SHINE

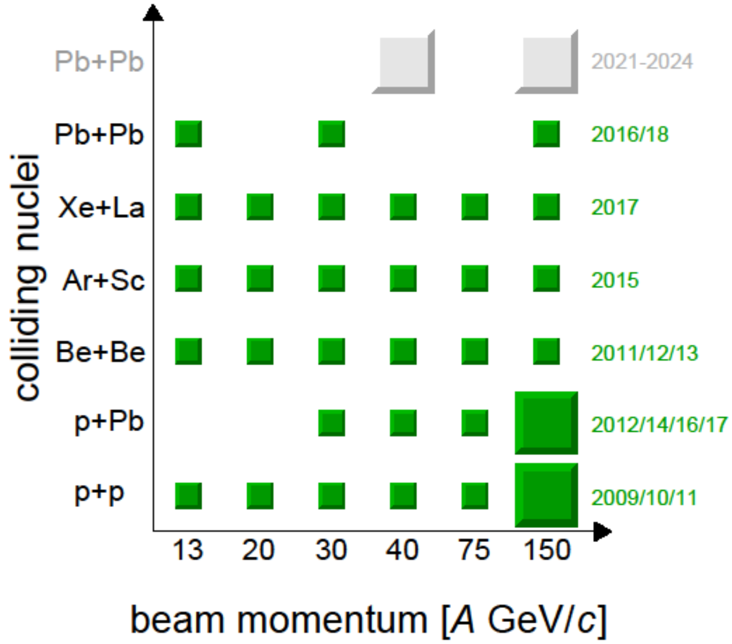
NA61/SHINE beyond 2020

Szymon Puławski
for NA61/SHINE

Analysis of data recorded in 2009-18

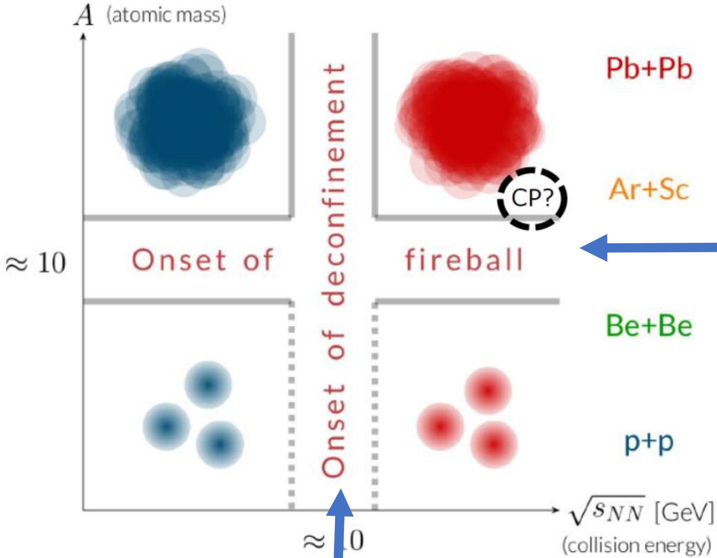
NA61/SHINE recorded unique data for:

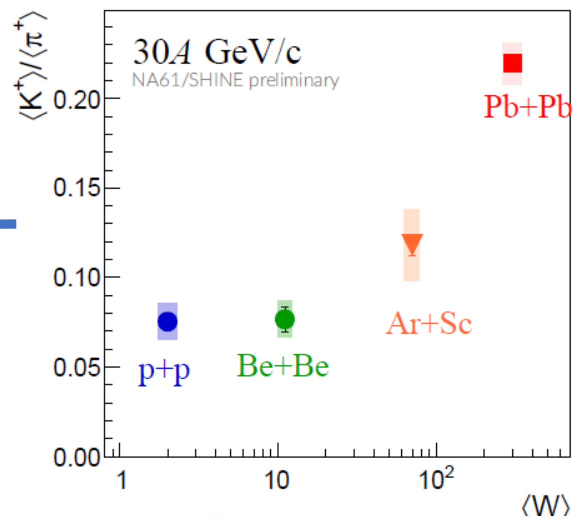
- Heavy ion physics
  - Onset of deconfinement
  - Onset of fireball
  - Critical point
- Neutrino physics
  - T2K at J-PARC
  - Fermilab experiments
- Cosmic-ray physics
  - Extensive air showers
  - Auger, Kaskade

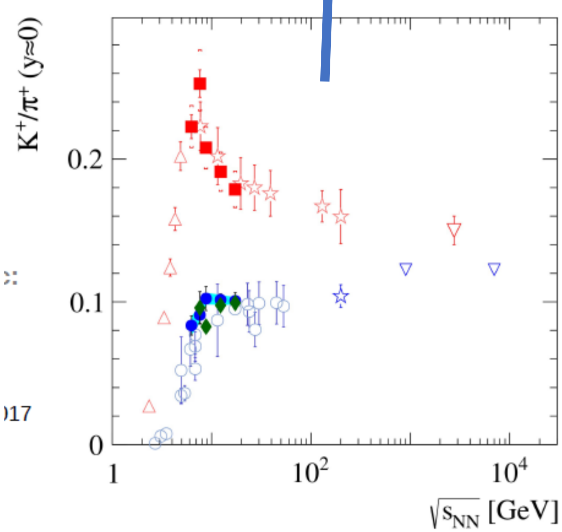


Data analysis will continue for at least five years

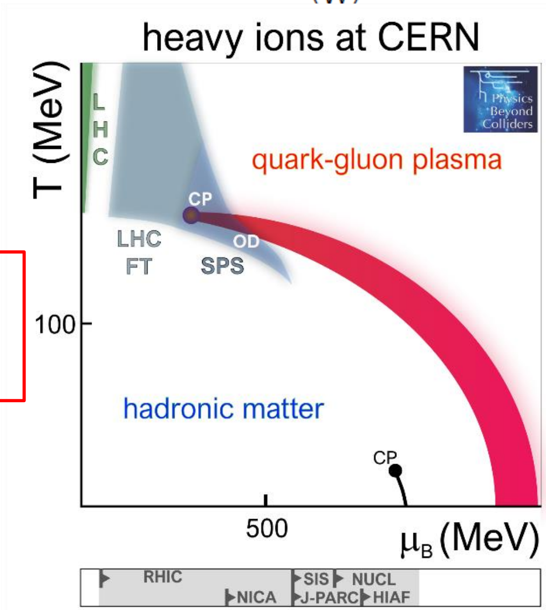
Uniqueness of heavy ion physics at the CERN SPS







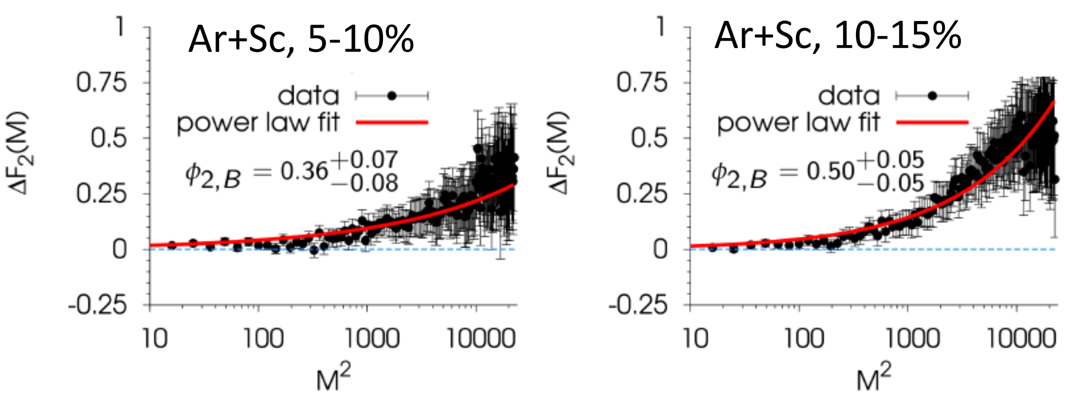
Two onsets at SPS.
Critical point at SPS?



Proton intermittency as signal of CP

- Second order phase transition → scale invariance → characteristic dependence of fluctuations on size δ of subdivision intervals of momentum space Δ
- $M = \Delta/\delta$ – numer of intervals
- $F_2(M) \equiv \sum_{i=1}^{M} < N_i(N_i - 1) > / \sum_{i=1}^{M} < N_i >^2$
- Where:
- N_i – particle number in bin i,
- <…> - averaging over events
    - At critical point power law dependence is expected $F_2(M) = F_2(\Delta) M^{\varphi_2}$

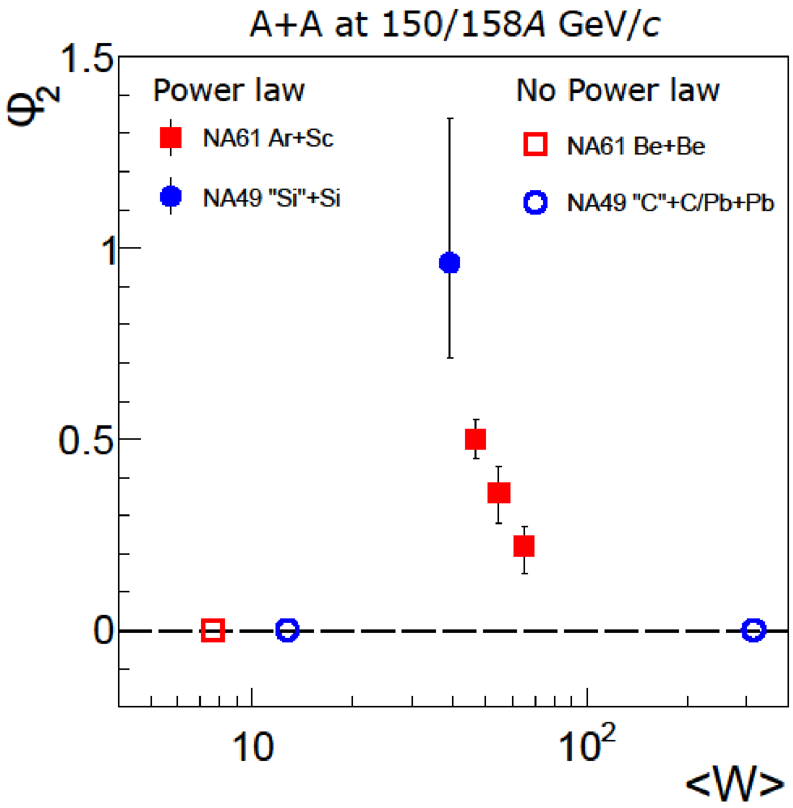
Ar+Sc at 150*A* GeV/c



Indication of intermittency effect in mid-central **Ar+Sc**

First possible indication for CP signal in NA61/SHINE

Proton intermittency



At critical point power law dependence is expected

$$F_2(M) = F_2(\Delta)\ (M^2)^{\varphi_2}$$

First possible indication for CP signal in NA61/SHINE

Only statistical uncertainties shown

NA61/SHINE program for 2021-2024

- Fundamental physics
  - Open charm production in Pb+Pb at SPS
- Reference measurements:
  - Nuclear fragmentation cross-section for cosmic-ray experiments
  - Hadron production for neutrino experiments

- Recent documents:

March 21, 2018, Addendum 10:
Study of Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN SPS: Early Post-LS2 Measurements and Future Plans,
CERN-SPSC-2018-008, SPSC-P-330-ADD-10

June 5, 2018, Addendum 11:
Reply to the SPSC questions on Addendum CERN-SPSC-2018-008,
CERN-SPSC-2018-019, SPSC-P-330-ADD-11

SPSC recommended data taking in 2021

Questions that motivate open charm measurements at the CERN SPS:

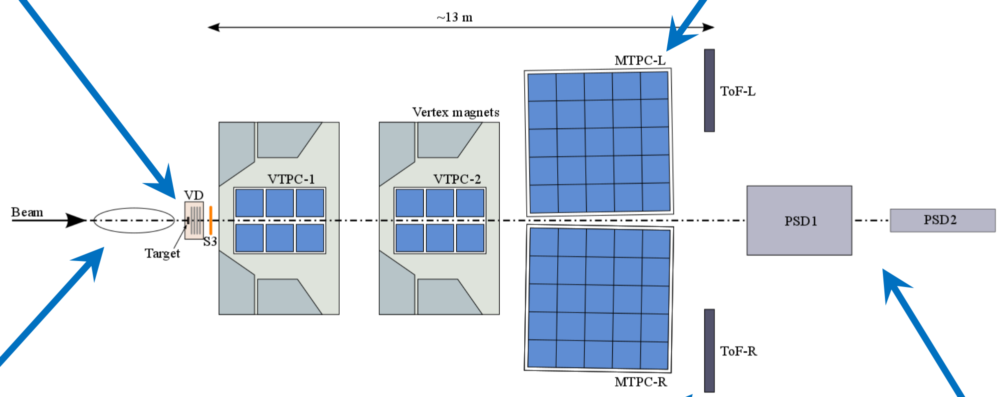
- What is the mechanism of open charm and J/ψ production?
- How does the onset of deconfinement impact open charm production?
- How does the formation of quark gluon plasma impact J/ψ production?

To answer these questions **mean number of charm quark pairs, $\langle c\bar{c} \rangle$**, produced in A+A collisions has to be known.
Up to now corresponding experimental **data does not exist** and **only NA61/SHINE can perform it in the near future**.

Detector upgrade during LS2

Construction of Vertex Detector (VD)
for D^0, $\overline{D^0}$ decay reconstruction

Replacement of the TPC
read-out electronics
to increase data rate to 1 kHz



New trigger and data
acquisition system

New Time-of-Flight
detectors (stage 2)

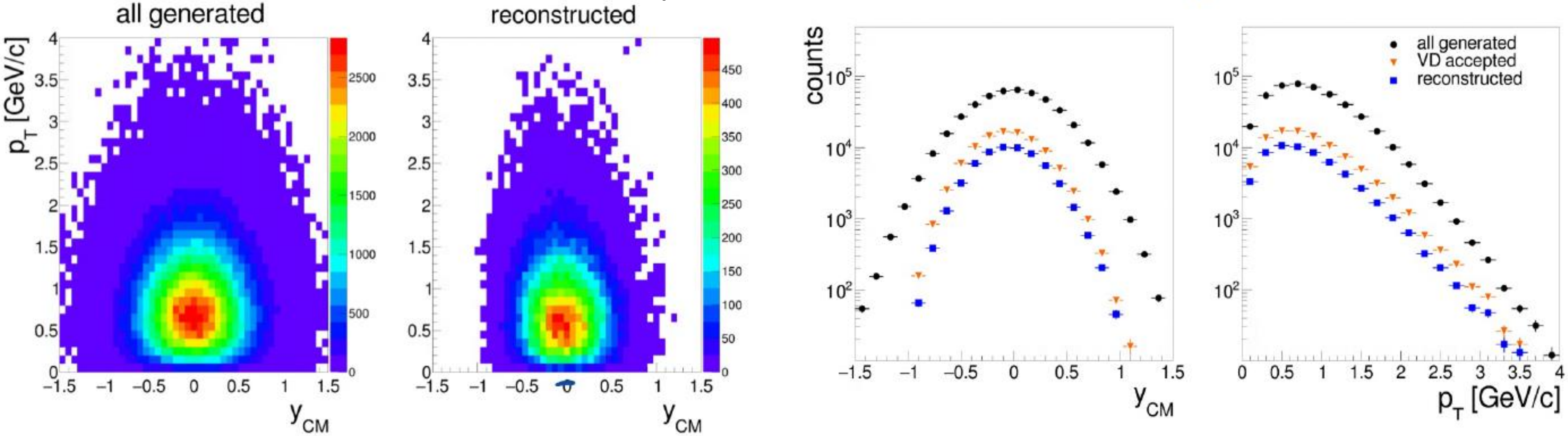
Upgrade of Projectile
Spectator Detector

In total 850k CHF (Hardware only, stage 1)
Moderate costs thanks to collaboration with
ALICE (TPC, VD) and CBM (PSD)

Data statistic (2021-24) and acceptance

Reaction	days	events	$\#(D^0 + \overline{D}^0)$	$\#(D^+ + D^-)$
Pb+Pb at 150A GeV/c	84	500M	76k	46k
Pb+Pb at 40A GeV/c	42	250M	3.6k	2.1k

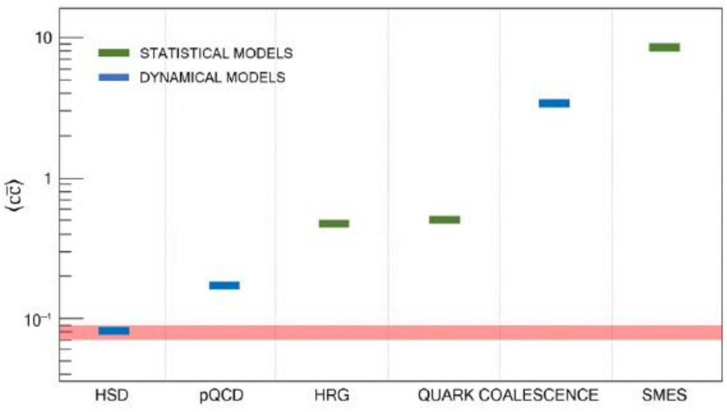
$D^0 + \overline{D^0}$ acceptance: Pb+Pb at 150A GeV/c



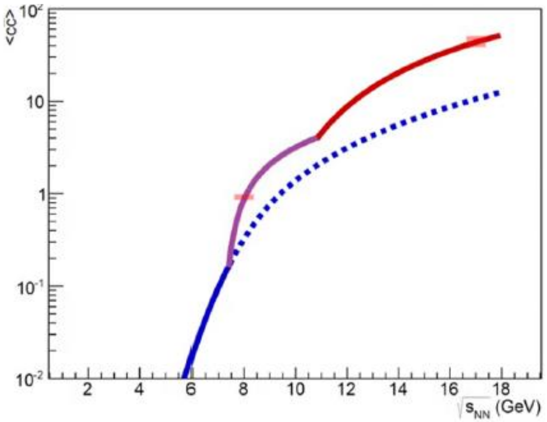
Centrality	0–10%	10–20%	20–30%	30–60%	60–90%	0–90%
$\#(D^0 + \overline{D}^0)$	31k	20k	11k	13k	1.3k	76k
$\#(D^+ + D^-)$	19k	12k	7k	8k	0.8k	46k

Expected physics impact of NA61/SHINE $\langle c\bar{c} \rangle$ measurements

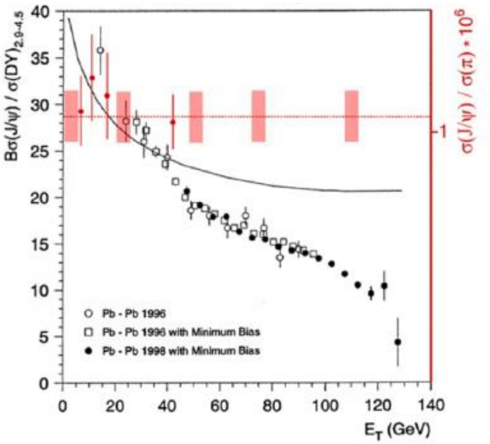
$\langle c\bar{c} \rangle$ and models



$\langle c\bar{c} \rangle$ and onset of deconfinement



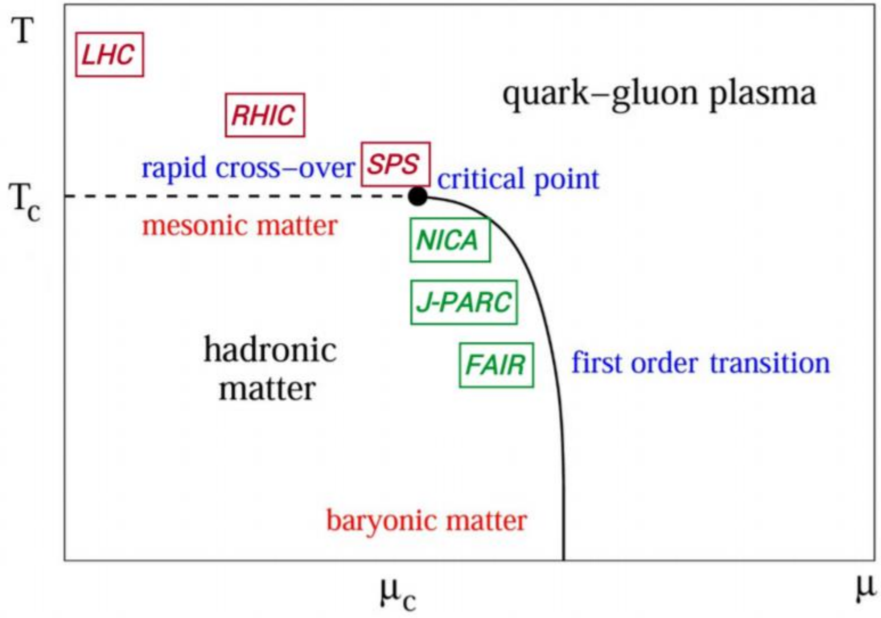
$\langle c\bar{c} \rangle$, $\langle J/\psi \rangle$ and QGP



Foreseen NA61/SHINE resolution is sufficient
to answer addressed questions

Uniqueness of NA61 open charm program

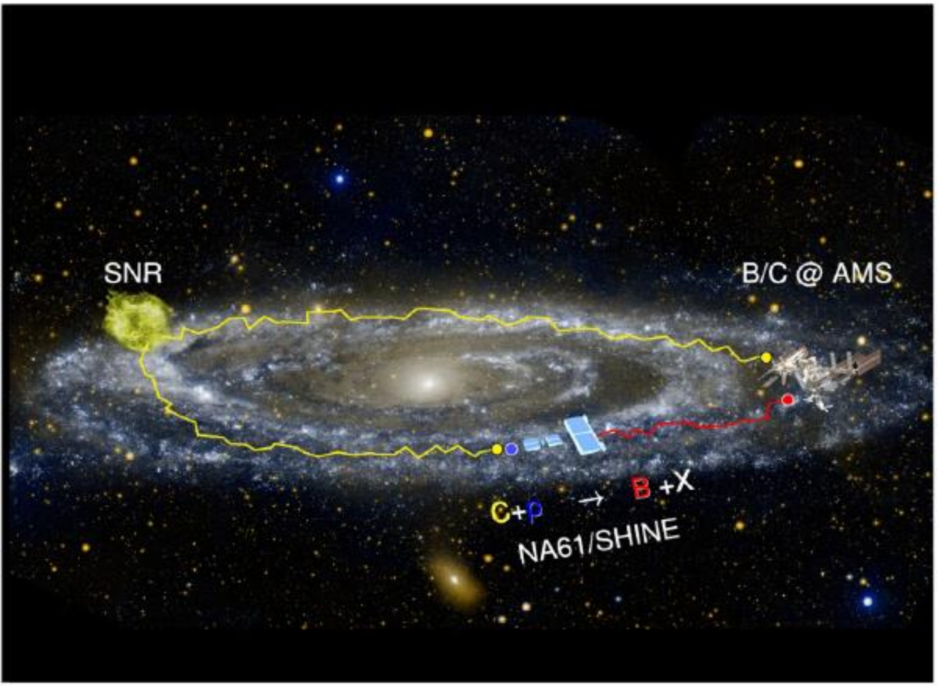
Landscape of present and future heavy ion experiments



Only NA61/SHINE is able to measure open charm production in heavy ion collisions in full phase space in the near future

- LHC and RHIC at high energies: measurements in small phase space due to collider geometry
- RHIC BES collider: measurement not possible due to collider topology
- RHIC BES fixed-target: measurement require dedicated setup, not under consideration
- NICA (< 80*A* GeV/*c*): measurement during stage 2 under consideration
- J-PARC (< 20*A* GeV/*c*): maybe possible after 2025
- FAIR (< 10*A* GeV/*c*): not possible

Reference measurements: Nuclear fragmentation cross section for cosmic ray experiments



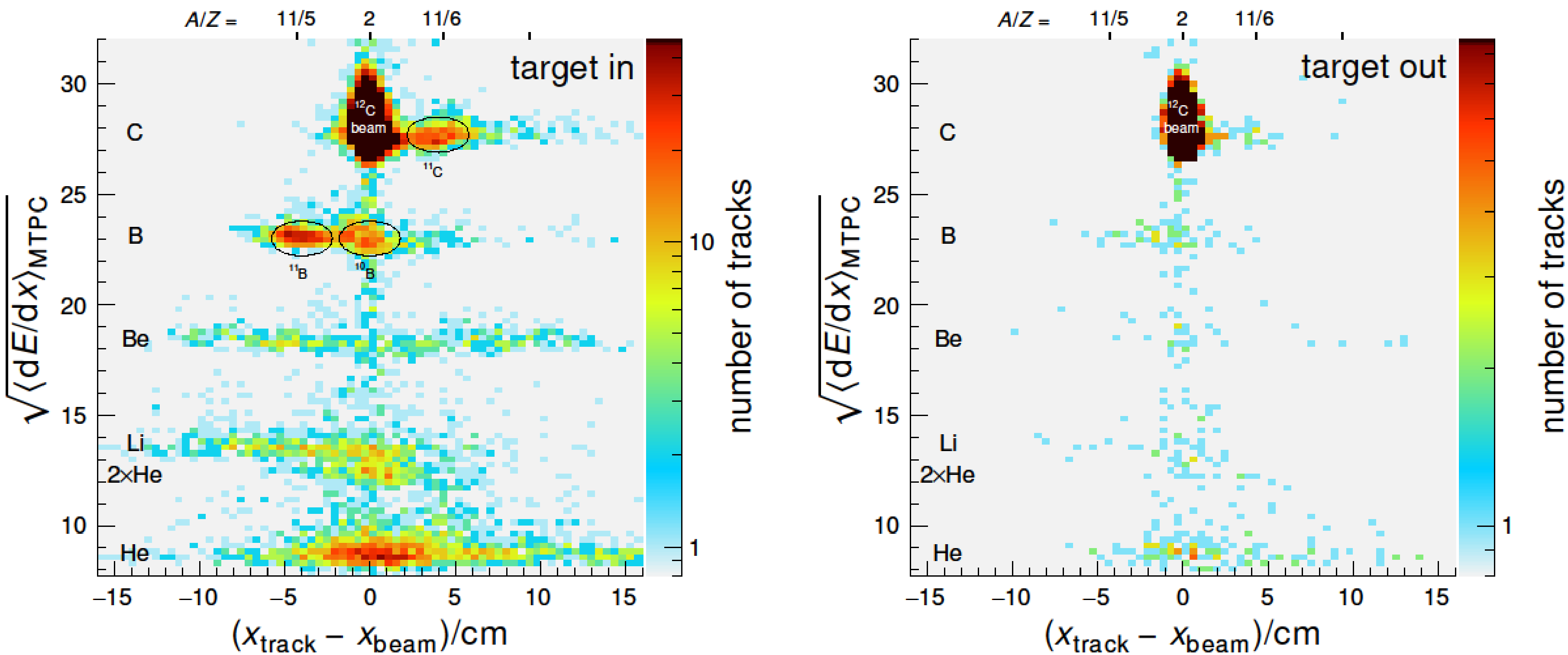
- Primary cosmic rays from supernova remnants
- Secondary cosmic rays from interactions with interstellar matter during propagation e.g.
  $^{12}\mathrm{C} + \mathrm{p} \overset{\text{frag.}}{\rightarrow} \mathrm{B} + \mathrm{X}$
  $^{12}\mathrm{C} + \mathrm{p} \overset{\text{frag.}}{\rightarrow} {}^{11}\mathrm{C} + \mathrm{p} \overset{\text{decay}}{\rightarrow} \mathrm{B} + \mathrm{Y}$
- Primary-to-secondary ratios (e.g. B/C) $\rightarrow$ traversed mass density
- Unstable-to-stable ratios (e.g. $^{10}\mathrm{Be}/^{9}\mathrm{Be}$) $\rightarrow$ traversed distance
- Important for the understanding of origin of Galactic cosmic rays and backgrounds for DM searches

Understanding of cosmic ray propagation limited by uncertainties of fragmentation cross sections

NA61/SHINE will significantly reduce the uncertainties (from 20% to 0.5%)

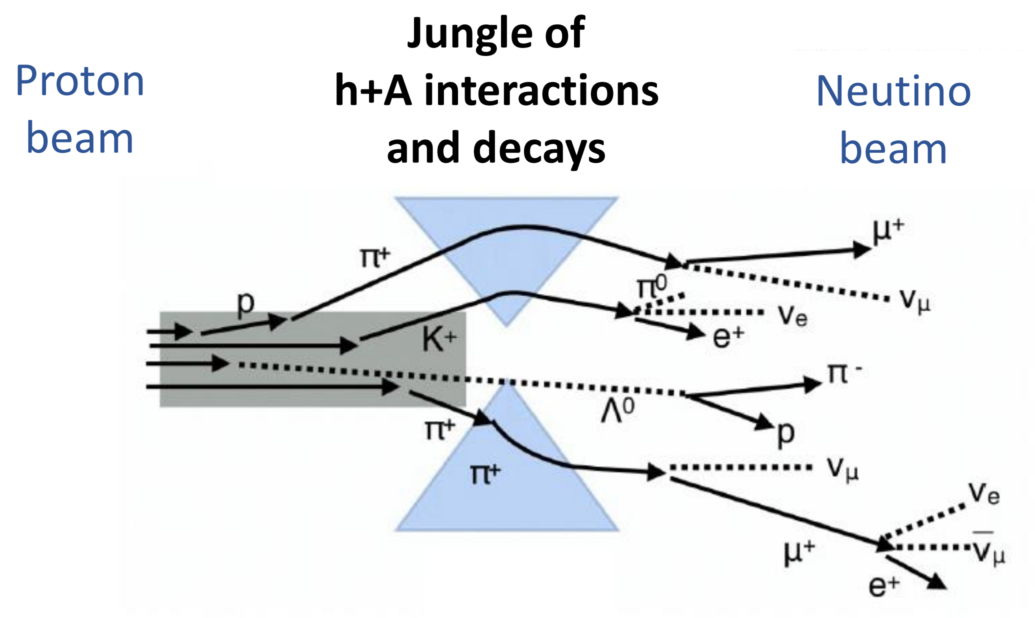
First look on 2018 test
Fragmentation cross sections

Pb at 13.5*A* GeV/c→ Secondary fragments with A/Z=1/2 at 13*A* GeV/c



NA61/SHINE setup allows to determine fragmentation cross section

Reference measurements: Hadron production for neutrino experiments



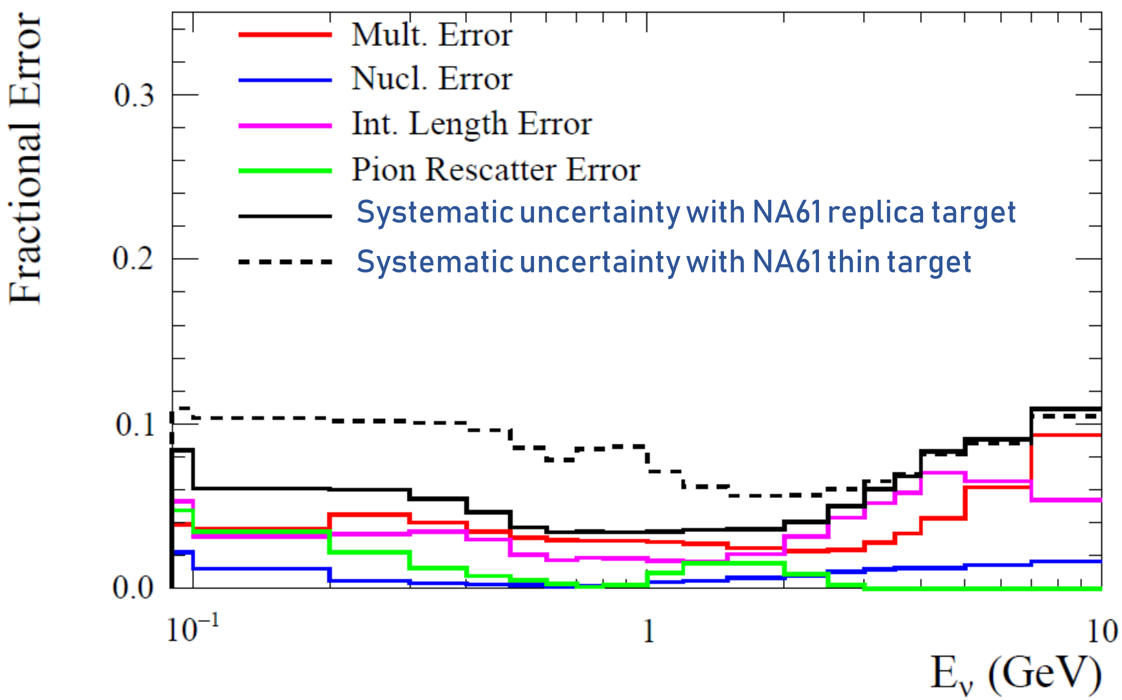
- Further improvement of the precision of measurements for the currently used T2K replica target,
- Measurements for a new target material (super-sialon) for T2K-II and Hyper-Kamiokande,
- Study of the possibility of measurements with beams <12 GeV/c for improved predictions of atmospheric and accelerator ν fluxes,
- Ultimate hadron production measurements with prototypes of Hyper-Kamiokande and DUNE targets.

NA61/SHINE will decrease systematic uncertainties on neutrino fluxes (for T2K-II, Hyper-K from 10% to 3%)

Neutrino-related accomplishments from NA61/SHINE first phase

NA61/SHINE took thin and thick target data with 31 GeV/c protons specifically for T2K in 2007, 2009 and 2010

T2K flux predictions (Phys.ReV.D87 2013 no.1, 012001) currently uses thin target data and incorporation of thick target data is in progress



2016/17 data collection:

- Thin target measurements with p and π beams at C, Be, Al targets at 30, 60 and 120 GeV/c

2018 data collection:

- 120 GeV/c p on NOvA replica target provided by Fermilab
- 18M events recorded

NA61/SHINE 2020+ collaboration

A. Aduszkiewicz[15], E.V. Andronov[21], T. Antićić[2], B. Baatar[19], M. Baszczyk[13], S. Bhosale[10], A. Blondel[23], M. Bogomilov[1], A. Brandin[20], A. Bravar[23], W. Bryliński[17], J. Brzychczyk[12], S.A. Bunyatov[19], O. Busygina[18], A. Bzdak[13], H. Cherif[6], M. Ćirković[22], T. Czopowicz[17], A. Damyanova[23], N. Davis[10], M. Deveaux[6], W. Dominik[15], P. Dorosz[13], J. Dumarchez[3], R. Engel[4], G.A. Feofilov[21], L. Fields[24], Z. Fodor[7,16], A. Garibov[0], M. Gaździcki[6,9], O. Golosov[20], M. Golubeva[18], K. Grebieszkow[17], F. Guber[18], A. Haesler[23], A.E. Hervé[4], S.N. Igolkin[21], S. Ilieva[1], A. Ivashkin[18], S.R. Johnson[25], K. Kadija[2], E. Kaptur[14], N. Kargin[20], E. Kashirin[20], M. Kiełbowicz[10], V.A. Kireyeu[19], V. Klochkov[6], V.I. Kolesnikov[19], D. Kolev[1], A. Korzenev[23], V.N. Kovalenko[21], K. Kowalik[11], S. Kowalski[14], M. Koziel[6], A. Krasnoperov[19], W. Kucewicz[13], M. Kuich[15], A. Kurepin[18], D. Larsen[12], A. László[7], T.V. Lazareva[21], M. Lewicki[16], K. łojek[12], B. łysakowski[14], V.V. Lyubushkin[19], M. Maćkowiak-Pawłowska[17], Z. Majka[12], B. Maksiak[17], A.I. Malakhov[19], D. Manić[22], A. Marchionni[24], A. Marcinek[10], A.D. Marino[25], K. Marton[7], H.-J. Mathes[4], T. Matulewicz[15], V. Matveev[19], G.L. Melkumov[19], A.O. Merzlaya[12], B. Messerly[26], Ł. Mik[13], S. Morozov[18,20], S. Mrówczyński[9], Y. Nagai[25], M. Naskręt[16], V. Ozvenchuk[10], V. Paolone[26], M. Pavin[3,2], O. Petukhov[18], R. Płaneta[12], P. Podlaski[15], B.A. Popov[19,3], M. Posiadała[15], S. Puławski[14], J. Puzović[22], W. Rauch[5], M. Ravonel[23], R. Renfordt[6], E. Richter-Wąs[12], D. Röhrich[8], E. Rondio[11], M. Roth[4], B.T. Rumberger[25], A. Rustamov[0,6], M. Rybczynski[9], A. Rybicki[10], A. Sadovsky[18], K. Schmidt[14], I. Selyuzhenkov[20], A.Yu. Seryakov[21], P. Seyboth[9], M. Słodkowski[17], A. Snoch[6], P. Staszel[12], G. Stefanek[9], J. Stepaniak[11], M. Strikhanov[20], H. Ströbele[6], T. Šuša[2], A. Taranenko[20], A. Tefelska[17], D. Tefelski[17], V. Tereshchenko[19], A. Toia[6], R. Tsenov[1], L. Turko[16], R. Ulrich[4], M. Unger[4], F.F. Valiev[21], D. Veberič[4], V.V. Vechernin[21], A. Wickremasinghe[26], Z. Włodarczyk[9], A. Wojtaszek-Szwarc[9], O. Wyszyński[12], L. Zambelli[3], E.D. Zimmerman[25], R. Zwaska[24]

- Present NA61/SHINE Collaboration:
  138 physicists from 27 institutions and 12 countries

- Addendum 10 co-authored by

The CERN Team:

N. Benekos (EP-NU), S. Bordoni (EP-NU), N. Charitonidis (EN-EA)[1], R. Fernandez (BE-OP), U. Kose (EP-NU), P. Martinengo (EP-DT), A. de Roeck (EP-NU), D. Sgalaberna (EP-NU), A. Weber (EP-NU), L. Whitehead (EP-NU)

- Two limited membership institutes will apply for funding for the future NA61/SHINE neutrino and cosmic ray measurements:
  - KEK, Japan
  - University of Manoa, Hawaii

Requested beams

- 2021:
  - 6 weeks for detector commissioning
  - 5 weeks of proton beam at 31 GeV/c for data taking for neutrino fluxes
  - 4 weeks of Pb beam at 150A GeV/c for open charm measurement

Recommended by SPSC

- 2022-24:
  - Hadron, light ion (secondary) and Pb beams in accordance to the proposed physics program
  - PBC->ESPP->SPSC

NA61/SHNIE at H2 Beam line

H2 beam line optimal status and configuration **vital** for the many different beam conditions necessary for NA61/SHINE

The beam (very high) purity, (quite small) divergence and (small) spot size **are key factors** for the acquired data quality

→Close collaboration with and support by the CERN EN-EA liaison physicists is **crucial** for the experiment current and future operation – hoping to continue the excellent team work and communication during the last years !

Some of the known limitations of the infrastructure and the NA61 dedicated zones **need to be studied/implemented** during LS2 for the post-LS2 (2021 & after..) operation, in the PBC context :

-Intensity protection system of the TPC, via the beam line magnets ;
-Custom radiation shielding in the PSD zone allowing for higher ion intensities ;
-Possibilities of proton-pure and/or Low energy beams ;

Summary

- NA61/SHINE plans fundamental open charm measurements in Pb+Pb collisions at SPS as well as reference measurements for cosmic ray and neutrino experiments

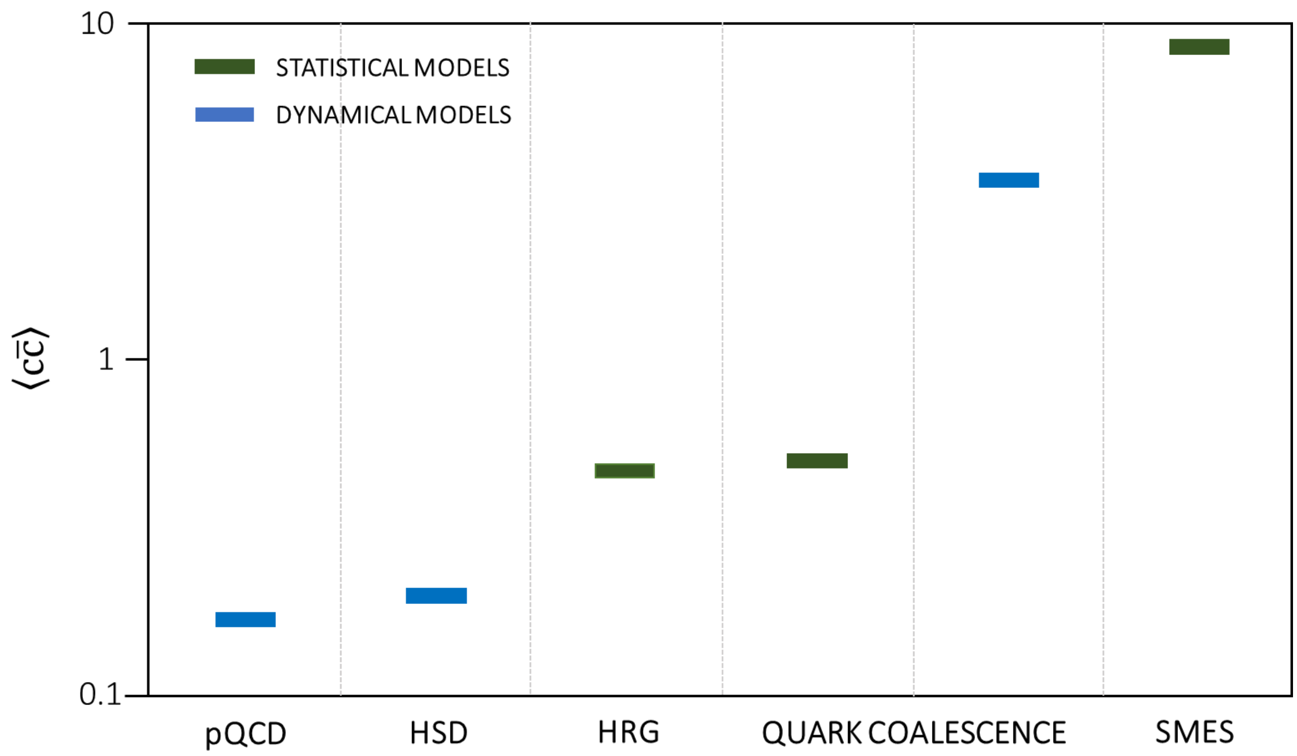
- Data taking in 2021 is recommended by SPSC on June 8 2018
- Data taking in 2022-2024 depend on ESPP

- Work on detector upgrades has started

Backup slides

Models of open charm and J/ψ production

Predictions for $\langle c\bar{c}\rangle$ in central Pb+Pb at 158A GeV/c differ by a factor of about **50**.



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

HSD
Linnyk, Bratkovskaya, Cassing, IJMP E17 1367

HRG, Quark Coalesc. Stat.
Gorenstein, Kostyuk, Stoecker, Greiner, PL B 509, 277.

Quark Coalesc. Dyn.
Levai, Biro, Csizmadia, Csorgo, Zimanyi, JP G 27, 703

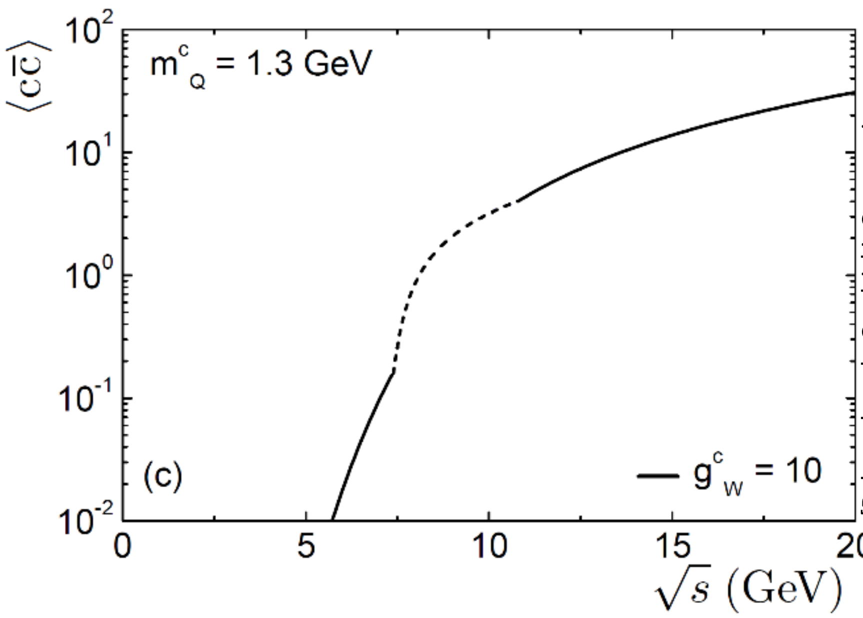
SMES
Gazdzicki, Gorenstein, APP B30, 2705.

Open charm yield as the signal of deconfinement

confined matter	→	**deconfined matter**
$\mathrm{D\overline{D}}$ mesons	→	charm quarks
$2m_{\mathrm{D}} = 3.7$ GeV	→	$2m_{\mathrm{c}} = 2.6$ GeV
$g_{\mathrm{D}} = 4$	→	$g_{\mathrm{c}} = 24$

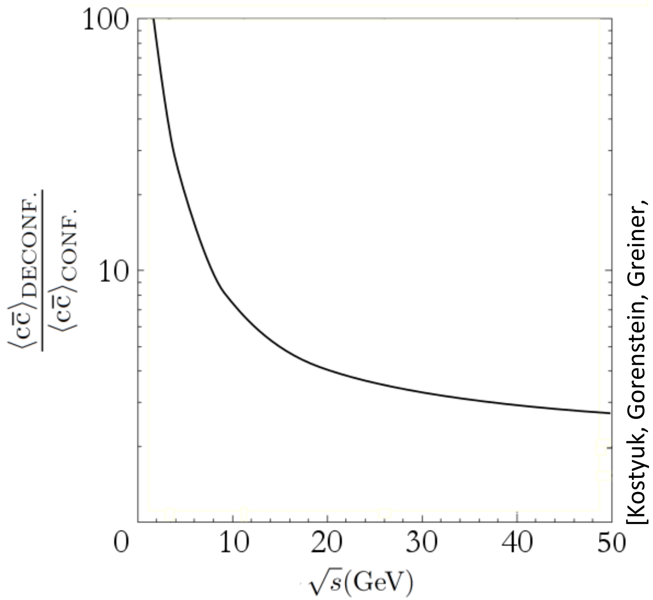
central Pb+Pb collisions

Statistical Model of the Early Stage



[Poberezhnyuk, Gazdzicki, Gorenstein, ACTA PHYS POL B 9 48(2017)]

QCD-inspired calculations

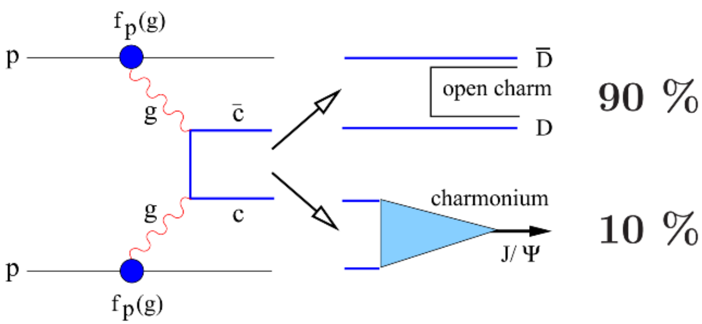


[Kostyuk, Gorenstein, Greiner, PL B519 207]

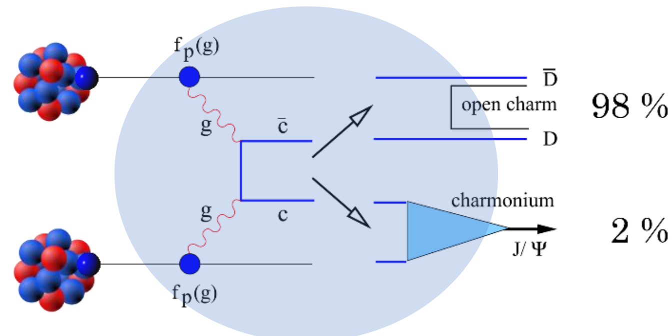
J/ψ production as the signal of deconfinement

Open charm and J/ψ production within Matsui-Satz model
[PL B178 416]

vacuum



medium



$$P(c\bar{c} \to J/\psi) \equiv \frac{\langle J/\psi \rangle}{\langle c\bar{c} \rangle} \equiv \frac{\sigma_{J/\psi}}{\sigma_{c\bar{c}}}$$

$$P_{\text{vacuum}}(c\bar{c} \to J/\psi) \quad > \quad P_{\text{medium}}(c\bar{c} \to J/\psi)$$

Medium reduces probability of J/ψ production

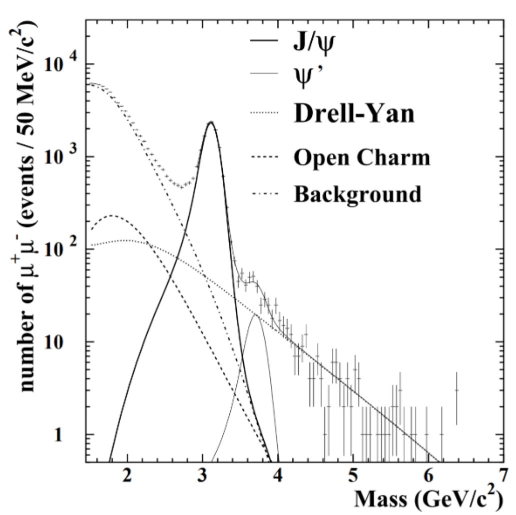
J/ψ production as the signal of deconfinement

Calculation of $P(c\bar{c} \to J/\psi)$ requires data on:

- $\langle J/\psi \rangle$ – precise data at SPS by NA38, NA50, NA60
- $\langle c\bar{c} \rangle$ – not available up to now, NA61 has just started the corresponding measurements

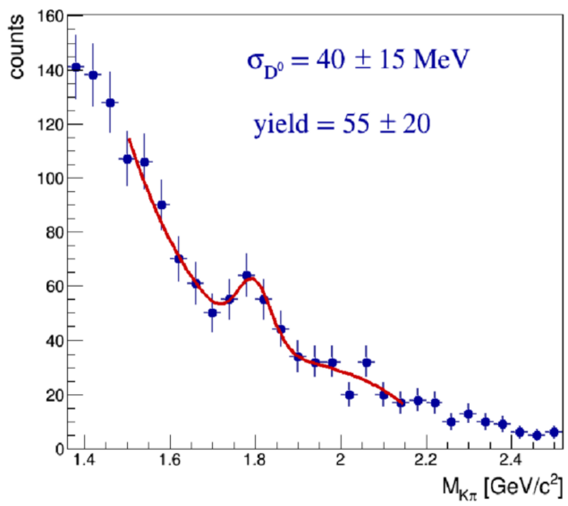
central Pb+Pb at 150-158A GeV/c

NA50



[NA50, arXiv:hep-ex/0412036v1]

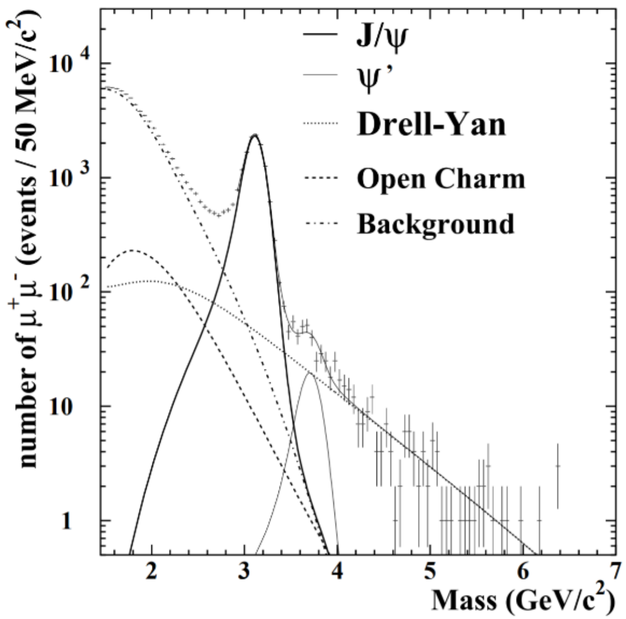
NA61



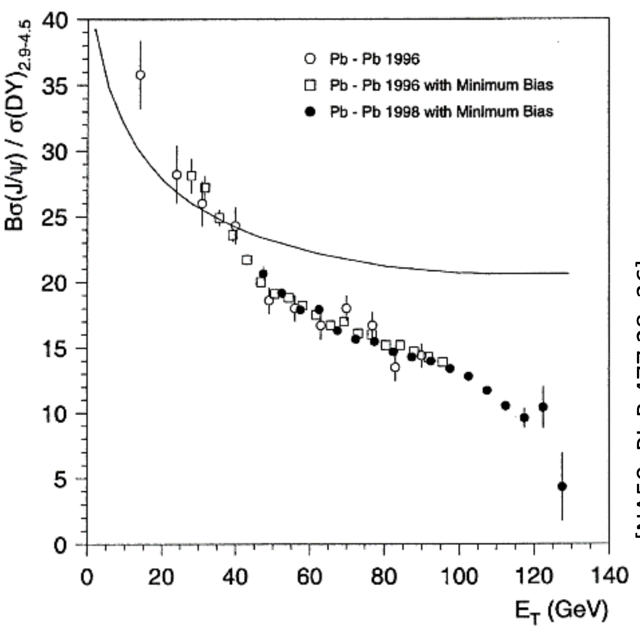
[CERN-SPSC-2017-038]

J/ψ production at the CERN SPS

Data on J/ψ production has been normalized by the Drell-Yan yield



[NA50, arXiv:hep-ex/0412036v1]



[NA50, PL B 477 28–36]

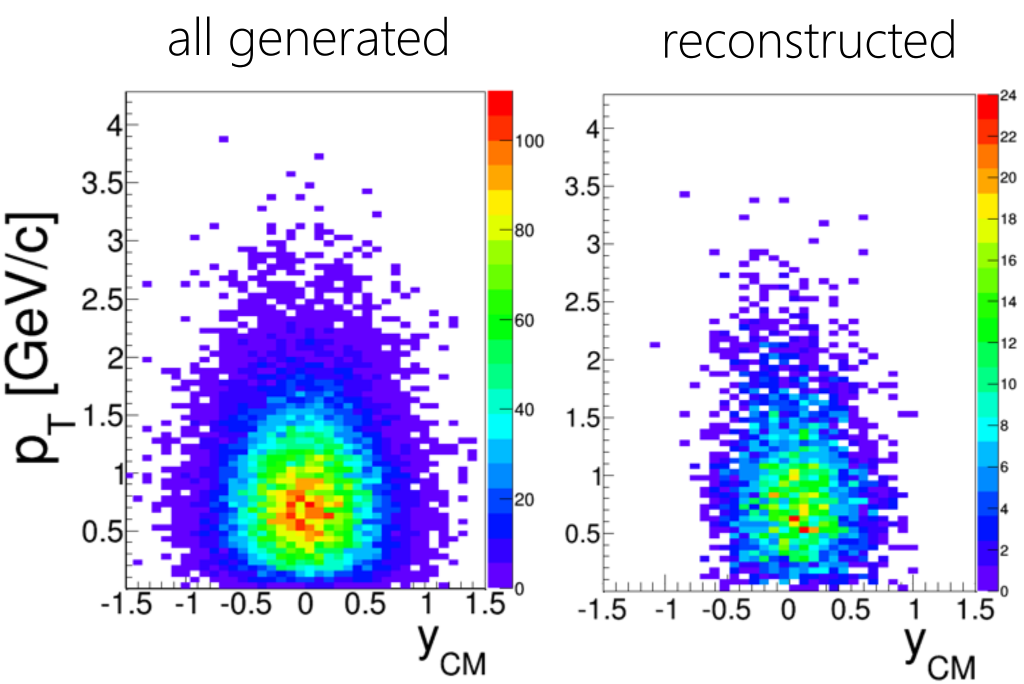
Interpreting these results one frequently assumes:

$$\langle c\bar{c} \rangle \sim \langle \mathrm{DY} \rangle$$

This assumptions may be incorrect due to many effects: shadowing, parton energy losses, etc.

Performance for open charm measurements

Two weeks in 2022 (1kHz + LAVD) ≈ $\mathbf{40\,000}\ D^0 + \overline{D^0}$
in 40M central Pb+Pb collisions at 150*A* GeV/*c*

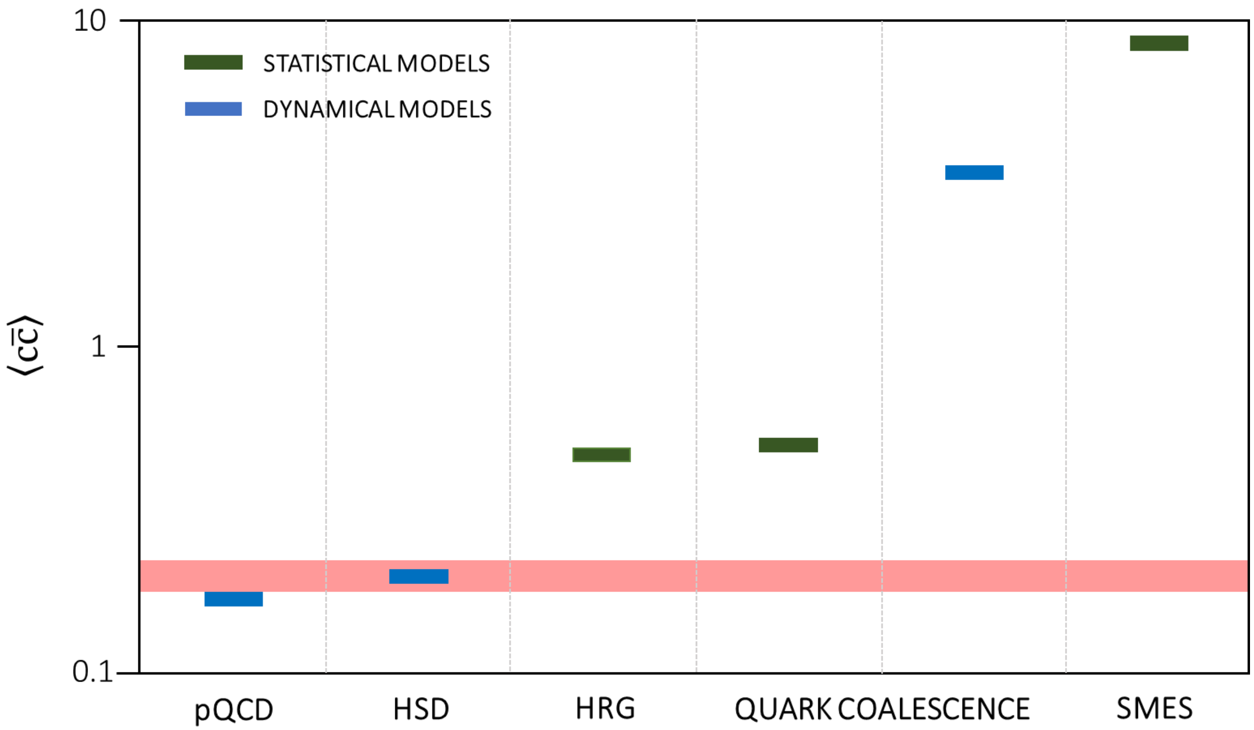


Based on AMPT one estimates that fully corrected results will refer to ≈ **99%** of the total $D^0 + \overline{D^0}$ yield.

Systematic uncertainty related to extrapolation to full phase space is close to zero.

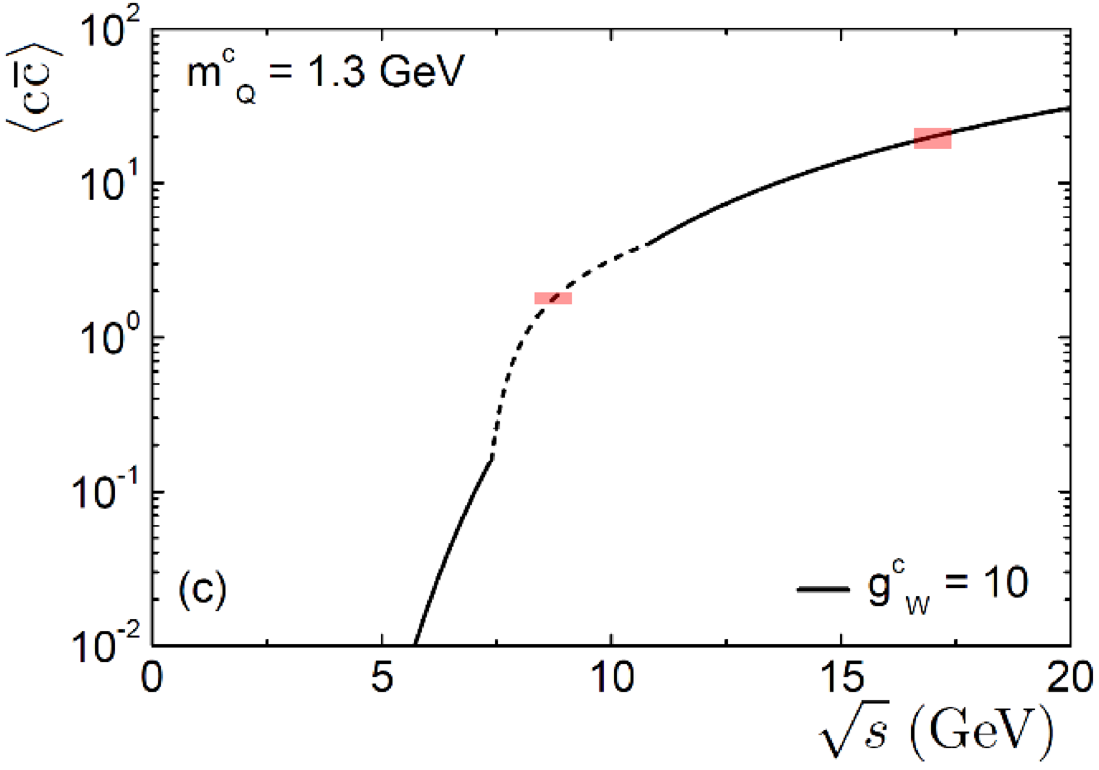
Total systematic uncertainty of $\langle c\bar{c}\rangle$ is expected to be about 10%.

Impact of open charm measurements



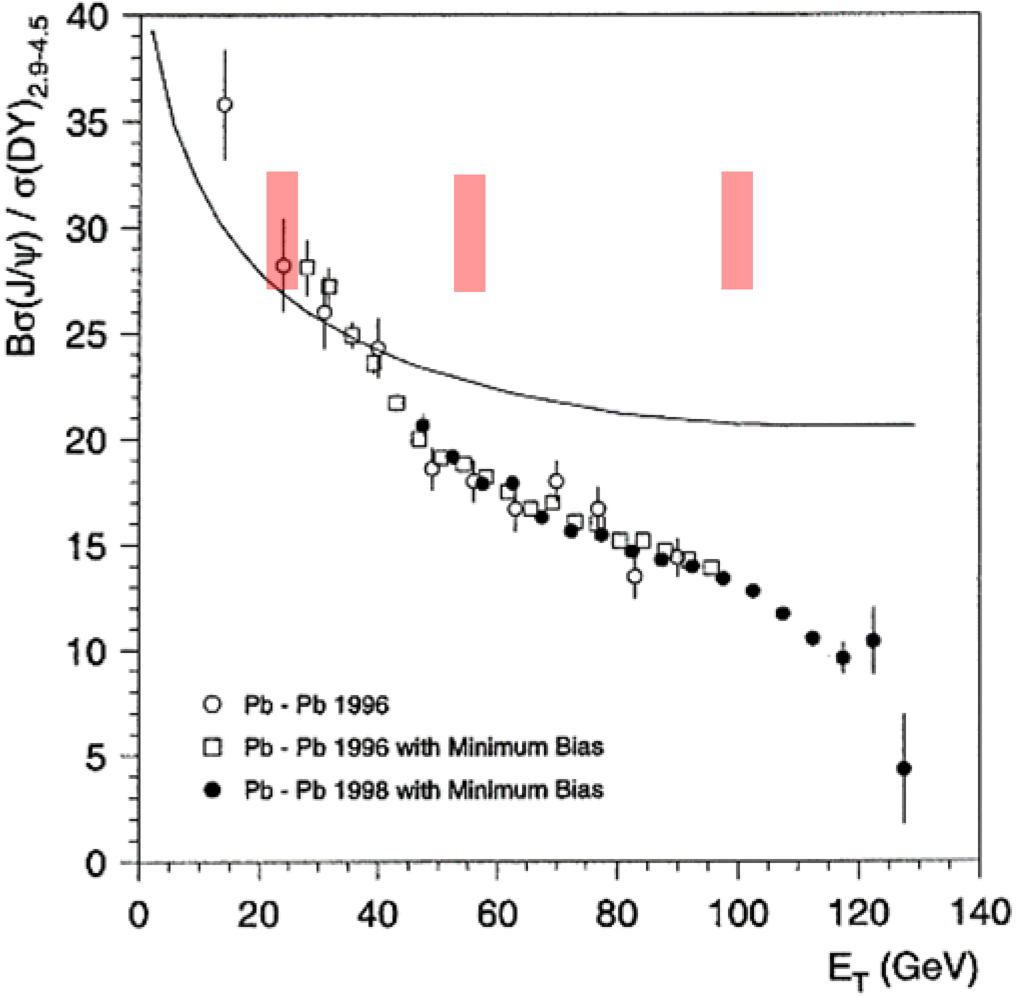
accuracy of NA61++ result assuming HSD yield

Impact of open charm measurements



accuracy of NA61++ result
assuming SMES yield

Impact of open charm measurements



accuracy of NA61++ result assuming

$$\langle c\bar{c}\rangle \sim \langle \pi \rangle$$

and scaling to

$$\langle J/\psi\rangle / \langle \mathrm{DY}\rangle$$

for peripheral collisions

Measurements for galactic cosmic rays and neutrino experiments

Many requests for new data

Neutrinos

NA61 ' s measurements for T2K have been critical for T2K to reduce flux systematic errors by a factor of two, and further improvement is expected as the long target results are added into T2K's flux model.

Many accelerator and atmospheric neutrino experiments expressed interest in thin-target measurements. These range from very low beam momenta to 120 GeV/c.

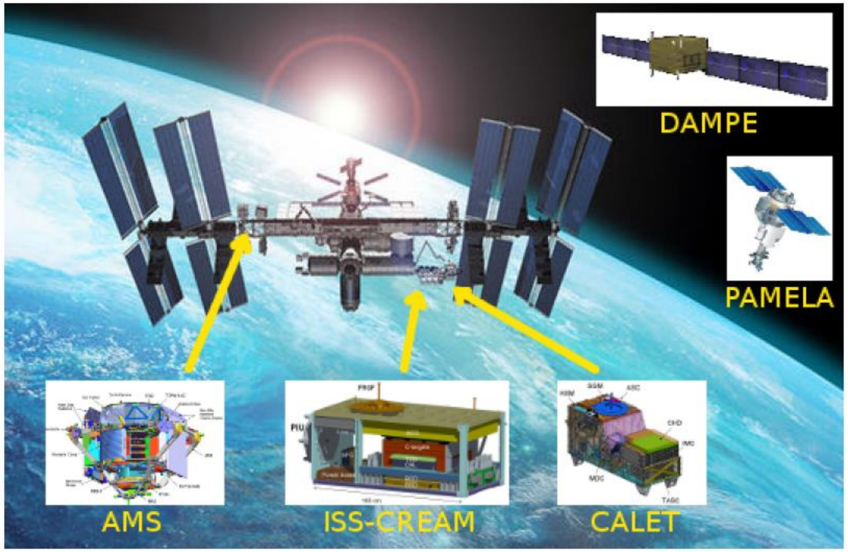
https://indico.cern.ch/event/629968/timetable/

Galactic cosmic rays

High precision data from cosmic-ray experiments require measurements of production of anti-nuclei and fragmentation cross-sections of light nuclei (see next slides).

The History of Cosmic Rays in the Milky Way

cosmic ray experiments



- primary cosmic rays from supernova remnants
- secondary cosmic rays from interactions with interstellar matter during propagation, e.g.

$$\mathrm{C} + \mathrm{p} \xrightarrow{\text{frag}} \mathrm{B} + \mathrm{X}$$

$$\mathrm{C} + \mathrm{p} \xrightarrow{\text{frag}} \mathrm{Li} + \mathrm{X} \xrightarrow{\text{frag}} \mathrm{B} + \mathrm{Y}$$

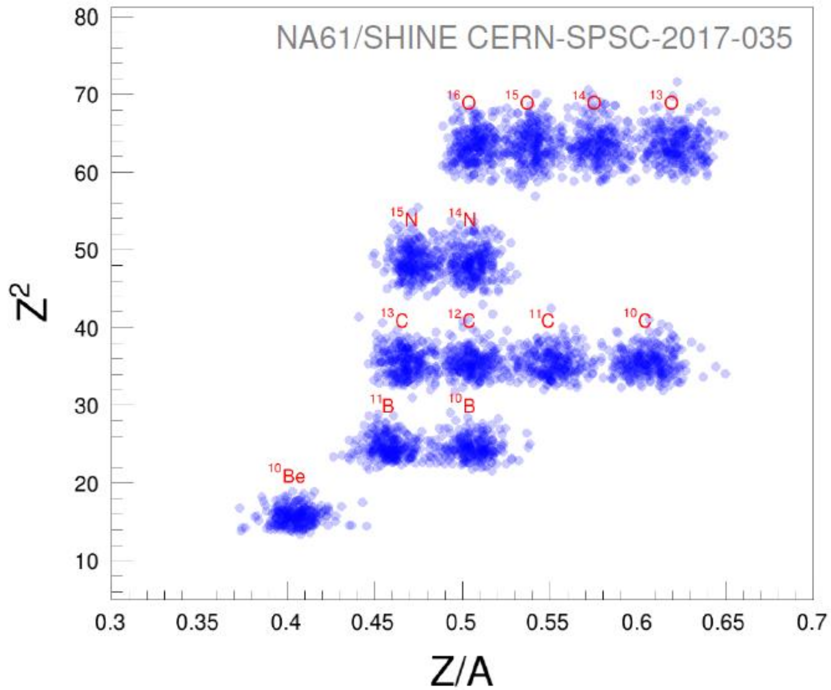
- primary-to-secondary ratios (e.g. $\mathrm{B/C}$) → traversed mass density
- unstable-to-stable ratios (e.g. $^{10}\mathrm{Be}/\,^{9}\mathrm{Be}$) → traversed distance
- important for the understanding of
  - origin of Galactic cosmic rays
  - backgrounds for Dark Matter searches

understanding of cosmic-ray propagation limited by uncertainties of fragmentation cross sections!

Measurement of Fragmentation Cross Sections

Request for two weeks of secondary light ion beams at 13*A* GeV/*c* in 2022
(produced from primary Pb beam at 14*A* GeV/*c*)

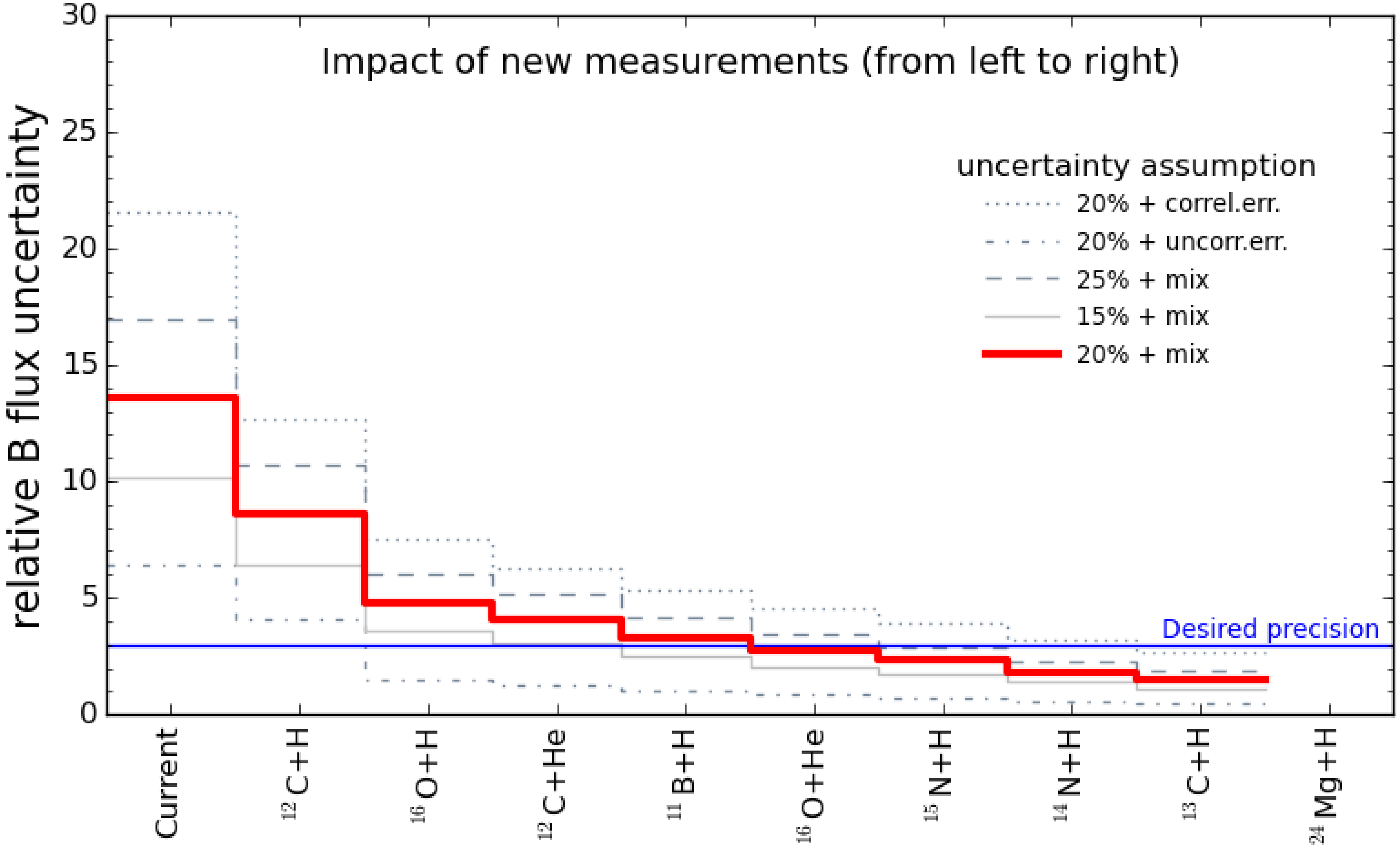
NA61 fragment identification



Reaction	Number of interactions
$^{12}C + p$	200k
$^{16}O + p$	100k
$^{11}B + p$	4k
$^{15}N + p$	2k
$^{14}N + p$	2k
$^{13}C + p$	2k
$^{12}C + He$	50k
$^{16}O + He$	50k

Impact of fragmentation measurement

Contributions from different reactions

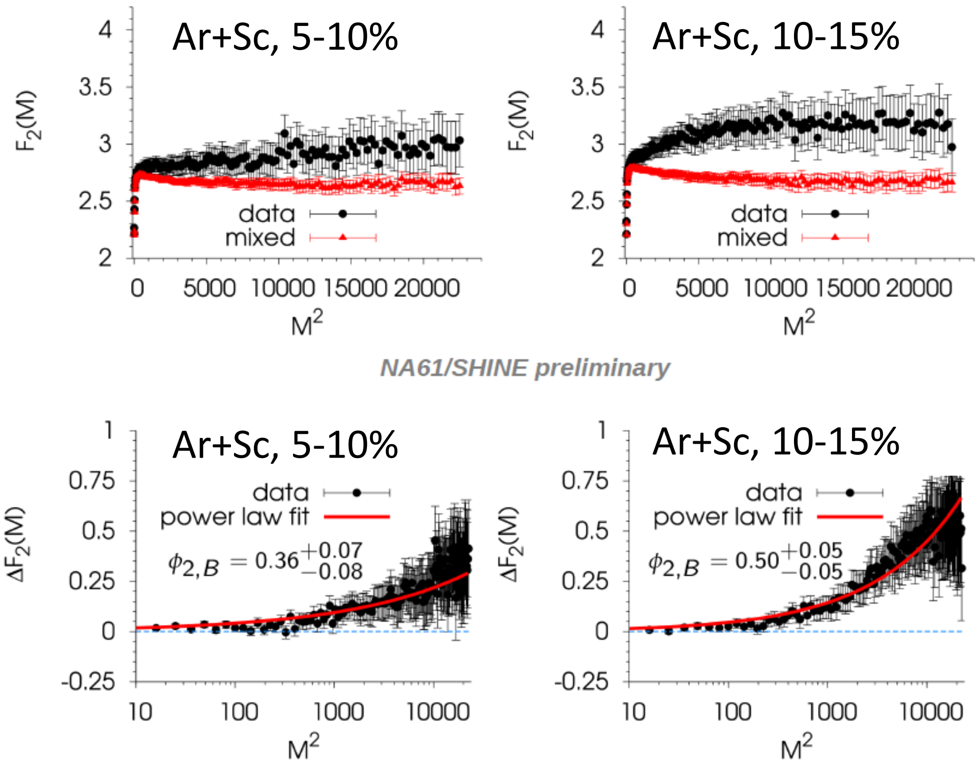


NA61/SHINE program for 2021-2024

- Open charm production in heavy ion collisions
- Measurements for physics of galactic cosmic rays and neutrino experiments
  - Many requests for new data
  - Example: measurement of fragmentation cross sections

Based on the workshop:
https://indico.cern.ch/event/629968/timetable/

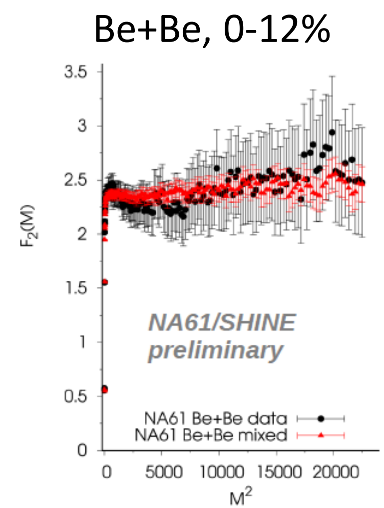
Proton intermittency
Ar+Sc and Be+Be at 150*A* GeV/*c*



Indication of intermittency effect in

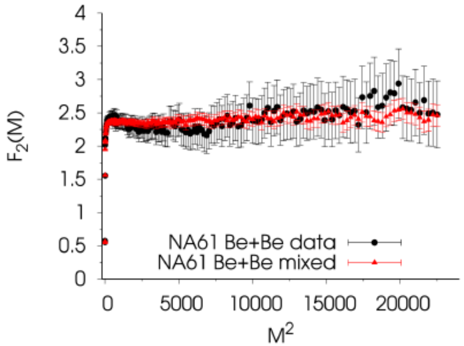
mid-central **Ar+Sc**

- First possible evidence for CP signal in NA61/SHINE
- No intermittency signal in Be+Be

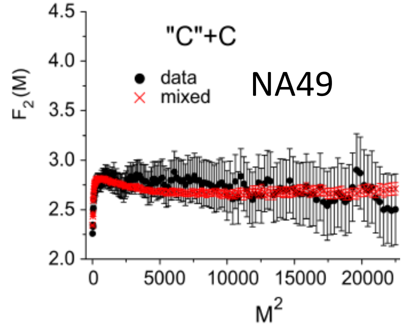


Proton intermittency at 150/158A GeV/c

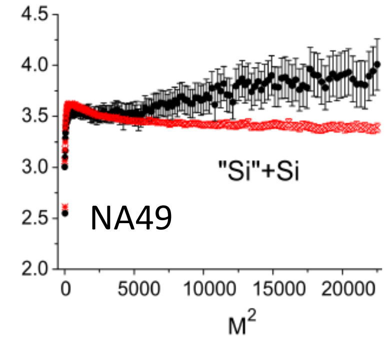
Be+Be, 0-12%



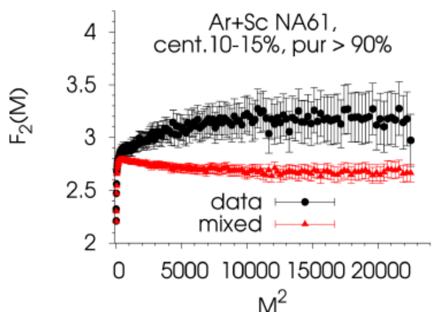
“C”+C, 0-12%



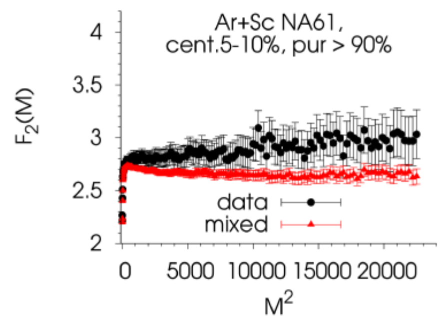
“Si”+Si, 0-12%



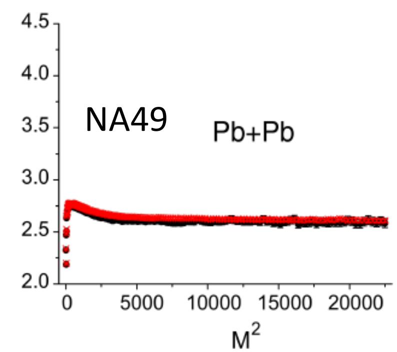
Ar+Sc, 10-15%



Ar+Sc, 5-10%

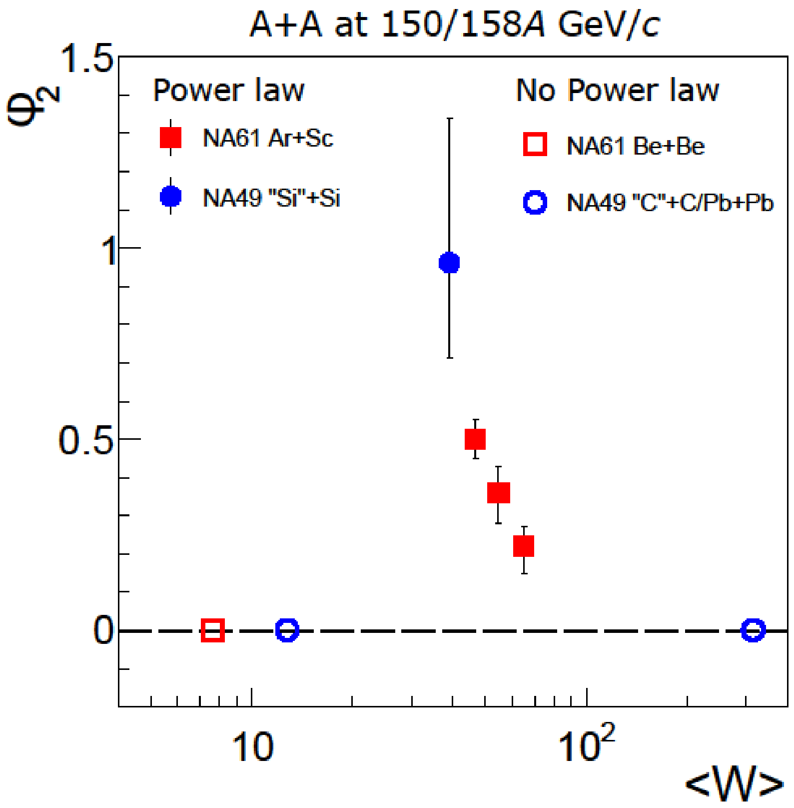


Pb+Pb, 0-10%



NA49 results:
EPJC 75, 587, 2015

Proton intermittency



At critical point power law dependence is expected

$$F_2(M) = F_2(\Delta)\ \ (M^2)^{\varphi_2}$$

First possible evidence for CP signal in NA61/SHINE

Only statistical uncertainties shown

NA61 neutrino history

- Major program for T2K-related measurements 2007-2010
  - KEK was a major collaborating institution
  - Thin-target results have been critical for understanding T2K flux, reducing systematic error by roughly half
  - Long-target results still being integrated into T2K analysis, will improve flux errors further
- US-NA61 program began 2012 for LBNF/DUNE related measurements
  - Project funded in FY 2015-16-17
  - Upgrades (commissioned for 2017 run):
    - Forward TPCs
    - DRS4 electronics for TOF readout
  - Data collected 2015-16-17 so far, expect more in 2018

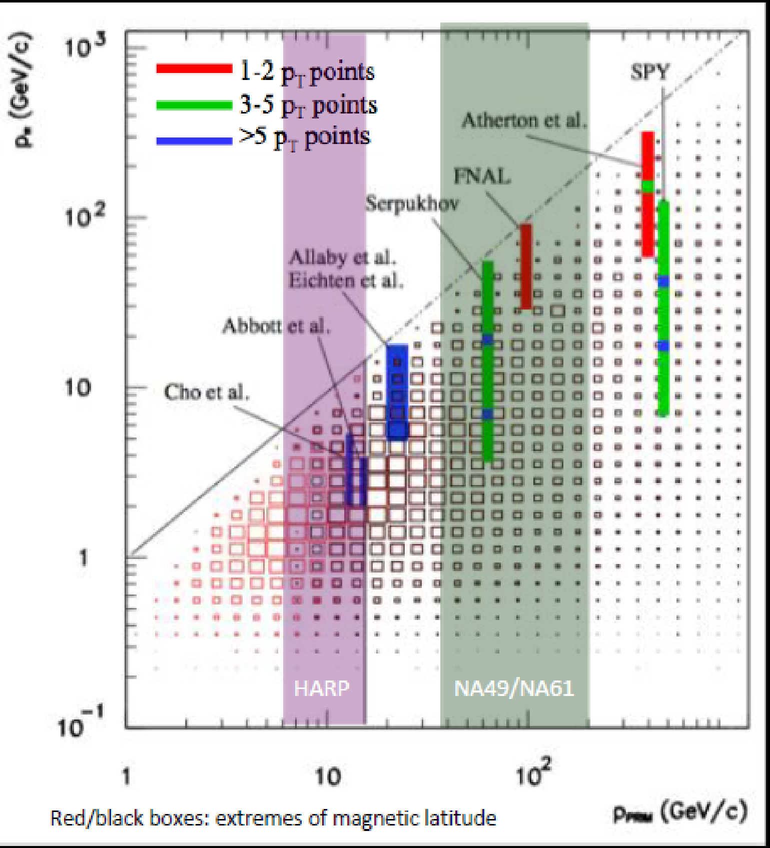
Neutrino program highlights beyond 2020

- A workshop was held in late July in Geneva to discuss the future of the experiment. Neutrino physicists from around the world were well represented. Ideas presented included:
  - New data for NuMI/LBNF/DUNE
    - NuMI replica target data
    - More detailed thin-target (and possibly intermediate target) measurements to build a complete table of primary and secondary production cross-sections:
      - 120 GeV and below, protons and pions on C and Al, possibly Be.
    - Replica targets for LBNF when they are designed
  - New data for T2K-II/Hyper-K
    - Secondary and out-of-target interactions: take data on different targets (Al, Fe, Ti, H_2O?), at lower beam energies (down to ~10GeV)
  - Atmospheric neutrino production measurements at lower energies

Low-energy measurements

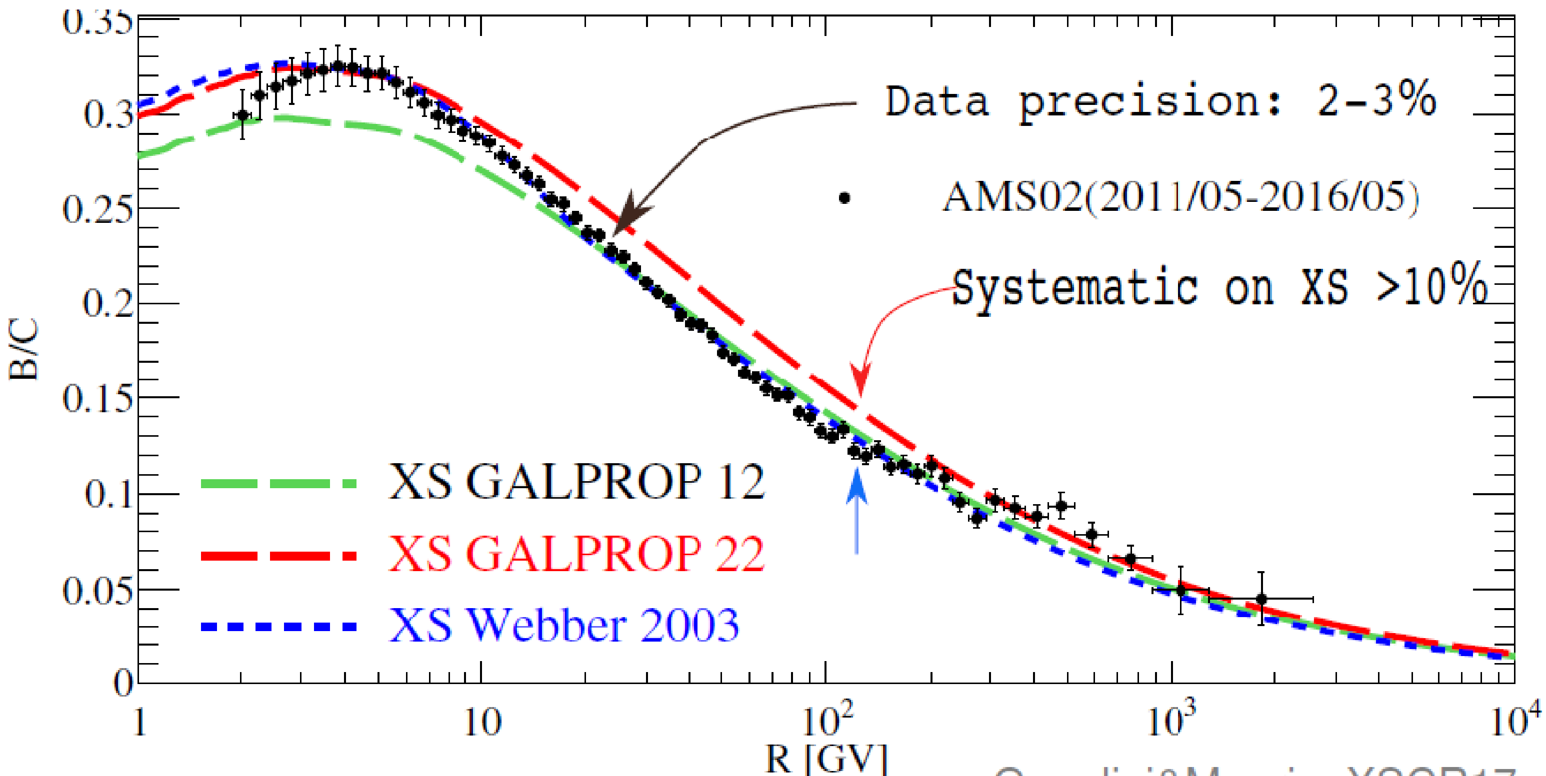
- SPS beams group (Nikos Charitonidis) planning to implement capability for NA61 to take lower-energy beams in future, down to a few GeV.
- Motivations for low-energy running include:
  - Studies for simulation of atmospheric neutrino production. There is a problematic lack of measurements below 10 GeV (right).
    - Kaons may be particularly important
  - 8 GeV proton data may be important for understanding flux from the Booster Neutrino Beam at Fermilab (MicroBooNE, SBND)

Atmospheric pion production (boxes) and approx. cross-section measurements (bars) vs. primary momentum



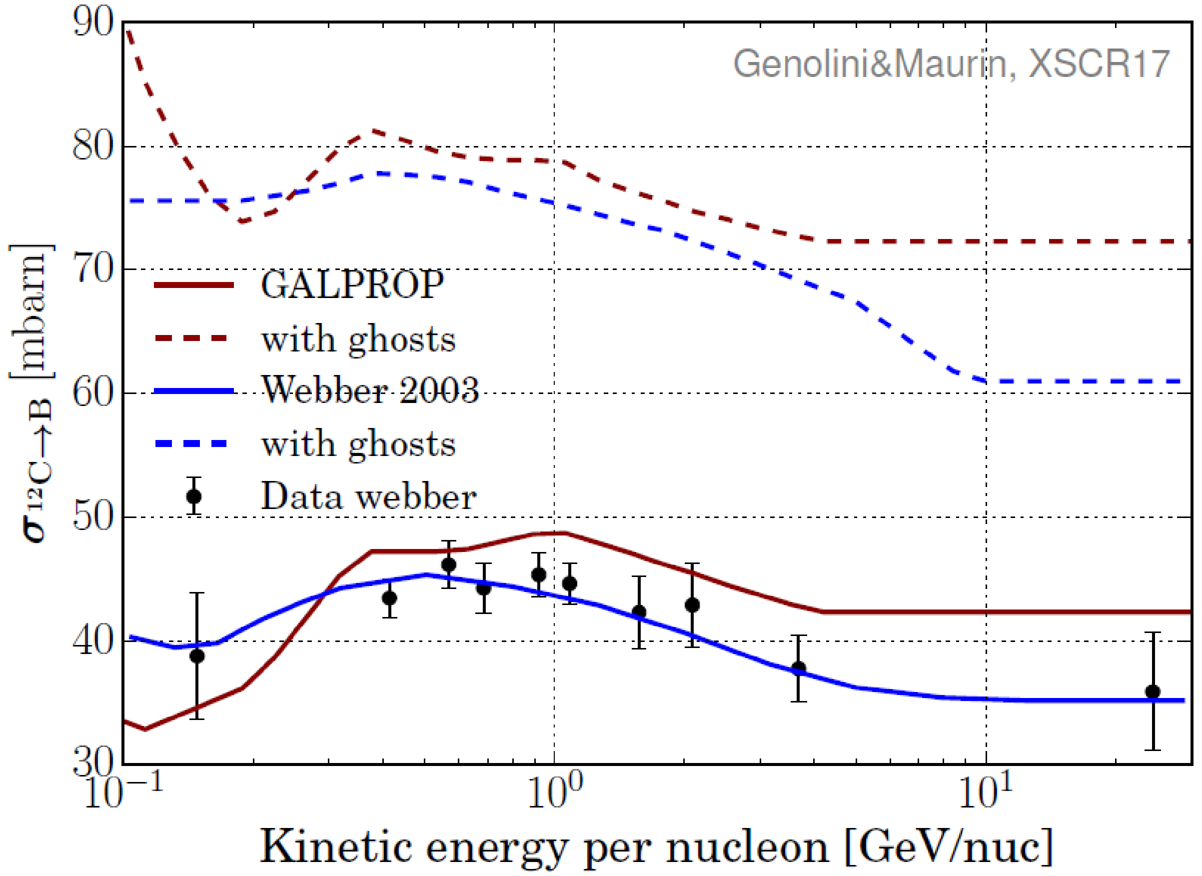
Adapted from G. Barr, “NA61 Beyond 2020” Workshop

Interpretation of boron-to-carbon ratio

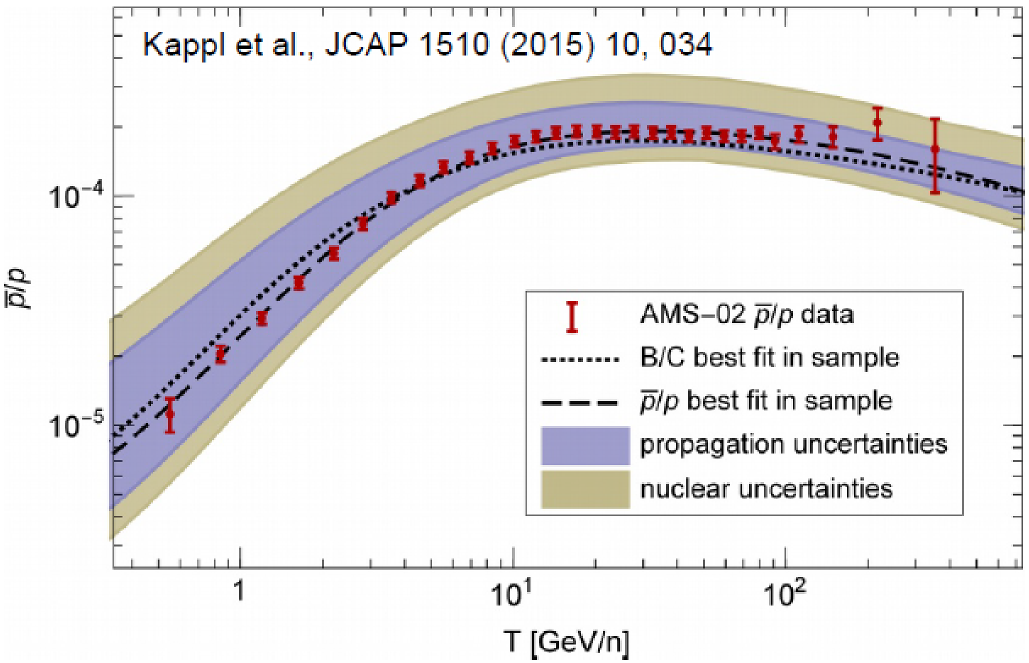


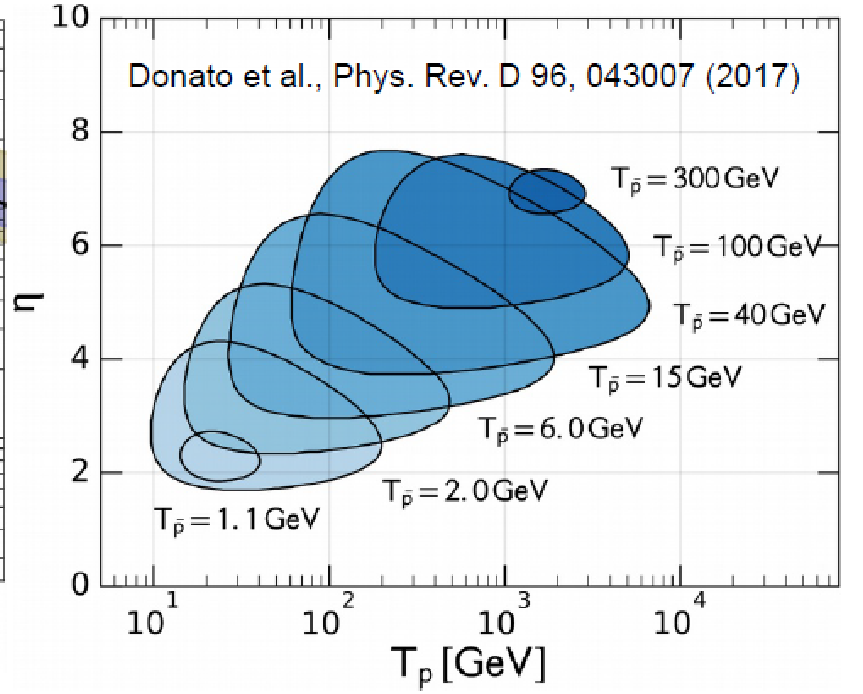
Genolini&Maurin, XSCR17

Current $^{12}C+p \rightarrow B + X$ cross sections



Cosmic-ray Antiprotons

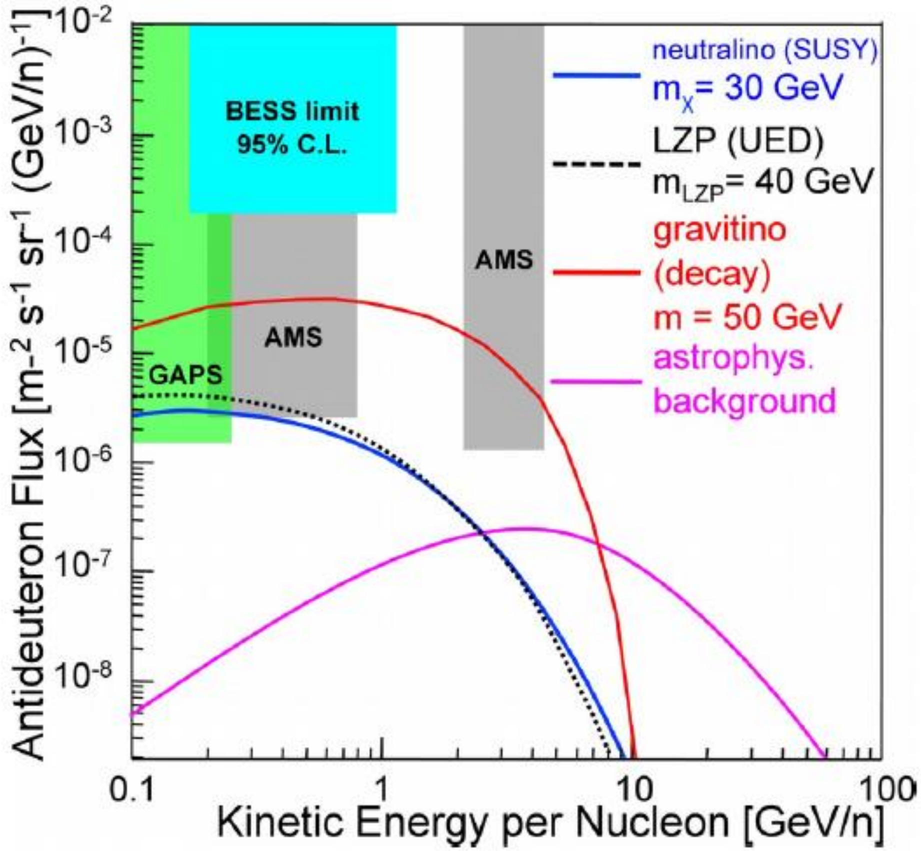




- (Left) Latest cosmic-ray antiproton results from AMS-02 are heavily discussed, but it is inconclusive if a conventional astrophysical explanation is enough or an additional component (e.g., from dark matter annihilations) is needed
  - key uncertainty: antiproton production of primary cosmic rays with the interstellar medium (p-p, p-He, He-p, He-He)
  - **more measurements with NA61/SHINE are needed**

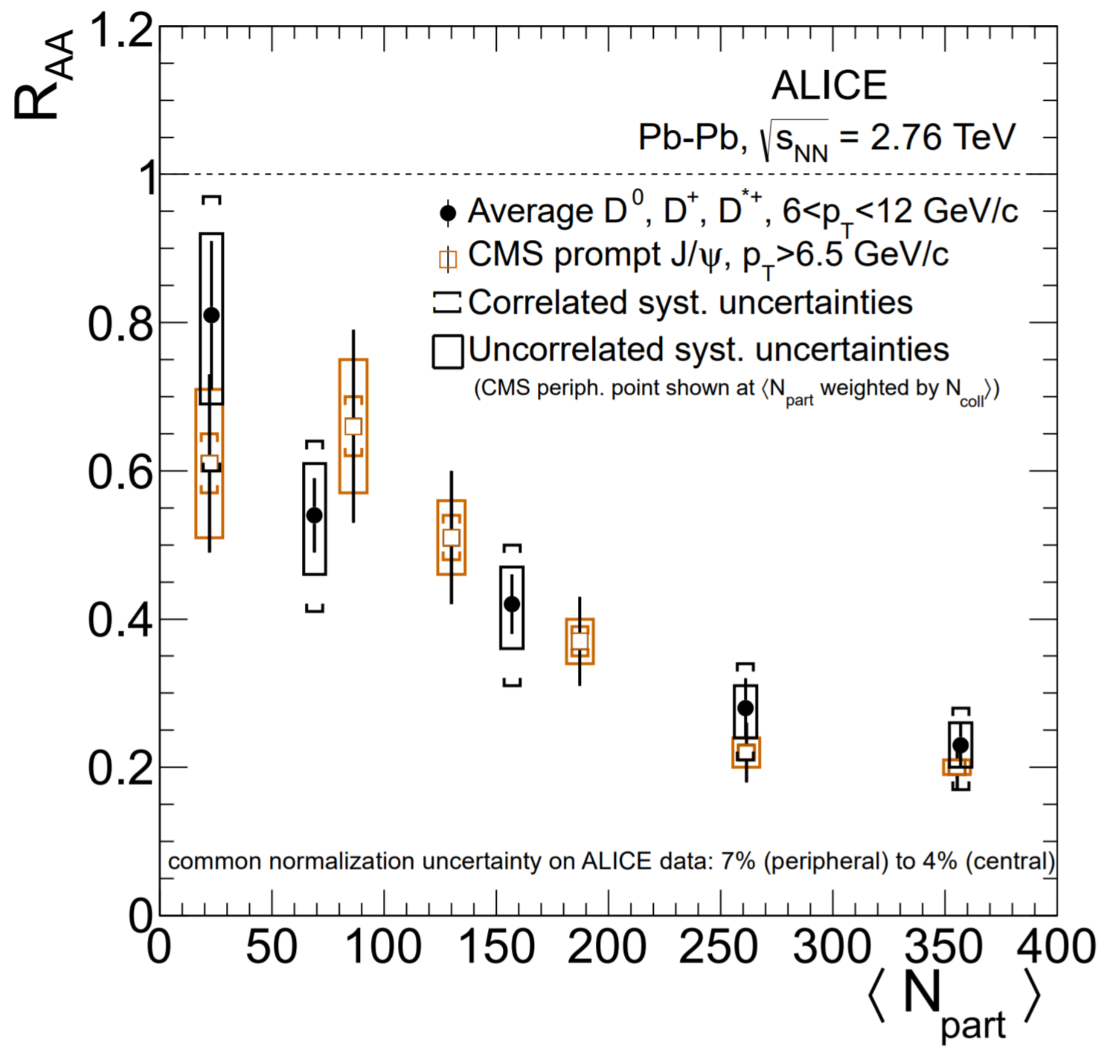
- (Right) Parameter space of the pp to $\bar{p}$ cross section necessary to determine the antiproton source term with the accuracy reached by recent AMS-02 measurements. Cross section has to be known by 3% within the blue shaded regions and by 30% outside the contours.

Cosmic-ray Antideuterons

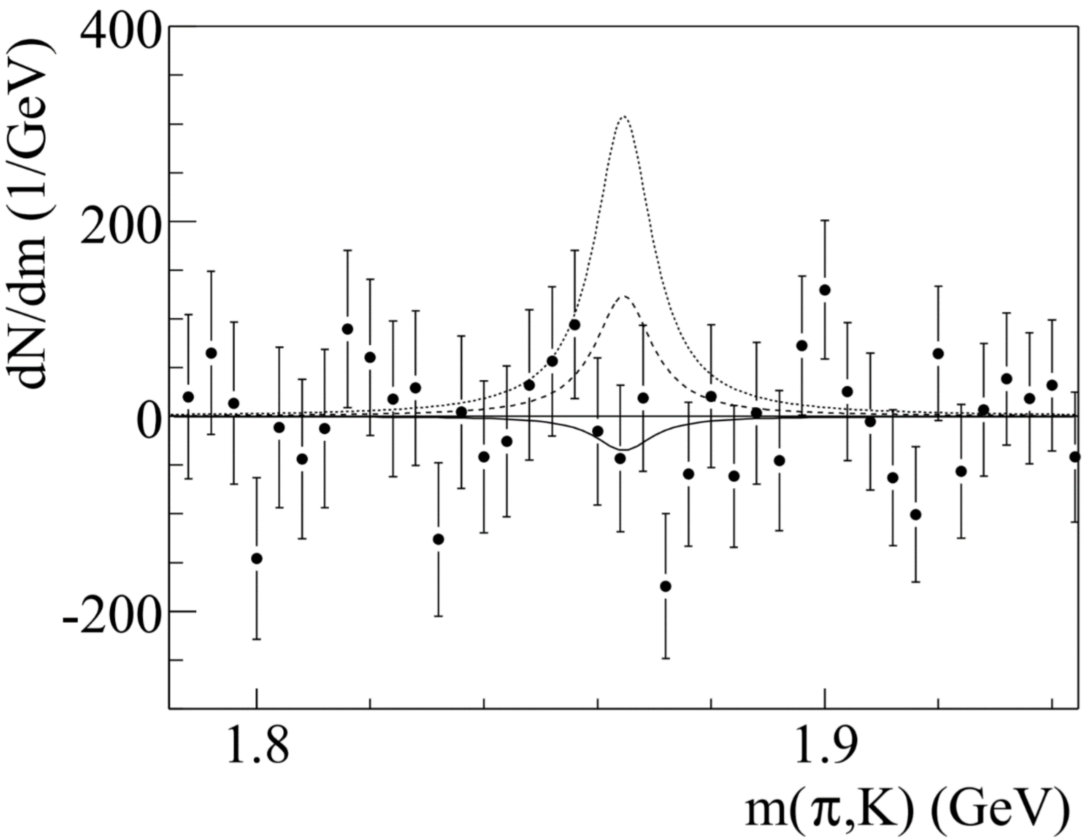


- Antideuterons are the very important unexplored indirect dark matter detection technique
- Key uncertainty: Formation of antideuterons is not well understood (about a factor of 10)
- Hadronic generators do not include coalescence formation
  - **high statistics measurements of p-p, p-He, He-He interactions with NA61/SHINE will improve understanding of antideuteron production and modeling**

LHC open charm and J/ψ

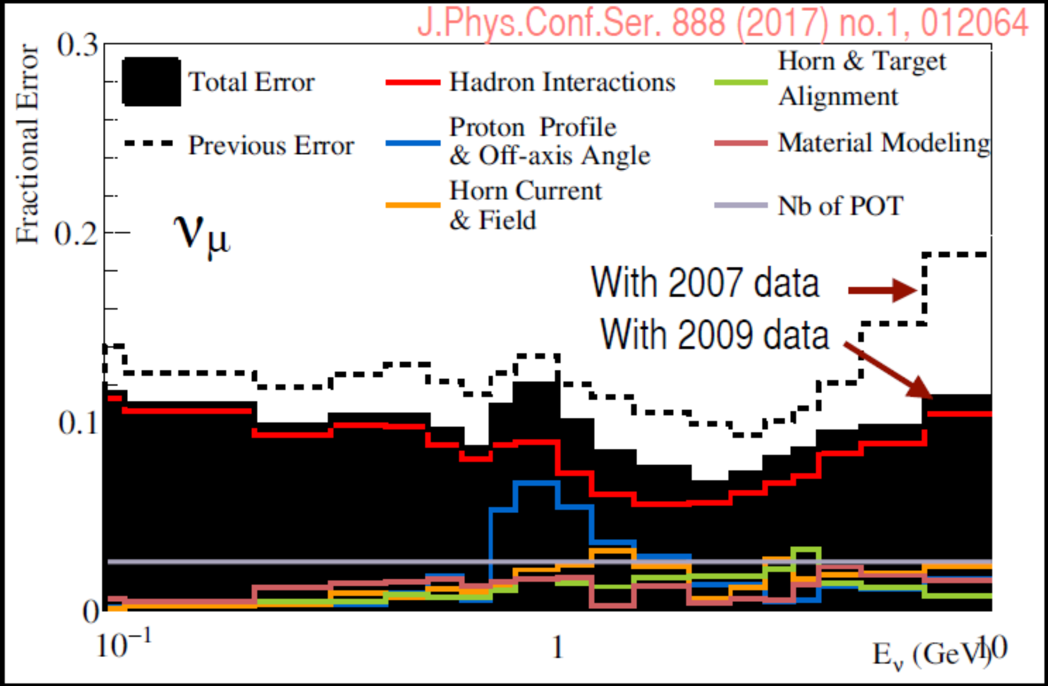


NA49 open charm upper limit

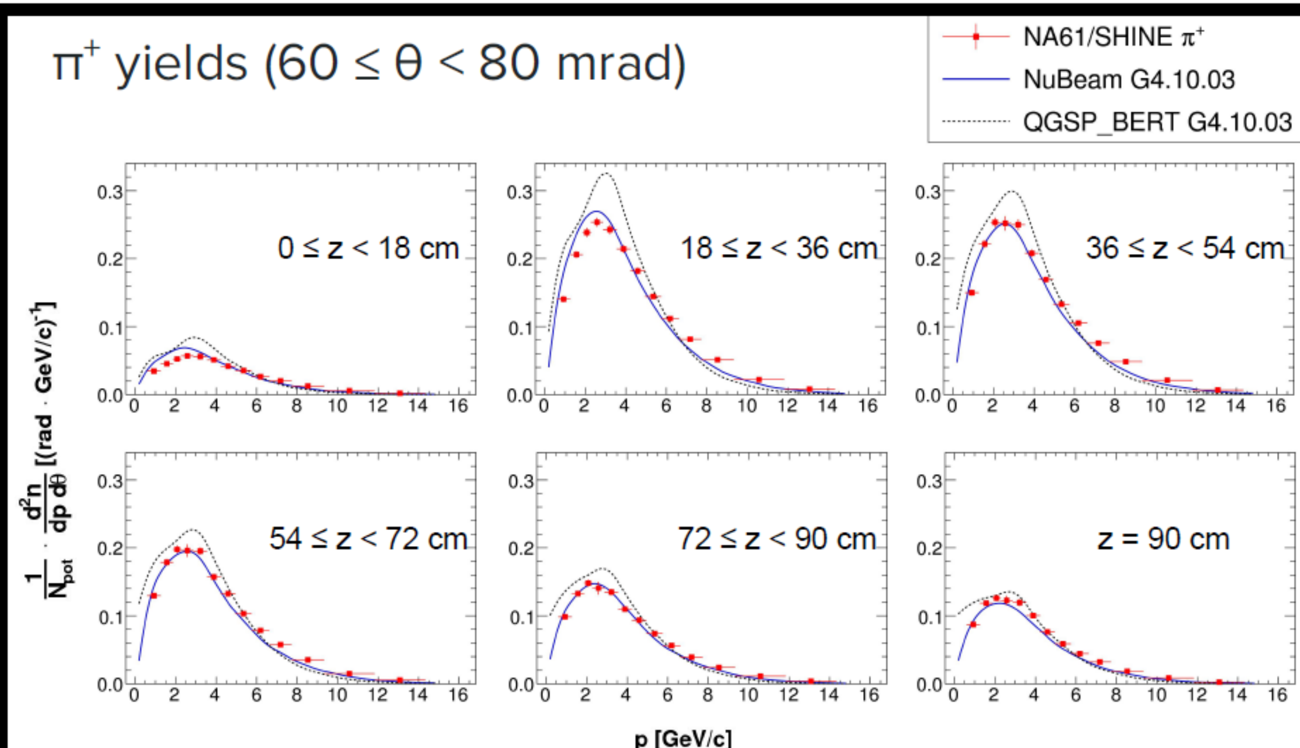


Neutrino-related accomplishments from NA61's first phase

- NA61/SHINE took thin and thick target data with 31 GeV/*c* protons specifically for T2K in **2007**, **2009**, and **2010**.
- T2K flux prediction (described in Phys.Rev. D87 (2013) no.1, 012001 and J.Phys.Conf.Ser. 888 (2017) no.1, 012064) currently uses thin target data, and incorporation of thick target data is in progress



Recent result: full yields from T2K replica target



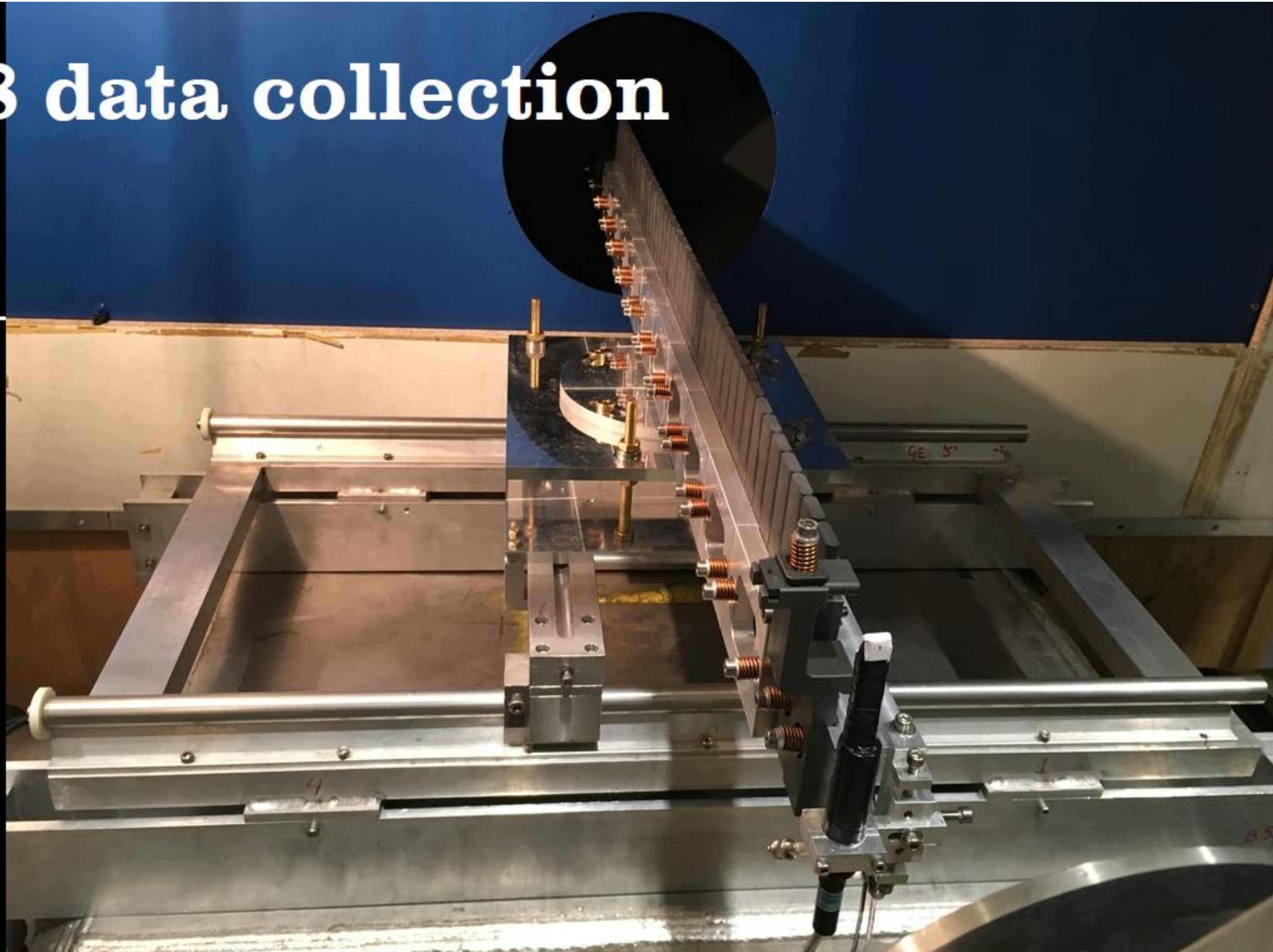
- e-Print: arXiv:1808.04927
- Showing π^+ for illustration. Also have π^-, $K^\pm$, p yields
- One more analysis (high magnetic field run) in progress

NA61 2016-17 neutrino data
Thin targets

2016	2017
p + C @ 120 GeV/c	π⁺ + Al @ 60GeV/c
p + Be @ 120 GeV/c	π⁺ + C @ 30 GeV/c
p + C @ 60 GeV/c	π⁻ + C @ 30 GeV/c
p + Al @ 60 GeV/c	p + C @ 120 GeV/c (w FTPCs)
p + Be @ 60 GeV/c	p + Be @ 120 GeV/c (w FTPCs)
π⁺ + C @ 60GeV/c	p + C @ 90 GeV/c (w FTPCs)
π⁺ + Be @ 60 GeV/c	

Highest analysis priority

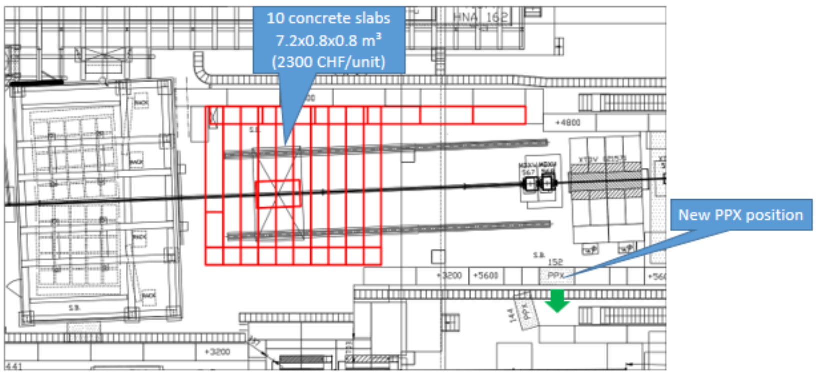
2018 data collection



- 120 GeV *p* on NOvA replica target provided by Fermilab
- 15M events recorded in summer; a final run next week should add 30-50%

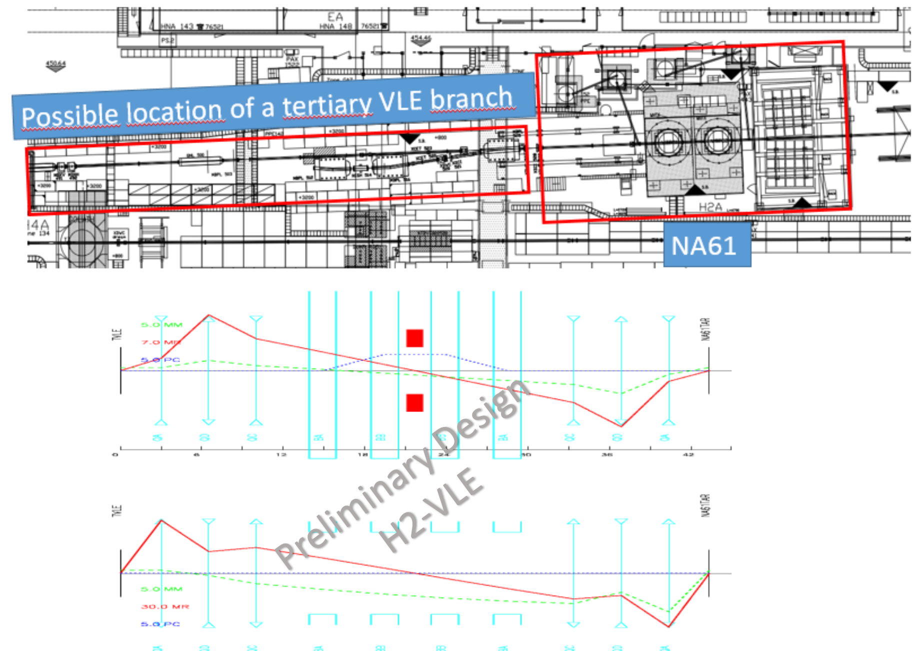
NA61 @ H2 beam line – 2021++

2021 ion run shielding with roof



Courtesy: N. Charitonidis

Possibilities of new shielding configuration (pending funding clarifications) are being studied in collaboration with EN-EA / HSE-RP



Courtesy: N. Charitonidis

Continue the studies for a possible very-low energy beam (< 10 GeV/c)