(Anti)nuclei with NA61/SHINE

Anirvan Shukla

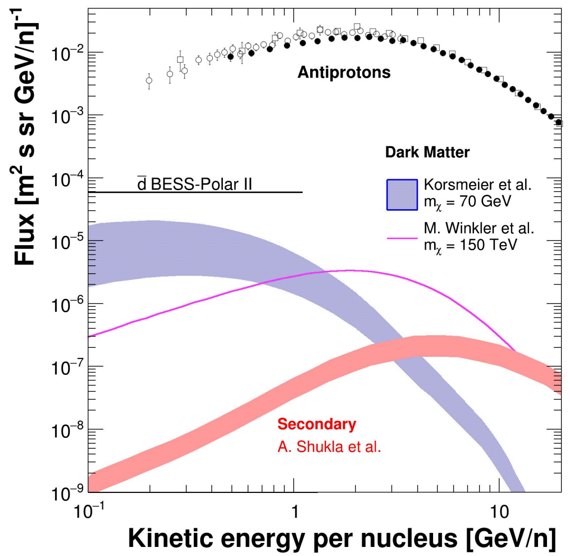
University of Hawaii at Manoa

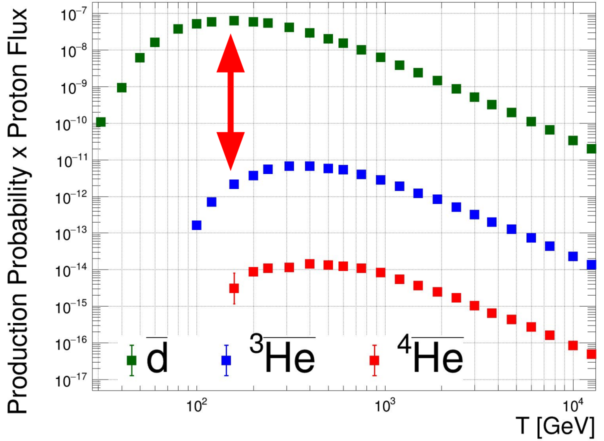
August 19 2024

JENAA workshop on Nuclear Physics at the LHC and connections to astrophysics

Cosmic antinuclei as a probe of dark matter

- **Antideuterons** are unexplored probes for indirect dark matter detection:
  - Situation comparable to the mid 70s before the first detection of a handful of cosmic-ray antiprotons in 1979.
  - Predicted in a broad range of dark matter models.
  - Expected astrophysical background at low energies is many orders of magnitude lower.
- Antihelium candidates have been announced by AMS-02 (~1/year):
  - Puzzling due to mass hierarchy of cosmic-ray flux.
  - Secondaries, DM, or even nearby antistars?
- Large uncertainties in both astrophysical production and Galactic transportation.



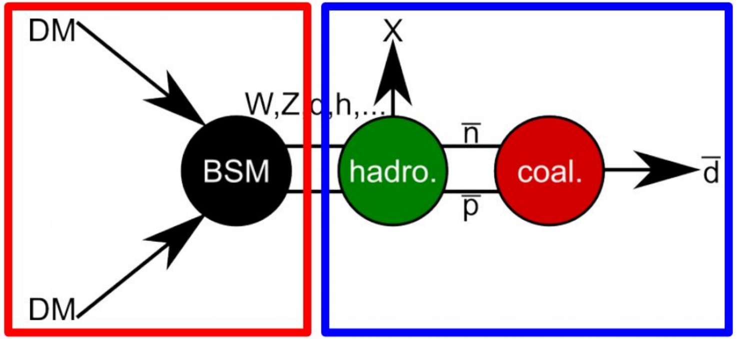


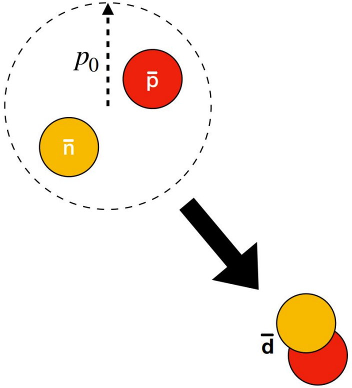
(Anti)deuteron formation: coalescence model

- Formation of light nuclei and antinuclei is poorly understood.
- Typical hadronic models (Geant4, EPOS) do not produce (anti)deuterons.

- Coalescence model:
  - Simple (analytical) coalescence, OR
  - Event-by-event coalescence in hadronic generators.
  - (Anti)deuteron formed if (anti)proton-(anti)neutron pair has small relative momentum.

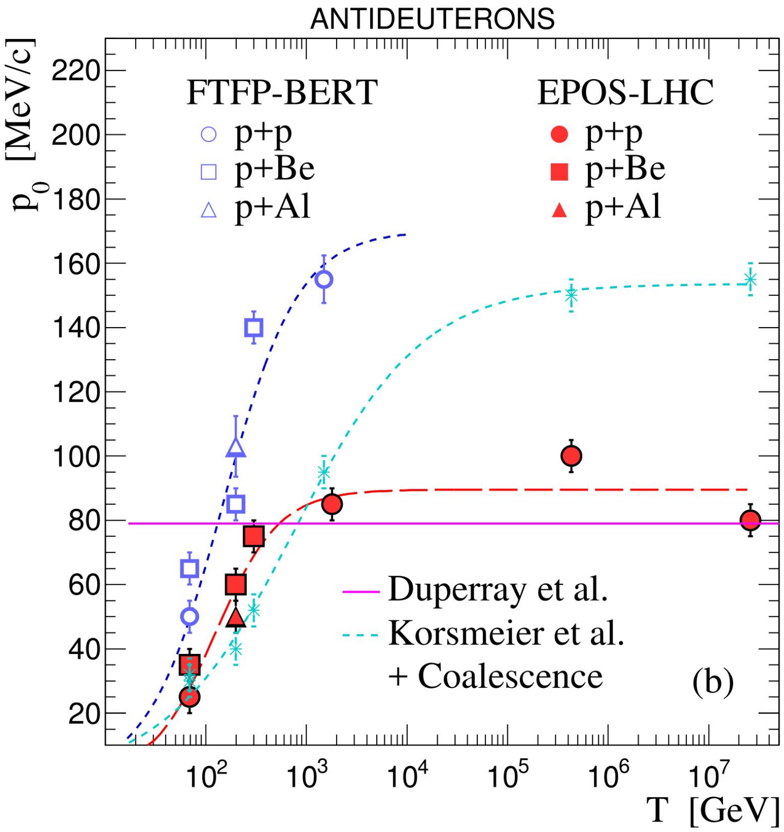
- This "coalescence momentum" $\boldsymbol{p_0}$ is determined through fits to experimental data.





Coalescence momentum p_0

- Find p_0 for each data set with both antiproton and antideuteron measurements
  - Sparse data: one low energy p+p point.
  - Supplement with p+A points.
- EPOS-LHC model was best match to available (anti)proton and (anti)neutron spectra.
- Fitted p_0 showed strong energy dependence
  - in the energy range which is most important for cosmic antinuclei production.

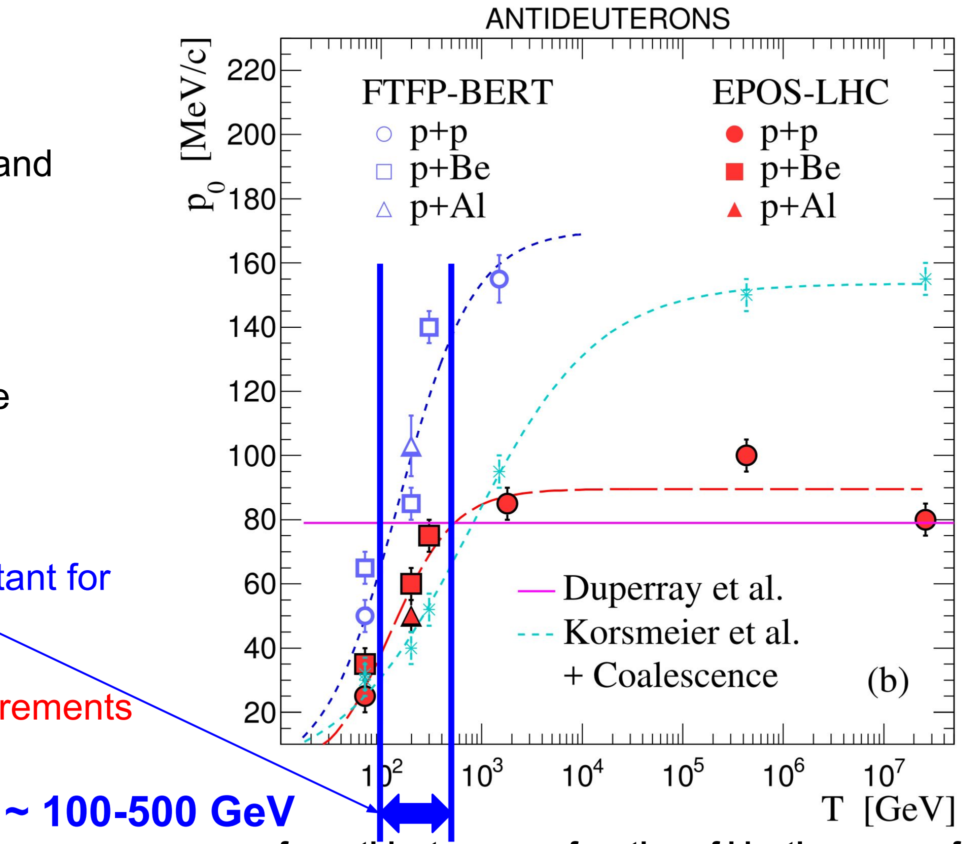


p_0 for antideuterons as function of kinetic energy of the incoming proton

Gomez et. al. (Phys. Rev. D 98, 023012 2018)

Coalescence momentum p_0

- Find p_0 for each data set with both antiproton and antideuteron measurements
  - Sparse data: one low energy p+p point.
  - Supplement with p+A points.
- EPOS-LHC model was best match to available (anti)proton and (anti)neutron spectra.
- Fitted p_0 showed strong energy dependence
  - in the energy range which is most important for cosmic antinuclei production.
- Need new accelerator-based precision measurements for better constraints.



p_0 for antideuterons as function of kinetic energy of the incoming proton

Gomez et. al. (Phys. Rev. D 98, 023012 2018)

Limitations of the coalescence model

- Hadronic generators not tuned for antiparticle production.
    - 10-30% mismatch for antiprotons!

- (Anti)neutrons are challenging to measure.
- Many factors like spin, size of the formation region, not considered.
- Constraints usually only in momentum space.
- Highly sensitive to two-particle correlations between produced (anti)nucleons.
    - Not available for the ~ 100-500 GeV energies ($\sqrt{s}$ ~ 15-25 GeV).

All such differences automatically shifts the calculated p_0.

New coalescence model approach: Femtoscopy

- Typically, coalescence Parameter B_2:

$$E_{\bar{d}} \frac{d^3 N_{\bar{d}}}{dp^3_{\bar{d}}} = \underbrace{\frac{8\pi}{3} \frac{p_0^3}{m_{\bar{p}}}}_{= B_2} \left(E_{\bar{p}} \frac{d^3 N_{\bar{p}}}{dp^3_{\bar{p}}} \right) \left(E_{\bar{n}} \frac{d^3 N_{\bar{n}}}{dp^3_{\bar{n}}} \right)$$

- But new recipe which takes into account:
  - interaction source size (R).
  - Two-particle interaction potential, and
  - (anti)deuteron wave function.
- Possible alternative definition for B_2:
  - $R(p_T)$: interaction source size.
  - D(q): deuteron Wigner function from Φ_d, the (anti)deuteron wave function (various models).

$$B_2(p_T) \approx \frac{3}{2m} \int d^3q D(q) e^{-R^2_{p_T} q^2}$$

$$D(q) = \int d^3r |\phi_d(r)|^2 e^{-iq\cdot r}$$

- $R(p_T)$ needs to be experimentally determined:
  - Need proton-proton correlation measurements.
- Along with precision (anti)proton and (anti)deuteron production measurements.

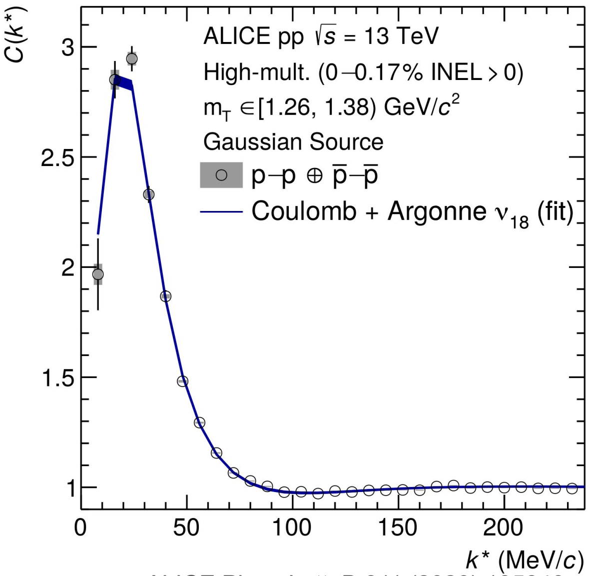
F. Bellini and A. Kalweit, Phys.Rev.C 99 (2019) 5, 054905
K. Blum and M. Takhimoto, Phys.Rev.C 99 (2019) 4, 044913
F. Bellini, K. Blum, A. Kalweit, M. Puccio, Phys.Rev.C 103 (2021)
Laura Fabbietti, 24.11.2021, Particle and Astroparticle Physics Colloquium Hamburg
ALICE, Phys. Lett. B 811 (2020) 135849

Modelling astrophysical antideuterons with femtoscopy

- ALICE successfully extracted B_2 to describe antideuteron data from source size measurements with:
  - Gaussian antideuteron wavefunction.
  - Argonne-v18 potential for the two-proton interaction potential.
  - But at very high energies.

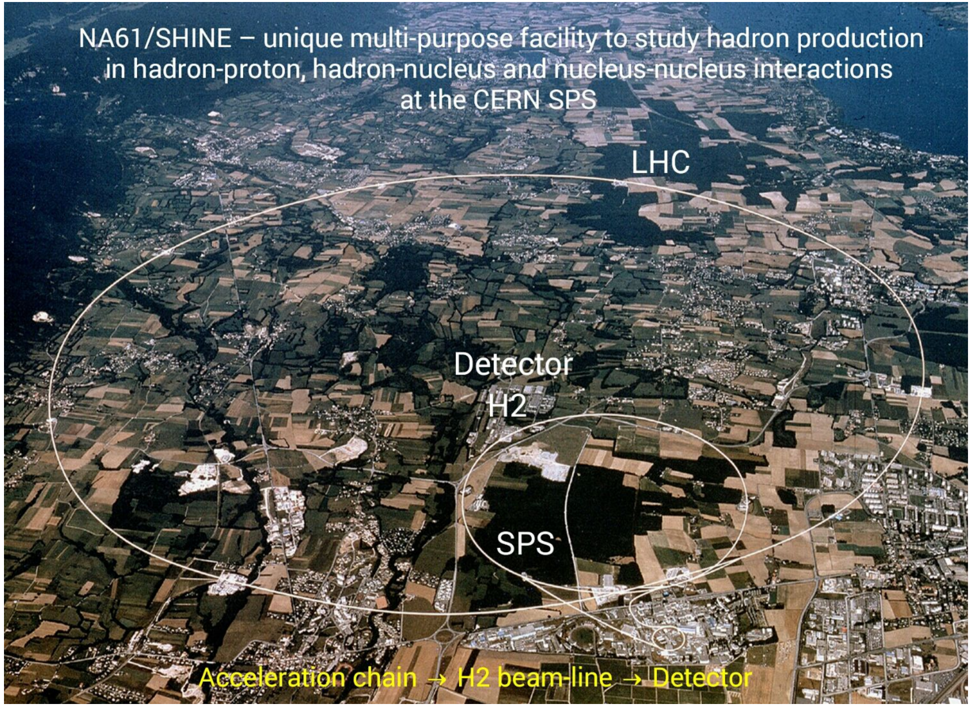
- Cosmic antideuteron production peaks for p+p collisions at p_{Lab} ~ 300 GeV/c ($\sqrt{s}$ ~ 20 GeV).
  - No p-p correlation measurements at these lower energies yet.

- NA61/SHINE at CERN/SPS is ideal to help!
  - Correlation function measurements → source size → B_2.
    - New coalescence model.
  - Proton and deuteron measurements → validate B_2.
  - Precision antiproton measurements → antideuteron modelling.
  - Energy scan near the production thresholds ($\sqrt{s}$ ~ 10-30 GeV) (?)

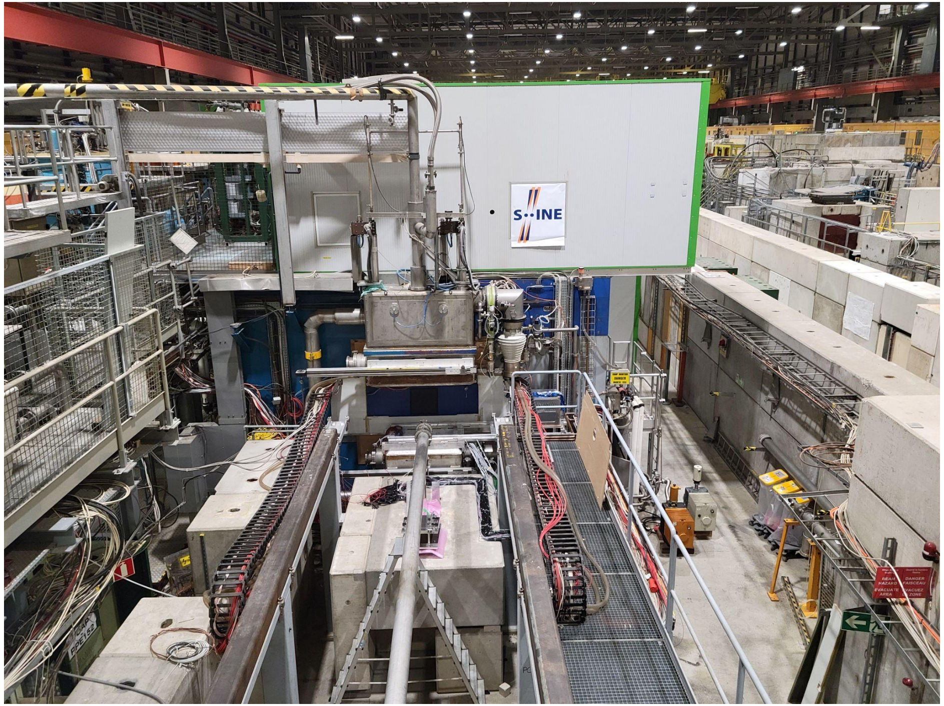


ALICE Phys. Lett. B 811 (2020) 135849
Mahlein et. al. Eur. Phys. J. C (2023) 83:804

NA61/SHINE (SPS Heavy Ion and Neutrino Experiment)

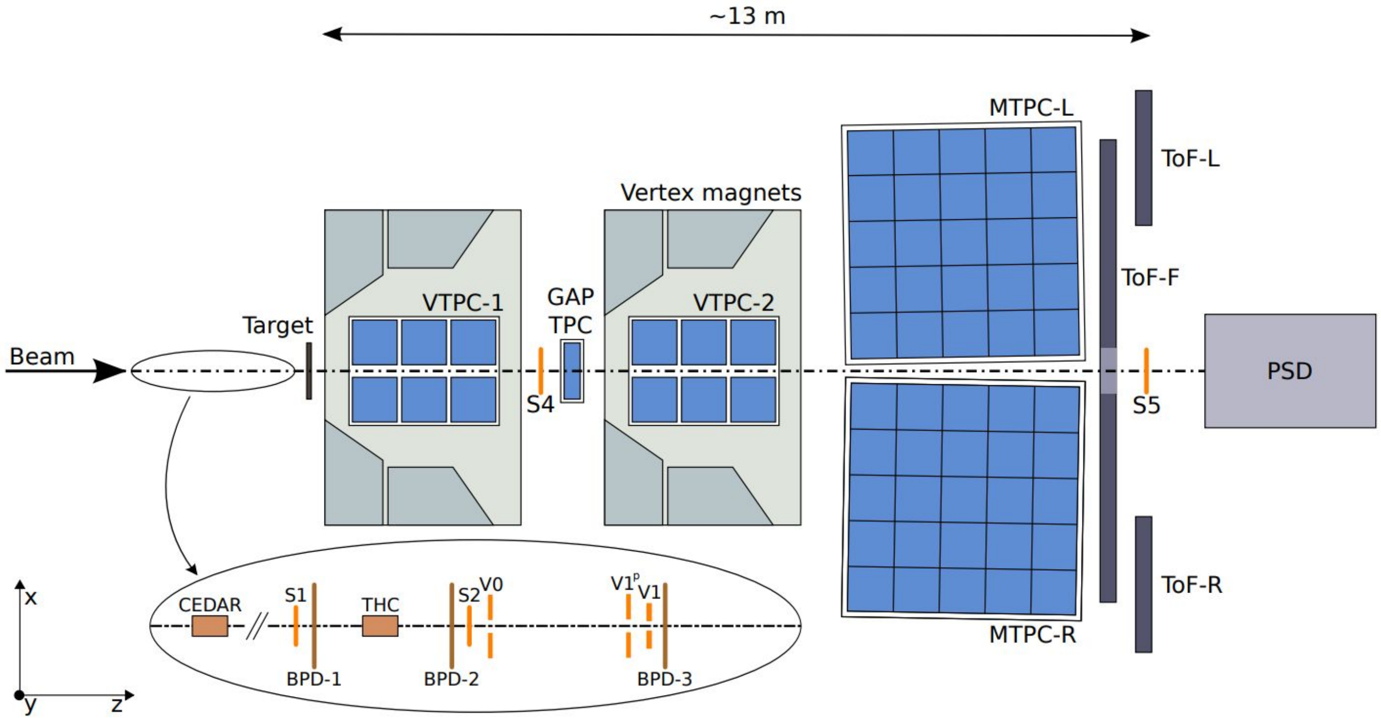


Bird's-eye view of CERN in Geneva



NA61/SHINE in the experiment hall

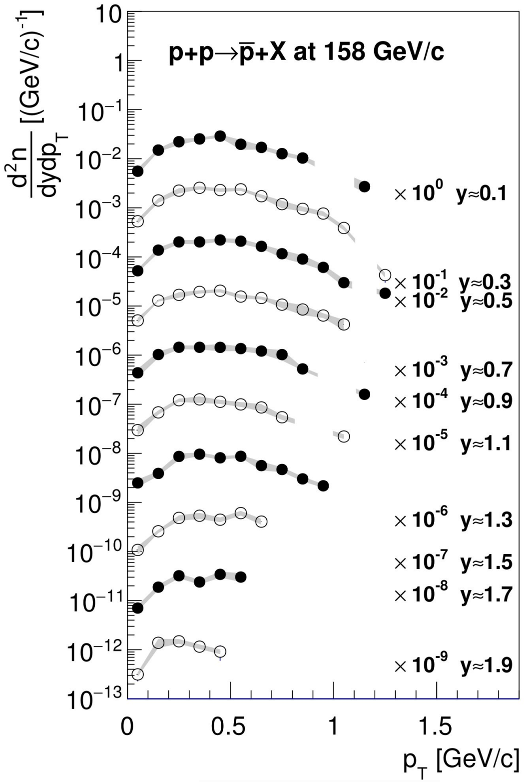
NA61/SHINE detector layout



- Fixed-target, large-acceptance spectrometer (details: [Abgrall at. al. JINST 9 (2014) P06005]).
- TPCs are main tracking detectors. ToF placed downstream.
- Momentum resolution: ~ 1%, dE/dx energy resolution: ~ 4%, TOF resolution: ~ 100ps.

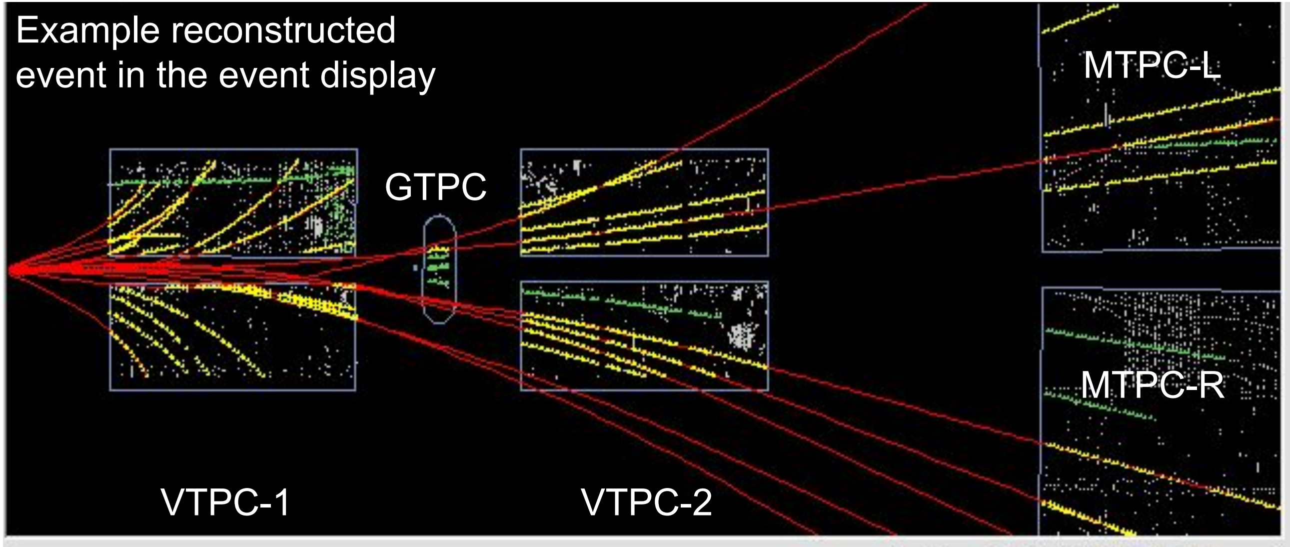
Previous results from NA49 and NA61/SHINE

- Cosmic-ray antiproton studies have already benefited from NA49 and NA61/SHINE measurements:
  - di Mauro et. al. (Phys. Rev. D 90, 085017).
  - Winkler (JCAP02 (2017) 048).
  - Korsmeier et. al. (Phys. Rev. D 97, 103019).
- Antiproton data from p+p energy scan at NA61/SHINE at different beam momenta:
  - 20, 31, 40, 80, and 158 GeV/*c*.
  - $\sqrt{s}$ = 6.3, 7.7, 8.8, 12.3 and 17.3 GeV, respectively.
- Now with **~15✖ p+p events** available in the new high-statistics data set.



Aduszkiewicz et al.
Eur. Phys. J. C (2017) 77: 671

Proton-proton collisions at 158 GeV/c



About 10% of the data were collected with an empty target for background corrections.

Run	Total p+p events (millions)	After event selection (millions)
2009	4	1
2010	44	16
2011	14	4

→ Already published in Aduszkiewicz et al. Eur. Phys. J. C (2017) 77: 671

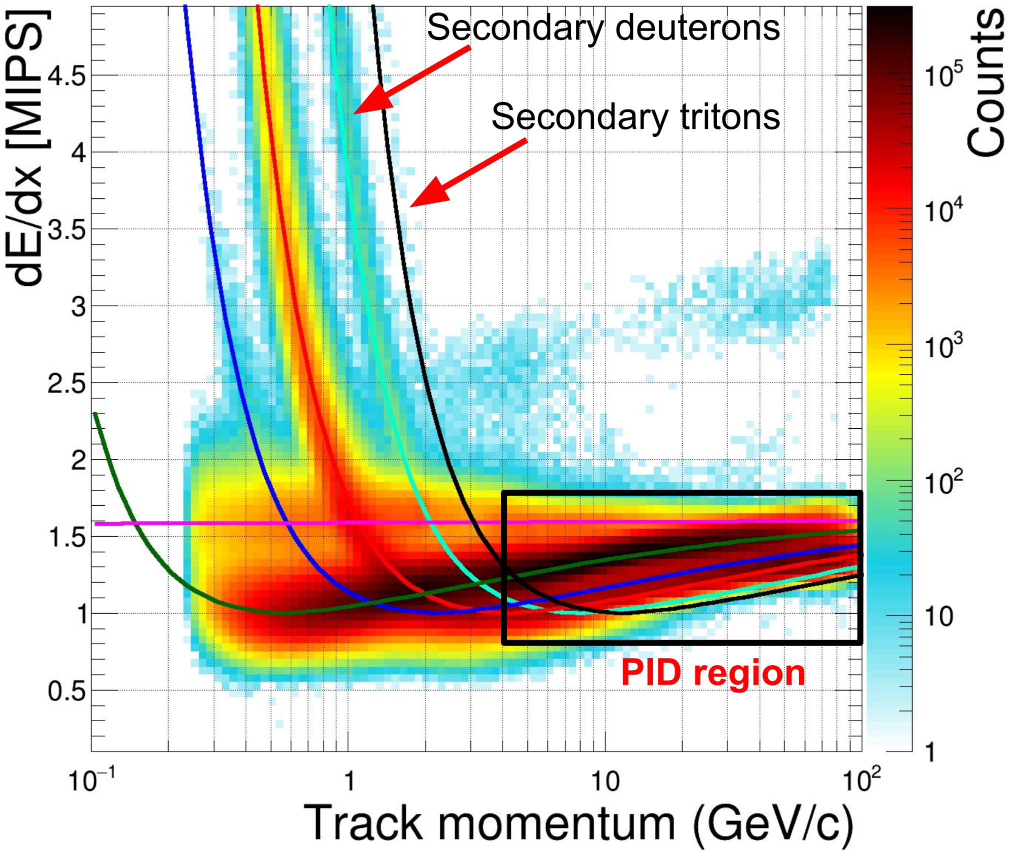
Selection of p+p events and particle tracks

- Series of quality cuts applied to select clean, well reconstructed inelastic collision events and particle tracks.
- Instrumental background was subtracted using data taken without target.
- Detector acceptance & efficiencies and feed down effect corrected with MC simulations.

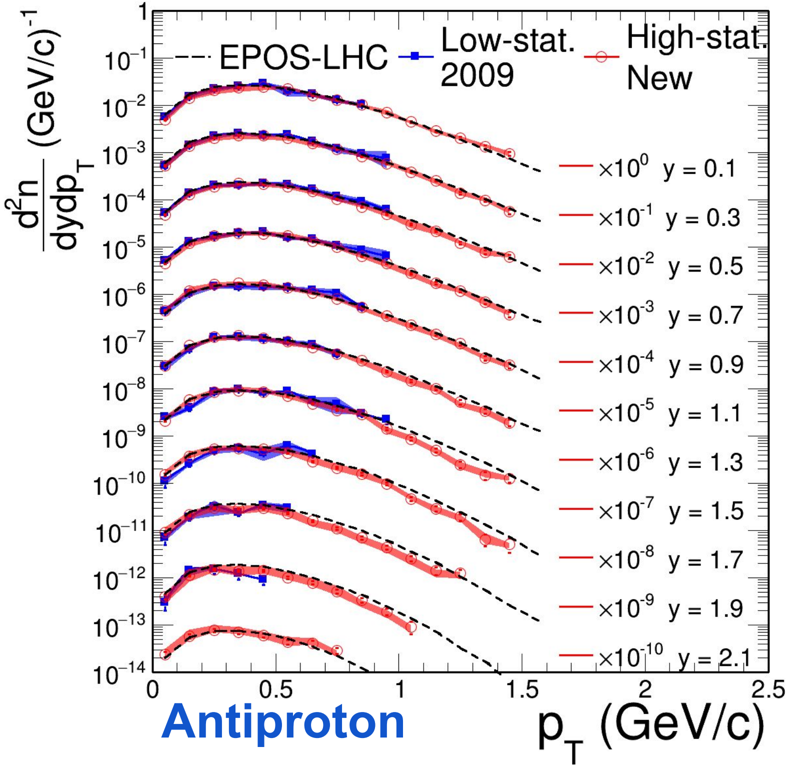
- **60 million events → 30 million events after selection.**
- **750 million tracks → 60 million tracks after selection.**

Particle identification using dE/dx

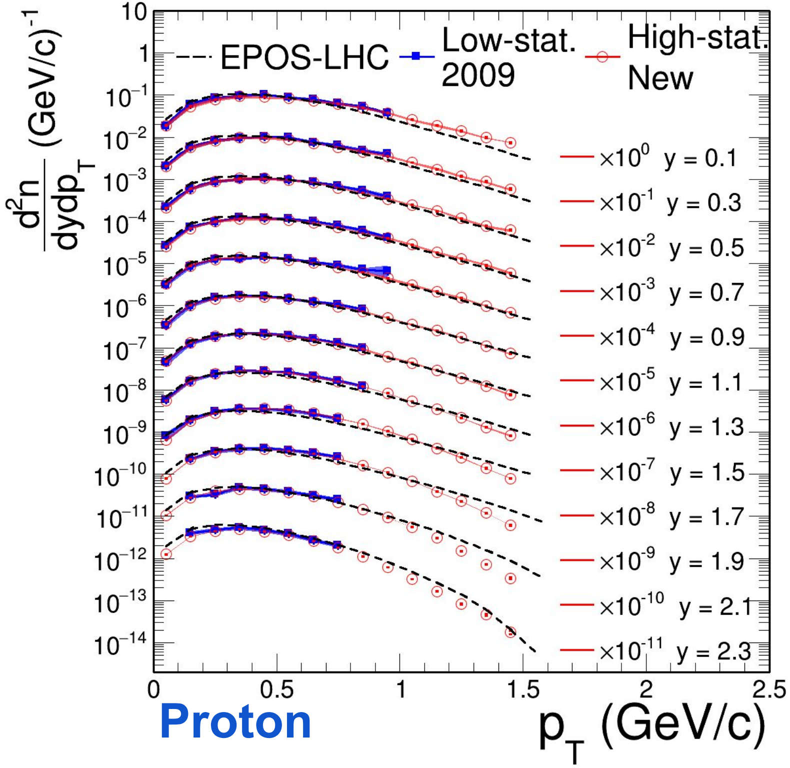
- dE/dx vs momentum distribution for all selected tracks.
- Particle identification possible in the black box region.
- Production of secondary deuterons seen at very low momentum.
  - Not from primary p+p interactions!
- Bethe-Bloch curves are shown for:
  - positrons (magenta)
  - pions (green)
  - kaons (blue)
  - protons (red)
  - deuteron (azure), and
  - tritons (black).



Measured particle spectra (NA61/SHINE Preliminary)



Antiproton

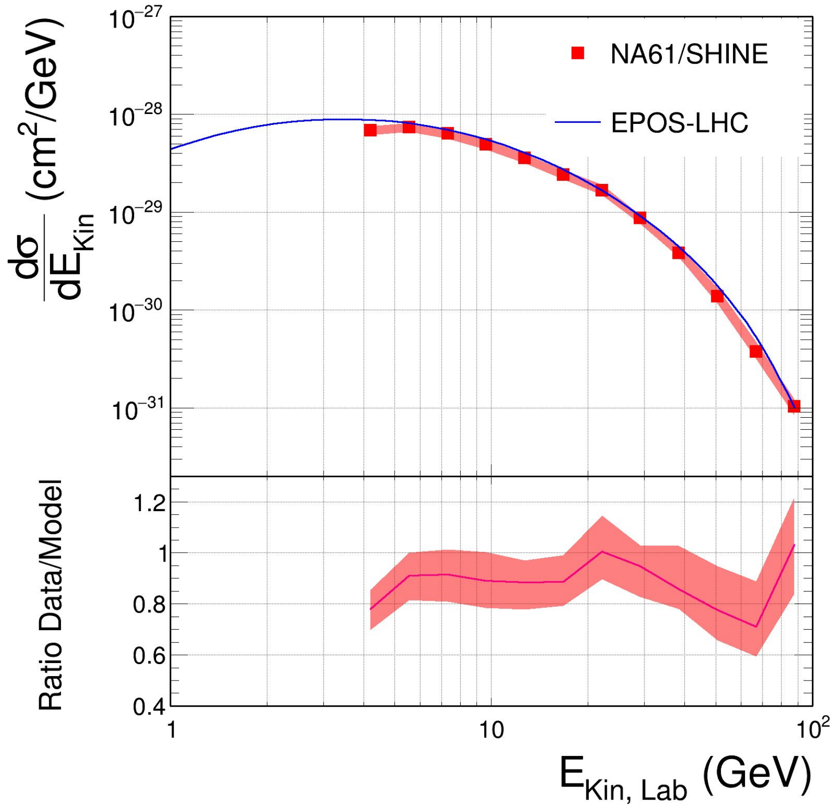


Proton

- $\pi^{\pm}$ and $K^{\pm}$ spectra also obtained.

Antiproton differential production cross sections

- Released by NA61/SHINE as preliminary. Publication coming later this year.
- Hadronic generators don't model antiprotons well.
- At low kinetic energies with the highest production, EPOS-LHC overpredicts by ~10–20%.
- Future models need to be further fine-tuned to reduce uncertainties related to astrophysical antinuclei production in our Galaxy.

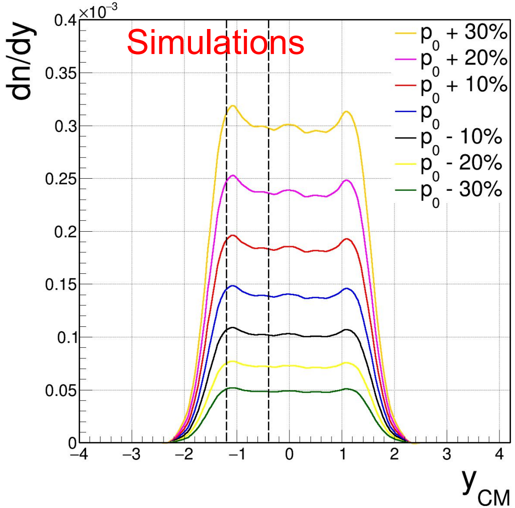


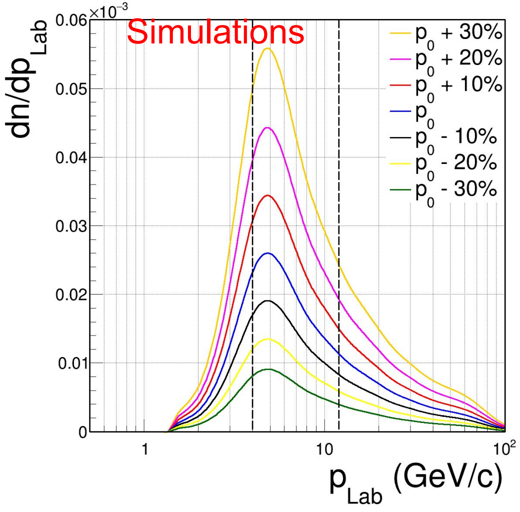
Deuteron measurements in NA61/SHINE

- Crucial to understand antideuteron formation in cosmic-ray interactions.
  - Same coalescence production mechanism as antideuterons.
  - ~100x more easily produced at SPS energies.

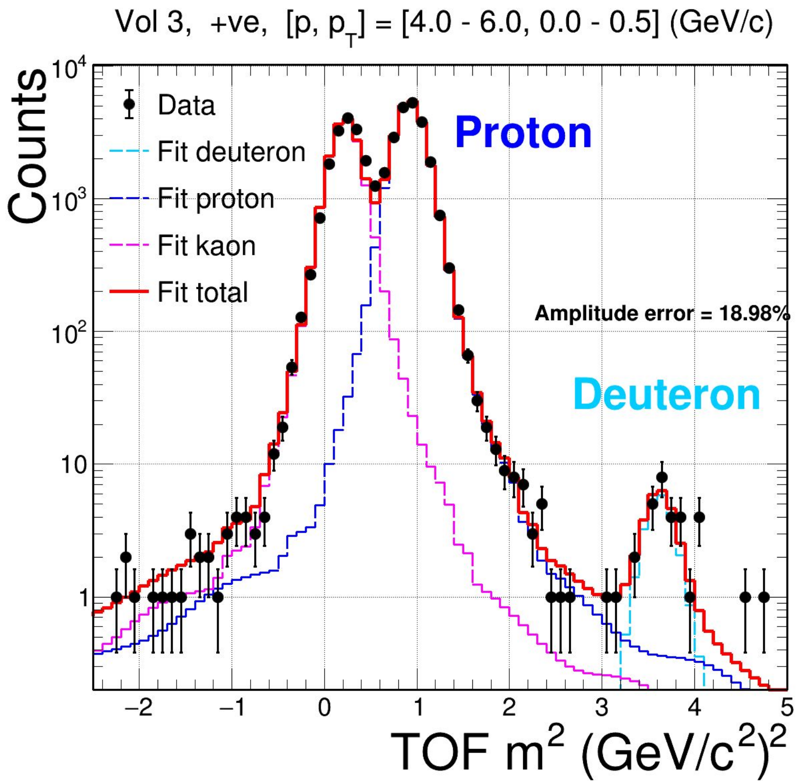
- Challenging measurement in p+p interactions:
  - Predicted production probability is still low: 0.02%–0.09%.
  - Large foreground of other positive charge particles.

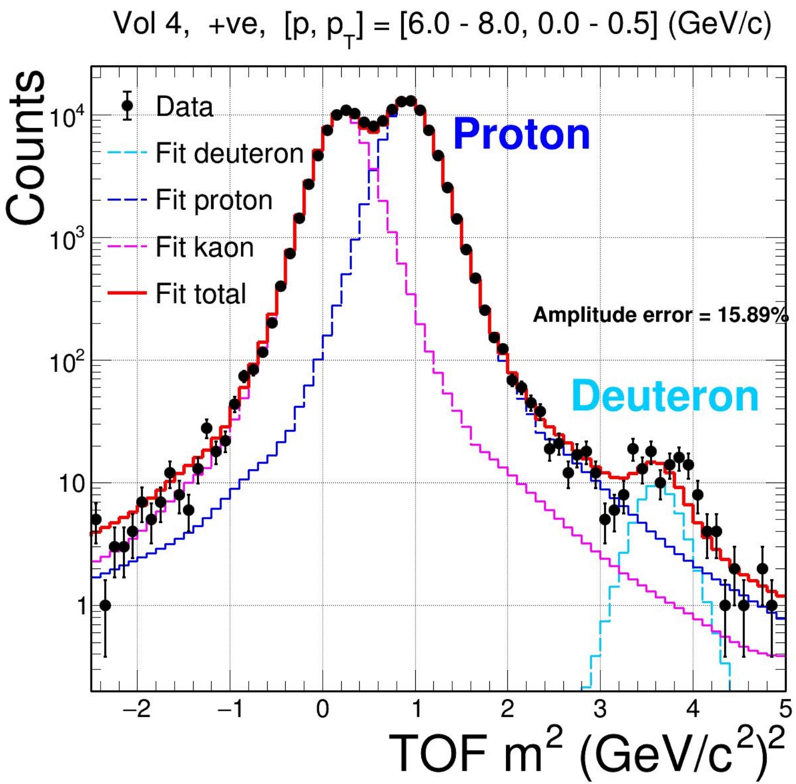
- Advantages in NA61/SHINE:
  - Using Time-of-Flight (ToF) detectors along with measured momentum to calculate particle mass → deuteron identification.
  - ToF acceptance is ~1%, but covers the phase space where deuteron production is maximum.
  - First measurements at energies relevant for production in cosmic rays.





Measured deuteron signals

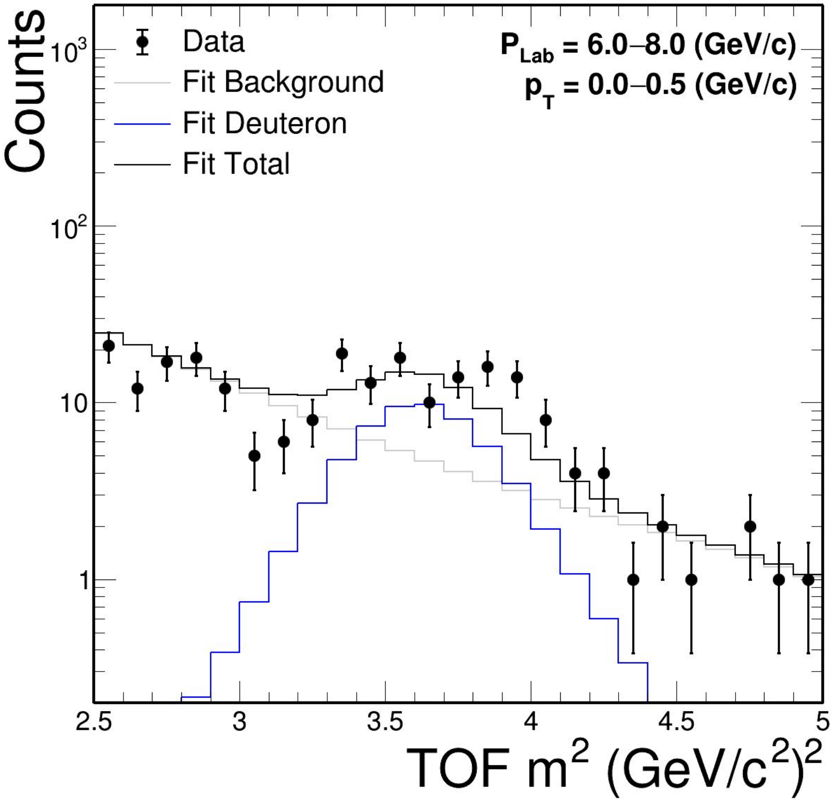




Realistic estimation of the proton tail in the deuteron mass region is crucial.

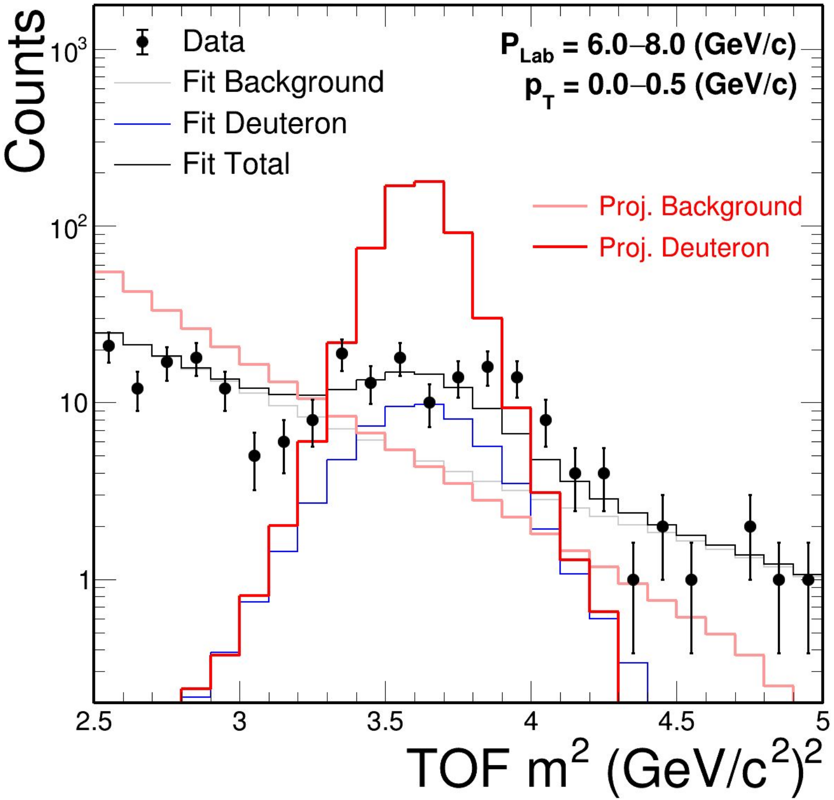
First deuteron production measurements in p+p at SPS energies

- ~150-200 deuteron identified.
- Many cross checks ongoing, including for secondary deuterons (from secondary protons, from detector materials etc.)
- Analysis is ongoing.
  - Uncertainties are still large.
  - Publication expected next year.



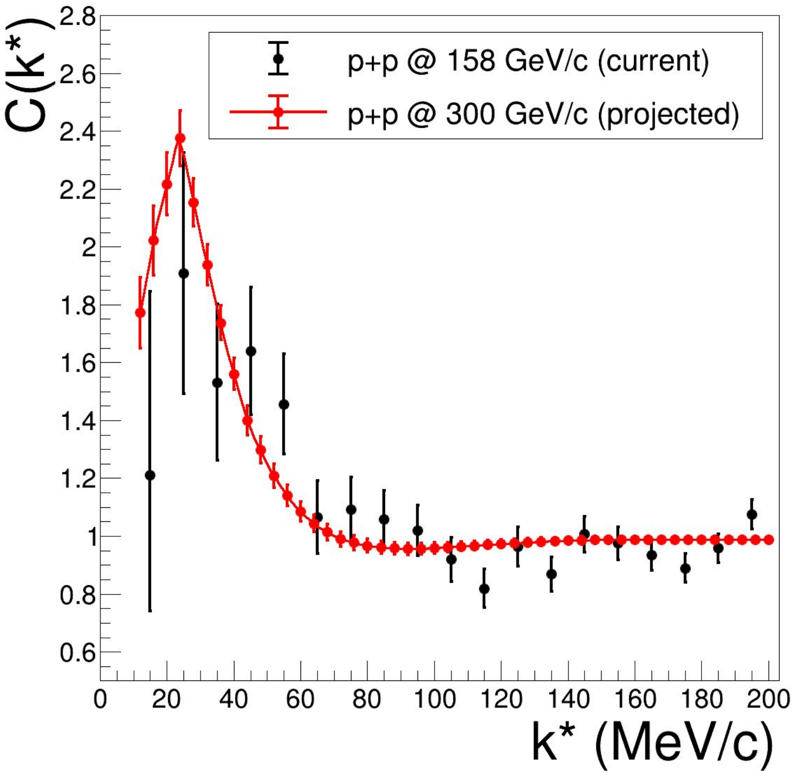
First deuteron production measurements in p+p at SPS energies

- ~150-200 deuteron identified.
- Many cross checks ongoing, including for secondary deuterons (from secondary protons, from detector materials etc.)
- Analysis is ongoing.
  - Uncertainties are still large.
  - Publication expected next year.
- **Precision measurements possible in 2025** with upgraded NA61/SHINE:
  - 10x recorded p+p collisions with new DAQ.
  - dE/dx resolution: 2x better.
  - ToF resolution: 120ps → 80ps.
  - New forward TPCs, new reconstruction software etc.



Proton-proton correlations in NA61/SHINE

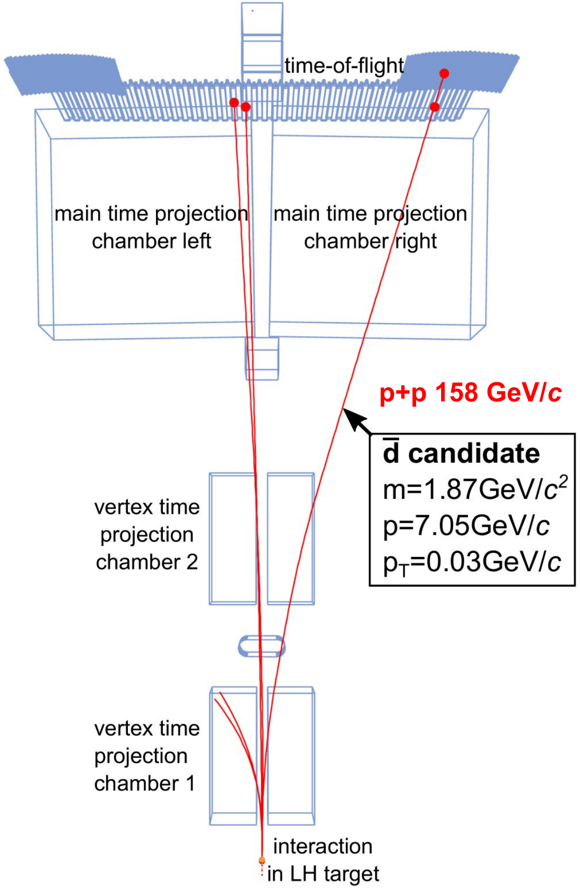
- First source size measurement using proton pairs in this energy range.
  - Complement high-energy RHIC & ALICE.
  - Two-pion correlations in Be+Be collisions recently measured by NA61/SHINE **(Eur. Phys. J. C 83, 919 2023)**.
- Preliminary correlation function fit suggests a source size (R) of 1–2 fm.
- But multiple challenges:
  - Only ~ 40 proton-proton pairs around the peak.
  - Efforts to increase signal ongoing.
- Precision measurements would need 10x data with the upgraded NA61/SHINE.
  - Potential 5x reduction in uncertainty of fitted R.



Path Forward

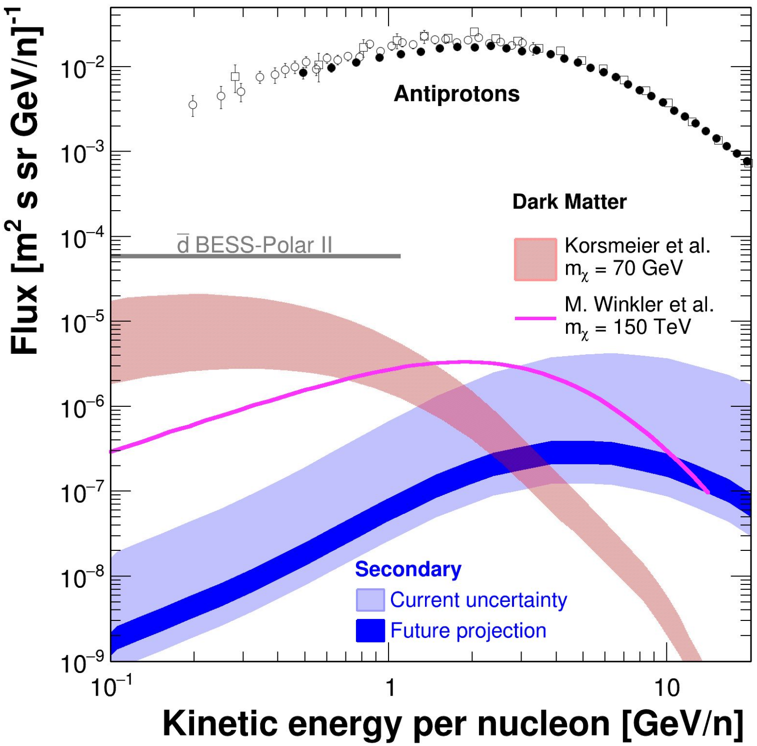
- **p+p 400 GeV/*c* data:**
  - ~10 million events.
  - Calibration and analysis to start soon.

- **Future p+p 300 GeV/c data-taking with the upgraded detector:**
  - 10x events (~ 600M p+p collisions).
  - Precision deuteron and antiproton differential cross sections.
  - Correlation measurements: p-p, pbar-pbar etc.
  - Many more…
    - (Anti)nucleon production channels, with detailed accounting of pions, protons, antiprotons, etc. in association with deuterons.
    - Energy scan at different collision energies.
  - Antideuteron direct measurements (?)



Conclusion

- New coalescence modelling for antideuterons:
  - First measurements of the proton-proton correlation function in p+p interactions at SPS energies.
  - First measurement of deuteron production in p+p interactions close to the deuteron production threshold.
  - Updated measurements of proton and antiproton differential production cross sections.
- Future measurements anticipated with upgraded NA61/SHINE in 2025:
  - Decisively reduce uncertainties in the cosmic antideuteron background.
  - Enable evaluation of the hypothesized dark matter origin of the AMS-02 antideuteron candidates.




Thanks!

Backup

Standard event & track selection cuts for analysis of data and simulated events

Event and track selection for data:

- **For rec events in data**
  - Has main vertex.
  - T2 cut.
  - Has primary fitted vertex “ePrimaryFitZ”.
  - Main vertex fit quality is perfect.
  - Vertex Z position is within target region (-600 cm < vtxZ < -560 cm).
  - Reject events with elastic collisions (single positive charge track with momentum close to beam momentum).
- **For rec tracks in data**
  - Vertex track has at least one track.
  - Vertex track status is perfect.
  - Cuts on impact parameters: $|B_x| < 4$cm and $|B_y| < 2$ cm.
  - Track status is perfect.
  - At least 30 total points along track.
  - At least 15 points in VTPC 1 and 2, or at least 4 points in GTPC.
  - RST cut (i.e. $p_x * q$ should be positive).

Event and track selection for MC events:

- **For sim events in MC**
  - Has main vertex.
- **For sim tracks in MC**
  - RST cut - add extra factor of 2 in the MC correction factor.
  - Sim track must be of type “eGeneratorFinal”.
- **For rec events in MC**
  - **All cuts applied for rec events in data.**
  - Instead of T2 cut, ensure no energy deposited in S4 (an effective T2 trigger cut).
- **For rec tracks in MC**
  - All cuts applied for rec tracks in data.
  - Additional cut:
    - Rec track must have a matched sim track. (Particle ID of each rec track in MC is done by finding its corresponding sim track).

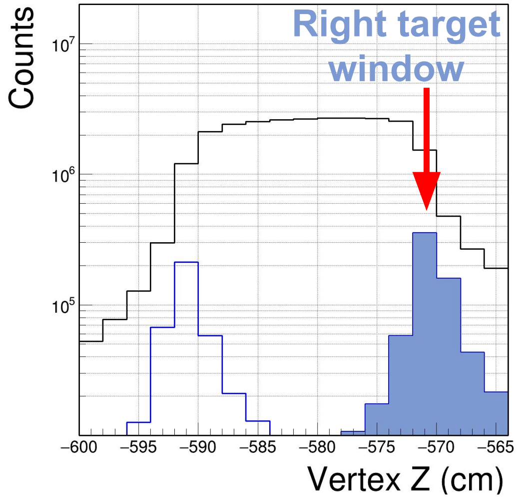
Statistics after particle ID and background correction

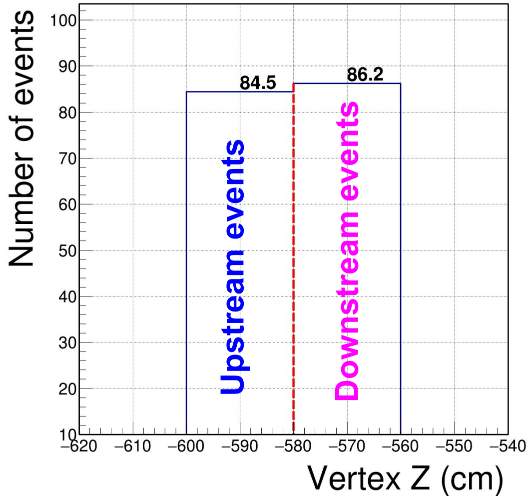
	High-statistics combined p+p data
Before cuts	
Number of events with target in	55,461,598
Number of events with target out	5,146,310
After cuts	
Number of events with target in	30,355,687
Number of events with target out	1,110,946
Identified particle counts	
Pi+	21,386,856
Pi-	16,182,016
Proton	7,343,452
Antiproton	563,675
K+	1,899,210
K-	1,252,074

Cross checks for primary deuterons

- Contribution from primary proton + Detector:
  - Subtracted using target-out data.
- Contribution from primary and secondary proton + C (production via fragmentation of C in target holder)
  - Deuterons seen in momentum range of 4 to 8 GeV/c or rapidity range of -1.2 to -0.8.
  - Sufficiently high in momentum/rapidity to rule this out.
- Contribution from secondary proton + C in the **right target window**.
  - Using target-out data-based estimation, essentially zero contribution found.
- Contribution from secondary proton + LHT.
  - Bkg-subtracted deuteron events upstream and downstream of target-midpoint.
  - Estimated 2% contribution.

Measured deuteron signal is not secondary!





Precision measurements needed

- Ideal range for relevant cosmic-ray antinuclei cross section studies is p+p at p_{Lab} = 100-500 GeV/*c*.
  - Energy scan near the production thresholds.
  - √s ~ 10-30 GeV.

- Precision measurement of (anti)proton, (anti)neutron and (anti)deuteron production.
  - Differential production cross sections

- No angular correlation measurements available in p+p interactions at these energies.
  - Proton-proton and antiproton-antiproton pairs.

- **NA61/SHINE at CERN/SPS is ideal to help!**