MUON-NEUTRINO ν_μ

Like its first-generation sibling lepton the electron-neutrino, the **MUON-NEUTRINO** is extremely difficult to detect (hence the bandit's mask). Discovered in 1962, it is emitted in the decay of a muon. Its mass is about one-third of an electron.

Acrylic felt with poly fill for minimum mass.

$10.49 PLUS SHIPPING

The PARTICLE ZOO

The search for heavy neutrinos at NA62

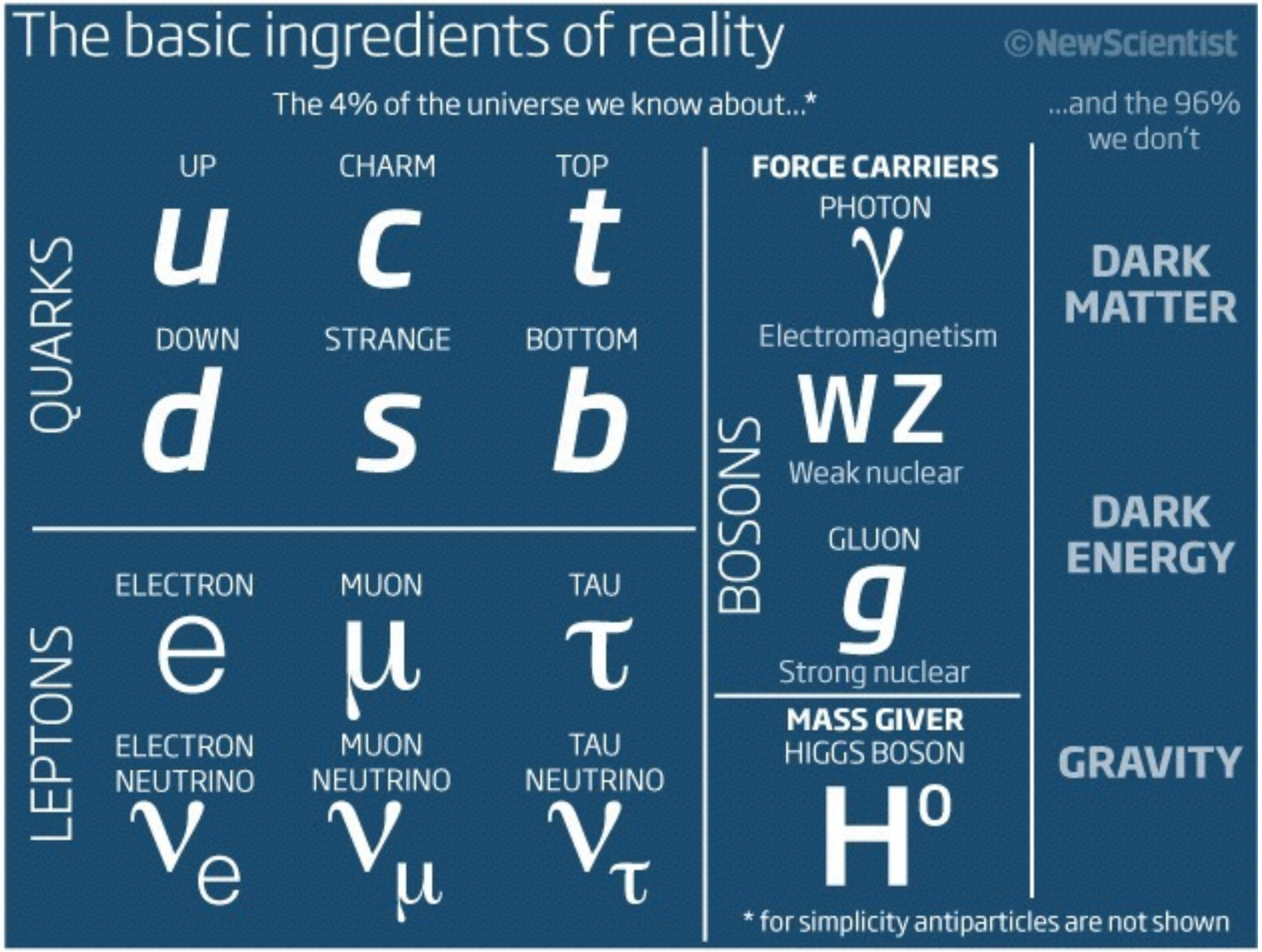
Theory of heavy neutrinos
The NA62 R_K detector
Analysis strategy
Background suppression
Outlook

Francis Newson | 20th May 2014

NA62
UNIVERSITY OF BIRMINGHAM

Neutrino mass

Standard Model Particles



SM particle charges

Field	$SU(3)$	$SU(2)_L$	T^3	$Y/2$	$Q = T^3 + Y/2$
g^a_μ(gluons)	**8**	**1**	0	0	0
$(W^\pm_\mu, W^0_\mu)$	**1**	**3**	$(\pm 1, 0)$	0	$(\pm 1, 0)$
B^0_μ	**1**	**1**	0	0	0
$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	**3**	**2**	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	1/6	$\begin{pmatrix} 2/3 \\ -1/3 \end{pmatrix}$
u_R	**3**	**1**	0	2/3	2/3
d_R	**3**	**1**	0	-1/3	-1/3
$\chi_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	**1**	**2**	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	-1/2	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
e_R	**1**	**1**	0	-1	-1
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	**1**	**2**	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	1/2	$\begin{pmatrix} 1 \\ 0 \end{pmatrix}$
$\widehat{\Phi} = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix}$	**1**	**2**	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	-1/2	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$

Mass terms

- A mass term in the SM Lagrangian:

$$m\bar{\psi}\psi = m(\bar{\psi}_R\psi_L + \bar{\psi}_L\psi_R)$$

- Eg: down quark mass:

$$m\bar{d}d = m(\bar{d}_R d_L + \bar{d}_L d_R)$$

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T^3: $+1/2 + 0 = +1/2$

$Y/2$: $-1/6 \; -1/3 = -1/2$

- Not invariant under SU$_L$(2)xU(1) symmetry -> FORBIDDEN

SM particle charges

Field	$SU(3)$	$SU(2)_L$	T^3	$Y/2$	$Q = T^3 + Y/2$
$g^a_\mu(\text{gluons})$	$\mathbf{8}$	$\mathbf{1}$	0	0	0
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BEH and all that

- We can make an allowed term with an extra scalar field:

$$\mathcal{L}_{\text{Yukuwa}} = -Y_d \bar{d}_L \phi^0 d_R$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \xrightarrow{\textbf{SSB}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

T^3:	+1/2	−1/2	+0	= 0
Y/2:	−1/6	+1/2	−1/3	= 0

- After spontaneous symmetry breaking, we see a mass term and a Higgs coupling term:

$$\mathcal{L}_{\text{Yukuwa}}(e) = -\frac{Y_d v}{\sqrt{2}} \bar{d} d - \frac{Y_d}{\sqrt{2}} \bar{d} d H$$

Yukuwa couplings

down type quarks

$$\mathcal{L}_{\text{Yuk}}(d) = Y_d \left[\bar{q}_L \Phi d_R + \bar{d}_R \Phi^\dagger q_L\right]$$

charged leptons

$$\mathcal{L}_{\text{Yuk}}(e) = Y_e \left[\bar{\chi}_L \Phi e_R + \bar{e}_R \Phi^\dagger \chi_L\right]$$

up type quarks

$$\mathcal{L}_{\text{Yuk}}(u) = Y_u \left[\bar{q}_L \widehat{\Phi} u_R + \bar{u}_R \widehat{\Phi}^\dagger q_L\right]$$

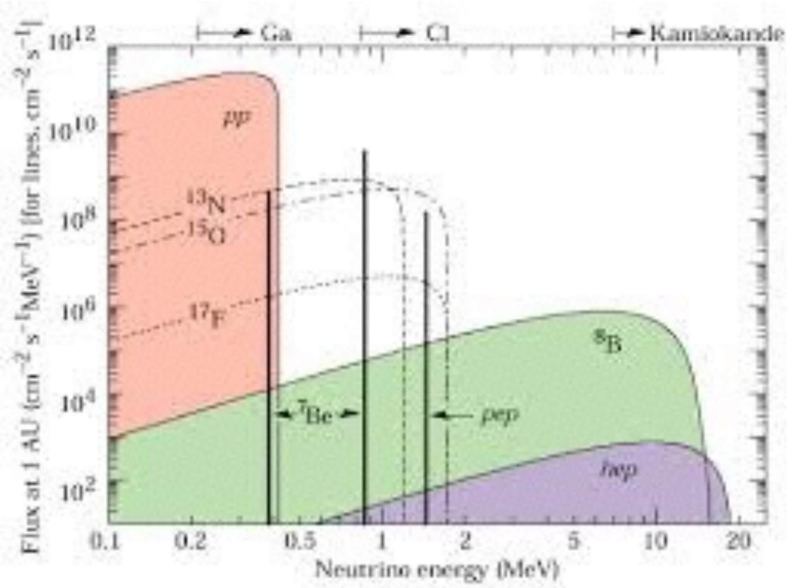
neutral leptons

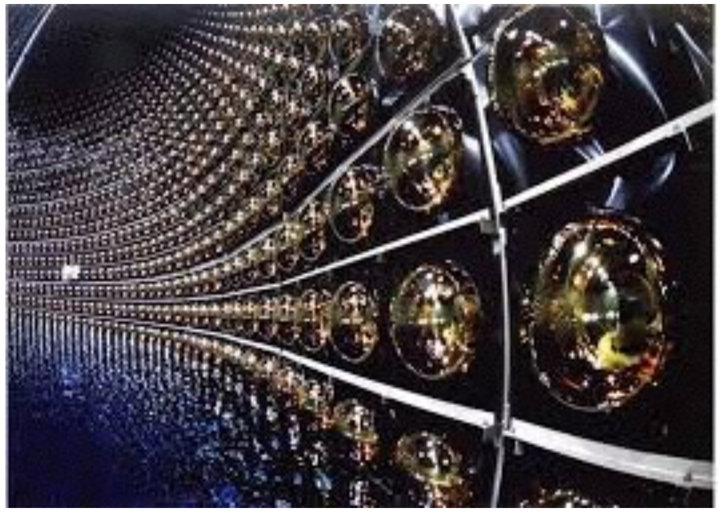
$$\mathcal{L}_{\text{Yuk}}(\nu) = Y_\nu \left[\bar{\chi}_L \widehat{\Phi} \xcancel{\nu}_R + \xcancel{\bar{\nu}}_R \widehat{\Phi}^\dagger \chi_L\right]$$

- By construction, there are no right-chiral neutrinos in the SM so we cannot construct the Yukuwa term corresponding to neutrino mass.

Neutrino oscillations

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$





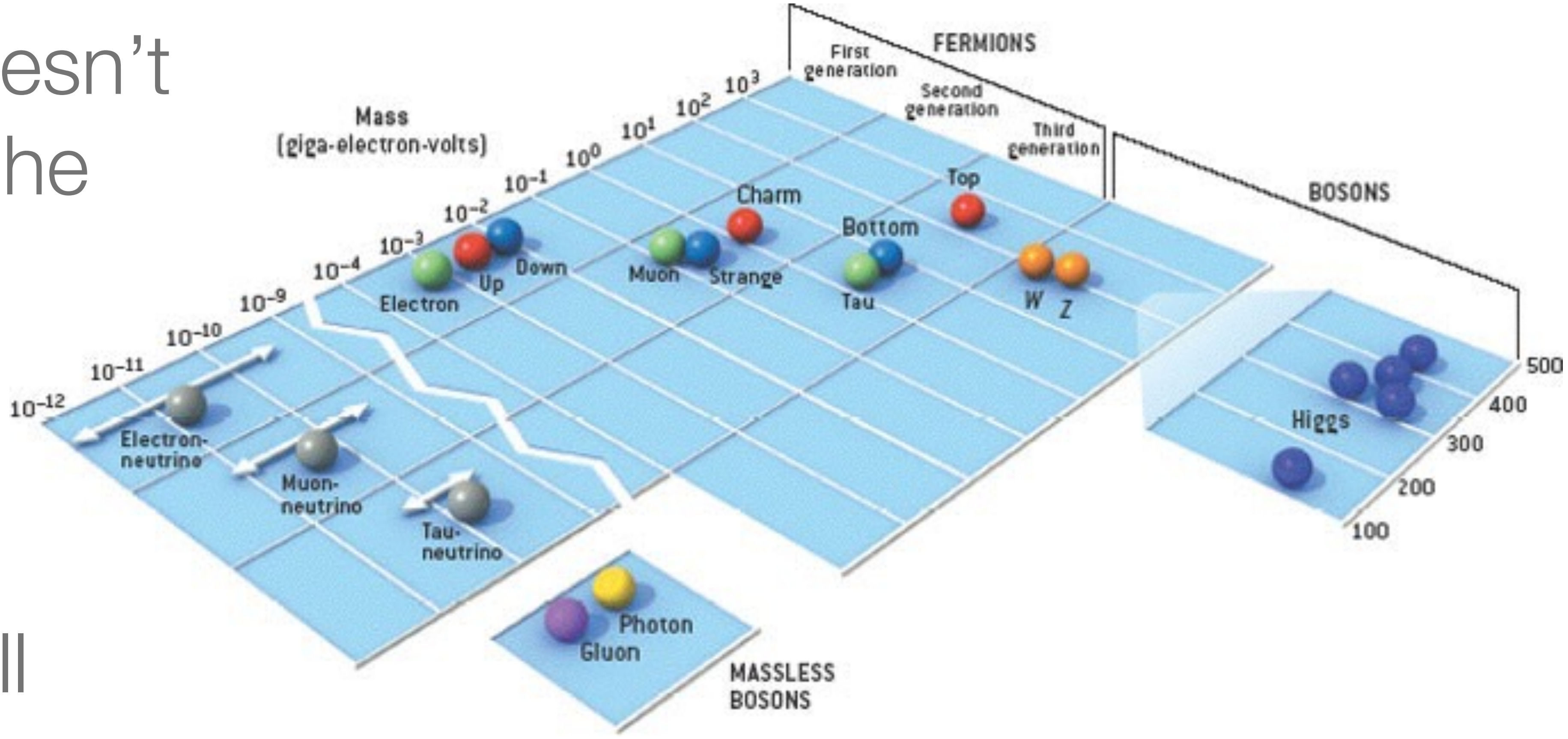
Evidence for neutrino oscillation and, hence, neutrino mass is now overwhelming

What do the neutrino mass terms look like?

- Just introduce ν_R? (analogous to u_R)

$$\mathcal{L}_{\rm Yuk}(\nu) = Y_\nu \left[\bar{\chi}_L \widehat{\Phi} \nu_R + \bar{\nu}_R \widehat{\Phi}^\dagger \chi_L\right]$$

- It works, but doesn't help to explain the small neutrino masses



- Y_ν has to be unnaturally small

Right handed neutrinos are more flexible

- RH neutrinos are singlets of SU(2)$_L$ and U(1)$_Y$.

$$-\mathcal{L}_{\text{bare}} = \frac{1}{2} B \overline{\widehat{\nu}}_L \nu_R + h.c.$$

$$-\mathcal{L}_{\text{bare}} = \frac{1}{2} \sum_{l,l'} B_{ll'} \overline{\widehat{N}}_{lL} N_{l'R} + h.c.$$

mixing between mass and flavour states $N_{lR} \equiv \sum_{\alpha} V_{l\alpha} \nu_{\alpha R}$

- This term violates lepton number (an accidental symmetry) but does not violate the gauge symmetries of the SM

See-saw mechanisms

- The combined neutrino mass term looks like:

$$-\mathcal{L}_{\text{mass}} = \frac{1}{2}\begin{pmatrix}\bar{\nu}_L & \overline{\widehat{N}}_L\end{pmatrix}\begin{pmatrix}0 & M \\ M^T & B\end{pmatrix}\begin{pmatrix}\widehat{\nu}_R \\ N_R\end{pmatrix} + h.c.$$

mass matrix from
Higgs coupling

mass matrix from lepton
number violating terms

- Diagonalizing this matrix gives the mass eigenstates. If B ≫ M:

$$m_1 \approx \frac{M^2}{B} \quad , \quad m_2 \approx B.$$

SM neutrino

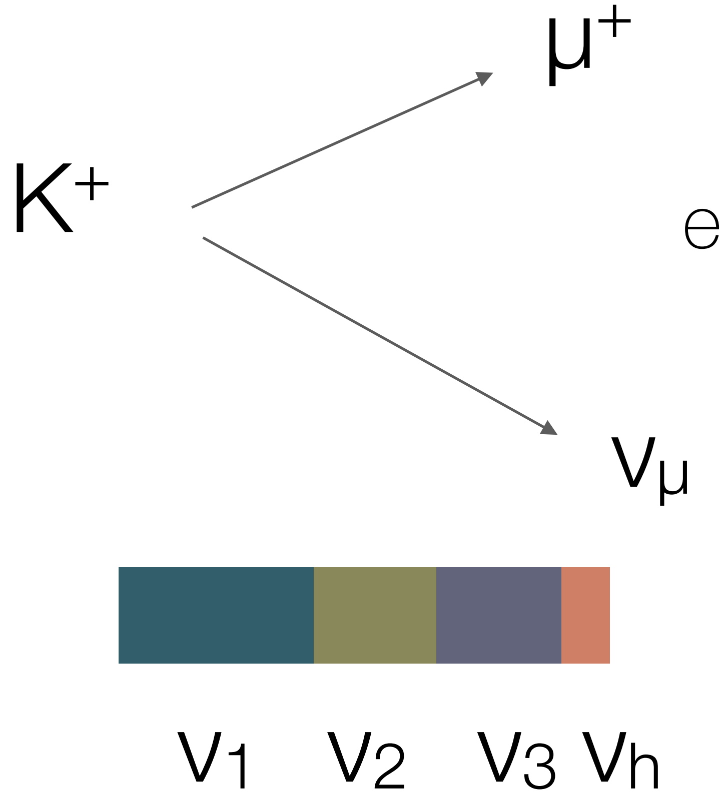
heavy neutrino

Models

- Many BSM models result in a see-saw effect. E.g.
  - **Additional symmetries** at high energy $SU(2)_L x SU(2)_R x U(1)_Y$
  - **Expanded Higgs sector** $\Delta = (\Delta^0\ \Delta^-\ \Delta^{--})$
- Careful parameter choice can help solve other problems:
  - **vMSM** (Neutrino Minimal Standard Model)
    Fixing heavy neutrino masses at the electroweak scale, produces a dark matter candidate and a source of baryon asymmetry

Neutrinos in kaon decay

- Weak decays produce neutrinos in flavour eigenstates
- A flavour eigenstate is a superposition mass eigenstates
- We can look for heavy mass state component



$$R_{0h} \equiv \frac{\Gamma(K^+ \to \mu^+ \nu_h)}{\Gamma(K^+ \to \mu^+ \nu_\mu)_{123}}$$

kaon physics cancels

experiment

$$R_{0h} = |U_{\mu h}|^2 \kappa$$

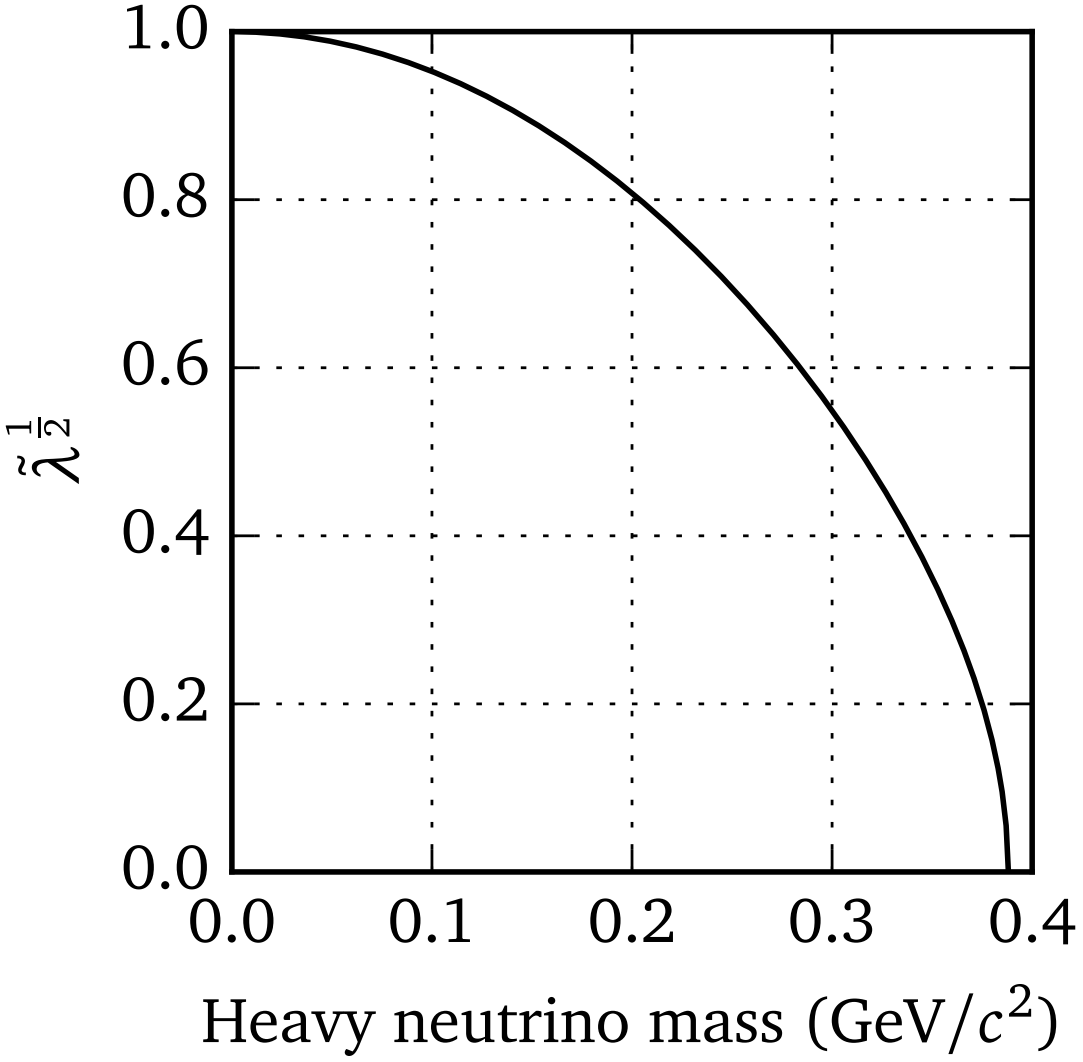
theory: extended PMNS matrix

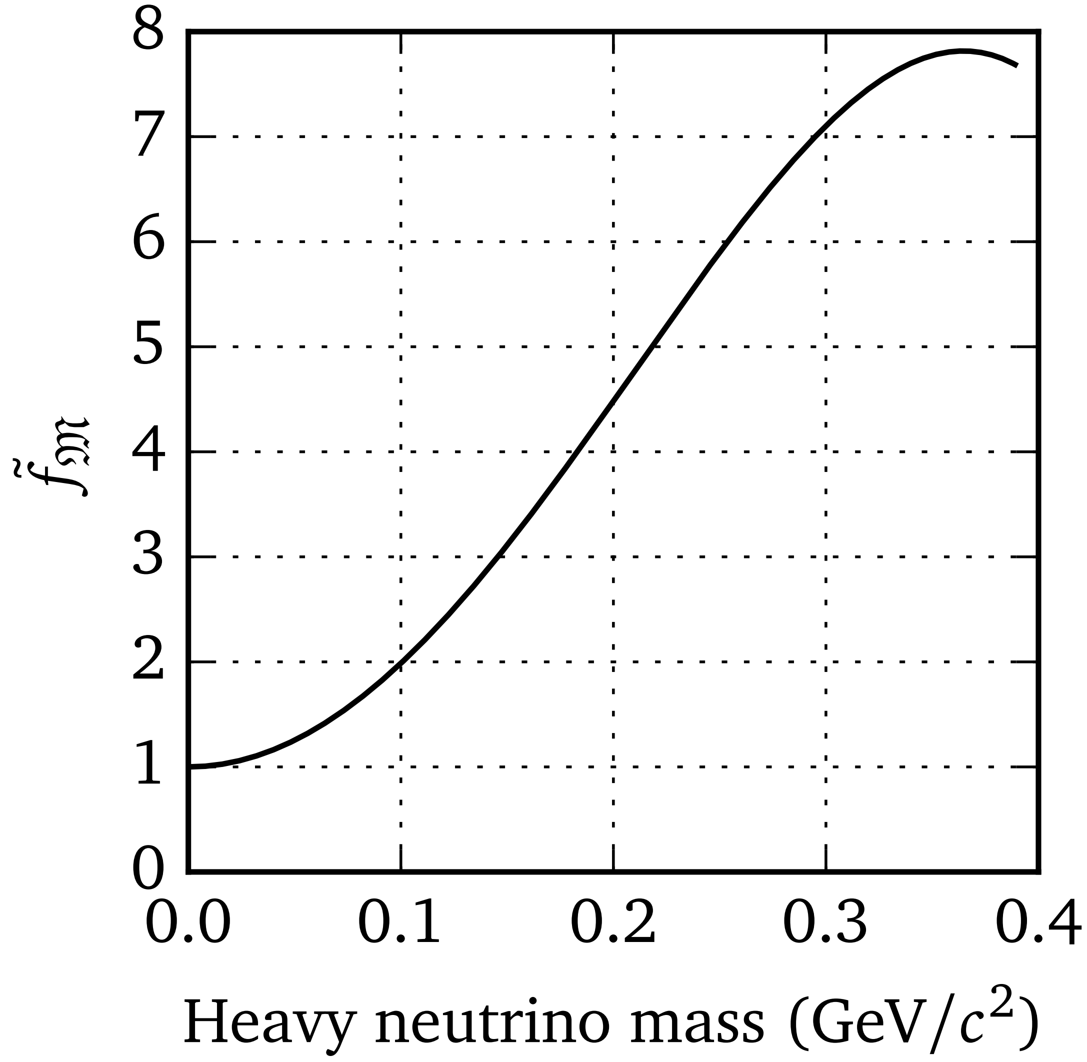
kinematic factors

Heavy neutrino kinematics

$$\kappa = \lambda^{\frac{1}{2}} f_{\mathfrak{M}}$$

- Increasing neutrino mass decreases phase space
- Increasing neutrino mass releases helicity constraints

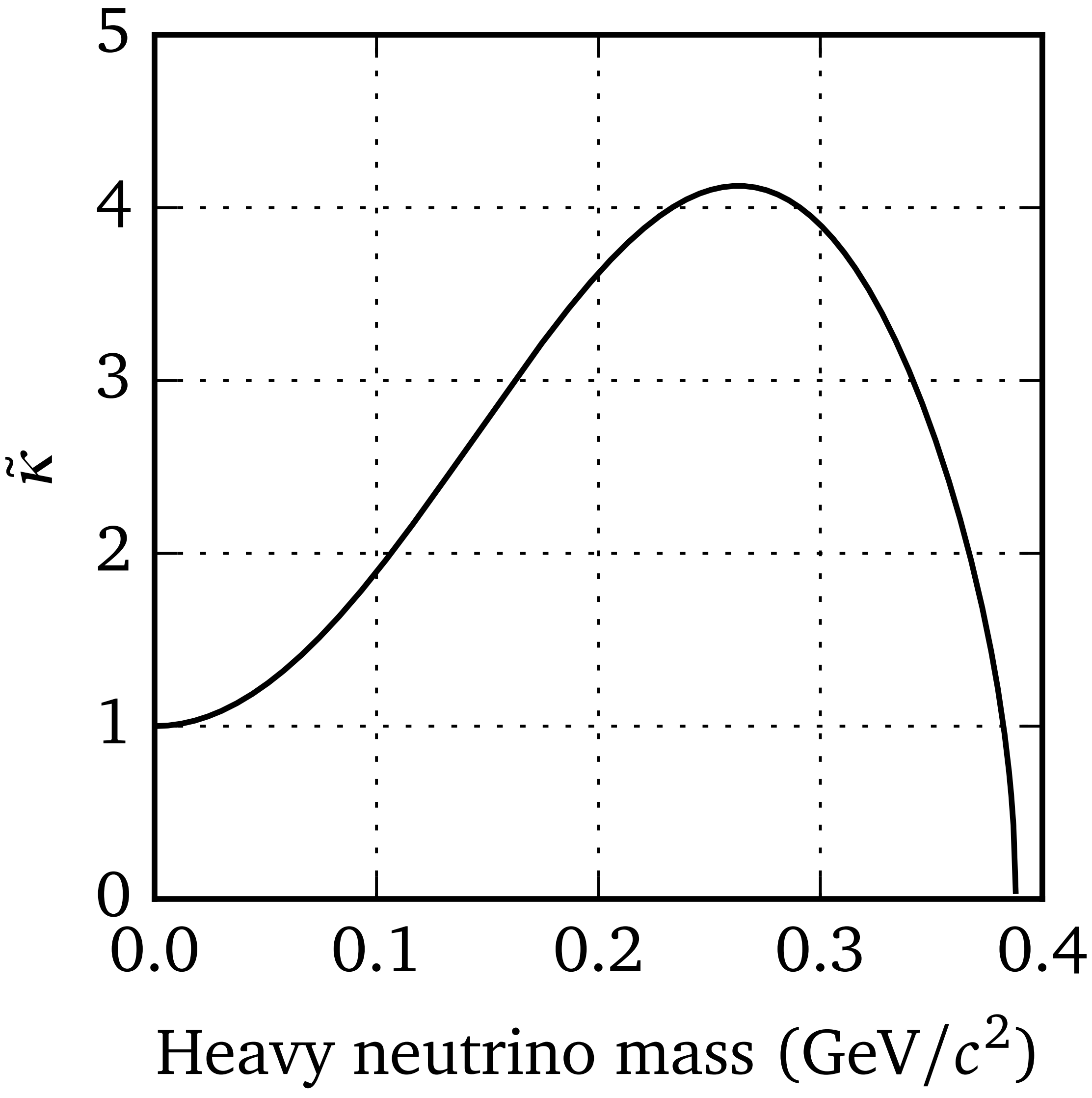




Heavy neutrino kinematics

experiment → $R_{0h} = |U_{\mu h}|^2 \kappa$ ← maths

↑ theory



- Kinematic endpoint occurs when $m_\nu = m_K - m_\mu$
- Then neutrino is produced at rest in kaon frame.

Heavy neutrino searches

Neutrino decay searches

- Look for heavy neutrino decay products
- Strong limits but tied to model of neutrino decay

Peak searches

- Look for peaks in reconstructed neutrino mass
- Weaker limits but model independent

MY ANALYSIS

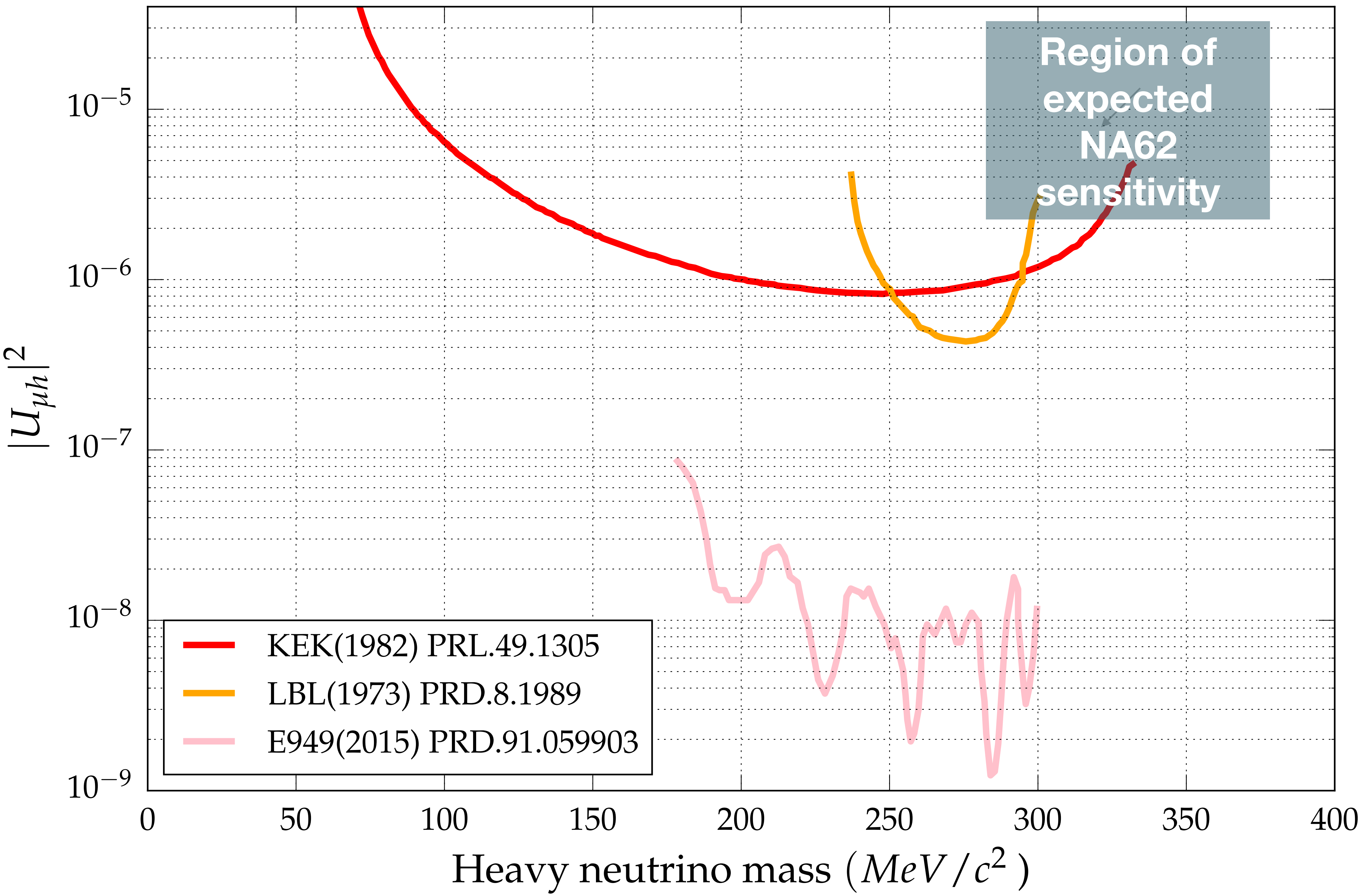
Peak search strategy

- Collect $K^+ \rightarrow \mu^+ \nu_\mu$ events
- Reconstruct neutrino mass from kaon and muon momenta

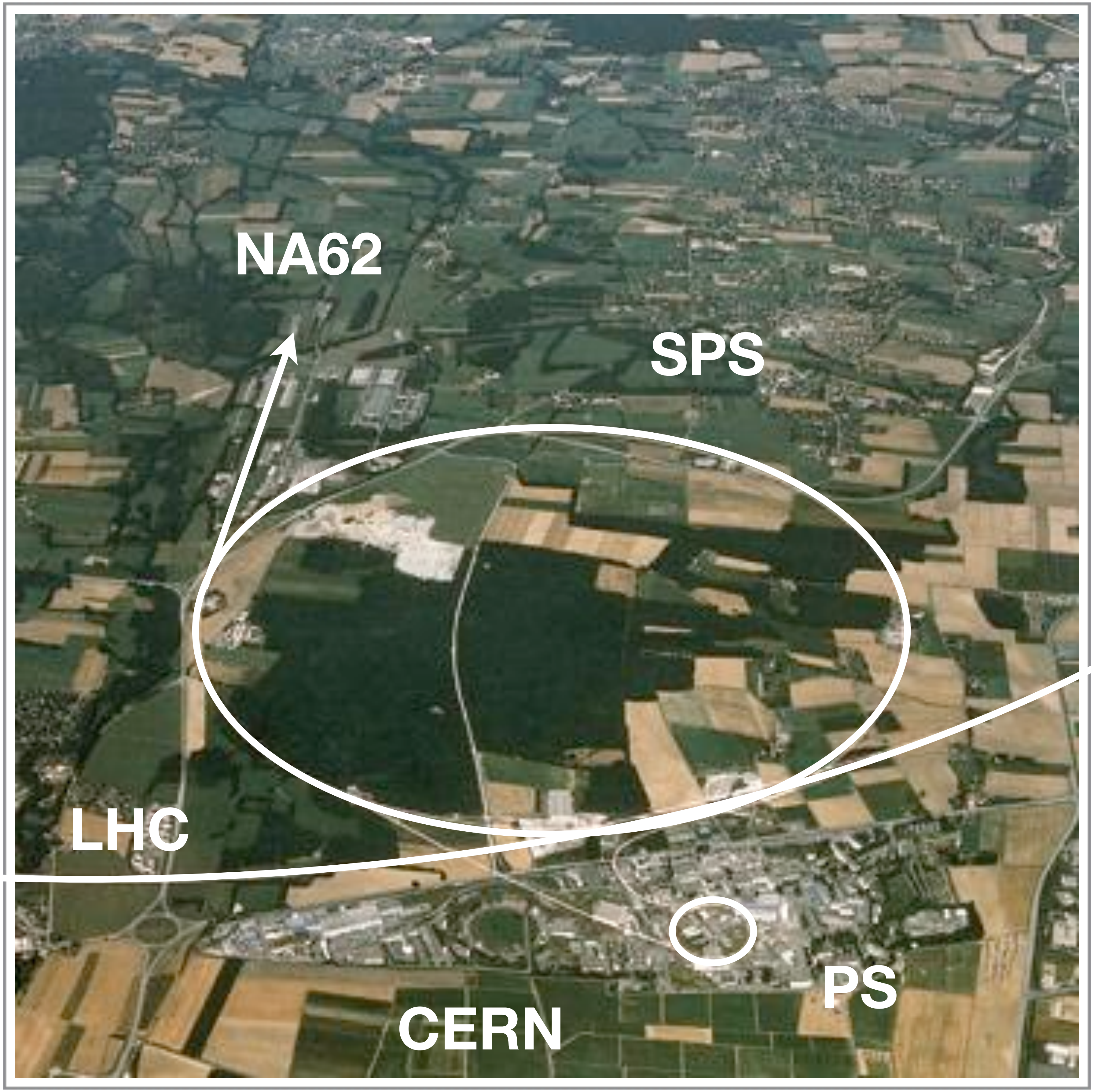
$$m_{\text{miss}}^2 = (p_K - p_\mu)^2$$

- Look for a peak at non-zero missing mass

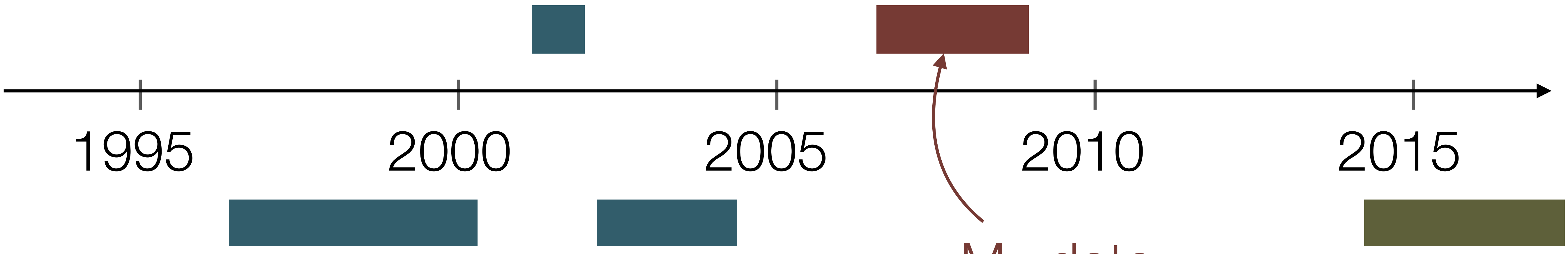
Existing limits



NA62



NA48/1/2 NA62:R_K NA62
Fixed target kaon decay-in-flight experiments



NA48/1
K_S and hyperon
rare decays

NA62:R_K
Lepton universality
in K^+,K^- decays

My data

NA48
Re(ε′/ε) in K_S and K_L
Discovery of direct CPV

NA48/2
Direct CP violation
in K^+,K^- decays

NA62
Ultra rare
kaon decays

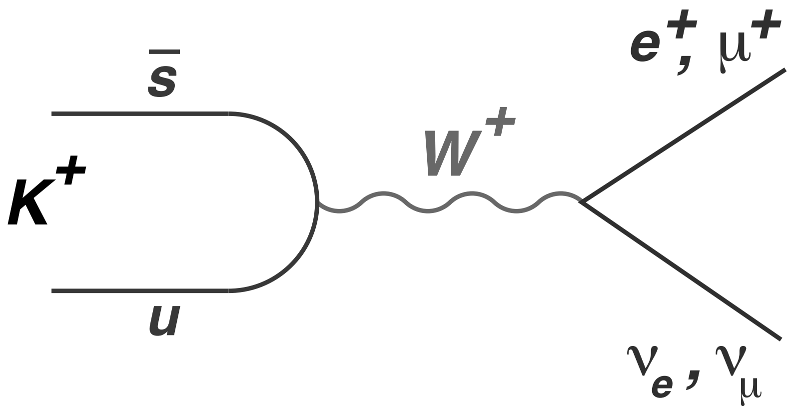
R_K 2007

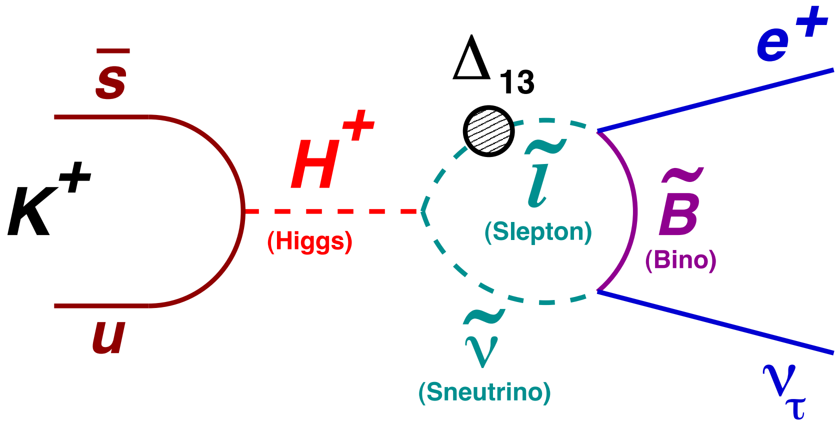
$$R_K = \frac{\Gamma(K \to e\nu)}{\Gamma(K \to \mu\nu)}$$

branching ratio ~ 1.5x10-5
(helicity suppressed)

branching ratio ~ 0.64

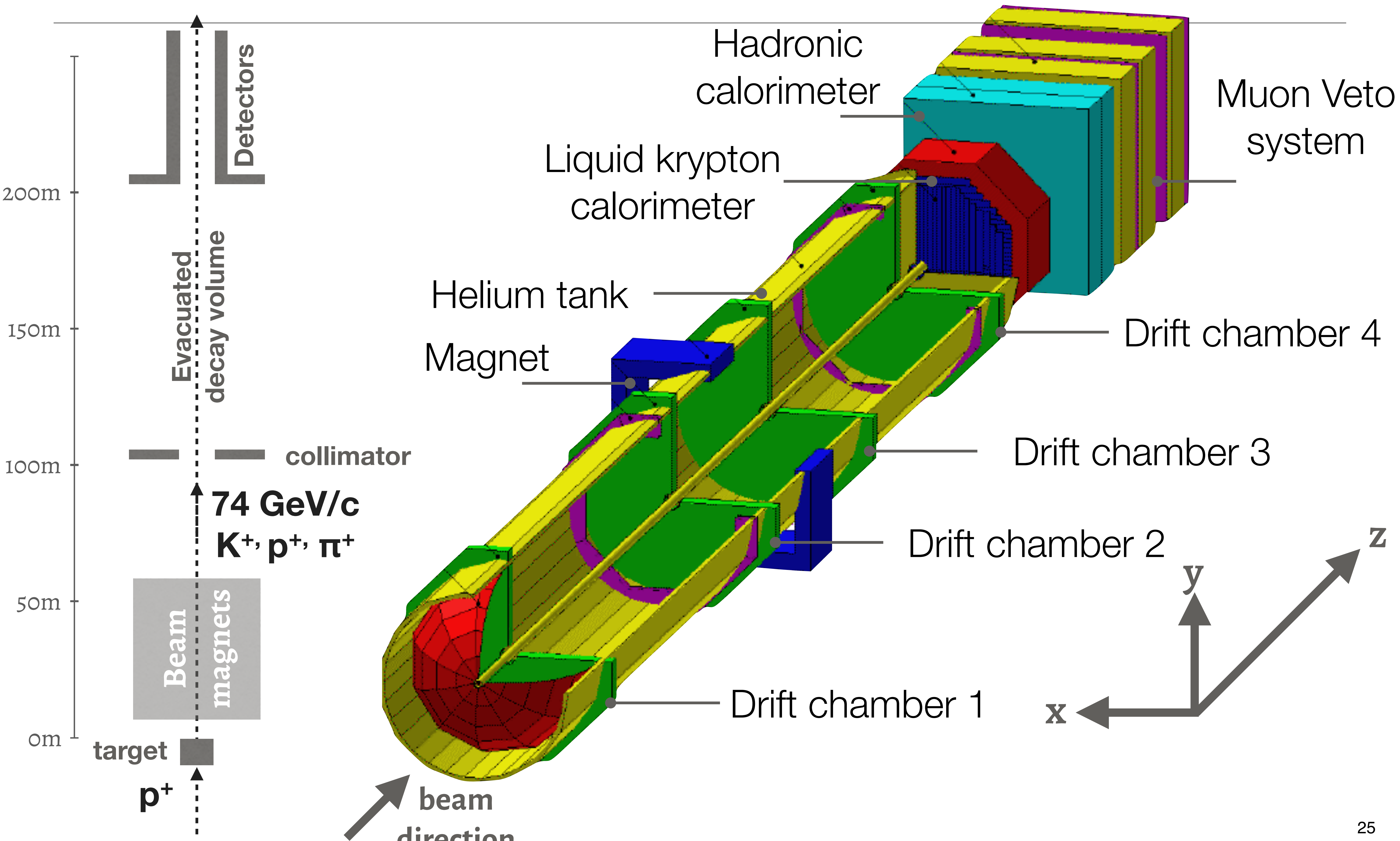
my source of
heavy neutrinos





- Accurately predicted in the SM and sensitive to NP.
- 2007 data set used to measure R_K with 0.4% precision
- 4 months of data taking
- Minimum bias sample of K^+ decays: ~10^7 in the μ channel

Detector

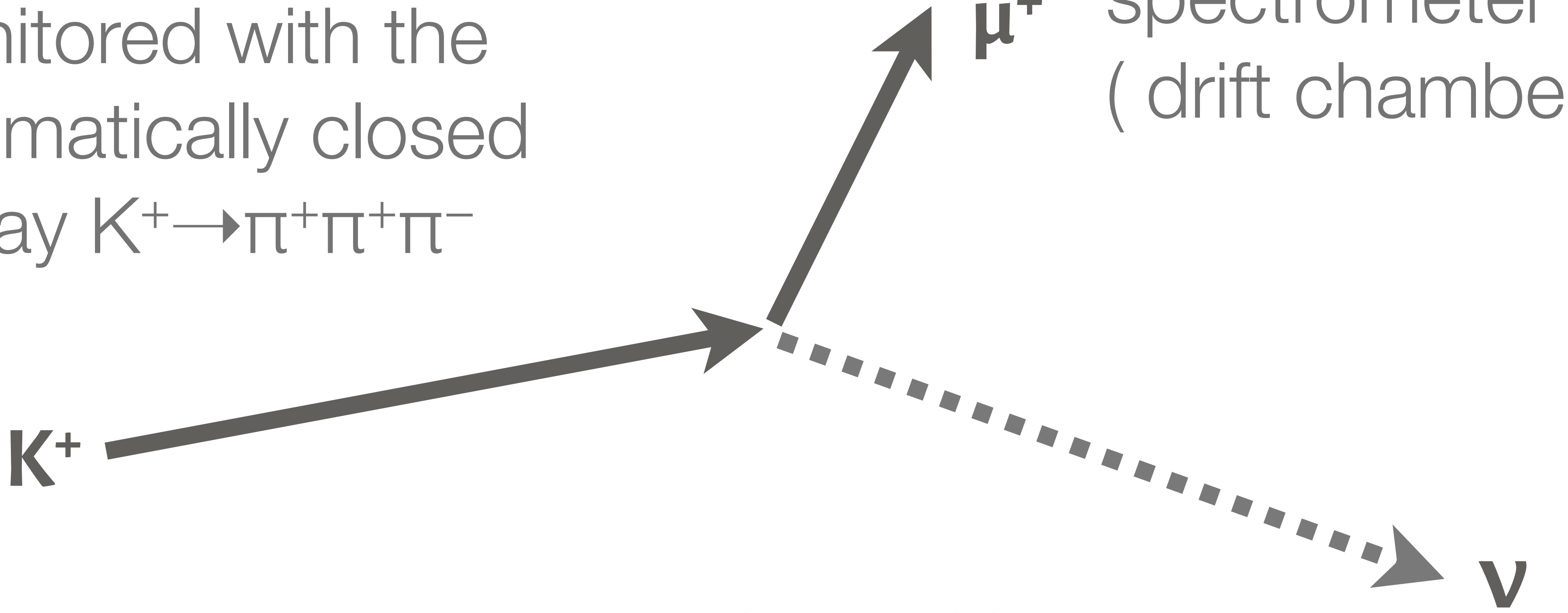

Detectors
200m
150m
100m
50m
0m
Evacuated decay volume
collimator
74 GeV/c
K^+, p^+, π^+
Beam magnets
target
p^+
Hadronic calorimeter
Muon Veto system
Liquid krypton calorimeter
Helium tank
Magnet
Drift chamber 4
Drift chamber 3
Drift chamber 2
Drift chamber 1
y
z
x
beam direction

Heavy neutrino analysis

Analysis strategy

Kaon position and momentum monitored with the kinematically closed decay $K^+ \rightarrow \pi^+\pi^+\pi^-$

Muon momentum measured in the spectrometer
(drift chambers 1-4)



Neutrino mass reconstructed from K^+ and μ^+ momenta:

$$m_\nu^2 = p_\nu^2 = (p_K - p_\mu)^2$$

Single track selection

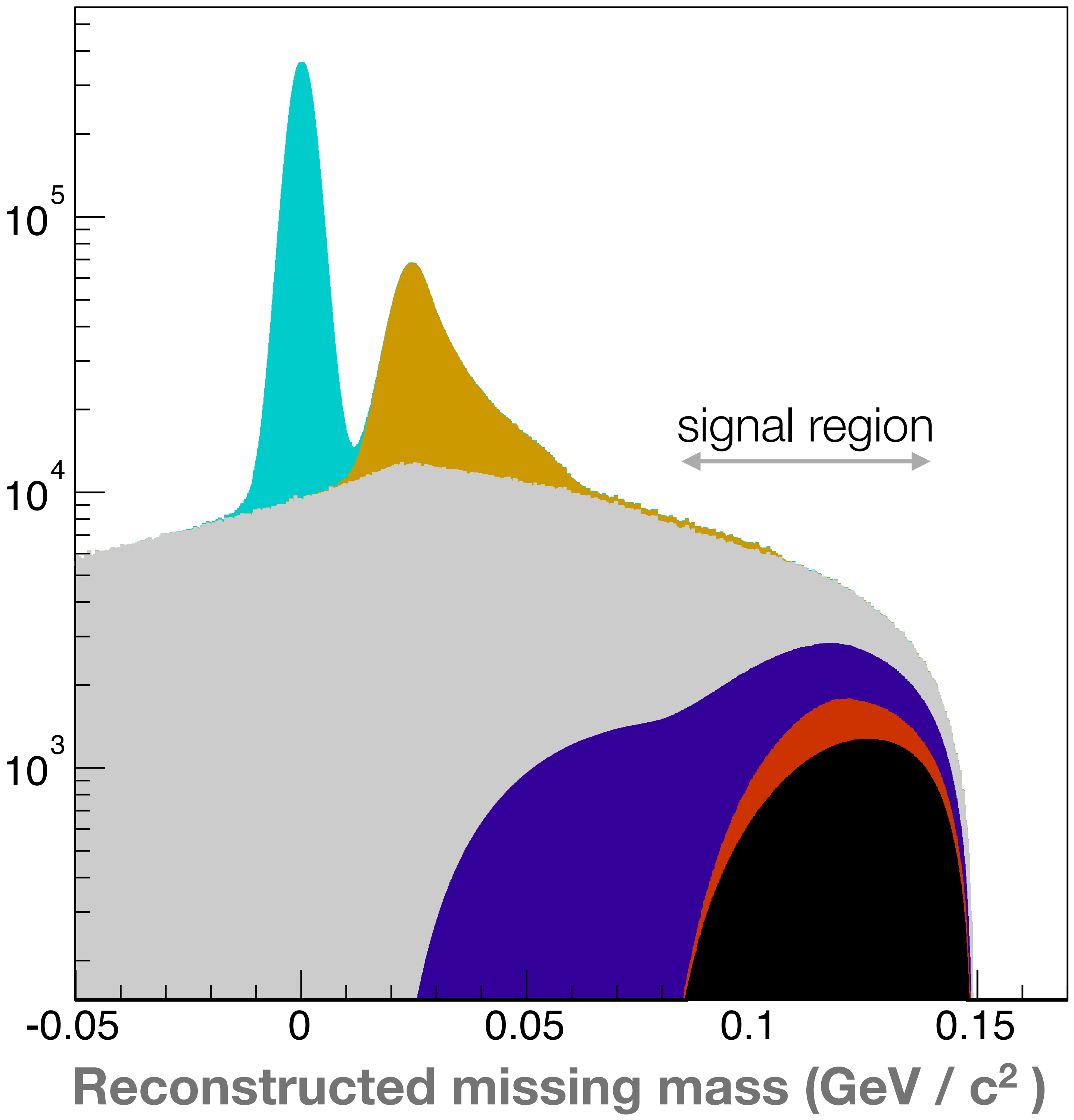
- Select events with 1 ‘good’ track in the drift chambers (additional ‘ghost’ tracks can be ignored)

Good tracks:

- In time with the trigger $|\Delta t| < 62.5$ ns
- In momentum range $3 < p < 65$ GeV/c
- Closest distance of approach to $K^+ < 10$cm
- Estimated vertex within 110m decay volume

- **Selected Tracks**
  - positive charge
  - CDA < 3.5cm
  - track quality > 0.7

Single track backgrounds in MC



Decays producing a single charged track

- $K^+ \to \mu^+ \nu$
- $K^+ \to \pi^+ \pi^0$
- Halo
- $K^+ \to \pi^+ \pi^+ \pi^-$
- $K^+ \to \mu^+ \nu \pi^0$
- $K^+ \to \pi^+ \pi^0 \pi^0$

Required:

particle identification to distinguish π^+ and μ^+

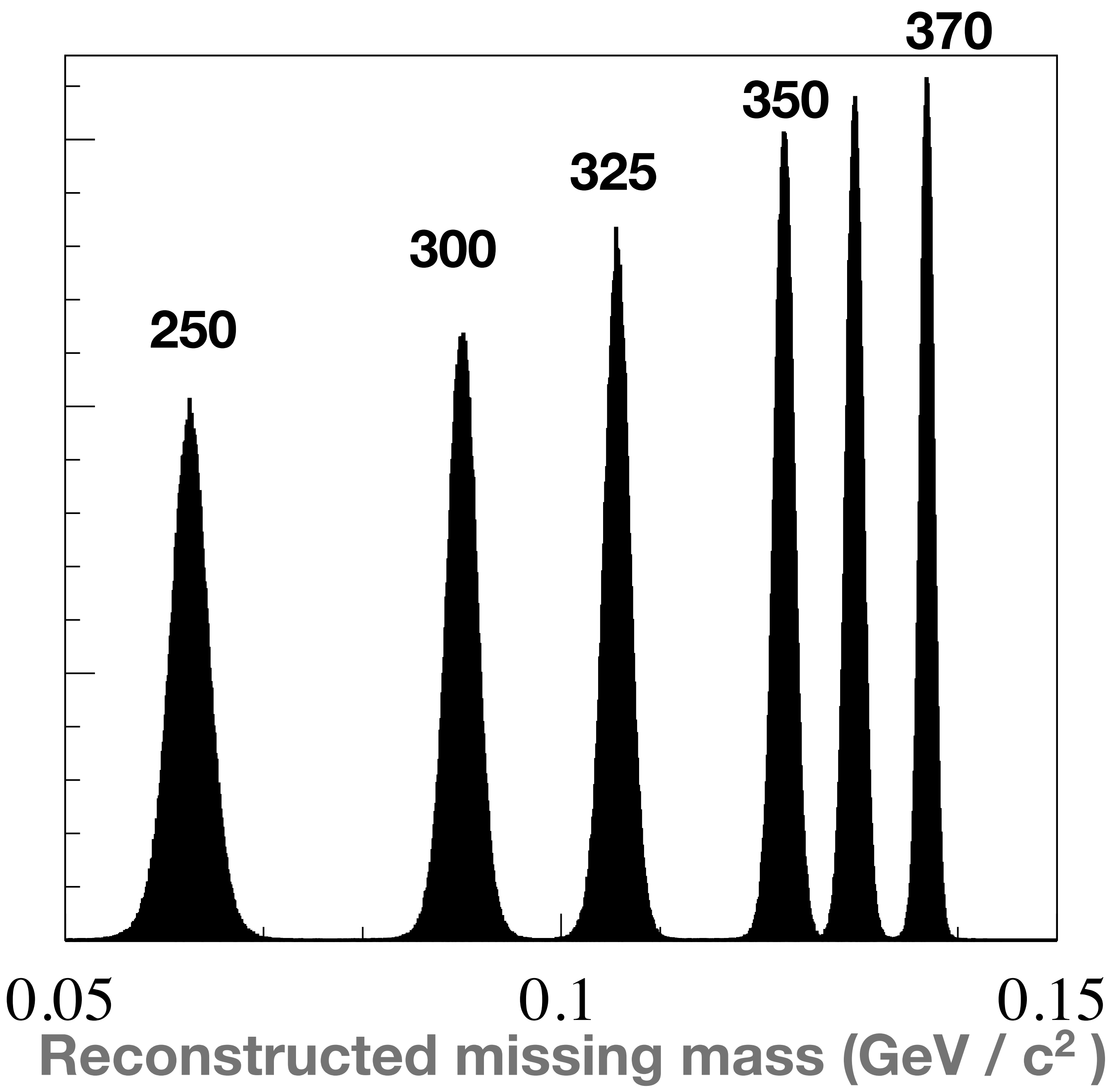
photon vetoing to suppress π^0

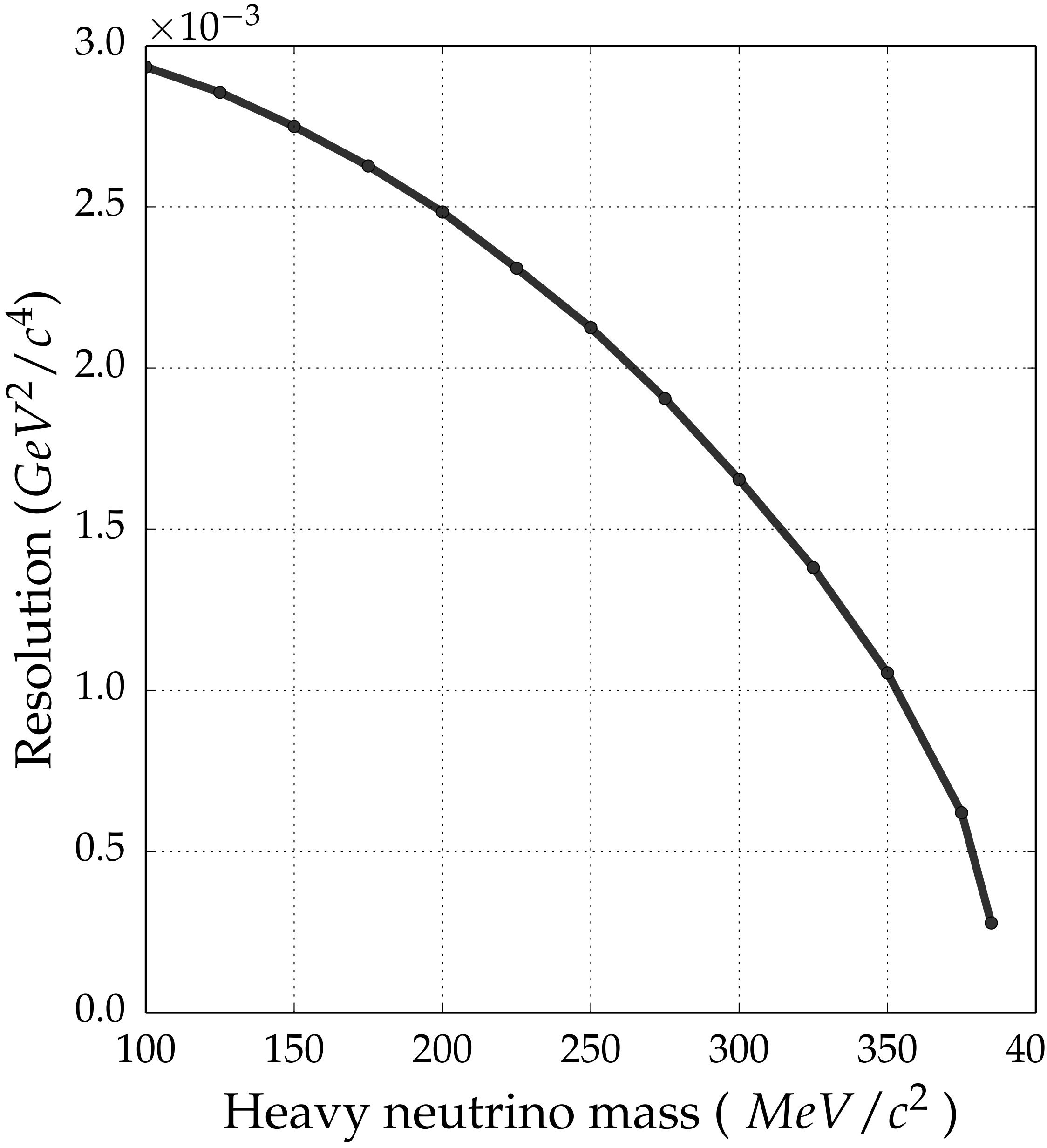
kinematics to suppress halo

Heavy neutrino signals

-

resolution

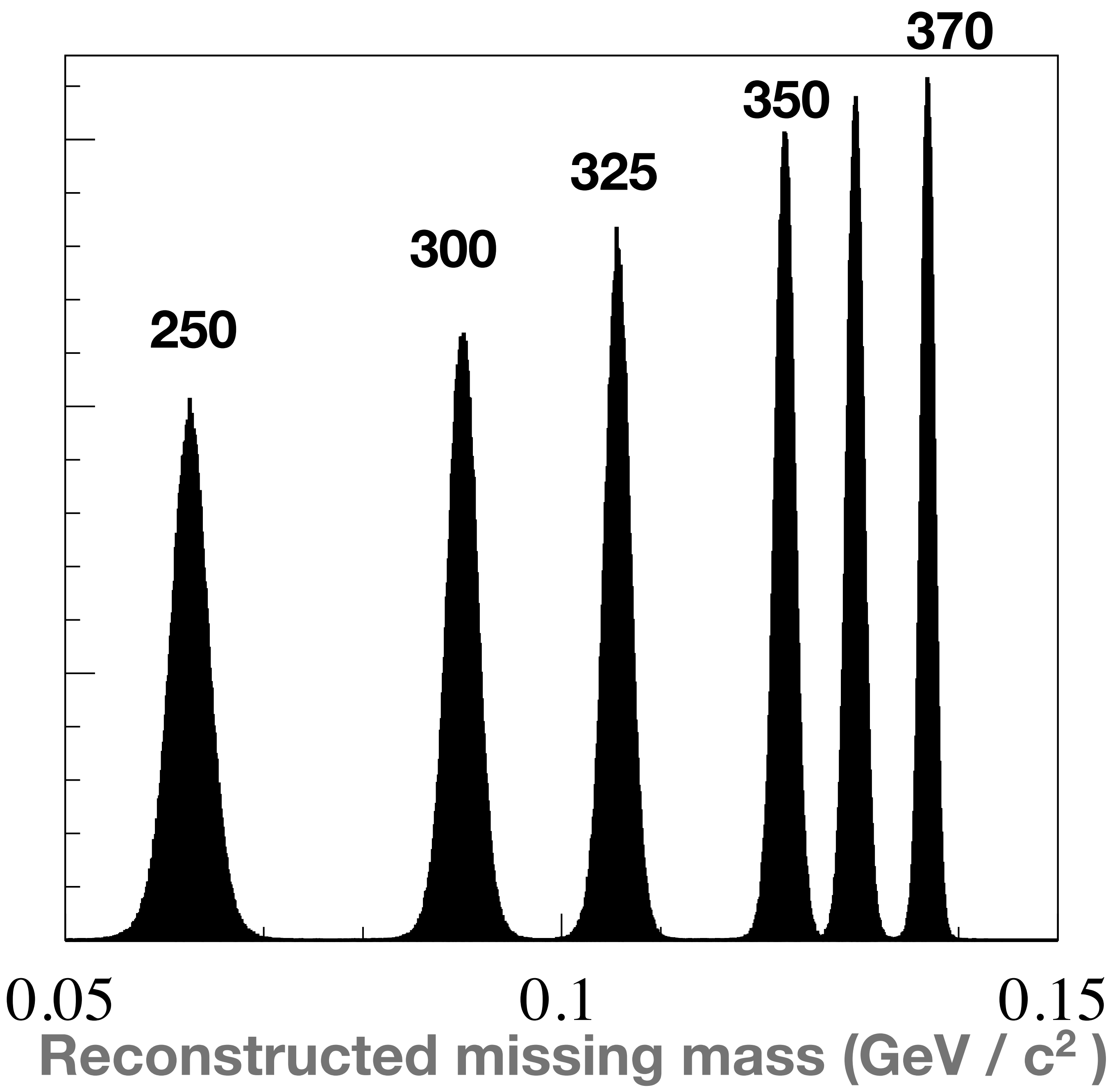


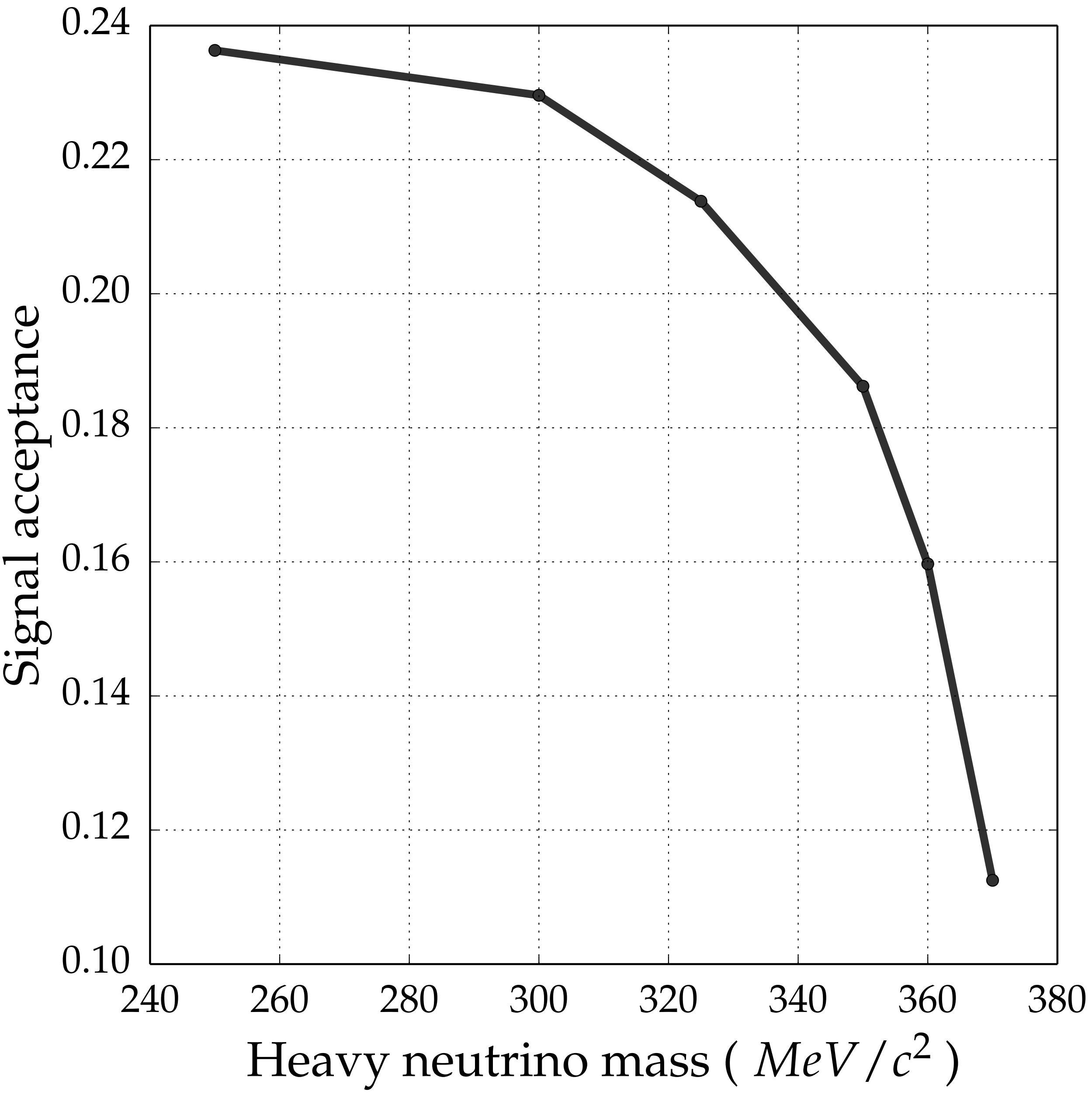


Heavy neutrino signals

•

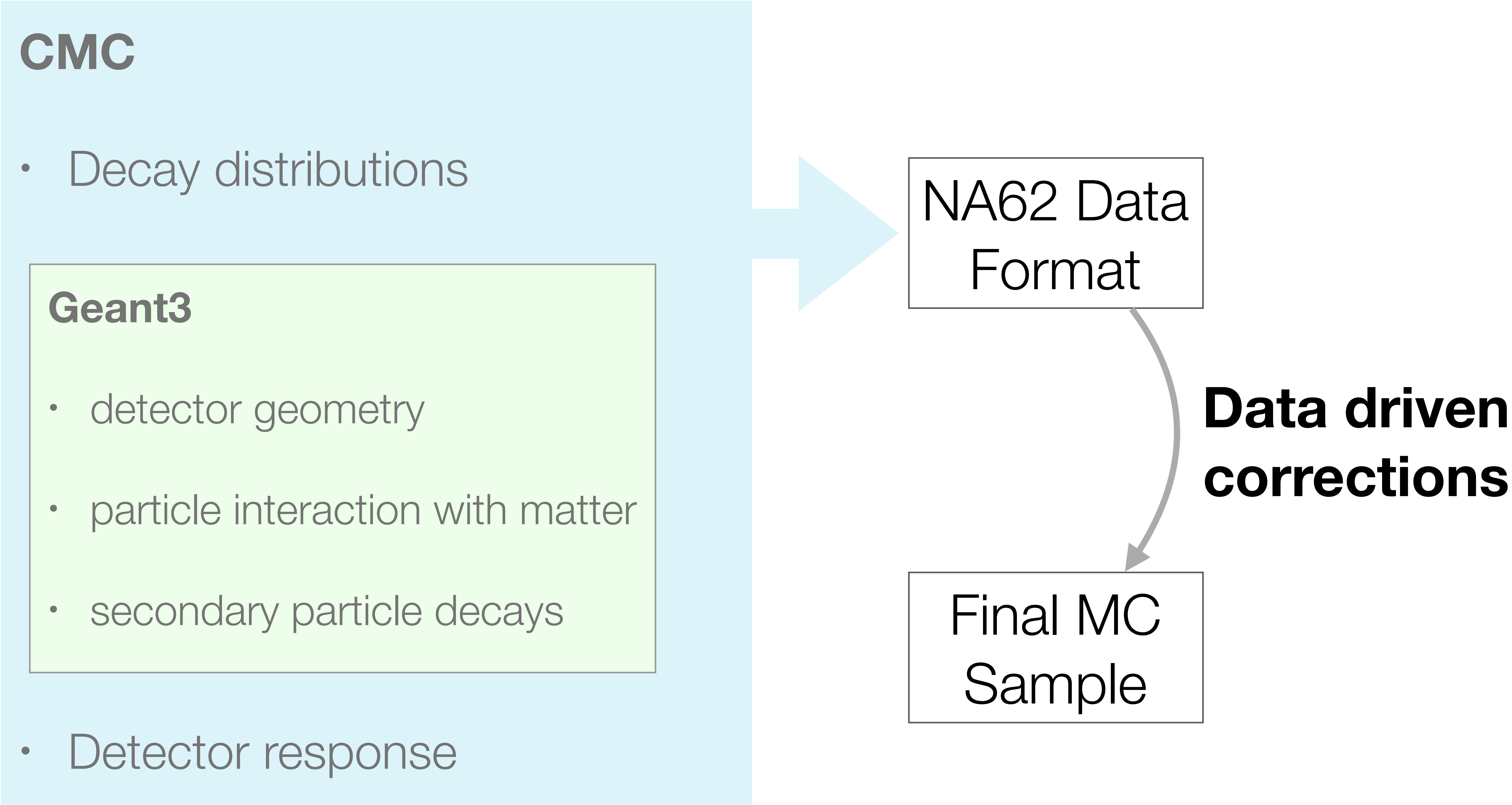
acceptance





Background studies

MC simulation



CMC

- Decay distributions

Geant3

- detector geometry
- particle interaction with matter
- secondary particle decays

- Detector response

NA62 Data Format

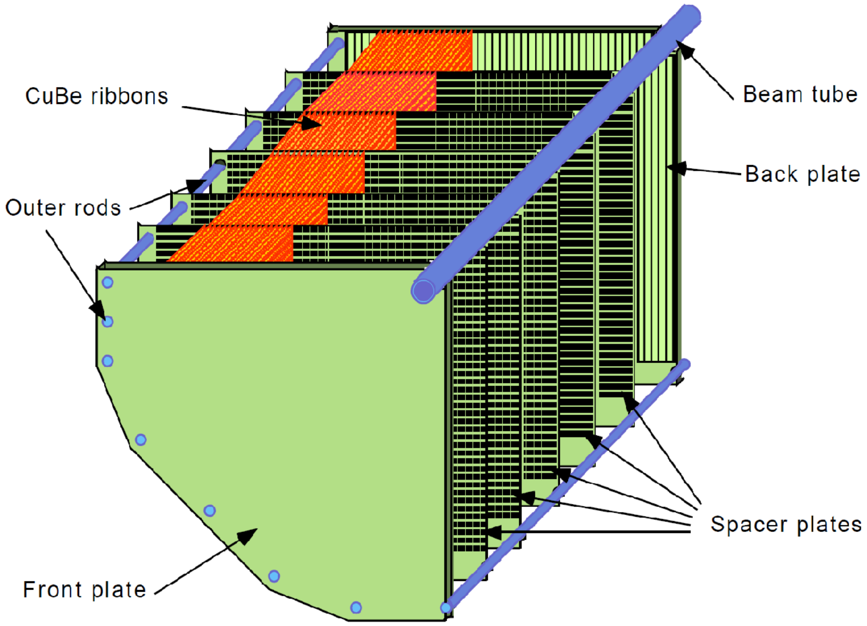
Data driven corrections

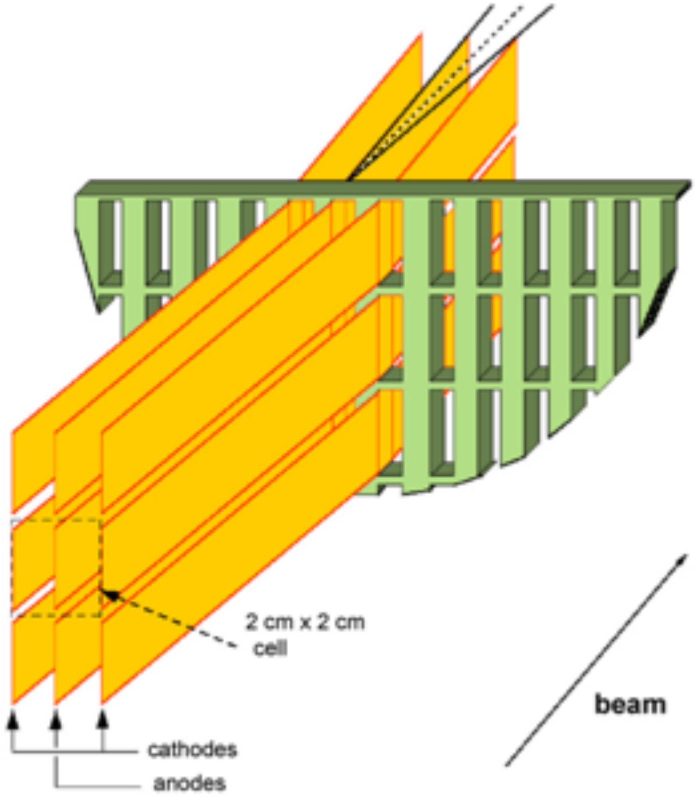
Final MC Sample

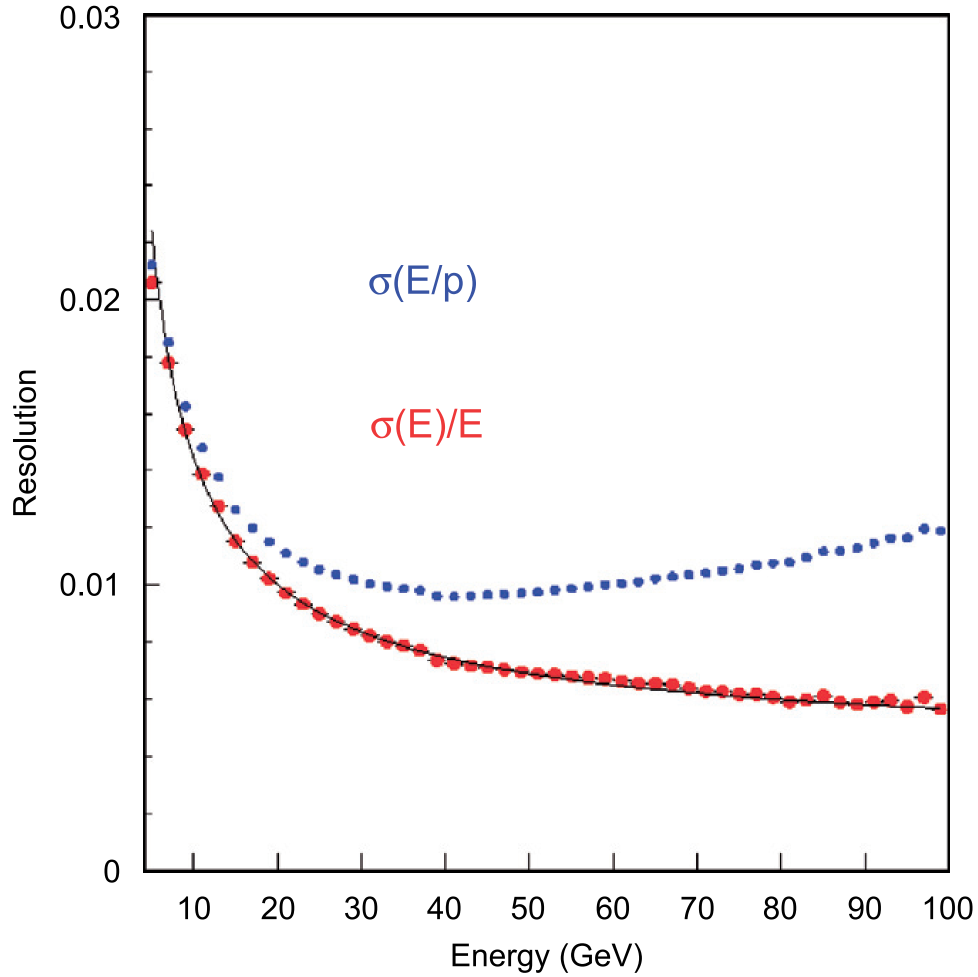
Photon vetoing: LKr Calorimeter

- Liquified noble gas calorimeter used as an ionisation chamber

$5.3m^2$
x
$127cm^3$



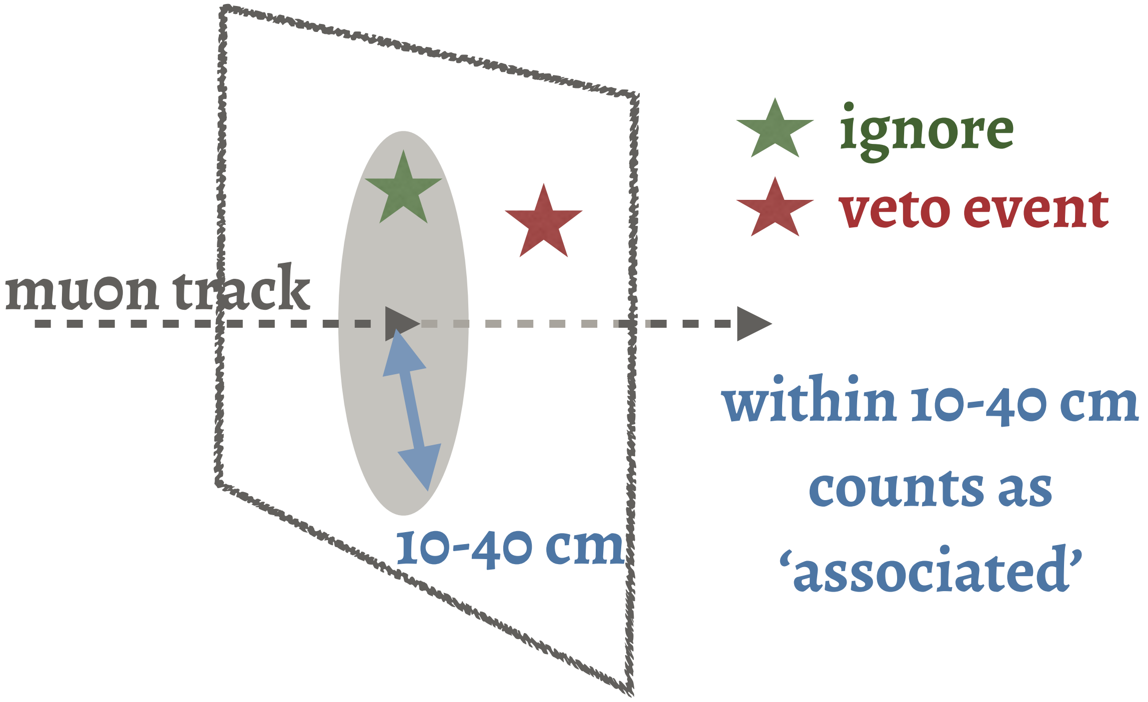




Photon veto

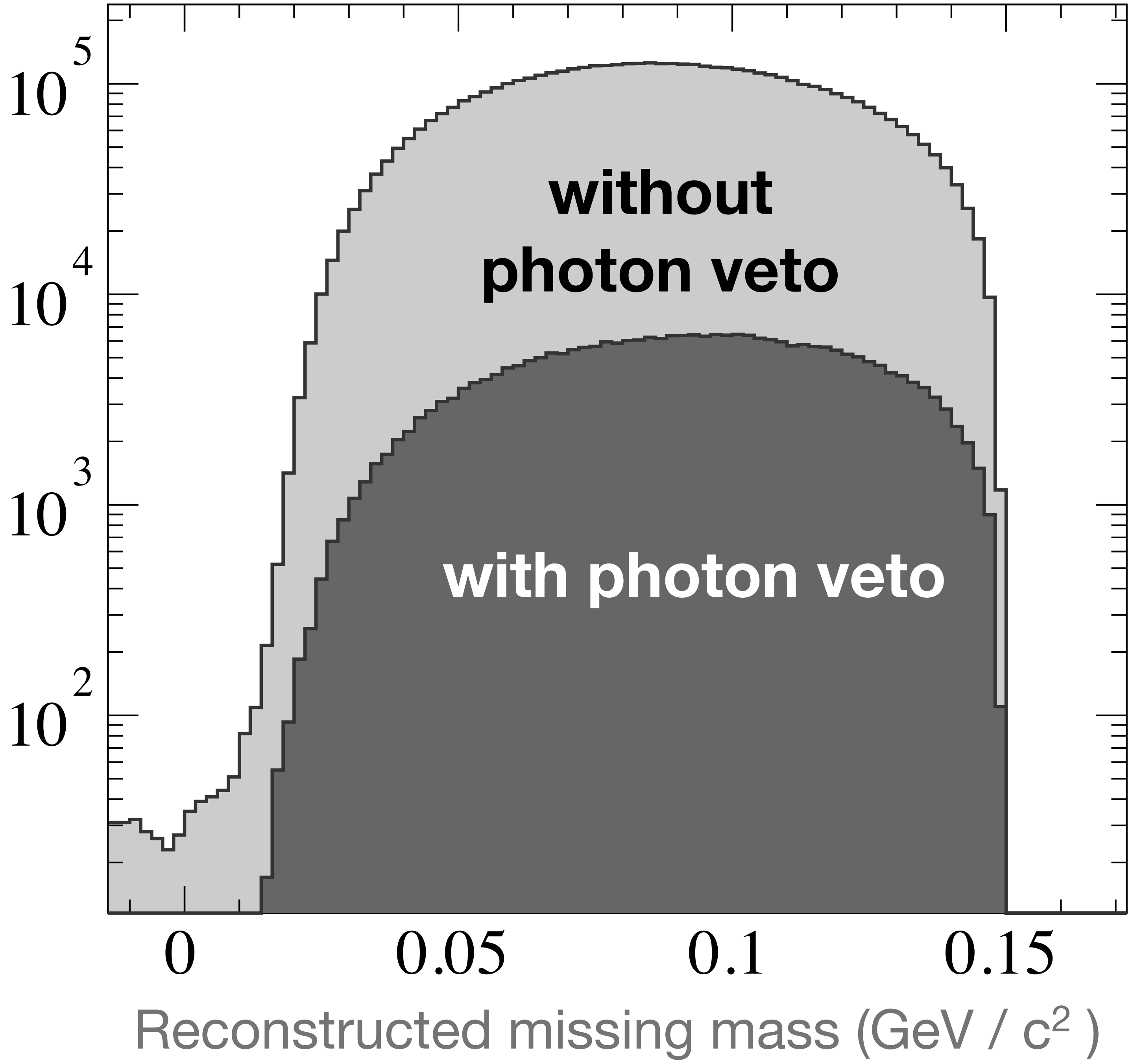
Liquid krypton EM calorimeter

- Veto events with clusters (above a noise threshold) that are not associated with the muon track



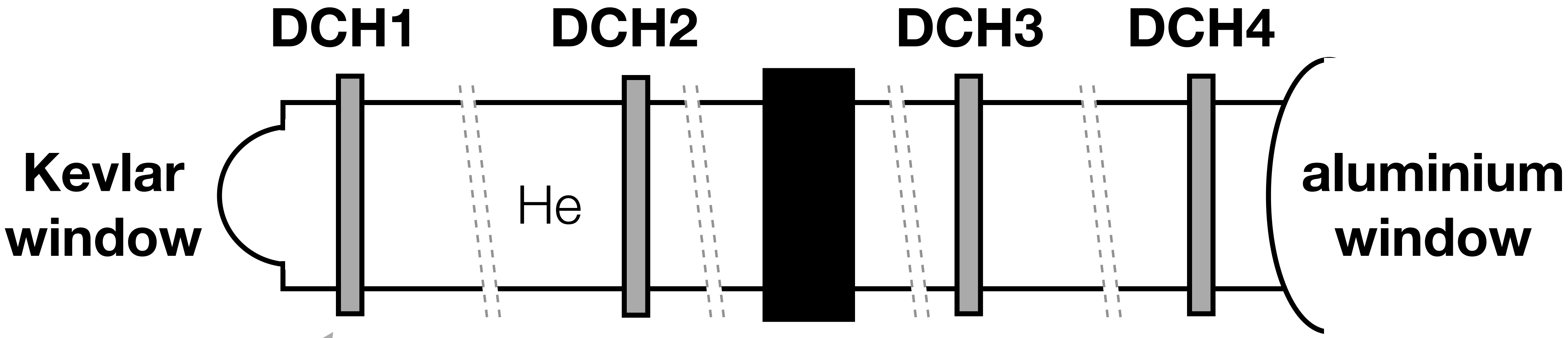
within 10-40 cm counts as 'associated'

Effect on $K^+ \to \mu^+ \nu \pi^0$



Drift chamber spectrometer

- Resolution was important in R_K measurement for μ-e separation



DCH1 **DCH2** **DCH3** **DCH4**

Kevlar window

He

aluminium window

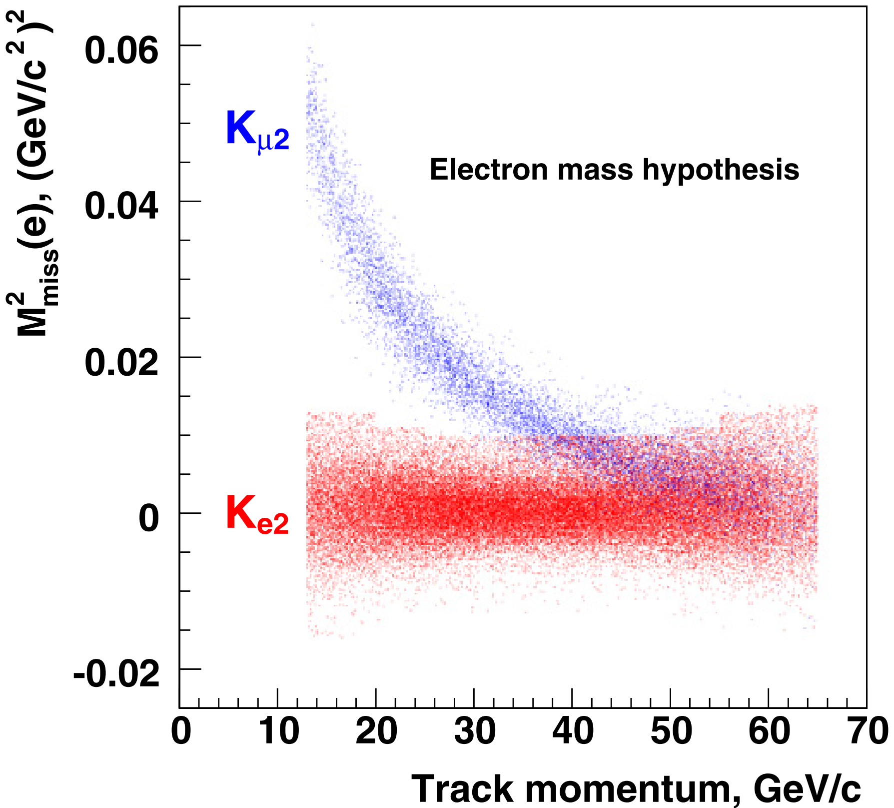
8 planes of sense wires:
X,Y,U,V
(in staggered pairs)

Magnet
p_x kick of 256 MeV

$$\sigma_p/p = 0.48\% \oplus 0.009\% p\ [GeV/c]$$

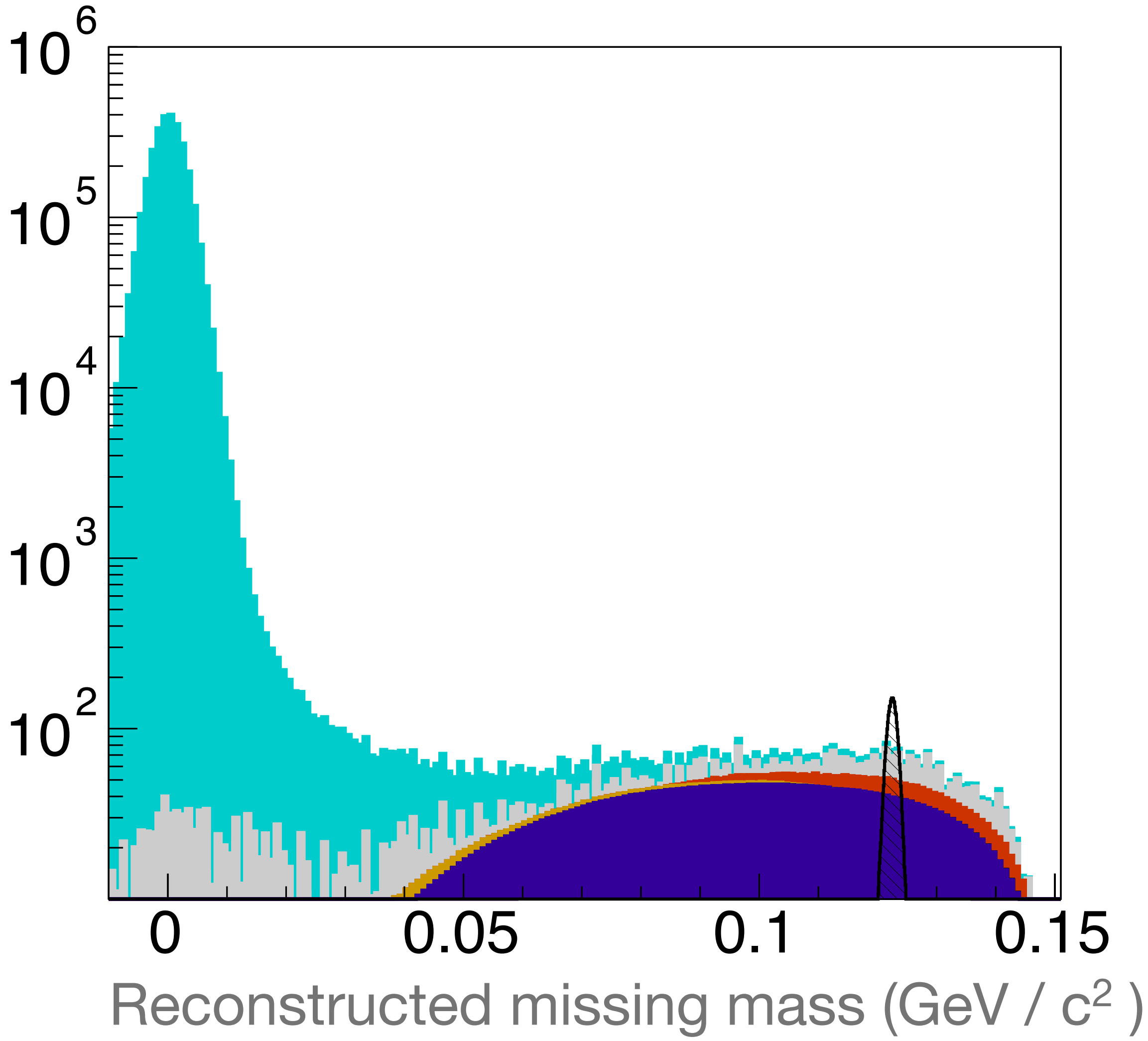
multiple Coulomb scattering

spatial resolution



Spectrometer resolution

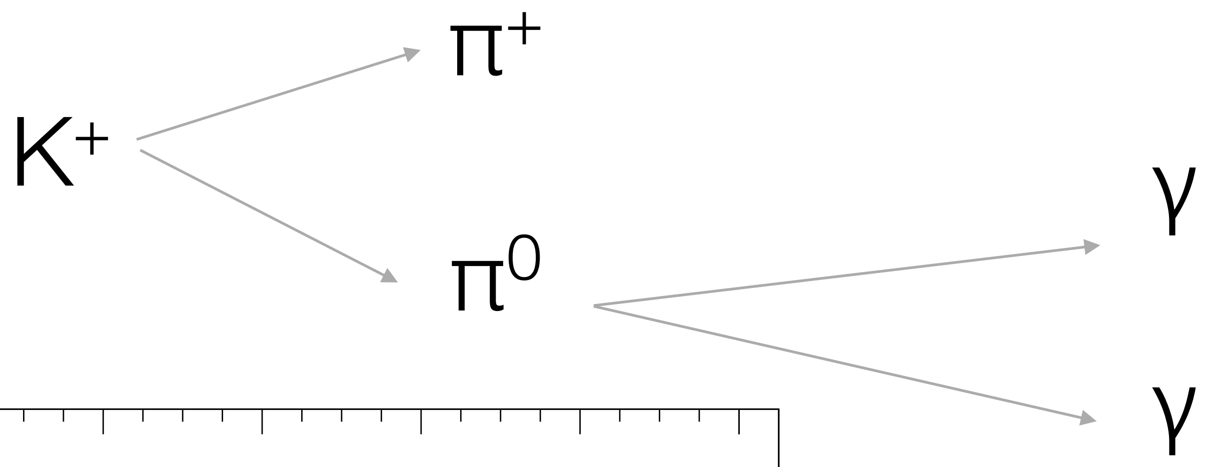
- Signal region lies in the far tail of the $K_{\mu2}$ missing mass spectrum, so far tails of momentum resolution matter



- Far tails of multiple Coulomb scattering are not well simulated in GEANT3

Using the calorimeter to study the spectrometer

- $K_{2\pi}$ is closed: all particles can be detected



K^+

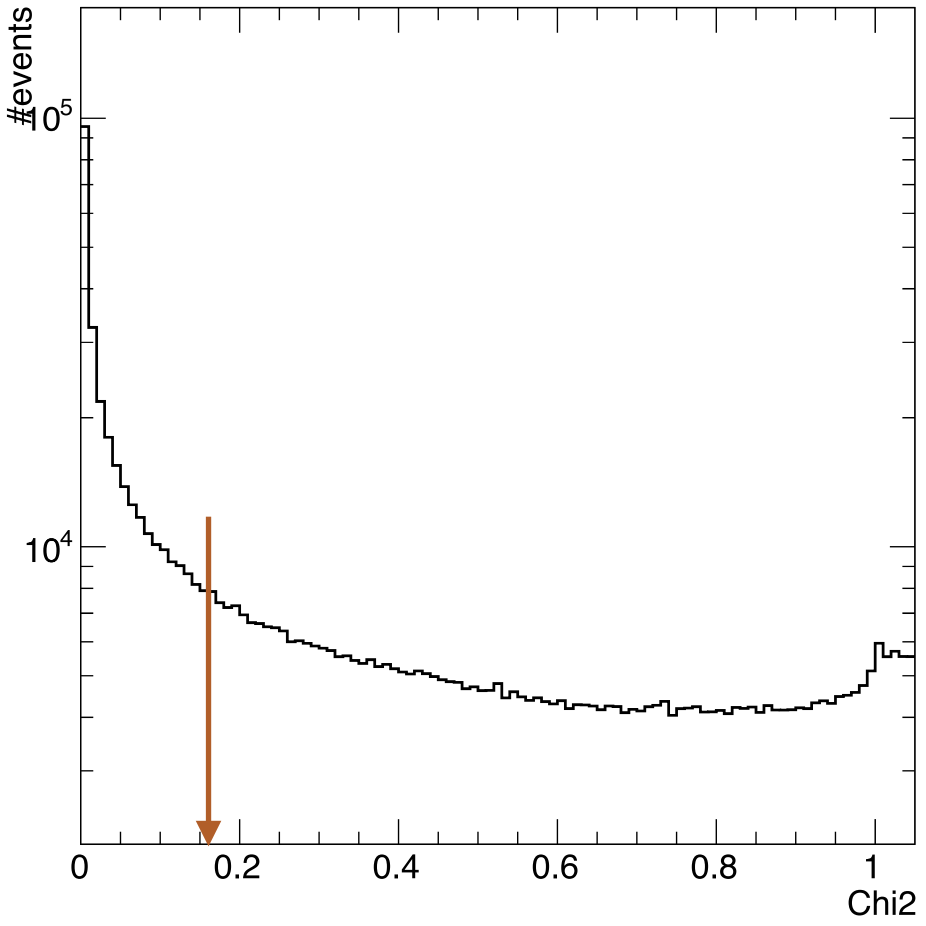
π^+

π^0

γ

γ

Can reconstruct entire event from photons in LKr and kaon momentum

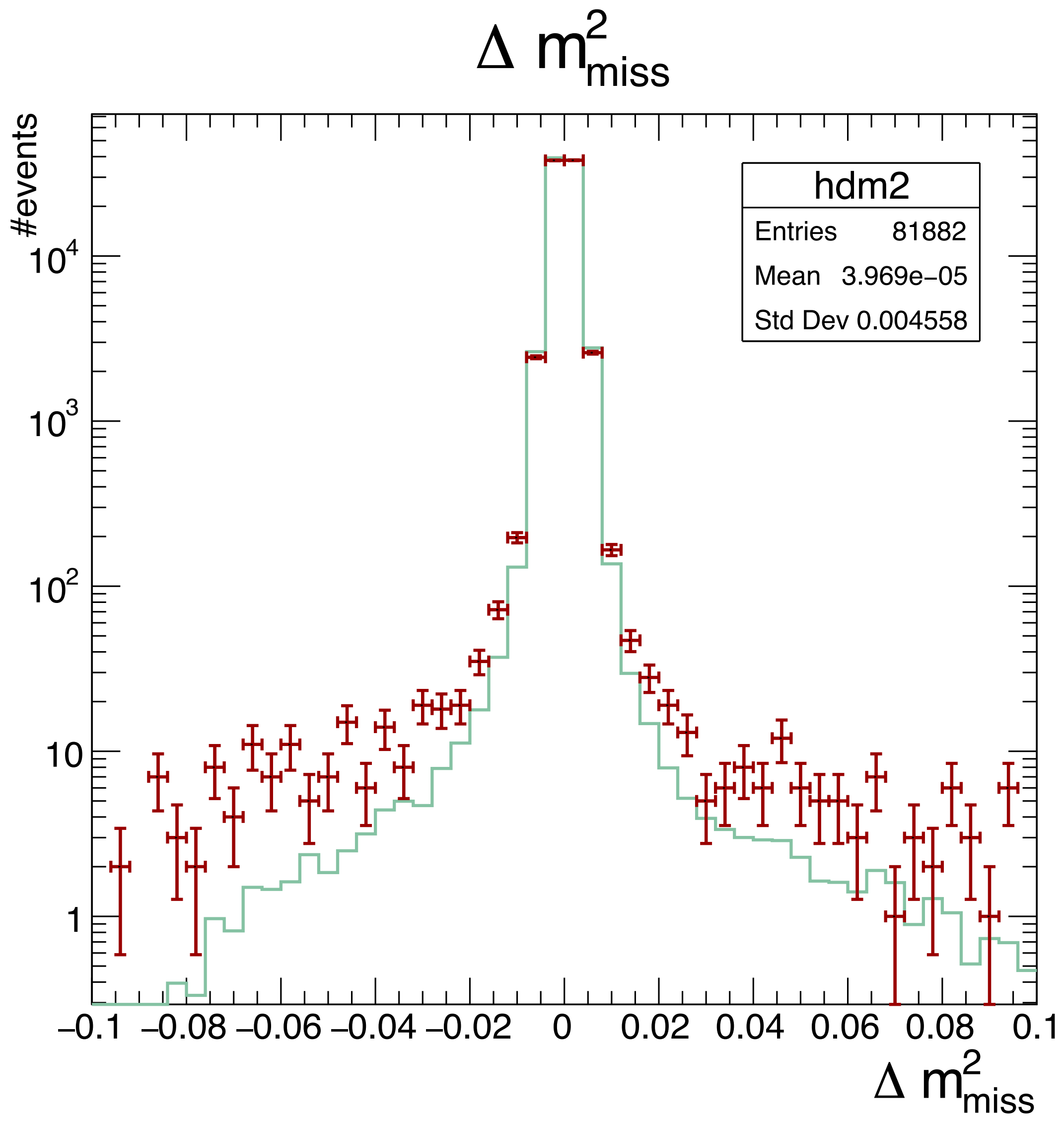


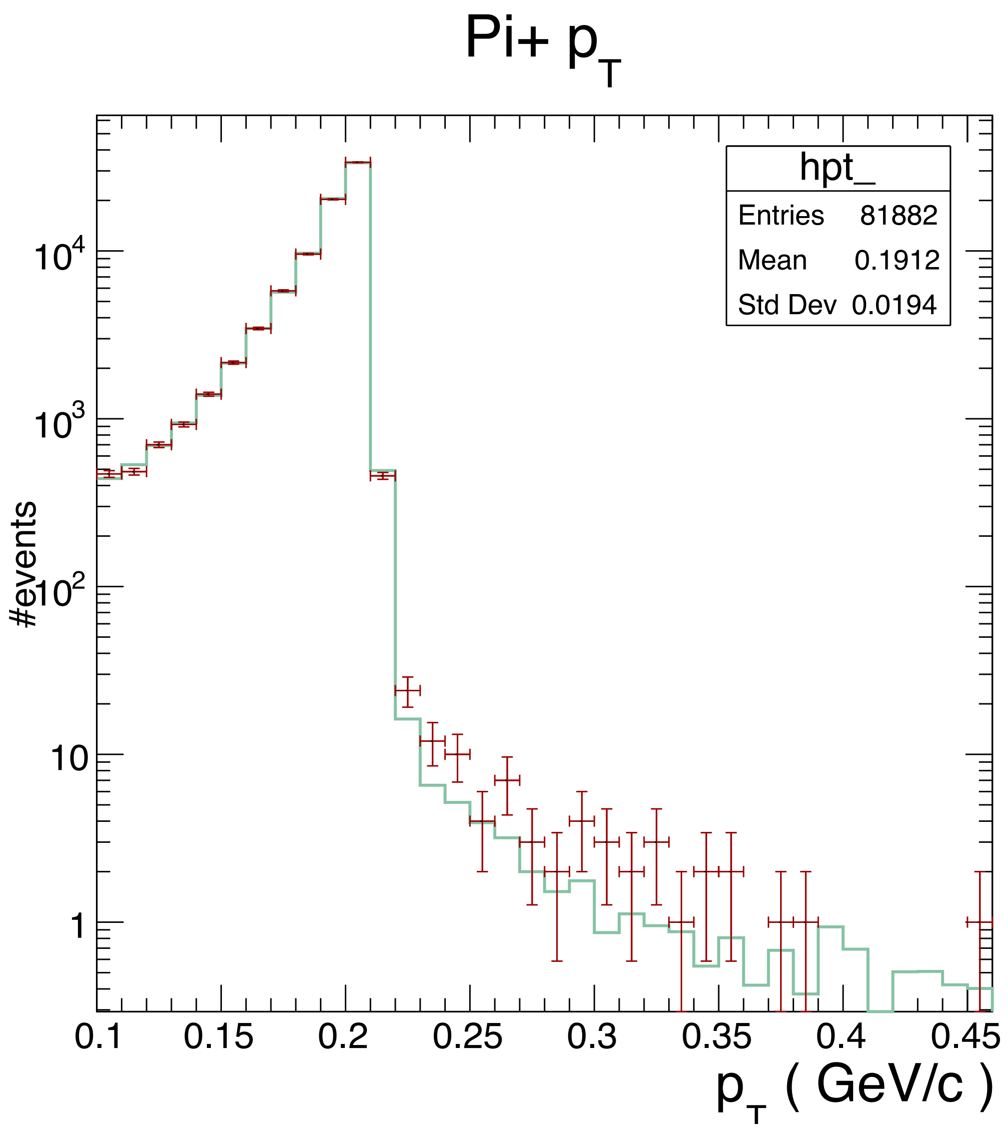
- Kinematic fit results in χ^2 with 1 degree of freedom

- Cut at $\chi2 < 0.16$ to obtain very pure $K_{2\pi}$ sample, **independently of spectrometer**

Kinematic distributions: data and MC

- Use spectrometer to reconstruct π^0 mass and p_T spectrum

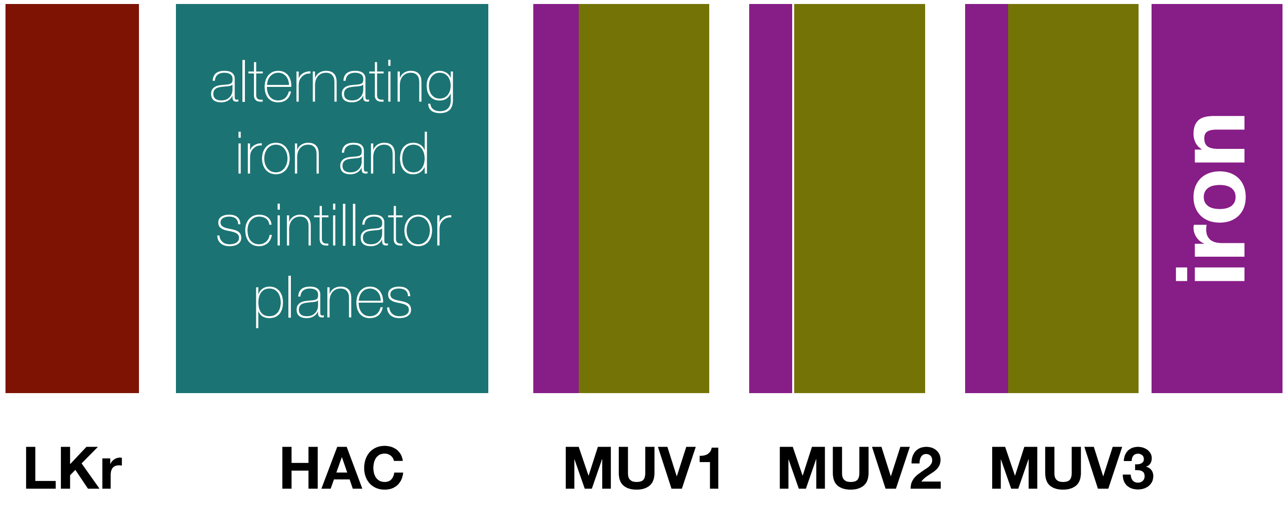


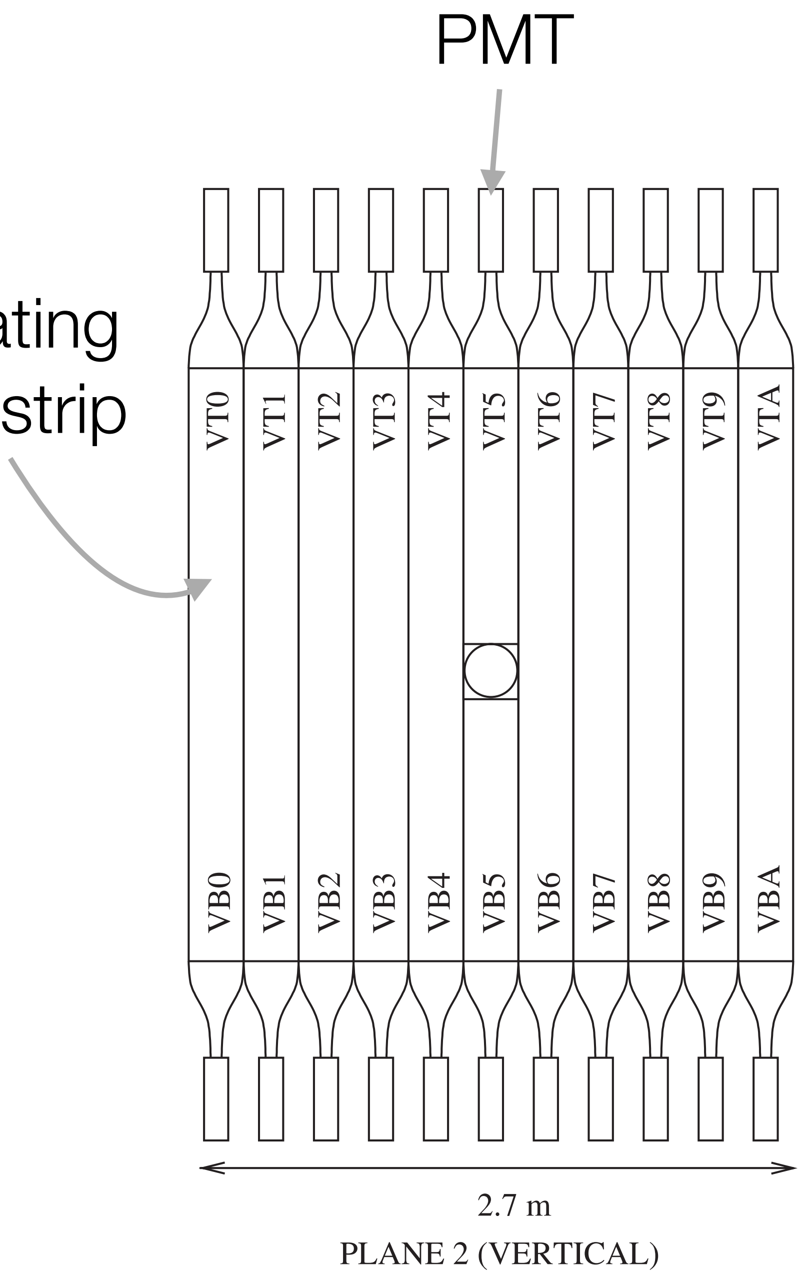


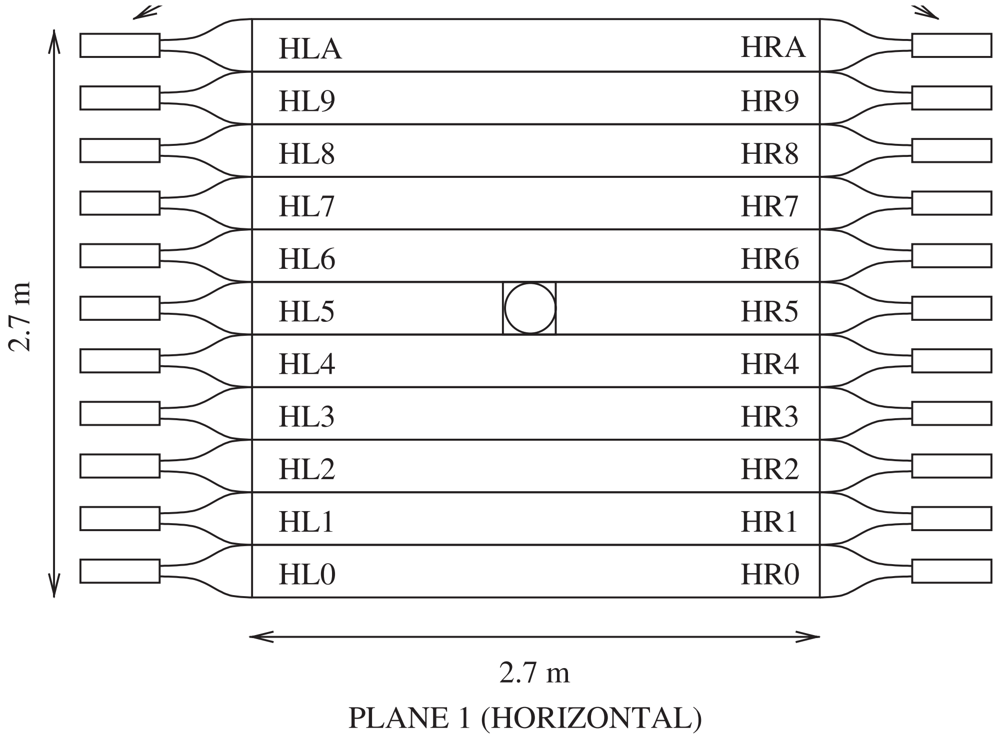
- Discrepancies are corrected by artificially introducing additional scattering in MC

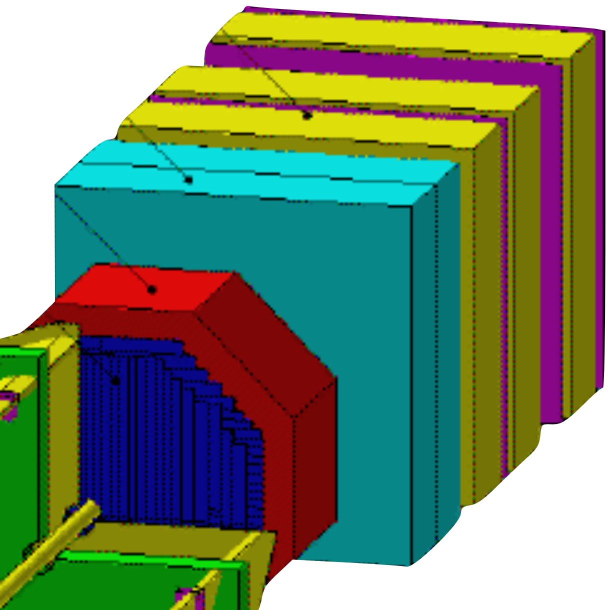
Particle Identification: Muon veto

- Originally used to reduce trigger rates from $K^+ \rightarrow \mu^+ \pi^0 \nu$



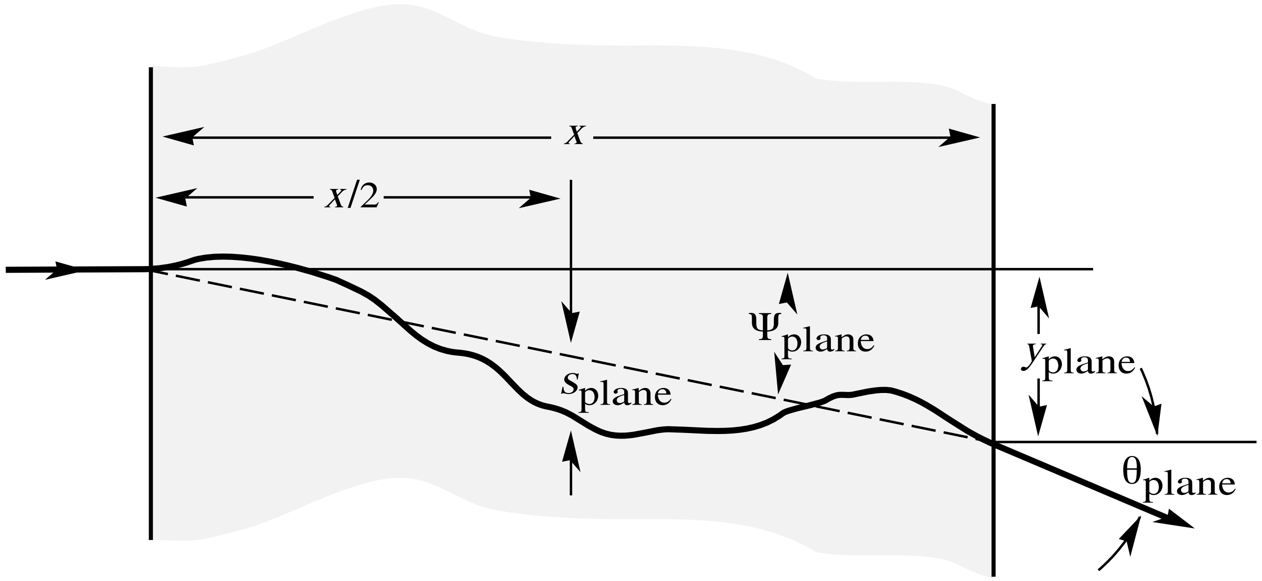






Muon detection condition

- Require a hit in both planes 1 and 2 (ignore MUV3)
- Match hit position to extrapolated track position (with momentum dependent tolerance)



$$\sigma_{\text{scatter}} = (z_{\text{MUV}n} - z_{\text{Lkr}}) \frac{13.6\,\text{MeV}}{pc} \sqrt{\frac{N^{\text{rad}}}{3}}$$

$$N^{\text{rad}} = \frac{l_{\text{LKr}}}{X^0_{\text{LKr}}} + \frac{l_{\text{HAC}}}{X^0_{\text{iron}}} + \frac{l_{\text{iron}}}{X^0_{\text{iron}}} \times n_{\text{MUV}}$$

$$\sigma_{\text{DCH}} = \left(1 \times 10^{-4} + \frac{0.9\,\text{GeV}}{pc}\right)(z_{\text{MUV}} - z_{\text{DCH}})$$

cut on track-muon hit distance in MUV plane

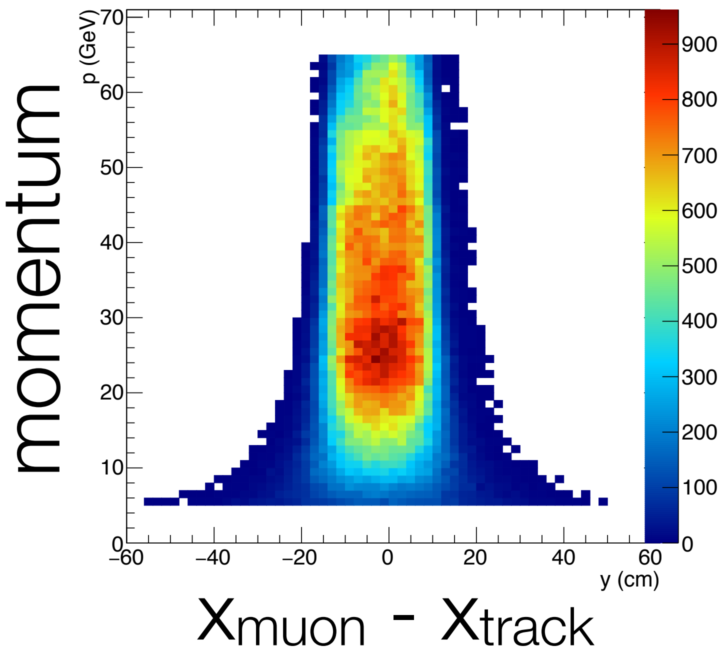
$$s_{\text{cut}} = \xi \sqrt{\sigma^2_{\text{DCH}} + \sigma^2_{\text{scatter}}} + \frac{1}{2} d_{\text{strip-width}}$$

scale factor = 4

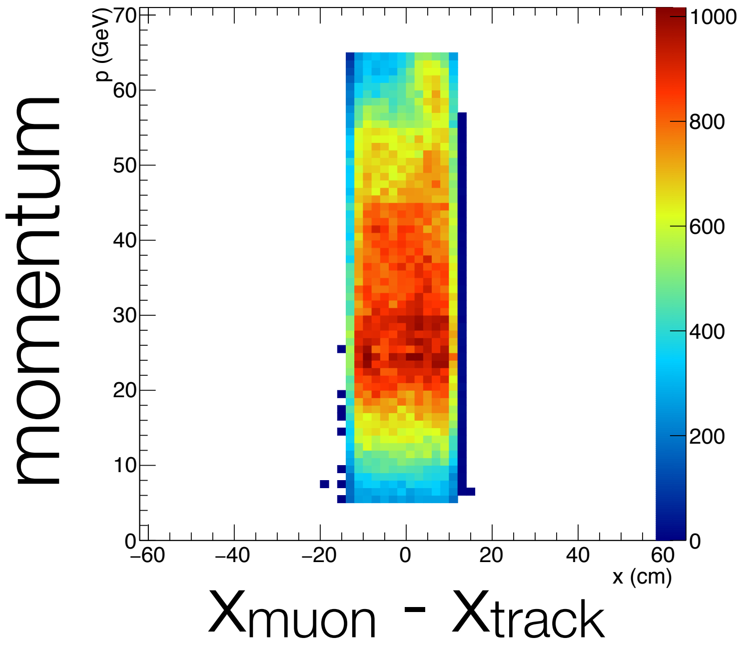
Simulation

- In my MC samples, official simulation stops at LKr.
- Simulate muon scattering by hand then re-weight to match efficiency distributions in data.

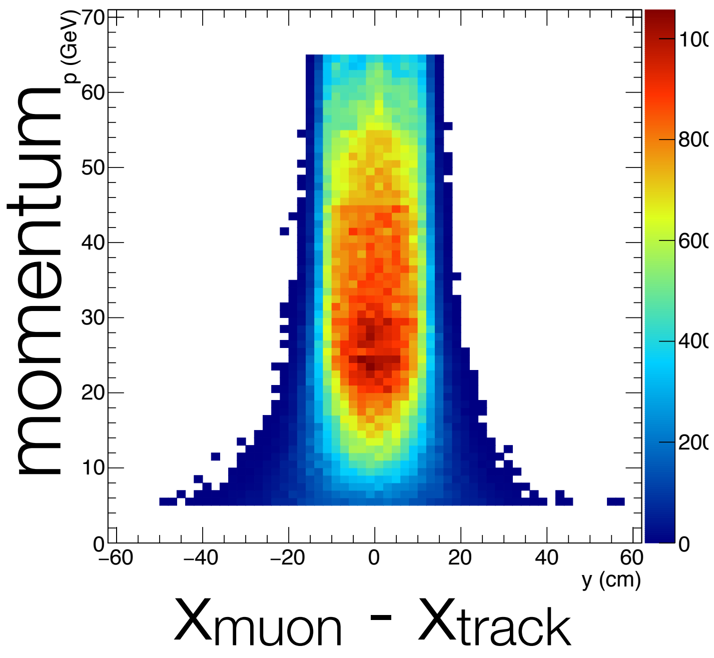
$K_{\mu 2}$ data



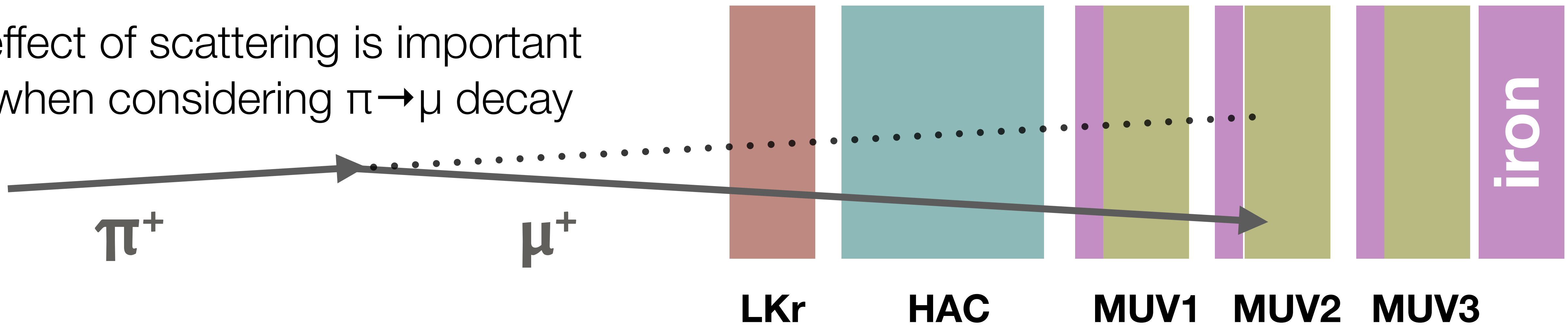
$K_{\mu 2}$ raw MC



$K_{\mu 2}$ corrected MC

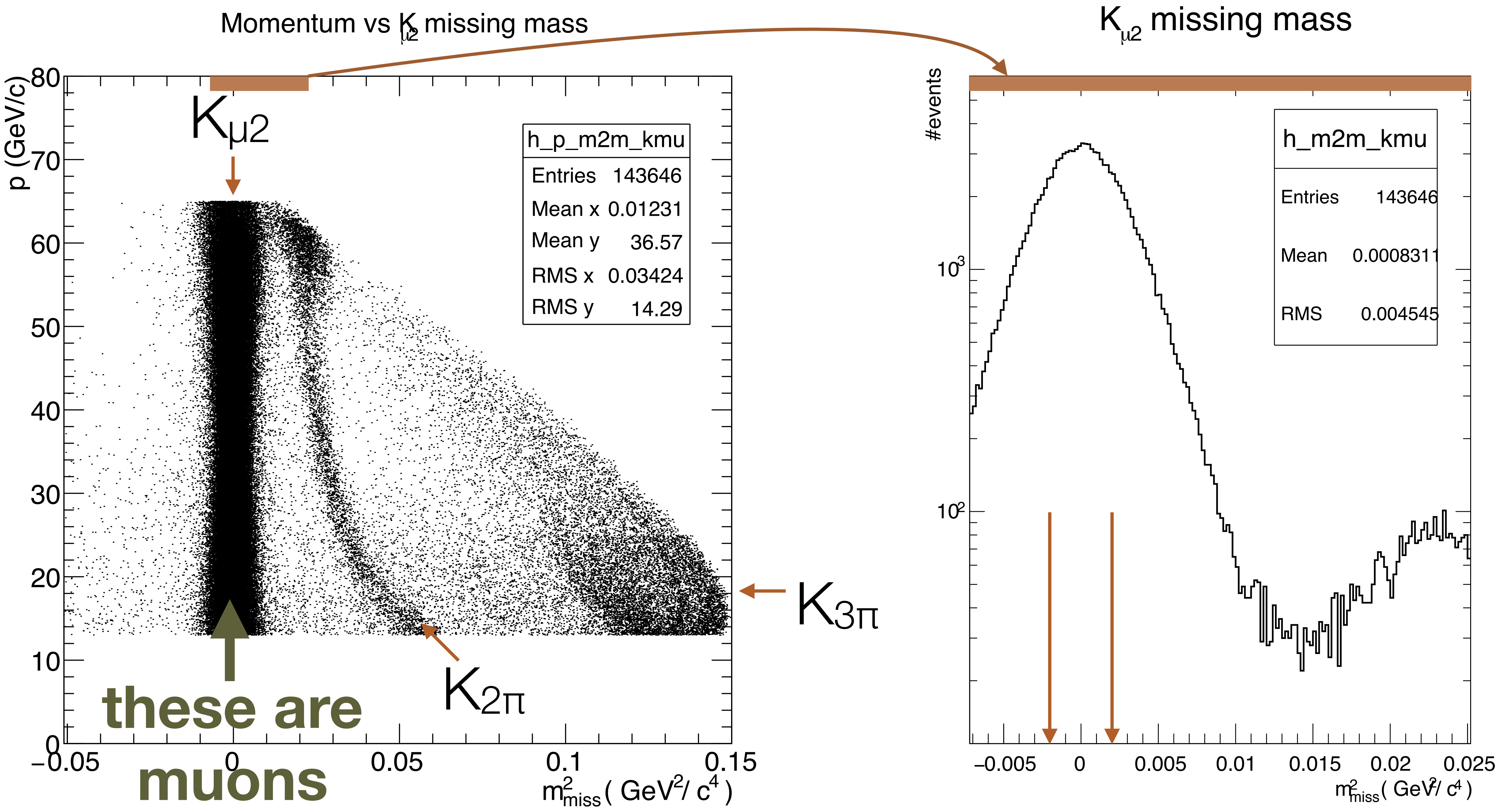


effect of scattering is important when considering π→μ decay



Muon detection efficiency

- Select a pure sample of muons, independently of MUV, with a tight kinematic selection
- Then look for associated muon hits



$K_{\mu 2}$

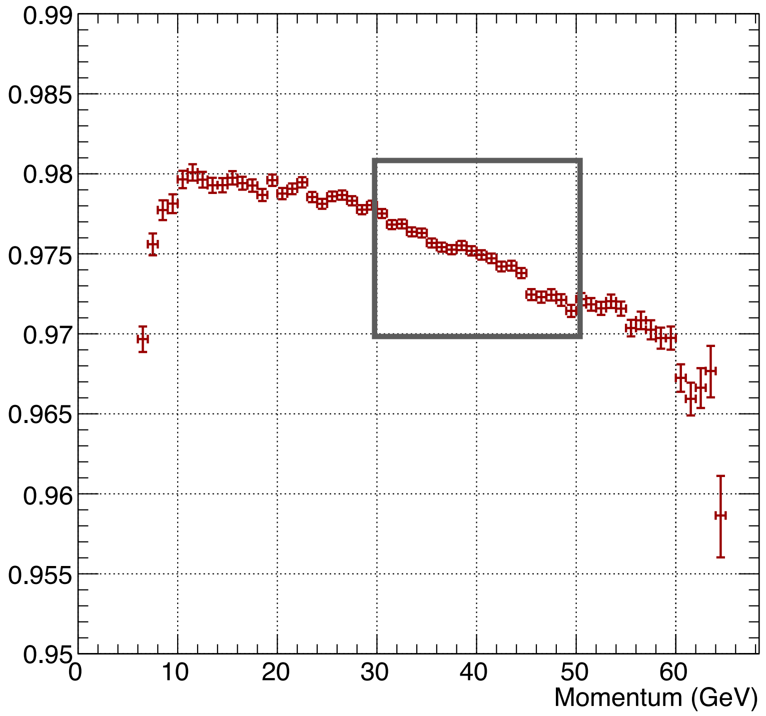
$K_{3\pi}$

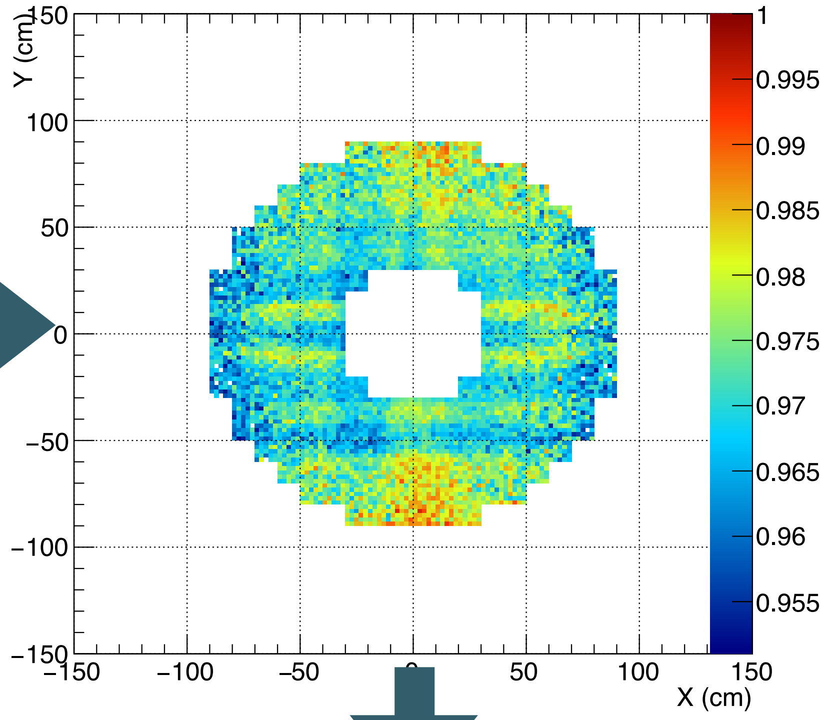
$K_{2\pi}$

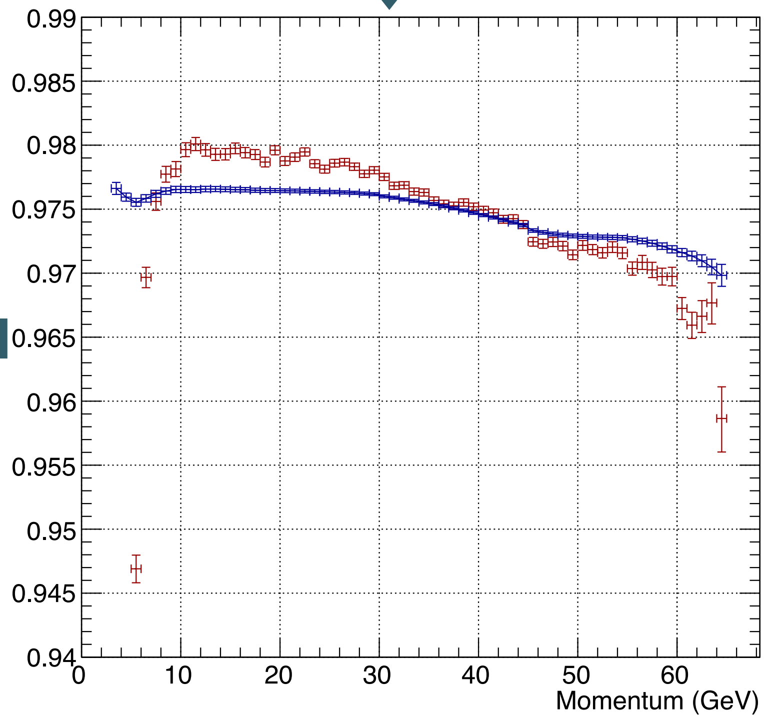
these are muons

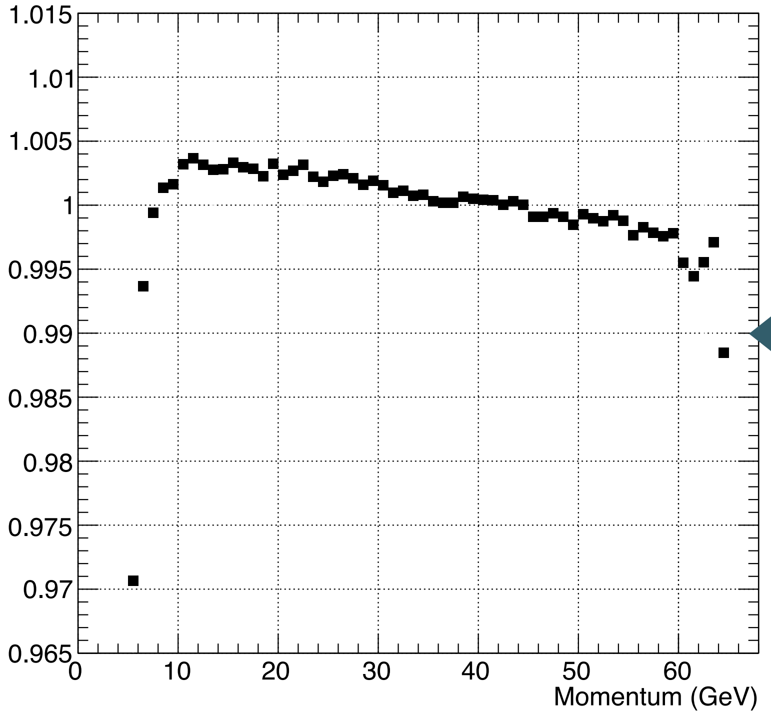
Efficiency measurements

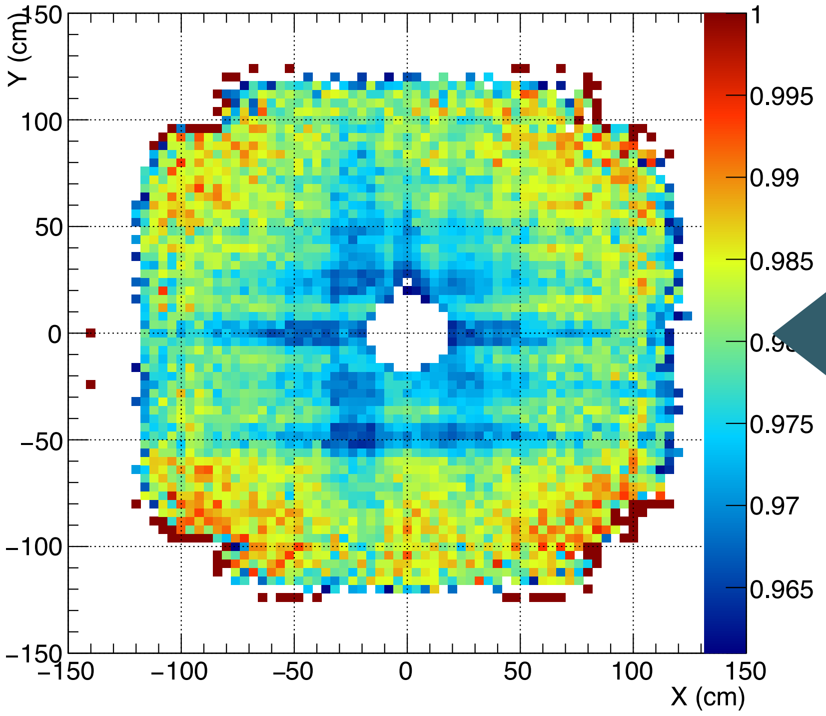
- Iterate between measurements as a function of **momentum** and **xy position** in MUV plane









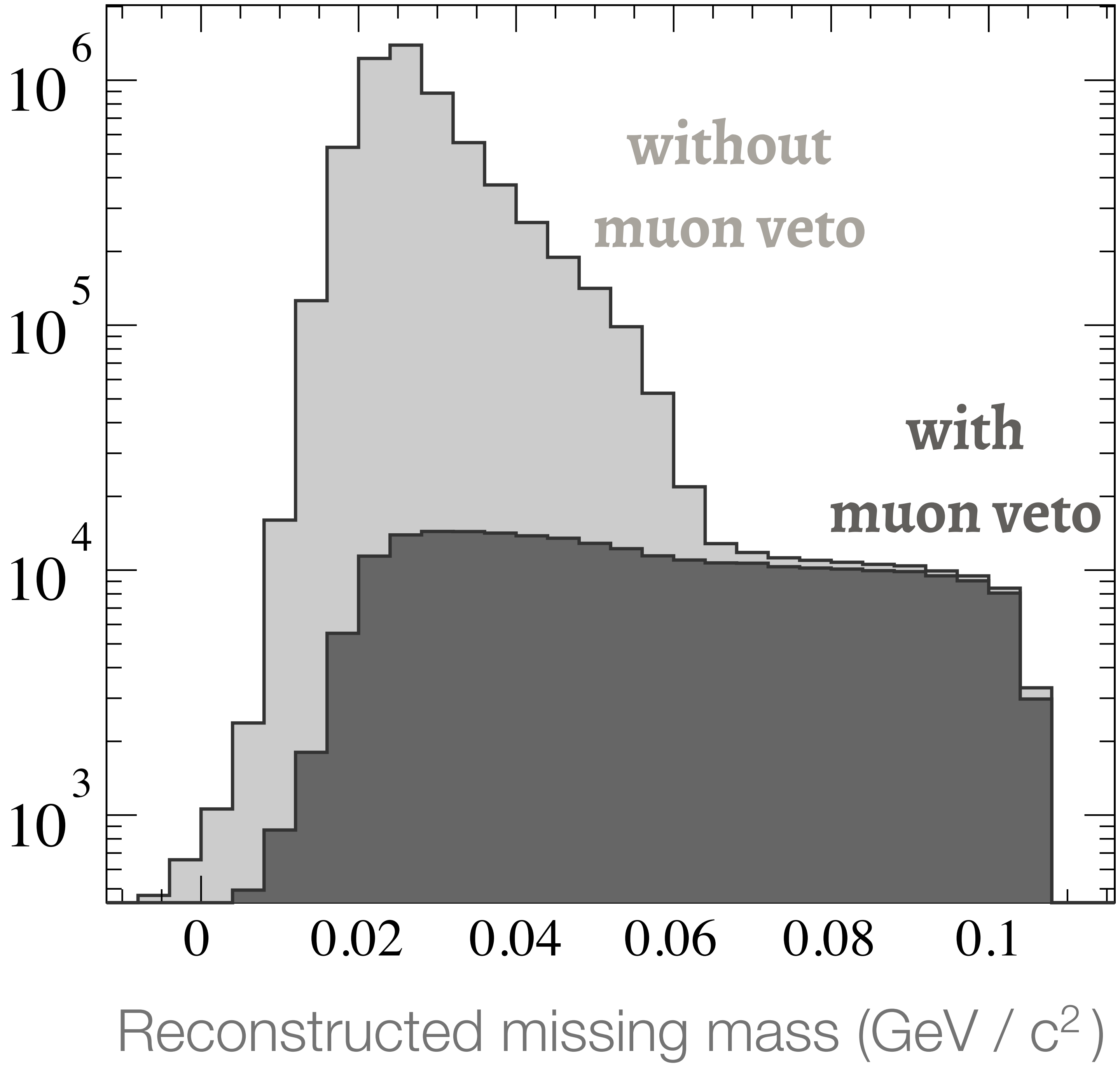


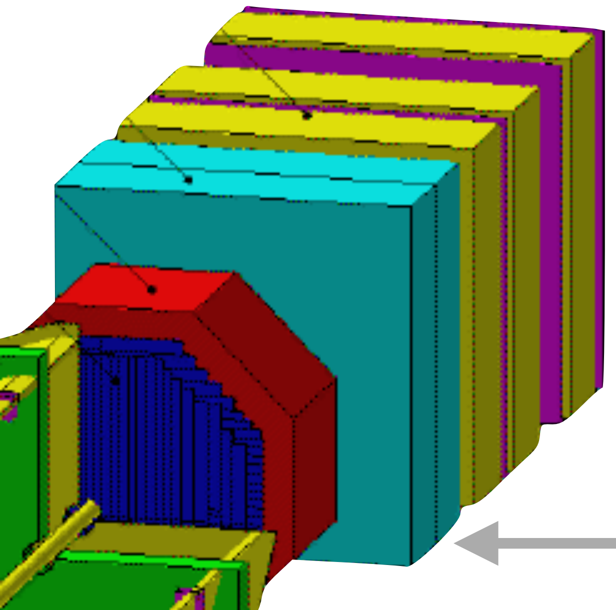
Particle identification

Muon Veto

- Suppress decays to pions by rejecting events with no muon signal
- Events with $\pi^+ \rightarrow \mu^+$ decays remain

Effect on $K \rightarrow \pi^+\pi^0$



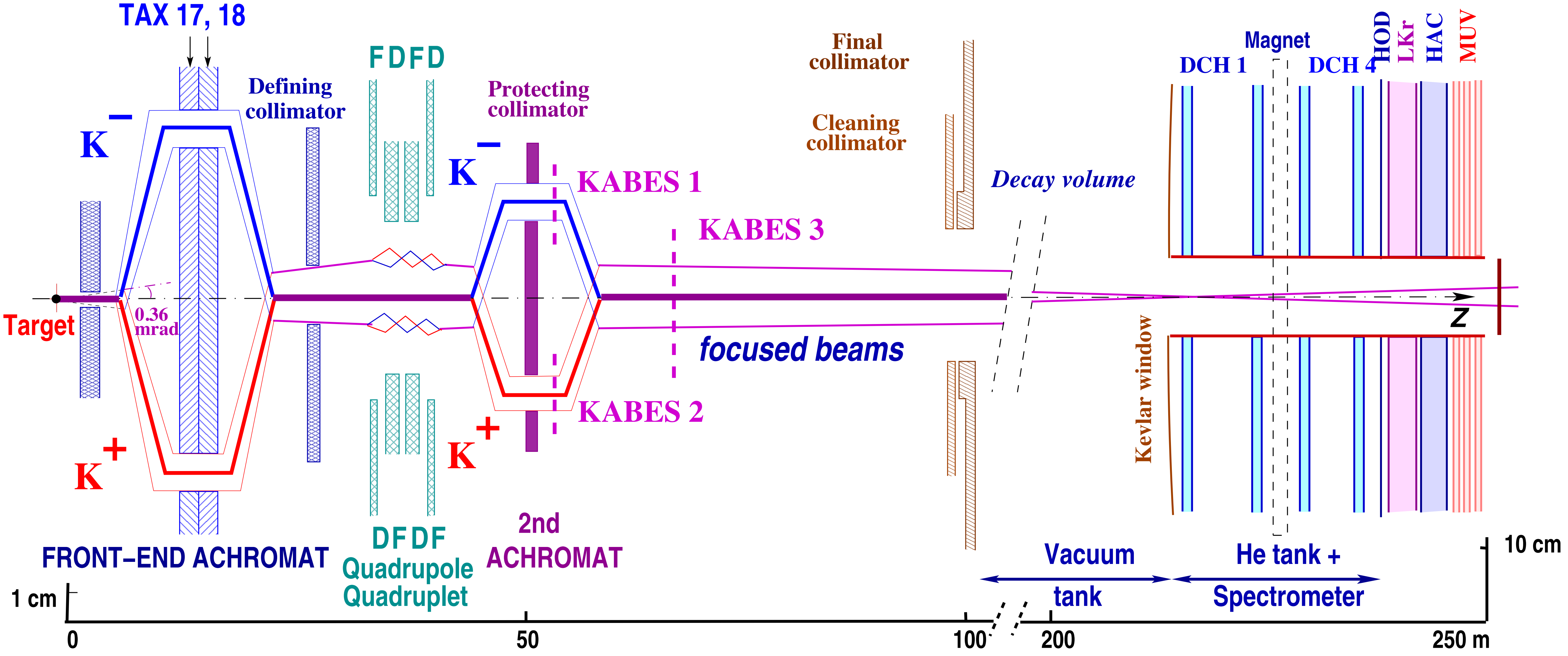


Muon Veto system

Hadronic Calorimeter

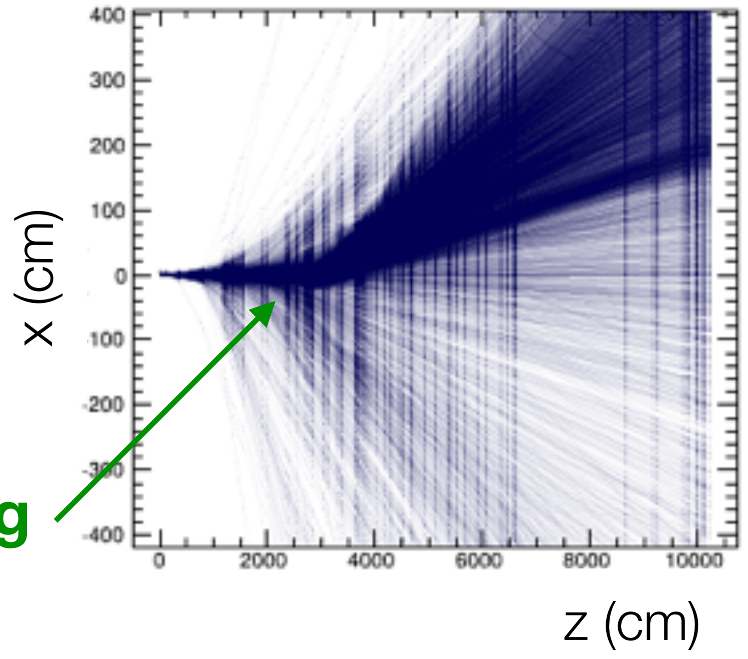
Beam halo

- A flux of muons, coming from beam kaon and pion decays upstream of the decay volume.

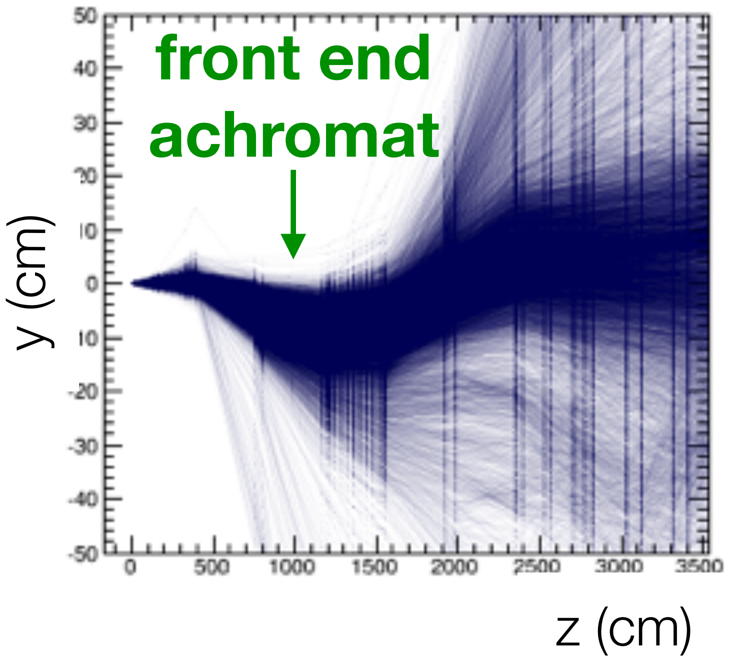


HALO simulation program

- Dedicated program for simulating beam halo muons: **transfer matrix approach**



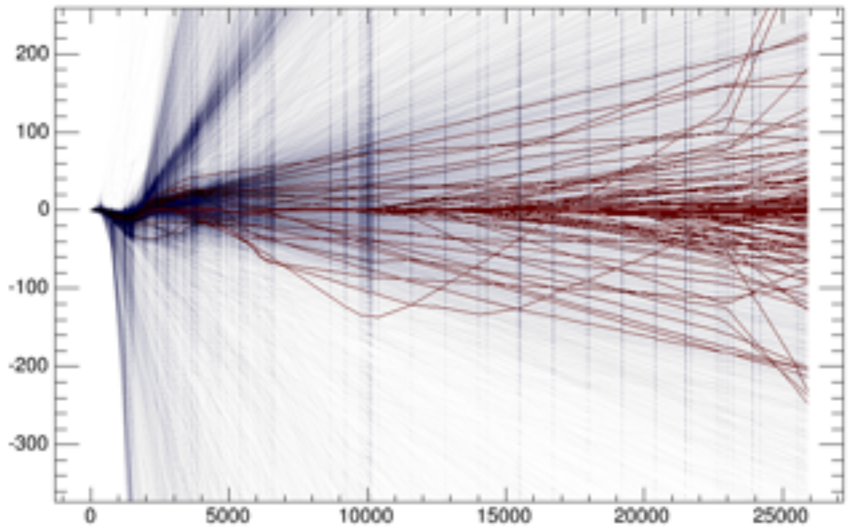
MBPL sweeping magnet



front end achromat

simulations run on
Birmingham
Blue Bear Cluster

- Muons which pass through DCH1 are highlighted in red

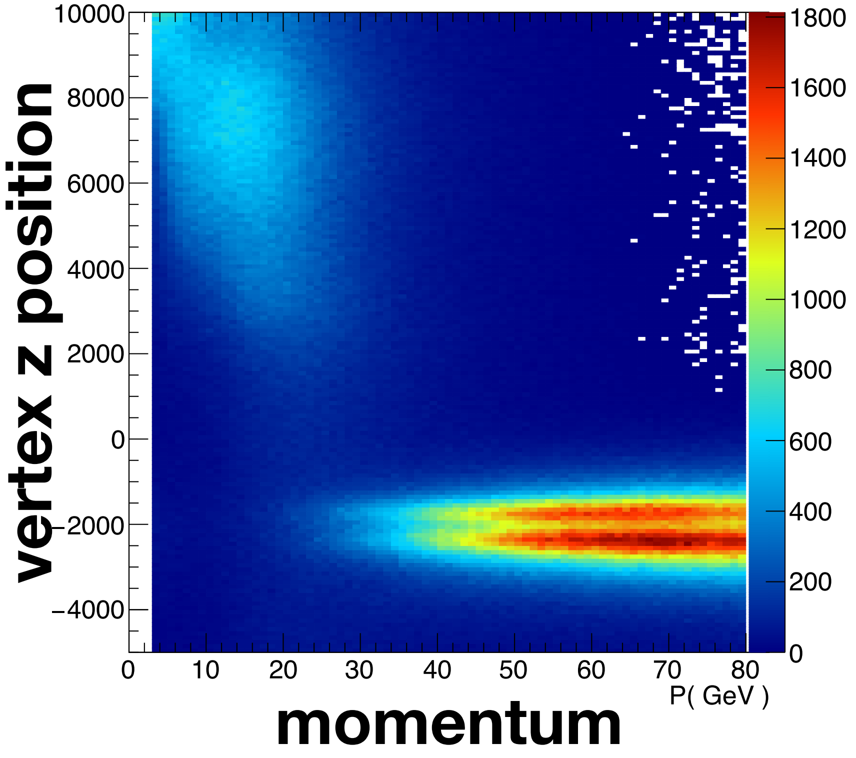


- One muon halo event reconstructed for every 5 million kaons simulated

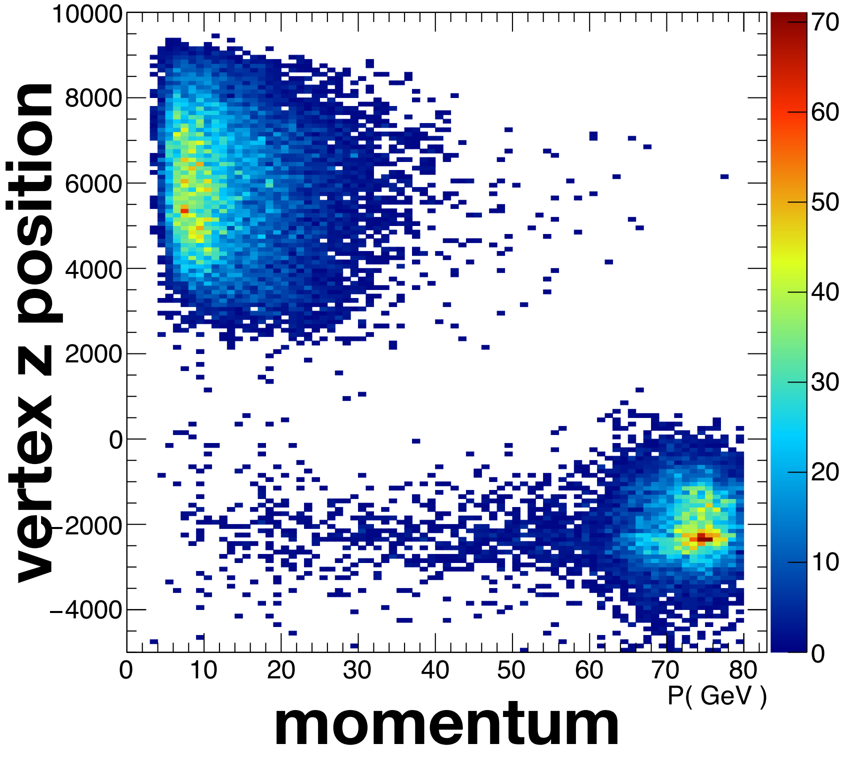
Qualitative agreement

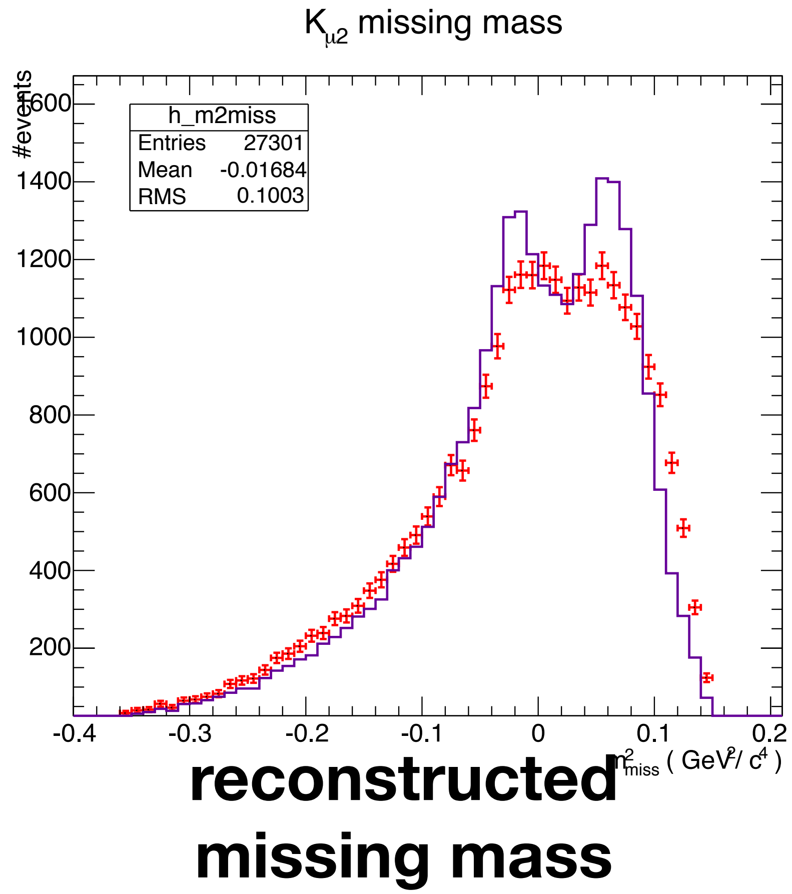
- Qualitative features of the data are reproduced

Data



HALO MC



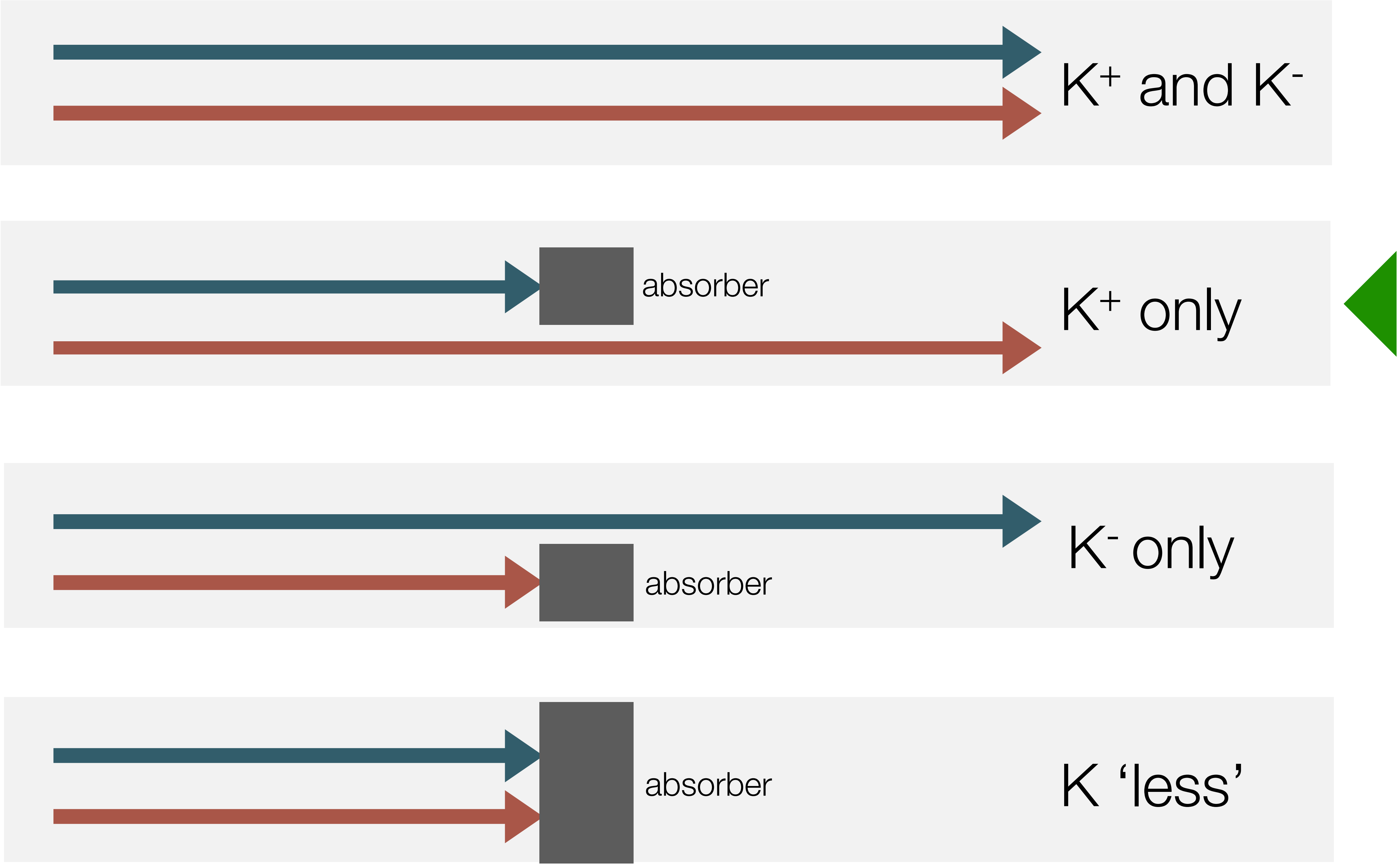


- Ultimately, MC simulation is not good enough for quantitative studies

- Use a data driven approach instead

Data driven halo estimate

- NA62 ran with various combinations of K^+ and K^- beams



K^+ and K^-

absorber

K^+ only

my data set

absorber

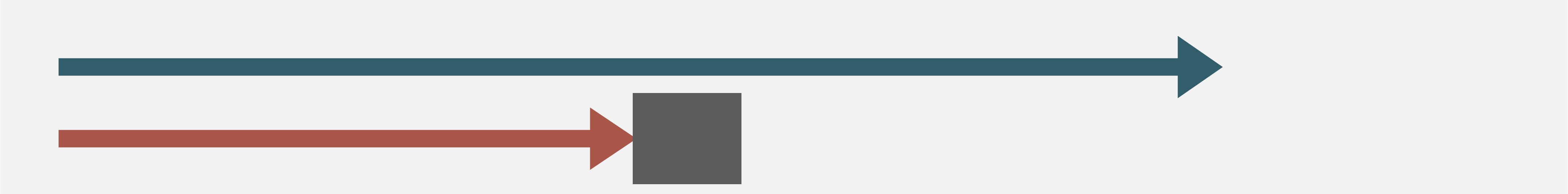
K^- only

absorber

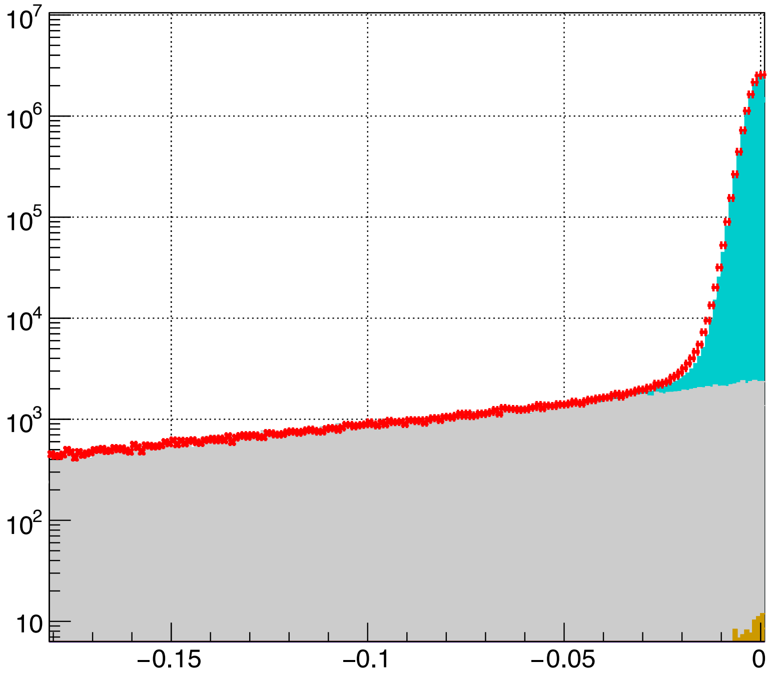
K ‘less’

Data driven halo estimate

- Apply my K^+ selection to data-sets without any K^+ in them:



- Any positive tracks must come from K^+ decays **before** the absorber, i.e. the beam halo (or $K^- \rightarrow \pi^+\pi^-\pi^-$, a small correction from MC)



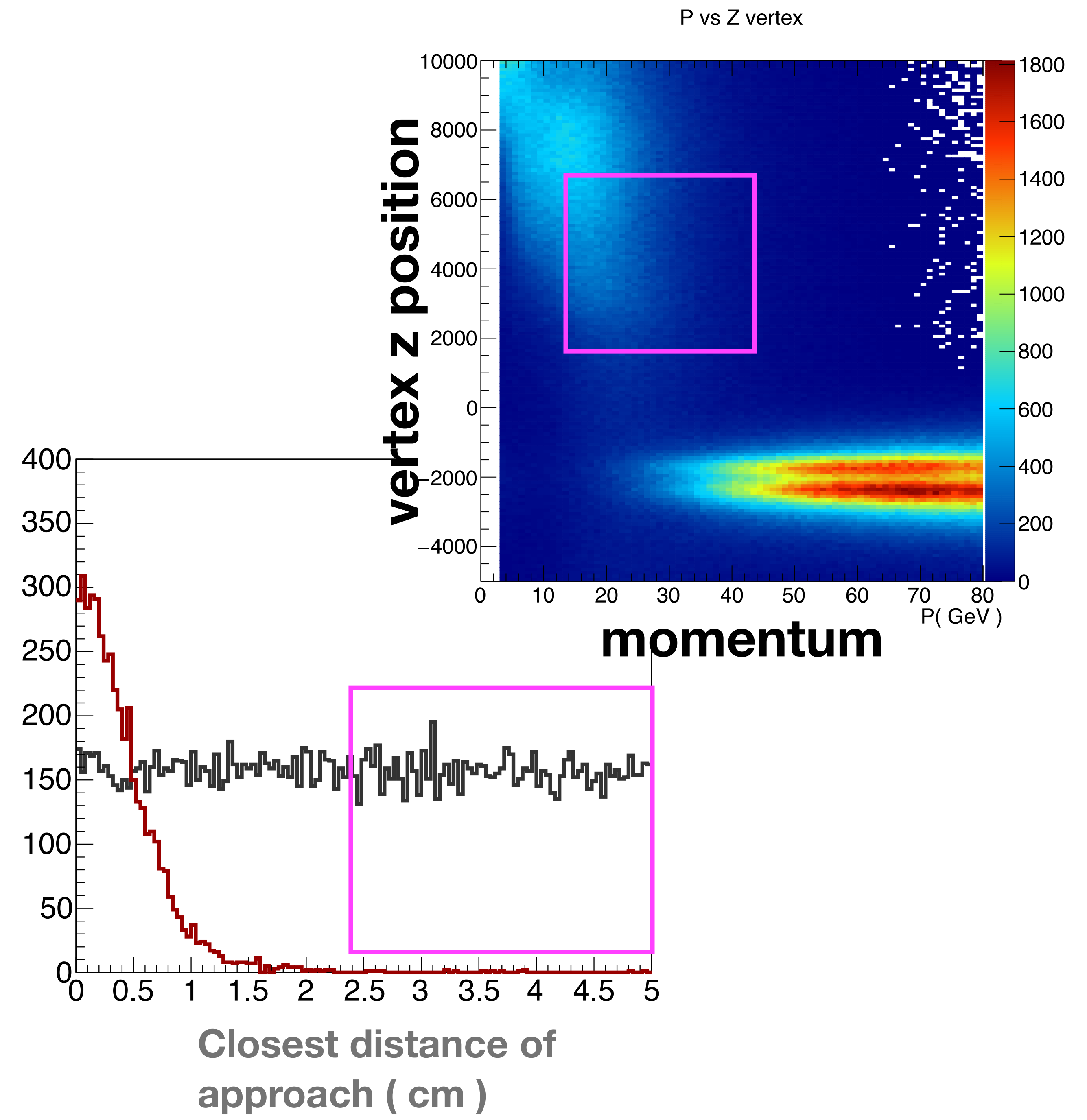
Reconstructed missing mass (GeV / c^2)

- Measured shape is scaled to my data set using the region $m^2_{miss} < 0$

Data driven results

- Test halo estimate studying regions where halo dominates

- 11 GeV/c < p < 40 < GeV/c
- 2000 cm < zvertex < 7200cm
- 2.5 cm < CDA < 6.5 cm (enrich halo vs kaon decays)
- θ < 0.013 (heavy neutrinos are at low θ so very high θ is irrelevant)



Data driven results

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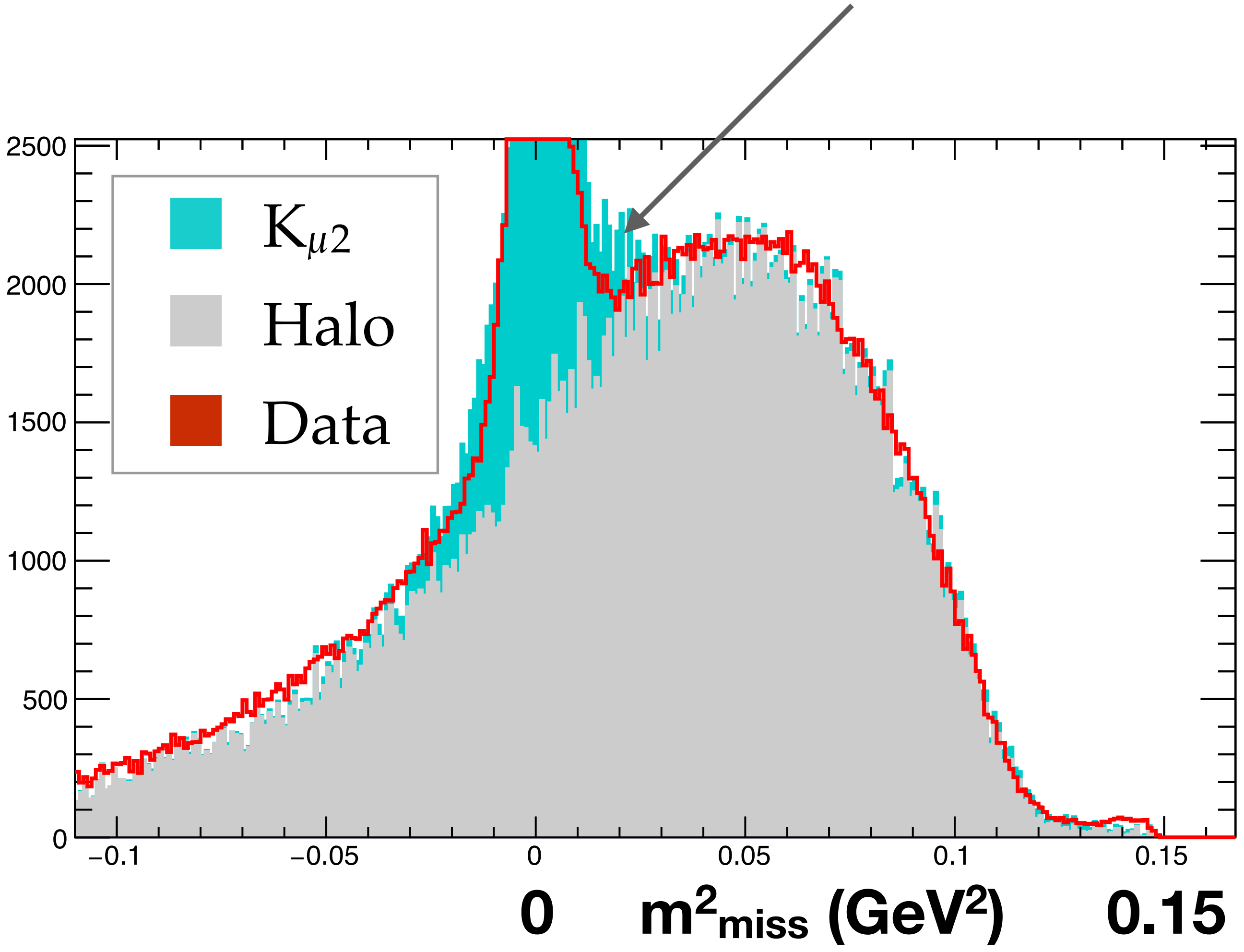
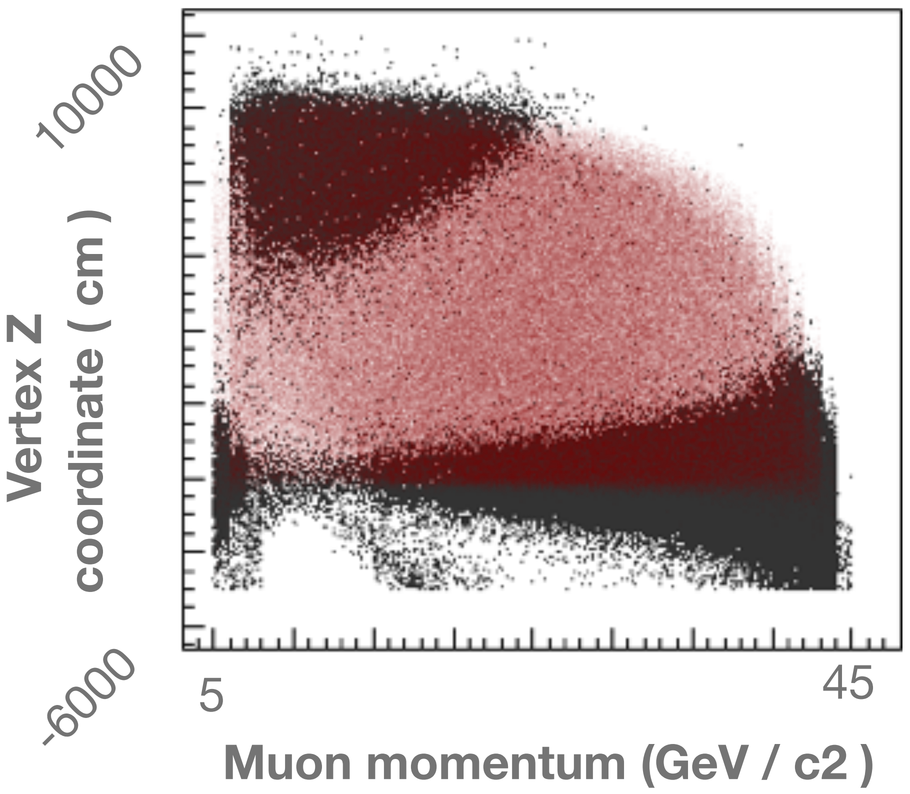
- 11 GeV/c < p < 40 < GeV/c
- 2000 cm < zvertex < 7200cm
- 2.5 cm < CDA < 6.5 cm
  (enrich halo vs kaon decays)
- θ < 0.013 (heavy neutrinos are at low θ so very high θ is irrelevant)

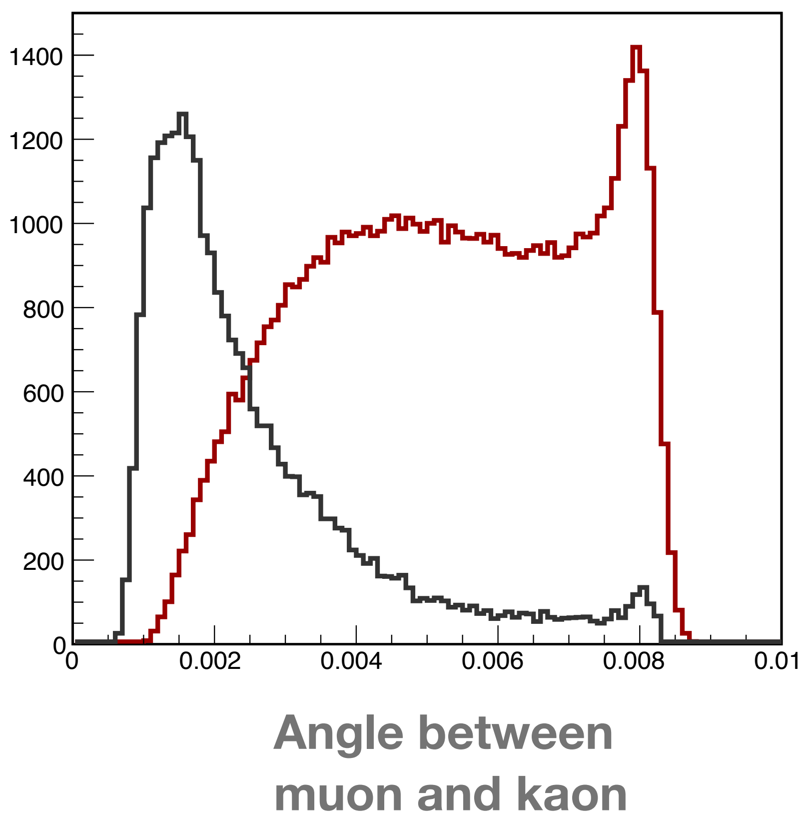
in this kinematic region, $K_{\mu 2}$ peak is not well described

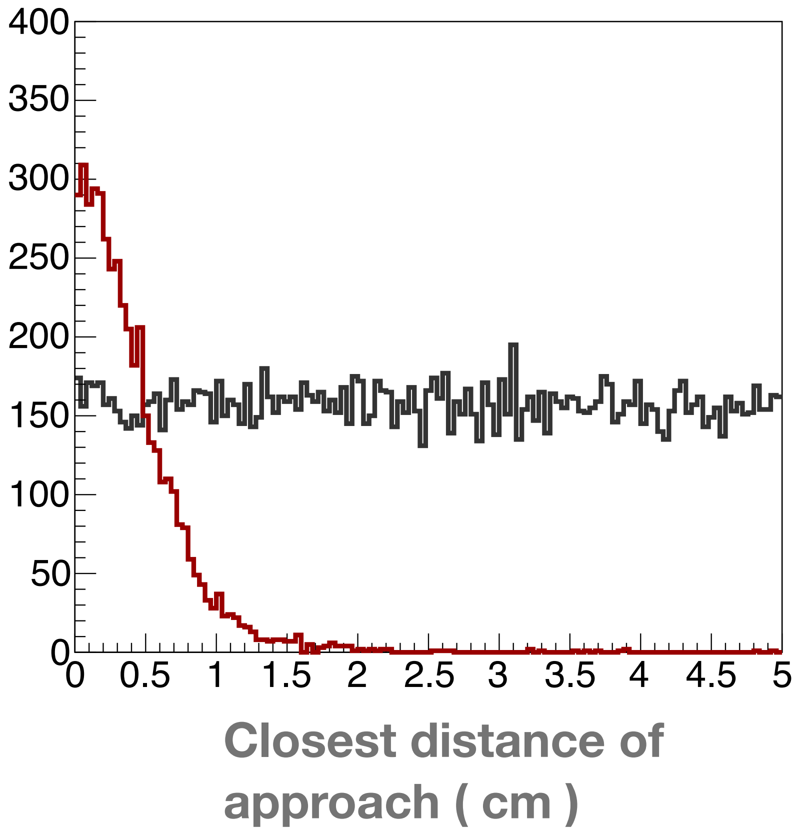


Kinematic cuts

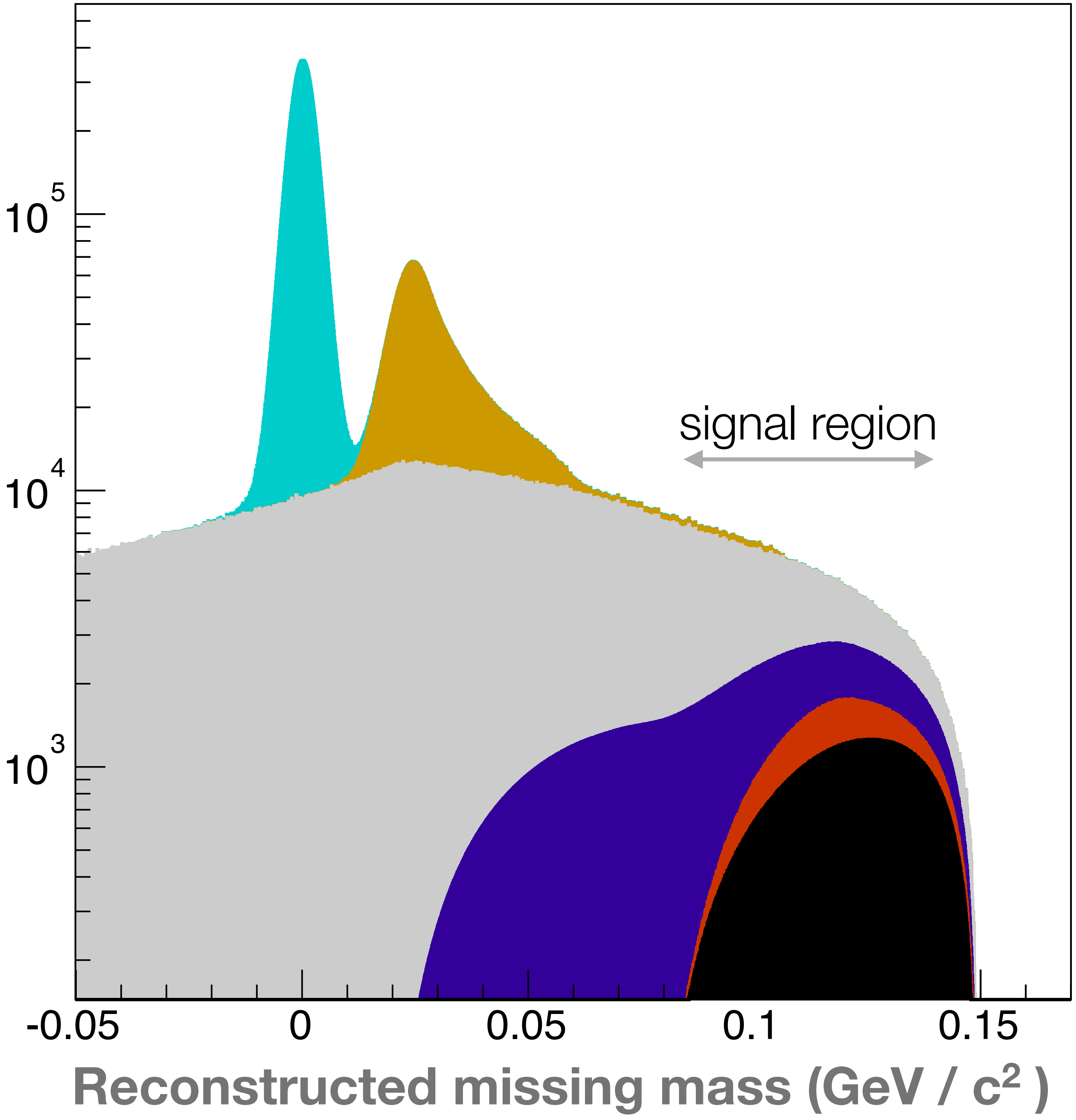
- Optimise to reject **halo** but preserve **signal** (plots show m_ν = 300 MeV/c^2)
- Cut simultaneously in:
  - z coordinate of vertex
  - muon momentum
  - angle between K and μ directions
  - closest distance of approach between K and μ







Single track backgrounds in MC



Decays producing a single charged track

$K^+ \to \mu^+ \nu$

$K^+ \to \pi^+ \pi^0$

Halo

$K^+ \to \pi^+ \pi^+ \pi^-$

$K^+ \to \mu^+ \nu \pi^0$

$K^+ \to \pi^+ \pi^0 \pi^0$

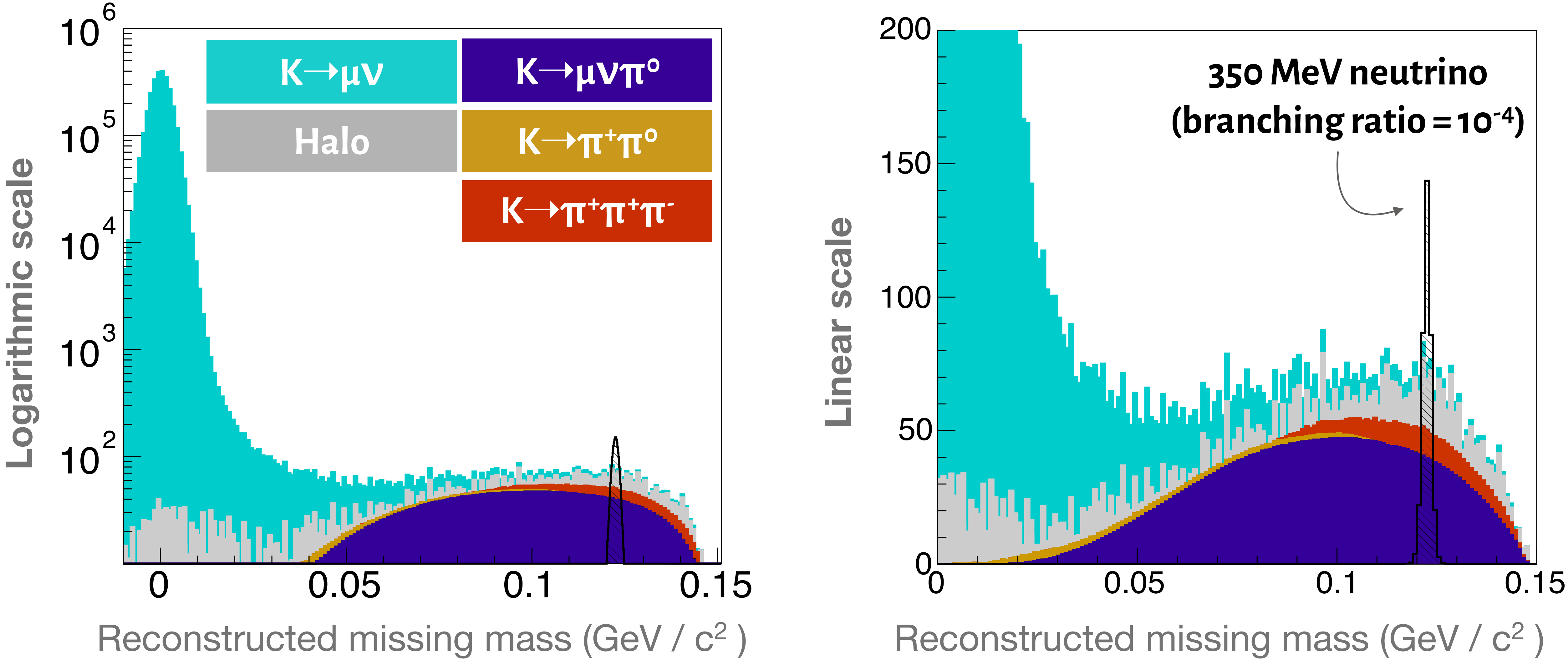
Required:

particle identification to distinguish π^+ and μ^+

photon vetoing to suppress π^0

kinematics to suppress halo

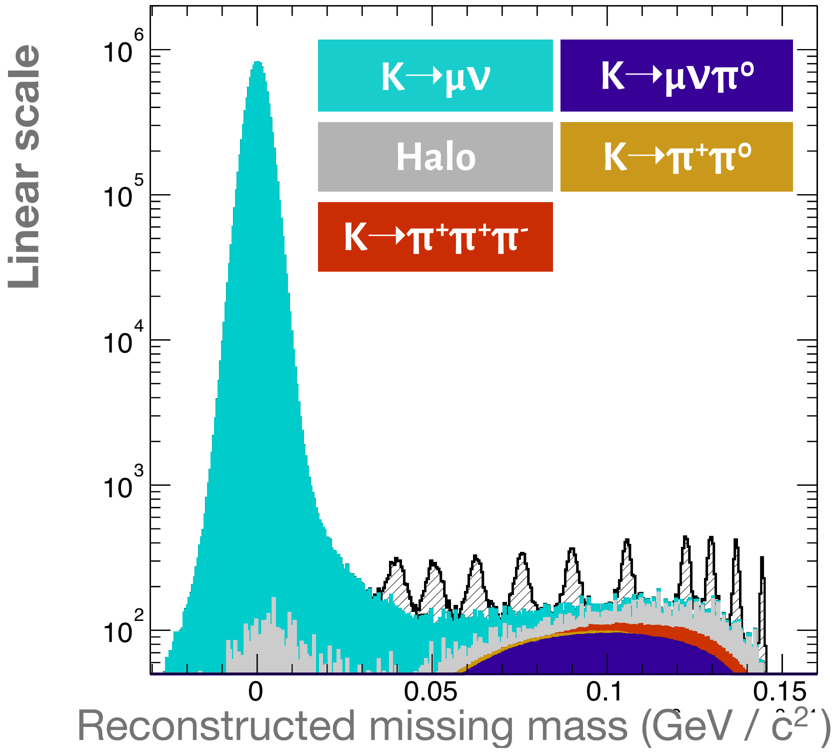
Optimised selection

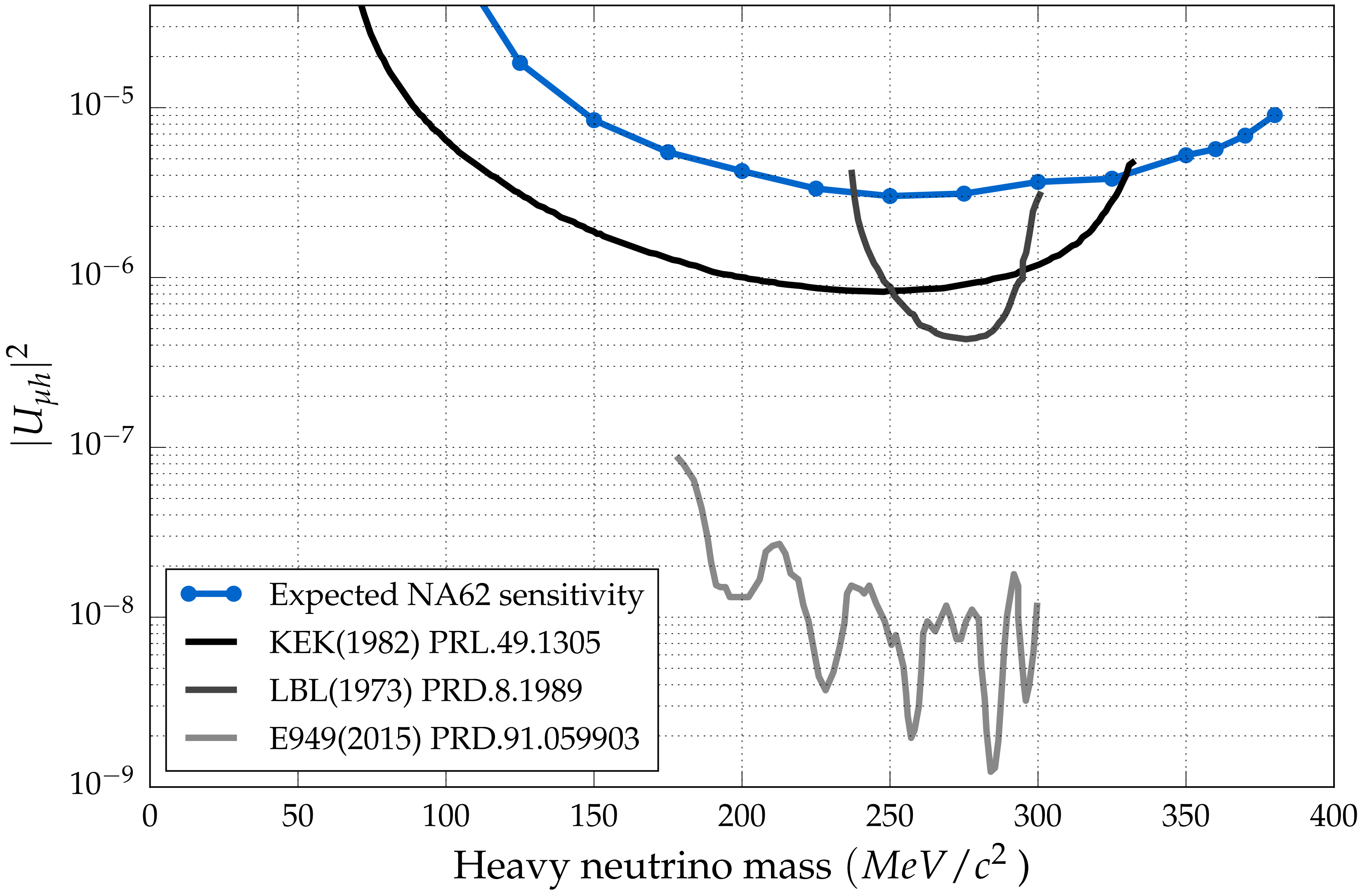


- $K_{\mu 3}$ is the main background

Expected sensitivity

- Full systematics calculations in process. Result is expected to be statistics limited.





The future

- Current analysis limited by **statistics** and **$K_{\mu3}$ background**
- The **beam halo** is also a tricky background
- The new NA62 detector benefits from a **hermetic photon veto** and event by event **kaon momentum measurement**
- A $K_{\mu2}$ sample with **10x my statistics** could easily be collected.
- NA62 is well placed for a future search for heavy neutrinos

Conclusions

- The current search for heavy neutrinos at NA62 will extend the range neutrino masses excluded by peak searches in kaon decays.
- A future analysis could significantly improve on the current limits.

Spares

Field notation

- From Pal and Mohapatra:

$$\psi(x) = \int \frac{d^3p}{\sqrt{(2\pi)^3 2E_p}} \sum_{s=\pm\frac{1}{2}} \left(a_s(\vec{p})u_s(\vec{p})e^{-ip\cdot x} + \widehat{a}_s^\dagger(\vec{p})v_s(\vec{p})e^{ip\cdot x}\right)$$

$$\overline{\psi} = \psi^\dagger\gamma_0$$

$$\widehat{\psi} = \gamma_0 C\psi^*$$

$$\overline{\widehat{\psi}} = \widehat{\psi^\dagger}\gamma_0 = \psi^T C^{-1}$$

$$C^{-1}\gamma_\mu C = -\gamma_\mu^T$$

a	annihilates particle
$a^\dagger$	creates particle
$\widehat{a}$	annihilates anti-particle
$\widehat{a}^\dagger$	annihilates particle

Chirality

- The anti-particle of a left-chiral neutrino is a right-chiral neutrino

$$\widehat{\psi_L} = \hat{\psi}_R$$

Majorana neutrinos

$$-\mathcal{L}_{\text{mass}} = M\overline{\nu}_L\nu_R + B\overline{\widehat{\nu}}_L\nu_R + h.c.$$

$$-\mathcal{L}_{\text{mass}} = M\overline{\nu}_L N_R + B\overline{\widehat{N}}_L N_R + h.c.$$

$$\tan 2\theta = 2M/B$$

$$n_1 = n_{1L} + n_{1R} = \cos\theta(\nu_L - \widehat{\nu}_R) - \sin\theta(\widehat{N}_L - N_R)$$

$$n_2 = n_{12} + n_{2R} = \sin\theta(\nu_L + \widehat{\nu}_R) + \cos\theta(\widehat{N}_L + N_R).$$

$$-\mathcal{L}_{\text{mass}} = m_1\overline{n_1}_L n_{1R} + m_2\overline{n_2}_L n_{2R} + h.c.$$

$$n_1 = -\widehat{n_1} \qquad\qquad n_2 = -\widehat{n_2}$$

KEK

- 2.54x10^6 muons in final spectrum

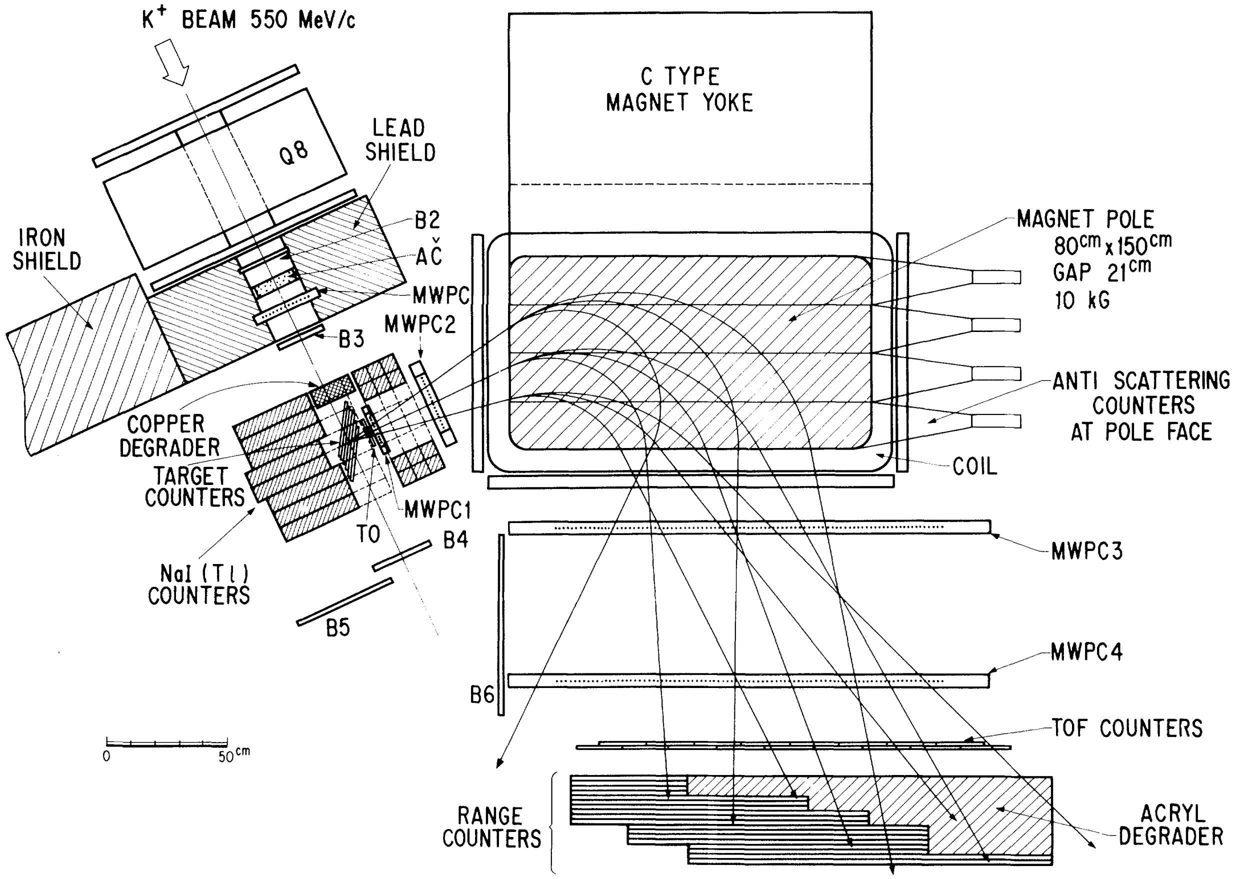
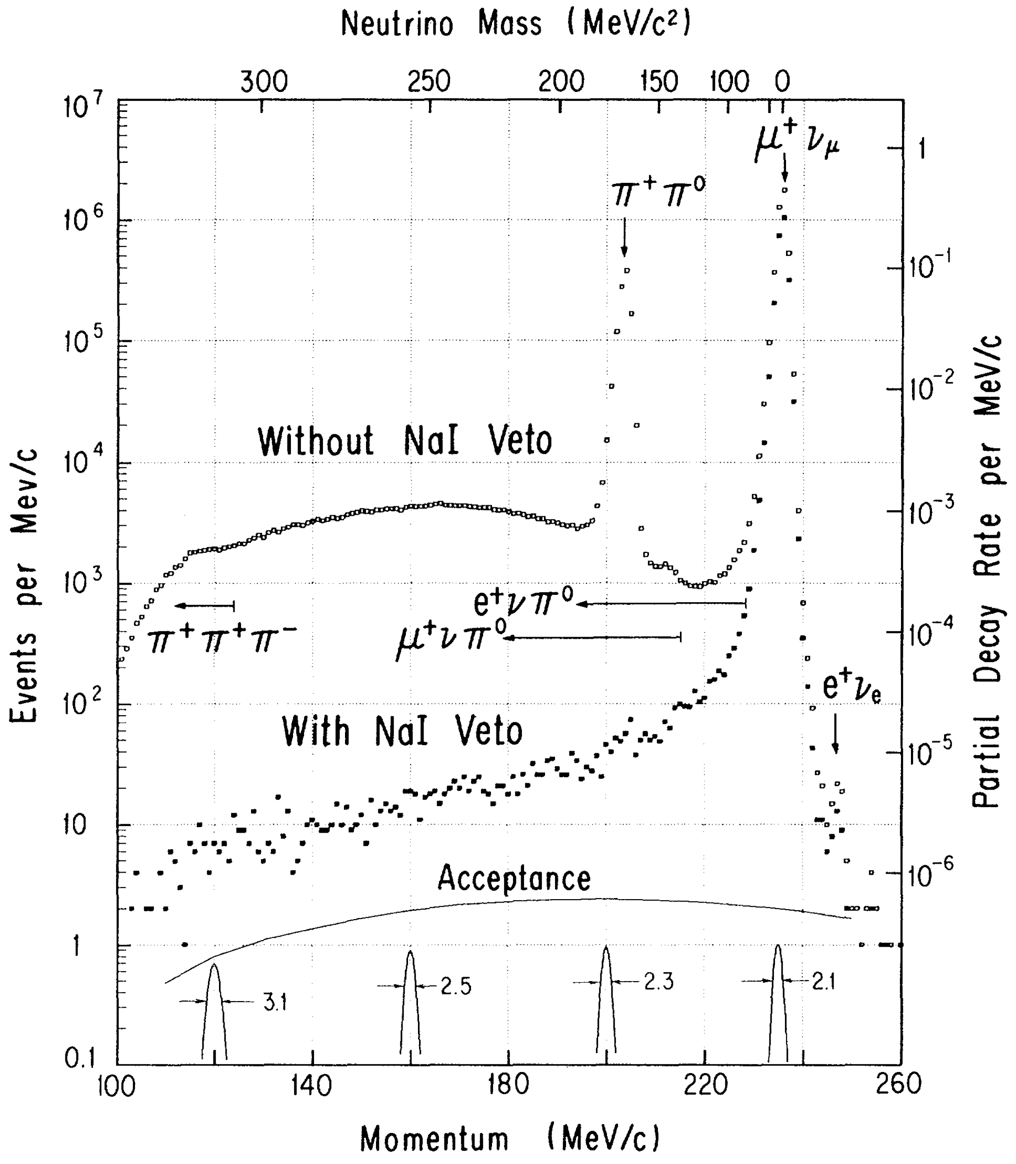
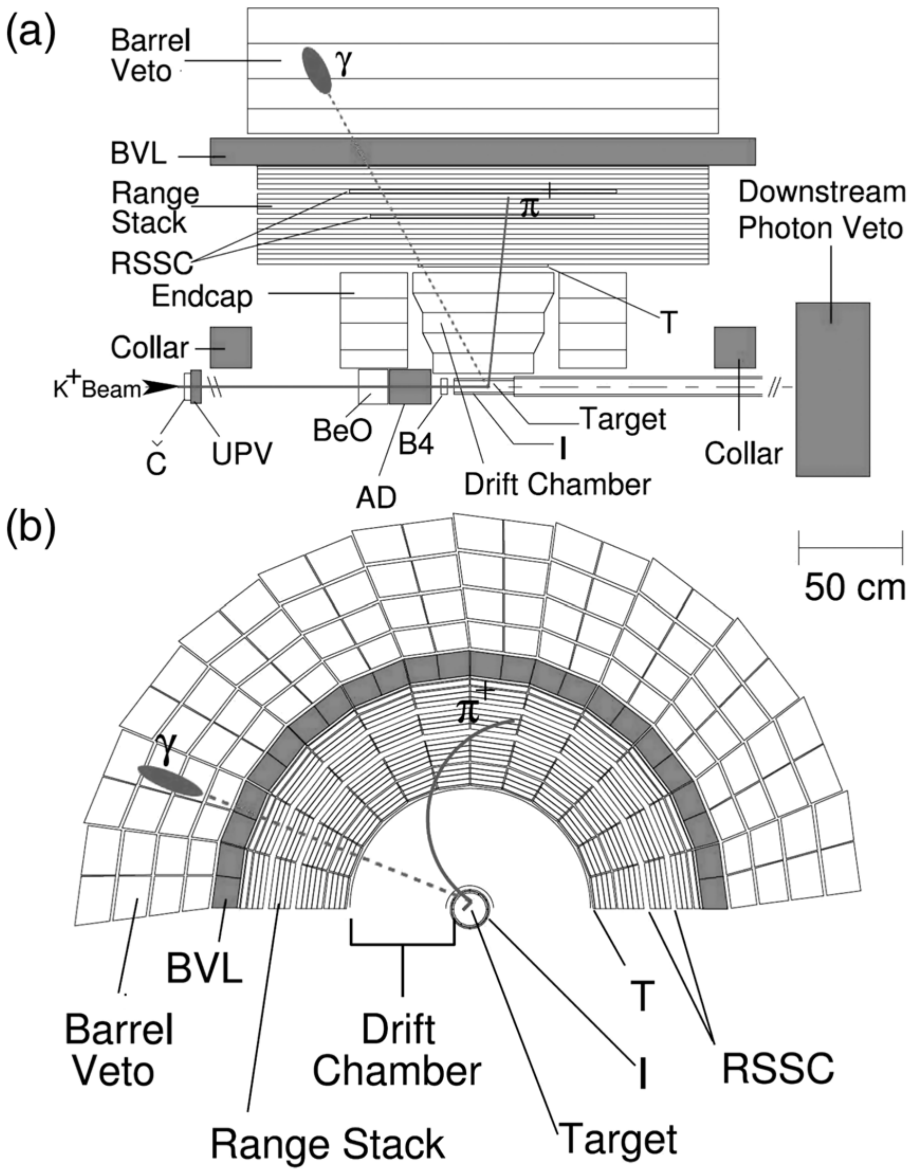


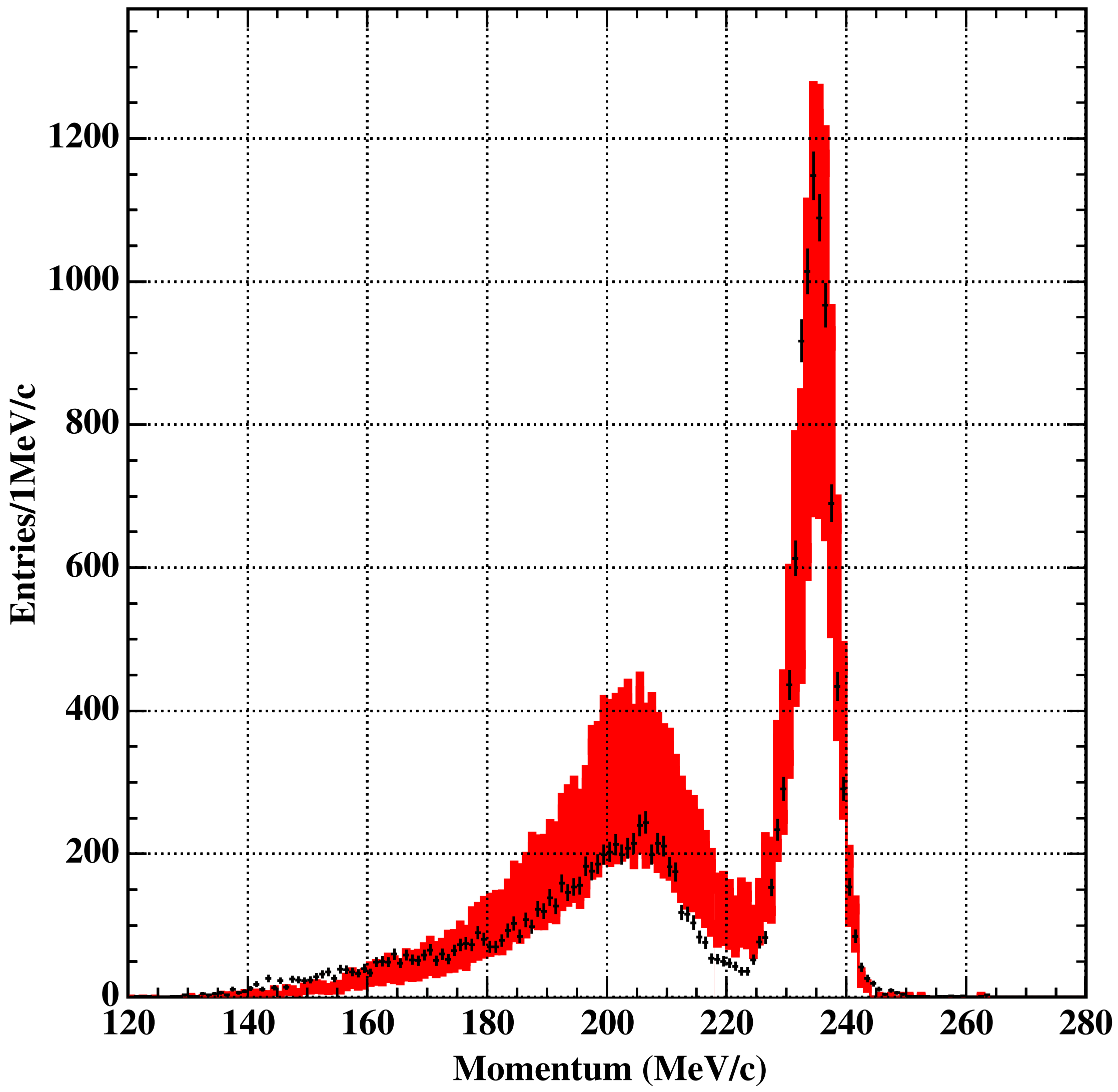
FIG. 1. Plan view of the neutrino mass spectrograph.



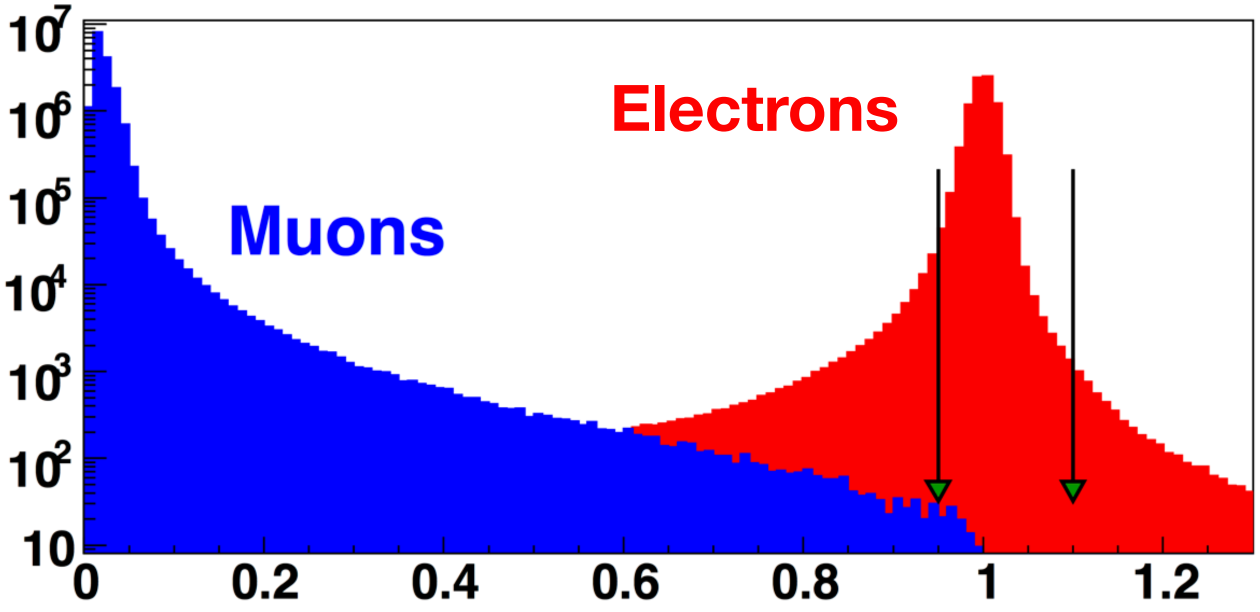
E949

- 1.70×10^{12} stopped kaons





LKr



[GeV, cm, ns]

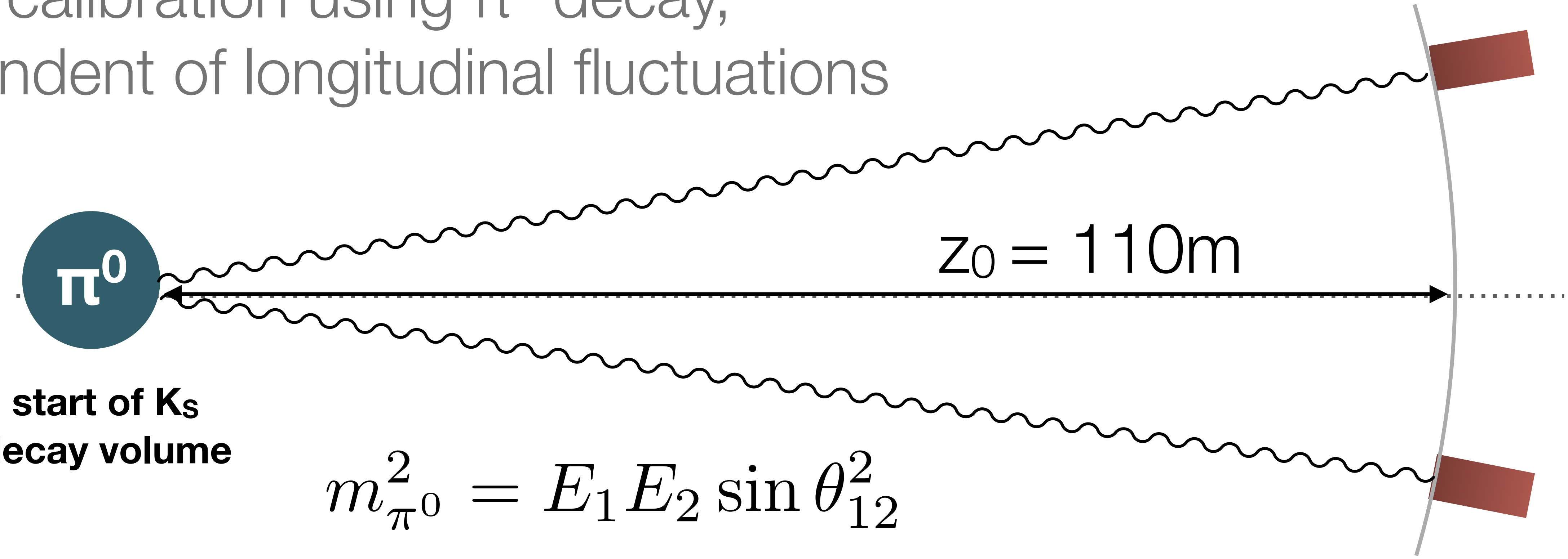
$$\frac{\sigma_E}{E} = \frac{0.032}{\sqrt{E}} \oplus \frac{0.09}{E} \oplus 0.0042$$

$$\frac{\sigma_{X,Y}}{E} = \frac{0.42}{\sqrt{E}} \oplus 0.06$$

$$\sigma_t = \frac{2.5}{\sqrt{E}}$$

LKr: Projective geometry

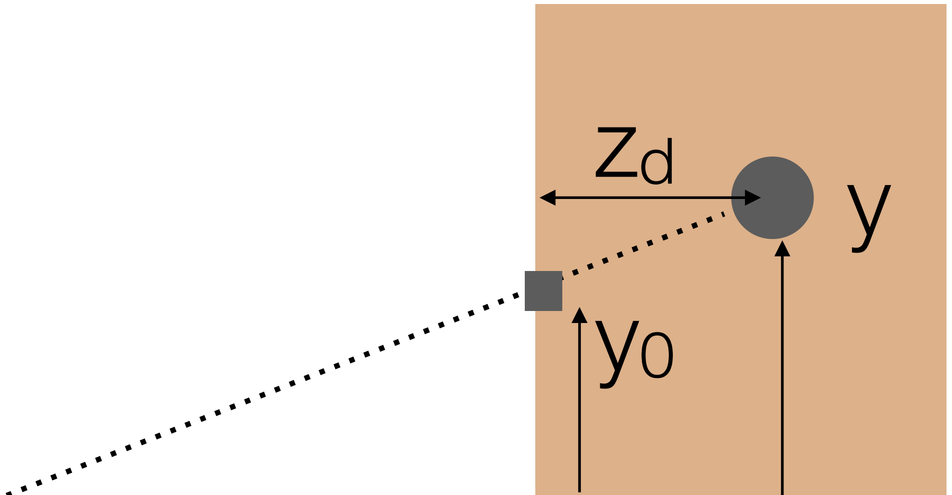
- Projective tower structure converges 110m upstream
- Allows calibration using π^0 decay, independent of longitudinal fluctuations



$$m_{\pi^0}^2 = E_1 E_2 \sin\theta_{12}^2$$

- In normal use, this geometry must be corrected for:

$$y = y_0\left(1+\frac{z_d}{z_0}\right) \qquad z_d = k_z + k_E \ln\left(\frac{E}{E_0}\right)$$



Neutral trigger

- Scintillating fibres installed inside LKr calorimeter

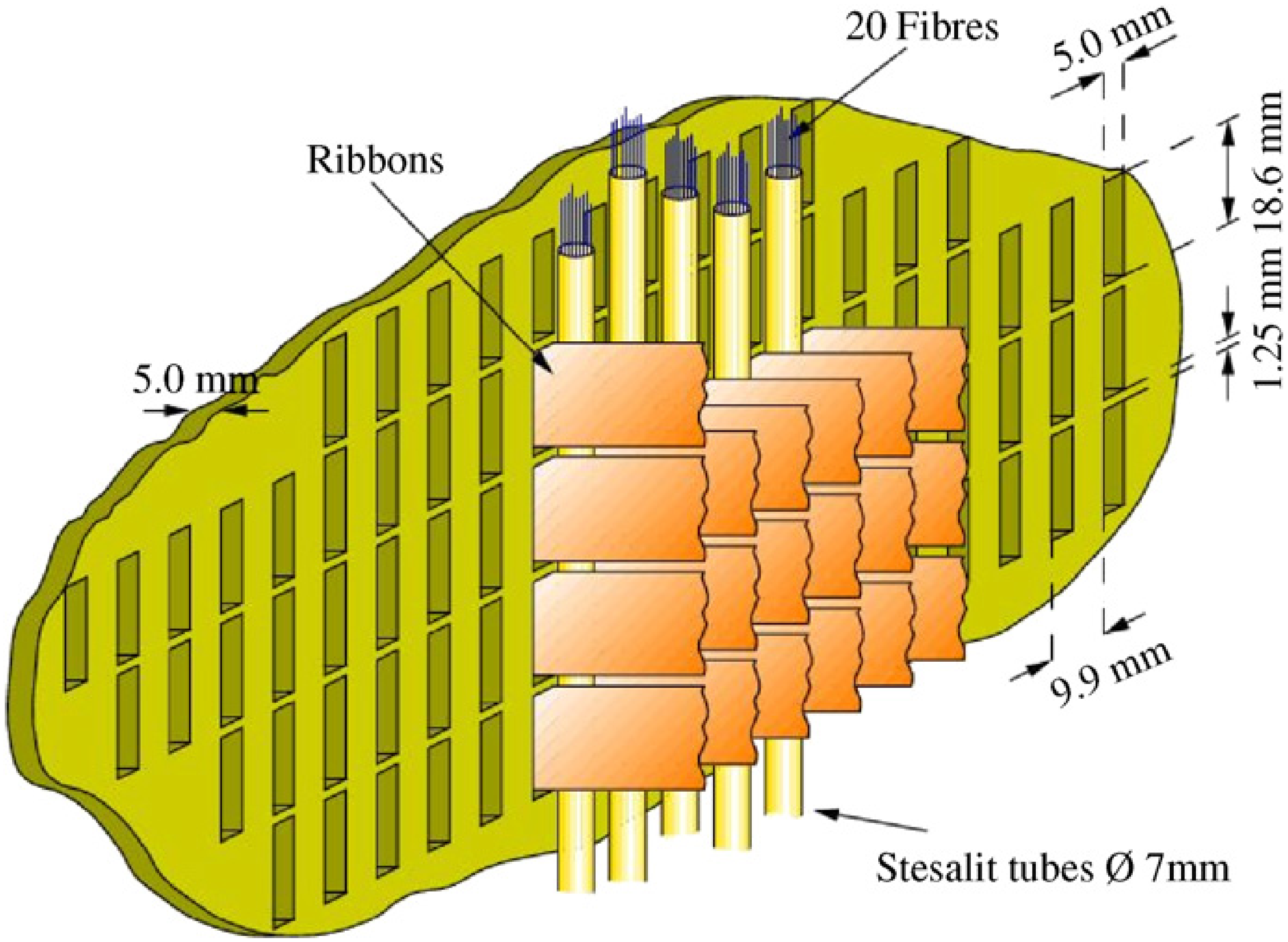
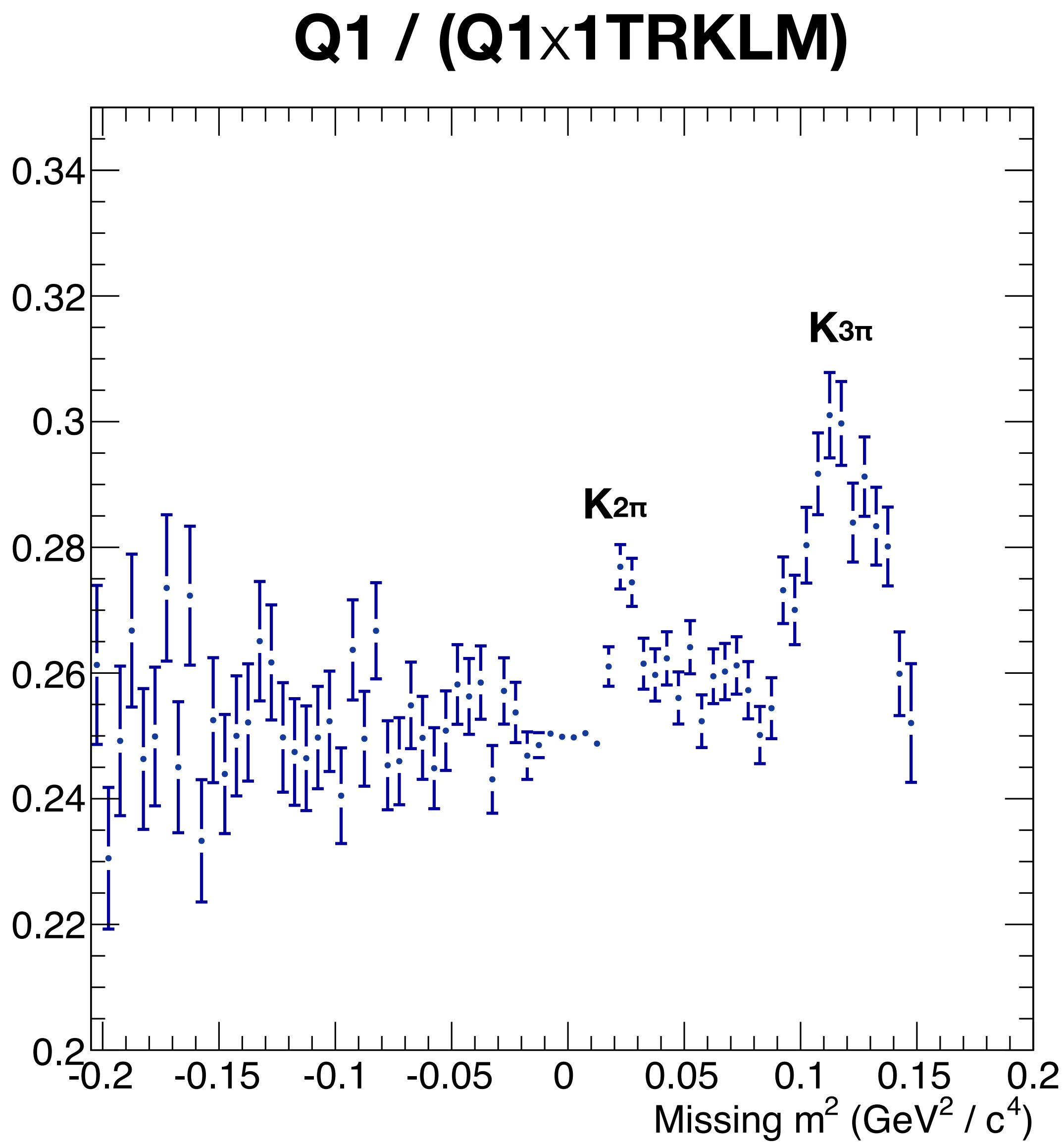


Fig. 23. Neutral hodoscope.

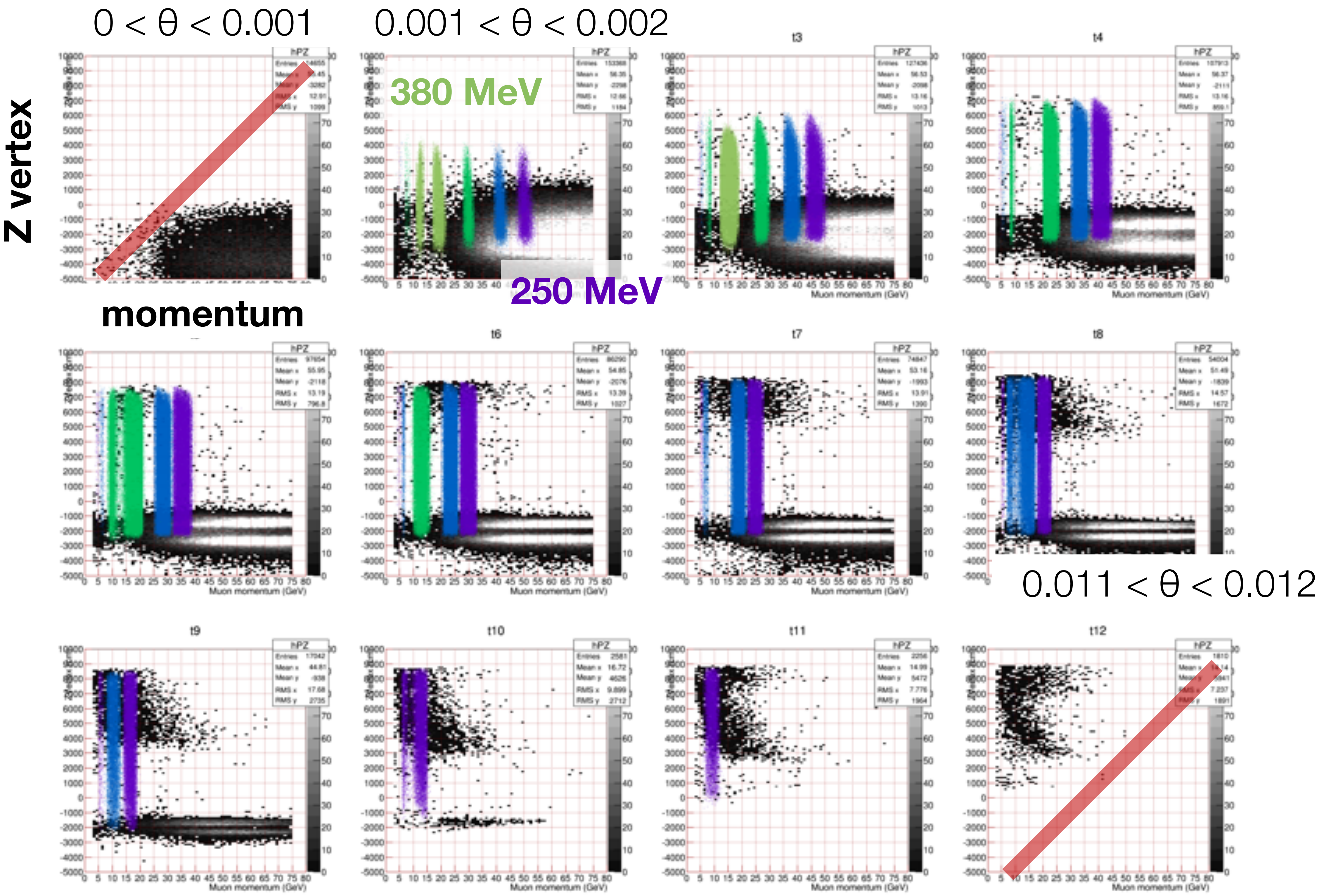
Trigger

- Q1: hit in the charged hodoscope (downscaling = 600)
- Q1X1TRKLM : additional maximum DCH multiplicity cut (DS = 150)



- Use Q1x1TRKLM sample for maximum statistics
- Use Q1 sample to measure Q1x1TRKLM efficiency

Kinematics optimisation to remove halo



0 < θ < 0.001

0.001 < θ < 0.002

380 MeV

250 MeV

0.011 < θ < 0.012

Geant3 vs Geant4