NA61/SHINE cross section measurements for cosmic-ray studies and antinuclei formation

Light Anti-Nuclei as a Probe for New Physics
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partially on behalf of the NA61/SHINE collaboration

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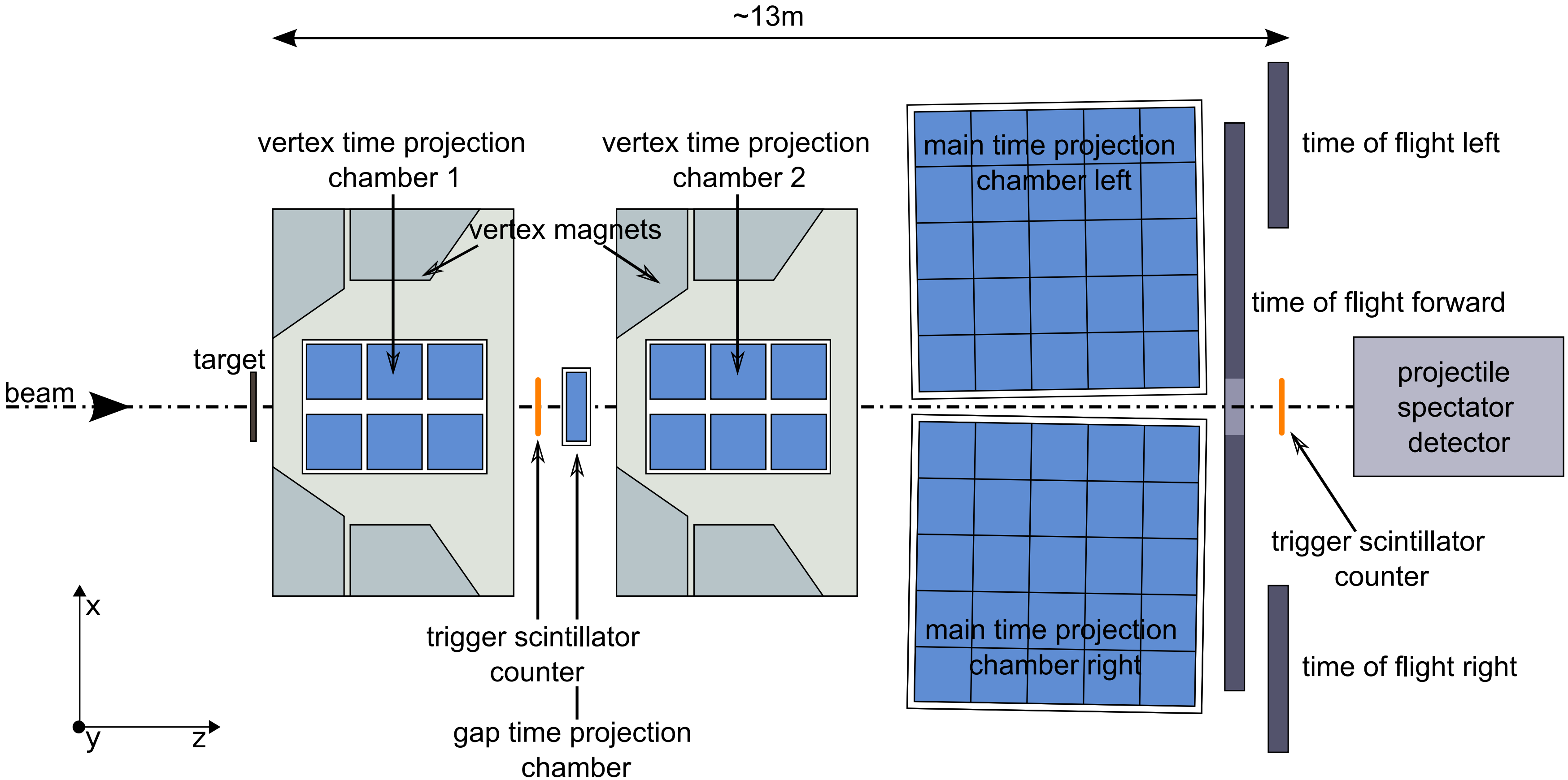
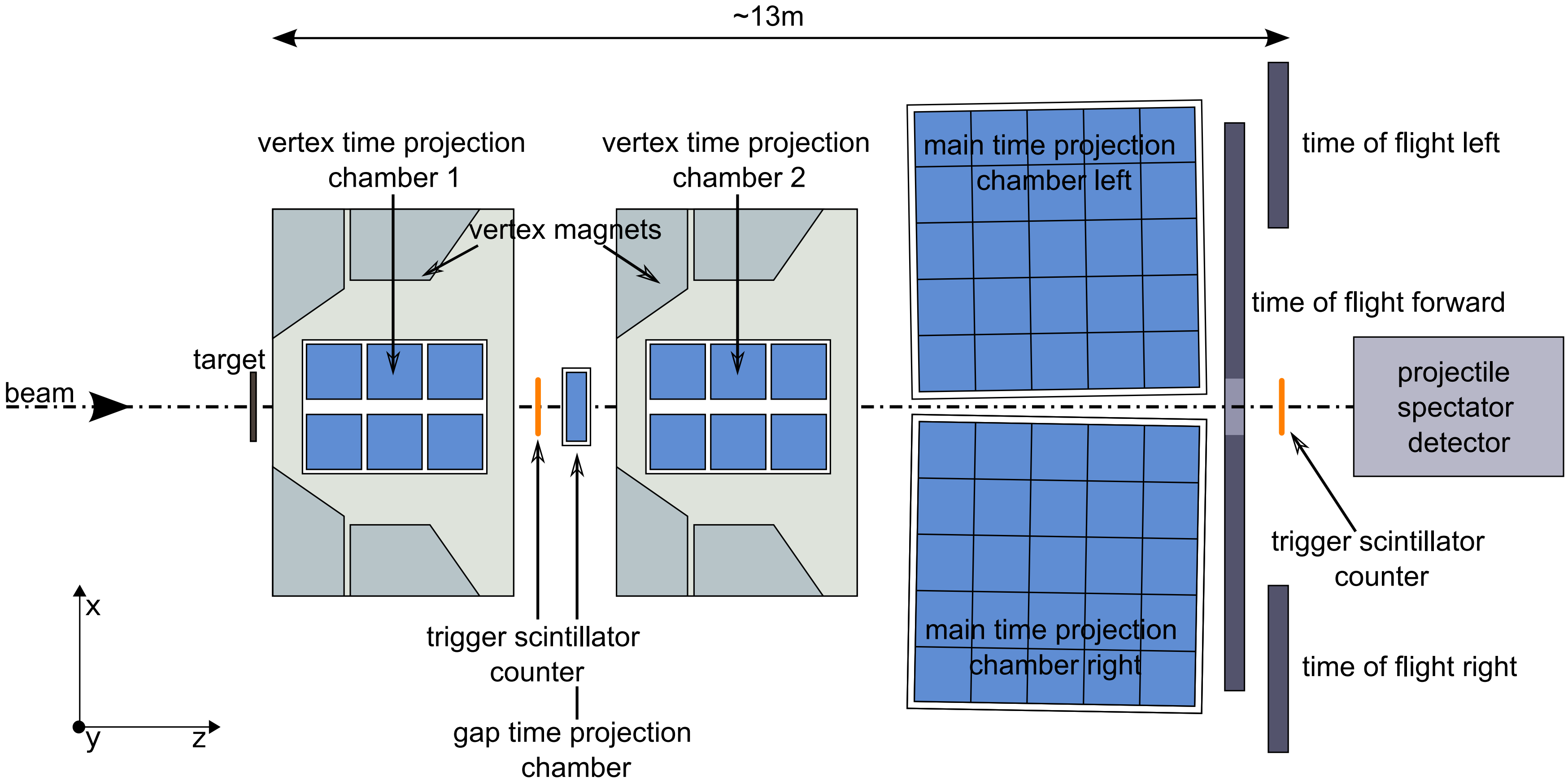
NA61/SHINE at CERN



- multi-purpose, fixed-target experiment at the CERN SPS (NA61/SHINE facility paper: JINST 9 (2014) P06005)
  - precise measurements of properties of produced particles: q, m, p
- cosmic-ray antideuteron production happens between 40 and 400GeV
  - SPS energies from 9 to 400GeV are ideal
- data under discussion from the NA61/SHINE strong interactions program:
  - p+LH data taken at 13, 20, 31, 40, 80, 158, 400GeV/c

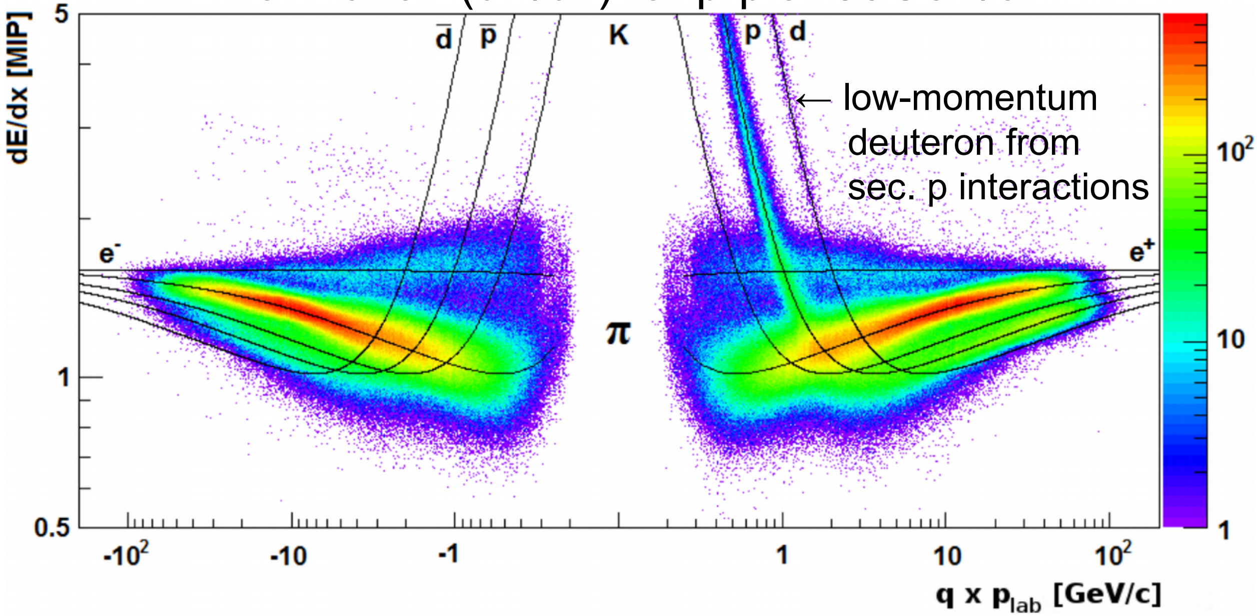
NA61/SHINE at CERN



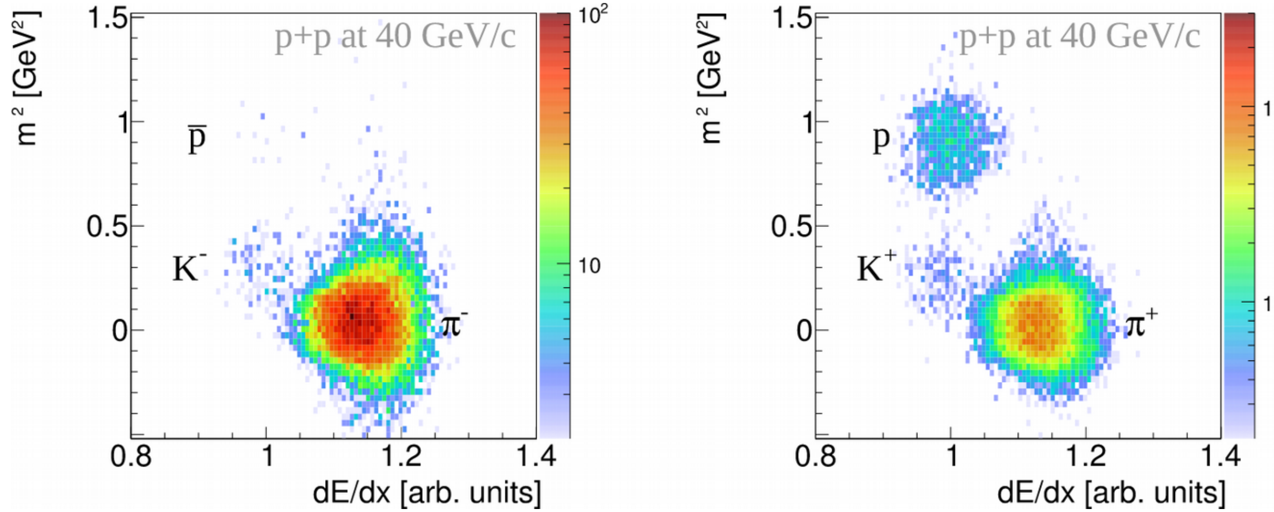
- high momentum resolution: $\sigma(p)/p^2 \approx 10^{-4}(\mathrm{GeV}/c)^{-1}$ (at full B=9Tm)
- ToF walls resolution: ToF-L/R: $\sigma(t) \approx 60$ps, ToF-F: $\sigma(t) \approx 120$ ps
- Good particle identification: $\sigma(dE/dx)/\langle dE/dx \rangle \approx 0.04$, $\sigma(minv) \approx 5$ MeV
- high detector efficiency: > 95%
- event rate: 70Hz → will be upgraded to ten-times faster after LS2

Particle identification

Ionization (dE/dx) for p-p at 80GeV/c

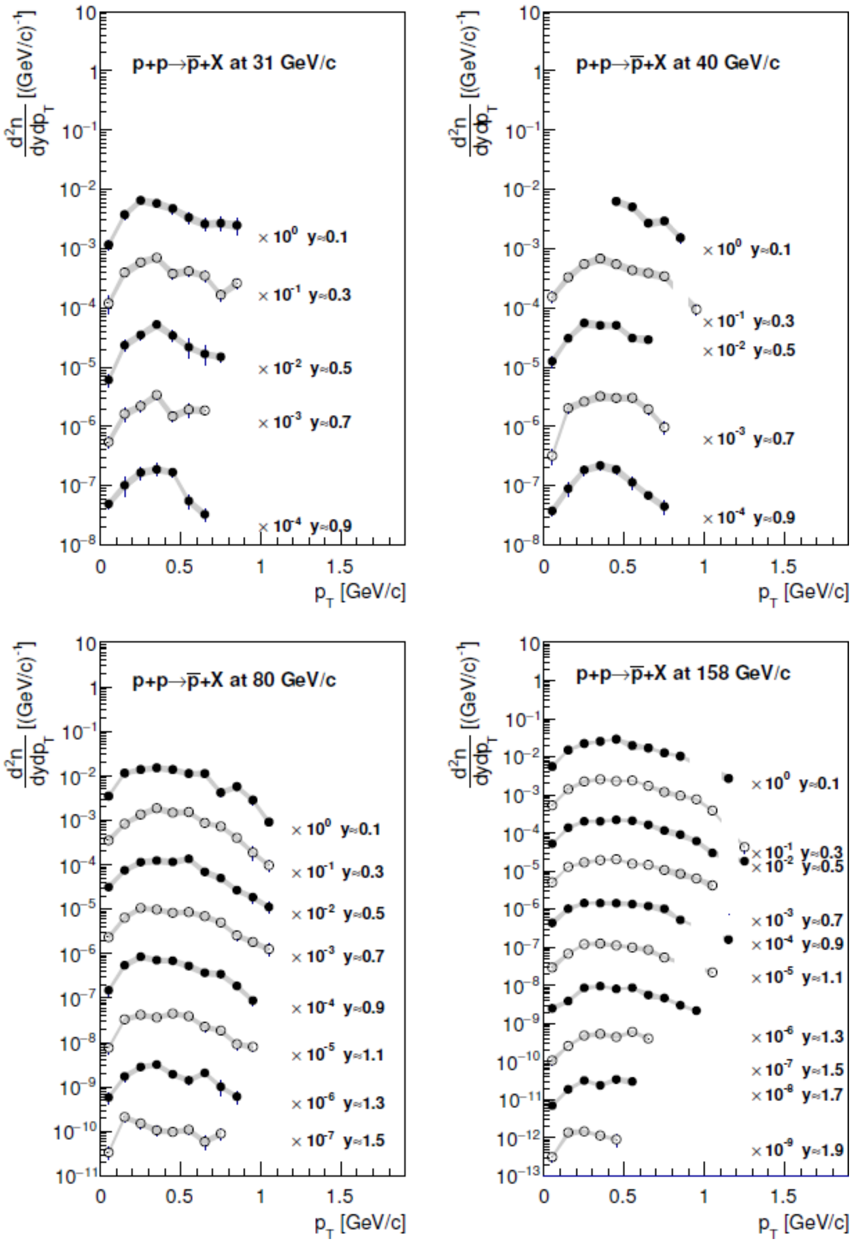


Ionization (dE/dx) combined with TOF and momentum for p-p at 40GeV/c



Eur. Phys. J. C77 10, 671 (2017)

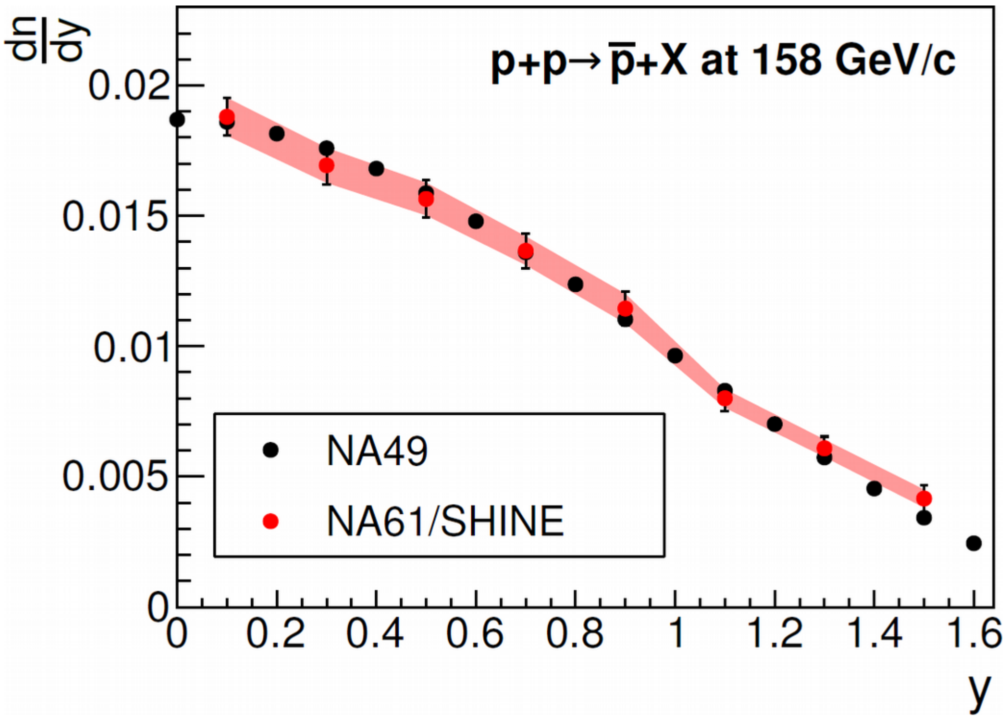
Antiproton yields

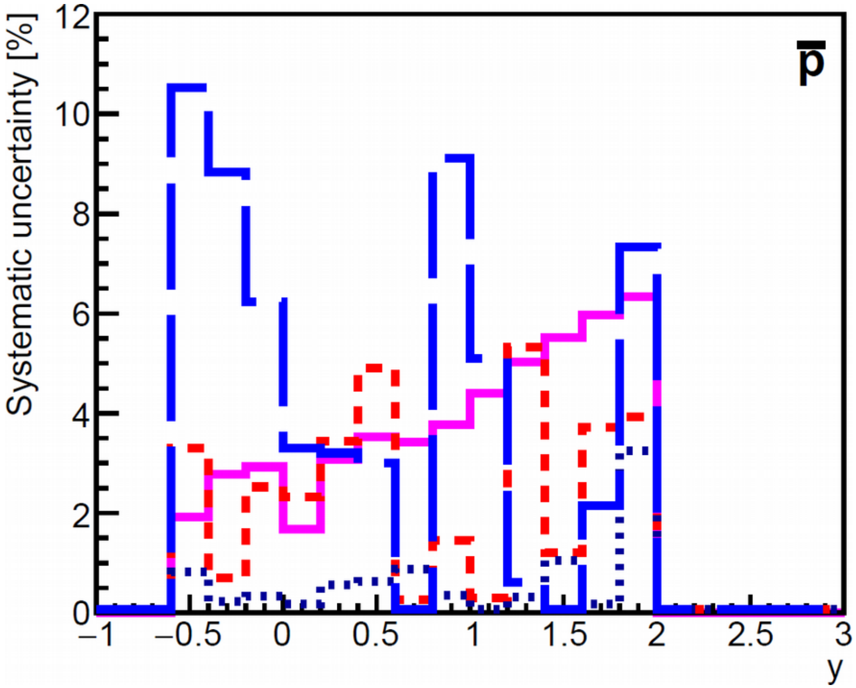


Eur. Phys. J. C77 10, 671 (2017)

- results based on 2009 p-p runs
- NA61/SHINE results are important to update cosmic-ray antiproton flux interpretation
- production cross-section of antiprotons needs to be known on percent level to match AMS-02 precision
- analysis for large 158GeV/c and 400GeV/c p-p data sets ongoing

Comparison of NA61/SHINE and NA49



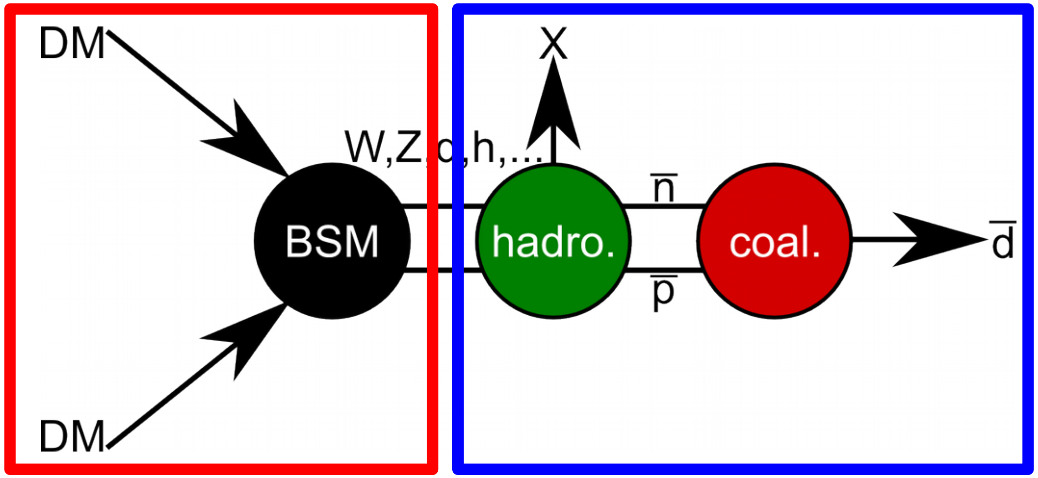


systematic uncertainties:

- event losses: inefficiency of trigger for removal of elastic events
- track selection criteria: variation of hits in TPCs
- vertex z position
- fit uncertainty: dE/dx parameter variation

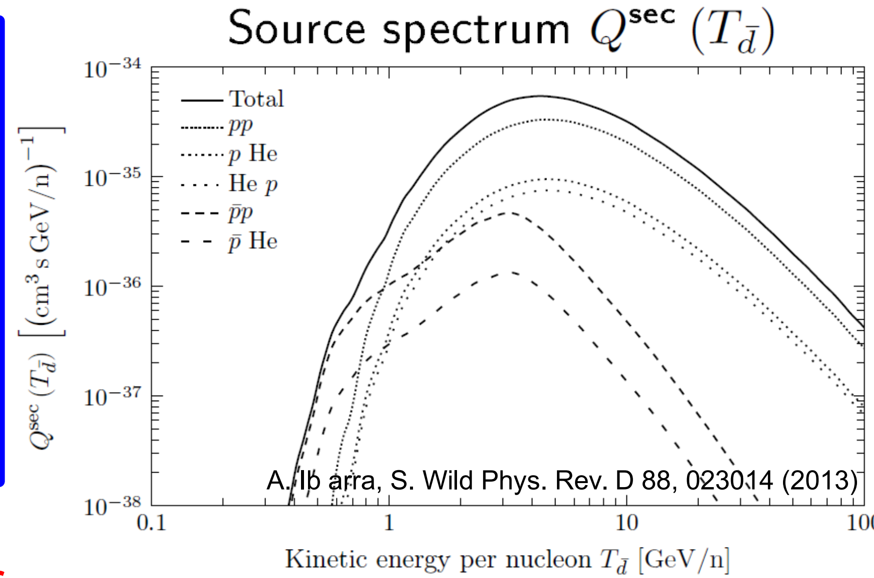
Eur. Phys. J. C77 10, 671 (2017)

(Anti)deuteron formation



dark matter

conventional production (e.g., p+ISM) & dark matter



- d ($\bar{d}$) can be formed by an p-n ($\bar{p}$-$\bar{n}$) pair if coalescence momentum p_0 is small

$$\gamma_d \frac{d^3 N_d}{dp_d^3} = \frac{4\pi}{3} p_0^3 \left(\gamma_p \frac{d^3 N_p}{dp_p^3}\right)\left(\gamma_n \frac{d^3 N_n}{dp_n^3}\right)$$

- use an event-by-event coalescence approach with hadronic generators

Schwarzschild &Zupancic, Physical Review 129, 854 (1963)
Ibarra & Wild, Physical Review D88 020314 (2013)
Aramaki et al., Physics Reports 618, 1 (2016)

Issues of the coalescence model

- **phase space for ion production depends on the available energy in the formation interaction**
  - 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)

- **p_0 is small**
  - coalescence is highly sensitive to two-particle correlations between the participating (anti)nucleons
    → no a-priori reason to expect two-particle correlations from one generator to be more reliable than from another
  - important for (anti)deuteron production close to the production threshold energy, which favors an anti-correlation of (anti)protons and (anti)neutrons

- **spatial separation**
  - nuclear interactions have a scale of a few femtometers
  - antinucleons originating from weakly decaying particles with macroscopic decay lengths are produced too far from the primary interaction vertex

A. Ibarra, S. Wild Phys. Rev. D 88, 023014 (2013)

Issues of the coalescence model

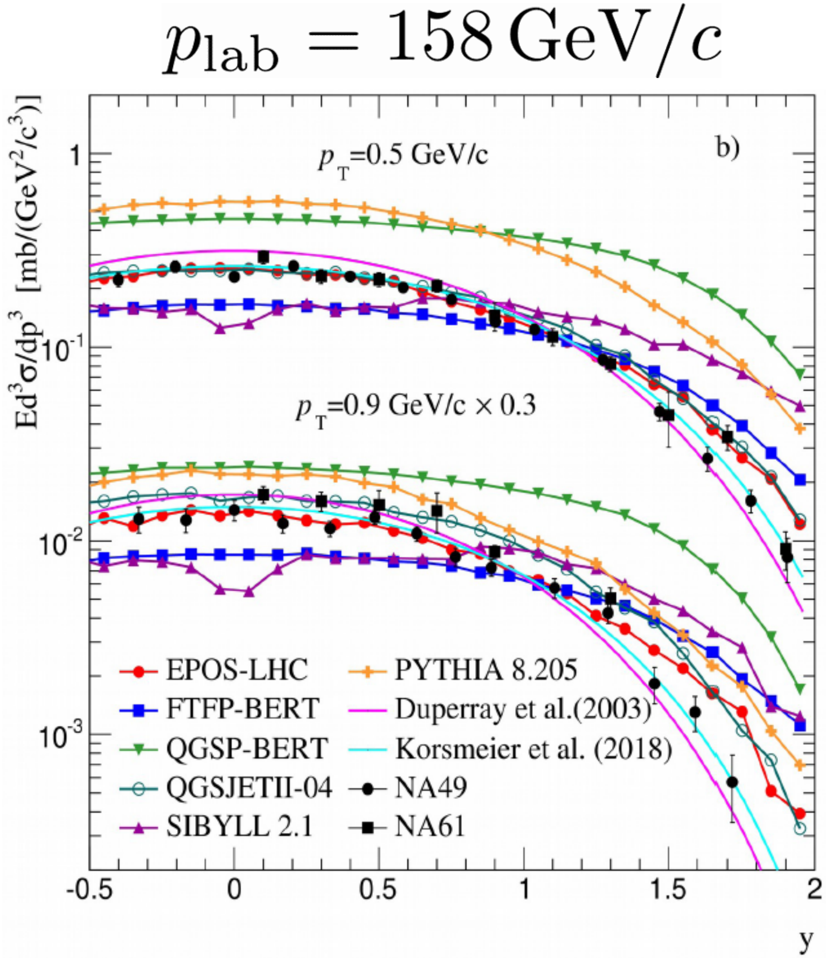
- **(anti)neutron spectra are very challenging to access**
  - common approach is to assume that the antiproton and antineutron production cross sections are equal
  - potential asymmetries should be evaluated

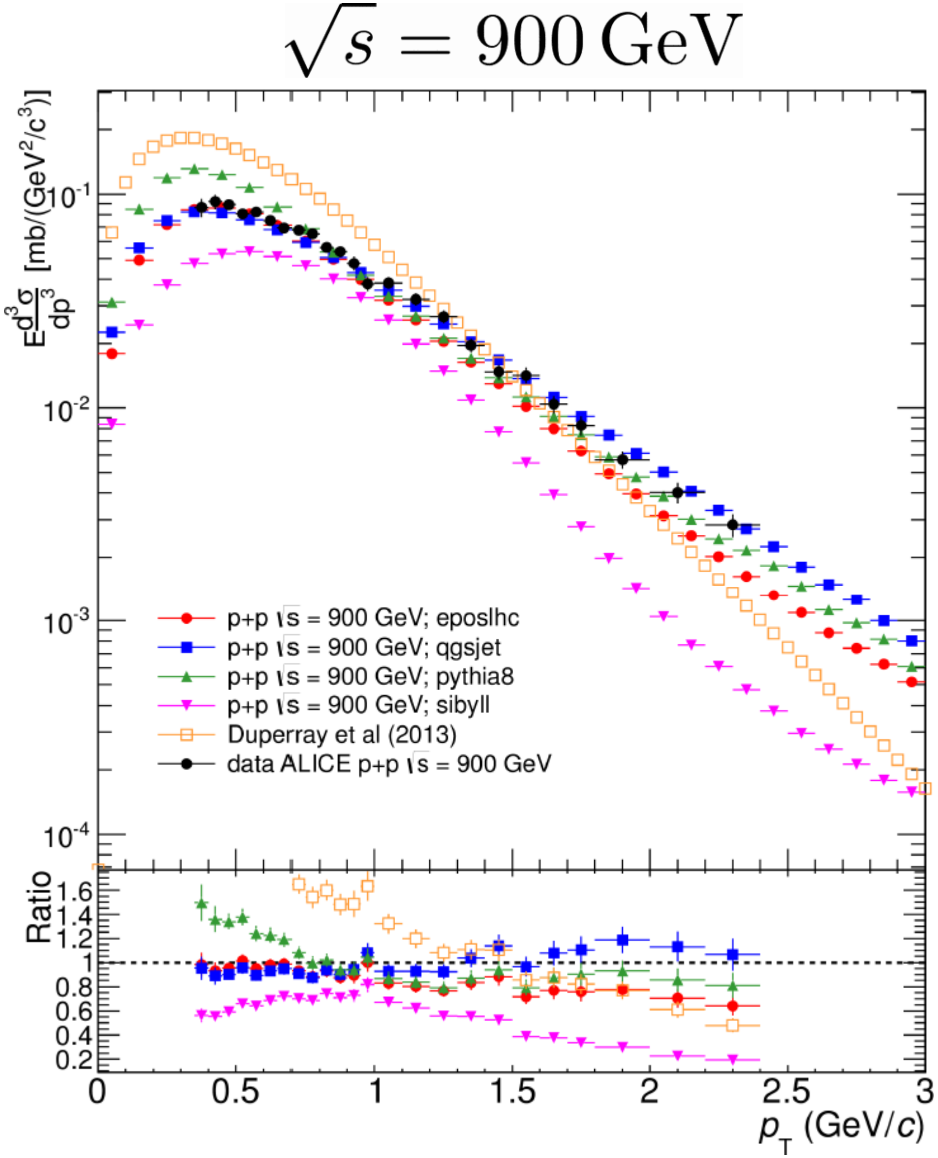
Fischer, Acta Physica Hungarica Series A, Heavy Ion Physics 17, 369 (2003)

- hadronic generators failing to describe (anti)proton and (anti)neutron spectra automatically result in a shift of p_0
  - parameterize the antiproton mismatch to have p_0 only describe the coalescence process
- formation probability in the per-event simulation coalescence approach is taken to be exactly 100%, e.g., spin is not considered
- generators not really tuned for antiparticle production
  → tune with antiproton, deuteron, and antideuteron data

Generator tests: antiprotons

D. Gomez-Coral et al. 2018



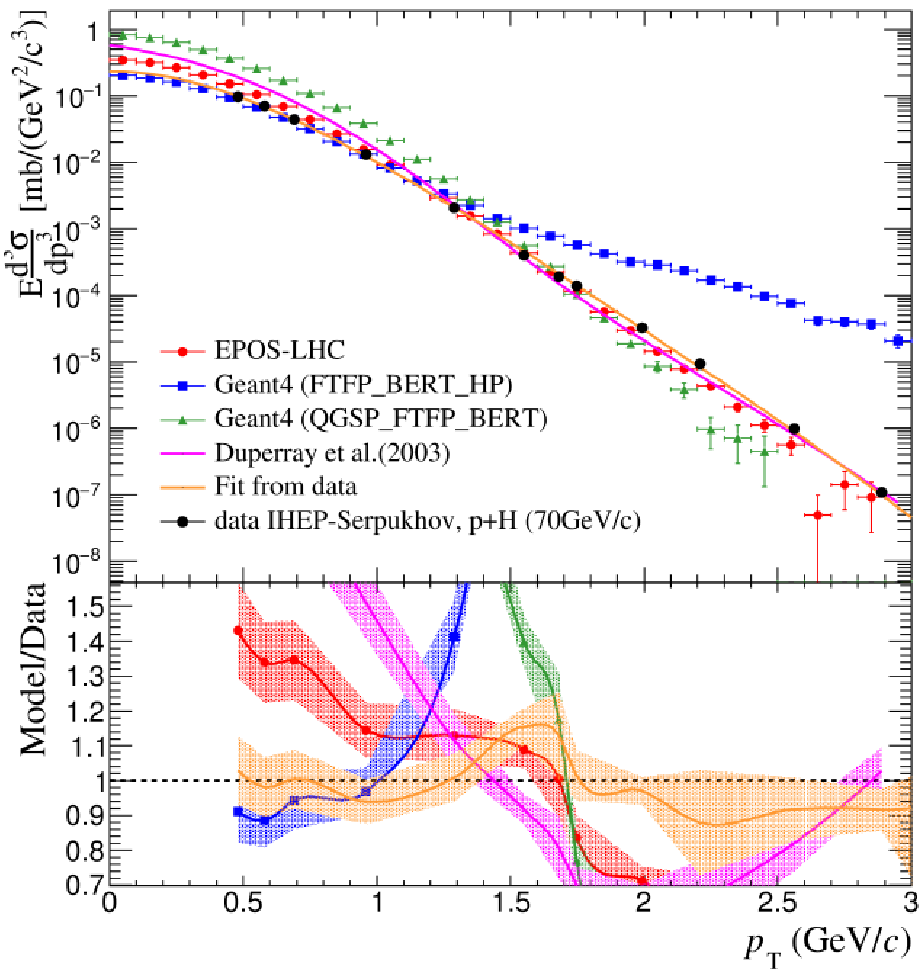


- EPOS-LHC works best over most energies

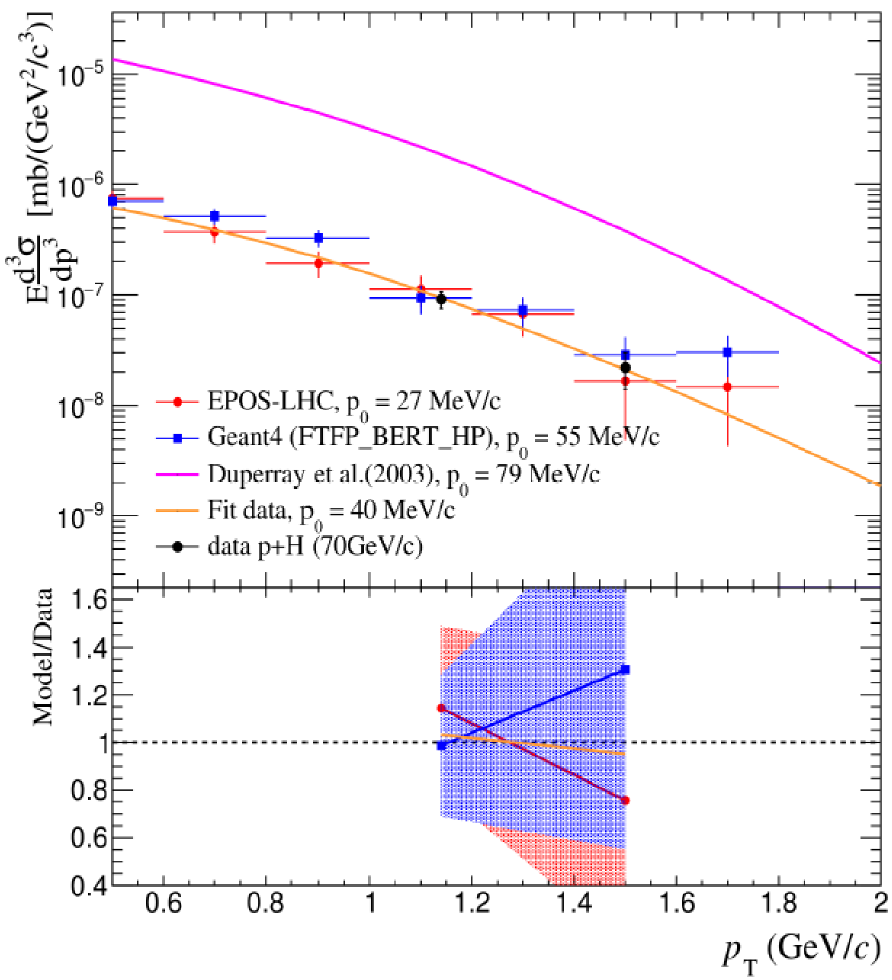
More generator tests: Geant4

D. Gomez-Coral et al. 2018

Antiprotons



Antideuterons

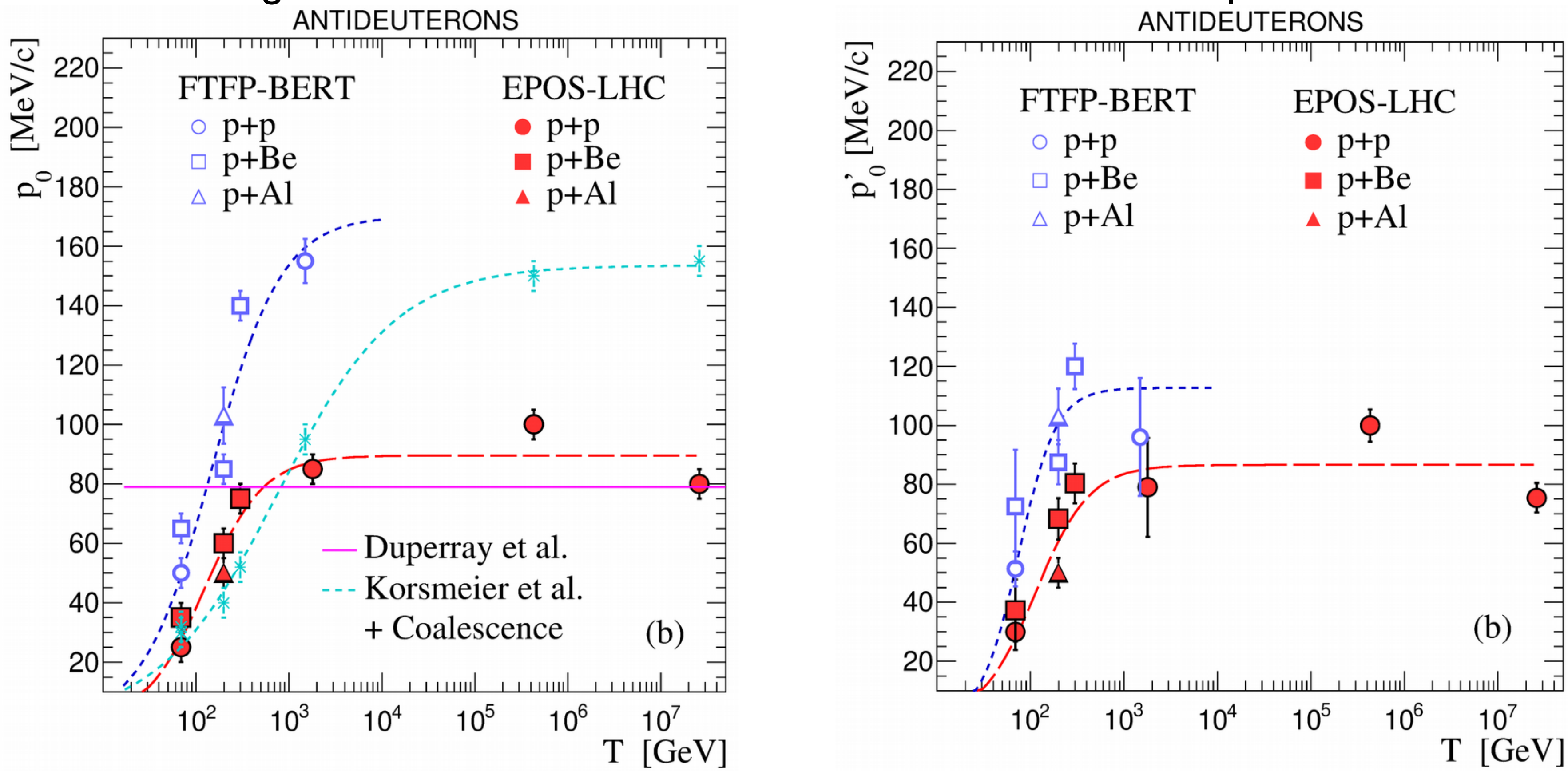


- Geant4 useful for experimentalists to, e.g., predict instrumental background
- find p_0 for each data set where antiproton and antideuteron results exist

Modified antideuteron coalescence

D. Gomez-Coral et al. 2018

regular coalescence | factorized antiproton mismatch

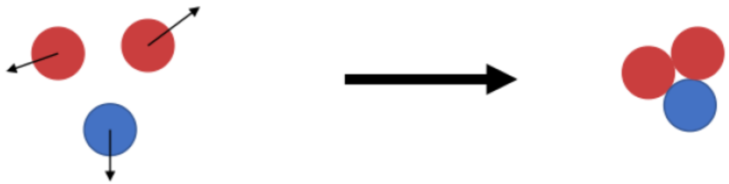


- more p-p data in threshold region needed
- factorize out antiproton mismatch from data/MC comparison:

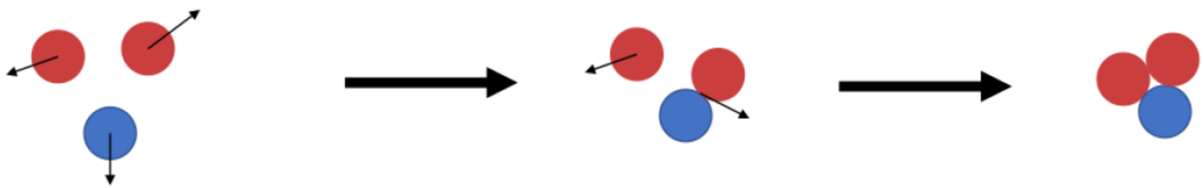
$$\kappa = \frac{f_{\bar{p}}^{data}(p_T)}{f_{\bar{p}}^{MC}(p_T)} \Rightarrow f_{\bar{d}}(p_T) \propto (\underbrace{p_0' \cdot \kappa^{\frac{2}{3}}}_{=p_0})^3 \cdot (f_{\bar{p}}^{MC}(p_T))^2$$

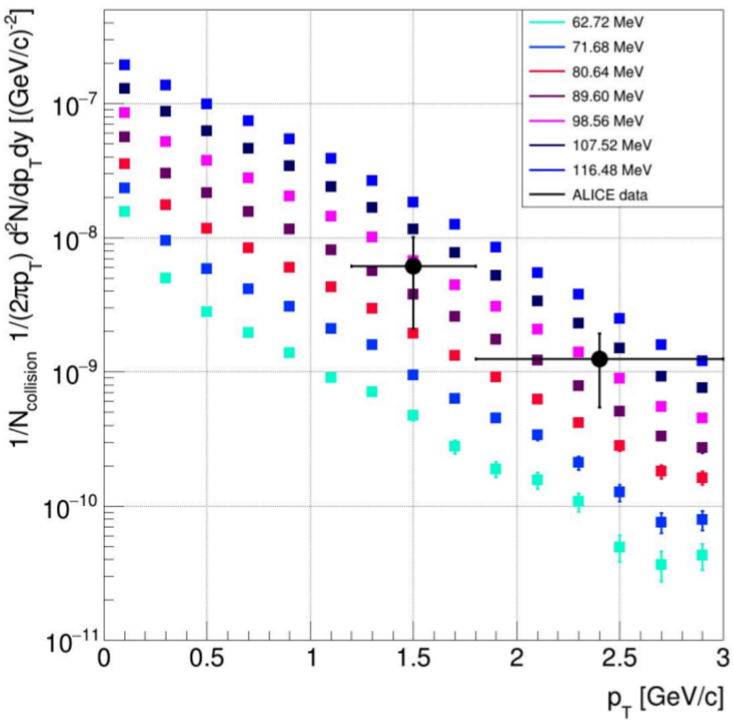
Antihelium-3 coalescence

All at the same time:



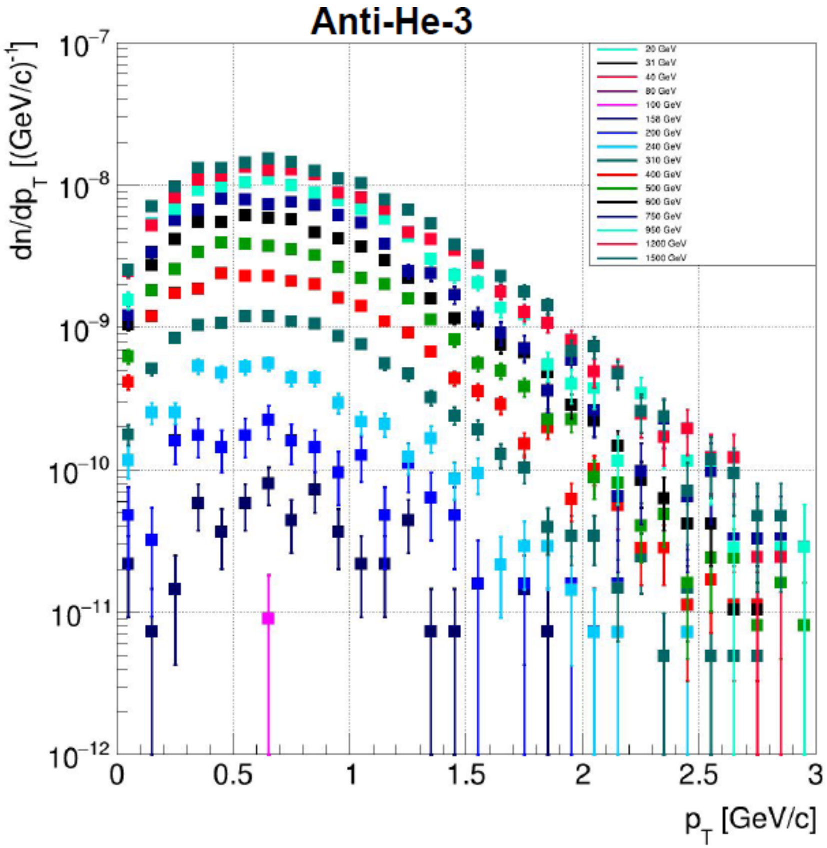
In an iterated process:

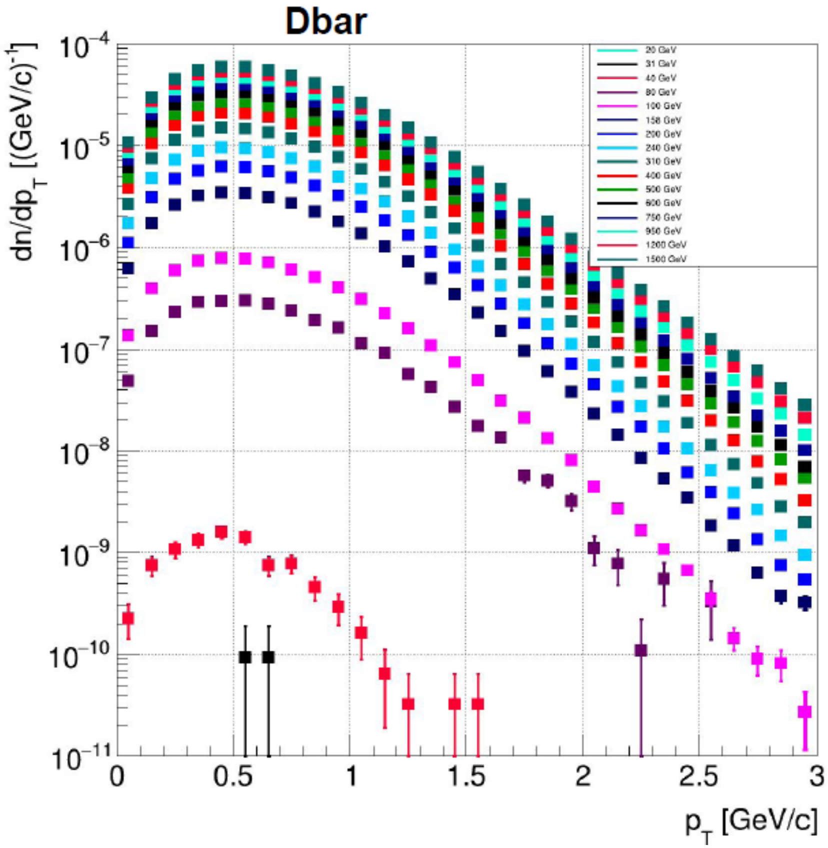




- expanded modified MC coalescence model to merging 3 antinucleons from p-p interactions
  → requires quite a bit of computing power (~2000 years so far)
- use the p0 behavior from antideuterons to antihelium-3
- Very good agreement with ALICE antihelium-3 data (p-p at $\sqrt{s}$=7TeV)
- Use model for antihelium-3 prediction at other p-p energies

Antihelium-3 and antideuterons

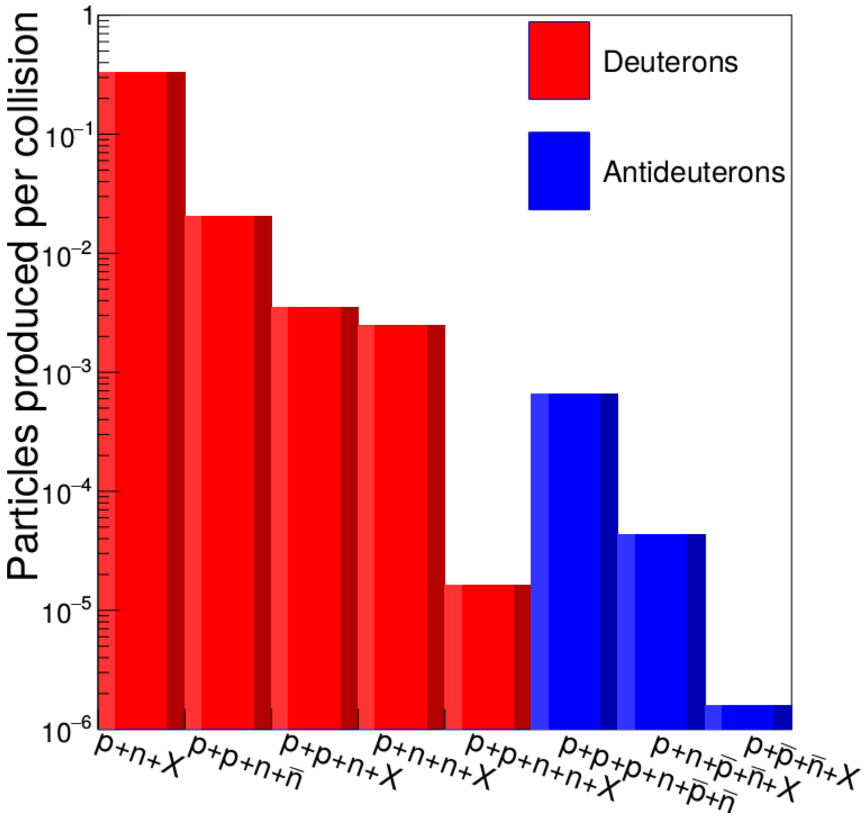




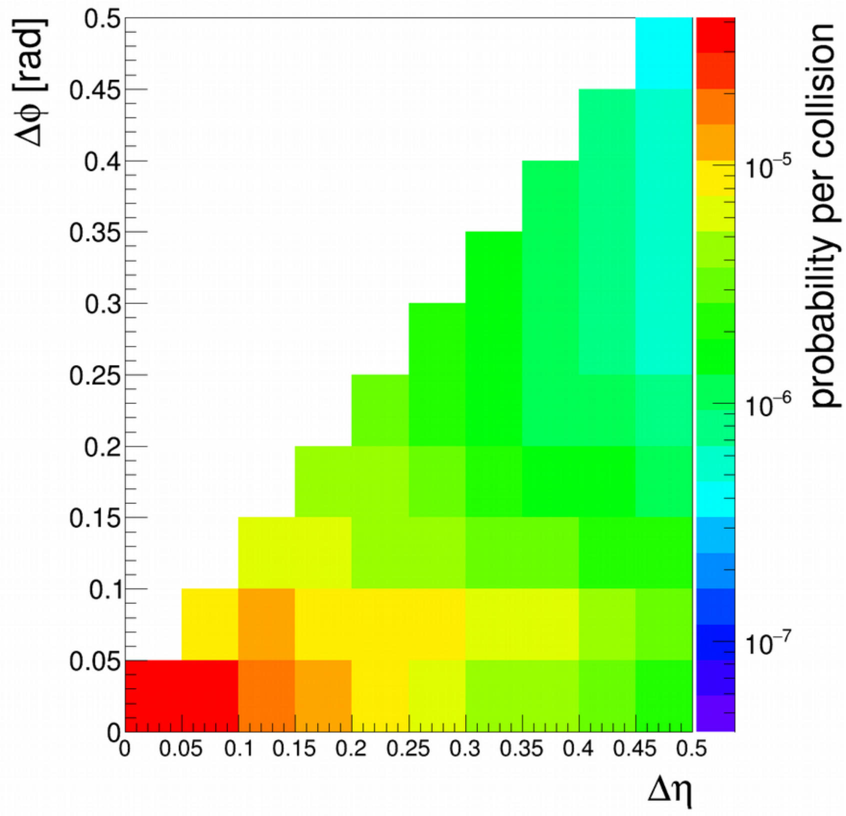
- Antihelium-3 spectrum becomes clearly defined with our current simulations from about 200GeV
- Antideuterons from about 40GeV, big jump in yield from 40GeV to 80GeV

Needed measurements

EPOS-LHC for p-p at 158GeV/c



Predicted production of nucleons



Angular correlation of p-p pairs within a radius of Δp=100MeV/c

Tune hadronic generators with more information on nucleon correlations

Alternative approach: thermal model

- Particle production directly at freeze-out (thermal model):

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

Cleymans et al., Phys. Rev. C 84, 054916 (2011)

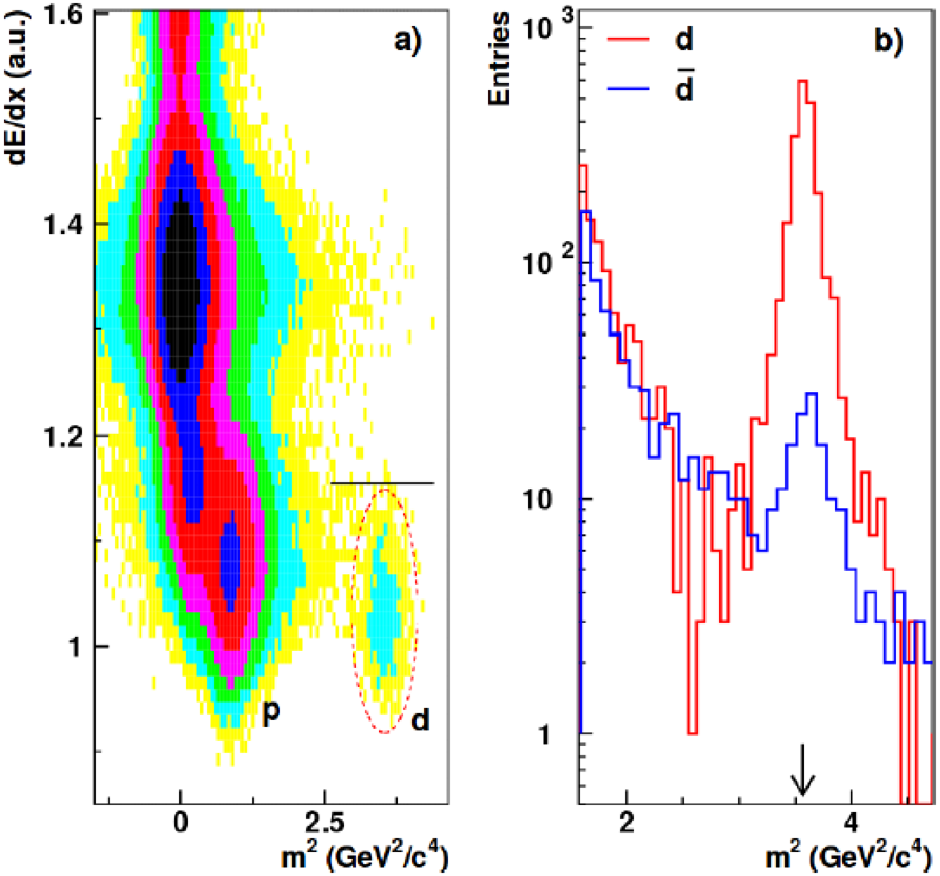
- at freeze-out all hadrons follow equilibrium distributions → particle spectra offer insight into conditions

- important question whether (anti)nuclei are produced at freeze-out from a quark-gluon plasma or at a later stage via coalescence:
  - results of NA49 for Pb-Pb interactions at 20-158AGeV/c are in agreement with both the statistical and the coalescence model.
  - ALICE data at LHC energies suggests that the thermal model works well for Pb-Pb interactions, but deuteron-to-proton ratio is overpredicted for p-p interactions → light (anti)nuclei puzzle (Bellini et al. 2018)

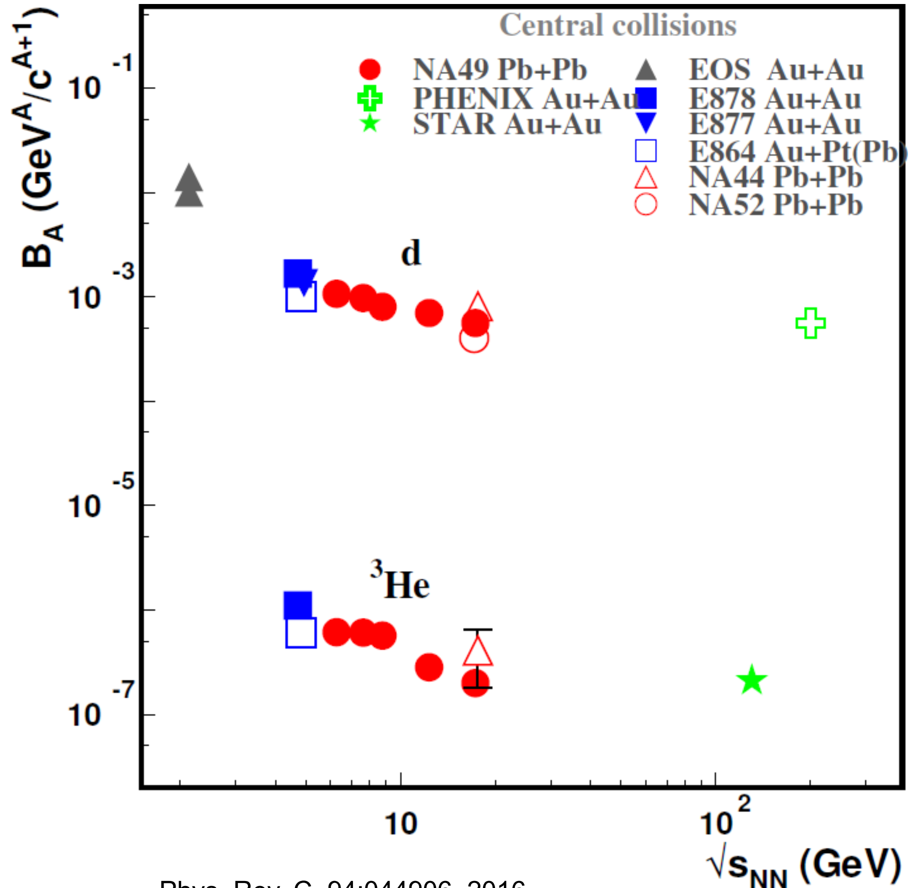
- NA61/SHINE measurements for d/p at lower energies will help to discriminate

NA49 nuclei and antideuterons

Credit: NA49 collaboration



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



Phys. Rev. C, 94:044906, 2016

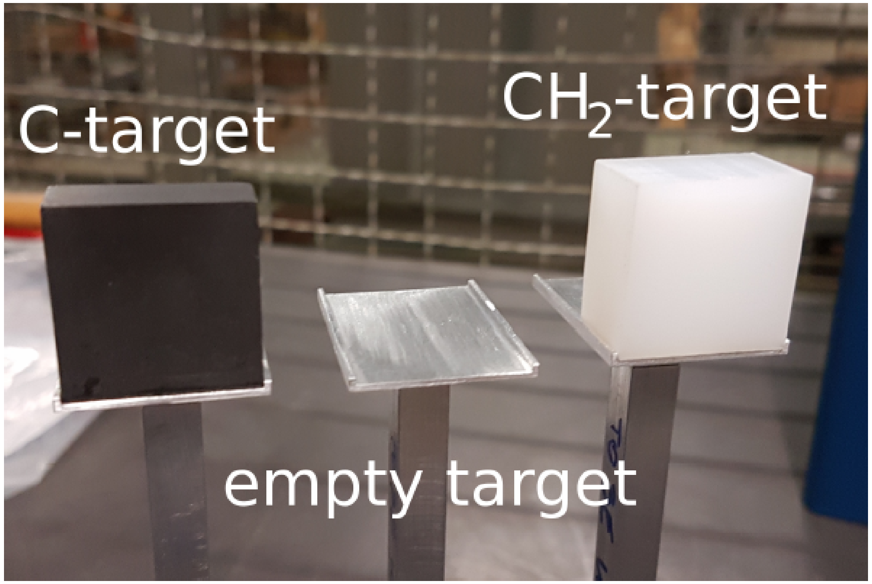
- Light nuclei and antideuteron results from NA49 in Pb-Pb were published
- Coalescence parameter B_A from central A-A collisions as a function of collision energy shows weak energy dependence

Fragmentation measurements

- PAMELA and AMS provided percent-level fluxes of leptons, nuclei and antiprotons → probe cosmic-ray propagation in the Galaxy

- amount of particle production in the Galaxy depends on the integrated traversed matter density
→ ratio of secondary-to-primary cosmic rays, e.g., Boron/Carbon

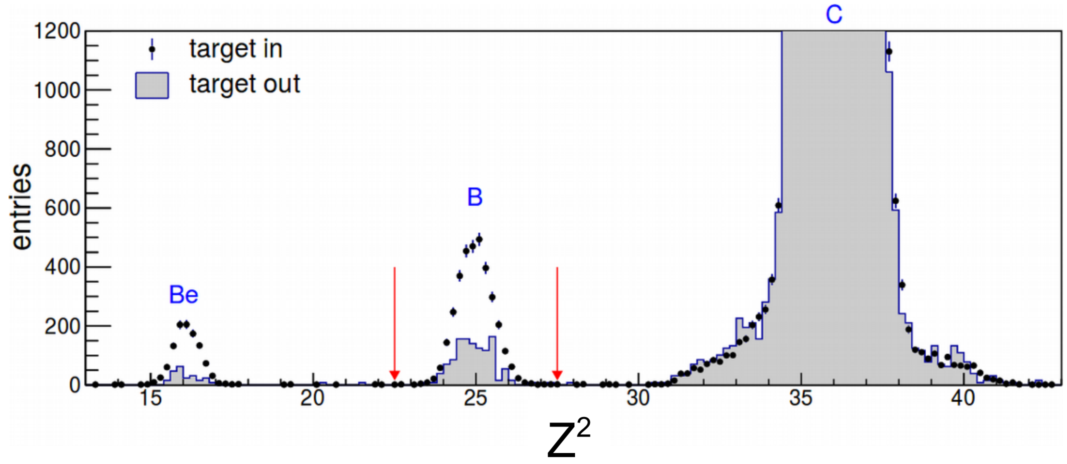
- Need to know fragmentation cross sections from laboratory measurements
→ **limitation:** cross sections are known on the 10-20% level



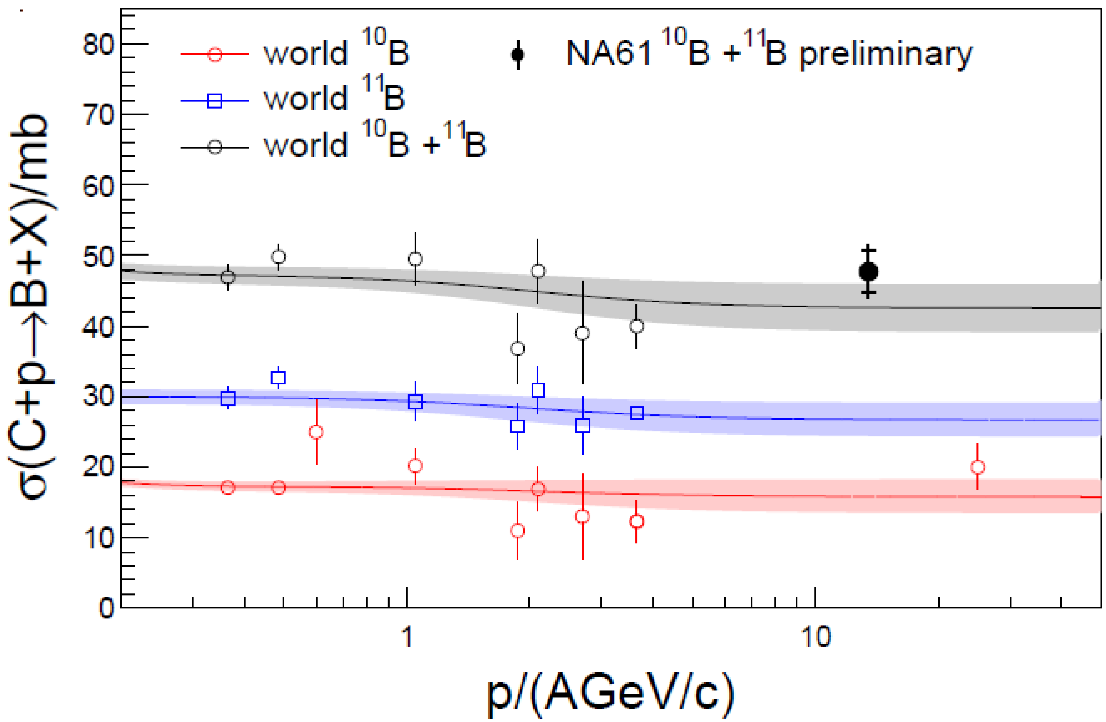
- NA61/SHINE pilot run for C-p cross section in Dec 2018 (3 days)
- Subtract C-C from C-CH_2 to get C-H

Carbon fragmentation cross section

- analysis is ongoing: ^{11}C, ^{11}B, ^{10}B, Be, Li fragments were observed



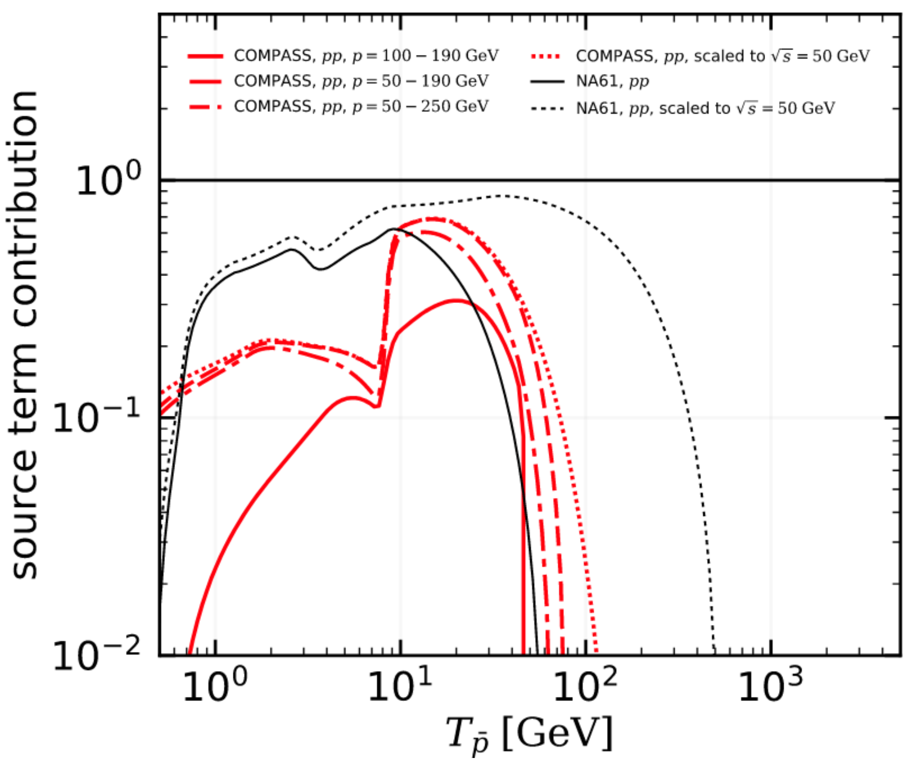
- asymptotic value of the cross section above 10 A GeV/c is very important to interpret the B/C ratio measured by AMS-02 up to ~TeV



Summary and outlook

- p-p analysis of NA61/SHINE 2009 data for $\bar{p}$ was presented

M. Korsmeier



- NA61/SHINE analysis of larger p-p data is ongoing:
  - high-statistics proton and antiproton analysis for 158GeV/c (2010/11)
  - 400GeV/c data set coming up
- NA61/SHINE light nuclei studies in p-C, π-C, Be-Be, Ar-Sc were started
- resolve ambiguities in (anti)deuteron formation modeling
- more dedicated NA61/SHINE data taking for cosmic-ray studies is possible in the future after LS2