Deutsche Physikalische Gesellschaft DPG

ANTIPROTON PRODUCTION MEASUREMENT FOR INDIRECT DARK MATTER SEARCH AT THE AMBER EXPERIMENT AT CERN

INFN

CERN

AMBER
Apparatus for Meson and Baryon Experimental Research

Davide Giordano @DPG-Frühjahrstagung 2025

Dark matter nature – hypothesis

Several main explanations for the dark matter

- Baryonic nature (MACHOs, PBH)
- Modified gravity (MOND)
- New particle models (neutrino, SUSY, axion, WIMPs,…)

Dark matter nature – hypothesis

$$\Omega_{DM}h^2 \sim 0.112$$
WMAP

WIMP miracle?

$\Omega = \rho/\rho_c$
$\chi\chi \leftrightarrow ll, qq, \ldots$
Cold relic

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- Modified gravity (MOND)
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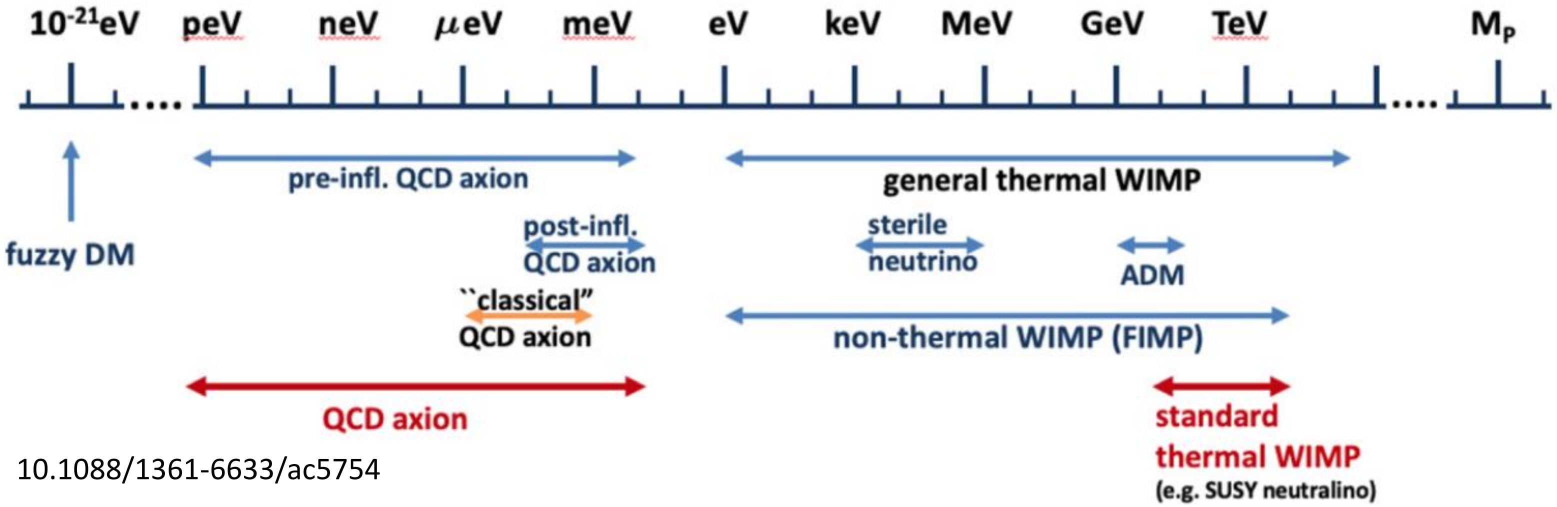
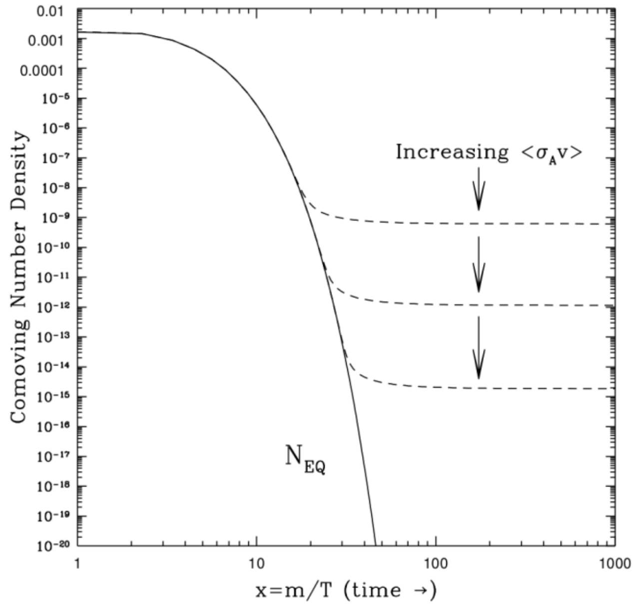
$$\Omega_\chi h^2 \simeq 0.1 \times \left(\frac{\langle \sigma v \rangle_{fo}}{3 \cdot 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}} \right)^{-1}$$

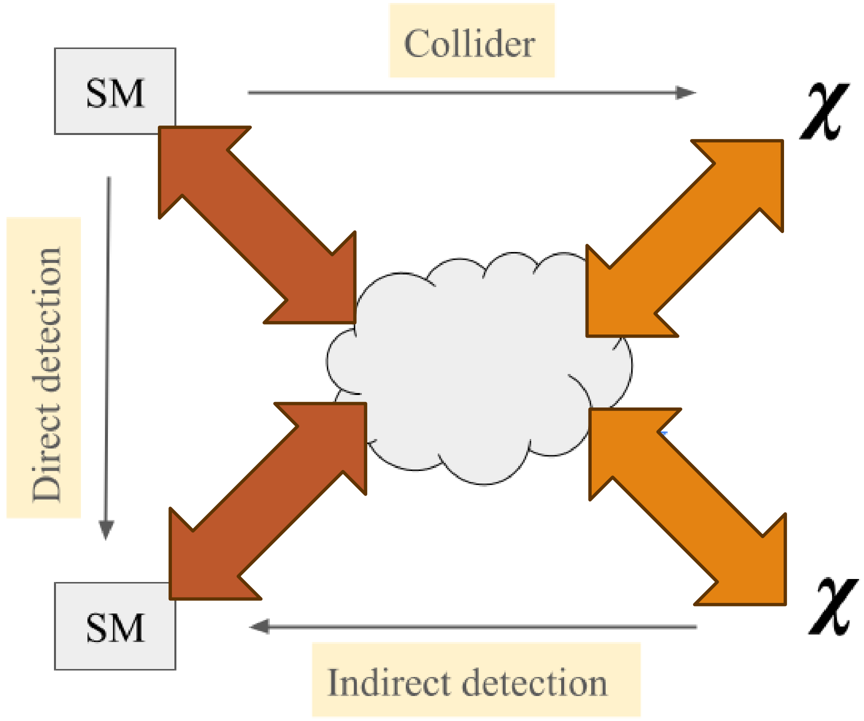




10.1088/1361-6633/ac5754

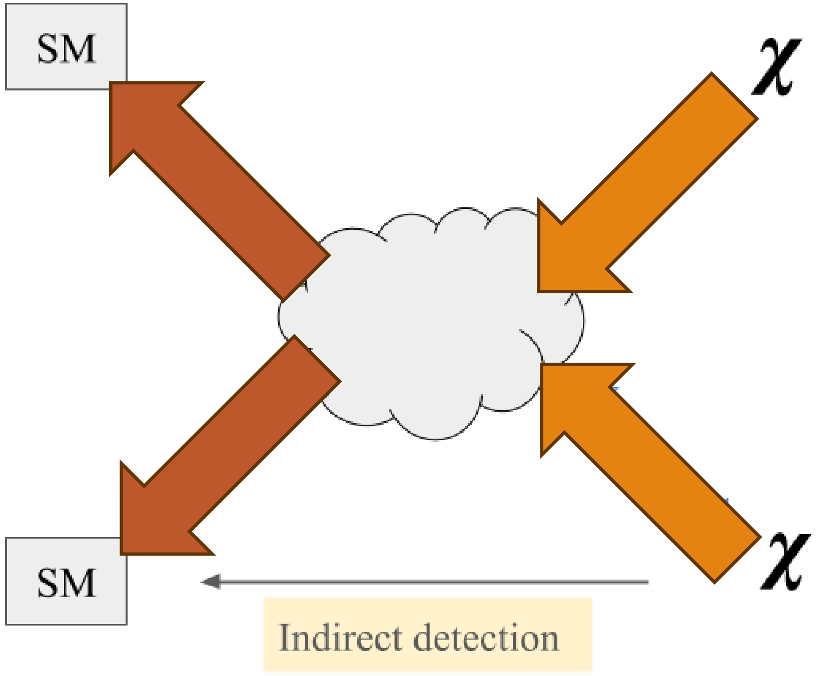
Dark Matter detection

3 COMPLEMENTARY ways to probe the particle nature of Dark Matter



Dark Matter detection - indirect

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



DM particles annihilate/decay 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)

Question is: do we know how many CR are produced and accelerated in the Galaxy? And how many of them reach our detectors ?

CR production and propagation

Fundamental belief: majority of CR arriving @Earth have Galactic origin (observation with EGRET)

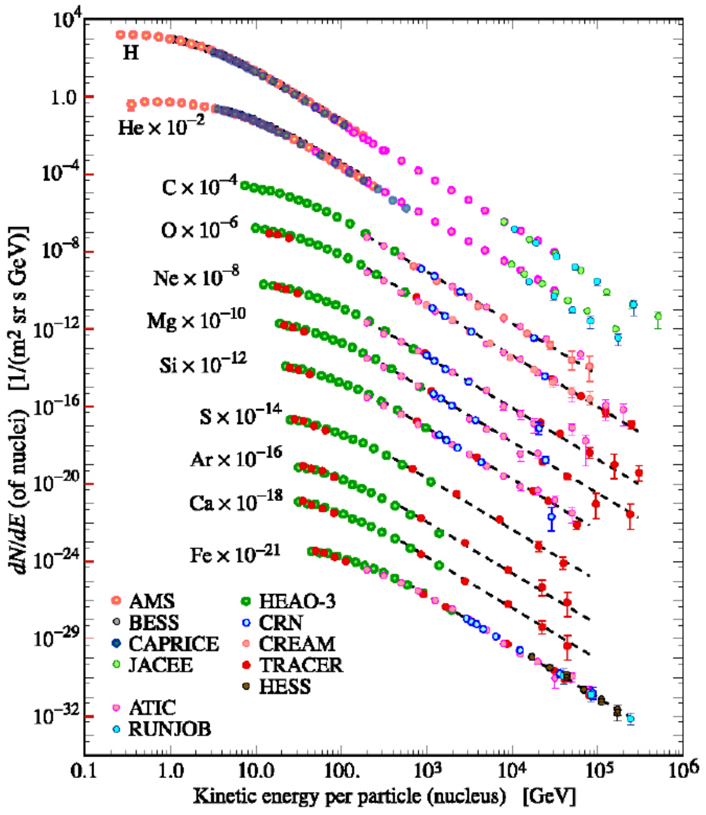
$$R = pc/Ze$$

Rigidity spectra show similar power law index of ~ - 2.7 for very different elements!

Baade and Zwicky (1934) suggested that a new class of novae, the super-novae (SN), were the source of the cosmic rays and predicted the presence of heavier CR elements (Z>2).

Nowadays it is firmly believed that SN produce most of the power required to generate and accelerate the Galactic CR in the so-called diffusive shock acceleration (DSA)

1. SN ejecta
2. Interstellar material (ISM)



doi:10.3847/1538-4365/ab4b58

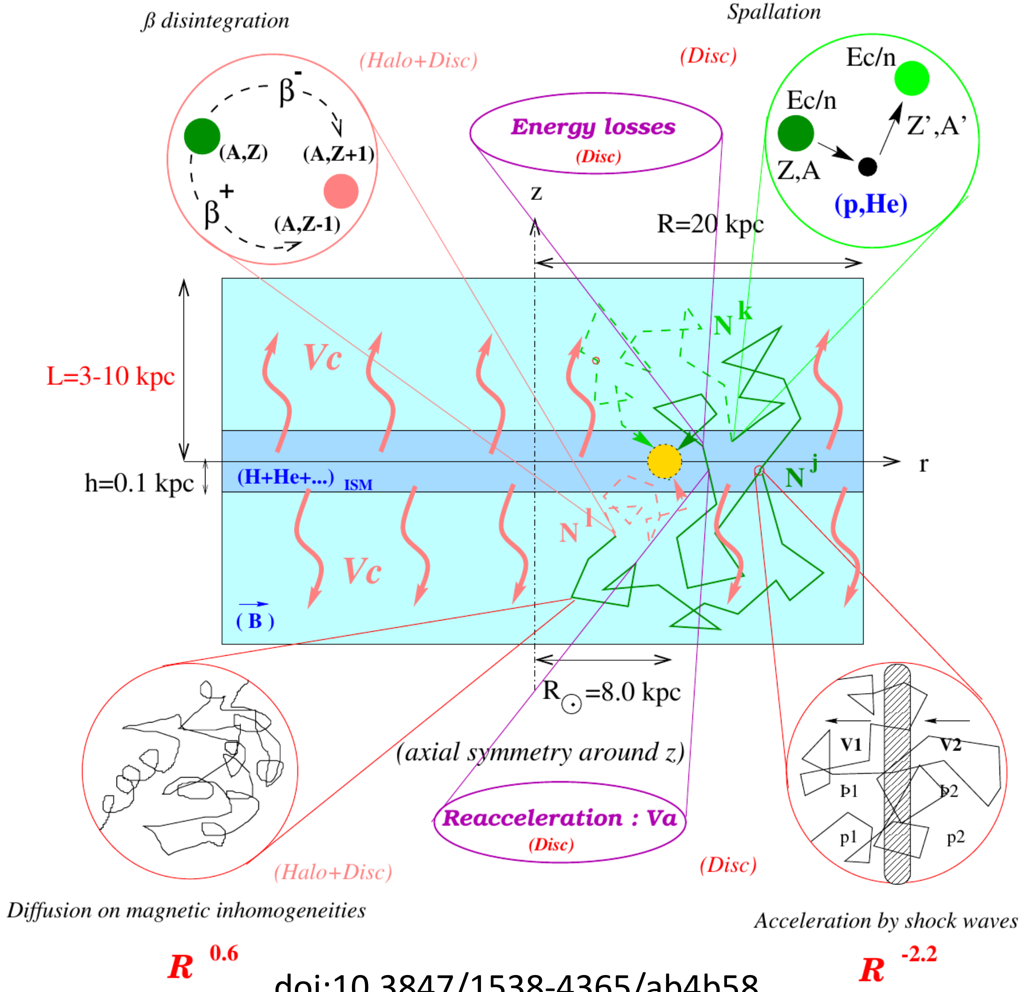
CR production and propagation

- ISM ~1 particle/cm^3 composed of Hydrogen (90%) and Helium (10%)
- Galactic halo ~20 kpc
- Galactic disk ~0.2 kpc
- Diffusive Turbulent propagation
- Alfven velocities
- Reacceleration and galactic wind
- Solar wind

CR are then divided in 2 main categories, depending on their production, that share the same propagation destiny:

1. Primary
2. Secondary

(+ tertiary)



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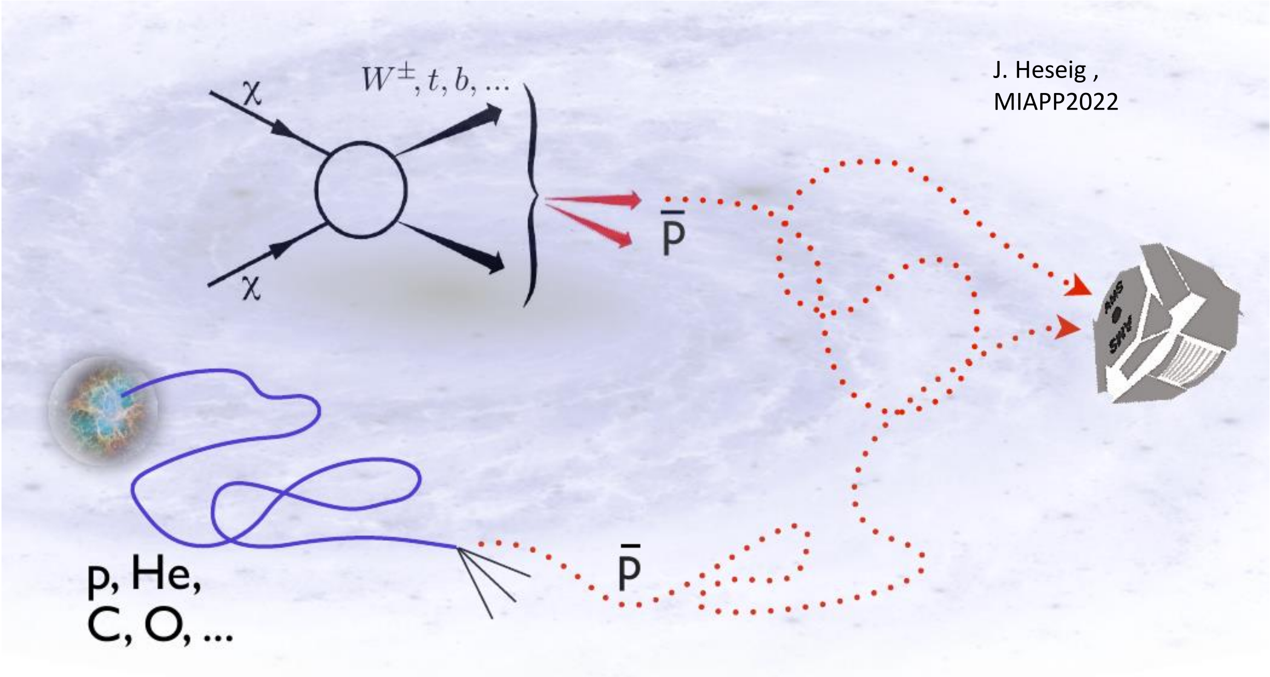
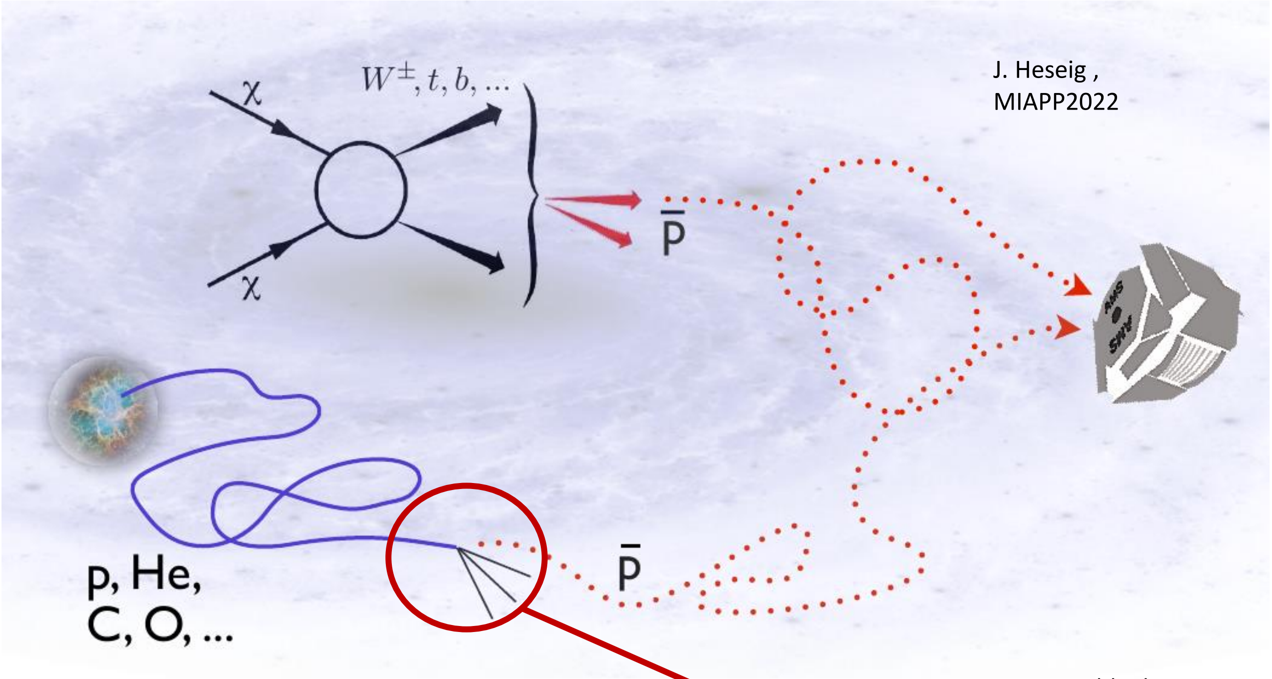
Antiproton production

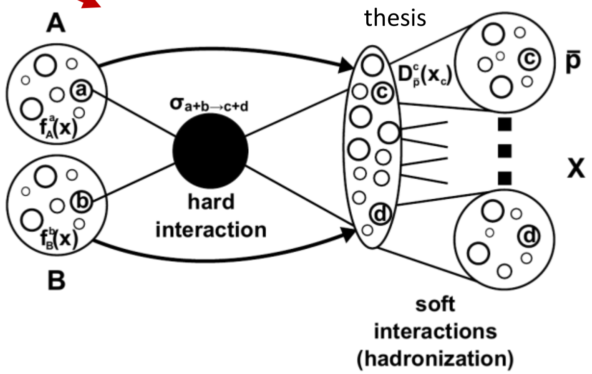


J. Heseig ,
MIAPP2022

Antiproton production



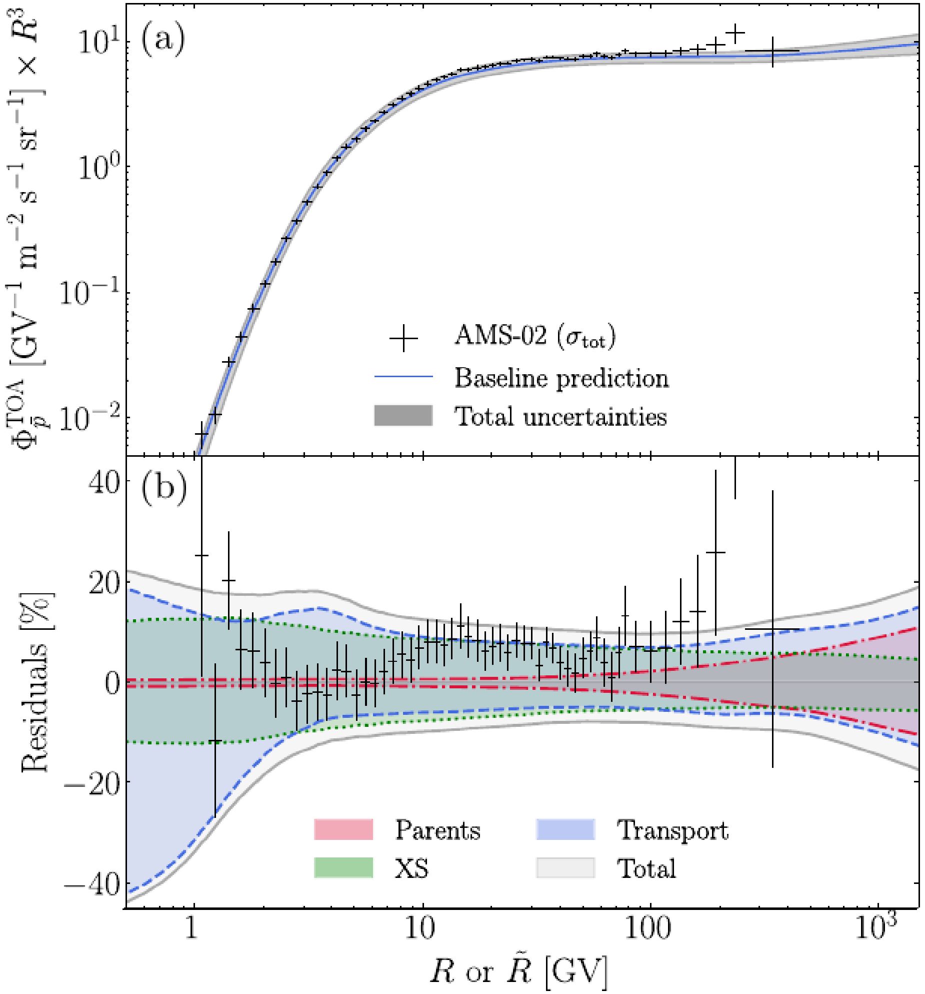
T.Poeschl, PhD thesis



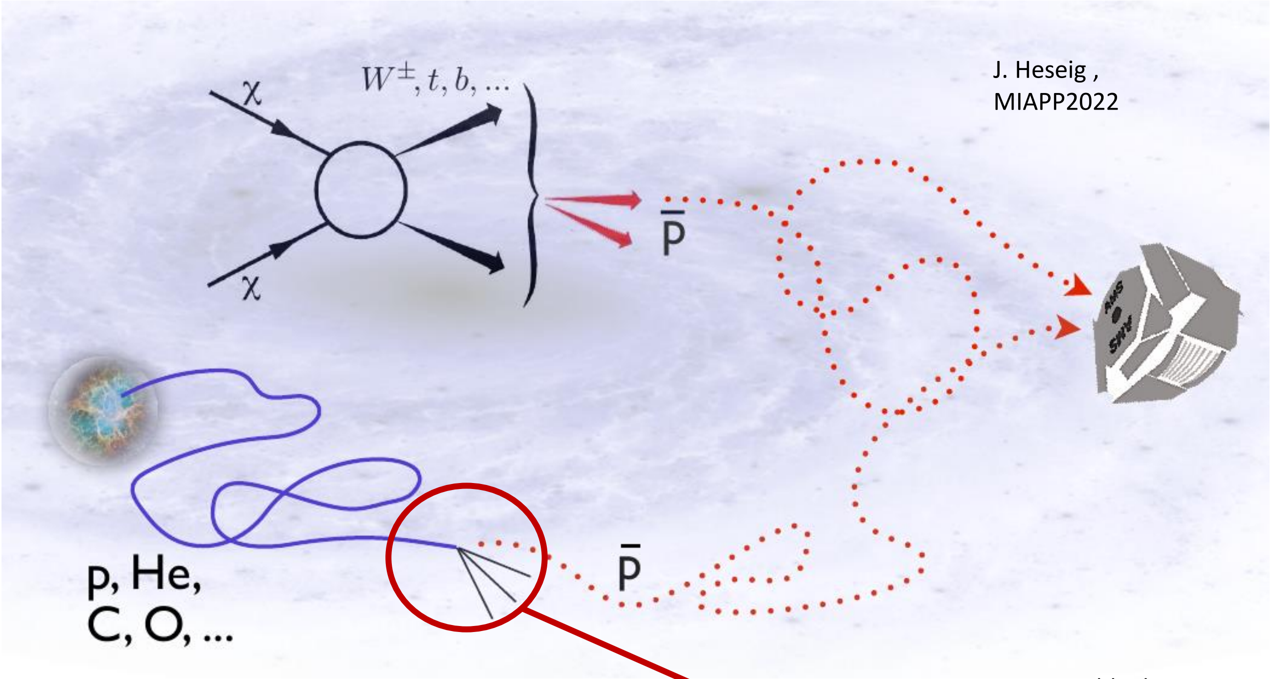
$$f = f_{\bar{p}}^{0} \left(2 + \Delta_{\mathrm{IS}} + 2\Delta_{\Lambda}\right)$$

Antiproton production

doi:10.1103/PhysRevResearch.2.023022



$R = pc/Ze$



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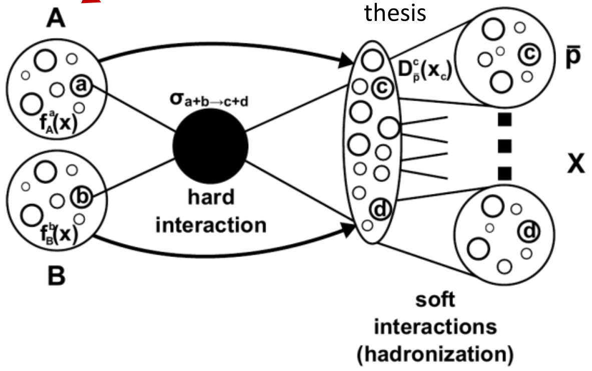
Unprecedented results from AMS-02 at few percent level error

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

T.Poeschl, PhD thesis



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

CR propagation equation and source term

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

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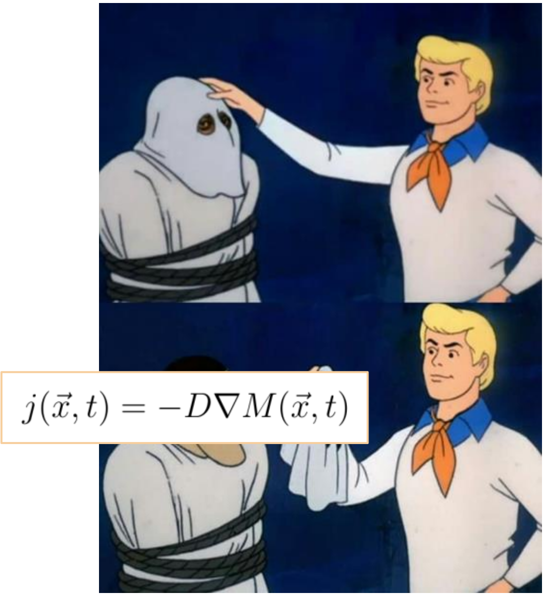

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Full propagation equation
Typically solved in stationary condition $\frac{d\Psi}{dt} = 0$

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Pure primary CR source term

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

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

CR propagation equation and source term

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

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

CR propagation equation and source term

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

Antiproton production cross section

Which are the main contributor to the antiprotons production?

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doi:10.1103/PhysRevD.97.103019

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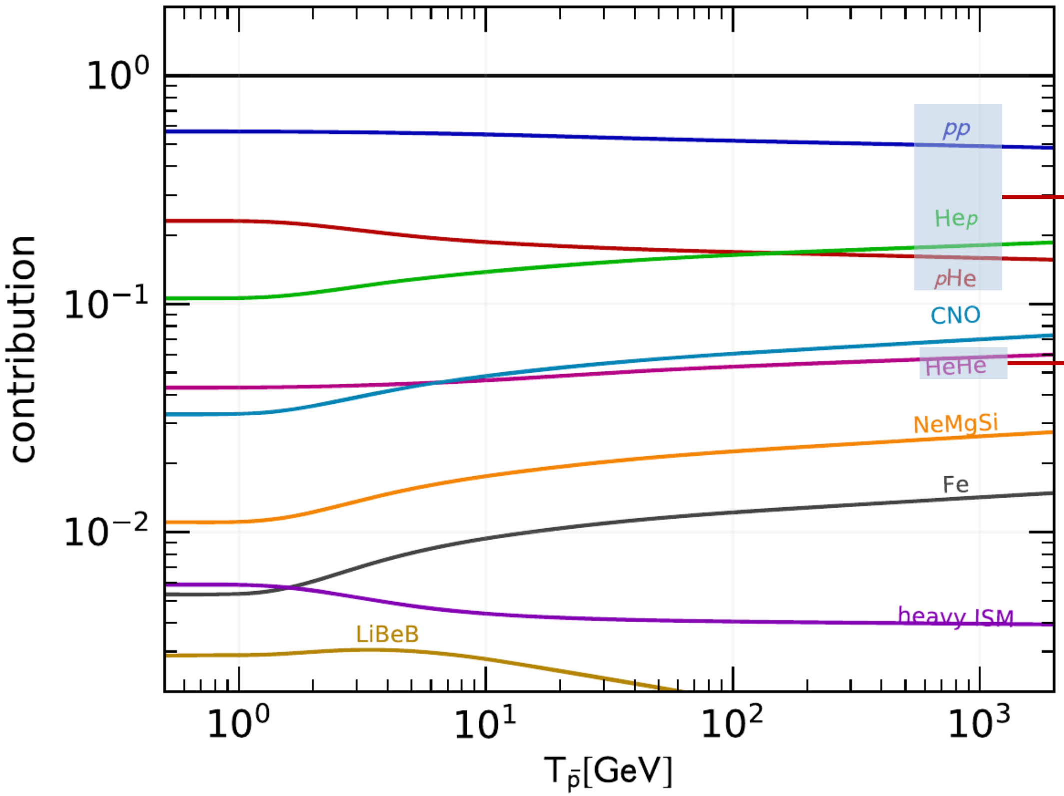

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90% of the reactions involve p and Helium (main ISM component)

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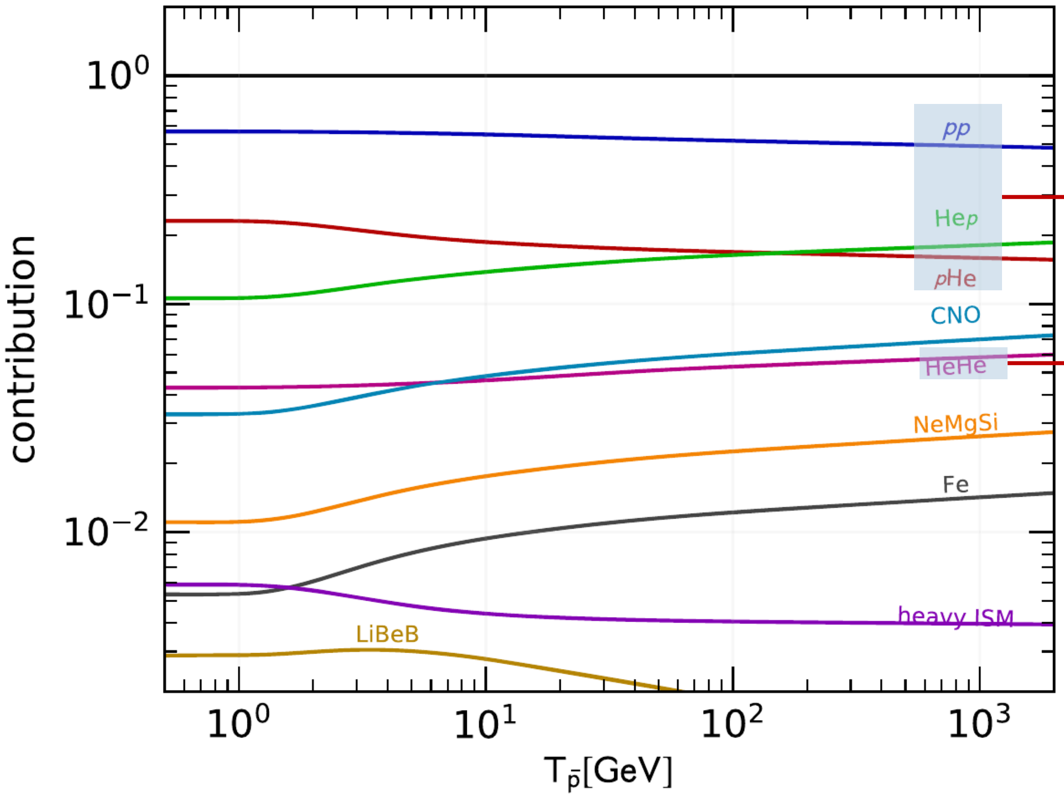

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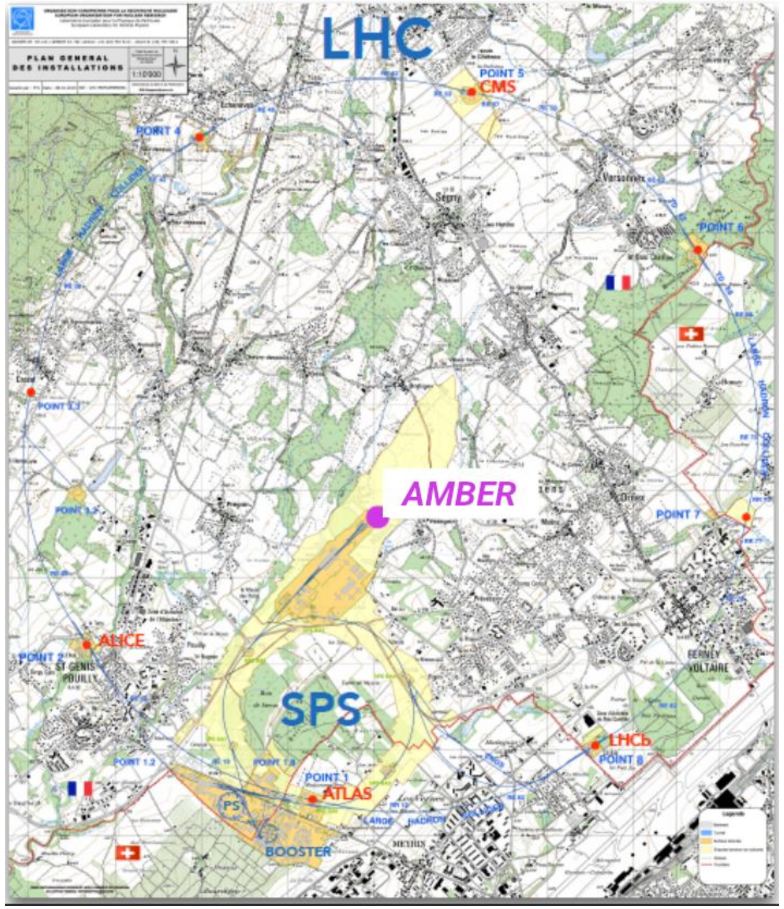
90% of the reactions involve p and Helium (main ISM component)

$\mathrm{p} + \mathrm{p} \rightarrow \bar{\mathrm{p}} + X$ 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 $\sqrt{s_{NN}}$~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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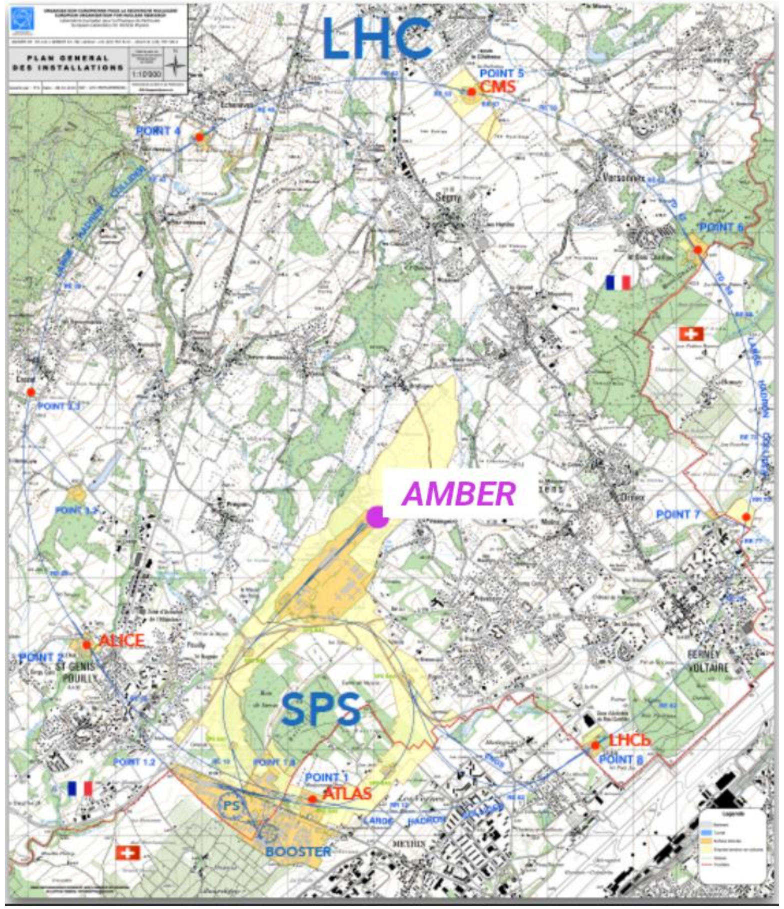

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$$f = f^0_{\bar{p}}(2 + \Delta_{IS} + 2\Delta_{\Lambda})$$

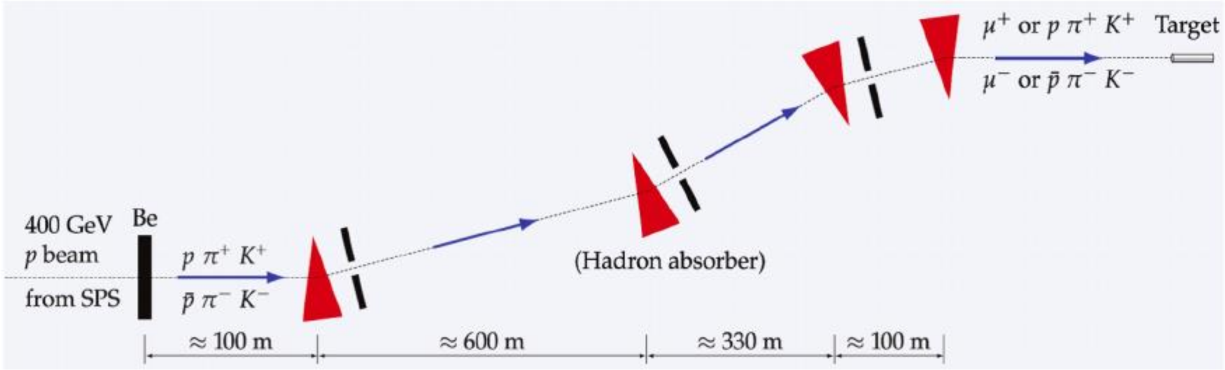
Oct 2022	May-July 2023	May-July 2024
	$p + He \rightarrow \bar{p} + X$	$p + H \rightarrow \bar{p} + X$ $p + D \rightarrow \bar{p} + X$
1 week Test run APXS	Physics APXS	Physics APXS

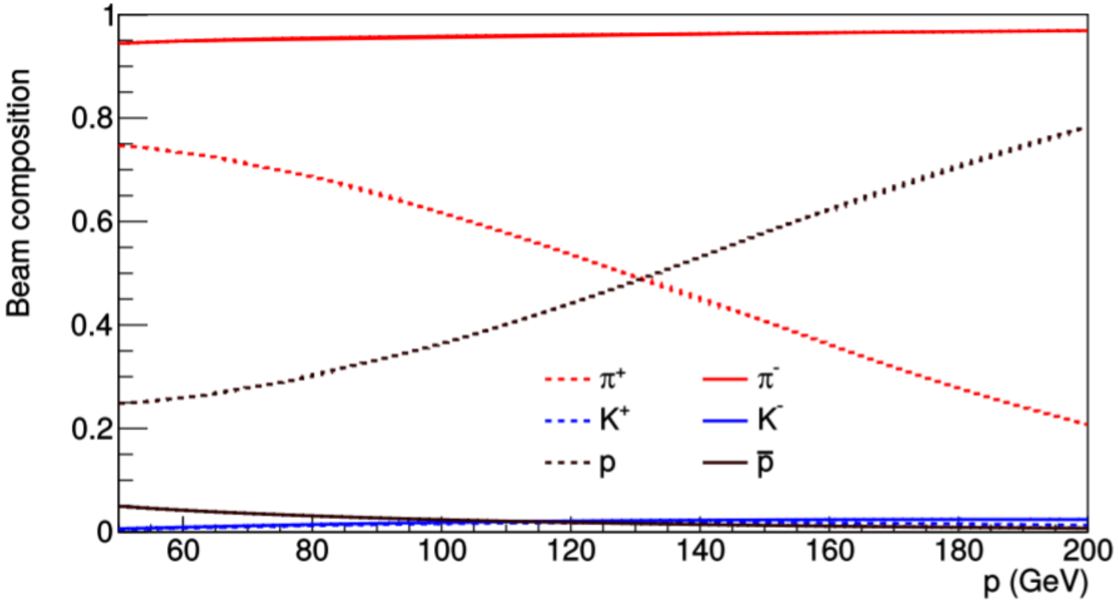
p+He: beam **@60, 80, 100, 160, 190, 250 GeV/c**
p+H / p+D : beam **@80,160,250 GeV/c**
Minimum bias trigger: beam trigger with veto on non-scattered beam particle

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

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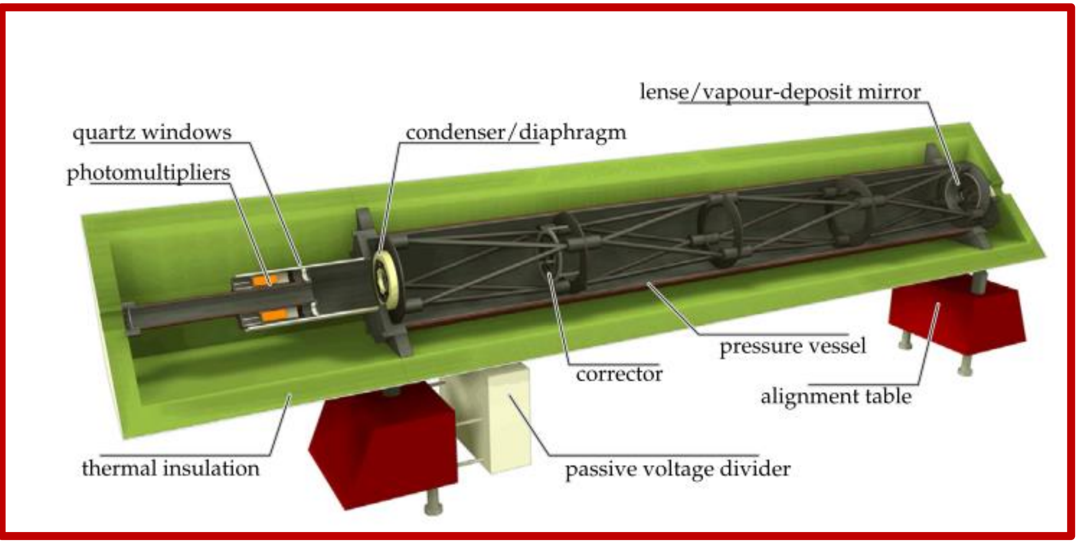

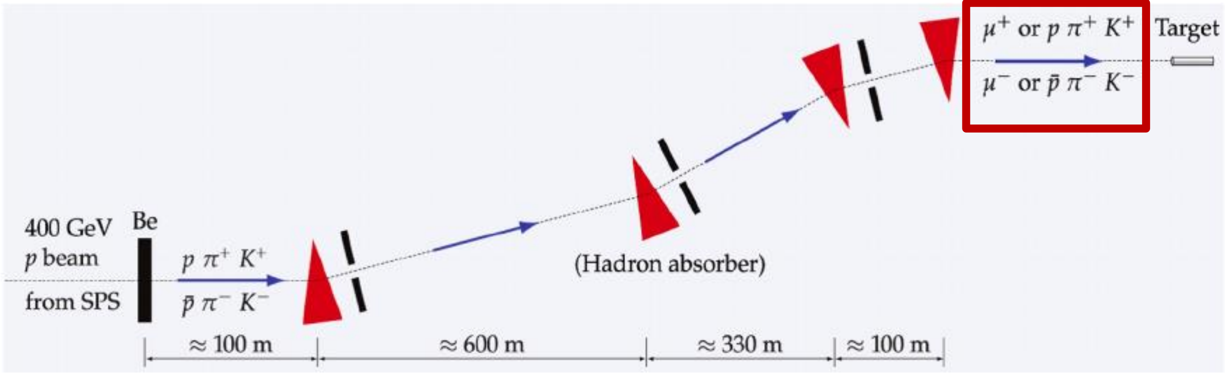

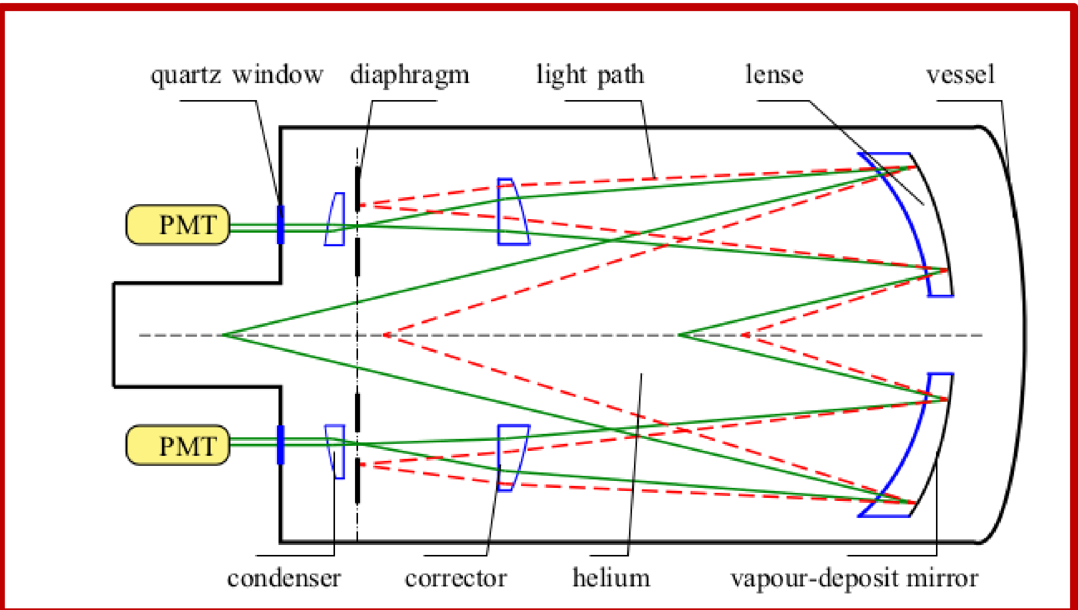

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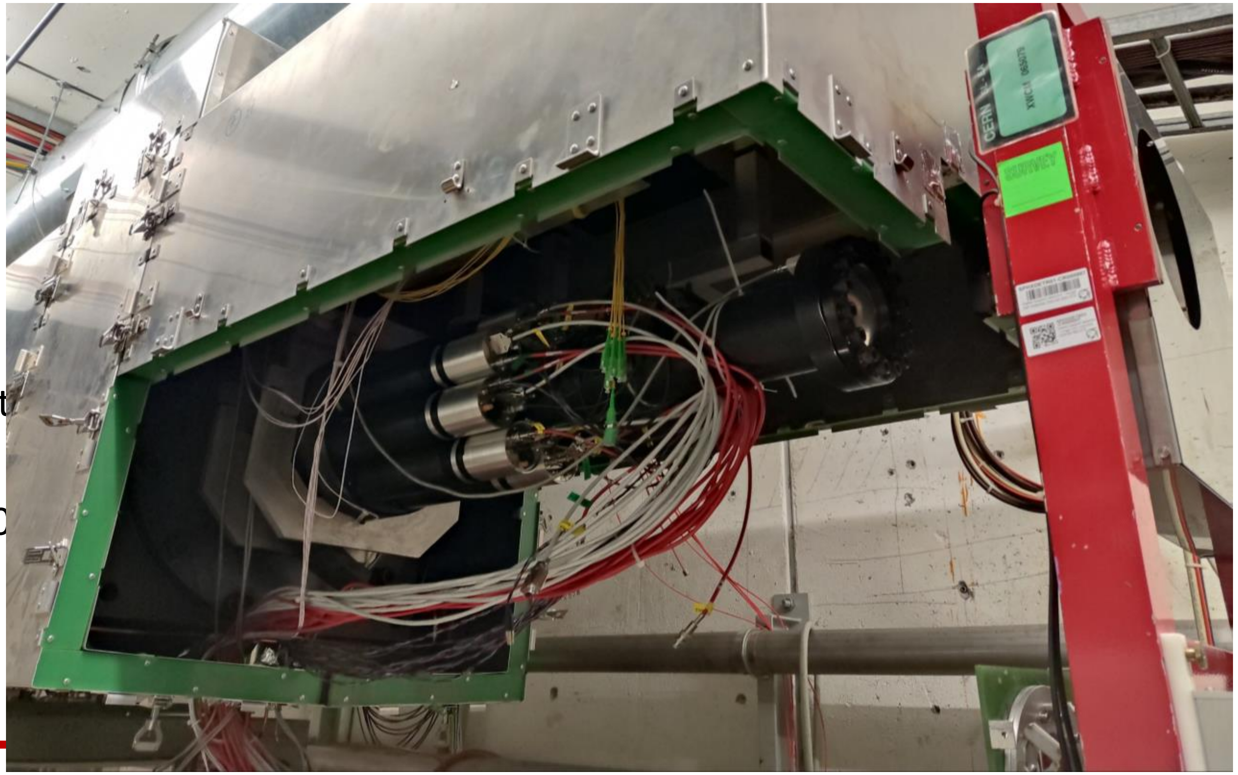

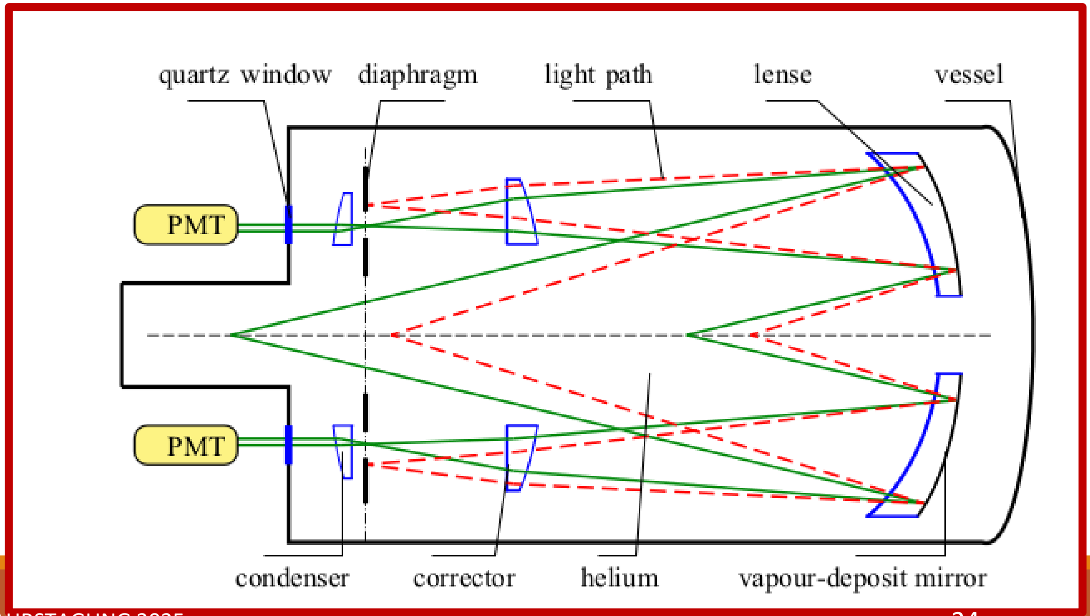

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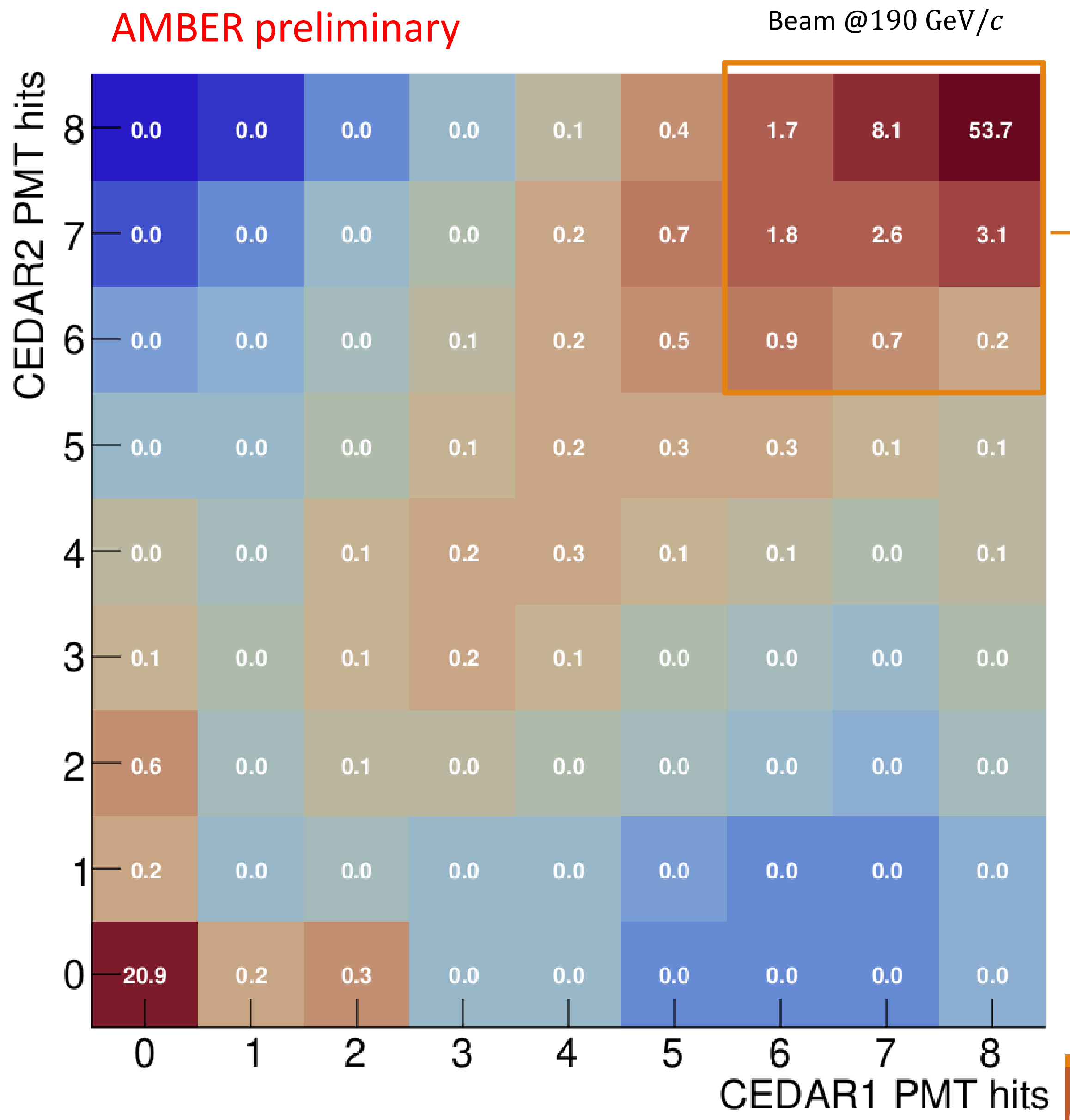
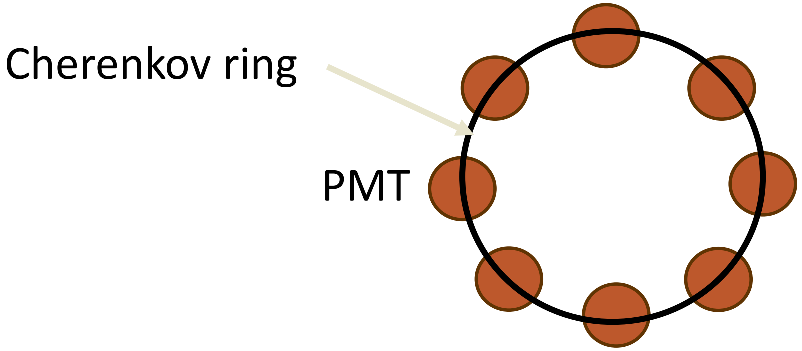


Expected fraction of protons in the beam is ~75%

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



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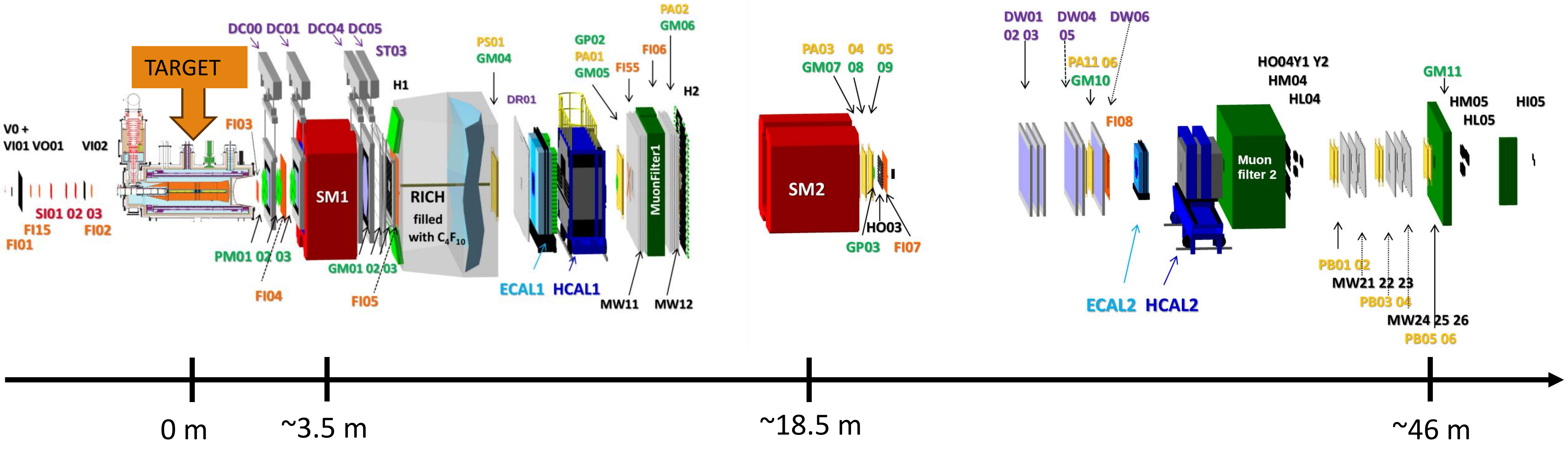

Large Angle Spectrometer (LAS)
- Mainly small+medium size trackers
- SM1
- RICH
- Muon filter
- ECAL

Small Angle Spectrometer (SAS)
- Mainly medium+large area tracker
- SM2
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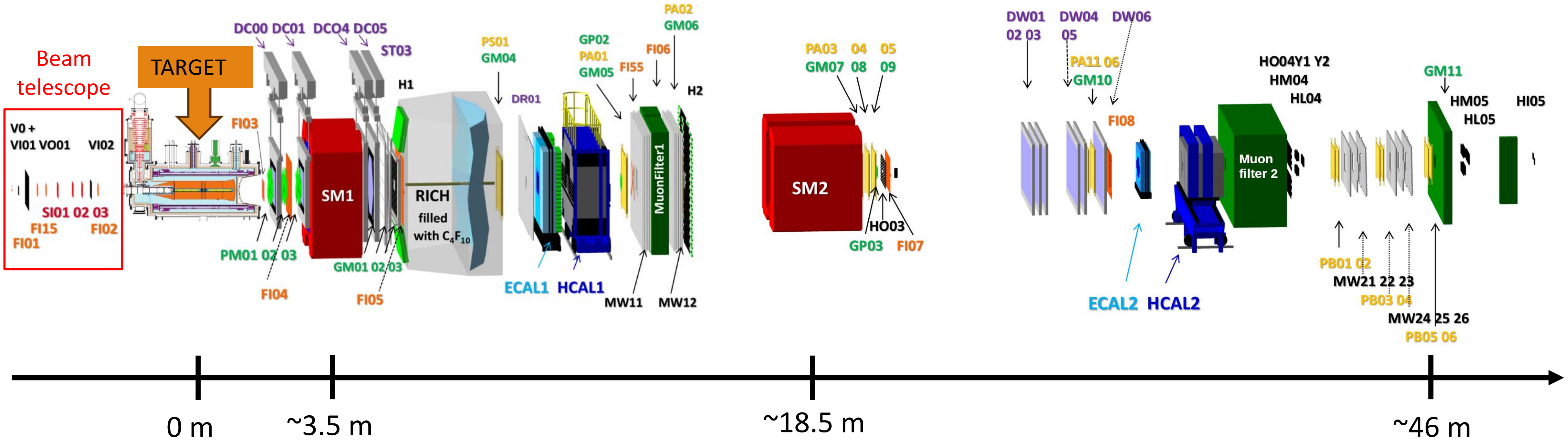

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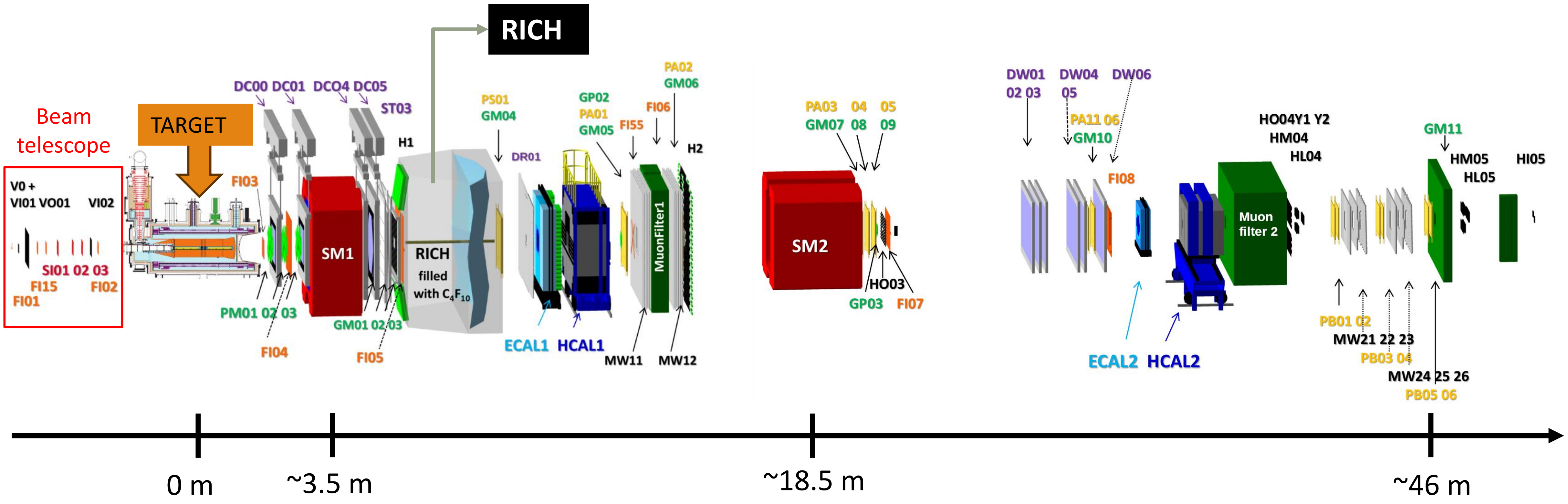

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Analysis outline

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

Analysis outline

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

Alignment + reconstruction:

- > 200 tracking planes to align

Analysis outline

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

target

Alignment + reconstruction:

- > 200 tracking planes to align

Analysis of the data

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

Analysis outline

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

PID target PID

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PID

- RICH characterization
- CEDAR PID efficiency/purity

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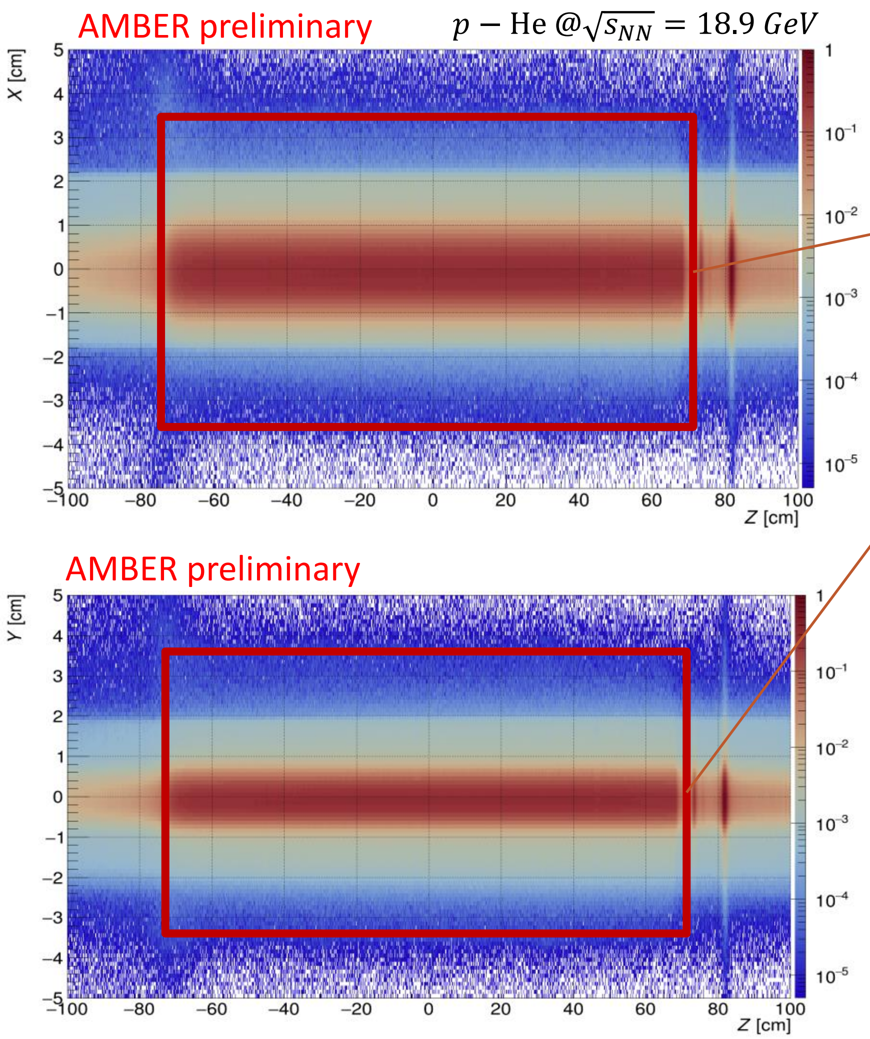
Monte Carlo

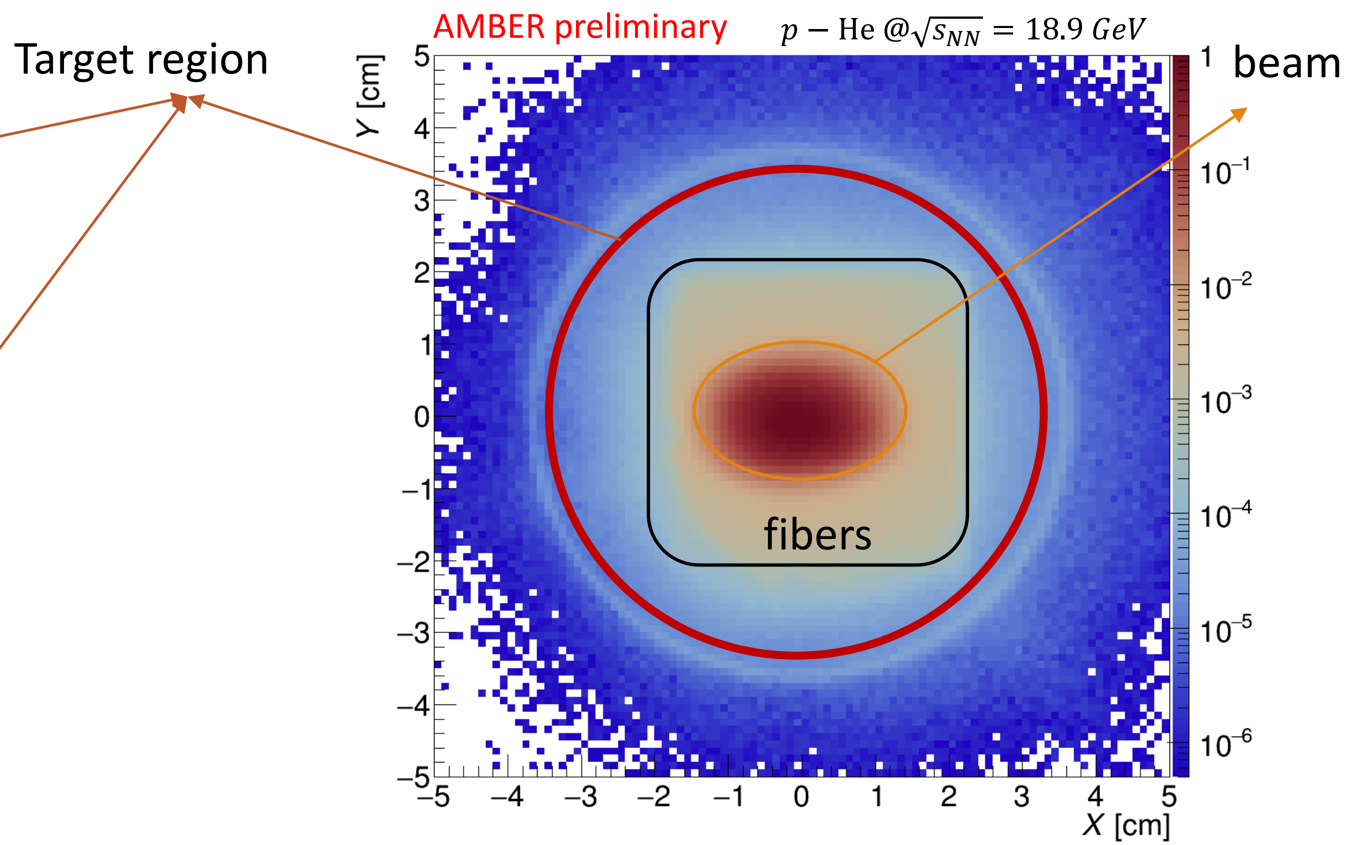
- Tune event generator
- Detector efficiencies
- Acceptance corrections
- Bins size optimization

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

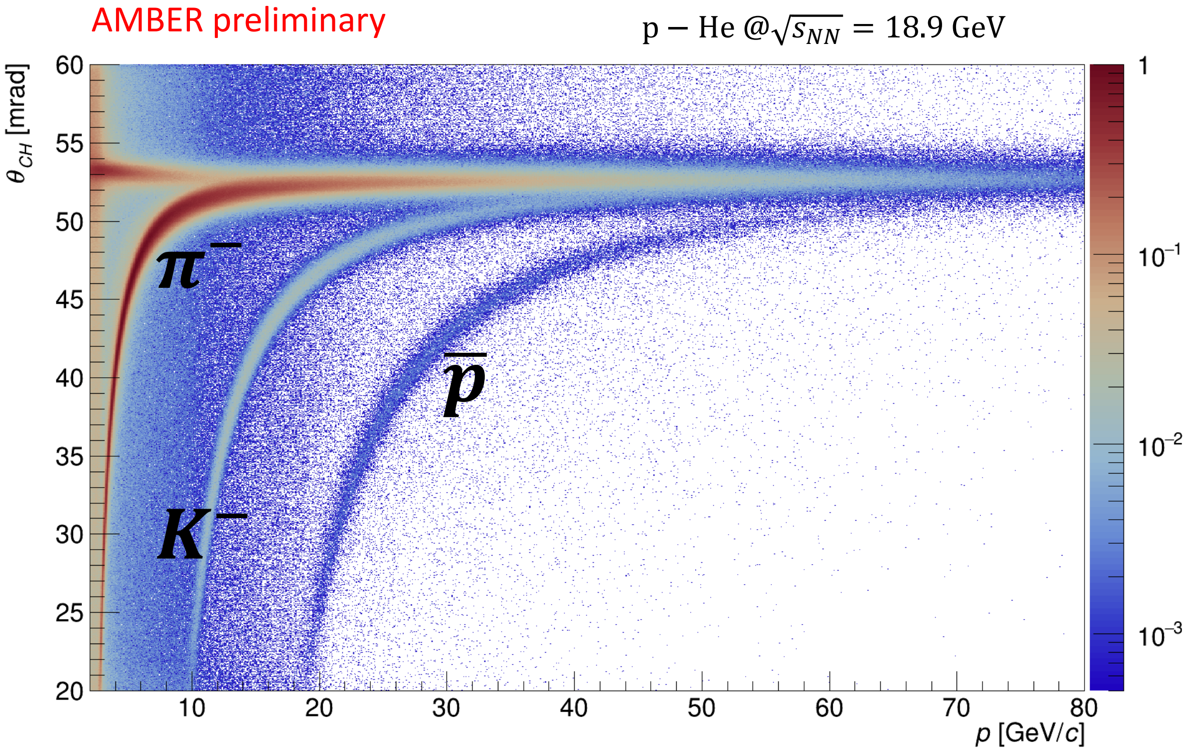
$$\mathcal{L}_M = \exp\left[-\left(S_M + B\right)\right] \prod_{j=1}^{N} f_M\left(\theta_j, \varphi_j\right)$$

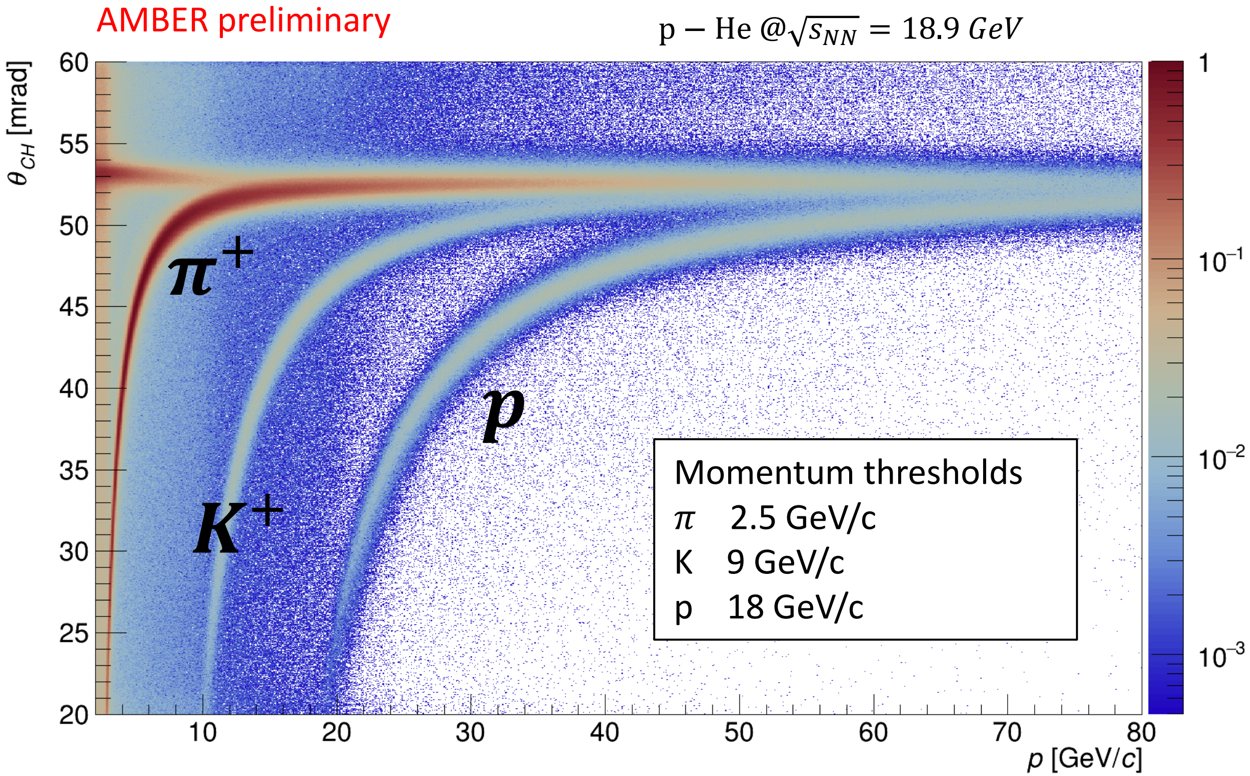
$$f_M(\theta, \varphi) = s_M(\theta, \varphi) + b(\theta, \varphi)$$

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

$$S_m = \int s_m(\theta, \varphi) d\theta\, d\varphi$$

$$B = \int b(\theta, \varphi)\, d\theta d\varphi$$





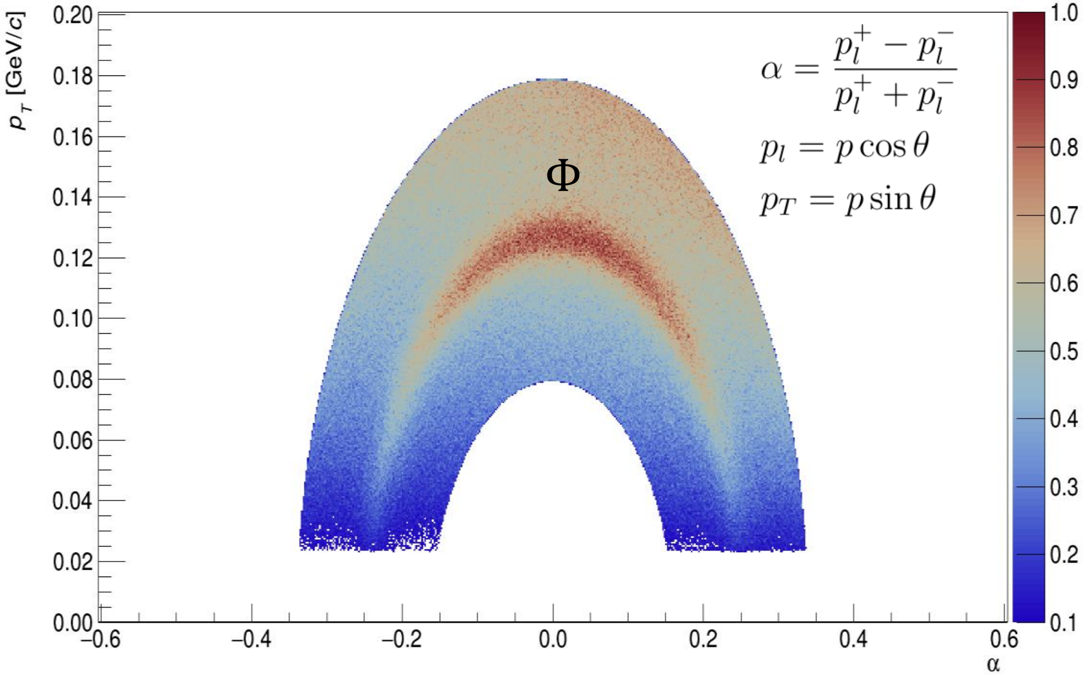
RICH-1: final state hadrons PID

RICH PID matrix estimated from real data V0s decays

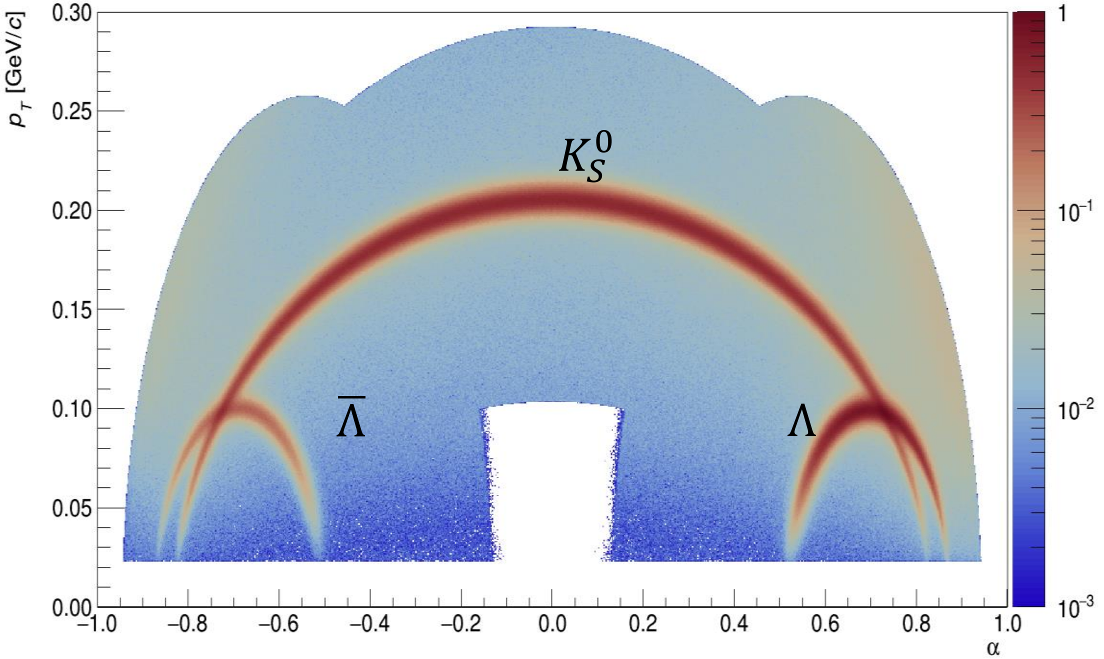
Hadrons	Decays	
	Channel	BR
K_S	$\pi^+\pi^-$	$(69.20 \pm 0.05)\%$
ϕ	K^+K^-	$(48.9 \pm 0.5)\%$
$\Lambda(\bar{\Lambda})$	$p\pi^-$ $(\bar{p}\pi^+)$	$(63.9 \pm 0.5)\%$

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

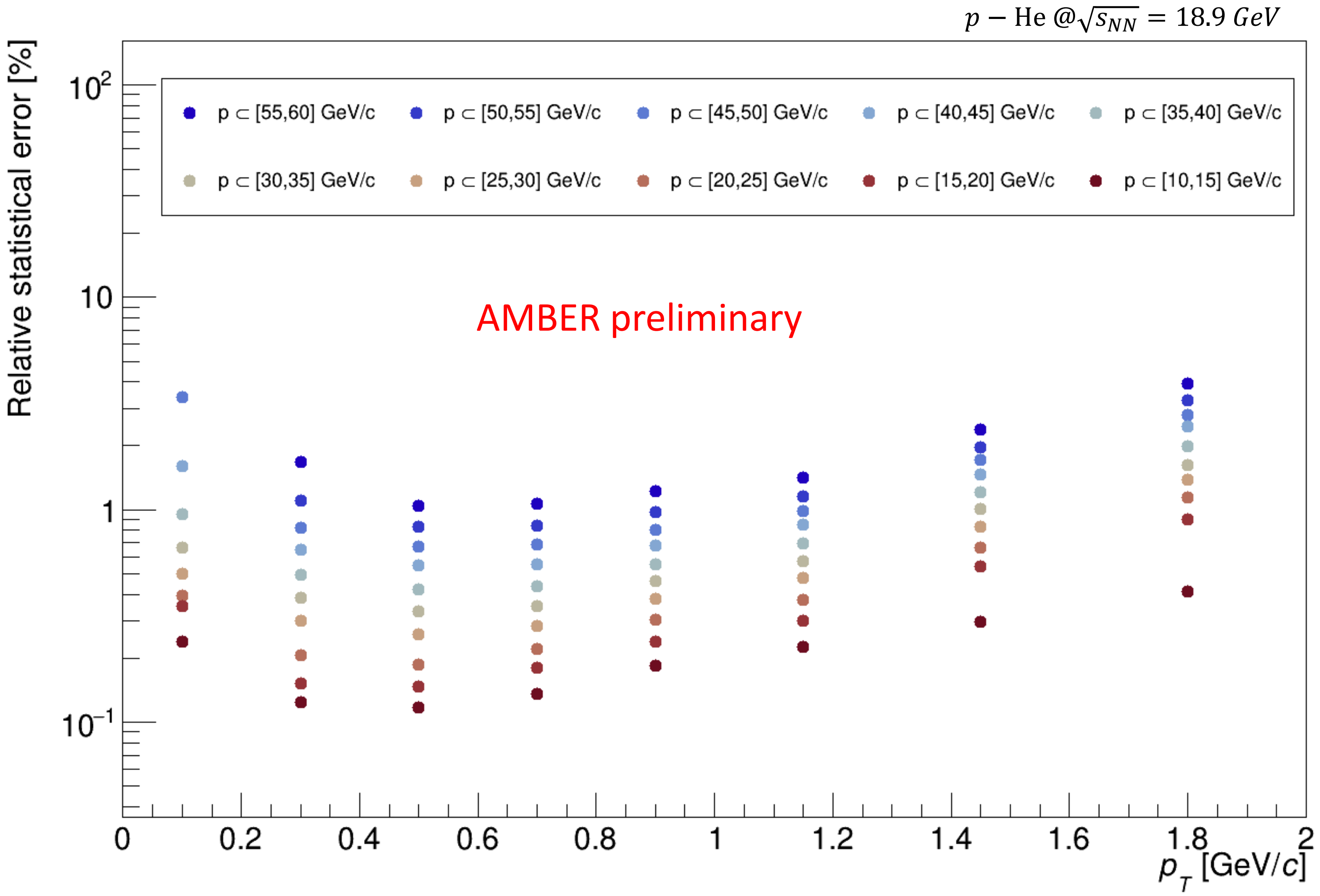
AMBER preliminary $p-\text{He}\ @\sqrt{s_{NN}} = 18.9\ GeV$



AMBER preliminary $p-\text{He}\ @\sqrt{s_{NN}} = 18.9\ GeV$



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

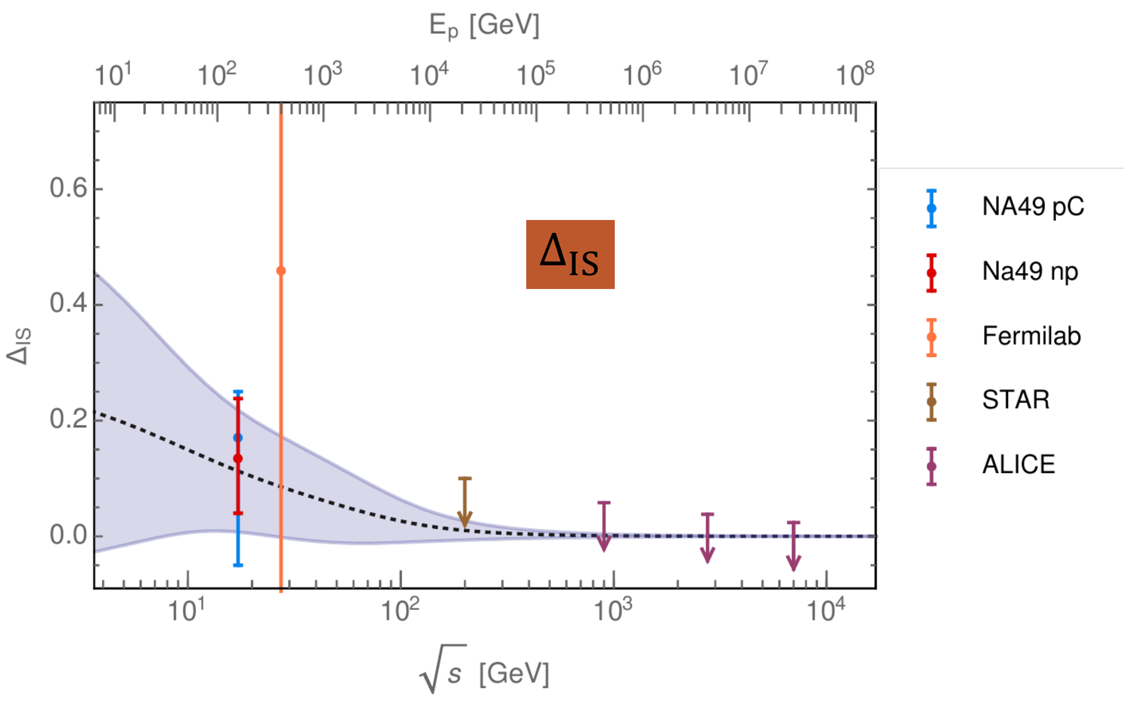
$$f = f_{\bar{p}}^{0}\left(2 + \Delta_{\mathrm{IS}} + 2\Delta_{\Lambda}\right)$$

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

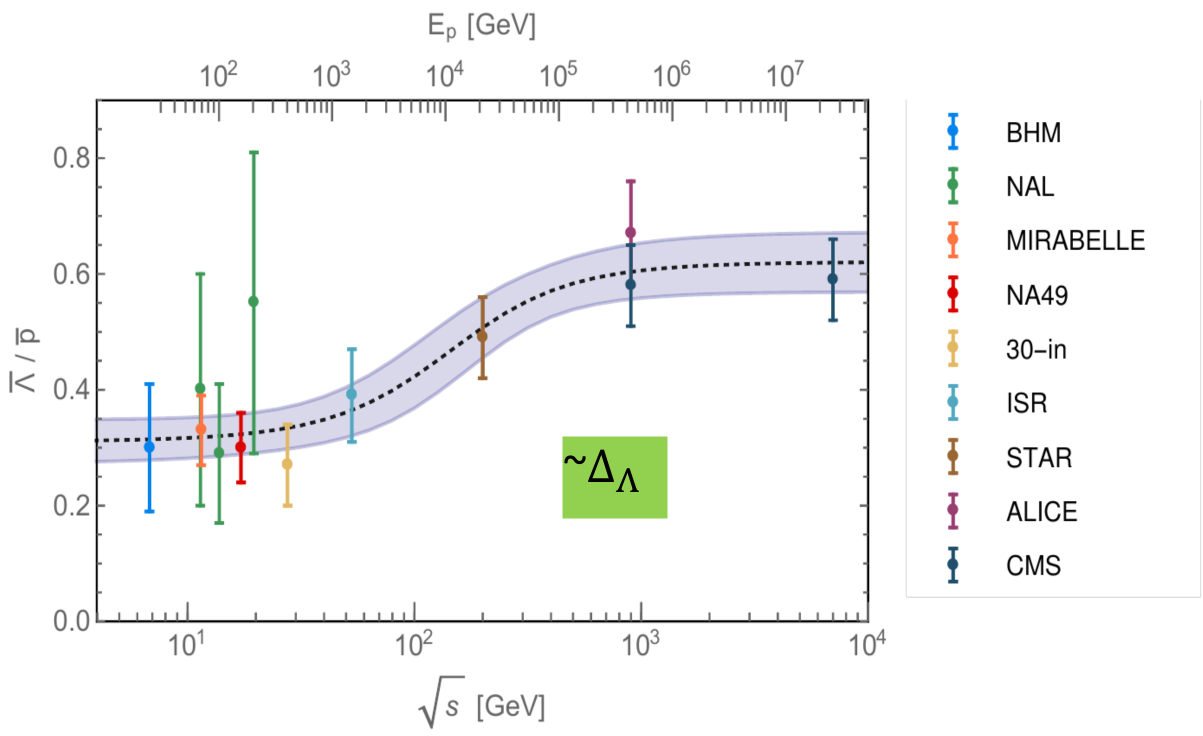
Antiproton production from decays

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

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



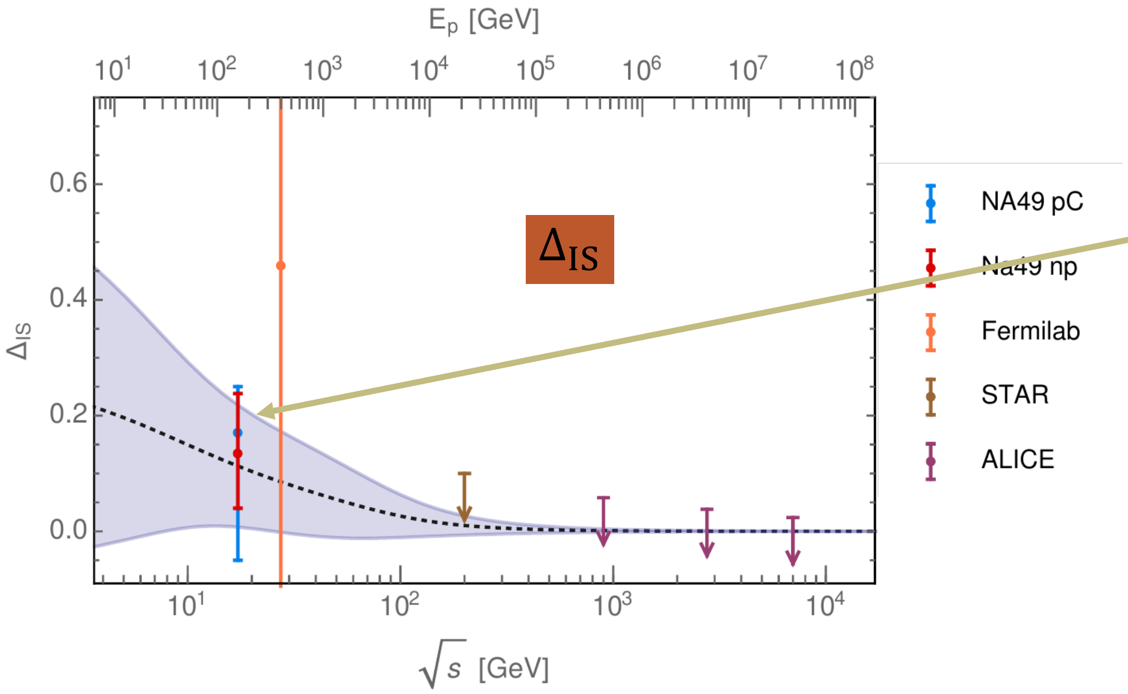
https://doi.org/10.1016/S0927-6505(01)00107-4

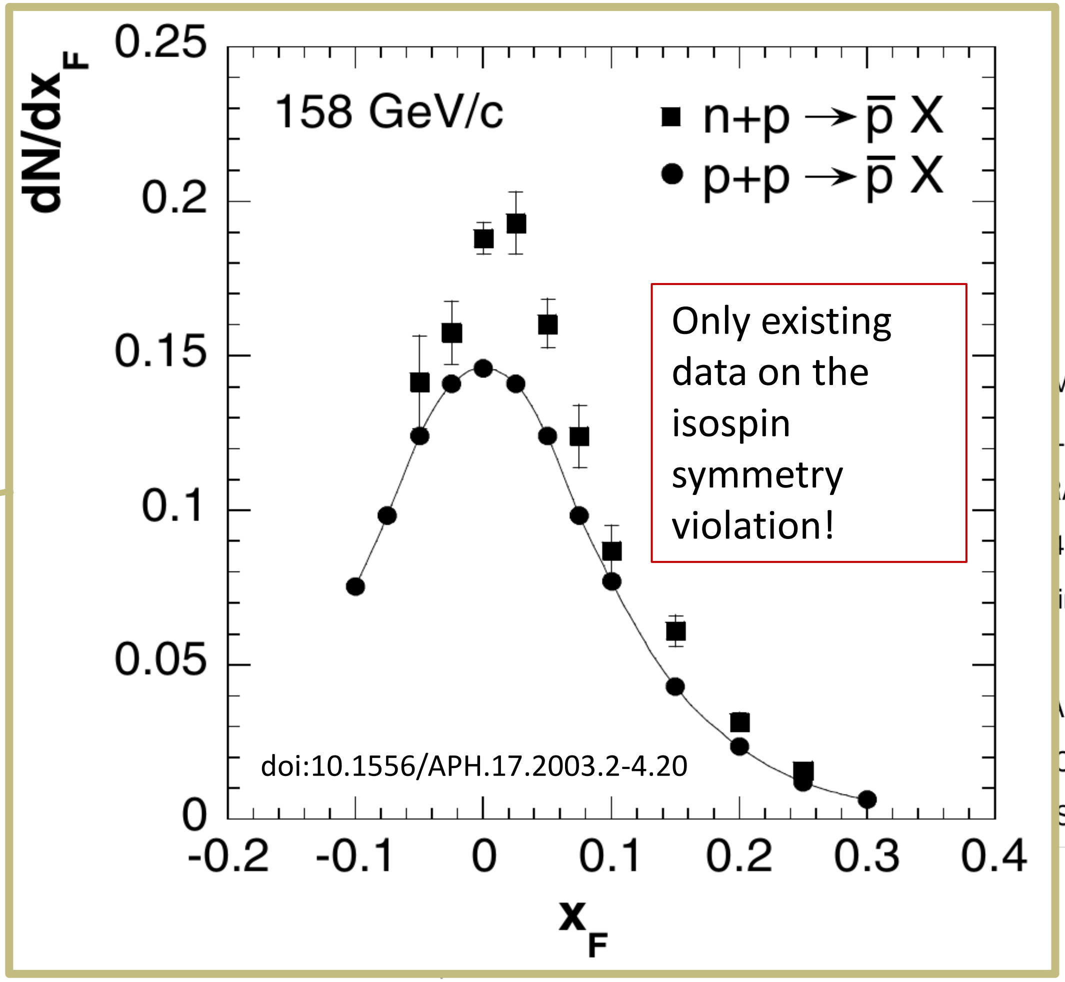


Production asymmetry $p\bar{n}/\bar{p}n$

Antiproton production from decays

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





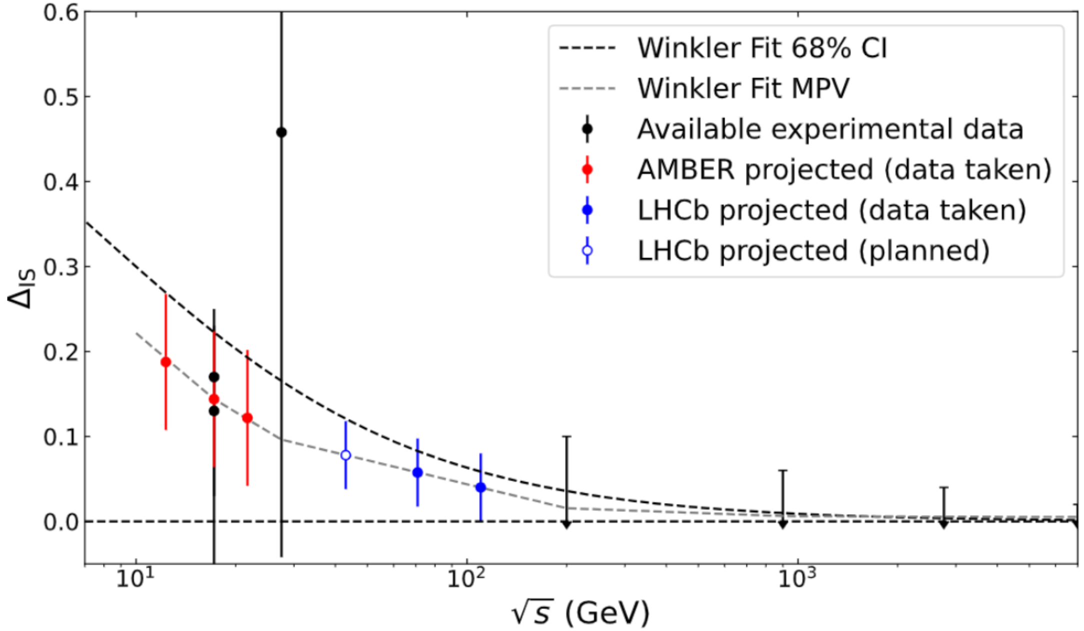
$p\bar{n}/\bar{p}n$

Expected impact from 2024 data

In 2024 data collected with 2 targets
1. liquid Hydrogen
2. liquid deuterium

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

(publication in preparation)



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

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"

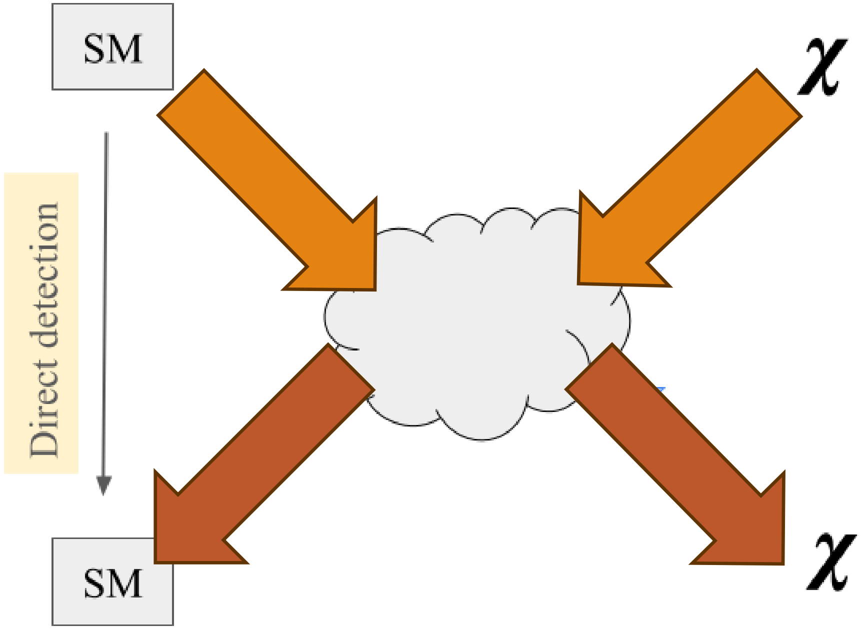
AMBER collected data on p-He in 2023 and p-H / p-D in 2024. These dataset are expected to give a significant impact in the antiproton production modeling

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

Dark Matter detection - direct



Direct interaction with SM particles

Any positive signal would give unambiguous confirmation of particle nature

Typical experiments:

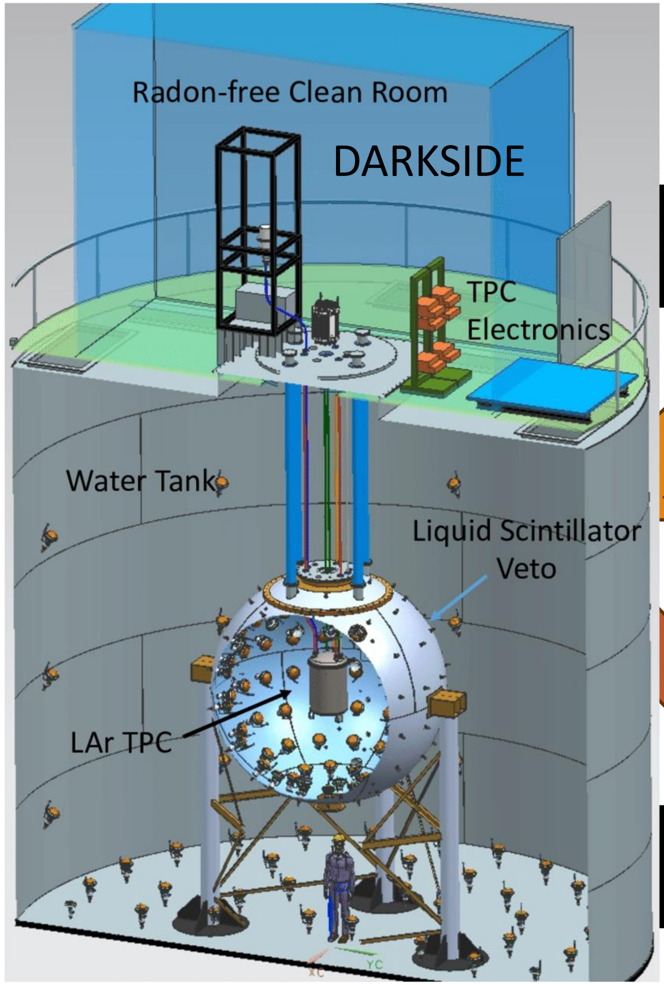
- Underground, low-background lab
- Target with large mass → defines the limit of detection in a certain time
- Excitation of nuclei and scintillation signals

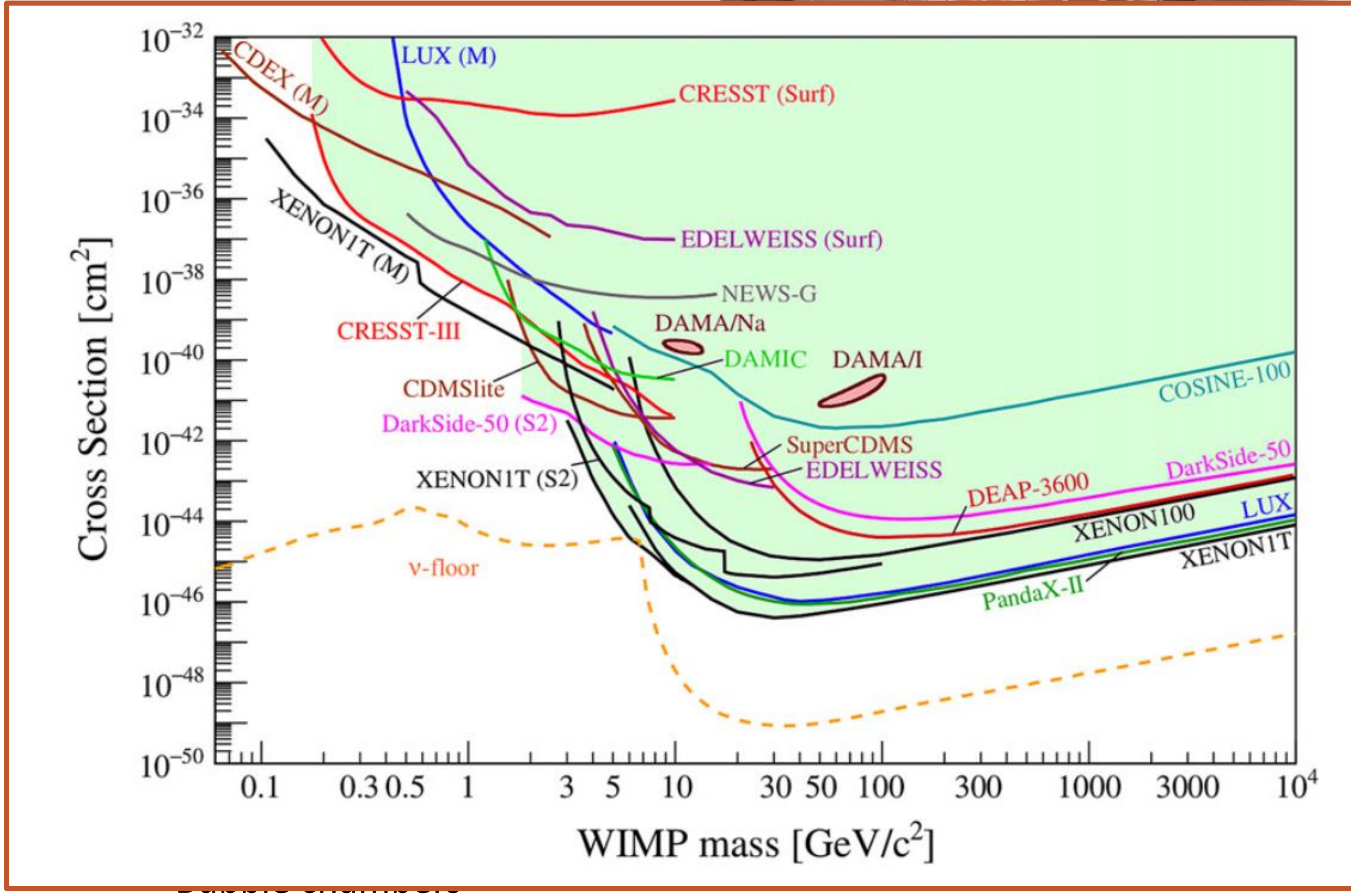
$$\frac{\mathrm{d}R}{\mathrm{d}E_{\mathrm{nr}}} = \frac{\rho_0 M}{m_{\mathrm{N}} m_\chi} \int_{v_{\mathrm{min}}}^{\infty} v f(v) \frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{nr}}} \mathrm{d}v \propto \exp\left(-\frac{E_{\mathrm{nr}}}{E_0} \frac{4 m_\chi m_{\mathrm{N}}}{(m_\chi + m_{\mathrm{N}})^2}\right) F^2\left(E_{\mathrm{nr}}\right)$$

Divided in categories according target material:

- Cryogenic
- Liquid noble gases
- Scintillating crystals
- Bubble chambers
- Directional detector

Dark Matter detection - direct

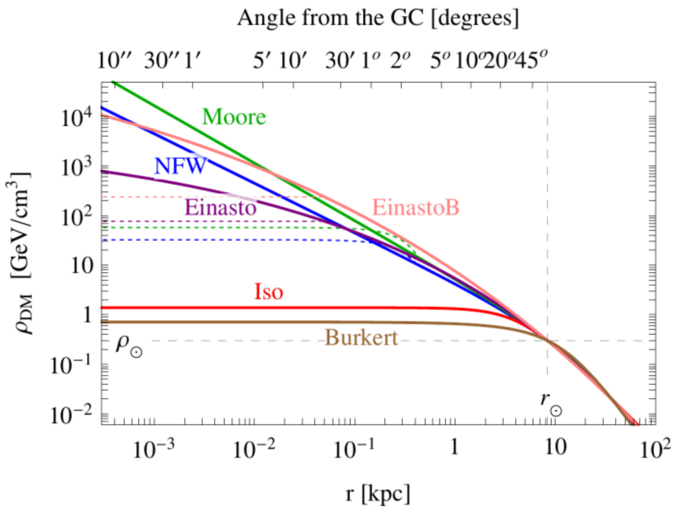




- Directional detector

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

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

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

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

$hh,$

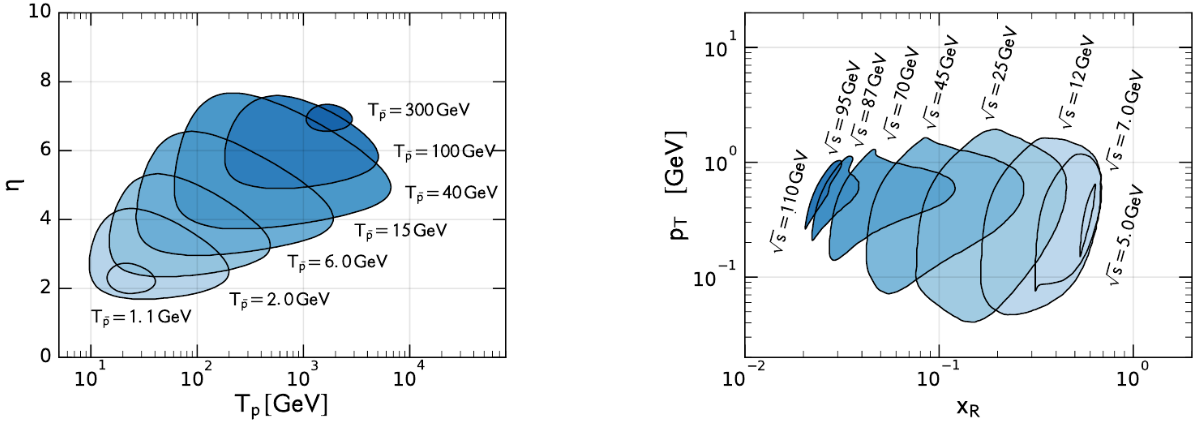
$\nu_e\bar\nu_e,\ \nu_\mu\bar\nu_\mu,\ \nu_\tau\bar\nu_\tau,$

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

3.

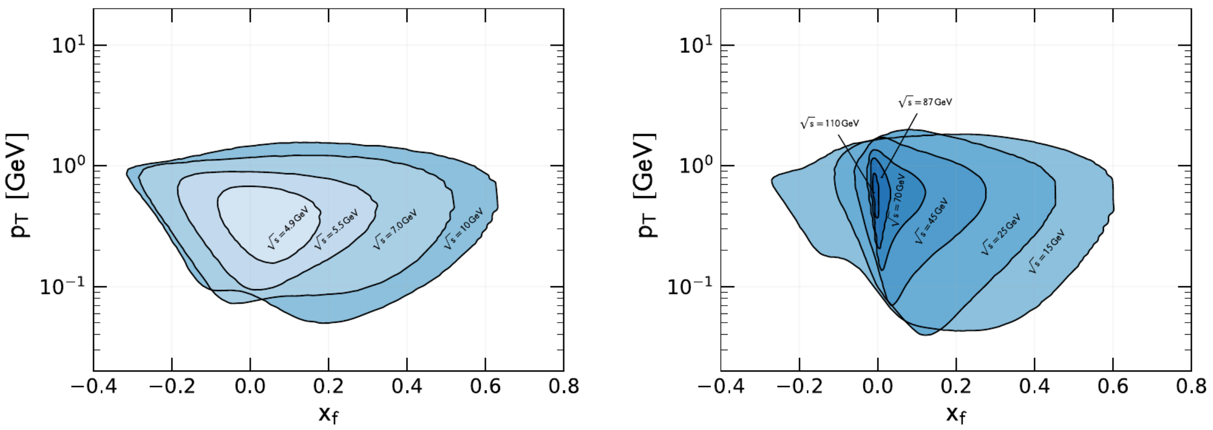
Hadronization → need input from generator (HERWIG, PYTHIA,..)
+
Numerical solution of **propagation** equation (DRAGON, GALPROP,…)

doi:10.1103/PhysRevD.96.043007



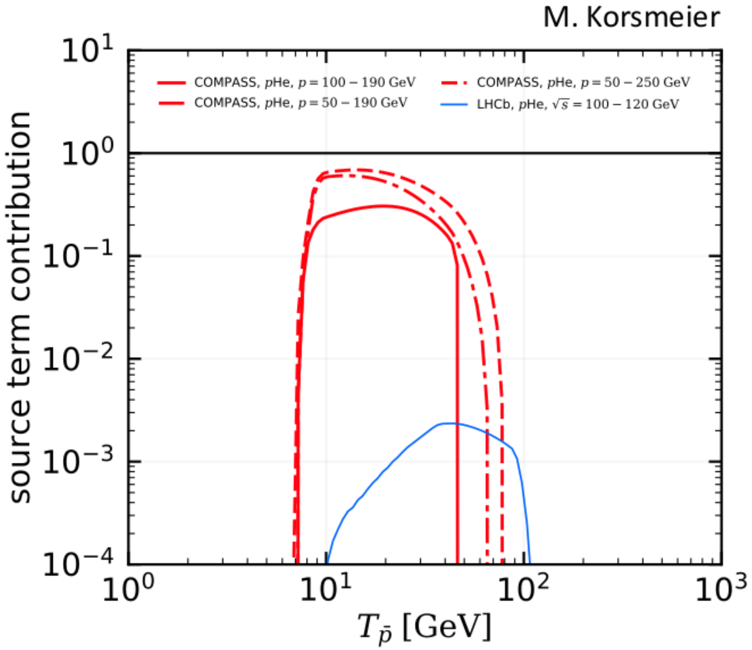
(a) LAB frame (b) CM frame

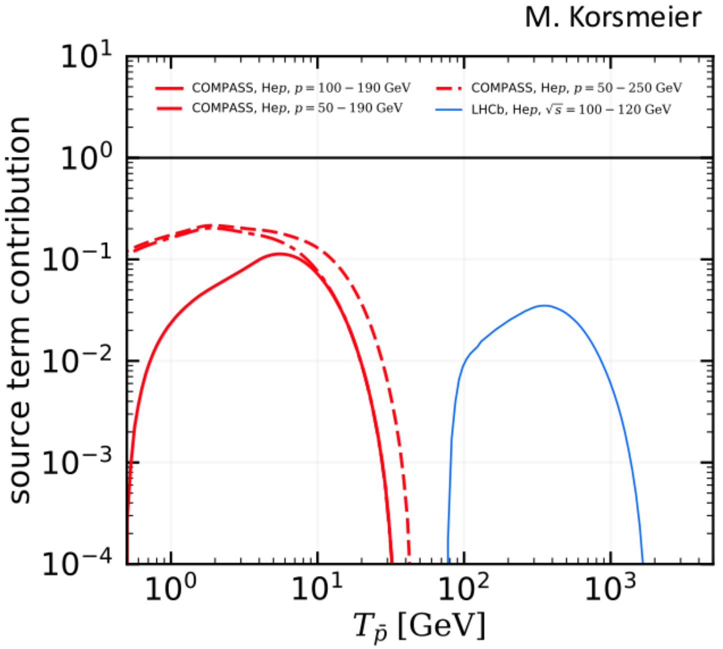
10.1103/PhysRevD.97.103019



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

$$x_F = \frac{p^*_L}{\sqrt{s}/2}$$

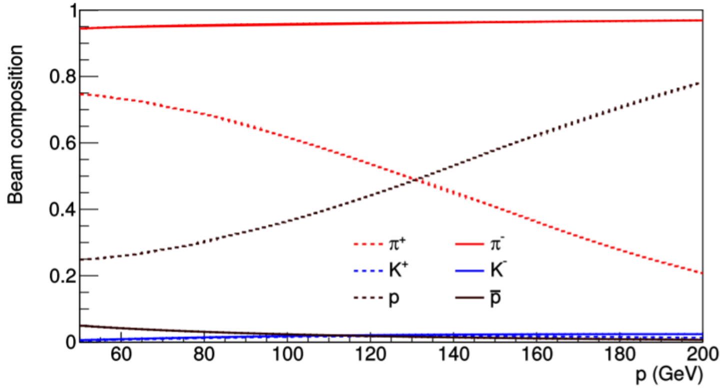




The 2023 p-He data sample

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

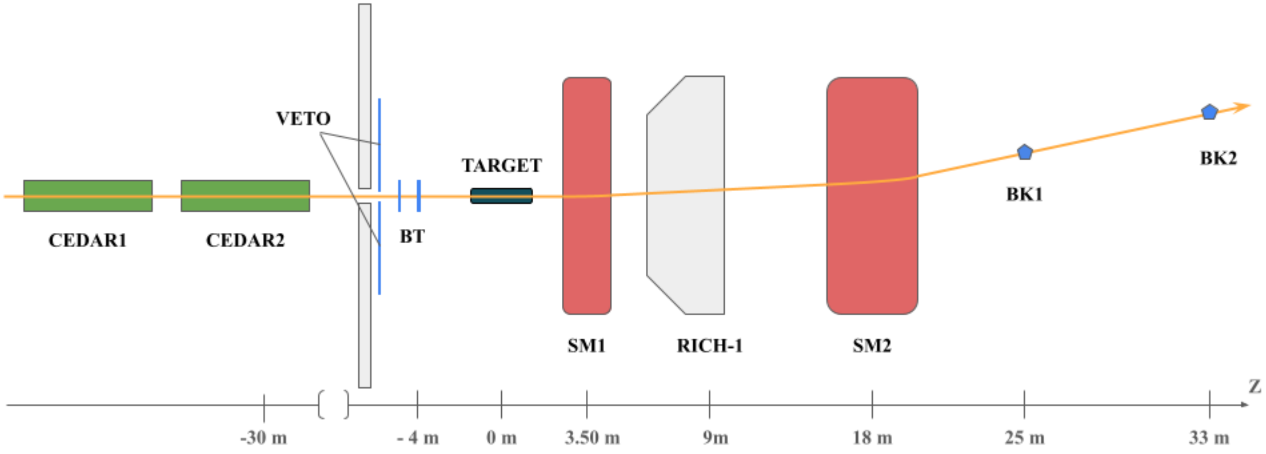


Beam mom. [GeV/c]	Collision energy $\sqrt{s_{NN}}$ [GeV]	Start Date	End Date	Number of spills
60	10.7	24.05	30.05	37000
80	12.3	17.06	25.06	13400
100	13.8	01.06	11.06	13700
160	17.3	14.06	17.06	8500
190	18.9	19.05	24.05	11000
250	21.7	11.06	14.06	7300

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

@190 GeV/c ~75% protons

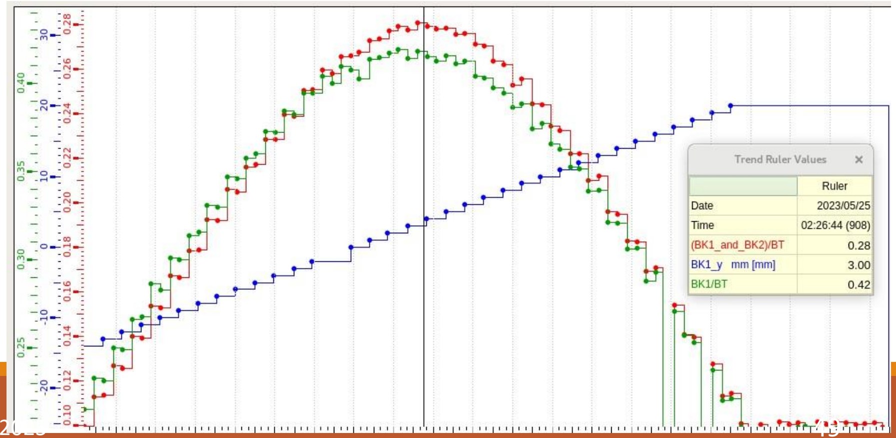
The AMBER experiment @CERN – trigger in 2023



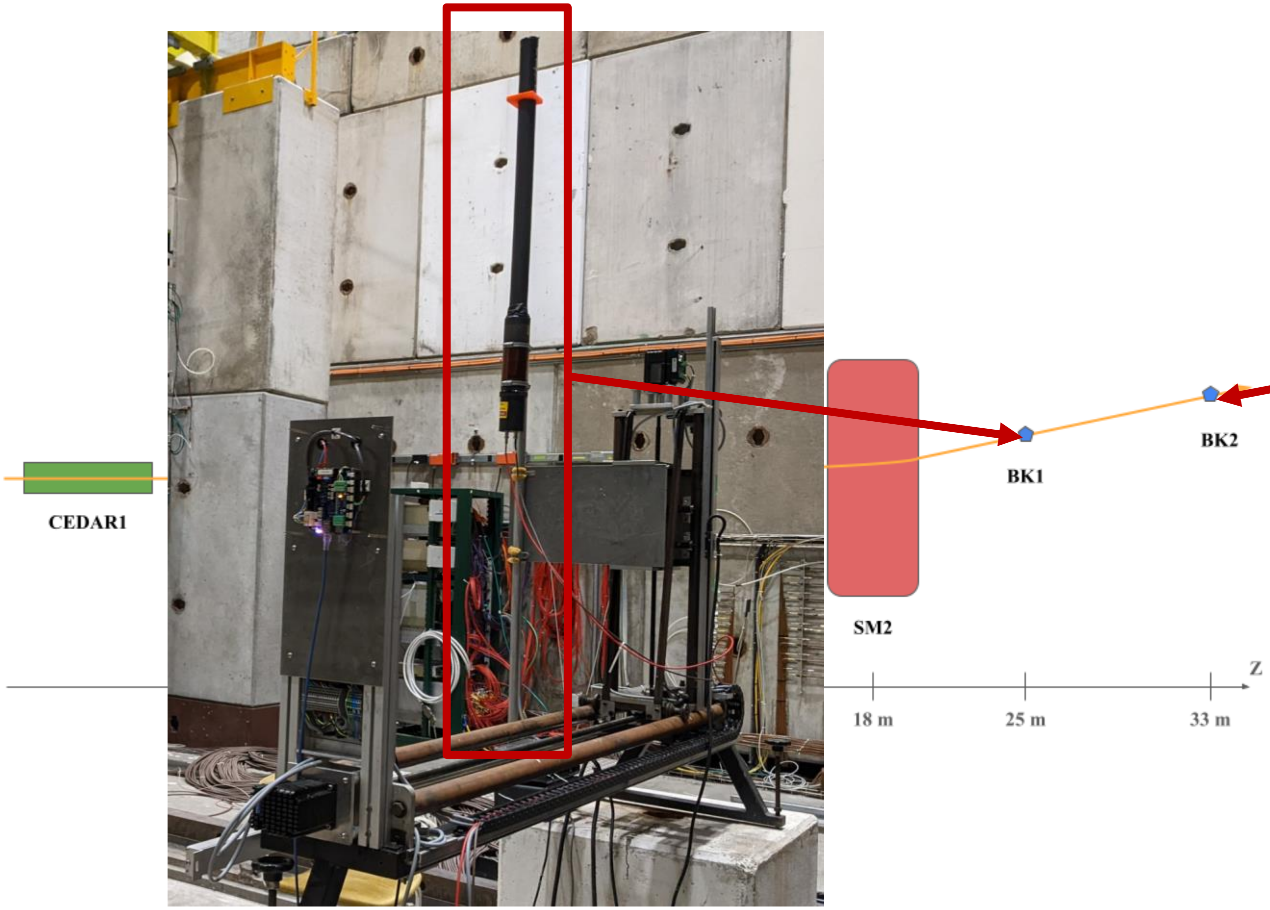
Trigger system:

- 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

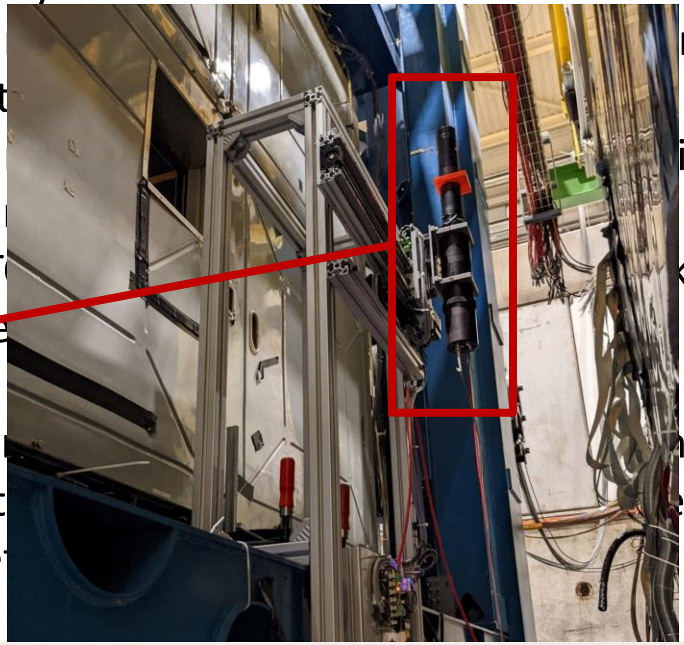


The AMBER experiment @CERN – trigger in 2023

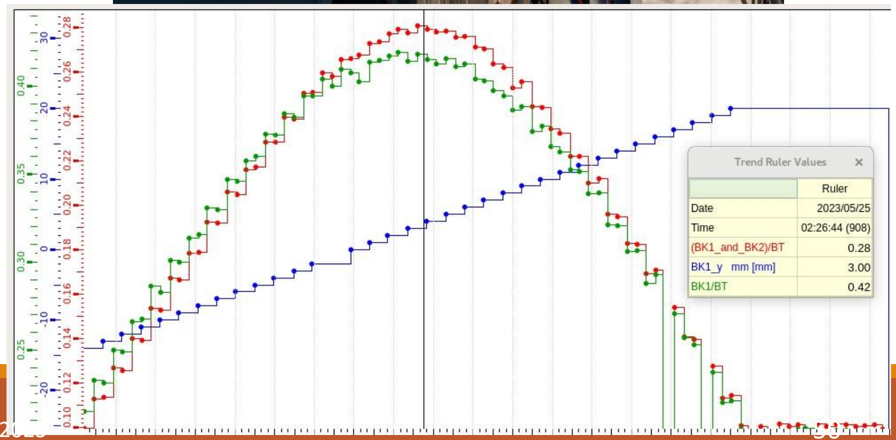


Trigger system:

- Bea … m part
- Bea … ing bea
- VET … ks (halo + dive



Positio … nulation and int … ent magne



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

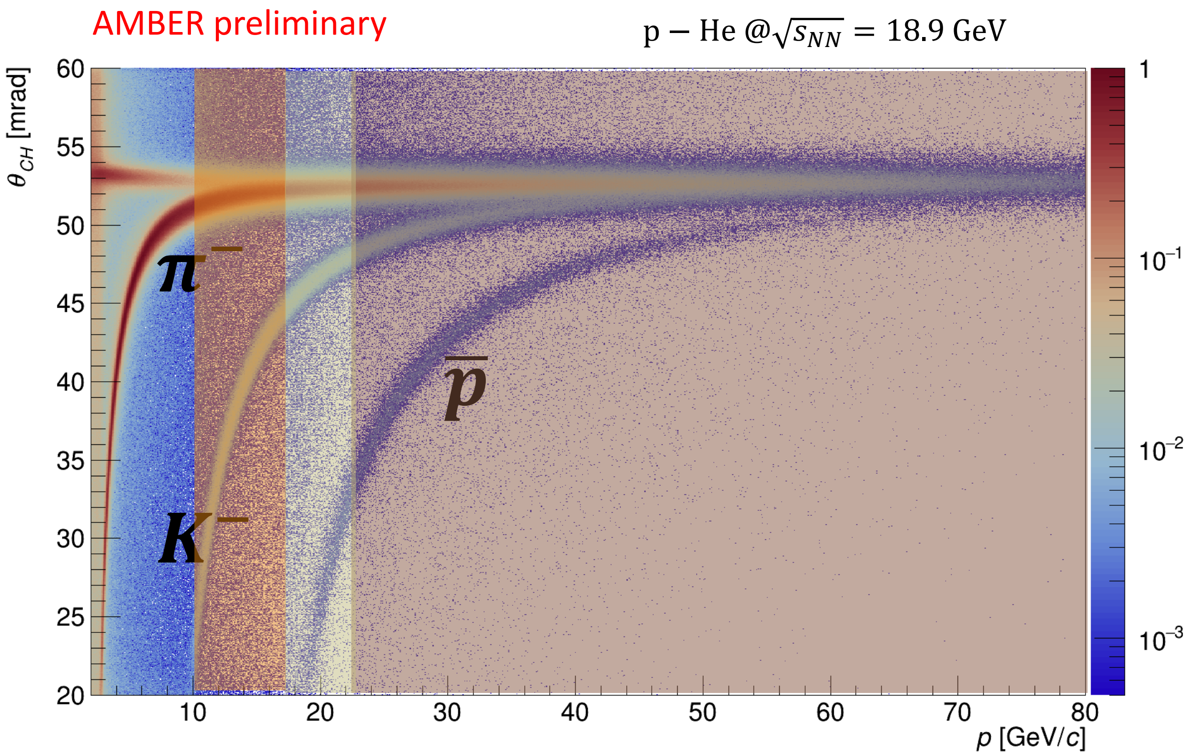
$$\mathcal{L}_M = \exp\left[-\left(S_M + B\right)\right] \prod_{j=1}^{N} f_M\left(\theta_j, \varphi_j\right)$$

$$S_m = \int s_m(\theta,\varphi) d\theta\, d\varphi$$

$$B = \int b(\theta,\varphi)\, d\theta d\varphi$$

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

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



3 momentum intervals: