DEEP UNDERGROUND NEUTRINO EXPERIMENT

Sensitivity to Heavy Neutral Leptons With SAND detector at DUNE-ND

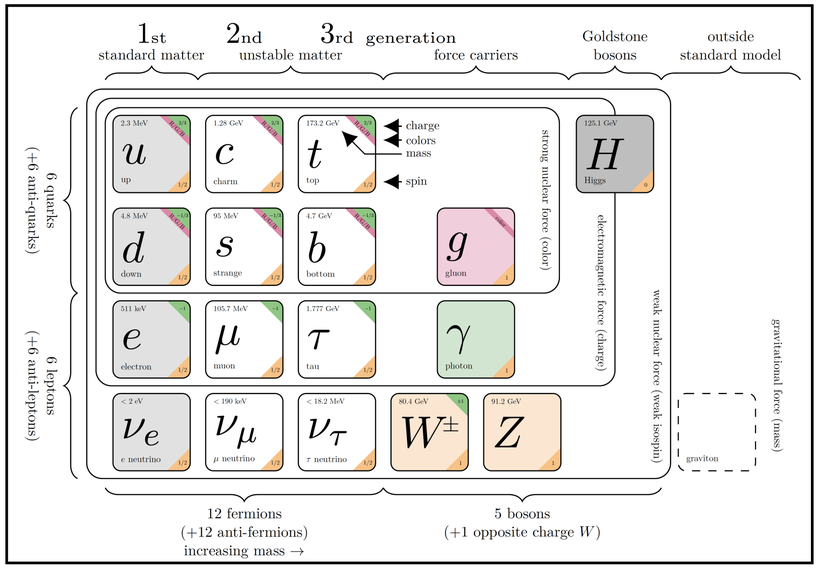
Zahra Ghorbani Moghaddam
University of Perugia and INFN Genova
"On behalf of the DUNE Collaboration"

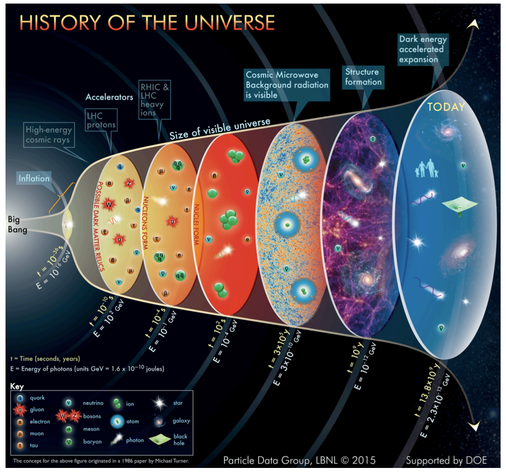
BEYOND STANDARD MODEL PHYSICS

✷ Why going beyond Standard Model?

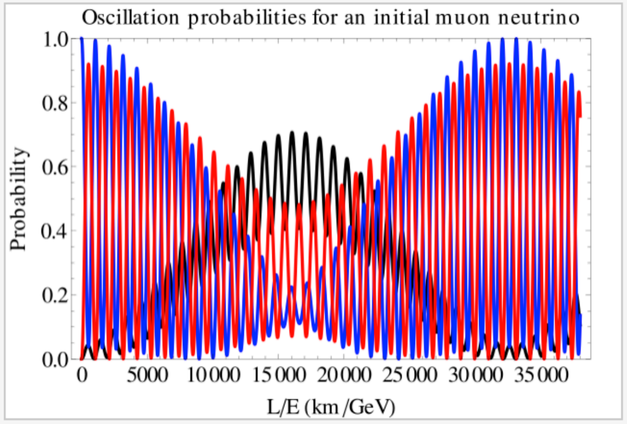
vMSM

- Observed Matter anti-matter asymmetry (BAU) requires BSM
- Dark matter (Bullet cluster, Galaxy rotation, GR lensing)
- Neutrino oscillation, CPV and neutrino masses
  - SeeSaw models (low-SeeSaw, …)

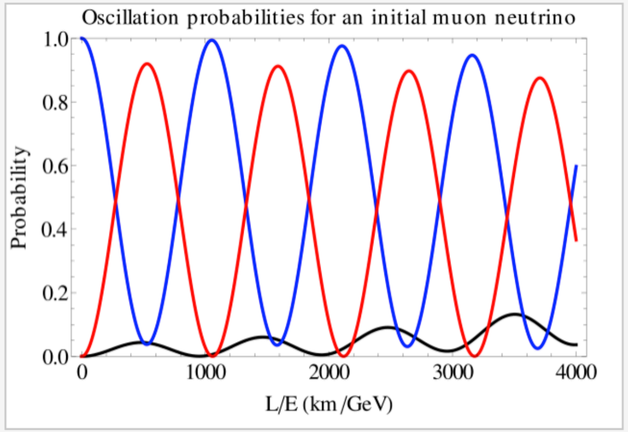




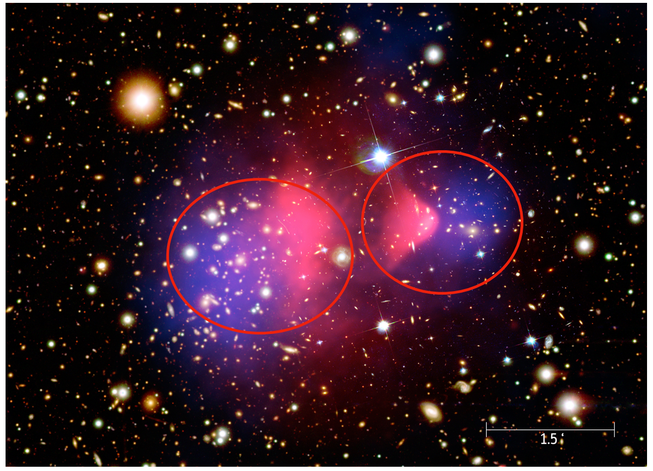
ν_e–
ν_μ–
ν_τ–



Muon neutrino oscillations, long range



Muon neutrino oscillations, short range



BEYOND STANDARD MODEL PHYSICS

$$\mathscr{L}_{\nu MSM} = \mathscr{L}_{MSM} + \bar{\tilde{N}}_I i\partial_\mu \gamma^\mu \tilde{N}_I - F_{\alpha I}\bar{L}_\alpha \tilde{N}_I \tilde{\Phi} - \frac{\Delta M_{IJ}}{2}\bar{\tilde{N}}_I^c \tilde{N}_J - M\bar{\tilde{N}}_2^c \tilde{N}_3 + h.c.$$

$$\begin{cases} f_e^2 : f_\mu^2 : f_\tau^2 \approx 52 : 1 : 1 \\ f_e^2 : f_\mu^2 : f_\tau^2 \approx 1 : 16 : 3.8 \\ f_e^2 : f_\mu^2 : f_\tau^2 \approx 0.061 : 1 : 4.3 \end{cases}$$

Particle	Channel
D_s	$\to eN_{2,3}$
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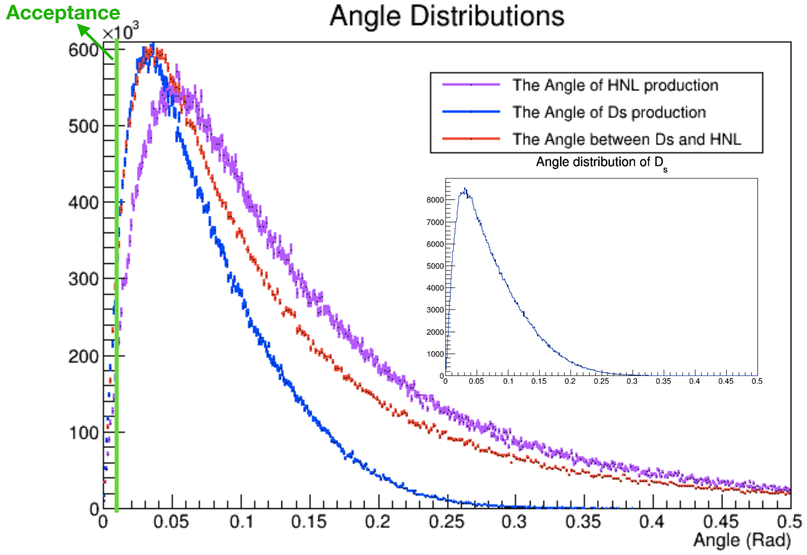
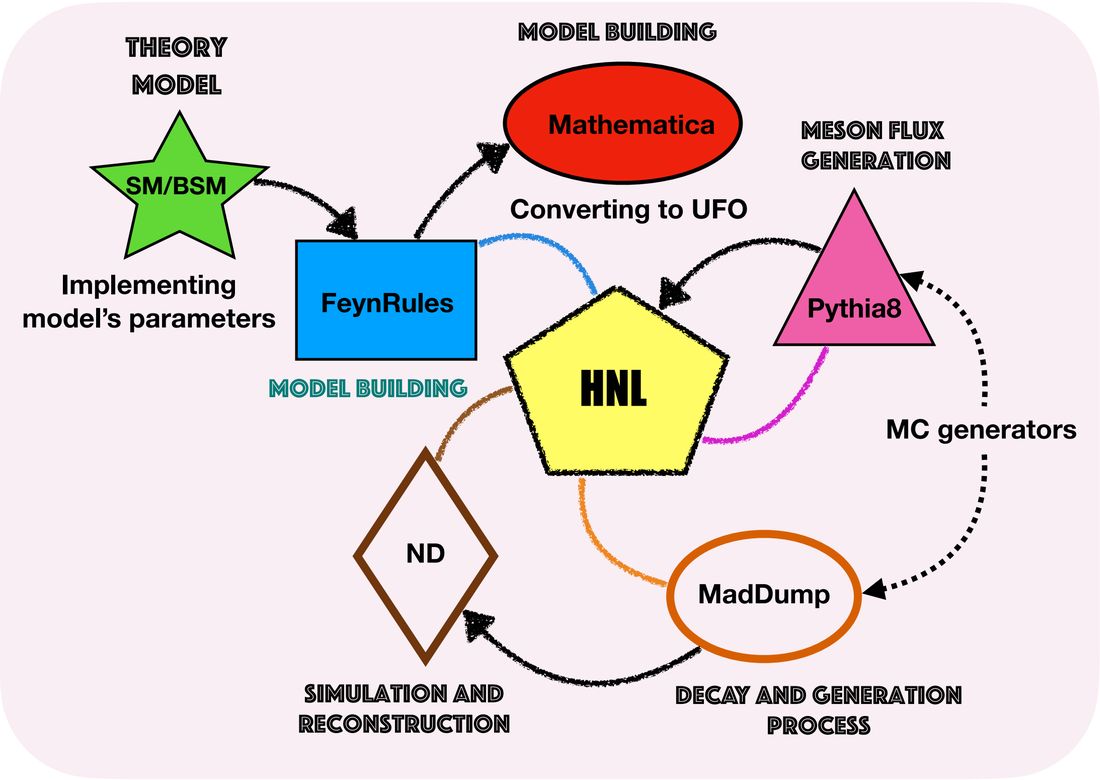
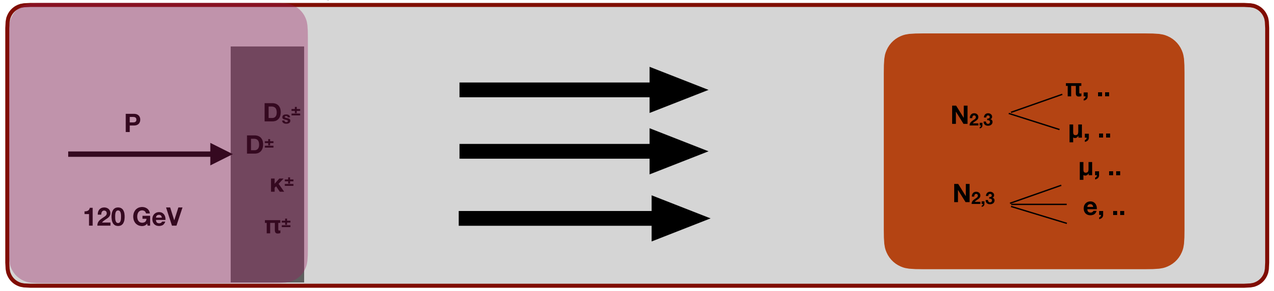




- **# Mesons:**
  - Primary
  - Secondary
- **# Heavy Fermions:**
  - Long lived.



https://arxiv.org/abs/0705.1729
https://arxiv.org/abs/1812.06771

✺ Steps

- **FeynRules:** Building the model based on Lagrangian Parameters and included Channels
- **Pythia:** External meson Flux (D_s)
- **Mad-Dump:** Built model + Meson flux: HNL flux and decay
- **EdepSim ➡ Digitization ➡ Reconstruction (Kalman Filter)**

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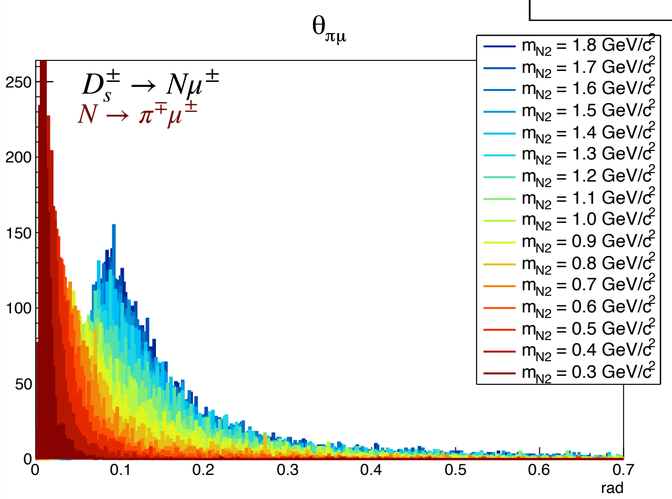

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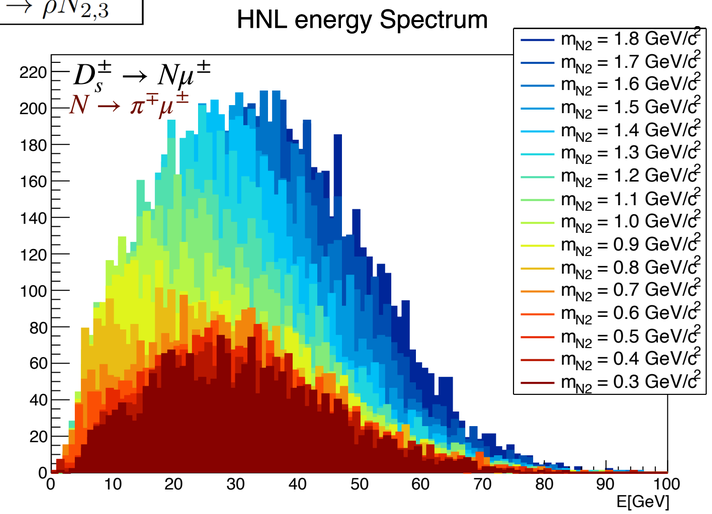

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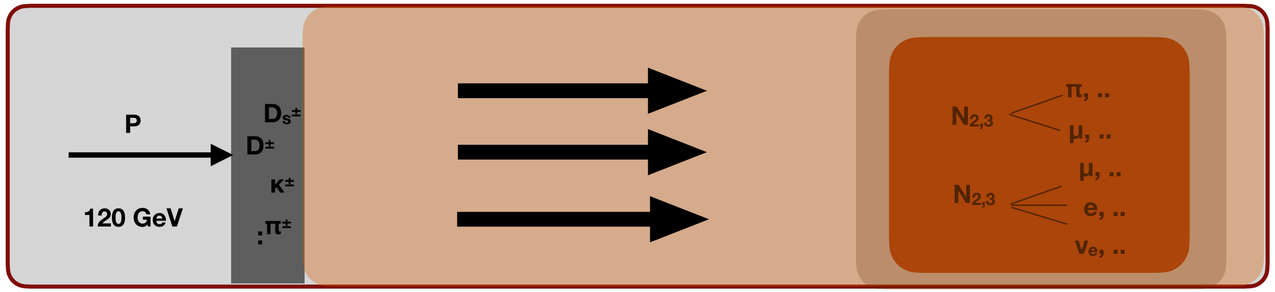

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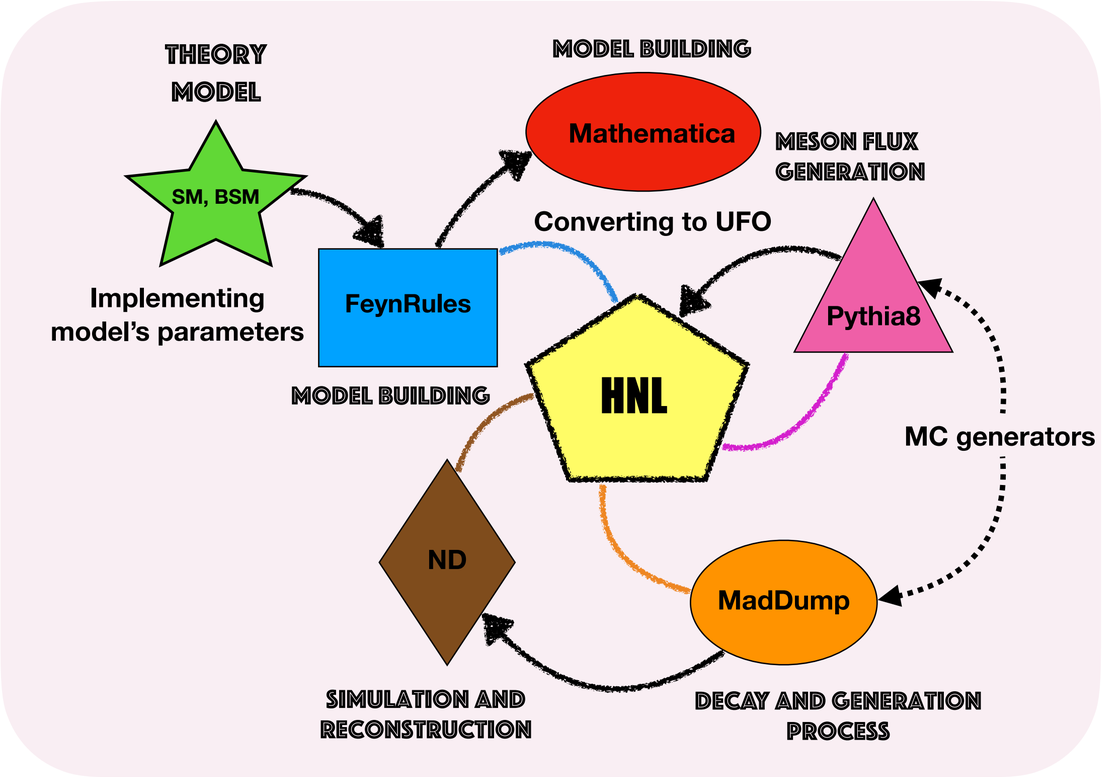

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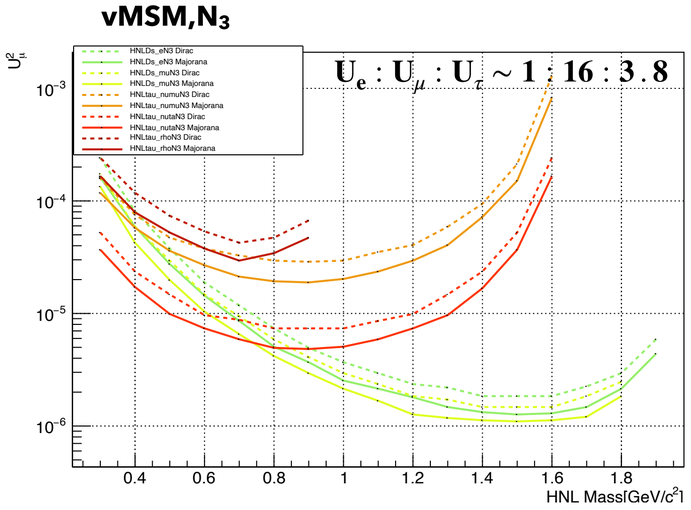
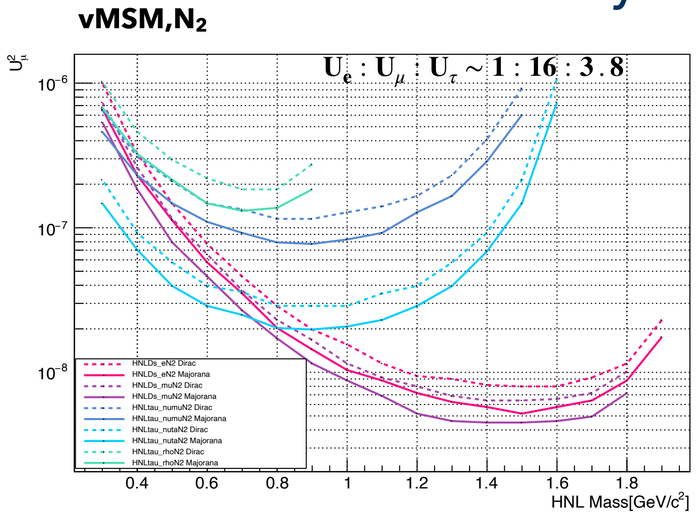
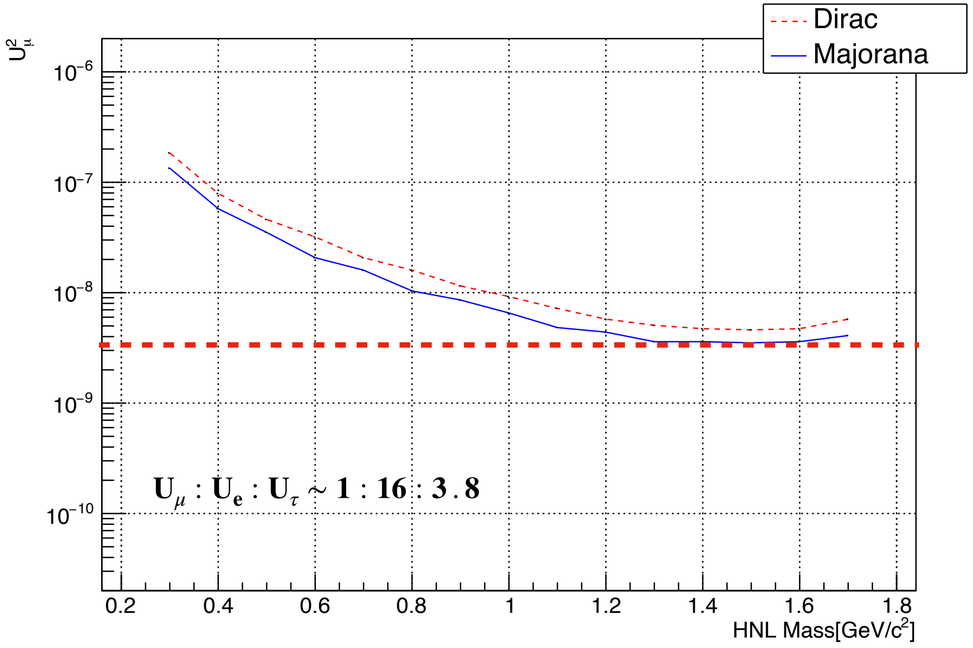
Pheno-Sensitivity







✺ Pheno-Sensitivity

- **6** years exposure, 1.1×10^{21} **NPOT/1yr**
- Coupling benchmark model for the plots is **II**
- Small mixing between **N_2** and **N_3** due to BAU lower bound
- Detector's Geometry has been modified to fit with **SAND** transversally
- **D_s** channel is dominant in this range. All **D_s** channels has been covered
- Regarding the model parameters and simulation tools, the estimated Pheno-sensitivity is in the ballpark of the previous studies in the **D_s** dominant region.

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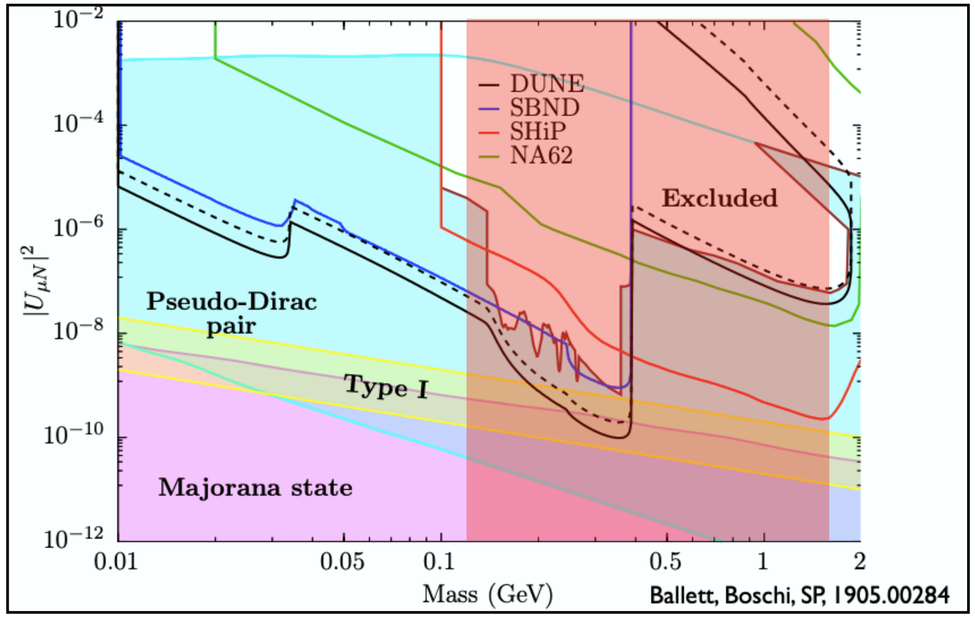
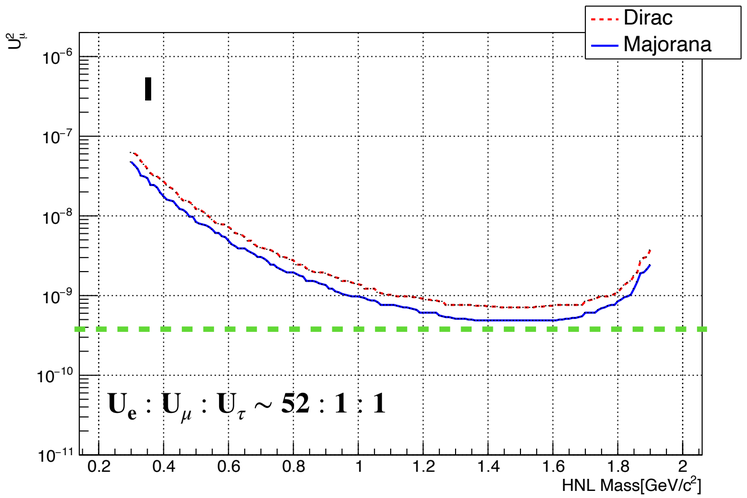
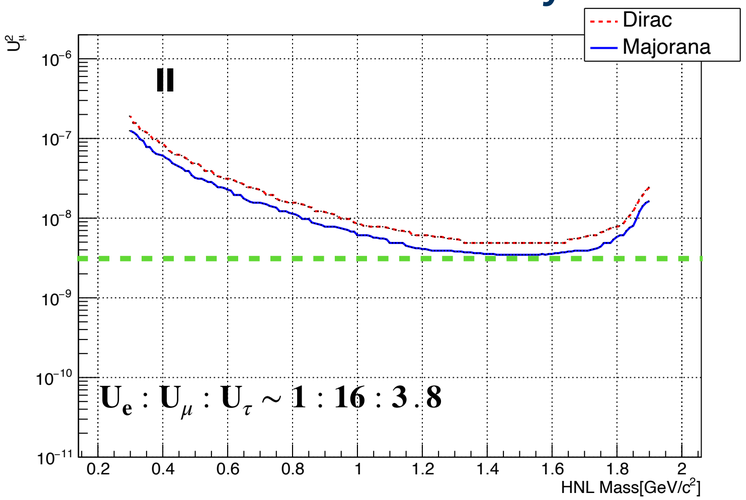


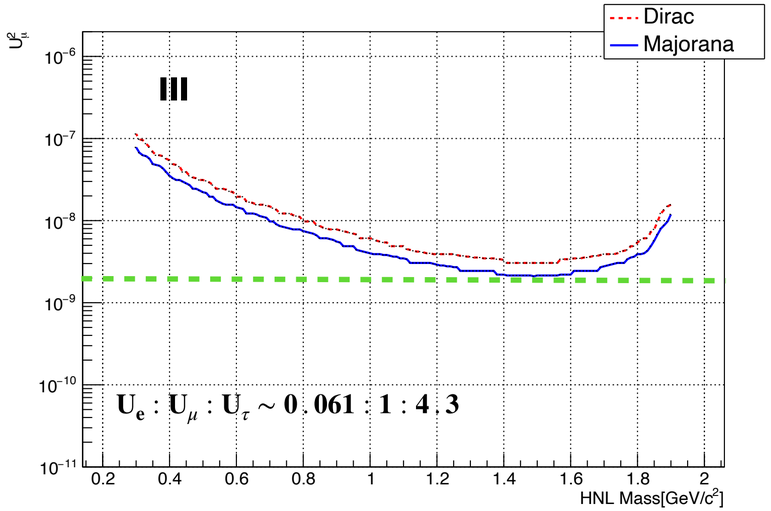
✺ Steps to Reconstruction

- Mad-Dump output file is converted to a Genie-like output including a ***RooTracker*** tree
- Running Edepsim
- Digitizing
- Existing Reco didn't work for this particular event: Motivation for implementing a customized Kalman Filter

Pheno-Sensitivity







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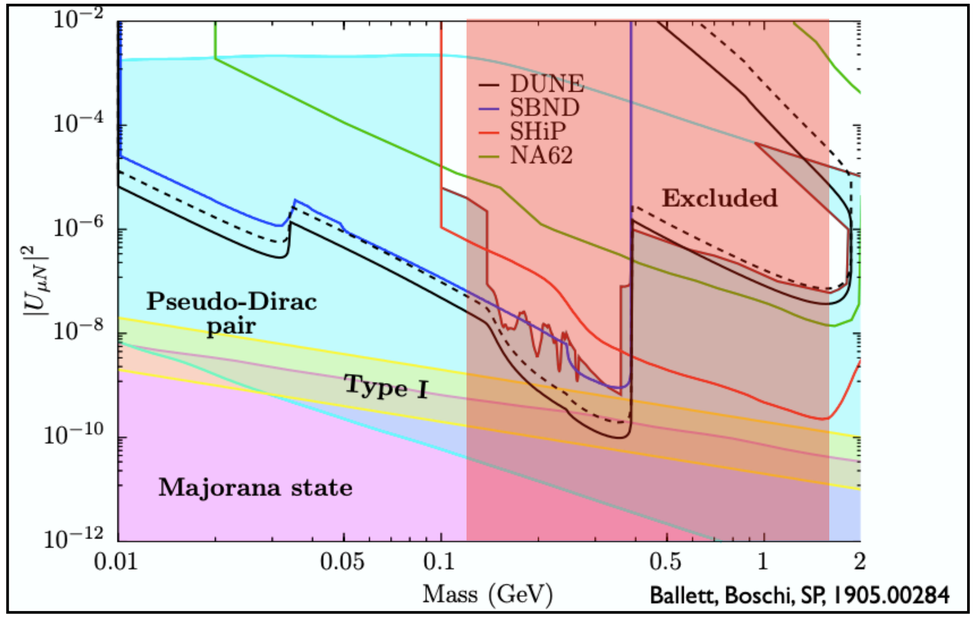

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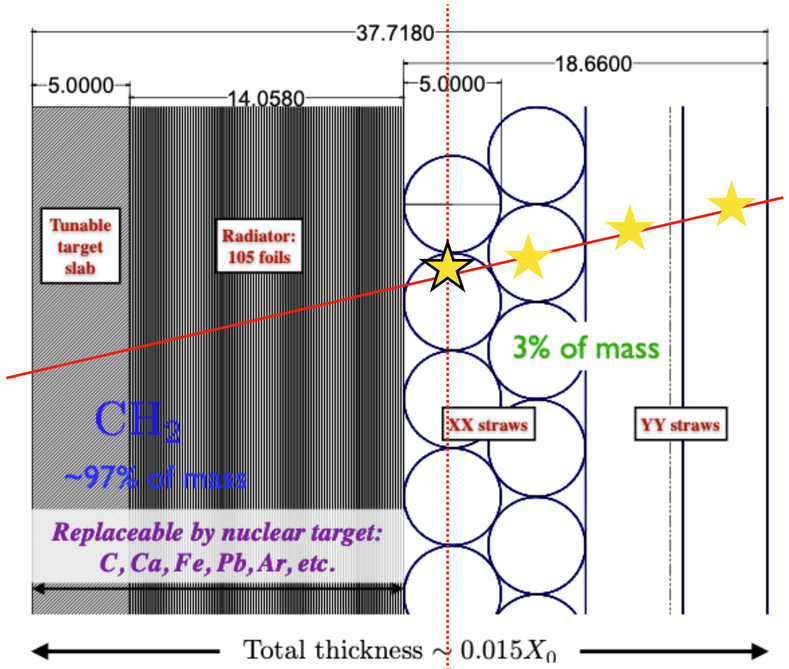
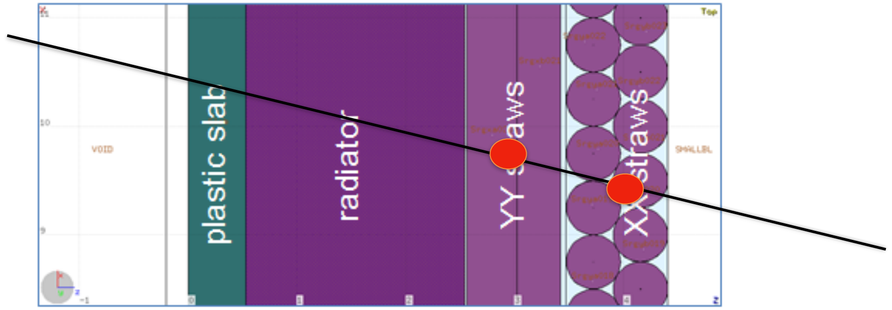
DUNE Near Detector, SAND

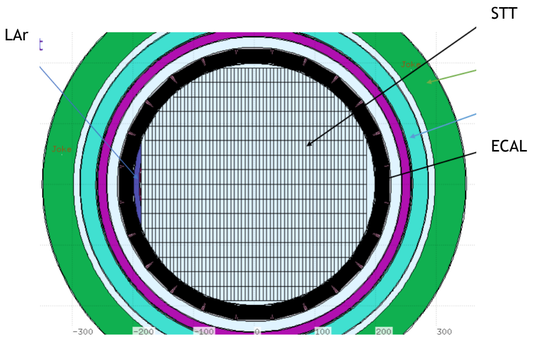
✷SAND (System for on-Axis Neutrino Detection)

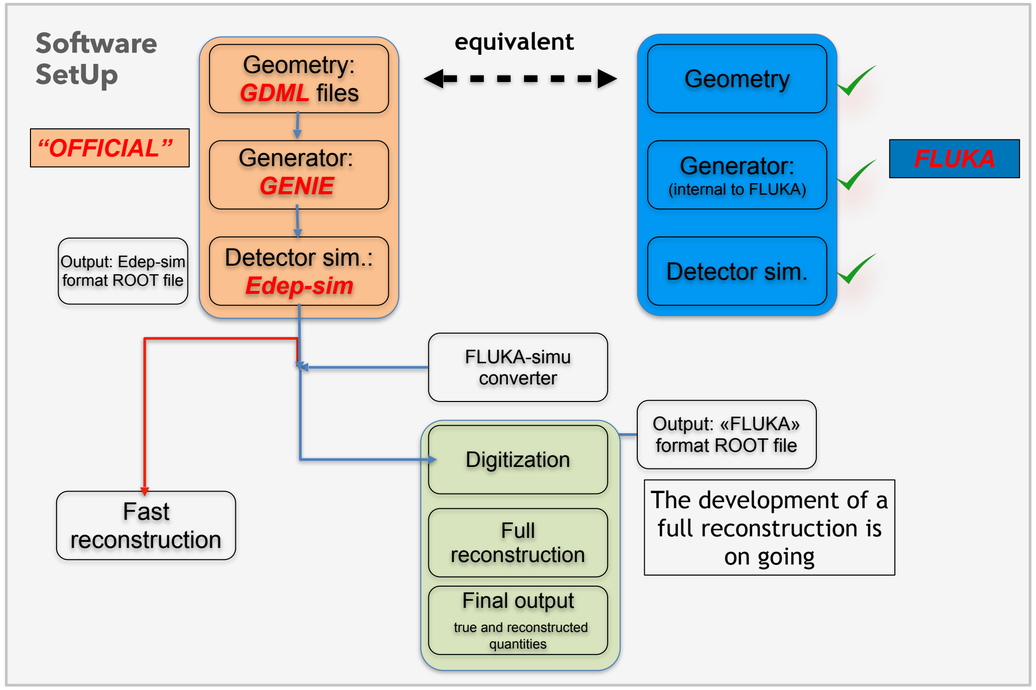
- **Detector tracker design inside KLOE magnet**
- **Tracker: ECAL + STT + Grain (LAr meniscus)**
  - Simulation tools: GEANT4 and FLUKA event generators

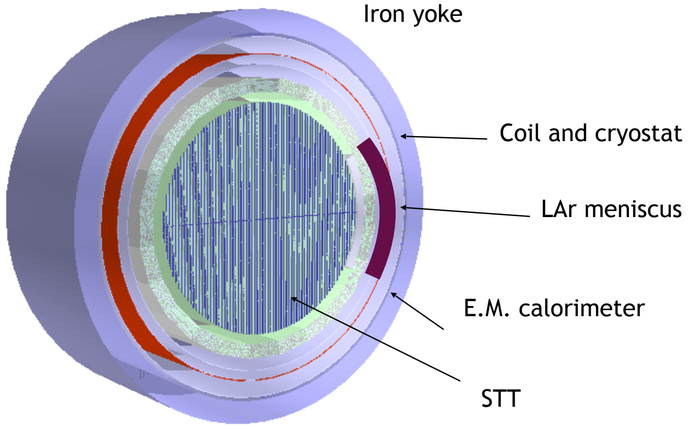




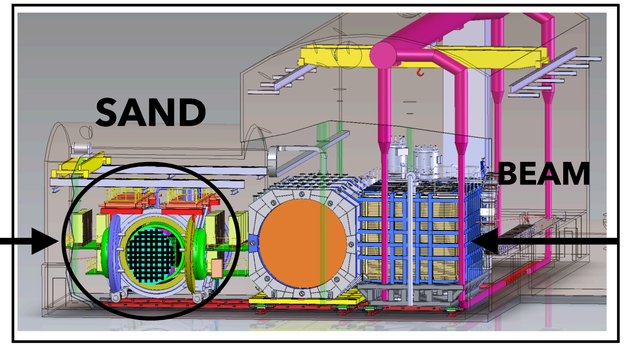
- FLUKA
  - HeaderTree
  - HitsTree
  - CellTree
  - STTTree
- EDEPSIM
  - TG4PrimaryVertex
  - TG4Trajectories
  - TG4HitSegment







Near Detector Facility



Reconstruction, Kalman Filter

- Kalman Filter is an algorithm that determines the trajectory of a state vector of a dynamical system from a set of measurements taken at different times, taking into account gaussian fluctuations
- It proceeds progressively from one measurement to the next, improving the knowledge about the trajectory with each new measurement.
- There are three steps for Kalman Filter
  - **Predicting**: an estimate is made for the next measurement from current knowledge of the state vector
  - **Filtering/Updating**: Kalman Filter in Theory updates the state vector using the measurement
  - **Smoothing**: recursive operation, step by step in the direction opposite to that of filter

Residuals

Predict

$$\tilde{x}_k^{k-1} = F_k \tilde{x}_{k-1} \qquad \tilde{r}_k^{k-1} = m_k - H_k \tilde{x}_{k-1}^k$$

$$\tilde{C}_k^{k-1} = F_k C_{k-1} F_k^T + Q_k \quad \text{(=MCS)} \qquad \tilde{R}_k^{k-1} = V_k + H_k C_{k-1}^k H_k^T$$

Update

$$K_k = C_{k-1}^k H^T (V_k + H_k C_{k-1}^k H_k^T)^{-1} \qquad r_k = (1 - K_k H_k) r_{k-1}^k$$

$$\tilde{x}_k = \tilde{x}_k^{k-1} + K_k (m_k - H_k \tilde{x}_{k-1}^k) \qquad R_k = (1 - K_k H_k) V_k$$

$$C_k = (1 - K_k H_k) C_{k-1}^k \qquad \chi_{k,F}^2 = r_k^T R_k^{-1} r_k$$

Smooth

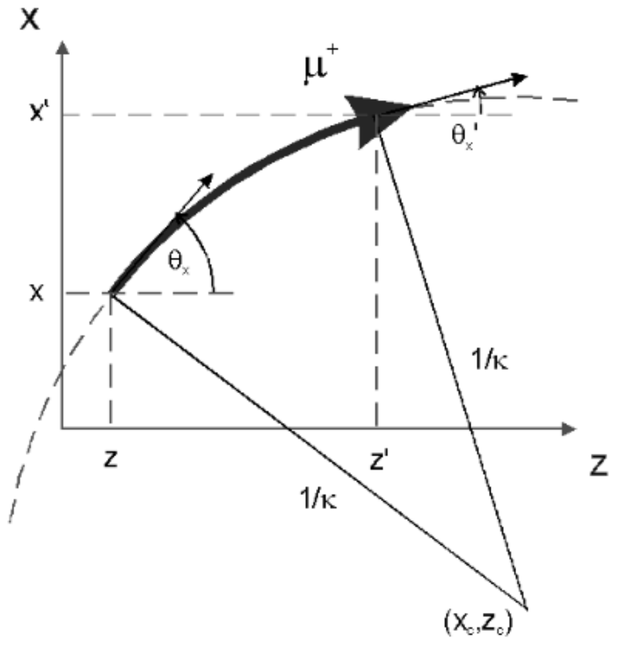
$$A_k = C_k F_{k+1}^T (C_{k+1}^k)^{-1} \qquad r_k^n = m_k - H_k \tilde{x}_k^n$$

$$\tilde{x}_k^n = \tilde{x}_k + A_k (\tilde{x}_{k+1}^n - \tilde{x}_{k+1}^k) \qquad R_k^n = R_k - H_k A_k (C_{k+1}^n - C_{k+1}^k) A_k^T H_k^T$$

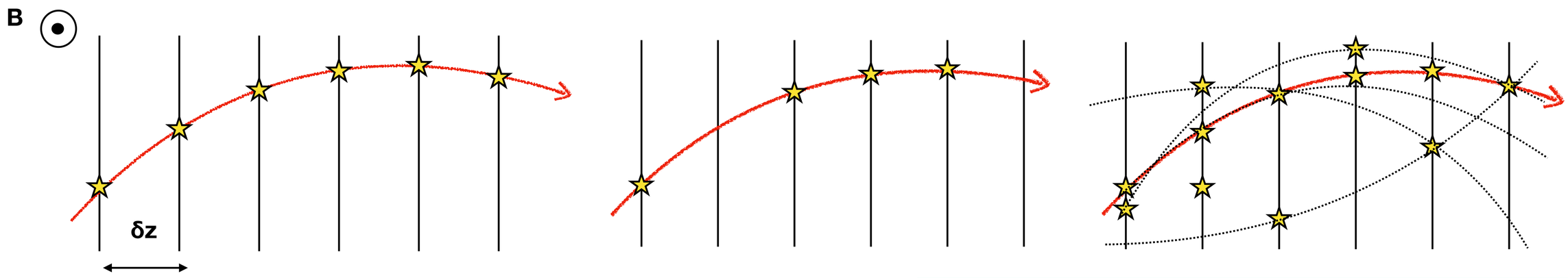
$$C_k^n = C_k + A_k (C_{k+1}^n - C_{k+1}^k) A_k^T$$

$$X = (x, y, t_x, t_y, \frac{q}{P_T})$$

$$\frac{q}{P_T}[\frac{e}{GeV}] = \frac{1}{R \times 0.3 \times B}$$



Kalman Filter, Toy MC



✺ Toy MC

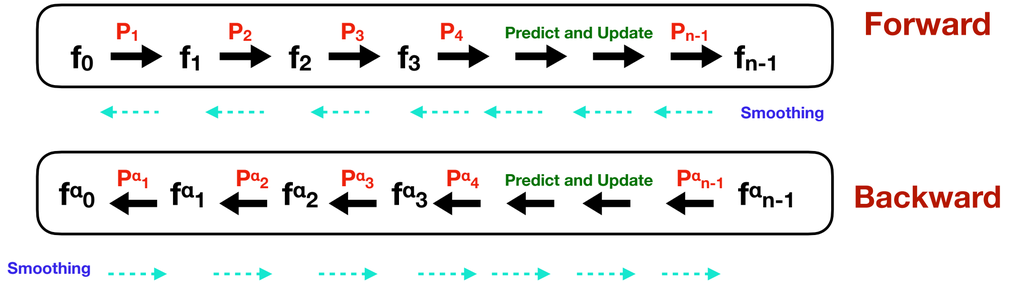
- Toy MC starting with one single track, moved to multiple tracks, noise hits added
- **Kalman Direction:** Forward/Backward
- **Measurements:**
  - Assuming uniform **B** field, 0.6 T, constant **δz** for the planes (ideal, zero thickness)
  - RN generation with uniform distribution for initial position and initial momentum
  - For each plane **X** , **Y** according to analytic extrapolation, with 95% efficiency
  - Smearing 0.1mm for **X** and **Y**

✺ Kalman Filter Procedure:

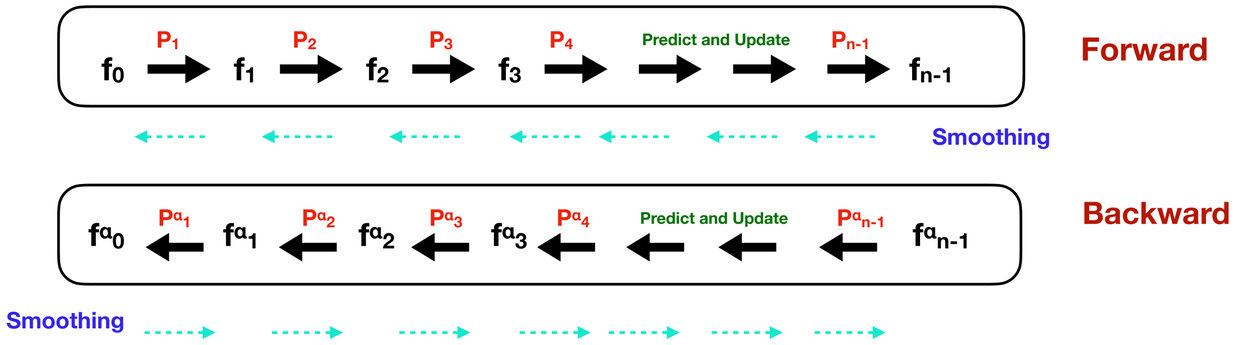
- Sequentially adding new information on each hits to get an optimal track
- **Strategy:**
  - Prediction and Update (Filtering, Residual , χ^2): forward and backward, Smoothing

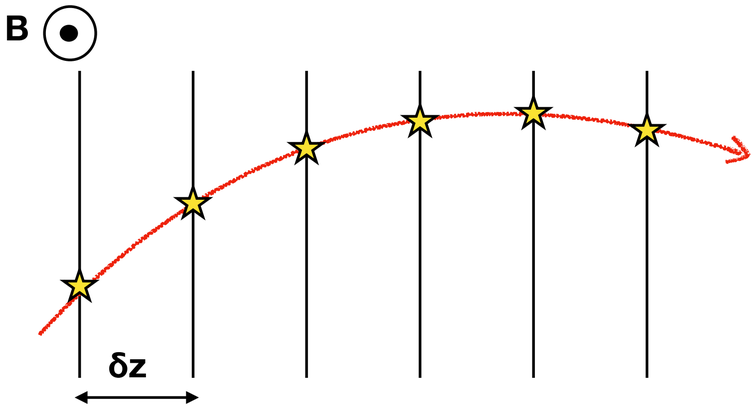
✺ Customized Kalman Filter General Assumption

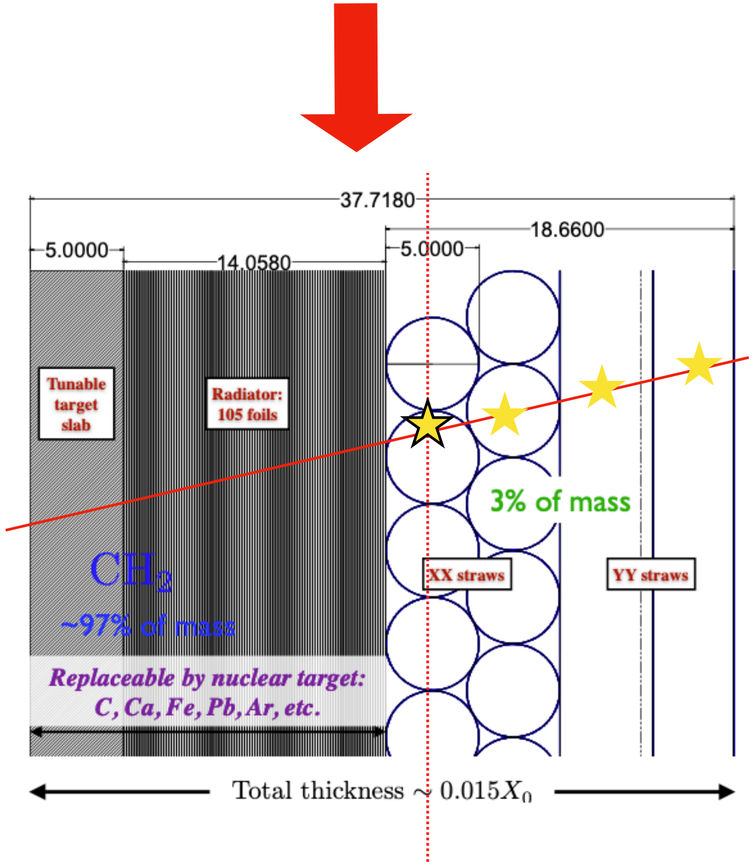
- Prediction step is an analytical extrapolation
- Discreteness in z direction



Kalman Filter, from Toy MC to **Geant4** MC







✺ Preparation for Geant4 MC

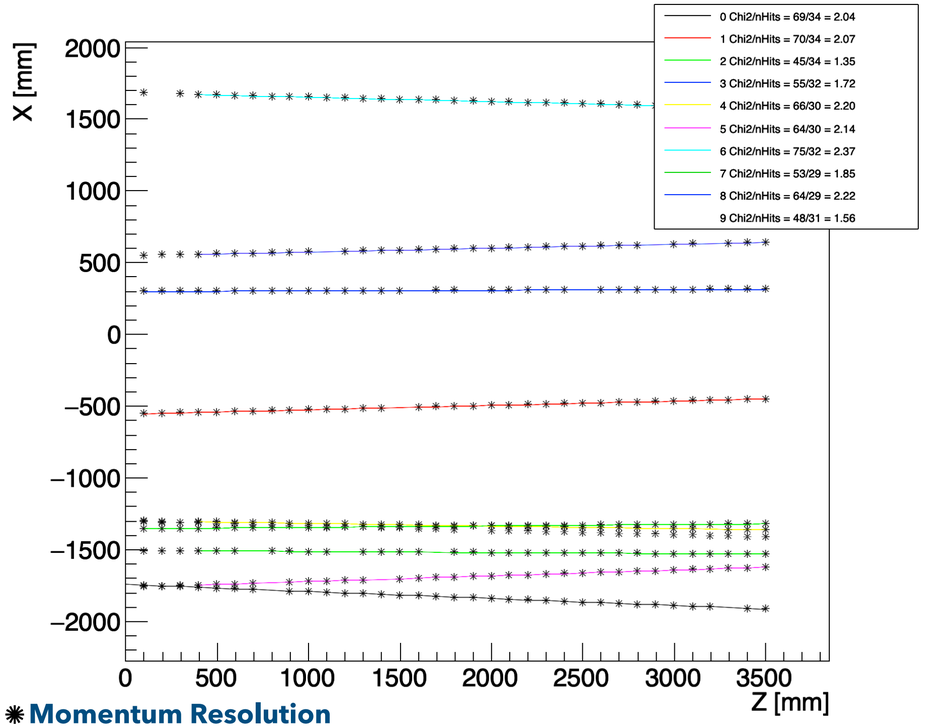
- Mad-Dump: Genie-like output
- EdepSim (*nd_hall_kloe_sttonly.gdml*): Edep-Sim output
- Digitization (200 μm smearing): wire position added (to meet with Kalman Filter discrete process that goes in steps, e.g. zero uncertainty on z coordinate of the plane)
- **X,Y** hits are combined into an extrapolated measurement at the z of the wire of the upstream plane of the module

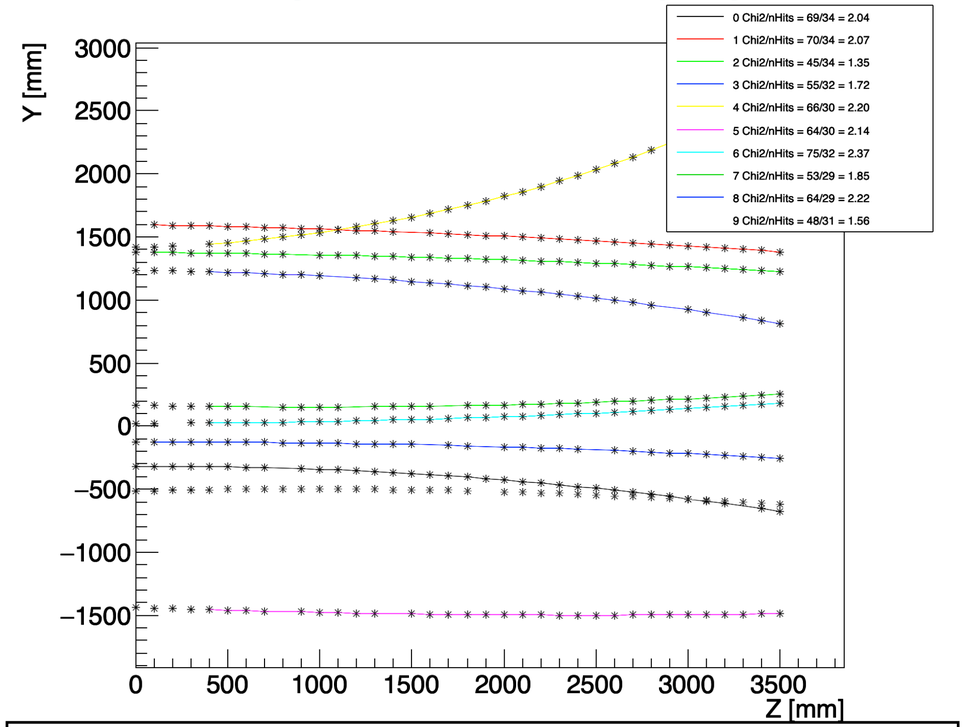
✺ Kalman Filter Geant4 MC

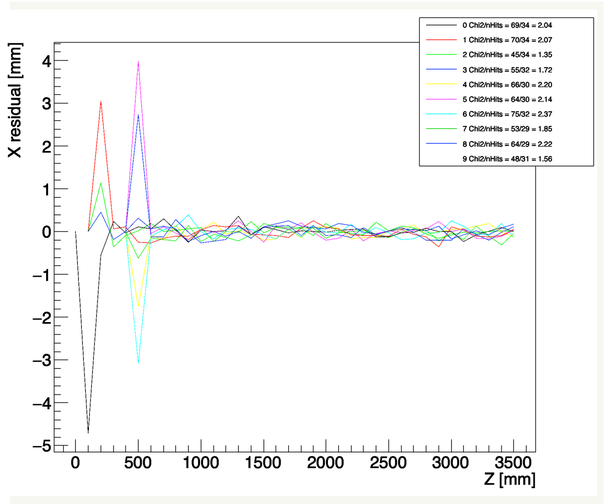
- HNL sample 1 GeV mass , $D_s \rightarrow N_2\mu$, $\mathbf{U_\mu : U_e : U_\tau \sim 1 : 16 : 3.8}$
- Forward/Backward
- **Customized Kalman Filter Assumptions**
  - Straw modules: XXYY or XXYYXX (present in this geometry)
  - Uniform **B** field, 0.6 T
  - Processing hits:

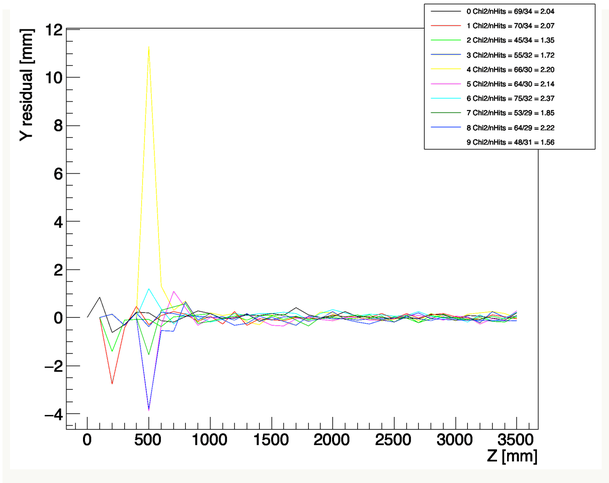
Separate measurement for X and Y are recombined to (X, Y) referring to the Z of the first straw layer of each module

Kalman Filter, Toy MC, Event Display



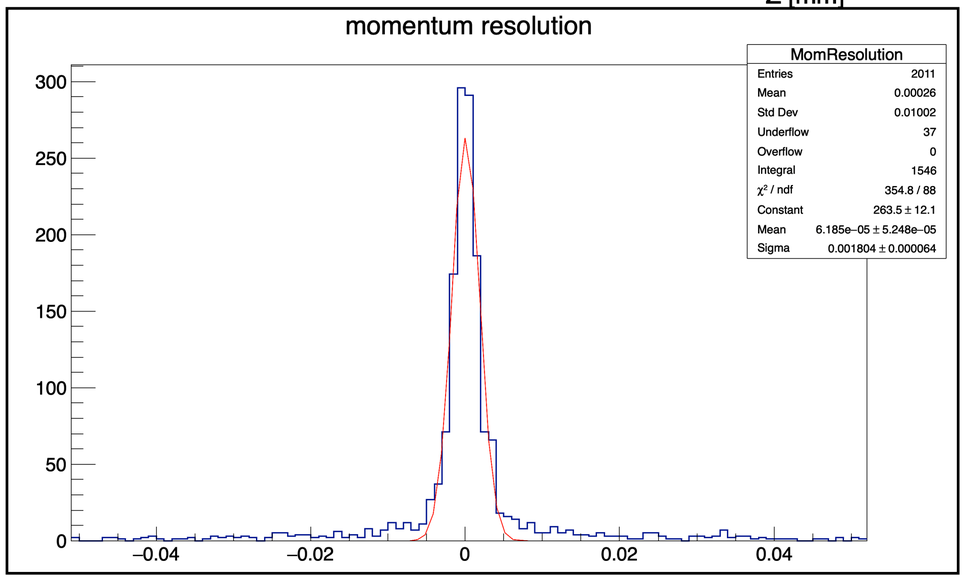






✺ Momentum Resolution

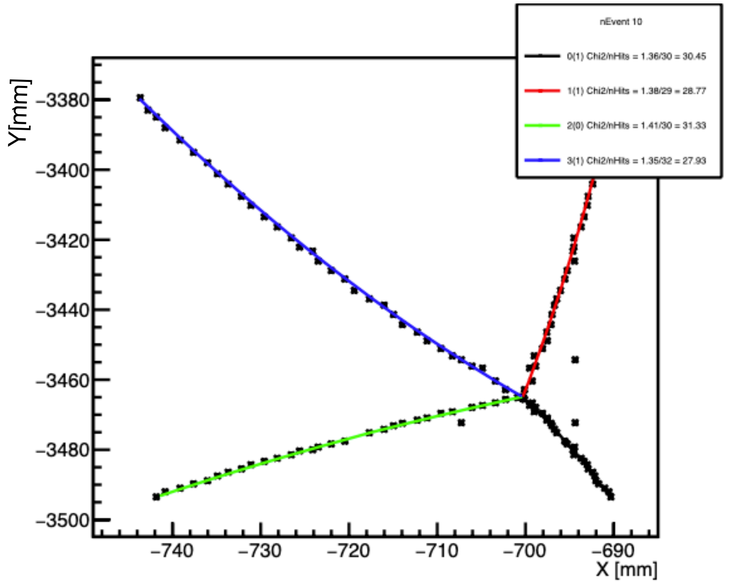
- Sigma 0.2% ➡ contribution of the Kalman Filter process to momentum resolution
  - Detector's contribution under-estimated by the simple simulation approach
- Toy MC could be improved:
  - Mimic a closer geometry to the real one, e.g. the separate measurements for X and Y
  - Individual effects like MS can be studied

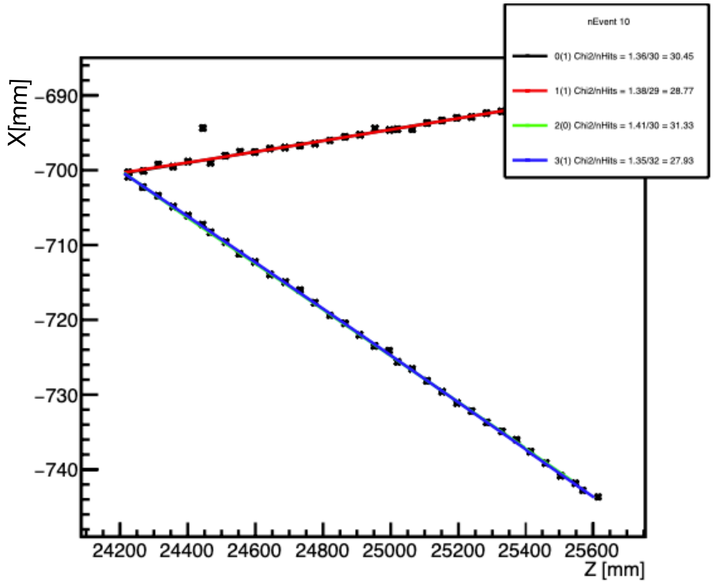


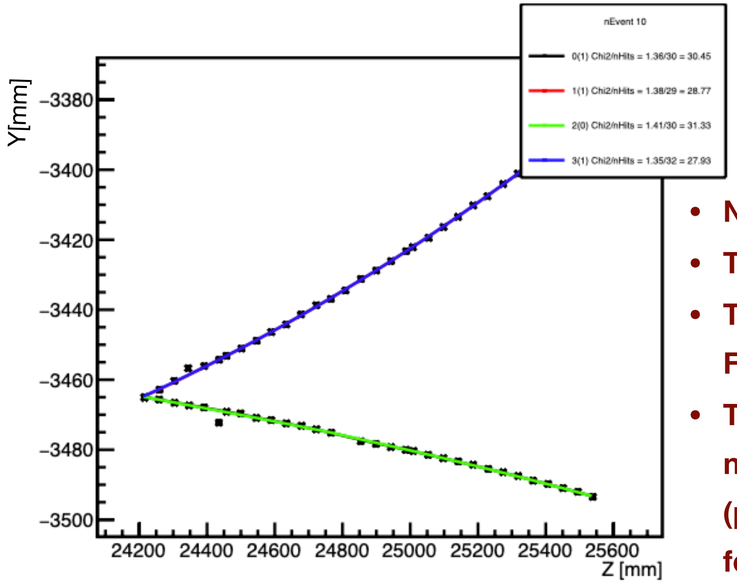
✺ Efficiency

- Seems to find all tracks up to 10 tracks but a realistic estimate on efficiency is not worth for this toy MC

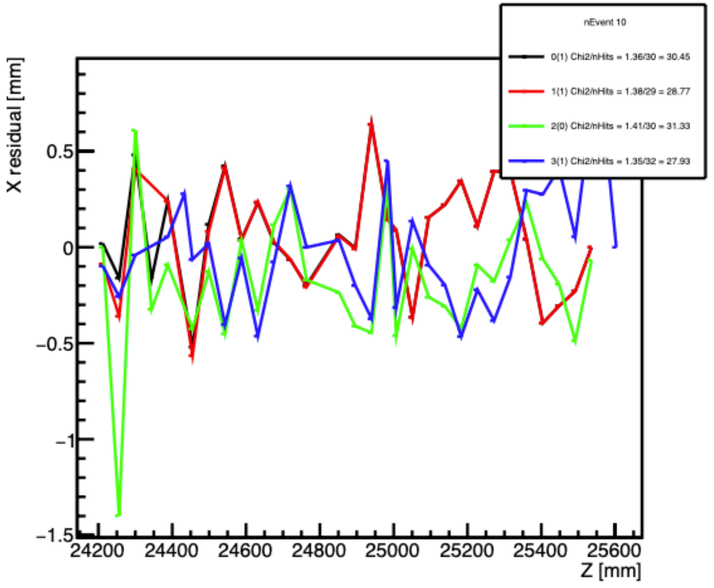
Kalman Filter, GEANT4 MC, Event Display

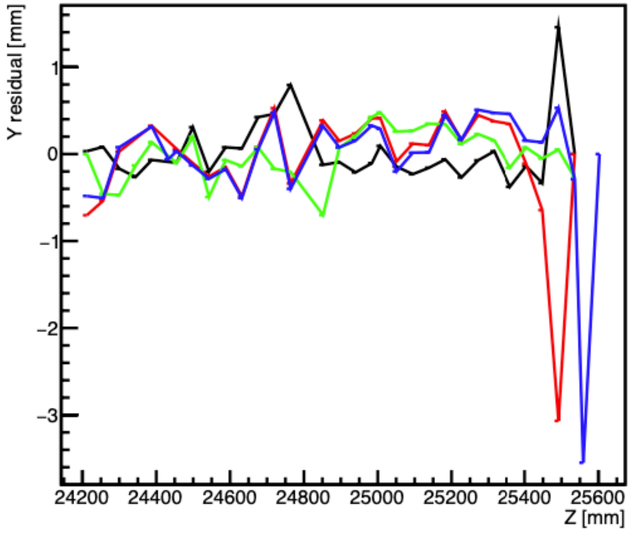




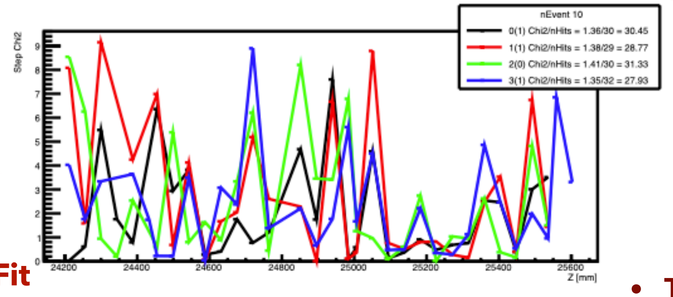


- No MC matching
- The hits: digitization
- The solid lines: Kalman Filter
- The ghosts usually are not back to back (potential discriminant for this channel)
- The χ^2 :
  - Point rejection(Update stage) $\chi^2_{threshold} \sim 30$
  - The external fit χ^2 for the tracks
- The bottom graphs show the spacial residual fluctuations

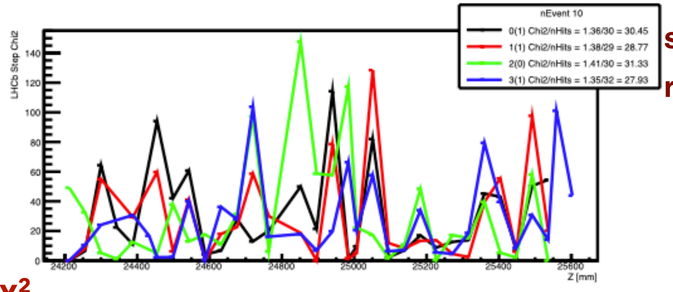




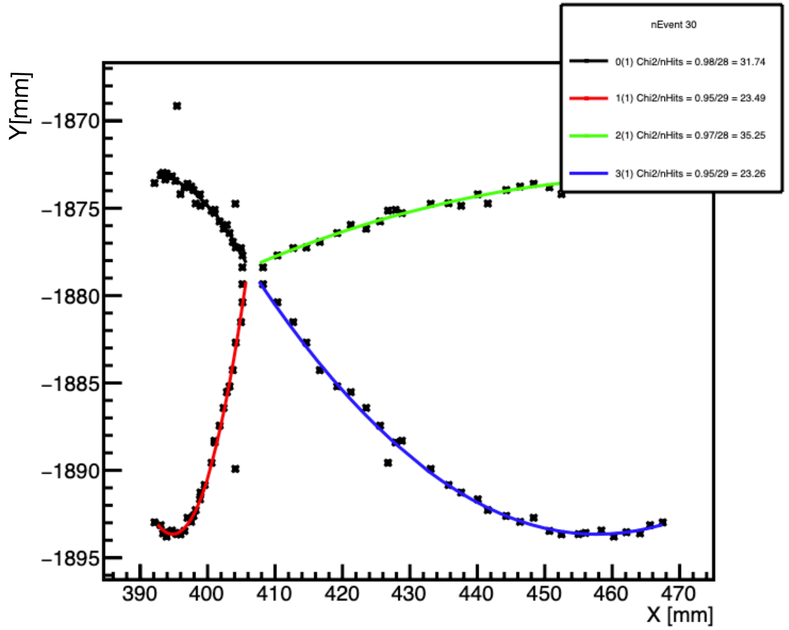
External Fit χ^2

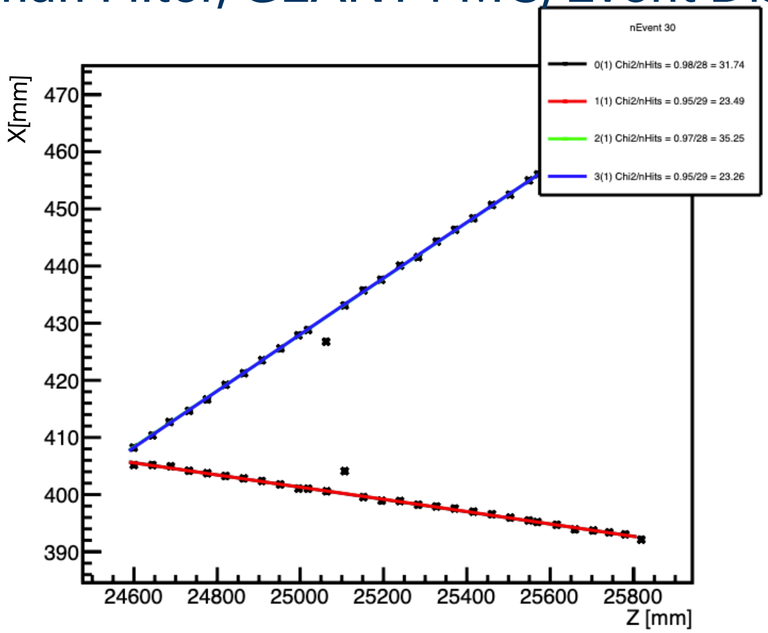


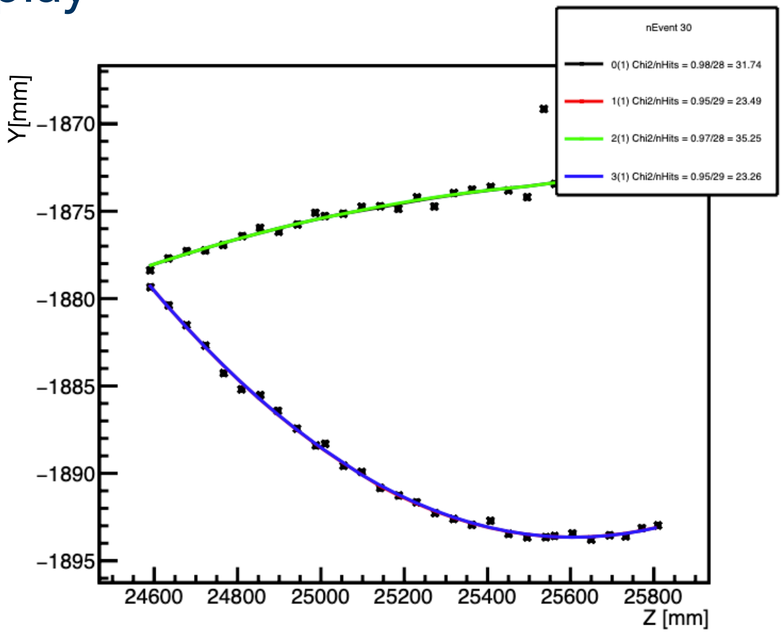
Point rejection χ^2

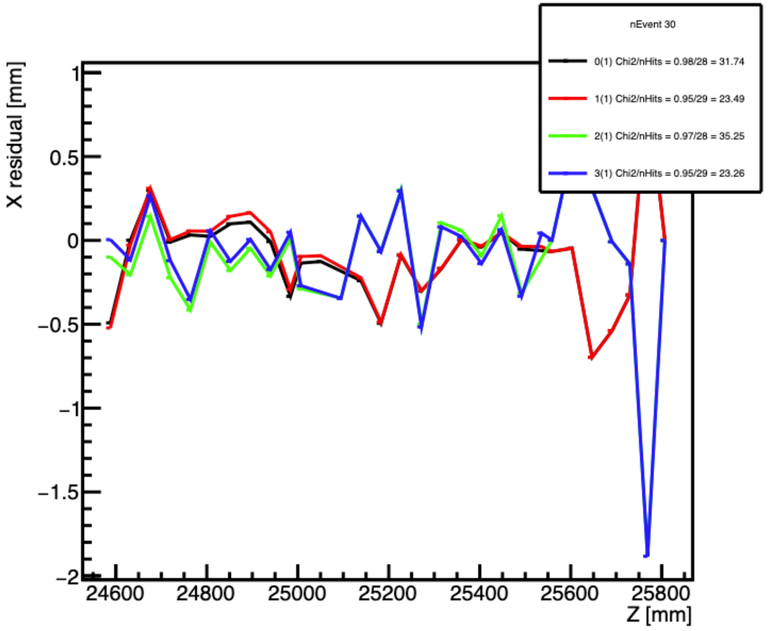


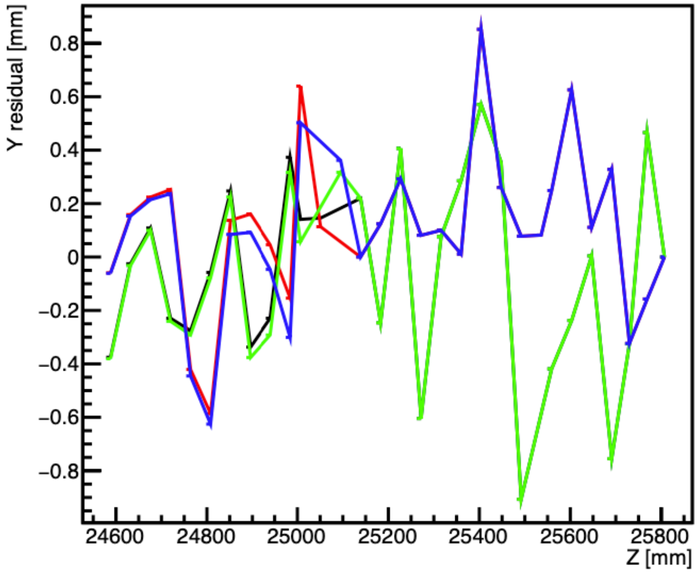
Kalman Filter, GEANT4 MC, Event Display

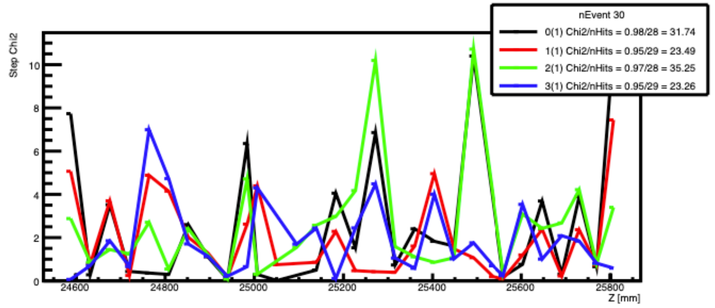


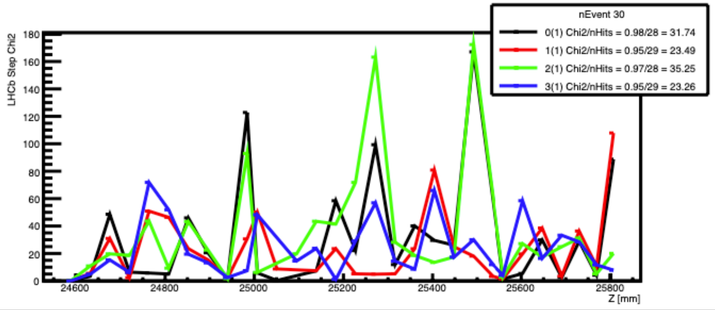




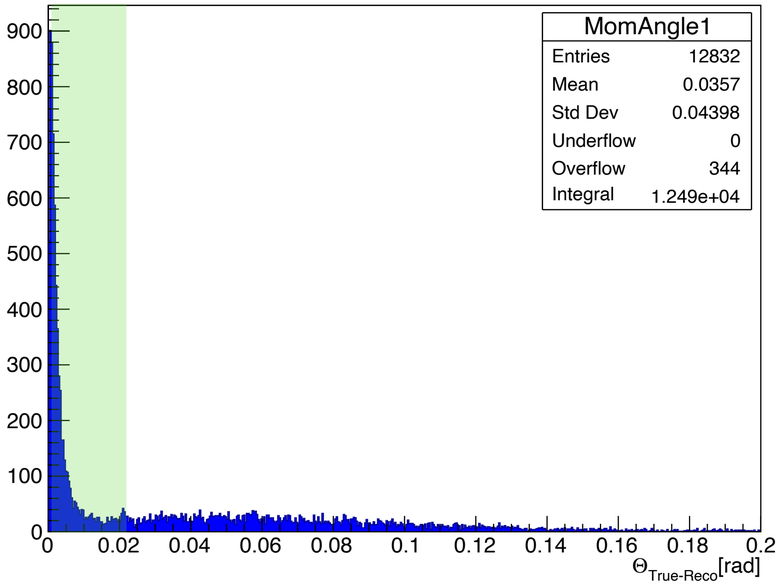


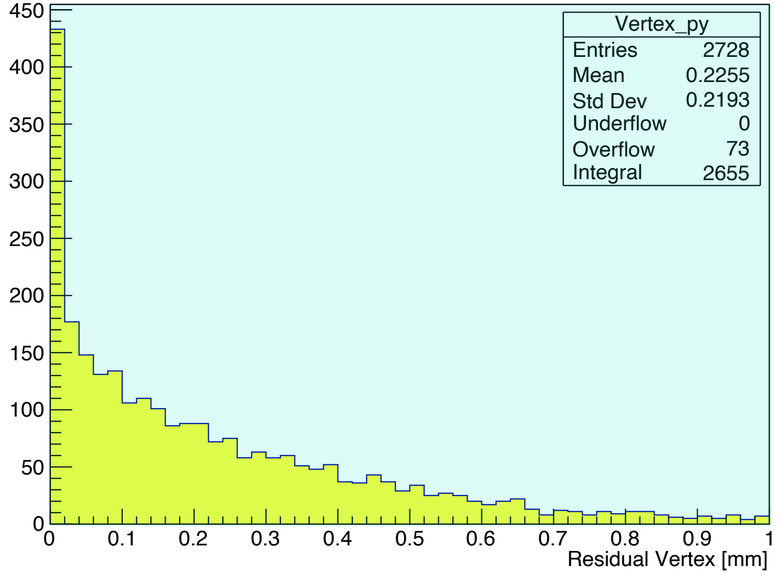


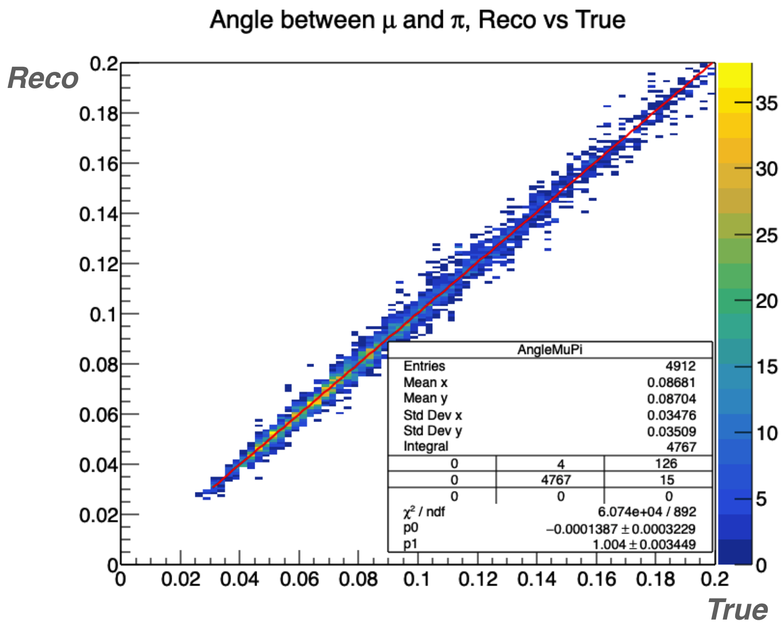


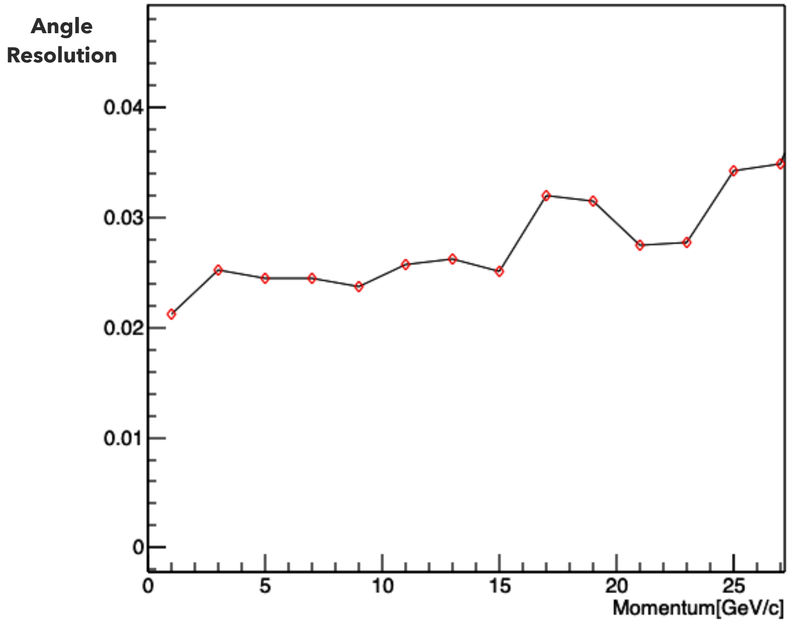


MC Truth Matching









- **Dominant contributions to Invariant Mass (besides Momentum)**
  - **Quality of the Vertex:** < 1mm (most of statistics)
  - **Quality of the Reco final product angle:** The final product angle resolution is around 30 [mrad] up to 25 [GeV]
  - **MC truth Matching angle (preliminary):**

    Significant tail on the single particle angle resolution (currently cut by MC truth matching ~ 20 [mrad])

Kalman Filter, GEANT4 MC

Features

- Backward Kalman direction implemented, in this case backward is more efficient: the initial hit is found easier and more precise (MCS not messing with the hits much)
- Multiple scattering has been added (changing the resolution by 0.1%)
- For better precision, external helical fit has been used (hits are coming from Kalman Filter, the used fit is the external one)

Items to have an eye on:

- Invariant Mass resolution
- Momentum resolution
- Kalman Filter parameters (Pull plots)
- Goodness of the fit (χ^2)

Procedure:

- Kalman Filter
  - Forward/Backward Kalman and smoothing.
    - External helical fit.
    - Reco tracks:
      A. Choosing either forward or backward as Reco tracks.
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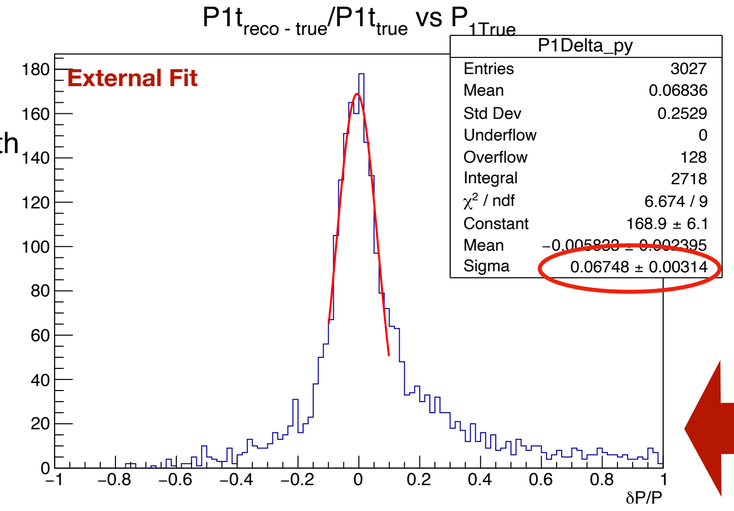
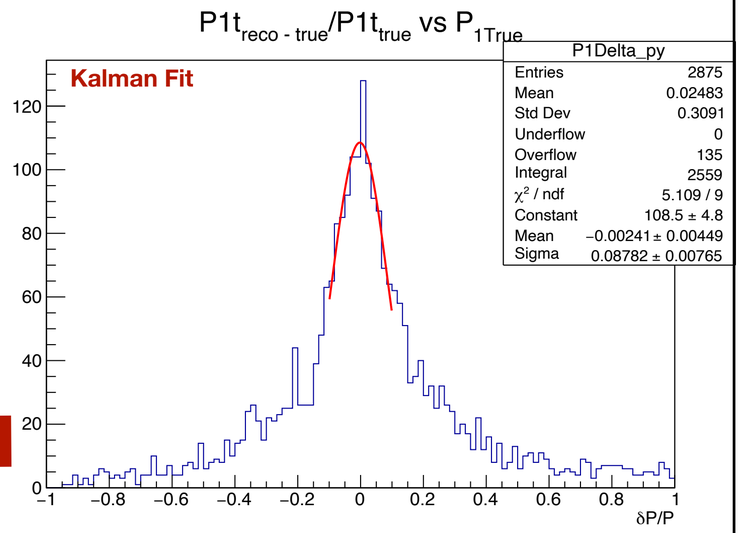
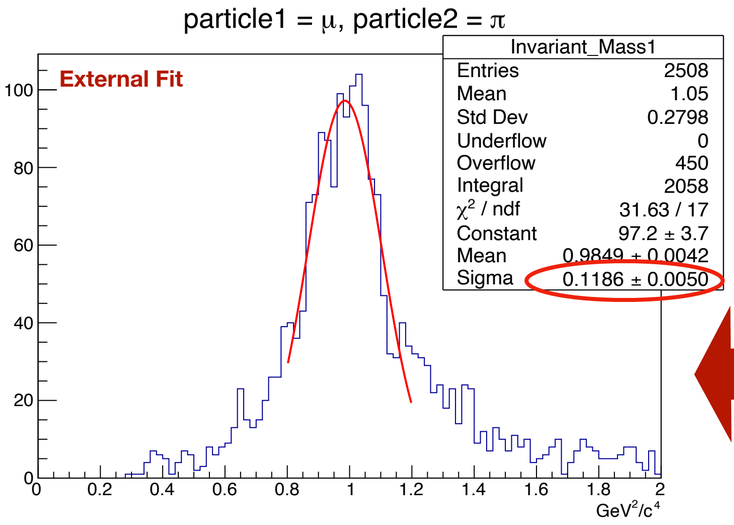
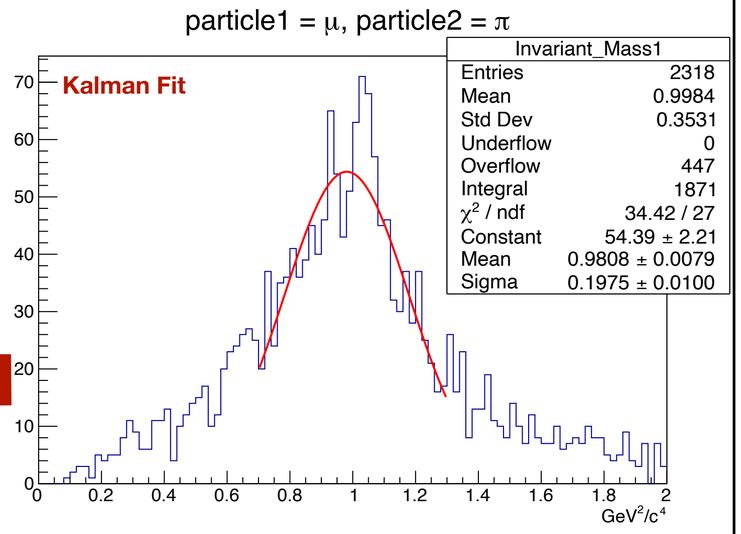
- Matching the Reco and the True
- Momentum resolution, invariant mass resolution, Pull plots









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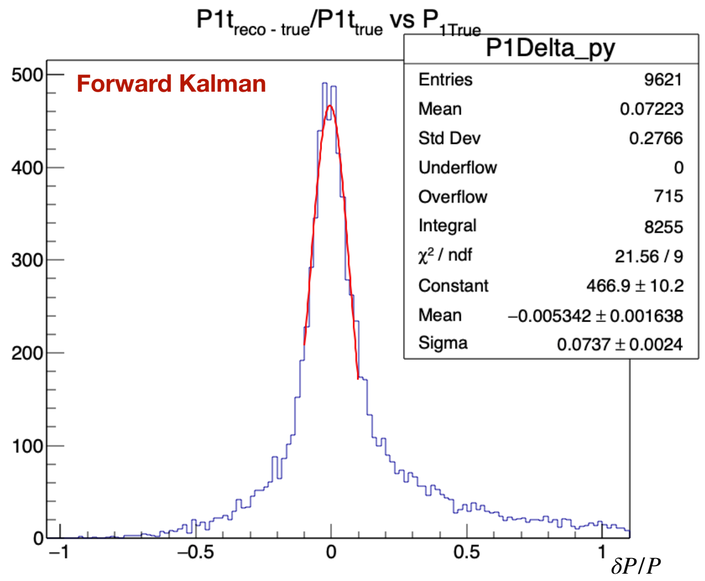

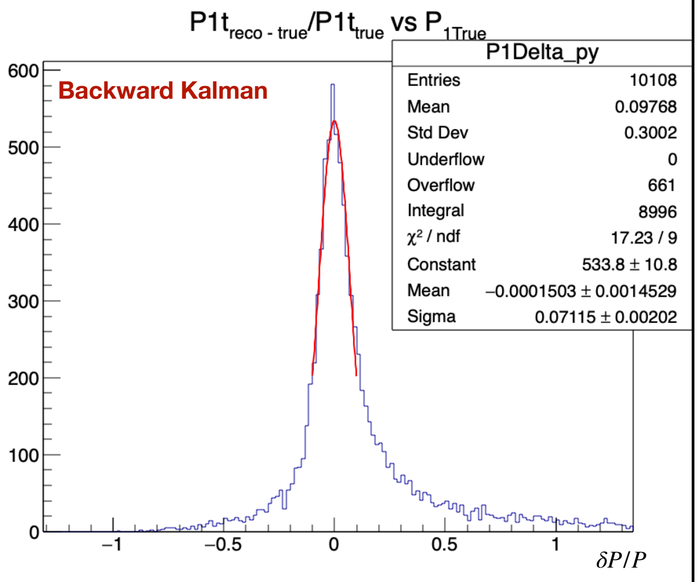

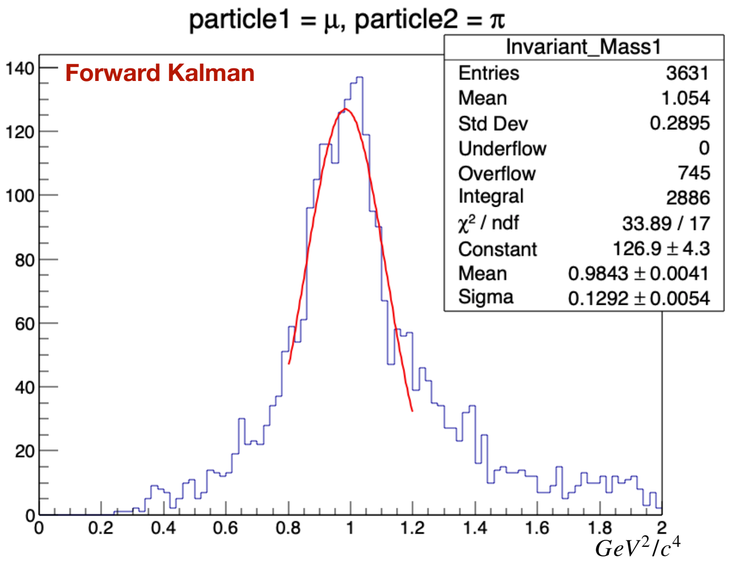

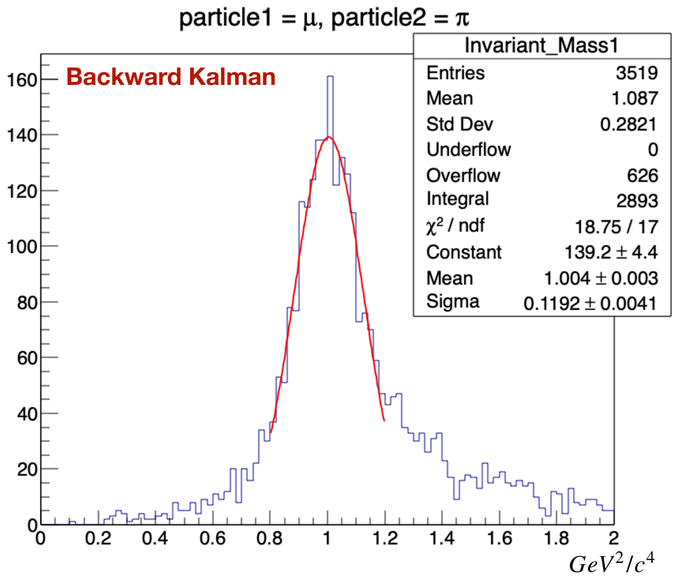

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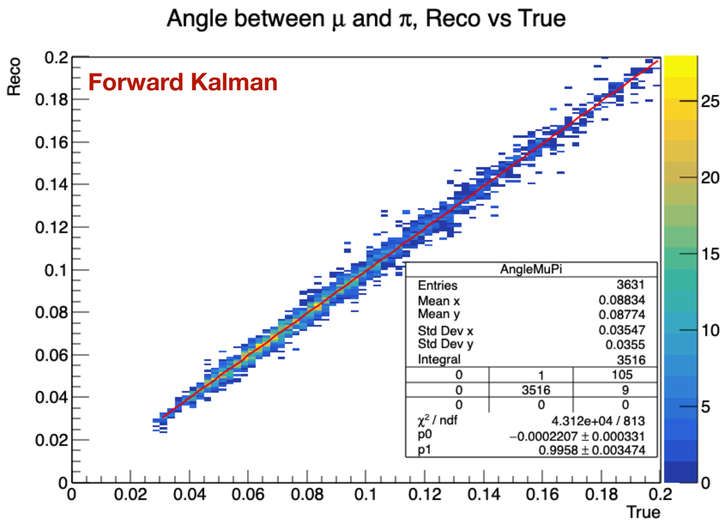

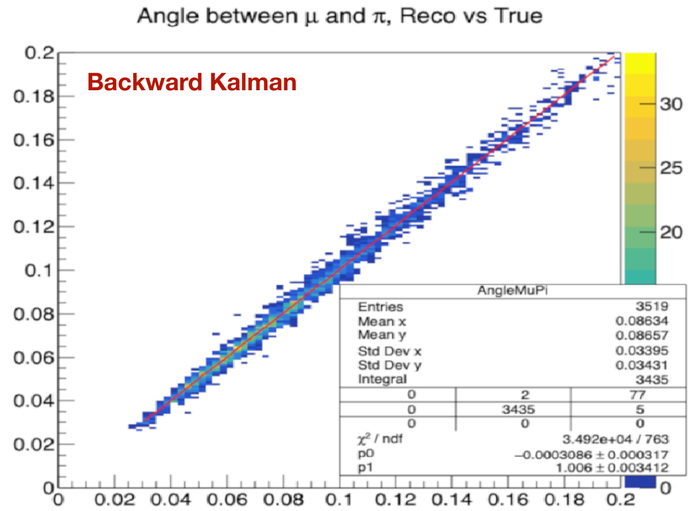

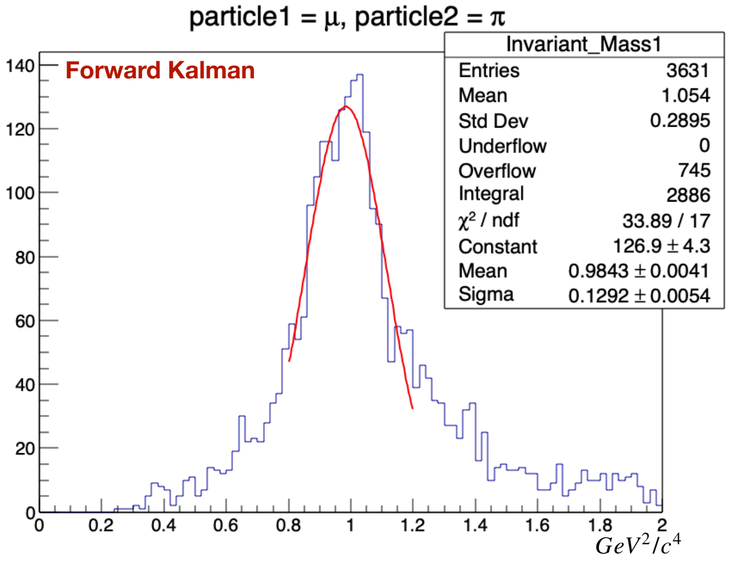

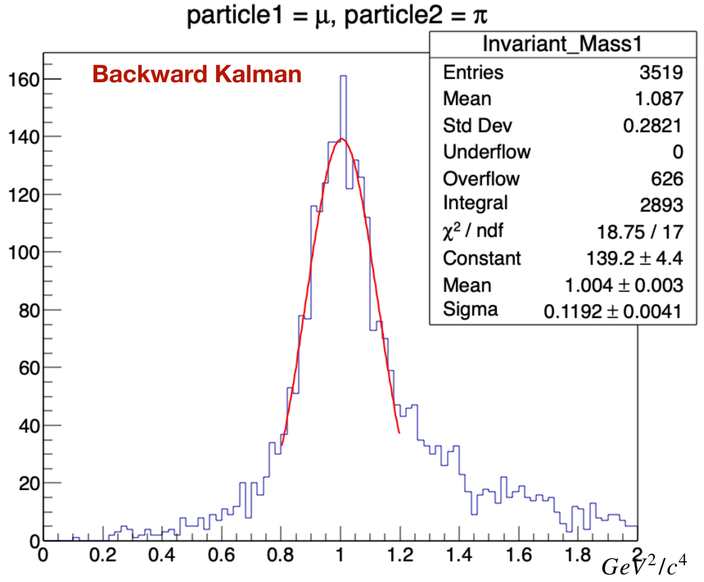

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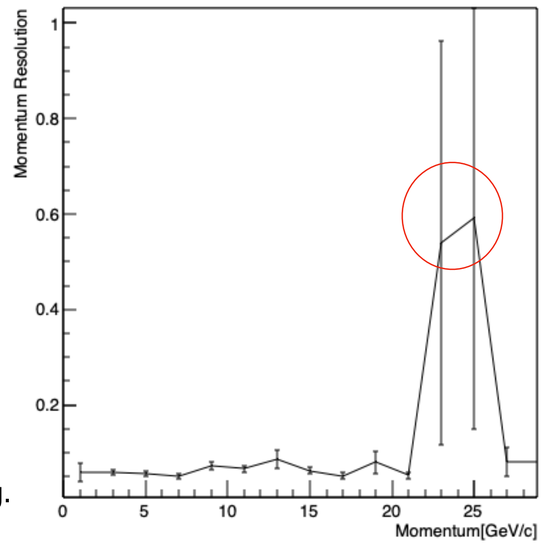

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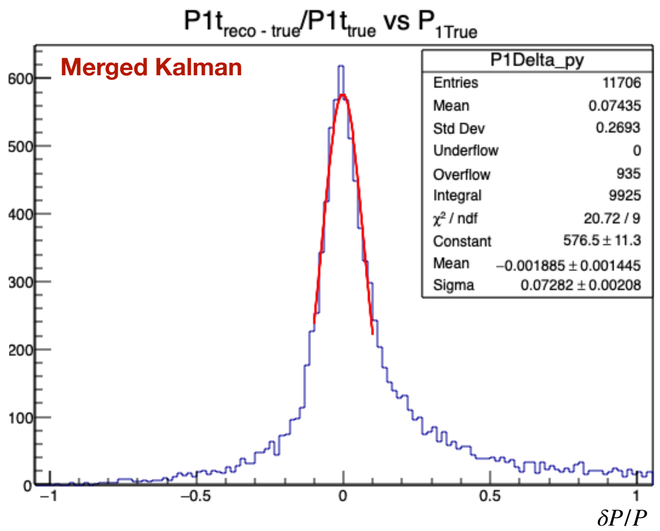
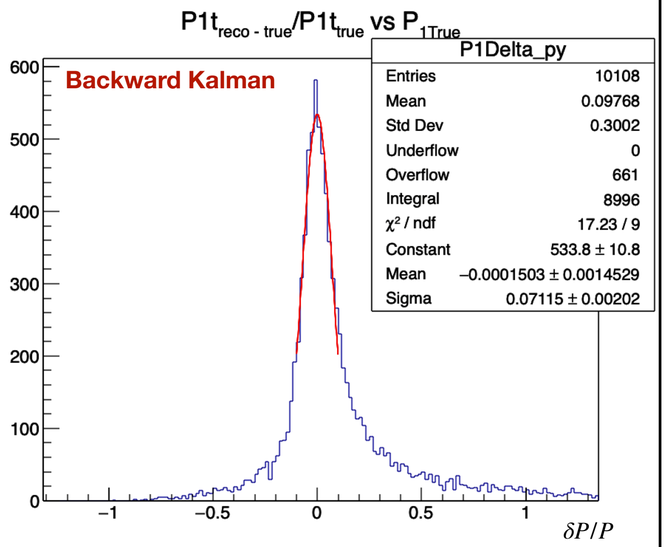
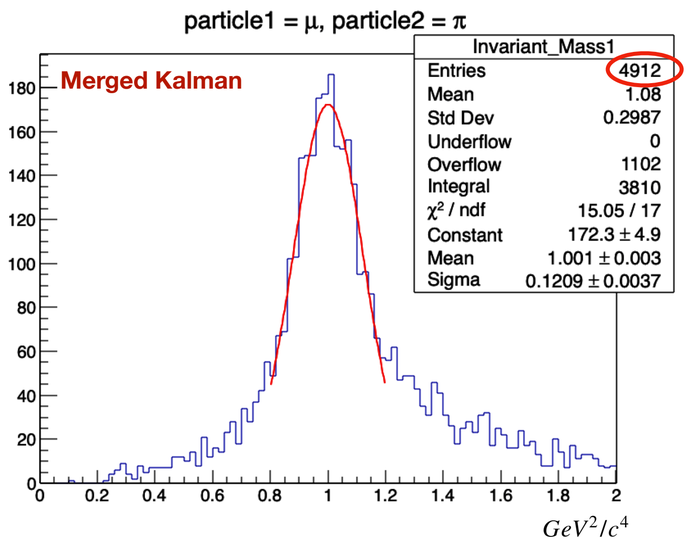
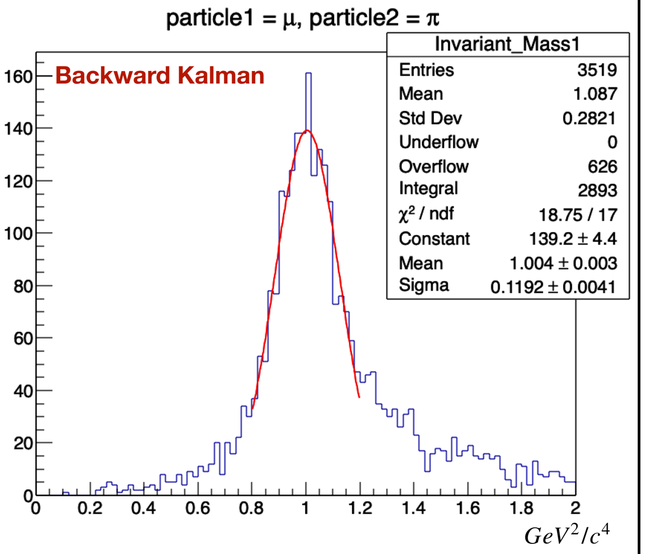
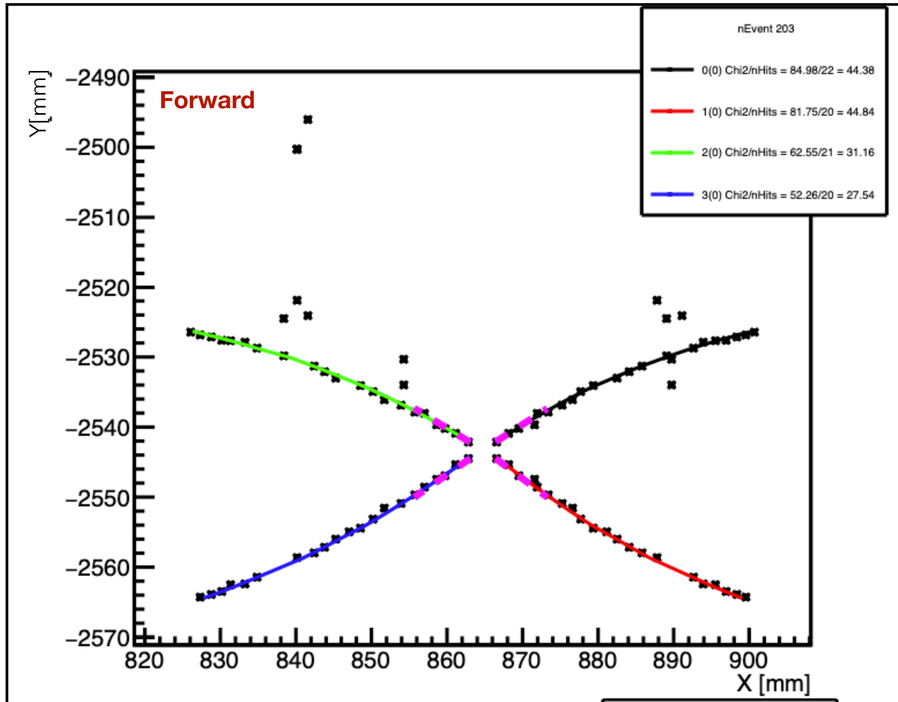


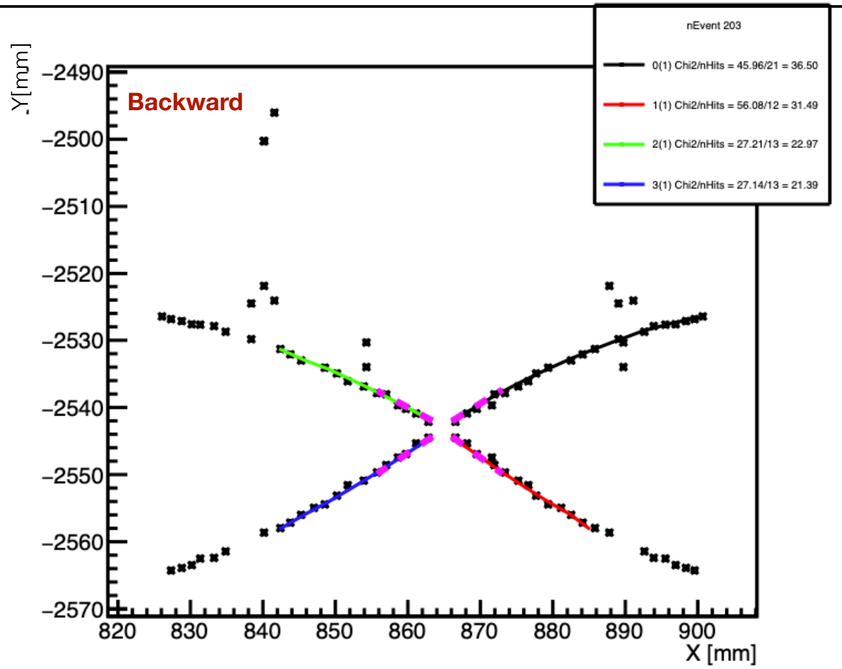


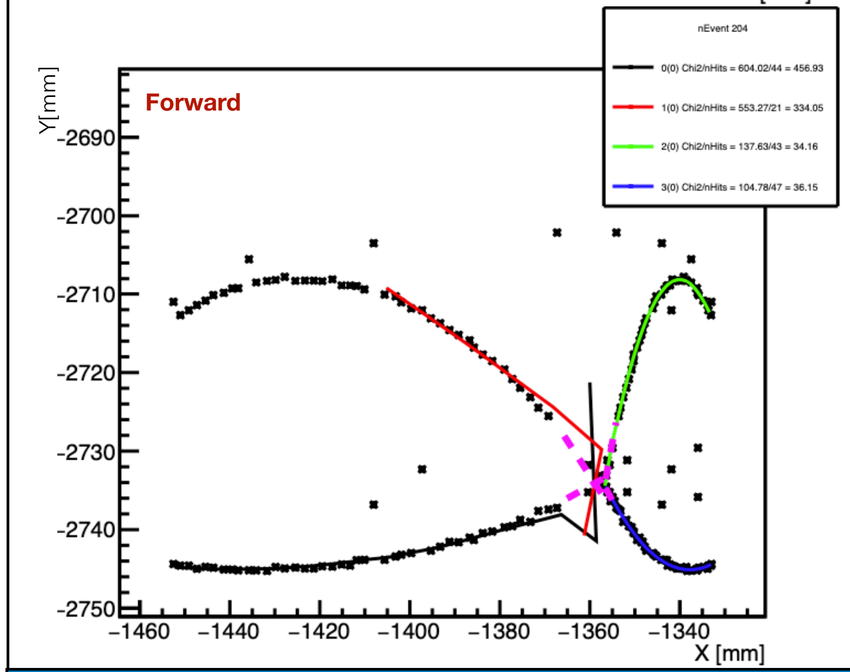


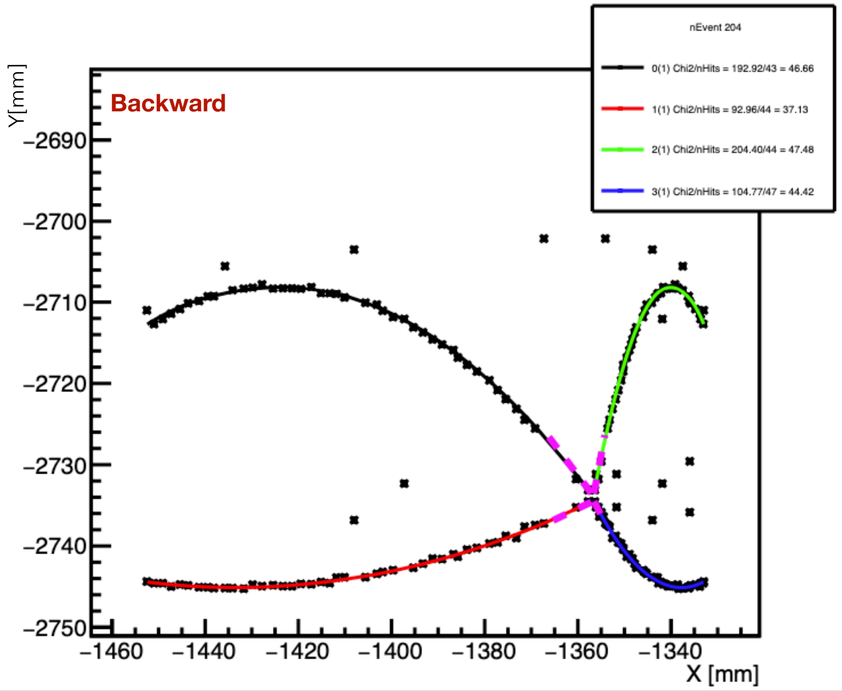


Event Reconstruction





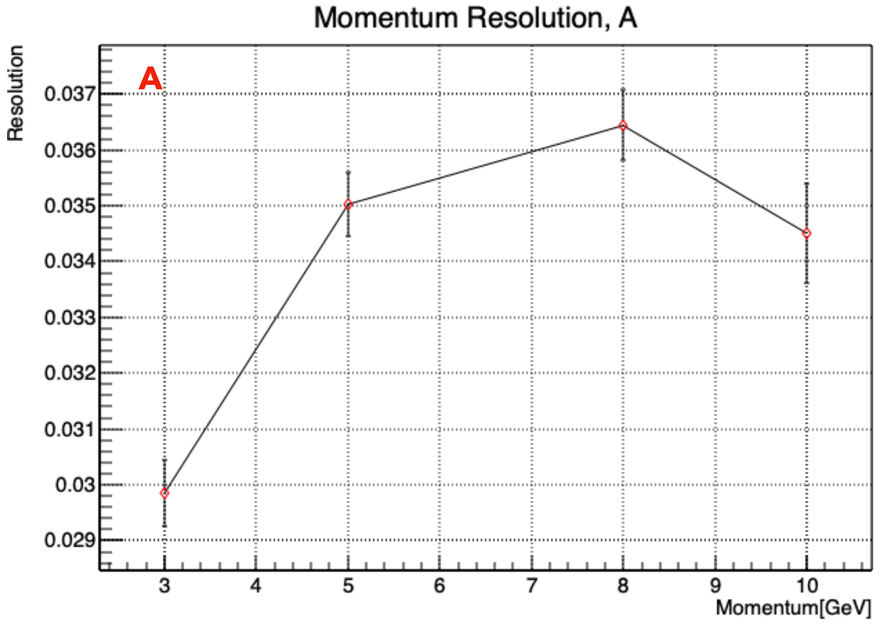




Kalman Event Reconstruction

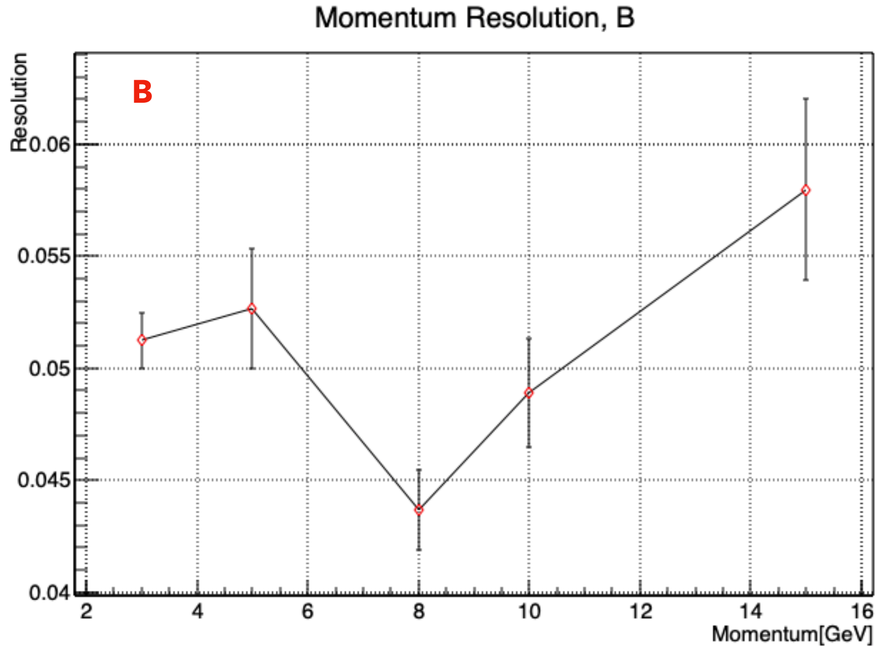
- **For/Backward tracks**
  - The more apart the hits the better the track recognition
  - Statistically, the backward Kalman is more efficient
- **Merged tracks**
  - Enhancing the InvarMass resolution
  - Recovering the events failed in either of For/Backward process
  - Saving the better reconstructed event
  - Any risk of double counting is eliminated by the selection
- **Preliminary Efficiency estimate**
  - Accepted tracks:
    - Extrapolation of the track up to the exiting point, count the # plane
    - Number of planes = 6
  - Single track efficiency ~ 80%
  - Event (pair of tracks with a vertex< 1mm) efficiency ~ 60%

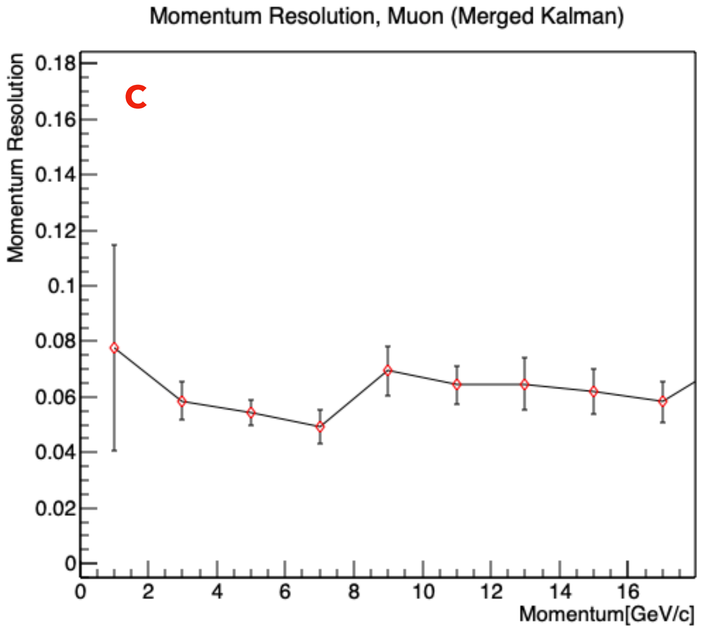
Resolution Comparison

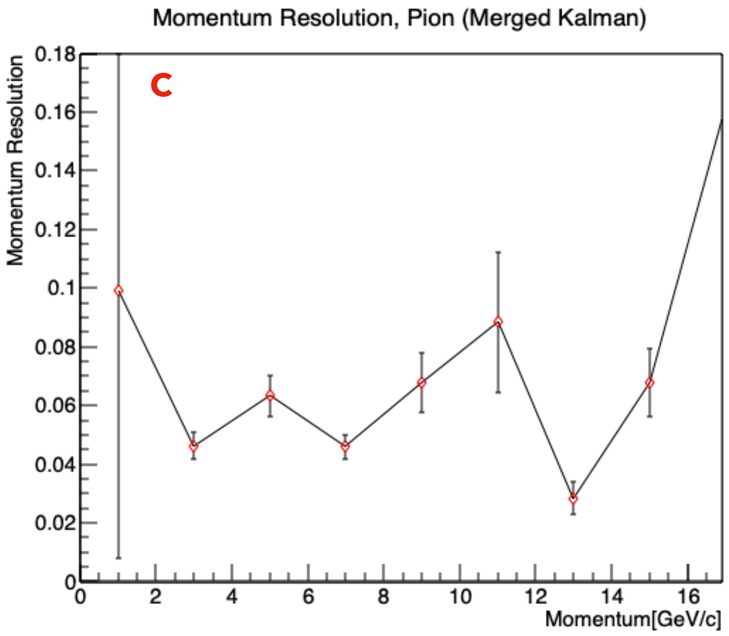


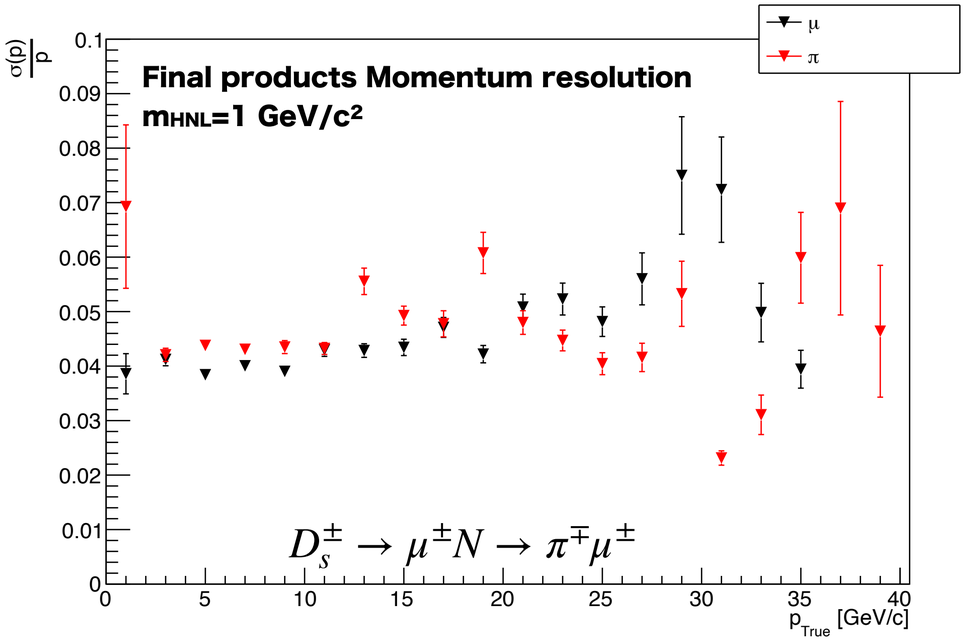
Samples

A. Monochromatic, simple single muon: fixed point, fixed direction (horizontal)
B. My event-like muons (Cylindrical distribution, comparable angle to my sample)
C. HNL sample









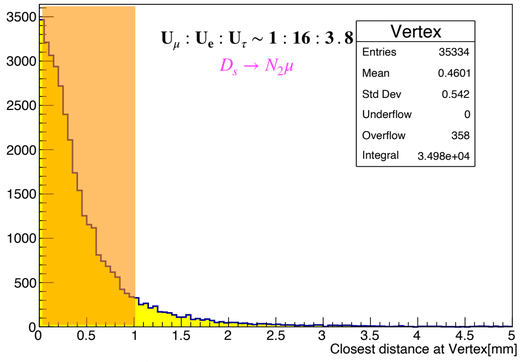
Event Selection

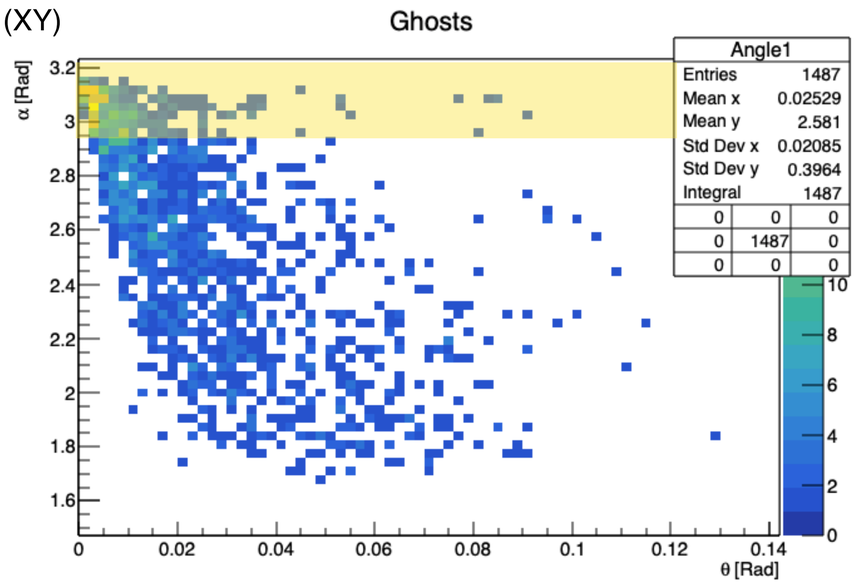
Events Kinematic

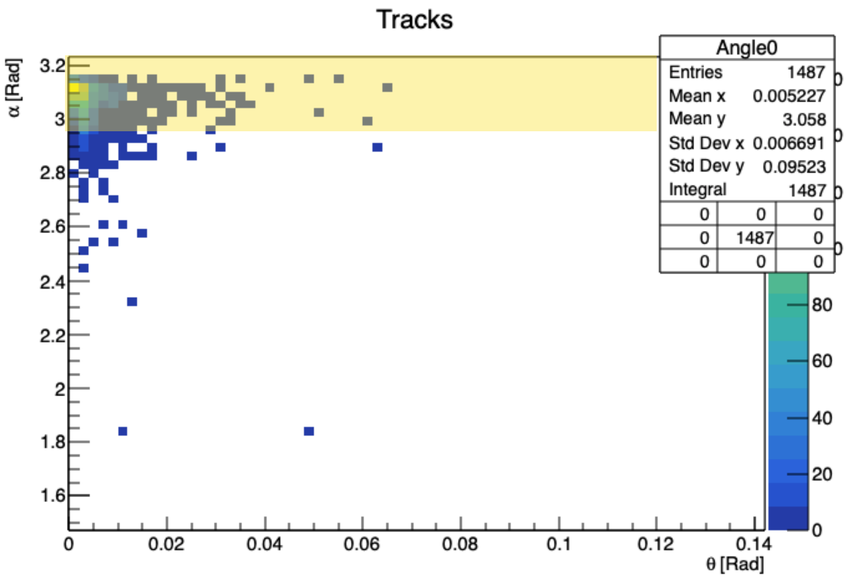
- Heavy Neutrino: High P, mostly with low **θ**: back to back (XY) 2-body decay

Vertex quality

- Vertex residual cut $< 1mm$



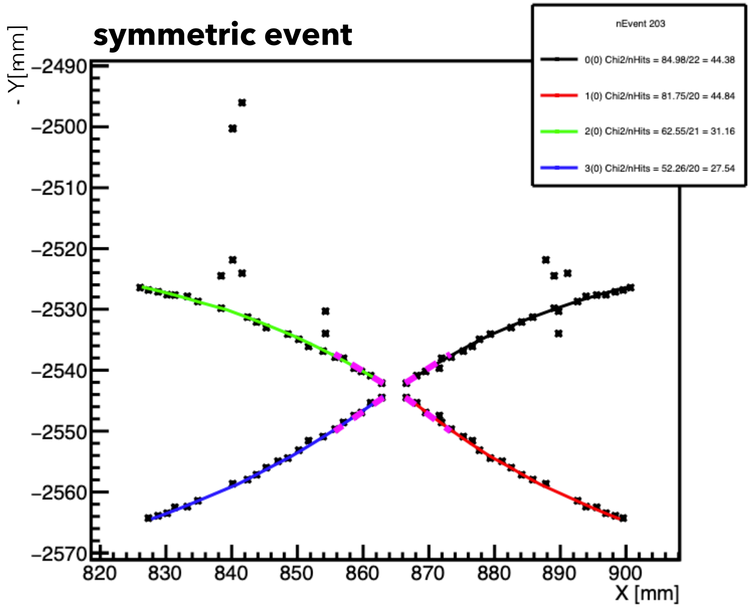


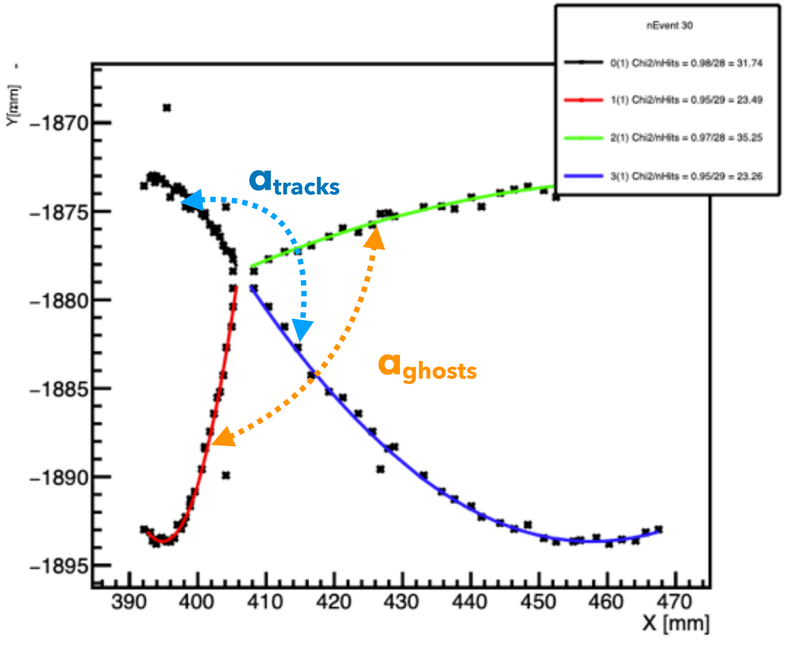


Treatment for Ghosts

- Opposite charges and tracks in opposite quadrants XY
- **α** angle in XY between the ghosts or the tracks
- Theta is the angle of HNL with respect to the z-axis
- Alpha is geometrically correlated with theta
- A cut can be made for selecting the tracks from ghosts:

  " $\alpha > 2.9, \theta < 0.02$ "
  - Removes most of the ghosts contaminating the signal
  - The remnant ghosts:
    - No effect on the resolution (very symmetric events)
    - Compensated by a correction factor





Particle ID

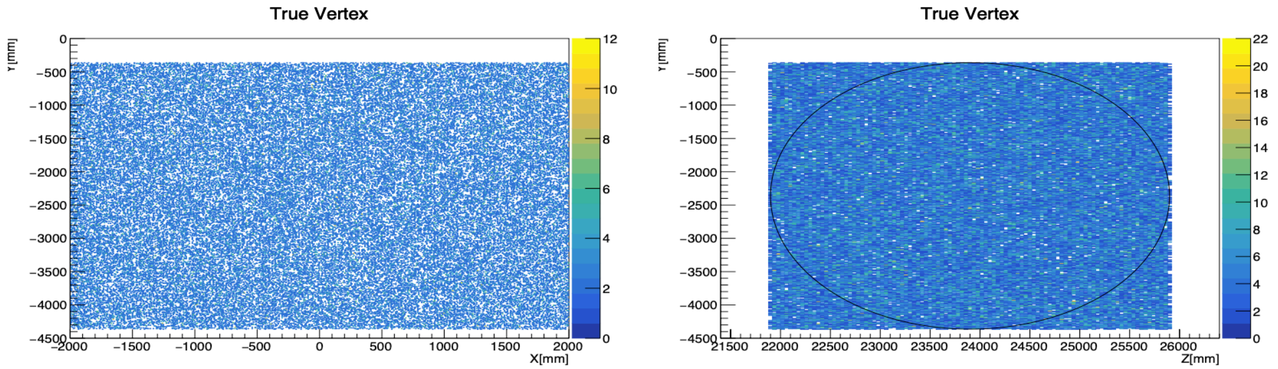
- Not necessary at this stage: Swapping π-μ has negligible effect on Invariant mass resolution

Acceptance and Efficiency

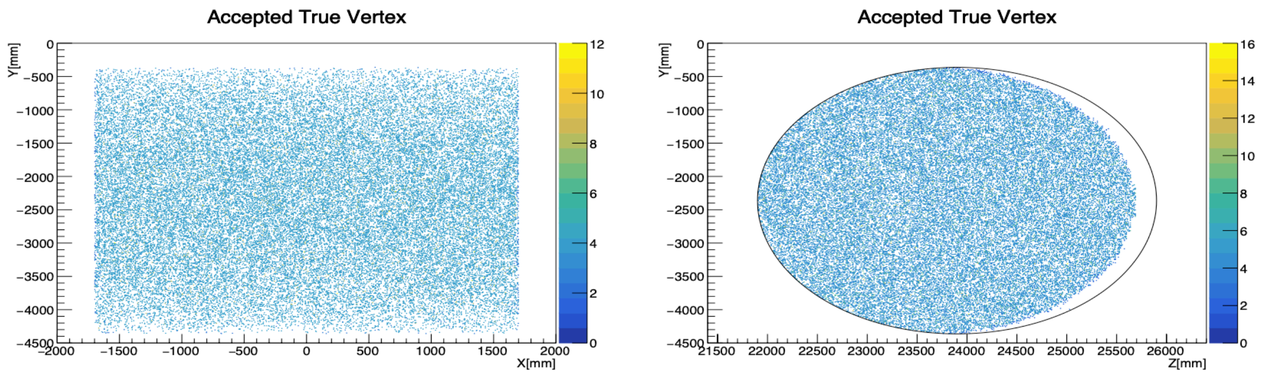
- **Acceptance**
  - Reconstructible fraction of the total number of generated signal
    - **Pre-selection FidVol**
      - Cubic fiducial cut at generation step enveloping the detector
    - **Reconstructible: Long tracks**
      - The extrapolation of the tracks to the detector walls must include 6 or more traversed planes
  - Accepted Events: A = Reconstructible/generated
- **Efficiency**
  - **Signal candidate:** Track pair with **opposite charge** forming the **invariant mass**
  - ε4 = 4 track events/Accepted events
  - ε = Selected signal candidates/Accepted events
  - g = physical tracks/ghost tracks

Acceptance | 4 trk efficiency | Selection efficiency | Ghosts

Acceptance and Efficiency						
Channel	Mass$[GeV/c^2]$	Total Number of Event	$A\%$	$\epsilon_4\%$	$\epsilon\%$	g%
$D_s \to \mu N_2$	1.7	168186	53	58	42	27
	1.6	217118	55	57	43	26
	1.5	212892	47	57	43	27
	1.4	181300	62	35	26	26
	1.3	197050	62	57	43	28
	1.2	186388	48	57	43	29
	1.1	170394	55	56	41	30
	1.0	154438	62	56	42	31
	0.9	136468	63	57	41	32
	0.8	119364	52	57	39	34
	0.7	92088	63	58	38	37
	0.6	92598	60	60	35	42
	0.5	85674	40	61	33	52
	0.4	80514	56	62	27	64
	0.3	76914	60	63	18	92

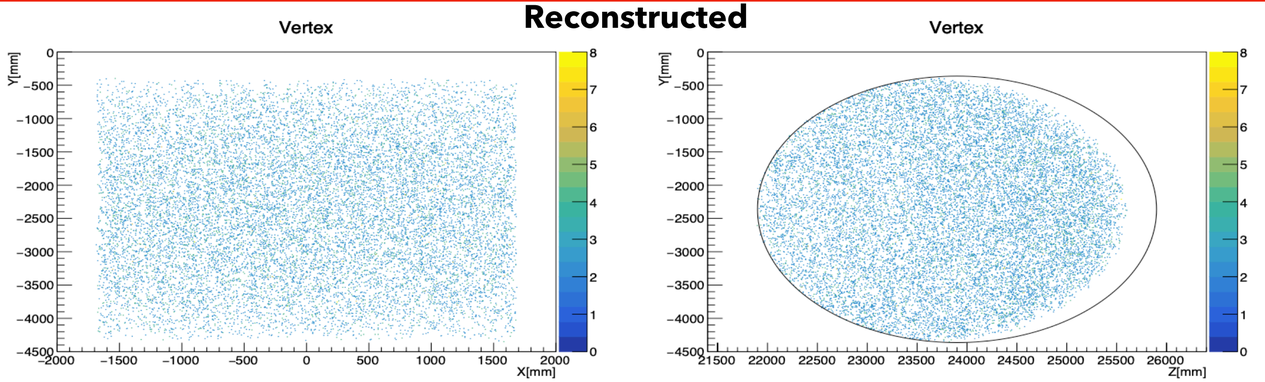


(a) (b)



(c) (d)

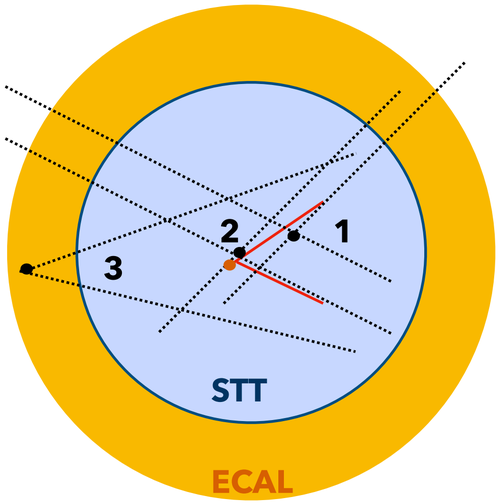
Reconstructed

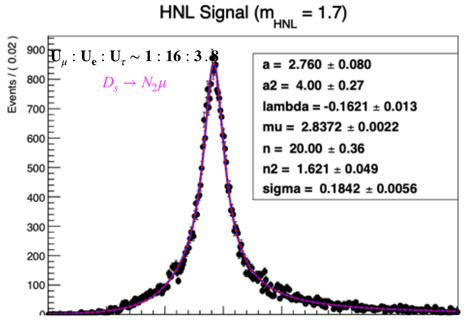


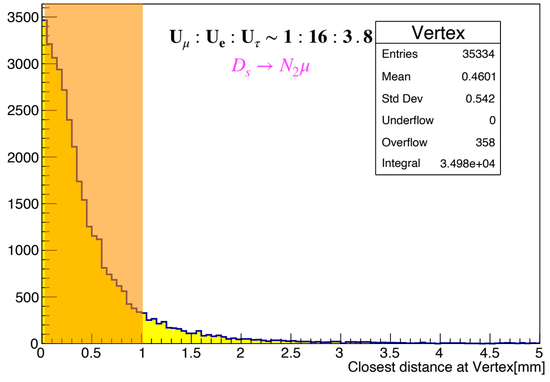
(e) (f)

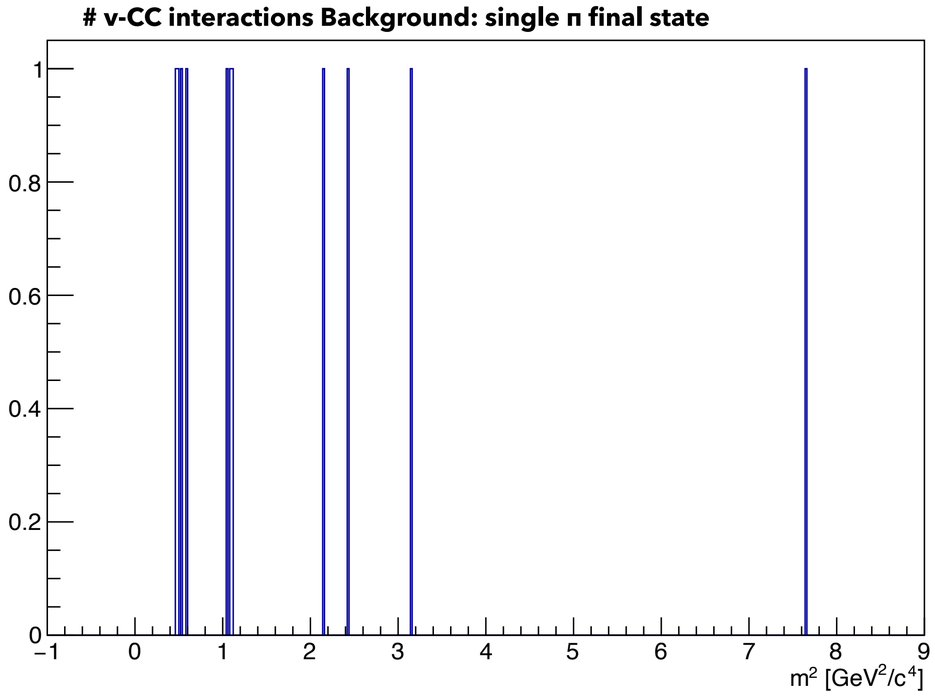
Background

- **Generic Background**
  - Neutrino interaction from the beam for 6 yrs of exposure
  - Single beam spill, T = 1.2s $\equiv 7.5 \times 10^{13}$ POT within the full body of detector: Number of ν interactions ~ 1.3×10^{10}
- **Computationally Affordable Background Generation**
  - **First approximation:**
    - ν CC interactions only inside SAND inner tracker (STT)
    - Interaction inside STT is 0.74 for one single spill: 117×10^6 ν CC interactions for 6 yrs of exposure
  - **Second Approximation (High statistic only at generation level):**
    - Most dangerous final state to the signal: $\pi\mu$
    - Cherry picking the final state -> choosing events with final state single π (~30% of total events)
    - 30×10^6 ν CC interactions for 6 yrs of exposure
  - Simulation and reconstruction steps the same as for the signal
  - Background invariant mass distribution mimicking the signal (2ph+2g tracks) ➡ **11 candidates for 6 yrs of exposure**
  - **Background Modeling**
    - Uniform or exponential p.d.f.
- **Subdominant Background Event Topology and selection "handles"**
  1. Accidental vertex
     - Vertex resolution
     - Invariant Mass
  2. Outside vertex
     - Vertex resolution either/or Invariant Mass







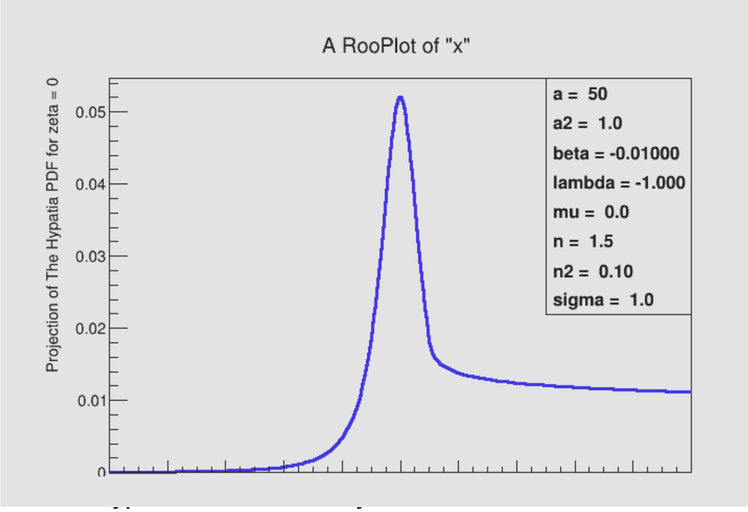


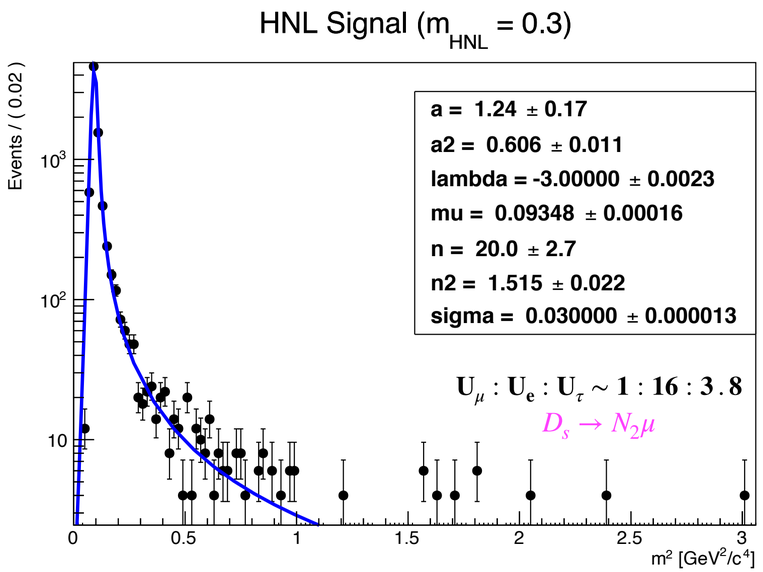
Detector element	Mass [t]	FHC	RHC
Magnet	511	68.9	36.6
ECAL	100	13.5	7.2
LAr+STT	8.2	1.1	0.59
STT fiducial volume	5.5	0.74	0.39
Total	619.2	83.5	44.39

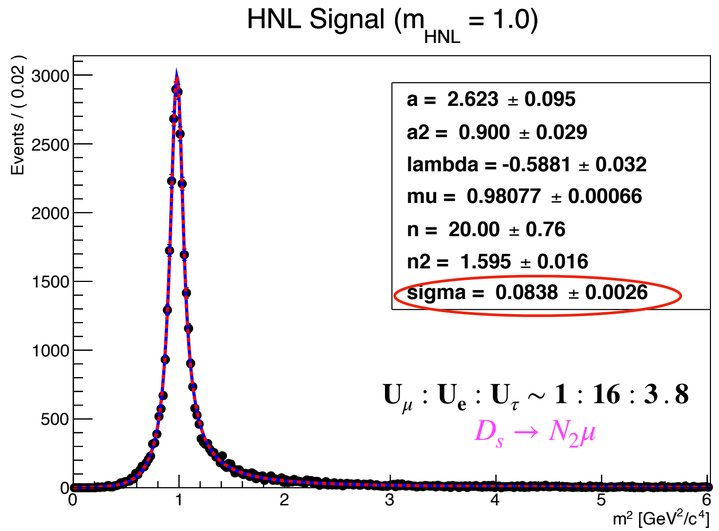
https://indico.cern.ch/event/806612/attachments/1813045/2962023/A_Near_Detector_for_DUNE.pdf

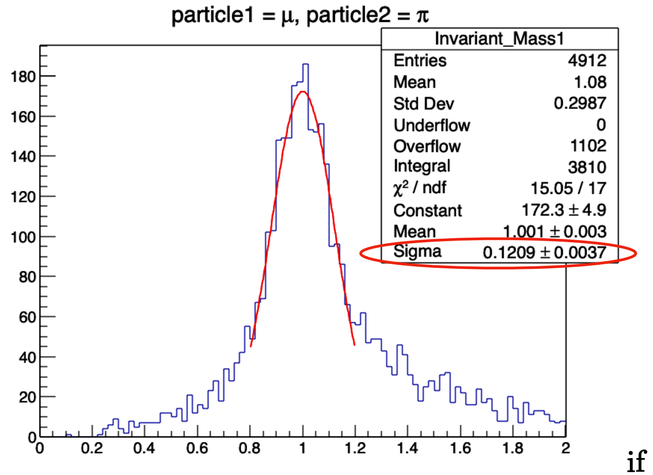
Signal Modeling

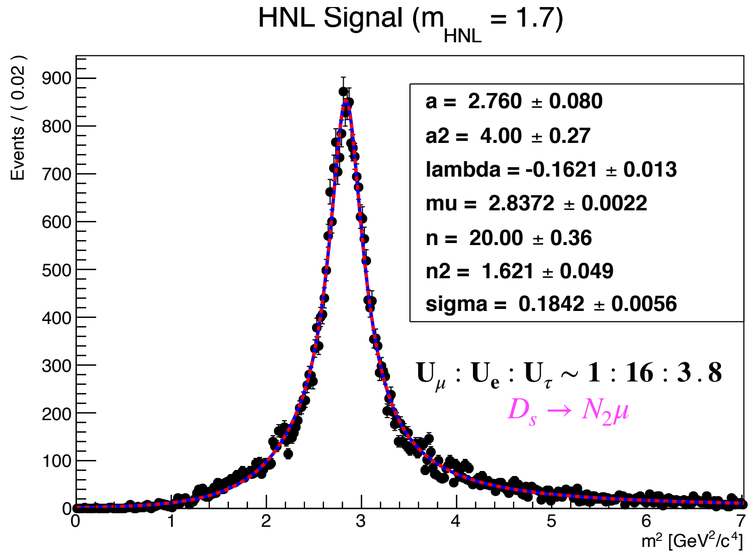
- **Signal Model (RooFit):**
  - Two-sided Hypatia distribution as signal p.d.f:
    - Hyperbolic core of a crystal-ball-like G function and two tails
    - Model the invariant mass distribution with generic tails
    - Fitting the signal with Hypatia gives a much better parametrization











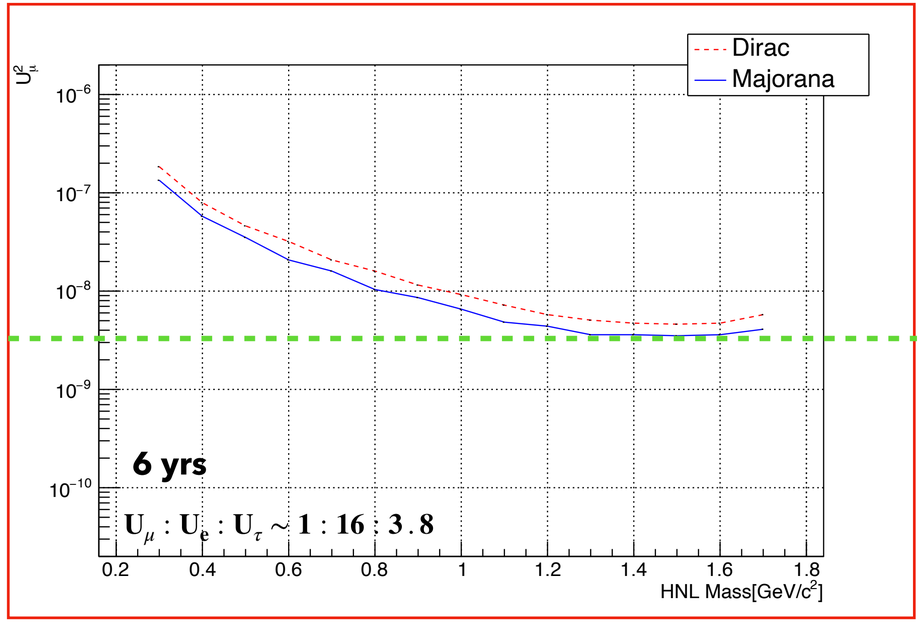
$$\mathrm{Hypatia2}(x,\mu,\sigma,\lambda,\zeta,\beta,a_l,n_l,a_r,n_r) = \begin{cases} \dfrac{G(\mu-a_l\sigma,\mu,\sigma,\lambda,\zeta,\beta)}{\left(1-\frac{x}{n_l G(\ldots)/G'(\ldots)-a_l\sigma}\right)^{n_l}} & \text{if } \frac{x-\mu}{\sigma} < -a_l \\ \left((x-\mu)^2 + A_\lambda^2(\zeta)\sigma^2\right)^{\frac{1}{2}\lambda-\frac{1}{4}} e^{\beta(x-\mu)} K_{\lambda-\frac{1}{2}}\left(\zeta\sqrt{1+\left(\frac{x-\mu}{A_\lambda(\zeta)\sigma}\right)^2}\right) \equiv G(x,\mu,\ldots) & \text{otherwise} \\ \dfrac{G(\mu+a_r\sigma,\mu,\sigma,\lambda,\zeta,\beta)}{\left(1-\frac{x}{-n_r G(\ldots)/G'(\ldots)-a_r\sigma}\right)^{n_r}} & \text{if } \frac{x-\mu}{\sigma} > a_r \end{cases}$$

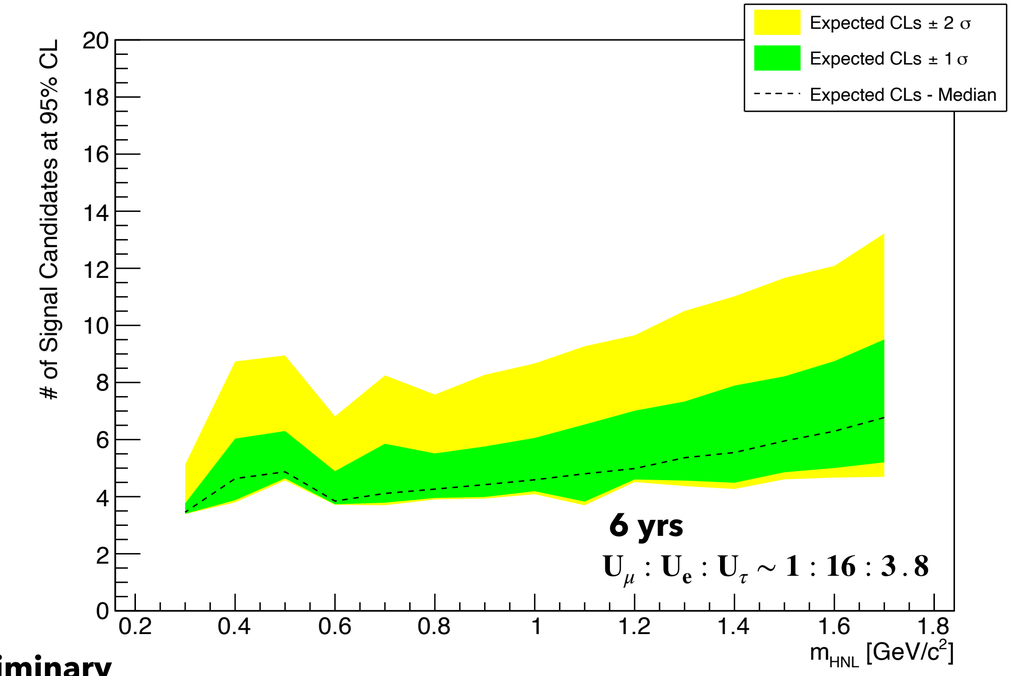
Final Sensitivity

- **Combining parameters in Pheno-sensitivity with statistical analysis of the Signal and Background**
  - **Signal Model:**

    Hypatia p.d.f. ➡ model the invariant mass distribution with generic tails
  - **Background Model:**

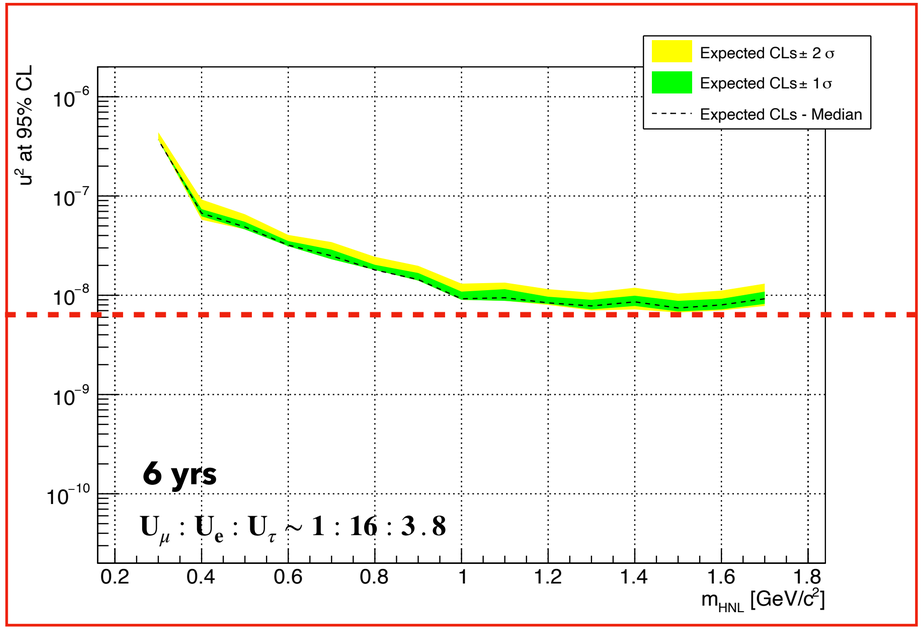
    Exponential or Flat p.d.f. ➡ model the most dangerous background
  - **CLs Calculation (RooStats):**
    - Inference calculation using frequentist approach based on likelihood ratio
    - Generating toy MC samples (~ 100 toys)
- **N_s ➡ U^2: N_s is not imposed to 1 but to the number of events is corresponding to 95% CL, taking into account A, ε and g**





Preliminary

~ 3



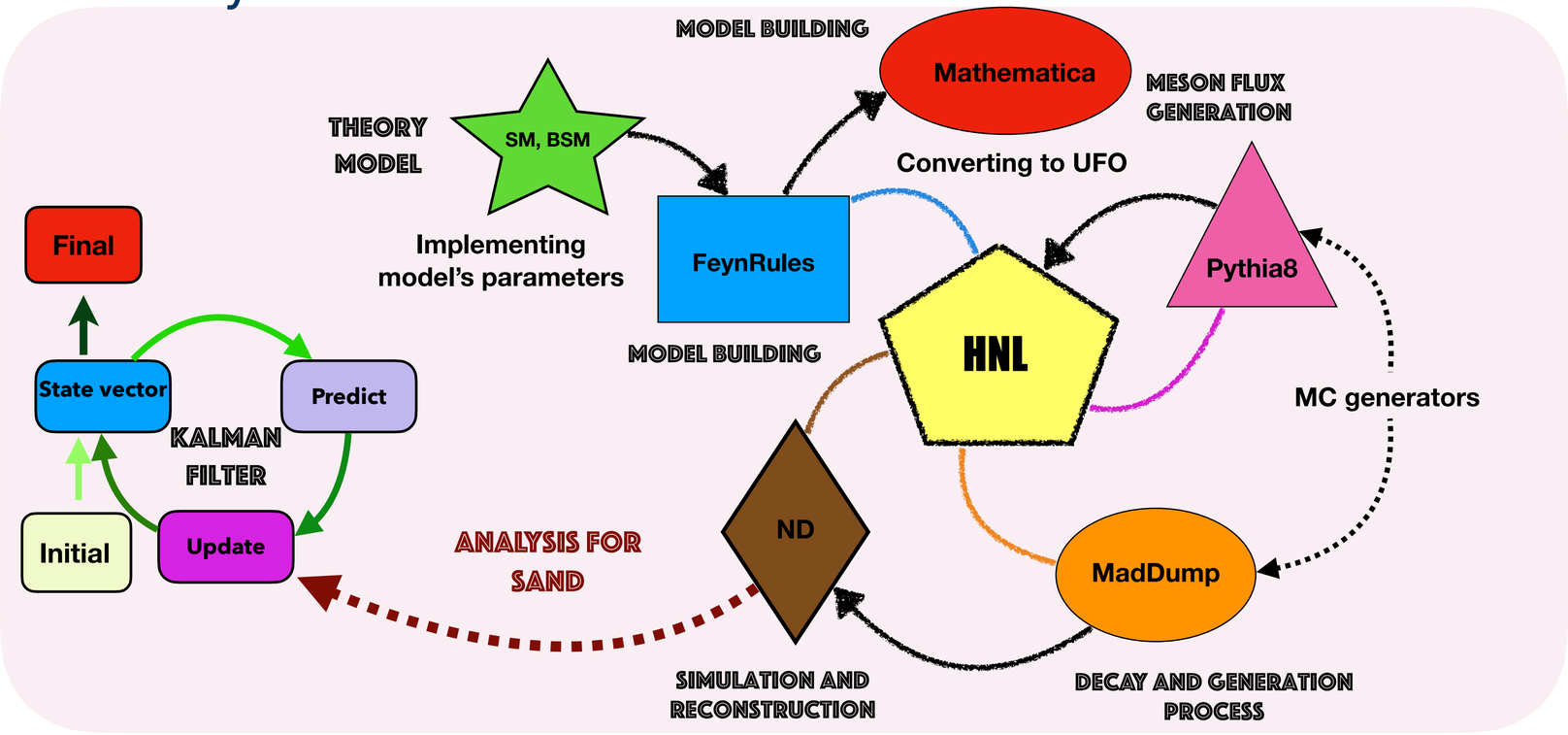
Summary and Outlook

✷ Summary

- Sensitivity to Heavy Neutral Lepton has been investigated: Pheno+Detector simulation
- Theory framework: vMSM
- Lagrangian conversion: FynRules+Mathematica
- Simulation Tools: Pythia8, Mad-Dump
- Pheno-sensitivity for three benchmark couplings and for 6 yrs of exposure $\sim 10^{-8} - 10^{-9}$
- Traget detector: SAND
- Reconstruction Tool: Kalman Filter
- Efficiency for single track: ~80%, track pair: ~60%
- Signal modeling: Two-sided Hypatia p.d.f.
- Most dangerous Background: ν_μCC +π
- Background Modeling: Uniform and exponential p.d.f.
- 11 candidates from background for 6 yrs of exposure
- Final Sensitivity for vMSM, coupling *model II,* degraded by factor ~ 3 from Pheno-Sensitivity

✷ Outlook

- **Pheno**: Adding more channels, HNL production/decay
- **Simulation**: More realistic picture adding pile up
- **Reconstruction**: Optimization of Kalman Filter



✷ Comments on Kalman Filter

- Each implementation of KF is unique with its challenges
- Customized for this work: working decently for high momentum
- Pattern recognition, an external fit is used due to better results
- Geometry dependent (implemented for full STT geometry)
- The Efficiency is ~ 80%, meets the need of this work
- It can be optimized to be used for any geometry and generic neutrino interaction event.

✷ Comments on Final Sensitivity

- The final sensitivity calculation has been demonstrated within vMSM and for benchmark II
- The final sensitivity for Majorana HNLs shows a factor ~ 3 degradation with respect to the Pheno, thanks to reconstruction efficiency and low background
  - Room for improvement through optimization, but no big difference is expected
- In higher mass region the sensitivity worsens due to the larger invariant mass resolution

Community Summer Study
SN WMASS
July 17-26 2022, Seattle

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

THANKS!