Status of NA61

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NA61 Presentation to SPSC

- Introduction to NA61/SHINE
- Data collection/operations summary
- Facility upgrades: last year and plans
- Software and Calibration
- Physics results
- 2016-18 run plans
- Possible extension of NA61 beyond LS2

Introduction to NA61/SHINE

- NA61/SHINE is a unique multi-purpose, multi-particle spectrometer for measurements of products of $h+p$, $h+A$, and $A+A$ in 13A-150A (400) GeV/c range.
- Approved physics program covers topics in
  - Strong interaction physics
  - Neutrino beam studies
  - Cosmic ray interactions

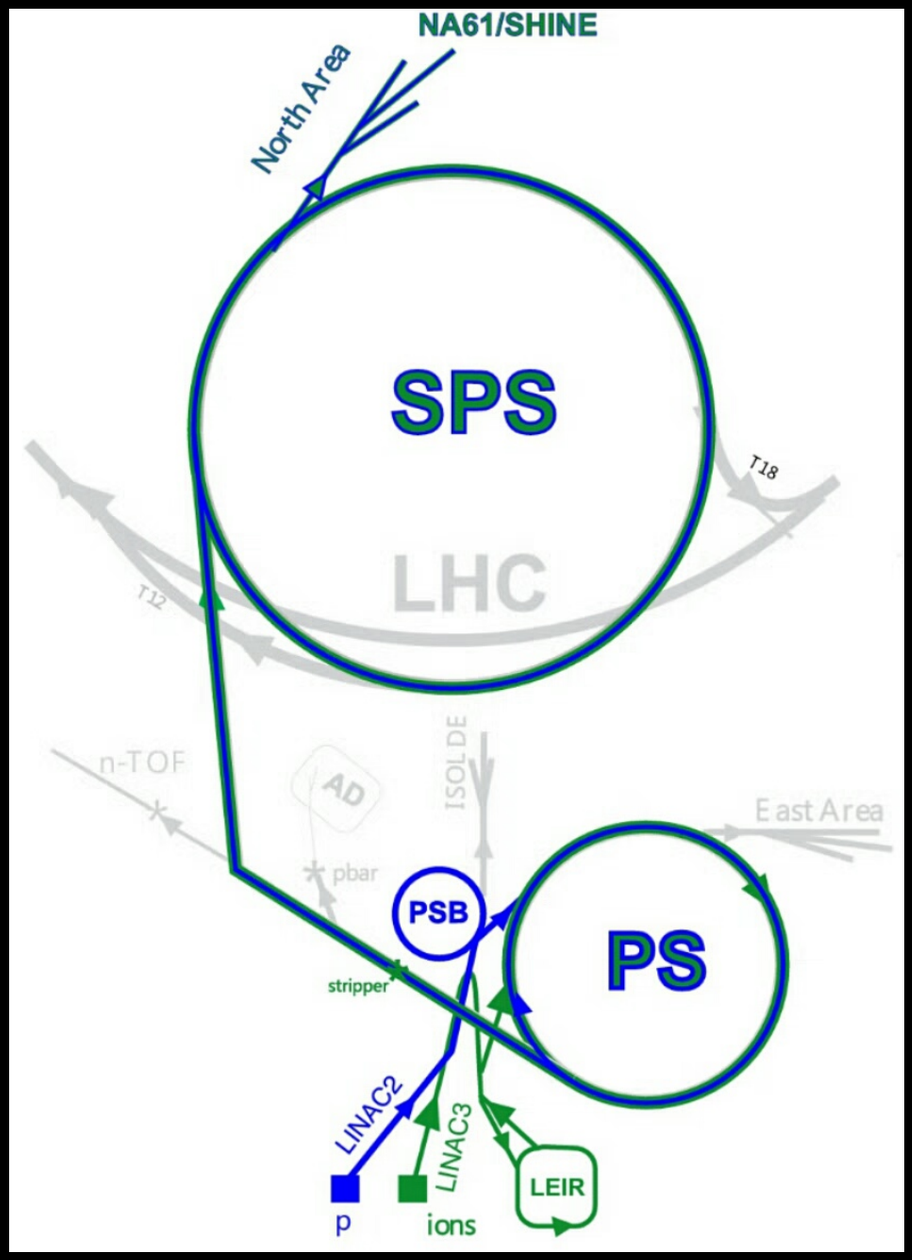
The NA61/SHINE collaboration

- Azerbaijan
  - National Nuclear Research Center, Baku
- Bulgaria
  - University of Sofia
- Croatia
  - Ruder Boskovic Institute
- France
  - Univ. of Paris VI and VII
- Germany
  - Karlsruhe Inst. of Tech.
  - Fachhochscule Frankfurt
  - Institut für Kernphysik, Goethe-Universität
- Greece
  - University of Athens
- Hungary
  - Wigner Research Center
- Japan
  - KEK
- Norway
  - University of Bergen
- Poland
  - J. Kochanowski Univ. Kielce
  - National Center for Nuclear Research
  - Jagiellonian Univ.
  - Univ. of Silesia
  - Univ. of Warsaw
  - Univ. of Wroclaw
  - Warsaw Univ. of Technology
  - H. Niewodniczanski Inst. of Nuclear Physics
- Russia
  - Inst. for Nuclear Research
  - Joint Inst. for Nuclear Research
  - St. Petersburg State Univ.
  - MEPhI
- Serbia
  - Univ. of Belgrade
- Switzerland
  - ETH Zürich
  - Univ. of Bern
  - Univ. of Geneva
- United States
  - Univ. of Colorado
  - Fermilab
  - Univ. of Hawaii
  - Los Alamos National Laboratory
  - Univ. of Pittsburgh

- PRIMARY INTERESTS:
  - STRONG INTERACTIONS
  - NEUTRINO BEAMS
  - COSMIC RAY PHYSICS

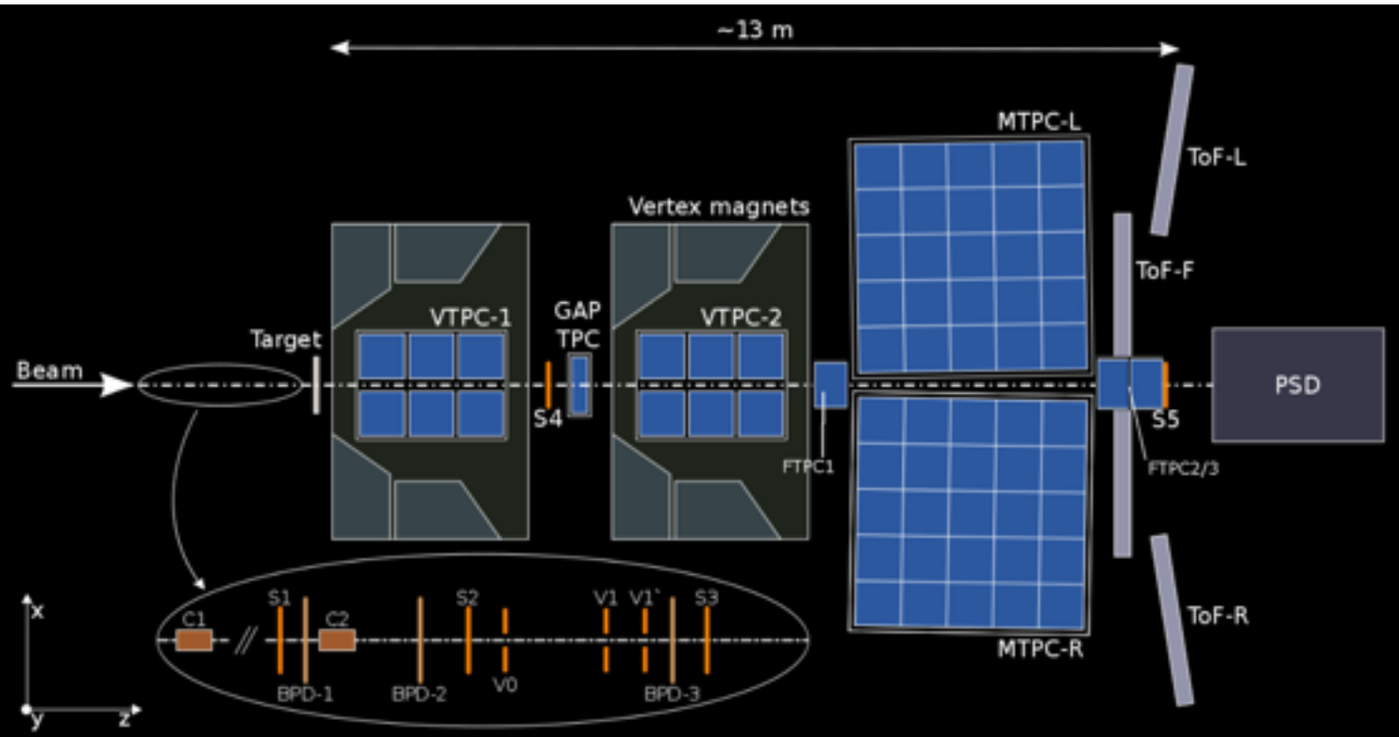
Introduction to NA61/SHINE: beam

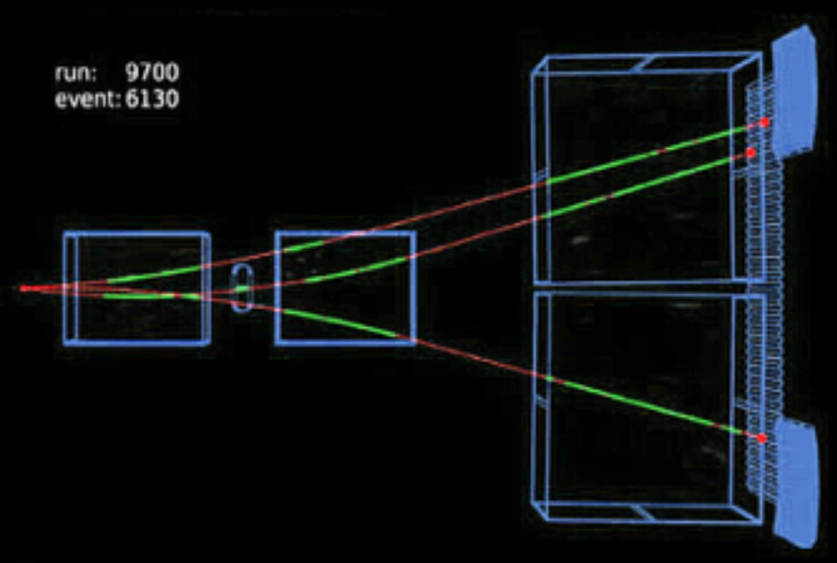
- Primary beams:
  - protons at 400 GeV/*c*
  - Ions (Ar, Xe, Pb) at 13*A*-150*A* GeV/*c*
- Secondary beams:
  - Hadrons ($\pi^{\pm}$, $K^{\pm}$, $p/\overline{p}$) at 13-400 GeV/*c*
  - Ions (Be) at 13*A*-150*A* GeV/c



Introduction to NA61/SHINE: detector

- Large acceptance (~50%) charged-particle spectrometer
- Beam particles tagged by counters, MWPCs
- Charged particles tracked by 5 (soon 7) TPCs
- Particle ID using d*E*/d*x*, ToF
- Projectile spectator calorimeter (PSD) for *A*+*A* event selection
- Small-acceptance vertex detector for precise vertex determination





Data collection/operations summary

- 2015-16 runs:
  - VTX-1 magnet failed in September 2015. Physics runs until May 2016 were taken without magnetic field. Very limited physics reach with this data set (basically just total cross-sections).

Without magnetic field

beam	target	beam momentum	number of events
π^+	C	31 GeV/c	1.11 M
π^+	Al	31 GeV/c	0.54 M
π^+	C	60 GeV/c	0.53 M
π^+	Al	60 GeV/c	0.35 M
K^+	Al	60 GeV/c	0.33 M
K^+	C	60 GeV/c	0.51 M
p	C	31 GeV/c	0.37 M
Pb	Pb	30A GeV/c	1.82 M

After magnet repair

beam	target	beam momentum	number of events
p	Pb	80 GeV/c	2.8 M
p	C	60 GeV/c	2.8 M
π^+	C	60 GeV/c	2.6 M
p	C	120 GeV/c	4.1 M
p	Al	60 GeV/c	3.2 M
p	Be	60 GeV/c	2.2 ~~3~~ M*
π^+	Be	60 GeV/c	2.4 ~~3~~ M*
p	Be	120 GeV/c	3 M*

STRONG INTERACTIONS

NEUTRINO BEAMS

Data collection/operations summary

- 2015-16 runs:
- Remainder of 2016 data after this week will be for strong interactions studies:
  - $p+p$ at 400 GeV/c
  - Pb+Pb at 13A, 30A, 150A GeV/c

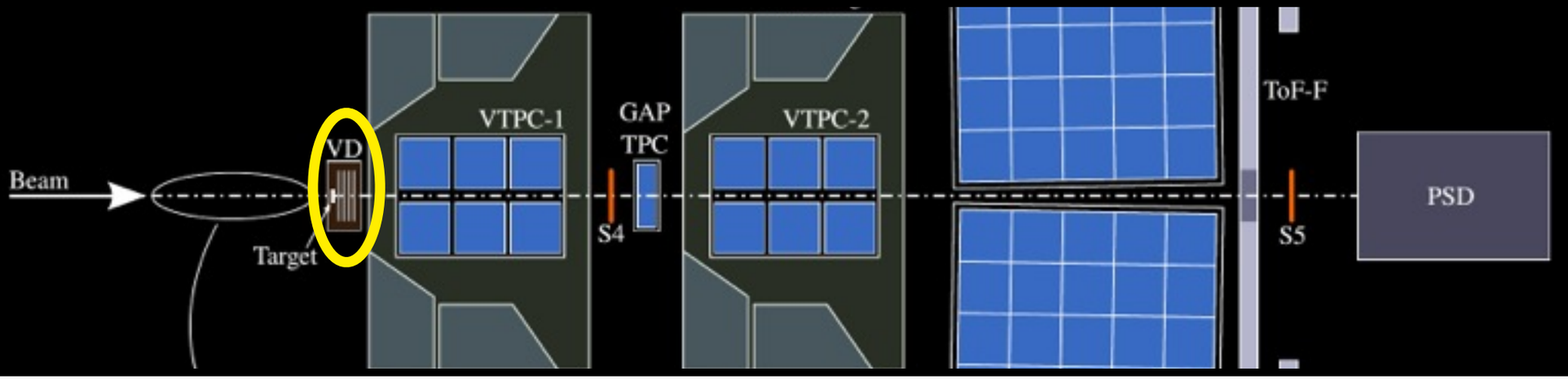
Facility upgrades

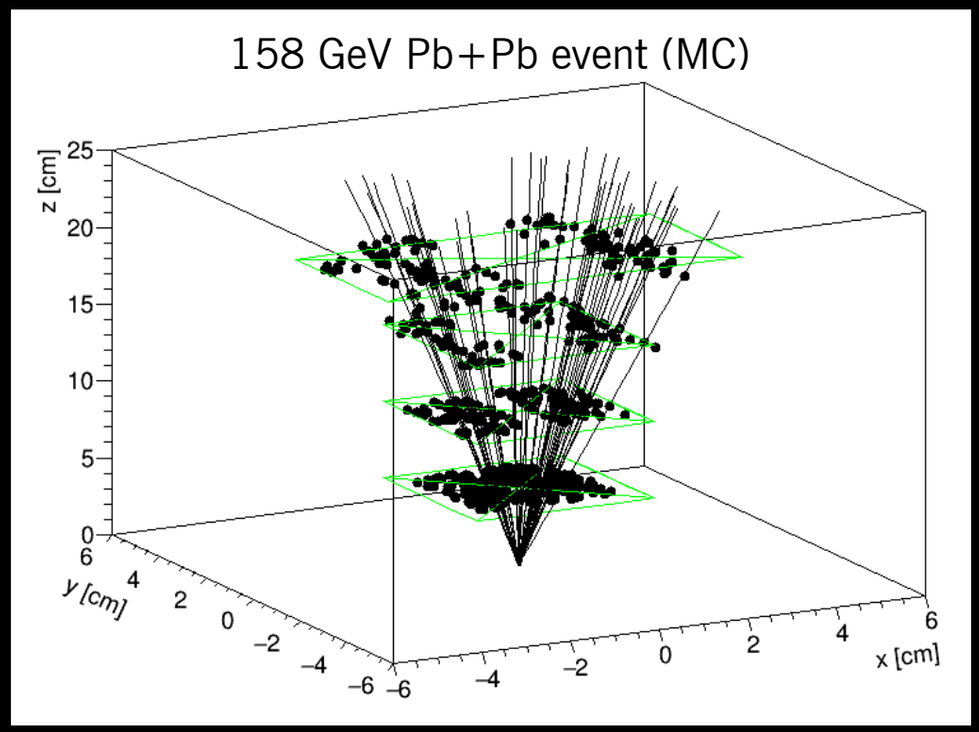
- Vertex magnets
- Vertex Detector
- Forward TPC
- PSD
- Electronics upgrade

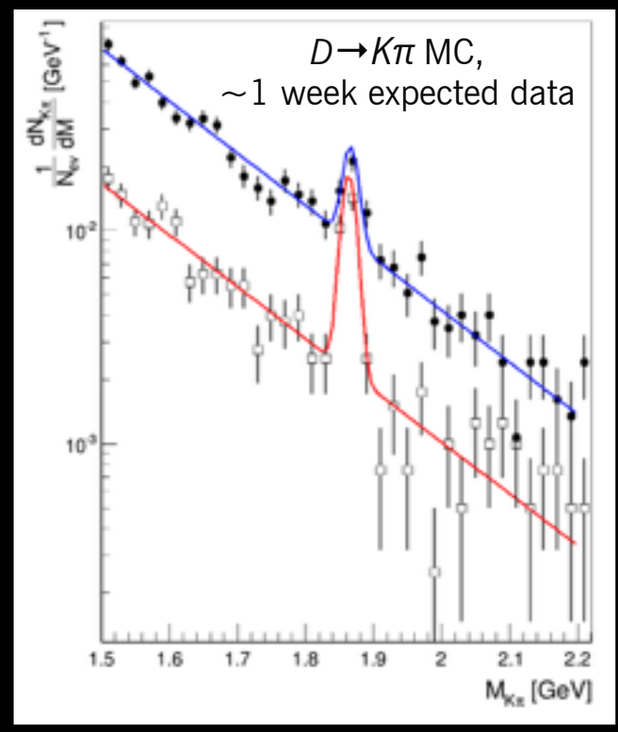
Vertex magnets

- Vertex-1 superconducting magnet turned off in September 2015 with helium cooling issues. It was unclear if the coil was damaged, and intrinsic problems in the quench protection system were found.
- Recommendation was made not to operate either vertex magnet until new Magnet Safety System (MSS) could be installed.
- MSS was developed and installed over winter; magnet operation resumed in May 2016.
- No damage evident; magnets have been working properly since May.
- Thanks to EP-ADO/DT, TE-CRG

Vertex Detector

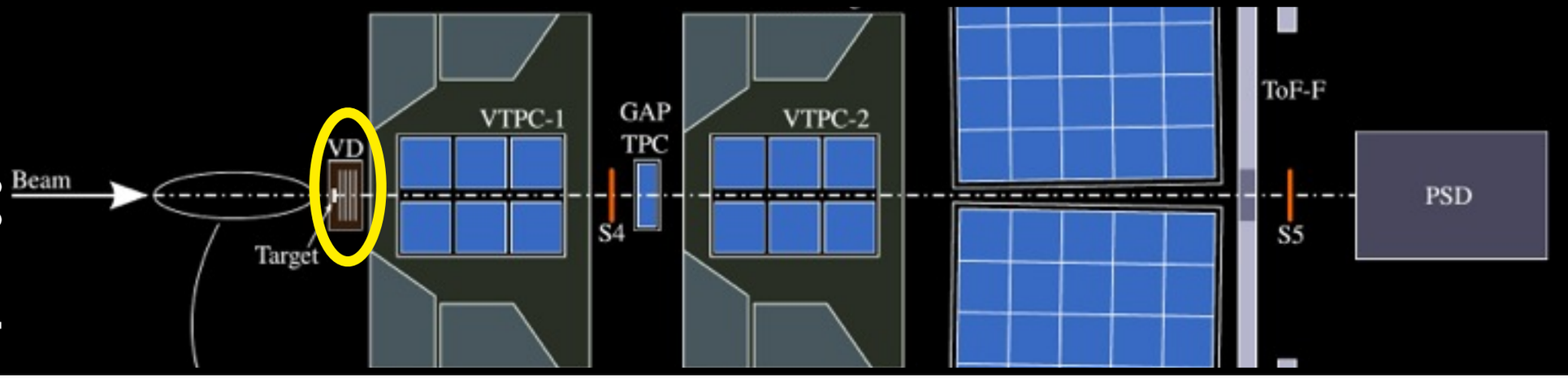




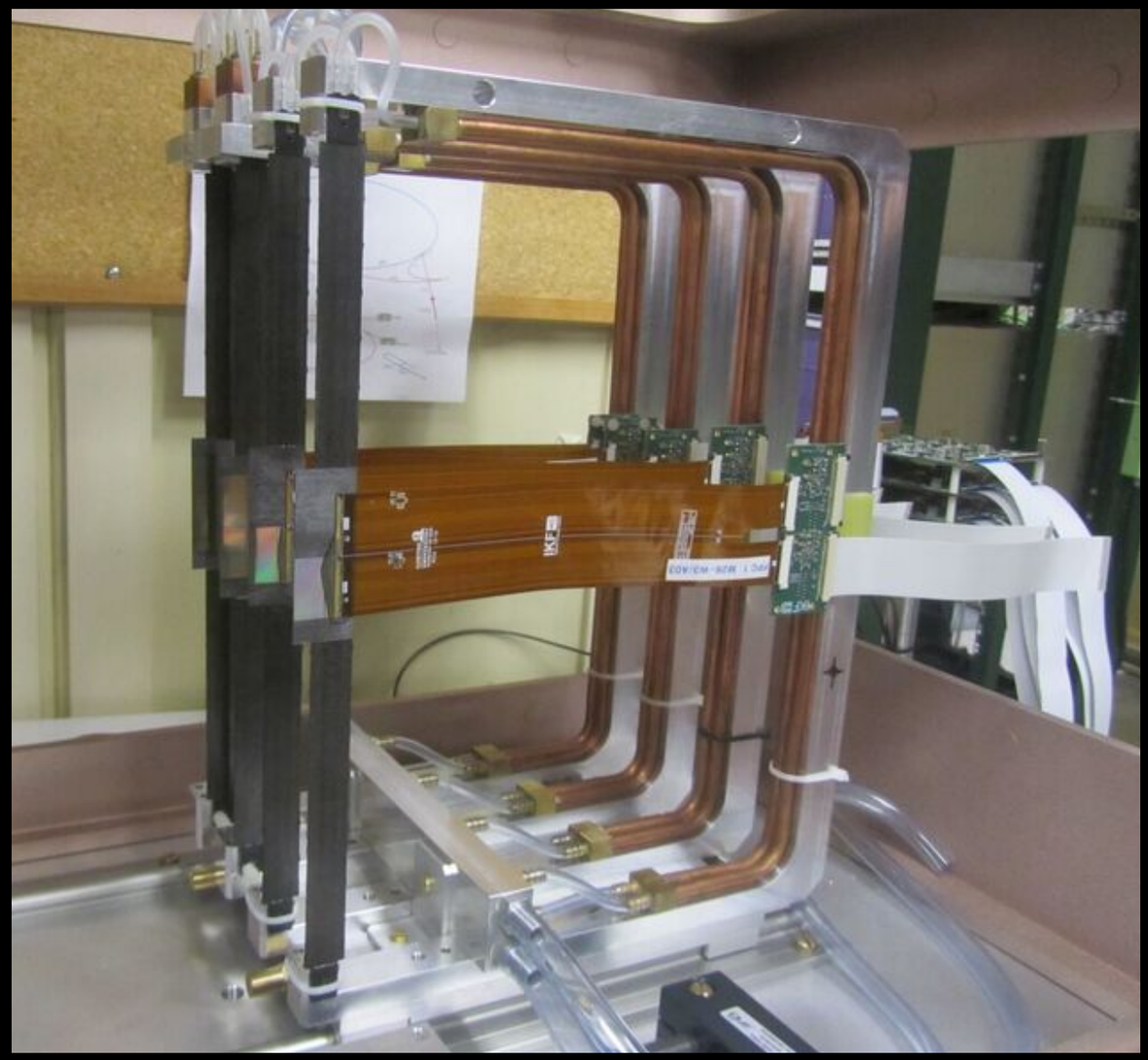


- Main physics goal is reconstruction of charm decays
- New CMOS silicon pixel detector under development
- Prototyping and beam tests in past year
- Technical collaboration with ALICE, CBM
- Collaborators from NA61: Krakow, Frankfurt, St. Petersburg, Warsaw Univ. of Tech.

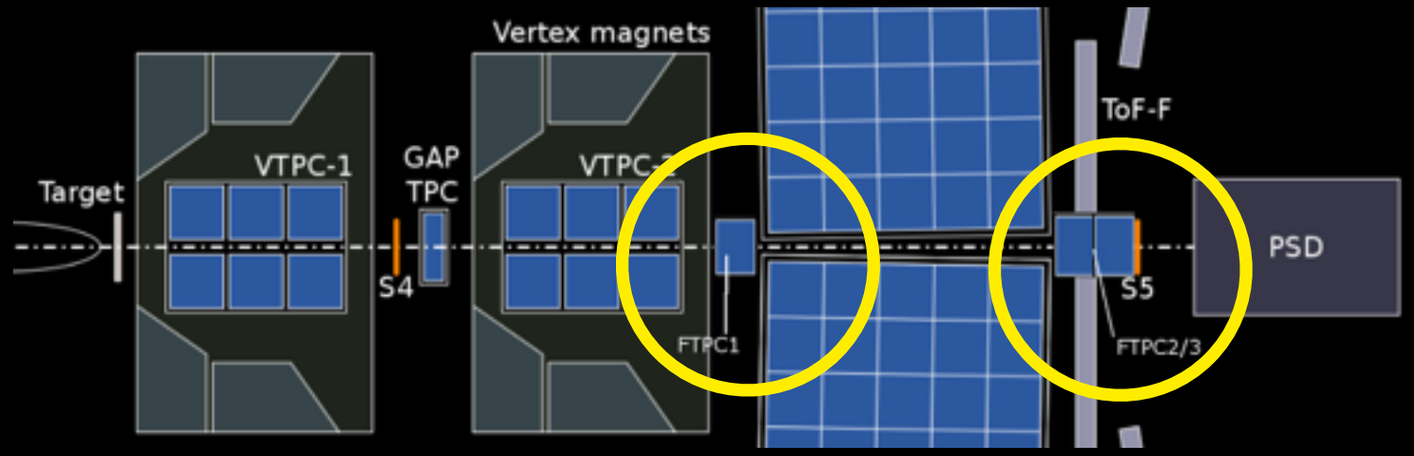
Vertex Detector: tests 2015-1



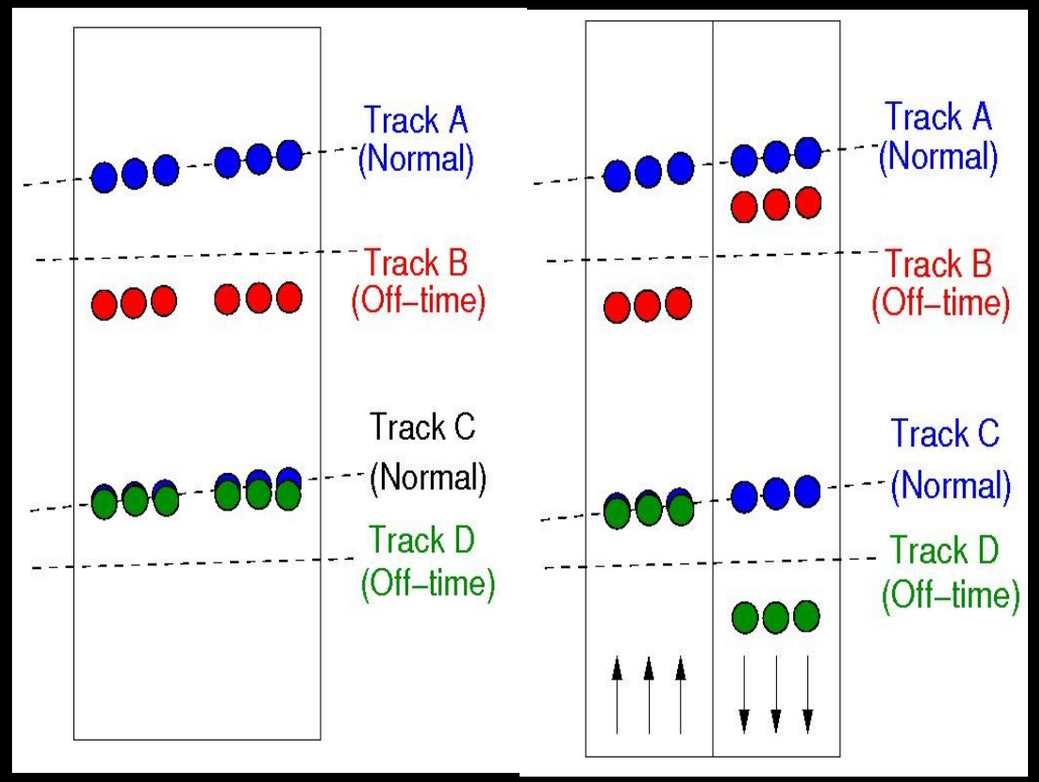
- November 2015: Test of sensor robustness to radiation near and in Pb beam spot
- July 2016: Test of resolution and vertex reconstruction
- December 2016: Full Small Acceptance Vertex Detector test with Pb+Pb collisions
- Physics runs: 2017-2018



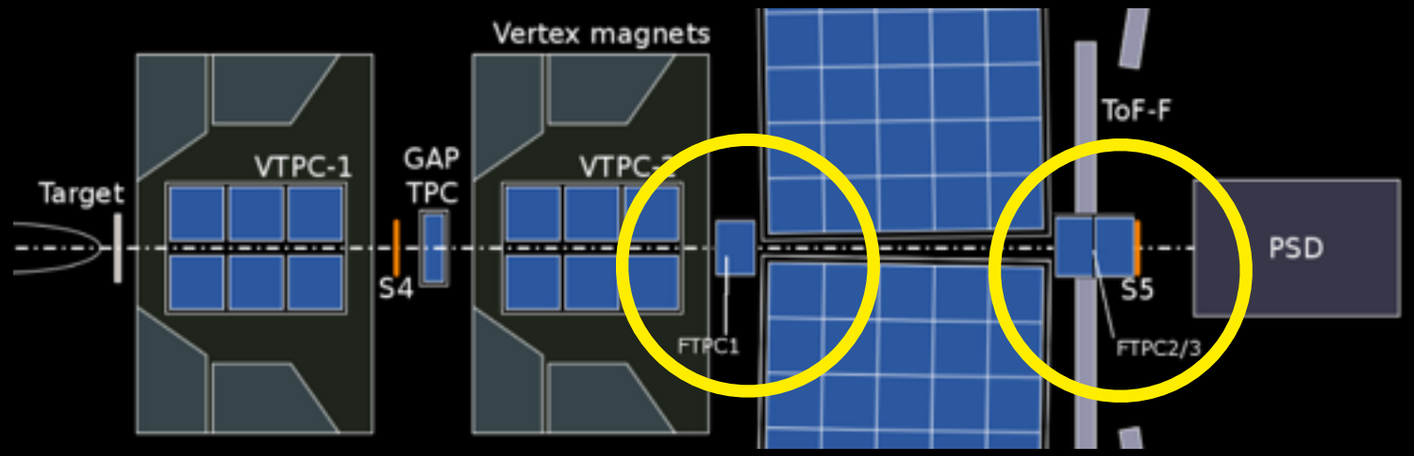
Forward TPC



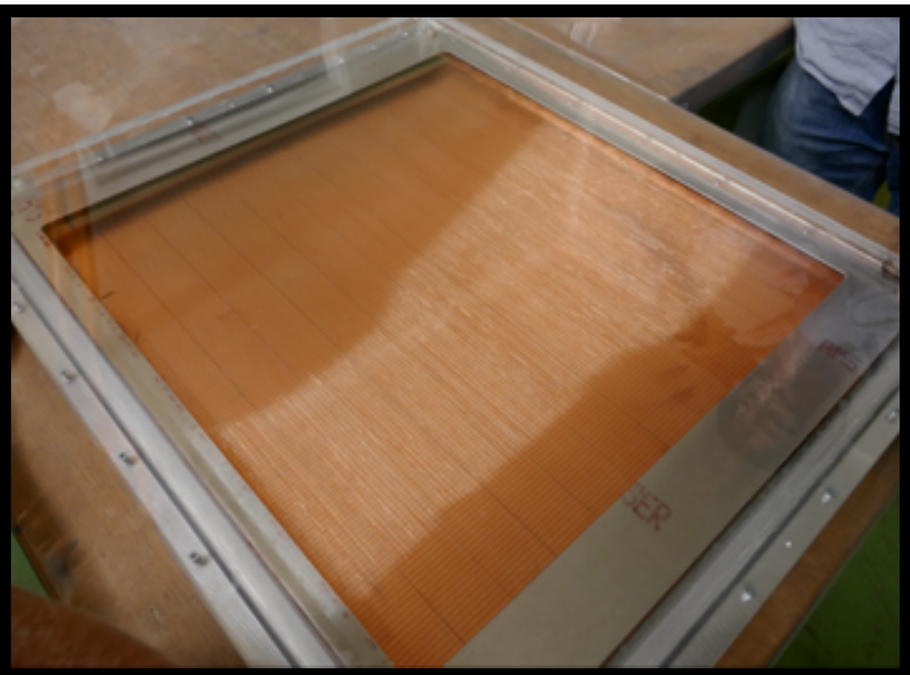
- New system designed to increase acceptance of forward tracks, primarily for neutrino program
- Two sets of chambers:
  - FTPC1 upstream of MTPC
  - FTPC2/3 downstream of MTPC
- New “tandem TPC” concept to reject out-of-time tracks
- Novel printed Kapton field cage
- Front-end electronics uses system from existing TPCs



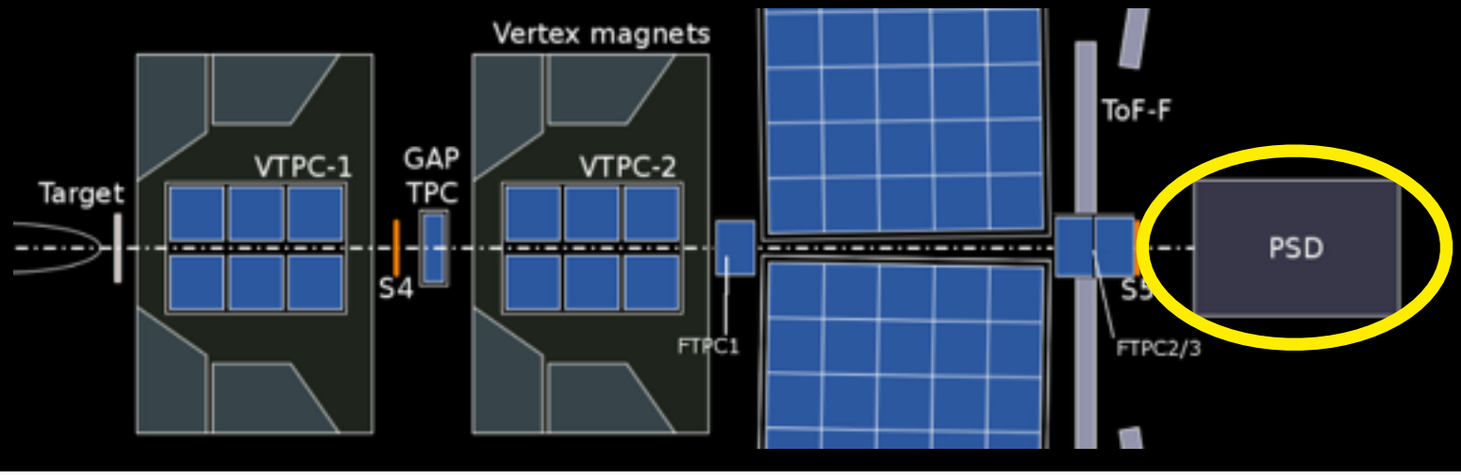
Forward TPC



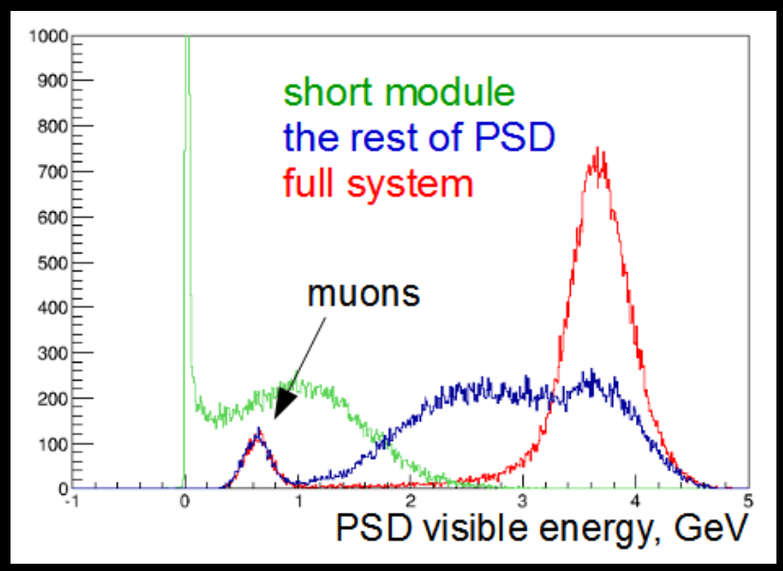
- FTPC parts produced at Colorado
- FTPC1 wire planes wound at KFKI-Wigner; FTPC2/3 planes to be wound in next two months
- Gas system developed by Univ. of Warsaw
- FTPC1 field cage assembled, tested on gas and HV
- Expect to finish assembly of FTPC1 in coning weeks, install before end of year
- FTPC2/3 field cage assemblies expected to begin next month
- Hope to have full system operational next summer



Projectile Spectator Detector

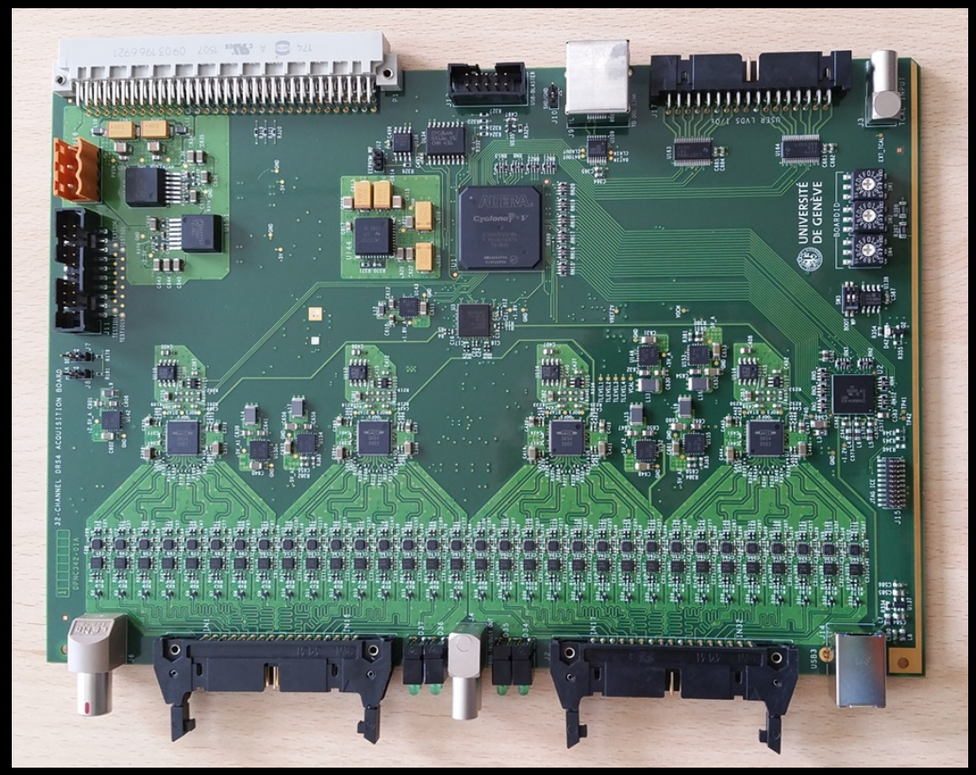


- Downstream-most detector: forward hadron calorimeter
- New short central module added to more fully contain highest-energy showers
  - Additional 1.2λ (adds to previous 5.7λ)
  - Pb-scintillator sandwich with new SiPMs, replacing old APDs.
- Tested with proton beams from 20-150 GeV over summer 2016.



Electronics upgrades

- Desire going forward to replace old FASTBUS electronics used in ToF systems.
- DRS digitizer developed at PSI has been selected for the upgrade.
- Development of new 32-channel boards at Univ. Geneva is near completion; production by Geneva and Univ. of Pittsburgh will begin soon.



Software and calibration

- Legacy software
- SHINE software

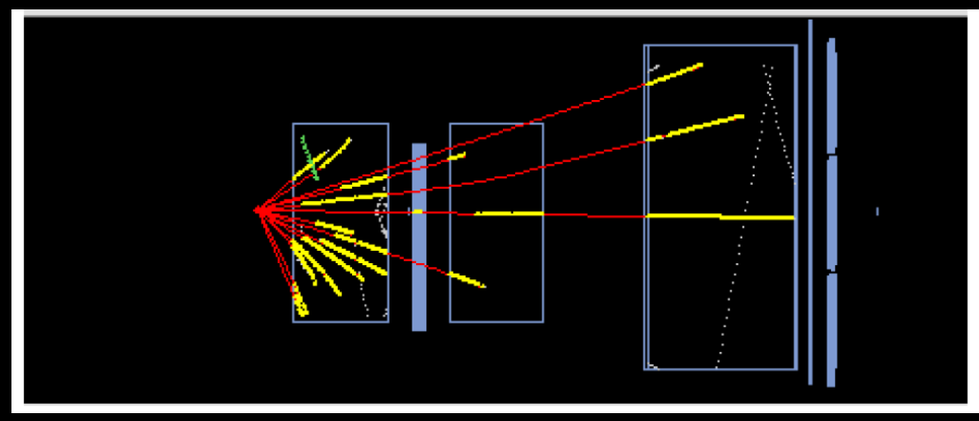
Legacy software

- We still use the legacy NA49 software framework for reconstruction and simulations.
- Work on this framework is limited to necessary updates and bug fixes
- Necessary software licenses and compiler support have been secured from CERN.

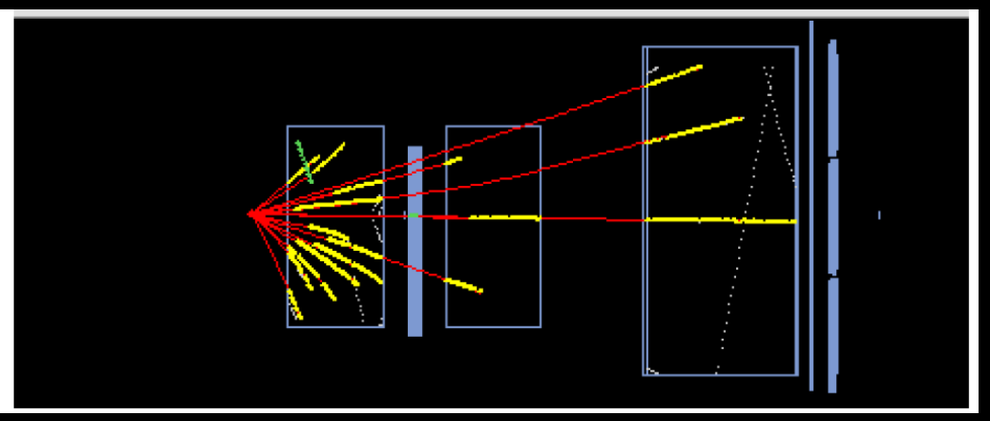
New SHINE software framework

- New software framework written in C++
- Major effort in last two years to develop this modern framework and replace legacy chain
- Contains:
  - Event data model including simulation, reconstruction information
  - Collection of processing models that can be assembled by user
  - Detector geometry description and configuration database

New SHINE software framework



Legacy MC (GEANT3)



Luminance MC (Geant4)

- Geant4-based MC (“Luminance”)
  - Detector description is fully implemented, including new detector systems
  - New simulations of charge drift and digitization
  - Validating by comparing identical interaction products simulated in legacy and new systems
- Framework is mostly functional now, final validations and bug fixes in progress.

SHINE calibration

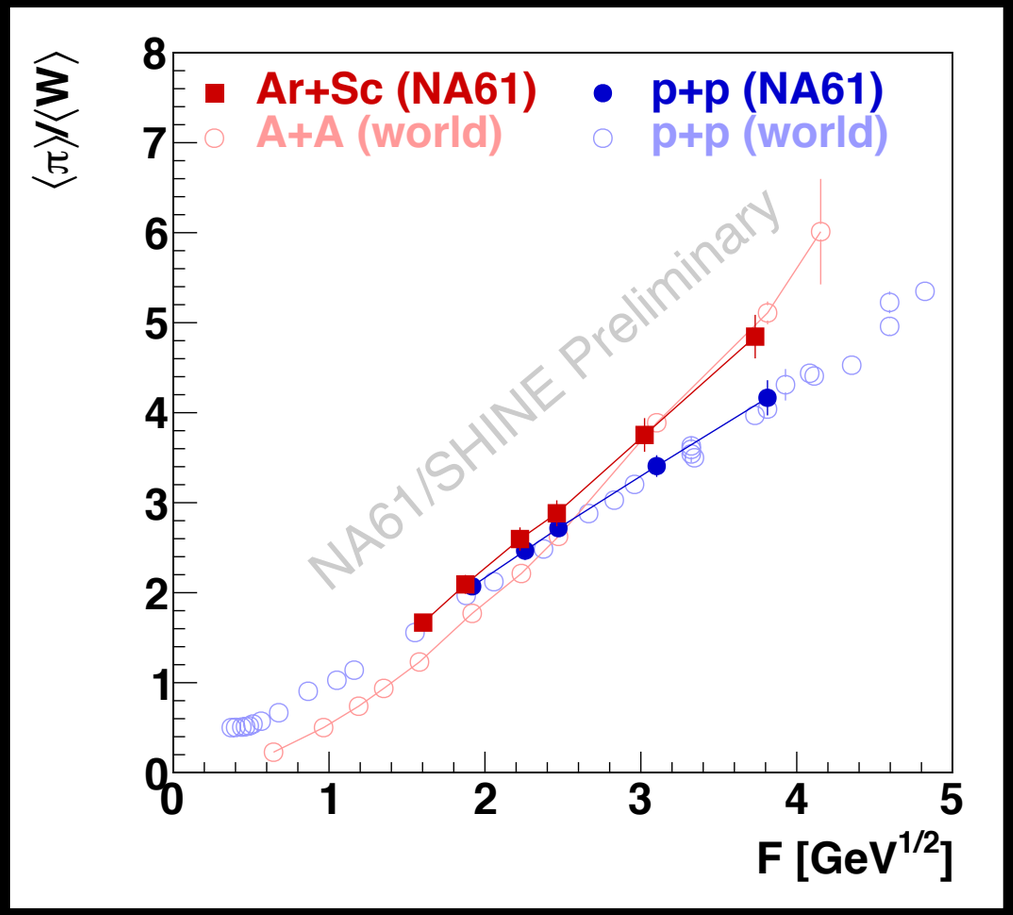
- Calibration chain now uses a mix of software from different sources, in different languages.
- New modules being developed (so far for ToF and TPC drift velocities) in the SHINE framework to replace these.

Physics results

- Strong interaction physics
  - Ar+Sc
  - Be+Be
  - p+p
- Neutrino beam physics
  - Measurements for T2K
  - Measurements for Fermilab neutrino beams
- Cosmic ray physics
- Recent publications

Strong interactions: onset of deconfinement

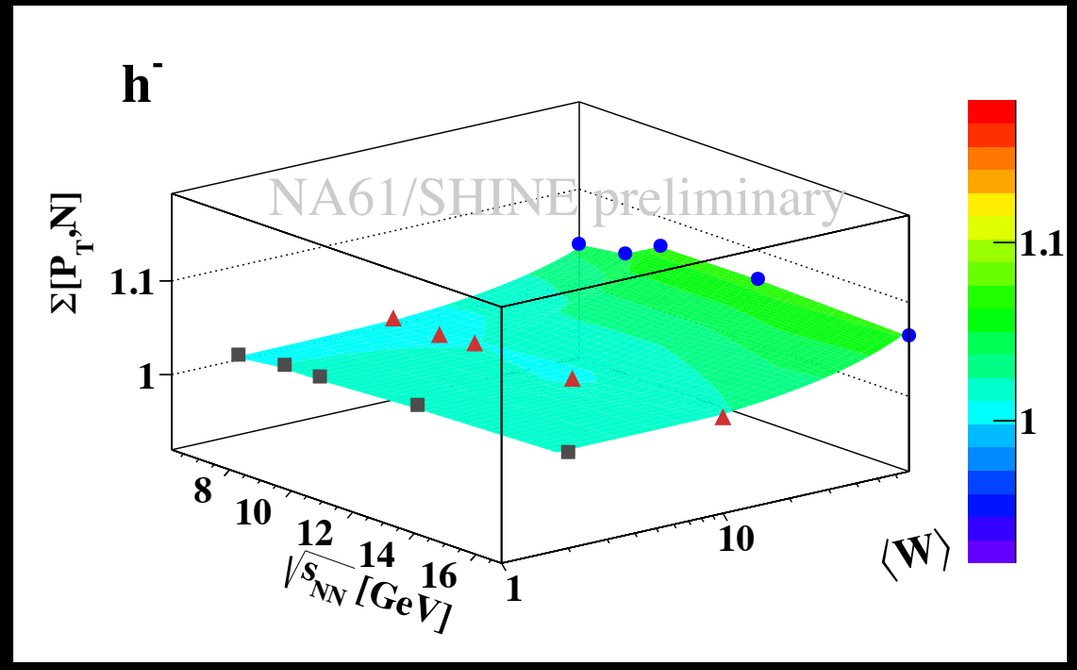
- Pion yields in Ar+Sc collisions are:
  - Similar to Pb+Pb and higher than *p*+*p* at high SPS energies
  - Similar to *p*+*p* and higher than Pb+Pb at low energies (reduced pion absorption for smaller systems)



Kink plot: mean pion multiplicity divided by mean number of wounded nucleons as a function of Fermi collision energy measure *F.*

Strong interactions: search for critical point

- Detailed study of fluctuations on $p+p$, Be+Be and Ar+Sc collisions is in progress
- Up to now, no evidence for the critical point of strongly interacting matter.



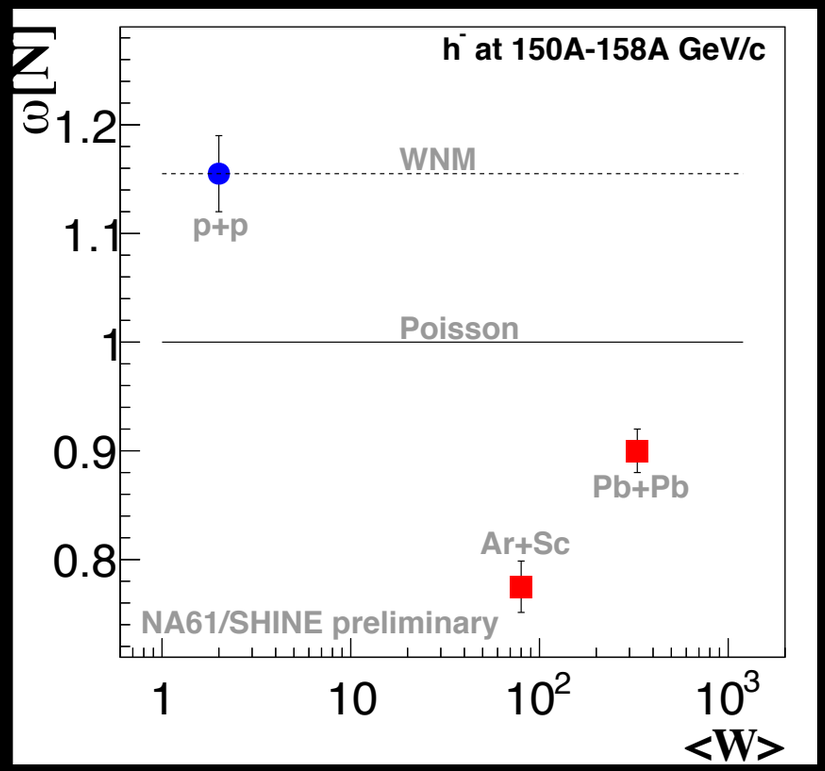
$$\Sigma[P_T,N]=\frac{1}{\omega[p_T]\langle N\rangle}\left[\langle N\rangle\omega[P_T]+\langle P_T\rangle\omega[N]-2\left(\langle P_T N\rangle-\langle P_T\rangle\langle N\rangle\right)\right]$$

$$\omega[P_T]=\frac{\langle P_T^2\rangle-\langle P_T\rangle^2}{\langle P_T\rangle} \qquad \omega[N]=\frac{\langle N^2\rangle-\langle N\rangle^2}{\langle N\rangle} \qquad \omega[p_T]=\frac{\overline{p_T^2}-\overline{p_T}^2}{\overline{p_T}}$$

$\Sigma[P_T, N]$ in inelastic $p+p$ (grey squares), 0-5% Be+Be (red triangles), and 0-5% Ar+Sc (blue circles) collisions obtained by NA61/SHINE at forward-rapidity, $0 < y_\pi < y_{beam}$, and in $p_T < 1.5$ GeV/c.

Strong interactions: statistical vs. dynamical models

- Multiplicity fluctuations in central Ar+Sc and Pb+Pb collisions at 150*A* GeV/*c* are significantly suppressed in comparison to *p*+*p* interactions and even narrower than the Poisson distribution.
- Result falsifies the Wounded Nucleon model
  - Thus it will be difficult to reproduce in string-hadronic models
- *A*+*A* data are in approximate agreement with predictions of statistical model with strict conservation laws.

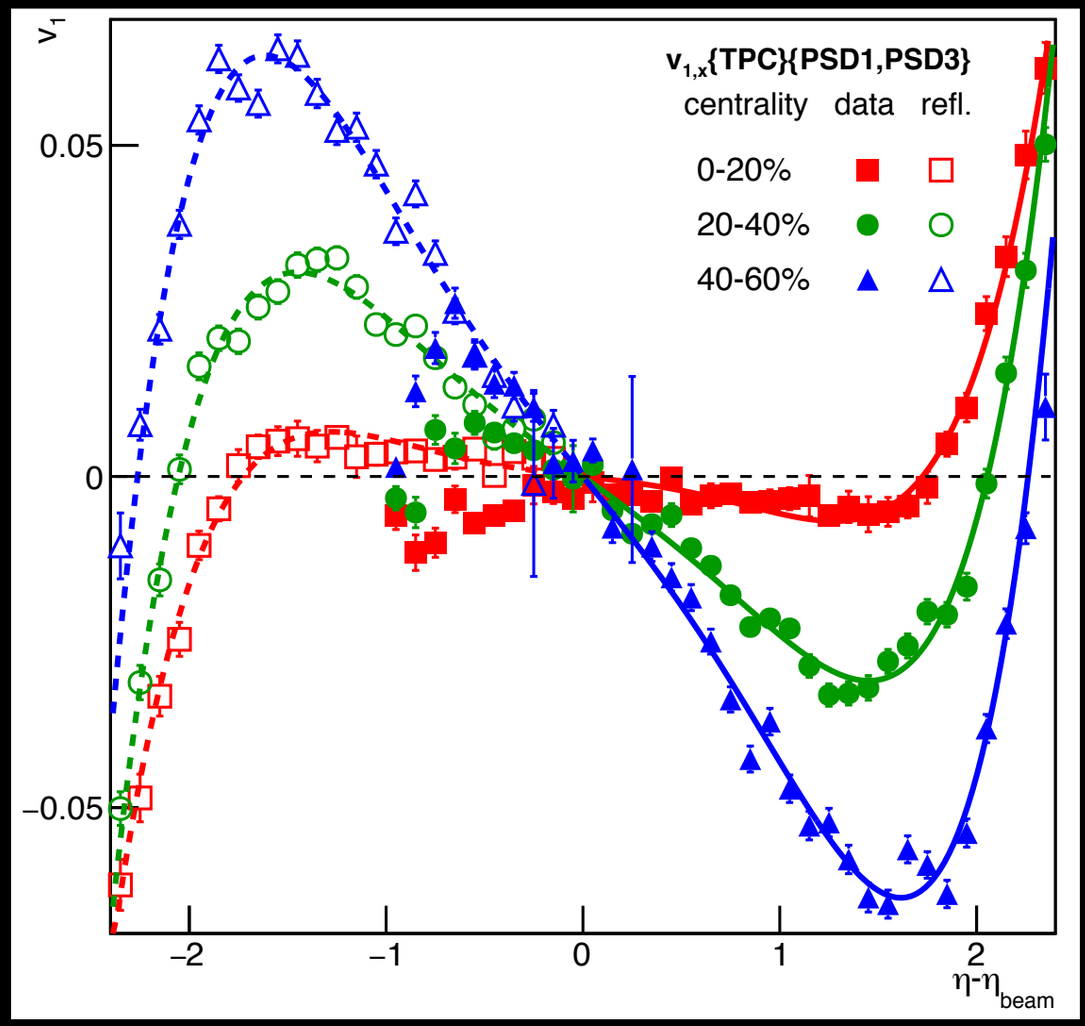


Scaled variance ($\omega[N]$) for negatively charged hadrons measured in *p*+*p*, 0-1% Pb+Pb, and 0-0.2% Ar+Sc collisions at 150/158*A* GeV/*c*. Results in $0 < y_\pi < y_{beam}$ and in NA49-B acceptance. Experimental data are compared to predictions of Wounded Nucleon Model.

Strong interactions: anisotropic flow measurements in Pb+Pb

- Test field-off data on Pb+Pb collisions at 30*A* GeV/*c* were used to study performance for anisotropic flow measurements using PSD data for event plane determination.

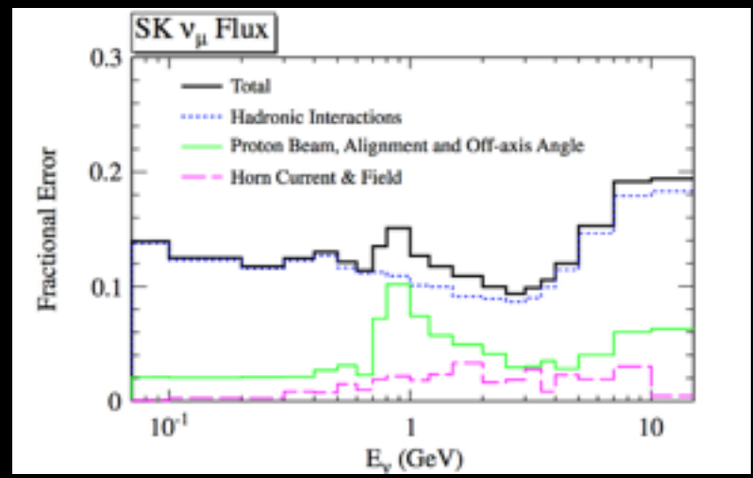
- Results are encouraging.



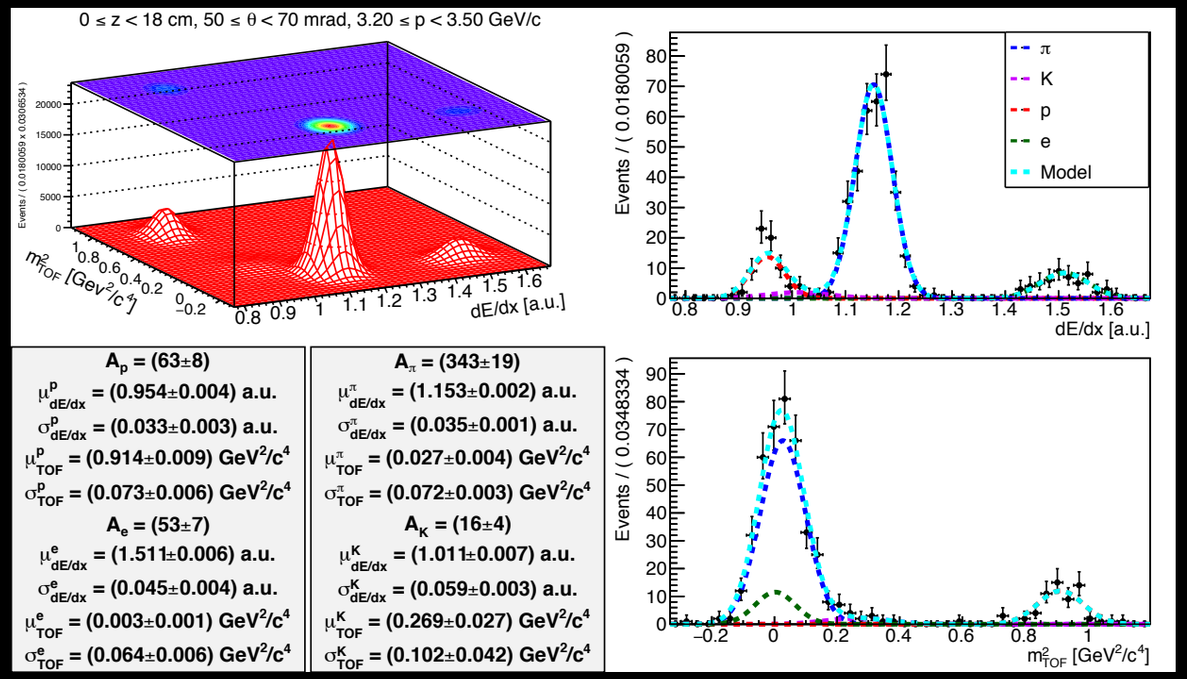
Uncorrected charged hadrons directed flow in three centrality classes obtained using the *x* components of the TPC **q**-vectors and PSD1 and PSD3 **Q**-vectors.

Neutrino beam physics

- T2K uses a 31 GeV/*c* proton beam on a long graphite target for pion/kaon production. Systematic errors on neutrino flux have been dominated by hadron production uncertainties.
  - NA61 has taken data on both thin carbon and T2K replica targets
  - Final results for 2009 thin target measurements published in the past year:
    - Inelastic and production cross-sections
    - Spectra of $\pi^{\pm}$, $K^{\pm}$, p, K^{0}_{S}, Λ
  - Replica target measurements:
    - 2009 data paper just accepted by EPJC
    - 2010 data analysis is underway
- 2015 data set for Fermilab neutrino beams being analyzed now
  - Due to lack of magnetic field, only total cross-sections can be extracted from this data set



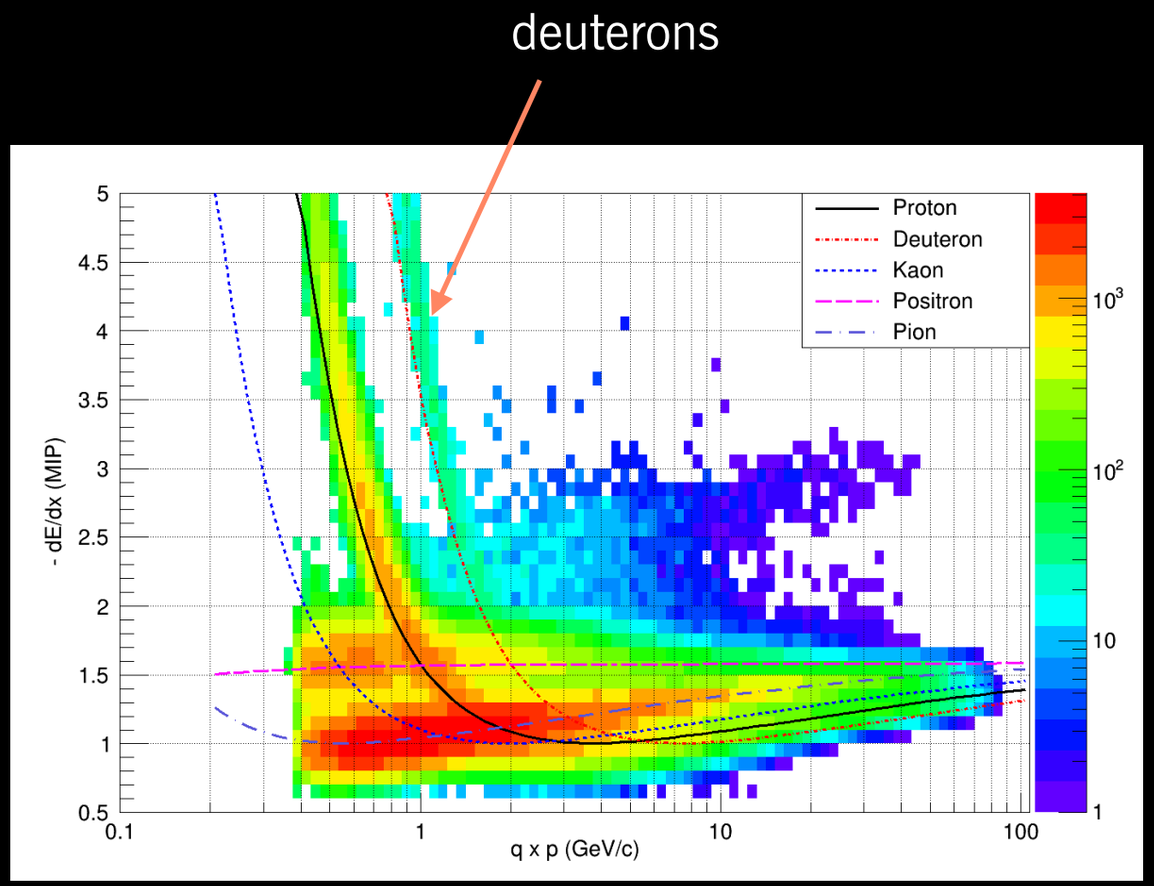
T2K flux errors from PRD 87 12001 (2013)



Particle yields in one (p, θ, z) bin from T2K replica target

Cosmic ray physics

- Measurements are motivated by need to understand hadronic processes in air showers to predict muon yields at the ground.
  - 2015: published pion and ρ^0 spectra from π^++C interactions at 158 and 350 GeV/c; more resonance results coming.
- Progress toward deuteron, antideuteron cross-sections. These results will be important for estimating astrophysical backgrounds to dark-matter searches looking for annihilation antideuteron signatures.



Recent publications

- *Multiplicity and transverse momentum fluctuations in inelastic proton-proton interactions at the CERN Super Proton Synchrotron*, arXiv:1510.00163 [hep-ex], accepted by *Eur. Phys. J. C*
- *Measurements of $\pi^{\pm}$, $K^{\pm}$, K^{0}_{S}, Λ^{0}, and proton production in proton–carbon interactions at 31 GeV/c with the NA61/SHINE spectrometer at the CERN SPS, Eur. Phys. J.* **C76** (2016) 84.
- *Production of Λ^{0} hyperons in inelastic p+p interactions at 158 GeV/c, Eur. Phys. J.* **C76** (2016) 198.
- *Measurements of $\pi^{\pm}$ differential yields from the surface of the T2K replica target for incoming 31 GeV/c protons with the NA61/SHINE spectrometer at the CERN SPS,* arXiv:1603.06774 [hep-ex], accepted by *Eur. Phys. J. C*
- *Two-particle correlations in azimuthal angle and pseudorapidity in inelastic p+p interactions at the CERN Super Proton Synchrotron,* arXiv:1610.00482 [nucl-ex], submitted to *Eur. Phys. J. C*

Proposed run schedule: 2017

Beam		Target	Momentum	Year	Days	Physics
Primary	Secondary		(A GeV/c)			
p			400			
	h^+	A	40-400	2017	21 days	installation/tests
p			400			
	p	Pb	30, 40	2017	28 days	SI
p			400			
	h^+	A	30–120	2017	42 days	ν
Xe		La	13, 19, 30, 40, 75, 150	2017	60 days	SI

- Note — does not include potential running proposed for SHiP studies.

Proposed run schedule: 2018

Beam		Target	Momentum	Year	Days	Physics
Primary	Secondary		(A GeV/c)			
p			400			
	p	Pb	13, 20	2018	28 days	SI
p			400			
	h^+	A	30–120	2018	42 days	ν
Pb		Pb	20, 40, 75, 150	2018	60 days	SI

Comments on proposed run schedule

- SHiP has proposed (CERN-SPSC-2016-034) working with NA61 to study muon flux emerging from its beam-dump target.
  - Goal is June 2017 data collection.
  - Forward TPCs significantly improve their measurement.
  - Schedule and resources for having FTPCs ready by then are very tight.
- H4 beamline has requested at various times that we run higher-energy beam for compatibility. We have been able to rearrange our schedule to accommodate this so far this year, but there is potential for it to become a more significant conflict in future.

NA61 beyond LS2

- The collaboration is considering the physics case and technical feasibility for operations beyond Long Shutdown 2. This would require significant renewal and upgrade of the detector.
- Main motivations are:
  - Strong interactions: precise measurements of open charm and multi-strange hyperon production, to distinguish between statistical and QCD-derived models of charm production in ion collisions
  - Additional measurements for understanding neutrino production in next-generation beams. Replica targets for LBNF in particular will not be available before LS2, and experience from T2K has shown importance of measurements using actual target geometry.

Summary

- Vertex magnet problems greatly reduced the physics reach of 2015 data set
- Since magnet repairs, NA61 has made planned measurements in 2016 run (and continues to do so)
- Many significant new physics results in strong interactions, neutrino beam physics, and cosmic ray shower physics.
- Planning full data runs in 2017 and 2018 to complete approved physics program (with possible addition of SHiP measurements)
- Considering options for a new phase of the experiment after Long Shutdown 2
- We would like to thank the CERN EP, BE and EN Departments for the strong support of NA61/SHINE.