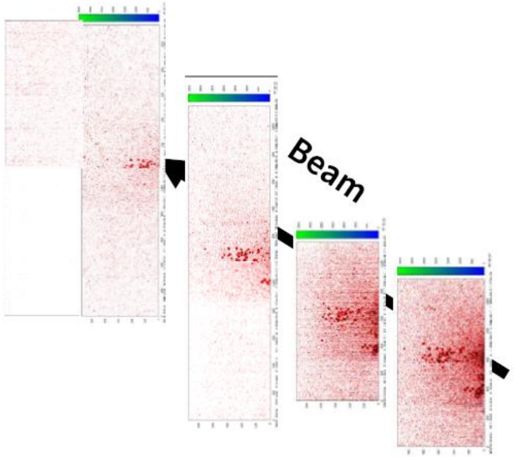


Results are plotted for the 0-20 % most central Pb+Pb collisions at 150*A* GeV/c and correspond to 4 million events.

NA61 – Vertex detector

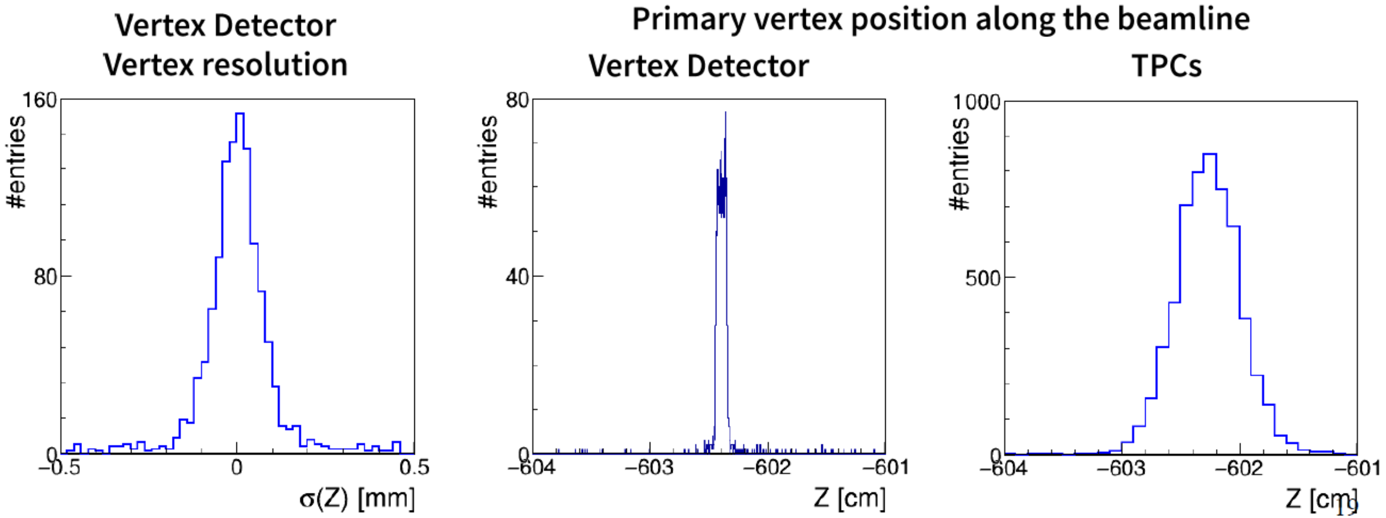
- Built for open charm measurements
- Based on Mimosa26 sensors
- Small Acceptance VD:
  4 stations, 16 sensors
- 5 μm tracking resolution





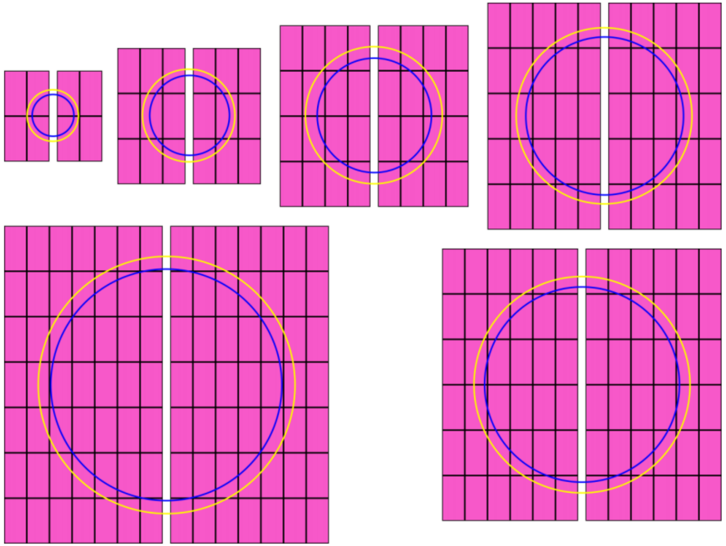
NA61 – Vertex detector

- Vertex detector was commissioned in December 2016
- Pb + Pb at 150*A* GeV/c data taking with 1 mm target
- Vertex resolution: 30 μm — possible to distinguish D^0 decays



Vertex Detector beyond 2020

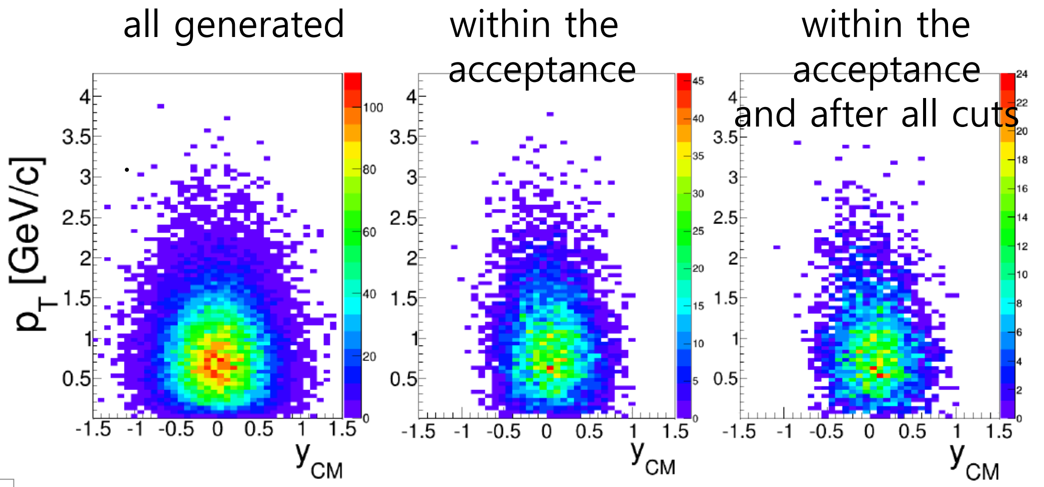
In the VD beyond 2020 the stations are located at the same distances as in the SAVD.

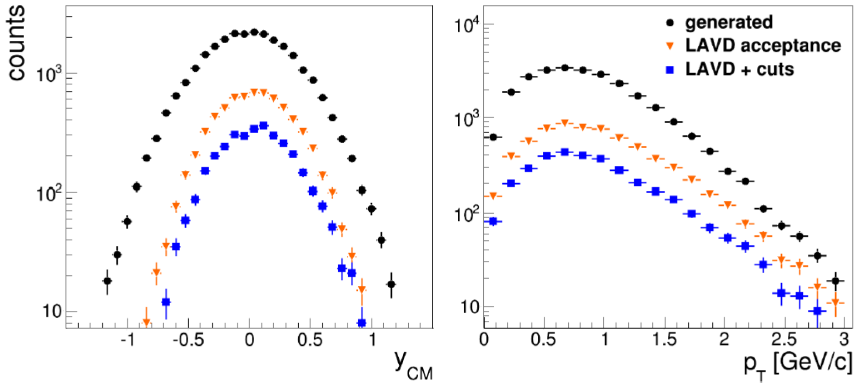


Approximately 6 layers with 400 ALPIDE sensors. Basically geometry of SAVD with additional sensors and layers.

Vertex Detector beyond 2020

Results are plotted for the 0-20 % most central Pb+Pb collisions at 150*A* GeV/c and correspond to 4 million events. –
1 day of data taking beyond 2020





10 days of Pb+Pb data taking in 2021 (40M events):

Beam momentum	40*A* GeV/c	75*A* GeV/c	150*A* GeV/c
D^0 candidates	1000	7000	40000

Summary

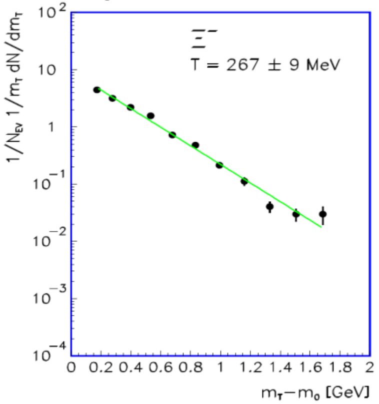
- NA61 beyond 2020 will be well suited to precisely measure open charm produced in Pb+Pb collisions at 40-150A GeV/c.

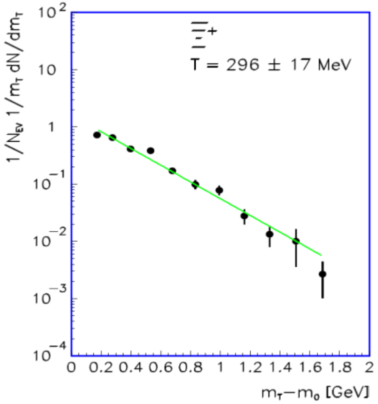
  Statistics should be sufficient to obtain two dimensional spectra of D^0 and their antiparticles.
- Fragmentation cross sections measurements needed for interpretation of AMS-02 data can be performed only by NA61 beyond 2020.
- Measurements for neutrino experiments are under consideration.
- Proposal for the new program should be ready by the end of the year.

Backup

Multi-strange hadrons beyond 2020

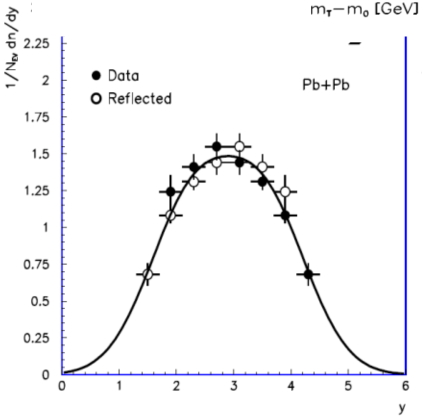
History

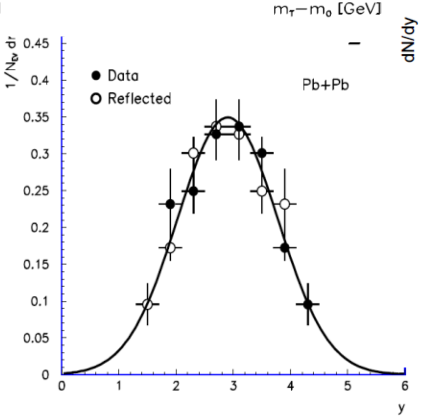


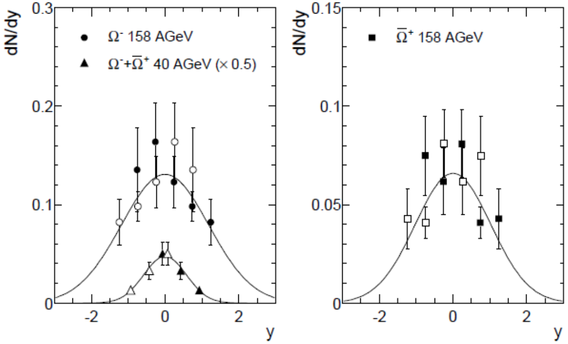


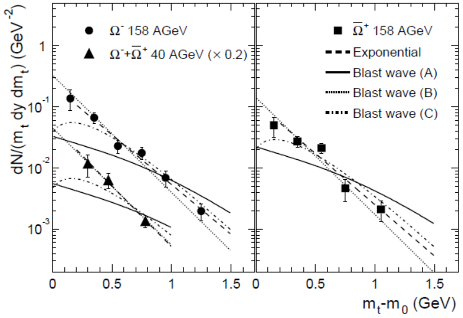
NA49 experiment measured Ω production in Pb+Pb collisions (with centrality window 22%) based only on candidates with decay length higher than 25 cm from interaction point

and Ξ production (with centrality window 7%) based only on candidates with decay length higher than 35 cm from interaction point





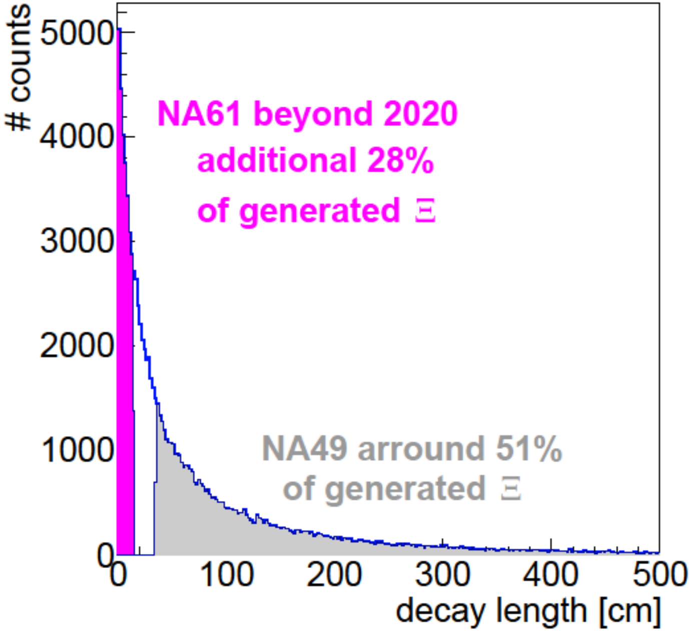




NA49 Collaboration: **Phys.Rev.Lett. 94 (2005) 192301, Phys.Lett. B538 (2002) 275-281**

Multi-strange hadrons beyond 2020

Impact of vertex detector for Ξ measurements



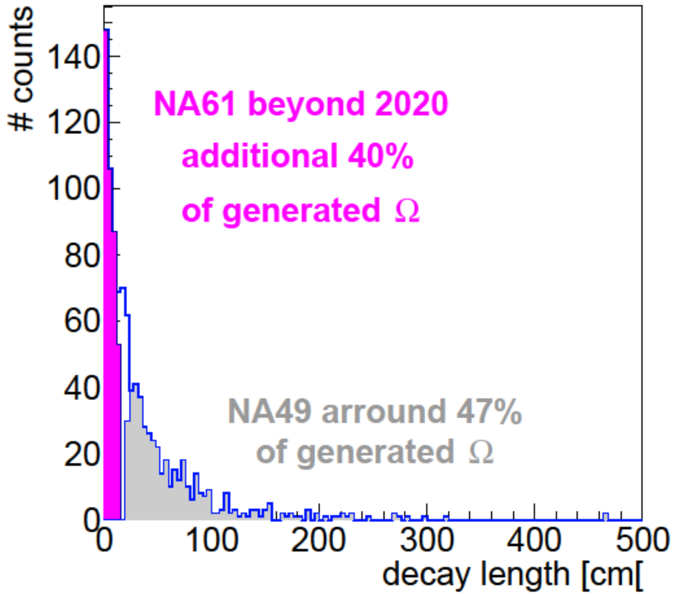
Precise vertex measurement should automatically reduce combinatorial background.
Acceptance similar to NA49.
Additional 28% of Ξ visible.

Pb+Pb at 158*A* GeV/c:

Source	Ξ^-	$\overline{\Xi}^+$
NA49 (400k events)	4800	900
VD improvement (400k events)	7400	1400
Readout rate (40M events)	740000	140000

Multi-strange hadrons beyond 2020

Impact of vertex detector for Ω measurements



Precise vertex measurement should automatically reduce combinatorial background.

Acceptance similar to NA49.

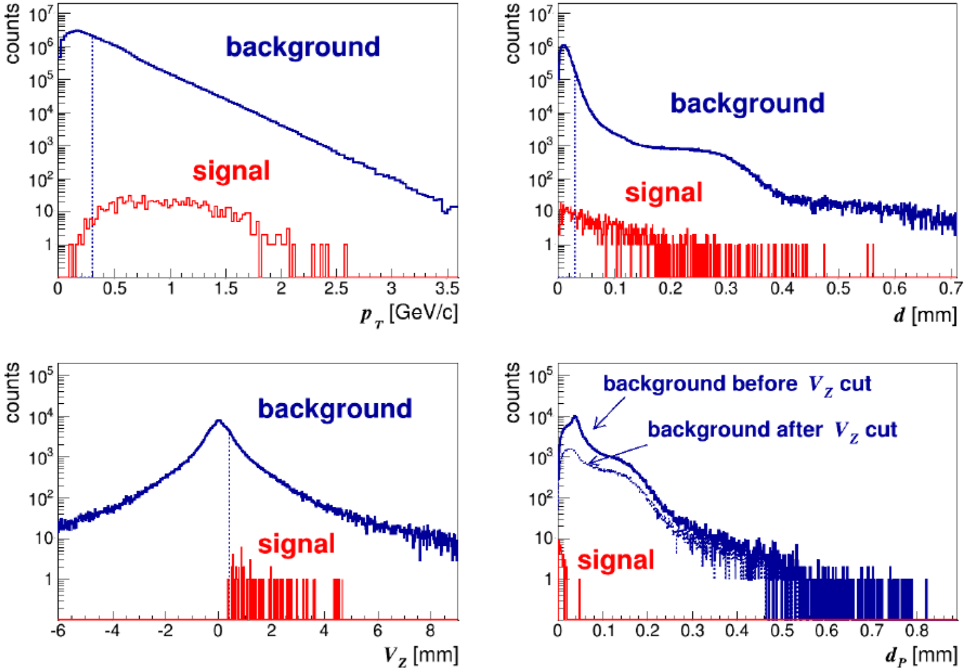
Additional 40% of Ω visible.

Pb+Pb at 158*A* GeV/c:

Source	Ω^-	$\overline{\Omega}^+$
NA49 (2.5M events)	~350	~100
VD improvement (2.5M events)	650	185
Readout rate (40M events)	10400	3000

The strategy for reconstructing open charm

In order to reduce the large combinatorial background, kinematical and topological cuts are applied:



(i) A cut on the track transverse momentum p_T,

(ii) a cut on the track impact parameter d,

(iii) a cut on the longitudinal distance V_Z between the D decay candidate and the interaction point,

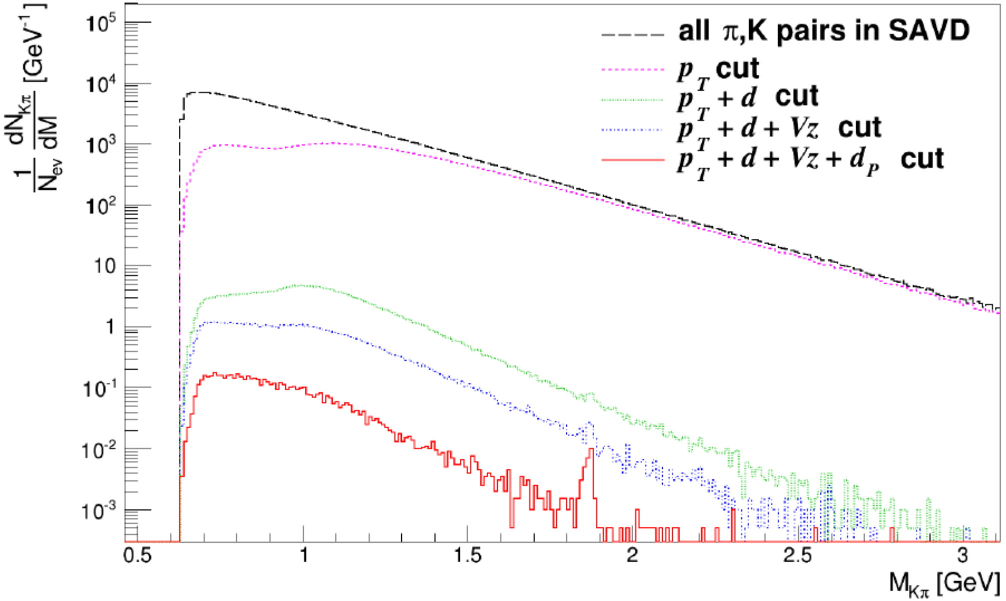
(iv) a cut on the impact parameter d_P of the back-extrapolated D candidate momentum vector.

We select tracks with $p_T > 0.31$ GeV/c, $d > 31$ μm, and track pairs with $V_z > 400$ μm, $d_P < 20$ μm.

Addendum to the NA61/SHINE Proposal SPSC-P-330 CERN-SPSC-2015-038 / SPSC-P-330-ADD-8

The strategy for reconstructing open charm

The cuts reduce the number of **signal pairs by a factor of 2**, while the number of **background** pairs in the signal region is reduced **by a factor of $2x10^5$**



The distributions were obtained assuming perfect particle identification.

Addendum to the NA61/SHINE Proposal SPSC-P-330
CERN-SPSC-2015-038 / SPSC-P-330-ADD-8