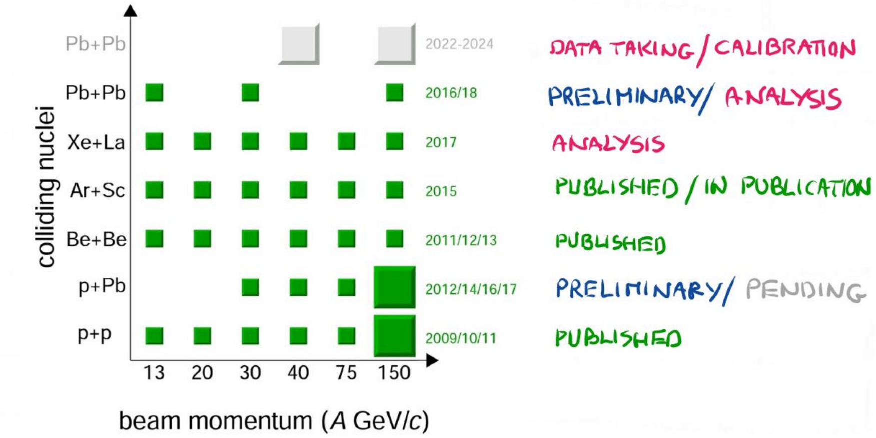
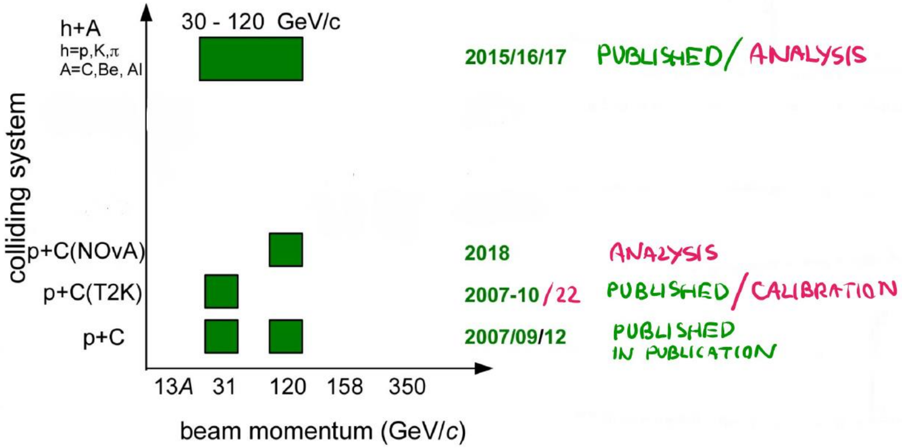
NA61++/SHINE: Physics opportunities from ions to pions

SHORT SUMMARY

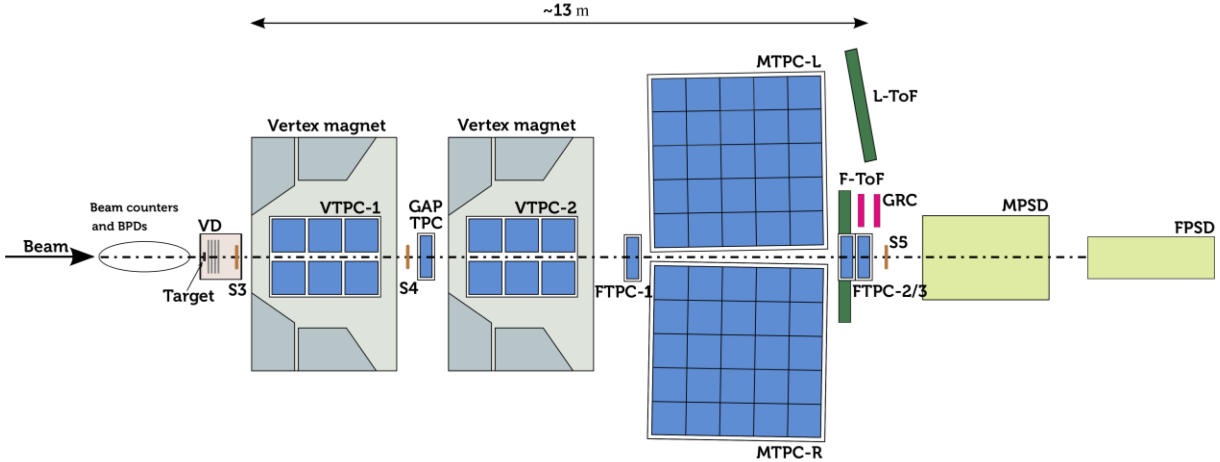
What is NA61/SHINE

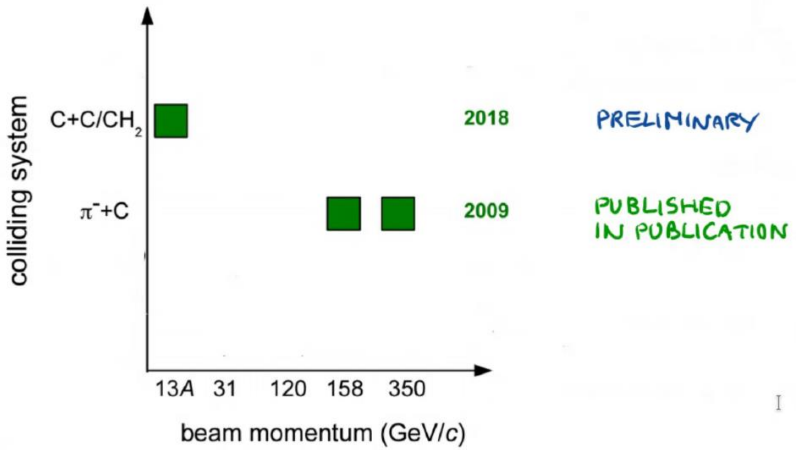
- Physics program
  - Strong interactions program
  - Hadron-production measurements for neutrino experiments
  - Hadron-production measurements for cosmic ray experiments





- Large acceptance hadron spectrometer
- Flexible detector set with possibilities for upgrades
- Use various types of beams (ions to pions)





Existing or new experiments

- NA60++

Measure:
- Thermal dimuons from QGP/hadronic phase: caloric curve for first order transition
- ρ-a_1 modifications: chiral symmetry restoration
- **Quarkonium suppression: signal of deconfinement**
- **Hadronic decays of charmed mesons/baryons: QGP transport coefficients**

  - Further discussions on possible synergies with the program of NA61++ will be a very important aspect, with the goal of building a solid ensemble of measurements for the next decade

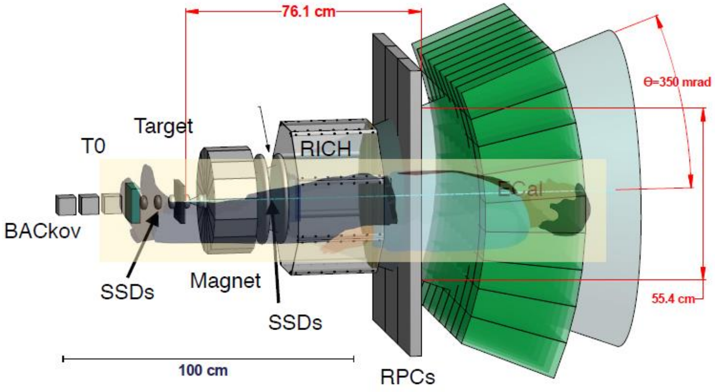
- COHERENT - Coherent elastic neutrino-nucleus scattering

◇ NA61++/SHINE can help! COHERENT will benefit from pion-production measurements with:
- Maximal angular coverage – decay-at-rest facilties need total production cross section
- Low-energy protons – SNS will operate using 1.3 GeV protons on ***thick*** targets

  $\Longrightarrow$ want measurements from 0.5 - 1.3 GeV incident protons, thin and thick targets?
- Wide range of nuclei – primarily Hg and W, but $\pi^{\pm}$ from Al, Ni, and Fe as well
- Production of $\pi^{\pm}$, π^0, η – primarily π^+ for ν, but others for dark matter studies

Existing or new experiments

- EMPHATIC - **E**xperiment to **M**easure the **P**roduction of **H**adrons **A**t a **T**est beam **I**n **C**hicagoland



- EMPHATIC offers a ***novel, table-top*** approach to reducing the hadron production uncertainties by at least a factor of 2 with measurements of both thin and thick targets.
- EMPHATIC is ***complementary*** to the existing efforts by NA61/SHINE to collect important hadron production data for improved flux predictions.

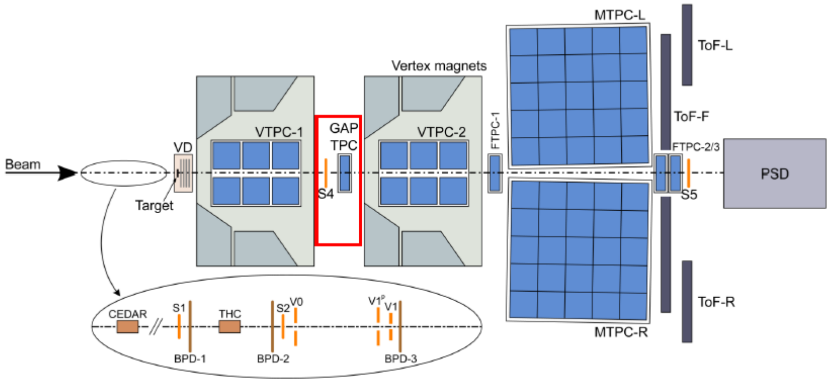
- The COMET Experiment

- **What would we want from a future NA61++/SHINE?**
  - In the first instance, any **relevant data with carbon production target** and **8 GeV proton beam**
  - Ideally, a **novel set-up to study <80 MeV/c backwards pion** production
  - Rates, energies and angular distributions
  - **Anti-protons** (in forward direction) as a function of primary beam energy near 8 GeV
  - Data on **heavier target materials**, like tungsten, would also be useful for Phase-II

Ideas for new technology in NA61++

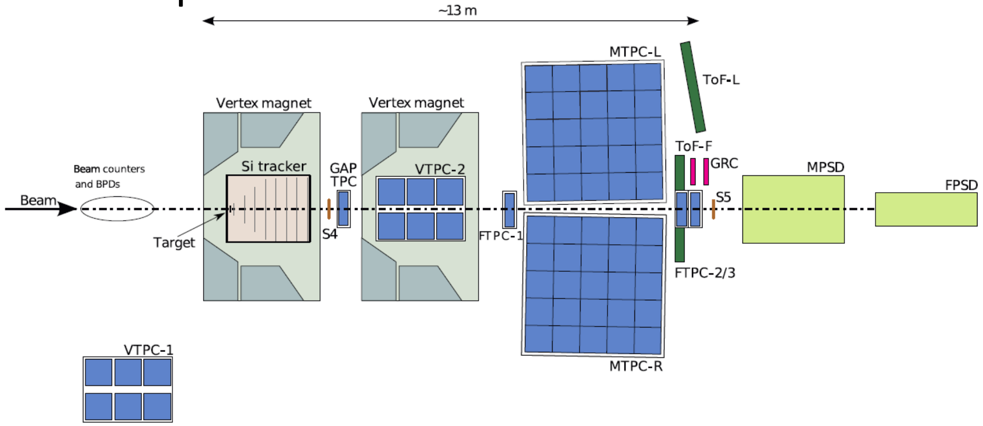
Resistive technologies for Time Projection Chambers

- Resistive Micromegas inherit from long and successful bulk Micromegas developments
- Strong interest of CERN for resistive technology
- Resistive readout shows good performances and large flexibility
- Highly interesting and promising R&D for resistive field cages

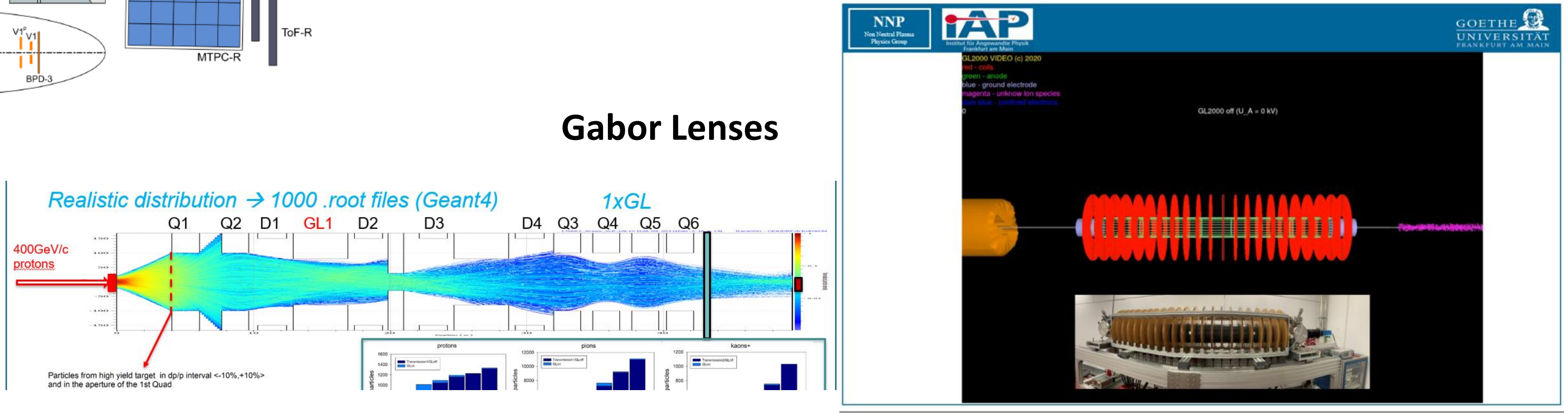


Si tracker in the magnetic field

- Setup for charm correlation measurements



Gabor Lenses

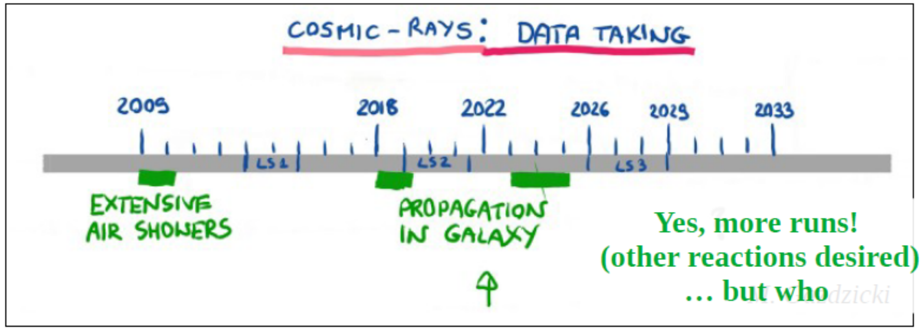


Hadron-production measurements for cosmic ray experiments

- Atmospheric neutrinos
  - At low energies (< 20GeV protons), there is data, some of it is good, but it is a struggle to make a consistent overall picture and there are large gaps in the phase space.
  - Further reduction in hadron production systematics:
    - 120 GeV NA61/SHINE data – reduce interpolation uncertainty between 31 and 158 GeV
    - Potential for new low energy measurements reduce uncertainty where hadron production is uncertain

Galactic cosmic-ray (GCR) propagation and nuclear production cross sections

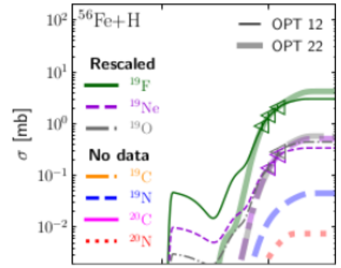
What next?



XS ranking (Génolini, DM, Moskalengo, Unger)
→ Up to Si, then up to Fe (Z=17-25 AMS data not yet published)
→ Provide progenitors/targets required and estimated beam time

XS modelling (DM, Génolini...)
→ Update our XS database (extracted from EXFOR)
→ Use machine learning to
- predict unmeasured XS
- ID key reactions (to measure) for models

XS measurement
→ (He) CNO, Ne, Mg, Si, and Fe main projectiles
→ (2H, 3He) LiBeB, F, and sub-Fe main fragments



Debate with F: primary source (Boschini et al. 2021), XS (Ferronato Bueno et al. 2022), spatial dependent diffusion (Zhao et al. 2022)

Hadron-production measurements for cosmic ray experiments

Measurmets for the Cosmic-ray Anti-nuclei

- Observation of $^3\overline{\text{He}}$ and $^4\overline{\text{He}}$ events would imply a drastic revision of cosmology and would request a more fundamental theory than the standard model of particle physics. A few routes have already been explored.

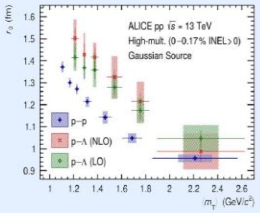
Antinuclei production studies

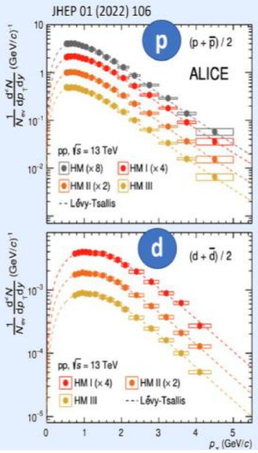
What do we need from NA61

- NA61 energy of $\sqrt{s}$~20 GeV is perfect to study antideuterons for cosmic rays
- Large acceptance for forward/backward rapidity give important insights for astrophysics (production at forward rapidity is poorly measured)

What we need from NA61 to study nuclei formation:

- Emission source size measurements via two-particle correlation
- (Anti)nucleon momentum distributions
- (Anti)nuclei production measurements

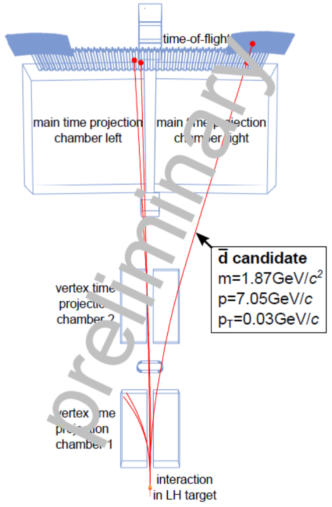




NA61/SHINE and NA61++ measurements for the understanding of cosmic antinuclei

Future studies and measurements

- Preliminary: current NA61/SHINE p-p data at 158GeV/c contains ~50 antideuteron candidates → ongoing
- Conduct the same analysis with existing p-p 400GeV/c data set
- **More very-high statistics p-p data needed:**
  - Take data with upgraded NA61/SHINE experiment (10-20x faster electronics, better TPC resolution, better TOF, etc.)
  - **Goal:** p-p data set on the order of 1-10 billion events
  - → high-statistics antideuteron measurements
  - → potential for seeing antihelium-3



Hadron-production measurements for cosmic ray experiments

Measurmets for the Cosmic-ray Anti-nuclei

- Observation of $^3\overline{\mathrm{He}}$ and $^4\overline{\mathrm{He}}$ events would imply a drastic revision of cosmology and would request a more fundamental theory than the standard model of particle physics. A few routes have already been explored.

p+p collision possible in the time window in 2024 (addendum July SPSC)

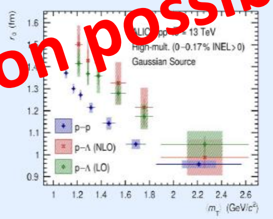
Antinuclei production studies

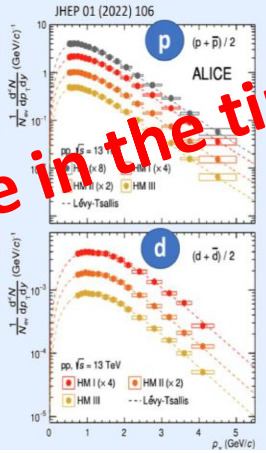
What do we need from NA61

- NA61 energy of $\sqrt{s}$~20 GeV is perfect to study antideuterons for cosmic rays
- Large acceptance for forward/backward rapidity give important insights for astrophysics (production at forward rapidity is poorly measured)

What we need from NA61 to study nuclei formation:

- Emission source size measurements via two-particle correlation
- (Anti)nucleon momentum distributions
- (Anti)nuclei production measurements





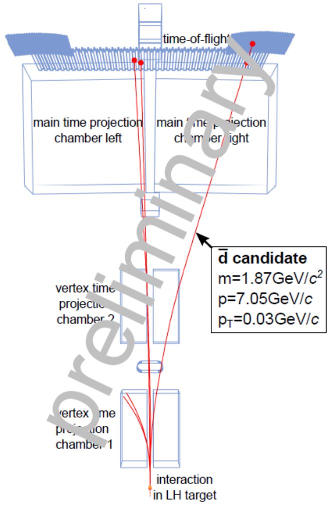
NA61/SHINE and NA61++ measurements for the understanding of cosmic antinuclei

Future studies and measurements

- Preliminary: current NA61/SHINE p-p data at 158GeV/c contains ~50 antideuteron candidates → ongoing
- Conduct the same analysis with existing p-p 400GeV/c data set
- **More very-high statistics p-p data needed:**
  - Take data with upgraded NA61/SHINE experiment (10-20x faster electronics, better TPC resolution, better TOF, etc.)
  - **Goal:** p-p data set on the order of 1-10 billion events

    → high-statistics antideuteron measurements

    → potential for seeing antihelium-3



Hadron-production measurements for neutrino experiments

Thanks to NA61/SHINE data, the current error for neutrino flux predictions was reduced but still is space for improvement

T2K/HK

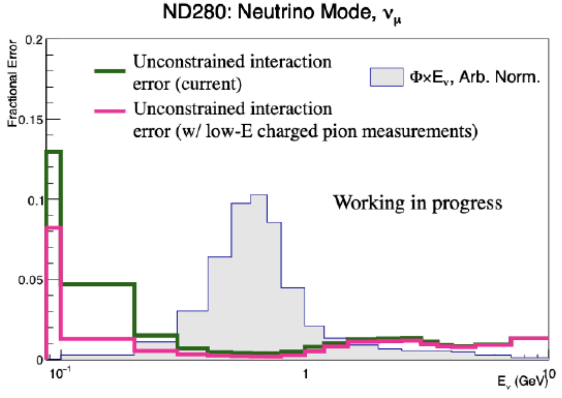
Plan of low momentum beam measurements

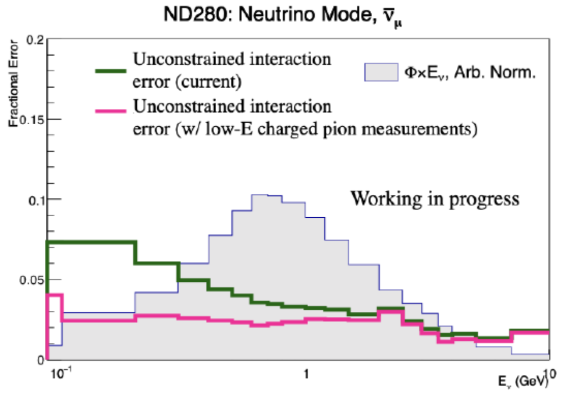
We will propose the following measurements

w/ 2cm thin target

- π^+ and π^- beam with 2 GeV/c for Al and Fe targets,
- π^+ and π^- beam with 8 GeV/c for Al, Fe and C targets

Expected improvements





We can improve the flux error less than 5%

14

DUNE FLUX AND MEASUREMENT NEEDS

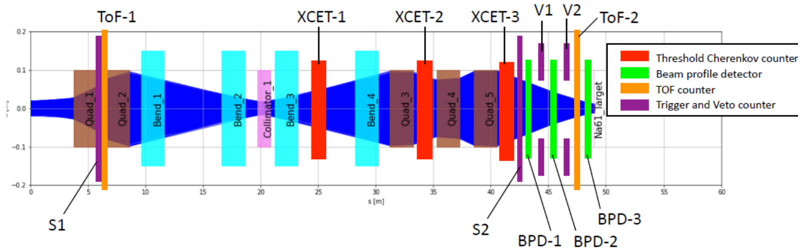
CONCLUSION

- DUNE will make precise measurements of **neutrino oscillation parameters** and search for CP-violation and a variety of **BSM physics**
- All of DUNE's accelerator-based measurements rely on an **accurate beam simulation**
- **Many of the interactions** that will create neutrinos in the LBNF beam line have **never been measured** and are not well understood theoretically
- Highest DUNE hadron production needs
  - **Replica target** measurements (but will have to make these repeatedly)
  - Interactions **not currently covered** by data
  - Data over a range of **incident energy and target nucleus**
  - **Covariance matrices** for all datasets
  - **Help from the HP community** using these data

Thank You for Listening!

29

Hadron-production measurements for neutrino experiments



- Low-Energy Physics Opportunities
  - Low-Energy Beamline at H2 (Low-Energy = 1-13 GeV (2-13 GeV/c))

Physics Cases

Accelerator-based neutrino experiments (to study secondary hadron scatterings not covered by current data)

- Long-baseline: T2K / Hyper-K at J-PARC, LBNF/DUNE at FNAL
- Short-baseline: Booster Neutrinos (SBND, MicroBooNE, ICARUS) at FNAL

Atmospheric neutrino experiments (to study cosmic ray proton scatterings)

- Sub-GeV and Multi-GeV neutrinos: Super-K, Hyper-K, DUNE

Spallation neutron source neutrino experiments

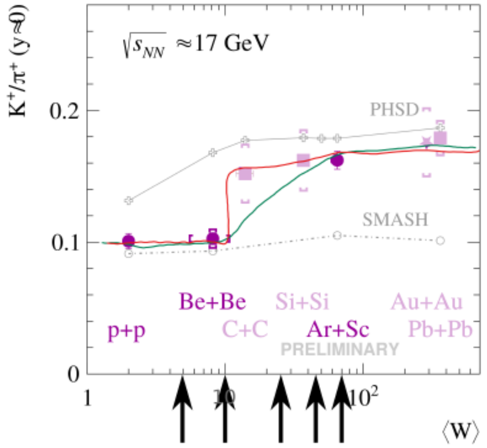
- JSNS^2 at J-PARC MLF (sterile neutrino search): hadron production on p+Hg at 3 GeV (3.82 GeV/c)
- COHERENT at ORNL (coherent drastic neutrino scattering): hadron production on p+Hg around 2 GeV/c

Muon experiments

- COMET at J-PARC (muon to electron): hadron production on p+X at 8 GeV (X = C, W, or heavy material)
- (potentially) Mu2e at FNAL: hadron production on p+W at 8 GeV

Strong interactions program

Proposal to **measure** collisions of **light** and **intermediate** mass nuclei



+

p_{beam} (A GeV/c)	$\sqrt{s_{NN}}$ (GeV)	^{10}B # days	^{16}O # days	^{24}Mg # days	^{40}Ar # days
13	5.1	7	7	7	7
30	7.6	7	7	7	7
150	16.8	7	7	7	7

- ∼ 100M events per reaction
- The solid/compact targets are in favor due to possibility of installation in VD.

projectile	^{4}He/^{10}B	^{16}O	^{24}Mg	^{40}Ar
target	^{4}He(liquid)/^{9}Be-^{12}C ^{7}Li	^{16}O(water) ^{19}F (LiF)	^{32}S ^{24}Mg	^{45}Sc ^{40}Ca

Strong interactions program

- c cbar – correlations
  - Measuring correlations of c and cbar quarks from the same pair forces one to seek for events with only a single c cbar -pair

Recall the requirement for a dominance of a single $c\bar{c}$-pair production: $\frac{P(N_{c\bar{c}}>1)}{P(N_{c\bar{c}}=1)} \ll 1$

	$\langle c\bar{c}\rangle = 0.1$	$\langle c\bar{c}\rangle = 0.2$	$\langle c\bar{c}\rangle = 0.5$	$\langle c\bar{c}\rangle = 1$
$P(N_{c\bar{c}} > 1)/P(N_{c\bar{c}} = 1)$	0.05	0.1	0.3	0.7
$N_{\text{true pairs}}/N_{\text{all pairs}}$	91%	83%	66%	50%

	$\langle c\bar{c}\rangle = 0.1$	$\langle c\bar{c}\rangle = 0.2$	$\langle c\bar{c}\rangle = 0.5$	$\langle c\bar{c}\rangle = 1$
1 kHz	$\sim$ 1000 days	$\sim$ 500 days	$\sim$ 200 days	$\sim$ 100 days
10 kHz	$\sim$ 100 days	$\sim$ 50 days	$\sim$ 20 days	$\sim$ 10 days
100 kHz	$\sim$ 10 days	$\sim$ 5 days	$\sim$ 2 days	$\sim$ 1 day

Organization - Options for the future

- ~~"It would be great for my experiment if NA61 would measure x+y->z reaction"~~
- Nice to hear this, and it's the beginning of a new measurement.
- But this will not make it happen. Measurements require resources, including scientists willing to do the actual work!
- How do we make the conditions right for people to join and do the work?

Organization - Options for the future

- Four options for future organization
    - Continuation of NA61: NA61++ = NA61
    - A new collaboration: NA61++ = NAXX
    - A hybrid model: NA61++ = NA61 + NAXX
    - Conversion to a facility: NA61++ = North Area Multiparticle Spectrometer Facility

Organization - Options for the future

- Four options for future organization
  - Continuation of NA61: NA61++ = NA61
  - A new collaboration: NA61++ = NAXX
  - A hybrid model: NA61++ = NA61 + NAXX
  - Conversion to a facility: NA61++ = North Area Multiparticle Spectrometer Facility

We need a strong physics case to continue measurements in the future

Organization - Options for the future

- Four options for future organization
  - Continuation of NA61: NA61++ = NA61
  - A new collaboration: NA61++ = NAXX
  - A hybrid model: NA61++ = NA61 + NAXX
  - Conversion to a facility: NA61++ = North Area Multiparticle Spectrometer Facility

We need a strong physics case to continue measurements in the future

The proposals for future measurements fit well with the current NA61 program

- Strong interactions program
- Hadron-production measurements for neutrino experiments
- Hadron-production measurements for cosmic ray experiments

Thank you very much for your excellent talks and participation in this workshop