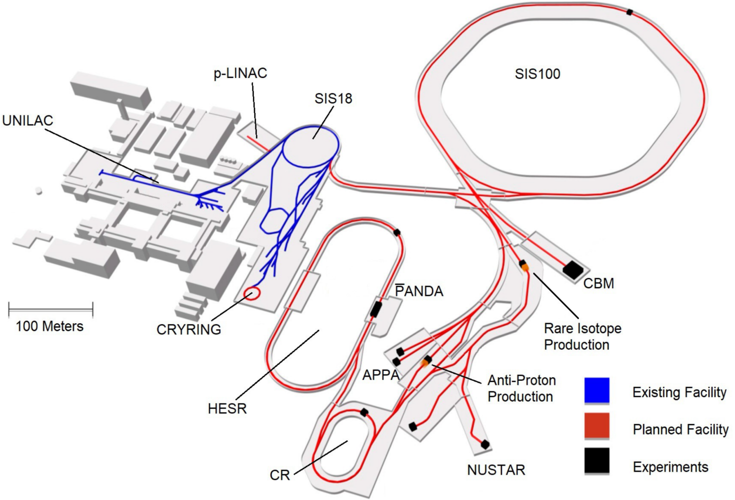
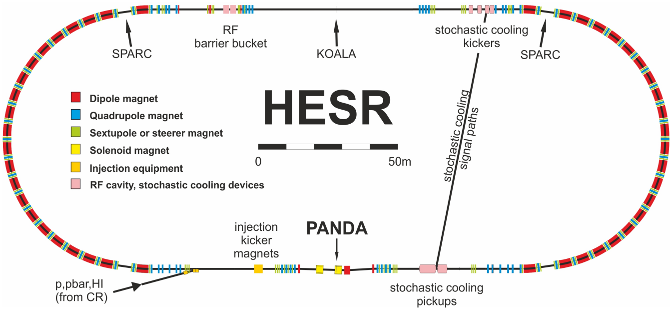
Luminosity Determination with Restgas Background from the Target for the PANDA Experiment

Jinxin Li
Ruhr-university Bochum | Experimental physics I
May 12, 2026

FAIR: Facility for Antiproton and Ion Research

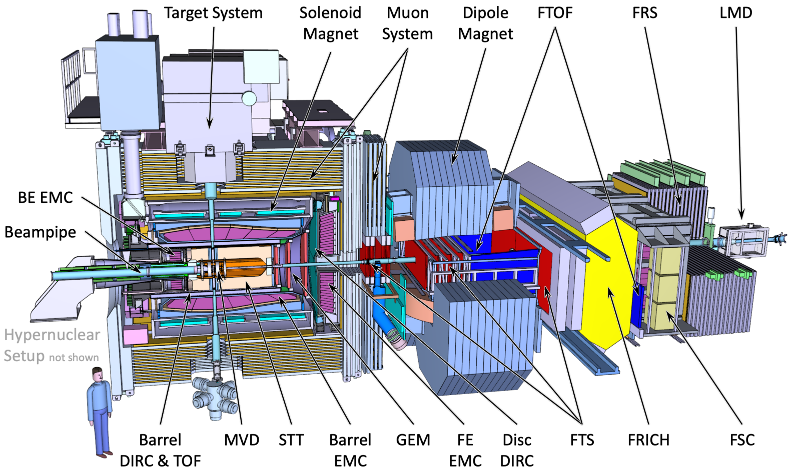


FAIR: Facility for Antiproton and Ion Research



Beam parameters	High Resolution (HR)	High Luminosity (HL)
p (GeV/c)	$1.5 - 15$	$1.5 - 15$
Stored Antiprotons ($N_{\bar{p}}$)	10^{10}	10^{11}
Momentum Resolution ($\Delta p/p$)	$\geq 4 \times 10^{-5}$	$\sim 1 \times 10^{-4}$
Peak Luminosity [$\mathrm{cm^{-2}s^{-1}}$]	2×10^{31}	2×10^{32}

The PANDA Detector



Physics program:

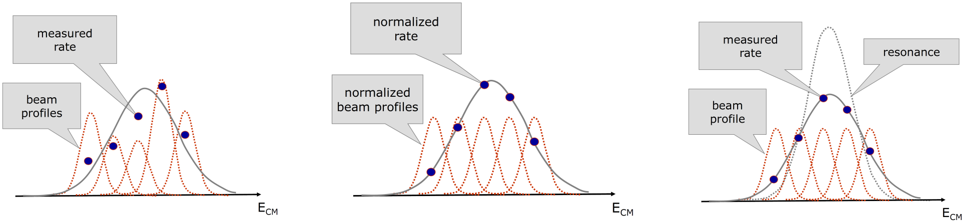
- Hadron spectroscopy
- Hadron structure
- Hadrons in medium
- Hypernuclear physics

Setup:

- Target Spectrometer
- Forward Spectrometer
- Luminosity Detector

Why to Measure the Luminosity

- Absolute time-integrated luminosity
  $\Rightarrow$ Determination of absolute cross section $N = \mathcal{L} \cdot \sigma$
- Relative time-integrated luminosity
  $\Rightarrow$ Scan experiments



How to Measure the Luminosity

- $\bar{p}p$ elastic scattering used, only $\bar{p}$ measured

$$\frac{dN(\theta)}{d\theta} = L \cdot \left[\frac{d\sigma(\theta)}{d\theta} \cdot \epsilon(\theta) \right] \otimes Res(\theta)$$

Number of Events

Time-integrated Luminosity

Differential Cross Section

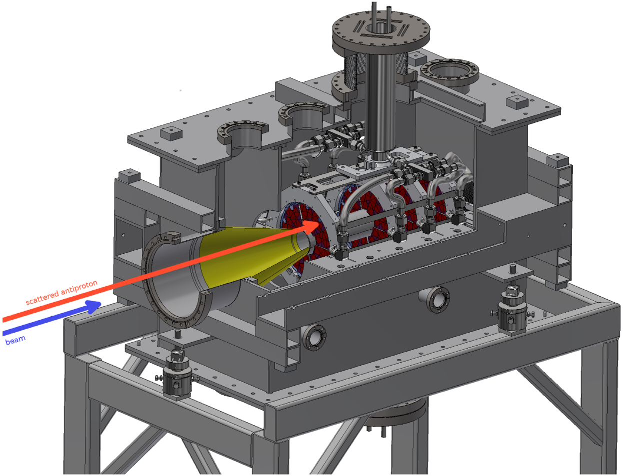
Reconstruction Efficiency

Detector Resolution

- Determine efficiency and resolution
- Determine Luminosity by comparing data and model

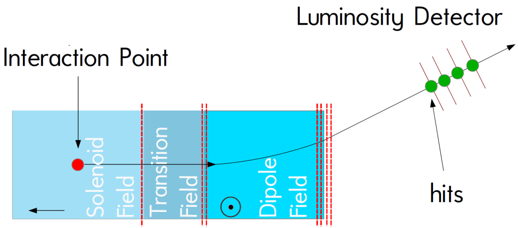
Luminosity Detector (LMD)

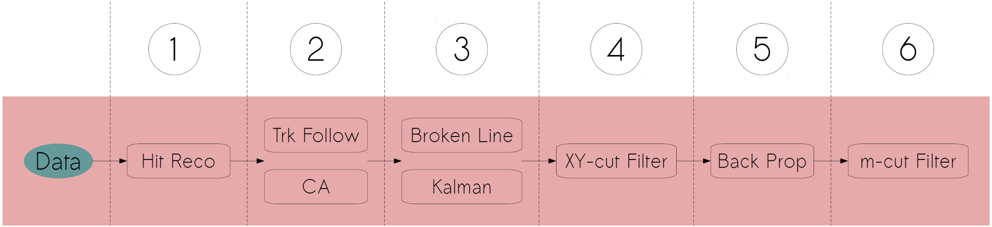
- Located $\sim 10.5\ \mathrm{m} - 12.5\ \mathrm{m}$
- Measure forward scattered $\bar{p}$
- 4 planar tracking stations
- Utilize HV-MAPS
- Covergence:
  $3.5\ \mathrm{mrad} \leq \theta \leq 10\ \mathrm{mrad}$
  $0 \leq \phi < 2\pi$



Track Reconstruction Software

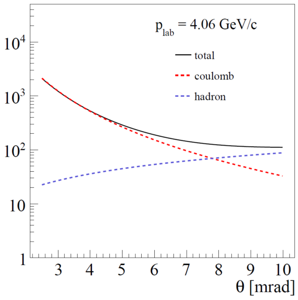
- Implemented within PandaRoot
- Hits in LMD
  $\Rightarrow$ Angular distributions at IP



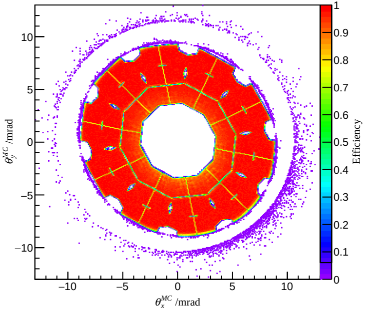


Luminosity Fit Software

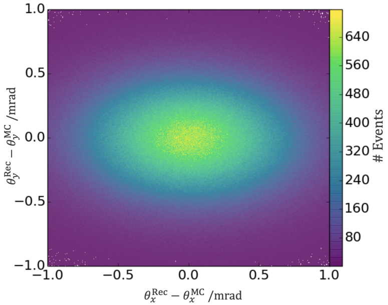
Preparation of the fit model: $\frac{d\sigma_{\bar{p}p}}{d\theta} \cdot \epsilon(\theta_x, \theta_y) \otimes R(\Delta\theta_x, \Delta\theta_y)$



Theoretical input



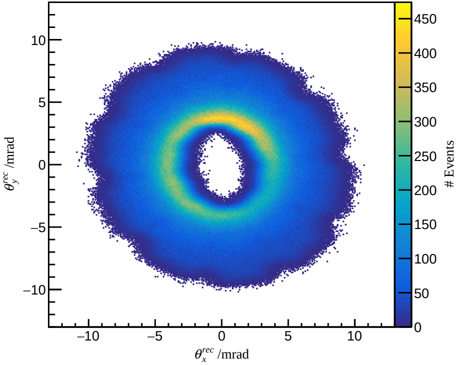
Acceptance

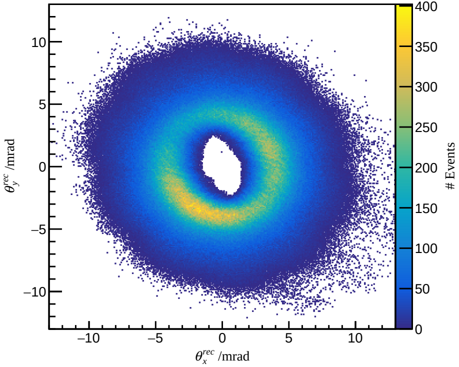


Resolution

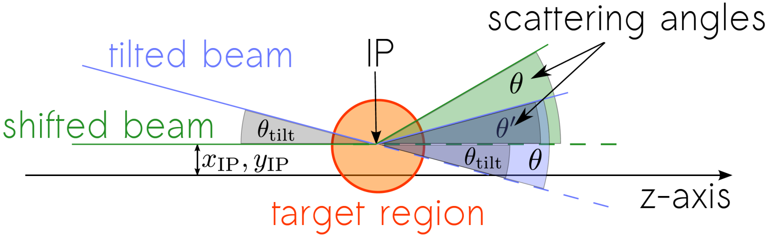
Luminosity Fit Software

Fit model to data



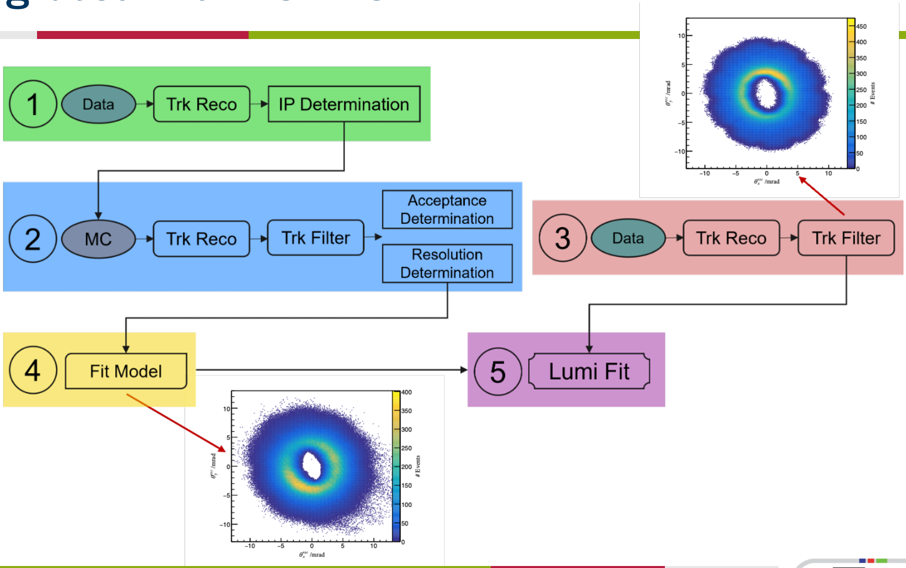


Effects of Beam Properties

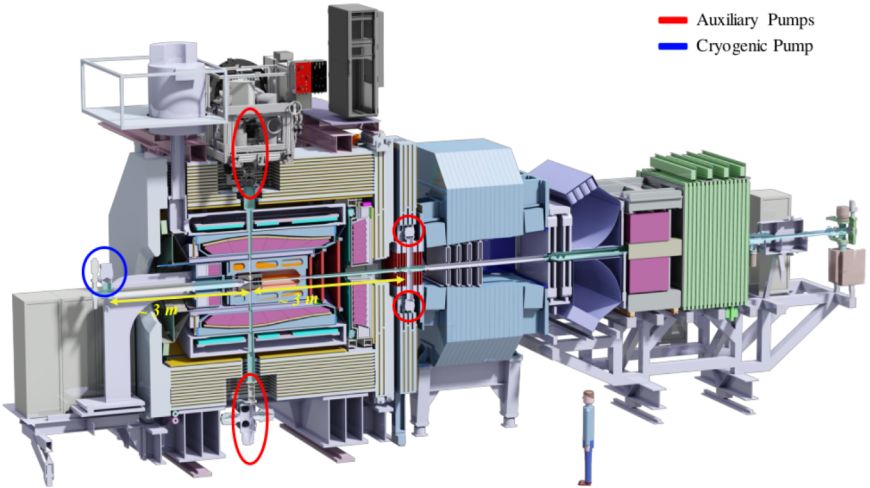


- Determine IP $\Rightarrow$ efficiency & resolution correction
  - IP position: measured by reconstructed tracks only in x and y
  - IP distribution: taken from target and accelerator group
- Determine beam corrections
  - Tilt and divergence: determined by LuminosityFit

Integrated Fit Workflow



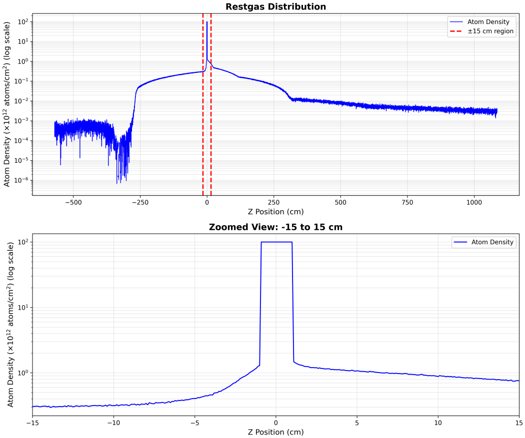
Origin of the Restgas



Restgas Distribution

The Restgas Profile

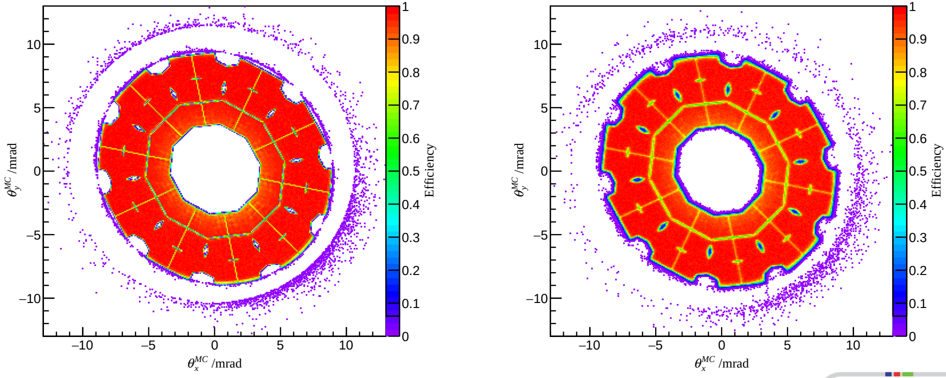
- Simulated from Münster.
- Continuous distribution along the beam pipe.



Restgas density distribution along the z-axis

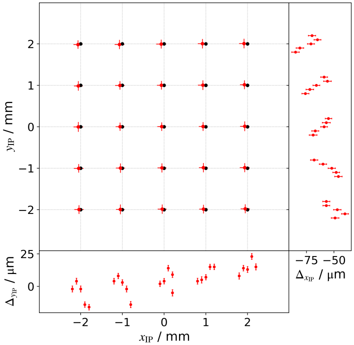
Effective Acceptance

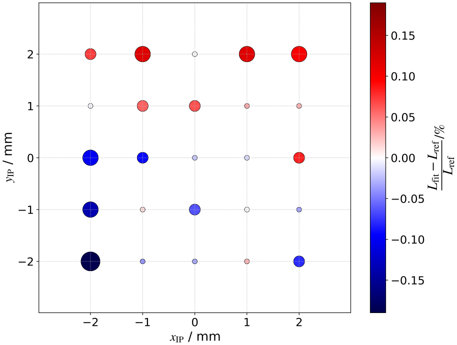
- $\epsilon_{eff}^{gas}(\theta_x, \theta_y)$ derived from simulations incorporating the Restgas distribution
- Preparation of the new fit model: $\frac{d\sigma_{\bar{p}p}}{d\theta} \cdot \epsilon_{eff}^{gas}(\theta_x, \theta_y) \otimes R(\Delta\theta_x, \Delta\theta_y)$



Single Parameter Performance with Restgas

Determination of IP shift ($p_{lab} = 4.06\ \mathrm{GeV}/c$)





IP Shift:

$|\Delta x| \leq 80\ \mu\mathrm{m}$
$|\Delta y| \leq 25\ \mu\mathrm{m}$
$|\Delta L/L| < 0.2\%$

Beam Tilt:

$|\Delta\theta_x| \leq 10\ \mu\mathrm{rad}$
$|\Delta\theta_y| \leq 10\ \mu\mathrm{rad}$
$|\Delta L/L| < 0.1\%$

Beam Divergence:

$|\Delta \mathrm{div}_x| \leq 40\ \mu\mathrm{rad}$
$|\Delta \mathrm{div}_y| \leq 45\ \mu\mathrm{rad}$
$|\Delta L/L| < 0.2\%$

Optimization of the Fitting Strategy

Challenge in realistic scenarios:

Simultaneous fit of $\mathcal{L}$, tilt and divergence
$\Rightarrow$ Convergence failure & unstable $\mathcal{L}$

Key results:

- Robust tilt determination
- Unstable luminosity

Simulated: $\mathrm{tilt}^{\mathrm{sim}}_{x,y} = 100\ \mu\mathrm{rad}, \mathrm{div}^{\mathrm{sim}}_{x,y} = 100\ \mu\mathrm{rad}$

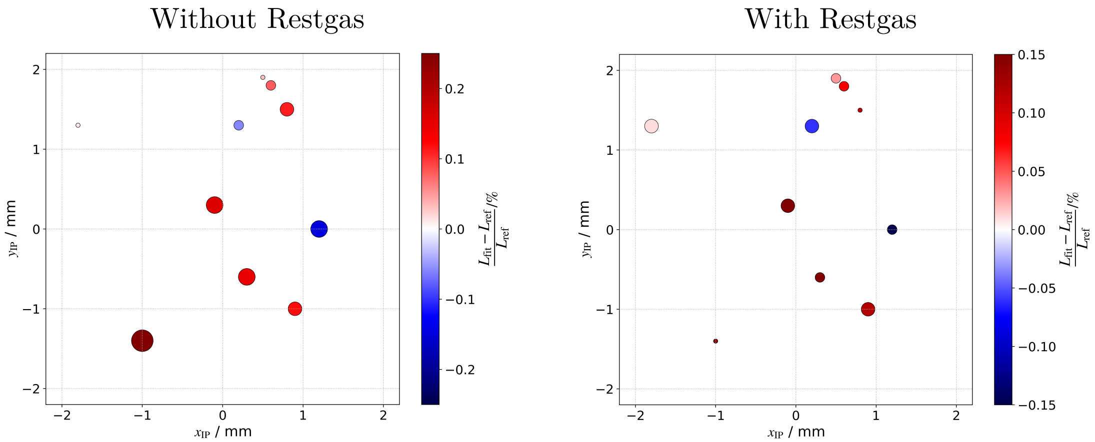
Fit Assumption $\mathrm{div}^{\mathrm{fix}}_{x,y}$ [μrad]	**Fitted tilt** $\mathrm{tilt}^{\mathrm{rec}}_{x}$ [μrad]	$\mathrm{tilt}^{\mathrm{rec}}_{y}$ [μrad]	**Luminosity** $\Delta\mathcal{L}/\mathcal{L}$ [%]
0	104.9 ± 1.3	96.3 ± 1.4	0.30 ± 0.07
100	105.0 ± 1.2	95.9 ± 1.3	-0.05 ± 0.07
200	104.0 ± 1.3	94.5 ± 1.4	-1.05 ± 0.07

Stable two-step fitting strategy

1. **Tilt determination:** Fix divergence ($0\ \mu\mathrm{rad}$) $\Rightarrow$ tilt.
2. **Divergence & luminosity:** Fix tilt (determined in step 1) $\Rightarrow$ divergence & $\mathcal{L}$.

A single iteration is sufficient to reach the required precision.

Performance in Realistic Scenarios

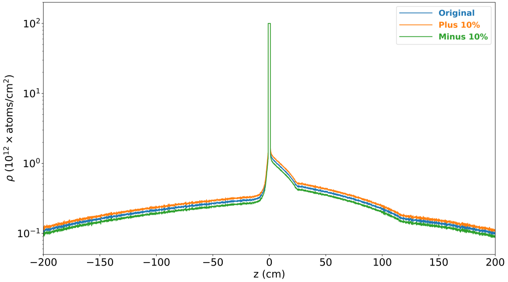


$|\Delta L/L| \leq 0.25 \pm 0.09\%$ $|\Delta L/L| \leq 0.15 \pm 0.21\%$

Reality in the Experiment

Simulated Restgas profiles may differ from the real distribution.

Sensitivity Study:



Fit Model

Original Simulated Restgas profile.

Real data

Original or $\pm 10\%$ Restgas profiles.

Reality in the Experiment

Simulated Restgas profiles may differ from the real distribution.

Sensitivity Study:

Target Profiles	$\Delta\mathcal{L}/\mathcal{L}$ with Consistent Model	$\Delta\mathcal{L}/\mathcal{L}$ with Original profile
-10% Restgas	-0.02 ± 0.08	-3.39 ± 0.08
Original	0.02 ± 0.08	0.02 ± 0.08
+10% Restgas	0.02 ± 0.08	3.39 ± 0.08

High precision in luminosity determination requires a precise Restgas profile.

Reconstruction Bottleneck

Why standard reconstruction fails for Restgas background?

- Beam-Restgas interactions distributed along the entire beam pipe.
- Standard Track finder (SttMvdGem/Barrel) optimized for IP at $(0, 0, 0)$.
- PID step back-propagated tracks to the z-axis for vertex determination.

Consequences of Displaced Tracks

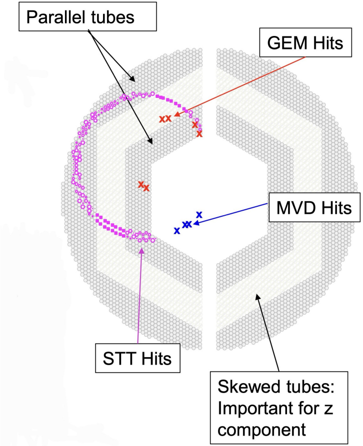
- Wrong reconstructed vertex.
- Bias in dE/dx and momentum vector measurements.
- Low reconstruction efficiency.

Track Finder for Displaced Vertices

Apollonius Triplet Track Finder - A Tailored Track Finder for Secondaries

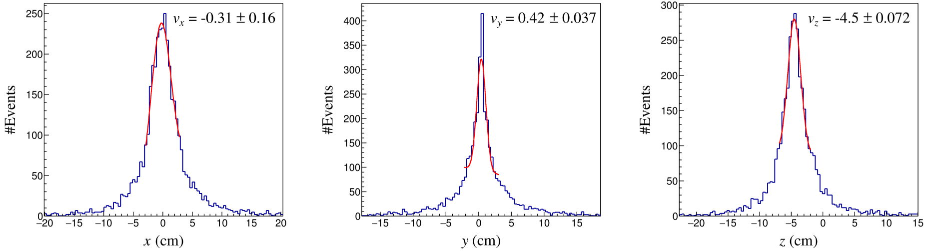
1. Apollonius circles in xy-plane
   - Select STT hits
   - Calculate circles
   - Chose a proper subset circle
2. Longitudinal reconstruction in z-axis
   - Pz Finder with skewed STT hits
   - Calculate z position and p_z
3. Global Tracking
   - KALMANFILTER with MVD & GEM hits.

Developed by Anna Alicke, JÜLICH



A POCA-First Approach:

1. PID step without back-propagation.
2. Vertex determination via POCA of all $\bar{p}p$ tracks.



simulated events with a true vertex at $x = -0.2\,\mathrm{cm},\ y = 0.4\,\mathrm{cm},\ z = -5.0\,\mathrm{cm}$

3. PID step with back-propagation to the POCA vertex (*POCA-to-point*).

Performance of POCA-First Approach

Comparison between POCA vertex and MC Truth

- Simulation: $\bar{p}p$ elastic scattering at $p_{beam} = 4.06\ \mathrm{GeV}/c$, DPM generator.

Parameter	**MC Truth**	**Prop to $\vec{v}_{\mathrm{MC}}$**	**Prop to $\vec{v}_{\mathrm{POCA}}$**
Vertex x [cm]	-0.200	-0.197	-0.198
Vertex y [cm]	0.401	0.397	0.399
Vertex z [cm]	-5.000	-5.001	-5.001
Efficiency	–	74.2%	74.4%

Performance of POCA-First Approach

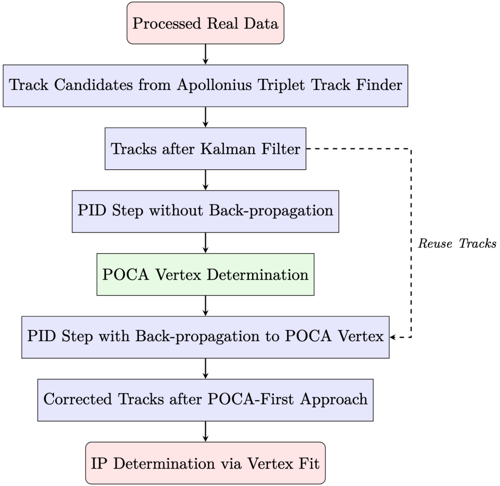
Comparison with POCA-to-axis

- Simulation: $\bar{p}p$ elastic scattering at $p_{beam} = 4.06\ \mathrm{GeV}/c$, DPM generator.

Parameters	**MC Truth**	**POCA-to-axis**	**POCA-First**
Vertex x [cm]	0.0	-0.0007	-0.0006
Vertex y [cm]	0.0	-0.0001	0.0002
Vertex z [cm]	0.0	-0.0038	-0.0006
Efficiency	–	84.4%	82.1%

Workflow for Restgas Determination

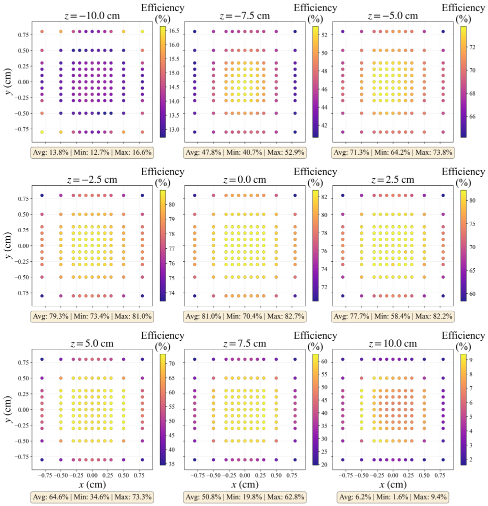
- Determine IP.
- Apply efficiency correction.



Efficiency Dependence on Vertex Position

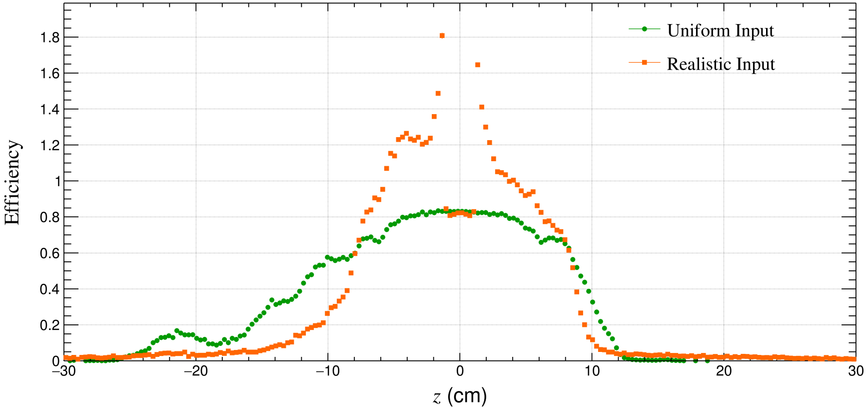
- $p_{beam} = 4.06\ \mathrm{GeV}/c$
- Stable within $|x|, |y| < 0.5$ cm.

1D longitudinal efficiency correction is sufficient.



Resolution Effect

The ”Spill-Over” Phenomenon



Resolution Effect

The Forward Modeling Approach

- Generate MC samples using a realistic input density profile $\rho_{in}(z)$.
- Calculate efficiency $\epsilon = N_{reco}/N_{gen}$

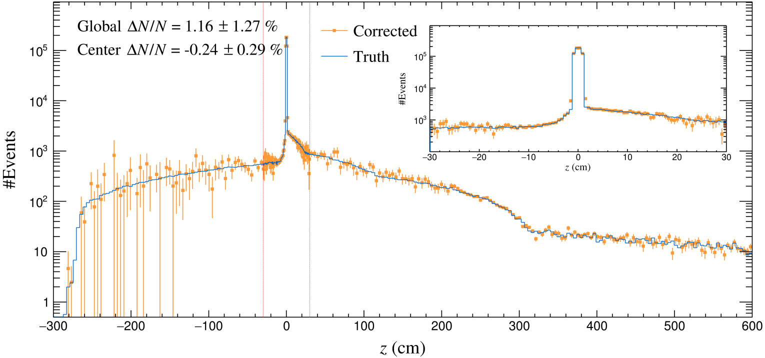
$\epsilon = N_{reco}/N_{gen}$ acting as a convolved correction function

effectively encapsulates both:

- Geometrical acceptance.
- Resolution-induced migration.

Baseline Validation

Input distribution for efficiency perfectly matches the data distribution.



The Circular Dependency

Restgas distribution needed for Restgas measurement.

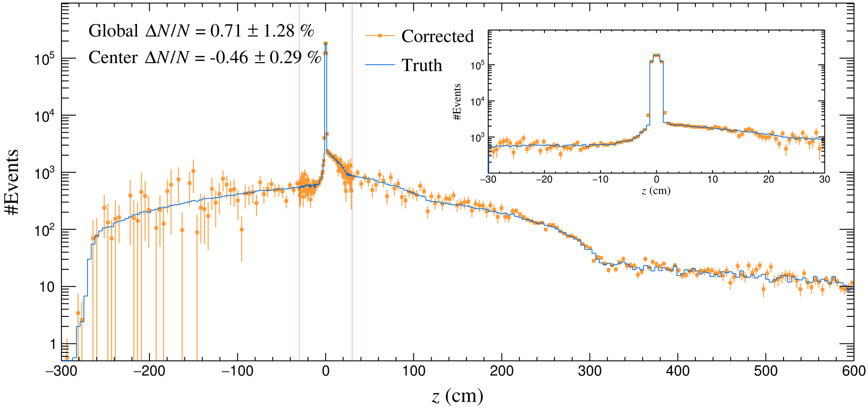
Convergence Verification

Stress Tests:

- A matrix of scenarios are generated:
  - Density of target region kept constant.
  - Density of Restgas background: $0\%, \pm5\%, \pm10\%, \pm20\%$ deviations.
- Each scenario acts as the data distribution and the distribution for efficiency.
- Relative deviation between data and model ranges from $0\% \text{ to} \pm 40\%$.

Convergence Verification

An Example of 10% Underestimation: *Input:* -5% vs. *True:* $+5\%$.



Iterative Workflow

- Analyzed over 30 mismatched scenarios.
- The magnitude of deviation is significantly smaller than the initial input bias.

The Iterative Results:

- Difference $< 10\%$ $\Rightarrow$ deviation in center $< 1\%$
  $\&$ global deviation $<$ its uncertainty
- Difference $> 10\%$ $\Rightarrow$ deviation significantly suppressed
  (most of the time in center $< 5\%$)

$\Rightarrow$ The iterative procedure.

Iterative Workflow

1. **Initialization:**
   Generate efficiency map (ϵ) using Restgas distribution from Target Group.
2. **Reconstruction:**
   Reconstruct IP distribution (ρ_{reco}) using (ϵ).
3. **Convergence Check:**
   If central deviation $< 1\%$
   $\&$ global deviation $<$ its uncertainty.
4. **Iteration:**
   If YES, stop and take ρ_{reco} as the determined Restgas distribution.
   If NOT, generate new ϵ using ρ_{reco} and repeat the loop.

Iteration Results

An example of iteration starting with 40% overestimation of the Restgas distribution.

Iteration Step	Global Difference[%]	Central Difference[%]
1	12.27 ± 5.69	1.58 ± 0.30
2	4.28 ± 1.19	1.18 ± 0.28
3	1.30 ± 1.32	-0.22 ± 0.29

The iterative procedure converges rapidly!

Luminosity Determination

- $p_{beam} = 4.06$ GeV$/c$.
- IP cut around reconstructed IP: $|x|, |y| < 1$ cm, $|z| < 5$ cm

Target Profiles	Fit Model	$\Delta\mathcal{L}/\mathcal{L}$
Point-like Target	Point-like Target	-0.04 ± 0.07
Target with Restgas	MC Target Distribution	0.02 ± 0.08
Target with Restgas	Determined Target Distribution	0.05 ± 0.07

Summary

$|\Delta\mathcal{L}/\mathcal{L}| < 0.5\%$ for $p_{\mathrm{beam}} = 1.5\text{–}15\,\mathrm{GeV}/c$

A Complete Workflow for Restgas Measurement established:

- **Reconstruction of Displaced Vertices:**
  The Apollonius triplet track finder combined with the POCA-First approach.
- **Efficiency Correction**
  A forward modeling approach with a rapidly converged iterative workflow.

Luminosity can be determined as precisely as with point-like target or with well-known Restgas distribution to be $\Delta\mathcal{L}/\mathcal{L} = 0.05 \pm 0.07$.

Thanks for your attention!