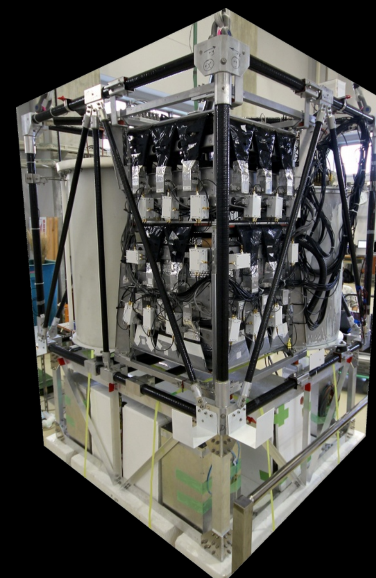
The need for antideuteron production cross section measurements



p-He cross section measurement workshop
July 2015

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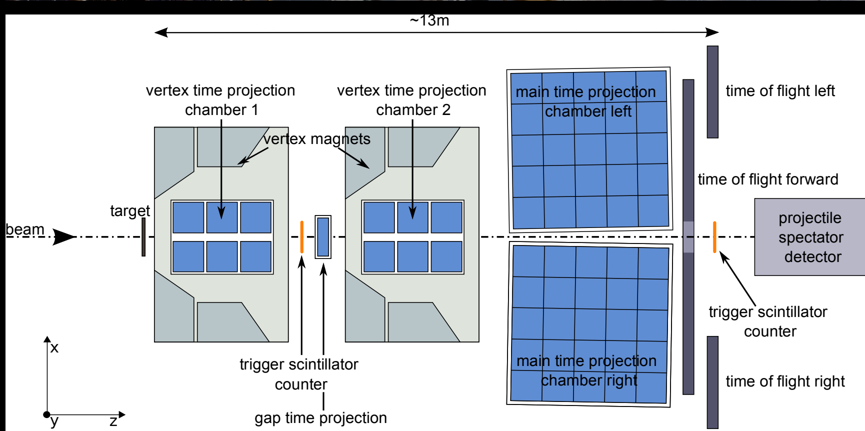

http://www.phys.hawaii.edu/~philipvd
www.antideuteron.com

Review of the theoretical and experimental status of dark matter identification with cosmic-ray antideuterons

under review at Physics Reports: arXiv:1505.07785

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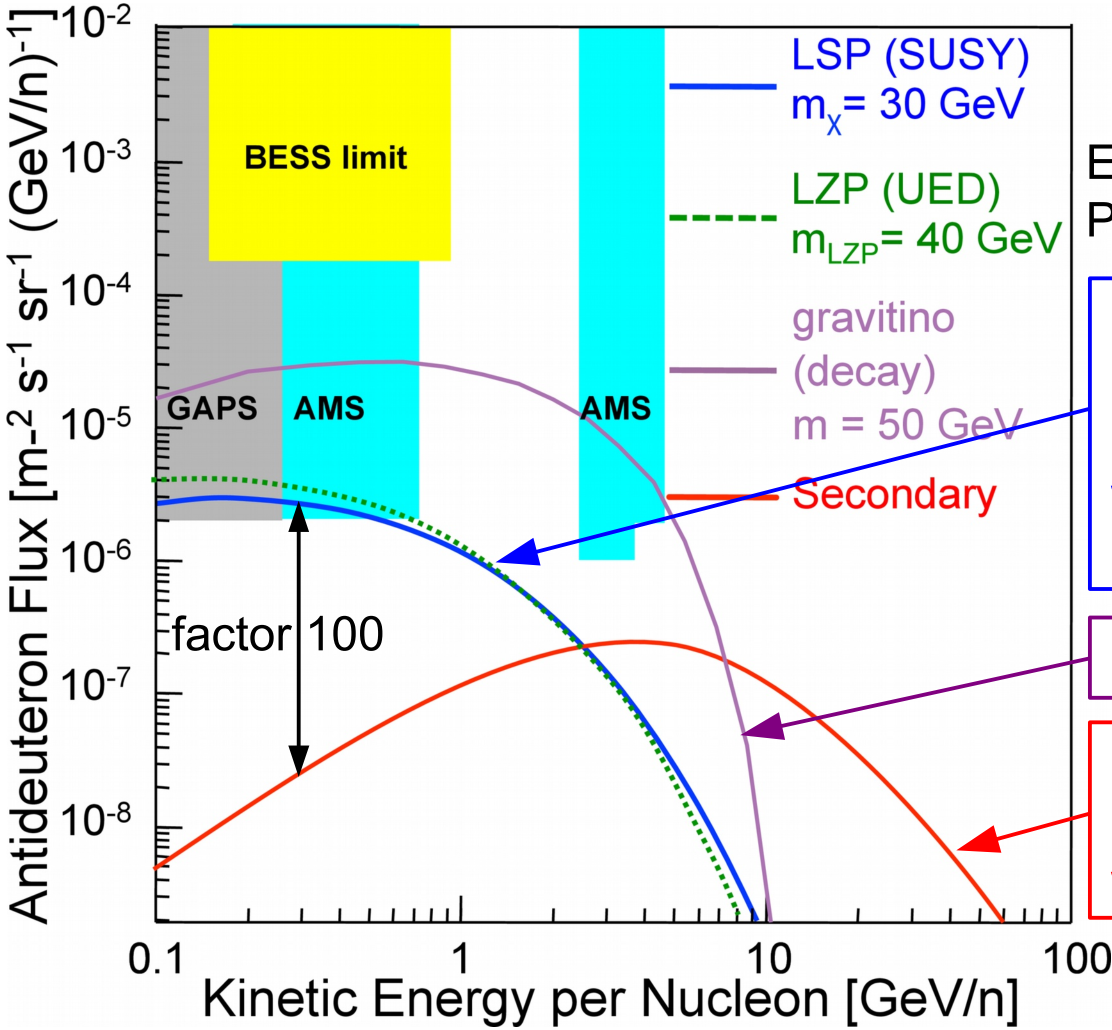
Status of cosmic ray antideuterons



Examples for beyond-standard-model Physics:

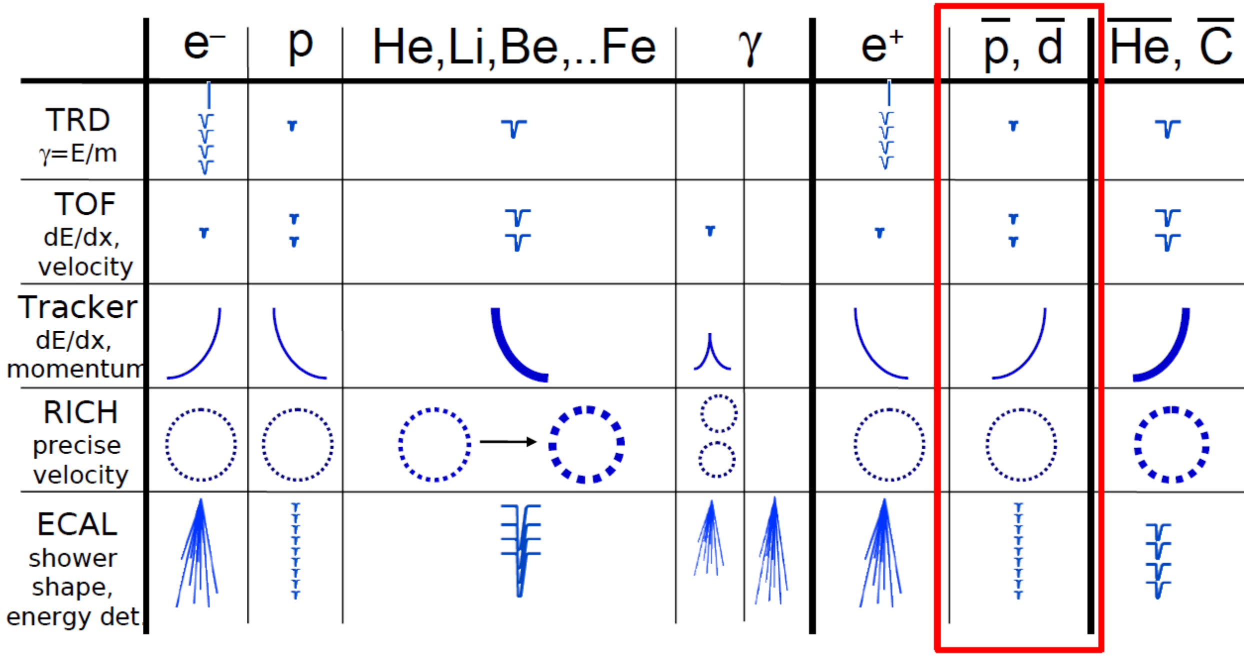
Neutralino:
SUSY lightest supersymmetric particle, decay into $b\bar{b}$, compatible with signal from Galactic Center measured by Fermi

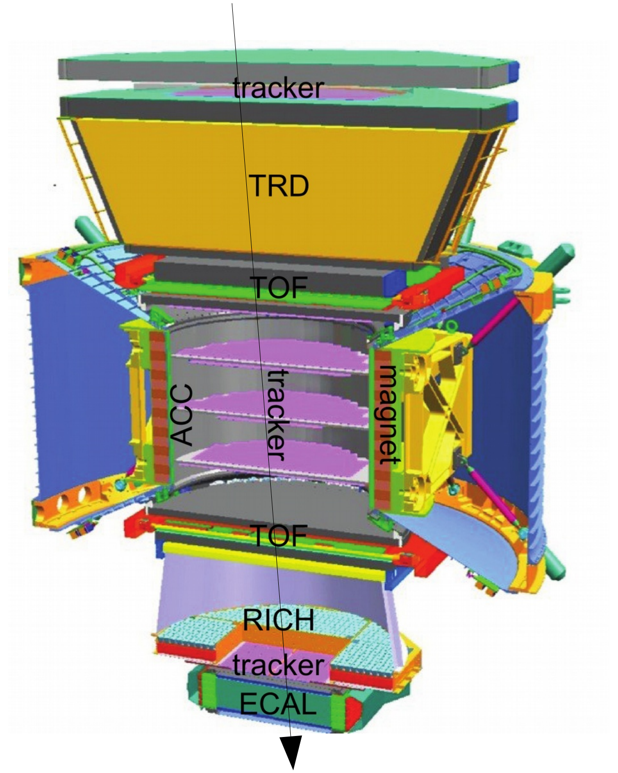
late decays of unstable gravitinos

astrophysical background:
collisions of protons and antiprotons with interstellar medium

Antideuterons are the most important unexplored indirect detection technique!

AMS antideuteron analysis





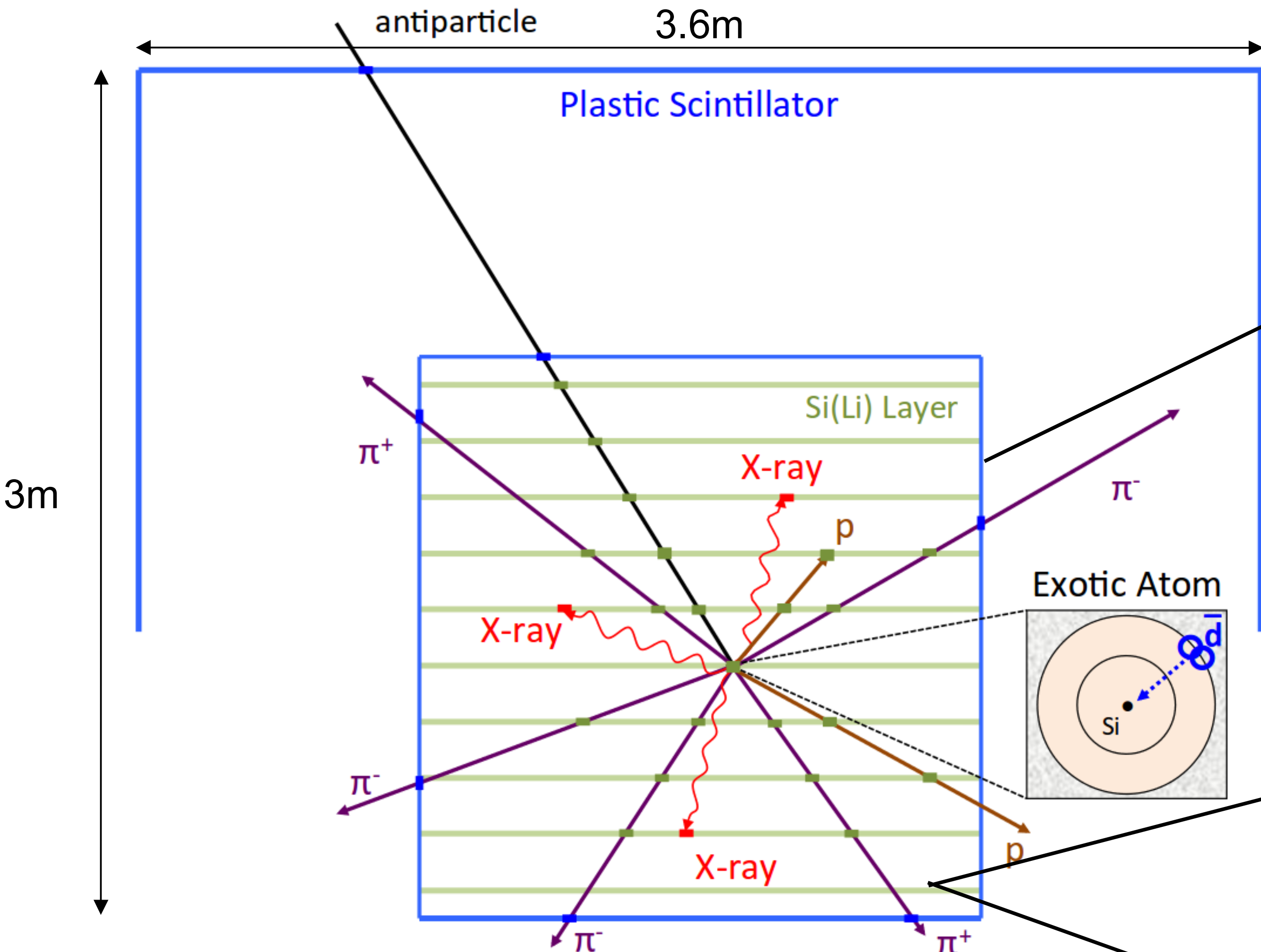
- **antideuteron identification:**
  - –momentum measured in the form of rigidity
  - –charge from TOF, TRD, tracker
  - –lower velocities: **T**ime **O**f **F**light scintillator system
  - –higher velocities: **R**ing **I**mage **Ch**erenkov detector

$$m = R \cdot Z \sqrt{\frac{1}{\beta^2} - 1}$$

- **self-calibrated analysis:**
  - –calibrate antideuteron analysis with deuterons and antiprotons (simulations and data)
  - –geomagnetic cut-off location is challenging: study low-energy protons and electrons to calibrate geomagnetic and solar effects

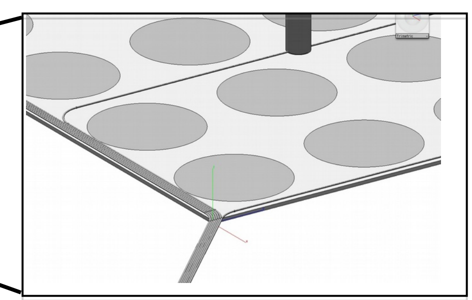
The GAPS experiment

Columbia U, UC Berkeley
UCLA, U Hawaii,
Haverford



plastic scintillators
with PMT readout

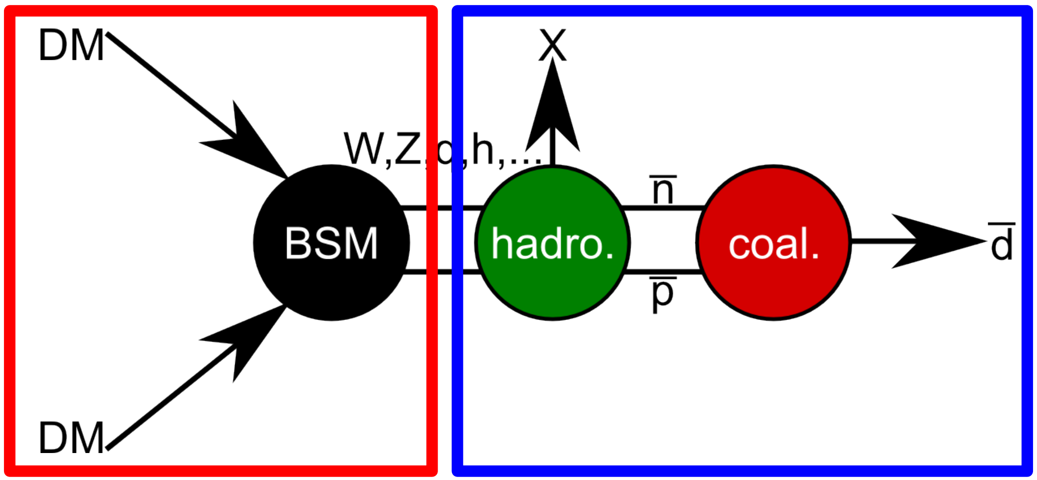
weight: 1700kg
power: 1.4kW
readout: ~100mW/ch
(preamp: ~15mW/ch)



~1400 Si(Li) wafers

- the **G**eneral **A**nti**P**article **S**pectrometer is especially designed for **low-energy antideuterons and antiprotons**
- identification by stopping and creation of an exotic atom
  [KEK testbeam measurements → Astropart. Phys. 49, 52 (2013)]
- LDB flights from Antarctica

Antideuteron formation

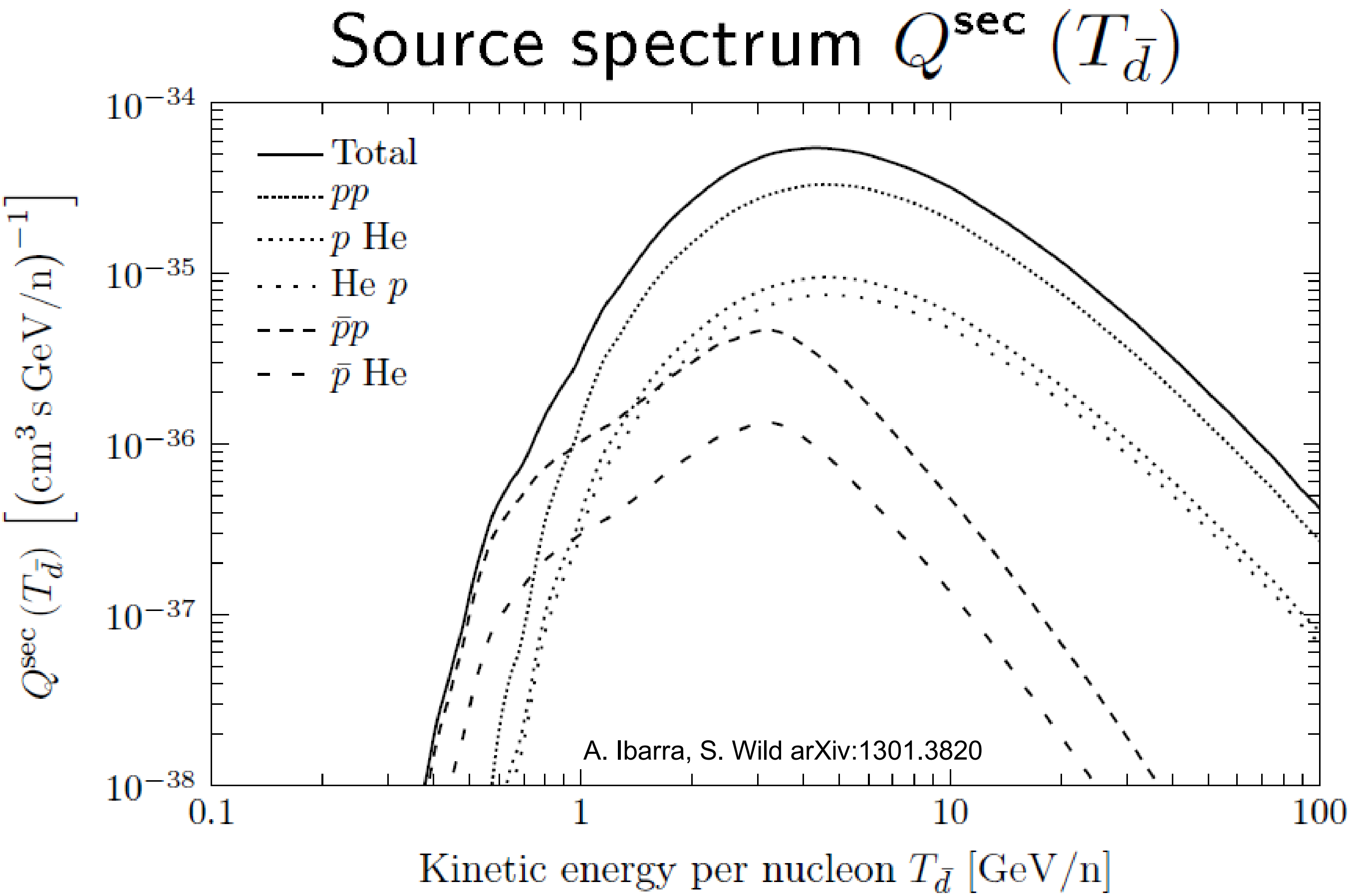


- antideuterons can be formed by an antiproton-antineutron pair if relative momentum is small (coalescence momentum p_0)

$$\frac{dN_{\bar{d}}}{dT_{\bar{d}}} = \frac{p_0^3}{6} \frac{m_{\bar{d}}}{m_{\bar{n}} m_{\bar{p}}} \frac{1}{\sqrt{T_{\bar{d}}^2 + 2 m_{\bar{d}} T_{\bar{d}}}} \frac{dN_{\bar{n}}}{dT_{\bar{n}}} \frac{dN_{\bar{p}}}{dT_{\bar{p}}}$$

- Coalescence does not affect antiproton/proton ratio → break degeneracy of antiproton and antideuteron

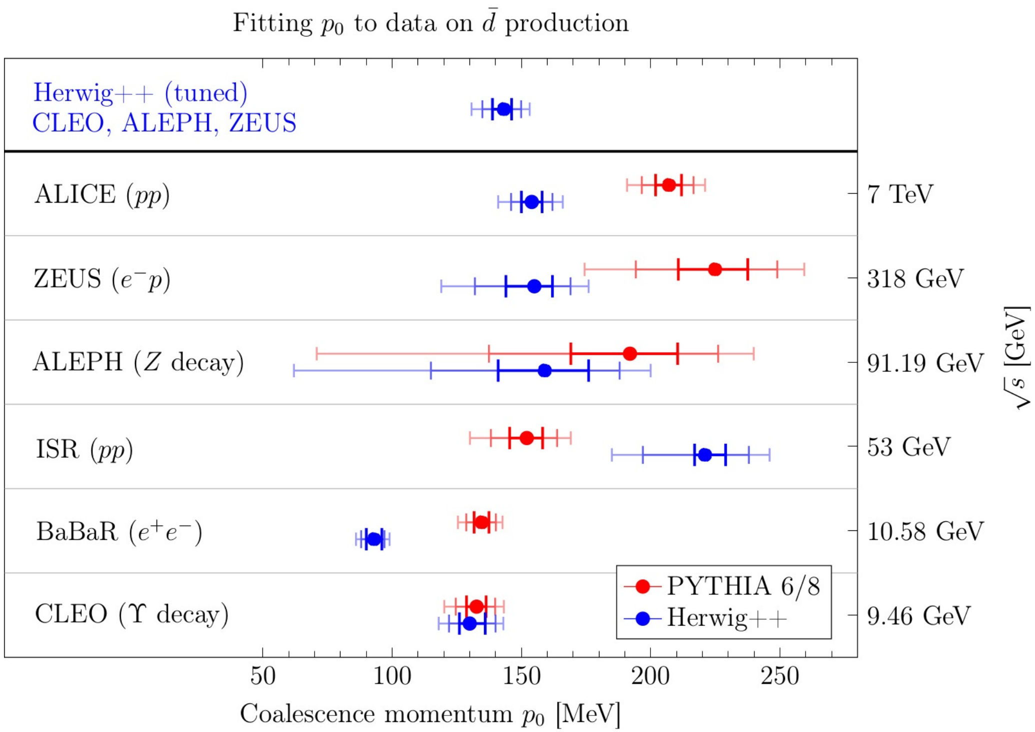
Antideuteron formation

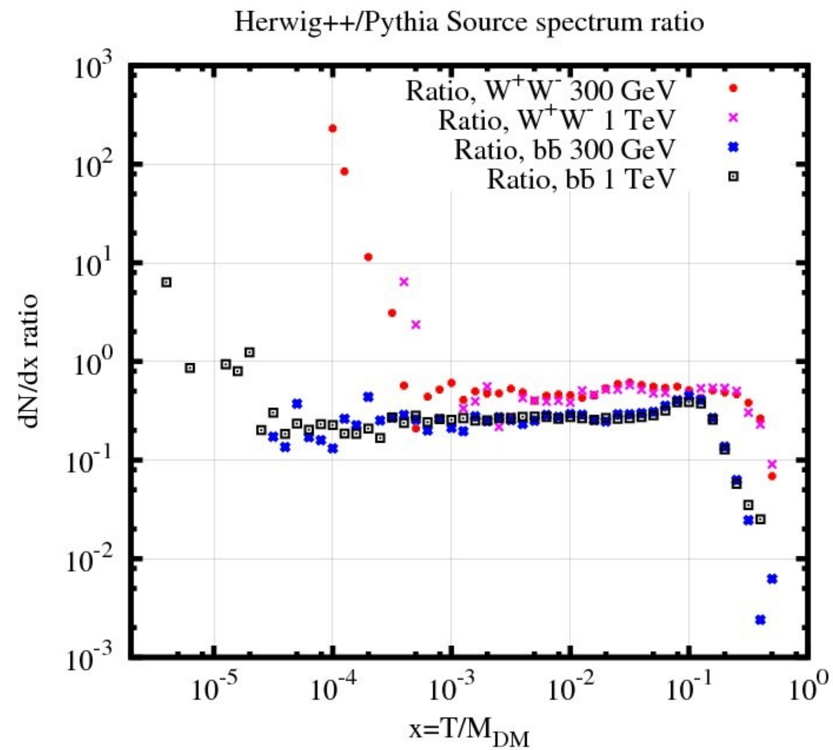


- major conventional production mechanisms of cosmic rays with ISM protons at rest:
  - $p+p \rightarrow \bar{d}+X$ (threshold 17GeV)
  - $\bar{p}+p \rightarrow \bar{d}+X$ (threshold 7GeV)

→ threshold is much lower
→ antiprotons are important

Coalescence uncertainty





- improvement during the last years using tools like Pythia and Herwig for hadronization:
  - produce antiprotons and antineutrons
  - respect jet structure
  - antiproton and antineutron have to be close in space and momentum space
- **Important differences for different experiments and MC generators exist!**

What is going on?

(1) Antideuteron production depends on the exact underlying process and the available center of mass energy:

- Cosmic-ray antideuteron production is most likely dominated by the production relatively close to the threshold (anti-correlation due to phase space considerations of antiprotons and antineutrons important)
- Different values of p_0 for different dark matter masses and different contributing background processes might be the right approach
- What is best value?
  → Z resonance (100GeV DM) or Υ resonance (10GeV DM)?
  → Different values for DM and astrophysical background?

(2) Monte Carlo generators are not reliable enough:

- Generators not really tuned for antiparticle production
- Tune with antiproton and deuteron data

Event-by-event coalescence model approach has to be validated against more data to reduce the production uncertainty for the cosmic ray antideuteron interpretation

Alternatives to coalescence model

- Heavy-ion collisions well-described in thermal model:

$$\frac{\mathrm{d}N}{\mathrm{d}y} \approx \exp\left(-\frac{m}{T_{\mathrm{chem}}}\right)$$

  - Antideuterons directly produced in thermal freeze-out or at a later stage via coalescence?

- Random event normalized to experimental data:

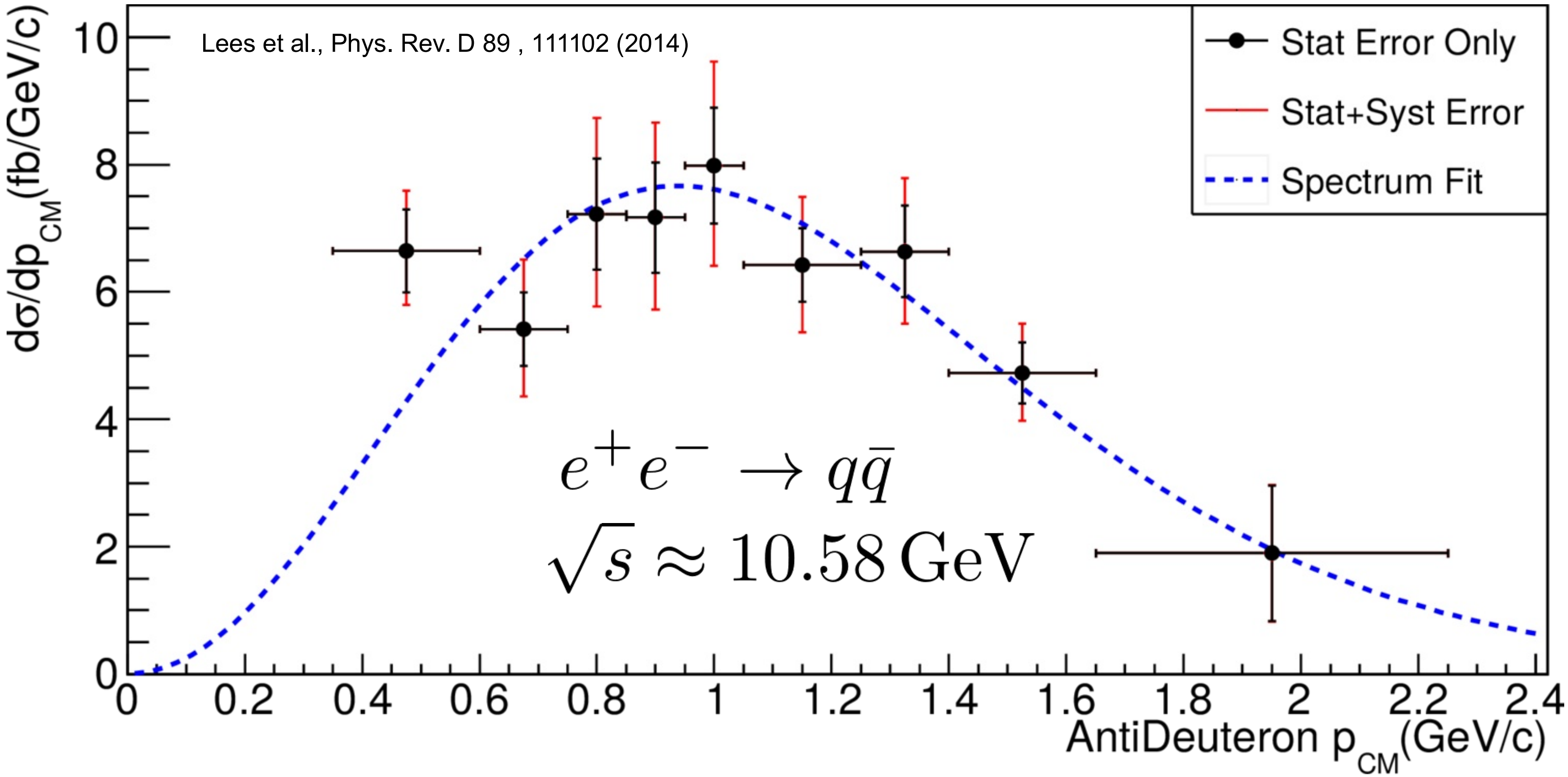
$$\frac{\sigma_{\bar{p}\bar{n}\to\bar{d}X}\left(\left|\vec{p}_{\bar{p}} - \vec{p}_{\bar{n}}\right|\right)}{\boxed{\sigma_0}}$$

free parameter

Dal, Raklev arXiv:1504.07242

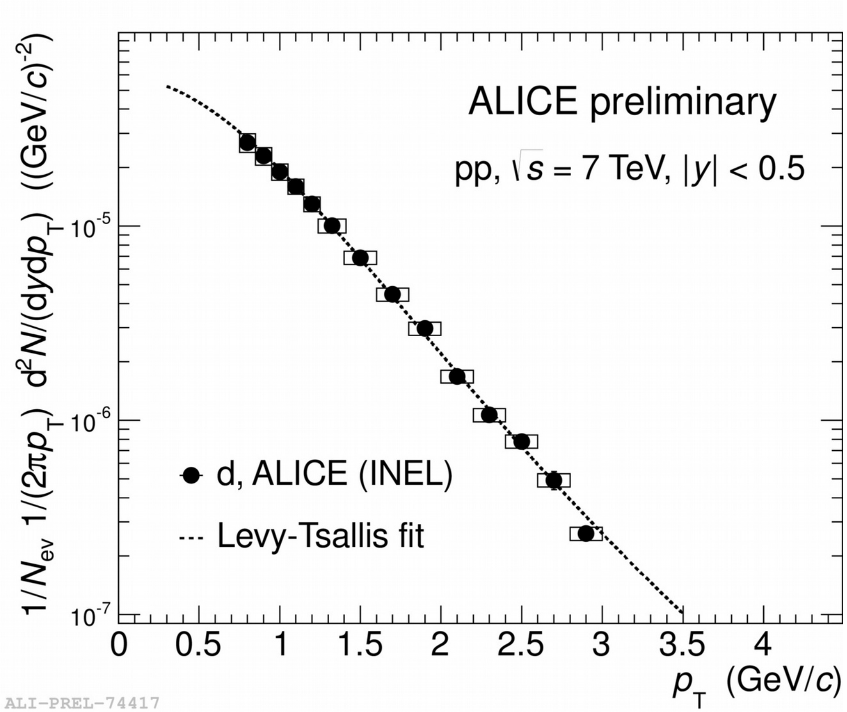
  - For coalesence $\left|\vec{p}_{\bar{p}} - \vec{p}_{\bar{n}}\right|$ is typically 100-200MeV and for this new model ~1GeV
    $\rightarrow$ allows Δ-resonance production

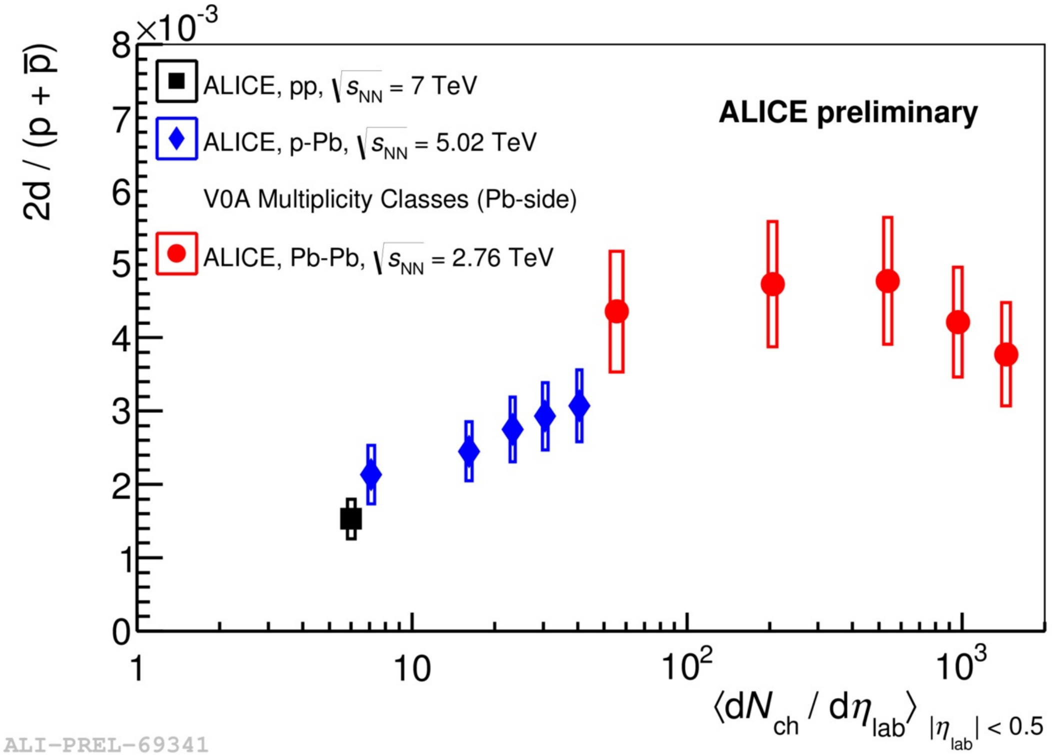
BaBar



- antideuteron production in hadronic decays of Υ resonances (Υ(nS), n=1,2,3)
- potentially very interesting for low-mass dark matter

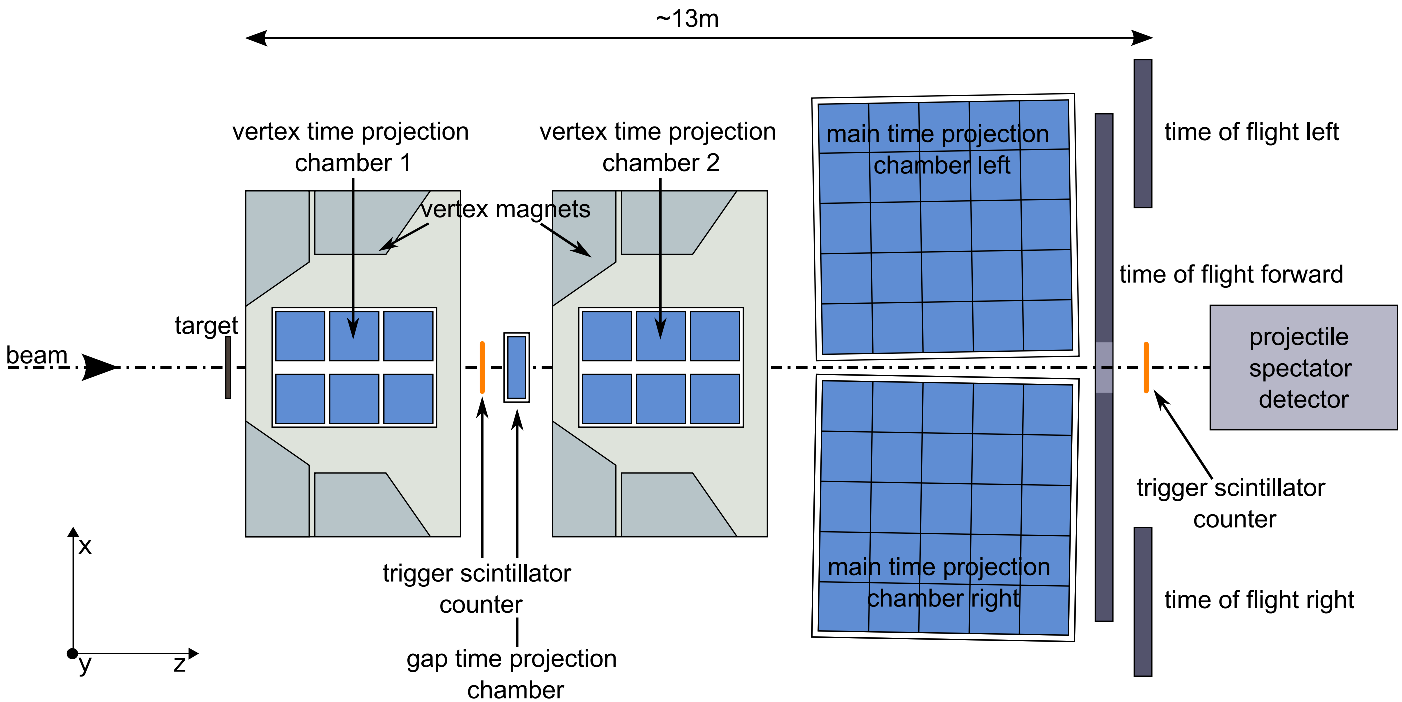
$$\frac{\sigma\left(e^+e^- \to \bar{d}X\right)}{\sigma\left(e^+e^- \to \mathrm{hadrons}\right)} = \left(3.01 \pm 0.13^{+0.37}_{-0.31}\right) \cdot 10^{-6}$$





- *pp* is main process for antideuteron production by cosmic-ray spallations
- *p*-Pb and Pb-Pb collisions are less relevant for studies of cosmic antideuterons due to the different dynamics
- *d*/*p* ratio determined by event multiplicity
  → goes in saturation for Pb-Pb (higher nucleon multiplicity vs. increasing volume)

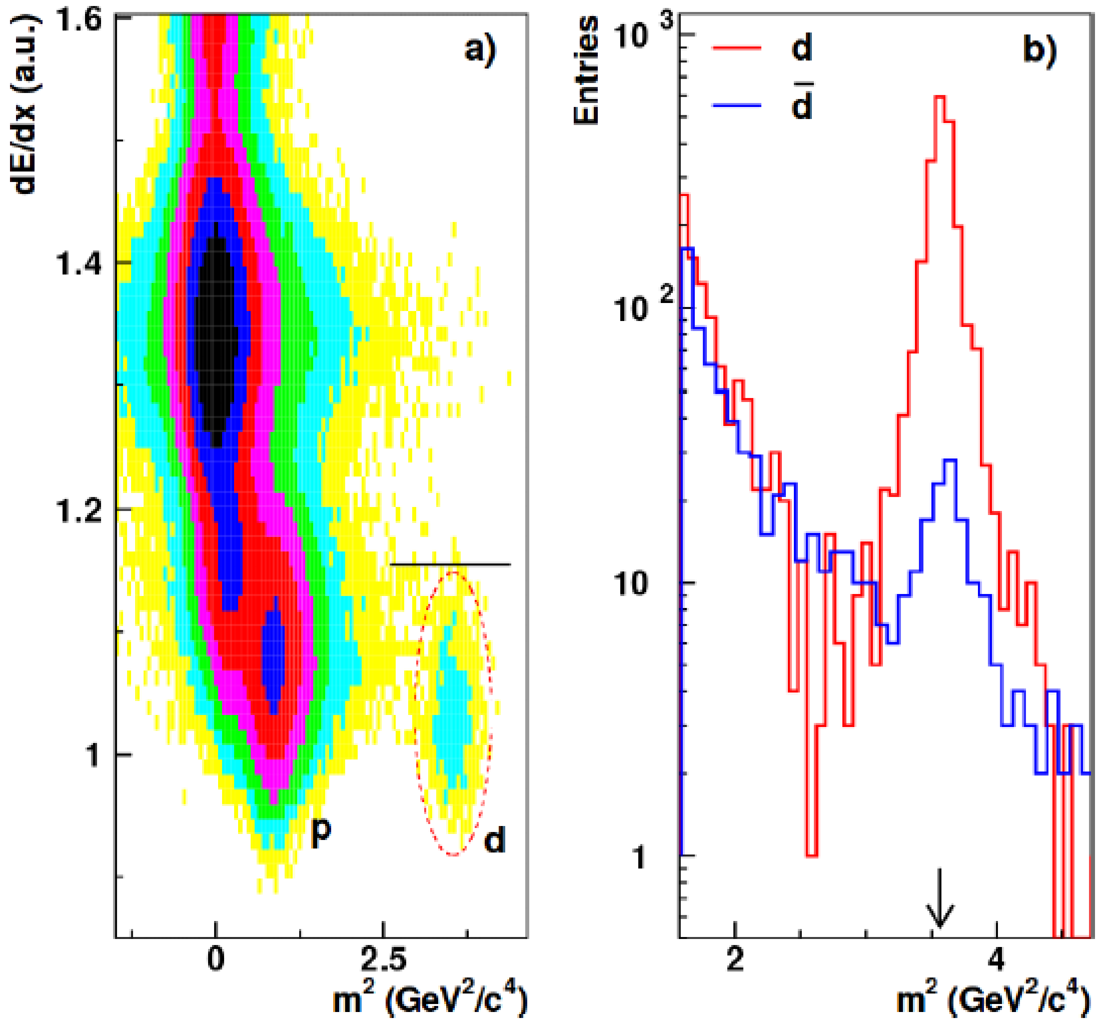
Antideuterons and NA61/SHINE



- Fixed target experiment: main motivation is QCD phase transition, but NA61 also has “customers“ from the UHECR and neutrino community
- Cosmic ray production happens between 40 and 400 GeV
  → SPS energies from 9 to 400 GeV are ideal
- proton-proton interactions with incident momentum between 13 and 158 GeV/c were already recorded in 2011
- 350GeV *p*-*p* run this fall and also 60GeV *p*-C

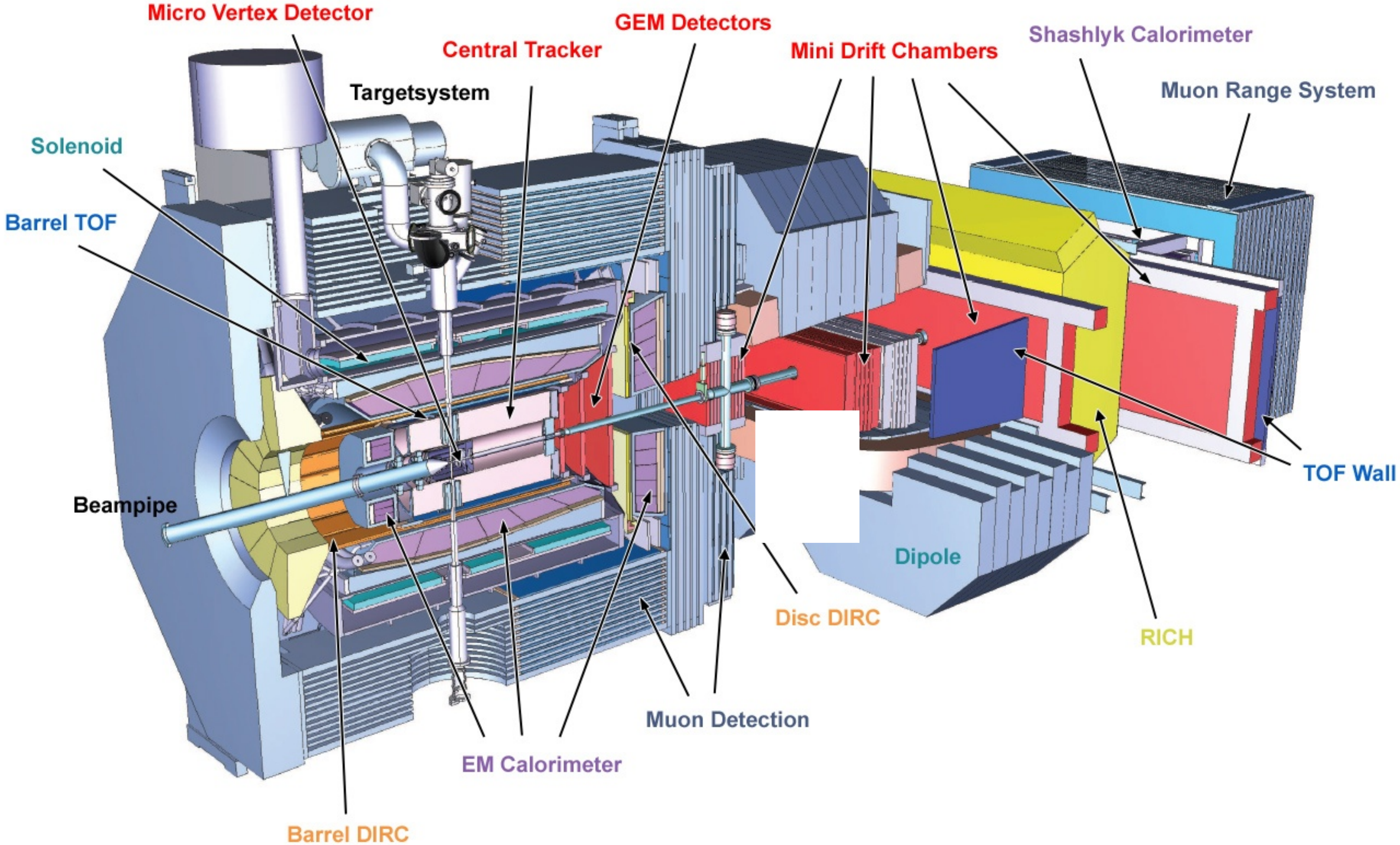
NA49 antideuterons

- NA49 is pre-decessor experiment
- NA49 lead-lead data were already analyzed for antideuterons
- important cross-check for the MC generators: measurement of the yield of antiprotons with the same data
- could in principle also select incident antiprotons



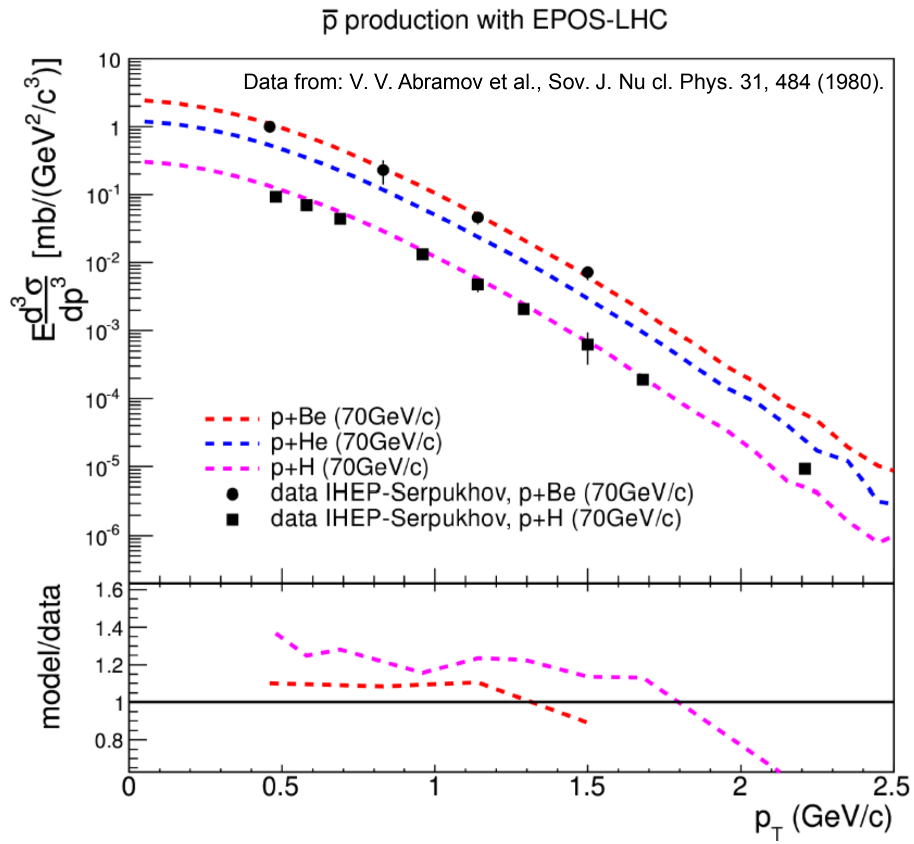
T. Anticic et al., Phys. Rev. C 85, 044913 (2012)

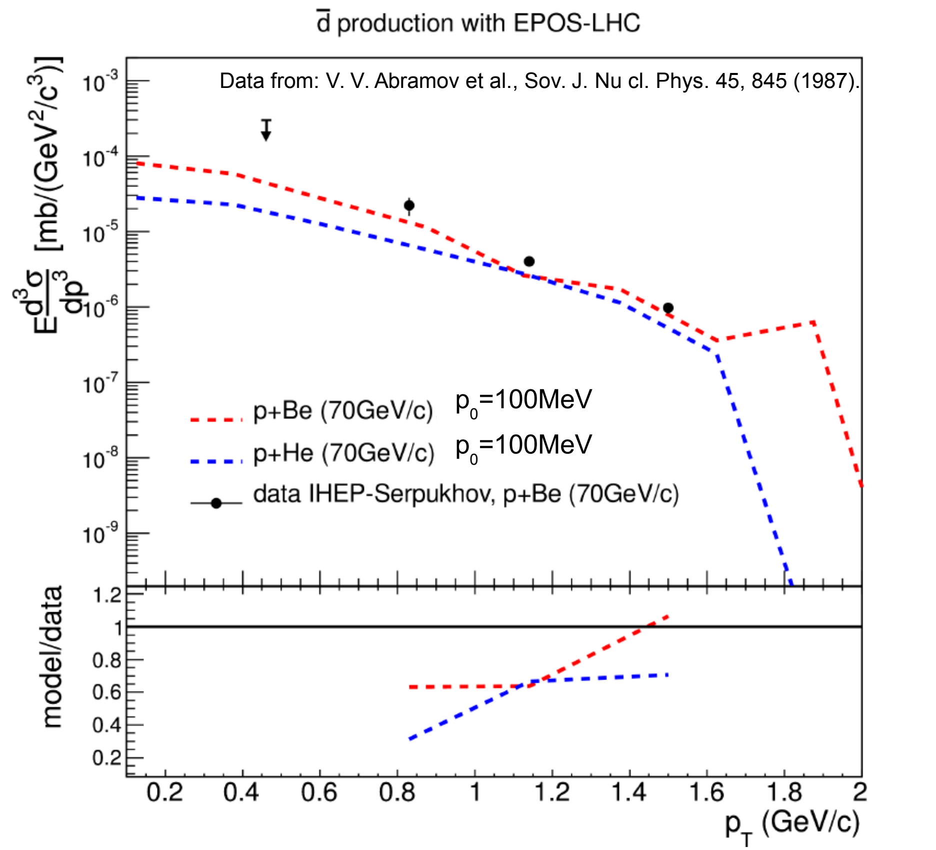
$\overline{\text{P}}$ANDA – fixed Target Experiment



- upcoming PANDA experiment at the FAIR collider in Darmstadt, Germany will study the interactions of a 1.5-15 GeV antiproton beam with different targets (e.g., hydrogen, deuterium, gold, etc.)
- prominent antideuteron production channel: $\bar{p}p \rightarrow \bar{d}X$

Antideuteron production with EPOS-LHC MC





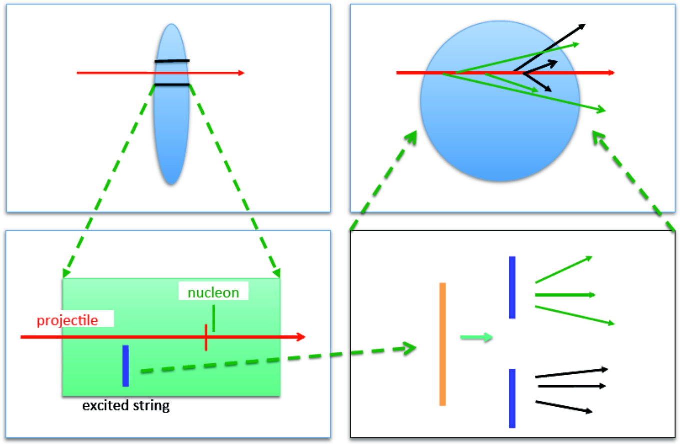
- Also production of antideuterons in collisions with heavier ions important for $p(\bar{p})$ interactions with detector materials or with the atmosphere

- EPOS-LHC has been optimized/tuned in recent years to describe minimum bias LHC events (*p*-*p*, *p*-Pb, Pb-Pb)
- Not a lot/only quite old data available → NA61 has more data on disk already

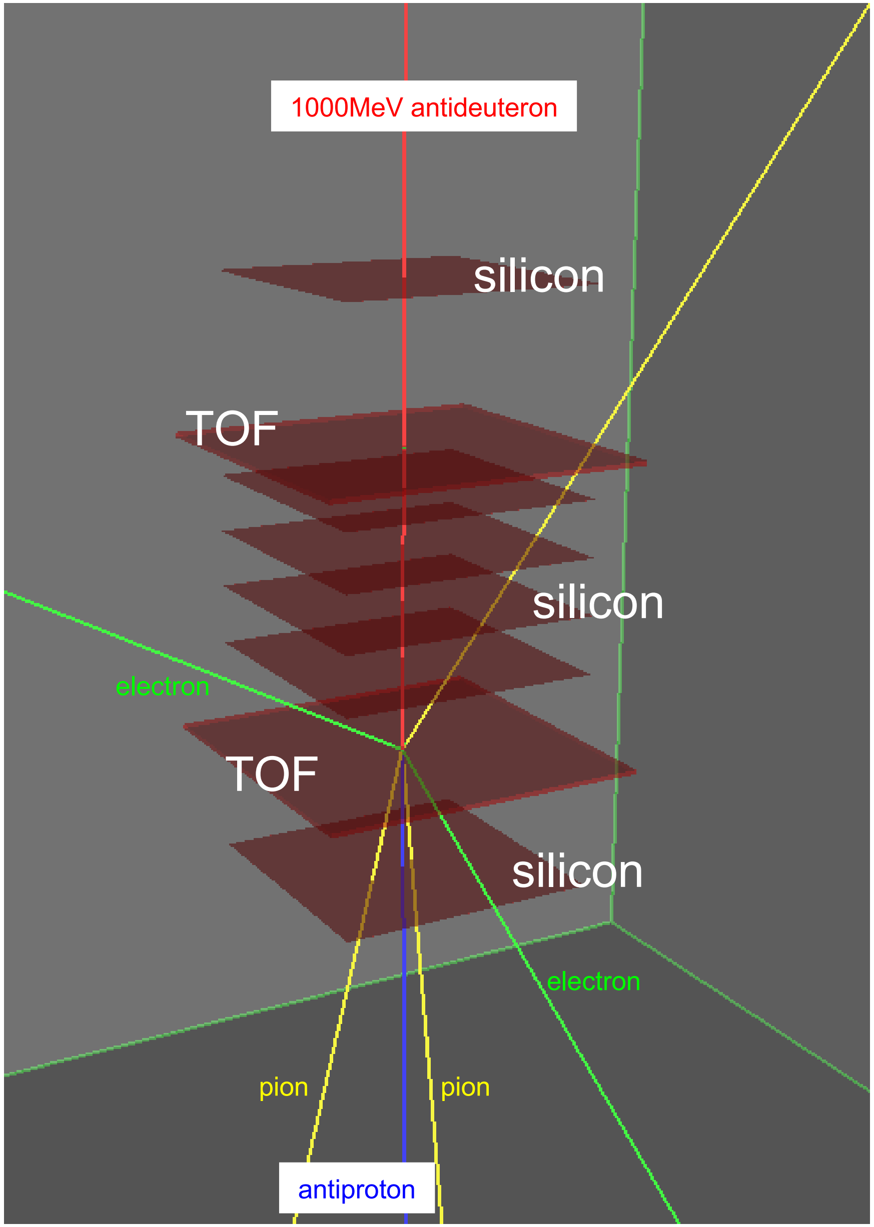
- Collaborators at UNAM, Mexico from ALICE: D. Gomez, A. Menchaca, V. Grabski

Geant4 - Model for $\bar{d}$ simulation

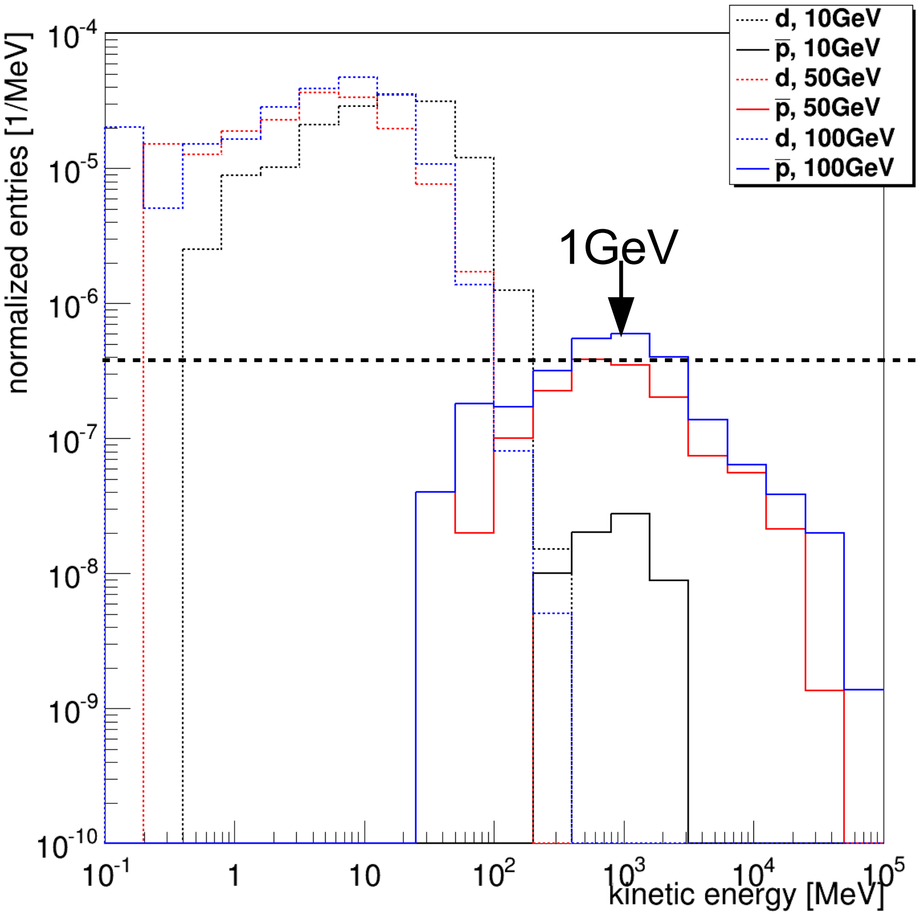
- recent implementation in Geant4: antideuteron simulations
- FTF model (diffractive string excitation with momentum transfer) was extended to handle nucleus-nucleus interaction down to 0GeV
- best model for antiprotons, antineutrons, antideuterons:
  - very little data for validation available
  - needed:
    - antideuteron formation
    - exotic model for antiproton and antideuteron (GAPS)



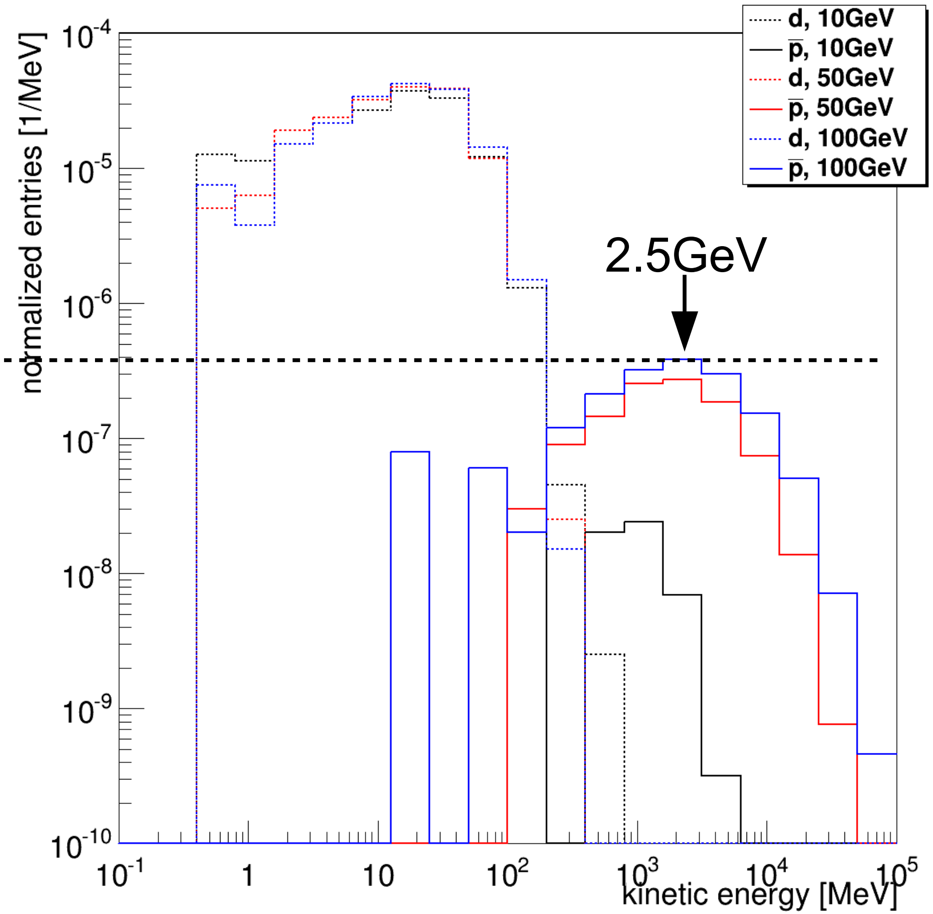
Galoyan, Uzhinsky arXiv:1208.3614



$\overline{p}$ and d production in p-He with Geant4



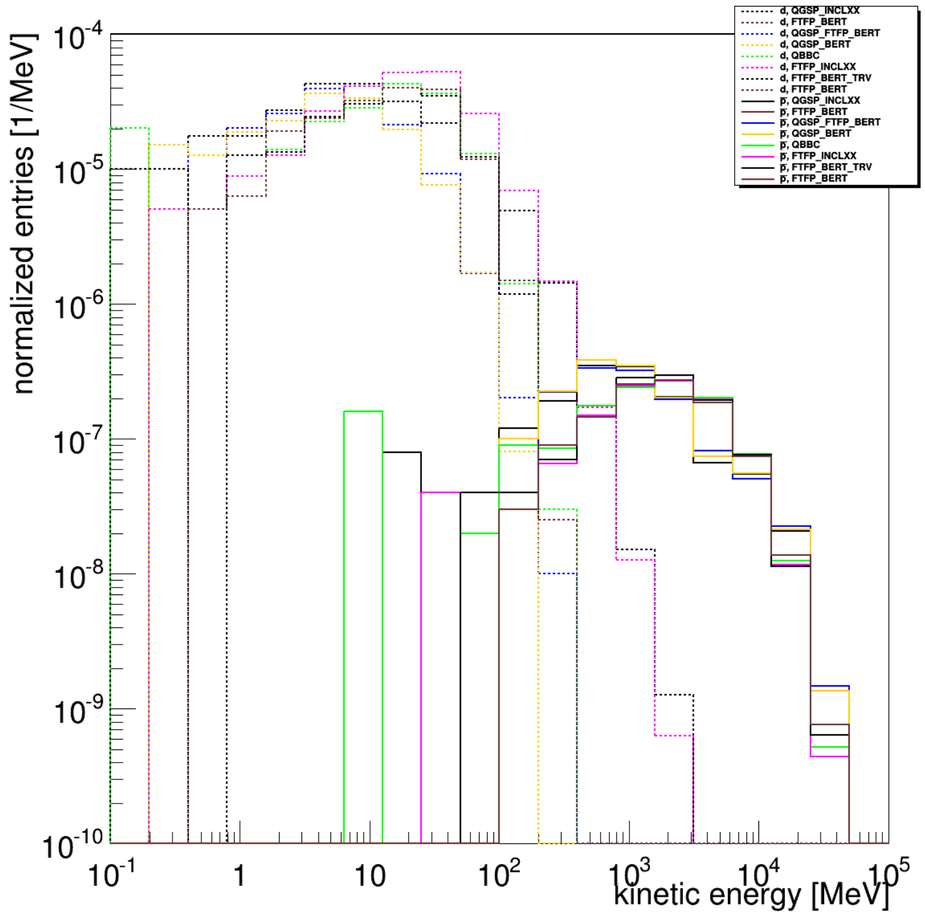
QGSP_BERT



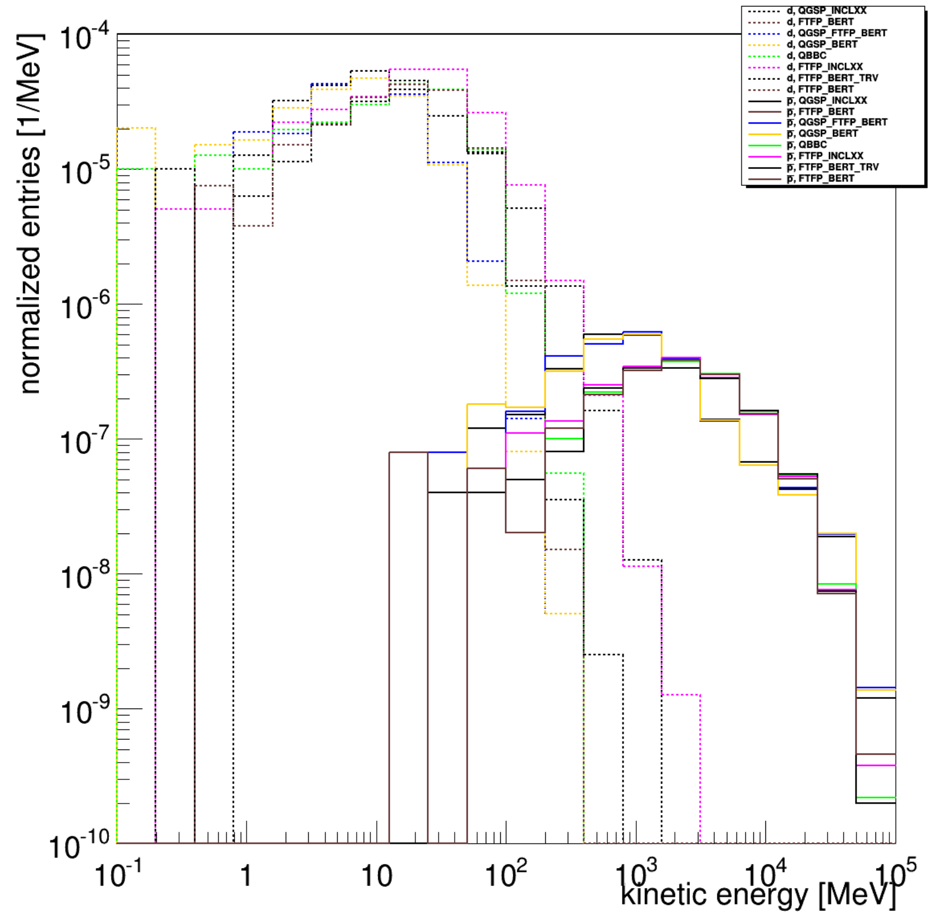
FTFP_BERT

- test of Geant4 physics for p-He production “as is“ for different models
- average yield for 8g/cm^2 of helium (→ if all the traversed matter in ISM for cosmic rays would be helium)

$\overline{p}$ and *d* production in *p*-He with Geant4



50GeV



100GeV

- antiproton and deuteron models show different energy peaks, steepness, and yield
- I have to understand more which model is preferred and describes the data the best

Conclusion & Outlook

- Measurement of antideuterons is a promising way for indirect dark matter search
- Antideuteron production is an important uncertainty
- More experimental data are needed
- Extended models and improved simulation tools needed
- Measurements with NA61/SHINE and hopefully PANDA will improve understanding of antideuteron production and modeling