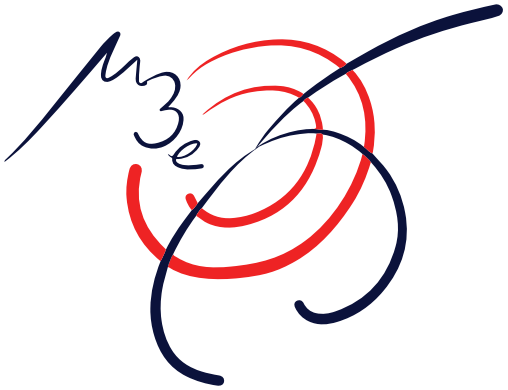
# Sensitivity Study for Mu3e Phase I



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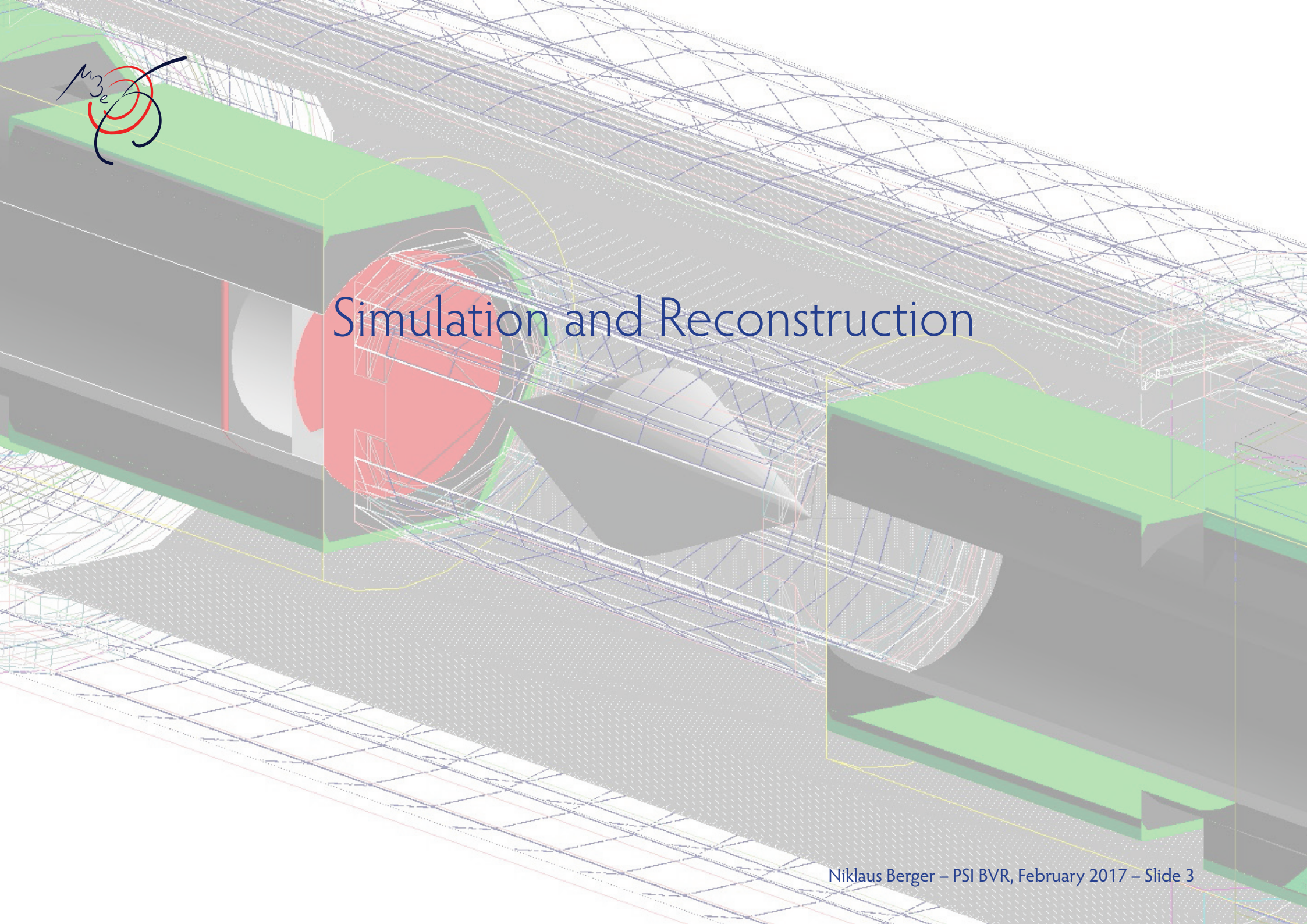
PSI BVR, February 2017

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

# Overview

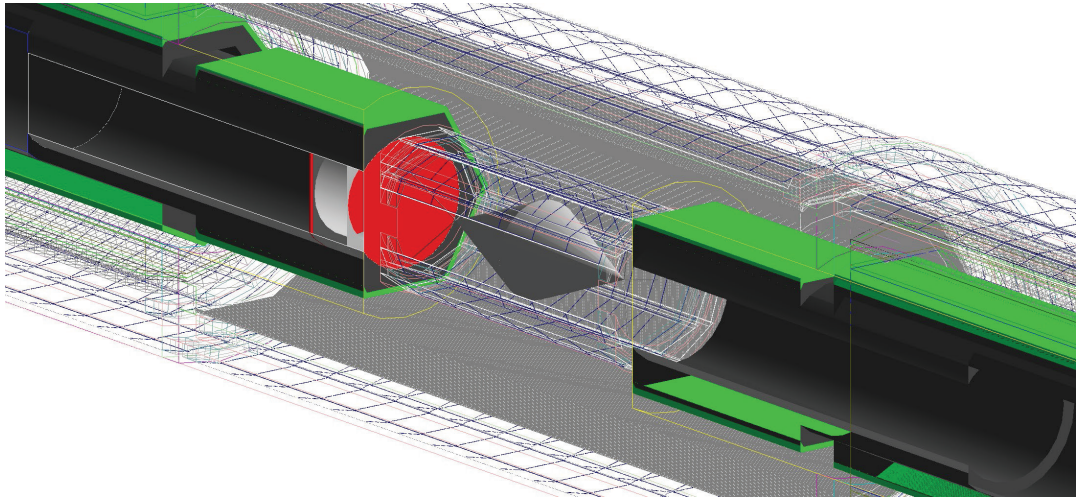
- Simulation and reconstruction
- Signal performance
- Background studies
- Expected sensitivity

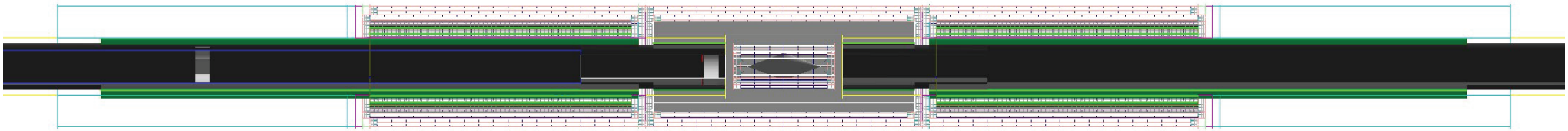


# Simulation and Reconstruction

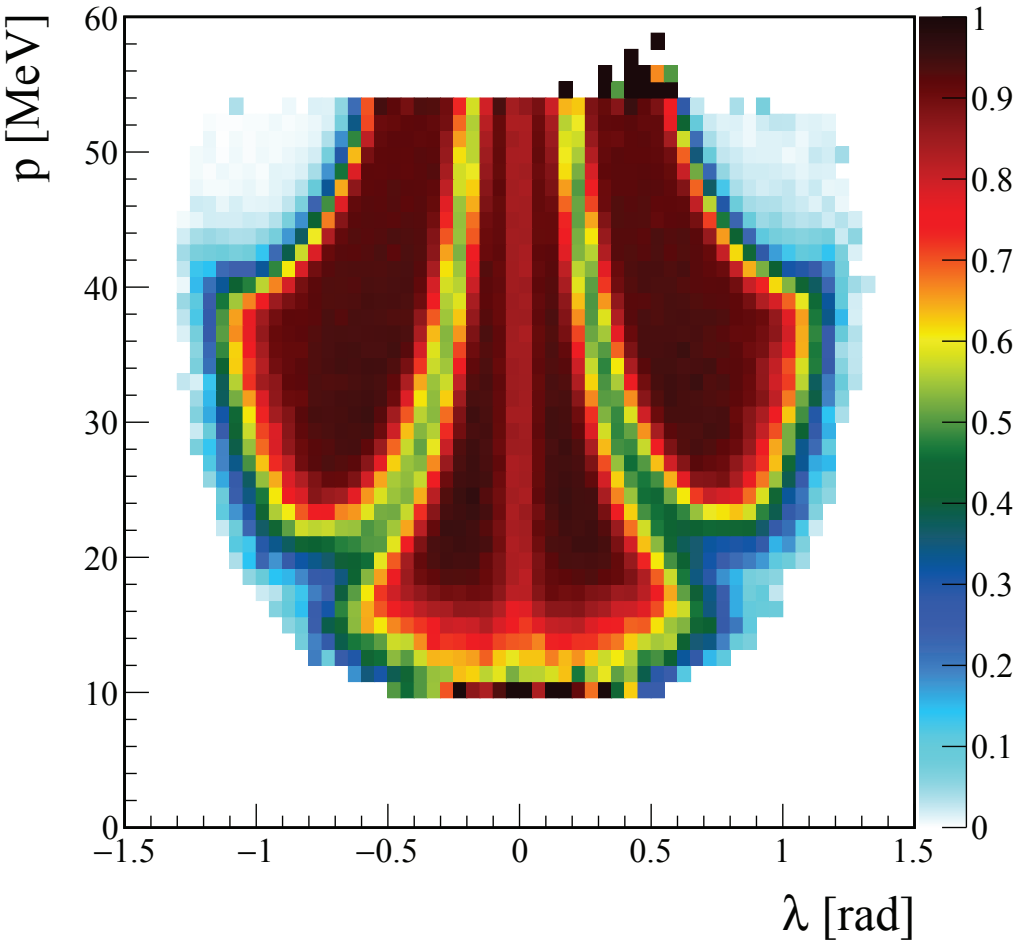
# Simulating the Phase I detector

- Full Geant4 simulation
- Best knowledge of geometry (parts of readout and cabling areas as plastic and metal blocks)
- Perfect efficiency of pixels, no misalignment, no pixel noise
- Assume $10^8$ muons/s stopped on target
- 50 ns reconstruction frames, better timing only from fibres and tiles
- Complete physics model, implementing NLO muon decays as they become available

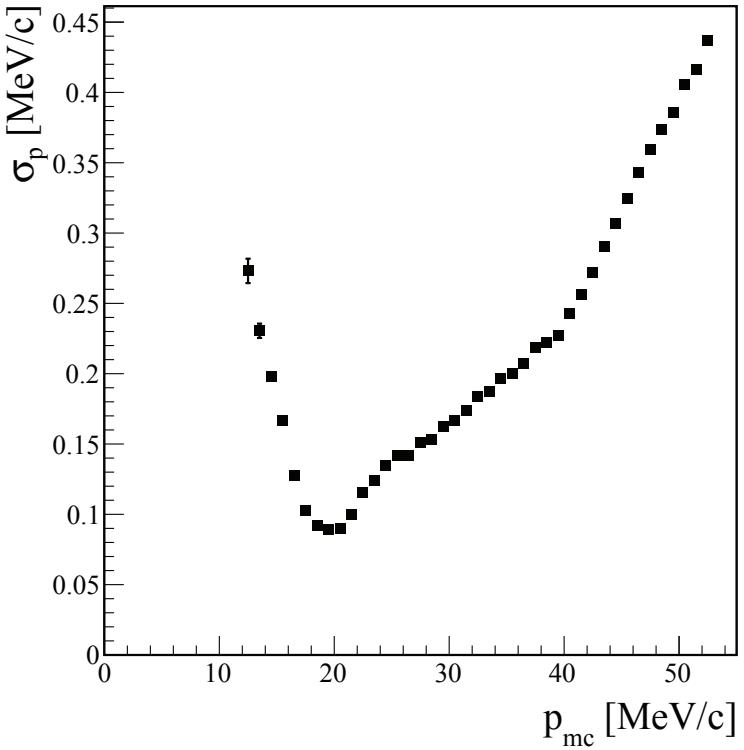




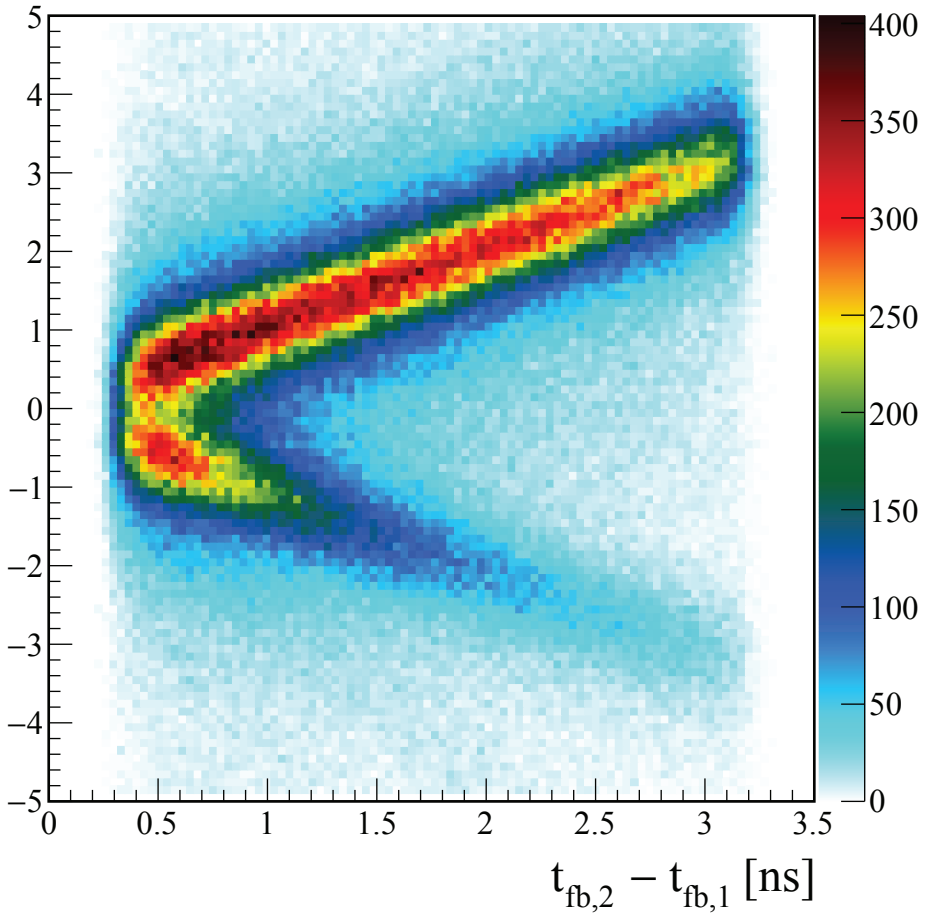
# Reconstruction




- Reconstruction program based on multiple scattering triplet fit (Nucl. Instrum. Meth. A844C, 135 (2017))
- Includes corrections for energy loss
- Very high efficiency, excellent resolution

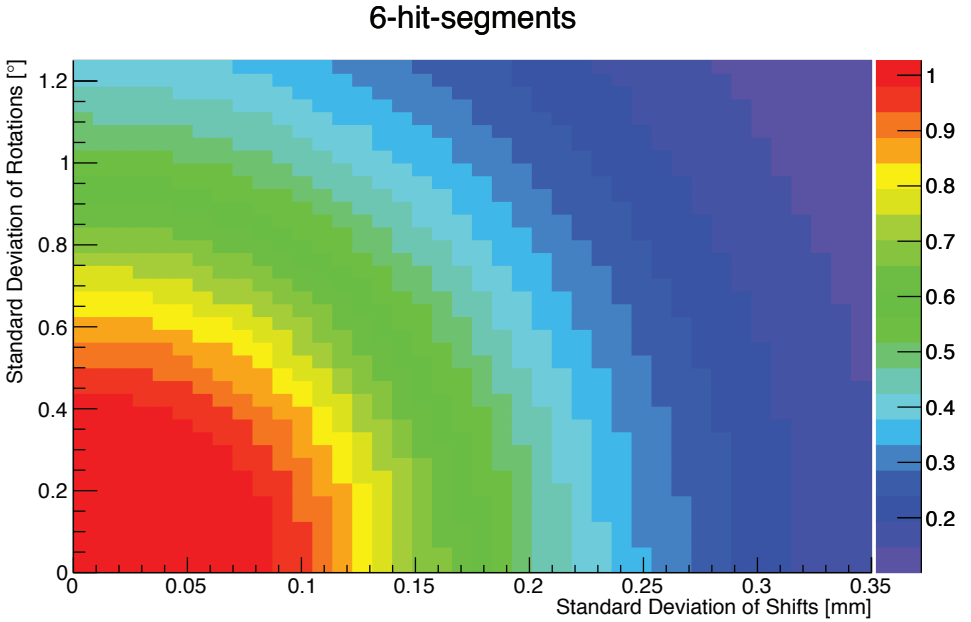


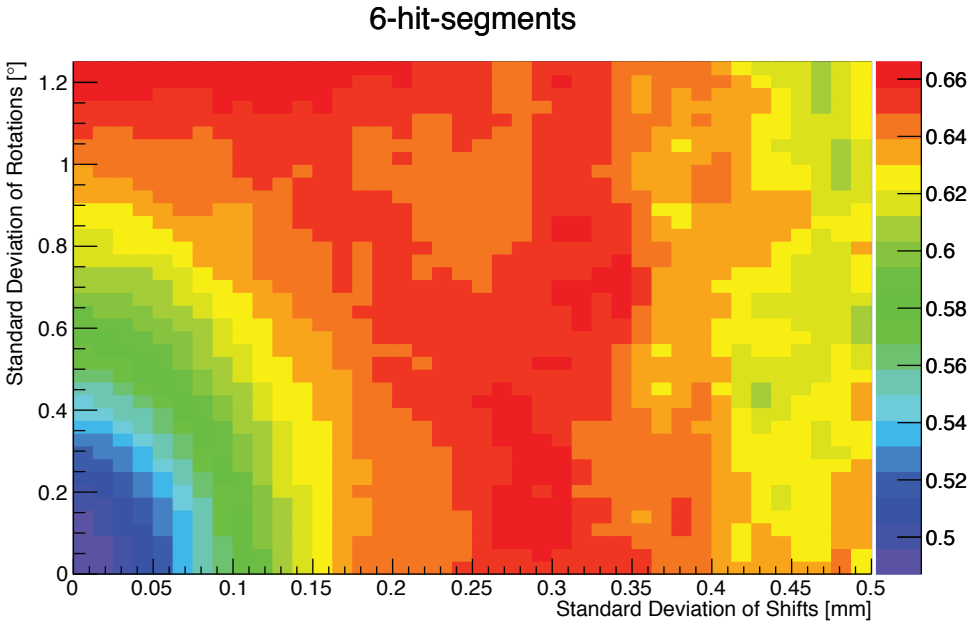
# Question: Charge assignment




- For tracks close to 90° to the beam, charge is ambiguous
- Fibre detector can resolve this
- At very low momenta, energy loss could be used (under study)

# Question: Detector alignment

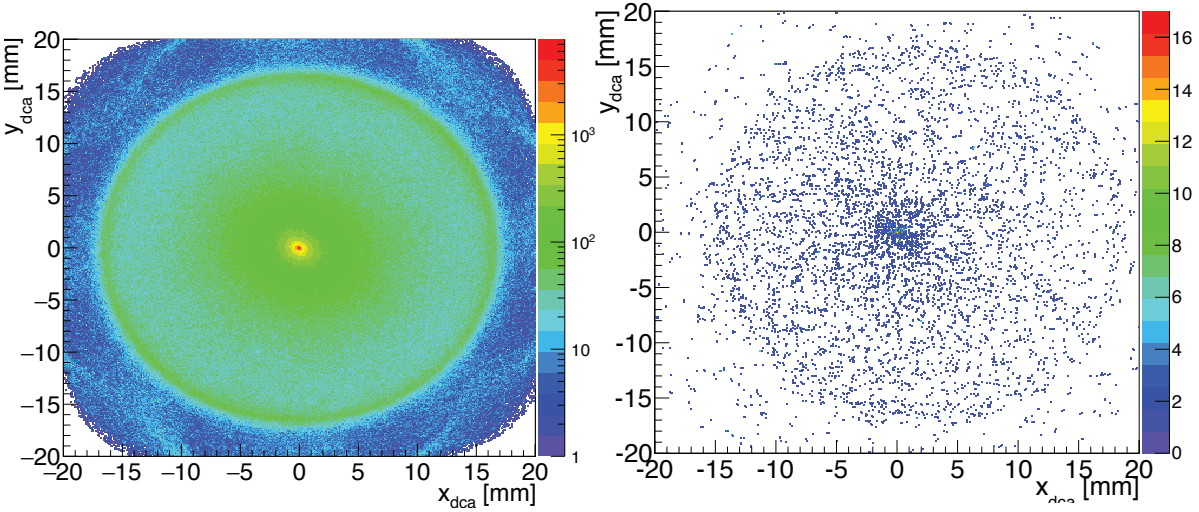


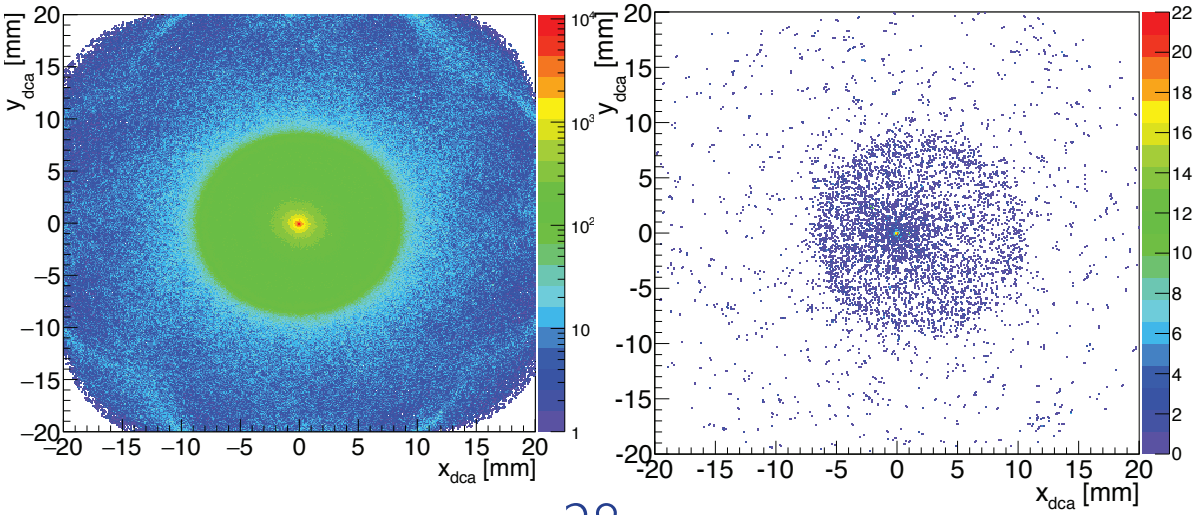




- Full detector alignment using general broken line fit and Millepede II (H1, CMS etc...) under construction (Ph.D. Uli Hartenstein, Mainz)
- Also taking into account sensor deformations
- Cosmics required for recurl station alignment - considering simple scintillator coincidence to keep respective frames

# Question: Target alignment

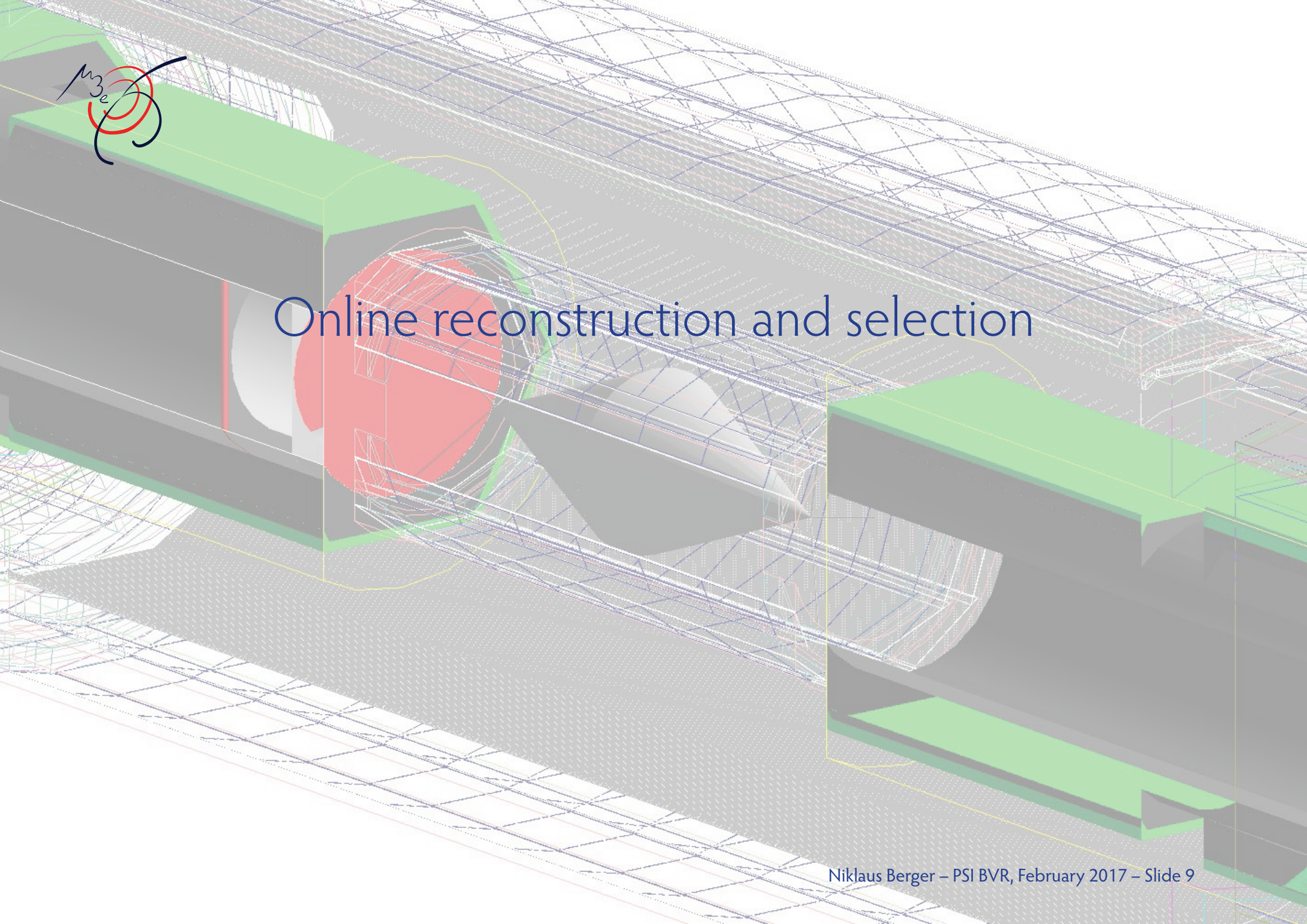
z = -6 mm




z = -28 mm

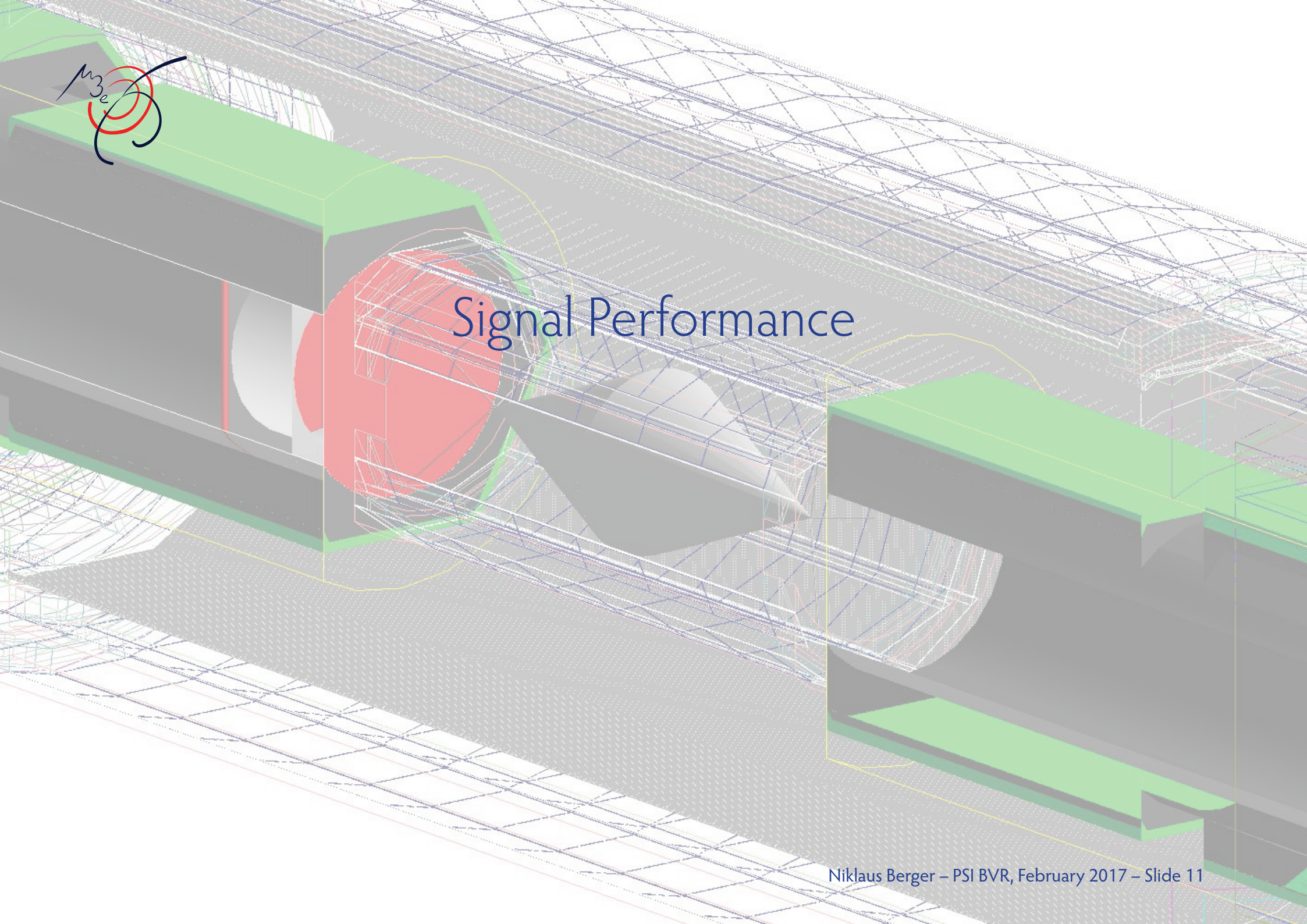
- Target position can be obtained from track dca (no vertexing)
- Vertex resolution 200-400 μm
- O(100K) tracks sufficient for alignment at that level
  1 KHz alignment at $10^8$μ/s:
  Shifts, rotations, non-circularity in 1 mm slices
- Resolution function can be obtained from central wire
- Current analysis does not use target position
- Cross-checks with Bhabha scattering and photon conversion at lower rates



# Online reconstruction and selection

# GPU selection running


- Reconstruct tracks in central detector (4 hits)
- Perform simplified vertex fit
- One GTX1080 processing $1.9 \cdot 10^6$ 50 ns reconstruction frames/s - 12 PCs for farm
- Data reduction by a factor 100 at 97.8% signal efficiency



# Signal Performance

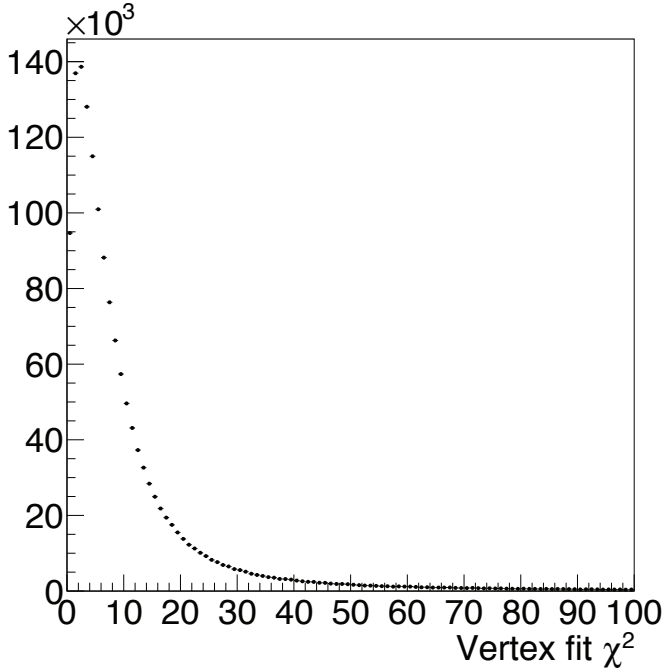
# Vertex fit and selection

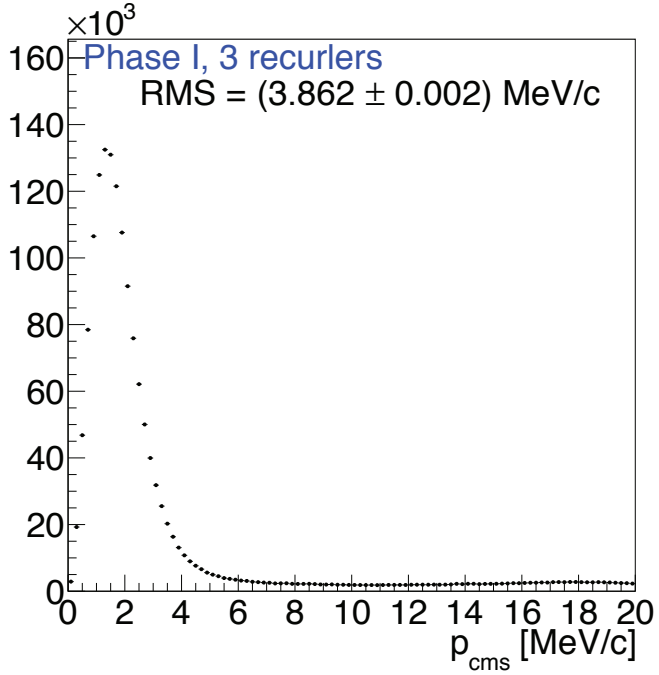
- Two positive, one negative track, all recurling (6 or more hits)
- Multiple scattering dominated 3D vertex fit
- Reconstruct 4-vector of 3 particle system

Simple, loose selection:

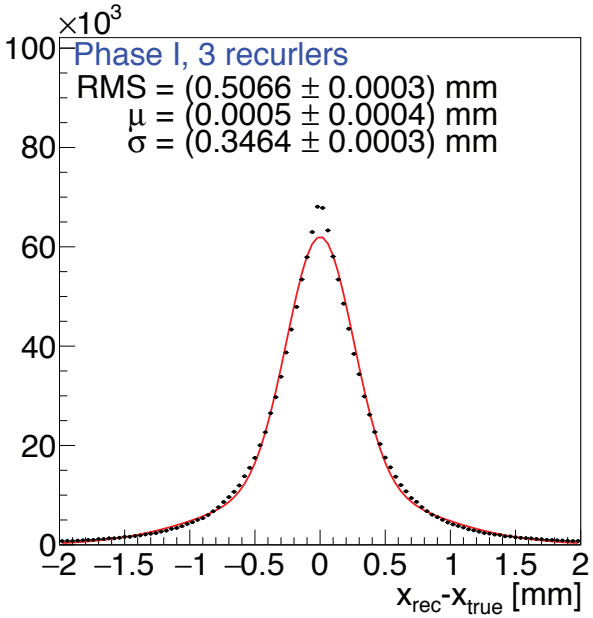
- $\chi^2$ of vertex fit < 30
- Momentum of 3 particle system < 8 MeV

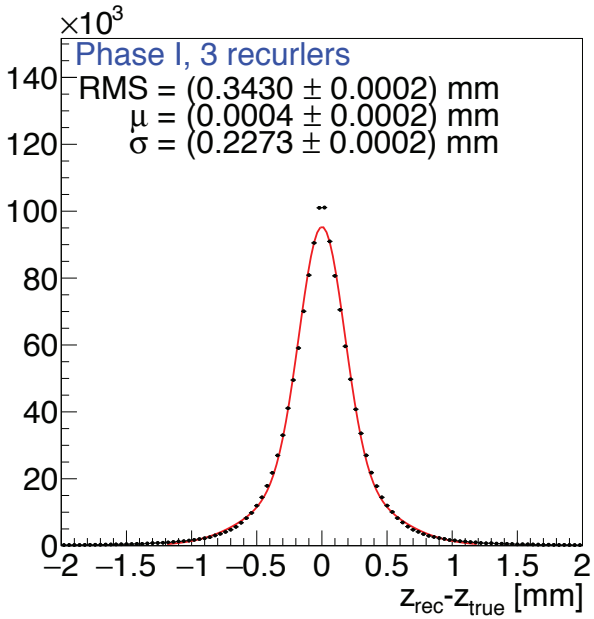
Both vertex fit and selection have improvement potential

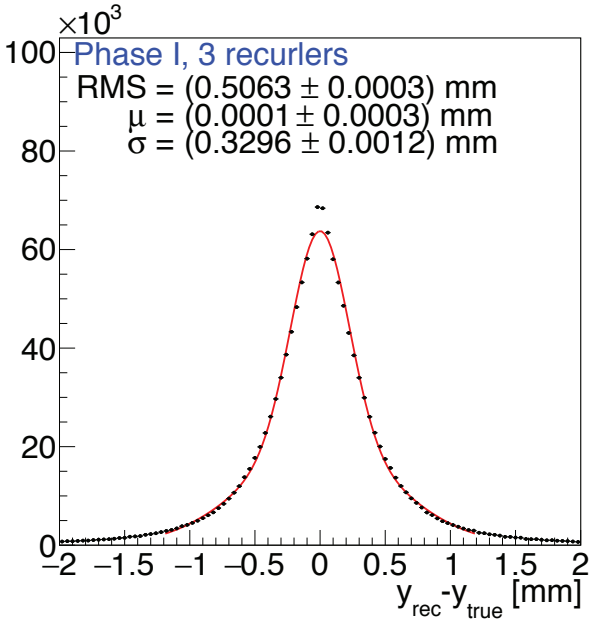


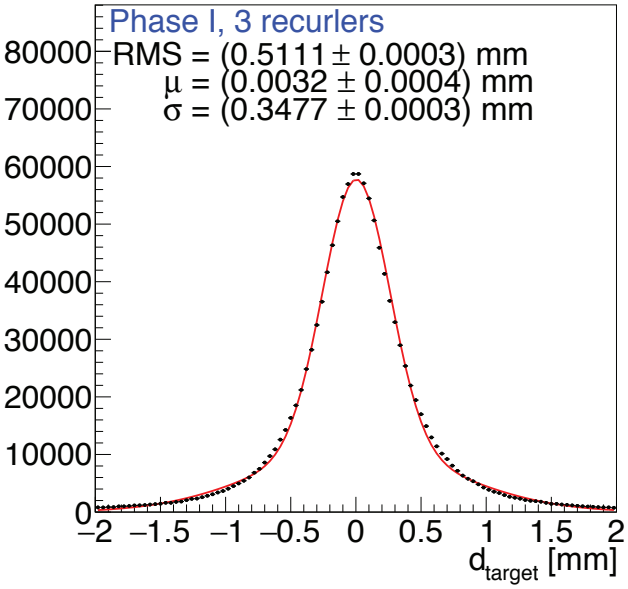



# Signal Performance: Vertexing

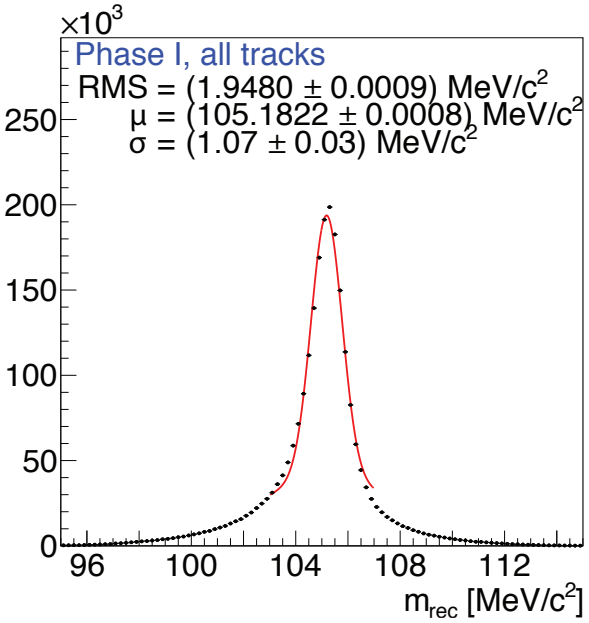


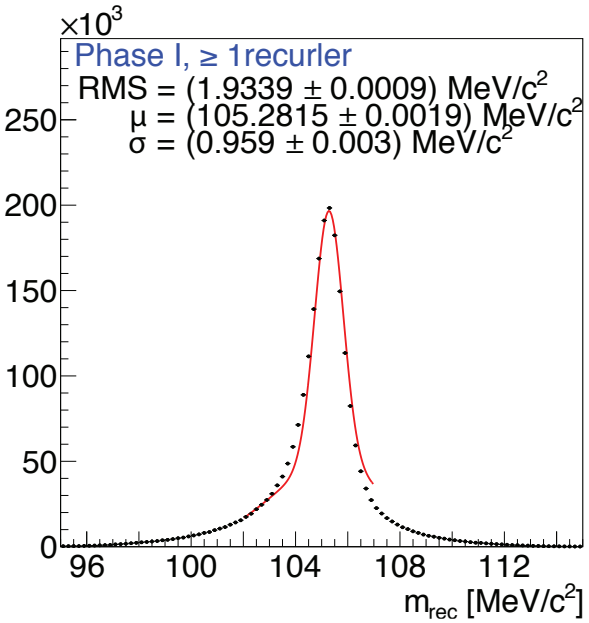



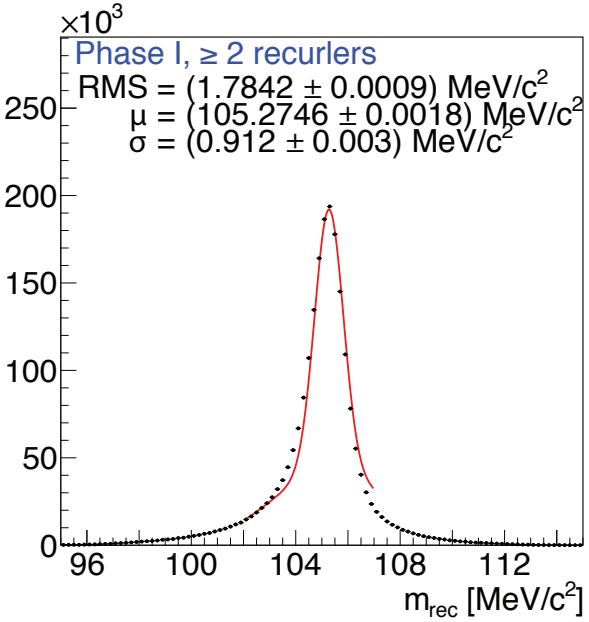



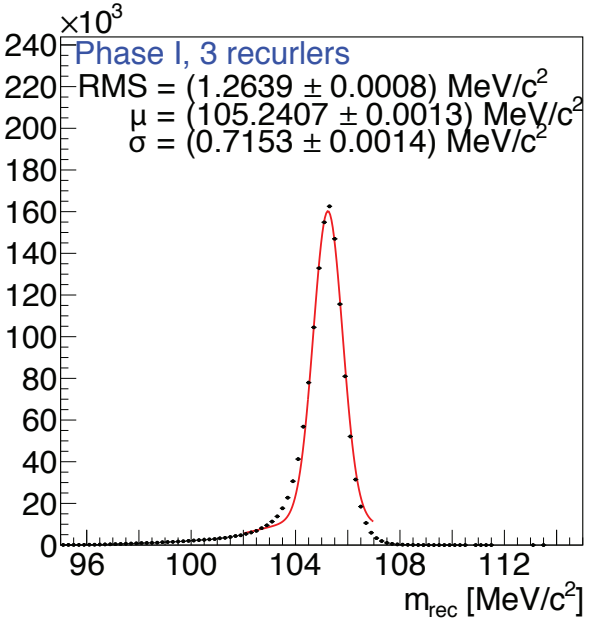



# Signal Performance: Muon Mass



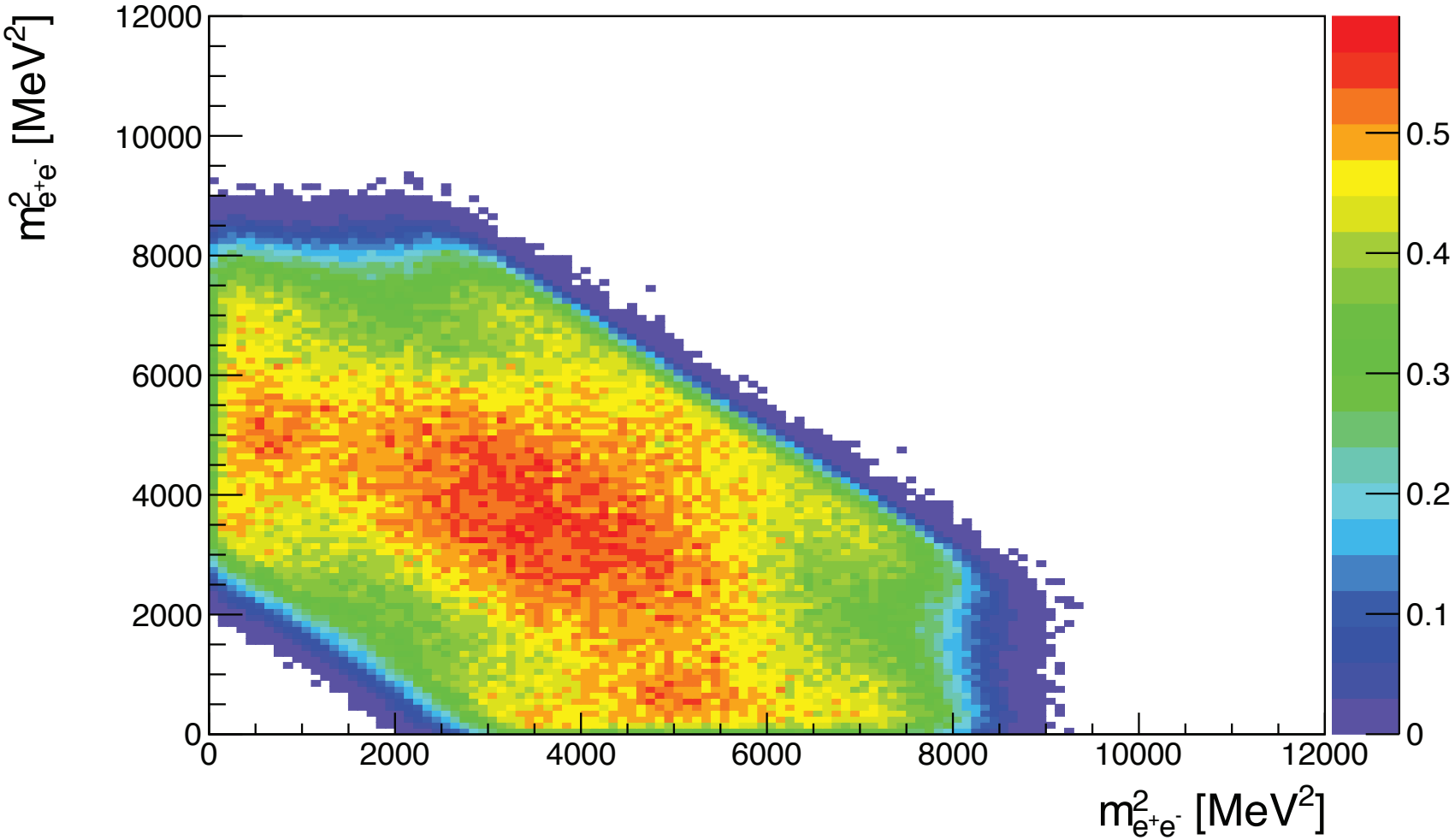



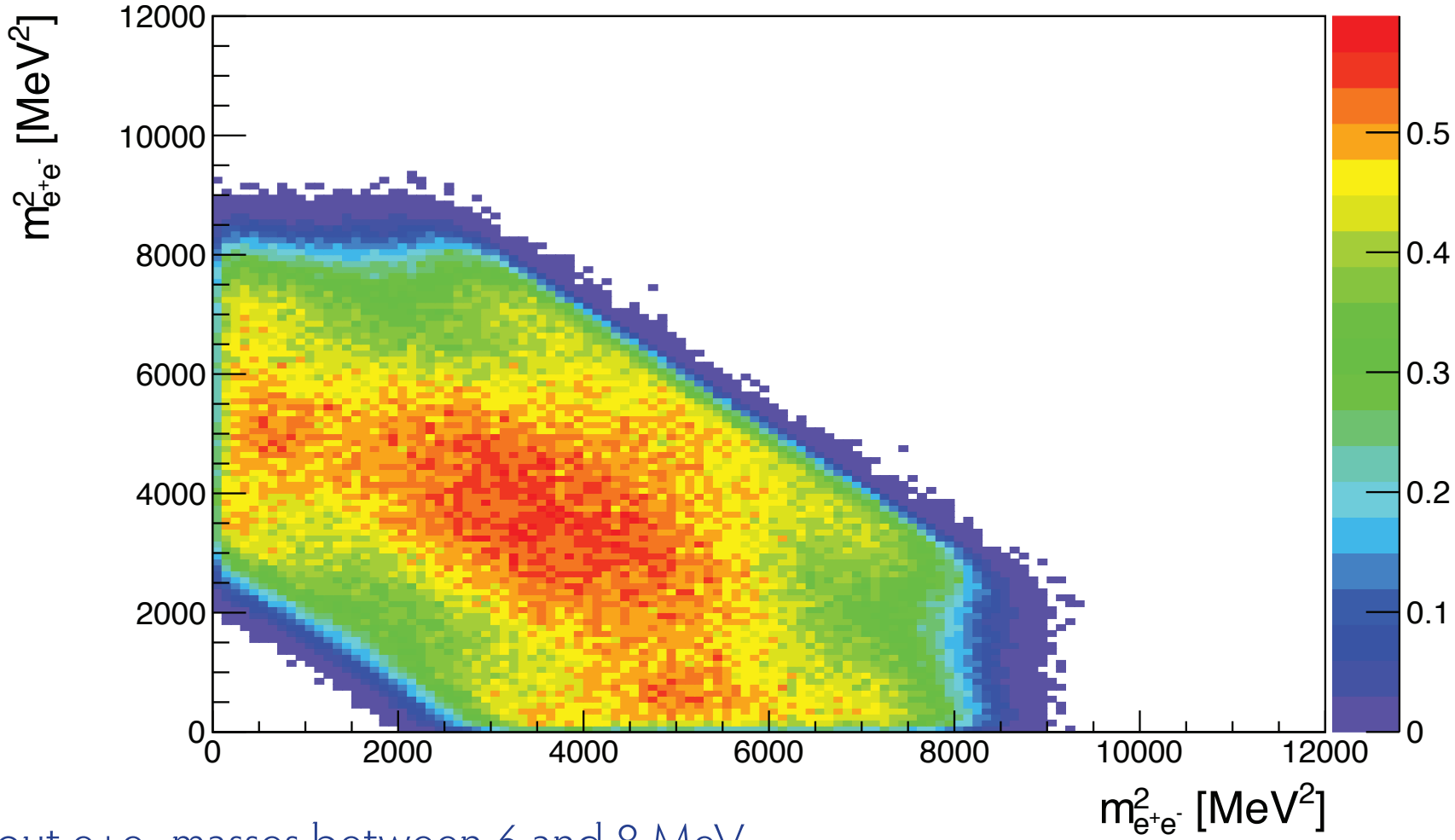
# Signal: Efficiency

| Step | Step efficiency | Total efficiency |
|---|---|---|
| Muon stops | 100% | 100% |
| Geometrical acceptance, short tracks | 42.3% | 42.3% |
| Geometrical acceptance, long tracks | 65.1% | 27.5% |
| Short track reconstruction | 98.9% | 41.9% |
| Long track reconstruction | 87.3% | 24.0% |
| Vertex fit | 99.8% | 24.0% |
| Vertex fit $\chi^2 < 30$ | 88.5% | 21.3% |
| CMS momentum $< 8\,\mathrm{MeV/c}$ | 88.9% | 18.9% |
| Timing | 98.0% | 18.4% |

# Efficiency Dalitz distribution (Question)



# Signal: Dalitz distribution with anti-Bhabha cut



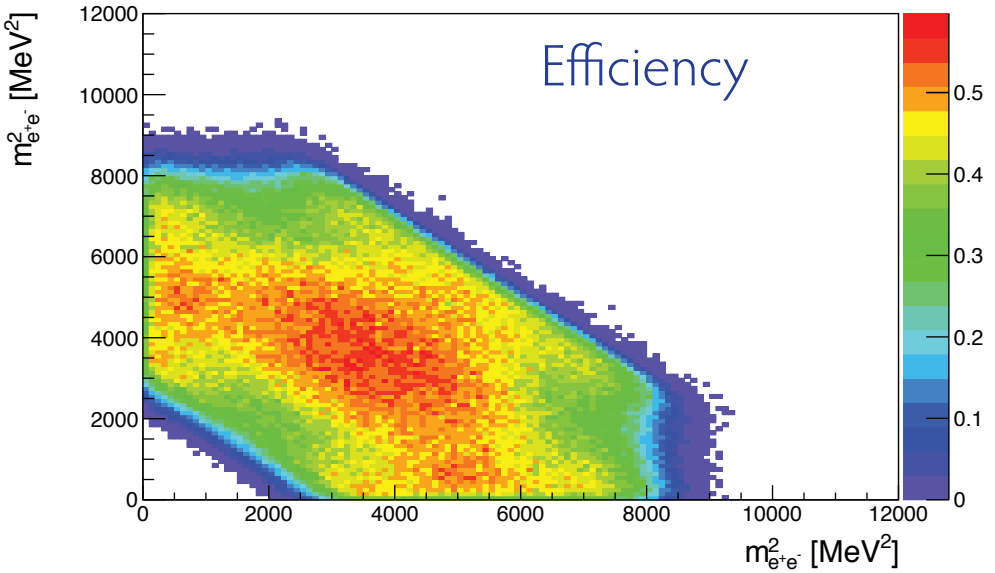

- Cut out e+e- masses between 6 and 8 MeV
- Loose 0.5% in efficiency

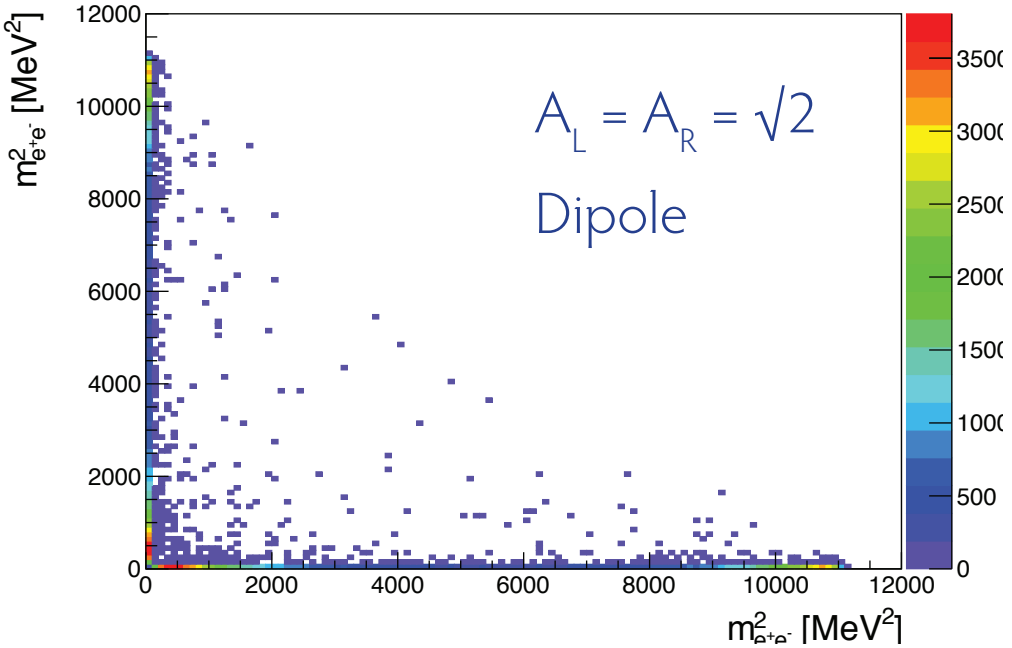
# Signal models

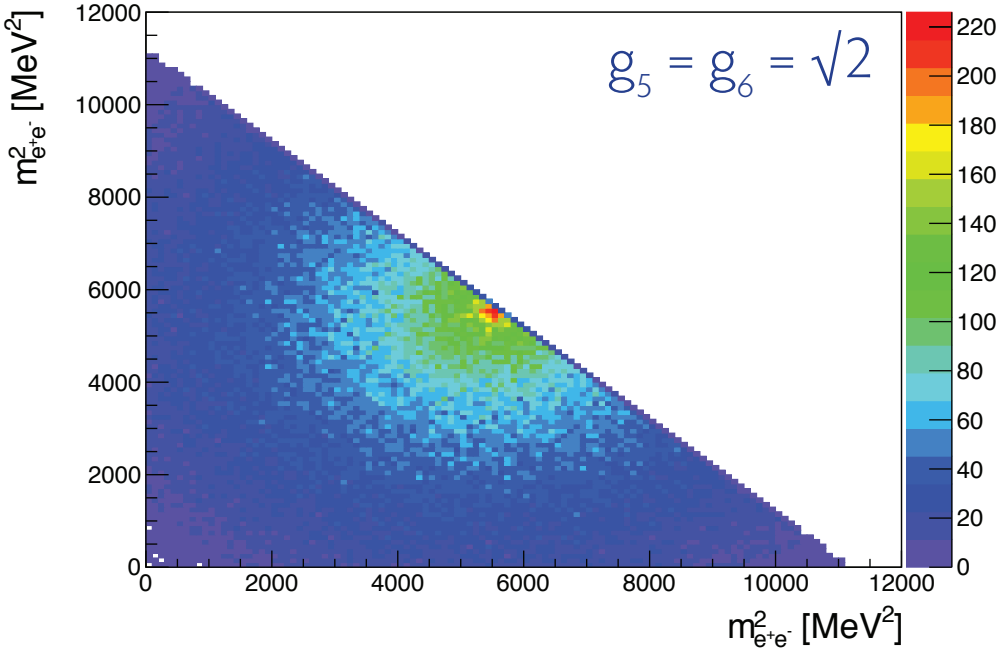
- Kuno-Okada Lagrangian
- Set pair of A or g to $\sqrt{2}$, others 0

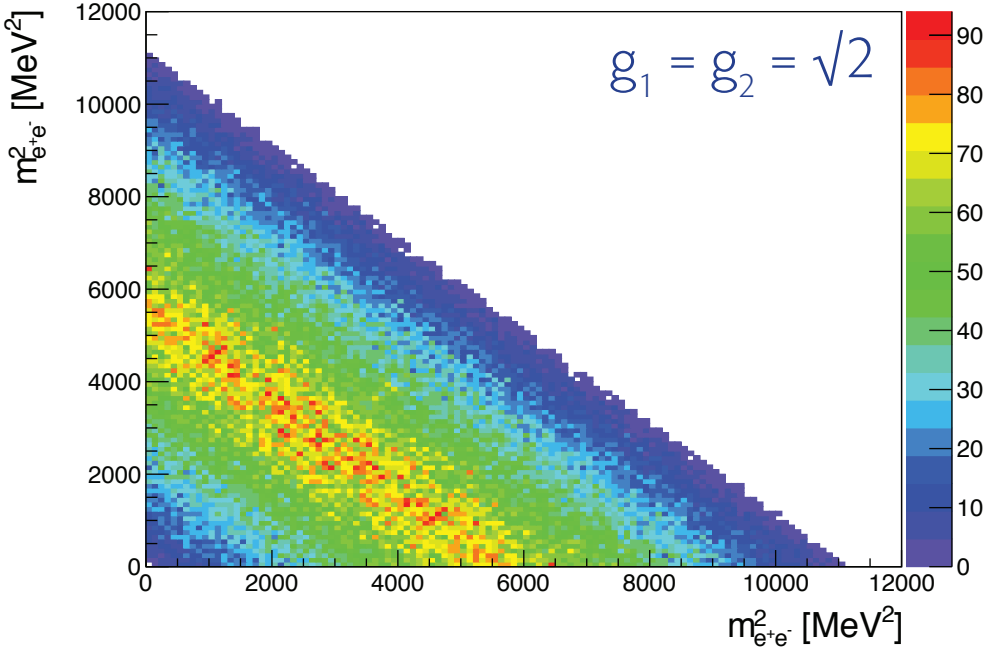
$$
\begin{aligned}
L_{\mu\to eee} \;=\; & -\frac{4G_F}{\sqrt{2}}\,[m_\mu A_R\,\overline{\mu_R}\sigma^{\mu\nu}e_L F_{\mu\nu} \\
& + m_\mu A_L\,\overline{\mu_L}\sigma^{\mu\nu}e_R F_{\mu\nu} \\
& + g_1\,(\overline{\mu_R}e_L)\,(\overline{e_R}e_L) \\
& + g_2\,(\overline{\mu_L}e_R)\,(\overline{e_L}e_R) \\
& + g_3\,(\overline{\mu_R}\gamma^\mu e_R)\,(\overline{e_R}\gamma_\mu e_R) \\
& + g_4\,(\overline{\mu_L}\gamma^\mu e_L)\,(\overline{e_L}\gamma_\mu e_L) \\
& + g_5\,(\overline{\mu_R}\gamma^\mu e_R)\,(\overline{e_L}\gamma_\mu e_L) \\
& + g_6\,(\overline{\mu_L}\gamma^\mu e_L)\,(\overline{e_R}\gamma_\mu e_R) \;+\; H.c.\,]
\end{aligned}
$$

# Models in the Dalitz plot

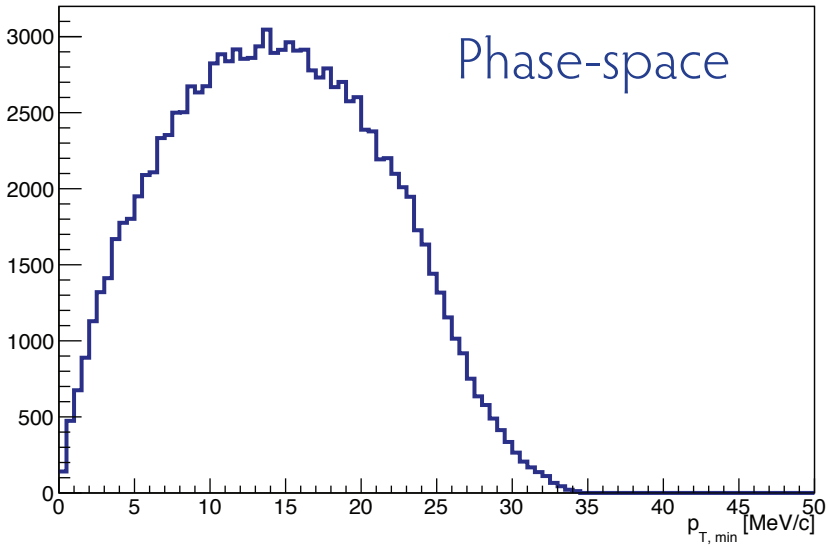


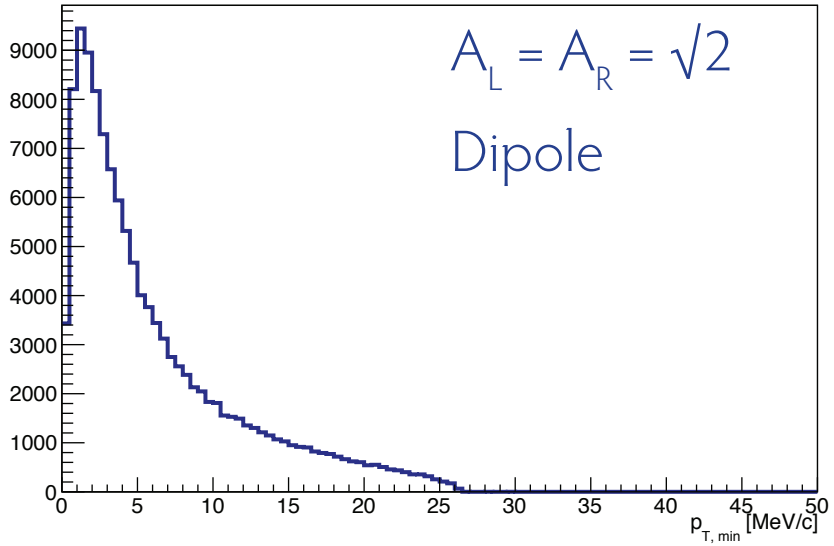



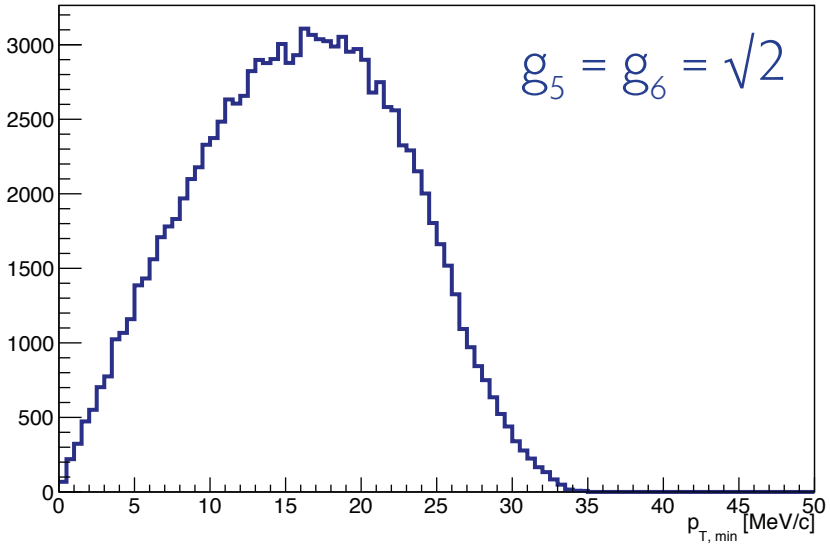



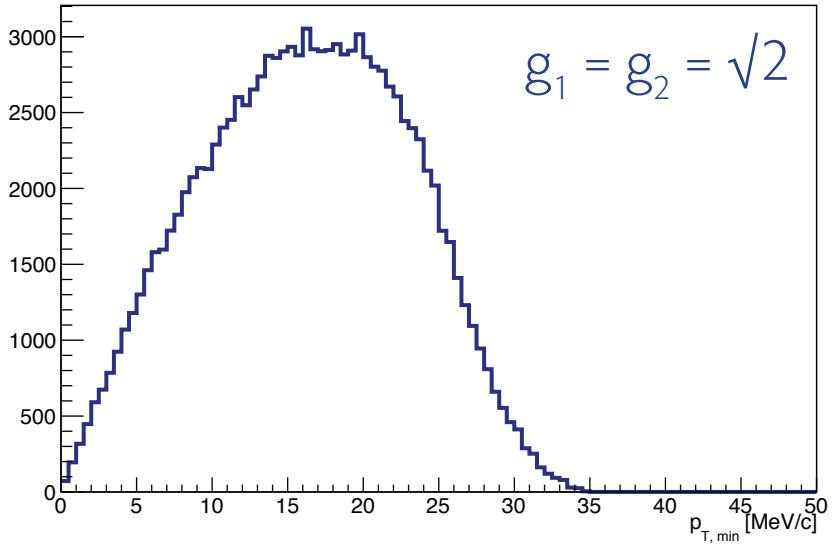



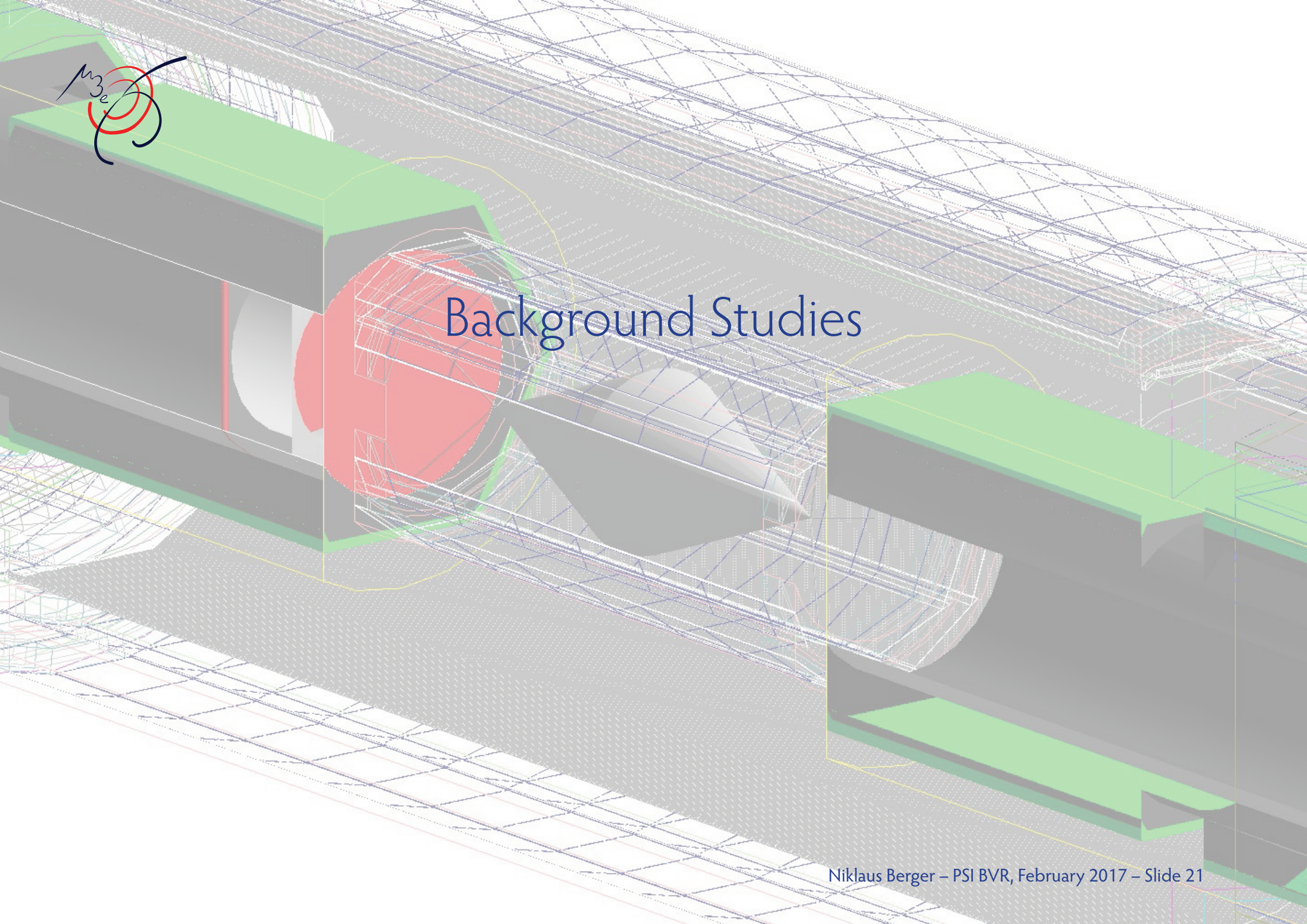
# Smallest transverse momentum



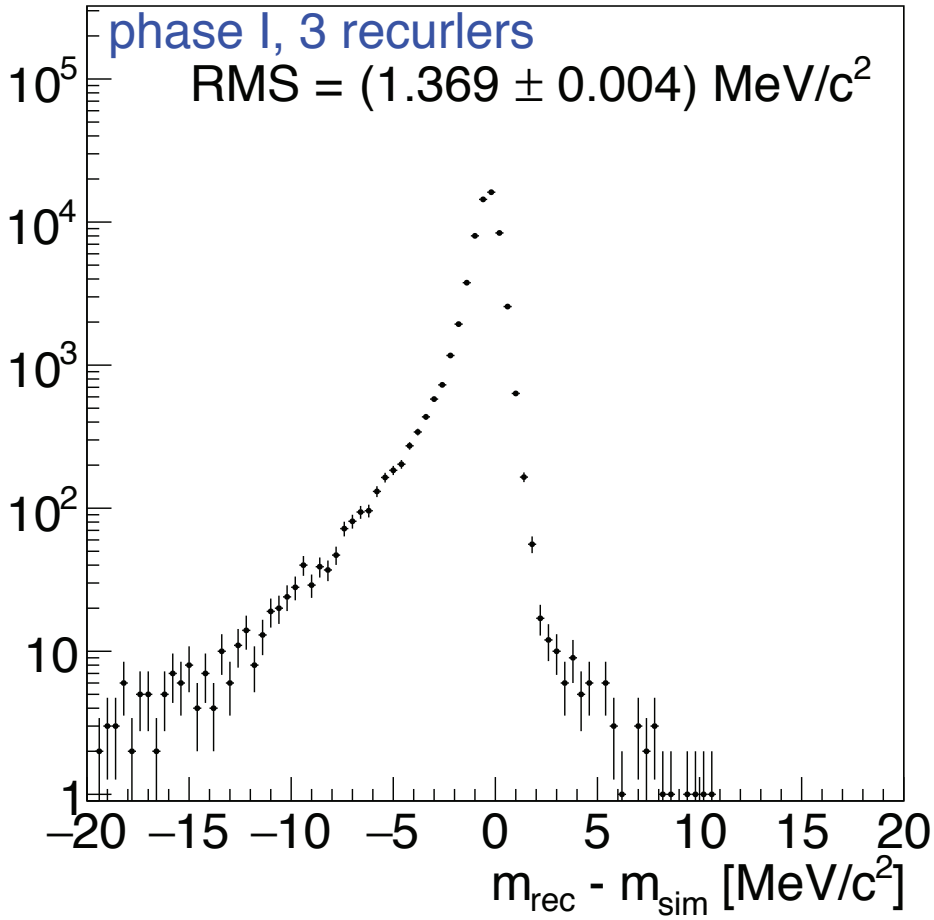





# Background Studies

# Background: Radiative decay with internal conversion

- $\mu \rightarrow e^+e^-e^+\bar{\nu}\nu$
- Good mass resolution, small tail on high side
- Simulation above visible mass of 90 MeV
- Small branching fraction allows for generous over-sampling

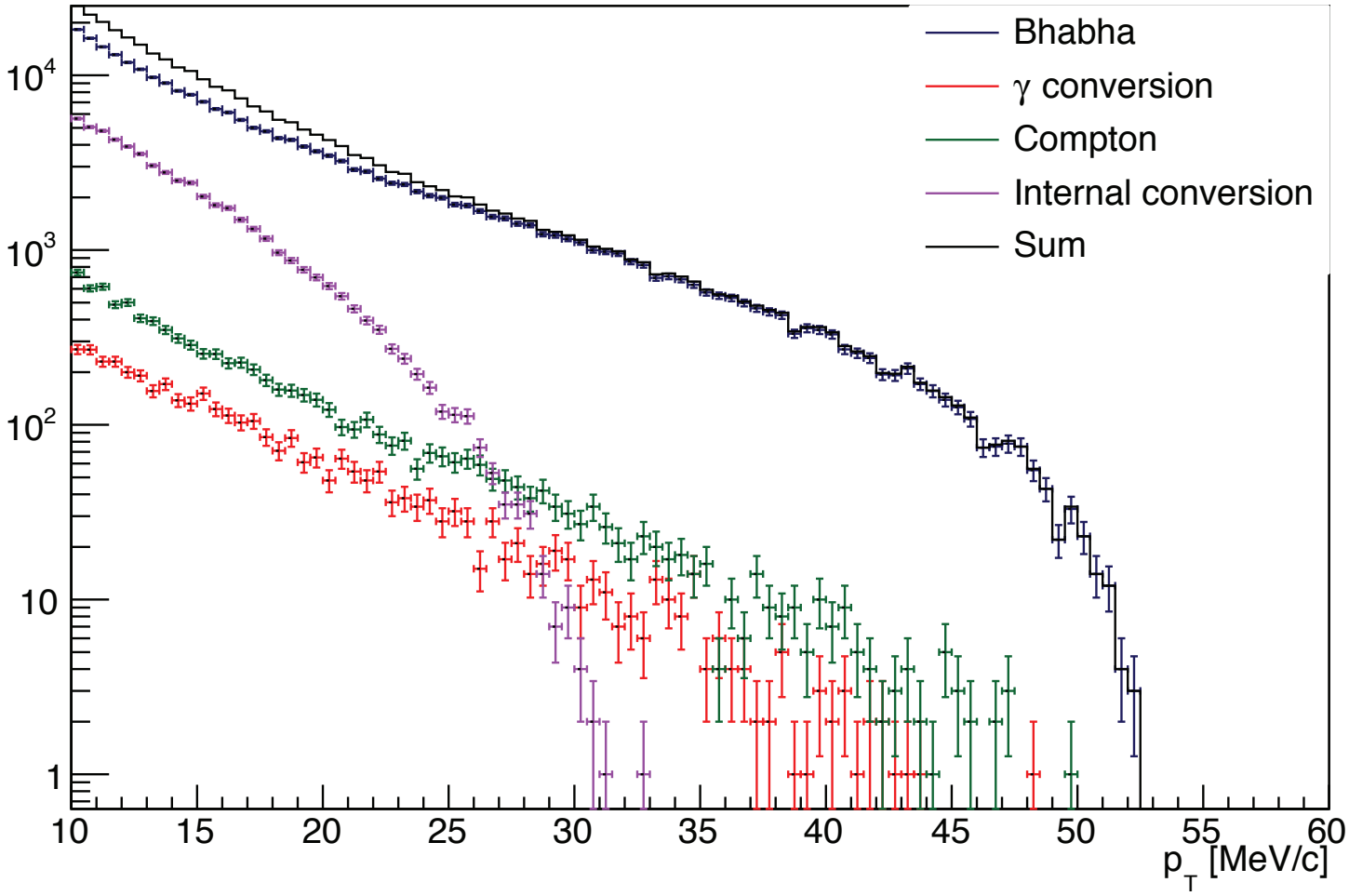


# Accidental background

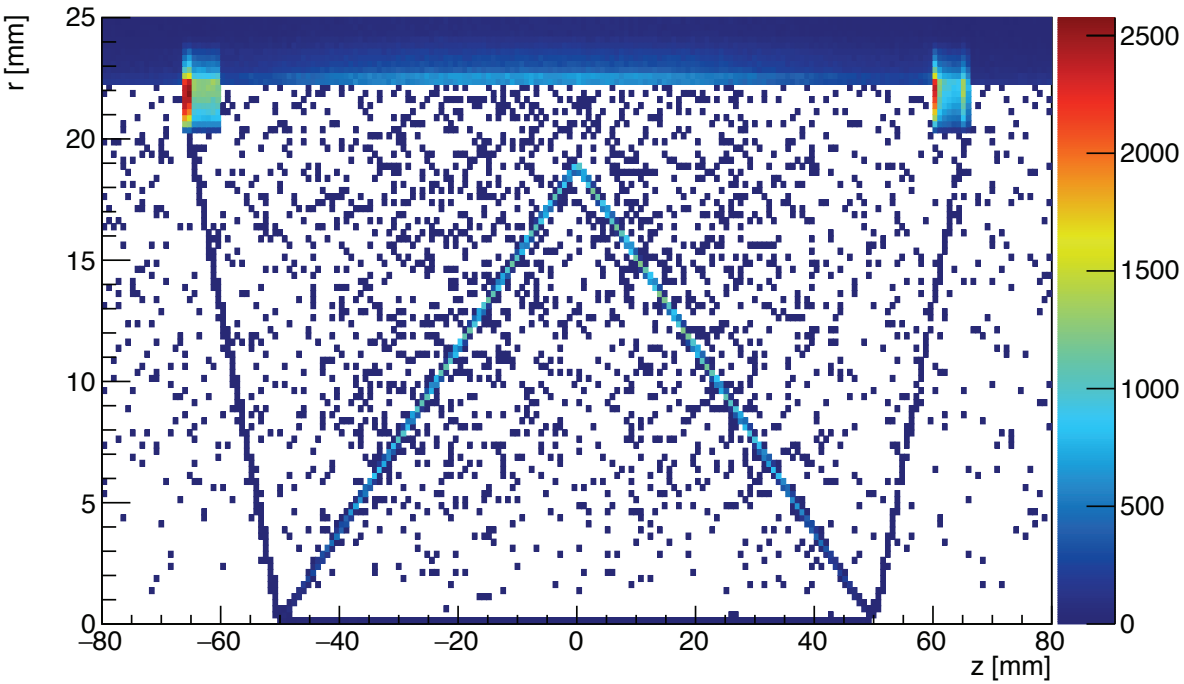
- Full simulation of > $10^{15}$ muon decays not possible
- Accidental background needs an electron
- Simulate few seconds of running, identify electron sources
- Bhabha scattering dominates
- Most worrying background is Bhabha with $e^+$ and $e^-$ in detector acceptance

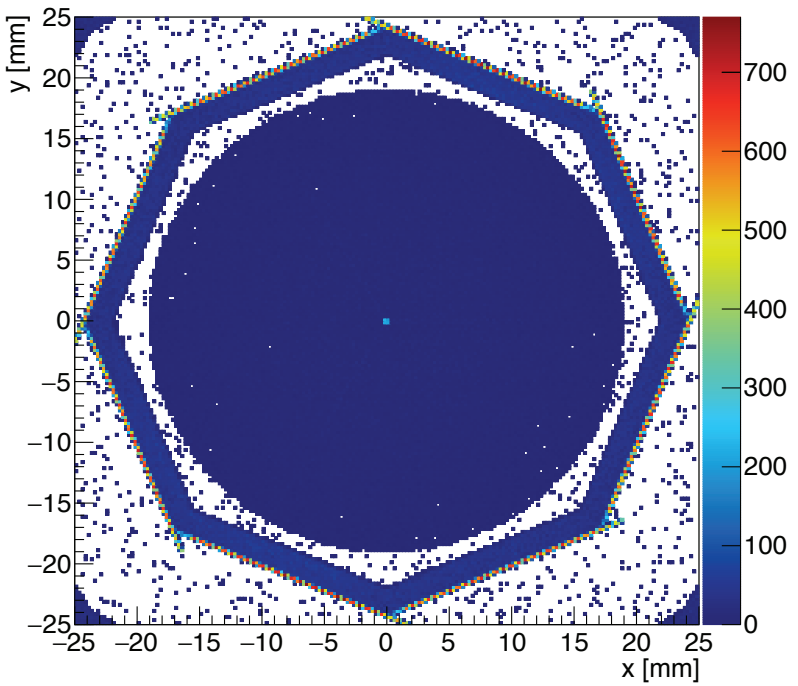
| Electron source | Electrons from target in acceptance per muon stop |
|---|---|
| Bhabha scattering | $1.2 \cdot 10^{-4}$ |
| both visible | $7.8 \cdot 10^{-5}$ |
| Photon conversion | $1.9 \cdot 10^{-6}$ |
| both visible | $1.7 \cdot 10^{-6}$ |
| Compton scattering | $4.3 \cdot 10^{-6}$ |
| Internal conversion | $2.8 \cdot 10^{-5}$ |
| two visible | $6.2 \cdot 10^{-7}$ |
| Total | $1.5 \cdot 10^{-4}$ |

# Electron $p_T$ spectra



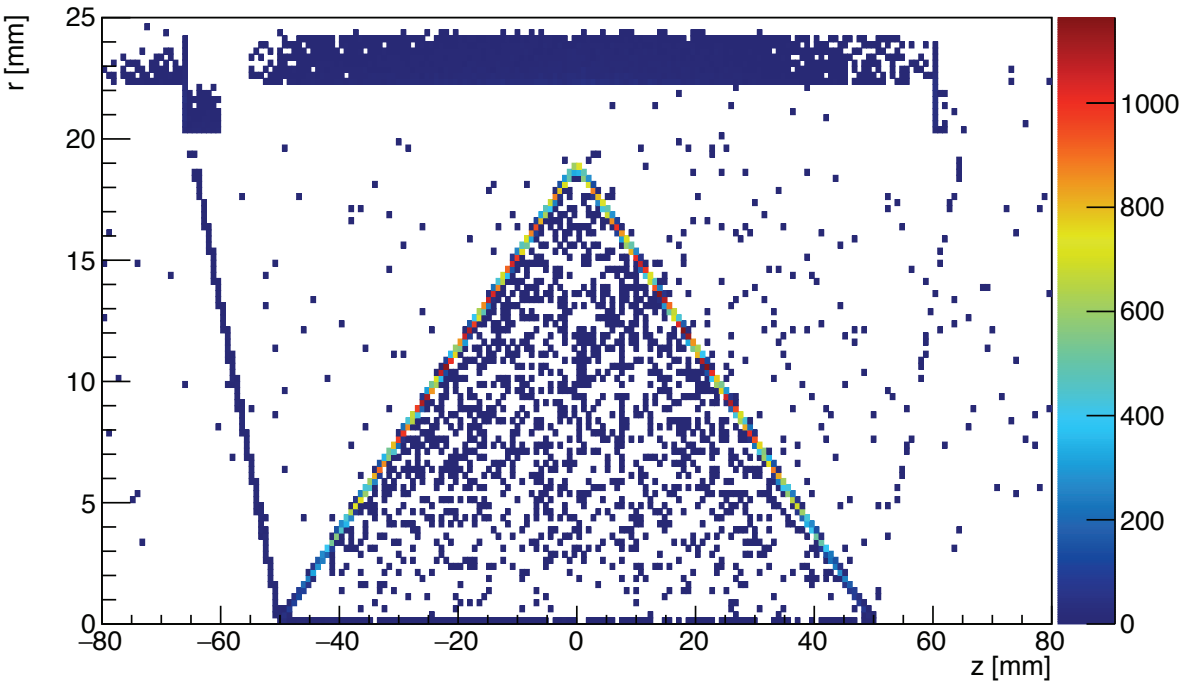
# Background: Bhabha vertices

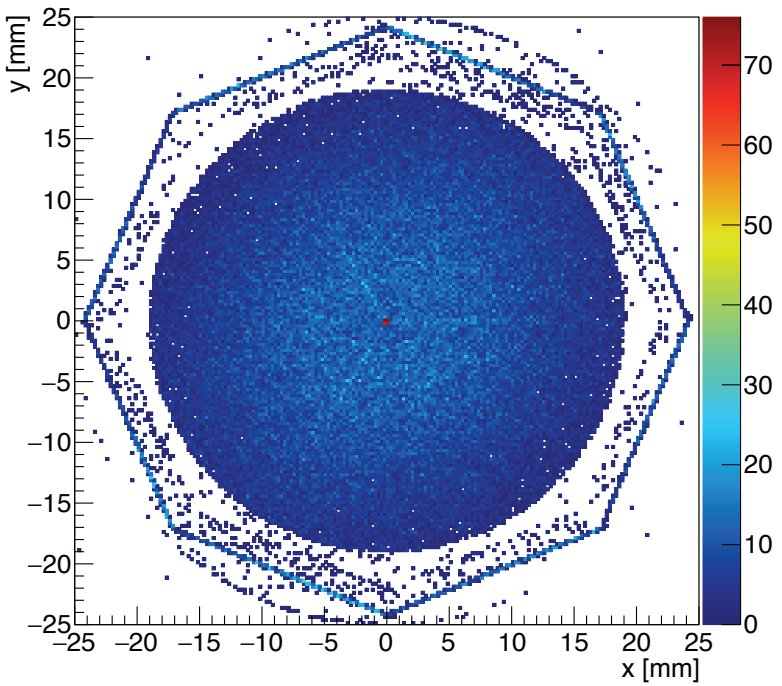



Vertices of Bhabha events

# Background: Bhabha positron vertices

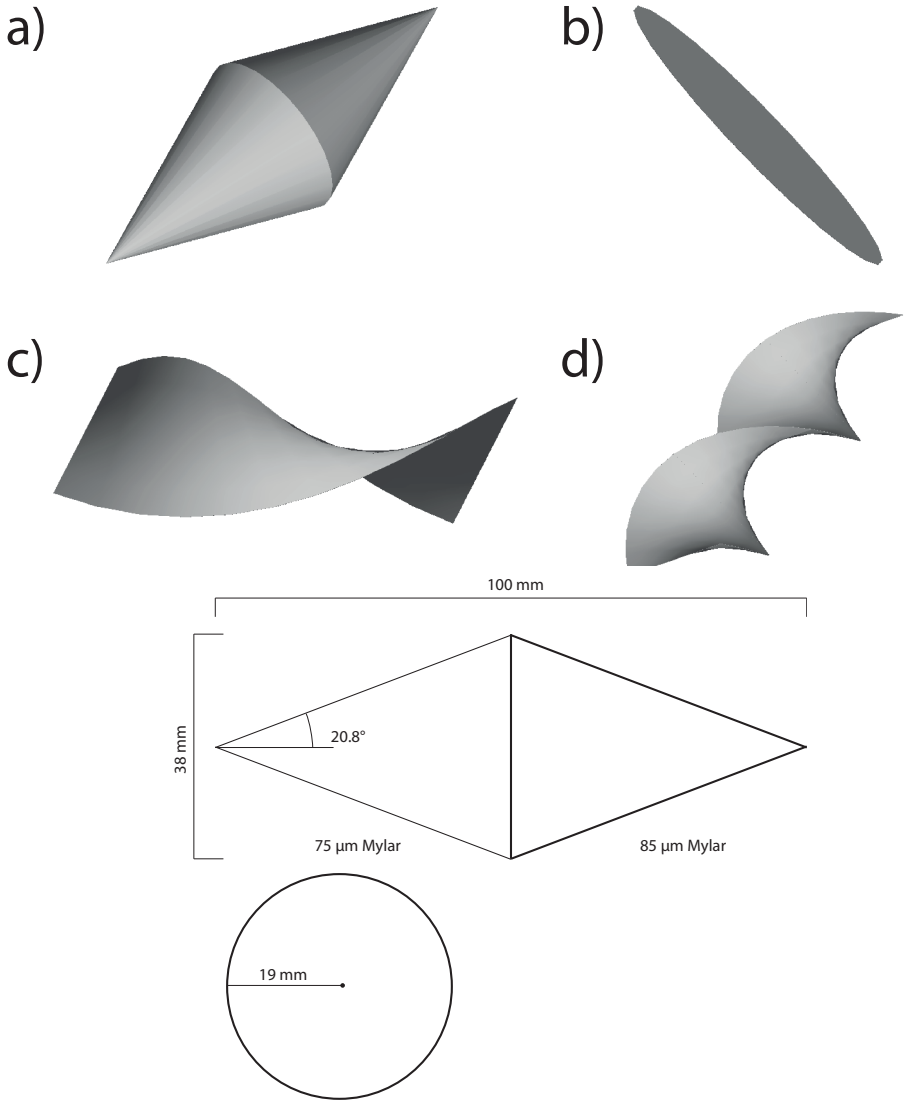



Vertices of positrons causing Bhabha events

# Target shape (Question)

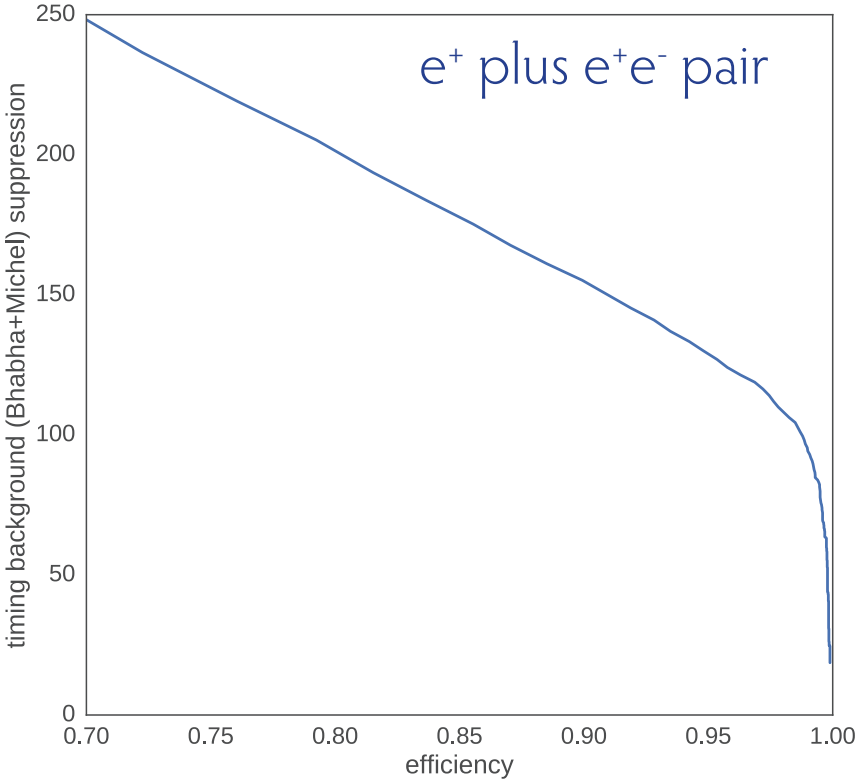
- Bhabha background scales with target mass and target Z
- Light, low Z target (Mylar)
- Need ~450 µm in beam direction, as little as possible perpendicular to it
- Tried several shapes with large inclination angles
- Double cone least mass for a given stopping fraction (second chance)
- Also helps for acceptance

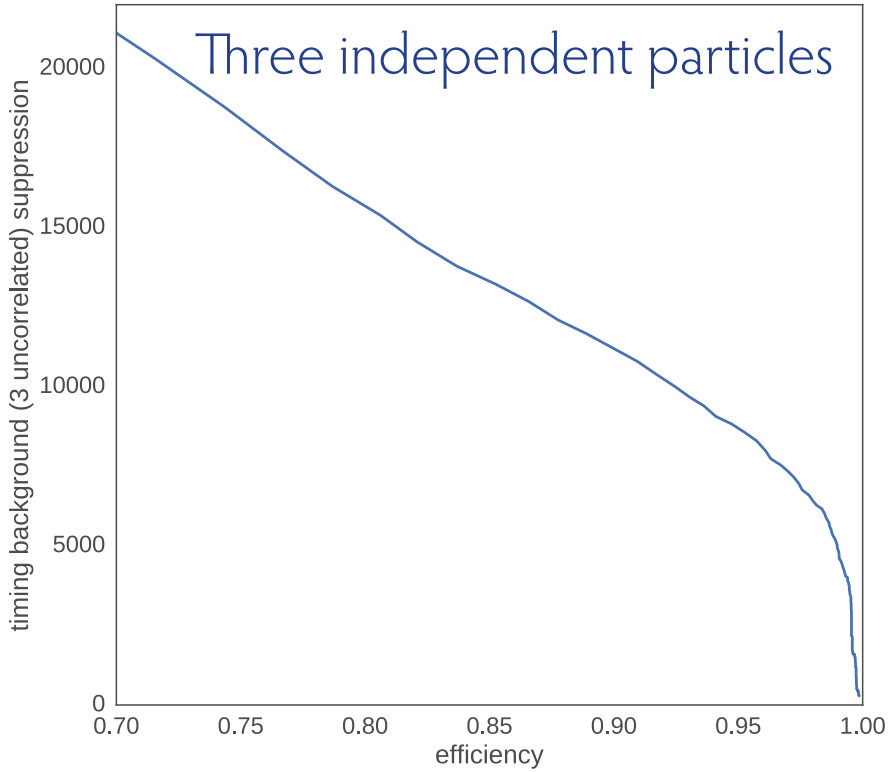


# Suppression of accidental background

- Produce few electrons
- Timing
- Vertexing
- Kinematics

# Timing suppression




- Use timing detectors as a veto
- Choose a 98% efficiency working point

# Bhabha simulation

- Use "special muons" which perform Bhabha scattering at the moment of decay
- Combine with normal $10^8$ muon stops/s running
- Perform full analysis as for signal

Approximations made:

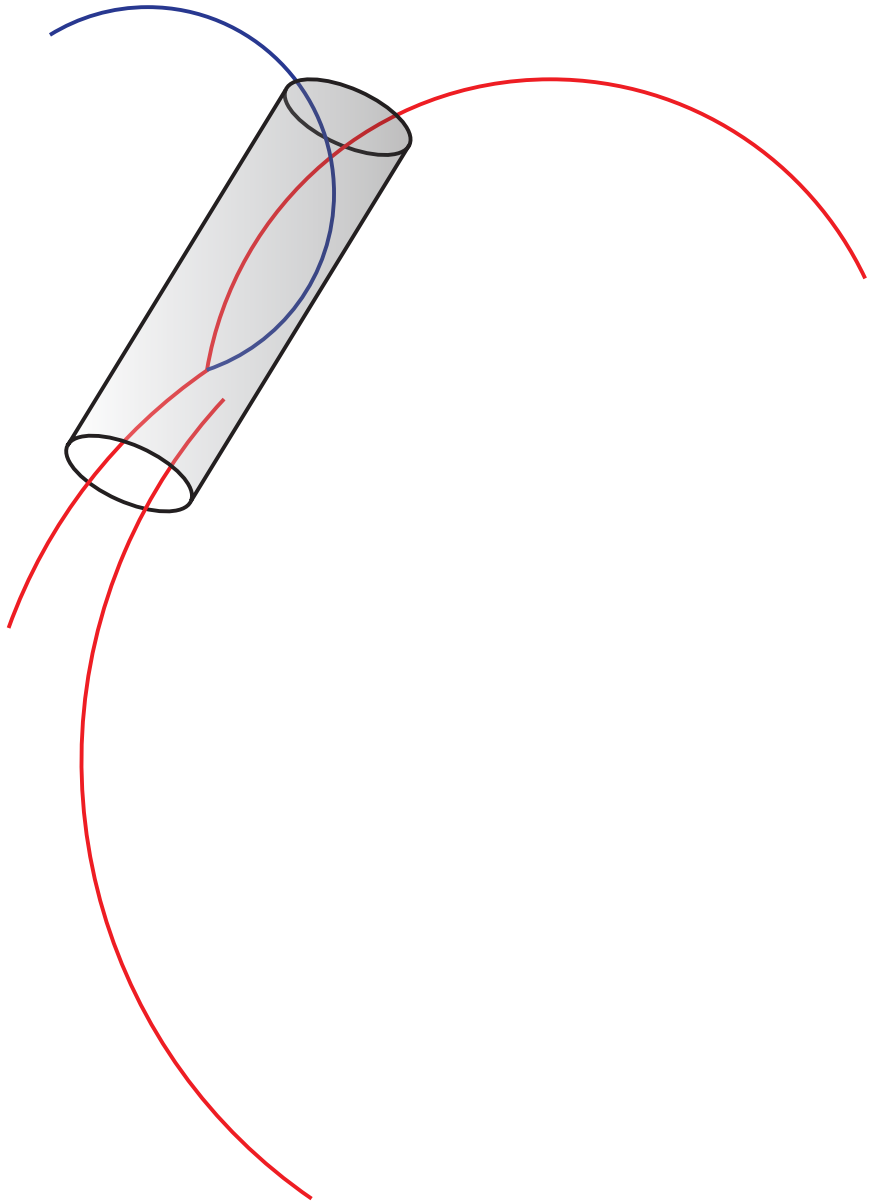
- Bhabha scattering location and decay location are the same
- "Bhabha muon" stop distribution slightly different from normal stop distribution
- Electron and positron are required to have at least 10 MeV
- Effective rate is higher due to extra decay

# Statistics

- $7.8 \cdot 10^{-5}$ of muon stops produce a Bhabha pair with electron and positron visible
- Assume (factorizing) timing suppression factor of 108
- Generate $5.25 \cdot 10^{8}$ frames with a Bhabha pair (one month on 32 cores)
- Corresponds to $7 \cdot 10^{14}$ muon stops

- After cuts, left with 0 Bhabha events in 95 to 115 MeV mass window
- Upper limit (90% C.L.) at $3.2 \cdot 10^{-15}$
- New, larger simulation under way

# Question: Bhabha vertex suppression



Combine Bhabha pair with another Michel positron

For "interesting" kinematics:

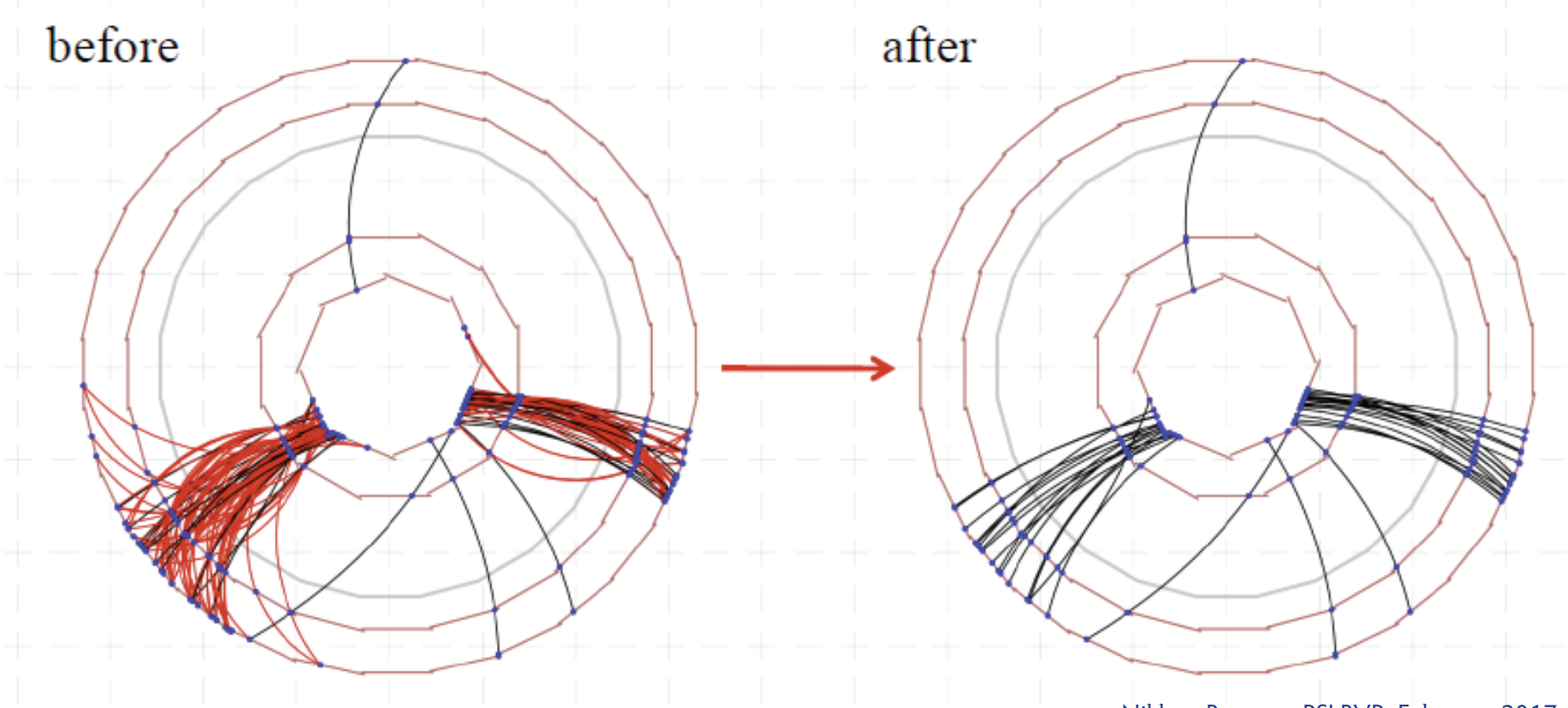
- Back-to-back
- Both positrons close to Michel edge

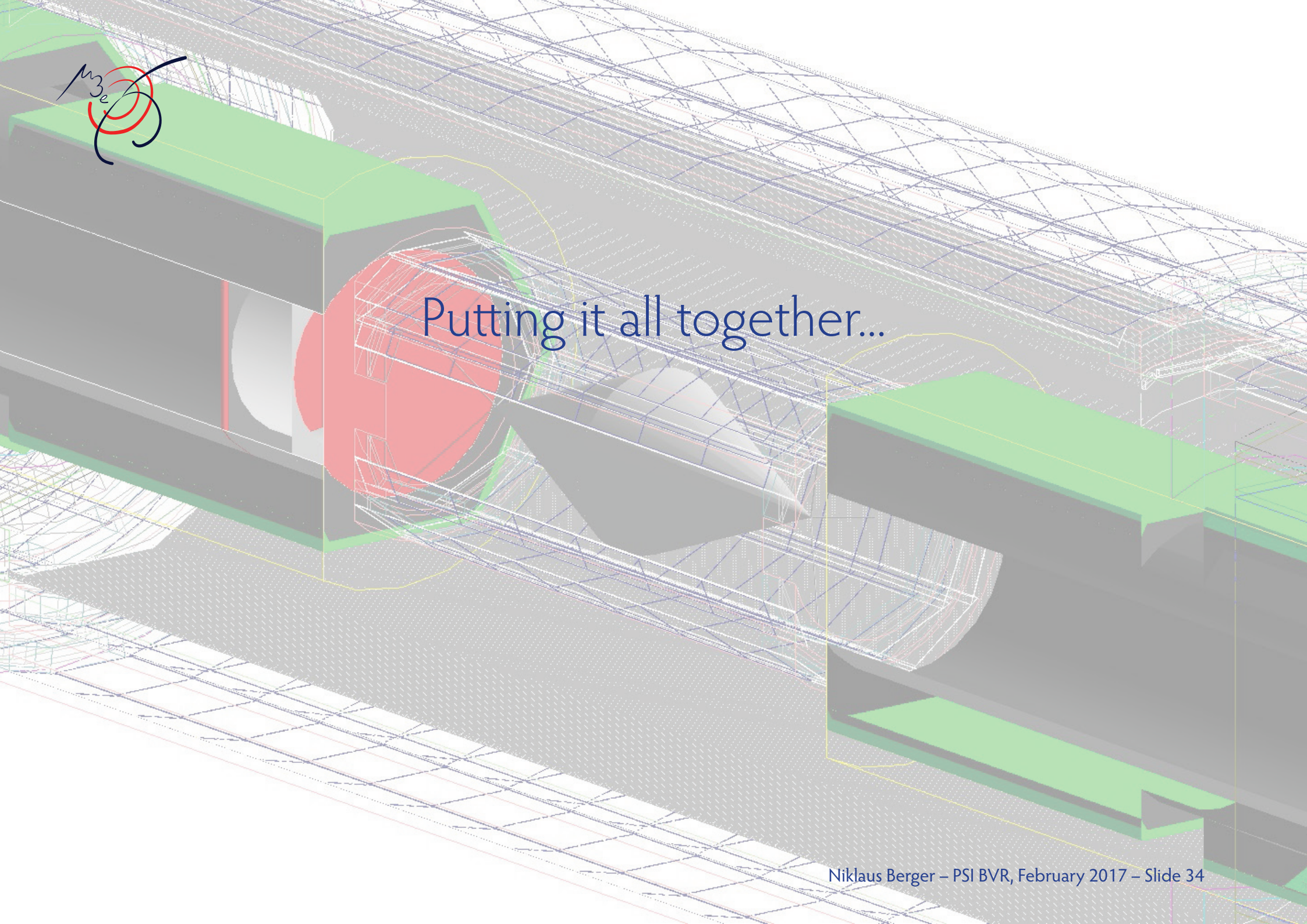
- Topology (vertexing rejection) and kinematic rejection do not factorize

- Excellent resolution transverse to tracks
  Cut on fit $\chi^2$ rather than target distance

# Question: Electrons from mis-reconstruction

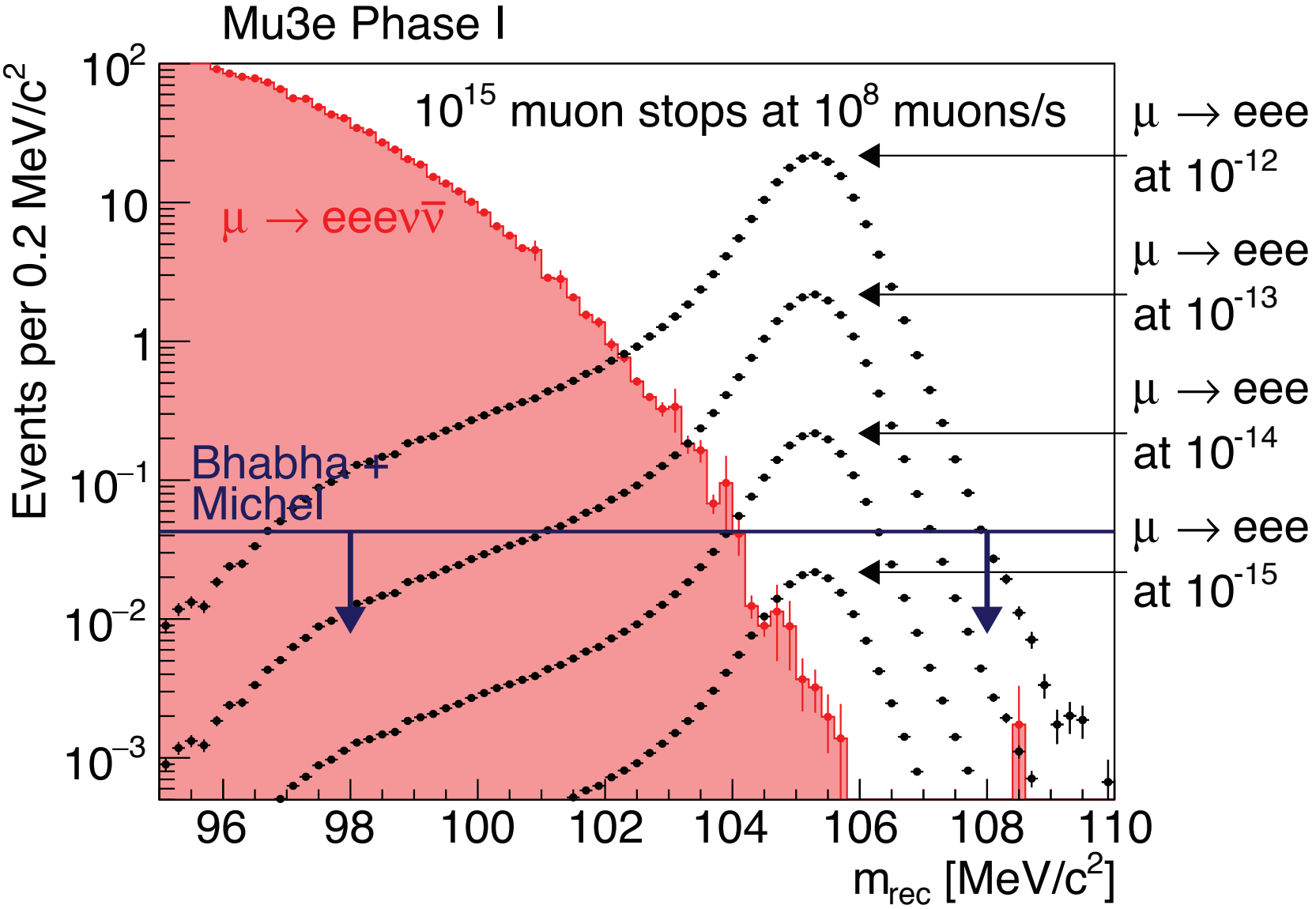
- Most misreconstruction related to multiple recurlers ($\theta \approx 90°$), not affecting charge assignment
- Can be mostly resolved
- We do see fake electrons in large simulations - origin and mitigation under study



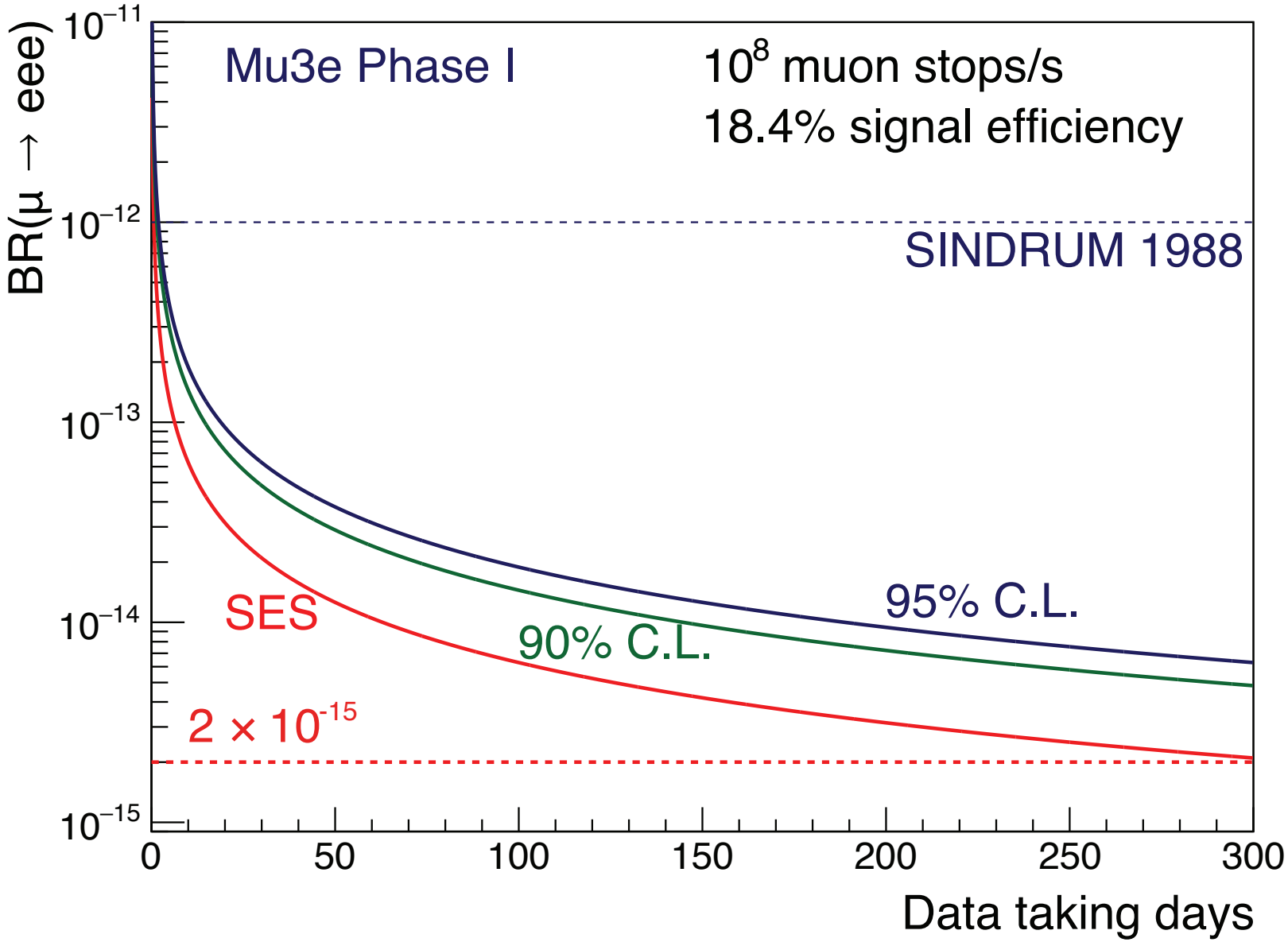


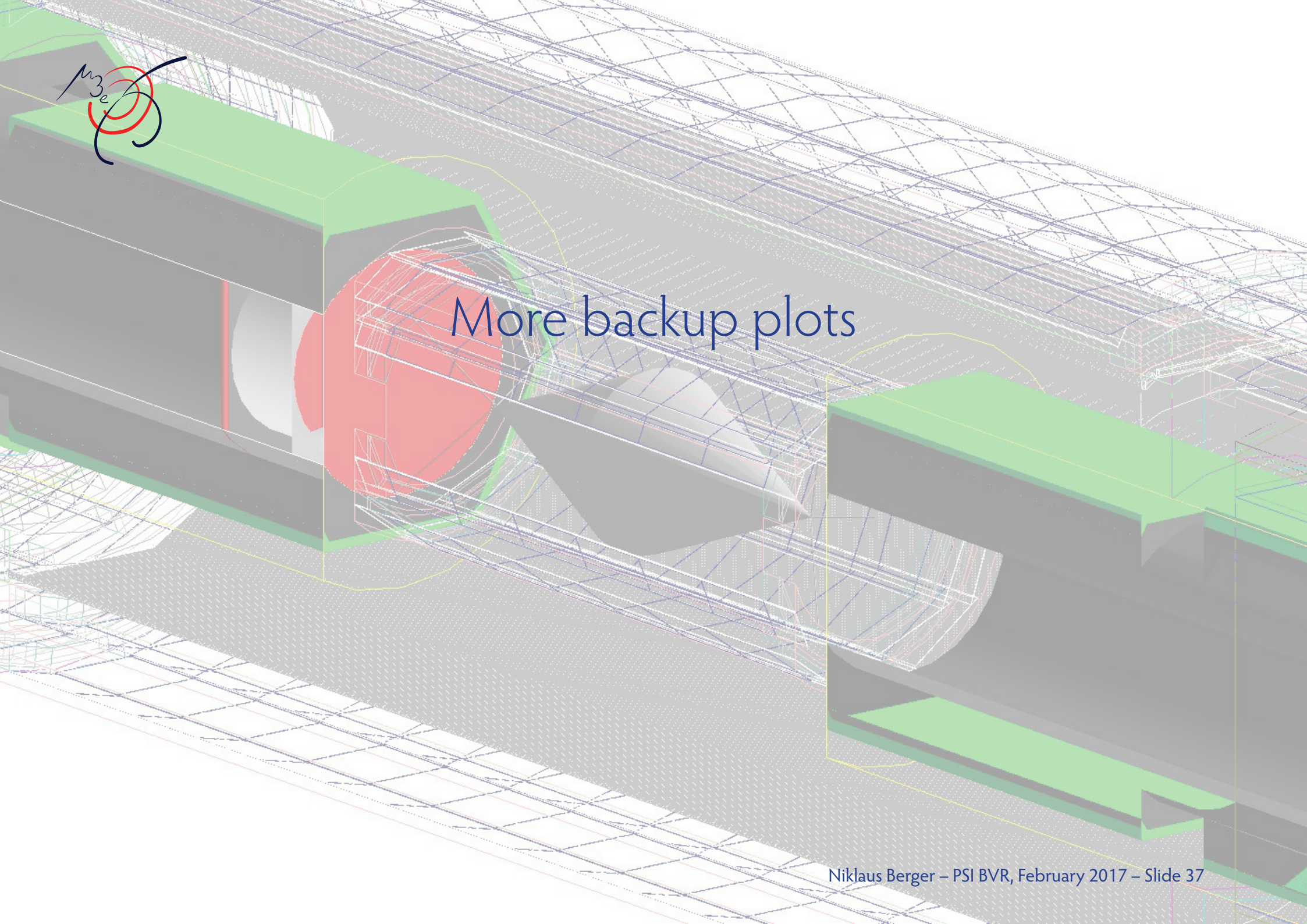
# Putting it all together...

# Mass distribution



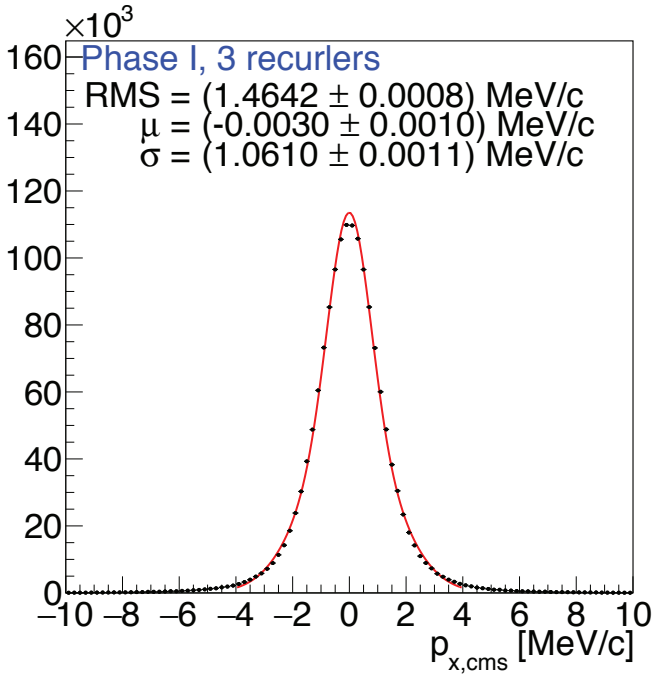
# Sensitivity vs. time

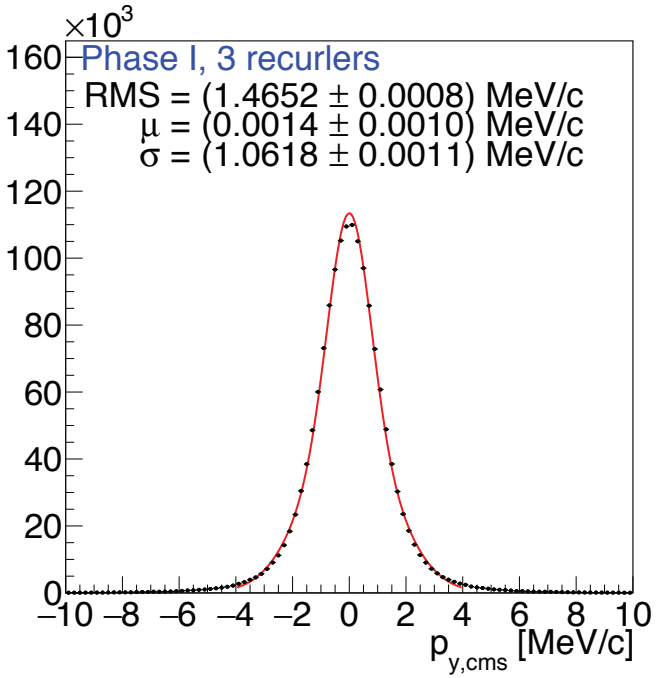


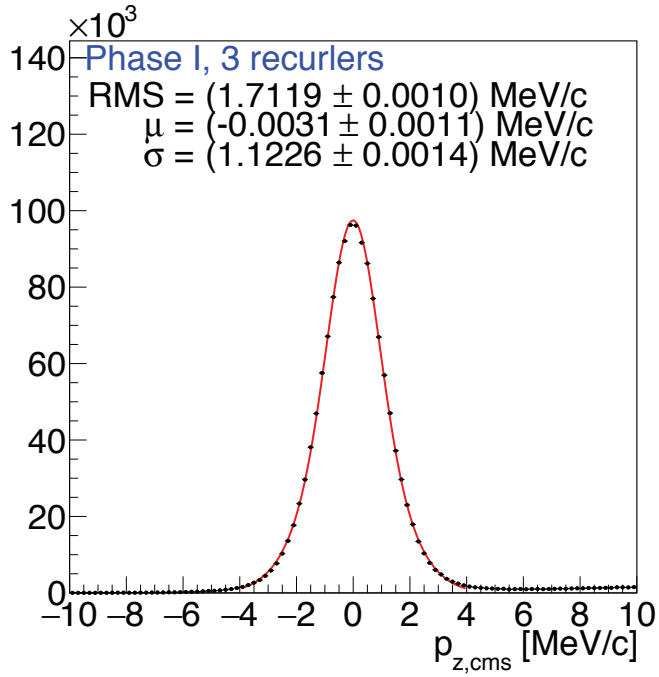


# More backup plots

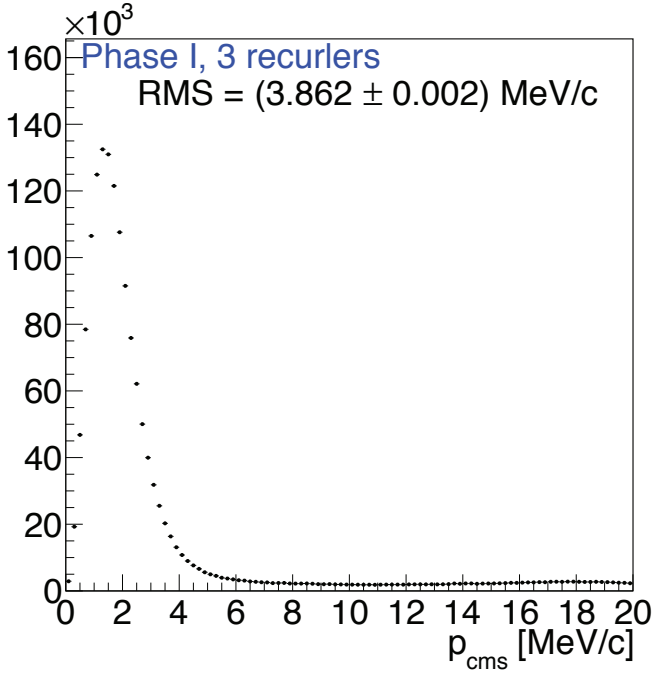
# Signal Performance: CMS Momentum

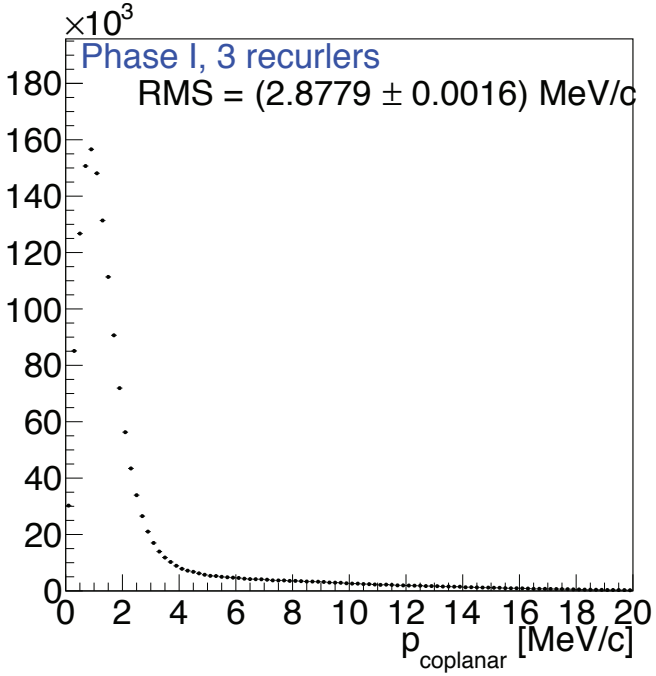


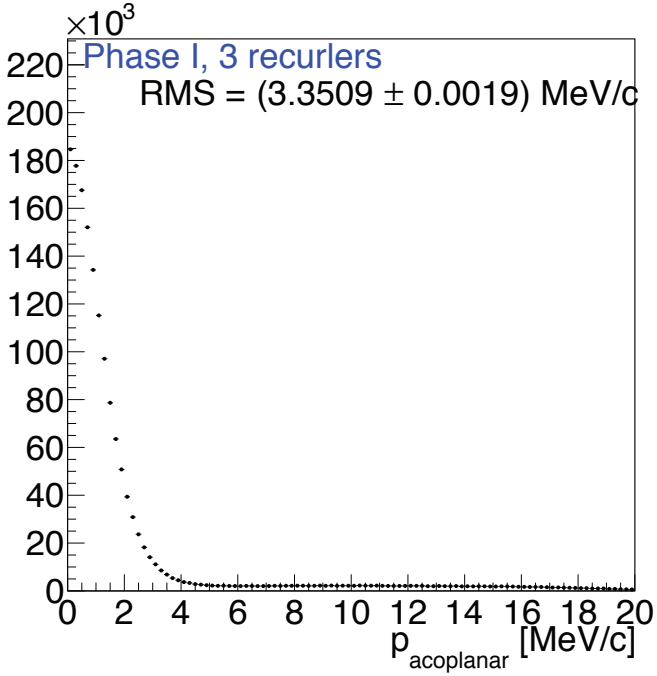



# Signal Performance: CMS Momentum



# Bhabha kinematics