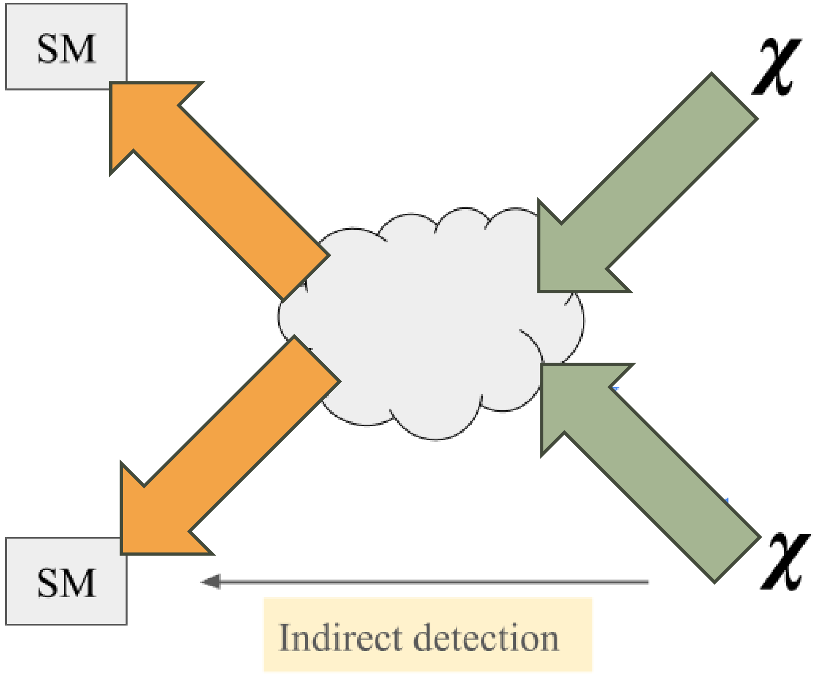
AMBER
CONTRIBUTION TO INDIRECT DARK MATTER SEARCH: ANTIPROTON PRODUCTION CROSS SECTIONS IN p-He / p-H / p-D

Apparatus for Meson and Baryon Experimental Research

Davide Giordano @XSCRC2024

Dark Matter detection - indirect

$\chi\chi \leftrightarrow ll, qq, \ldots$



Decays into SM particles: we can detect them!
The questions are: Where, What and How?

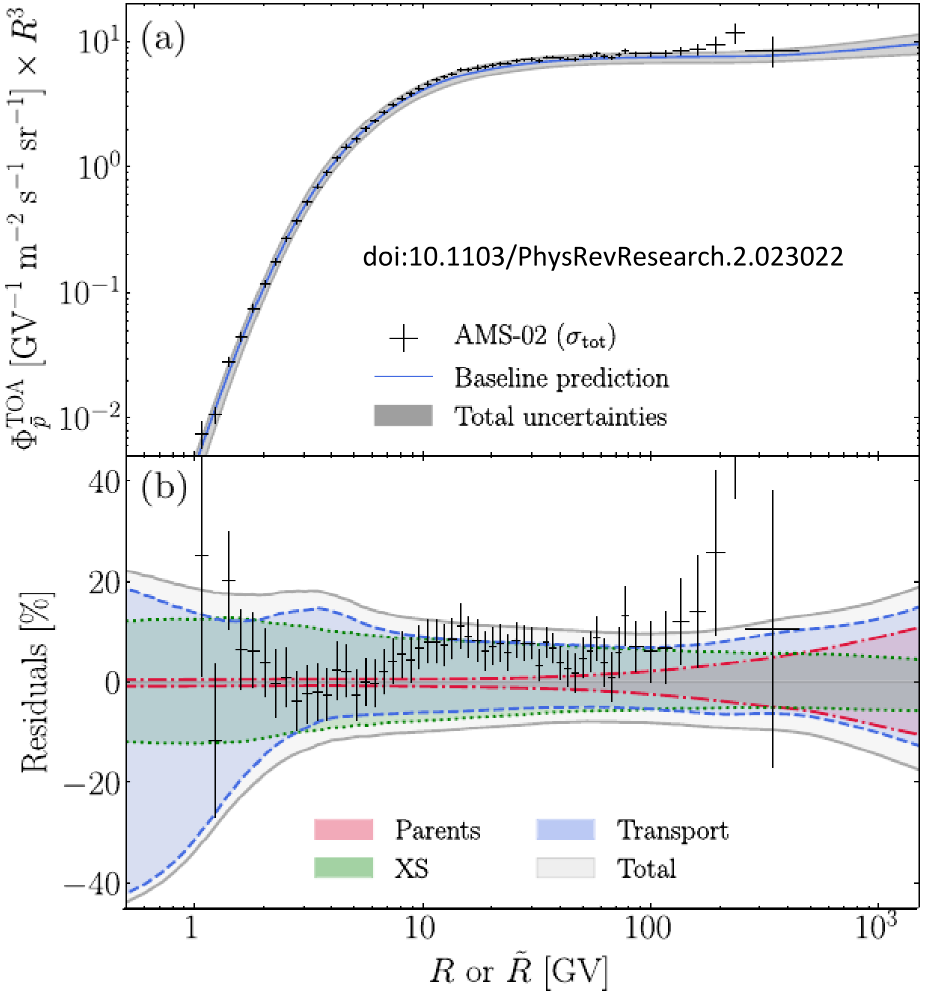
Cosmic rays

Multi-messenger CR fluxes measured by experiments are a powerful tool to test propagation models and dark matter hypotheses.

Few channels are considered “golden-probe”:

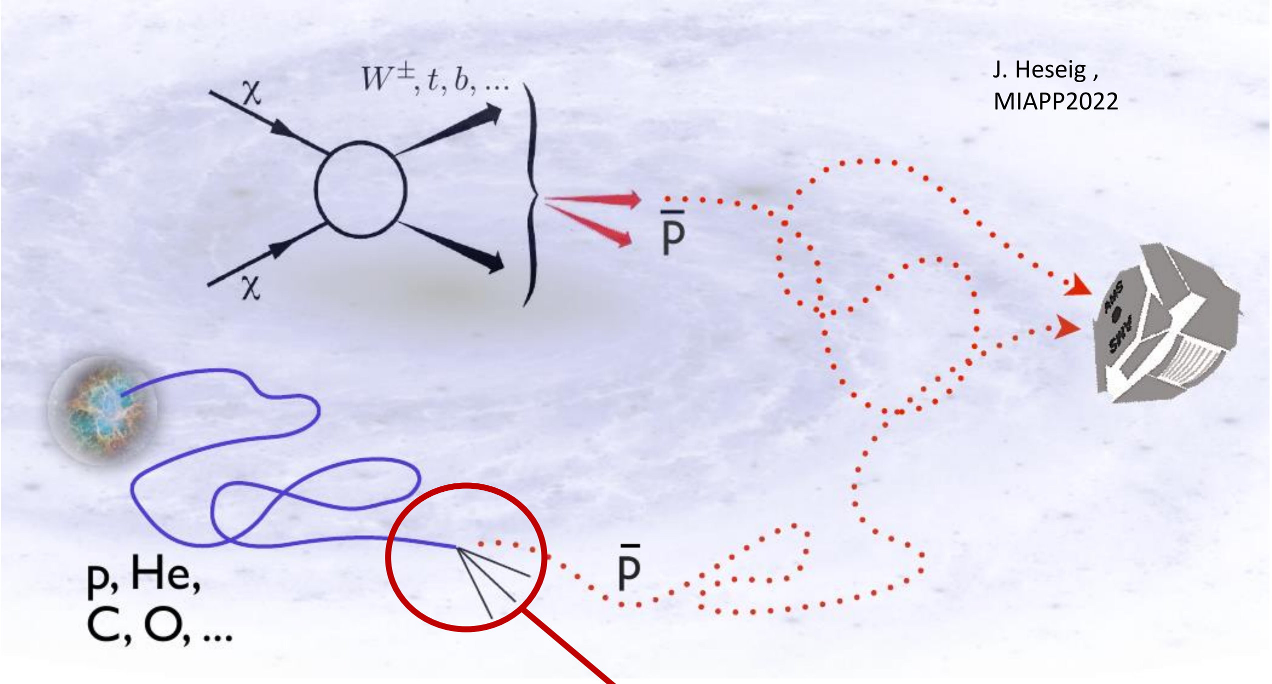
- Low-energy (anti-)nuclei (low statistic, low background)
- **Antiprotons** (high statistics, high background)

Antiproton production



doi:10.1103/PhysRevResearch.2.023022

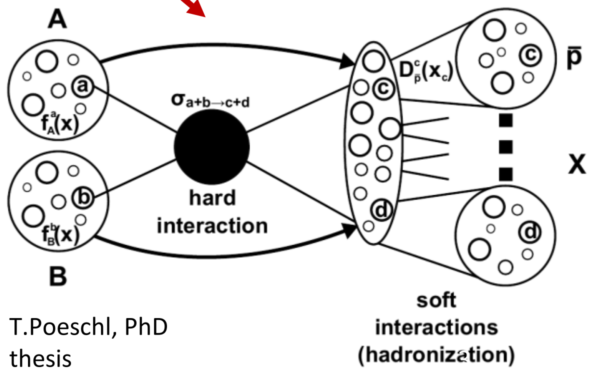
$$R = pc/Ze$$



J. Heseig ,
MIAPP2022

Unprecedented results from AMS-02 at few percent level error

~Flat ratio antiproton/proton with rigidity
NO cosmic primary source. Produced by spallation processes



T.Poeschl, PhD thesis

CR propagation equation and source term

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

Full propagation equation
Typically solved in stationary condition $\frac{d\Psi}{dt} = 0$

Pure primary CR source term

$$q_i(\boldsymbol{x},p) = q_i(r,z,R) = q_{0,i}q_{r,z}(r,z)q_R(R)$$

$$R = pc/Ze \qquad q_R(R) \propto (\mathcal{R})^{-\alpha}$$

Pure secondary CR source term (e.g. antiprotons)

$$q_{ij}(T_s) = \int_{T_{\rm th}}^{\infty} dT_i\, 4\pi\, n_{{\rm ISM},j}\, \phi_i(T_i)\, \frac{d\sigma_{ij}}{dT_s}(T_i,T_s)$$

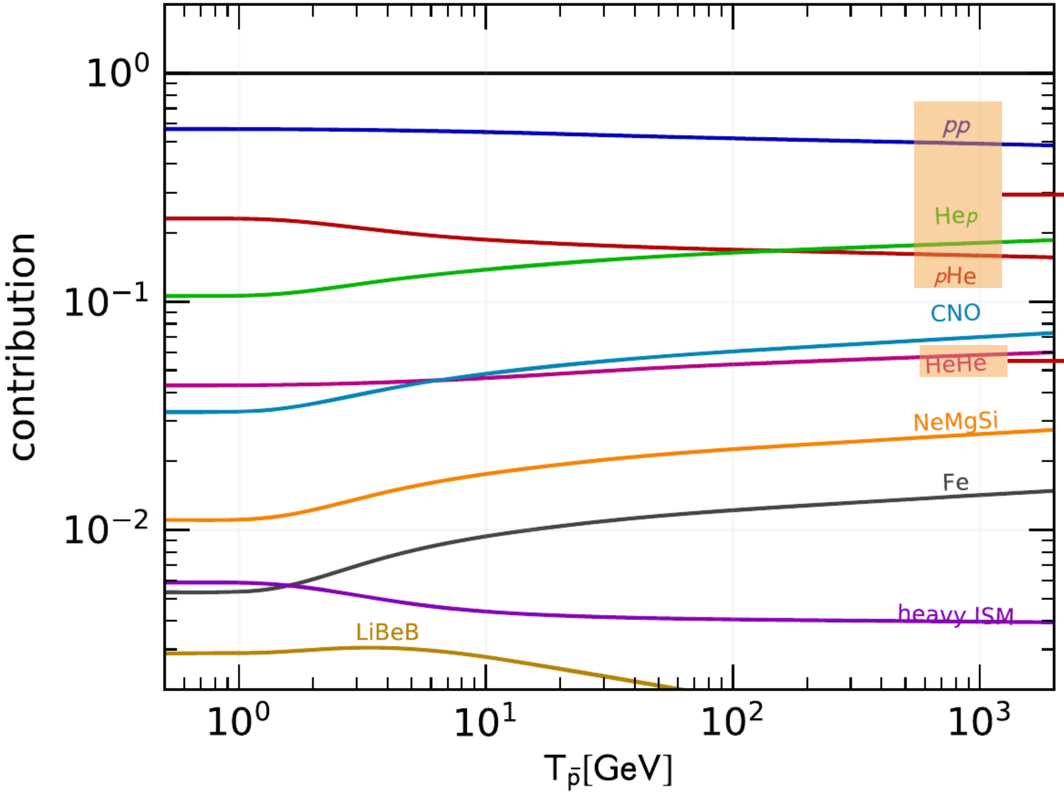
NUCLEAR PRODUCTION CROSS SECTION $\quad i + j \rightarrow s + X$

Antiproton production cross section

Which are the main contributor to the antiprotons production?

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

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



doi:10.1103/PhysRevD.97.103019

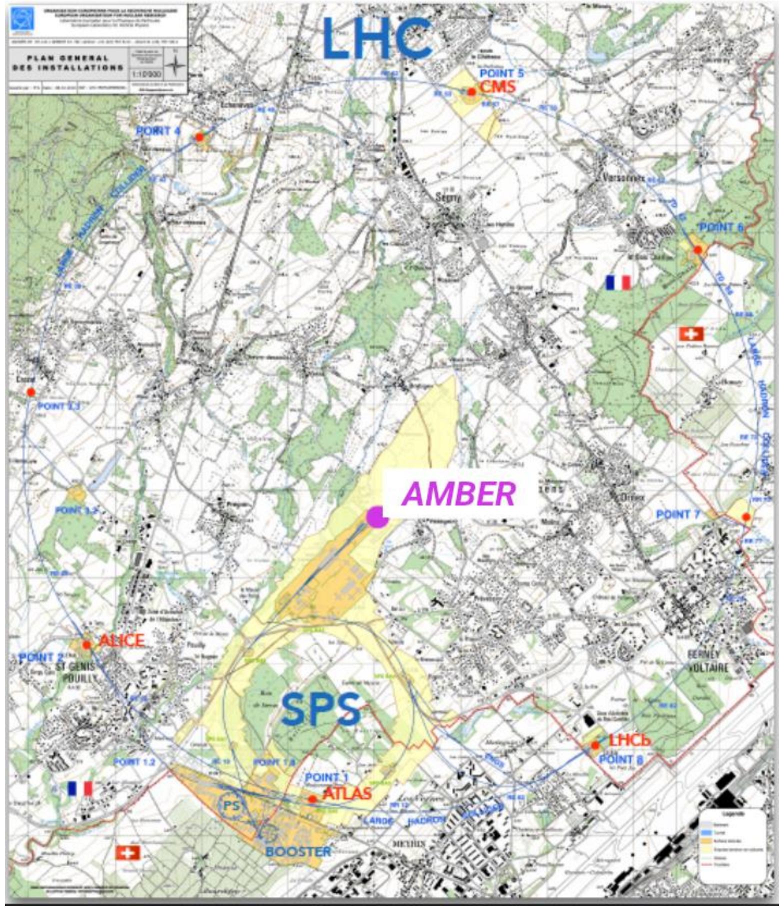
90% of the reactions involve p and Helium (main ISM component)

$\mathrm{p} + \mathrm{p} \rightarrow \bar{\mathrm{p}} + X$ NA61, NA49 $\sqrt{s_{NN}} \sim$ 6.3, 7.7, 8.8, 12.3 and 17.3 GeV;

$\mathrm{p} + \mathrm{He} \rightarrow \bar{\mathrm{p}} + X$ LHCb $\sqrt{s_{NN}} \sim$ 110 GeV (2017)
Scarcity of data, especially in the relevant energy regime for AMS-02

The AMBER experiment @CERN

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).



- proton radius measurement
- proton-induced antiprotons production cross sections for dark matter searches
- pion induced Drell-Yan process

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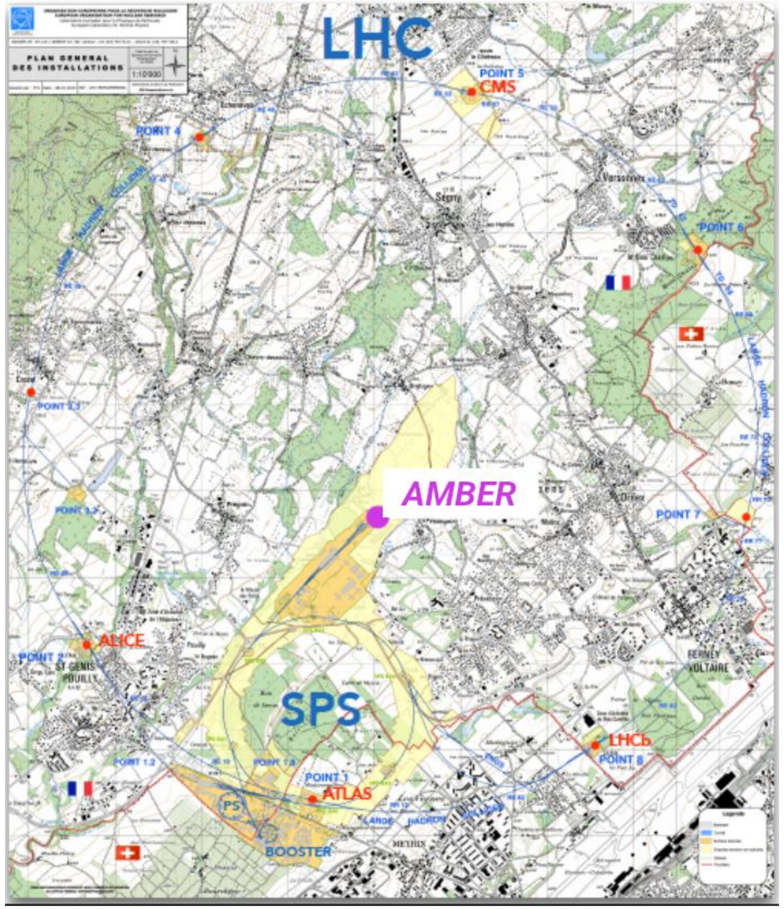

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$\mathrm{p} + \mathrm{He} \rightarrow \bar{\mathrm{p}} + X$

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

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

Oct 2022
1 week
Test run
APXS

May-July
2023
Physics
APXS

May-July
2024
Physics
APXS

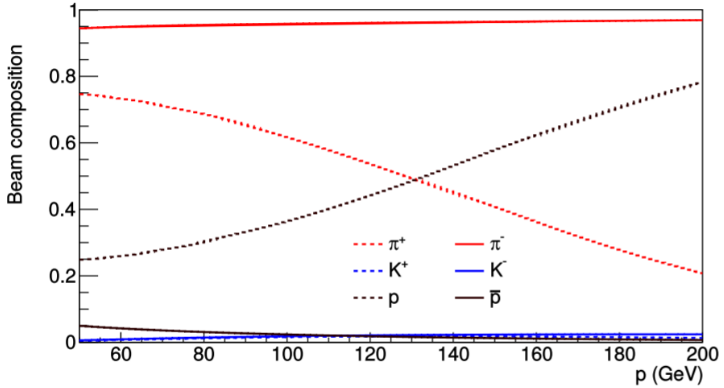
~2 months of data taking
Collected beam momenta **@60, 80, 100, 160, 190, 250 GeV/c**
Minimum bias trigger: beam trigger with veto on non-scattered beam particle

The 2023 p-He data sample

2 months of data taking
Collected beam momenta **@60, 80, 100, 160, 190, 250 GeV/c**

Minimum bias trigger: beam trigger with veto on non-scattered beam particle

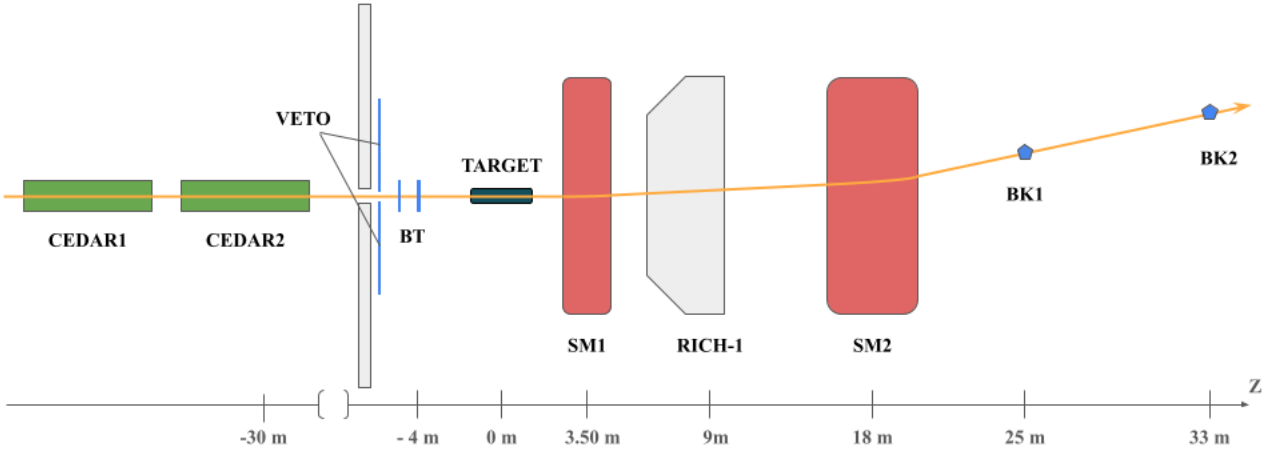
Beam mom. [GeV/c]	Collision energy $\sqrt{s_{\mathrm{NN}}}$ [GeV]	Start Date	End Date	Number of spills
60	10.7	24.05	30.05	37000
80	12.3	17.06	25.06	13400
100	13.8	01.06	11.06	13700
160	17.3	14.06	17.06	8500
190	18.9	19.05	24.05	11000
250	21.7	11.06	14.06	7300



Different number of spills per period to compensate different hadrons mixtures in the beam

@190 GeV/c ~75% protons

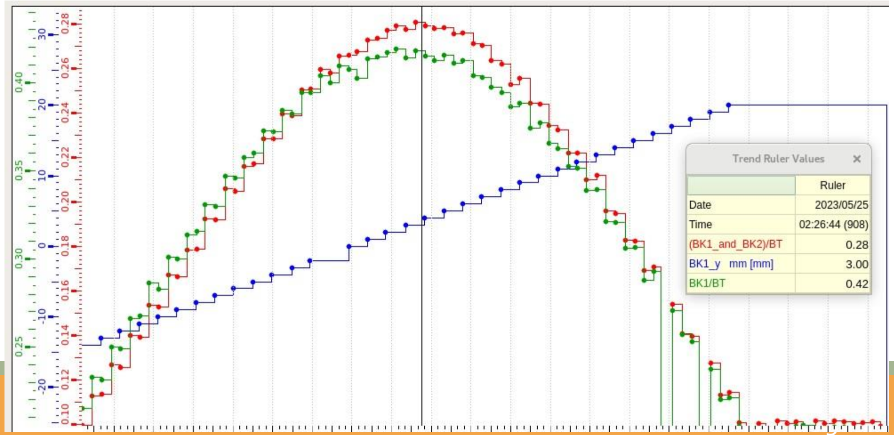
The AMBER experiment @CERN – trigger in 2023



Trigger system:

- Beam trigger (BT) → tags entering beam particles
- Beam killers (BKs) → tags non-interacting beam particles
- VETO → remove unwanted beam tracks (halo + divergent)

Position of beam killer optimized with simulation and intensity scan → changes with different magnets configuration



	Ruler
Date	2023/05/25
Time	02:26:44 (908)
(BK1_and_BK2)/BT	0.28
BK1_y mm [mm]	3.00
BK1/BT	0.42

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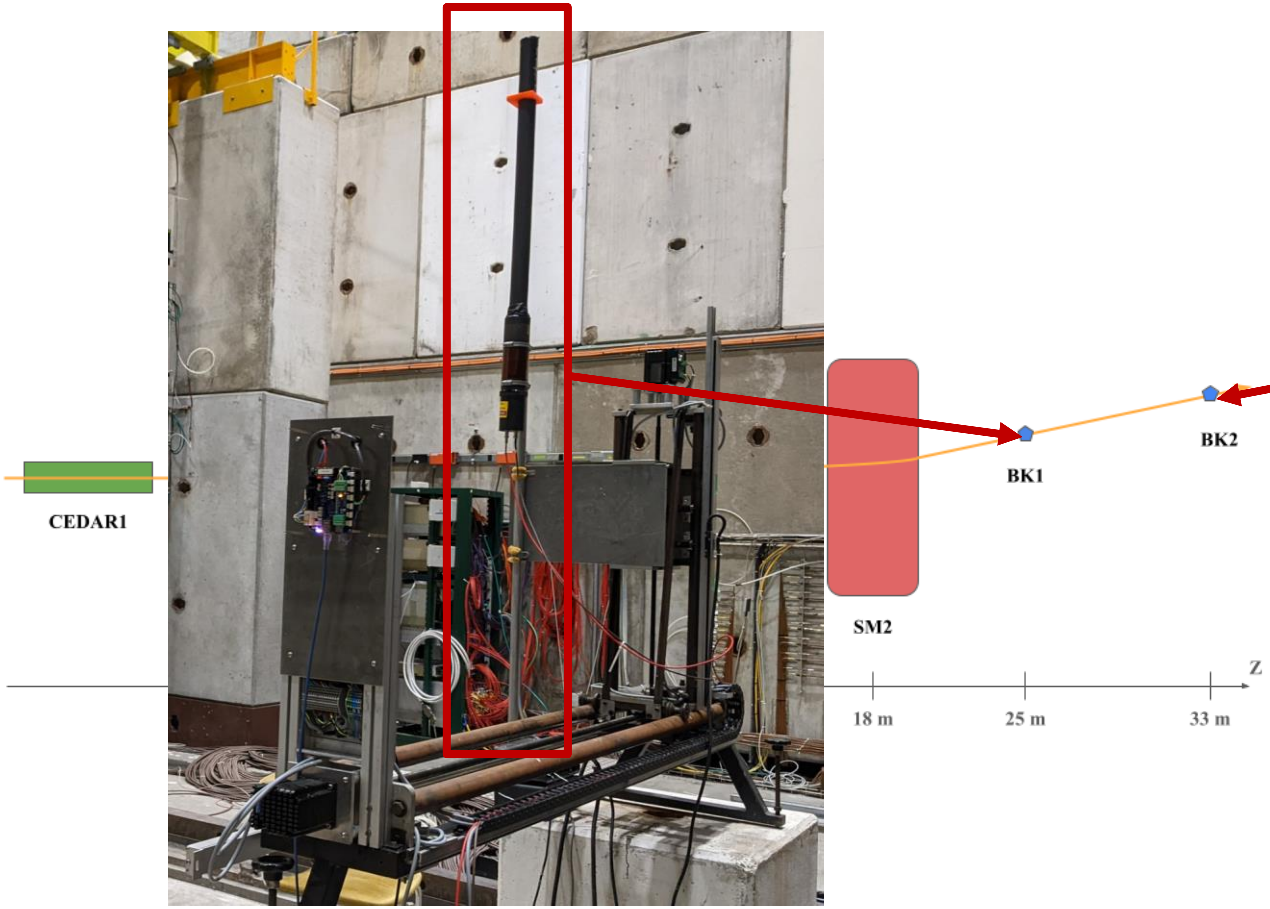
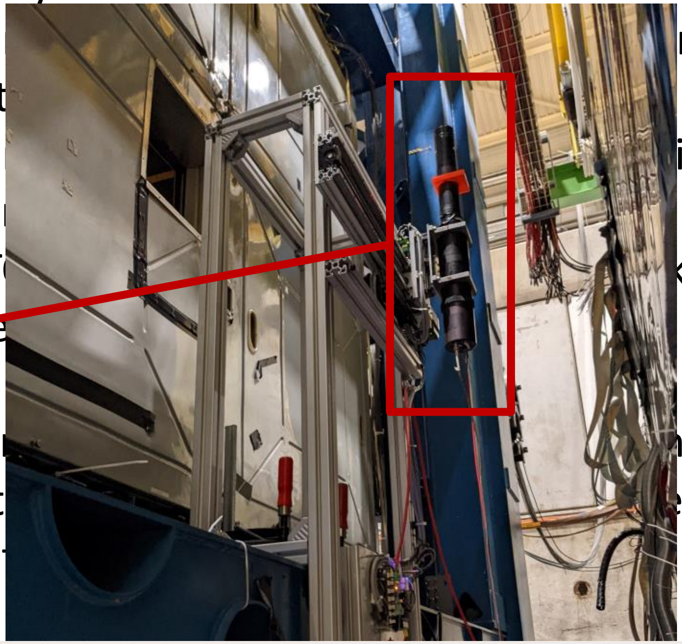
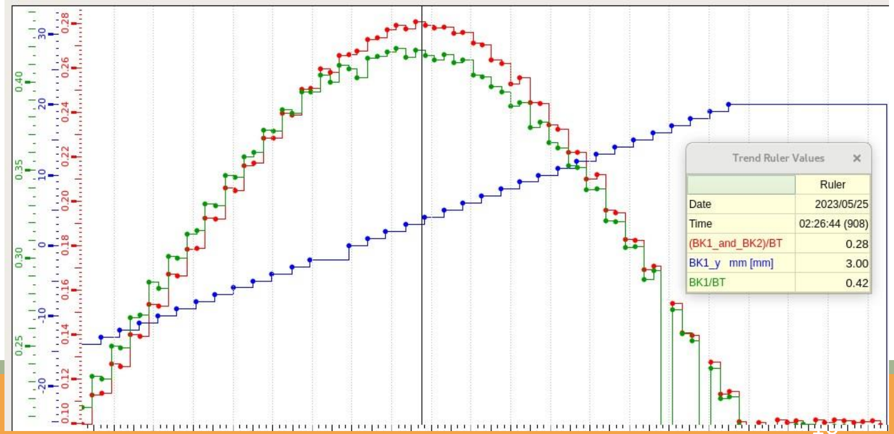




Trigger system:

- Bea m part
- Bea ing bear
- VETO ks (halo + dive

Positio nulation and int ent magnet



Trend Ruler Values

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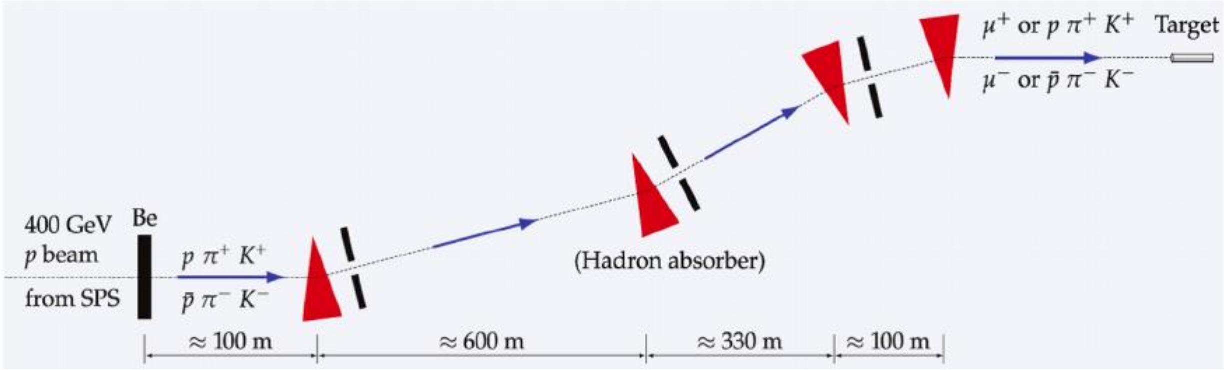
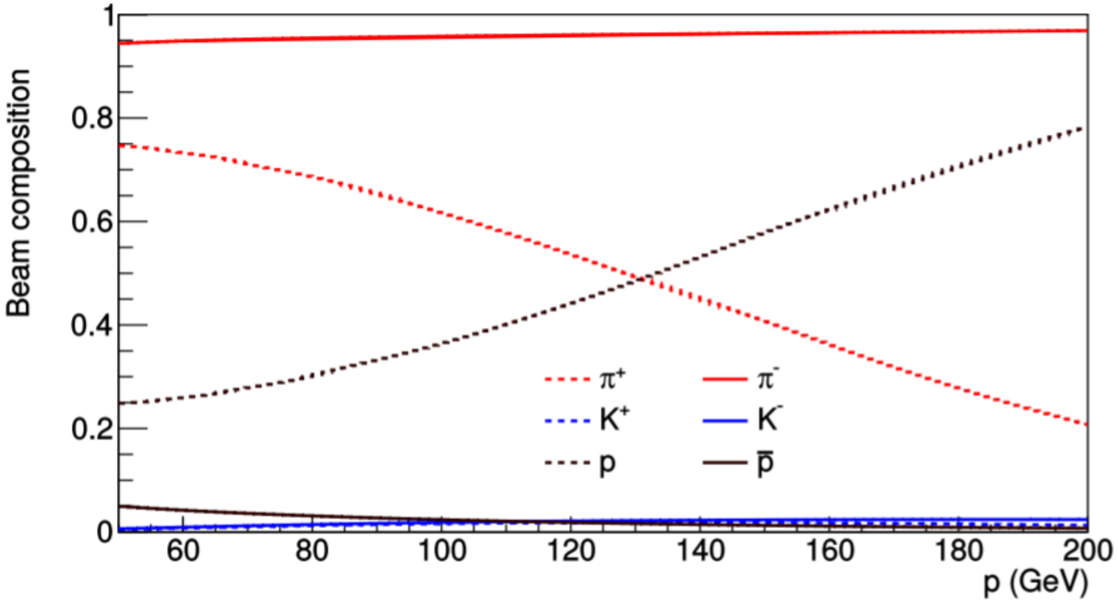
Beam @ AMBER

- Located @EHN2 → fixed target layout
- 400 GeV/c primary proton beam from SPS impinges on production target T6
- secondary beam collected (hadrons, muons or electrons) at 60-250 GeV/c
- beam PID: two CEDAR (Cherenkov light based) detectors

2023 rate ~25k particles/second
→ 130k events / spill





Beam @ AMBER

Located ~ -40 m before target

- Located @EHN2 → fixed target layout
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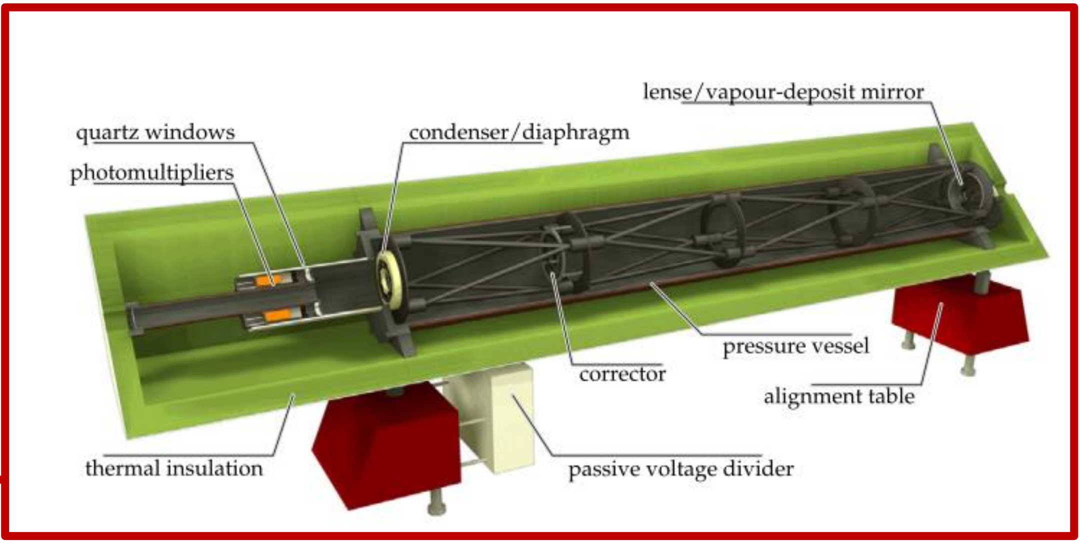
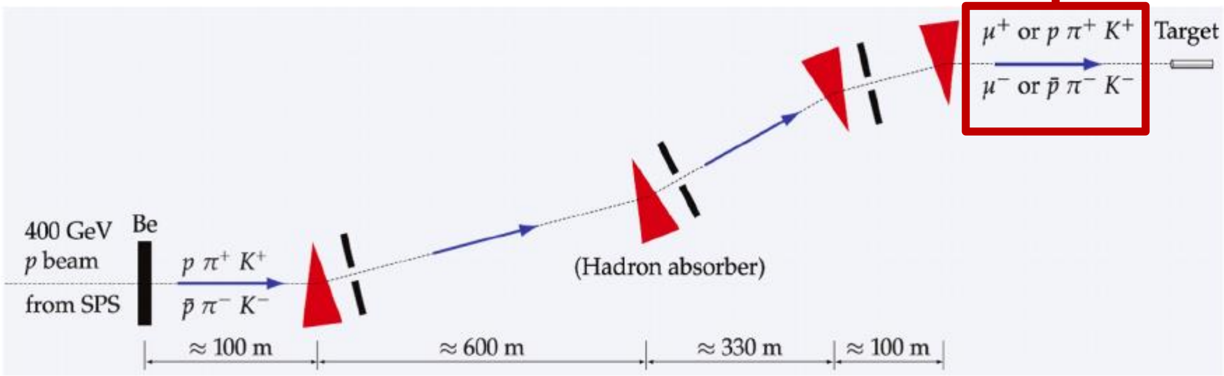
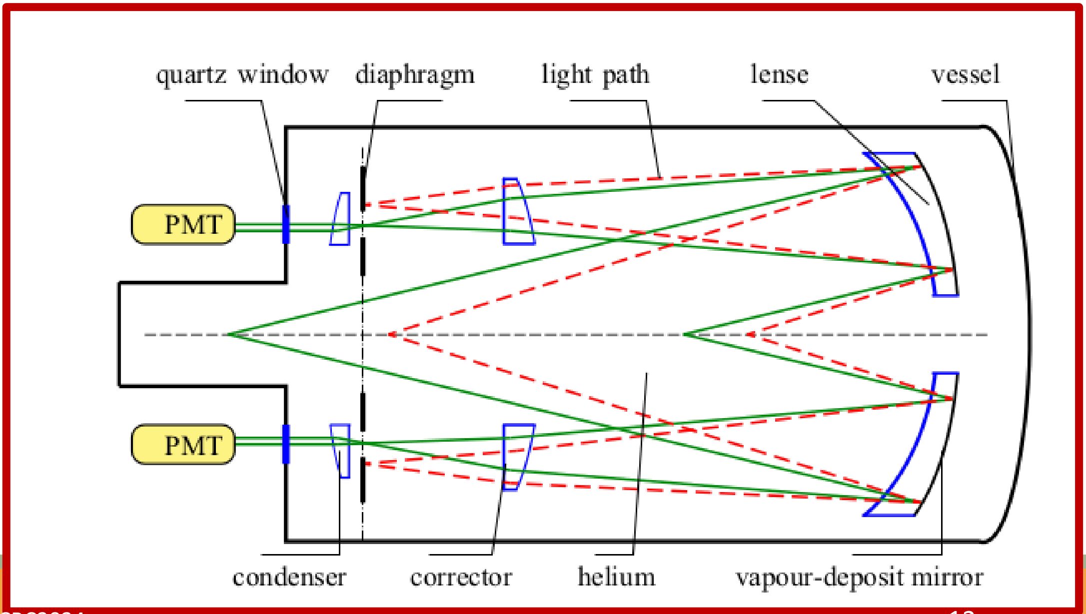
- beam PID: two CEDAR (Cherenkov light based) detectors







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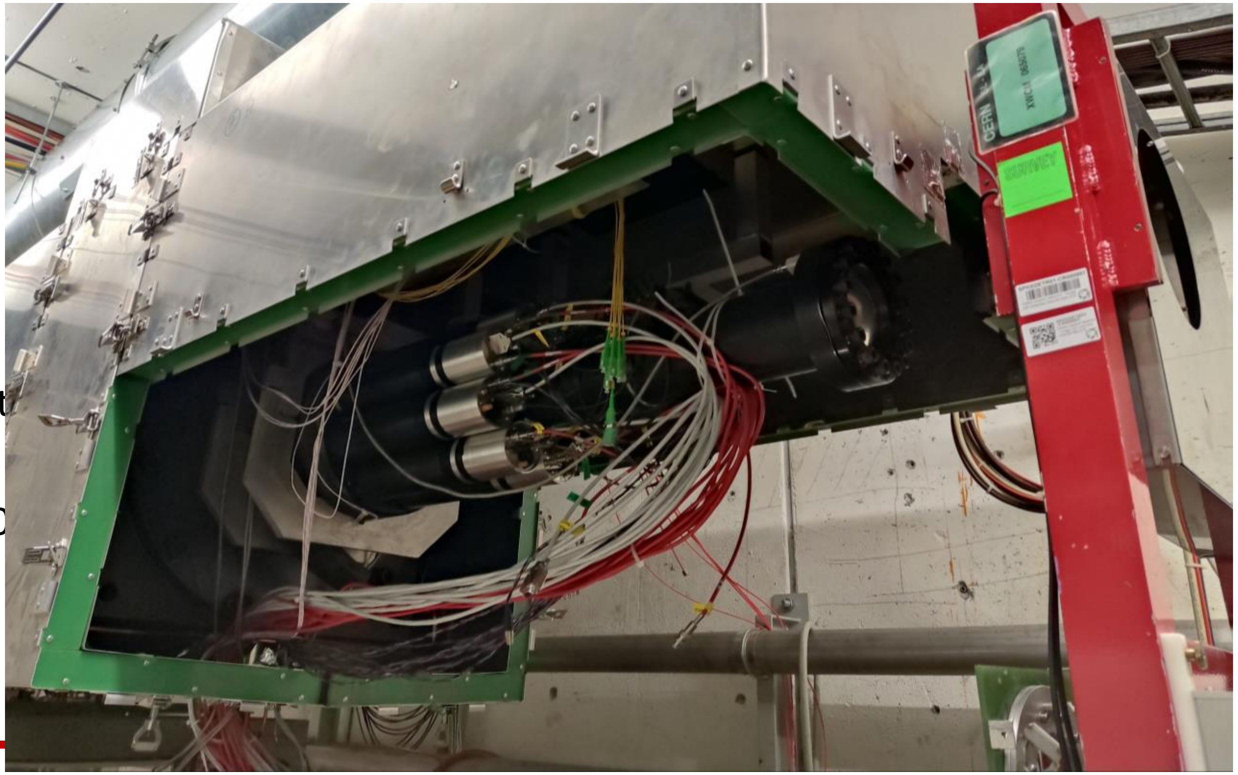
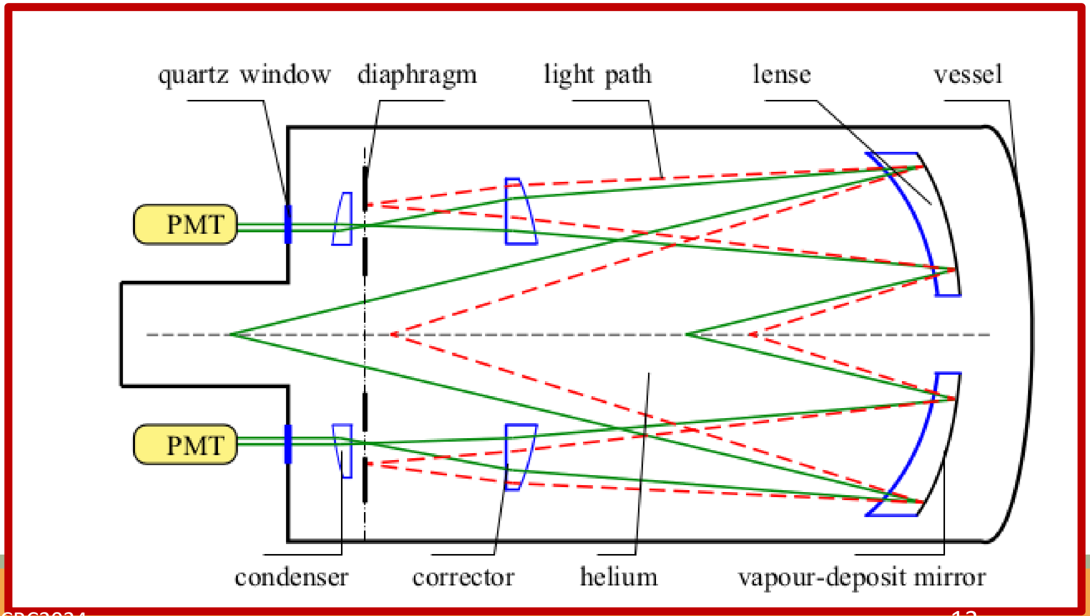
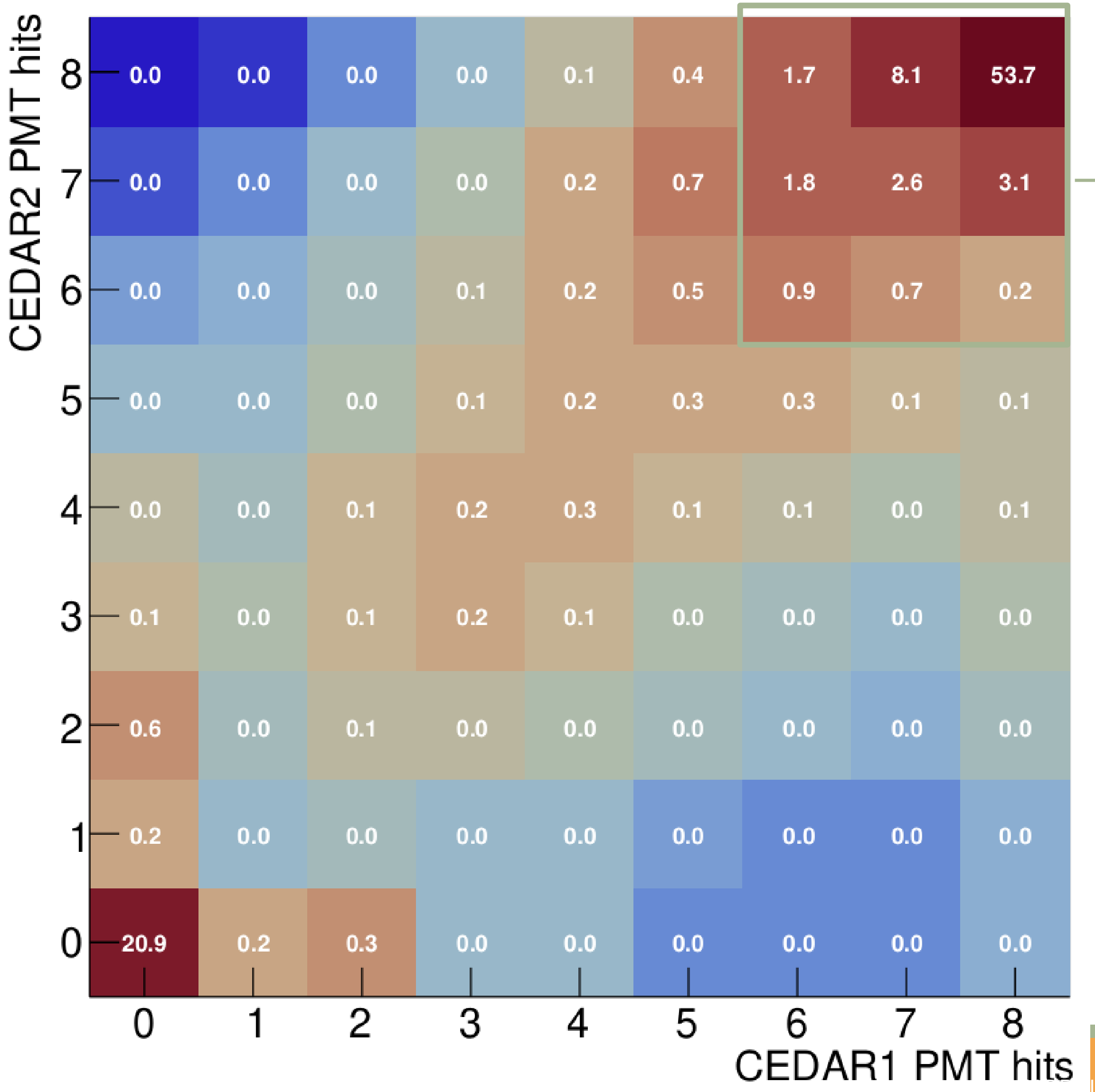




Beam @ AMBER

AMBER preliminary

Beam @190 GeV/c



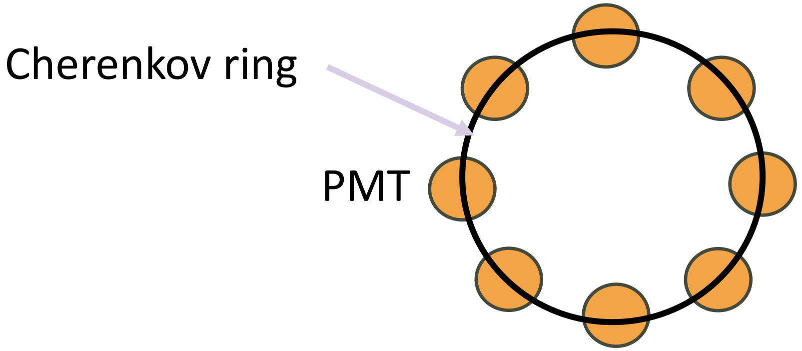
CEDAR2 PMT hits \ CEDAR1 PMT hits	0	1	2	3	4	5	6	7	8
8	0.0	0.0	0.0	0.0	0.1	0.4	1.7	8.1	53.7
7	0.0	0.0	0.0	0.0	0.2	0.7	1.8	2.6	3.1
6	0.0	0.0	0.0	0.1	0.2	0.5	0.9	0.7	0.2
5	0.0	0.0	0.0	0.1	0.2	0.3	0.3	0.1	0.1
4	0.0	0.0	0.1	0.2	0.3	0.1	0.1	0.0	0.1
3	0.1	0.0	0.1	0.2	0.1	0.0	0.0	0.0	0.0
2	0.6	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0	20.9	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0

Expected fraction of protons in the beam is ~75%

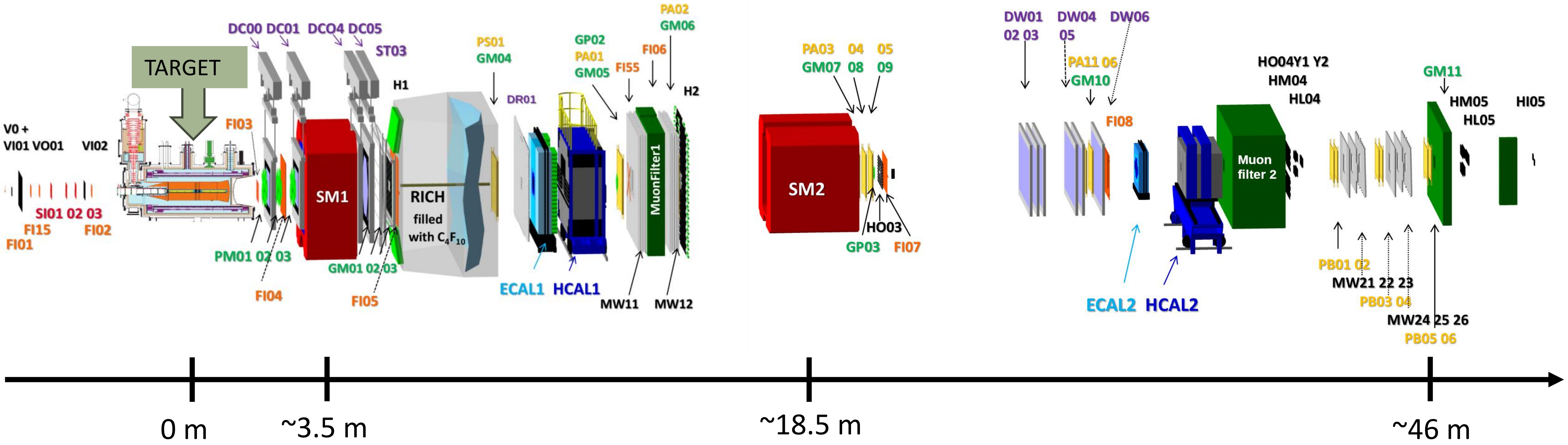
Proton signal well separated from pions and kaons

By selecting the top right region (PMT multiplicities >6 in CEDAR1 and CEDAR2) we get ~73 %

Resulting tagging efficiency of ~96% @190 GeV/c



The AMBER experiment @CERN – layout in 2023



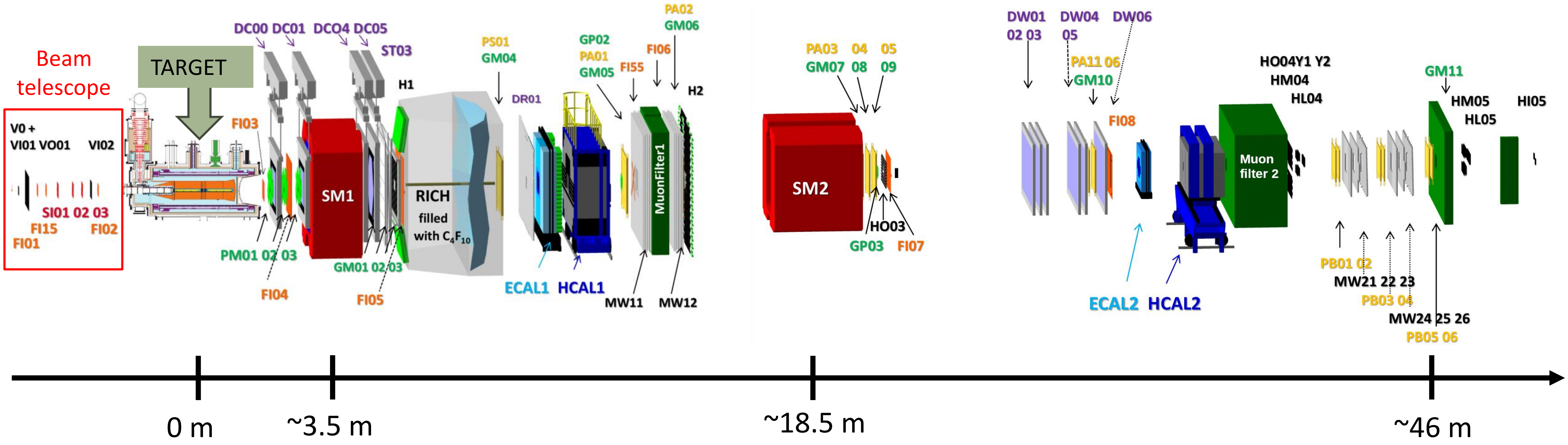
Large Angle Spectrometer (LAS)

- Mainly small+medium size trackers
- SM1
- RICH
- Muon filter
- ECAL

Small Angle Spectrometer (SAS)

- Mainly medium+large area tracker
- SM2
- Muon filter
- ECAL

The AMBER experiment @CERN – layout in 2023



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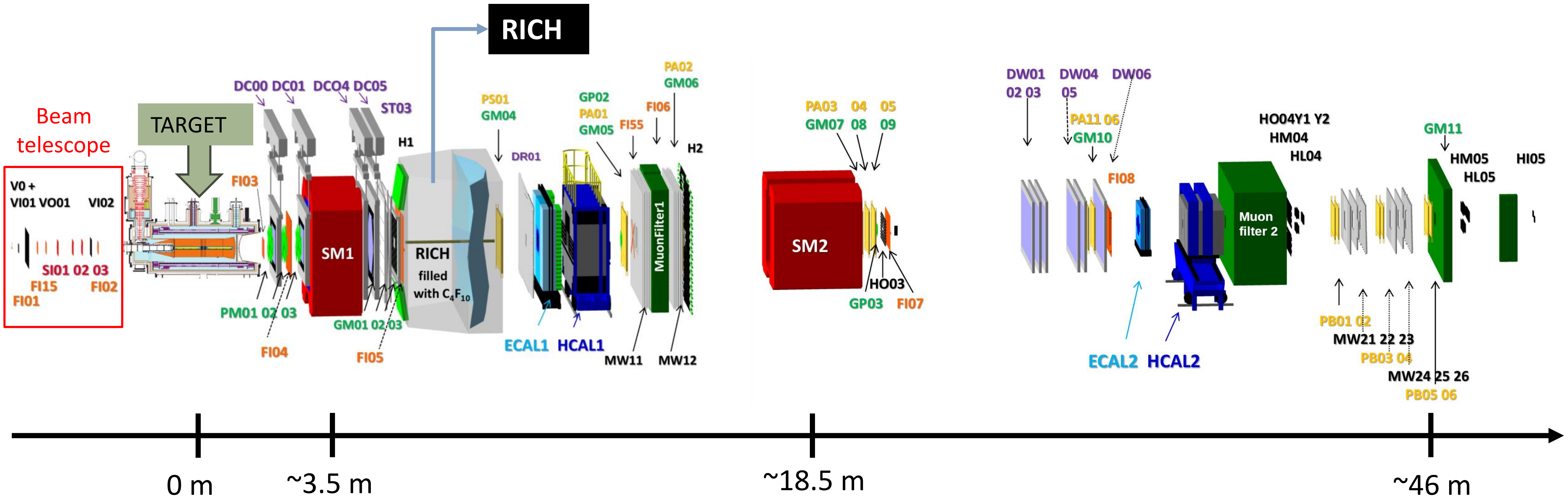

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Analysis outline

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p\,\mathrm{d}p_{\mathrm{T}}}(\mathrm{p}+\mathrm{He} \rightarrow \bar{\mathrm{p}}+X)$$

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Alignment + reconstruction:

- > 200 tracking planes to align

Analysis outline

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p\,\mathrm{d}p_{\mathrm{T}}}(\mathrm{p} + \underset{\text{target}}{\underset{\downarrow}{\mathrm{He}}} \rightarrow \bar{\mathrm{p}} + X)$$

Alignment + reconstruction:

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Analysis of the data

- Data quality (spills and runs rejection)
- Luminosity
- Lifetime DAQ+VETO
- Target position

Analysis outline

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p\,\mathrm{d}p_{\mathrm{T}}}\left(\underset{\text{PID}}{\mathrm{p}}+\underset{\text{target}}{\mathrm{He}}\rightarrow\underset{\text{PID}}{\bar{\mathrm{p}}}+X\right)$$

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PID

- RICH characterization
- CEDAR PID efficiency/purity

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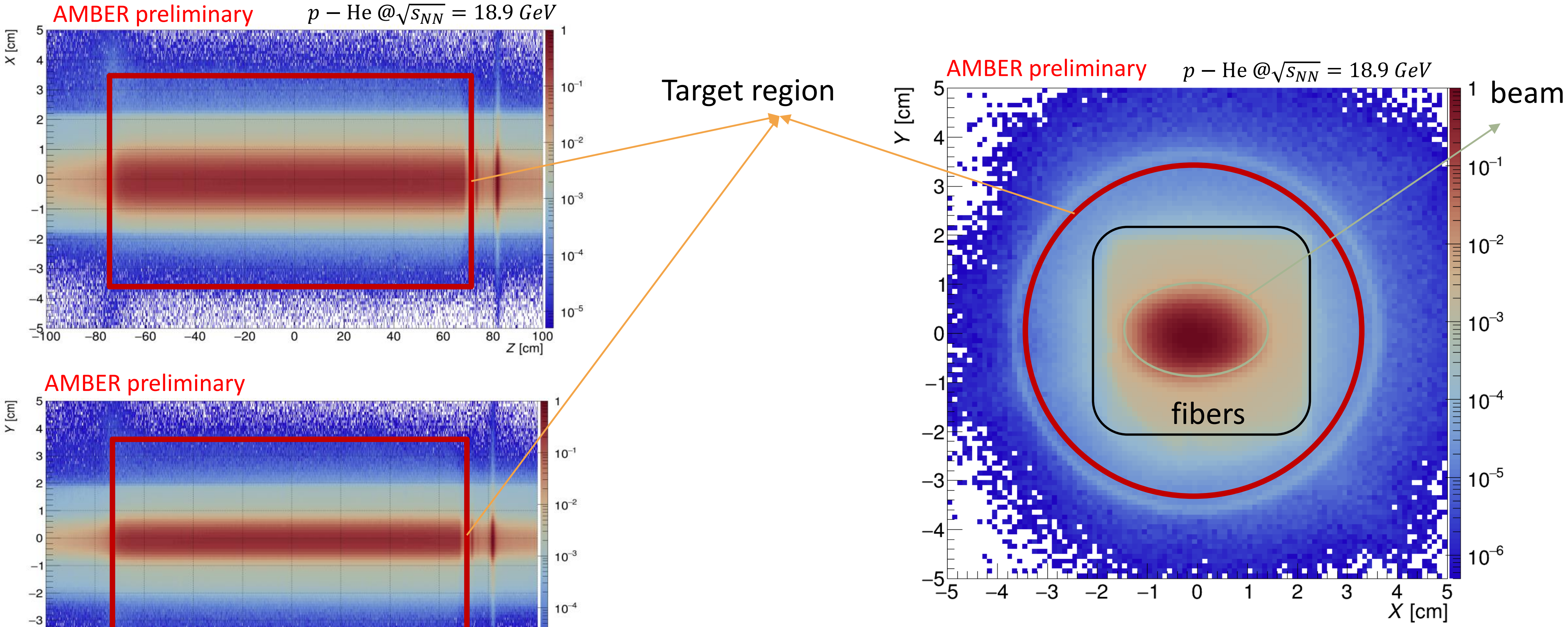
Monte Carlo

- Tune event generator
- Detector efficiencies
- Acceptance corrections
- Bins size optimization

Extraction of the hadrons spectra

- Event and tracks selection
- Corrections:
  - Acceptance
  - Re-interaction
  - RICH
  - …

Reconstructed interaction vertices in the target region



Position and dimension of the target were extracted with a dedicated study using the primary vertices distributions.

RICH-1: final state hadrons PID

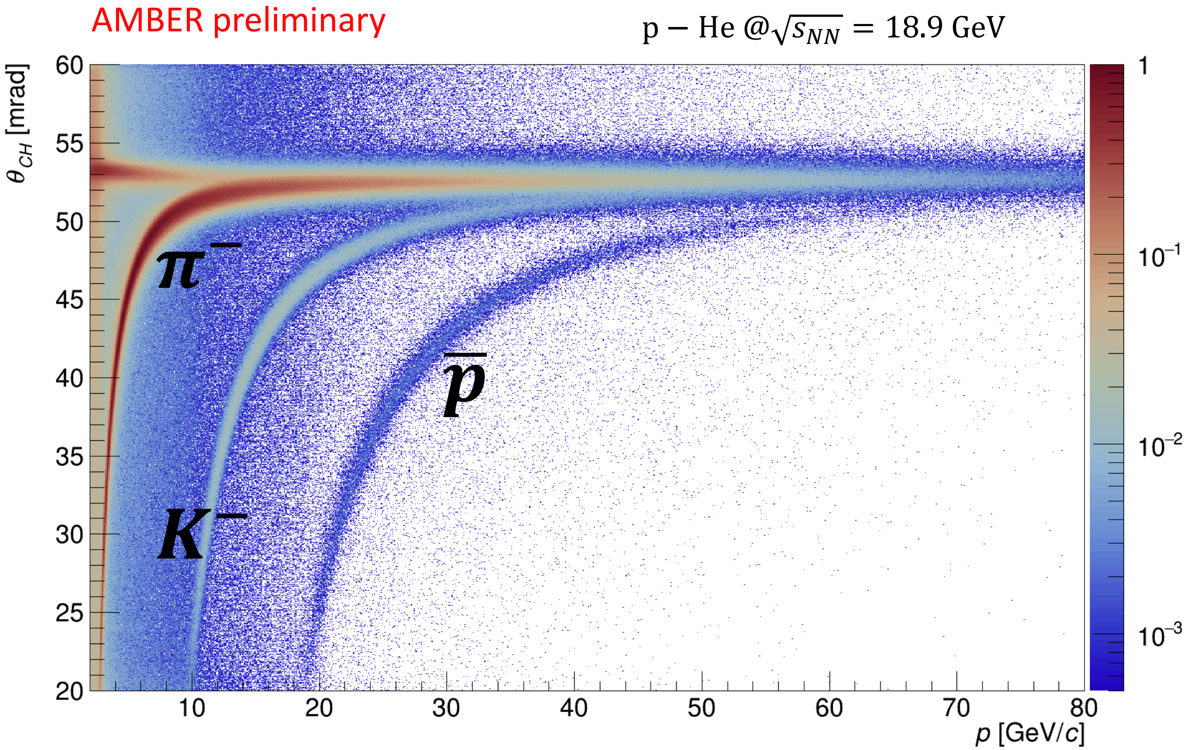
The PID method relies on an extended maximum likelihood approach, based on the parametrization of the expected Cherenkov angle and the position of collected photons

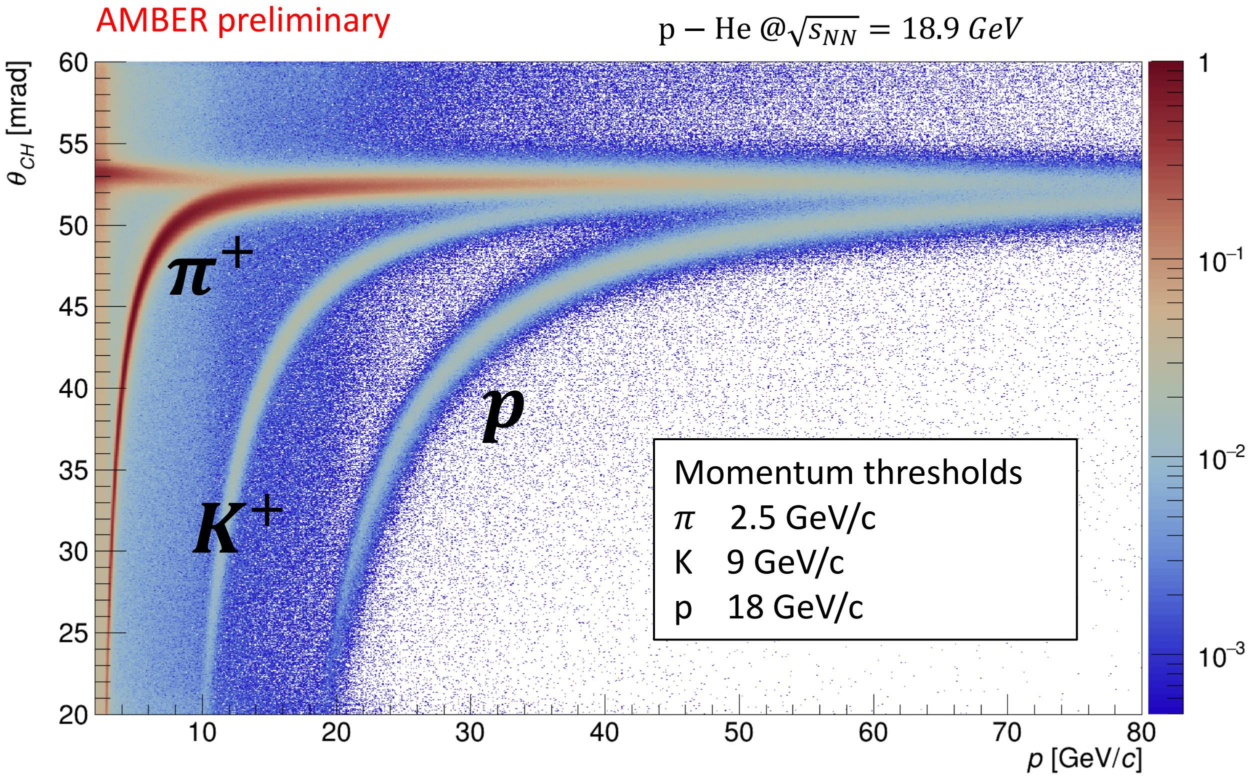
$$\mathcal{L}_M = \exp\left[-\left(S_M + B\right)\right] \prod_{j=1}^{N} f_M\left(\theta_j, \varphi_j\right)$$

$$\boxed{\begin{aligned} S_m &= \int s_m(\theta,\varphi)\,d\theta\, d\varphi \\ B &= \int b(\theta,\varphi)\, d\theta d\varphi \end{aligned}}$$

$$f_M(\theta,\varphi) = s_M(\theta,\varphi) + b(\theta,\varphi)$$

$$s_M\left(\theta_j,\varphi_j\right) = \frac{S_0}{\sigma_{\theta j}\sqrt{2\pi}} \exp\left[-\frac{1}{2}\frac{\left(\theta_j - \Theta_M\right)^2}{\sigma_{\theta j}^2}\right] \varepsilon_D\left(\theta_j,\varphi_j\right)$$



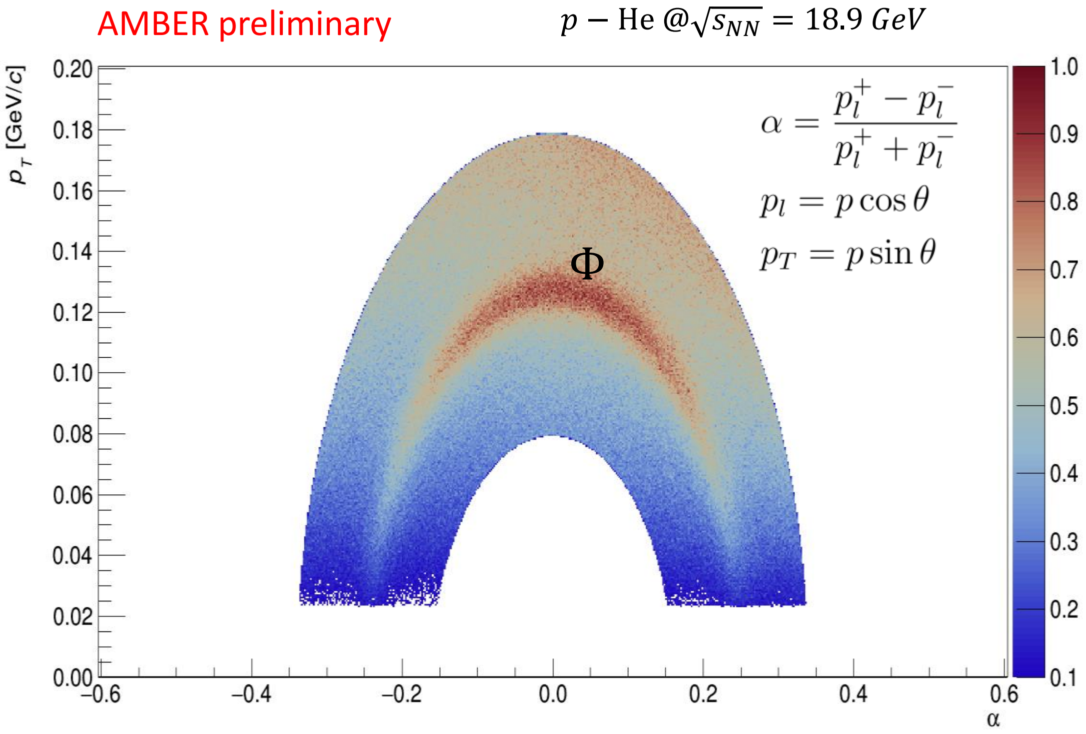


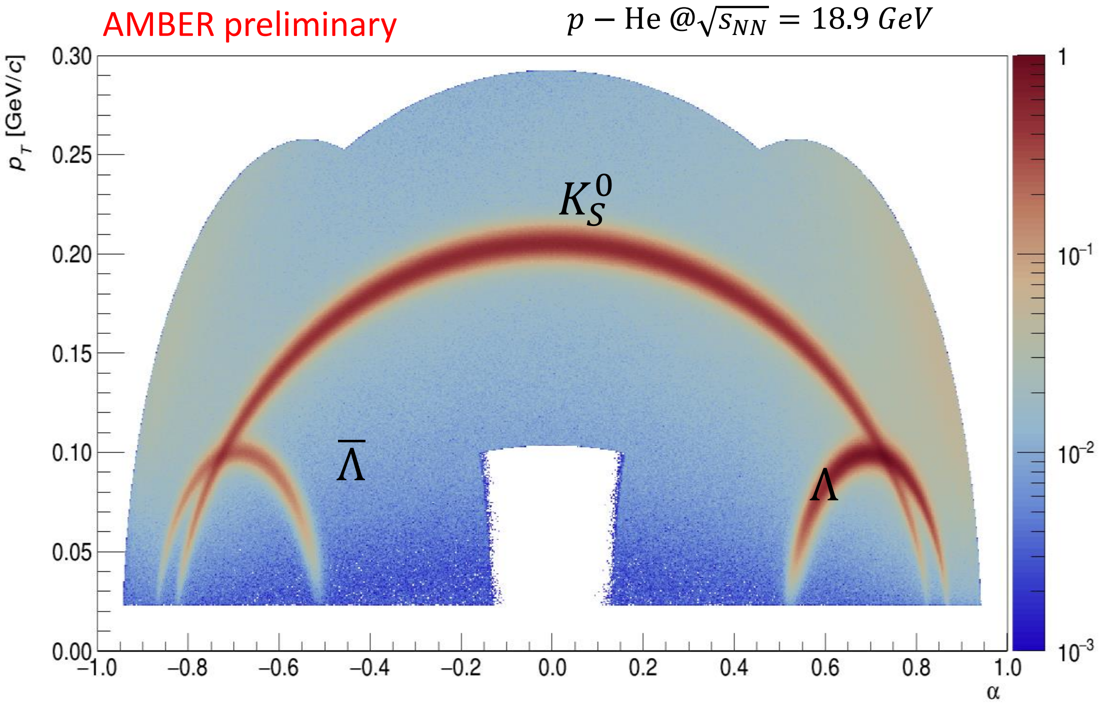
RICH-1: final state hadrons PID

RICH PID matrix estimated from real data V0s decays

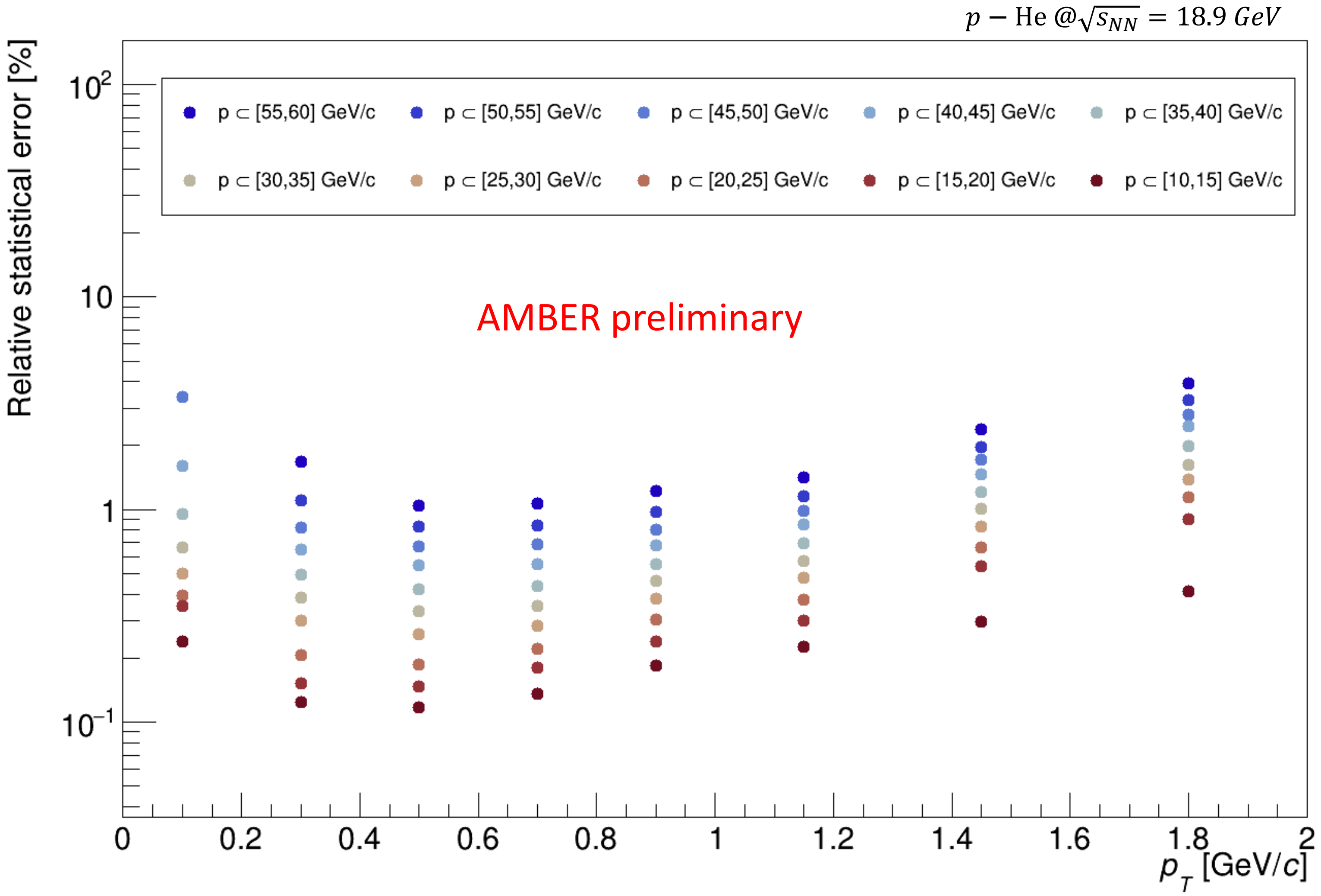
Hadrons	Decays	
	Channel	BR
K_S	$\pi^+\pi^-$	$(69.20 \pm 0.05)\%$
ϕ	K^+K^-	$(48.9 \pm 0.5)\%$
$\Lambda(\bar{\Lambda})$	$p\pi^-$ $(\bar{p}\pi^+)$	$(63.9 \pm 0.5)\%$

$$M^{+/-}_{RICH}(p,\theta) = \left(\begin{array}{ccc} \epsilon(\pi \to \pi) & \epsilon(K \to \pi) & \epsilon(p \to \pi) \\ \epsilon(\pi \to K) & \epsilon(K \to K) & \epsilon(p \to K) \\ \epsilon(\pi \to p) & \epsilon(K \to p) & \epsilon(p \to p) \\ \hline \epsilon(\pi \to X) & \epsilon(K \to X) & \epsilon(p \to X) \end{array}\right)$$





Relative statistical error on antiproton spectra



A preliminary unfolding shows that we collected ~6million antiprotons in

- p [10, 60] GeV/c
- p_T [0, 2] GeV/c

Statistical errors in most bins < 1%

Leading systematic errors expected from:

- Luminosity
- RICH unfolding

Antiproton production from decays

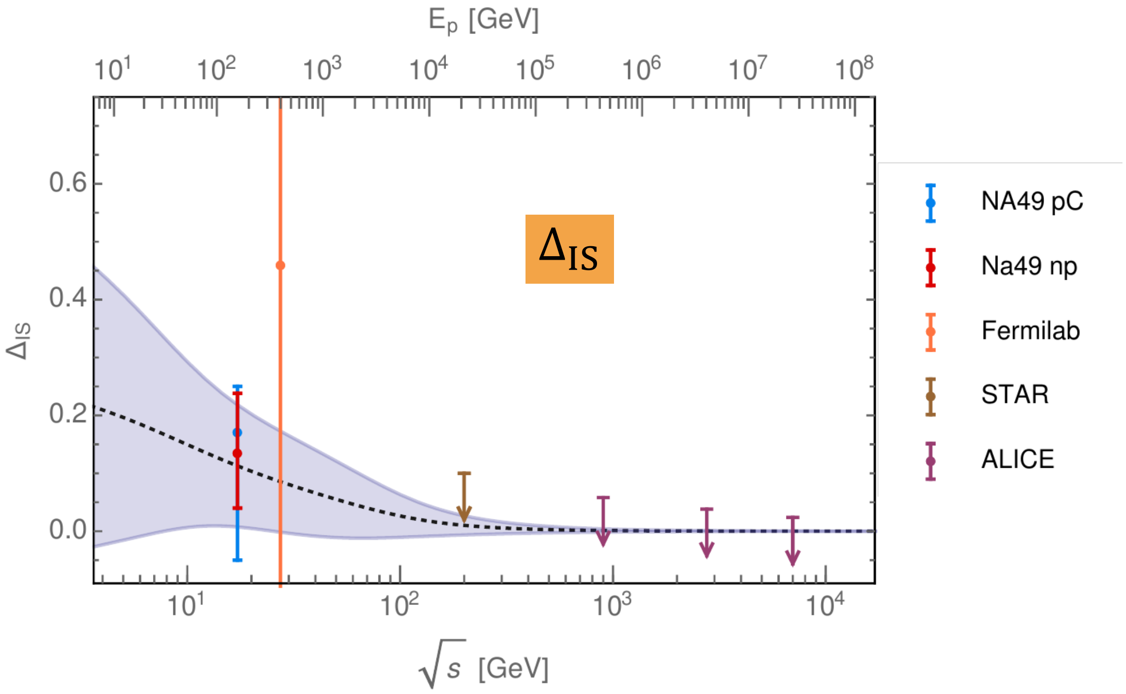
$$f = f^0_{\bar{p}} \left(2 + \Delta_{\mathrm{IS}} + 2\Delta_{\Lambda}\right)$$

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

Antiproton production from decays

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

https://doi.org/10.1016/S0927-6505(01)00107-4



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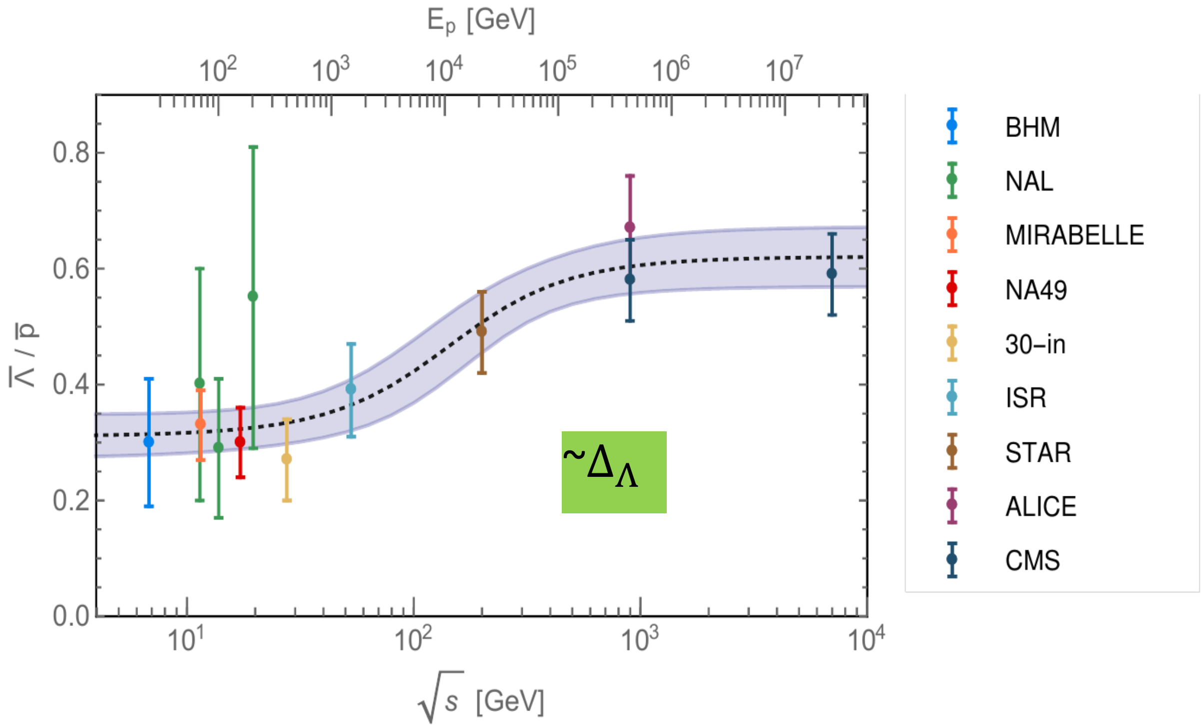

Production asymmetry $p\bar{n}/\bar{p}n$

Antiproton production from decays

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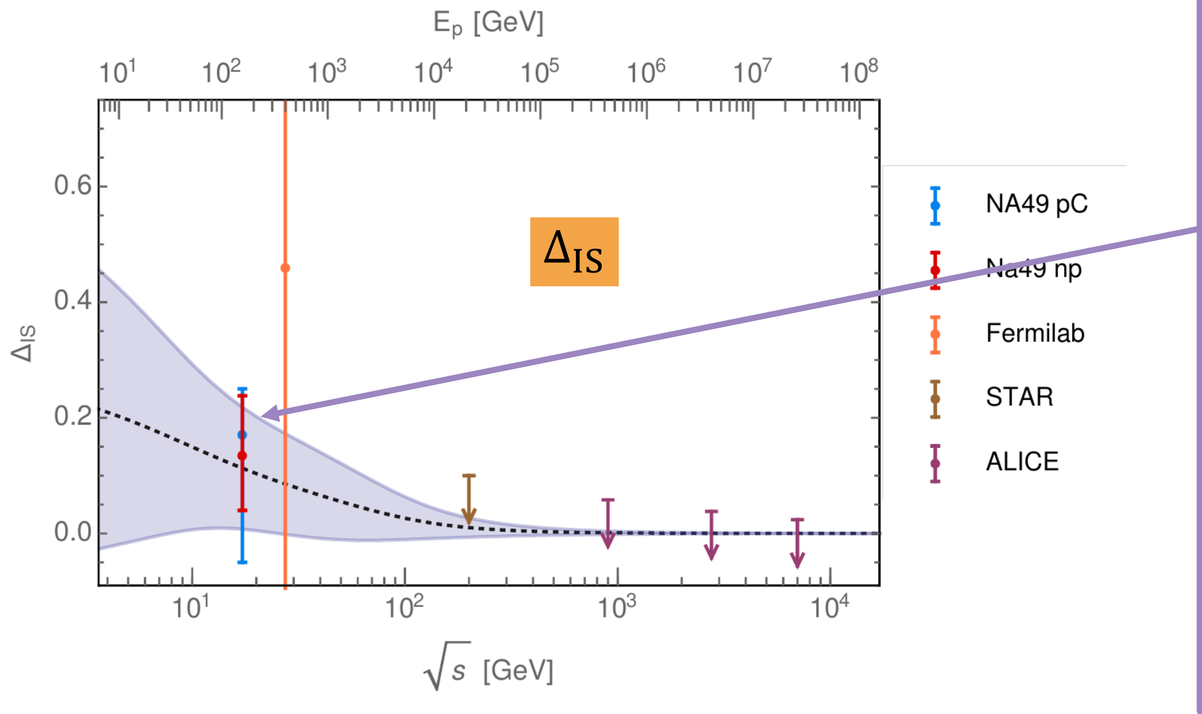
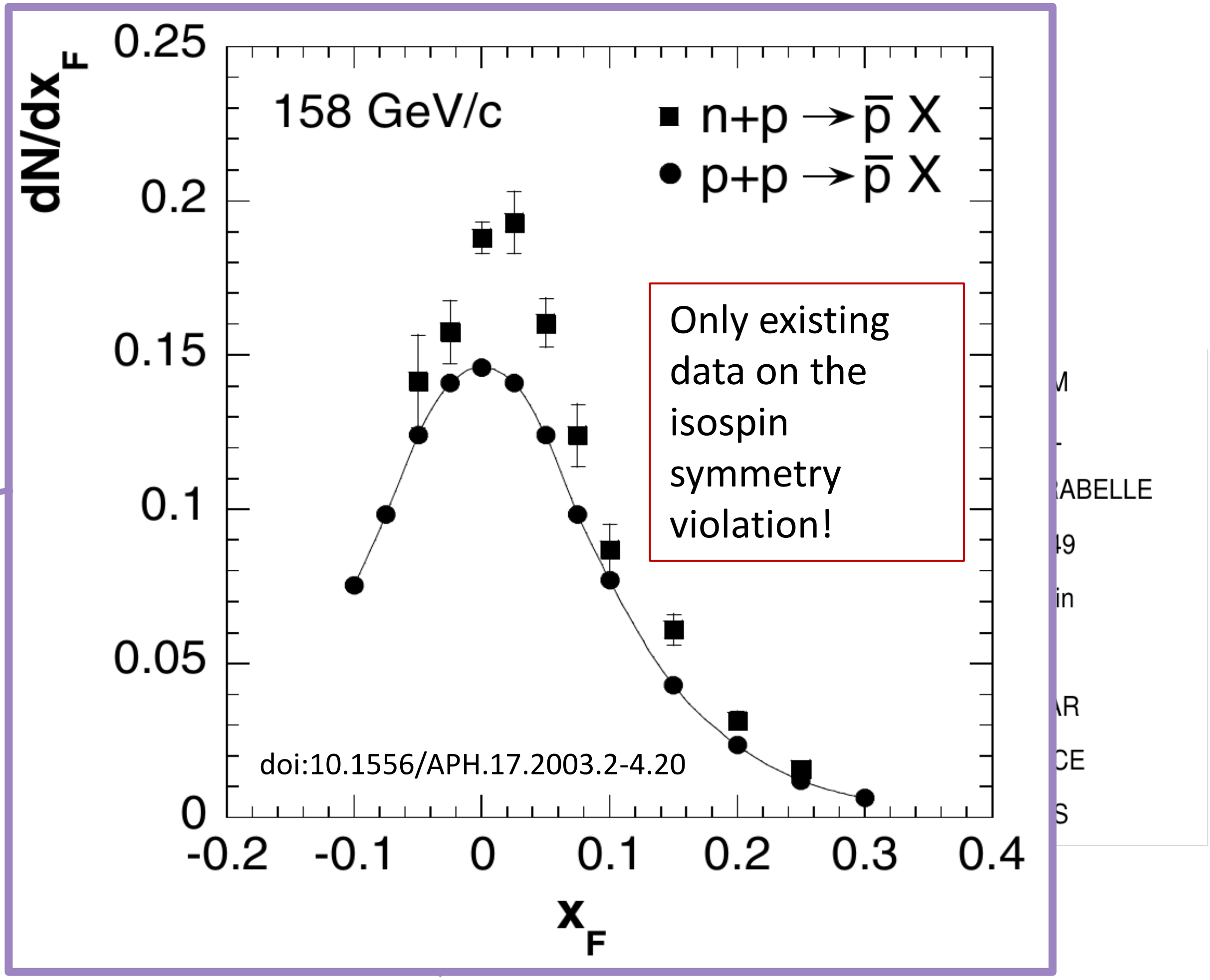




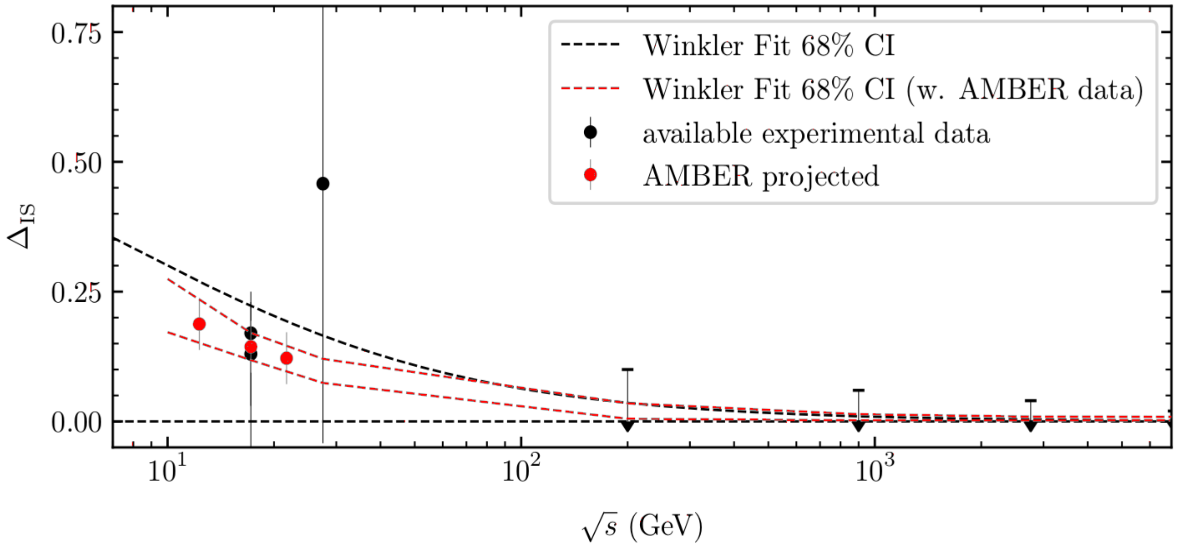
Only existing data on the isospin symmetry violation!

doi:10.1556/APH.17.2003.2-4.20

$p\bar{n}/\bar{p}n$

Data 2024 – just finished collecting!

Private exchange with T. Poeschl



This year running with 2 targets

1. liquid Hydrogen
2. liquid deuterium

With beam momenta @80,160,250 GeV/c

The data collected at the same energy with the different targets let us calculate the production rates in p-p and p-D that may confirm or not the presence of an isospin asymmetry.

In both cases, the error will be reduced and directly impact the antiproton production parametrization at low energies.

Summary

Apparatus for Meson and Baryon
Experimental Research

The dark matter indirect detection reached a "precision" era thanks to very precise data by experiments and more precise models in the propagation and creation of cosmic rays

A leading uncertainty comes from the scarcity of data in the relevant reaction channels (pp and pHe) at the cosmic "scale"

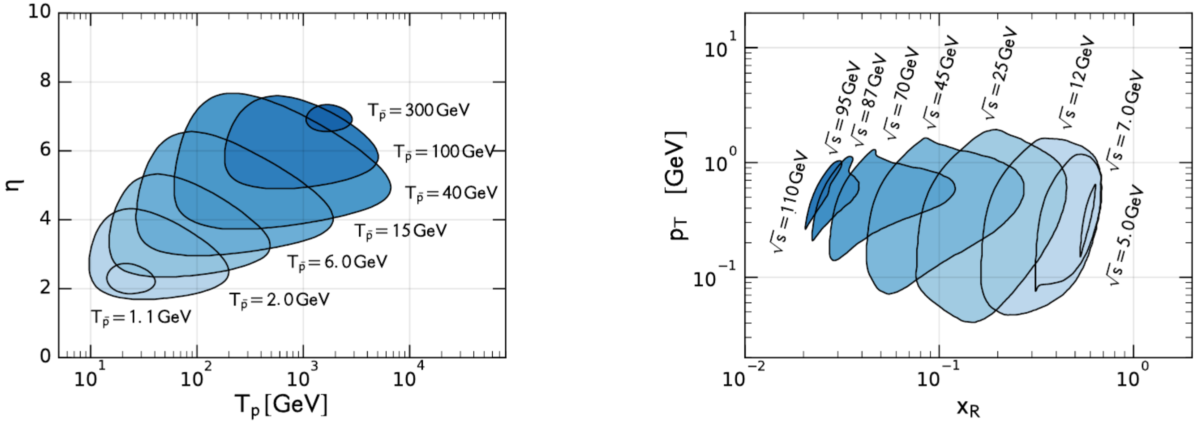
AMBER collected data on p-He in 2023 and p-H / p-D in 2024. These dataset are expected to give a significant impact in the antiproton production modeling

Preliminary results on 2023 p-He data are presented here. They show very good performance of the spectrometer and a very good coverage of the phase space with small statistical uncertainty between 10-60 GeV/c in momentum and 0-2 GeV/c in transverse momentum.

Analysis ongoing!

BACKUP

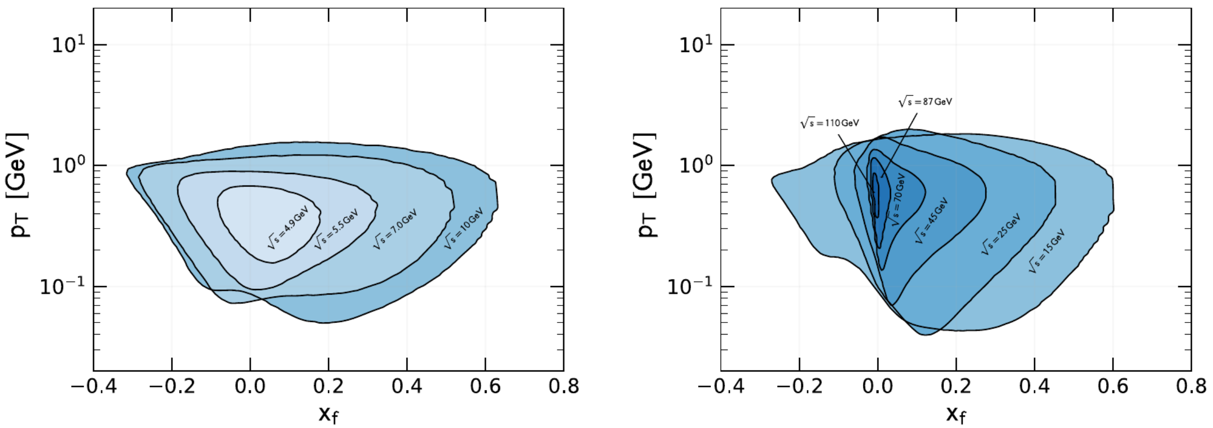
doi:10.1103/PhysRevD.96.043007



(a) LAB frame

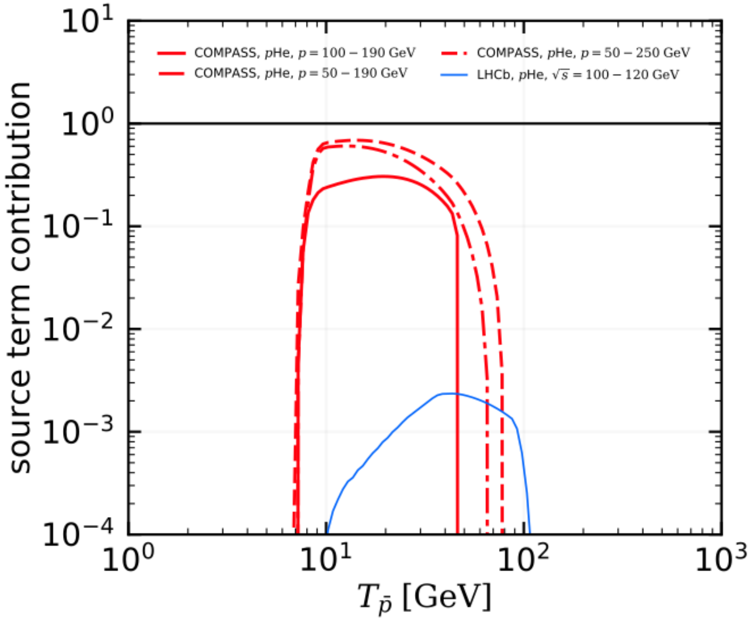
(b) CM frame

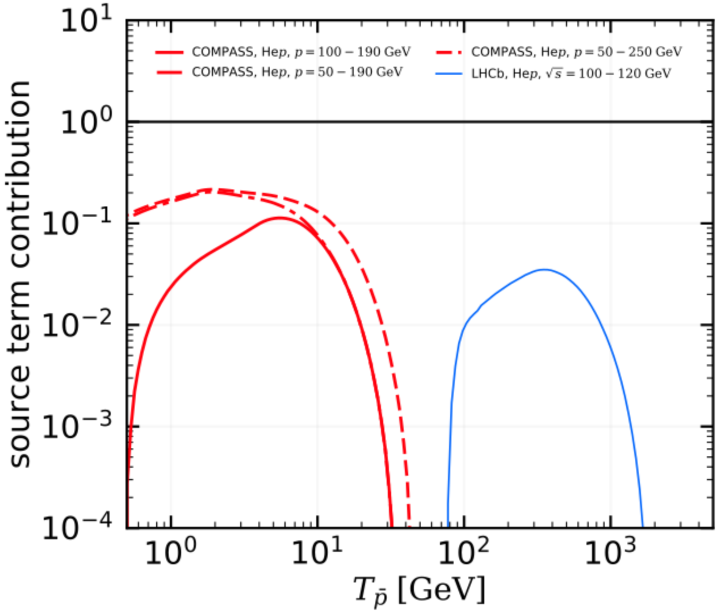
10.1103/PhysRevD.97.103019



$$x_R = \frac{E^*}{E^*_{\text{max}}}$$

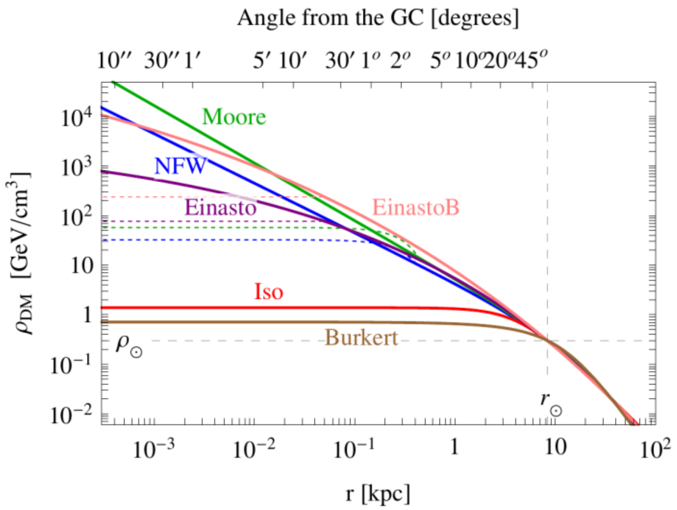
$$x_F = \frac{p^*_{\text{L}}}{\sqrt{s}/2}$$


M. Korsmeier


M. Korsmeier

How to add DM into CR flux interpretation

A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection, Cirelli et al.



$$\rho_{\rm NFW}(r) \;=\; \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

r_s [kpc]	ρ_s [GeV/cm^3]
24.42	0.184

2. Choose the injection source term
(don't forget the "standard" astro-production)

$$q = \frac{1}{2}\left(\frac{\rho}{M_{\rm DM}}\right)^2 f_{\rm inj}^{\rm ann} \qquad f_{\rm inj}^{\rm ann} = \sum_f \langle\sigma v\rangle_f \frac{dN_{\bar p}^f}{dE}$$

$$q = \left(\frac{\rho}{M_{\rm DM}}\right) f_{\rm inj}^{\rm dec} \qquad f_{\rm inj}^{\rm dec} = \sum_f \Gamma_f \frac{dN_{\bar p}^f}{dE}$$

… and decay methods

$e_L^+e_L^-,\ e_R^+e_R^-,\ \mu_L^+\mu_L^-,\ \mu_R^+\mu_R^-,\ \tau_L^+\tau_L^-,\ \tau_R^+\tau_R^-,$

$q\bar q,\ c\bar c,\ b\bar b,\ t\bar t,\ \gamma\gamma,\ gg,$

$W_L^+W_L^-,\ W_T^+W_T^-,\ Z_LZ_L,\ Z_TZ_T,$

$hh,$

$\nu_e\bar\nu_e,\ \nu_\mu\bar\nu_\mu,\ \nu_\tau\bar\nu_\tau,$

$VV\to 4e,\ VV\to 4\mu,\ VV\to 4\tau,$

3.

Hadronization → need input from generator (HERWIG, PYTHIA,..)

+

Numerical solution of **propagation** equation (DRAGON, GALPROP,…)

RICH-1: final state hadrons PID

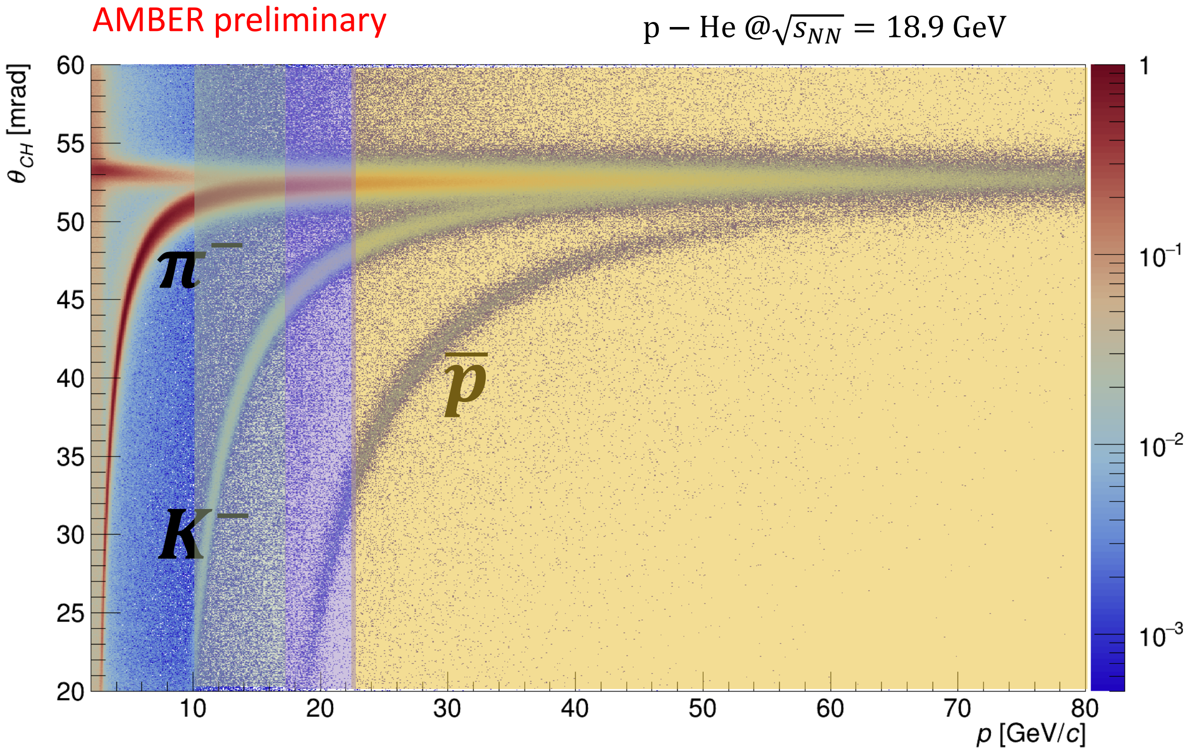
$$\mathcal{L}_M = \exp\left[-\left(S_M + B\right)\right] \prod_{j=1}^{N} f_M\left(\theta_j, \varphi_j\right)$$

$$f_M(\theta, \varphi) = s_M(\theta, \varphi) + b(\theta, \varphi)$$

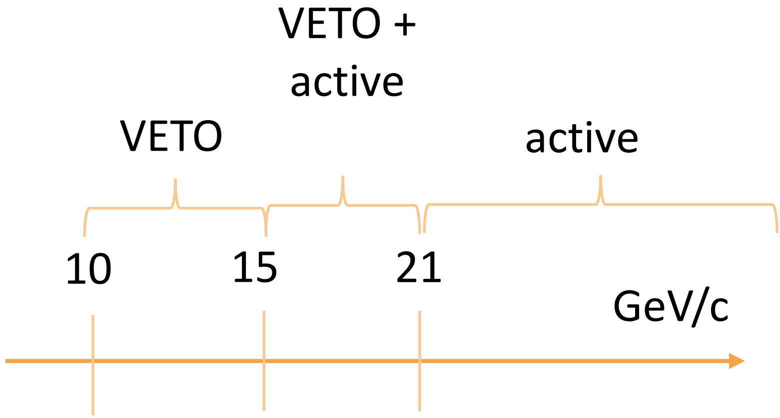
$$s_M\left(\theta_j, \varphi_j\right) = \frac{S_0}{\sigma_{\theta j}\sqrt{2\pi}} \exp\left[-\frac{1}{2}\frac{\left(\theta_j - \Theta_M\right)^2}{\sigma_{\theta j}^2}\right] \varepsilon_D\left(\theta_j, \varphi_j\right)$$

$$\boxed{\begin{aligned} S_m &= \int s_m(\theta, \varphi) d\theta\, d\varphi \\ B &= \int b(\theta, \varphi)\, d\theta d\varphi \end{aligned}}$$

The PID method relies on an extended maximum likelihood approach, based on the parametrization of the expected Cherenkov angle and the position of collected photons



3 momentum intervals:


VETO + active

VETO

active

10

15

21

GeV/c