Search for Majorana neutrinos in $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ decays Status Report

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NA62 Collaboration Meeting – Ferrara – 04/09/2014

Outline

- Motivations
- Method
- MC samples
- $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ Event selection
- Muon reconstruction and Efficiency
- Kaon flux
- Background sources
- Data-MC and Signal-Background study
- Statistical Framework
- Conclusions and Outlook

Motivations

- NA48/2 single event sensitivity for $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ decays ~ 10^{-11}
- Best UL: $BR(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) < 1.1 \times 10^{-9}$ @ 90% CL [Phys.Lett. **B697**, 107 (2011)]
  Based on 52 data events observed VS 52.6 ± 19.8 expected ($K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ MC)
- The world strongest constraints to the sterile-active mixing parameter $|U_{\mu 4}|$ for **heavy Majorana neutrinos** with $m_{\pi}+m_{\mu} < m_N < m_K-m_{\mu}$ can be obtained from $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ search in the NA48/2 data:

$$BR(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) \ll 10^{-13} \quad \text{for } m_N \ll m_K \text{ or } m_N \gg m_K$$

$$BR(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) = \tau_K \frac{G_F^4 m_K}{128\pi^2} f_K^2 f_{\pi}^2 |V_{us}V_{ud}|^2 \frac{m_N^5}{\Gamma_N} |U_{\mu 4}|^4 \varphi_{\mu\mu} \quad \text{for } m_{\pi}+m_{\mu} < m_N < m_K-m_{\mu}$$

$$\approx 10^{-19} GeV \times \frac{1}{\Gamma_N} |U_{\mu 4}|^4 \quad [@\ m_N = 300\ \text{MeV}/c^2]$$

$$\approx 10^{-7} ps^{-1} \times \tau_N |U_{\mu 4}|^4$$

To reach the same limit on $|U_{\mu 4}|$ for $m_{\pi}+m_{\mu} < m_N < m_K-m_{\mu}$ and same τ_N, the ULs on $BR(h^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm})$ [h = B, D and D_s] must be 10^6, 10^3 and 10^2 times smaller than the one on $BR(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm})$

Method

- Blind analysis: $m_{\pi\mu\mu} < 0.48$ GeV/c^2 for data [SR: $|m_{\pi\mu\mu} - m_K| < 5$ MeV/c^2]
  Event selection finalised by studying MC simulations (Signal + Bkg)

- Reconstructed 3-trk vertex: sensitive to neutrino lifetimes $\tau_N \leqslant 10$ ps
  lifetime scan $\tau_N = 0 \to 10$ ps: to be done soon

  [Future development: **displaced vertex** studies (to be done soon)]

- Number N_K of kaon decays in the fiducial volume from $K^\pm \to \pi^\pm\pi^+\pi^-$ decays
  - Same trigger used for the $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$ search
  - Similar kinematics ($m_\mu/m_\pi = 0.76$)

  } First order cancellation of systematic effects due to trigger inefficiency

- Signal acceptance $\varepsilon_{\pi\mu\mu}$ estimated from $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$ MC

- Upper Limit for the number of signal events $N(K^\pm \to \pi^\mp\mu^\pm\mu^\pm)$ in data to be obtained from statistical analysis: observed events VS expected (bkg only)

- Upper Limit for the $BR(K^\pm \to \pi^\mp\mu^\pm\mu^\pm)$ to be estimated using the relation

$$BR\left(K^\pm \to \pi^\mp \mu^\pm \mu^\pm\right) = \frac{N\left(K^\pm \to \pi^\mp \mu^\pm \mu^\pm\right)}{N_K\, \varepsilon_{\pi\mu\mu}}$$

MC Samples

Signal acceptance $\varepsilon_{\pi\mu\mu}$ study

- Three $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ samples, 10M each

  NEW 1. Resonance [Atre *et al.*, JHEP 0905,030 (2009)]: $K^{\pm} \to N\mu^{\pm} + N \to \pi^{\mp}\mu^{\pm}$
  [for this talk: $m_N = 300$ MeV, $\Gamma_N = 1$MeV; scan in m_N and in Γ_N in progress]

  2. "Scalar": flat phase space

  NEW 3. "Vector": $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$-like (with form factor $|W(z)| = 1$)

  } for comparison

  [contacts with J. Kamenik for model-independent treatment]

- Two $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ samples, 10G+12G produced with the FULL (optimised) MC mode (see my talk @ NA48/2 Analysis Meeting, 17/10/2013)
  - 1st: used exclusively to finalise the event selection;
  - NEW 2nd: used to estimate the number of expected bkg events
- Other bkg sources:
  - NEW $K^{\pm} \to \pi^{+}\pi^{-}\mu^{\pm}\nu$ (100M), $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ (10M) and $K^{\pm} \to \mu^{+}\mu^{-}\mu^{\pm}\nu$ (10M)

Final $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ event selection

- At least one 3-track vertex with
  - total Q = ±1 and $\chi^2 < 20$
  - all the vertex tracks with 3 GeV/c < p < 60 GeV/c and within DCH, LKr, MUV* acceptances * ~2 cm MUV shift detected (see my talk 19/12/13)
  - $P_t^2 < 0.0001$ GeV²/c² , $|P_{tot} - 60$ GeV/c$| < 5$ GeV/c
  - VtxZ within (-1800,8000) cm
  - Max 2-trk Vtx distance < 5 m + max 2-trk CDA < 3 cm
- π ID: E/p < 0.95, !(MUV1&MUV2)**
- μ ID: E/p < 0.2 , MUV1&MUV2**

** MUV search radius multiplier = 2.5

- $P_\pi > 15$ GeV/c, $P_\mu > 5$ GeV/c
- Trk-Trk Dist > 2 cm @ DCH, > 20 cm @ LKr, > 20 cm @ MUV1
- μ-μ dist > 0 (NO muon duplication), Max Trk-μ dist < 35 cm
- Signal Region: $|m_{\pi\mu\mu} - m_K| < 5$ MeV/c² (= 2σ)

NEW Comparison with $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ selection*

* Phys.Lett. **B697**, 107 (2011)

Published UL can be related to **single point $\tau_N = 0$**, no mass dependence

- 3-track vertex:
  - $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$: $\chi^2 < 40$
  - New: $\chi^2 < 20$ + max 2-trk Vtx dist < 5 m + max 2-trk CDA < 3 cm

  → Acceptance: -1.5% (abs.) or -7% (rel.)
- Total Momentum:
  - $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$: $P_t^2 < 0.0005$ GeV^2/c^2 , $|P_{tot} - 60$ GeV/c$| < 6$ GeV/c
  - New: $P_t^2 < 0.0001$ GeV^2/c^2 , $|P_{tot} - 60$ GeV/c$| < 5$ GeV/c

  → Acceptance: -2.5% (abs.) or -10% (rel.)
- Track Momentum:
  - $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$: $P_{trk} > 10$ GeV/c
  - New: $P_\pi > 15$ GeV/c, $P_\mu > 5$ GeV/c

  → Acceptance: +6% (abs.) or +42% (rel.)

NEW Comparison with $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ selection*

* Phys.Lett. **B697**, 107 (2011)

- Particle ID:
  - $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$: π: E/p < 0.95, no associated muon
    μ: E/p < 0.2, MUV1&MUV2
  - New: π: E/p < 0.95, !(MUV1&MUV2)**
    μ: E/p < 0.2, MUV1&MUV2** + μ-μ dist > 0
    + Max Trk-μ dist < 35 cm

  → Acceptance: +7% (abs.) or +47% (rel.)

** MUV search radius multiplier = 2.5

- Signal Region:
  - $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$: $|m_{\pi\mu\mu} - m_K| < 8$ MeV/c^2 (= 3.2σ)
  - New: $|m_{\pi\mu\mu} - m_K| < 5$ MeV/c^2 (= 2σ)

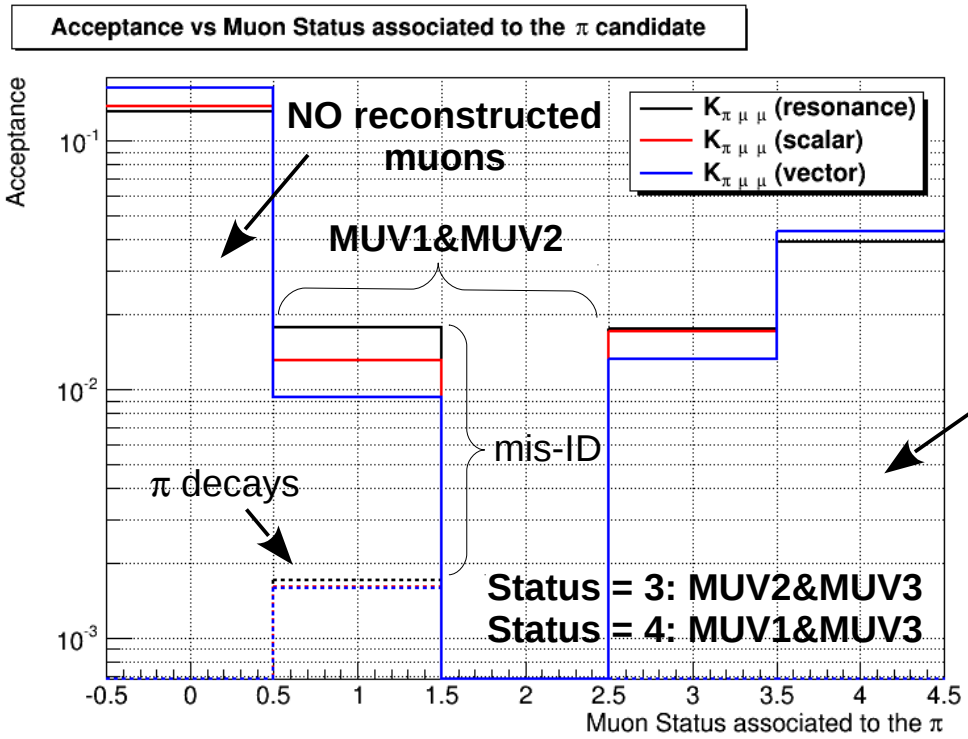
  → Acceptance: -1.2% (abs.) or -5% (rel.)

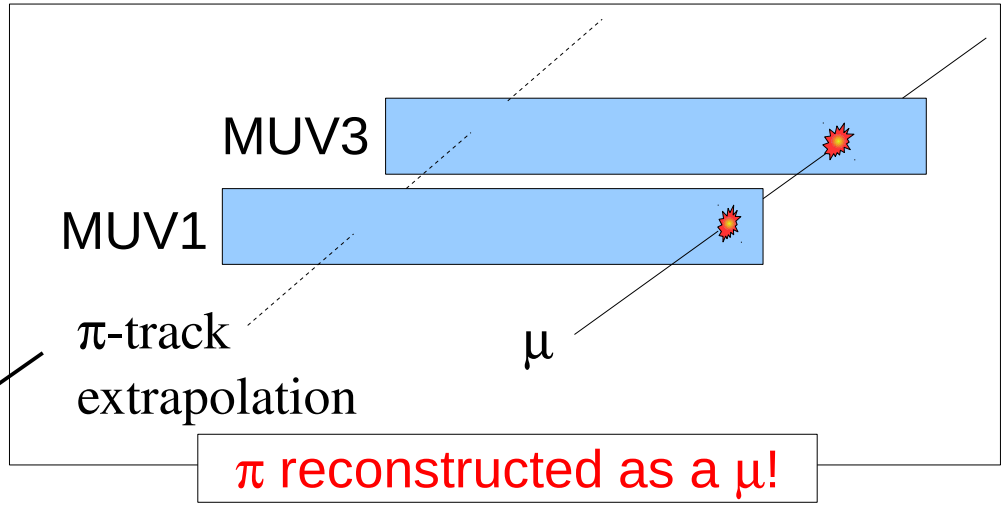
Published* acceptance:
$\varepsilon(K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}) = 16.97\%$

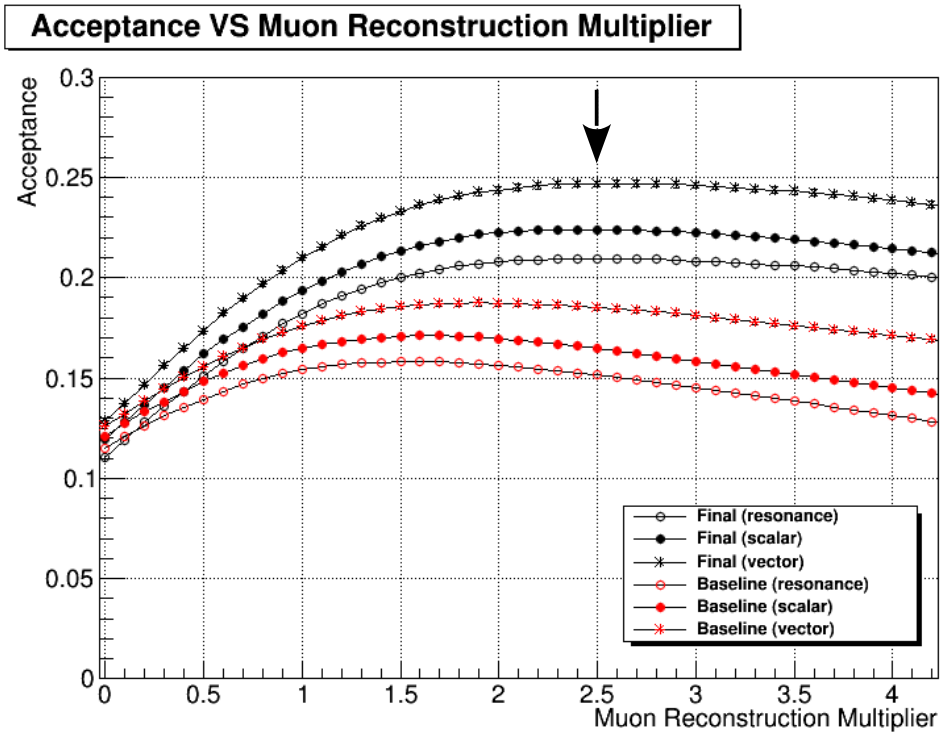
Total Acceptance: +6% (abs.) or +40% (rel.)

- $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$: $\varepsilon_{\pi\mu\mu}^{(r)} = (13.28 \pm 0.01)\%$ $\varepsilon_{\pi\mu\mu}^{(s)} = (14.73 \pm 0.01)\%$, $\varepsilon_{\pi\mu\mu}^{(v)} = (17.25 \pm 0.01)\%$
- New: $\varepsilon_{\pi\mu\mu}^{(r)} = (19.44 \pm 0.01)\%$ $\varepsilon_{\pi\mu\mu}^{(s)} = (20.62 \pm 0.01)\%$, $\varepsilon_{\pi\mu\mu}^{(v)} = (22.75 \pm 0.01)\%$

Muon Reconstruction







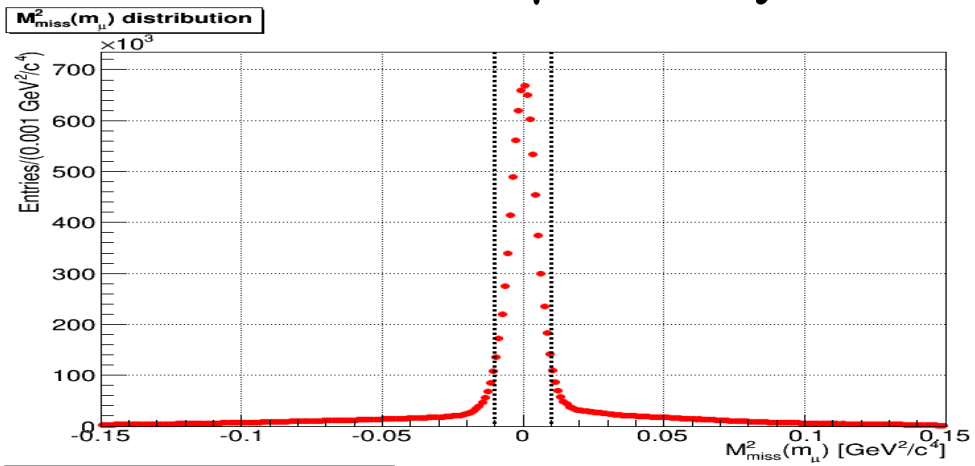
Pions are allowed to be associated to reconstructed muons with status 3 or 4
→ **Acceptance:** +6% (abs.) or +40% (rel.)

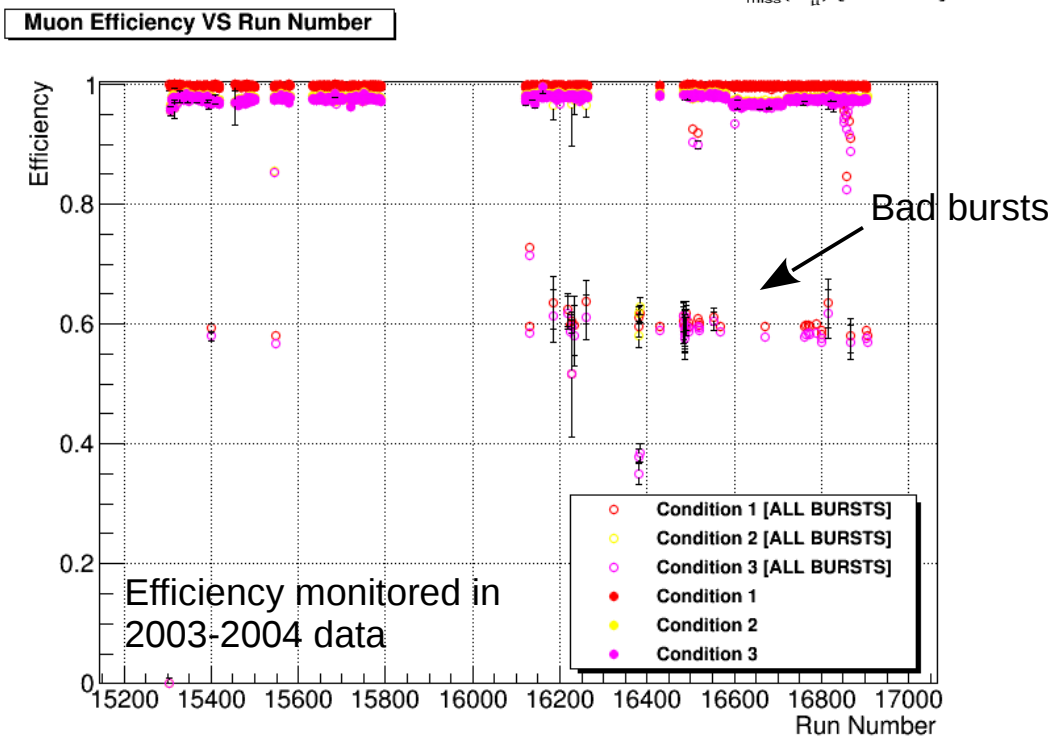
Search Radius Multiplier set to m=2.5
→ **Acceptance:** +1% (abs.) or +5% (rel.)

Total μ Reco: +7% (abs.) or +47% (rel.)

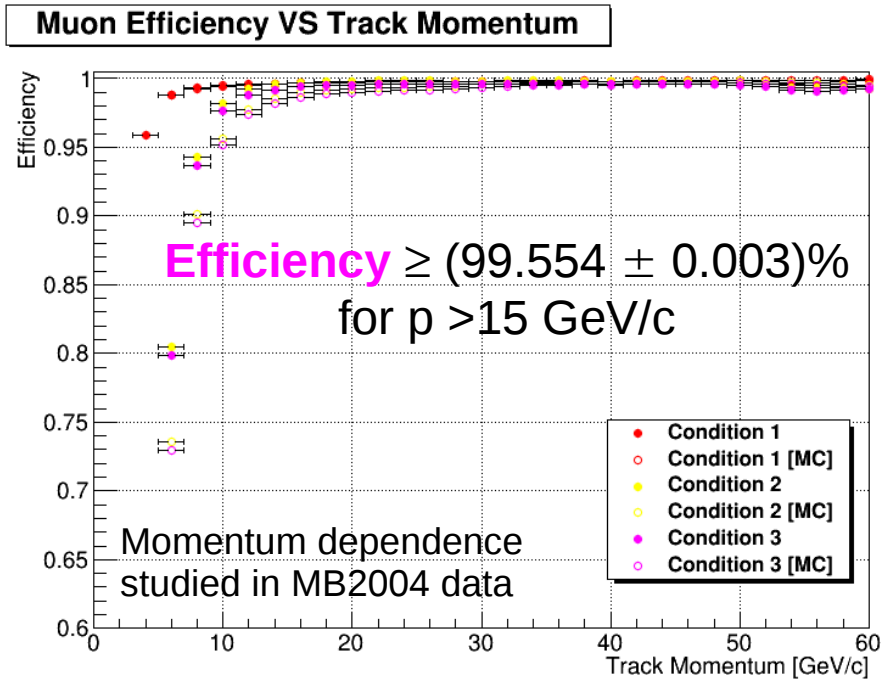
NEW Muon Efficiency

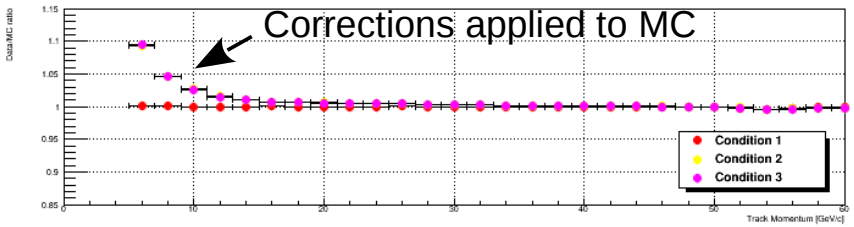
Reconstructed $K^{\pm} \to \mu^{\pm}\nu$ decays with applying NO μ-ID requirements





Condition 1: E/p<0.2
Condition 2: MUV1 & MUV2
Condition 3: Condition 1 & Condition 2





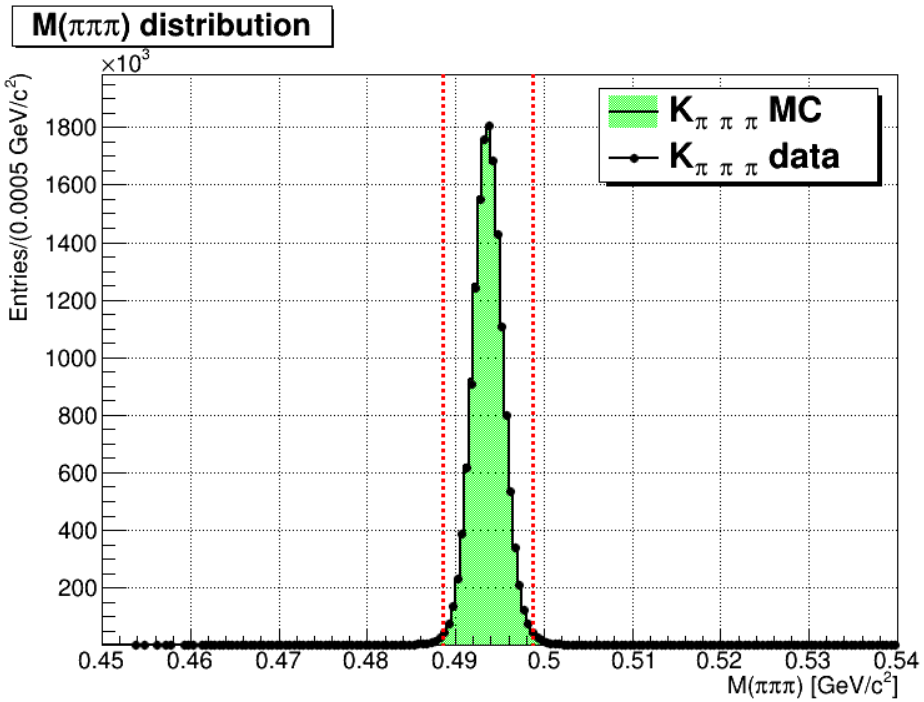
Kaon Flux

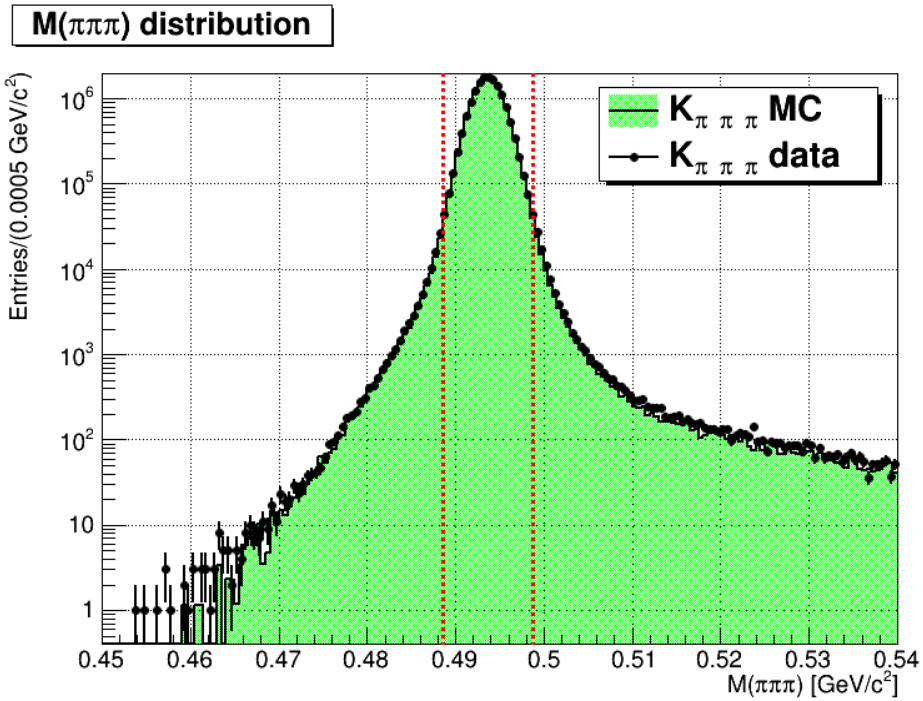
Published flux: $N_K^{tot} = 1.9 \times 10^{11}$

- $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ selection: same requirements as $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ except
  - No particle ID for same-sign tracks;
  - Requirement $|m_{\pi\mu\mu} - m_K| < 5$ MeV/c^2 replaced by $|m_{\pi\pi\pi} - m_K| < 5$ MeV/c^2
- Acceptance $\varepsilon_{\pi\pi\pi} = (14.721 \pm 0.004)\%$

No MUV bad bursts (-3.7%)

$$N_K^{tot} = (1.901 \pm 0.014) \times 10^{11}, \quad N_K = (1.832 \pm 0.014) \times 10^{11}$$

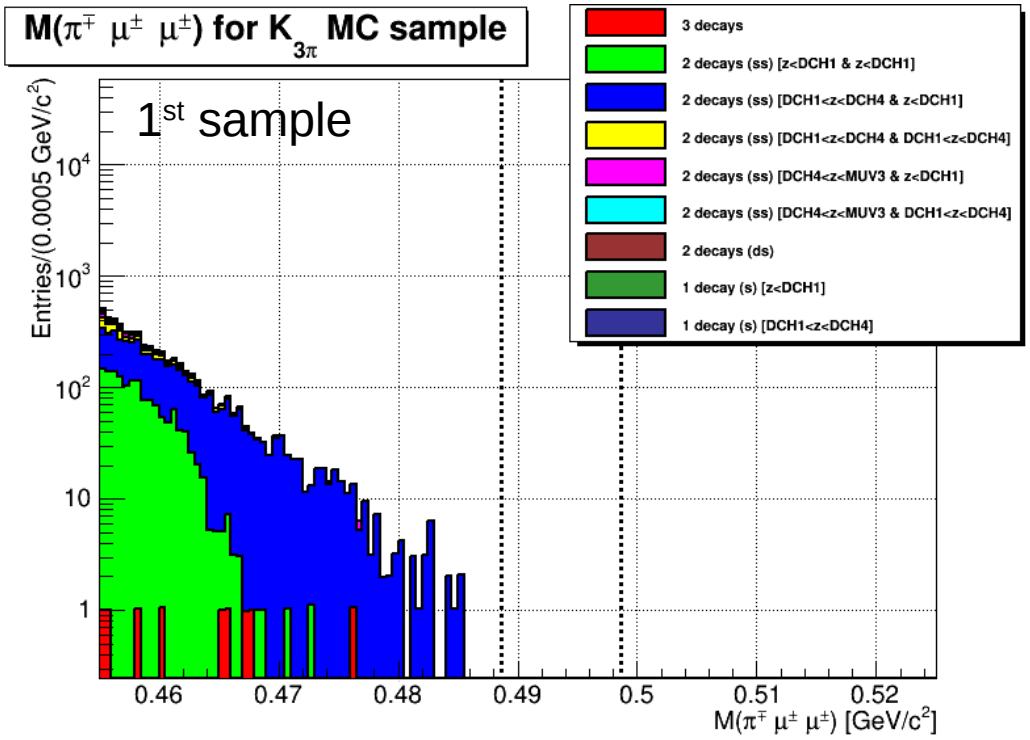


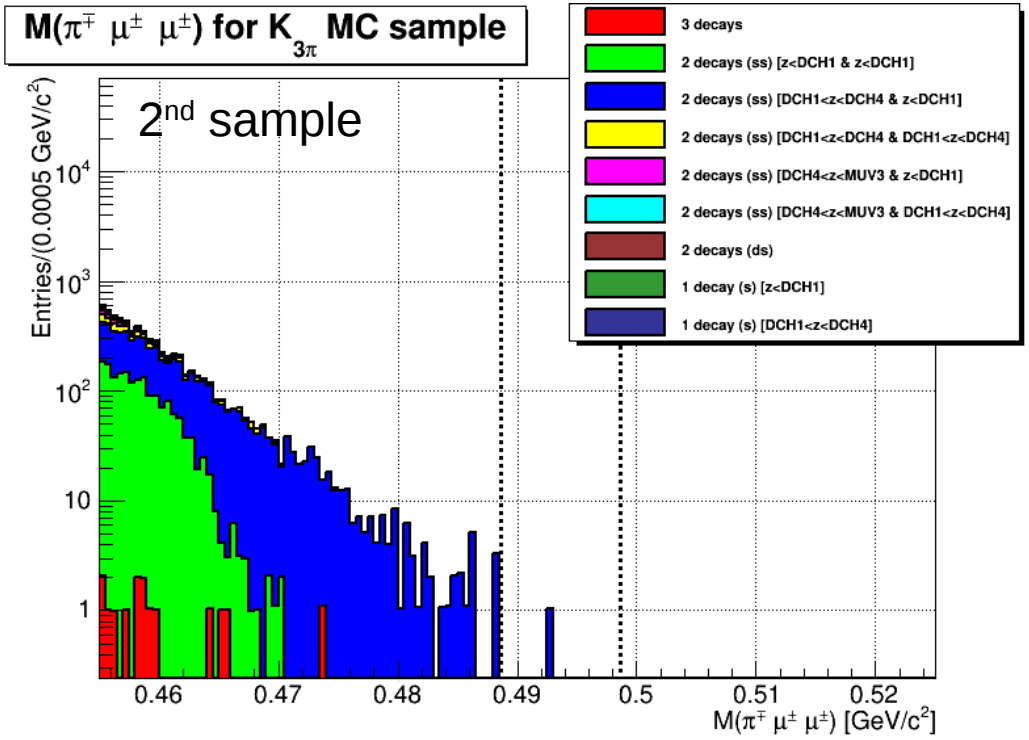


$K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ background

- Two MC samples to avoid bias due to the choice of $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ selection
  - 1st sample [10G, used exclusively to finalise the event selection]: 0 events
  - NEW – 2nd sample [12G, used to estimate the number of expected bkg events]: 1 event

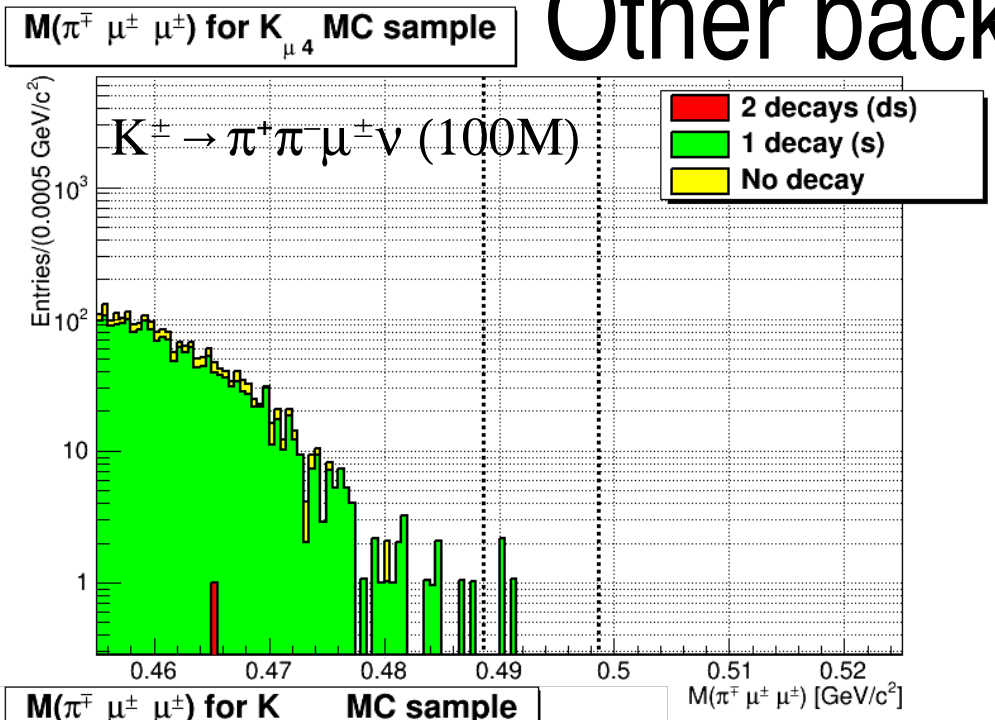
→ $0.97 \pm 0.97_{stat} \pm 0.01_{syst}$ expected $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ events



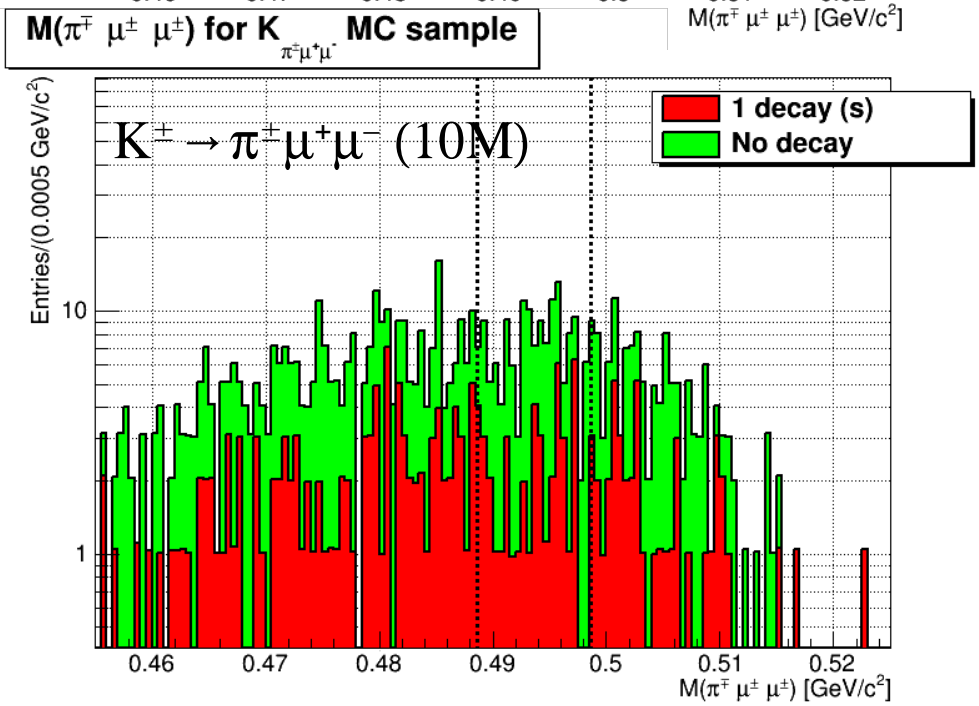


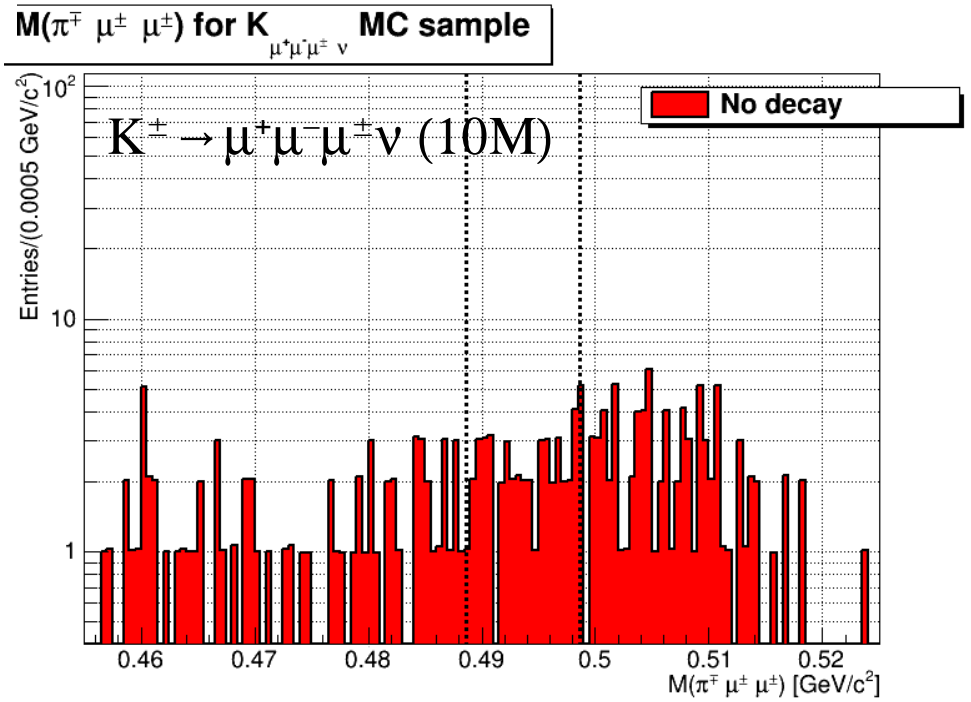
Other backgrounds

NEW



- $K^{\pm} \to \pi^{+}\pi^{-}\mu^{\pm}\nu$ (100M): 3 events
  → $0.09 \pm 0.05_{stat} \pm 0.06_{syst}$ expected
- $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ (10M): 147 events
  → $0.29 \pm 0.02_{stat} \pm 0.02_{syst}$ expected
- $K^{\pm} \to \mu^{+}\mu^{-}\mu^{\pm}\nu$ (10M): 48 events
  → $0.013 \pm 0.001_{stat} \pm 0.010_{syst}$ expected



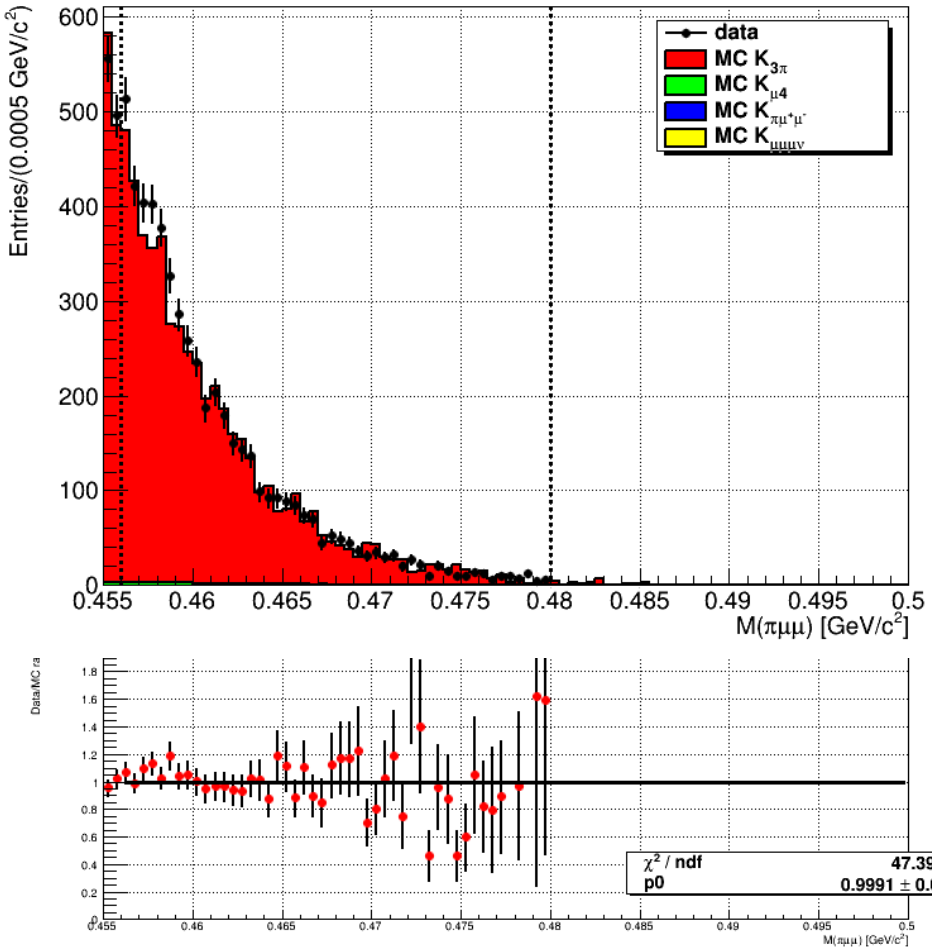


Data-MC comparison in CR

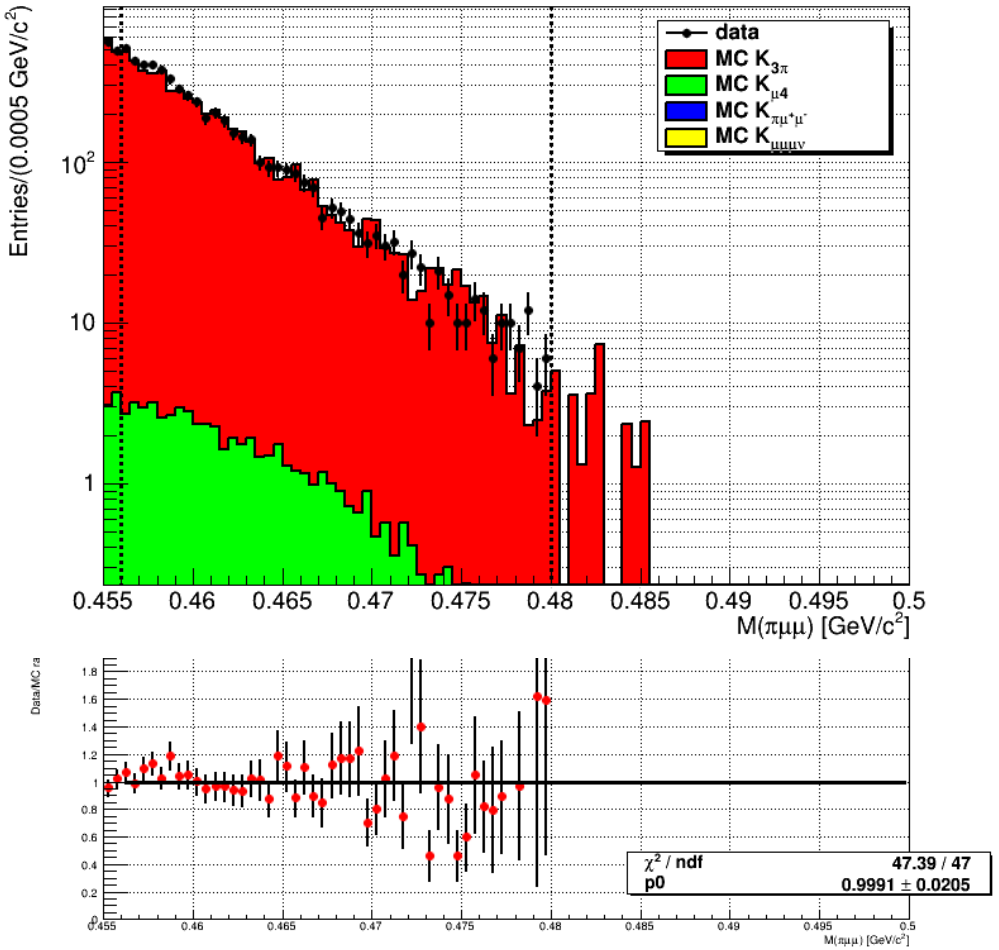
- For each variable, final $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ selection except
  - any cut on the variable itself
  - SR requirement changed on purpose to CR requirement

CR: 0.456 GeV/c² < $m_{\pi\mu\mu}$ < 0.48 GeV/c²

M(πμμ) distribution

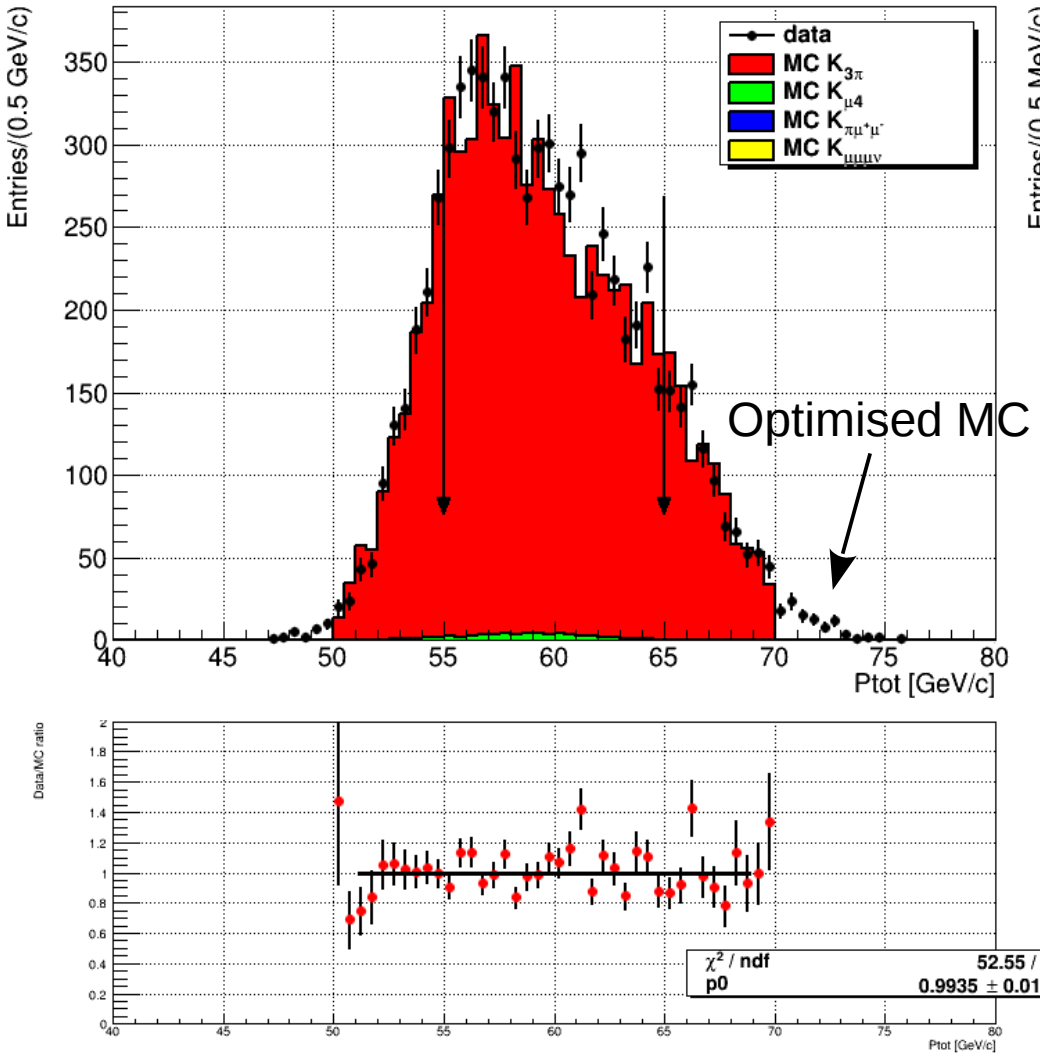


M(πμμ) distribution

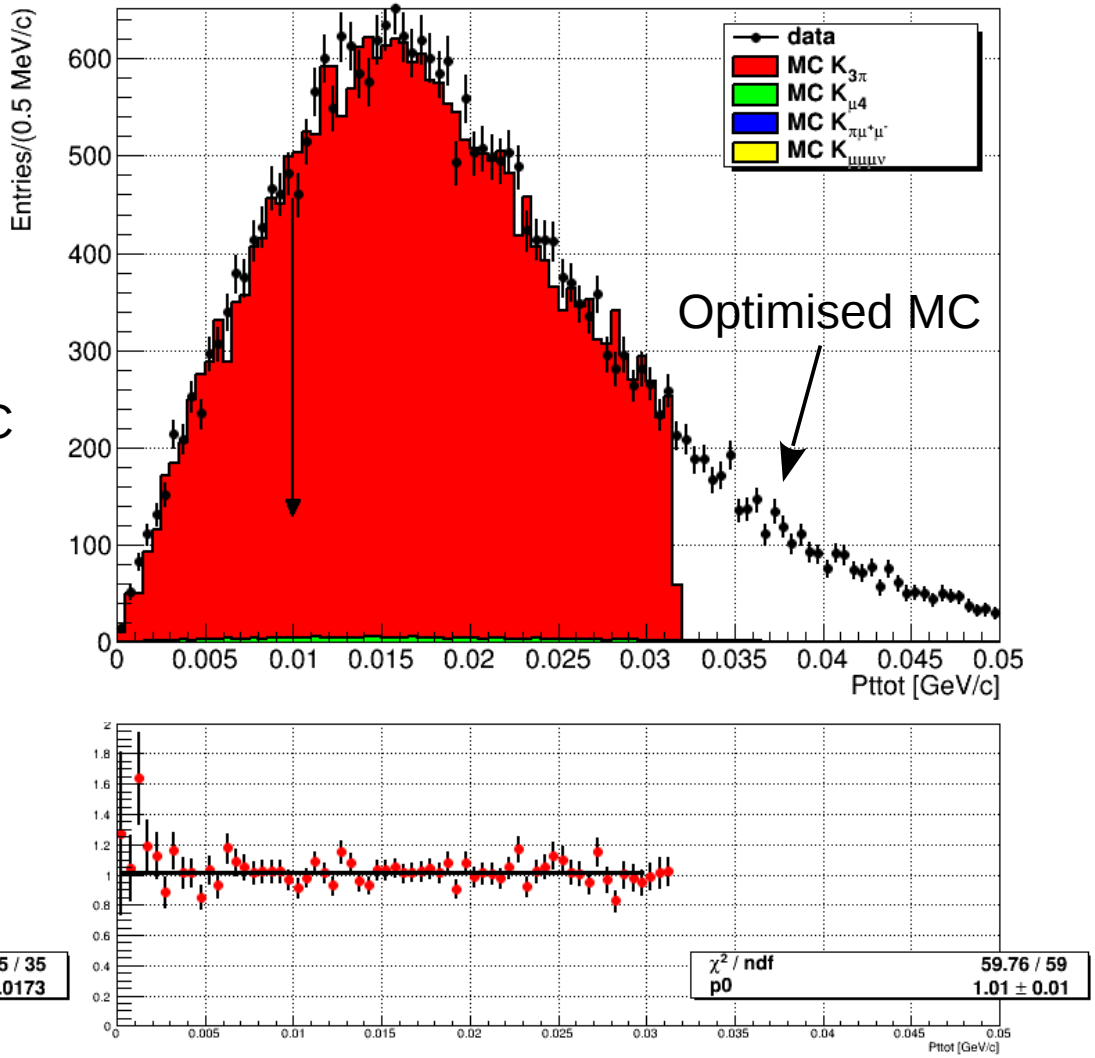


Data-MC comparison in CR

Total Momentum distribution

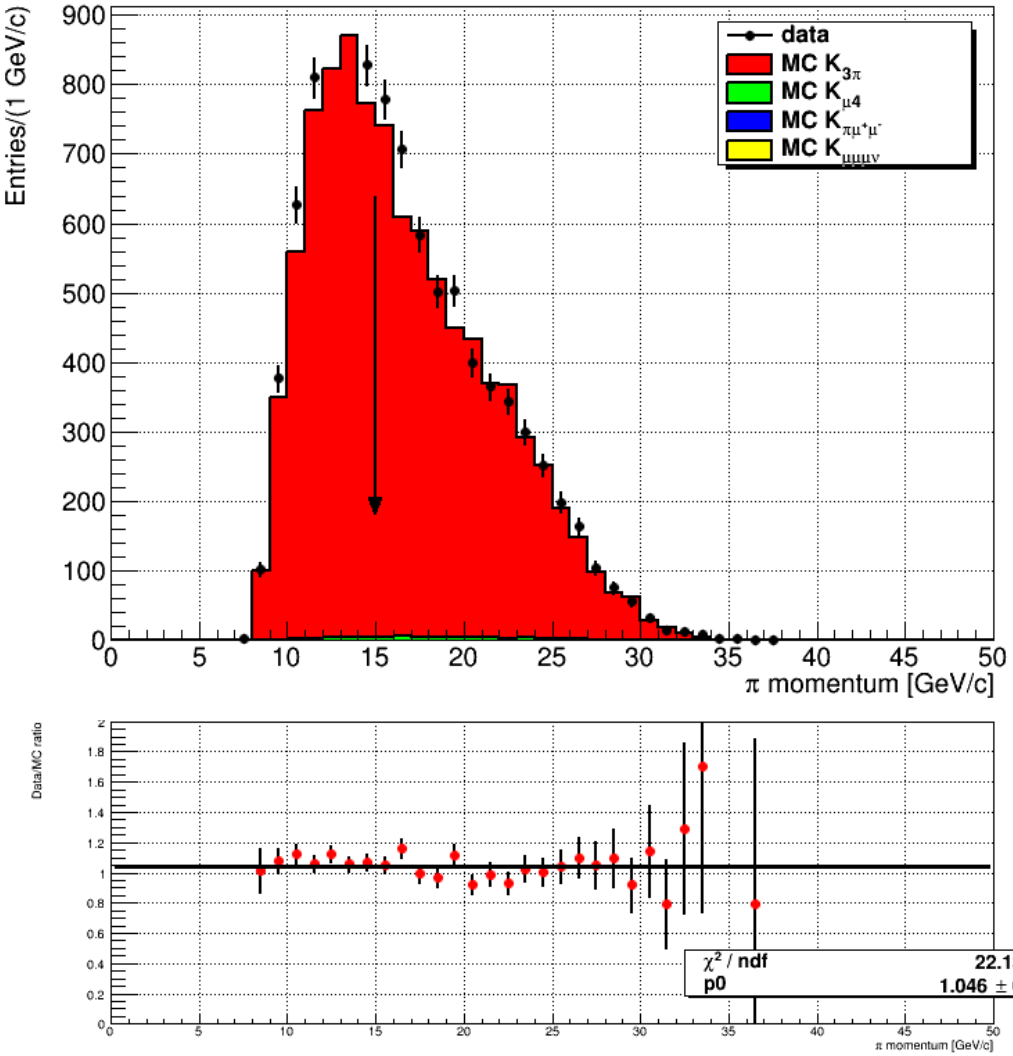


Total Transverse Momentum distribution

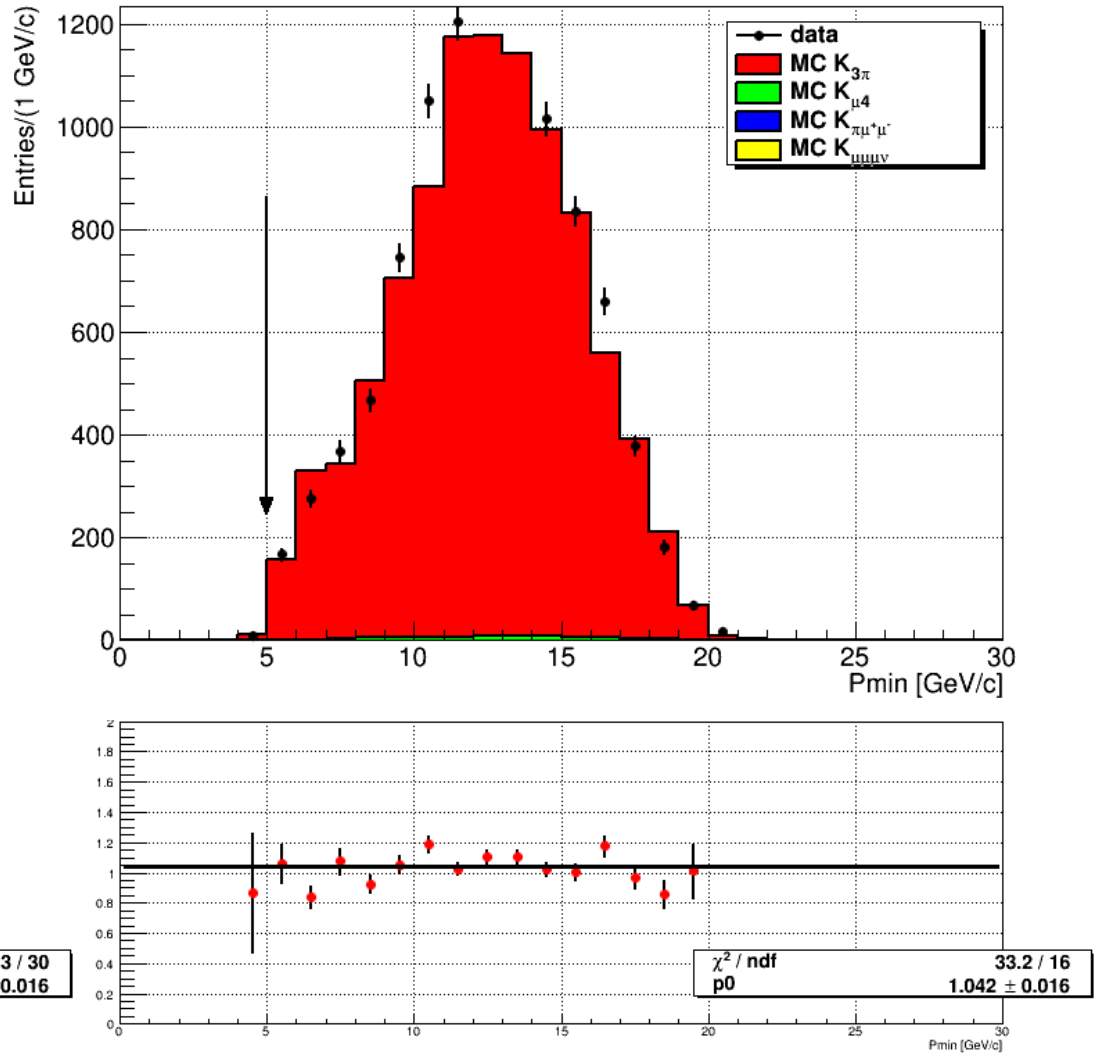


Data-MC comparison in CR

π candidate momentum distribution

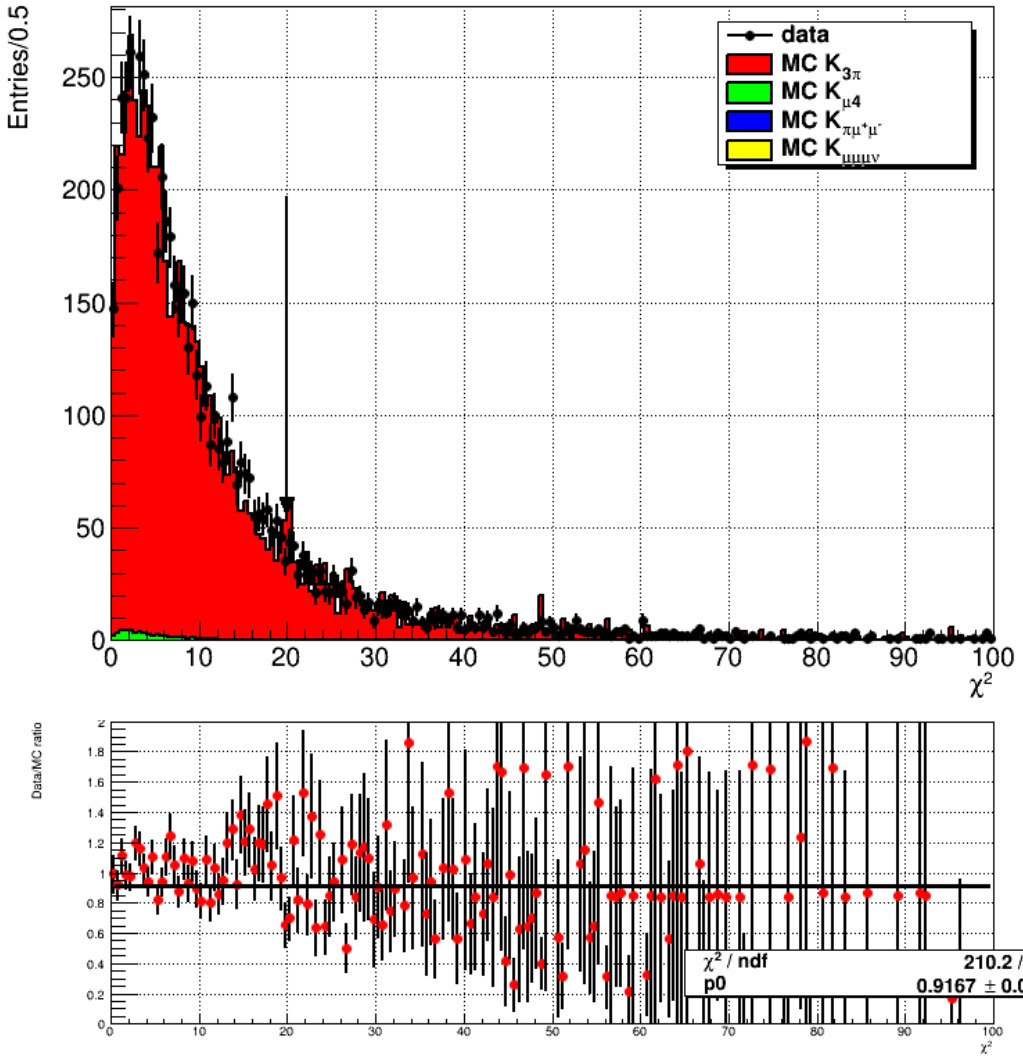


Momentum distribution of the lowest momentum track

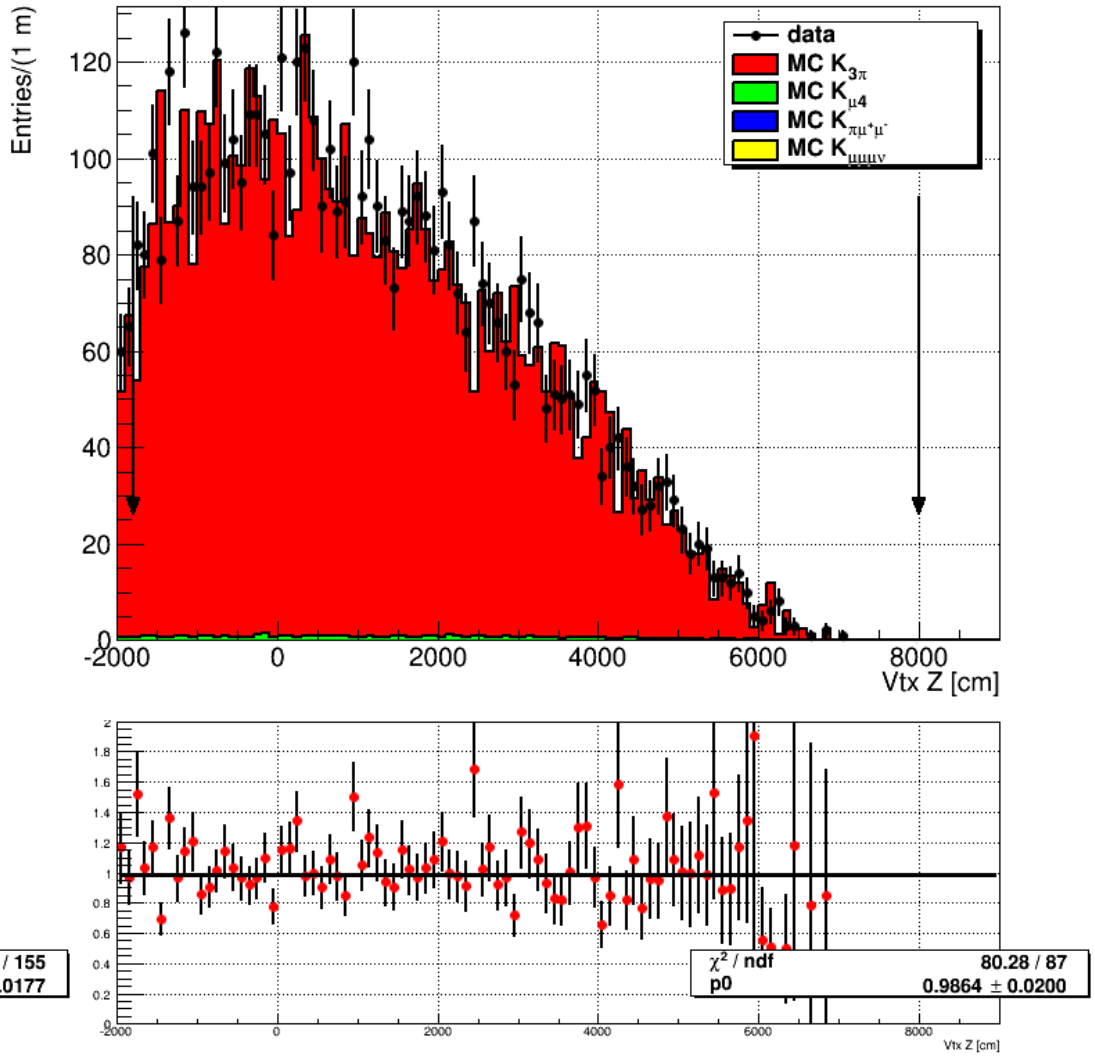


Data-MC comparison in CR

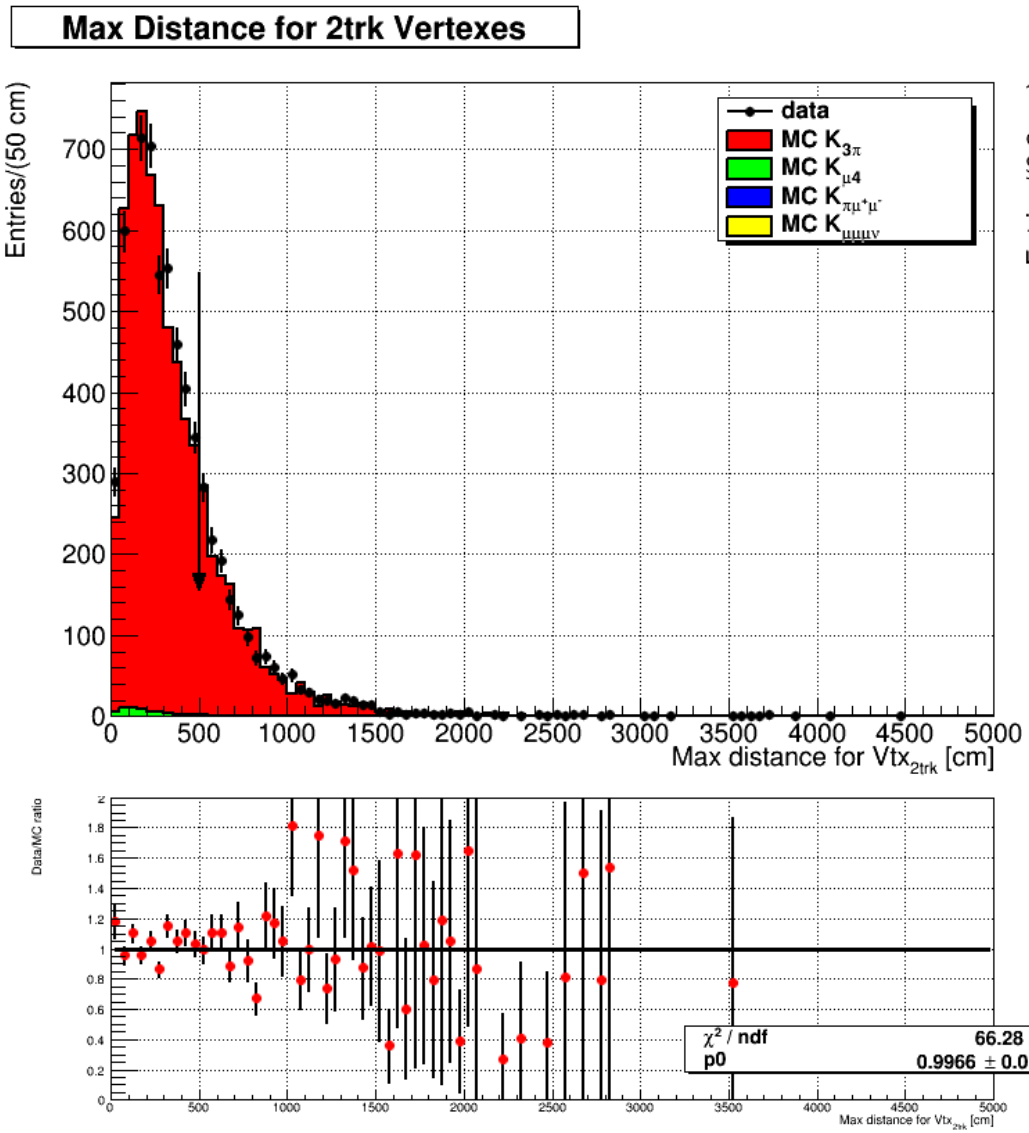
3-track χ^2 distribution

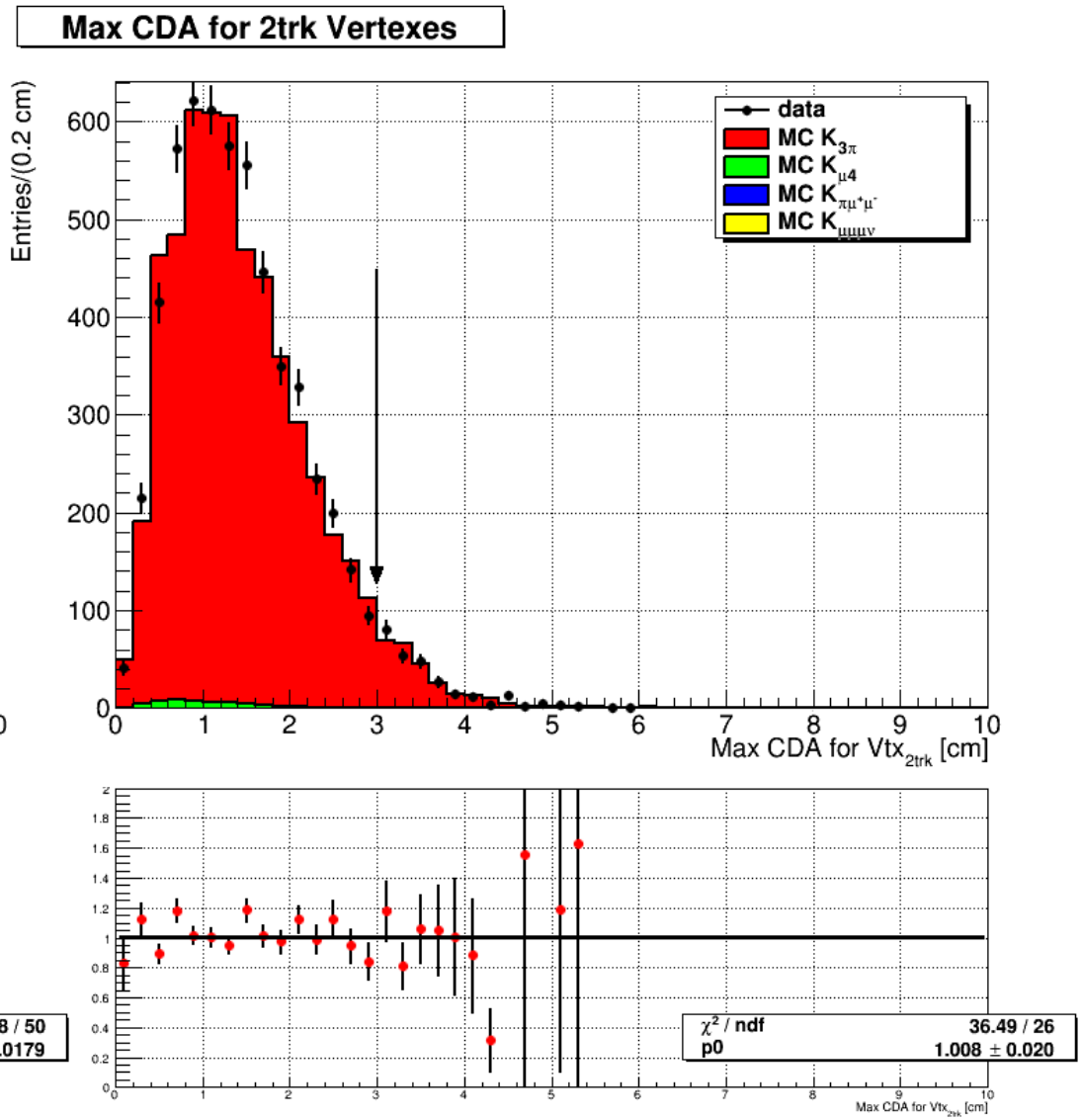


3-track Vertex z distribution



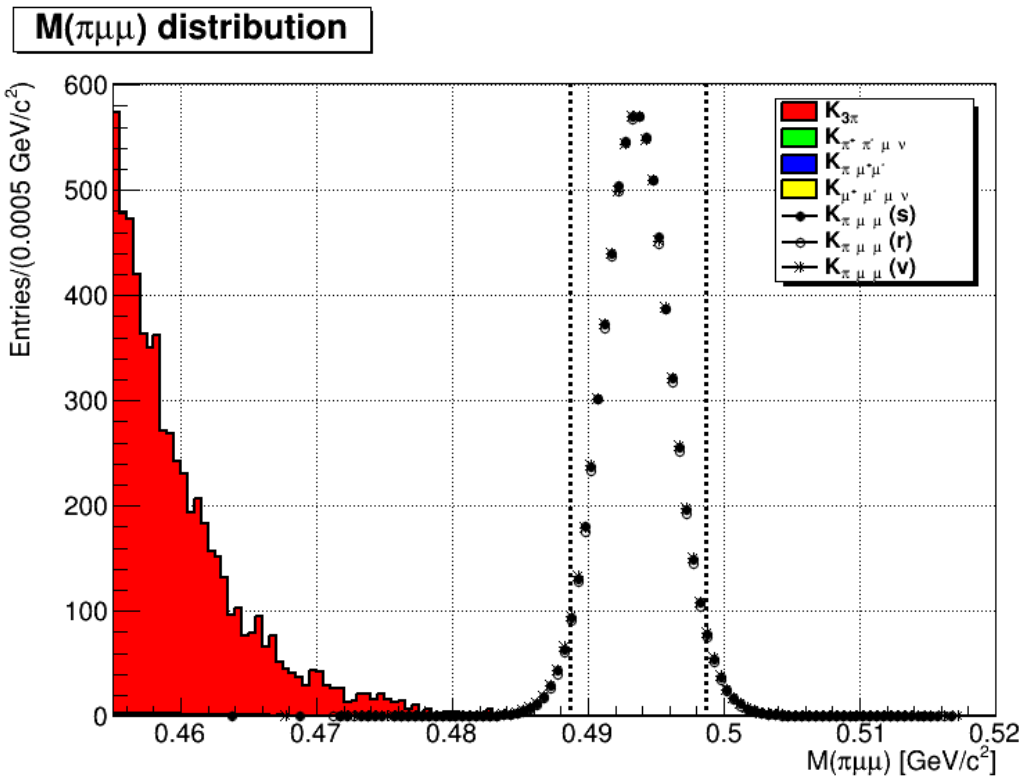
Data-MC comparison in CR

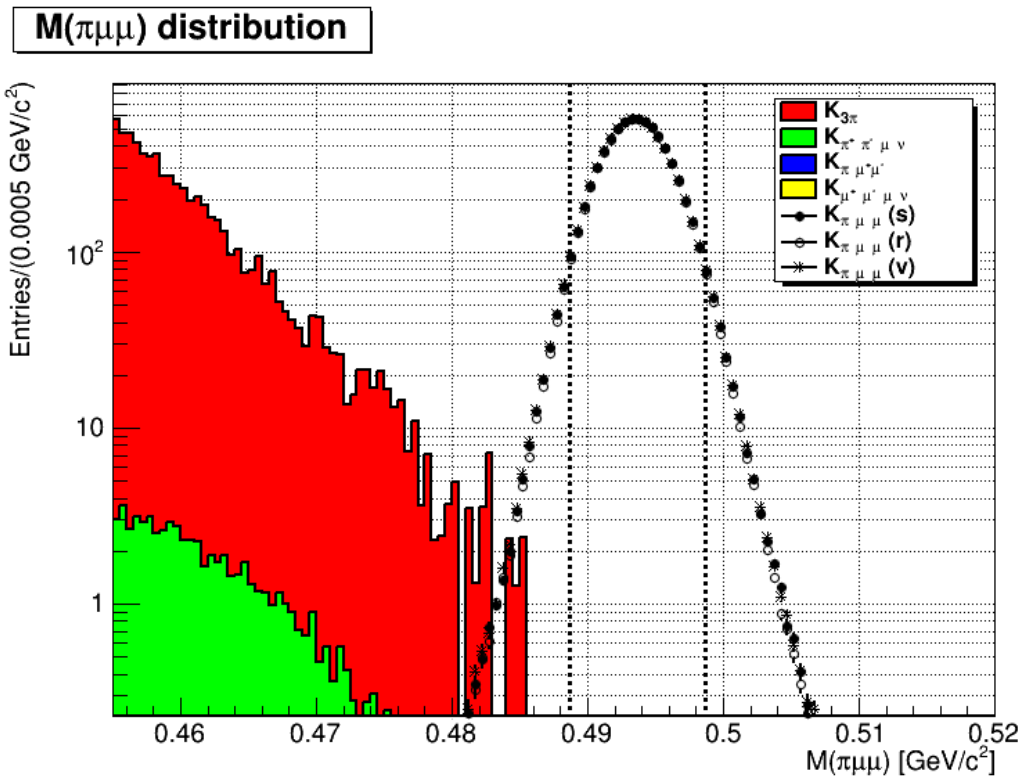




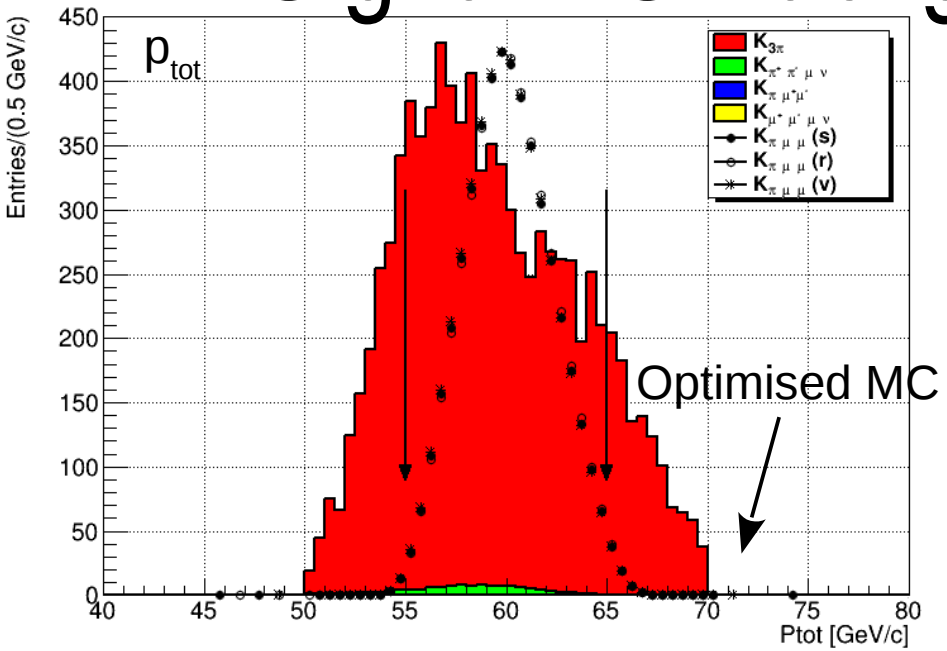
Signal VS Background (MC only)

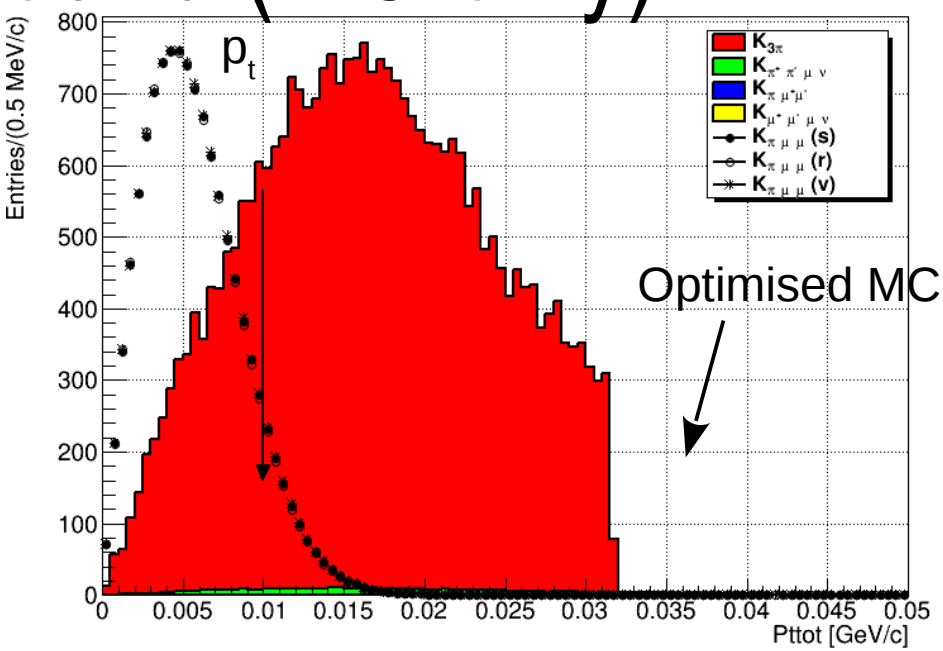
- For each variable, final $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ selection except
  - any cut on the variable itself
  - No $m_{\pi\mu\mu}$ cuts, to increase bkg statistics

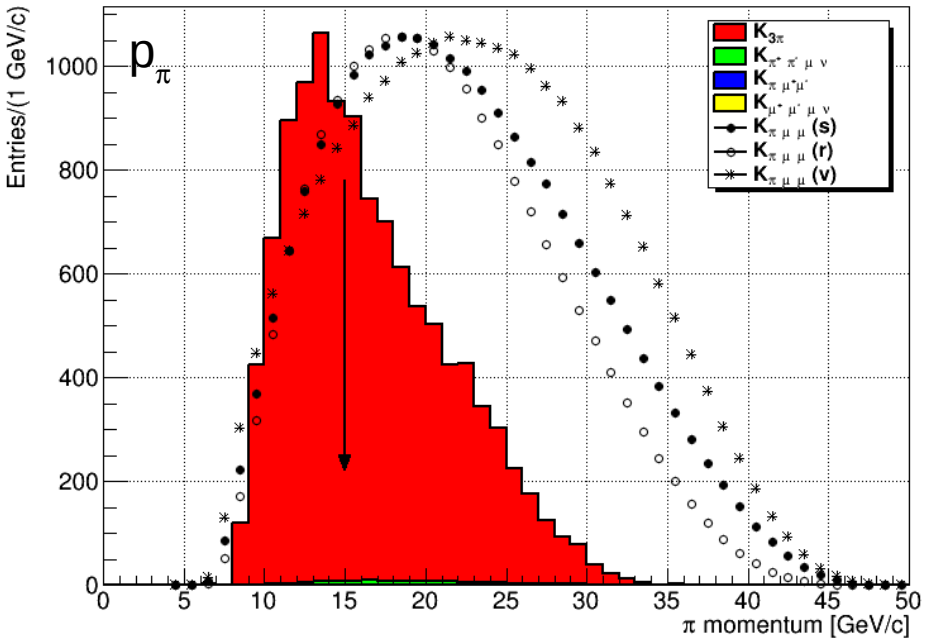


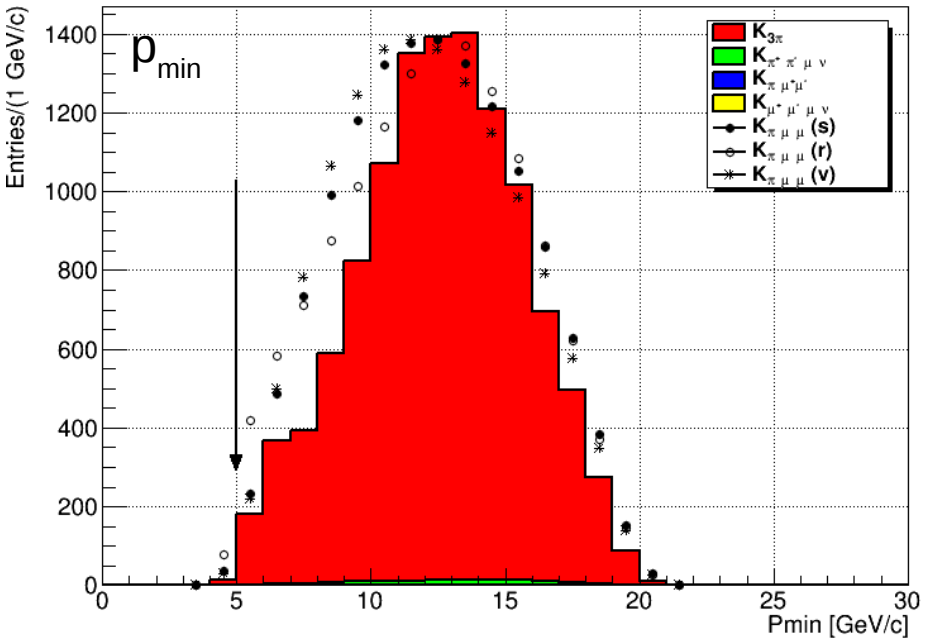


Signal VS Background (MC only)

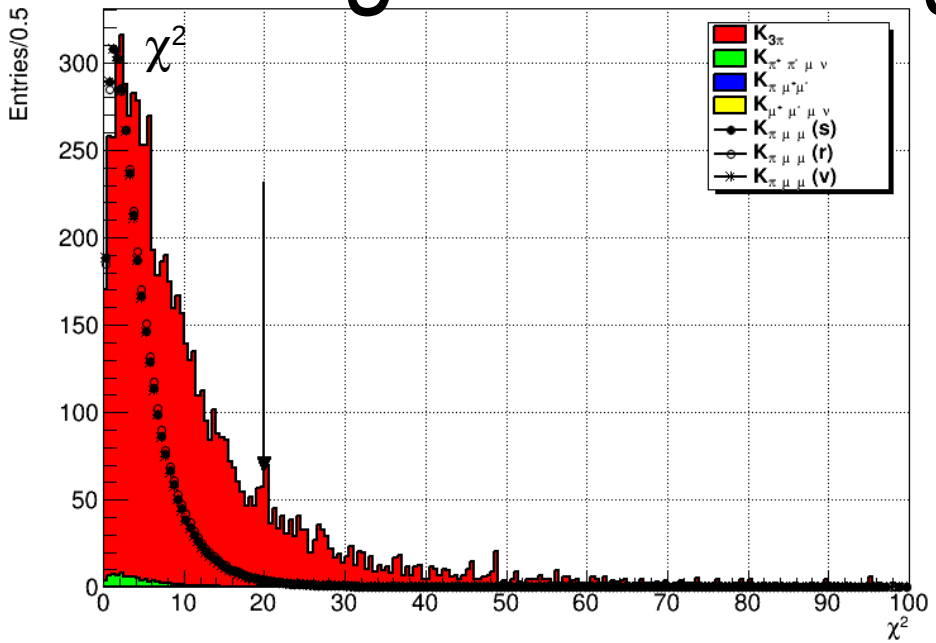


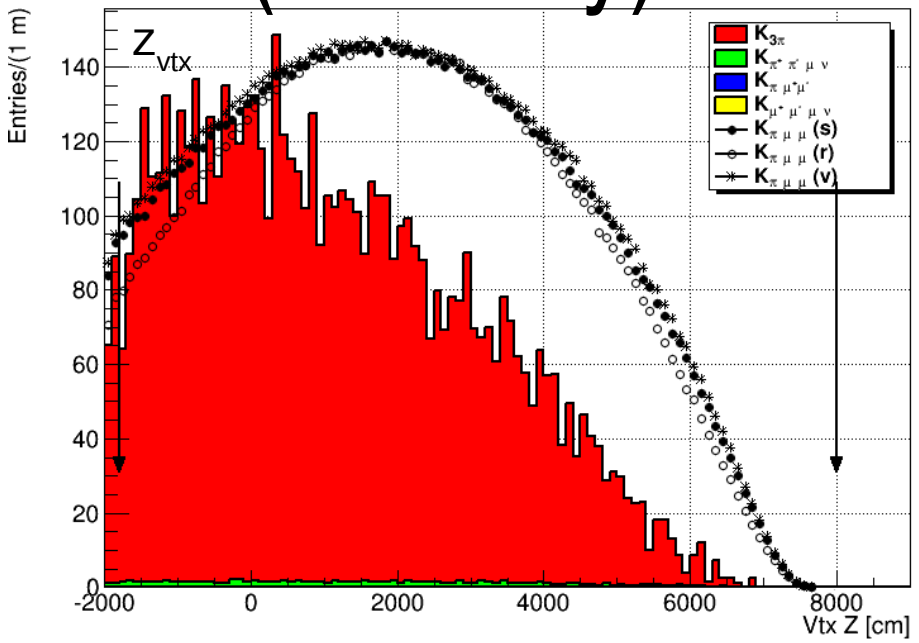


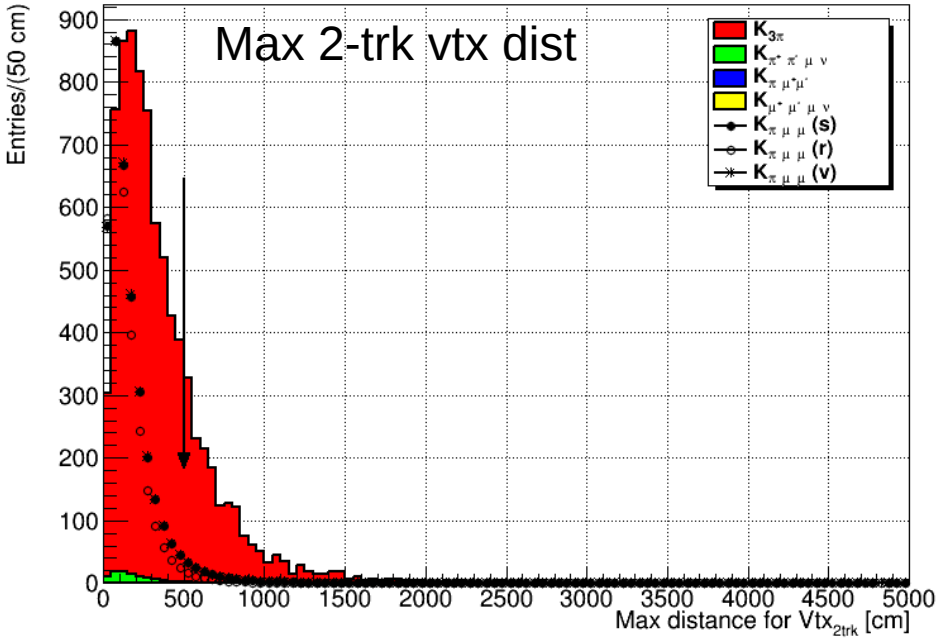


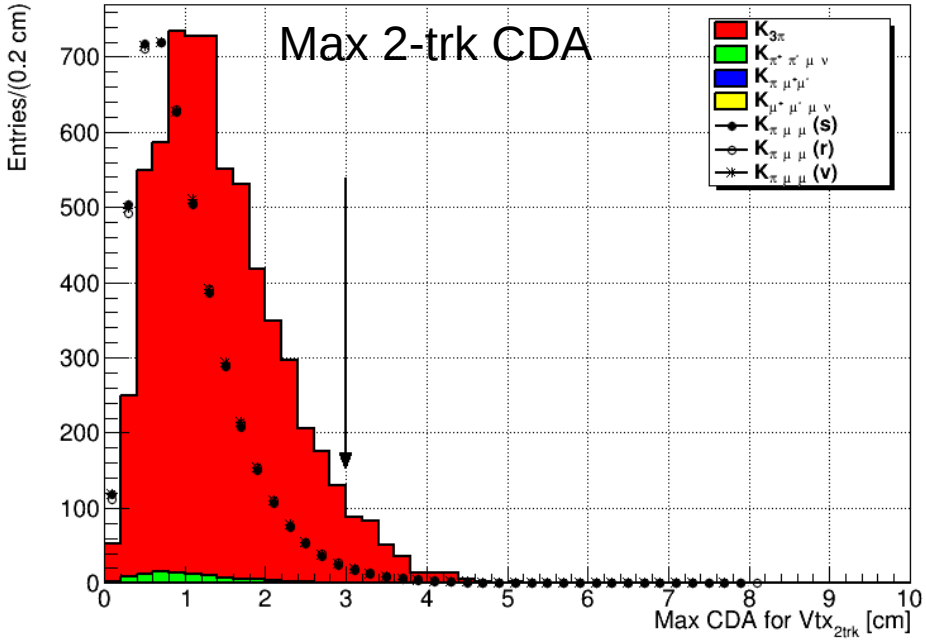


Signal VS Background (MC only)









Statistical Analysis

- Feldman-Cousins approach abandoned:
  Poisson-distributed signal with Poisson-distributed bkg with *known* mean
  → actually NOT suitable for this analysis!

  $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ background uncertainty dominated by statistics:
  Statistics fluctuations MUST be taken into account!

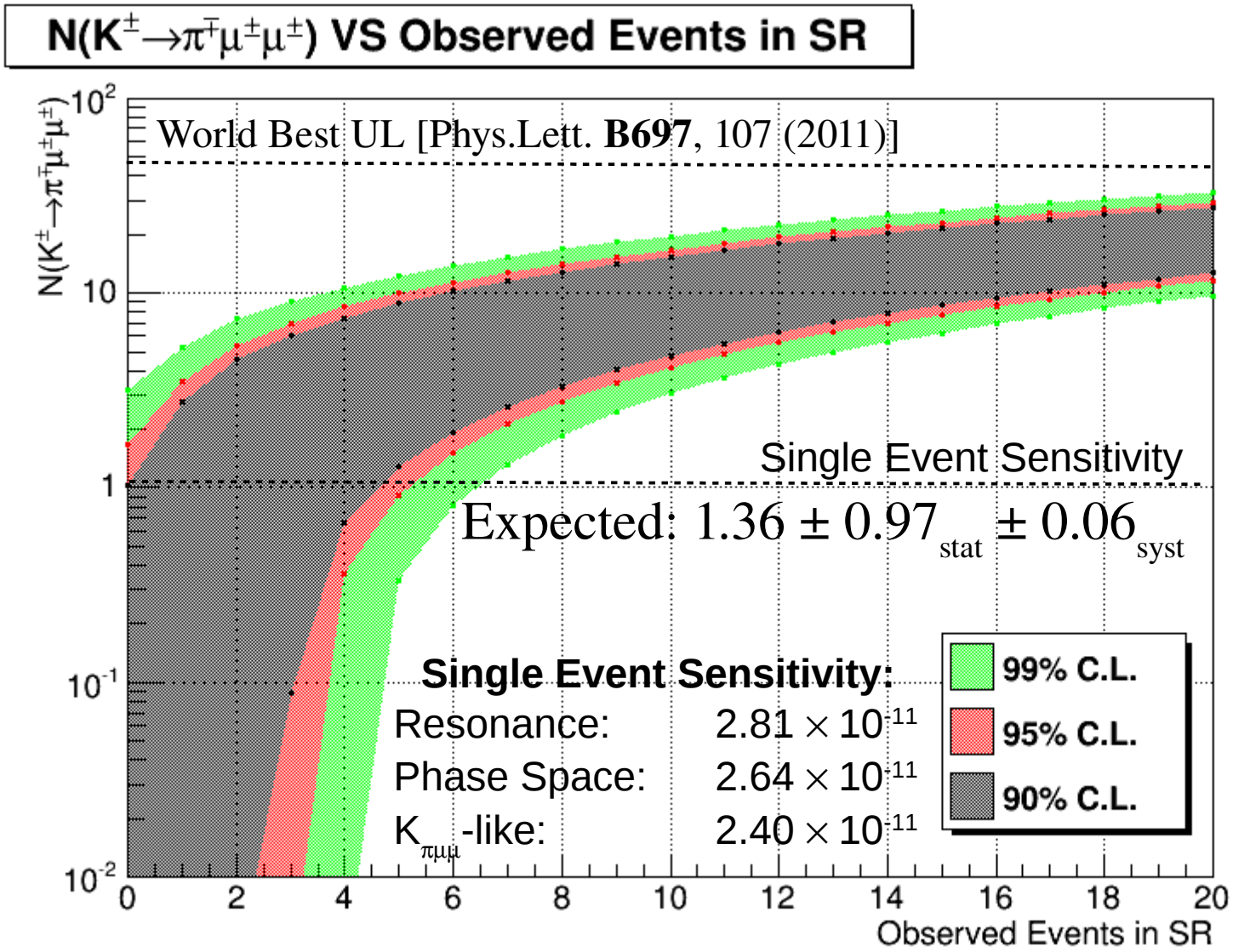
- Rolke-Lopez method [Nucl.Instrum.Meth. **A551**, 493 (2005)]
  Poisson-distributed signal with Poisson-distributed bkg with *unknown* mean

NEW

TRolke class not extendable to the case of interest with 4 bkg estimations
New framework "STAT62" developed for numerical evaluation
of Rolke-Lopez confidence intervals
[with improved convergence algorithms with respect to TRolke]
User-friendly and customisable environment ready: to be released soon

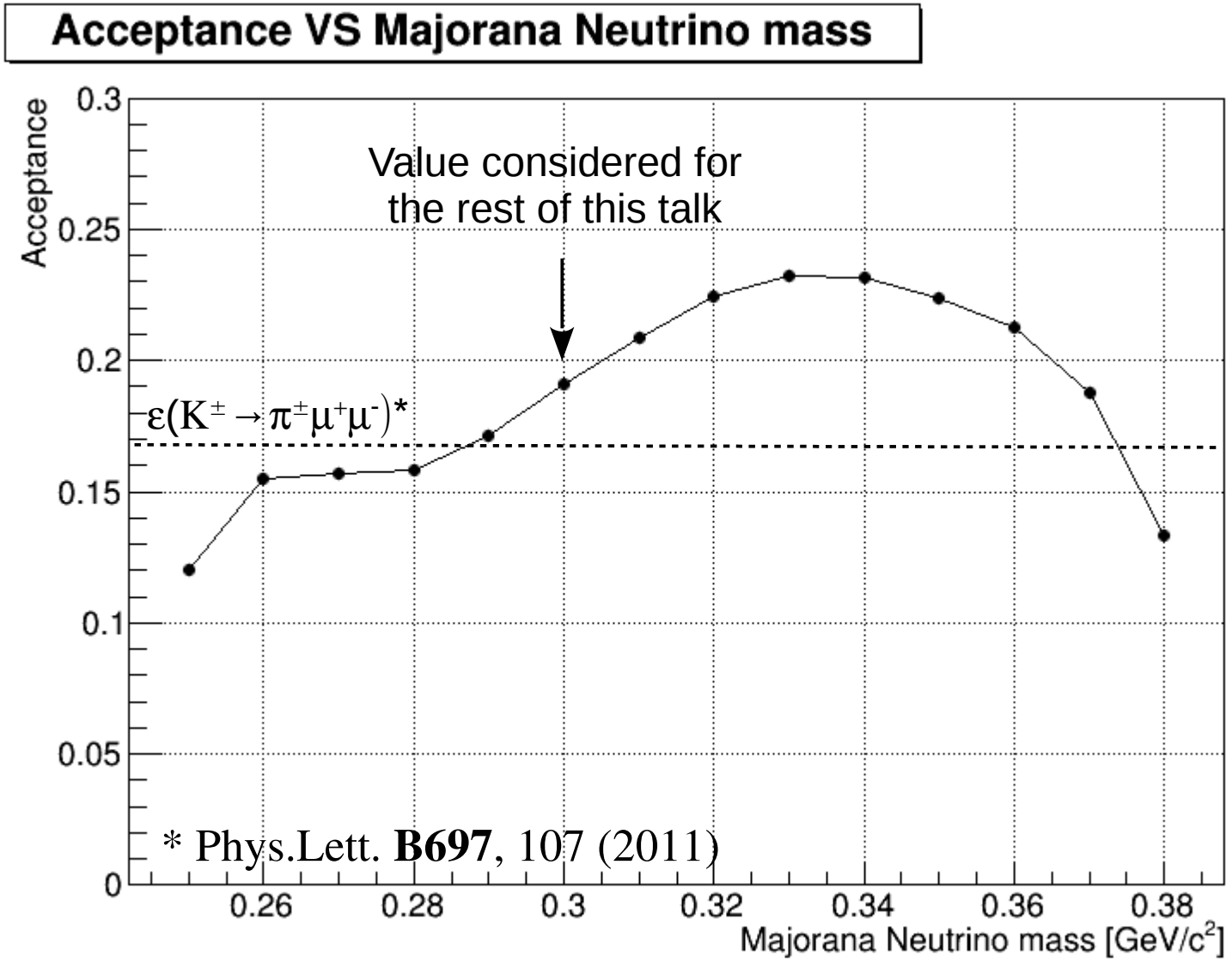
NEW Confidence Belt

Confidence Belt built using number of expected bkg events



NEW Neutrino mass scan (preliminary)

Signal acceptance $\varepsilon_{\pi\mu\mu}(m_N)$ for resonance model evaluated ($\tau_N \approx 0$)



Conclusions and Outlook

- Fine-tuning of the $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ Event Selection completed
- Final Selection: $1.36 \pm 0.97_{stat} \pm 0.06_{syst}$ background
- Potential sensitivity ~ 3×10^{-11} @ 90% C.L
- Muon efficiency evaluated (and bad bursts removed)
- Kaon flux evaluated (in agreement with previous results)
- New statistical analysis using the Rolke-Lopez method for a Poisson-distributed bkg with *unknown* mean

Next Steps:

- Scan in m_N and in τ_N to evaluate the signal acceptance $\varepsilon_{\pi\mu\mu}(m_N,\tau_N)$ for resonance model
- Independent "displaced vertex" analysis to cover region $\tau_N > 10$ ps

Conclusions and Outlook

- Standing items will be completed soon (< 1 week)
- **Asking for internal referees to be nominated**
- Internal "living" note describing the analysis about to be released next week, in order to receive feedback from referees
- Subsequently, asking the permission to open the box