Measurement of Antiproton-Production Cross Sections at AMBER

Thomas Pöschl (CERN) for the AMBER collaboration

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DFG Frühjahrstagung 2024, Gießen

AMBER

Apparatus for Meson and Baryon Experimental Research

Who is AMBER?

The AMBER collaboration

- ~200 members from ~34 institutes
- descended from the COMPASS collaboration
- currently 10 new groups (still growing)
- Memorandum-of-Understanding between CERN and groups signed in 2023

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-SPSC-2019-003
SPSC-I-250
January 28, 2019

Letter of Intent:

A New QCD facility at the M2 beam line of the CERN SPS*

COMPASS++[†]/AMBER[‡]

B. Adams[13,12], C.A. Aidala[1], R. Akhunzyanov[14], G.D. Alexeev[14], M.G. Alexeev[41], A. Amoroso[41,42], V. Andrieux[44], N.V. Anfimov[14], V. Anosov[14], A. Antoshkin[14], K. Augsten[14,32], W. Augustyniak[46], C.D.R. Azevedo[3], A. Azhibekov[25], B. Badelek[17], F. Balestra[41,42], M. Ball[19], J. Barth[4], R. Beck[5], Y. Bedfer[20], J. Berenguer Antequera[41,42], J.C. Bernauer[34,35], J. Bernhard[19,6], M. Bodlak[31], P. Bordalo[23,a], F. Bradamante[28], A. Bressan[28,29], M. Büchele[18], V.E. Burtsev[37], W.-C. Chang[24], C. Chatterjee[11], X. Chen[21], M. Chiosso[41,42], A.G. Chumakov[40], S.-U. Chung[11,b], A. Cicuttin[39,c], P. Correia[1], M.L. Crespo[39,c], S. Dalla Torre[29], S.S. Dasgupta[11], S. Dasgupta[38,39], N. Dashyan[50], I. Denisenko[14], O.Yu. Denisov[42], L. Dhara[11], N. d'Hose[20], F. Donato[41], S.V. Donskov[33], N. Doshita[49], Ch. Dreisbach[17], W. Dünnweber[2], R.R. Dusaev[40], M. Dziewiecki[16], A. Dzyuba[14], A. Efremov[14], P. Egelhof[15], A. Elagin[11], P.D. Eversheim[4], M. Faessler[2], J. Fedotova[26], A. Ferrero[20], M. Finger[31], M. Finger jr.[31], H. Fischer[17], C. Franco[23], J.M. Friedrich[18], V. Frolov[14], A. Futch[45], F. Gautheron[44], O.P. Gavrichtchouk[14], S. Gerassimov[28,18], S. Gevorkyan[14], Y. Ghandilyan[50], J. Giarra[25], I. Gnesi[41,42], M. Gorzellik[16], A. Grasso[41,42], A. Gridin[14], M. Grosse Perdekamp[44], B. Grube[18], R.J. Gushterski[14], A. Guskov[14], D. Hahne[2], G. Hamar[30], D. von Harrach[25], X. He[3], R. Heitz[44], F. Herrmann[19], N. Horikawa[36,e], C.-Y. Hsieh[30,f], S. Huber[18], A. Inglessi[14], A. Ilyichev[26], T. Isataev[37], S. Ishimoto[49,g], A. Ivanov[14], N. Ivanov[50], Yu. Ivanshin[14], T. Iwata[49], M. Jandek[31], V. Jary[32], C.-M. Jen[44], R. Joosten[4], P. Jörg[18], K. Juraskova[32], E. Kabuß[25], A. Kabyshev[37], F. Kaspar[18], A. Kerbizi[28,29], B. Ketzer[4], G.V. Khaustov[33], Yu.A. Khokhlov[33,h], M. Kim[1], O. Kiselev[18], Yu. Kisselev[14], F. Klein[9], J.H. Koivuniemi[43], V.N. Kolosov[33], K. Kondo[49], I. Konorov[28,18], V.F. Konstantinov[33], A.M. Kotzinian[42,i], O.M. Kouznetsov[14], A. Koval[46], Z. Kral[22], F. Krinner[18], Y. Kulinich[44], K. Kurek[47], R.P. Kurjata[46], K. Kuterbekov[3], I.I. Kuznetsov[40], A. Kveton[32], E.A. Levchenko[40], S. Levorato[29], Y.-S. Lian[10,k], Y. Liang[21], J. Lichtenstadt[36], P.-J. Lin[20], K. Liu[24], M.X. Liu[24],

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†COmmon Muon Proton Apparatus for Structure and Spectroscopy
‡Apparatus for Meson and Baryon Experimental Research

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-SPSC-2019-022
SPSC-P-360
October 13, 2019

Proposal for Measurements at the M2 beam line of the CERN SPS

– Phase-1 –

COMPASS++[†]/AMBER[‡]

B. Adams[14,13], C.A. Aidala[1], G.D. Alexeev[15], M.G. Alexeev[42,43], A. Amoroso[42,43], V. Andrieux[45,20], N.V. Anfimov[15], V. Anosov[15], A. Antoshkin[15], K. Augsten[15,32], W. Augustyniak[47], C.D.R. Azevedo[3], B. Badelek[48,5], F. Balestra[42,43], M. Ball[4], D. Banerjee[45,20], J. Barth[4], R. Beck[4], J. Berenguer Antequera[42,43], J.C. Bernauer[25,46], J. Bernhard[20,6], M. Bodlak[31], F. Bradamante[28], A. Bressan[39,40], M. Büchele[17], V.E. Burtsev[37], C. Butler[1], C. Chatterjee[39,40], M. Chiosso[42,43], A.G. Chumakov[41], S.-U. Chung[18,b], A. Cicuttin[40,c], M. Connors[3], A. Contin[8], P. Correia[1], M.L. Crespo[40,c], S. Dalla Torre[40], S.S. Dasgupta[11], S. Dasgupta[40,11], N. Dashyan[50], I. Denisenko[15], O.Yu. Denisov[15], L. Dhara[11], F. Donato[42], S.V. Donskov[33], N. Doshita[49], Ch. Dreisbach[18], W. Dünnweber[2], R.R. Dusaev[37], A. Dzyuba[15], A. Efremov[15], P. Egelhof[16], F. Ehrler[21], A. Elagin[15], P.D. Eversheim[4], P. Facciolli[28], M. Faessler[2], J. Fedotova[26], M. Finger[31], M. Finger jr.[31], H. Fischer[17], C. Franco[23], J.M. Friedrich[18], V. Frolov[15], A. Futch[45], F. Gautheron[25], O.P. Gavrichtchouk[15], S. Gerassimov[28,18], S. Gevorkyan[15], Y. Ghandilyan[50], J. Giarra[25], I. Gnesi[42,43], M. Gorzellik[17], A. Grasso[42,43], A. Gridin[15], M. Grosse Perdekamp[45], B. Grube[18], R.I. Gushterski[15,4], A. Guskov[15], G. Hamar[30], D. von Harrach[25], X. He[3], R. Heitz[45], F. Herrmann[17], M. Hoffmann[4], N. Horikawa[36,e], S. Huber[18], A. Inglessi[15], A. Ilyichev[26], S. Ishimoto[49,g], A. Ivanov[15], N. Ivanov[15], T. Iwata[50], M. Jandek[31], V. Jary[32], C.-M. Jen[25], R. Joosten[4], P. Jörg[17], K. Juraskova[32], E. Kabuß[25], A. Karpishkov[26], F. Kaspar[18], D. Keller[12], A. Kerbizi[28,40], B. Ketzer[4], G.V. Khaustov[33], Yu.A. Khokhlov[33,h], M. Kim[1], O. Kiselev[18], Yu. Kisselev[15], F. Klein[9], J.H. Koivuniemi[43], V.N. Kolosov[33], K. Kondo[49], I. Konorov[28,18], V.F. Konstantinov[33], A.M. Kotzinian[42,i], O.M. Kouznetsov[15], A. Koval[47], Z. Kral[22], F. Krinner[18], Y. Kulinich[45], K. Kurek[47], R.P. Kurjata[46], A. Kveton[32], S. Levorato[40], J. Lichtenstadt[36], K. Liu[24], M.X. Liu[24], F. Longo[48], W. Lorenzon[3], M.J. Losekamm[18], V.E. Lyubovitskij[41,26], E. Maev[15], A. Maggiora[43], V. Makarenko[26], N. Makins[45], N. Makke[40], G.K. Mallot[20], A. Maltsev[15], S.A. Mamon[37], B. Marianski[47], A. Martin[39,40], H. Marukyan[51], J. Marzec[46], N. Masi[1], J. Matoušek[39,40], T. Matsuda[27], G. Mattson[45], G.V. Meshcheryakov[15], W. Meyer[3], M. Meyer[45], Yu.V. Mikhailov[33], M. Mikhasenko[20], M. Minot[13],

*COmmon Muon Proton Apparatus for Structure and Spectroscopy
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SPSC 139, Oct. 2020

The Committee **recommends** approval of the proposal SPSC-P-360 by the AMBER Proto-Collaboration to use the M2 beam-line before LS3 to perform measurements related to:

(i) Drell-Yan and J/Psi production using the conventional M2 hadron beam;
(ii) proton-induced antiproton production cross sections for dark matter searches;
(iii) the proton charge radius using muon-proton elastic scattering.

The proton-radius program is contingent on a successful pilot run previously approved for the first year of SPS operation after the Long Shutdown LS2.

2018
LoI (arXiv:1808.00848)

2020
Approval of Proposal

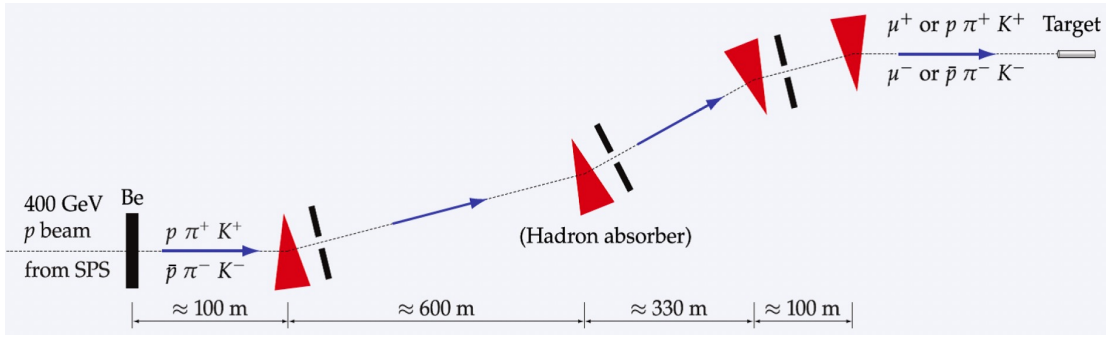
2023
Start of data taking

AMBER: A new QCD facility at the M2 beam line at CERN's SPS

To further exploit the M2 beam line at CERN and the former COMPASS spectrometer for further exploration of hadron structure and QCD physics

M2 secondary beam-line of CERN's SPS

- High intensity beams of $\mu^{\pm}$ and hadrons ($\pi^{\pm}, K^{\pm}, p^{\pm}$)
- Adaptable beam momentum between ~60 GeV/c – 250 GeV/c



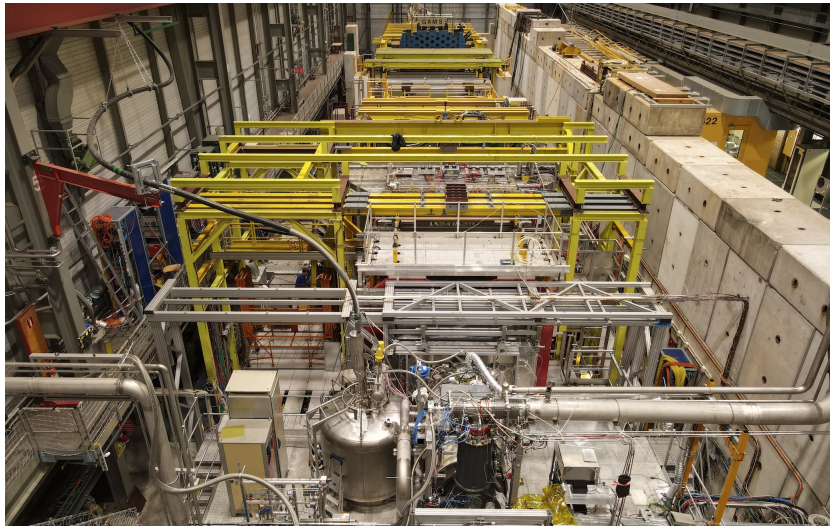
The M2 secondary beam line at CERN's SPS

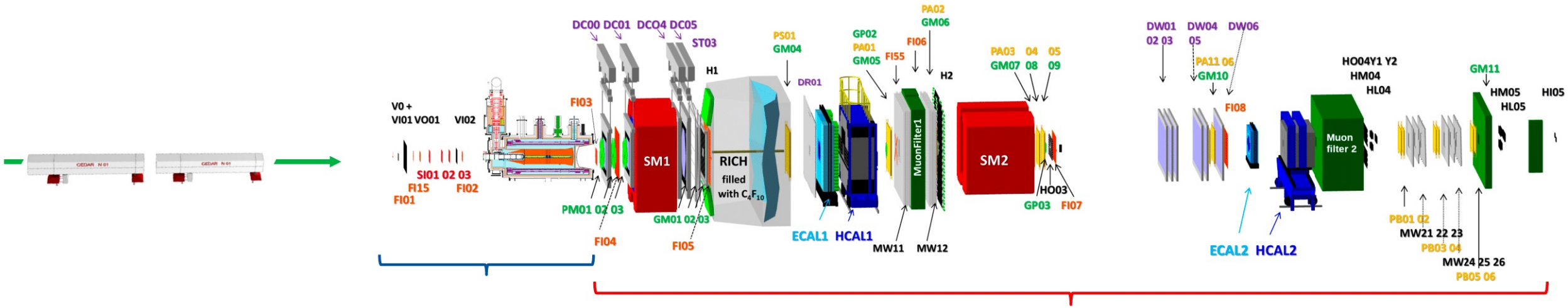
location of the AMBER experiment at CERN's North Area

The AMBER Spectrometer

- 2-stage magnetic spectrometer
- Precise particle tracking
- RICH and Calorimeters for PID
- Muon filter
- CEDAR detectors for beam PID
- Upgrade of DAQ for trigger-less data taking in future

Talks by J. Paschek HK29.1,
P. Henkel HK29.2,
K. Eichhorn HK70.4





Beam: p, μ, π, K, (e) **Target region:** program-specific **Spectrometer:** common for all measurements

AMBER Physics Program

Phase I (Approved)

Credit: Chris Gash

Measurement of the Proton-Charge Radius

- Elastic muon-hydrogen scattering using an active-target Hydrogen TPC
- Extraction of the proton's electric form factor at very low Q^2

Study of the pion PDF using the Drell-Yan process

Measurements of antiproton production (topic of today's talk)

Phase II (planning stage, beyond ~2030)

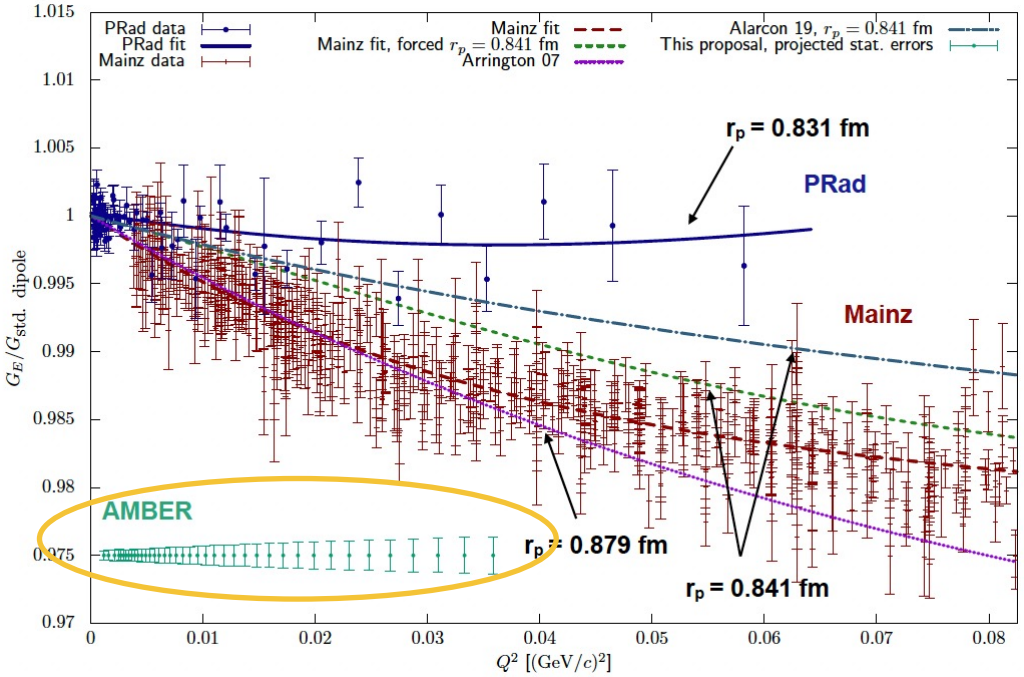


Figure taken from J. C. Bernauer EPJ Web Conf. 234 (2020)

Talk by M. Hoffmann
Do 15:45; HK70.1

AMBER Physics Program

Phase I (Approved)

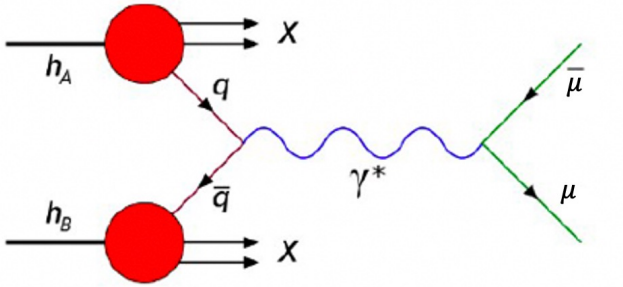
Measurement of the Proton-Charge Radius

Study of the pion PDF using the Drell-Yan process

- High-intensity hadron beam to study rare DY process
- Measurements with different beam polarity to separate valence and sea quark contribution to the pion PDF

Measurements of antiproton production
(topic of today's talk)

Phase II (planning stage, beyond ~2030)



Drell-Yan process in the muon channel

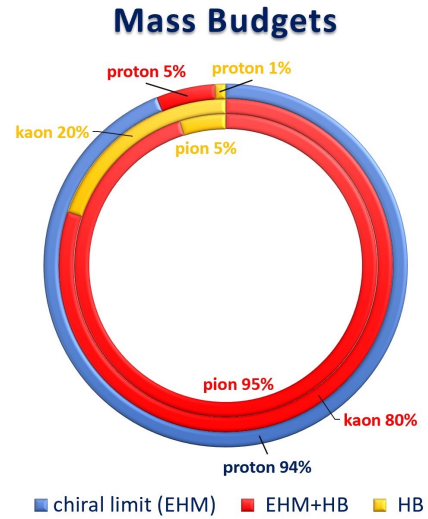


Figure taken from Craig Roberts "EHM via AMBER" at 5th AMBER EHM Workshop (2021)

AMBER Physics Program

Phase I (Approved)

Measurement of the Proton-Charge Radius

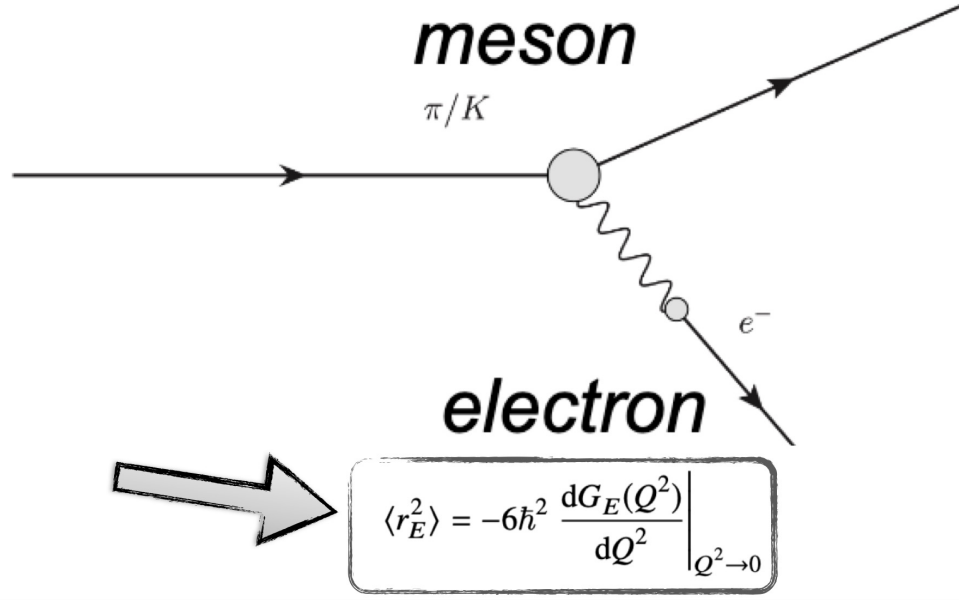
Study of the pion PDF using the Drell-Yan process

Measurements of antiproton production
(topic of today's talk)

Phase II (planning stage, beyond ~2030)

- Kaon-induced hadron spectroscopy
- Measurements of the Kaon PDF
- Meson charge radii,
- …

Talk by H. Pekeler
Do 15:45; HK70.1



measurement principle of charge radii of mesons

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AMBER Physics Program

Phase I (Approved)

Measurement of the Proton-Charge Radius

Study of the pion PDF using the Drell-Yan process

Measurements of antiproton production (topic of today's talk)

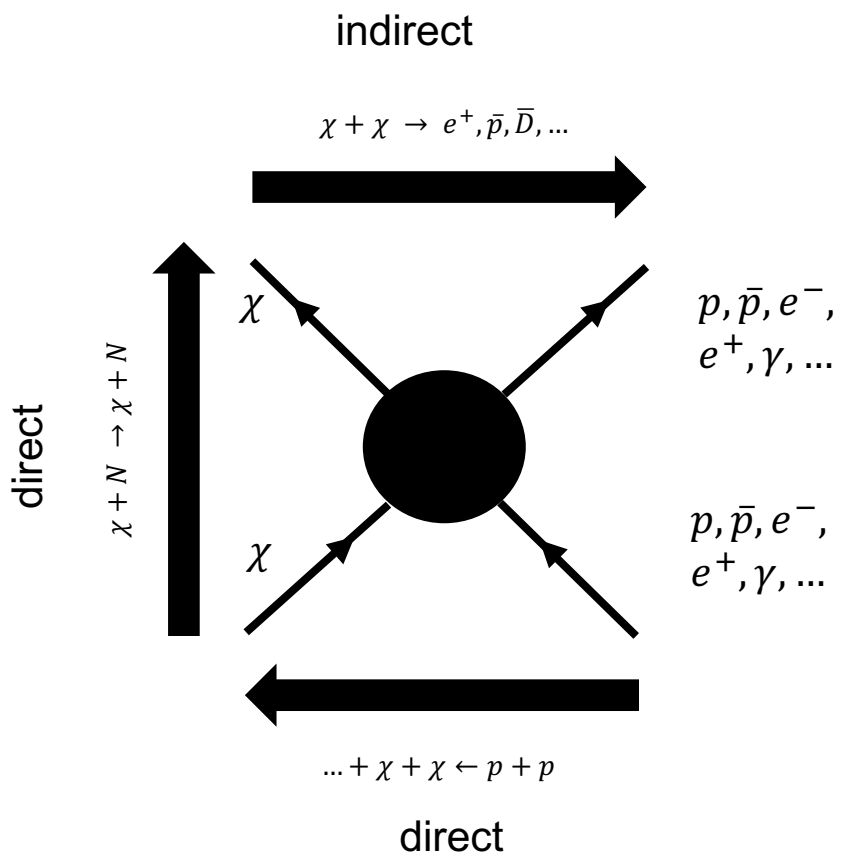
Phase II (planning stage, beyond ~2030)

Motivation: Galactic Cosmic-Ray Antiprotons

Antiprotons for Indirect Dark-Matter Search

- Antinuclei (antiprotons, antideuterons, ...) identified as promising channels for indirect dark-matter search
- Of them, only antiprotons identified so far in cosmic rays
- But they are also abundantly produced in ordinary cosmic-ray collisions

→ ***Interpretation of the antiproton flux requires accurate determination of the contribution from cosmic ray collisions***



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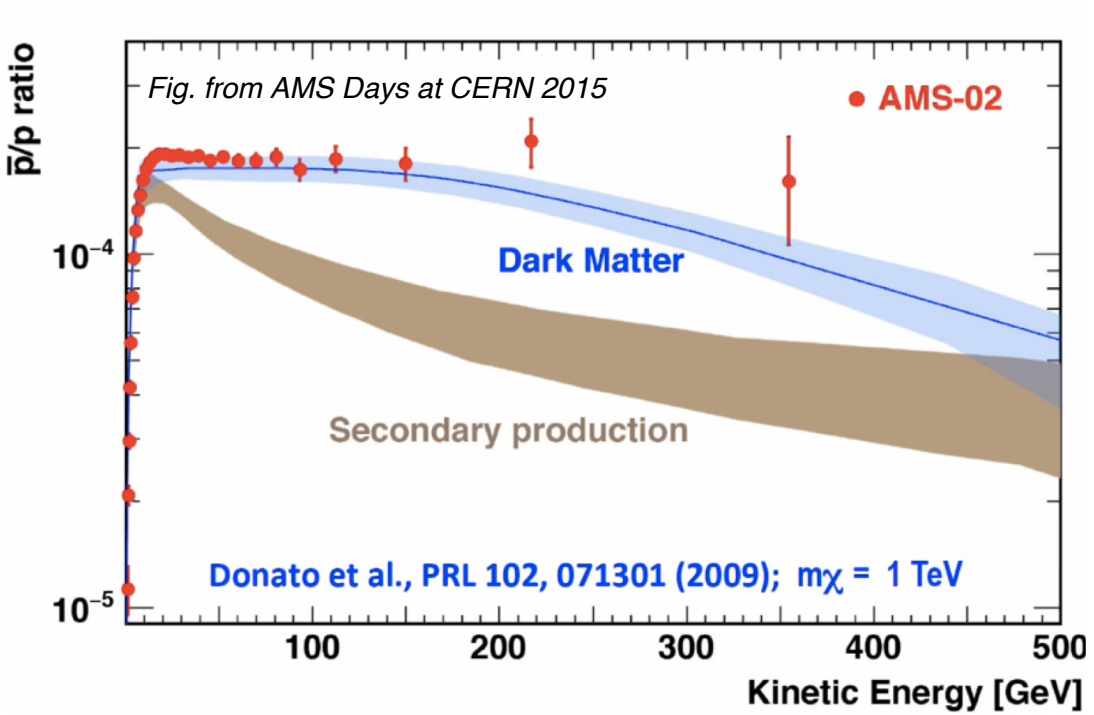
New precise experimental data of cosmic-ray antiprotons by AMS-02 (uncertainties ~%)



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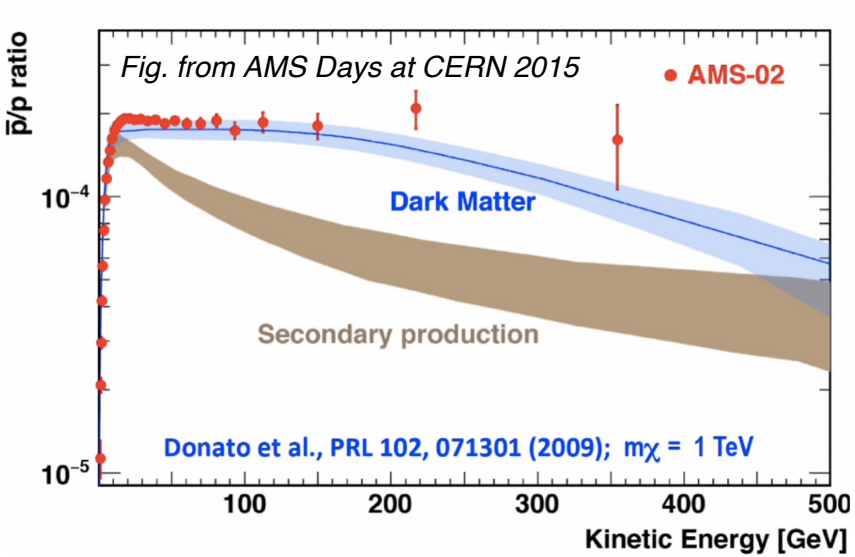
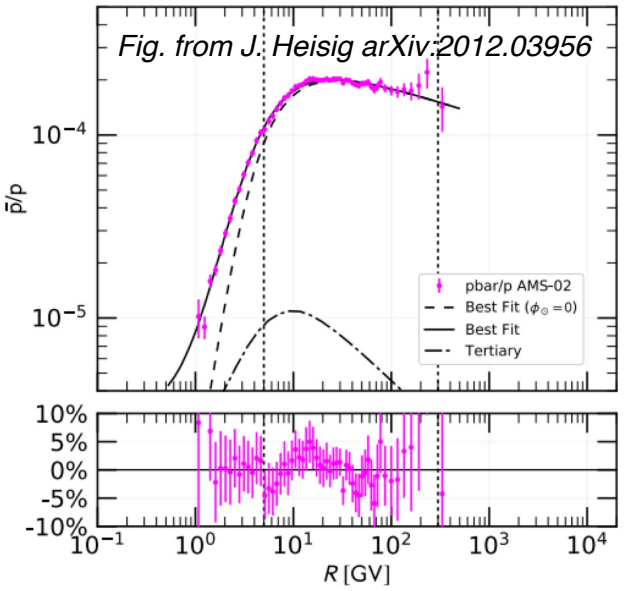
New precise experimental data of cosmic-ray antiprotons by AMS-02 (uncertainties ~%)

→ modeling of antiproton production needs to be on the same level





Antiproton-Production Mechanisms

Production Reactions

$$p + p \rightarrow \bar{p} + X$$

$$p + p \rightarrow \bar{\Lambda} + X \qquad p + p \rightarrow \bar{\Sigma}^{-} + X$$

$$p + He,\ He + p,\ He + He,\ \ldots$$

$$p + p \rightarrow \bar{n} + X$$

decreasing availability of data

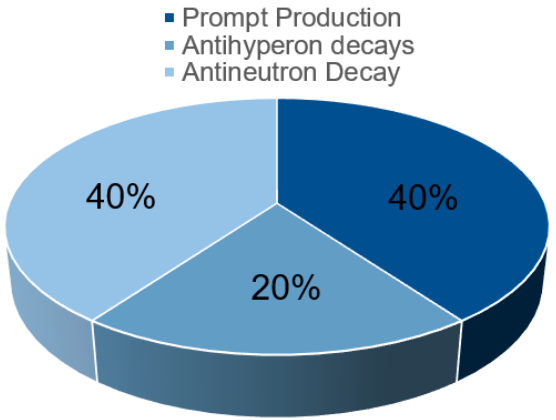
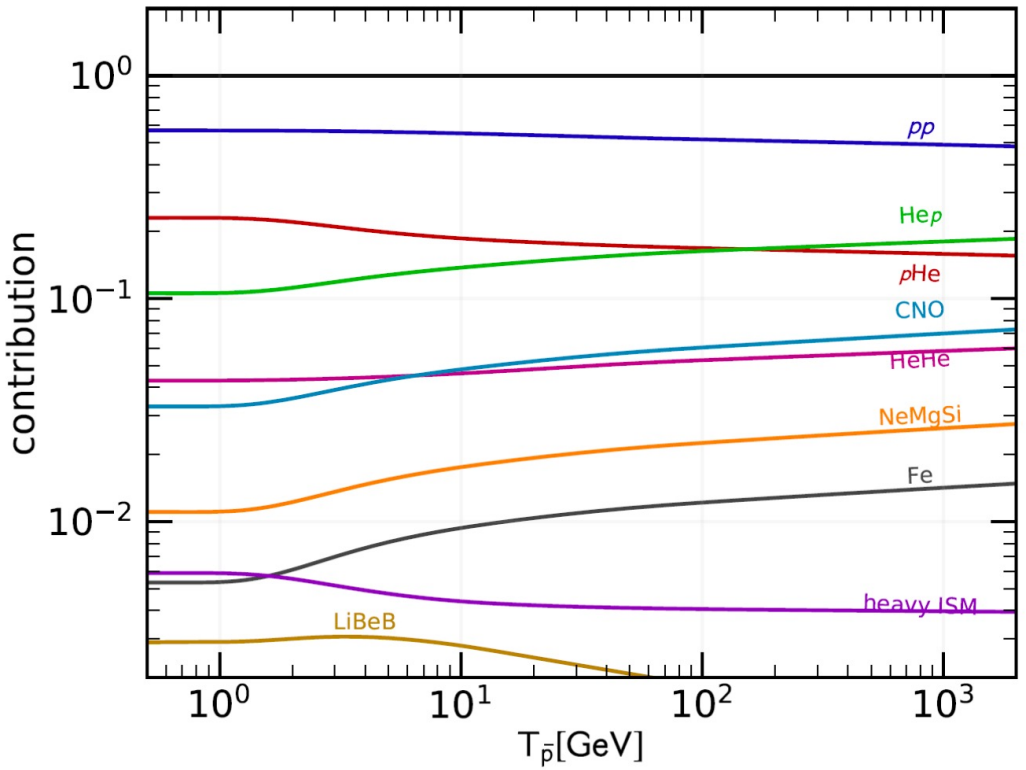
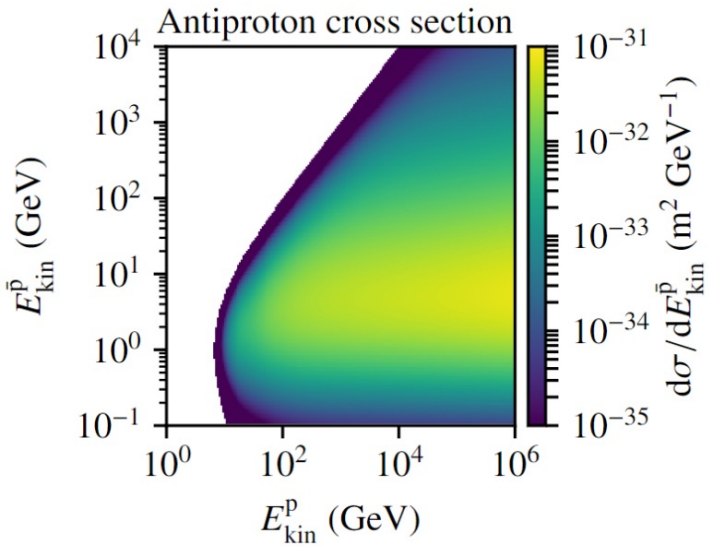


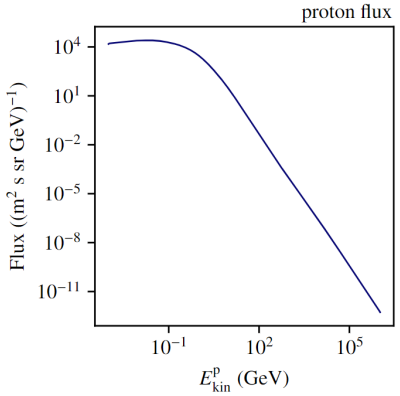
Figure taken from Di Mauro et al., Phys. Rev. D, Vol. 97, 103019 (2018)

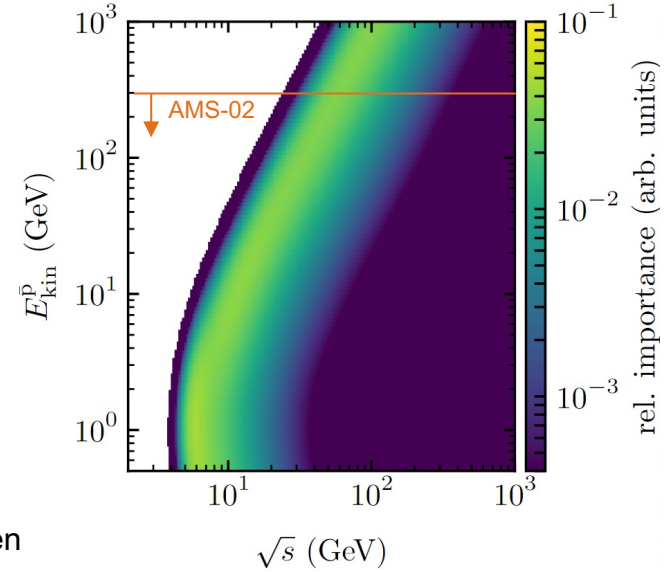


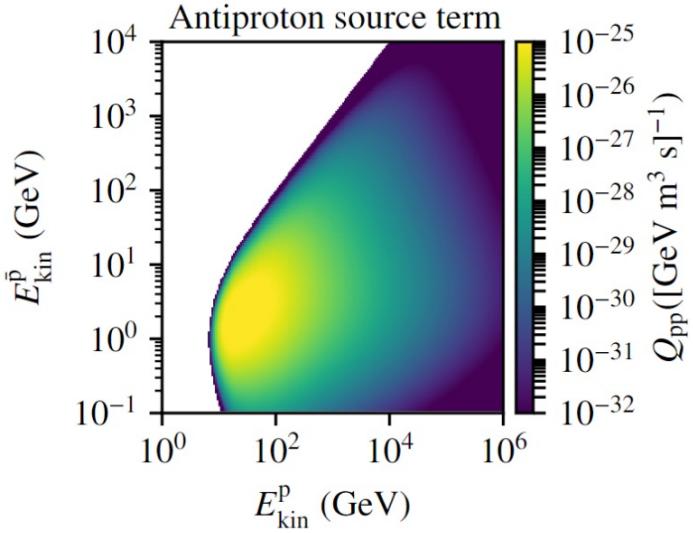
Antiproton-Production Mechanisms

Relevant Collision Energies









Only collision energies up to a few hundred GeV are relevant for AMS-02 antiprotons!

Overview of Experimental Data

$\mathbf{p + p \rightarrow \bar{p} + X}$ (prompt production)

- Many datasets at low and high energies
- Nearly full phase-space coverage at collision energies below 20 GeV (fixed target)
- Only limited phase-space coverage at higher energies

$\mathbf{p + p \rightarrow \bar{\Lambda} + X}$ $\mathbf{p + p \rightarrow \bar{\Sigma}^{-} + X}$
(non-prompt production)

$\mathbf{p + p \rightarrow \bar{n} + X}$
(non−prompt production)

$\mathbf{p + He, He + p, He + He, \ldots}$

experiment	$\sqrt{s}$ GeV	contribution from antihyperons	phase-space coverage (%)
Dekkers et al.	6.1	included	9.0
	6.7		6.3
NA61	7.7	excluded	99.6
	8.8		99.3
	12.3		98.8
	17.3		98.0
NA49	17.3	excluded	98.7
PHENIX	62.4	included[†]	12.3
	200.0		13.5
BRAHMS	200.0	included	0.2
ALICE	900.0	excluded	11.3

Selection of antiproton measurements in proton-proton collisions

data from EPJ C 77;10;671 (2017)

data from PRL 98;25;252001 (2007)

Overview of Experimental Data

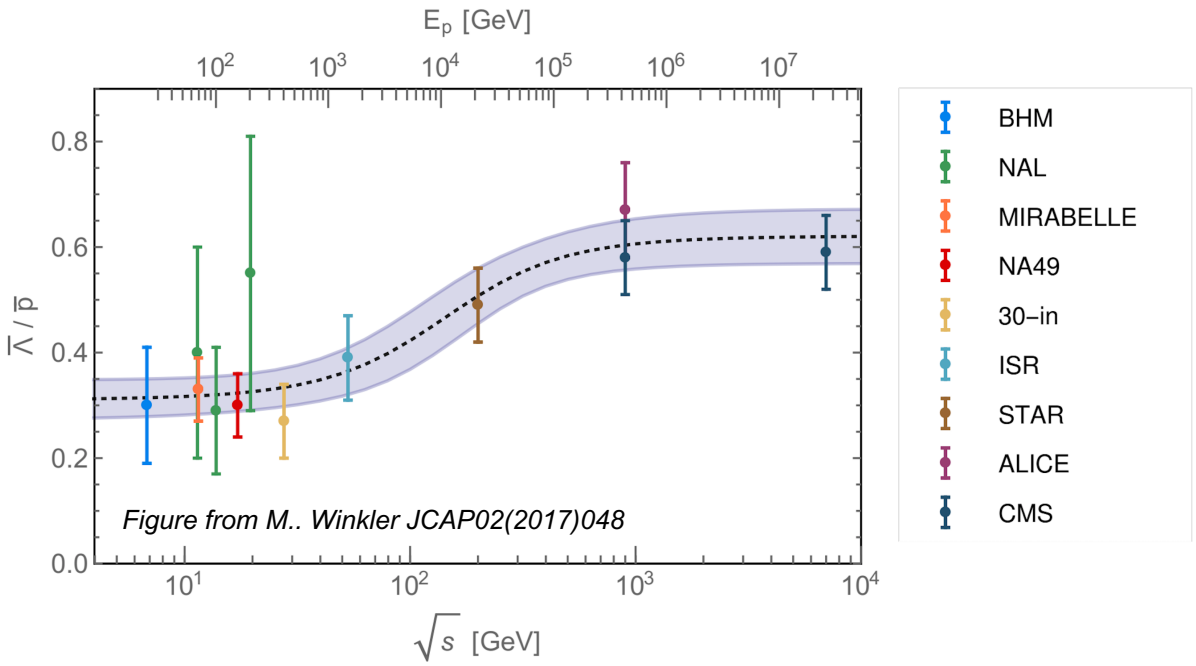
$\mathbf{p + p \rightarrow \bar{p} + X}$ **(prompt production)**

$\mathbf{p + p \rightarrow \bar{\Lambda} + X}$ $\mathbf{p + p \rightarrow \bar{\Sigma}^{-} + X}$
(non-prompt production)

- Largest contribution from antihyperons from $\bar{\Lambda}$ and $\bar{\Sigma}^{-}$ decays

$$\bar{\Lambda} \rightarrow \bar{p} + \pi^{+} \qquad (63.9 \pm 0.5)\%,$$
$$\bar{\Sigma}^{-} \rightarrow \bar{p} + \pi^{0} \qquad (51.57 \pm 0.30)\%.$$

- Similar experimental data then for prompt antiprotons



$\mathbf{p + p \rightarrow \bar{n} + X}$
(non−prompt production)

$\mathbf{p + He, He + p, He + He, \ldots}$

Overview of Experimental Data

$\mathbf{p + p \rightarrow \bar{p} + X}$ **(prompt production)**

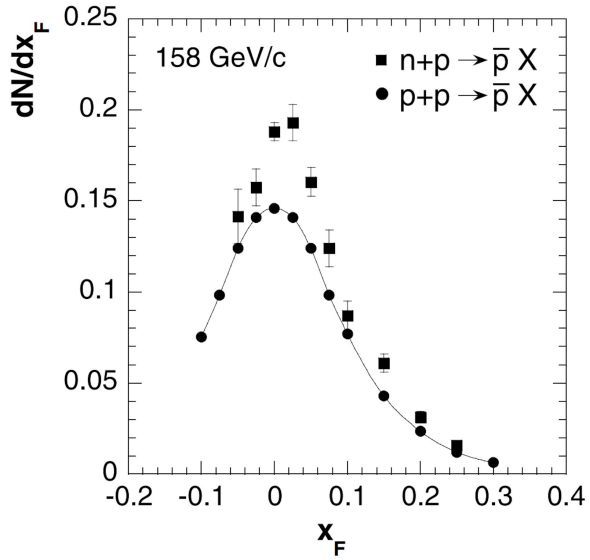
$\mathbf{p + p \rightarrow \bar{\Lambda} + X}$ $\mathbf{p + p \rightarrow \bar{\Sigma}^{-} + X}$
(non-prompt production)

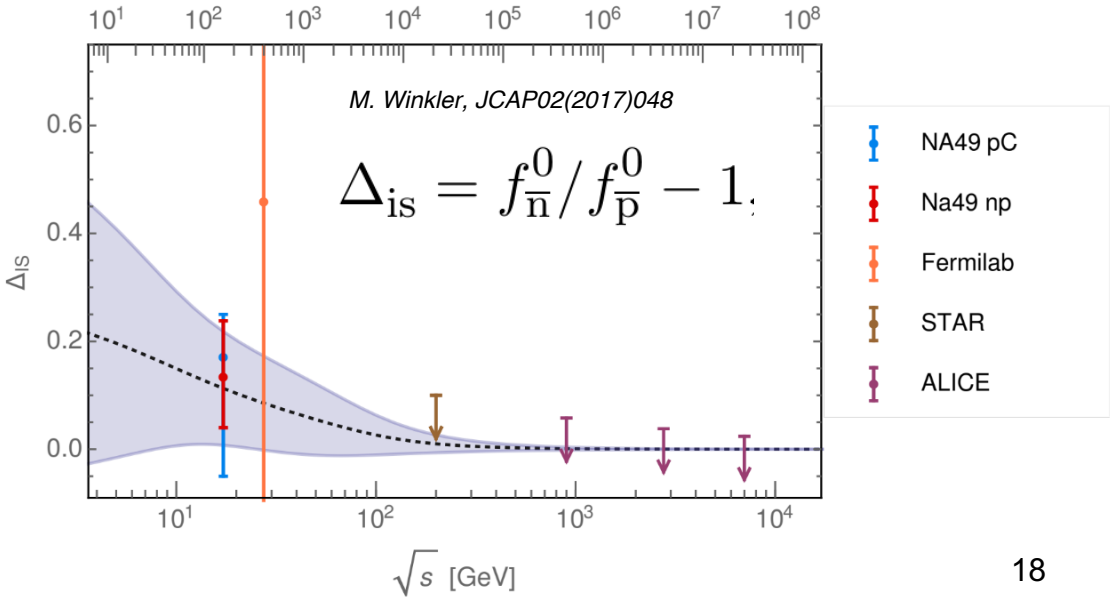
$\mathbf{p + p \rightarrow \bar{n} + X}$
(non−prompt production)

- Expect equal production of $\bar{p}$ and $\bar{n}$
- At low collision energies: Potential Isospin asymmetry in CR collisions due to proton-enhanced initial state
- Suggested by measurements of NA49 comparing the "*flipped reactions*" $p + p \rightarrow \bar{p} + X$ and $p + n \rightarrow \bar{p} + X$
- Dominant uncertainty for cosmic antiproton-production at low energies → ~20% flux uncertainty

$\mathbf{p + He, He + p, He + He, \ldots}$

Figure from NA49, Acta Phys. Hun. Ser. A 17(2003) 369-386





Overview of Experimental Data

$\mathbf{p + p \rightarrow \bar{p} + X}$ **(prompt production)**

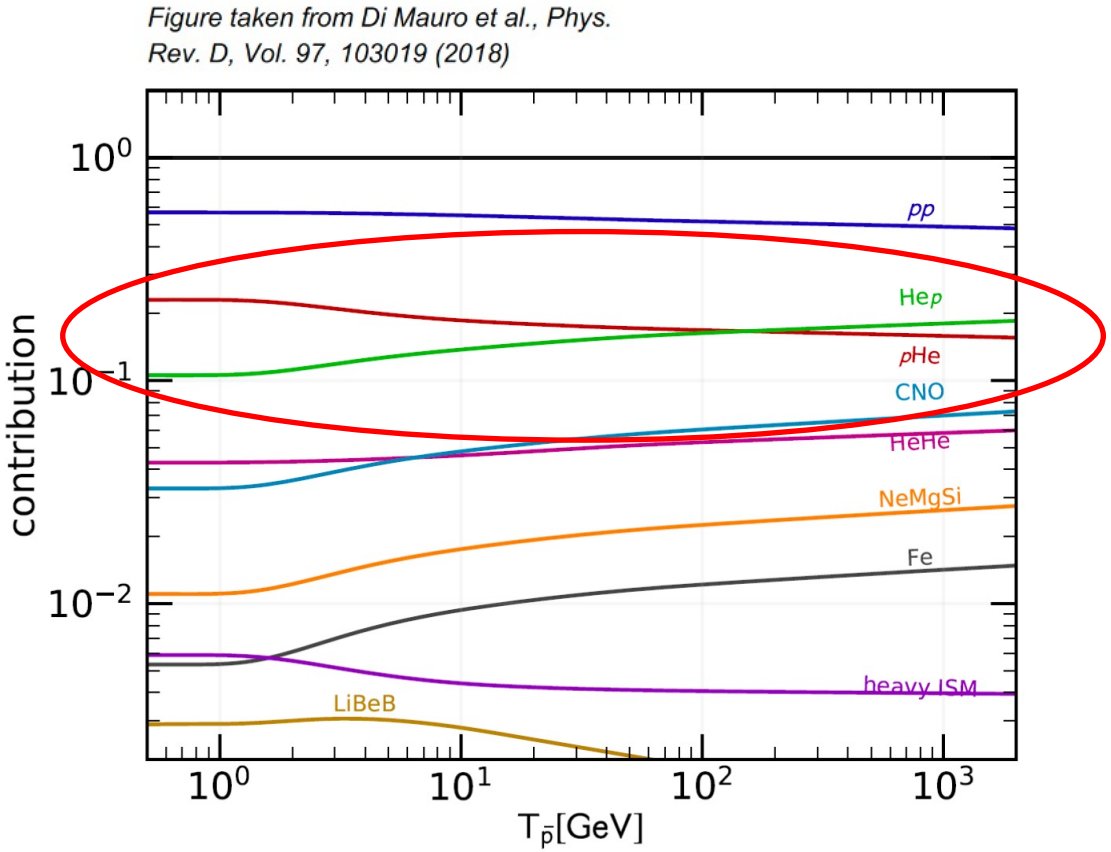
$\mathbf{p + p \rightarrow \bar{\Lambda} + X}$ $\mathbf{p + p \rightarrow \bar{\Sigma}^{-} + X}$
(non-prompt production)

$\mathbf{p + p \rightarrow \bar{n} + X}$
(non−prompt production)

$\mathbf{p + He}$, $\mathbf{He + p}$, $\mathbf{He + He}$, ...

- Significant contribution from light-ion collisions
- Collisions including Helium especially relevant
- Sparse experimental data for relevant collisions:
  - LHCb p + He @ $\sqrt{s_{NN}} = 110$ GeV

  → *no experimental data for low collision energies*



Overview of Experimental Data

$\mathbf{p + p \rightarrow \bar{p} + X}$ **(prompt production)**

$\mathbf{p + p \rightarrow \bar{\Lambda} + X}$ $\mathbf{p + p \rightarrow \bar{\Sigma}^{-} + X}$
(non-prompt production)

focus of AMBER measurements

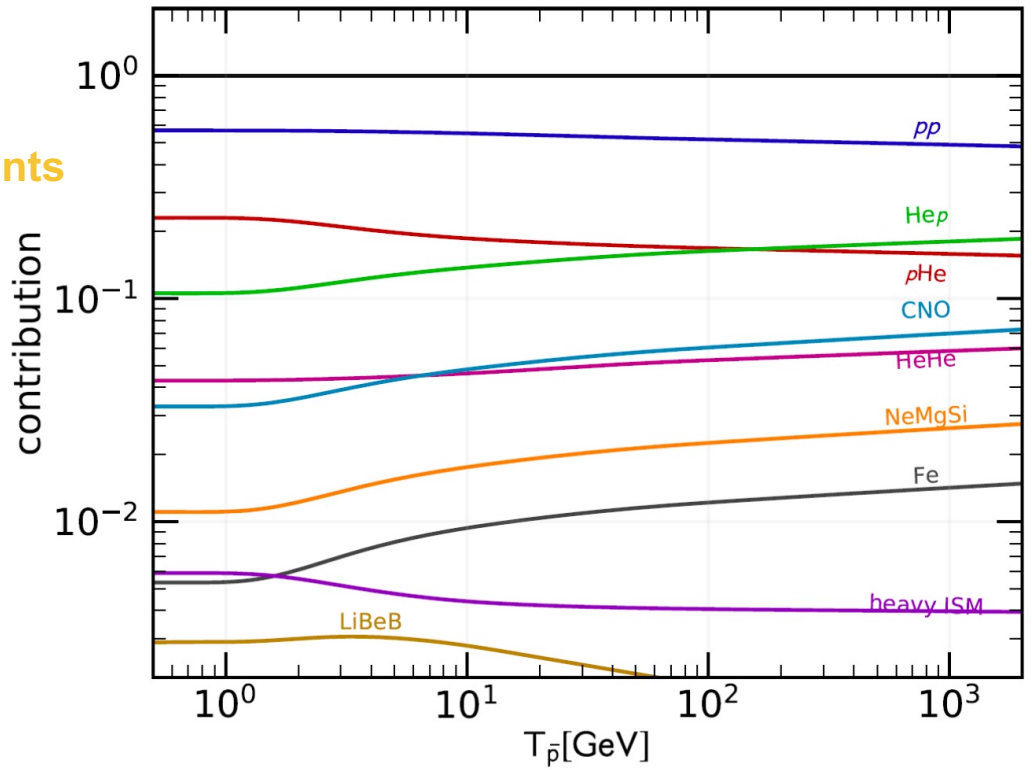
$\mathbf{p + p \rightarrow \bar{n} + X}$
(non−prompt production)

$\mathbf{p + He, He + p, He + He, \ldots}$

- Significant contribution from light-ion collisions
- Collisions including Helium especially relevant
- Sparse experimental data for relevant collisions:
  - LHCb p + He @ $\sqrt{s_{NN}} = 110$ GeV

→ *no experimental data for low collision energies*

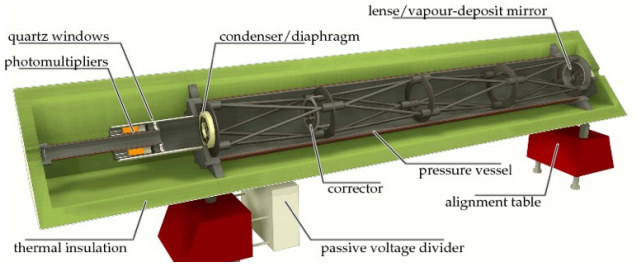
Figure taken from Di Mauro et al., Phys. Rev. D, Vol. 97, 103019 (2018)



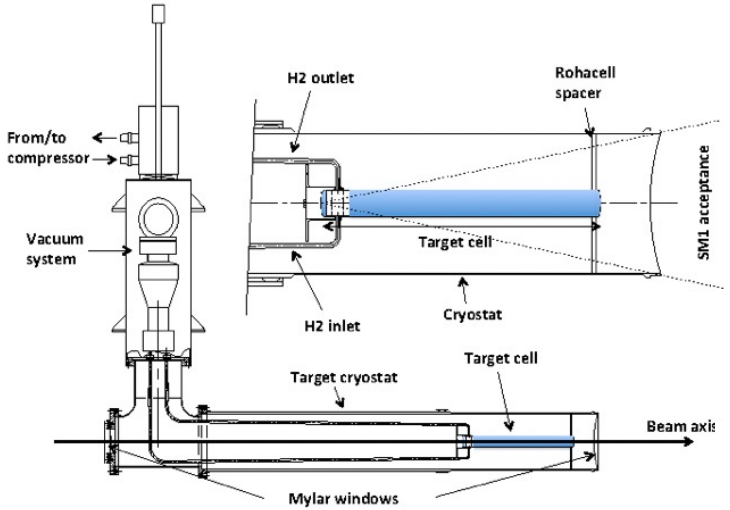
Measurement of the Antiproton-Production Cross Sections at AMBER

Antiproton-Production Measurements at AMBER

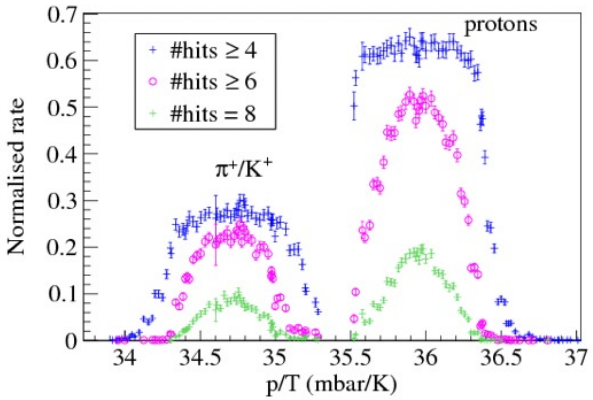
hadron beam
(p, π^+, K^+)



secondaries to spectrometer



CEDAR detectors for beam-particle identification

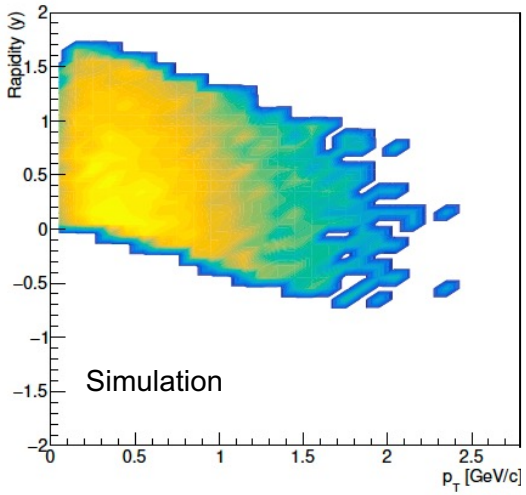


cryogenic target

2023: - liquid Helium

2024: - liquid Hydrogen

- liquid Deuterium



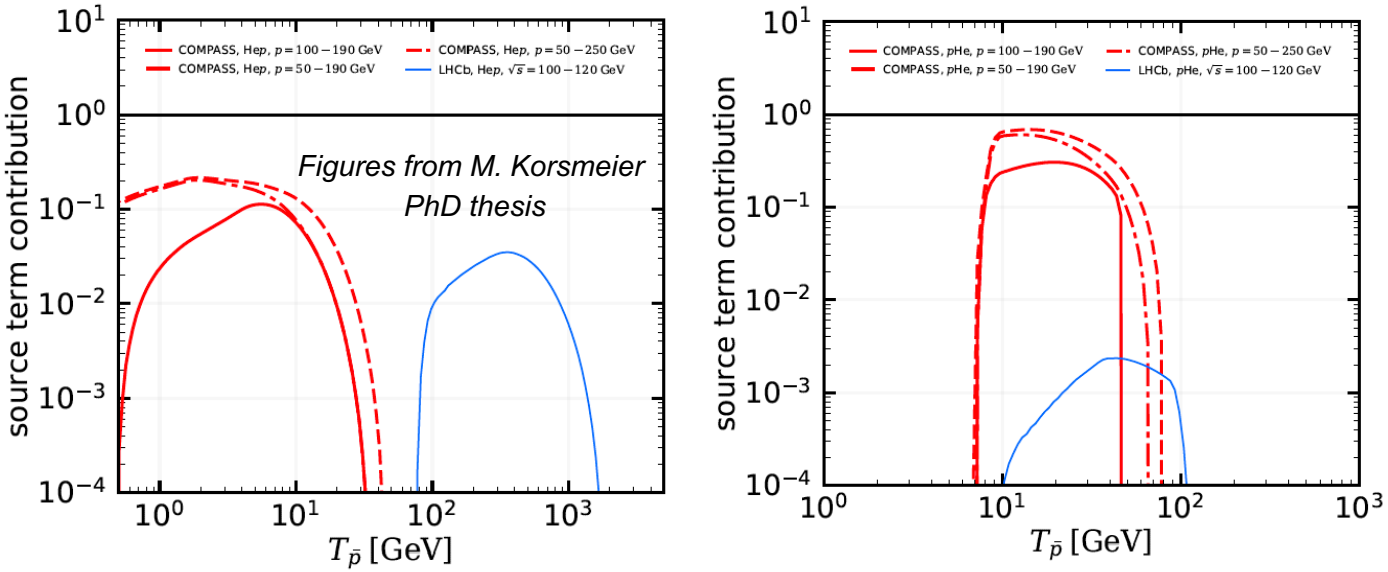
phase-space coverage of AMBER for antiprotons in 190 GeV/c collisions

2023 p + He Data Taking

Measurements at different collision energies

Beam momentum (GeV/c)	Collision energy ($\sqrt{s_{\mathrm{NN}}}$) (GeV)
60	10.7
80	12.3
100	13.8
160	17.3
190	18.9
250	21.7

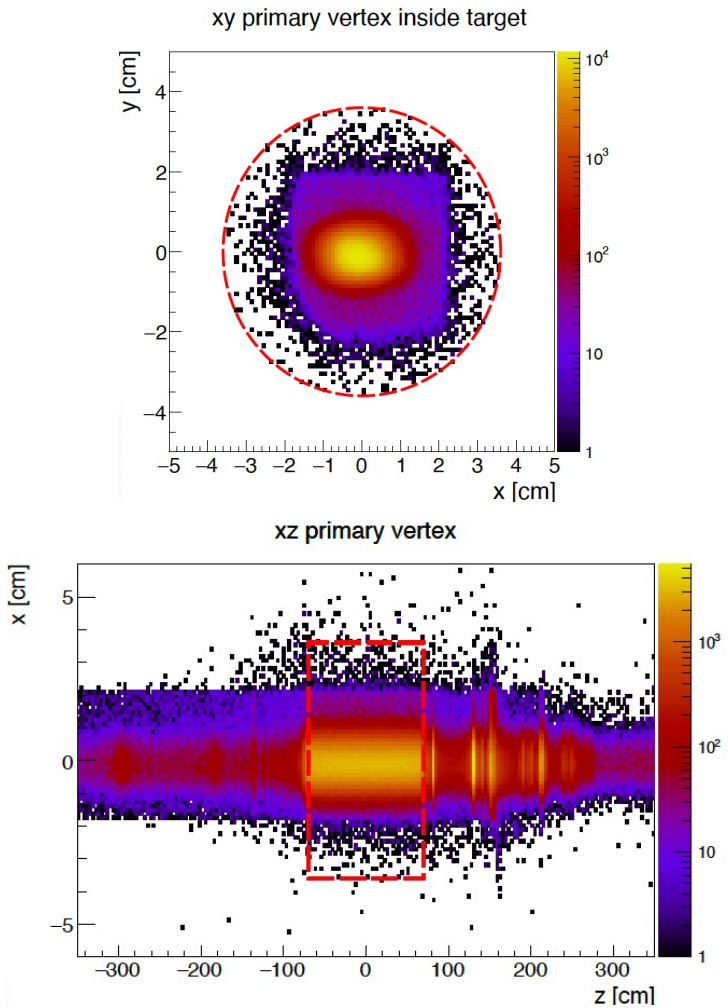
- Measurements between 60 GeV/c – 250 GeV/c
- Coverage of the low-p_t regime
- High-statistics data sets: statistical uncertainties below 1% for most of covered phase space



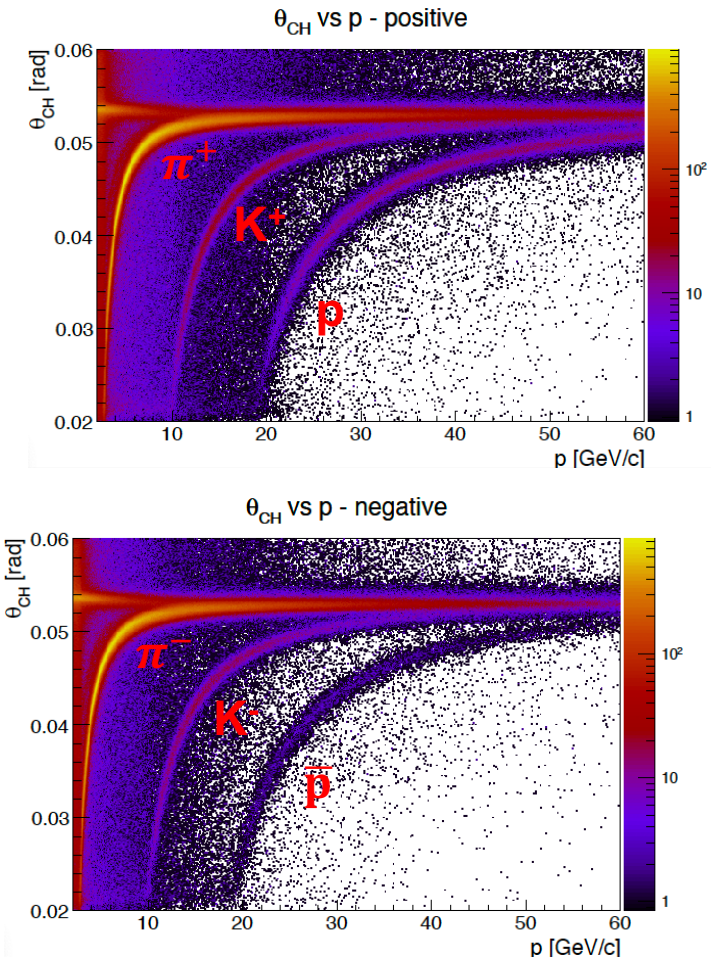
fraction of galactic source term probed by AMBER measurement (projection, left p + He, right He + p)

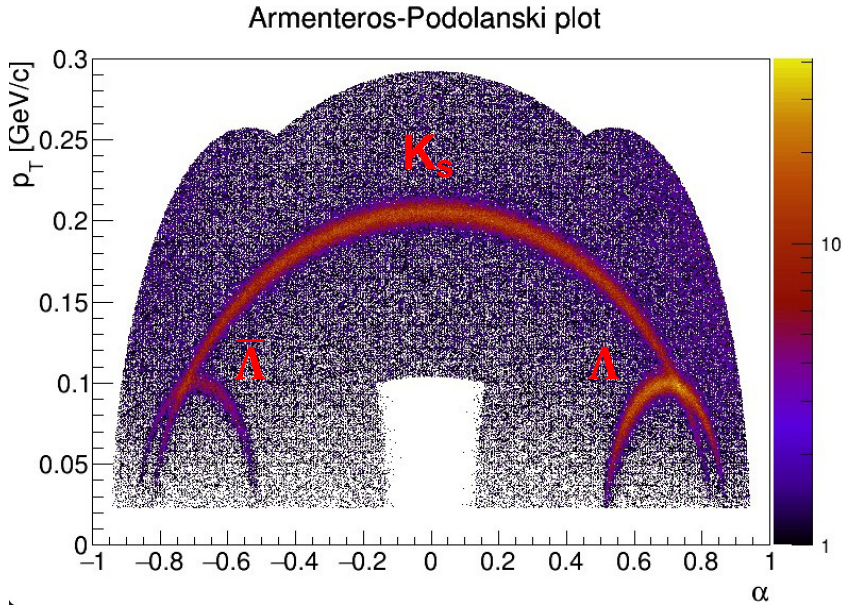
A First Glimpse into the 2023 p + He Data (work in progress)

Vertex distributions near the target
(1% of the 190 GeV/c data)



RICH PID
(1% of the 190 GeV/c data)





Identification of weakly-decaying particles from secondary vertices (1% of the 190 GeV/c data)

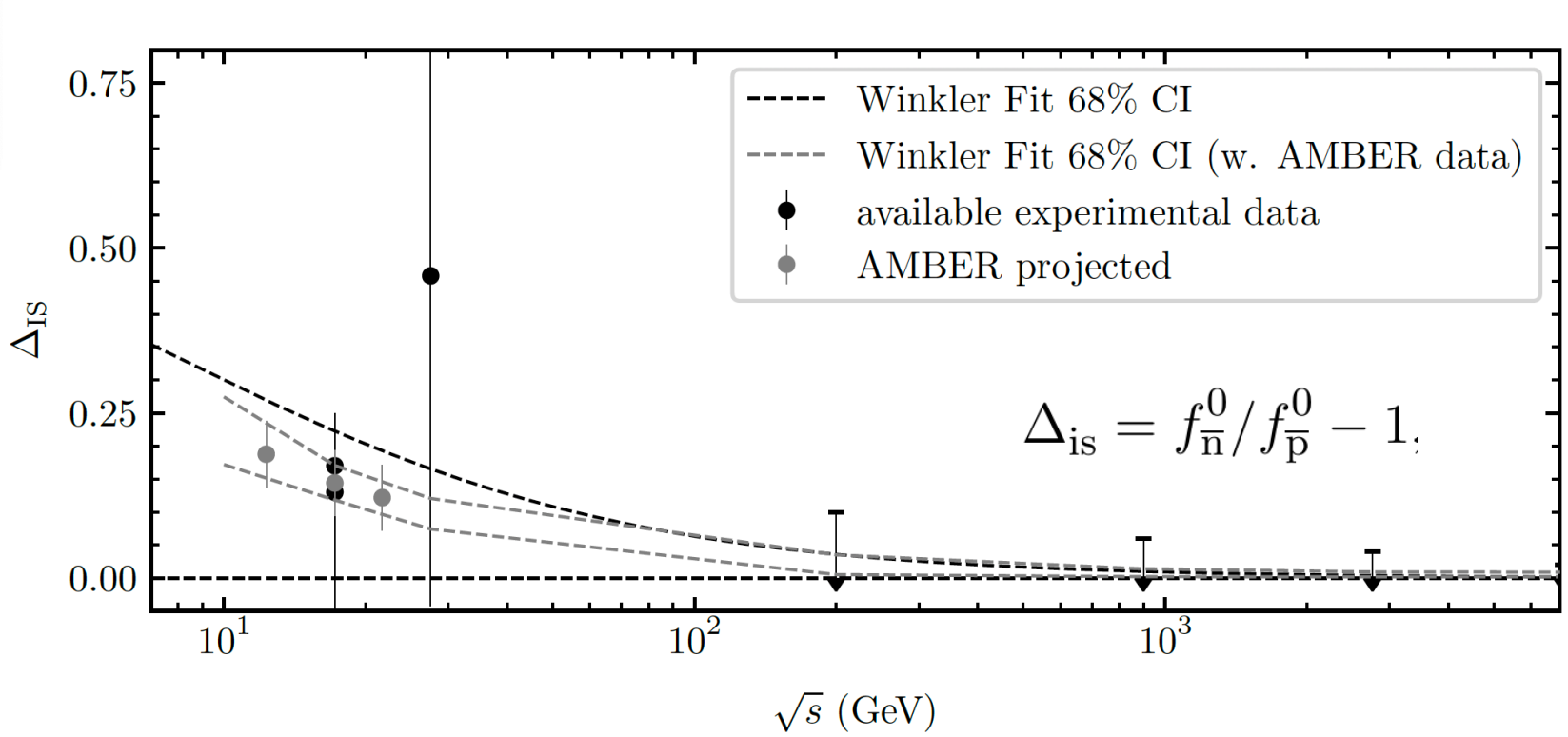
Plans for the 2024 Data taking with Hydrogen and Deuterium Target

Main Goal: Investigate a possible isospin asymetry in the production of antiprotons

Refine and extend NA49 measurements using a more controllable setup:

- Proton beam on Hydrogen and Deuterium target (exchange during data taking)
- Measurements at different collision energies to probe collision-energy dependence

→ individual cross-section measurements on the 5% level to constrain asymmetry below the 10% level



Apparatus for Meson and Baryon Experimental Research

Summary and Outlook

AMBER antiproton-production measurements for understanding galactic antiproton production:

- p + He collisions in 2023:
  first ligh-ion collision data at low energies
- p + H and p + D collisions in 2024:
  probe asymmetry in galactic antiproton and antineutron production

Future analyses from recorded data

- Production of antiprotons from antihyperons
- Measurements of π^0 production as input for background estimates for searches of galactic gamma-ray sources

Far future plans (after LS3, ~2030)

- Possible extension of AMBER measurements to antideuterons & antihelium

Thank you for your attention!

Apparatus for Meson and Baryon
Experimental Research

Production of antinucleons in collisions

- naively, we expect equal production of antiprotons and antineutrons in high-energy collisions due to isospin symmetry

→ *cosmic flux of prompt antiprotons would double*

Isospin $I = 1$					
Projectiles		n		p	
Produced particles	$\bar{p}n$		$p\bar{p}$ $n\bar{n}$		$p\bar{n}$
I_3	-1	$-1/2$	0	$1/2$	$+1$

- production of antiparticles in pairs (Baryon-number conservation) ($p\bar{p}, n\bar{p}$, $n\bar{n}, p\bar{n}$)

- however, collisions in Galaxy have highly-asymmetric I_3 component in initial state (far more *pp* than *nn* collisions)

  → what happens in collisions at low energies with highly isospin-asymmetric initial states (I_3 component)?