NA61/SHINE results from p+p interactions relevant for cosmic-ray antiparticles & Antideuteron coalescence studies

XSCRC
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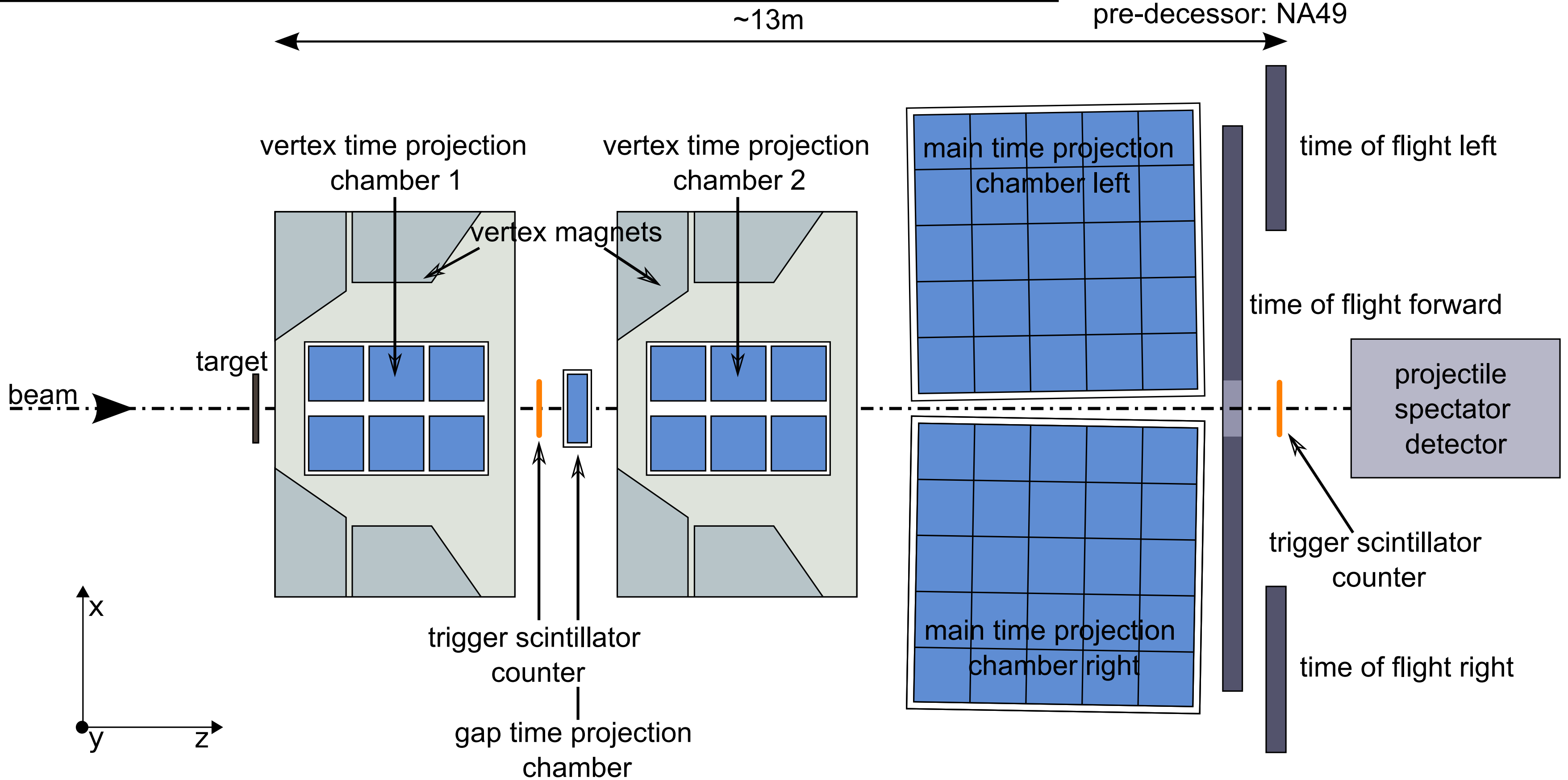
Philip von Doetinchem
Collaborators: Amaresh Datta (Hawaii), Anirvan Shukla (Hawaii), Diego Gomez (UNAM), Arturo Menchaca (UNAM)
NA61 results are on behalf of the NA61/SHINE collaboration
philipvd@hawaii.edu
Department of Physics & Astronomy
University of Hawai'i at Mānoa

NA61/SHINE at CERN

Credit: NA61/SHINE collaboration
SPS **H**eavy **I**on and **N**eutrino **E**xperiment
pre-decessor: NA49



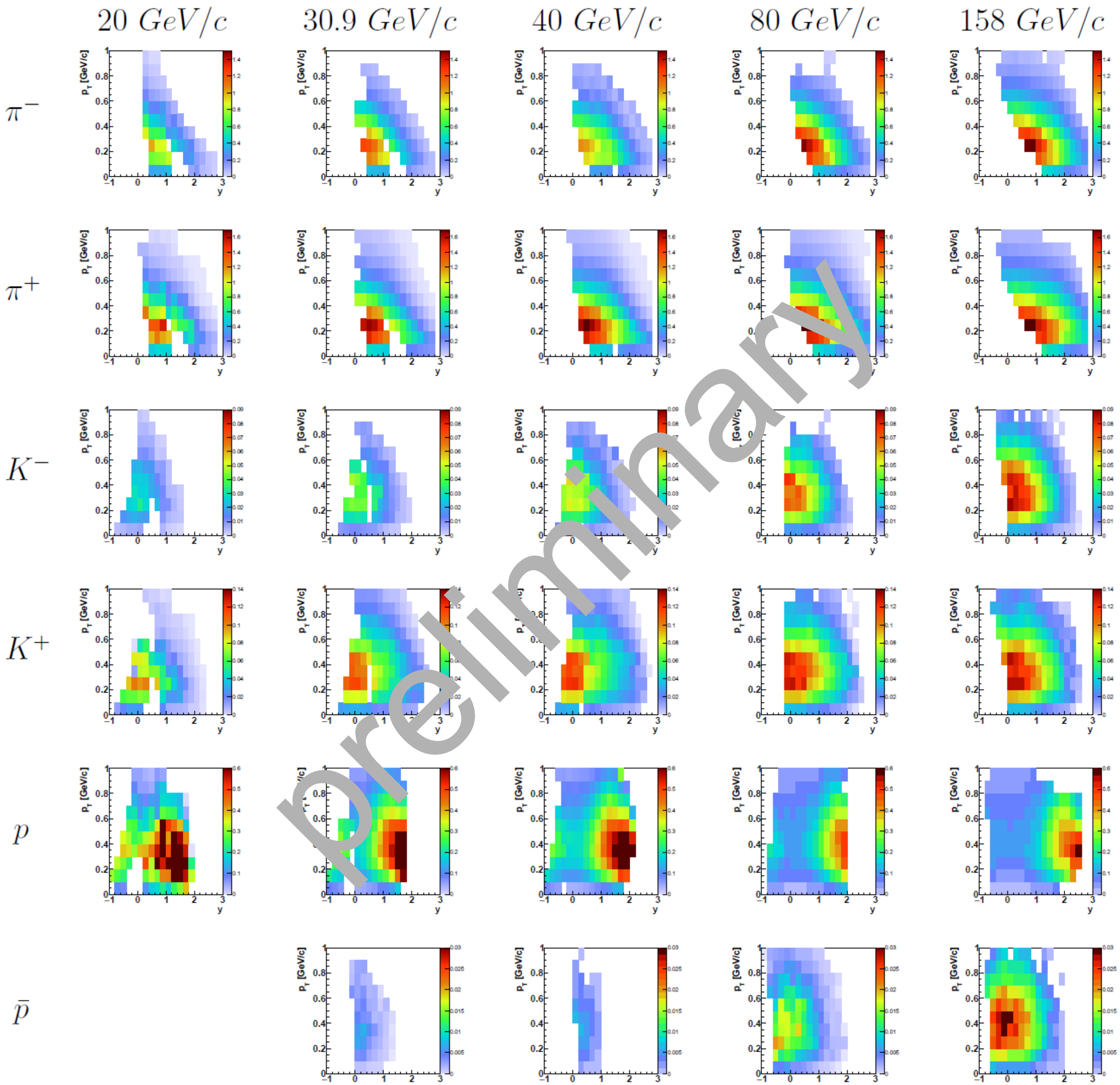
- multi-purpose, fixed-target experiment at the CERN SPS (NA61/SHINE facility paper: JINST 9 (2014) P06005)
  - precise measurements of properties of produced particles: q, m, p
- cosmic-ray antideuteron production happens between 40 and 400GeV
  - SPS energies from 9 to 400GeV are ideal
- data under discussion from the NA61/SHINE strong interactions program:
  - p+LH data taken at 13, 20, 31, 40, 80,158GeV/c + 400GeV/c (2016) (publication coming soon)

- 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:
  - $\sigma(dE/dx)/\langle dE/dx \rangle \approx 0.04$
  - $\sigma(m_{inv}) \approx 5$ MeV
- high detector efficiency: > 95%
- event rate: 70Hz

heavier ions → Michael Unger talk

Particle spectra from p+liquid hydrogen

Credit: NA61/SHINE collaboration

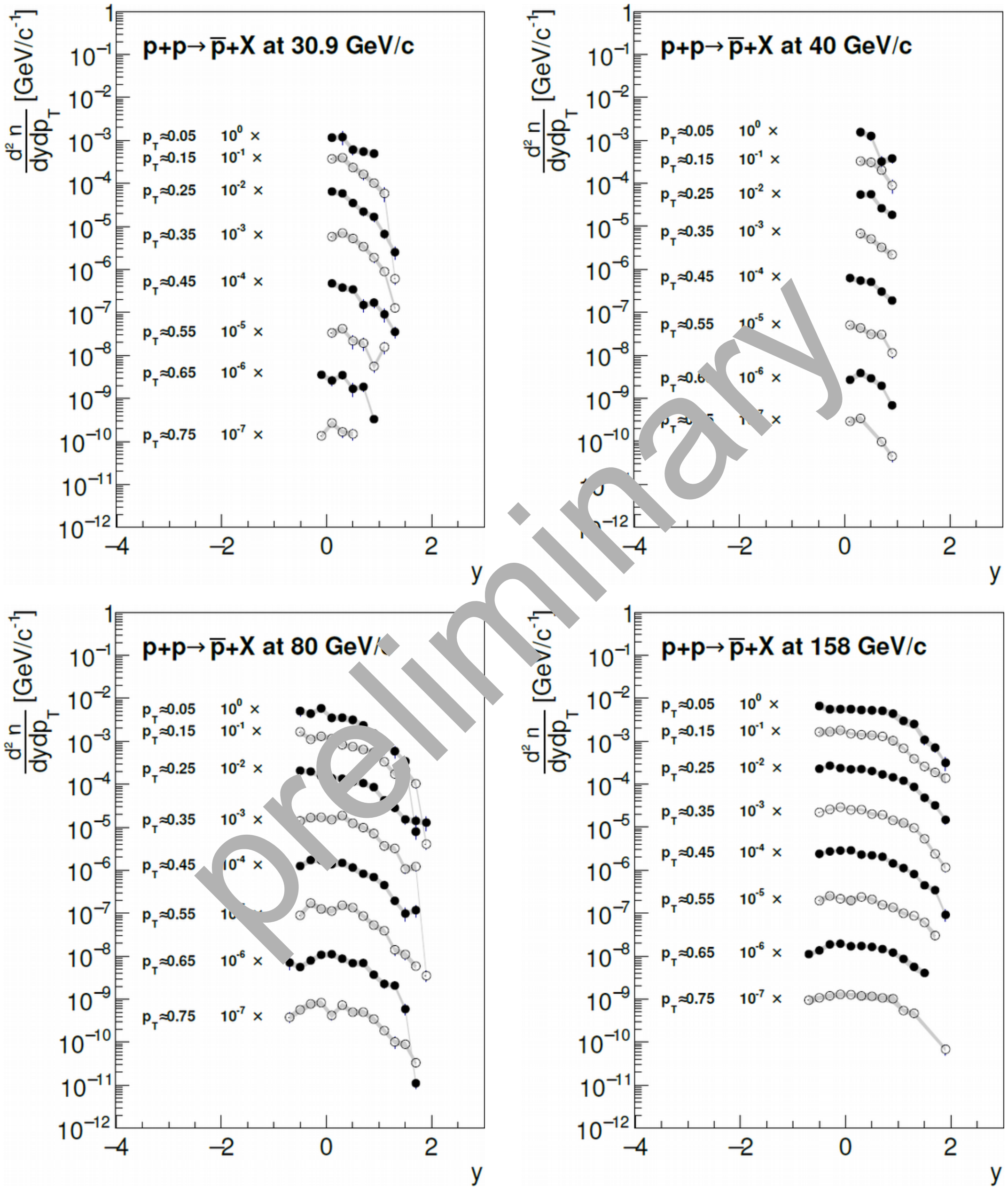


- identification based on combined time-of-flight and energy loss information dE/dx
- corrected for:
  - particles from weak decays (feed-down: 2% sys. error for $\bar{p}$)
  - detector effects using simulations
  - target interactions
- two dimensional spectra: color scale represents particle multiplicities normalized to the phase-space bin size: $\frac{dn}{dy dp_T}$
- particle production increases with collision energy

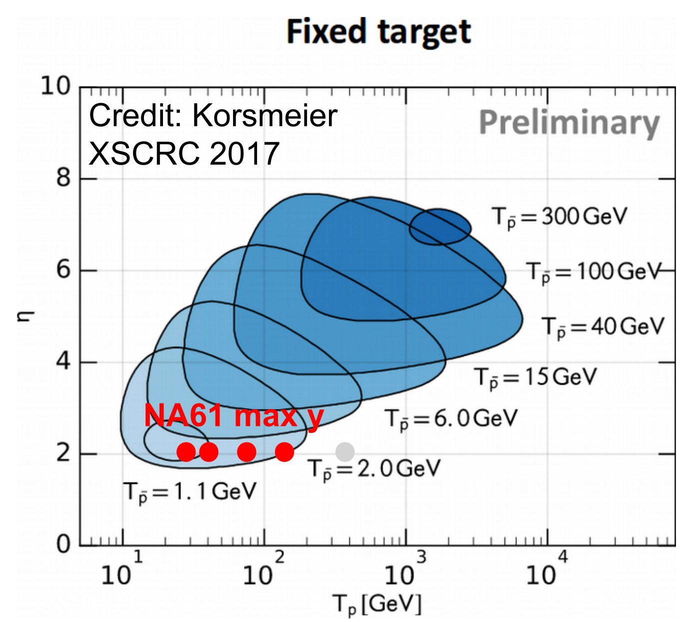
2009 pp data

Antiprotons as function of rapidity

Credit: NA61/SHINE collaboration

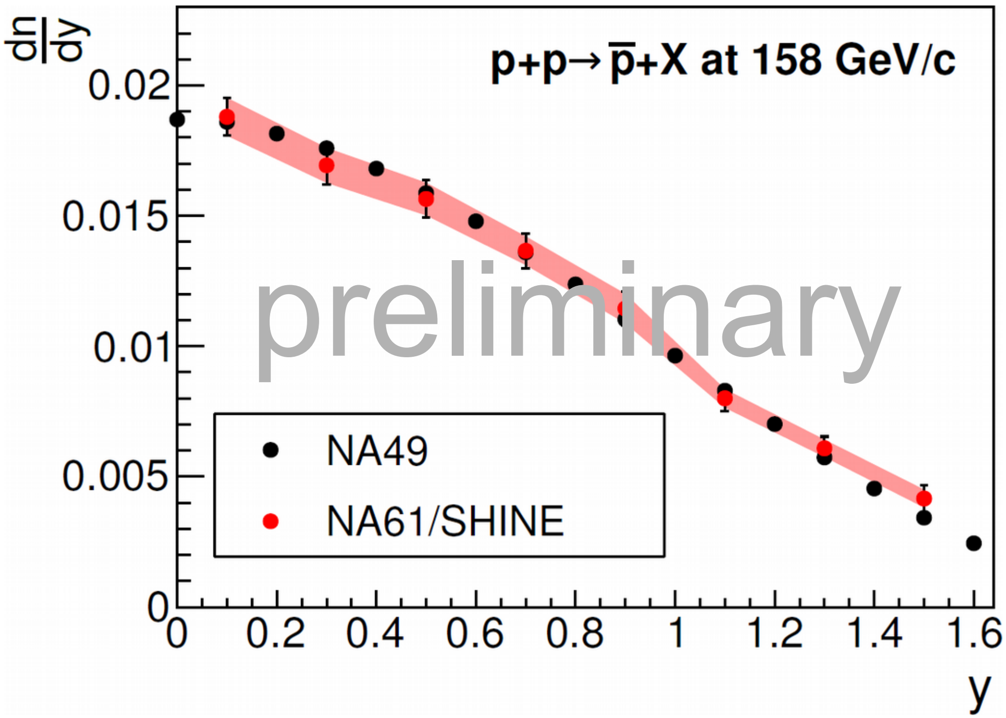


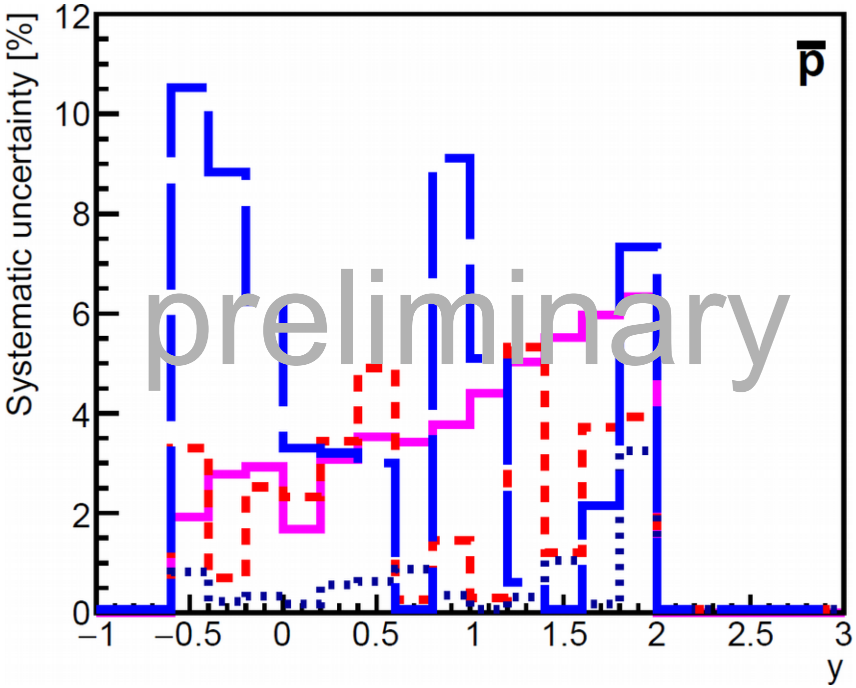
publication in preparation



Comparison of NA61/SHINE and NA49

Credit: NA61/SHINE collaboration

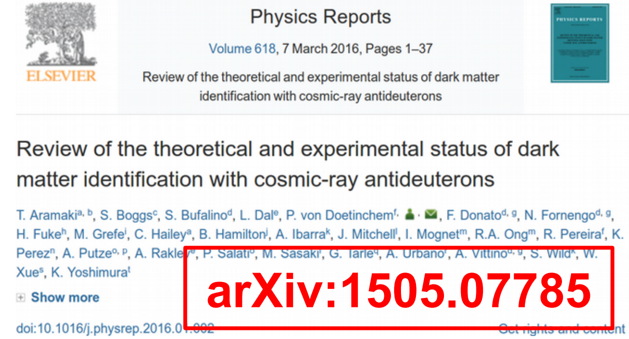




systematic uncertainties:

- 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

Status of cosmic-ray antideuterons



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

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

T. Aramaki[a, b], S. Boggs[c], S. Bufalino[d], L. Dal[e], P. von Doetinchem[f], F. Donato[d, g], N. Fornengo[d, g], H. Fuke[h], M. Grefe[i], C. Hailey[a], B. Hamilton[j], A. Ibarra[k], J. Mitchell[l], I. Mognet[m], R.A. Ong[m], R. Pereira[f], K. Perez[n], A. Putze[o, p], A. Raklev[e], P. Salati[o], M. Sasaki[l], G. Tarle[q], A. Urbano[r], A. Vittino[d, g], S. Wild[k], W. Xue[s], K. Yoshimura[t]

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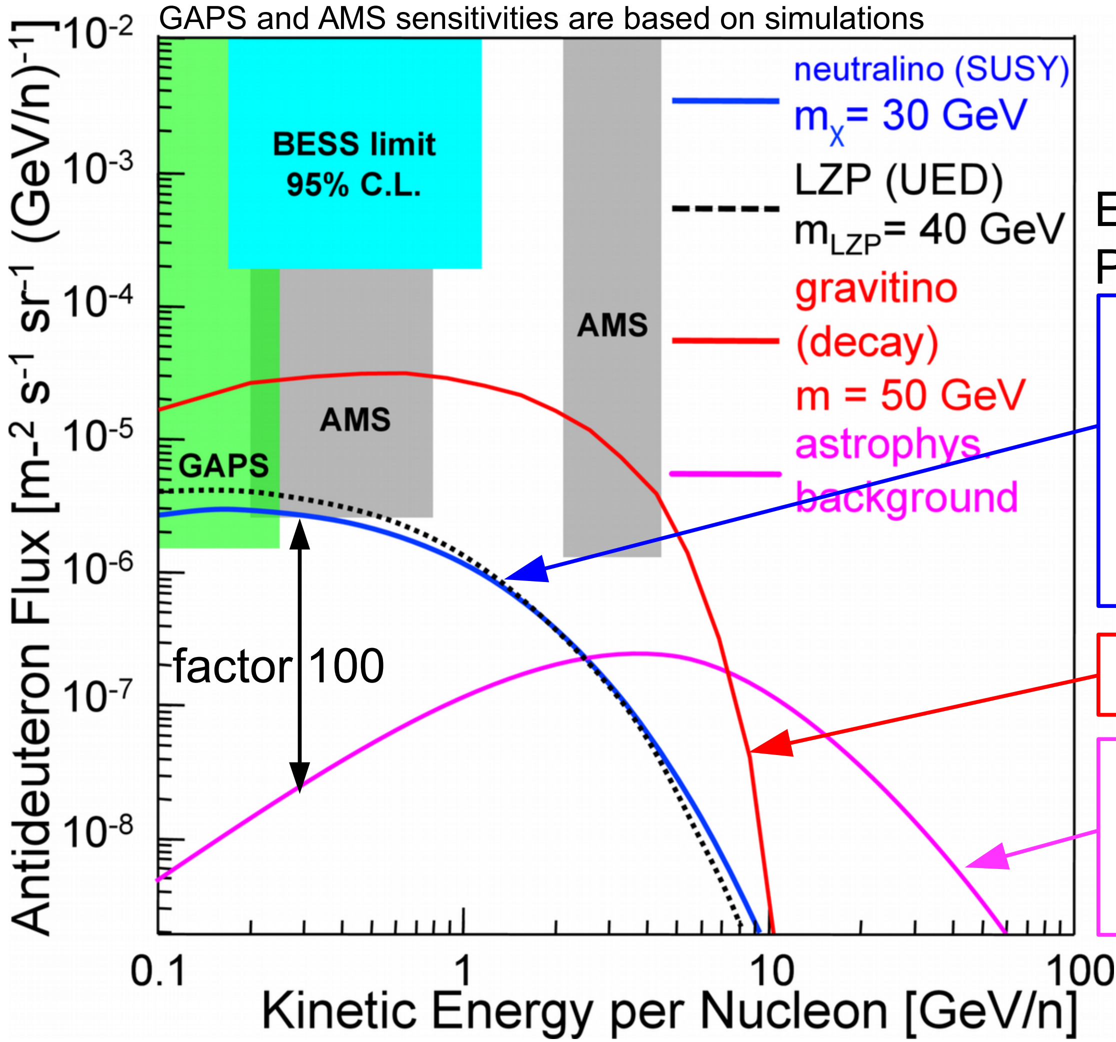
doi:10.1016/j.physrep.2016.01.002

arXiv:1505.07785



Examples for beyond-standard-model Physics (compatible with $\bar{p}$):

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

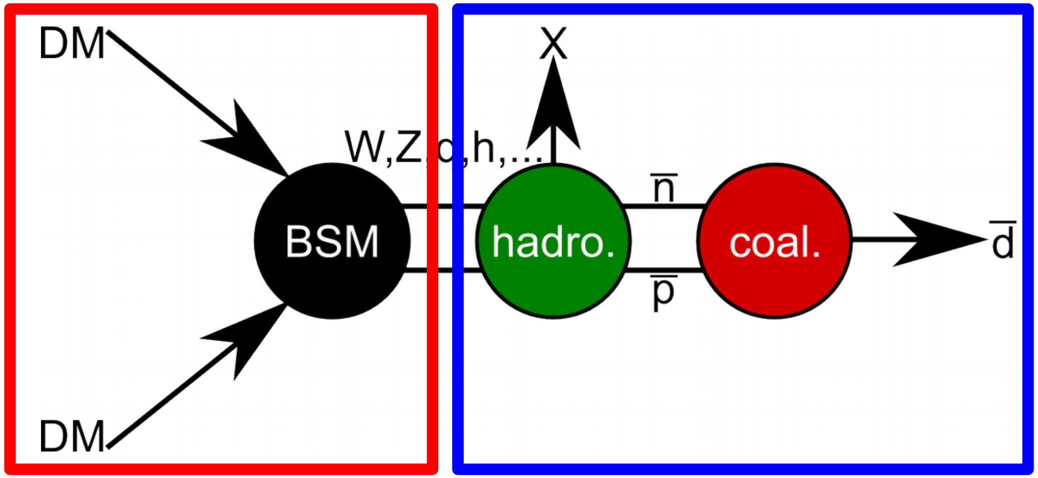
late decays of unstable gravitinos

astrophysical background: collisions of protons and antiprotons with interstellar medium

+ models with heavy dark matter

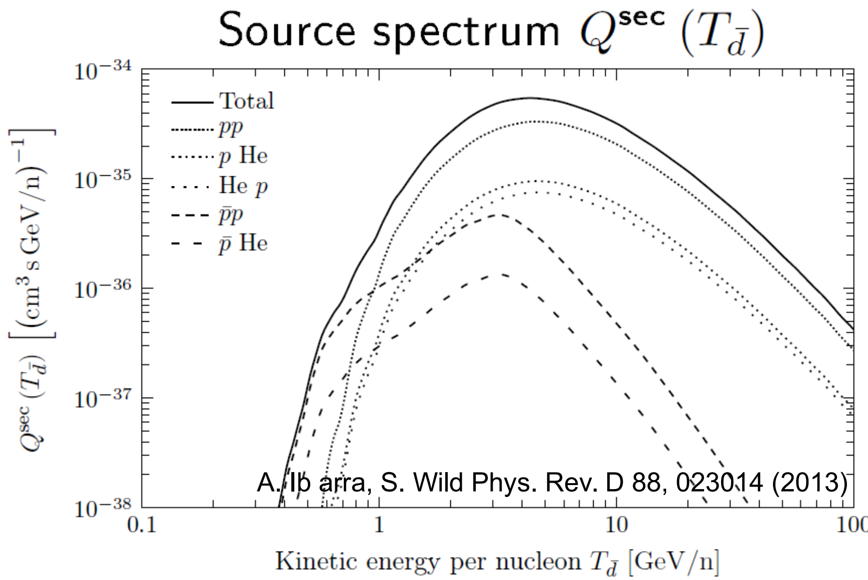
Antideuterons are the most important unexplored indirect dark matter detection technique → **antideuteron formation contributes important uncertainty**

(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

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

- 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**
  - using the same energy-independent p_0 for deuterons and antideuterons would result in suggesting the unphysical result of antideuteron production below the threshold
  - 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

- **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

Issues of the coalescence model

- **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)

- **(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

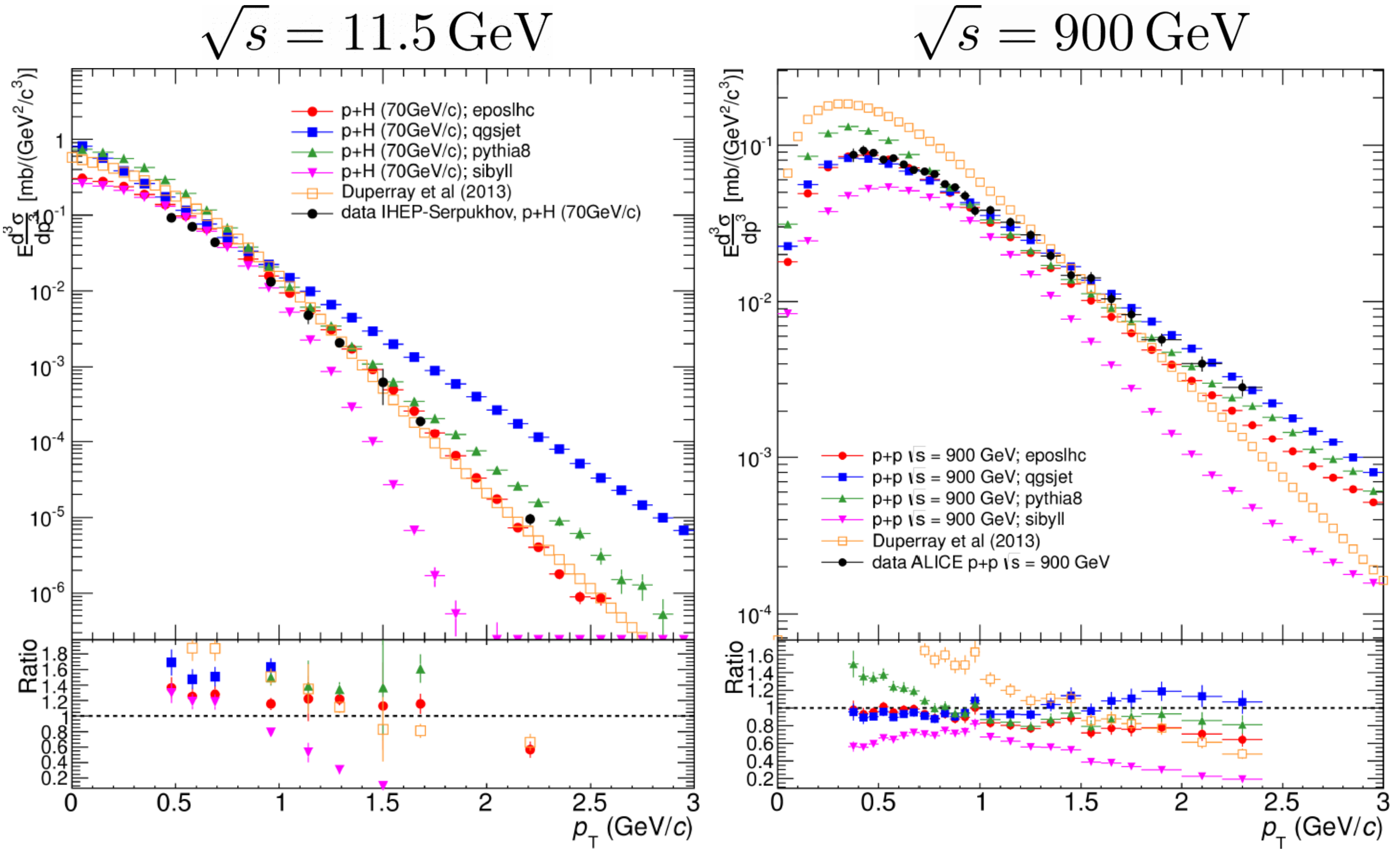
Fischer, Acta Physica Hungarica Series A, Heavy Ion Physics 17, 369 (2003)

Issues of the coalescence model

- 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
- I do not know any hadronic generator that includes coalescence (e.g., Geant4 includes deuterons from helium spallation)
  → construct “afterburner““

Generator tests: antiprotons

Credit: Gomez, Menchaca from UNAM

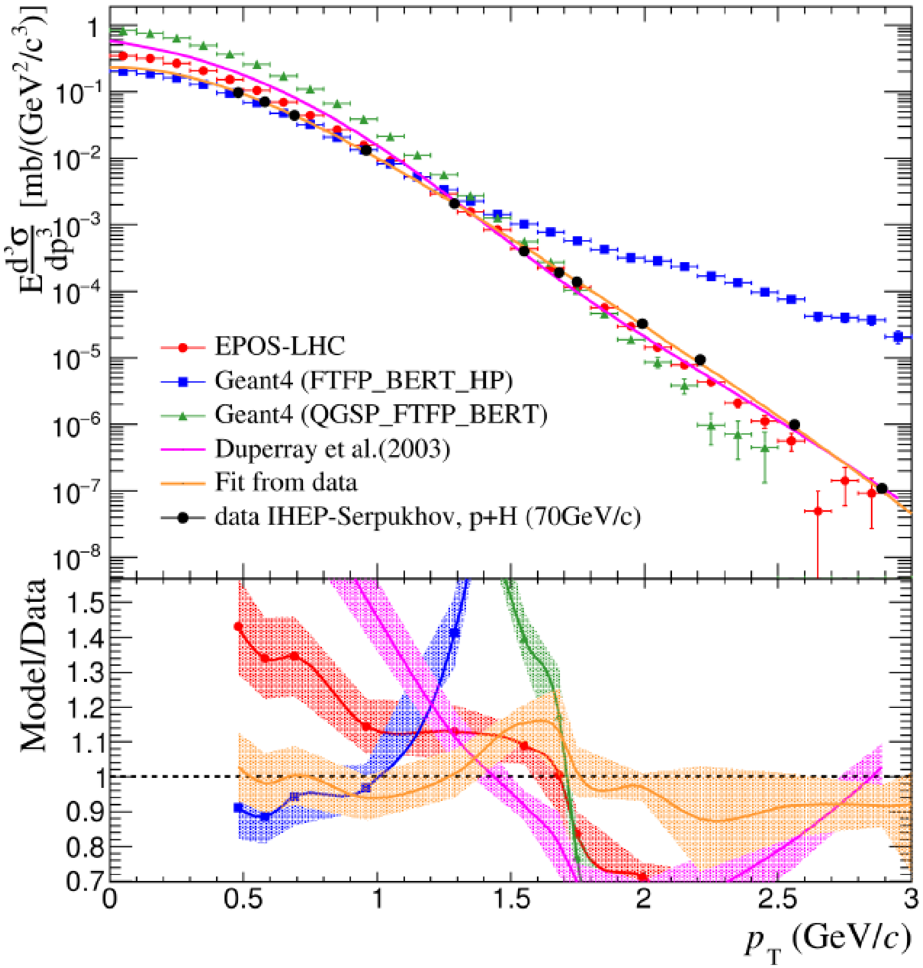


- EPOS-LHC works well → other models not great for antiprotons (study from 1.5years ago)

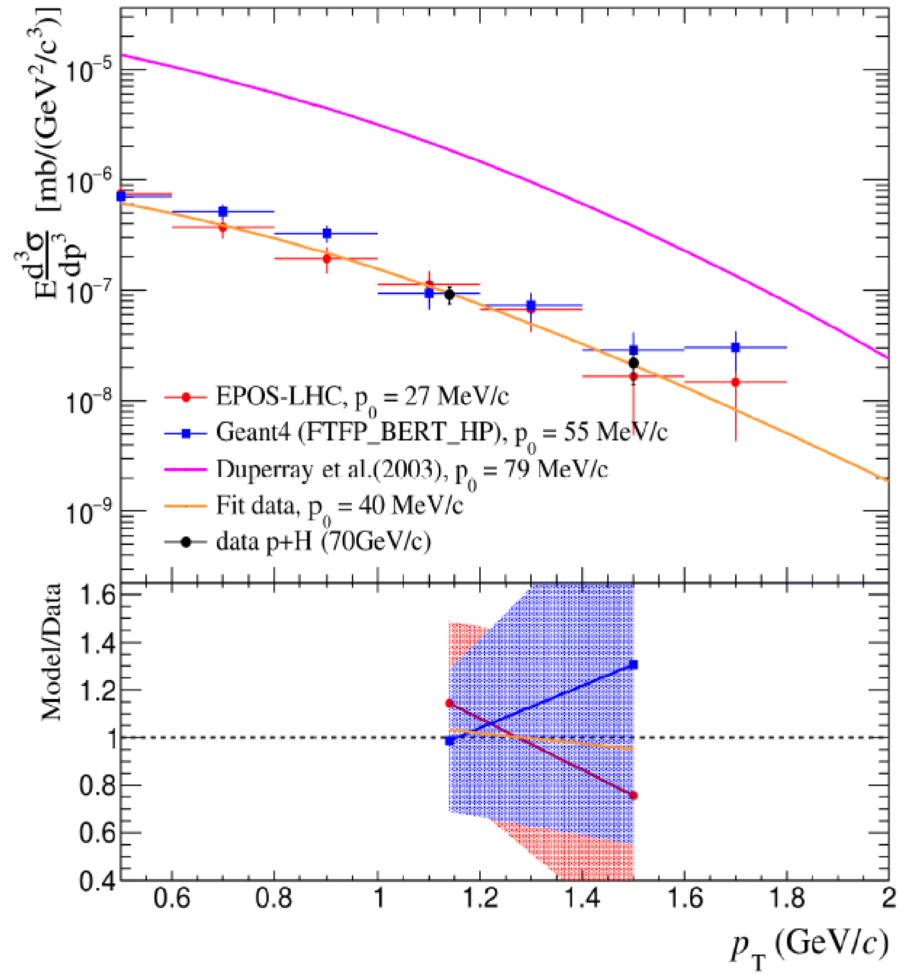
More generator tests: Geant4

Credit: Gomez, Menchaca from UNAM

Antiprotons



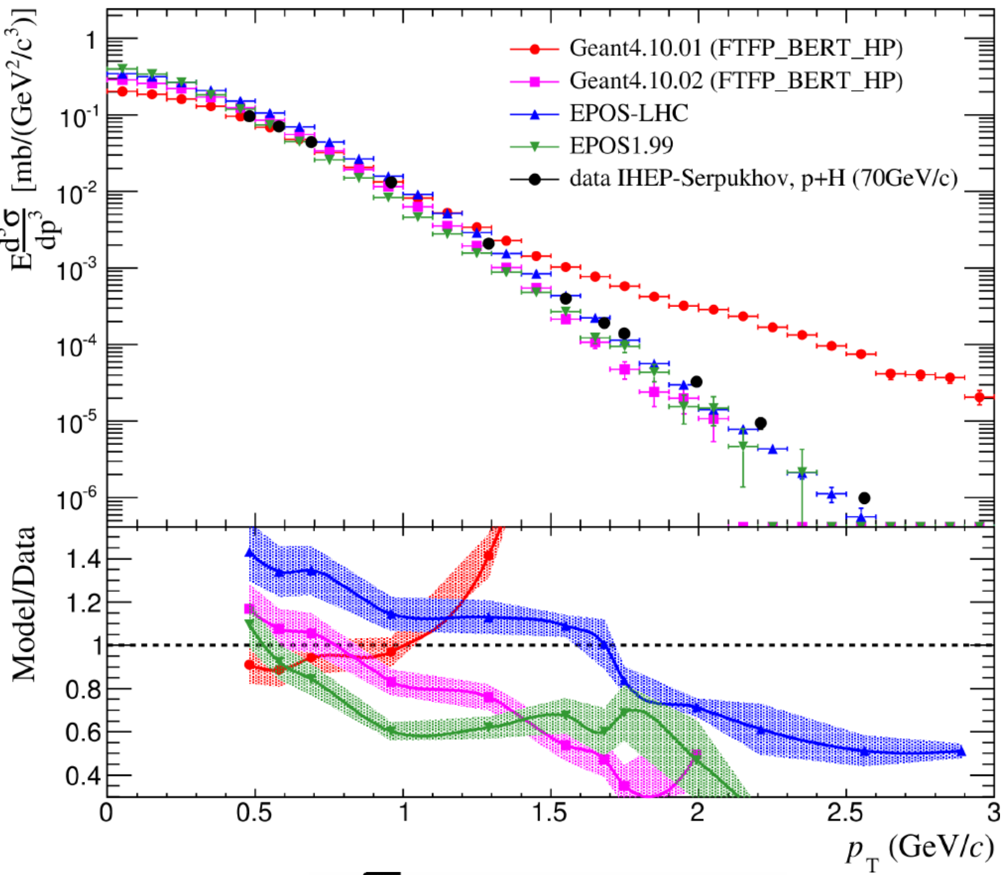
Antideuterons



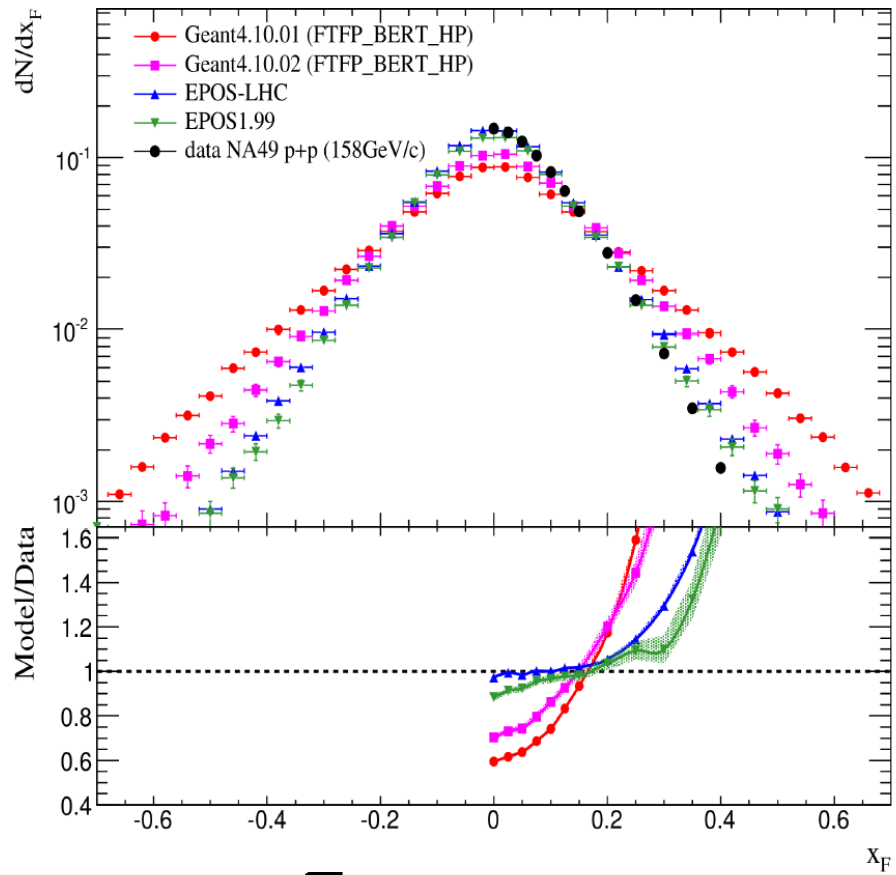
- Geant4 useful for experimentalists to, e.g., predict instrumental background (antideuteron interactions were implemented in 4.9.6) → **follow updates**
- find p_0 for each data set where antiproton and antideuteron results exist

Geant4 improvements for $\bar{p}$ production

Credit: Gomez, Menchaca from UNAM



$$\sqrt{s} = 11.5\,\mathrm{GeV}$$

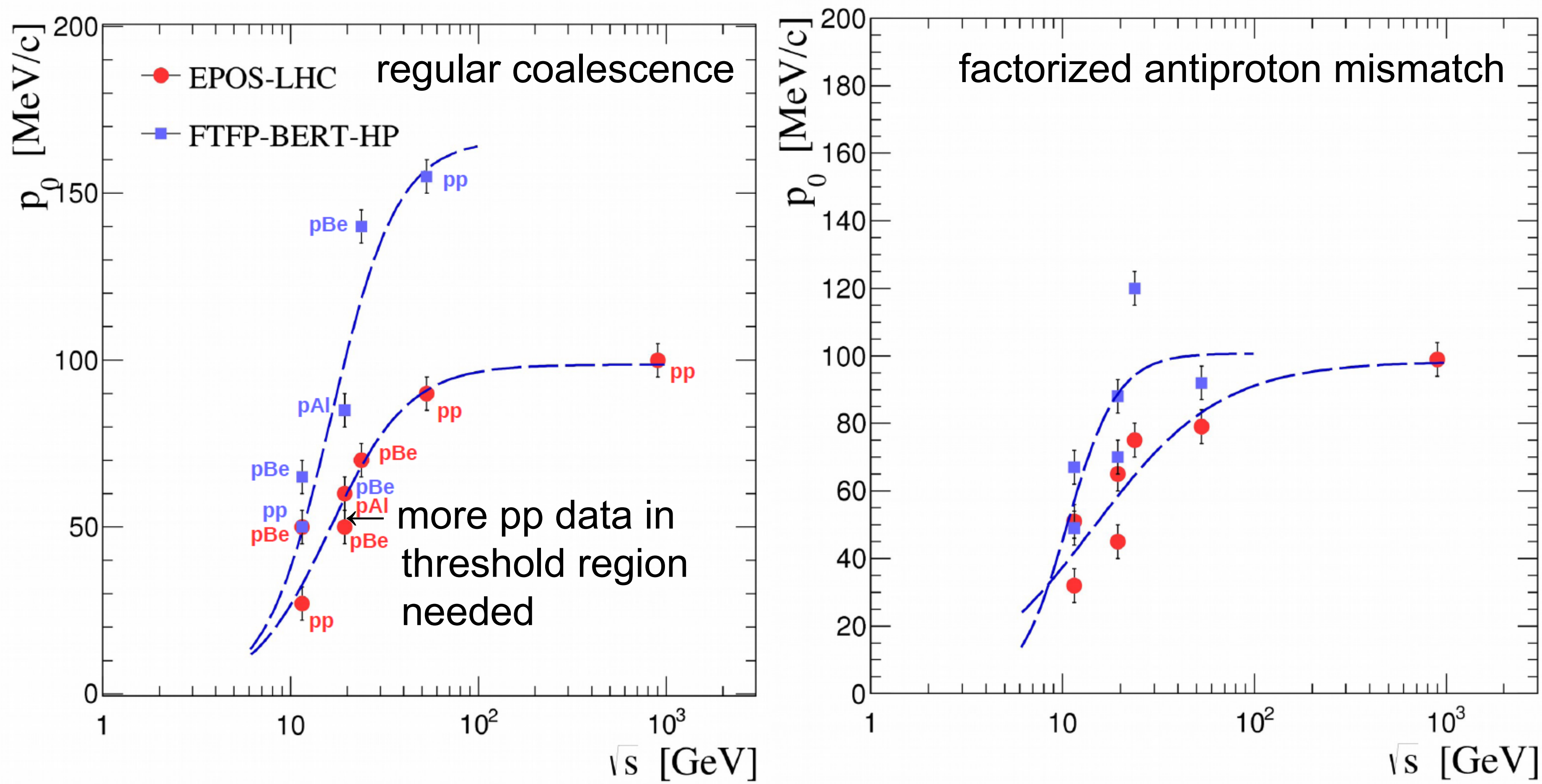


$$\sqrt{s} = 17.5\,\mathrm{GeV}$$

- newer Geant4 version describe data better: FTFP_BERT_HP seems to be the best

Modified antideuteron coalescence

Credit: Gomez, Menchaca from UNAM

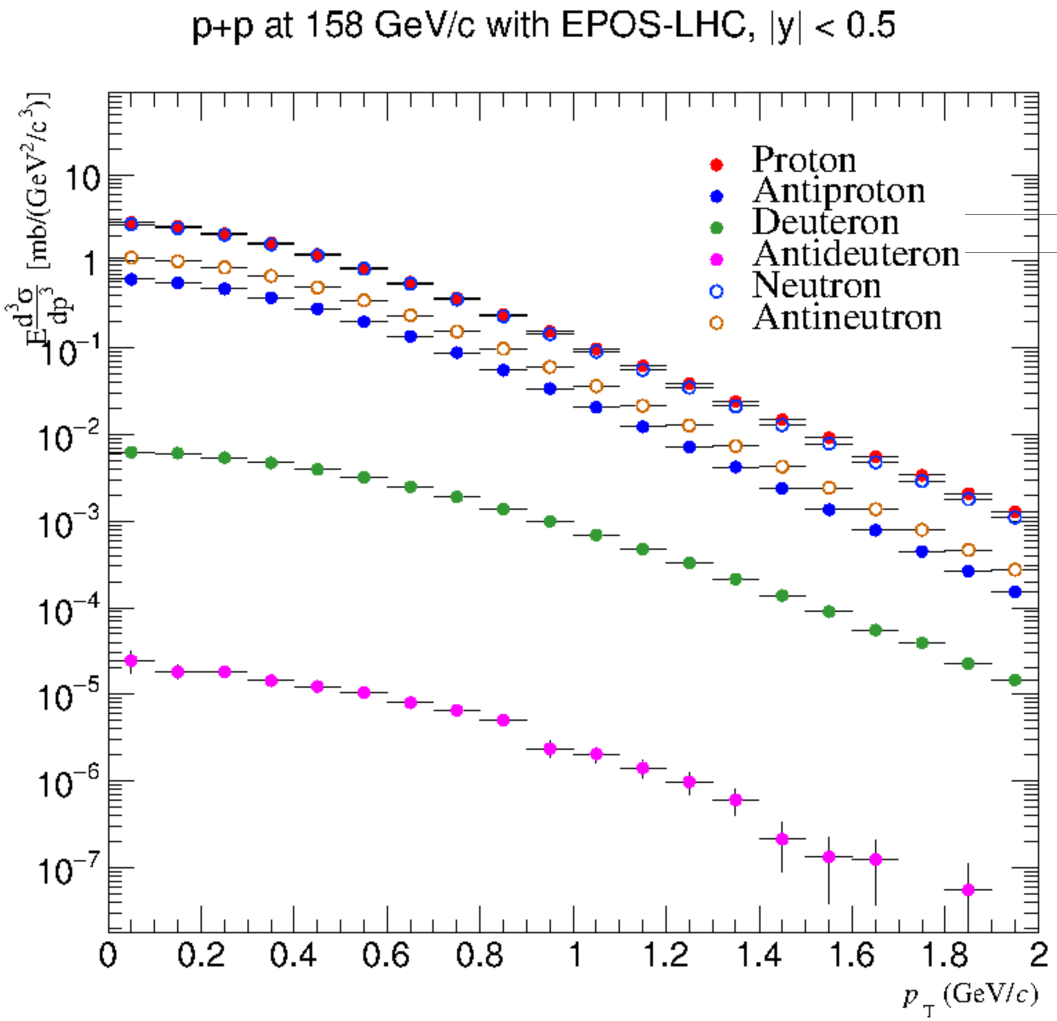


- factorize out antiproton mismatch from data/MC comparison:

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

Modified antideuteron coalescence

Credit: Gomez, Menchaca from UNAM



coalescence afterburner added to EPOS-LHC

- more data needed to constrain (anti)deuteron coalescence model
- EPOS-LHC produces more antineutron than antiprotons (isospin asymmetry implemented)

Alternatives approach: thermal model

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

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

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

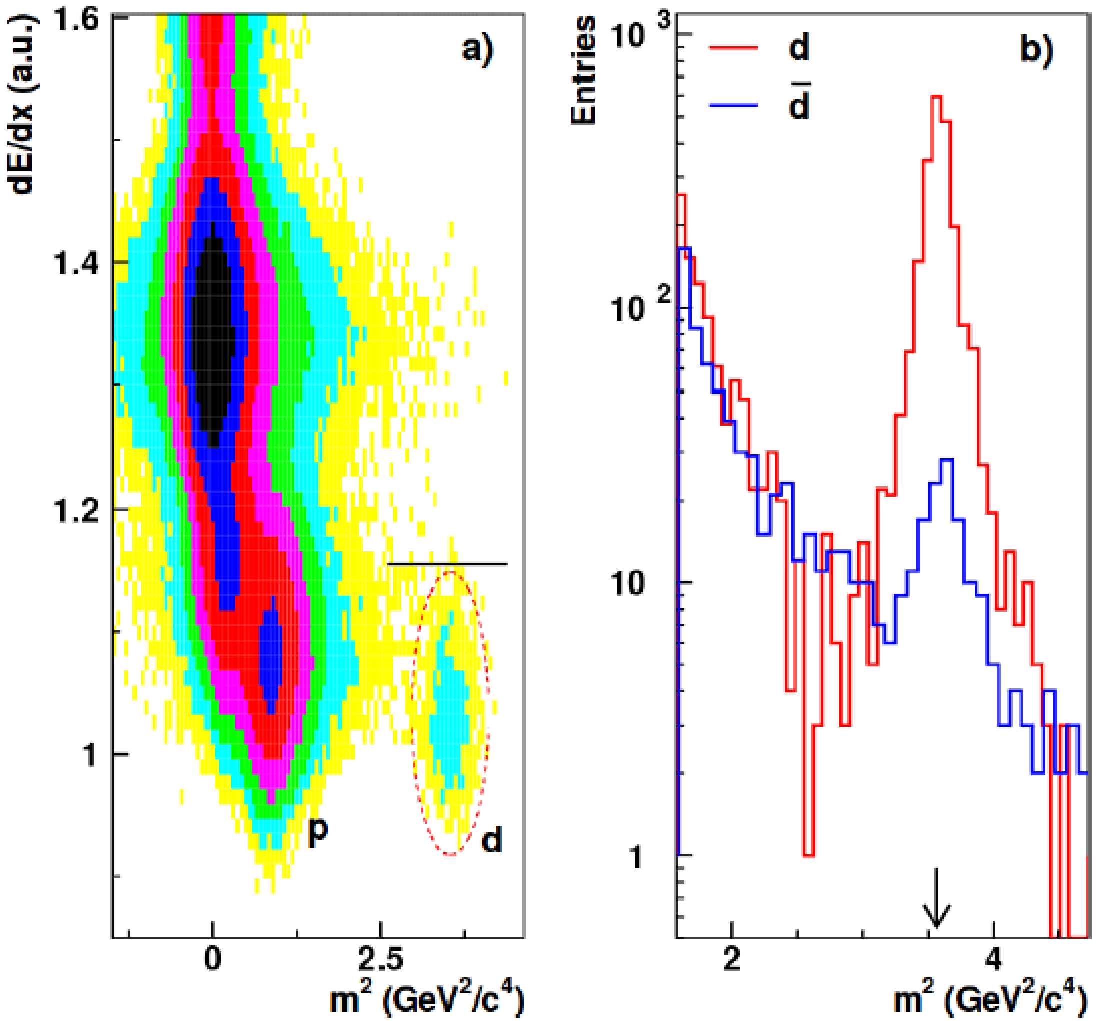
Cleymans et al., Phys. Rev. C 84, 054916 (2011)

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

  → d/p or $\overline{\mathrm{d}}/\overline{\mathrm{p}}$ ratios will help to discriminate

NA49 antideuterons

Credit: NA49 collaboration



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

NA61/SHINE analysis

- measure all deuterons: **p+p→d+X**
  however: **p+p→d+π⁺** has no equivalent in $\bar{\text{d}}$ production → not most helpful for $\bar{\text{d}}$

- search for deuterons in association with protons: **p+p→d+p+$\bar{\text{n}}$**
  equivalent for antideuteron production: **$\bar{\text{p}}$+p→$\bar{\text{d}}$+p+n**

- carry out $\bar{\text{p}}$ analysis (with and without hyperon correction)

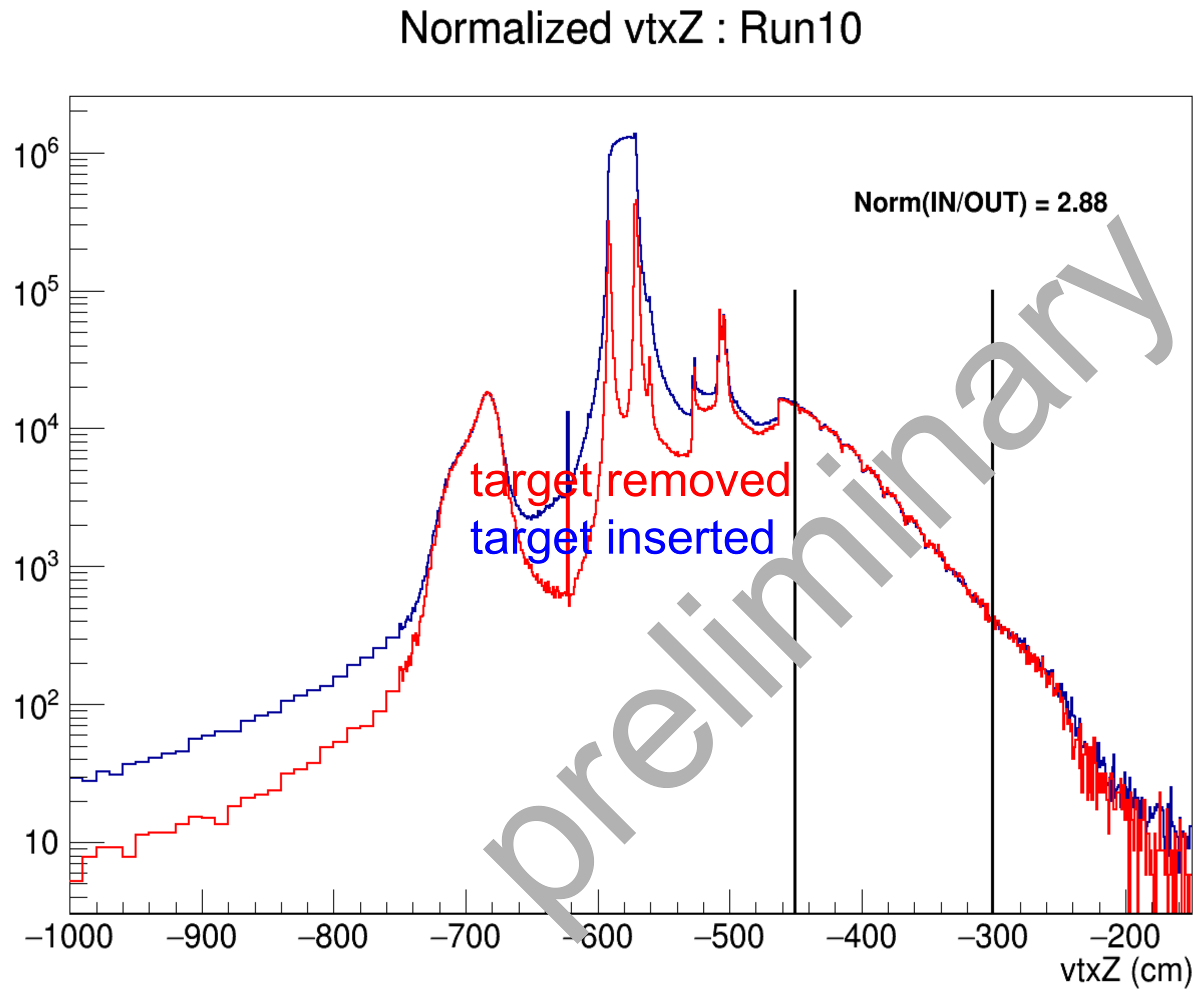
- use d/p and $\bar{\text{p}}$ as a function of transverse momentum to estimate what is happening for $\bar{\text{d}}$ → coalescence or thermal model?

$$\frac{dN_{\bar{d}}}{dp_T} = \frac{dN_{\bar{p}}}{dp_T} \cdot \frac{dN_d}{dp_T} \Big/ \frac{dN_p}{dp_T}$$

- search for antideuterons
  - clean antideuteron events should have three additional identified protons in the final state: **p+p→$\bar{\text{d}}$+n+p+p+p**
  - similar, but easier identifiable, production of deuterons in association with one antiproton: **p+p→d+$\bar{\text{n}}$+$\bar{\text{p}}$+p+p**

- Data sets currently used:
  - 2009 p+p (158 GeV): 4 million events → essentially complete for antiprotons
  - 2010 p+p (158 GeV): 44 million events
  - 2011 p+p (158 GeV): 14 million events
  - also look at other p+p energies to learn more about the energy dependence

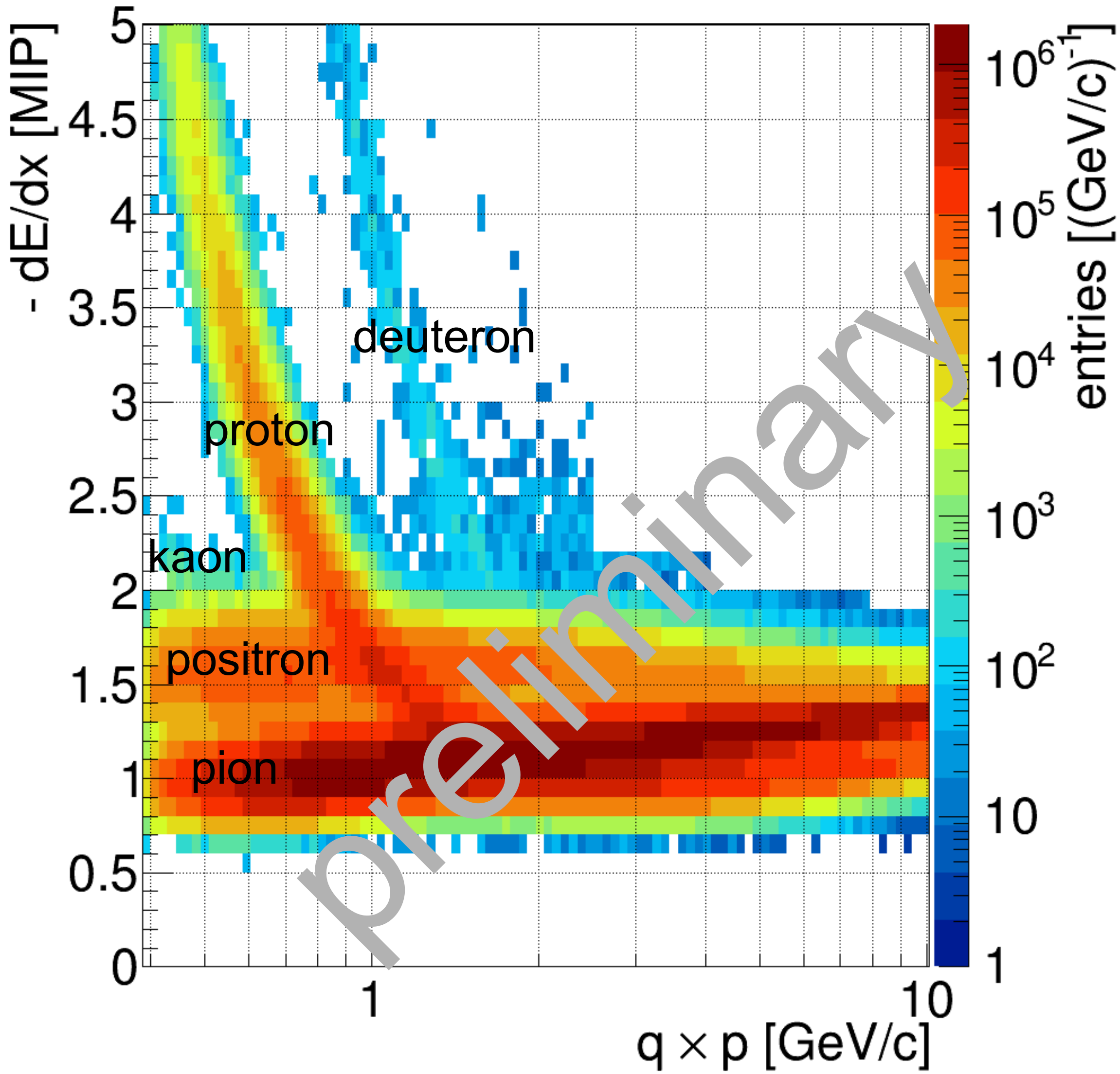
Normalization with vertex position



Statistics:

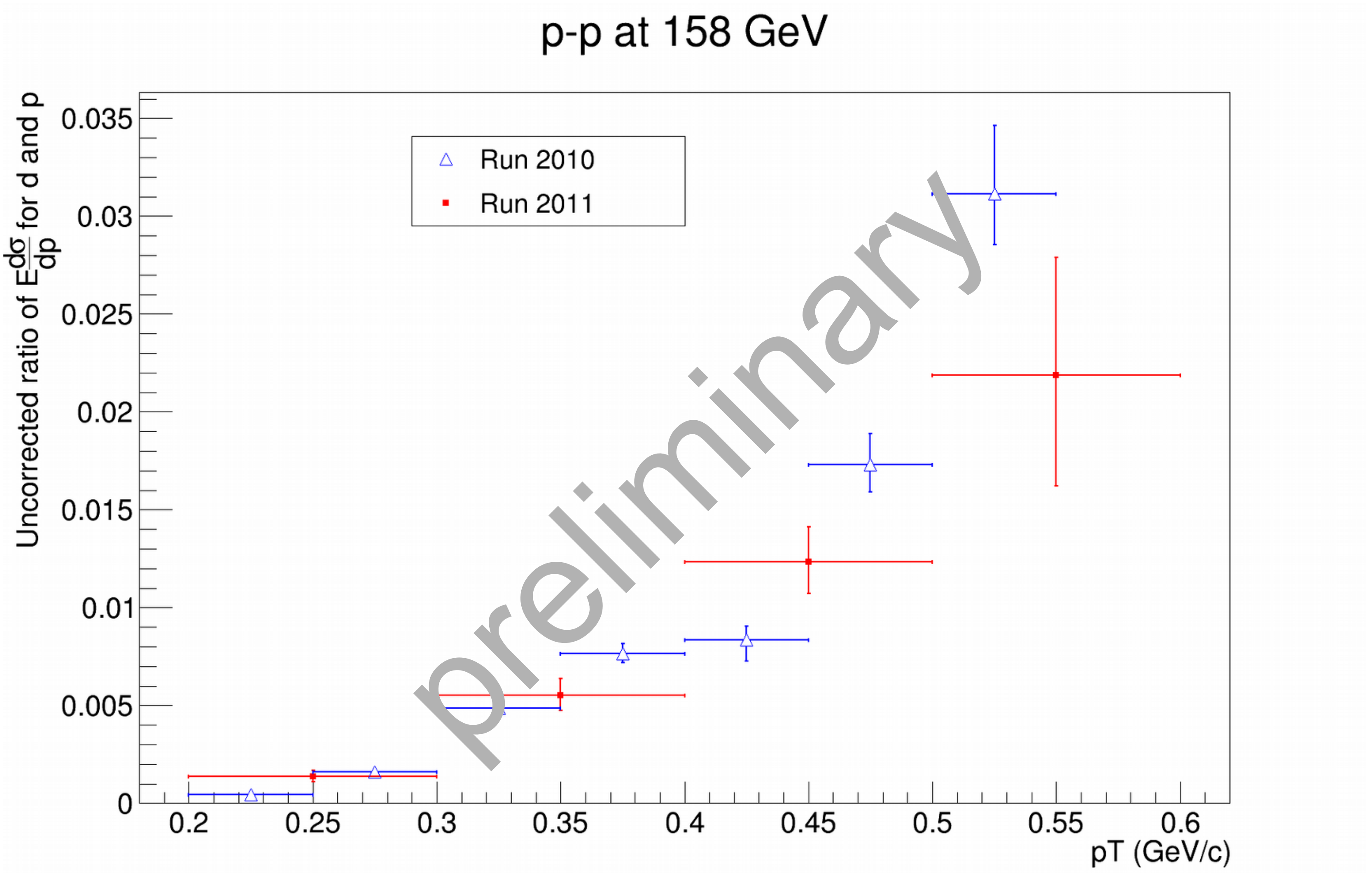
- **before cuts:**
  - target in: 39,926,226
  - target out: 3,685,479
- **after cuts:**
  - target in: 15,590,349
  - target out: 110,267

-dE/dx distributions



Preliminary selection cuts for 158GeV/c pp 2010 data
(corrected for detector and beam material interactions)

d/p ratio


p-p at 158 GeV
Uncorrected ratio of $E\frac{d\sigma}{dp}$ for d and p
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
pT (GeV/c)
Run 2010
Run 2011
preliminary

Summary and outlook

- p+p analysis of NA61/SHINE 2009 data for $\bar{p}$, publication coming soon

- NA61/SHINE analysis of 2009-2011 p+p (158 GeV) data is ongoing:
  - deuteron cross section calculation
  - antiproton analysis (2010/11)
  - antideuteron analysis

- resolve ambiguities in (anti)deuteron formation modeling

- dedicated NA61/SHINE data taking would be possible in the future for cosmic-ray studies
  → planning for beyond 2020 activities is ongoing (antiproton beam?, other targets?)

- next antideuteron workshop: Sep 20-22 at UCLA → please register:

$\bar{d}$17 2nd cosmic-ray antideuteron workshop

http://indico.phys.hawaii.edu/event/antideuteron2017