Measurement of the muon flux and σ_{charm} in a SHiP-like target

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<u>**Contributions of German institutes to testbeams**</u>

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Drift tubes:
D. Bick, S. Bieschke, C. Hagner, B. Opitz, W. Schmidt-Parzefall

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Pixel tracker:
M. Climescu, M. Cristinziani, V. Kostyukhin, N. Owtscharenko

CERN-SPSC-2017-020 *CERN-SPSC-2017-033* *arXiv:2001.04784, accepted by Eur. Phys. J. C*

Measurement of the μ flux

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10^{11} muons per spill will be produced in the target

- mostly from π, K, ρ, ω and charmed mesons
- SHiP aims at <0.1 background events in 5 years ($2 \cdot 10^{20}$ pot)
- i.e. $5 \cdot 10^{17}$ muons in total

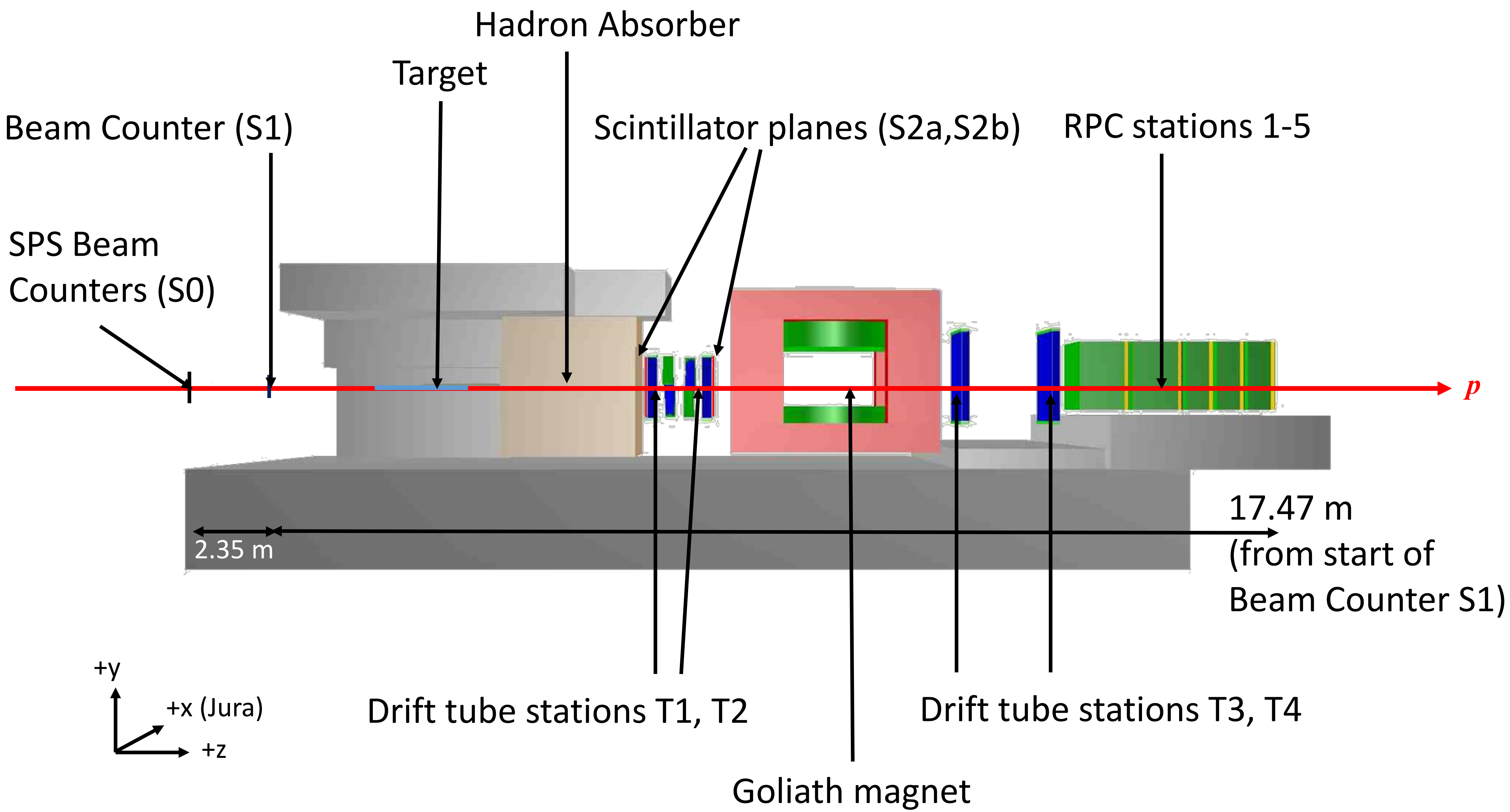
Magnetic shielding

- remove muons very efficiently over a large p-range ($\varepsilon \sim 10^{-5}$)
- optimisation based on simulation (Pythia, Geant4)

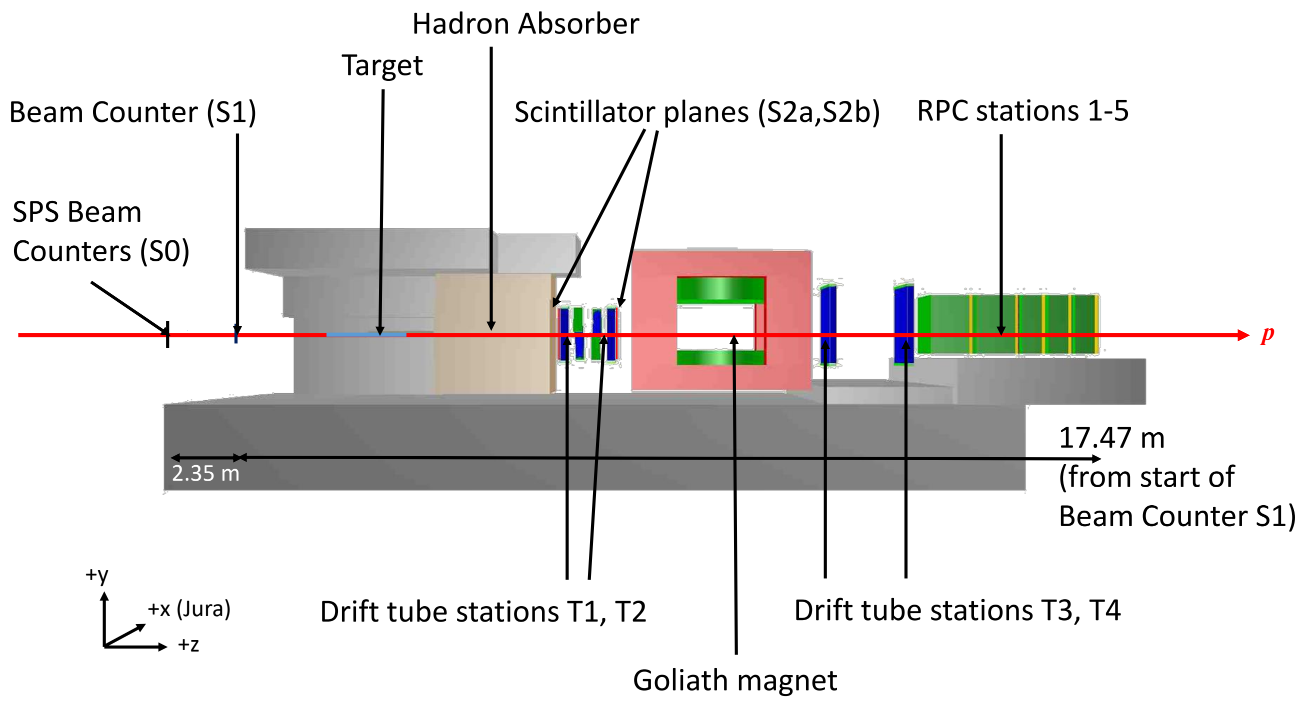
Need to validate simulation

- especially for p > 100 GeV/c and p_T > 3 GeV/c
- performed a 3-weeks test-beam with a full length SHiP-like target, collecting 1% of a SHiP spill at SPS H4 beam at CERN

μ-flux measurement layout: overview



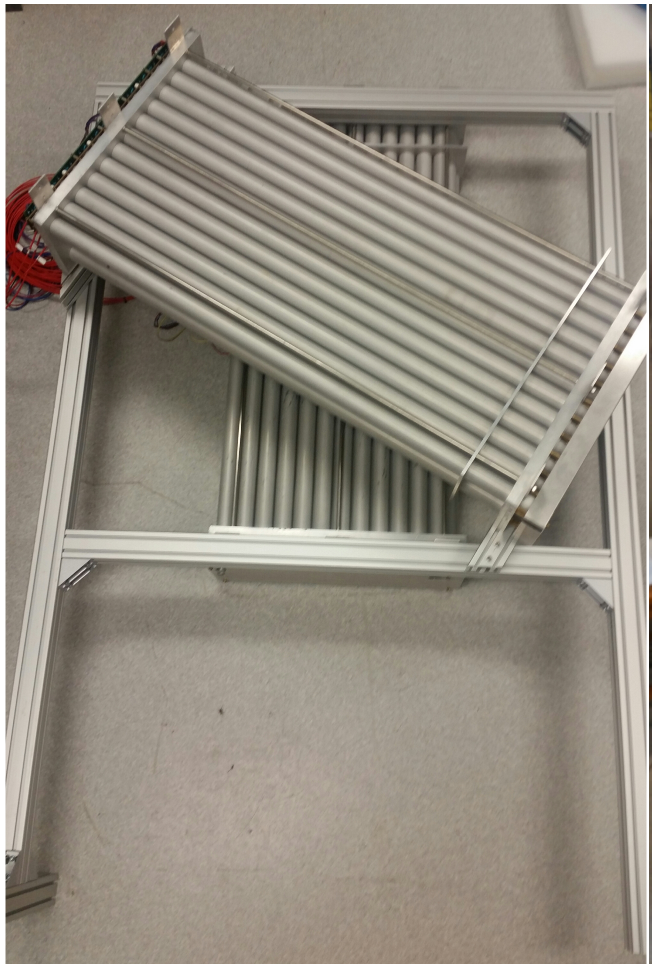
µ-flux measurement layout: target

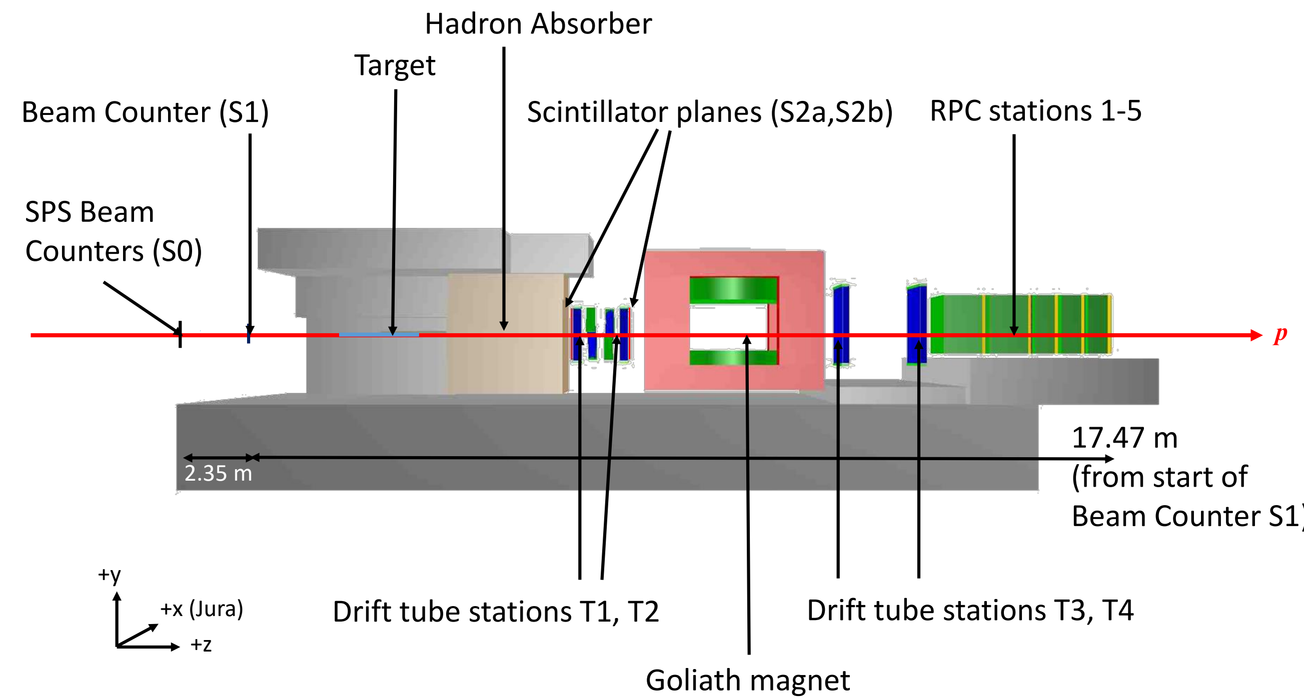


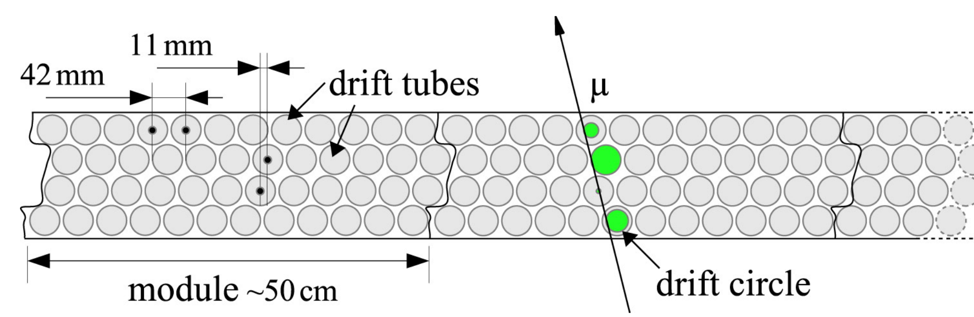
Target replica

- same TZM, W and Ta longitudinal distribution
- 100 mm diameter instead of 250 mm
- full length: interaction length preserved
- Ta-cladding replaced by Ta slabs
- water cooling replaced by PET slabs

μ-flux measurement layout: tracker



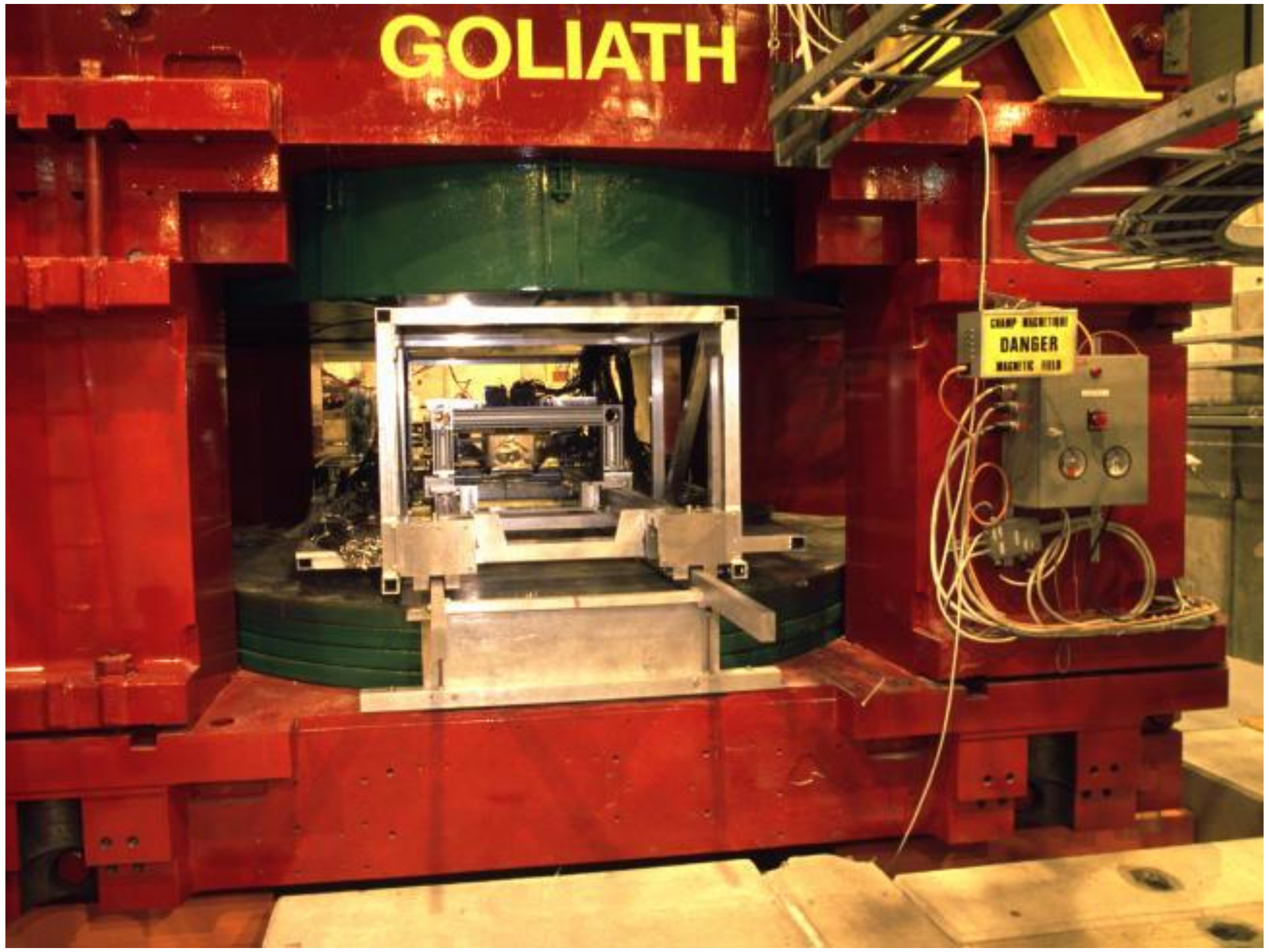


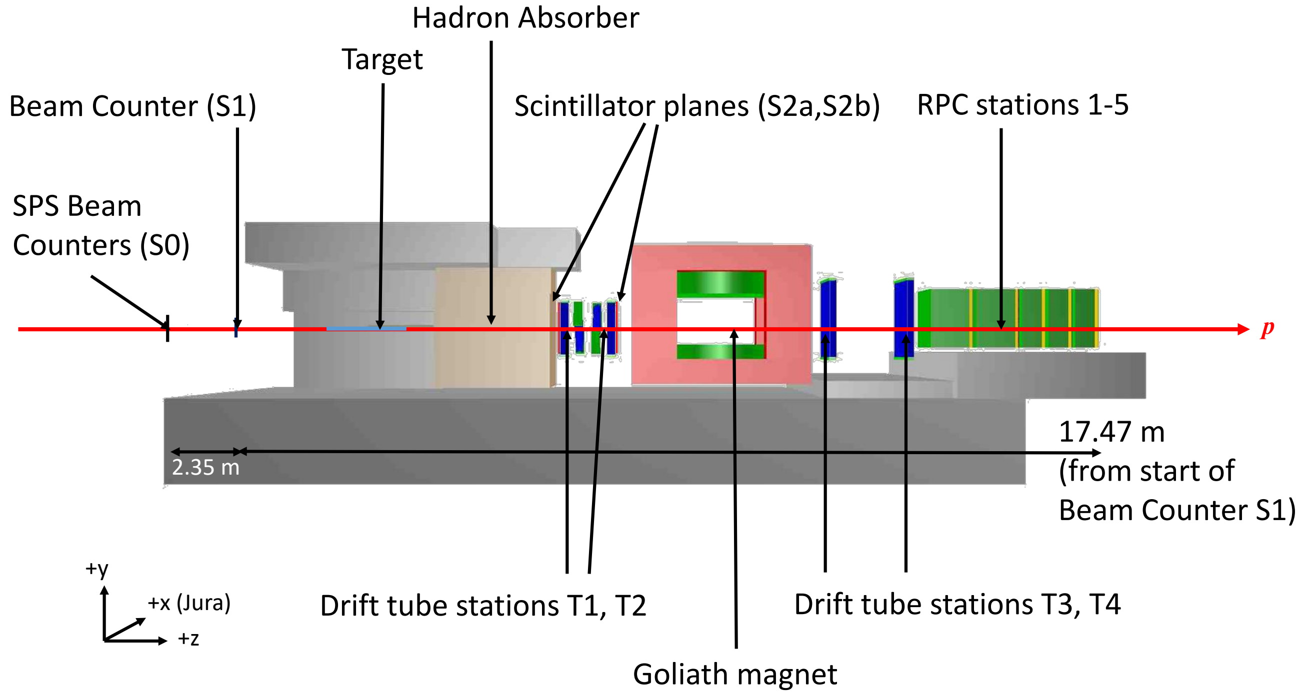


Drift tubes (DT)

- **OPERA test modules**
- **some used for Borexino**
- **alignment using Millepede in progress**

μ-flux measurement layout: magnet

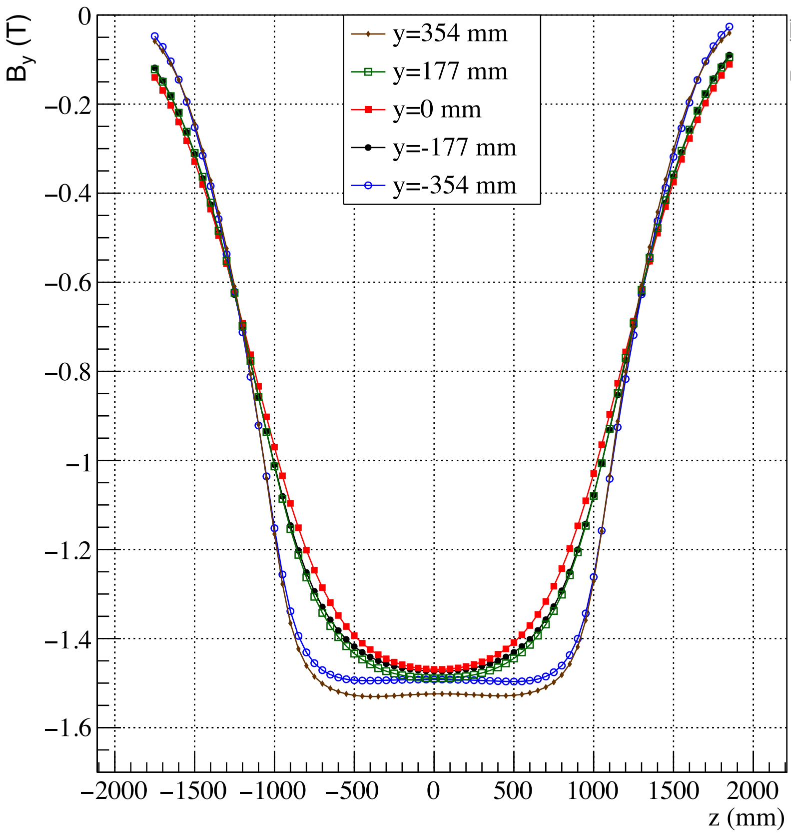




Goliath magnet

- Large spectrometer magnet located in H4
- 4.5m x 3.6m x 2.8m
- Field map re-determined accurately in 2017

CERN-ACC-NOTE-2018-0028



μ-flux measurement layout: muon filter

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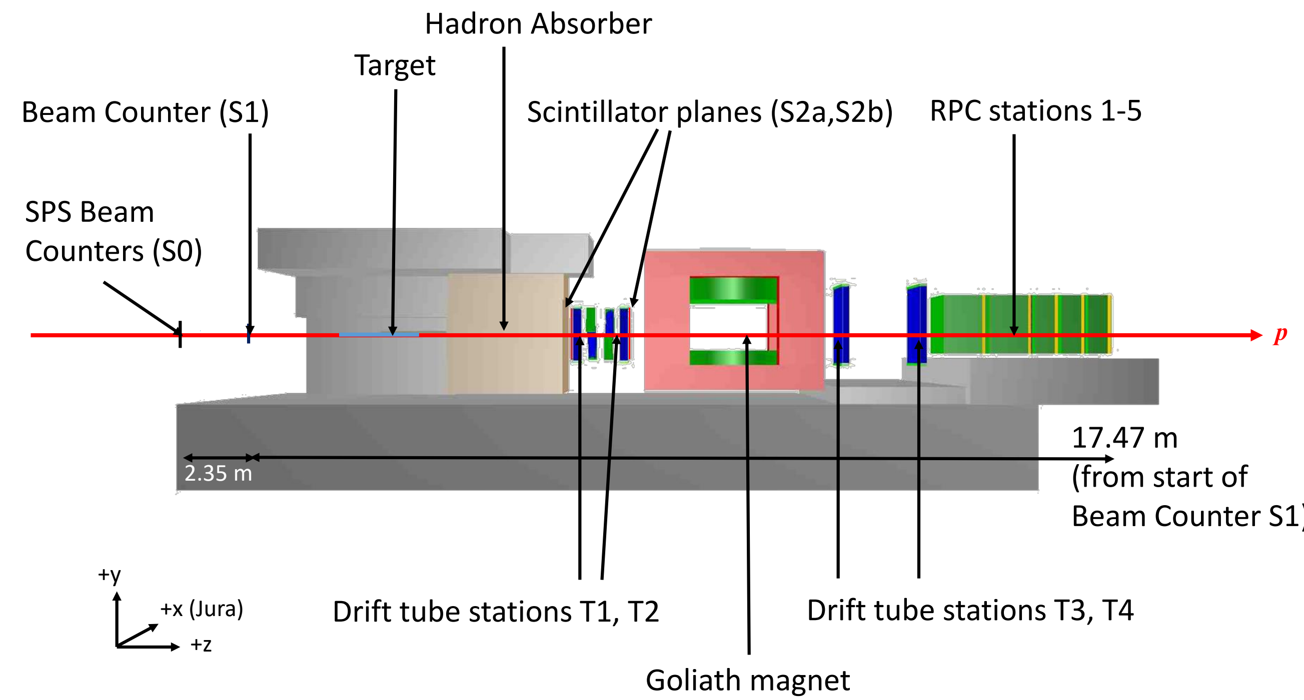
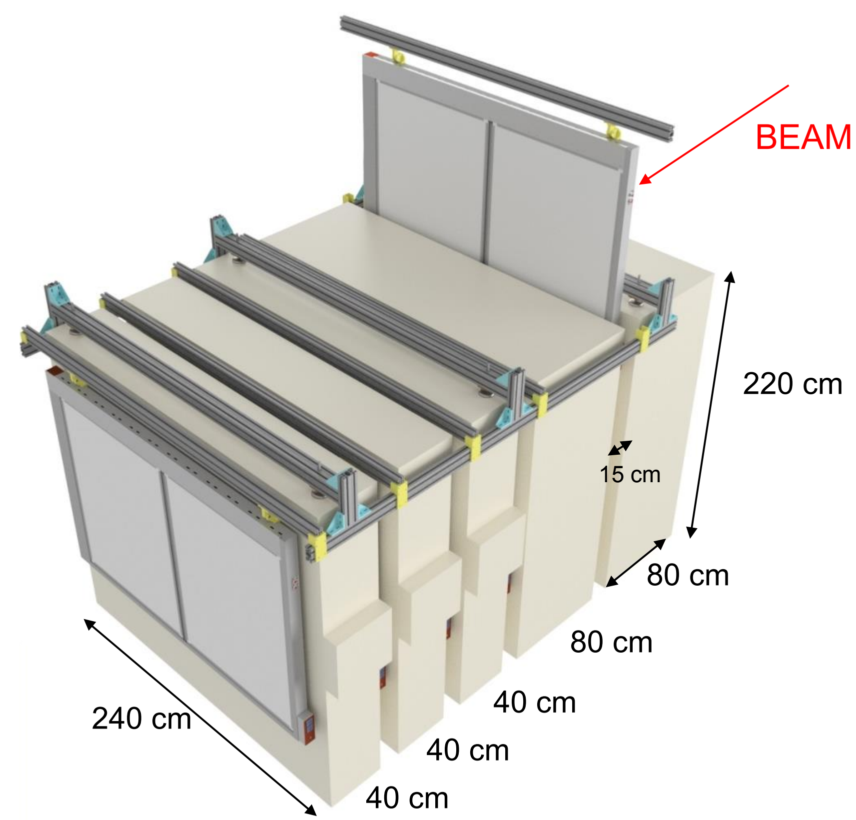


RPC

- five newly built single-gap bakelite RPCs
- operated in avalanche mode
- x/y digital readout, strip pitch 1 cm
- 106 horizontal, 172 vertical strips



Data-taking

Setup

- target: 154.3 cm, TZM (3.6λ), W (9.2λ), Ta (0.5λ)
- hadron absorber: Fe blocks V = $(240\ \text{cm})^3$
- Goliath magnet B = 1.5T
- 4 drift-tube stations: 4 (stereo) layers, hit resolution 0.35 mm
- muon tagger: 5 planes of single-gap RPC, and 40–80 cm Fe slabs

Beam

- 4.8 s (slow extraction) spills, 3×10^6 p/spill, beam spot 2 mm
- 20,128 spills → $(3.25 \pm 0.07) \times 10^{11}$ pot for data analysis

Muons

- One event with muons every 710 ± 15 pot

Normalization

Scintillators

- signal widths and dead times to be taken into account

Beam halo

- some protons might fall outside of beam counter acceptance

Low-intensity runs used for normalisation

- split in 0.1 s slices
- determine pots and reconstructed muons in each slice
- find 710 ± 15 (syst.)

Trigger inefficiency

- less than 0.1%

Tracking and p resolution

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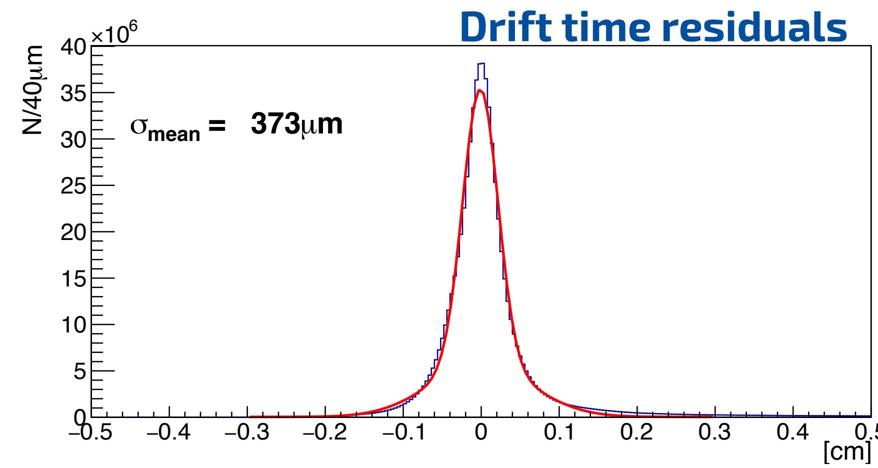
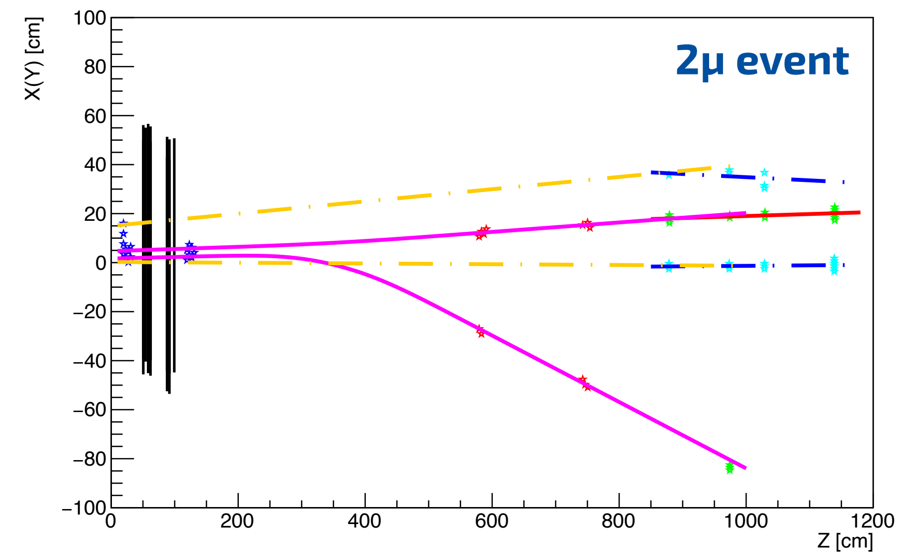
r–t relation in drift tubes

- obtained from TDC distribution in data



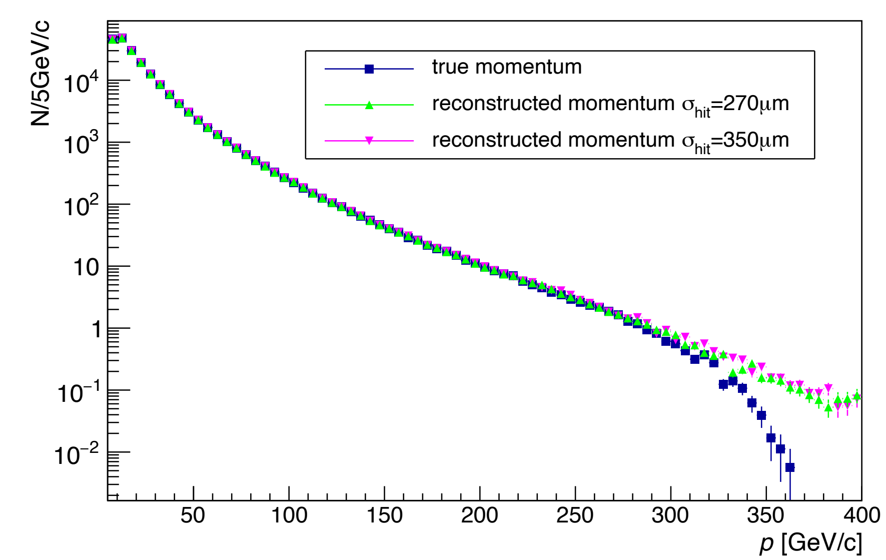
Tracking

- pattern recognition separately in DT and RPC
- DT tracks → RPC tracks
- tagged as μ if ≥ 3 RPC stations hit



Momentum resolution

- DT hit resolution a bit worse than OPERA due to imperfect r–t and residual misalignment
- effect on p resolution is negligible



Simulation

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Primary proton–nucleon interactions

- Pythia8

Transport in target & hadron absorber

- Geant4
- includes rare dimuon decays of low-mass resonances

Heavy-flavour production

CERN-SHiP-NOTE-2015-009

- Geant4 does not produce HF in secondary collisions
- used Pythia6 to explicitly simulate HF, tuned with data

arXiv:2001.04784, accepted by Eur. Phys. J. C

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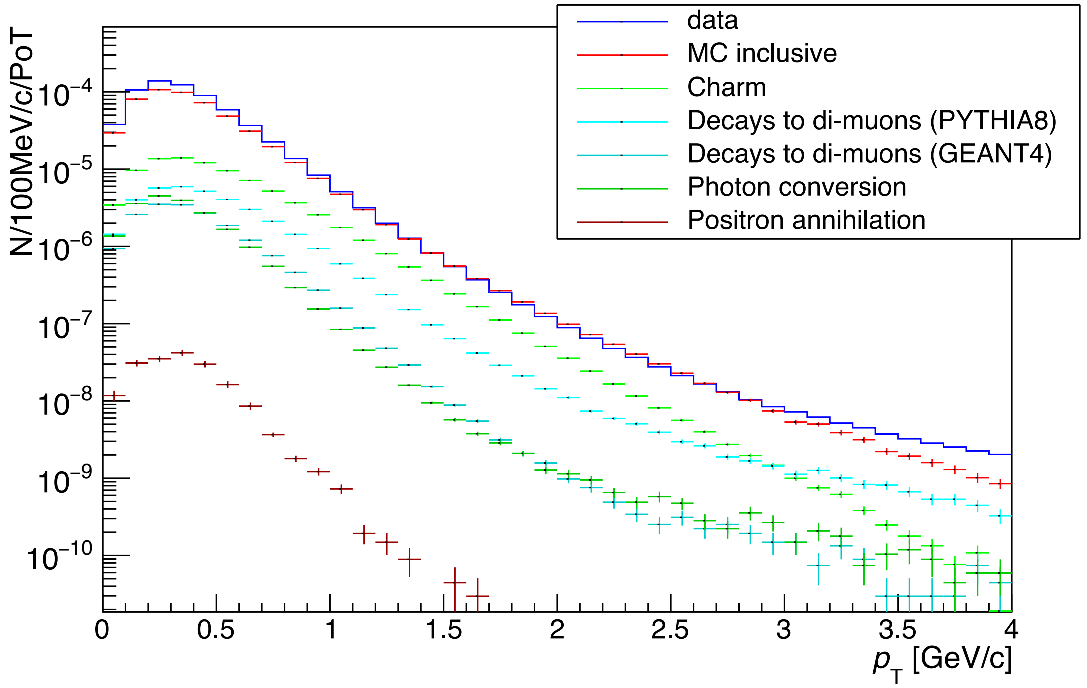
Compare data/simulation

- p = 5–300 GeV/c
- p_T < 4 GeV/c

Interval	data	Simulation	ratio
5 – 10 GeV/c	$(1.13 \pm 0.02) \times 10^5$	$(1.12 \pm 0.03) \times 10^5$	1.01 ± 0.04
10 – 25 GeV/c	$(2.40 \pm 0.05) \times 10^4$	$(1.85 \pm 0.06) \times 10^4$	1.29 ± 0.05
25 – 50 GeV/c	$(4.80 \pm 0.10) \times 10^3$	$(3.76 \pm 0.11) \times 10^3$	1.28 ± 0.05
50 – 75 GeV/c	$(9.83 \pm 0.2) \times 10^2$	$(8.0 \pm 0.2) \times 10^2$	1.23 ± 0.05
75 – 100 GeV/c	$(2.95 \pm 0.06) \times 10^2$	$(2.5 \pm 0.08) \times 10^2$	1.20 ± 0.05
100 – 125 GeV/c	$(1.1 \pm 0.02) \times 10^2$	$(0.9 \pm 0.03) \times 10^2$	1.14 ± 0.05
125 – 150 GeV/c	21.0 ± 0.4	20.1 ± 7.5	1.04 ± 0.04
150 – 200 GeV/c	6.4 ± 0.1	6.6 ± 0.3	0.96 ± 0.04
200 – 250 GeV/c	0.76 ± 0.02	0.88 ± 0.06	0.86 ± 0.06
250 – 300 GeV/c	0.26 ± 0.01	0.26 ± 0.03	0.97 ± 0.11

Good agreement

- within 20% for normalisation
- for p > 150 GeV/c
  - the simulation underestimates large p_T
  - probably caused by different amounts of μ from π and K
  - given the complexity of the processes, the agreement is remarkable



Also validated FLUKA

- used for radiation levels in SHiP

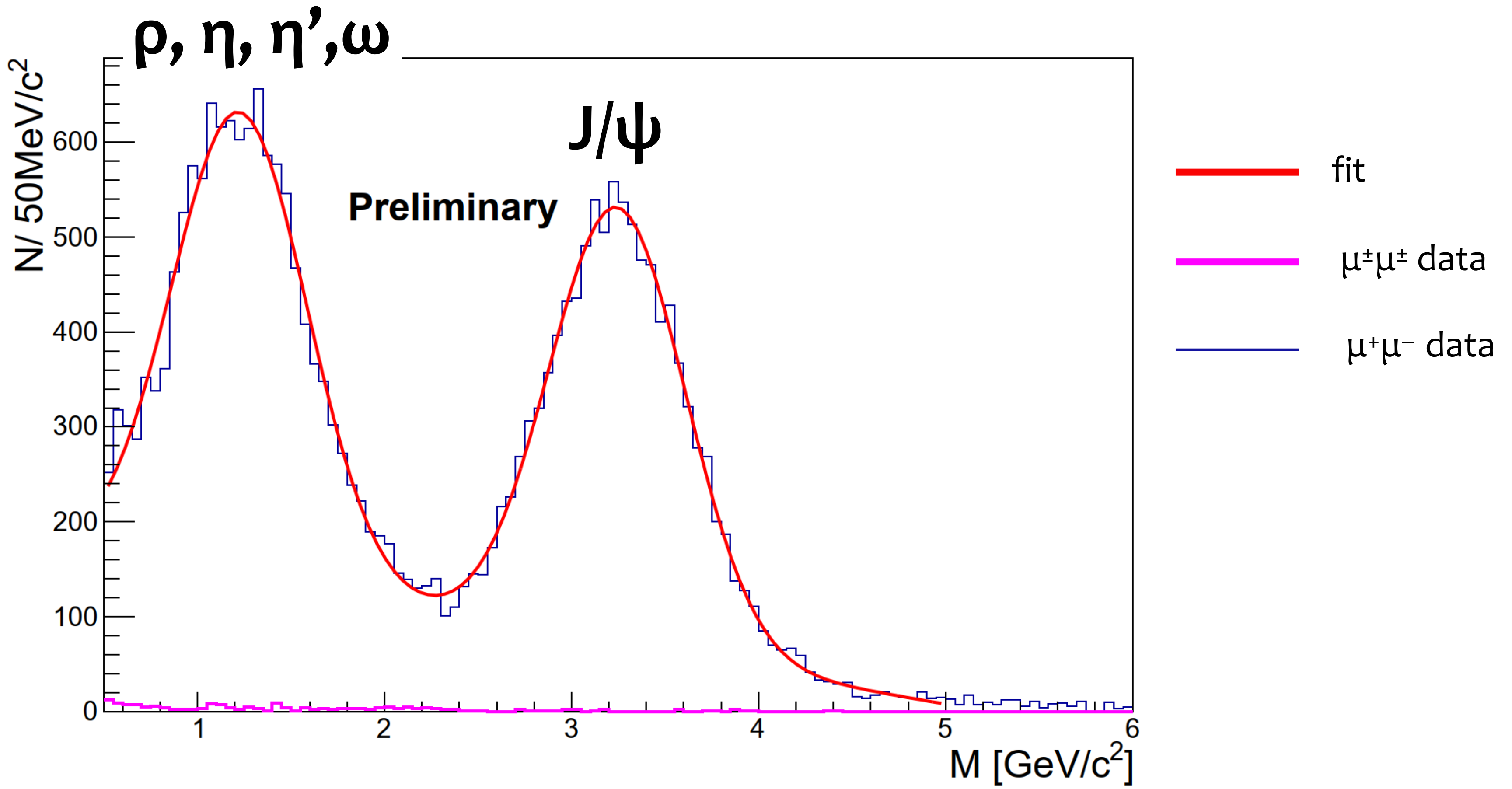
Outlook: dimuon events

Overall good agreement

- provides a solid confidence in using FairShip, also for the future optimisation of the muon shield and other detectors

Further understanding provided by dimuon events

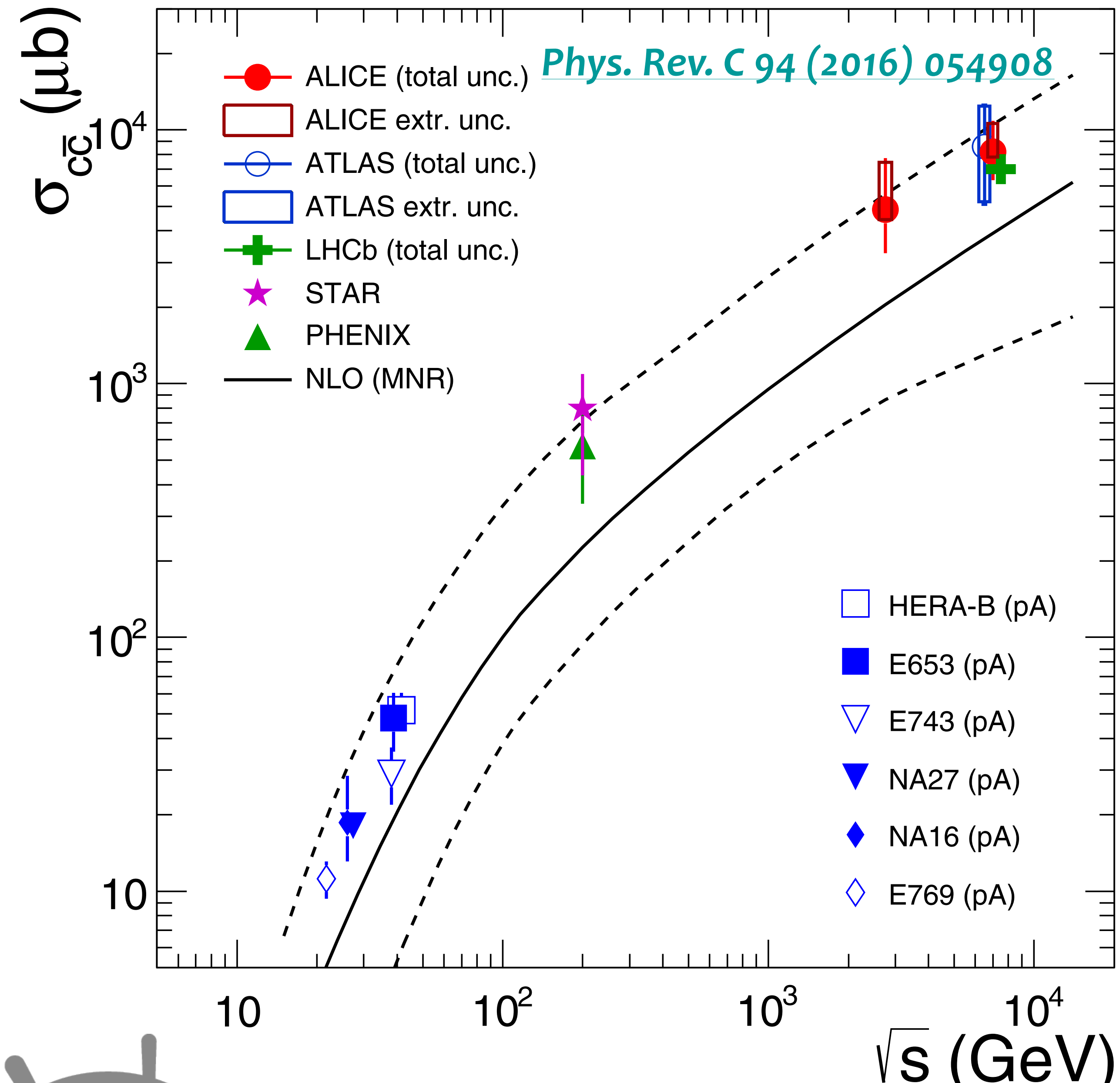
- more detailed studies are ongoing



SHiP–Charm: motivation

Important for Hidden Sector searches normal. and ν_τ cross-section measurement

- need to determine charm production in proton interactions and in hadron cascades in the SHiP target

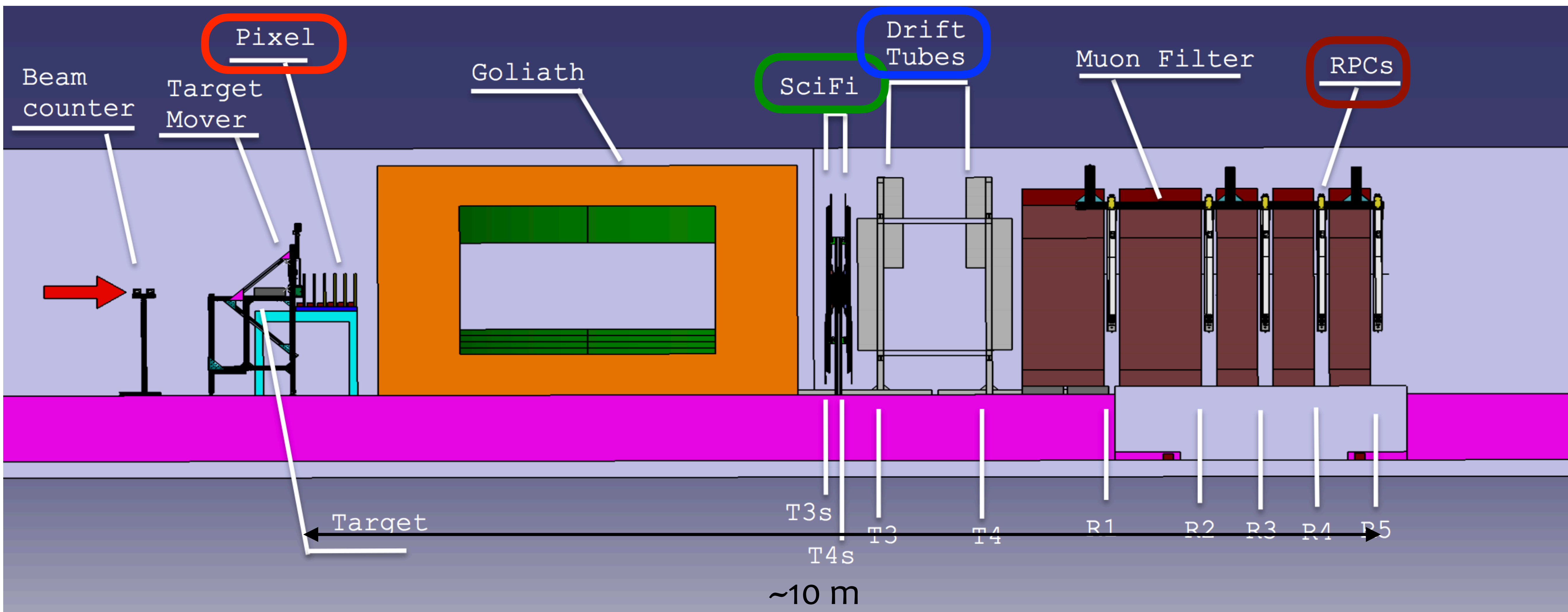


- Inclusive double-charm cross-section measured in NA27 using thin target
- Missing information: charm production in hadron cascades
- Charm yield from cascade expected 2.3 times larger than prompt contribution

SHiP–Charm: overview

1-week optimisation run performed in Summer 2018

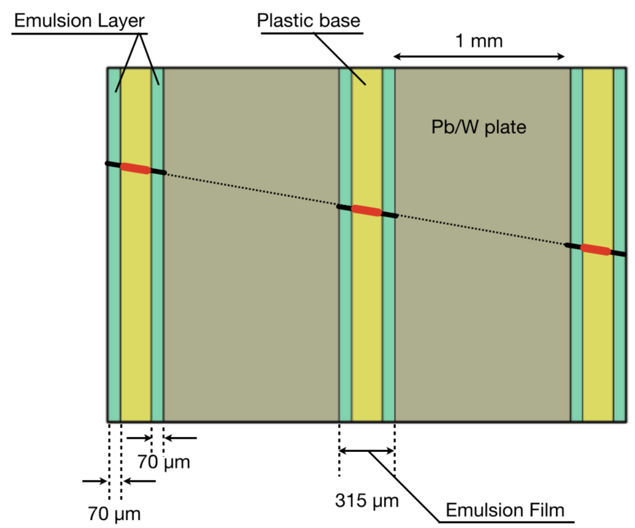
- hybrid setup to measure $\sigma_{c\bar{c}}$ in a thick target
- emulsion (ECC) used to identify charm-decay topology
- electronic detectors: Pixel, SciFi, Drift Tubes to measure the momentum of charged charm daughters, RPC to identify penetrating muons



SHiP-charm custom detectors

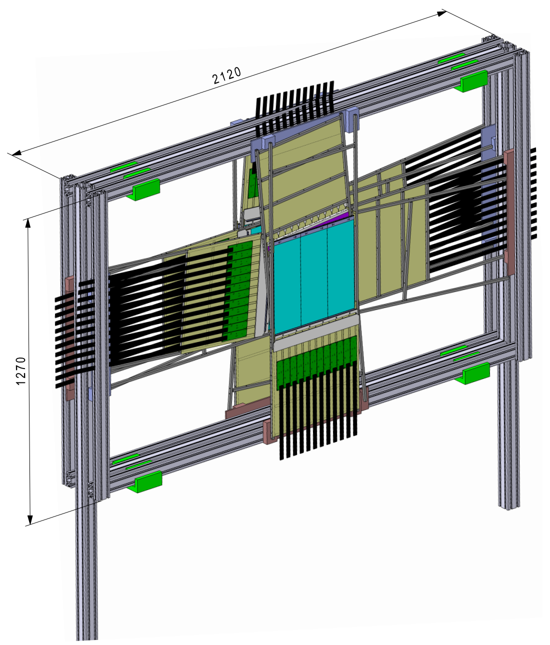
Emulsion Cloud Chamber

- based on OPERA design



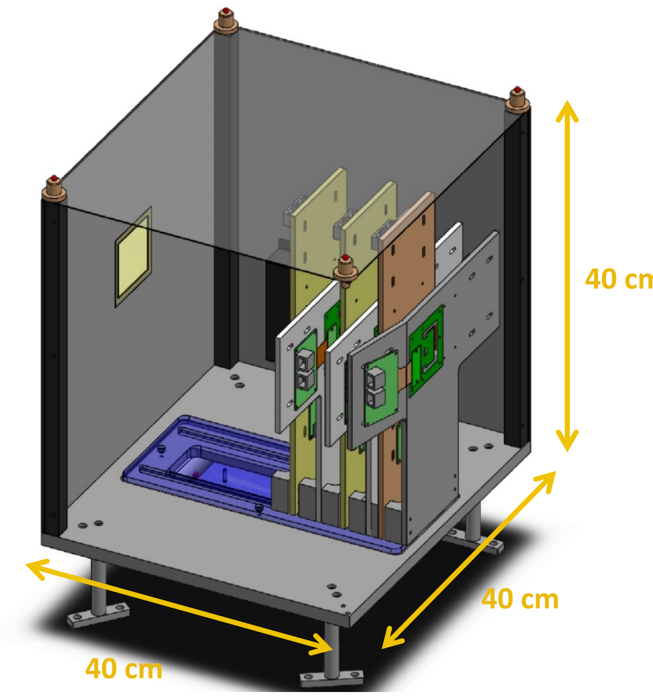
SciFi

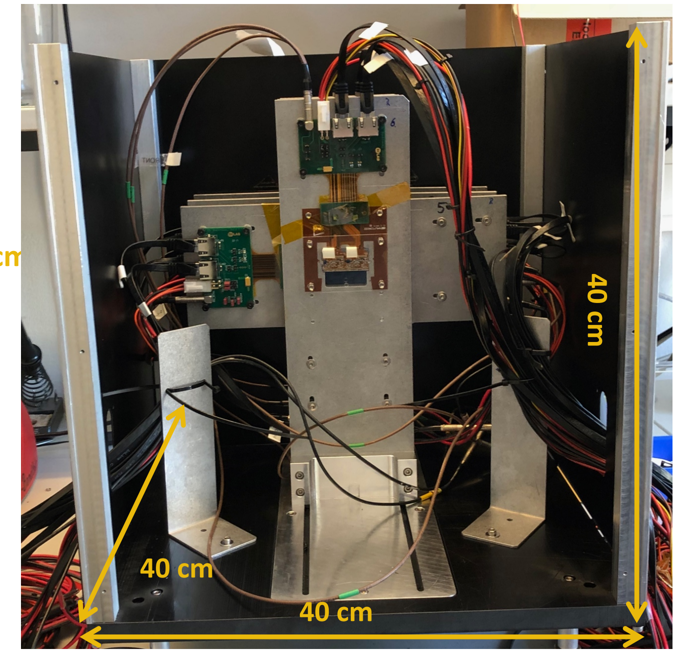
- based on LHCb upgrade Ia



Pixel Tracker

- based on ATLAS IBL





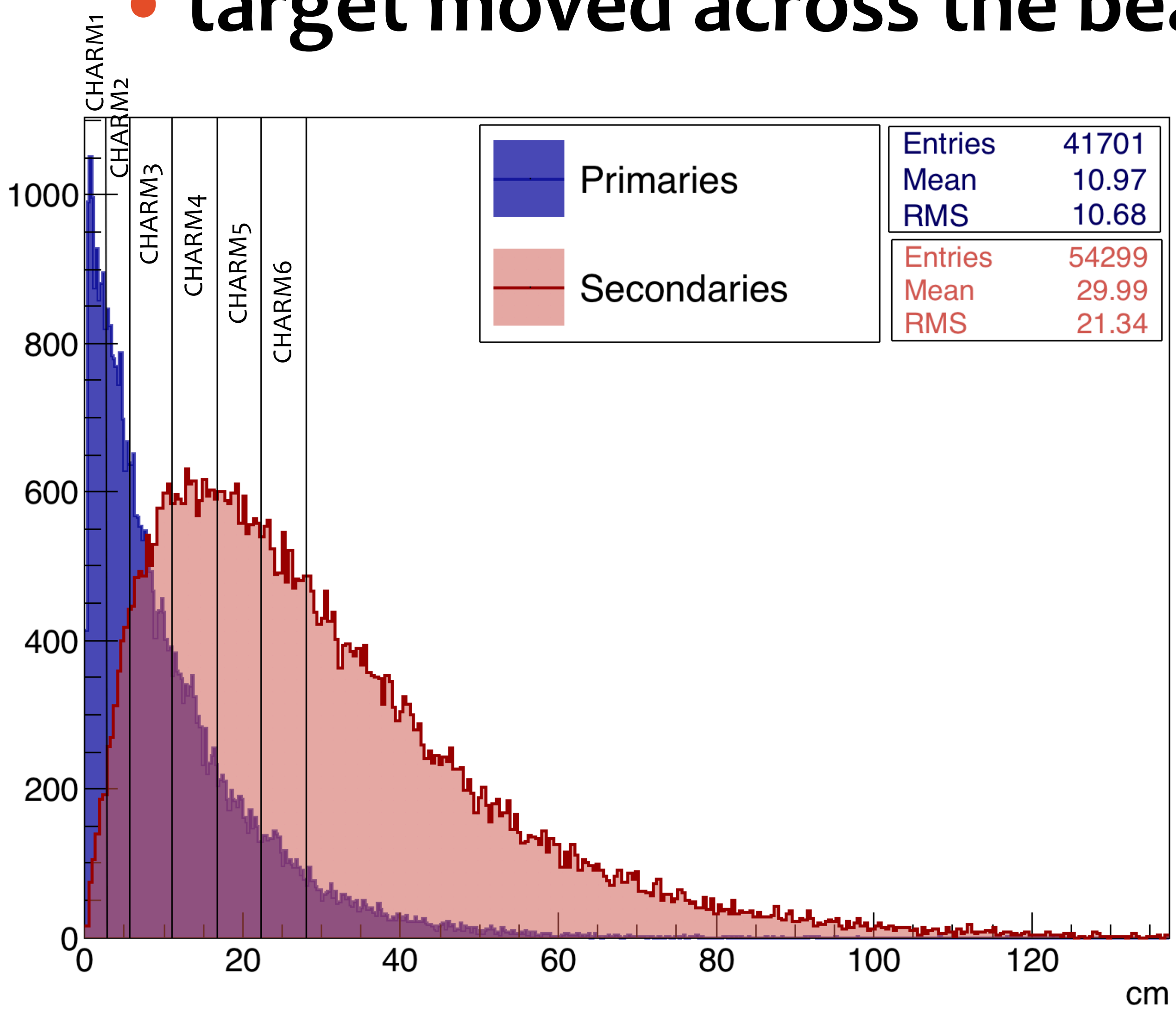
+ Drift Tubes

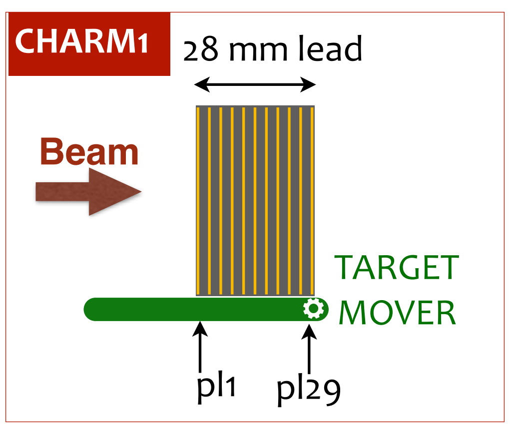
+ RPC

Emulsion target configurations

Six configurations to sample shower development

- up to ~ 2 λ_{int}
- 85% (52%) of primary (secondary) interactions sampled
- 1032 films exposed (12 m²)
- target moved across the beam for best acceptance





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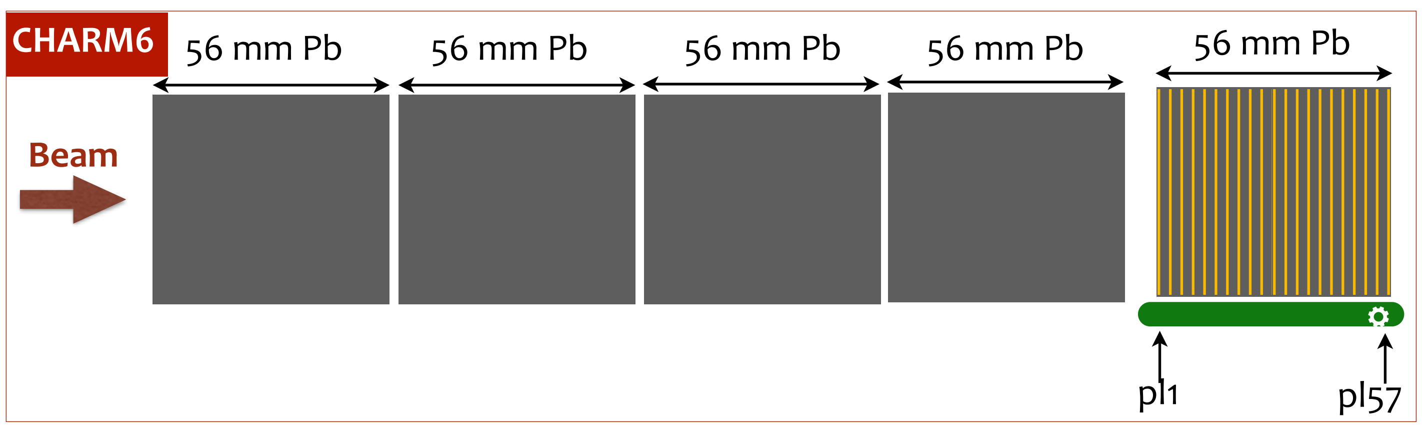
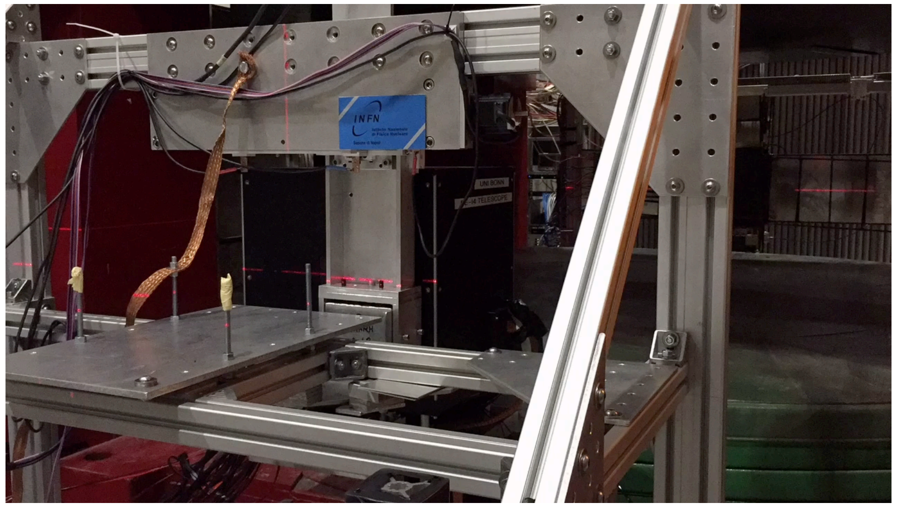
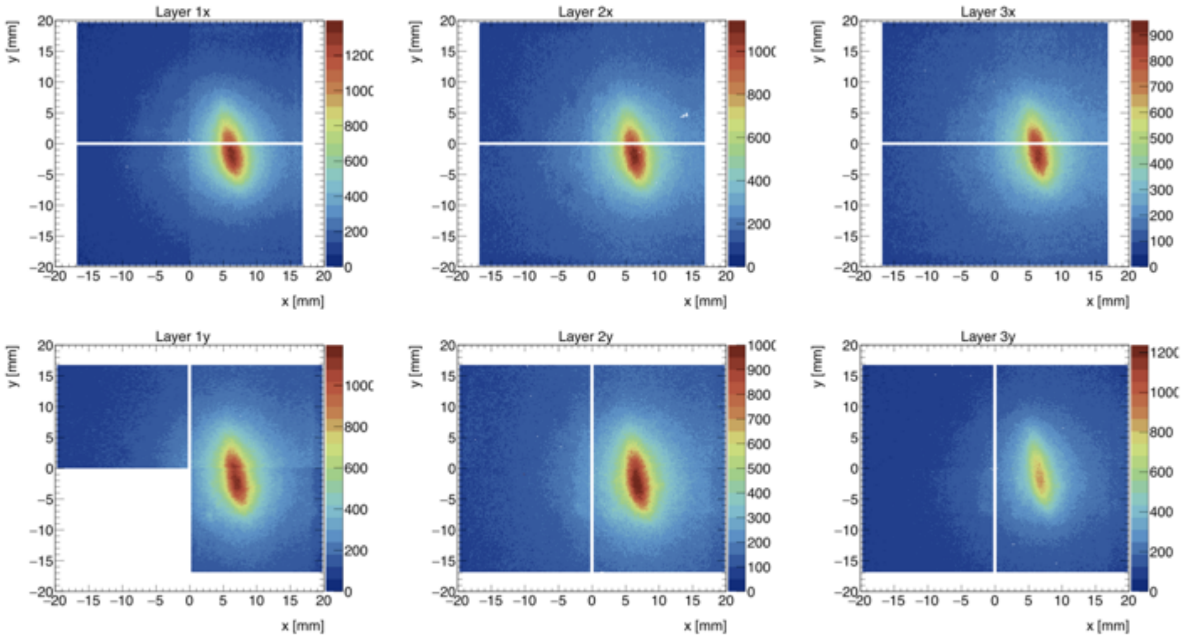




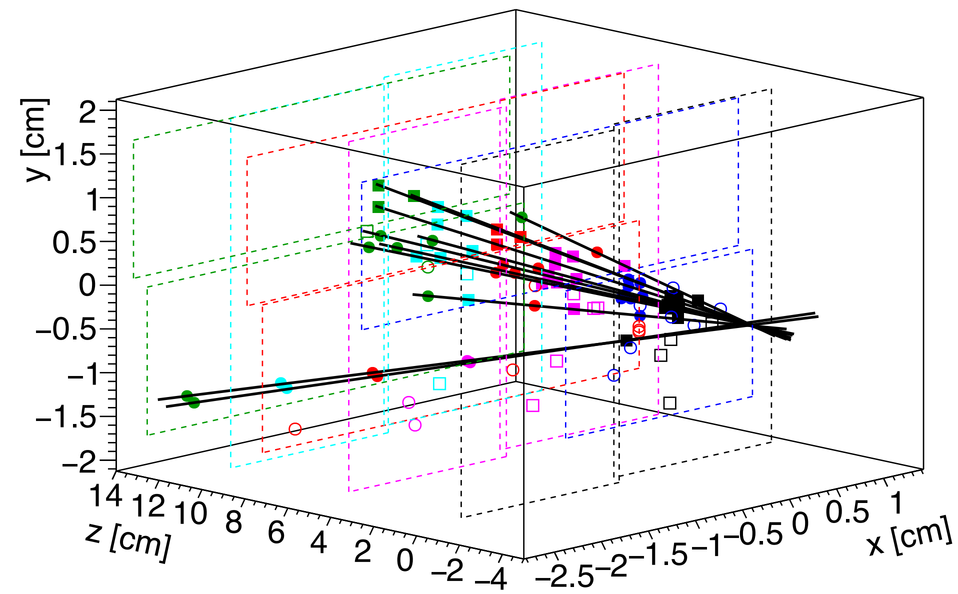
Target mover with emulsion brick

Event reconstruction

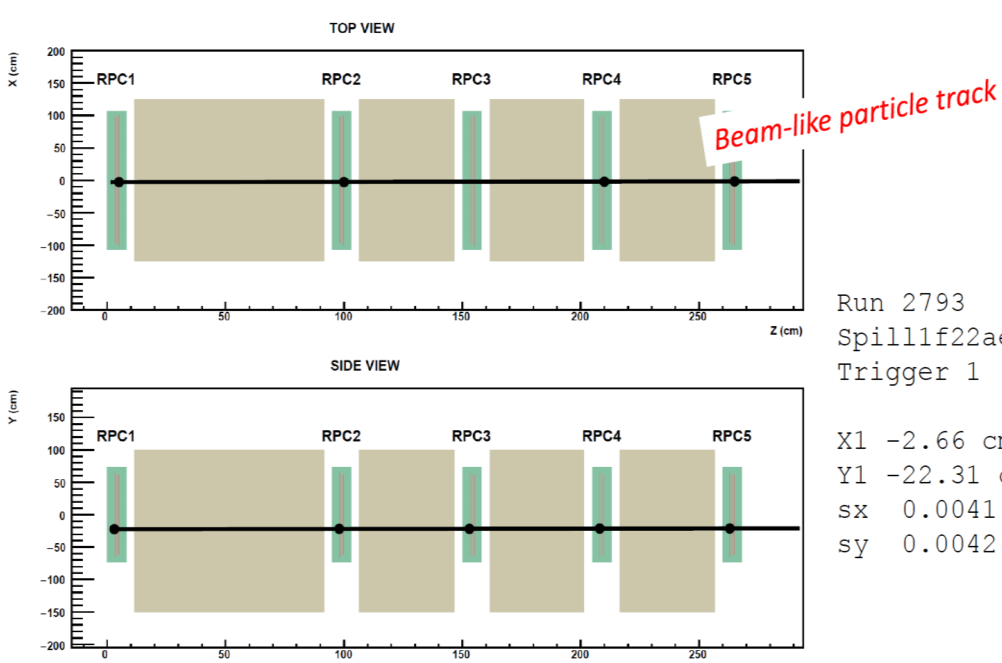
Pixel detectors



Tracks and vertices in pixel detector



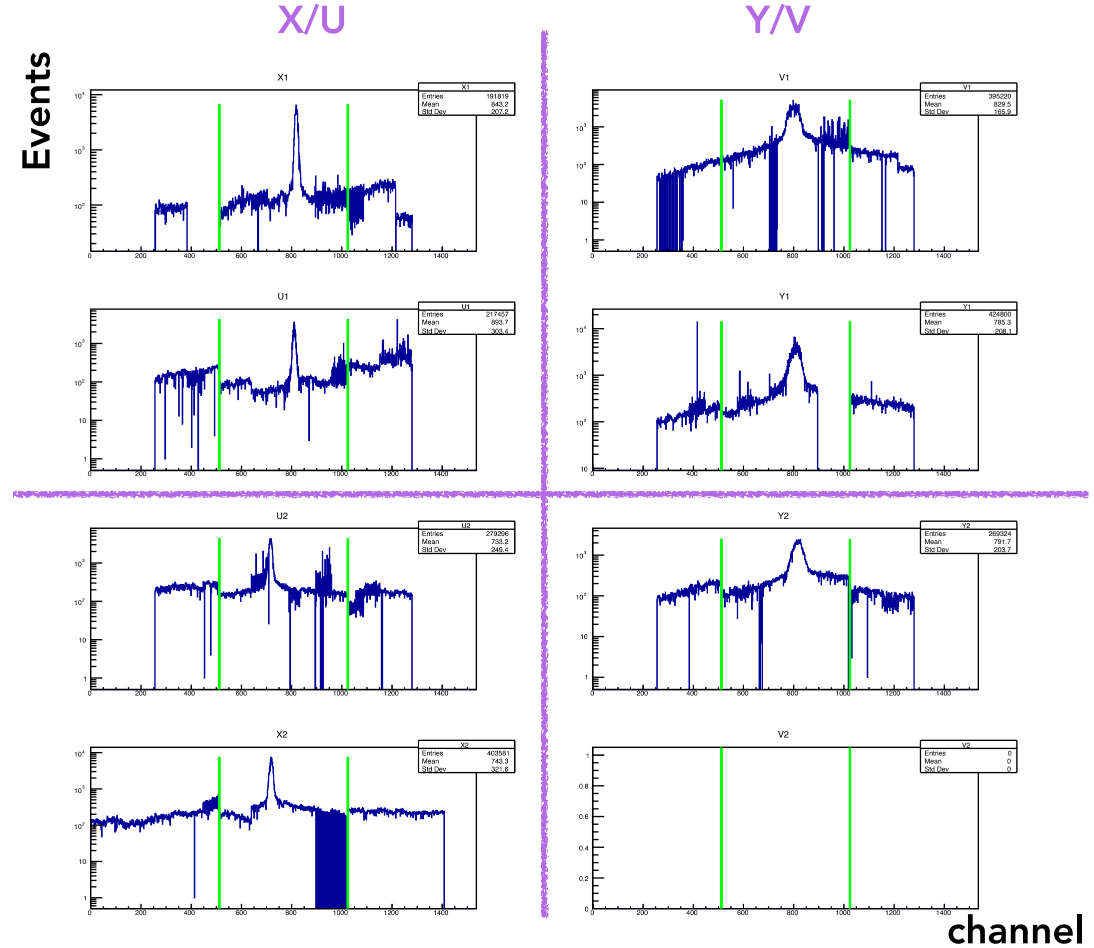
RPC



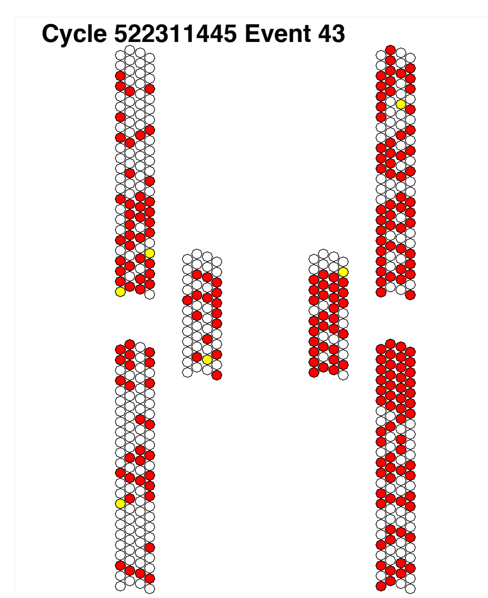

```
Run 2793
Spill1f22ae29
Trigger 1

X1 -2.66 cm
Y1 -22.31 cm
sx  0.0041
sy  0.0042
```

SciFi



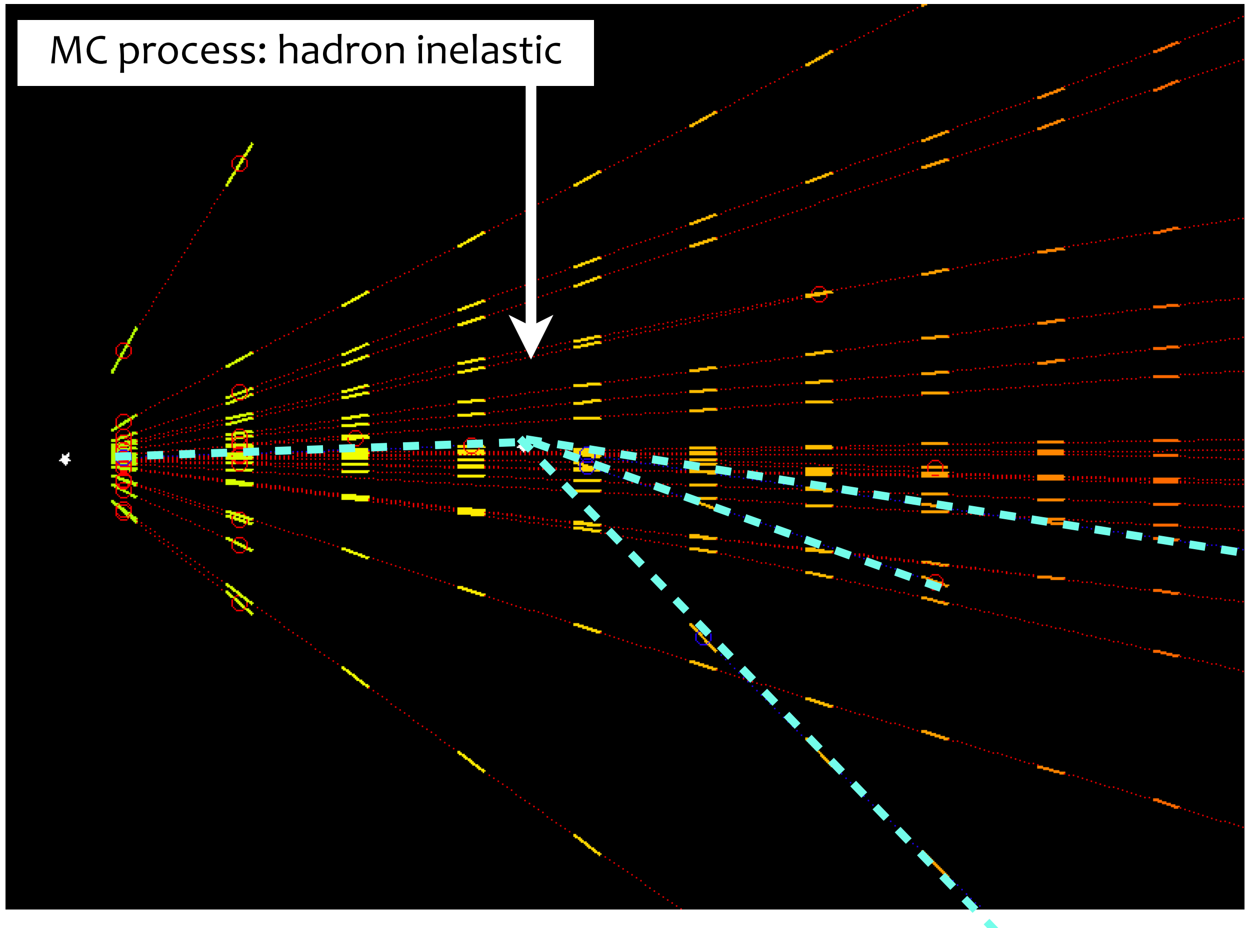
Drift tubes



Emulsion: backgrounds

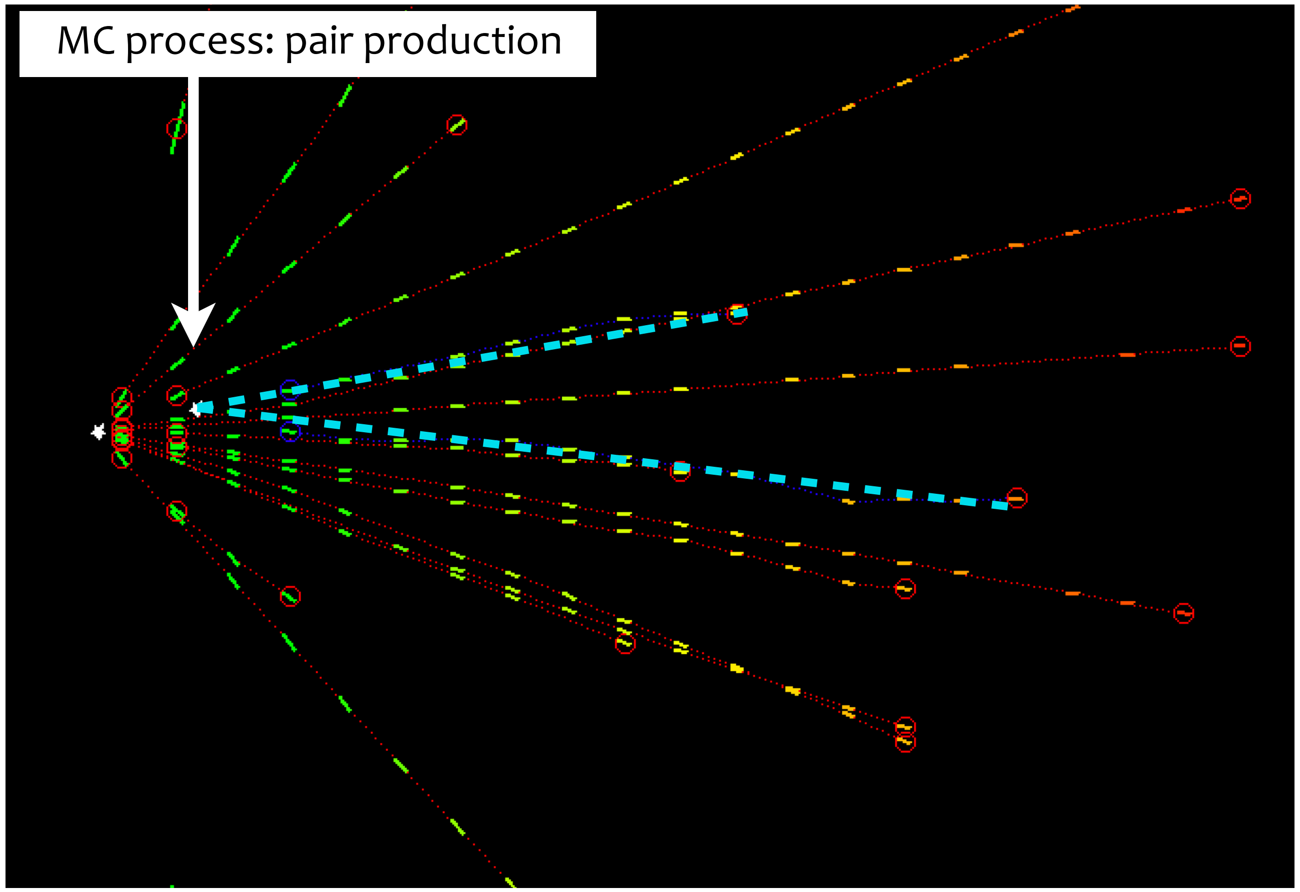
Hadronic re-interactions

- p_{avg} of hadrons is 11 GeV



Elect.-magn. showers

- induced by γ conversion
- on average 11 per event



Background events that survive the selection criteria show the same topology of charmed hadron decays

Double-charm candidate in data

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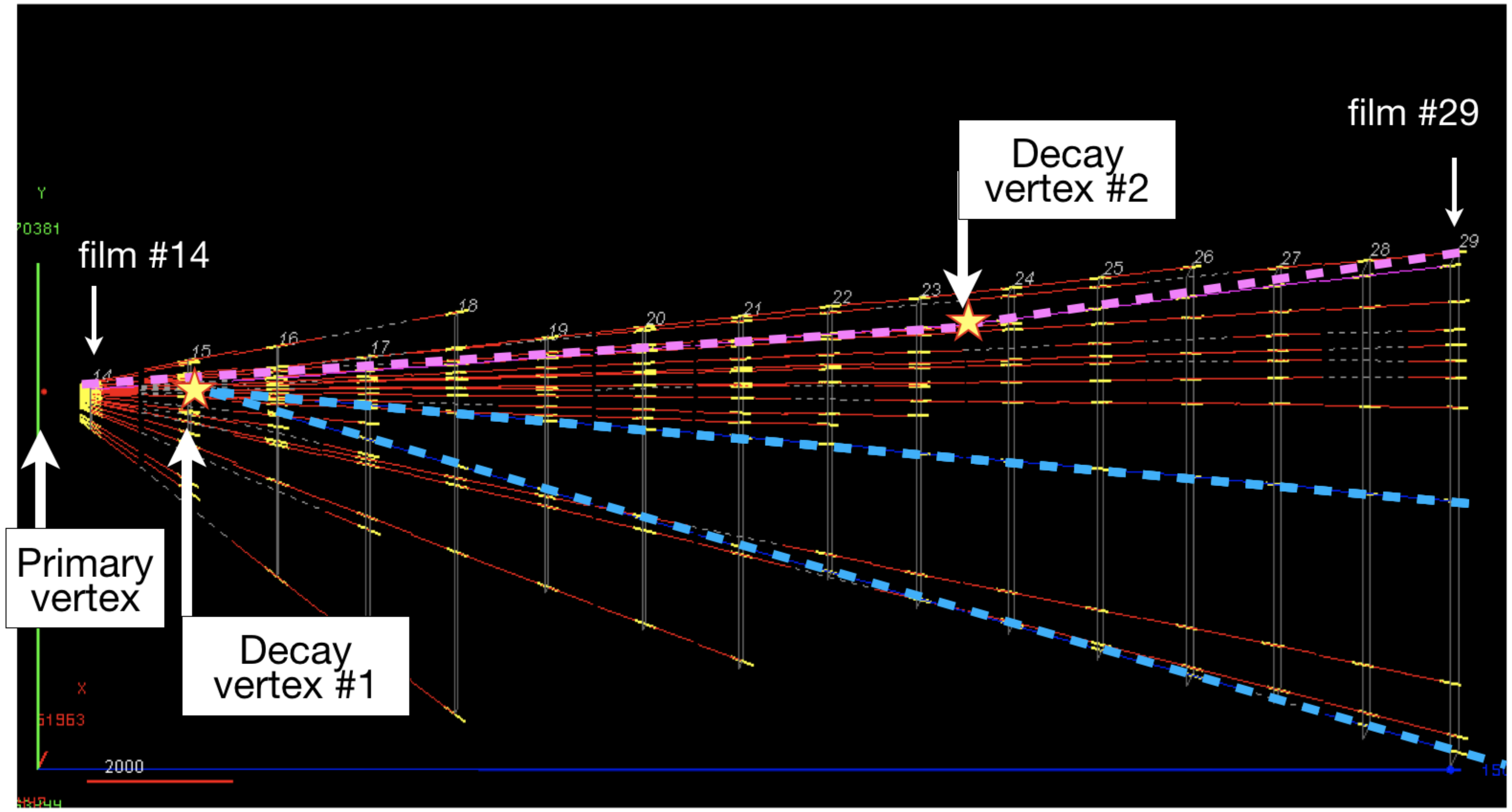


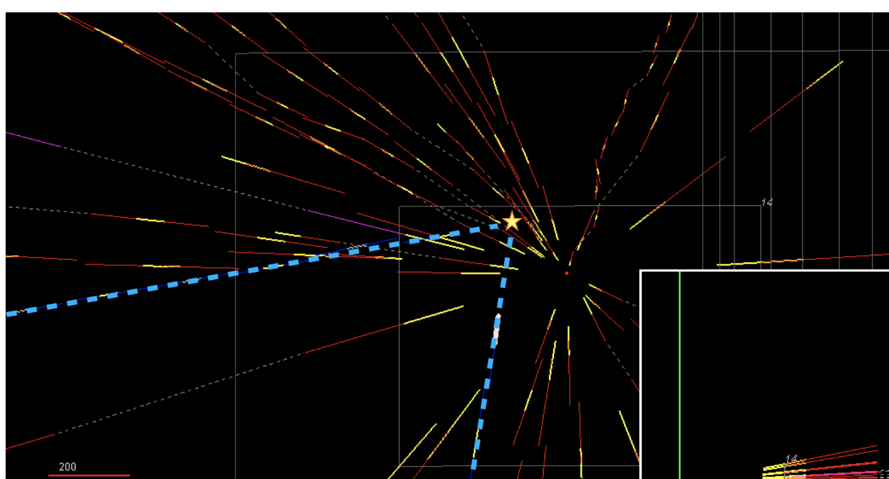
EVENT TOPOLOGY:

Primary vertex multiplicity: 31
Secondary vertices detected: 2

Decay vertex #1:
V0-like topology

Decay vertex #2:
kink-like topology

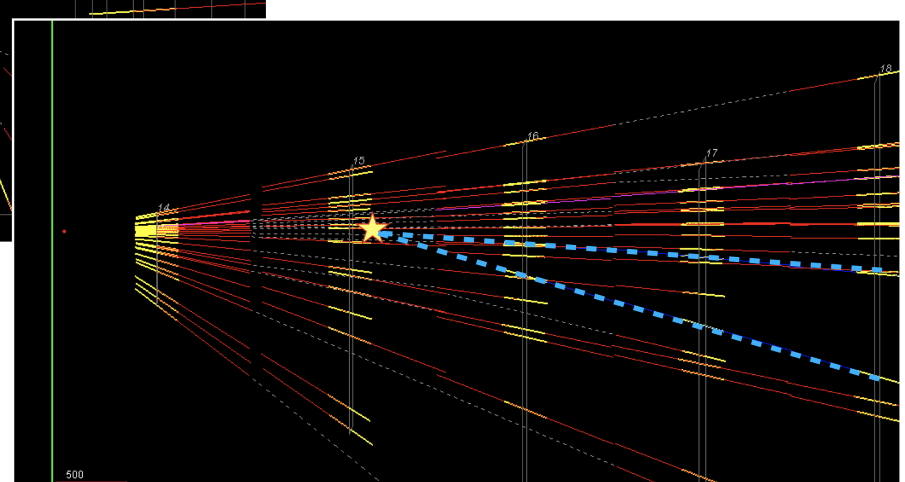
FRONT VIEW



DECAY VERTEX #1

- Number of prongs: 2
- Impact parameters to primary vtx: 594μm, 253 μm
- Flight length: 2.1 mm

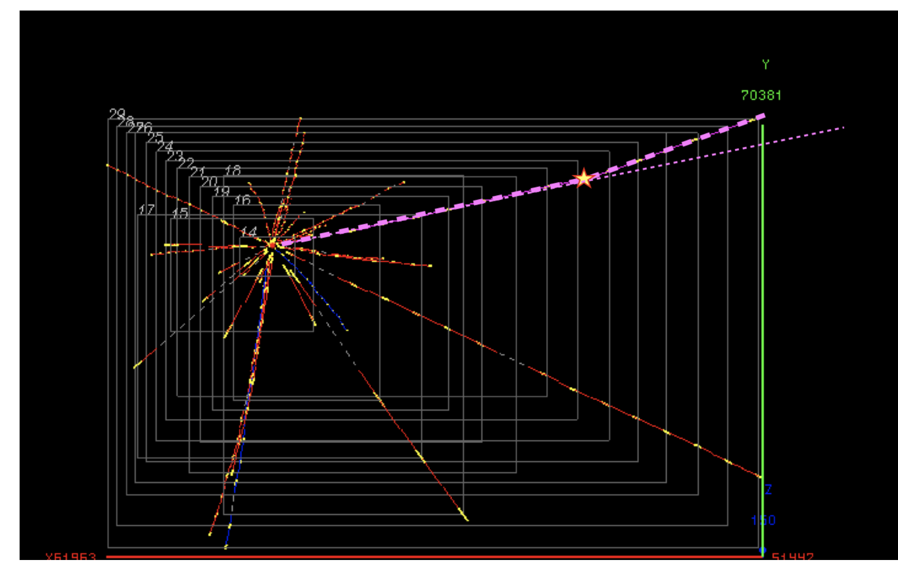
SIDE VIEW

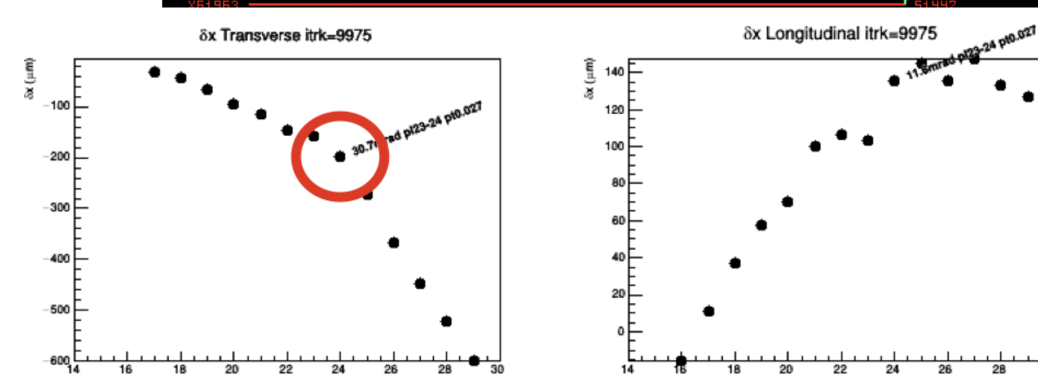


V0-like topology

kink-like topology

FRONT VIEW

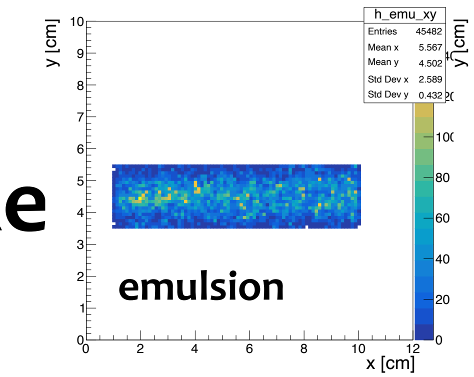


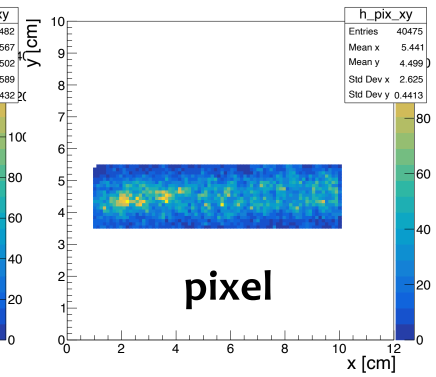


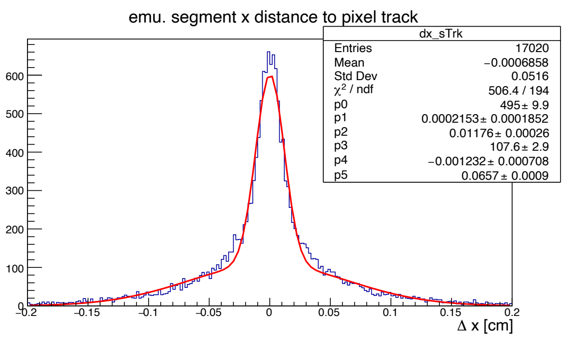
Event building: matching

Emulsion→ Pixel (2 cm)

- using multi-track events, take target moving into account
- alignment and matching over one spill (preliminary)



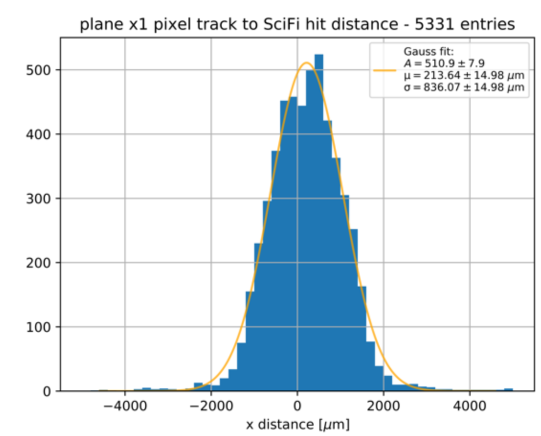




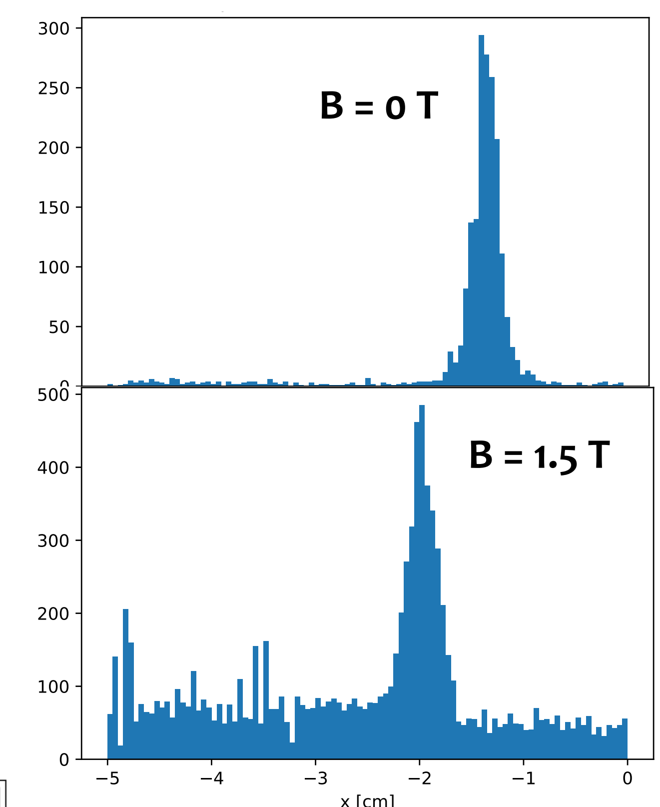
- σ_x = 120 µm, σ_y = 90 µm, $\sigma_{tx,\,ty}$ = 3 mrad

Pixel→ SciFi (4 m)

- aligning SciFi with single-track events, with magnet off and on



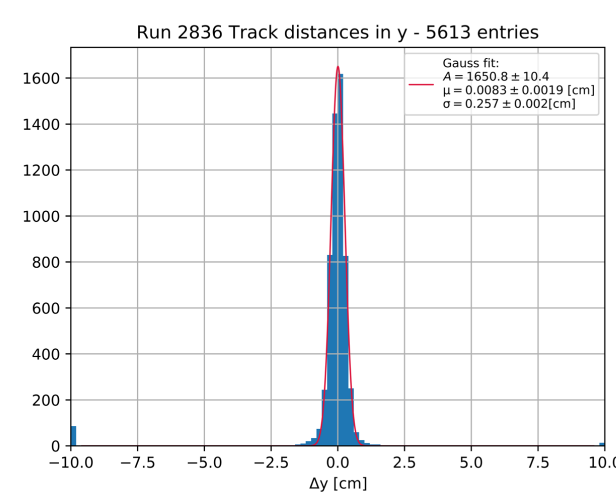
dominated by pixel track extrapolation uncertainty



beam position in first layer SciFi

Pixel→ RPC (8 m)

- match tracks from same event
  - σ_{tracks} = 2.57 ± 0.02 mm
- fakes from different events
  - σ_{tracks} = 7.68 ± 0.07 mm



Conclusion

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Muon flux

- potentially dangerous background
- measurement has been performed (paper accepted)
- validated simulation (Pythia, Geant, Fluka)
- additional studies ongoing

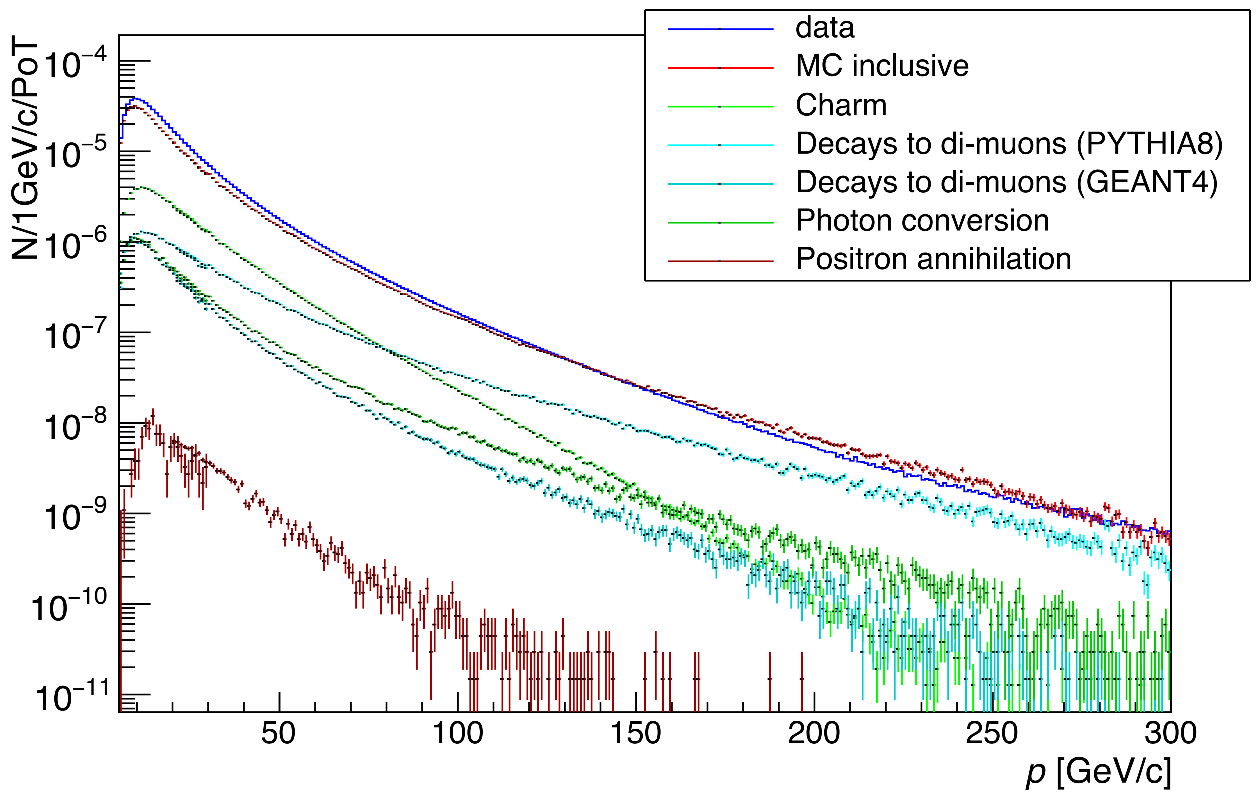
Charm cross-section

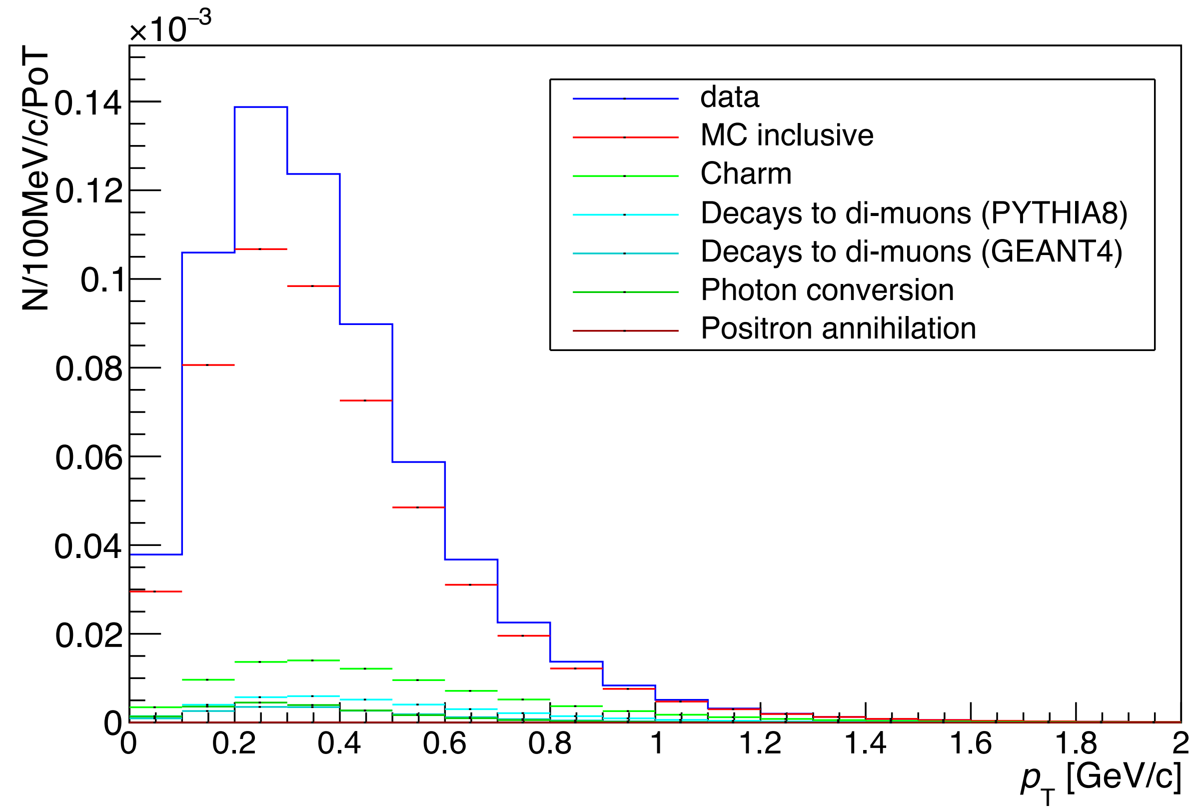
- important for normalisation (hidden sector and ν_τ)
- performed a feasibility testbeam in 2018
- identified first double-charm candidates with emulsion
- connection with electronic detectors in progress
- aiming for a full 4 weeks measurement when SPS resumes

Backup

Muon flux measurement

Good agreement between data and simulation

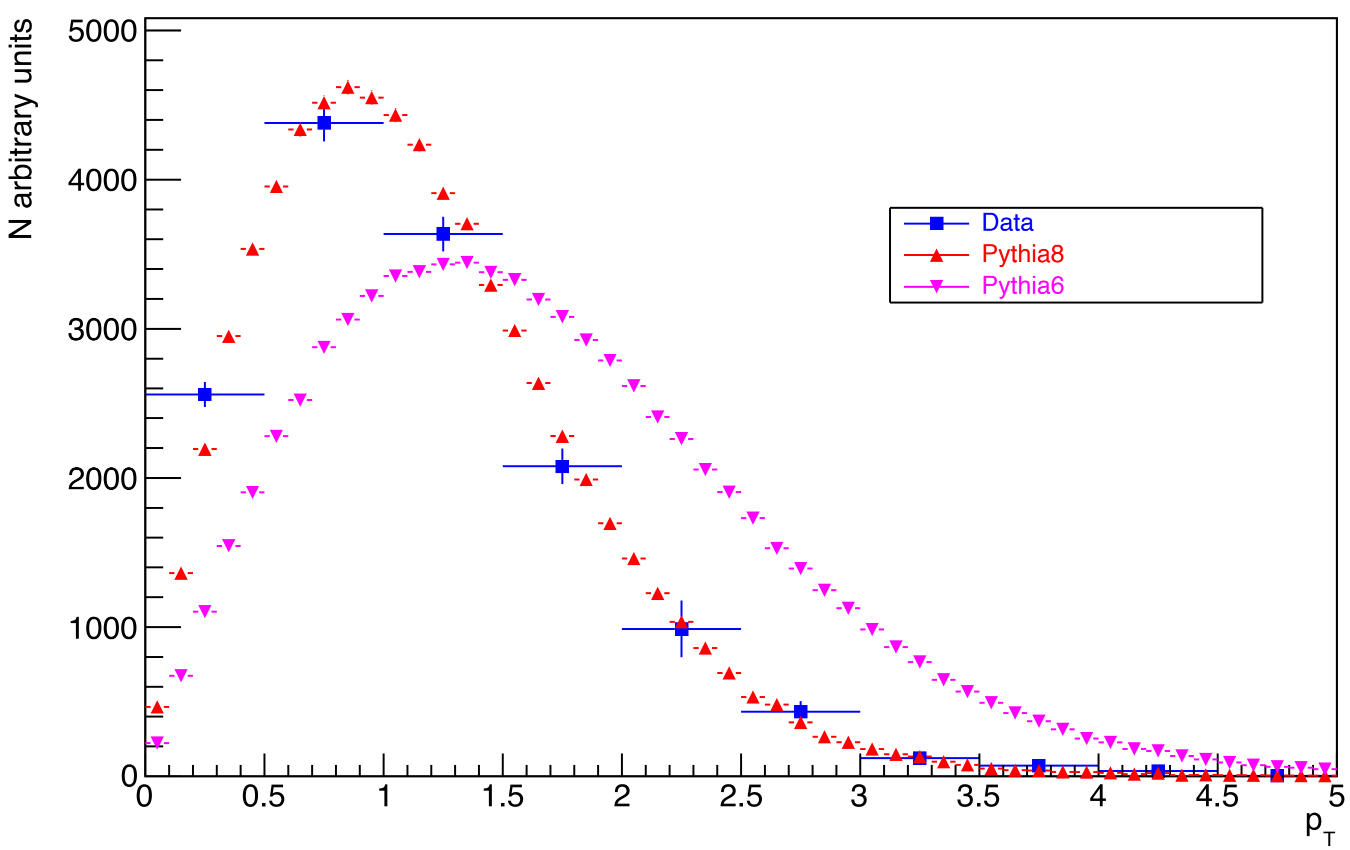




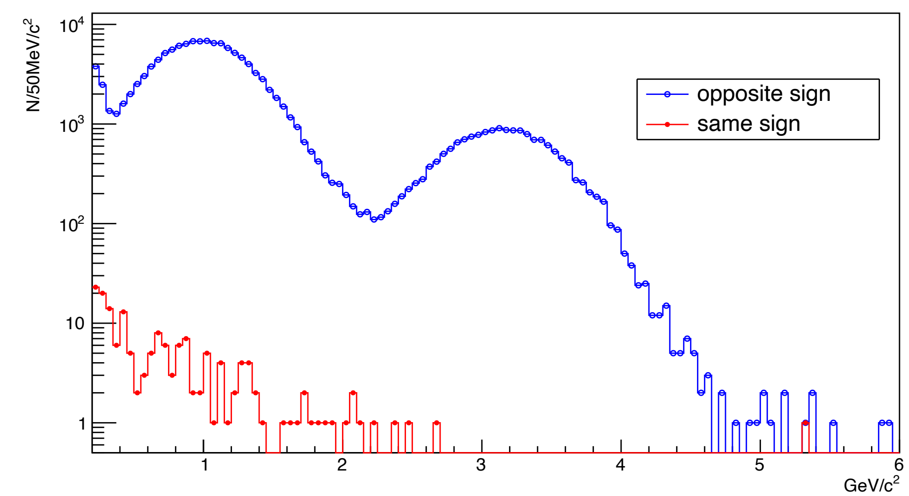
Dimuon events

- **J/ψ momentum matches Pythia8 simulation**
  - important for separation of charges in 1st part of active μ shield
- **J/ψ yield in simulation is overestimated by a factor 4.5**
  - however, J/ψ is not dominating, thus 2nd order effect
- **Low mass kinematics and yield match simulation**
  - good news concerning μ background and ALP production via meson decays

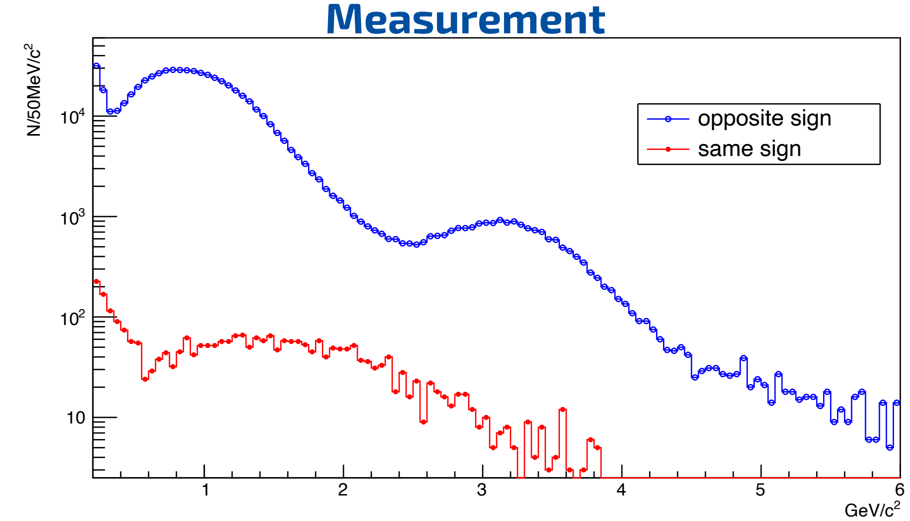
Measured J/ψ p_T distribution and simulation



Invariant mass: simulation



Measurement



Ship-charm

SHiP-charm project

- aims at measuring the differential charm production cross section in the SHiP target, including cascade production

Knowledge of the associated charm production yield in 400 GeV/c proton interactions

- crucial for the SHiP experiment both for Hidden Sector searches and Neutrino Physics studies

Optimization run performed in July 2018

- at H4 beam line of SPS
- 15x105 p.o.t. integrated, amounting to about 10% of the full statistics

Final measurement foreseen after LS2

Experimental Setup

Upstream of Goliath

Experimental Setup

DOWNSTREAM of Goliath

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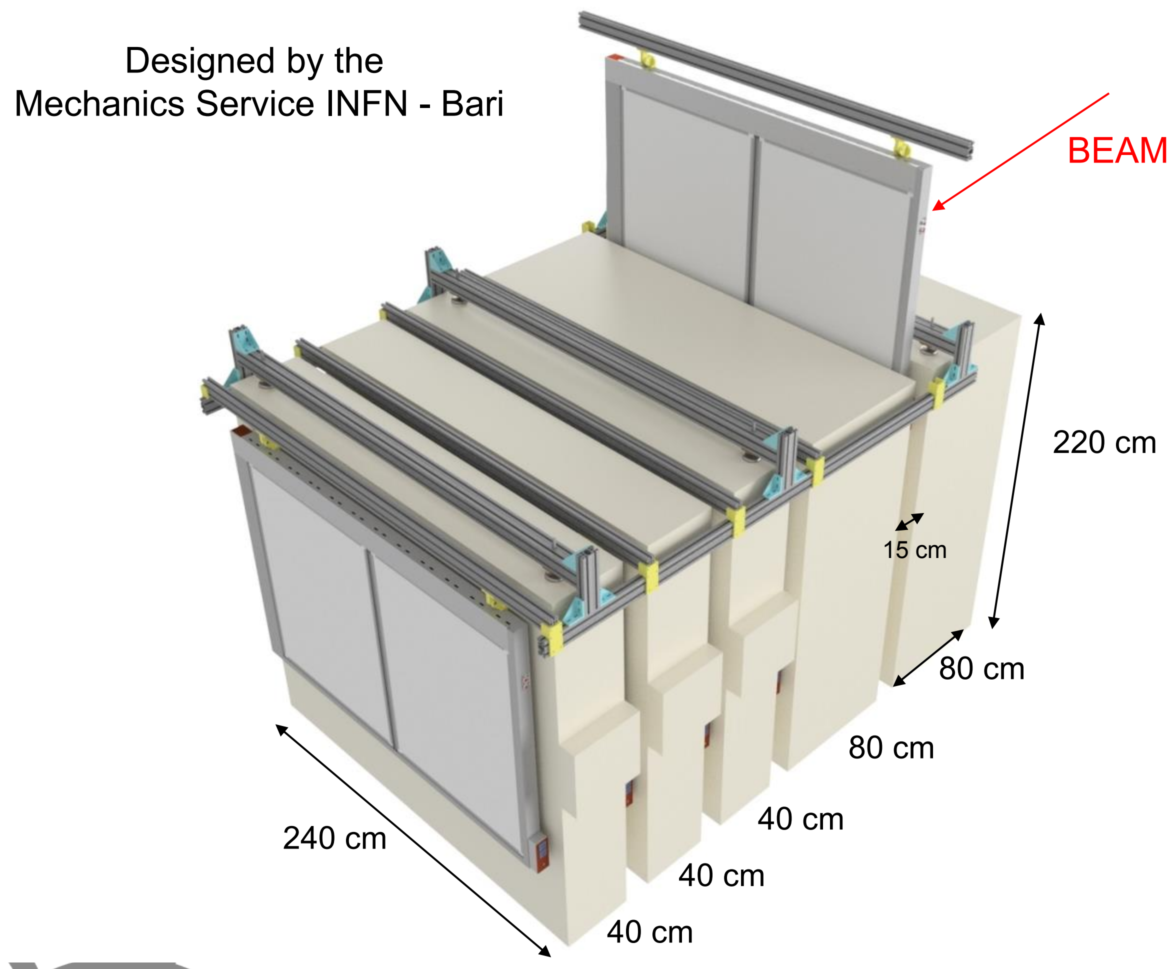
Experimental Setup

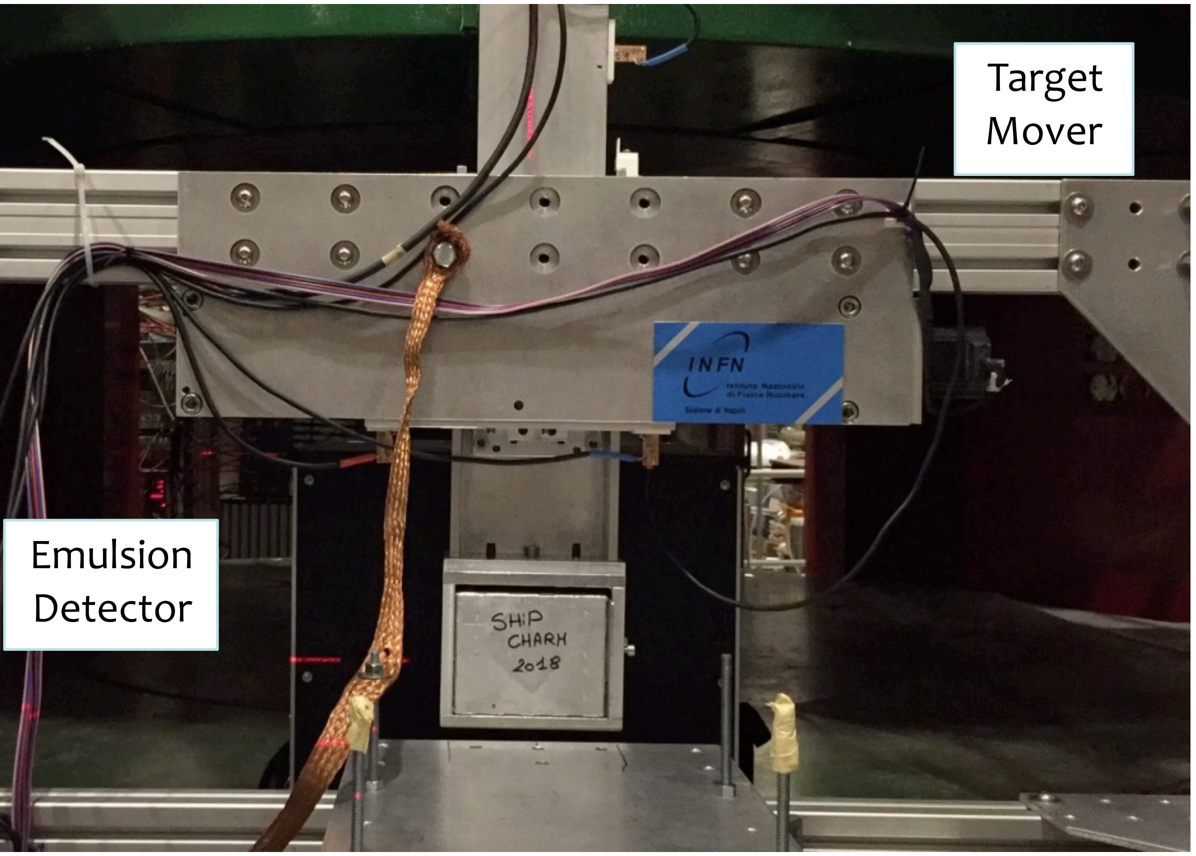
Data taken in Summer 2018 at H4 beam line, SPS NA

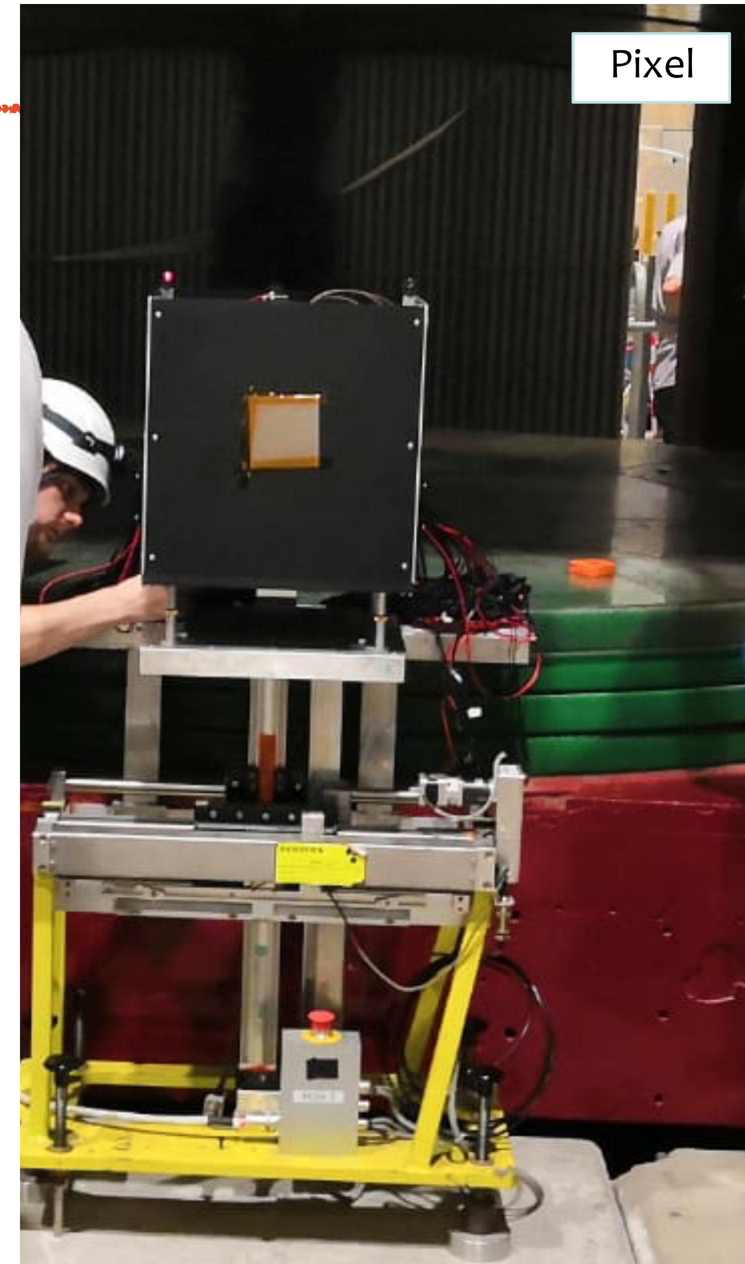
Instrumented muon tagger: RPC

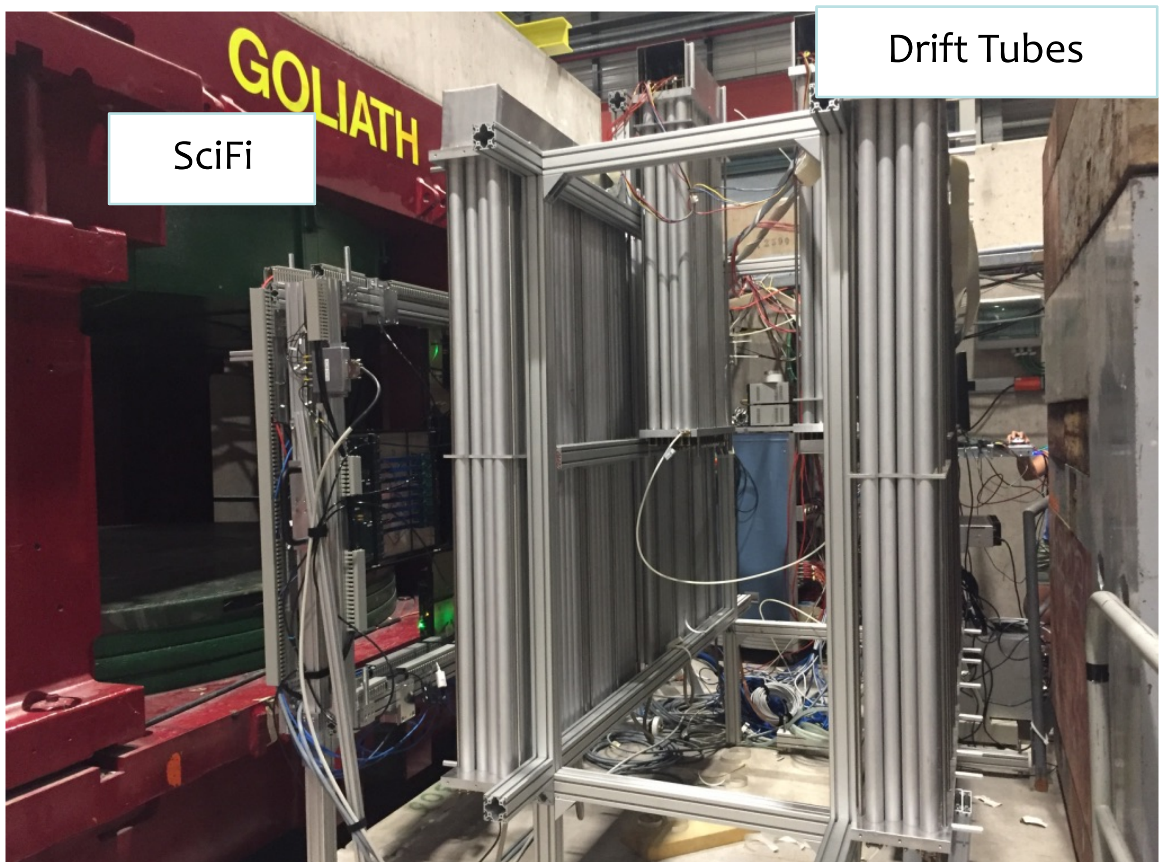
- (80 + 80 + 40 + 40 + 40) cm iron walls interleaved with 5 newly built single-gap bakelite RPCs, dim ~ 1950 x 1240 mm^2
- Chambers operated in avalanche mode
  Standard gas mixture: 95.2/4.5/0.3 $C_2H_2F_4/C_4H_{10}/SF_6$
- X/Y digital readout, strip pitch ~1 cm
  116 horizontal strips (active 106), 184 vertical strips (active 172)

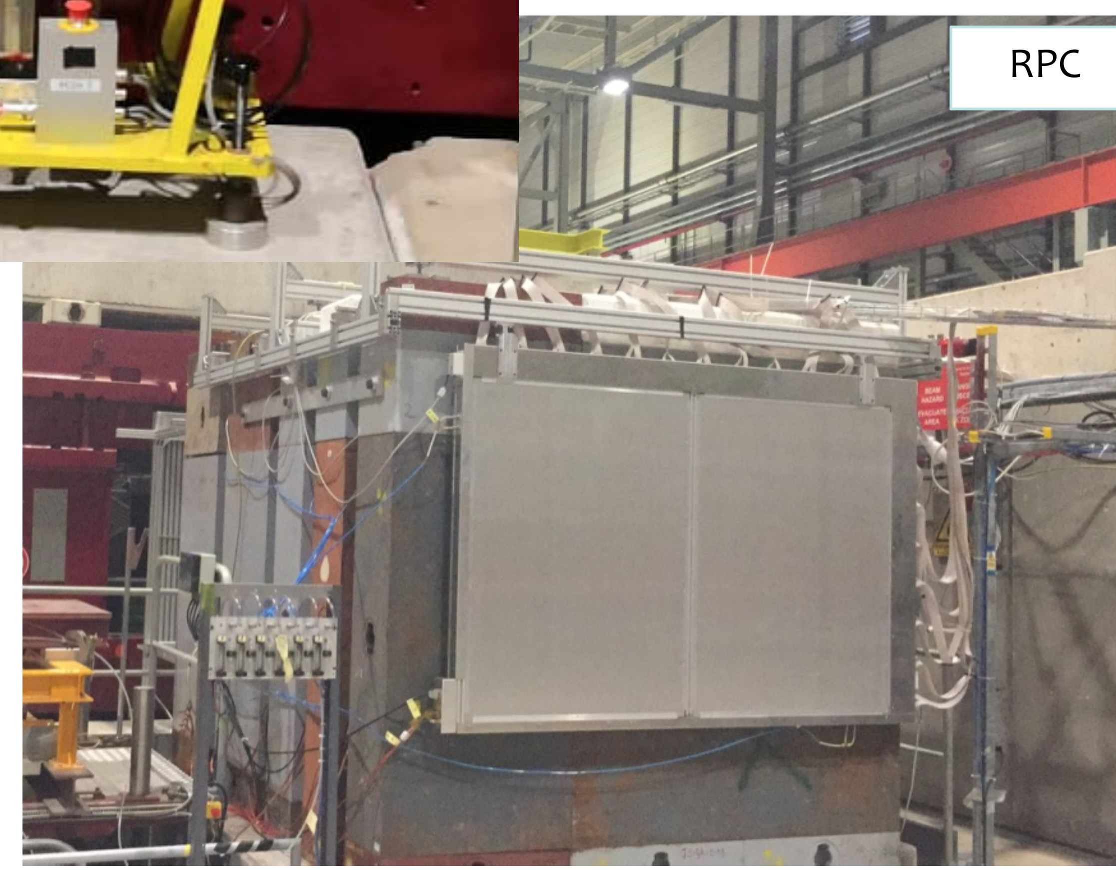


Experimental Setup

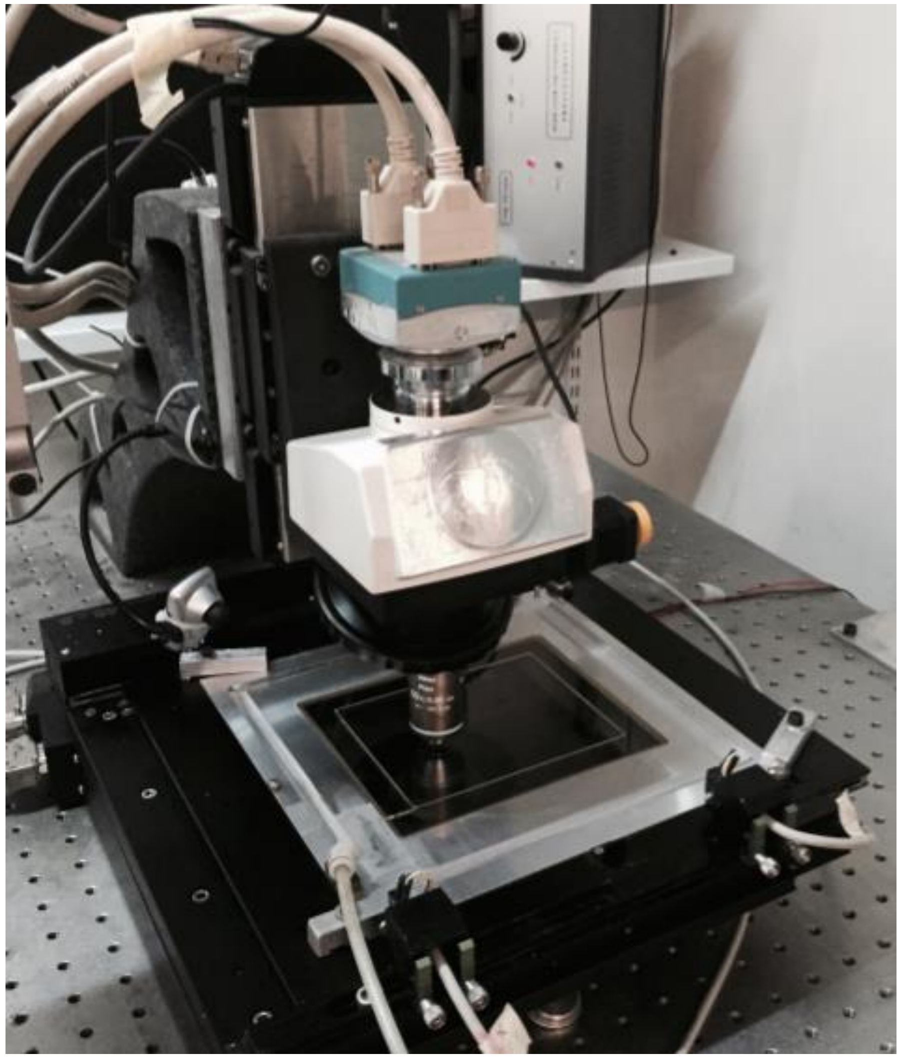




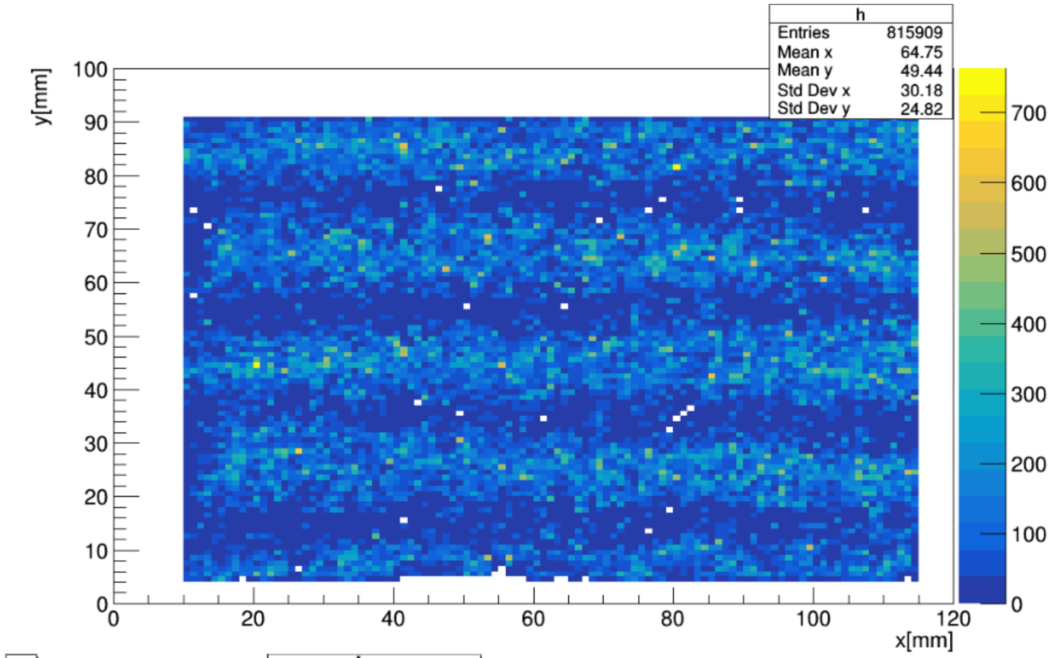




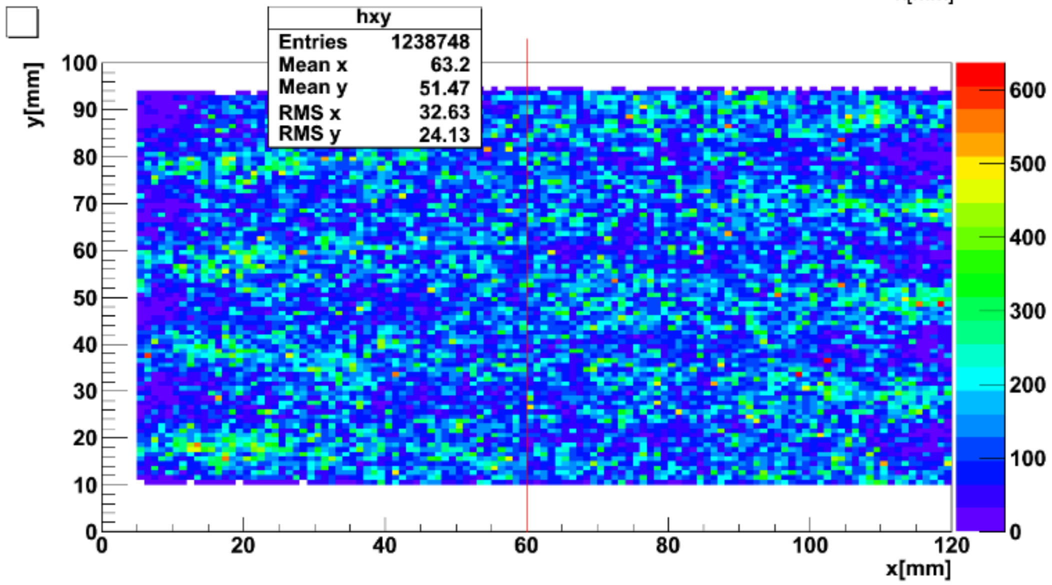
Emulsion scanning



5 spills exposure

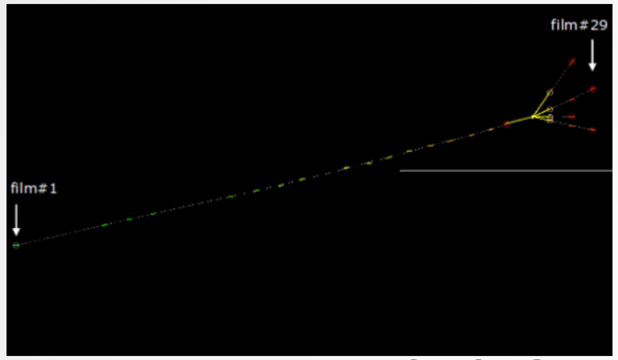


10 spills exposure

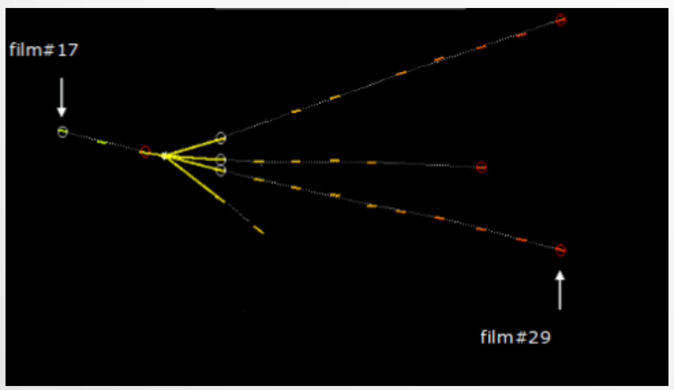


Emulsion vertex quality

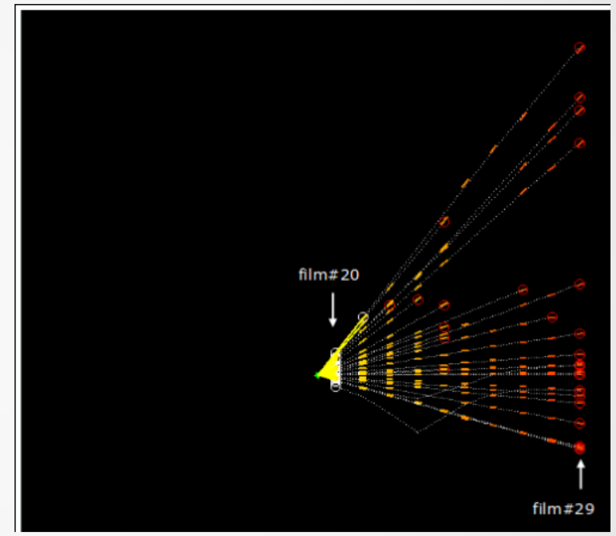
Good vertices, from CH1-R6 (RUN 2793, 28 mm W)



PRIMARY INTERACTIONS

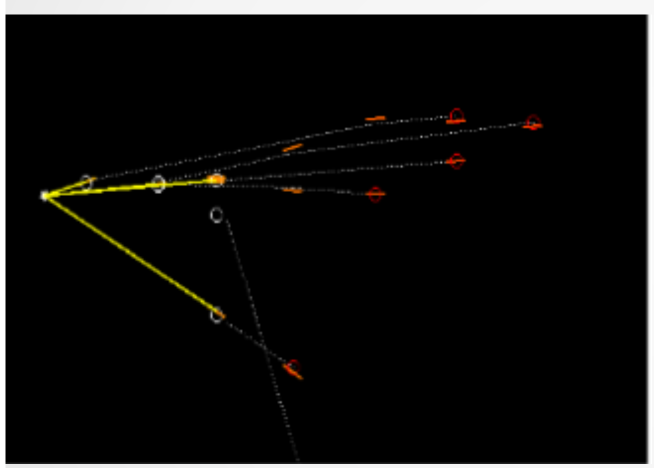


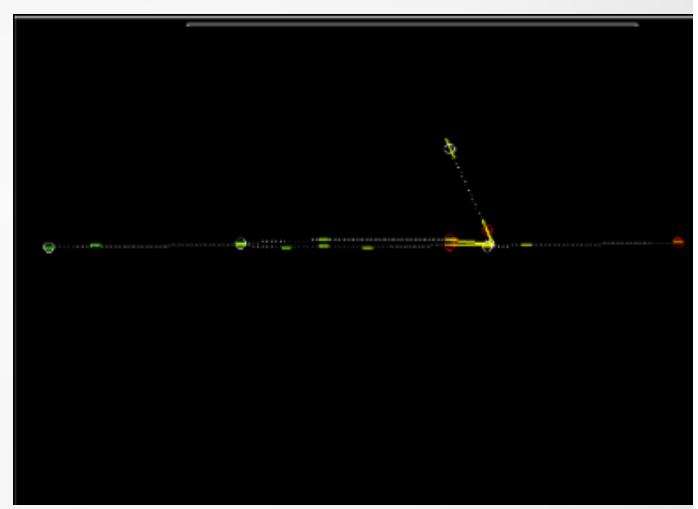
SECONDARY INTERACTIONS



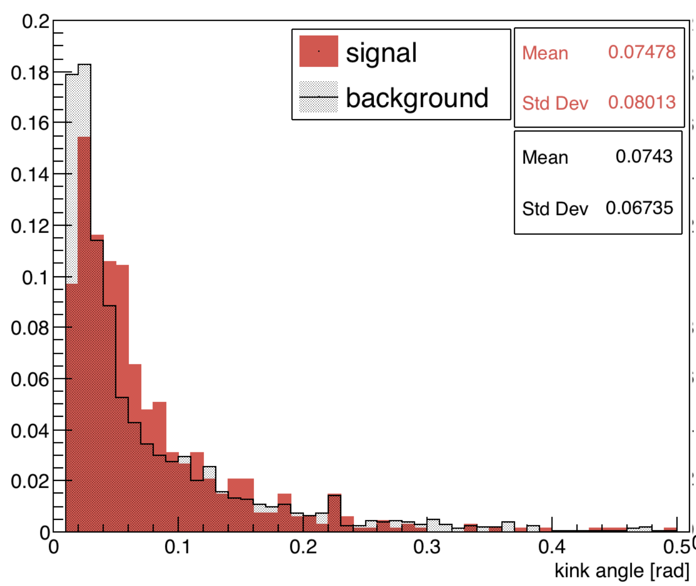
NO PARENT RECONSTRUCTED

Bad vertices, from CH1-R6 (RUN 2793, 28 mm W)

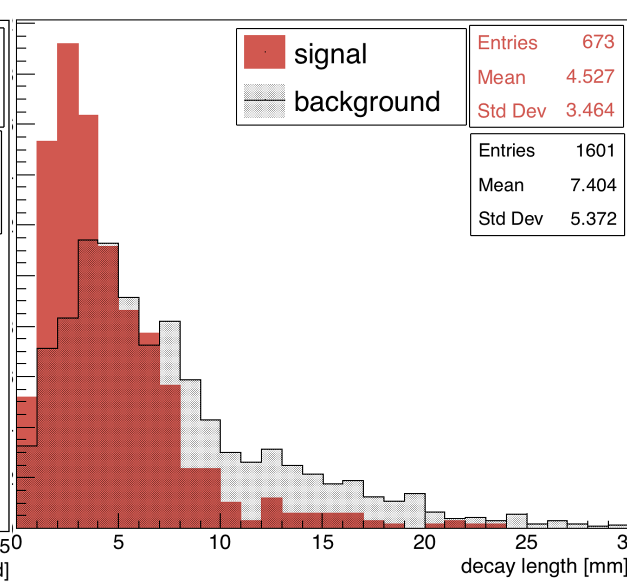

SHOWER-LIKE


RANDOM COINCIDENCES

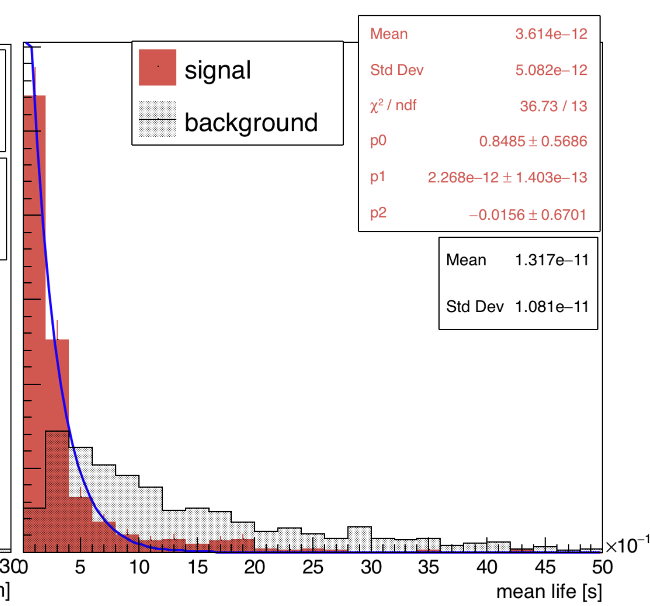
Emulsion: kinematic variables



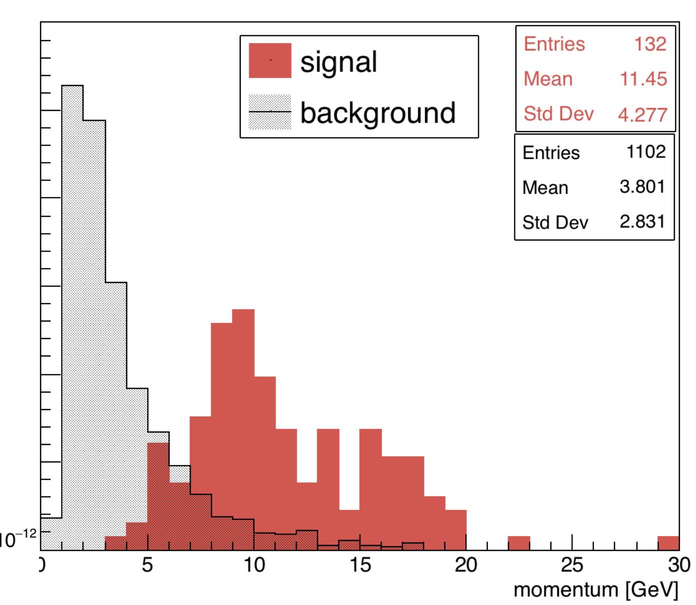
Kink angle



Decay length



Mean life



Total momentum

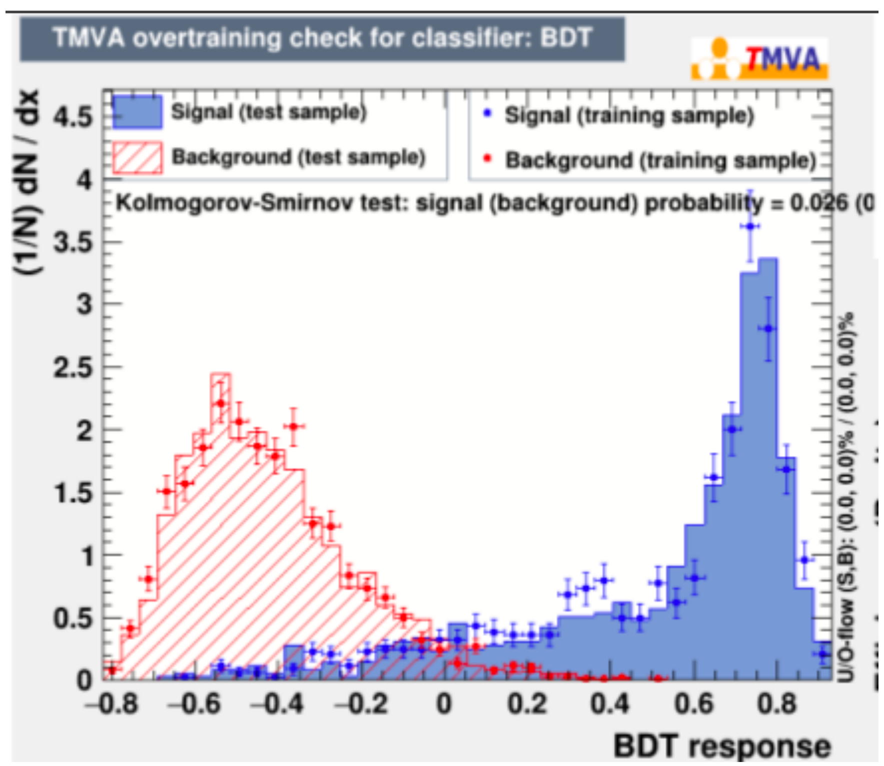
Emulsion MVA

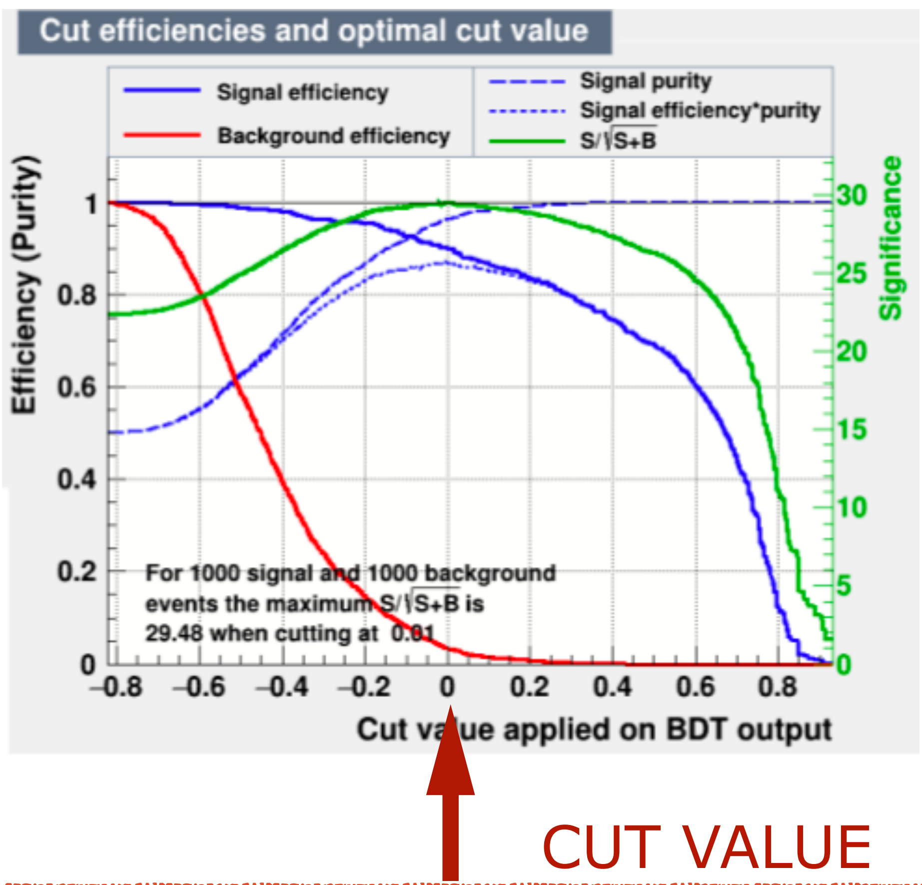
- The vertices sample is made by

Good-quality vertices:
- PRIMARY-LIKE
- SECONDARY-LIKE
- NO-PARENT

Bad-quality vertices:
- SHOWER-LIKE
- RANDOM COINCIDENCES

- Training an algorithm for the selection of good vertices from the composite sample provided by standard emulsion vertexing
- Input variables: max angular aperture, impact parameter, fill factor

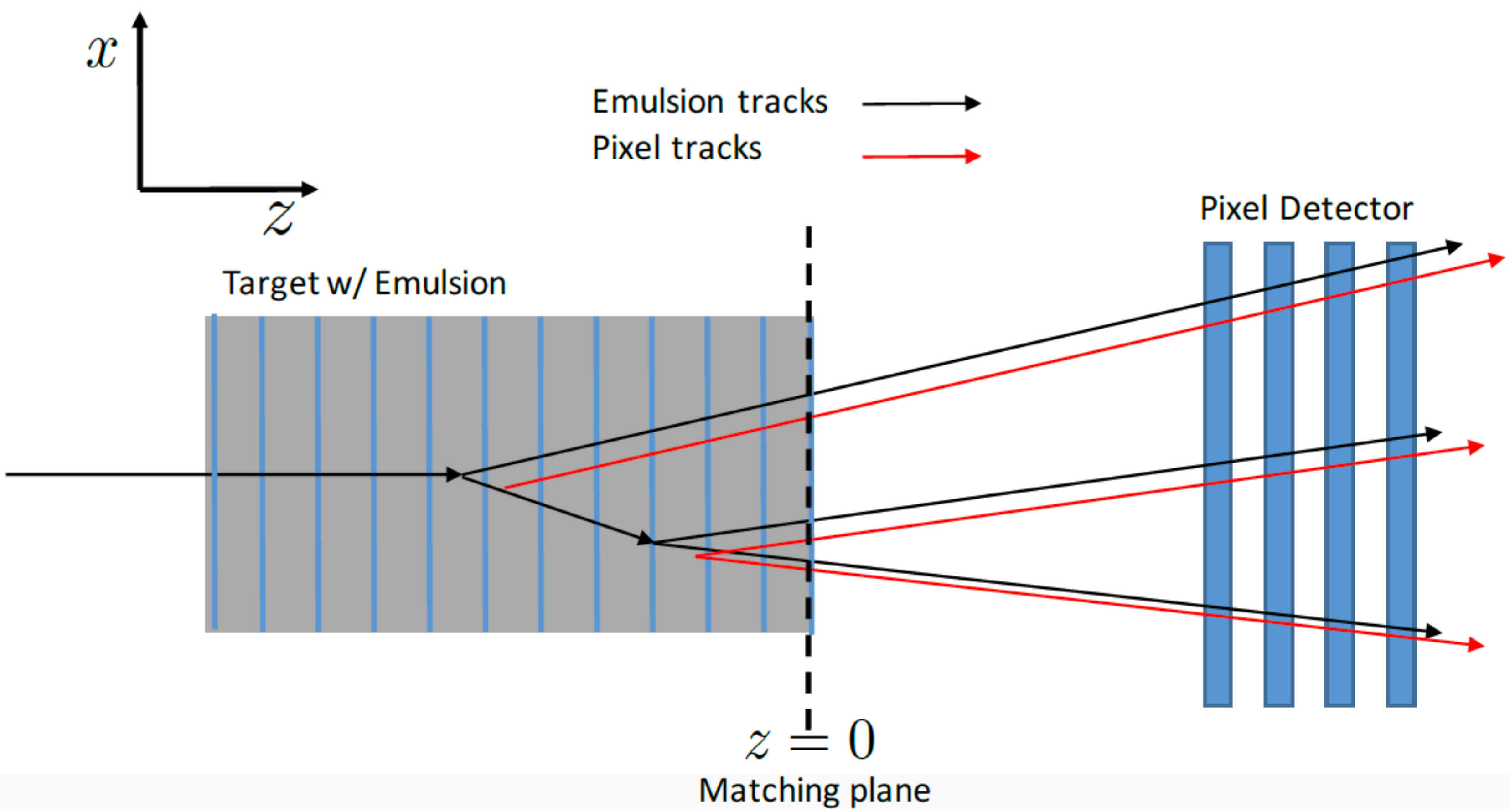




Emulsion–pixel matching

1. Extrapolate pixel track to $z = 0$ (last emulsion layer)
2. Calculate $\chi^2 = \boldsymbol{r}^T V^{-1} \boldsymbol{r}$ for each track pair
   where $\boldsymbol{r} = (\Delta x, \Delta y, \Delta\theta_{xz}, \Delta\theta_{yz})$ and $V = V_{pix} + V_{emu}$ is the covariance matrix at the matching point $z = 0$
   $\rightarrow \boldsymbol{r} = \boldsymbol{r}(\pi, \alpha)$
   - π: vector of track parameters (5)
   - α: vector of alignment parameters (7)
3. Alignment found by $d\chi^2/d\alpha = 0$
   New alignment parameters can be expanded in terms of old parameters

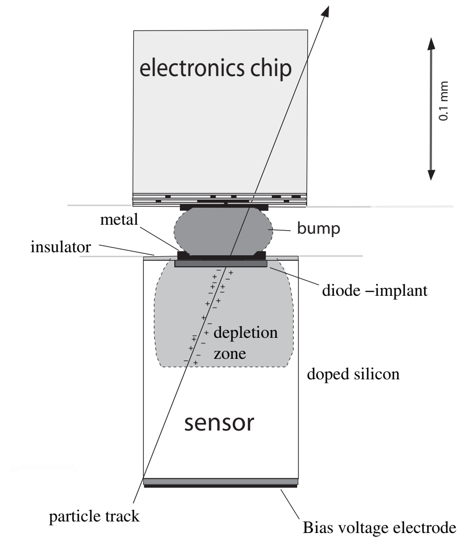
$$\alpha^{(1)} = \alpha^{(0)} - \left(\frac{d^2\chi^2}{d^2\alpha}^{(0)} \right)^{-1} \frac{d\chi^2}{d\alpha}^{(0)}$$



Pixel modules

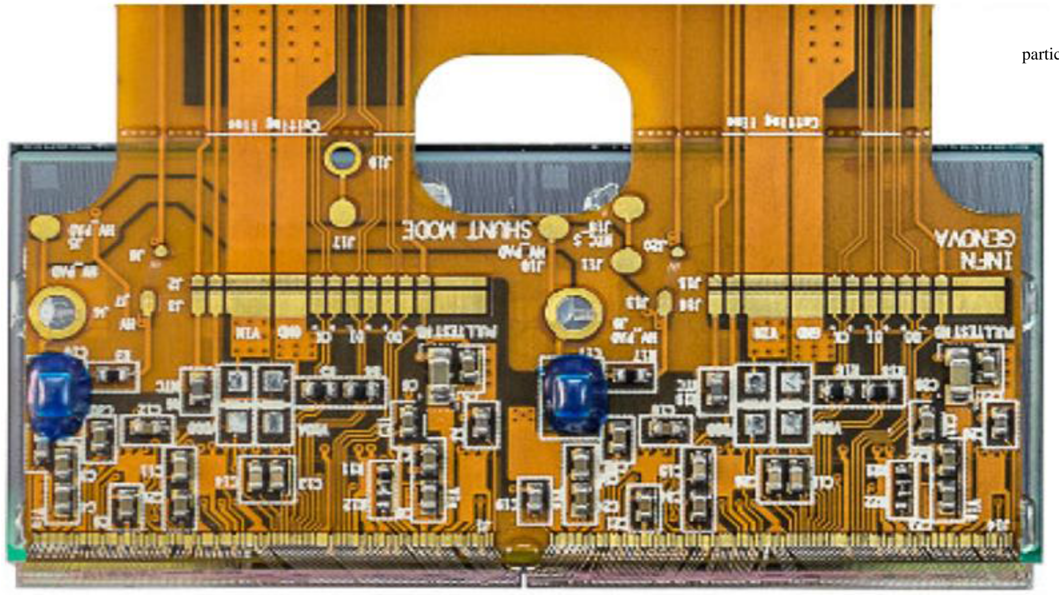
Hybrid pixel detectors

- n-in-p planar silicon sensors used in ATLAS IBL upgrade
- FE-I4B front end-chips



Characteristics

- (mostly) 250 µm x 50 µm pixels
- 80 x 336 matrix
- 25 ns time resolution



Detector

- 2 FE-I4B bump bonded to sensor
- PCB (flex) for control and data

Pixel tracker in 2018 testbeam

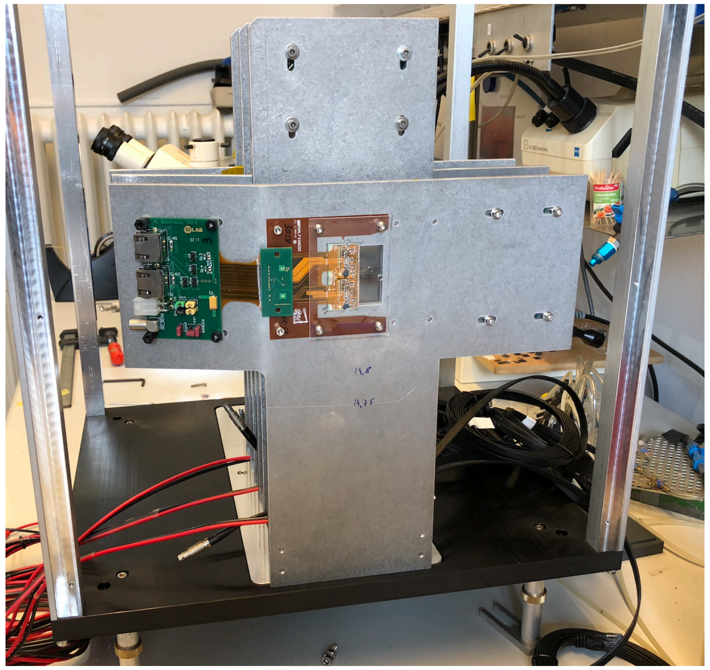
UNIVERSITÄT BONN

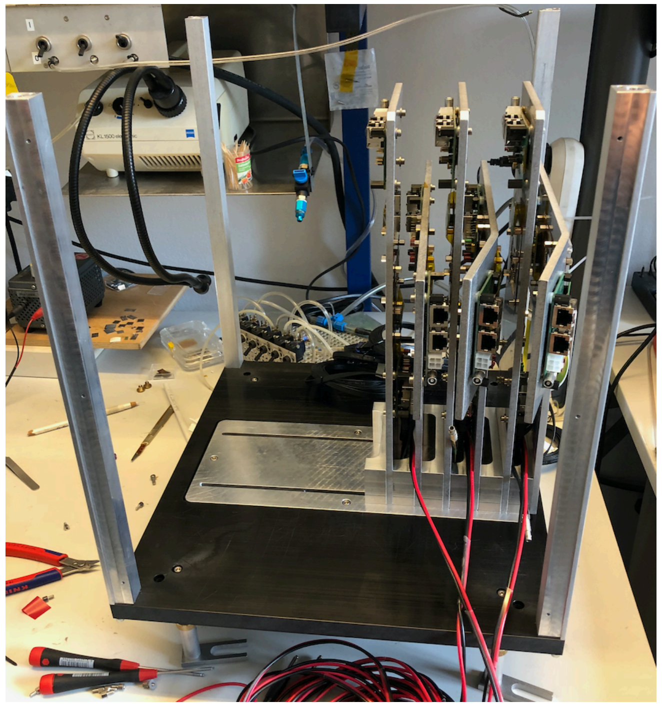
Total of 12 modules

- i.e. 24 FE chips, arranged in 6 planes
- planes are pairwise orthogonal to each other, i.e. resolution in x/y is similar

Design consideration

- first module as close as possible to emulsion





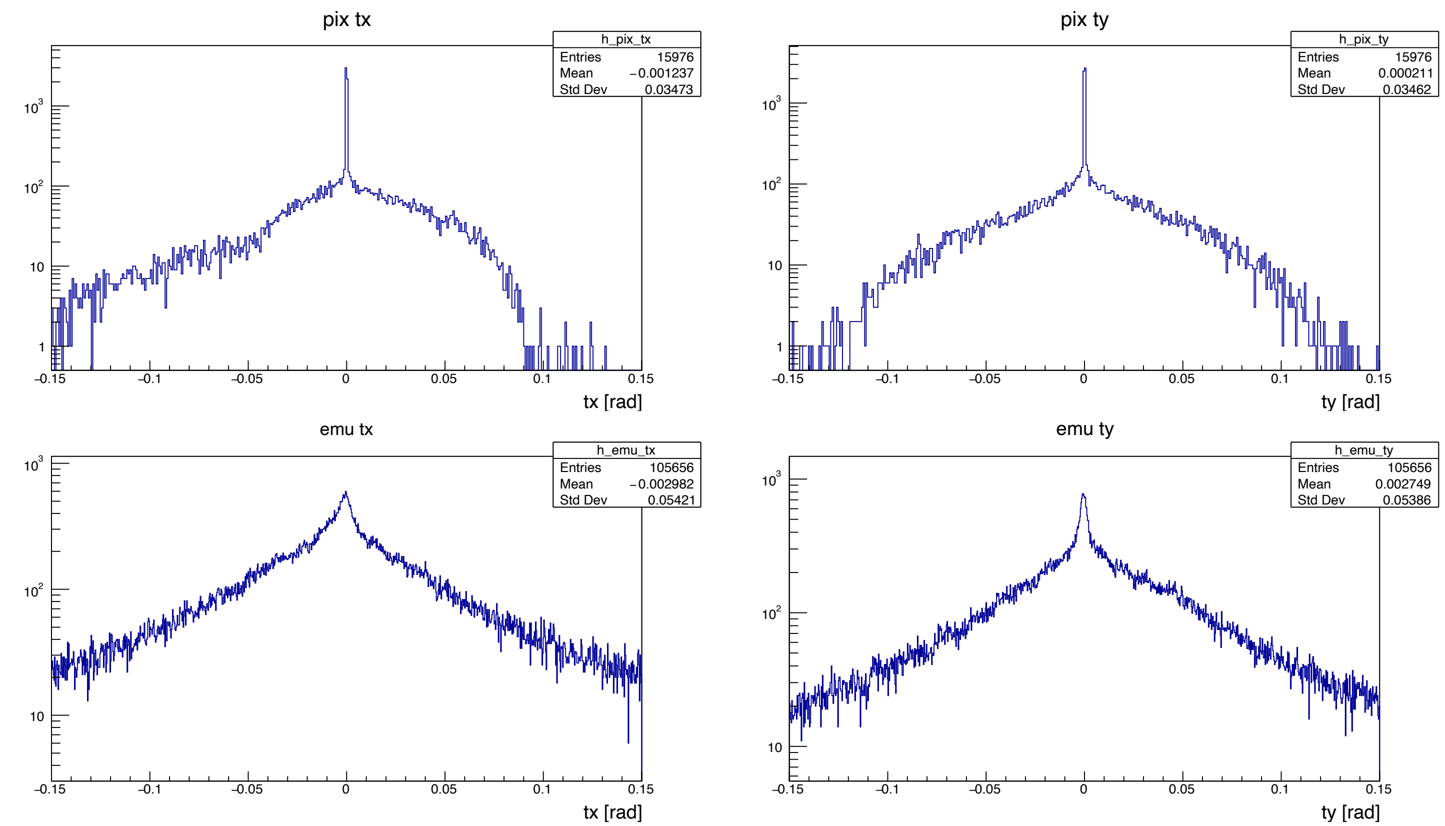
Pixel track reconstruction

Angular resolution

- ~200 μrad for beam peak

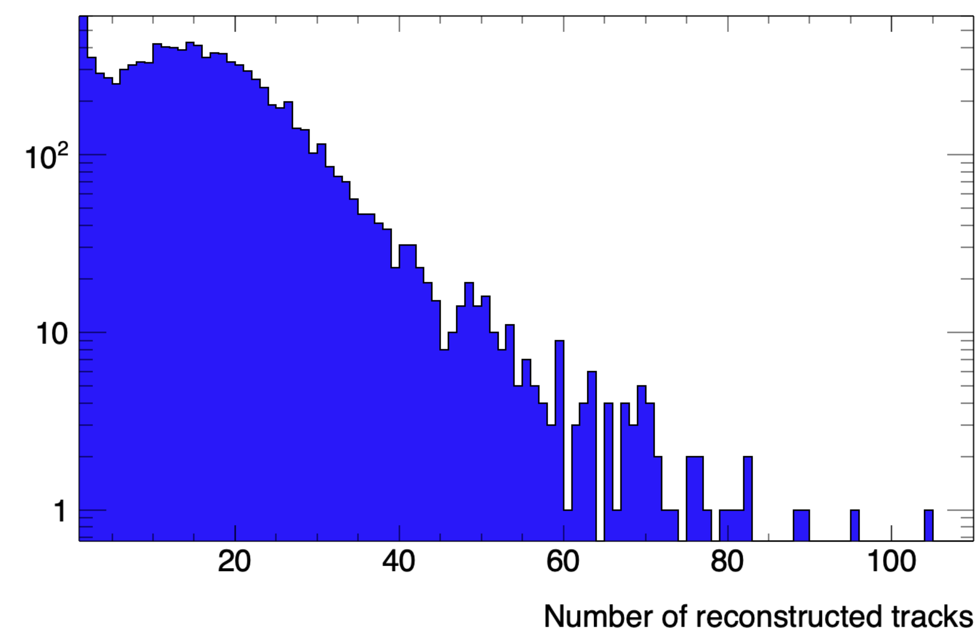
Acceptance

- 150 mrad, corresponds to pixel tracker geometry



Track multiplicity

- events with several tens of tracks reconstructed



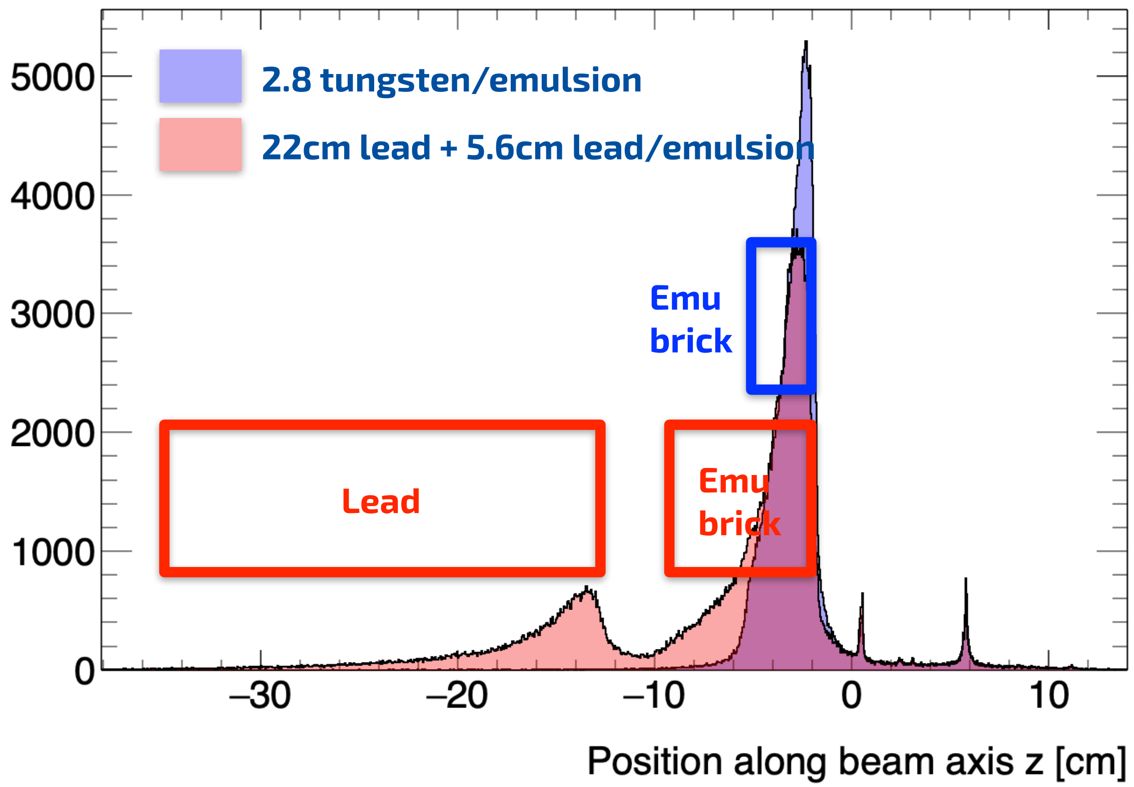
Pixel vertex reconstruction

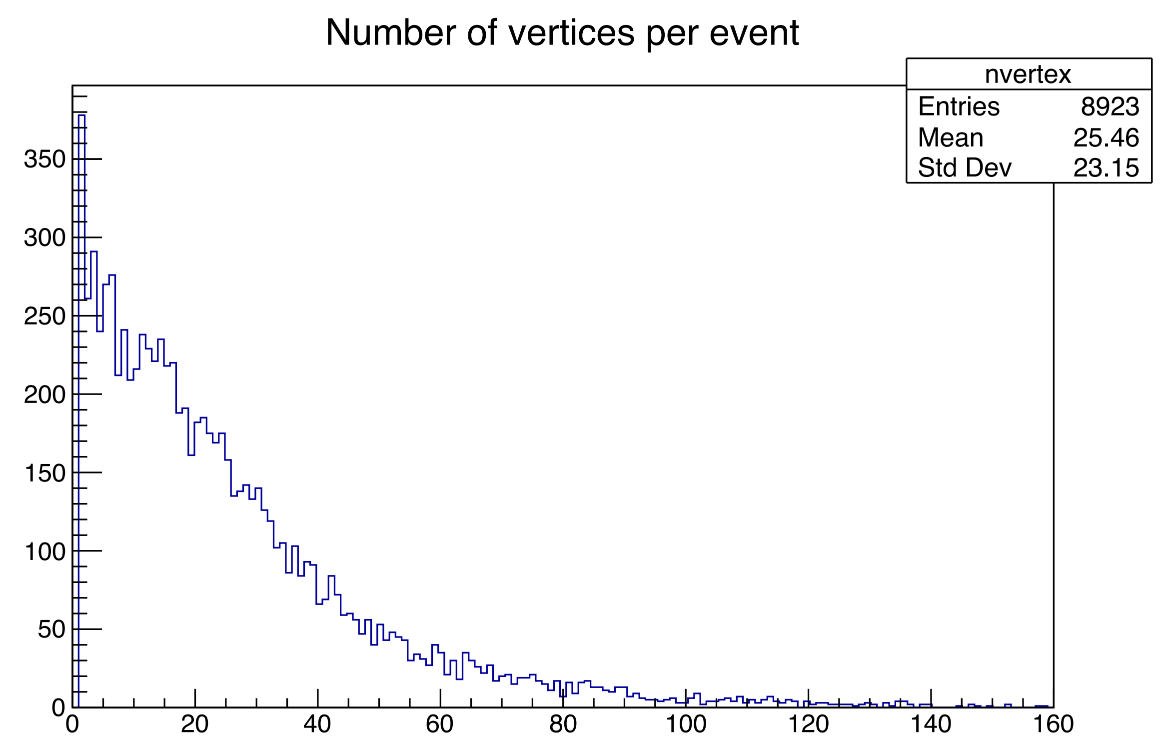
For each track pair

- find 3D point where track–track distance is minimal

Distribution in z corresponds to material

- compare two runs with different amount of material





SciFi issues

Problems detected

- Time stamp (PLL locked)
- Electronic reset
- Server writing
- High rate: buffer not properly cleared, bit flips in the time counters, missing data, old packets substituting good data

Could be mostly solved with calibrations