BMS
Beam Momentum Station

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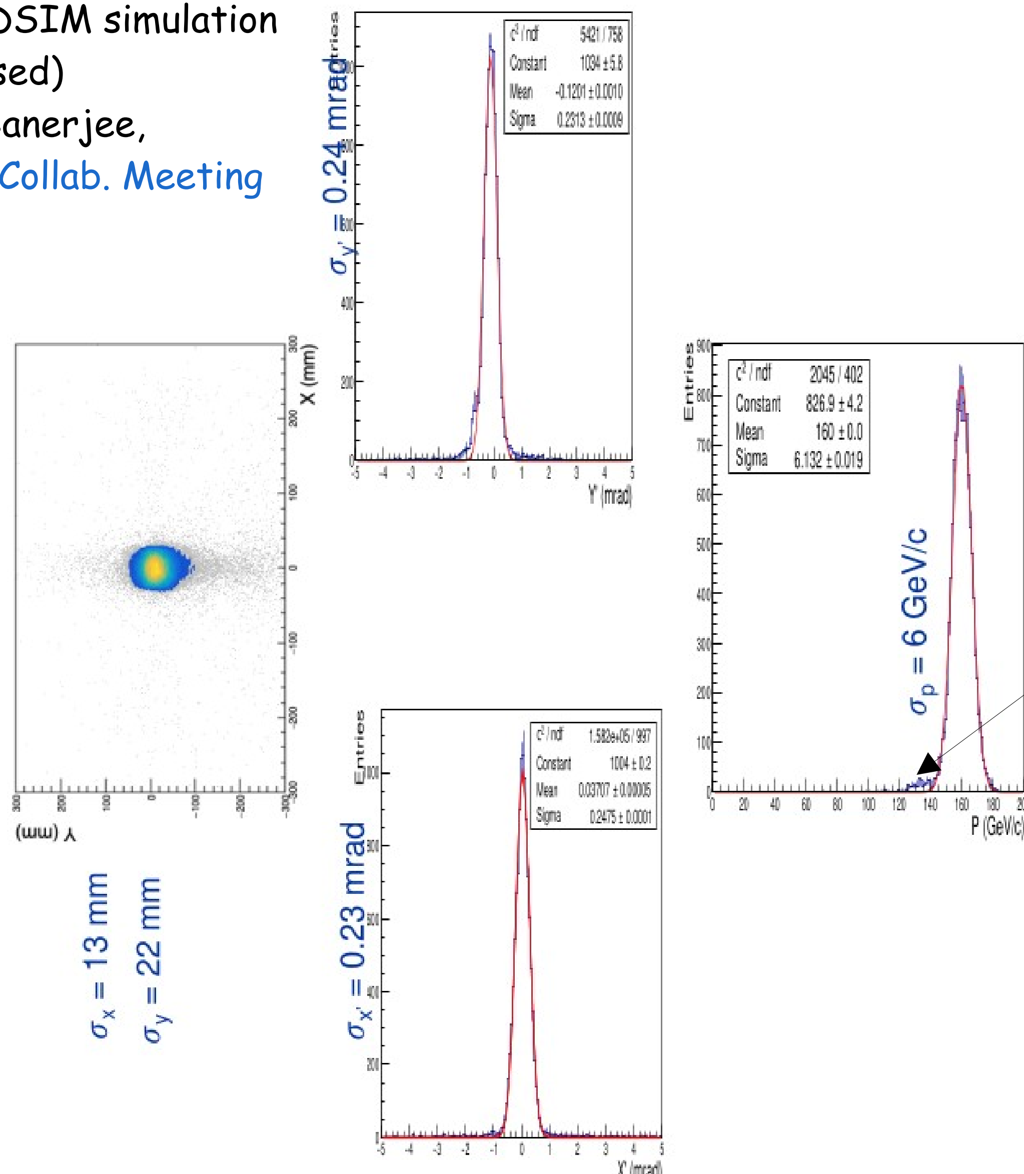
II Muon Precision Physics Workshop
9 November 2023

μ beam at the Experiment entrance

Beamline BDSIM simulation
(Geant4 based)
Dipanwita Banerjee,
4th MuonE Collab. Meeting

Beam Parameters

Parallel beam



$E_{\mu\ beam}$ = 160 GeV

$RMS_E / E_{\mu\ beam}$ = 3.75%

+ possible background contamination, tails

Effect of beam energy spread on scattering spectra in MUonE

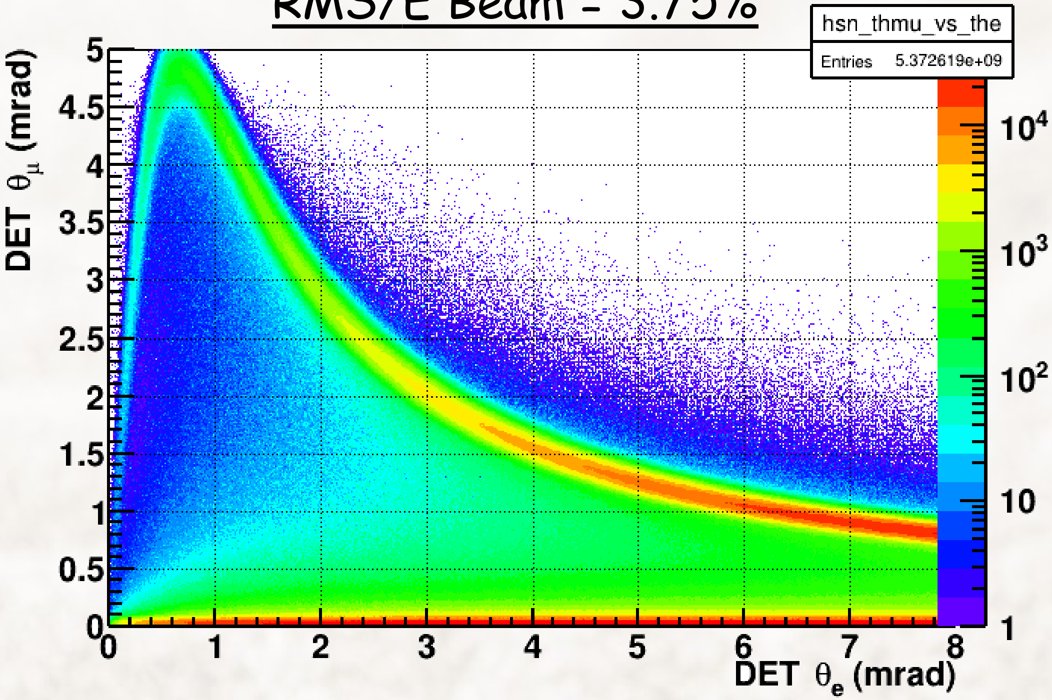
MS: at X/X0 = .03654 (1.5cm Be + 1.28 mm Si)

Det: σ_θ = 0.02 mrad (10μm hit resolution)

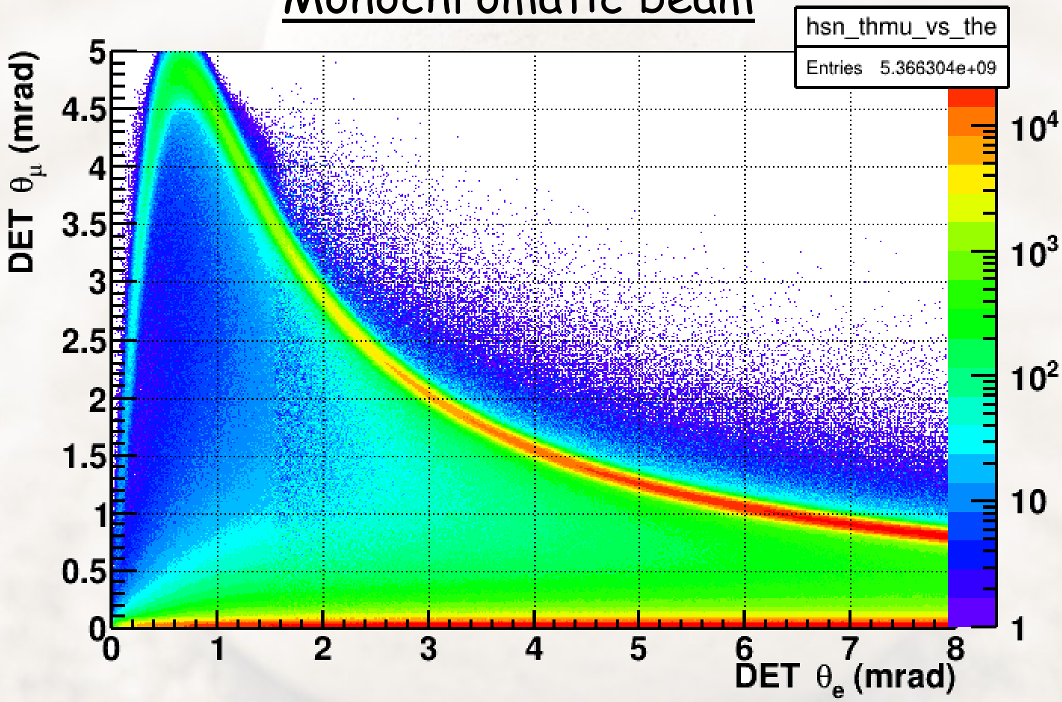
Fast sim with Mesmer

Plot for ~0.06% of targeted L=1.5x10^7 nb^{-1}

RMS/E Beam = 3.75%



Monochromatic beam



Scattering band is twice wider because of the beam energy spread

Sensitivity over background twice worse

Effect of beam energy spread on scattering spectra in MUonE

MS: at X/X0 = .03654 (1.5cm Be + 1.28 mm Si)

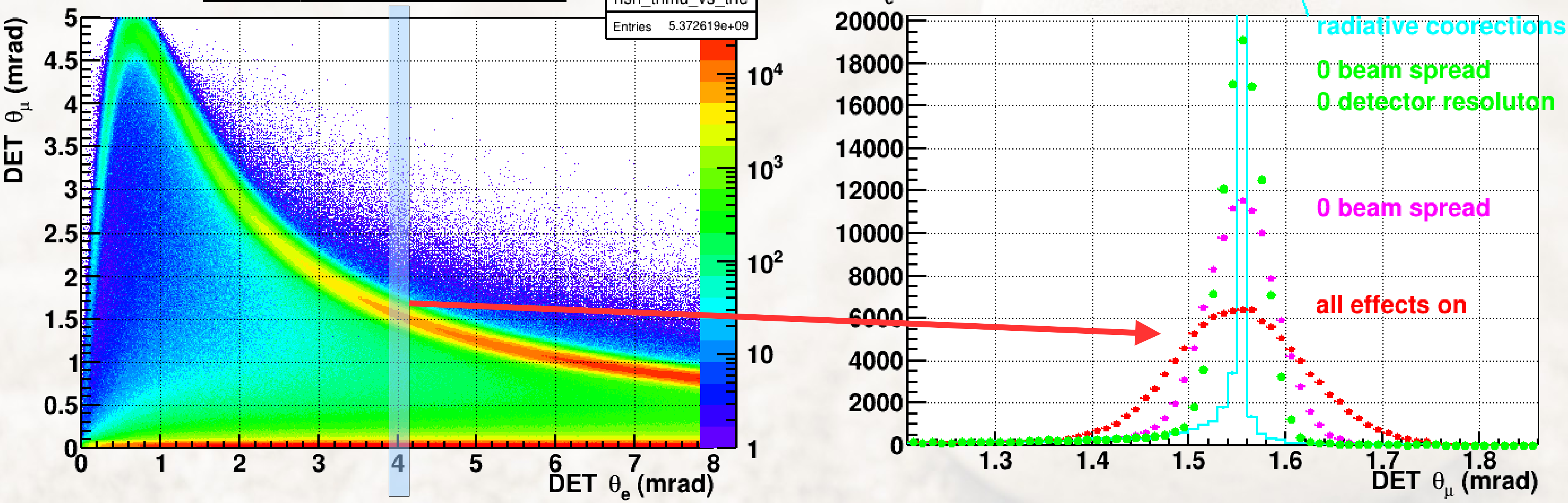
Det: σ_θ = 0.02 mrad (10μm hit resolution)

Fast sim by Mesmer

Plot for ~0.06% of targeted L=1.5x10^7 nb^{-1}

Θ_μ spectra at θ_e = 4 mrad

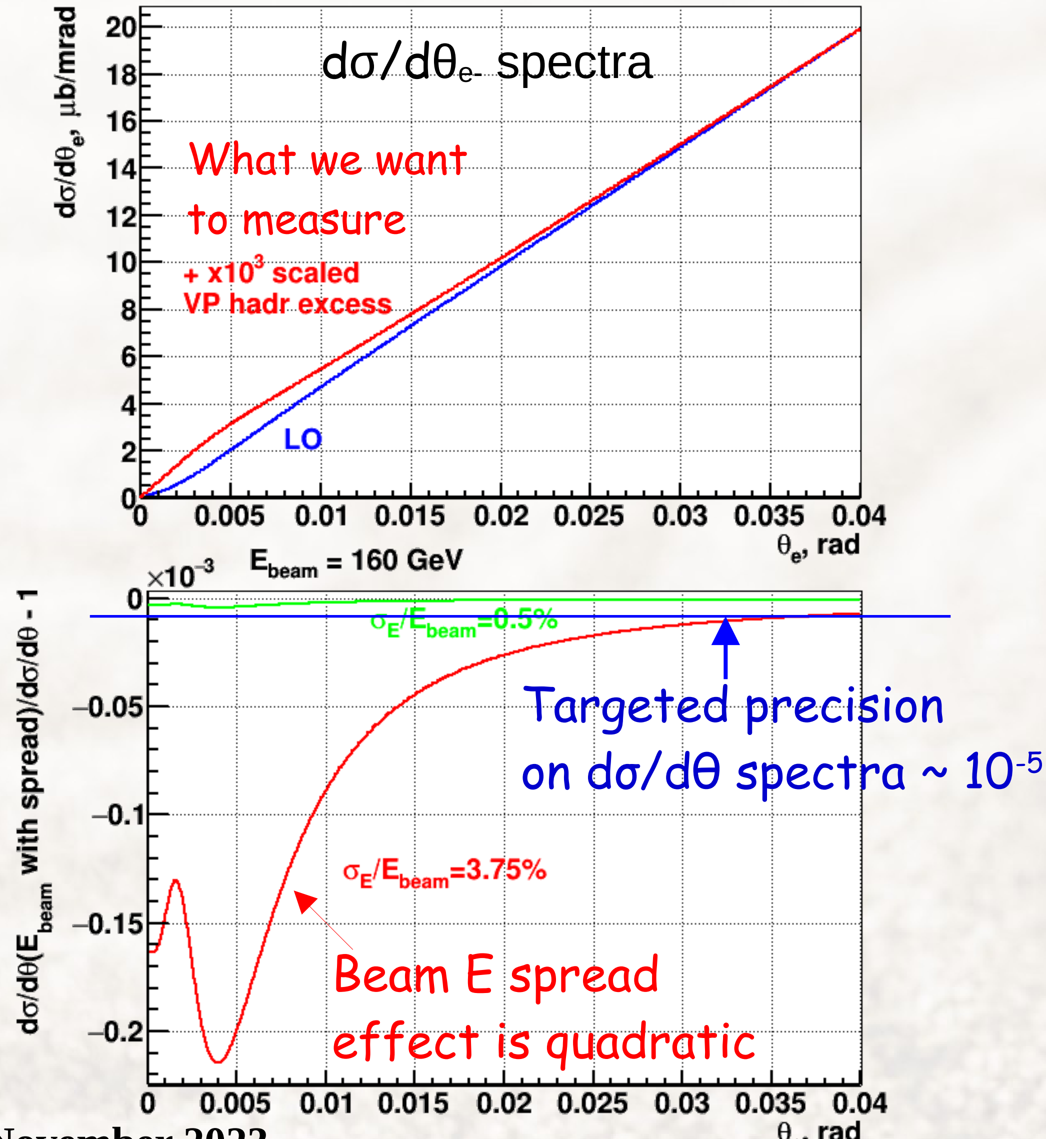
RMS/E Beam = 3.75%



Scattering band is twice wider because of the beam energy spread

Sensitivity over background twice worse

Effect of beam energy spread on $d\sigma/d\theta_{e-}$ spectra



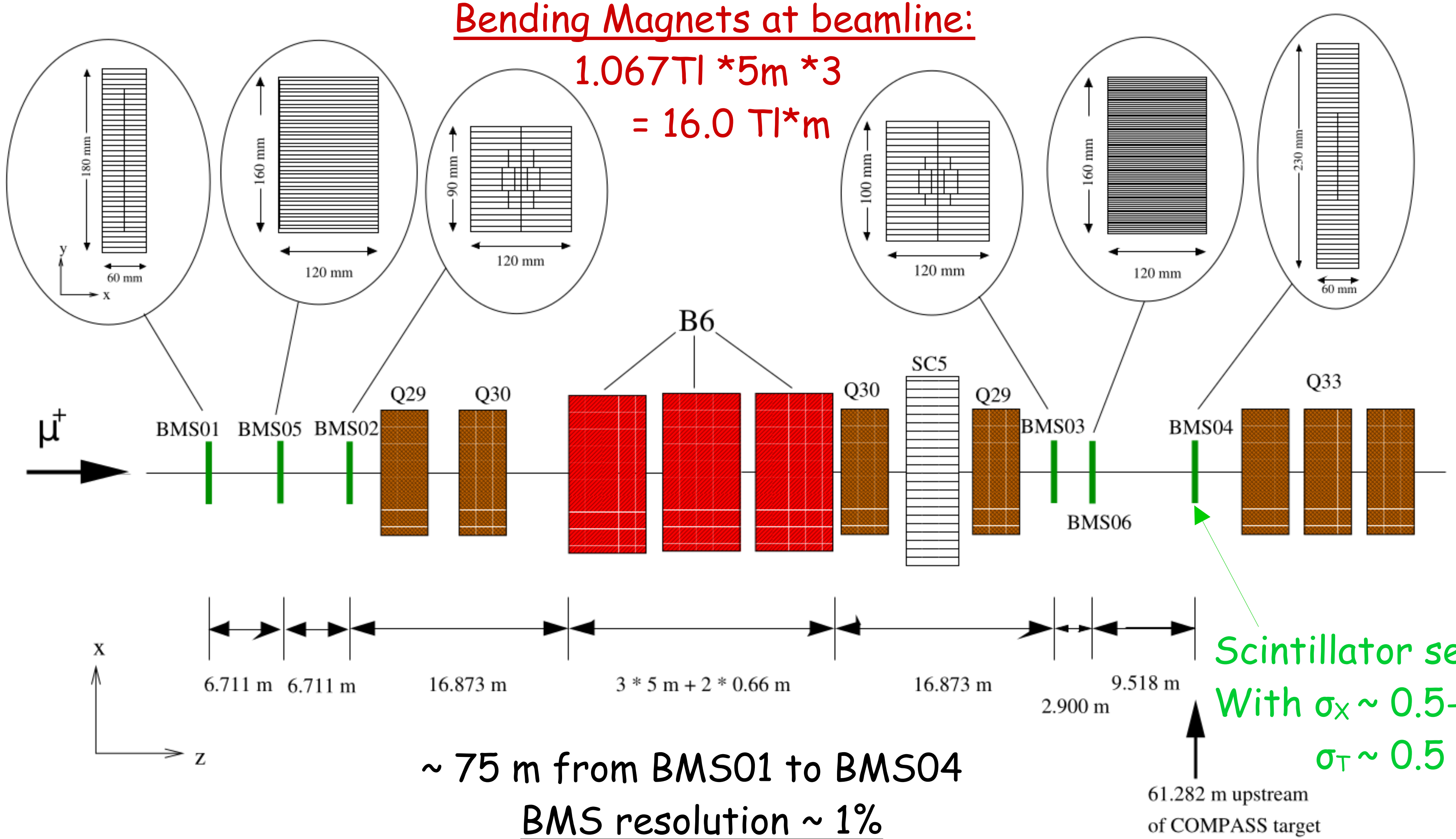
<u>Beam energy spread change measured angle spectra</u>

gives effect
x22 higher relative to the requirement

→ beam spread must be known
with ~1%xRMS (or 0.04%xE_{beam})

Having knowledge on event-by-event μ-momentum at <0.5% will suppress this effect

BMS (Beam momentum station)



Bending Magnets at beamline:

1.067Tl *5m *3

= 16.0 Tl*m

Scintillator sensors

With σ_X ~ 0.5-2 mm,

σ_T ~ 0.5 nsec

~ 75 m from BMS01 to BMS04

BMS resolution ~ 1%

Figure 5.1: The schematic view of the Beam Momentum Station (BMS) setup. The green elements are the BMS detector planes. Their dimensions and division into channels is presented. The setup is positioned on two sides of the Bend 6 magnet group (B6). Elements marked with "Q" are the quadrupole magnets while the SC5 is a scraper. (The plot is not up to scale). Figure comes from Ref. [87].

Konrad Klimaszewski, PhD Thesis 2010
https://inspirehep.net/literature/1231365


Bending
Magnets
MBN58
BMS-1
BMS-2
BMS

Simulation

- Geometry for M2 beamline: M2_BMS_To_CEDARs.gdml (update with Air in Scrapper (updated version since 21.07.23 MUonE weakly meeting, +42% Nevents after track selection)
- Full magnetic fields in "parallel" configuration: Bends, Quadrupoles, Scarper
- Beam profile: MuOnE_Muon_Beam_160GeV.root
- Scintillator material of Hodoscope replaced by Air
- 4 layers of 300μm Si sensors were added (in place of BMS1-4) – (for completeness, the material is not a issue)

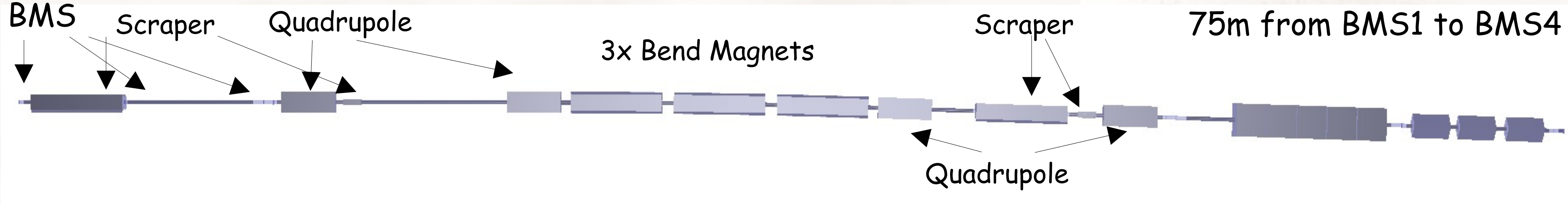
Provided by Fabian Metzger from accelerator group

N.B. The additional geant4 tuning is required because of tracking over large volumes, and tracking precision is crucial

Transported Muon

Thanks to Dipanwita and Fabian for providing the GDML description from BDSIM

detail GDML model



Test beam area

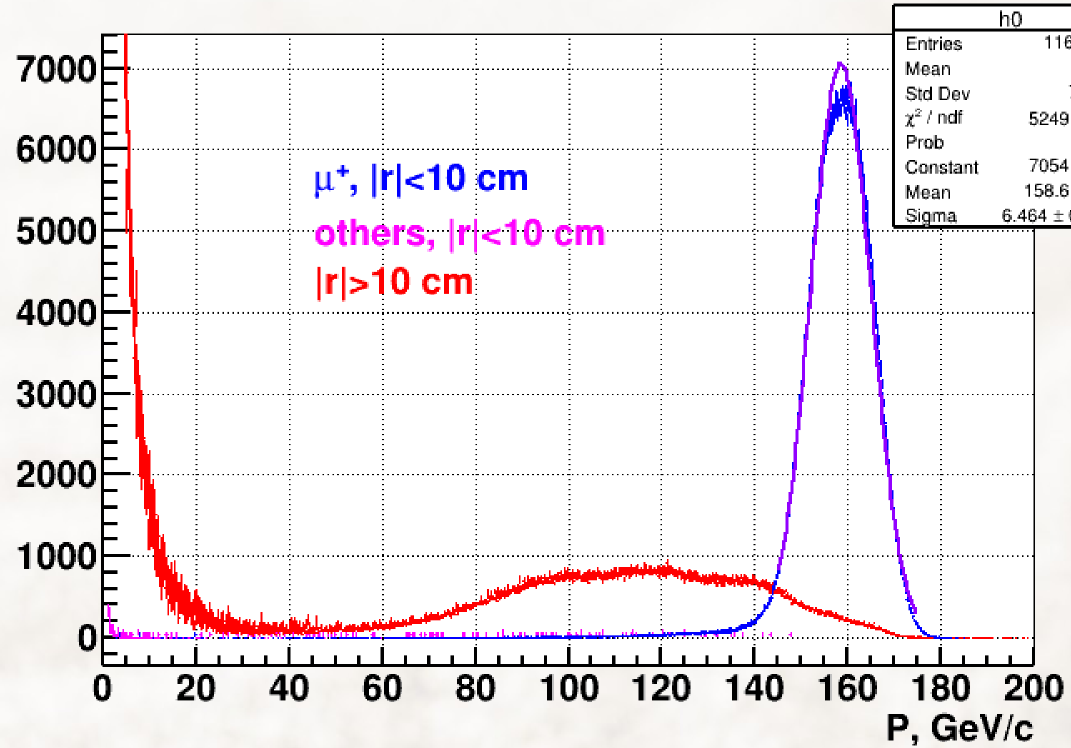
Material budget:

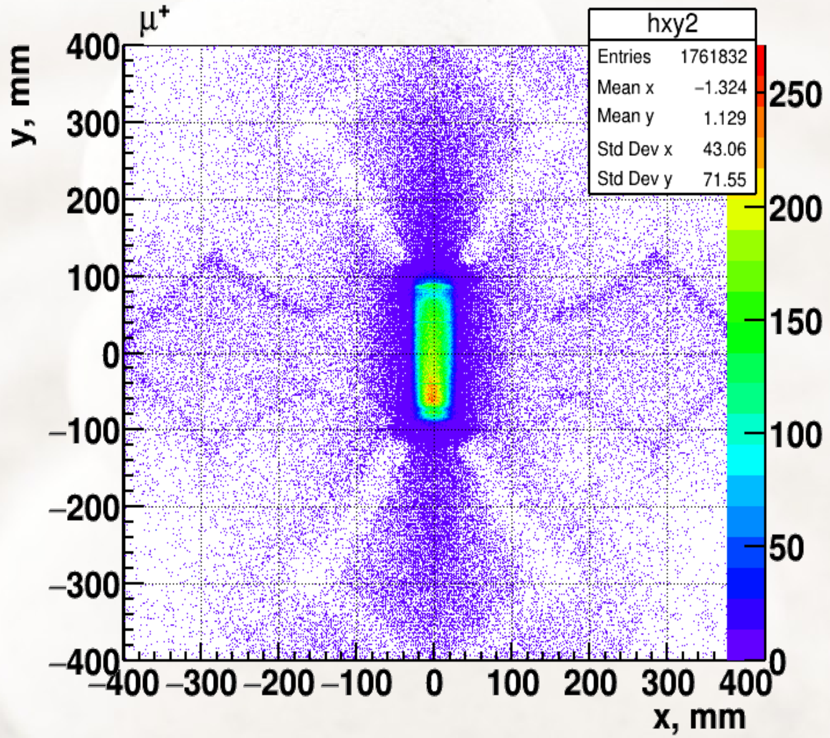
BMS01-06	~ 112 mm of Scintillator	= ~0.34 X0
Air gaps	14.3m	= 0.050 X0
Mylar windows	8*0.02 cm	= 0.019 X0
		Σ = 0.4X0

material of Si detector will be negligible:
150μm Si = 0.0016 X0
equivalent to 0.45m of Air

0.5 X/X0 → Θ_{MS} ~ **3.5×10^{-5} rad** ,
1 arm (13m) Hodoscope detector Θ resolution ~ **2×10^{-4} rad**,
$\sigma_P/P < 0.1\%$ require ~ **3×10^{-5} rad**

Beam at first BMS1

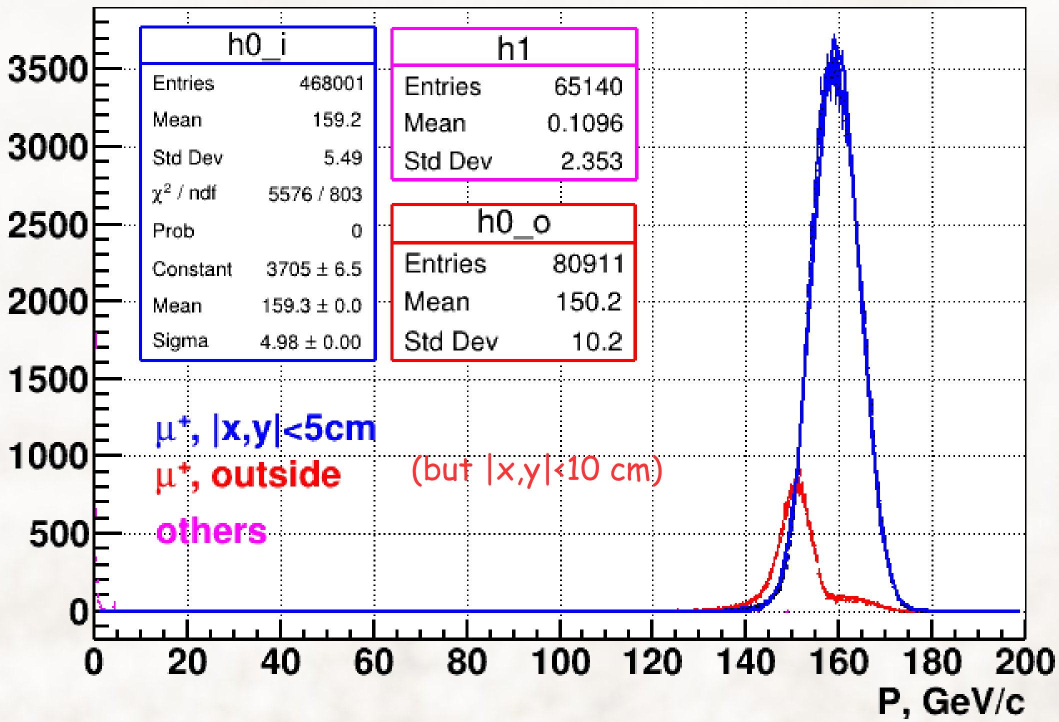


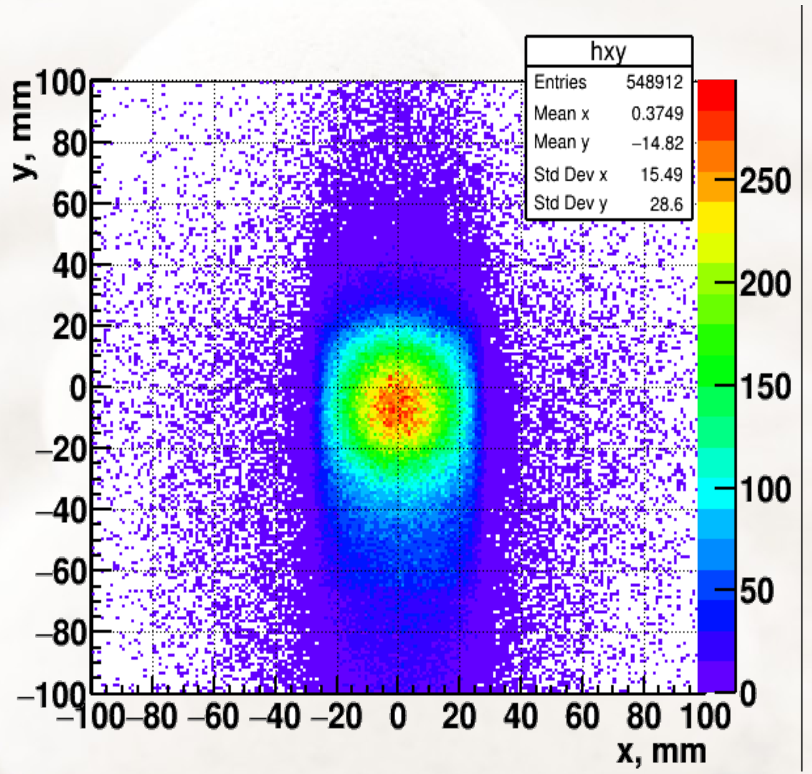


Beamspot ~ 10x20 cm

Beam at entrance to CEDAR area

After passing BMS





at 20x20 cm area:

15% outside 10x10 cm area

Low momentum tail:

7.6% γ, 4.1% e- , 0.2% e+, 0.001% π+-

σ_x ~ 13.3 mm,

σ_y ~ 24.0 mm,

Beam profile along beamline

μ+ beam

1m sim events

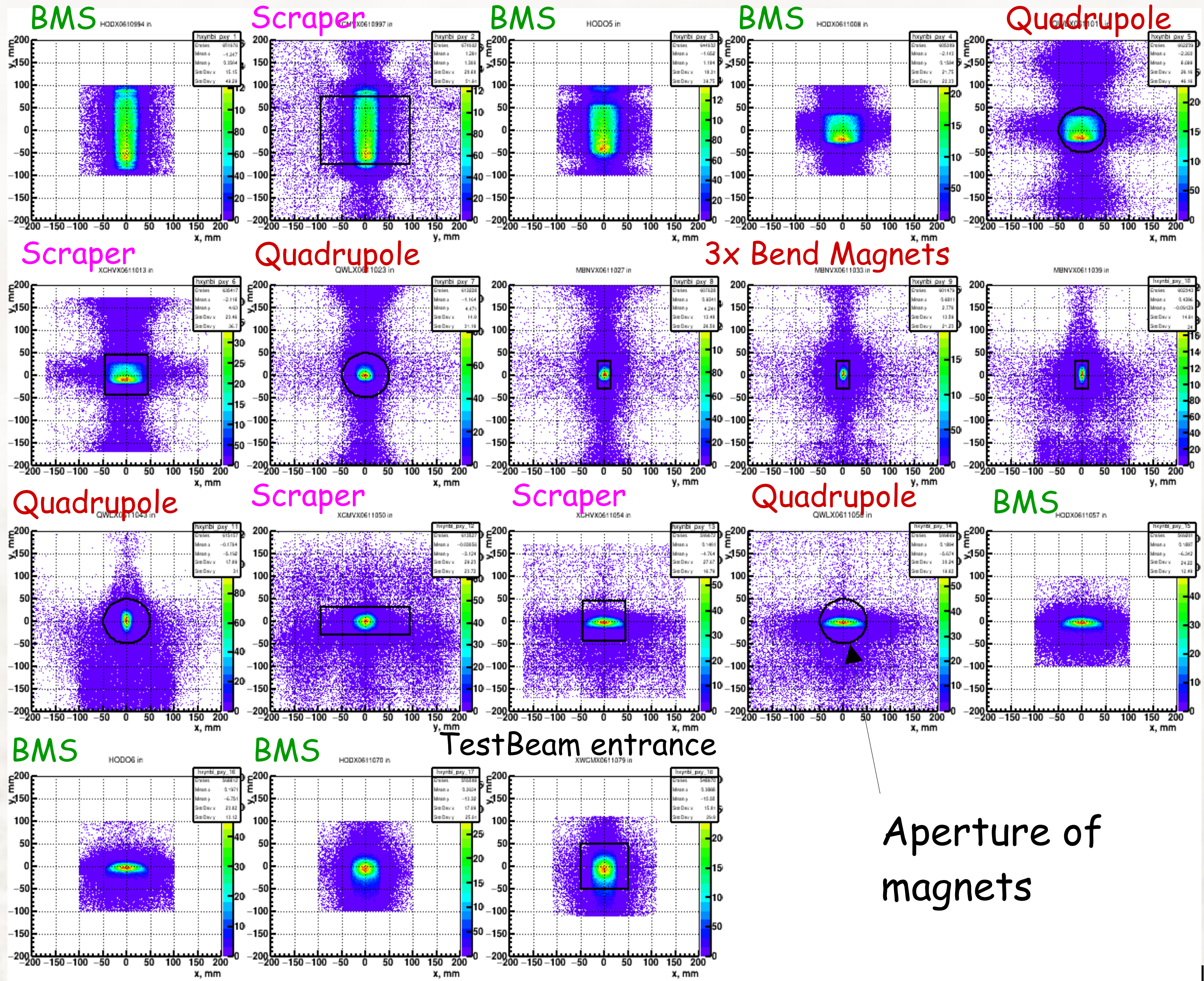
0.65m μ+ (|r|<10cm)

without weights

<u>transfer rate:</u>

x71.8% to 10x10cm area

(x84.2% to 20x20cm area)



Reconstruction

in/out tracks defined by two Si sensors
propagated throw quadrupole magnets (L=2.95m each) to the faces of Bend magnets

Momentum is taken from angle difference after passing the Bend magnets :

$$P = 160 \text{ GeV} * 0.03 \text{ rad}/(\theta^{out}_y - \theta^{in}_y)$$

Propagation is done assuming ideal quadrupole field $B=(B_0*y, B_0*x)$ (but full field in geant4)

Equation of motion (depend on sign of B_0):

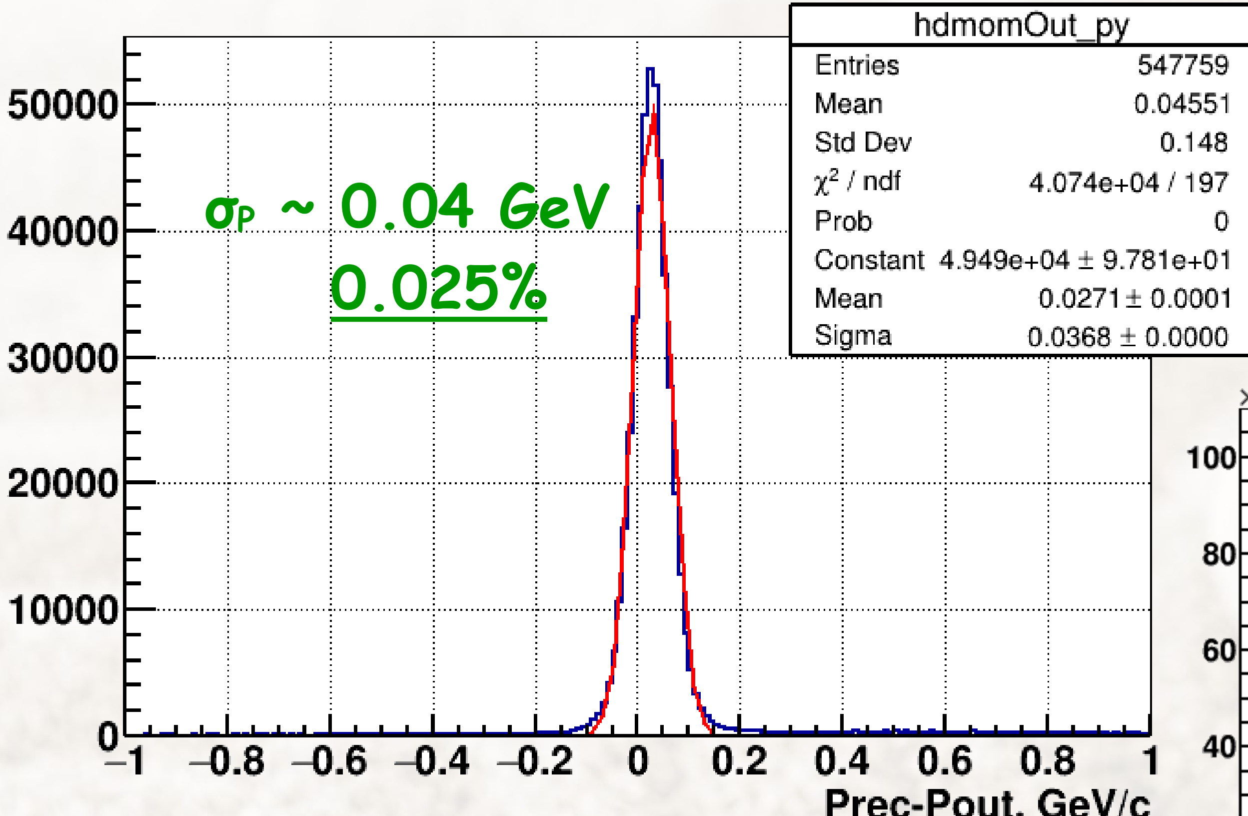
$y = c_1*\exp(a*z) + c_2*\exp(-a*z)$

or $y = c_1*\cos(a*z) + c_2*\sin(a*z)$

The exact field map can be used in the future (for trajectories at edge of acceptance)
Matching between In/Out track position can be also used, resolution from MS ~ O(mm) will be useful to suppress background and overlaps (maybe can give also something for momentum resolution)

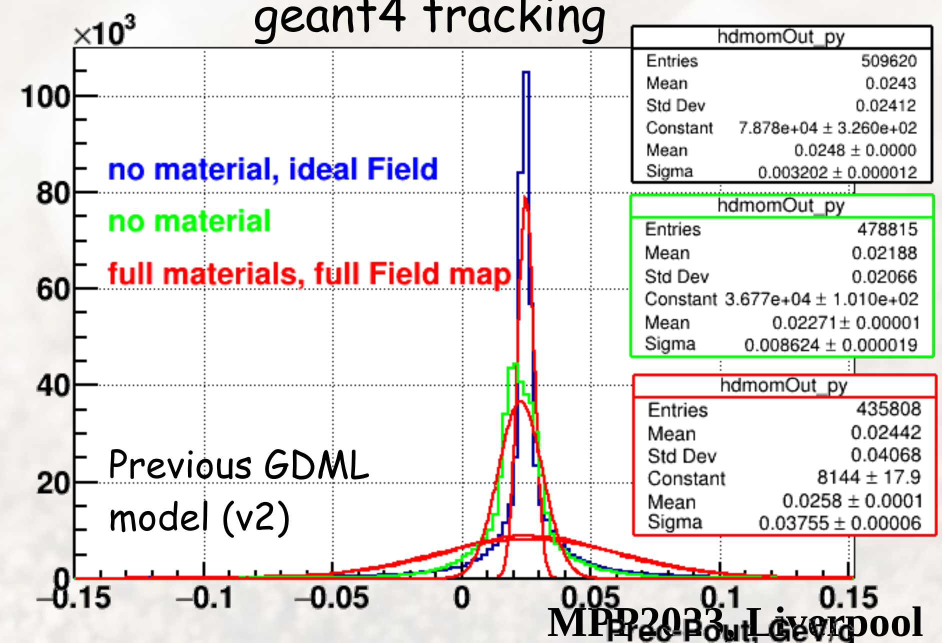
Momentum resolution (with 0 hit resolution)

With exact position at Si planes (zero hit resolution)
Muons which cross all 4 Si planes (r=10 cm) and last volume within 20x20cm (84% from initial)



Small bias is probably from the geant4 tracking precision (non-continuous field)

Effect of material and non-homogeneous B field, geant4 tracking

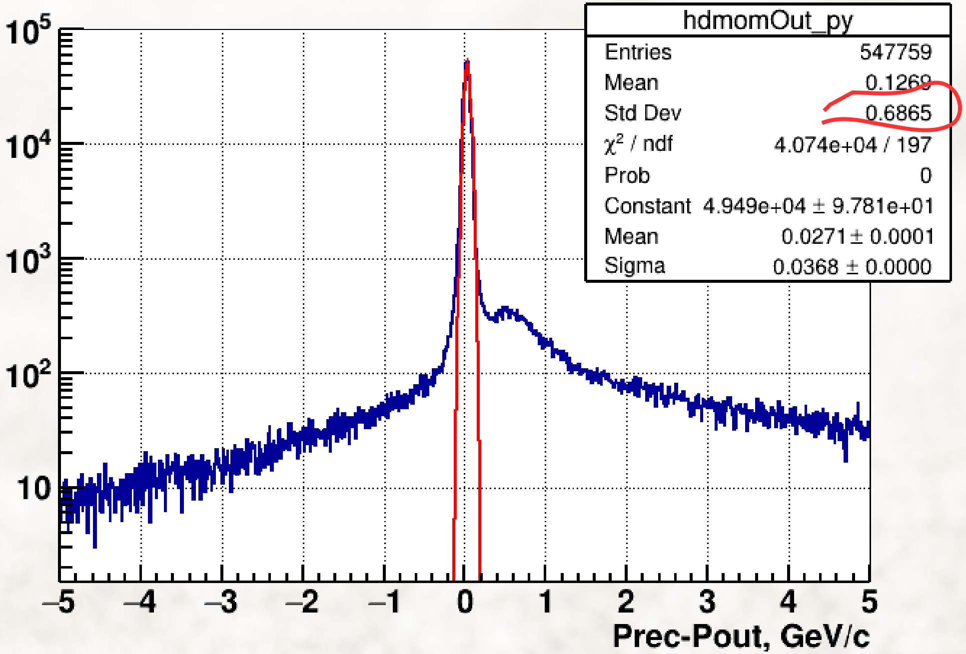


Momentum resolution tails

With exact position at Si planes (zero hit resolution)

Muons which cross all 4 Si planes (r=10 cm) and last volume within 20x20cm (84% from initial)

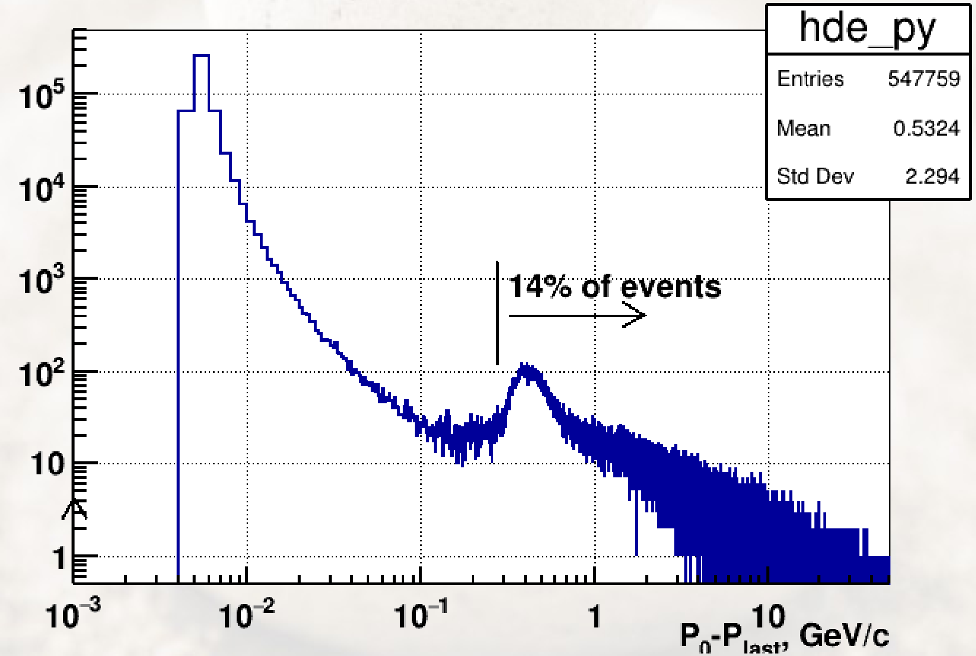
Tails in reconstructed P



$RMS/P_0 = 0.4\%$

13.7% in |dP|>0.32 GeV/c

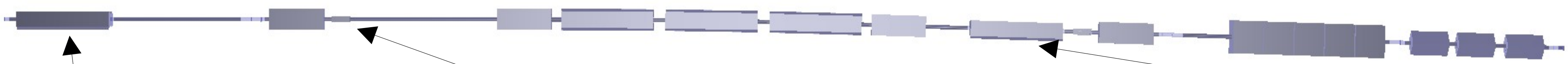
Energy loss of μ+ over M2 beamline



14% muons have loss >0.3 GeV

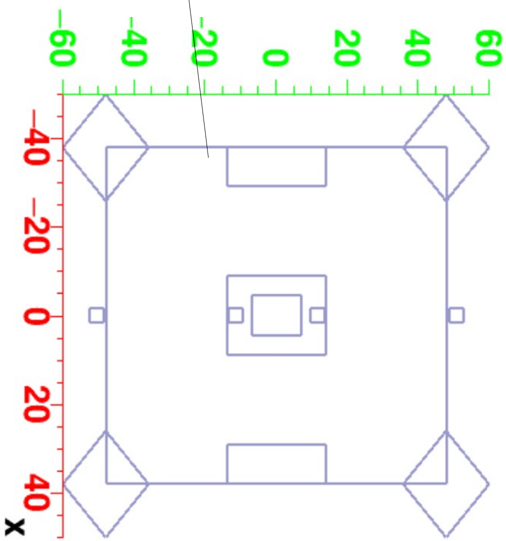
Scraper

Muon beam doesn't fit to all beamline element acceptance



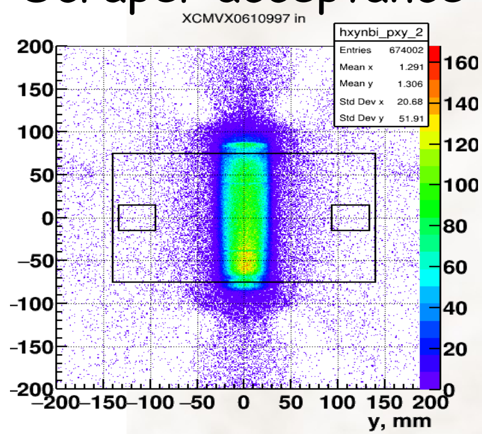
L=5m

scrapers operates in Air



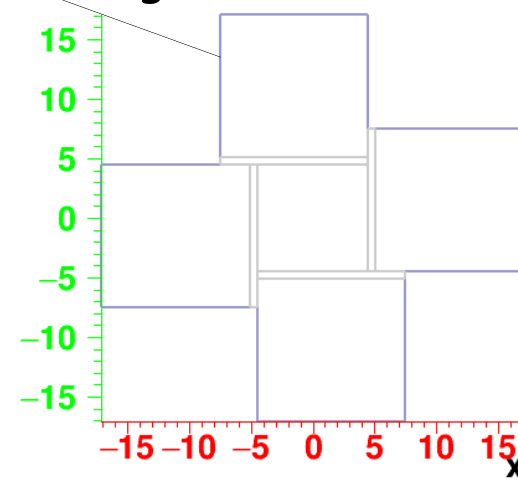
Prev GDML model was with iron vacuum tube

Scraper acceptance



Build from iron, tungsten bricks

L=1m



First GDML version was for the electron beam configuration (much narrower inner acceptance of Iron bricks) 2nd version with iron vacuum tube in 1st Scrapper (now just Air)

Track filtration can be performed by reconstructed trajectory:

on Bend entrance/exit: 31.5-2.x14.-2 mm

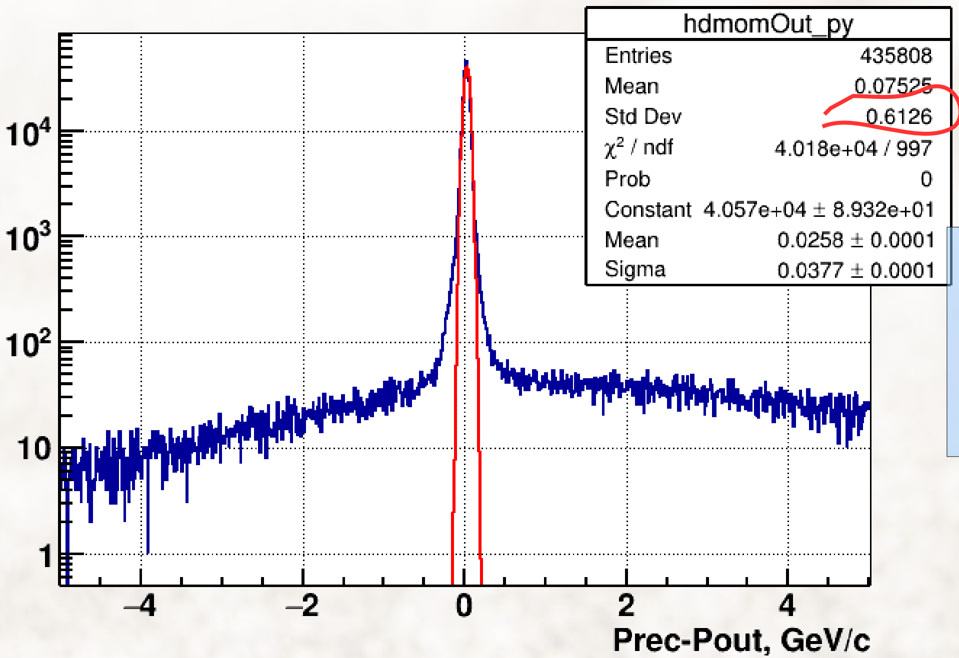
Quad4 out face: r=49mm, Scraper1 : 75x94. Mm

Can be performed more accurate on all elements

Momentum resolution tails

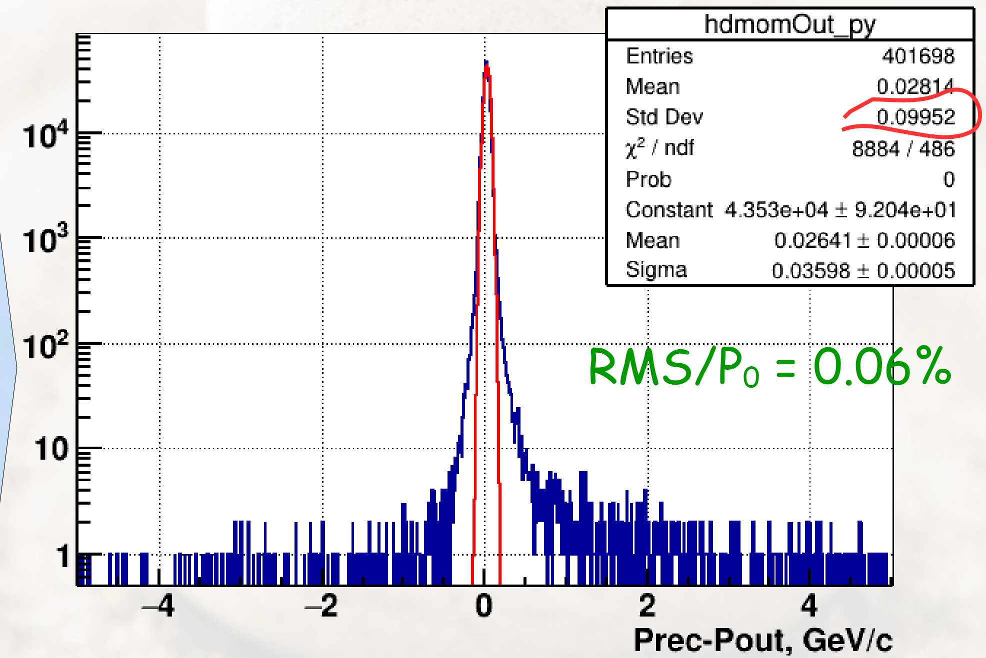
Track filtration can be performed by reconstructed trajectory:

10x10 cm vtx area at entrance to CEDAR
Crossing all 4 BMS
|P rec – 160 | < 15 GeV



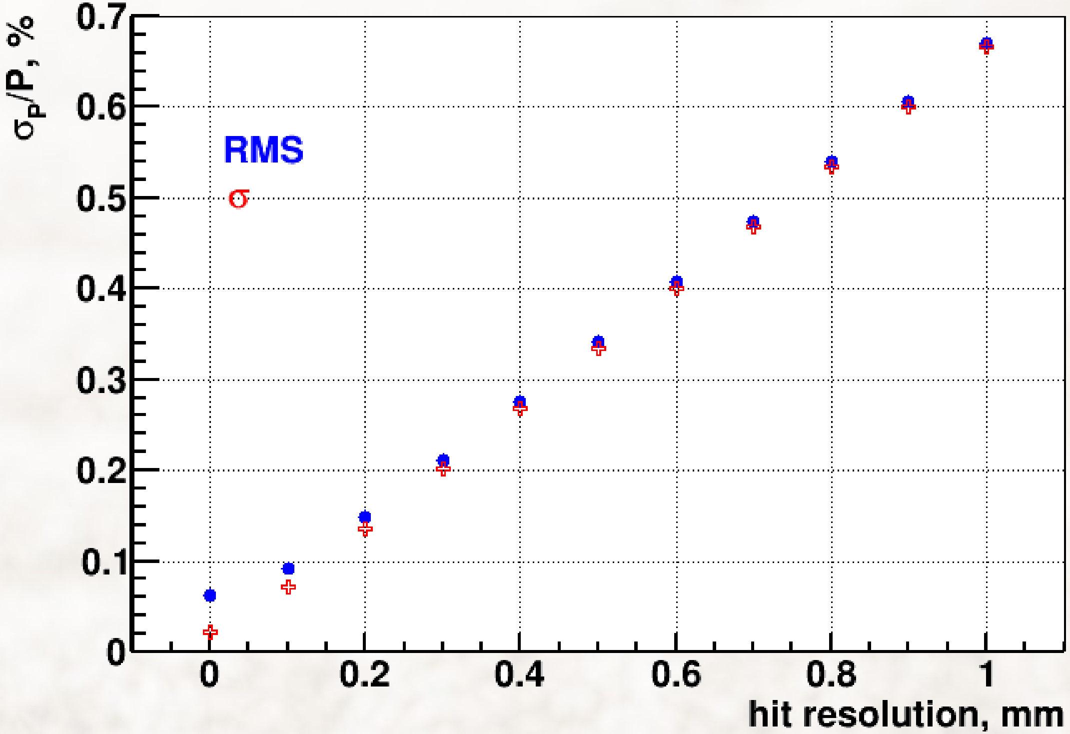
6.3% in |dP|>0.32 GeV/c

Additional cut with help of reconstructed trajectory by not crossing beamline elements (some of them)

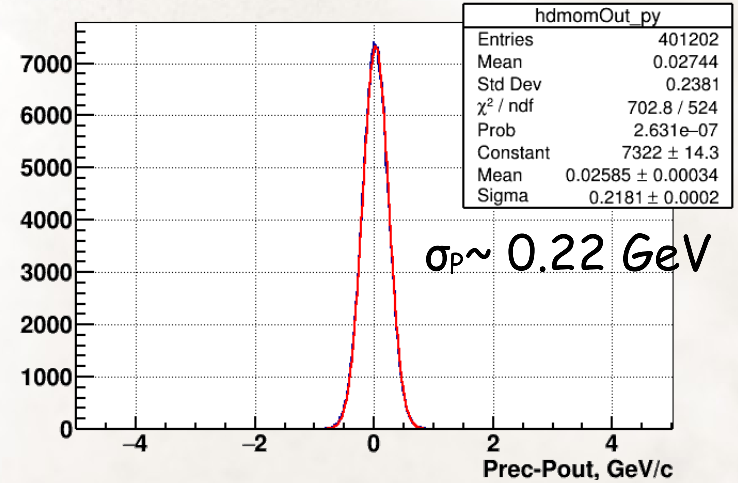


Selection efficiency
85.8% relative to left plot
still 0.3% in |dP|>0.32 GeV/c

Momentum resolution vs Hit resolution



Hit resolution 200 μm



$\sigma_P \sim 0.22$ GeV

Conclusion

- BMS potentially can provide momentum resolution ~ 0.1%
- BMS with event-by-event matching with MuonE scattering:
  - can increase MUonE sensitive by factor 2 (at cost of 1 additional station over 40)
  - works as active filter to clean-up contaminations and tails in used beam

Sensor requirements:

Few of them must be 20x10cm , most 10x10 cm

X-Y planes to reconstruct trajectory over not crossing beam elements

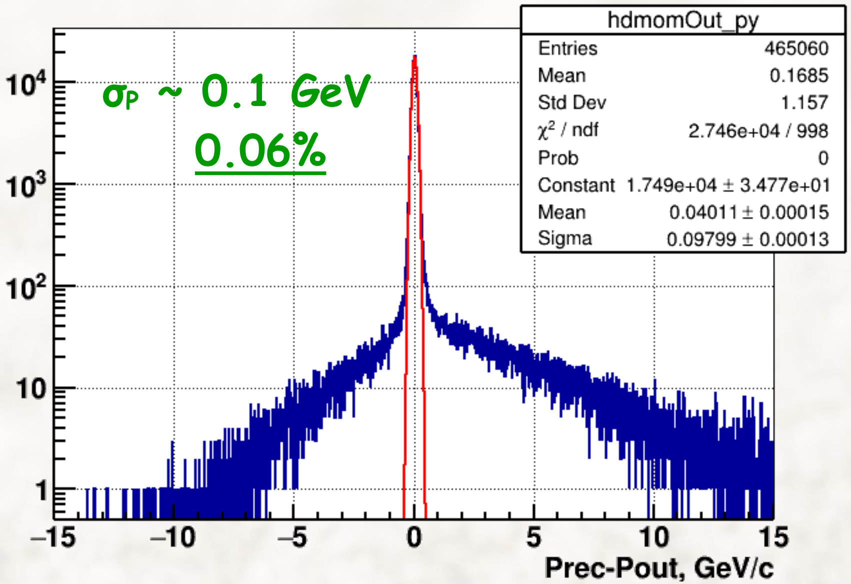
Timing to ease matching with main MUonE tracker

Redundancy (at least 2x3x2 layers) to have high efficiency

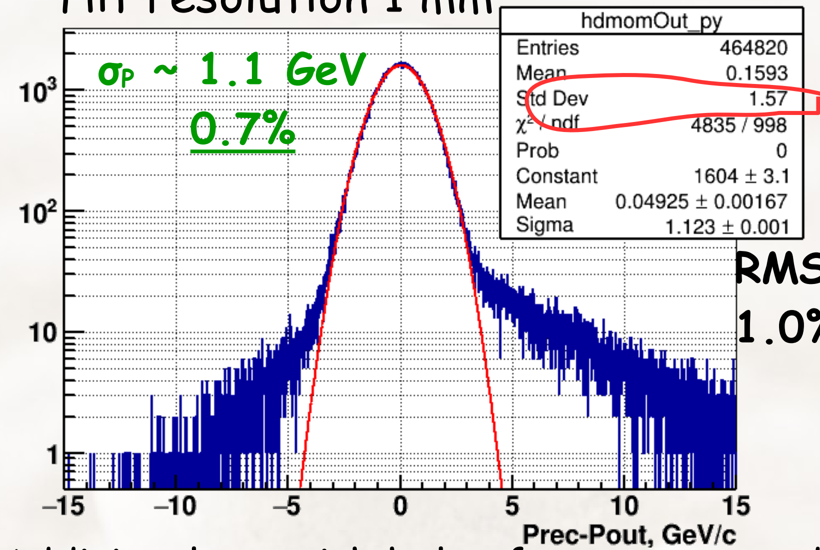
Momentum resolution with original Hodoscope

μ selected by passing 10x10 cm vtx area at entrance to CEDAR & |P rec – 160 | < 15 GeV

Effect of Scintillator material, hit resolution = 0

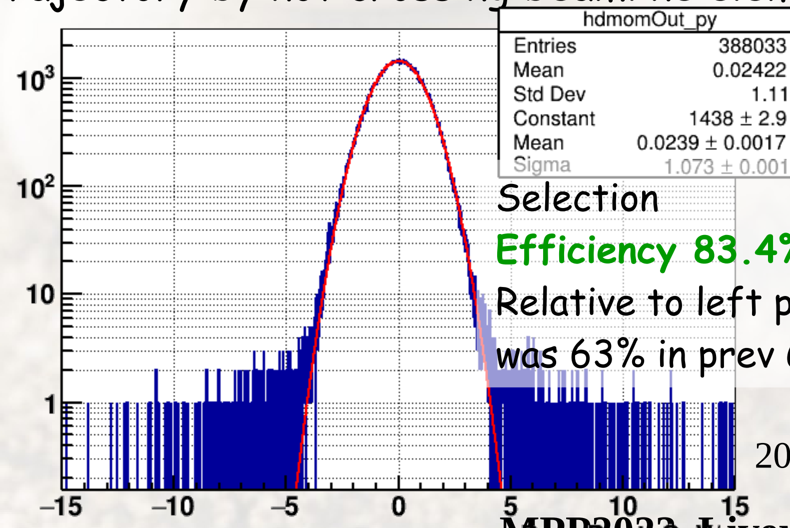


Hit resolution 1 mm



RMS/P_0
1.0%

Additional cut with help of reconstructed trajectory by not crossing beamline elements



Selection
Efficiency 83.4%
Relative to left plot
was 63% in prev GDML

Momentum resolution

Requirement for σ_P/P ~0.1%:

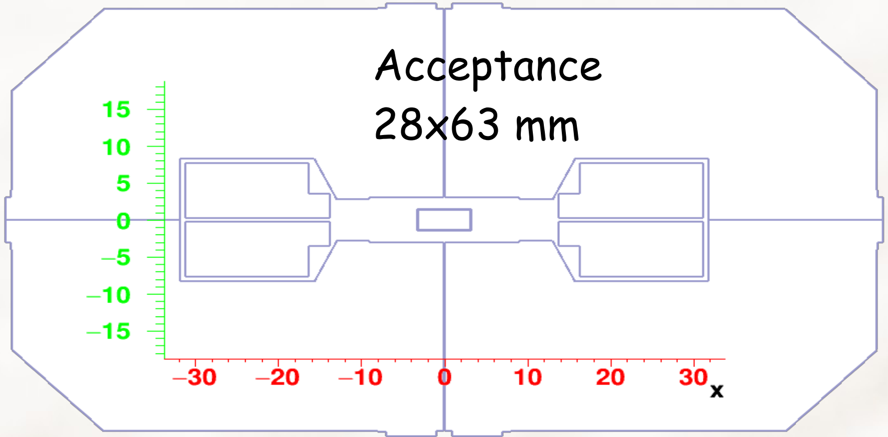
- ✗ Bend magnet knowledge ~0.1%
- ✗ Quadrupole magnet knowledge ~1%
- ✗ Angle resolution of in/out arm: 0.02mrad
  - → hit resolution (on 10 m arm) : 150 μm
- ✗ Impact point on Quadrupole magnet: ~200μm
- ✗ Alignment: < 150 μm

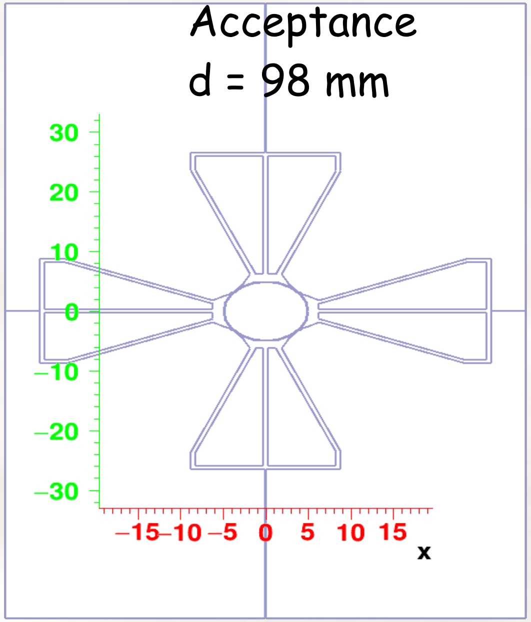
Questions:

- ✗ B field knowledge and stability
- ✗ Alignment
- ✗ Background events (when tracks crossed vacuum tube)
- ✗ Geometry optimization
- ✗ Timing layers

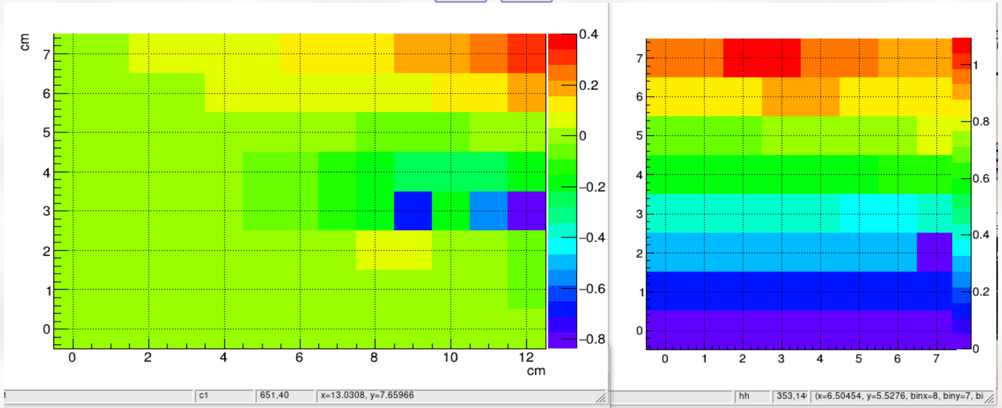
Field Maps

+rotated 90deg

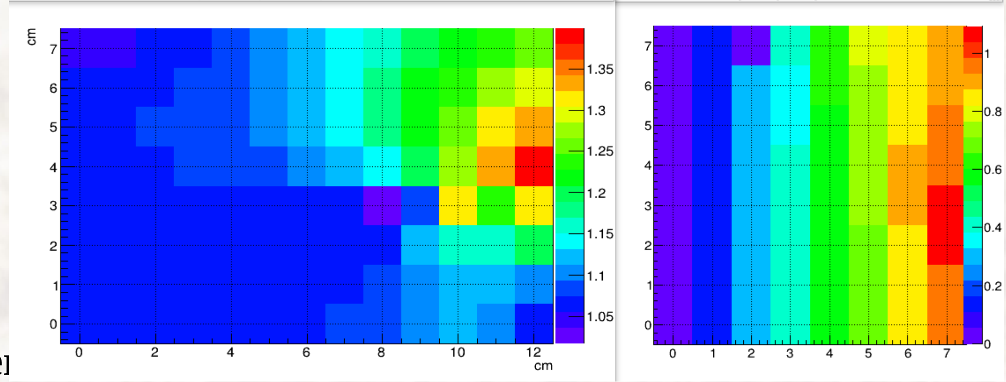




Bx

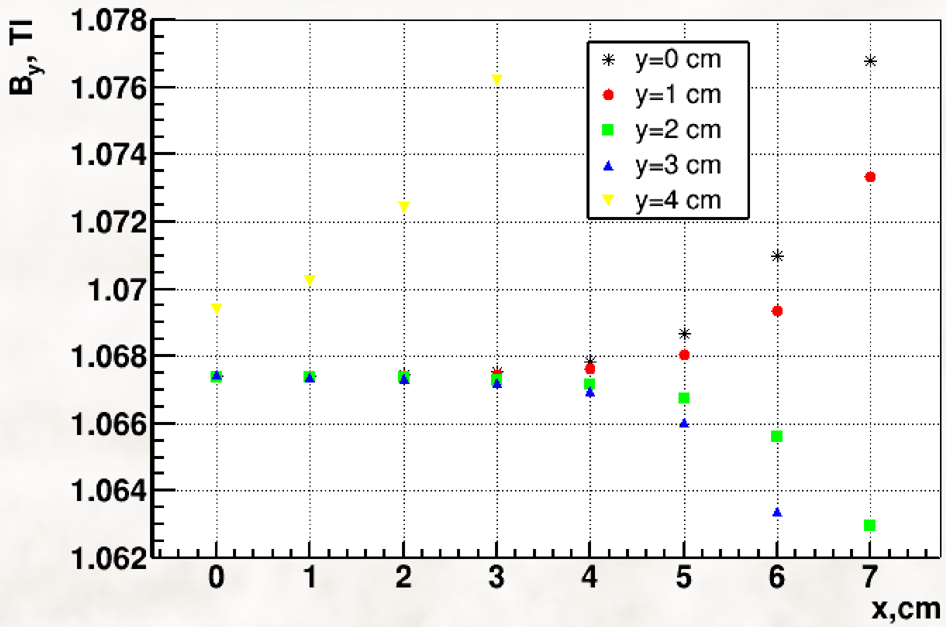


By

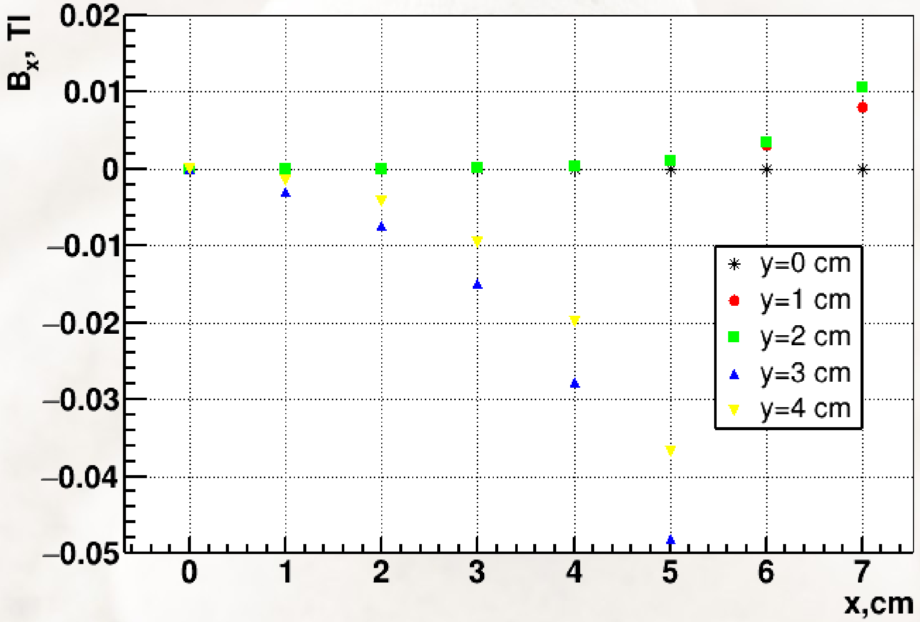


2D Field map is provided with 1x1 cm step
Symmetrical over origin
B_y is constant at ~0.02% Inside of 60x60mm

Bx By field



B_y, Tl
1.078
1.076
1.074
1.072
1.07
1.068
1.066
1.064
1.062
0 1 2 3 4 5 6 7
x,cm
y=0 cm
y=1 cm
y=2 cm
y=3 cm
y=4 cm



B_x, Tl
0.02
0.01
0
−0.01
−0.02
−0.03
−0.04
−0.05
0 1 2 3 4 5 6 7
x,cm
y=0 cm
y=1 cm
y=2 cm
y=3 cm
y=4 cm

BMS hodoscope

The COMPASS experiment at CERN, 2007
https://inspirehep.net/literature/747655

Station	# of dets.	Planes per det.	# of ch. per det.	Active area $X \times Y$ (cm^2)	Resolution
			Beam detectors		
BM01-04	4	Y	64	$6-12 \times 9-23$	$\sigma_s = 1.3-2.5\,\text{mm}$, $\sigma_t = 0.3\,\text{ns}$
BM05	2	Y	64	12×16	$\sigma_s = 0.7\,\text{mm}$, $\sigma_t = 0.5\,\text{ns}$
BM06	2	Y	128	12×16	$\sigma_s = 0.4\,\text{mm}$, $\sigma_t = 0.5\,\text{ns}$

Bending Magnet:

1.067Tl *5m *3 =16.0 Tl*m

Or deflection power $\Delta\varphi = (B*L)*0.29979/P \rightarrow 0.03$ rad for P=160 GeV

4 Quadrupole magnets (L=2.95m): $B=(B_0*y, B_0*x)$,

"Parallel" optic: B_0 = 0.1397, -0.1128, -0.2067, 0.1462 Tl/cm

"short" optic: B_0 = 0.1397, -0.1128, -0.2127, 0.1761 Tl/cm

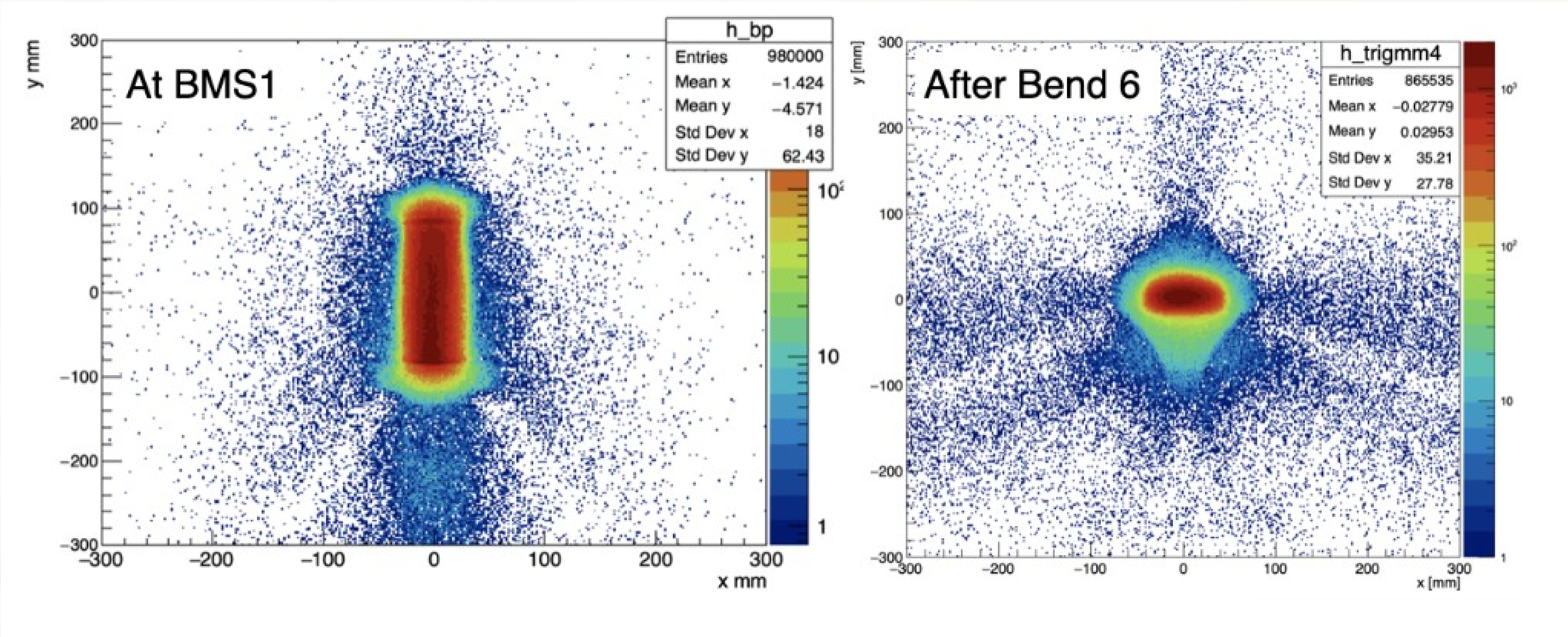
$\Delta\varphi/r \sim 1\text{x}10^{-4}$ rad/mm

$0.5\ X/X0 \rightarrow \Theta_{MS} \sim 3.5\text{x}10^{-5}$ rad ,

1 arm (13m) Hodoscope detector Θ resolution ~ $2\text{x}10^{-4}$ rad

$\sigma_P/P = \sqrt{2}*2\text{x}10^{-4}$ rad / 0.03 rad ~ 1%

Beam profile at BMS

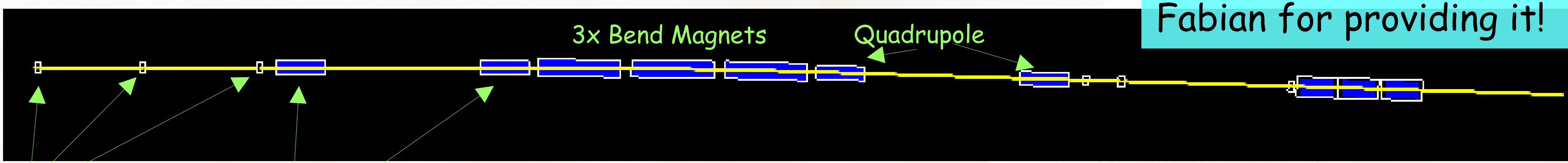


NA64 Status Report 2022
https://cds.cern.ch/record/2811174/files/SPSC-SR-316.pdf

Transported Muon

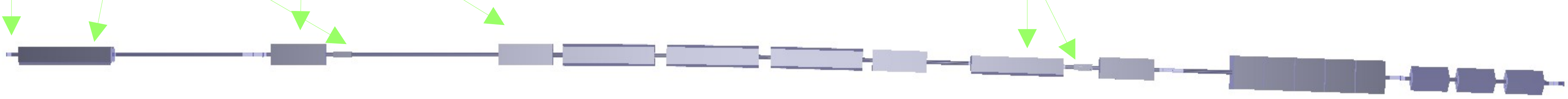
First simplified geometry with muon track

Thanks to Dipanwita and Fabian for providing it!



More detail GDML model

75m from BMS1 to BMS4



Material budget:

BMS01-04 ~ 20 mm of Scintillator -> ~0.06 X0 per station (x4)
BMS05-06 ~ 16 mm → ~0.05 per station (x2)

4 Air gaps 0.46 + 1.44 + 1.45 + 0.84 = 4.3m = 0.014 X0
2x Scraper (with QP Field) in Air : 10. m = 0.036 X0
Mylar window 8*0.02 cm = 0.019 X0

Σ = 0.4X0

X/X0 of Si detector will be negligible:
Can be compared as
150μm Si → 0.0016 X0
or 0.45m of Air

Half of total X/X0 → Θ_{MS} ~ **3.5×10^{-5} rad** ,
1 arm (13m) Hodoscope detector Θ resolution ~ **2×10^{-4} rad**,
σ_P/P < 0.1% require ~ **3×10^{-5} rad**

Simulation

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- ✗ Beam profile: MuOnE_Muon_Beam_160GeV.root
- ✗ Scintillator material of Hodoscope replaced by Air
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Provided by Fabian Metzger from accelerator group

N.B. When tracking precision is crucial and large volumes are used, the default geant4 configuration of the track propagator in field should be tuned. The tracking can be checked by doing trajectory reconstruction with switched off materials, etc effects in simulation.

Runge Kutta propagator doesn't like a non-continuous field behaviour → some small residual bias effect will be seen on the momentum resolution plots.