PAW'24 - Physics at AMBER international Workshop
Antiproton production cross section at AMBER

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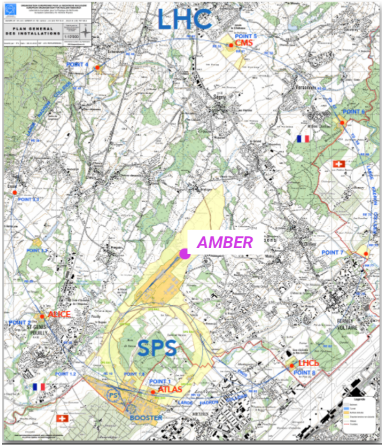
AMBER @CERN

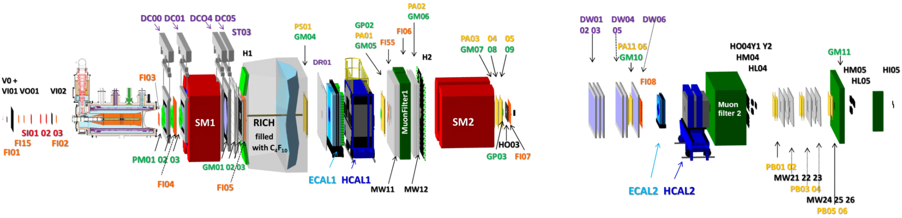


AMBER is located in the experimental hall EHN2 in the NA @CERN:

- Availability of both hadron and muon beams (M2 beam line)
- Re-use of large aperture dipole magnets from COMPASS
- Re-use of major part of COMPASS detectors

AMBER Spectrometer

Apparatus for Meson and Baryon Experimental Research



- Using existing spectrometer with several upgrades
- Large-acceptance two-stages spectrometer
- Precise tracking ($\sim$ 350 planes) and PID (CEDAR for beam, RICH-1 for final state hadrons, calorimeters, muon system)

AMBER Program

In 2019 the AMBER collaboration proposes to establish a "New QCD facility at the M2 beam line of the CERN SPS" (LoI: http://arxiv.org/abs/1808.00848). Submitted and approved by CERN Research Board in Dec 2020.

- proton radius measurement
- pion induced Drell Yan
- **proton-induced antiprotons production cross sections for indirect dark matter searches:**
  - $p +^4 He \rightarrow$ 2023 data collected
  - $p + D \rightarrow$ 2 months run starting 10 April 2024
  - $p + H_2 \rightarrow$ 2 months run starting 10 April 2024
  - From the 3 datasets, we are capable of measuring:
    - prompt produced $\pi^{+/-}$, $K^{+/-}$, $p/\bar{p}$ spectra
    - $\pi^0 \rightarrow \gamma\gamma$
    - Antihyperons $\Lambda/\bar{\Lambda}$

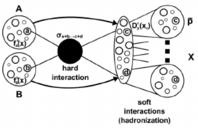
Uncertainties on $\bar{p}$ flux

$$\frac{\partial \psi(\vec{r}, p, t)}{\partial t} = q(\vec{r}, p, t) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi)$$
$$+ \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

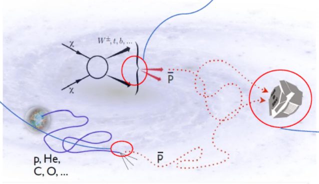
Antiproton production cross sections

$$q_{ij}(T_{\bar{p}}) = \int_{T_{\mathrm{th}}}^{\infty} dT_i \, 4\pi \, n_{\mathrm{ISM},j} \, \phi_i(T_i) \frac{d\sigma_{ij}}{dT_{\bar{p}}}(T_i, T_{\bar{p}})$$

$$q_{\bar{p}}^{(\mathrm{DM})}(\boldsymbol{x}, E_{\mathrm{kin}}) = \frac{1}{2} \left(\frac{\rho(\boldsymbol{x})}{m_{\mathrm{DM}}} \right)^2 \sum_f \langle \sigma v \rangle_f \frac{dN_{\bar{p}}^f}{dE_{\mathrm{kin}}}$$



Thomas Poeschl, PhD thesis



Uncertainties in measurements

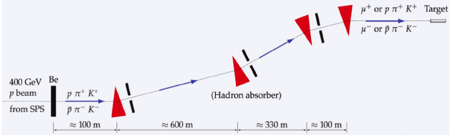
picture from Jan Heisig @MIAPP2022

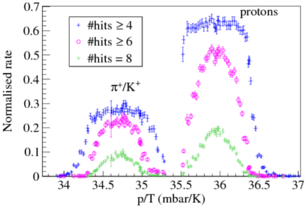
Major uncertainties of the predicted $\bar{p}$ flux from cosmic rays (CR) interaction with Interstellar Medium (ISM):

- $\bar{p}$ production cross sections
- CR propagation in the galaxy

Experimental setup - BEAM

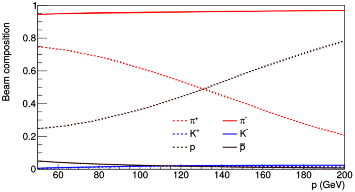
M2 beamline





The COMPASS setup for physics with hadron beams,https://doi.org/10.1016/j.nima.2015.01.035

- 400 GeV/c proton beam impinging on a 500 mm thick primary Beryllium production target (T6) $\Rightarrow$ Secondary beam 60-280 GeV/c
- beam PID: two CEDAR (Cherenkov light based) detectors installed 30 m upstream the target region.
- Proton PID efficiency $> 90\%$, purity $> 95\%$ (extracted with beam intensity of $5 \cdot 10^6$ p/s).
- low beam intensity $5 \cdot 10^5$ p/s $\rightarrow$ avoid trigger prescaling



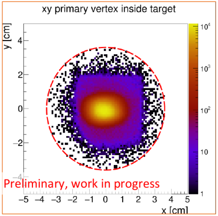
AMBER, Proposal for Measurements at the M2 beam line of the CERN SPS - PHASE I

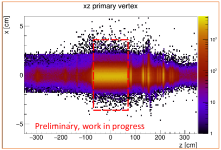
Experimental setup - TARGET

We started from the COMPASS SIDIS 2021/22 setup with target swap to Liquid Helium and minor rearrangement for the trigger reconfiguration

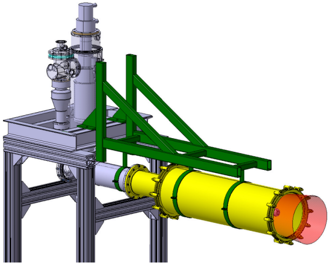
140 cm target holder filled with Helium (radius $\sim$ 3.5cm)

2023 *pHe* ($<$ 1% data sample)





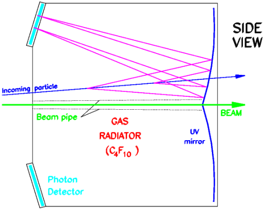
- 2024: *pH* and *pD* collision $\rightarrow$ new target holder developed. Similar dimension as in 2023

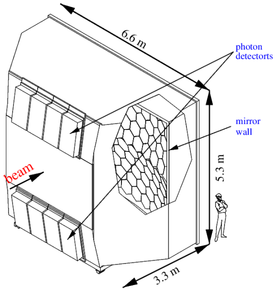


2024 target system

Experimental setup - PID

- Ring Imaging CHerenkov detector: separates π, K, p in 10 $\rightarrow$ 60 GeV/c
- RICH-1 detector: covers horizontal and vertical angular acceptances downstream of the SM1 magnet (250 mrad x 180 mrad)
- focusing technique + photon detectors (MWPC, MAPMT based detectors and MPGD)





$$(n-1)_{UV} \sim 1457 ppm$$

$$cos\theta_c = 1/n\beta$$

$$p_{th} = \frac{m}{\sqrt{n^2-1}}$$

Momentum thresholds:

- π 2.5 GeV/c;
- K 9 GeV/c;
- p 18 GeV/c;

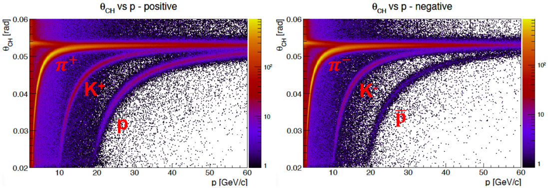
Experimental setup - PID

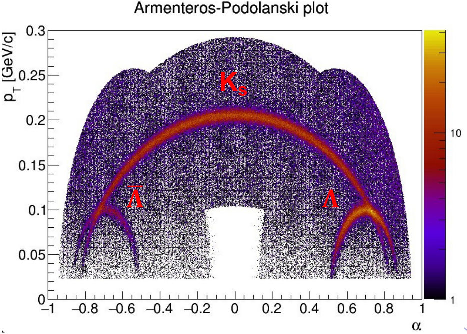
The PID efficiencies are extracted from real data using the decay products of the so-called V_0

Hadrons	Decays	
	Channel	BR (%)
K_S^0	$\pi^+\pi^-$	(69.20 ± 0.05)
ϕ	K^+K^-	(48.9 ± 0.5)
$\Lambda(\bar{\Lambda})$	$p\pi^-\ \left(\bar{p}\pi^+\right)$	(63.9 ± 0.5)

$$\alpha = \frac{p_l^+ - p_l^-}{p_l^+ + p_l^-}$$

2023 pHe ($<$ 1% data sample)





Cross sections experimental setup summary

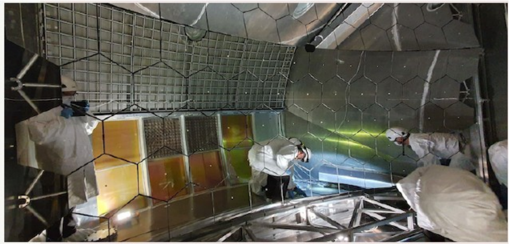
- Secondary hadrons beam from SPS
- Proton beam particle identification provided by CEDARs
- Target (2023: liquid Helium; 2024: liquid hydrogen and deuterium)
- RICH-1 detector to identify final state hadrons
- Count all the inelastic events in the target (N_{tot})
- Count hadrons ($h = p, K, \pi$) produced in inelastic events vs reconstructed momentum and angle ($N_h(p, \theta)$)
- Calculate the double differential cross section as

$$\frac{d^2\sigma_h}{dp d\theta}(p, \theta) \propto \frac{N_h(p, \theta)}{N_{\text{tot}}}$$

(proportionality given by: DAQ dead time, detector efficiencies and acceptance, luminosity...)

2023 Data collected overview

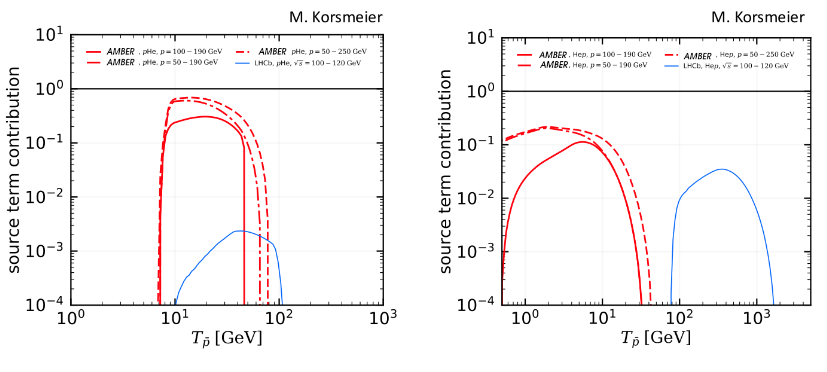
Beam momentum (GeV/c)	Collision energy ($\sqrt{s_{\mathrm{NN}}}$) (GeV)	Number of spills	Estimated num. *pHe* collisions
60	10.7	37000	$\sim 400 \cdot 10^6$
80	12.3	13400	$\sim 230 \cdot 10^6$
100	13.8	13700	$\sim 280 \cdot 10^6$
160	17.3	8500	$\sim 250 \cdot 10^6$
190	18.9	11000	$\sim 340 \cdot 10^6$
250	21.7	7300	$\sim 300 \cdot 10^6$



Expected source term contribution from *pHe* data

$$q_{ij}\left(T_{\bar{p}}\right) = \int_{T_{\mathrm{th}}}^{\infty} dT_i \; 4\pi \; n_{\mathrm{ISM},j} \; \phi_i\left(T_i\right) \frac{d\sigma_{ij}}{dT_{\bar{p}}}\left(T_i, T_{\bar{p}}\right)$$

Ratio q_{ij}^{AMBER}/q_{ij} determines the contribution of the AMBER experiment to the source term

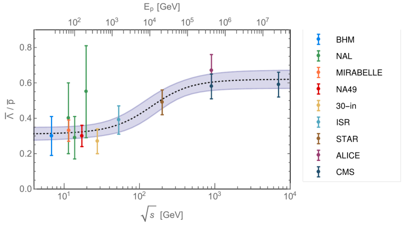


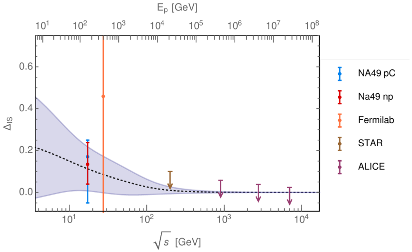
Contribution of 2024 data sample

Other contributions to the total flux of antiprotons include antihyperon decays and neutron decays.

$$f = f^0_{\bar{p}}\left(2 + \Delta_{\mathrm{IS}} + 2\Delta_{\Lambda}\right)$$

Both having large uncertainties from experimental data fits!

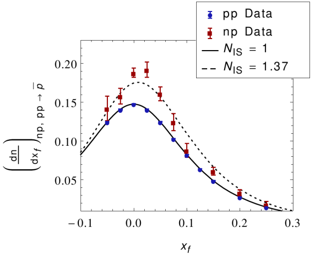




$$\Delta_{IS} = f^0_{\bar{n}} / f^0_{\bar{p}} - 1$$

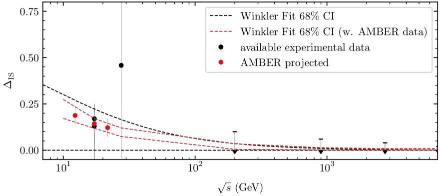
Martin Wolfgang Winkler JCAP02(2017)048, http://dx.doi.org/10.1088/1475-7516/2017/02/048

Contribution of 2024 data sample



Rolf Kappl and Martin Wolfgang Winkler JCAP09(2014)051

Projected impact on the isospin asymmetry:



Thomas Poeschl (adapted)

With *pp*, *pD*, *pHe* @ 250, 190, 80 GeV/c (beam lab frame):

- cross sections scaling
- anti-hyperon production
- prompt hadrons cross section
- isospin asymmetry

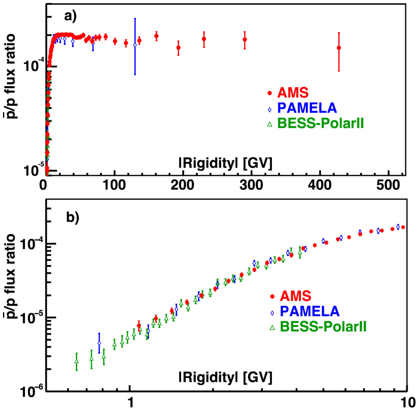
2024 setup almost identical to 2023 → reduced systematics !

Summary

- poor knowledge of $\bar{p}$ production cross sections influences dark matter signals sensitivity
- NA61 $p + p$ data beam momenta of 20, 31, 40, 80, and 158 GeV/c (+ heavier nuclei targets)...
- $p + He$ performed by LHCb at 6.5 TeV/c...
- ... but no data on Helium in typical collision energies of cosmic rays (yet :-))
- $p +^4 He$: AMBER collected data in June 2023, analysis ongoing! ✓
- $p + H_2$ and $p + D$: important contribution for isospin asymmetry + cross section scaling!
  Run starts 10 April 2024

BACKUP

AMS-02 data on $\bar{p}/p$

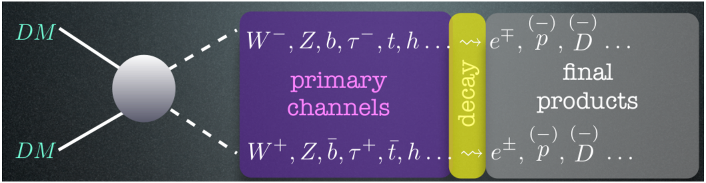


M.Aguilar et al. (AMS02), Phys. Rep. 894, 1

- AMS-02 published high precision data ($< 5\%$) on $\bar{p}$ flux over 1-450 GV range in rigidity
- promising channel in which testing models of production and primary sources

Dark Matter hypothesis

- **WIMP** hypothesis: thermal dark matter particle candidate interacts via decays and annihilation cross section $\langle \sigma v \rangle \sim 3 \cdot 10^{-26} cm^3/s$

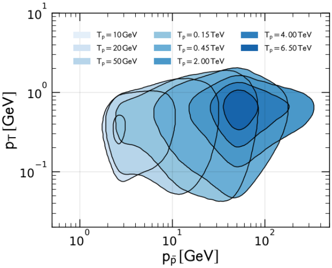


- indirect detection of dark matter (DM) $\Rightarrow$ search of **products of DM annihilation or decay** as excesses in the spectra of rare cosmic ray components like positrons, antiprotons
- Necessity to better validate models: need of higher accuracy of the **predicted natural flux** (spallation of primary cosmic rays with interstellar medium)

Prescriptions on $\bar{p}$ XS data

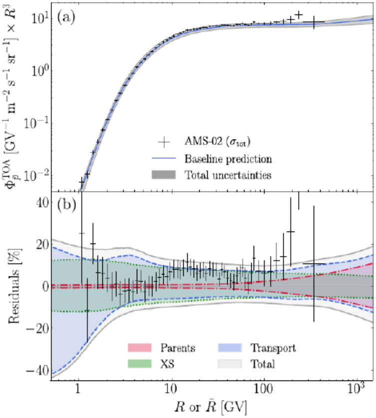
High accuracy is required in the parameter space regions where the cross section is the dominant contribution.

p+He channel

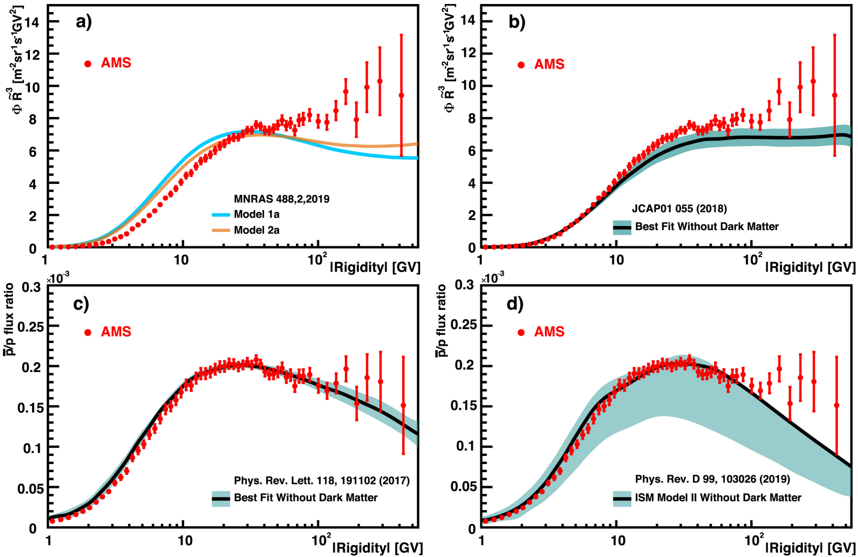


M. Korsmeier et al, Phys. Rev. D 96, 043007

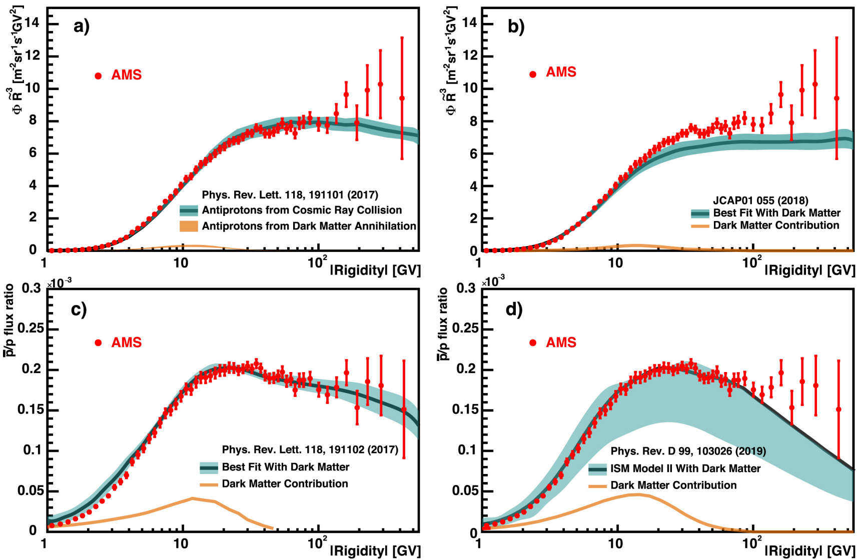
3% relative error within the blue regions (30% outside)



M. Boudaud, Y. Génolini, L. Derome, J. Lavalle, D. Maurin, P. Salati, and P. D. Serpico, Ams-02 antiprotons' consistency with a secondary astrophysical origin, Phys. Rev. Res. 2 (2020) 023022.

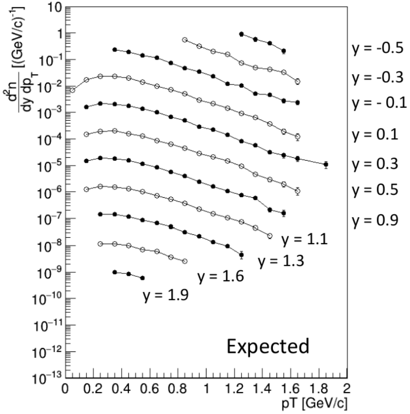


M.Aguilar et al. (AMS02), Phys. Rep. 894, 1

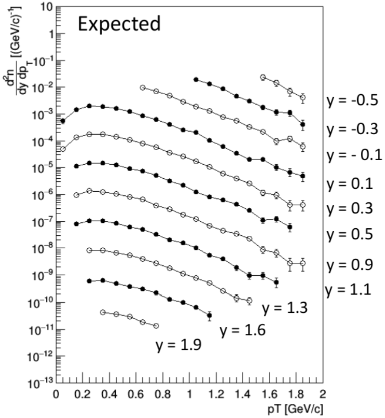


M.Aguilar et al. (AMS02), Phys. Rep. 894, 1

pT yields



190 GeV/c on LH2 (P. Zuccon)



190 GeV/c on LHe (P. Zuccon)

PID algorithm

PID relies on the Extended Maximum Likelihood algorithm. Several mass hypothesis are taken into account and the $\mathscr{L}_m$ is computed:

$$\mathscr{L}_m = \left(\prod_{j=1}^{N} (s_m + b) \right) \frac{\exp\left(-\left(S_m + B\right)\right)}{N!}$$

Each photon is an event, no reference to a reconstructed ring.
Signal term:

$$s_m(\theta_j, \phi_j) = \frac{S_0}{\sigma_{\theta_j}\sqrt{2\pi}} \exp\left\{ -\frac{1}{2} \frac{\left(\theta_j - \Theta_m\right)^2}{\sigma_{\theta_j}^2} \right\} \cdot \epsilon(\theta_j, \phi_j)$$

with:
- Θ_m Cherenkov angle from kinematics for the mass hypothesis
- S_0 number of photons from Frank & Tamm equation: $S_0 = N_0 \sin^2 \Theta_m$