Measurement of the branching fractions and form factors of $K^{+} \rightarrow \pi^{0} l^{+} \nu_{l}$ decays

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Outline

- Role of K_{l3} decays
- Branching ratios
- Form factors
- NA62 detector
- Analysis strategy
- Selection
- Variables and correlations
- Conclusion and next steps

Role of semileptonic kaon decays

- $K^+ \to \pi^0 e^+ \nu$ (K_{e3}) and $K^+ \to \pi^0 \mu^+ \nu$ ($K_{\mu 3}$) provide one of the cleanest way of extracting V_{us}
  - Both the branching fractions and form factors come into the calculation
  - Precise V_{us} determination leads to stringent tests of CKM unitarity

- Experimental inputs contribute slightly more than theoretical ones to the overall V_{us} uncertainty

Semileptonic decay width

- $K^+ \to \pi^0 l^+ \nu \ (l = e, \mu)$ decay width is given by:

$$\Gamma_{Kl3} = \frac{G_F^2 m_K^5}{192\pi^3} C_K^2 S_{EW} \left(|V_{us}| f_+^{K^0\pi^-}(0) \right)^2 I_{Kl} \left(1 + \delta_{EM}^{Kl} + \delta_{SU(2)}^{K\pi}\right)^2$$

Experimental inputs:

- Γ_{Kl3} kaon branching ratios
- I_{Kl} phase integral, dependant on the form factors

Theory inputs:

- G_F is the Fermi constant
- m_K is the kaon mass
- C_K is the Clebsch-Gordan coefficient (1 for K^0 and $1/\sqrt{2}$ for $K^\pm$)
- S_{EW} is the short-distance electroweak correction
- $f_+^{K^0\pi^0}(0)$ is the vector form factor at zero-momentum transfer for $K^0 \to \pi^-$
- δ_{EM}^{Kl} are the channel-dependent long-distance EM corrections
- $\delta_{SU(2)}^{K\pi}$ is the isospin breaking correction

Semileptonic form factors

- $K^+ \to \pi^0 l^+ \nu \ (l = e, \mu)$ decays are described by:

$$\frac{d^2\Gamma(K_{l3})}{dE_{l^+} dE_{\pi^0}} = N(Af_+^2(t) + Bf_+(t)f_-(t) + Cf_-^2(t))$$

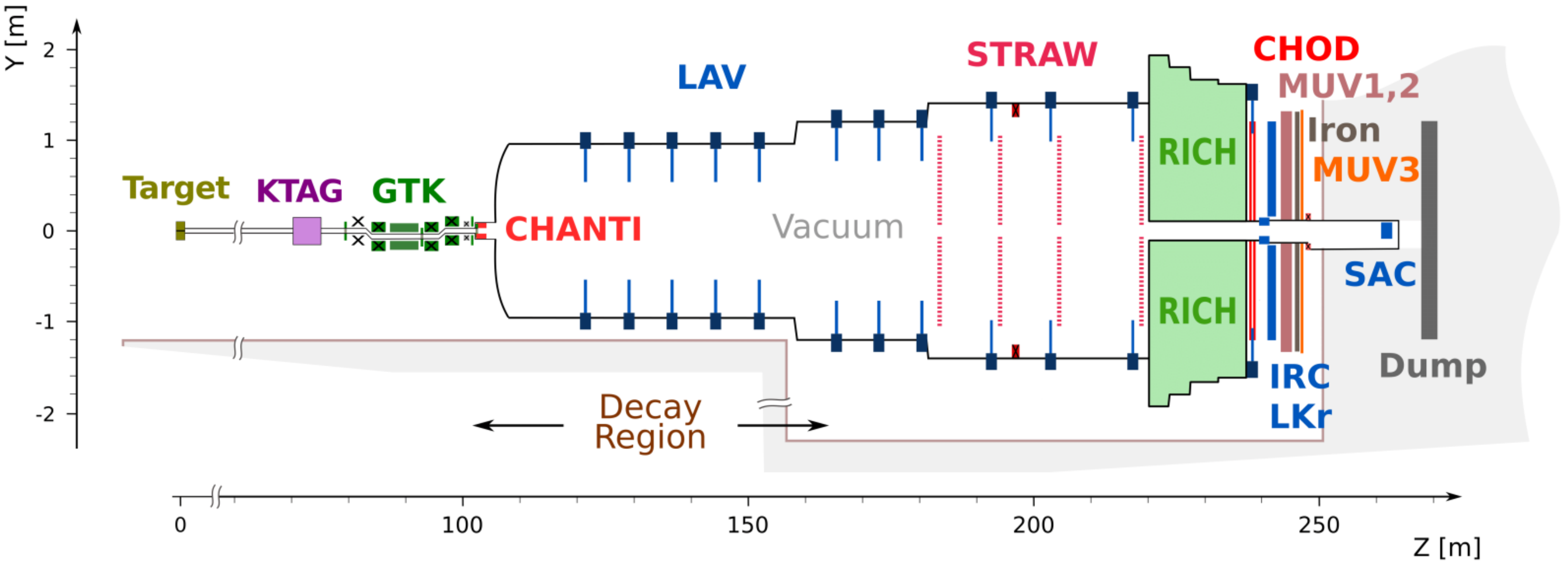
$t = (P_K - P_\pi)^2$
N = normalisation factor

$$f_0(t) = f_+(t) + \frac{t}{m_K^2 - m_\pi^2} f_-(t)$$

$$A = m_K\left(2E_l E_\nu - m_K(E_\pi^{max} - E_\pi)\right) + m_l^2 \left(\frac{E_\pi^{max} - E_\pi}{4 - E_\upsilon}\right)$$

$$B = m_l^2 \left(E_\upsilon - \frac{E_\pi^{max} - E_\pi}{2}\right), \qquad C = m_l^2 \frac{E_\pi^{max} - E_\pi}{4}$$

NA62 detector



Primary beam
- 400 GeV/c protons from SPS

Secondary beam
- 6% kaons, 75 GeV/c momentum
- Rest: 70% pions, 24% protons

Fiducial volume
- 60m region
- 10^{-6} mbar vacuum
- ~5 MHz K^+ decay rate

Sub detectors
- Upstream: KTAG, GTK, CHANTI
- Downstream tracking: STRAW, CHOD, NewCHOD
- PID: RICH, MUV1/2/3
- Photon veto: LAV, LKr, IRC, SAC

Analysis strategy

- Analysis benefits from having precise measurements of the momentum of both parent and daughter particles
- Use $K^+ \to \pi^+\pi^0$ as a normalisation channel
- Keep selection the same for the different channels until the very end
  - One (downstream) track selection
  - Kaon selection + downstream track matching
  - π^0 tagging + photon veto
  - Charged track identification

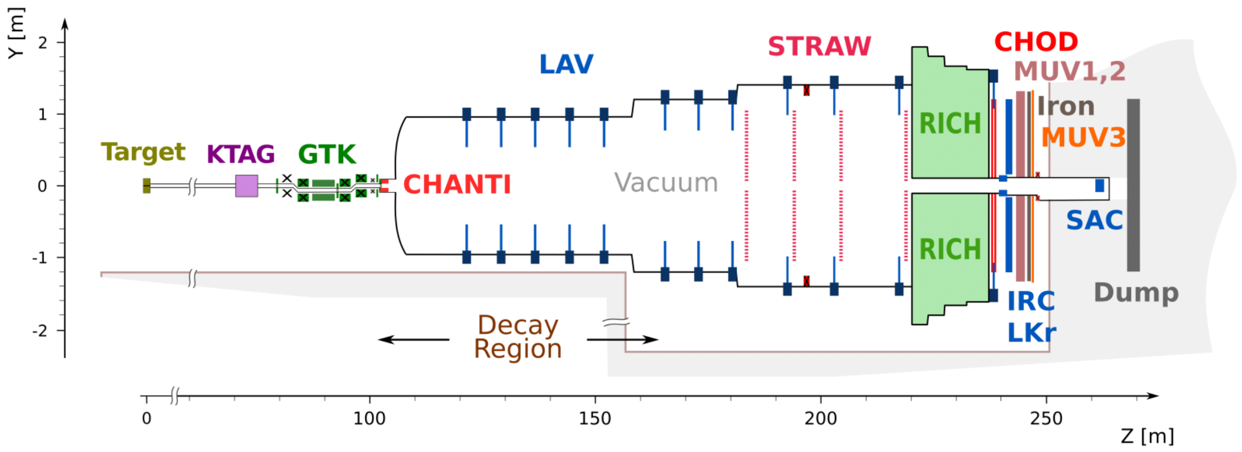
} common to $K_{\mu3}$, K_{e3}, and $K_{2\pi}$

K^+ branching fractions

Decay	Branching fraction
$K^+ \to \mu^+ \nu_\mu$	63.56%
$K^+ \to \pi^+ \pi^0$	20.66%
$K^+ \to \pi^+ \pi^+ \pi^-$	5.58%
$K^+ \to \pi^0 e^+ \nu$	5.07%
$K^+ \to \pi^0 \mu^+ \nu$	3.35%
$K^+ \to \pi^+ \pi^0 \pi^0$	1.76%

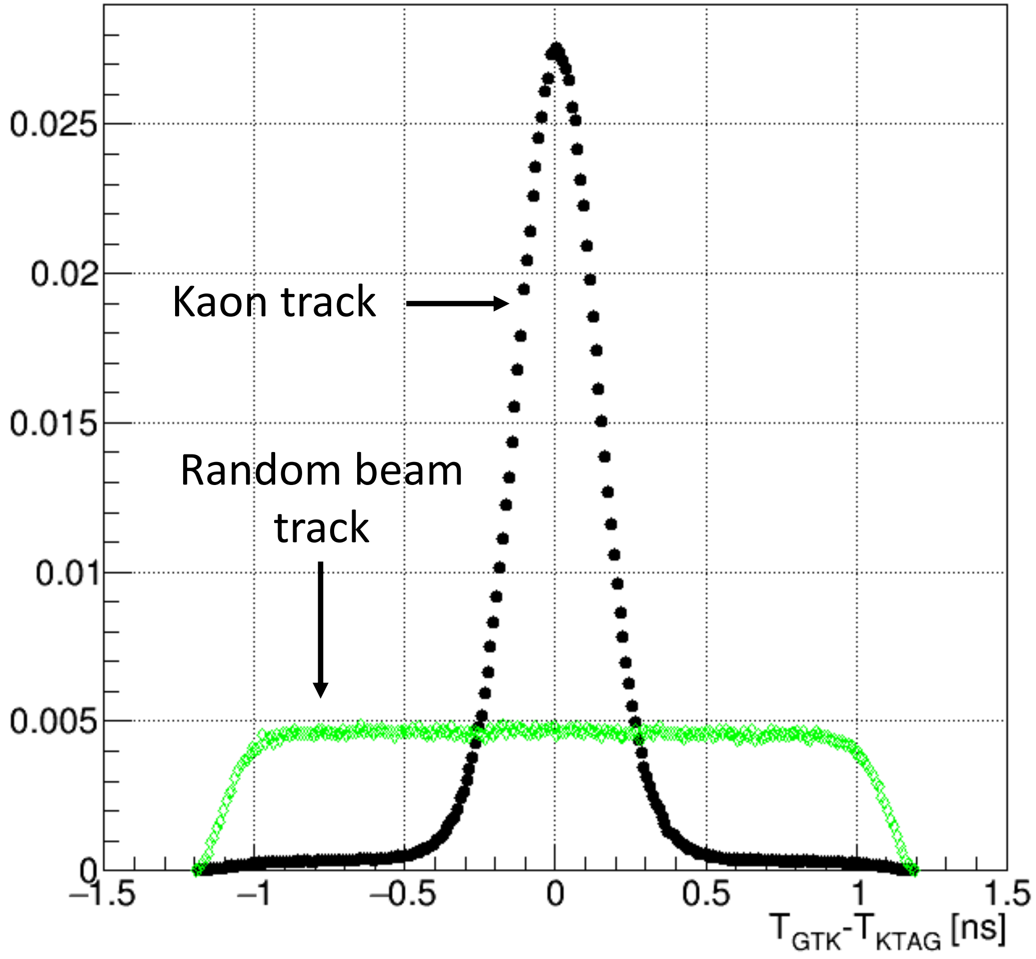
Track selection

- Minimum-bias trigger (CHOD)
- Hits in all four chambers of the spectrometer (STRAW)
- Positively charged
- Associated with a signal in CHOD, LKr, and MUV



Track-kaon matching

- Kaon selection
  - Hits in all 3 GKT stations
  - Signal in KTAG, $t_{KTAG} - t_{GTK} < 400\ ps$
- Kaon-track matching
  - In time, $t_{KTAG} - t_{trigger} < 10\ ns$
  - Closest distance of approach (CDA) < 5 mm
  - Decay vertex between 110m and 180m



π^0 tagging + photon veto

- π^0 tagging + photon veto
  - Two photons in the LKr,
    - In time with each other and track, $t_{\pi^0} - t_{KTAG} < 5\ ns$
    - Distance between each other > 30 cm
    - Reconstructed π^0 mass: $110\ MeV/c < m_{\pi^0}^{reco} < 150\ MeV/c$

- Photon veto
  - No in-time signal in LAV, IRC, SAC

Track ID

- Aim: explore different strategies to distinguish between the 3 decays using **few** variables and/or detectors
- Variables
  - Missing masses: $m^2_{miss}(l^+) = (P_K - P_{l^+})^2$ or $m^2_{miss}(l^+ + \pi^0) = (P_K - P_{l^+} - P_{\pi^0})^2$
  - Transverse momentum: P_t
  - Energy/momentum (LKr/STRAW): e/p
- Detectors: ID or veto
  - LKr
  - MUV

$m^2_{miss}(l^+)$, $m^2_{miss}(l^+ + \pi^0)$ and P_t

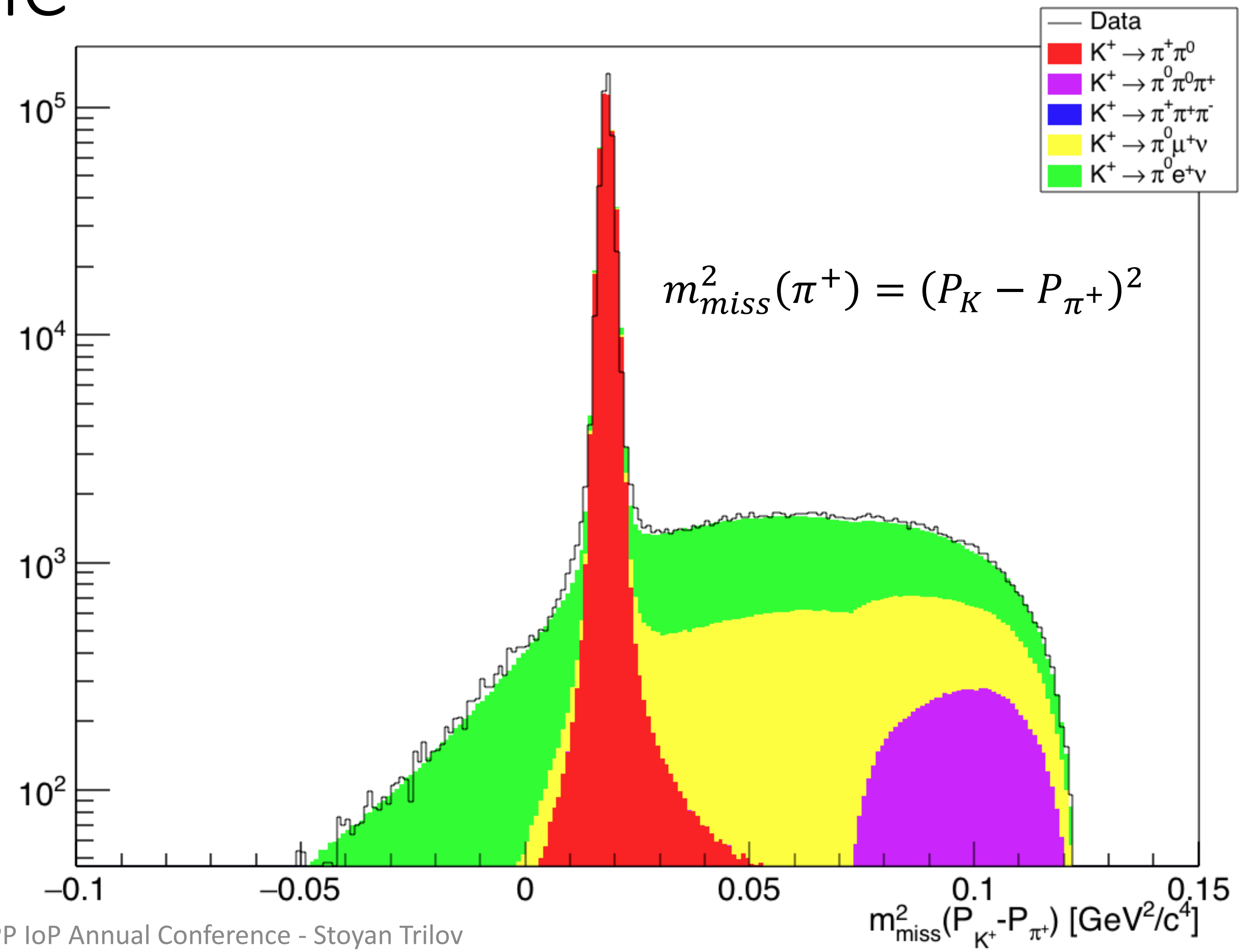
- $m^2_{miss}(l^+/l^+ + \pi^0)$: powerful in distinguishing between K_{e3} vs $K_{\mu3}$ / $K_{2\pi}$
  - Mass of the electron is well separated from μ/π
  - Issue of $\pi \to \mu$ decay in flight

- Track/π^0 P_t
  - P_t spectra are distinctive for 2 vs 3 body decays
  - However, highly correlated with missing mass

- m_{K^+}= 493.7 MeV
- m_{π^+}= 139.6 MeV
- m_{π^0}= 135.0 MeV
- m_{μ^+}= 105.7 MeV
- m_{e^+}= 0.5 MeV

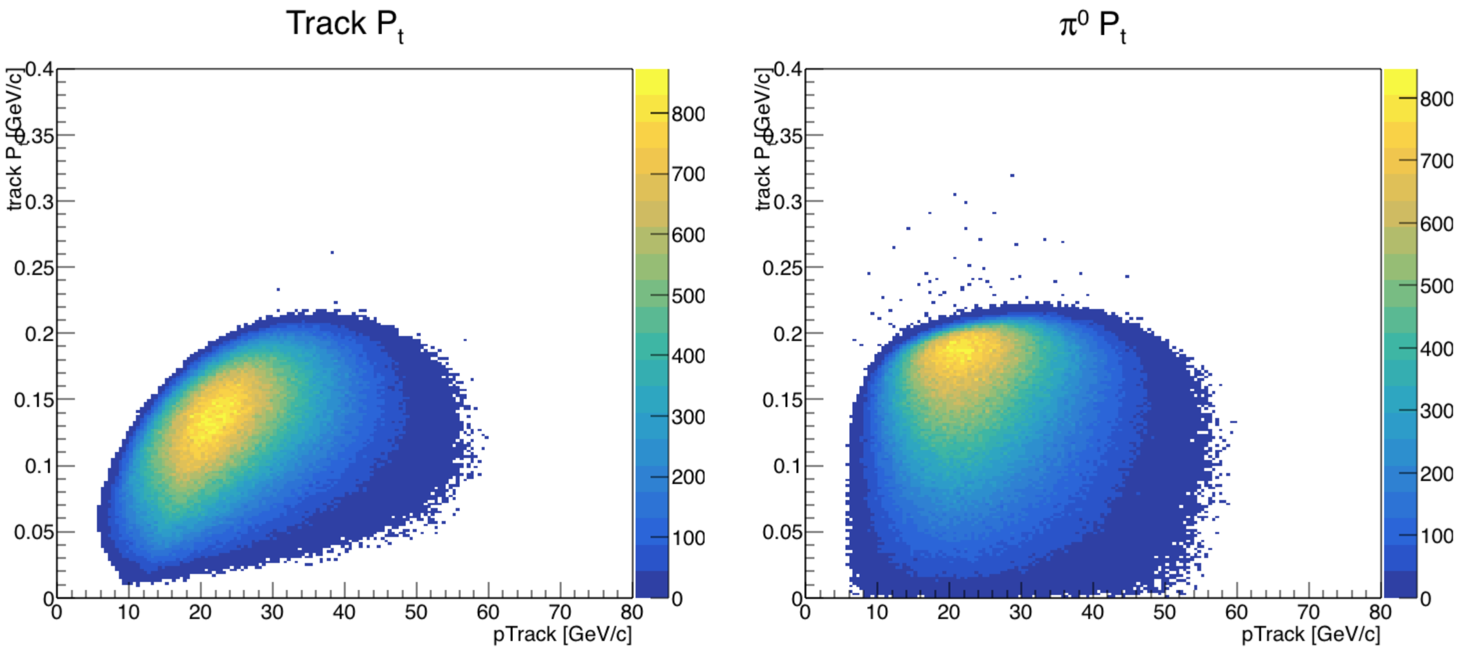
m^2_{miss} spectra: data vs MC

- After π^0 tagging and photon veto
- # data events: 580, 154
- MC integral normalised to the same number



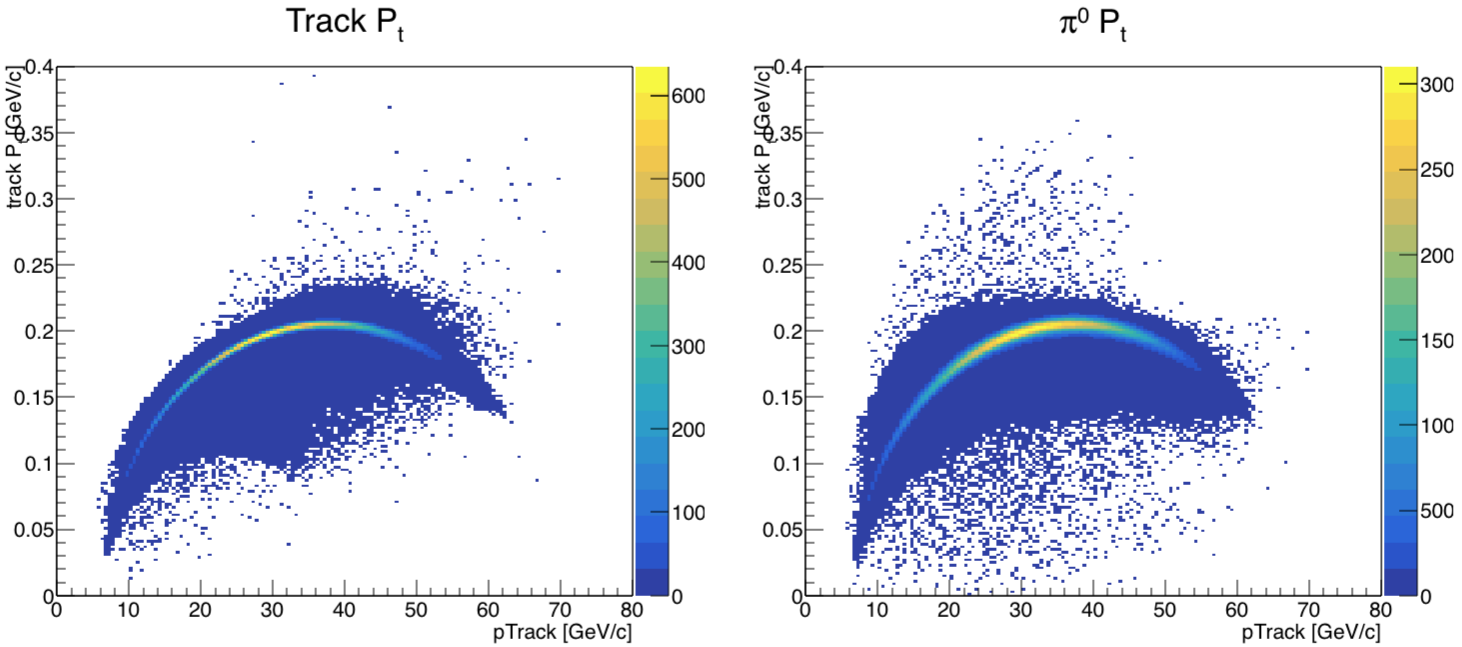
P_t spectra: MC

$K_{\mu 3}$ sample



- After π^0 tagging and photon veto

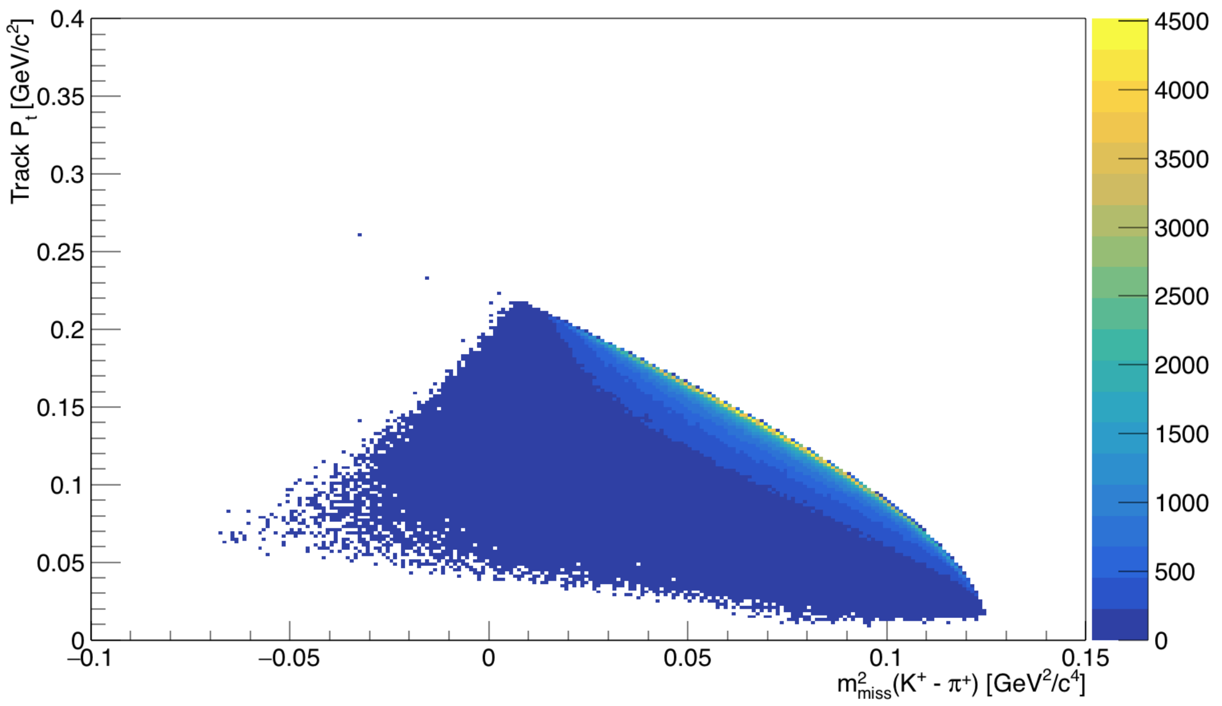
$K_{2\pi}$ sample



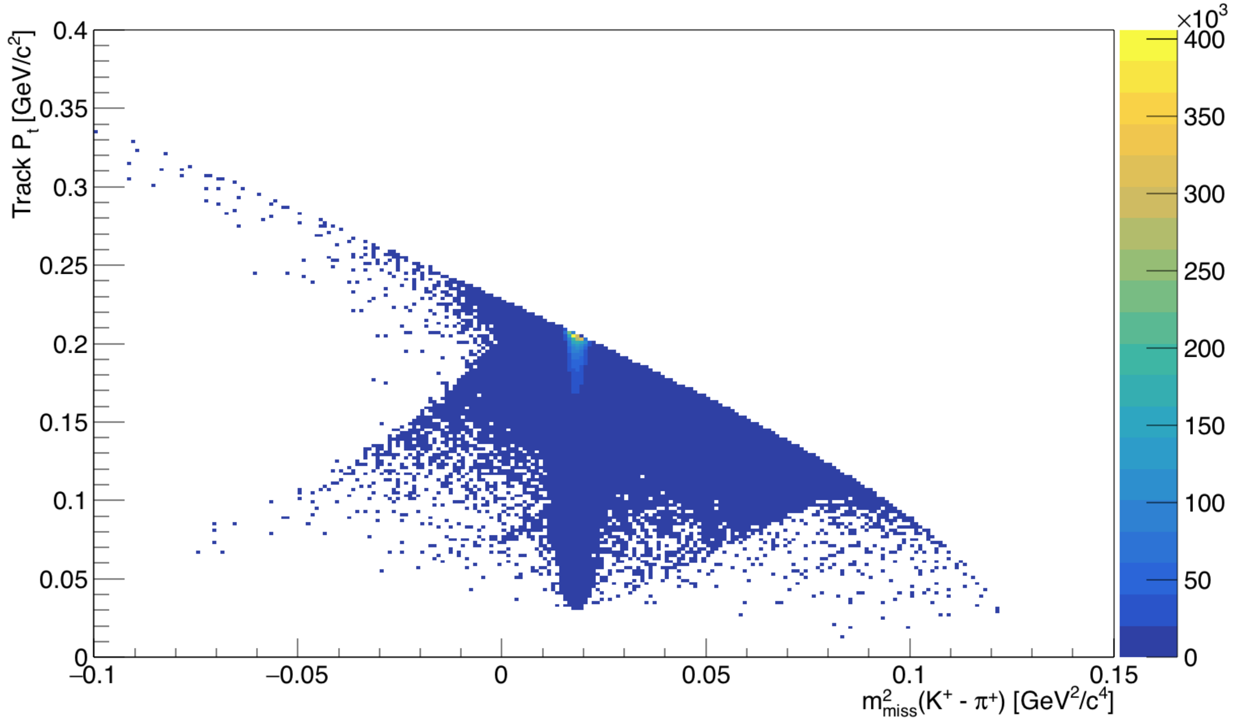
$m^2_{miss}(\pi^+)$ vs track P_t: MC

After π^0 tagging and photon veto

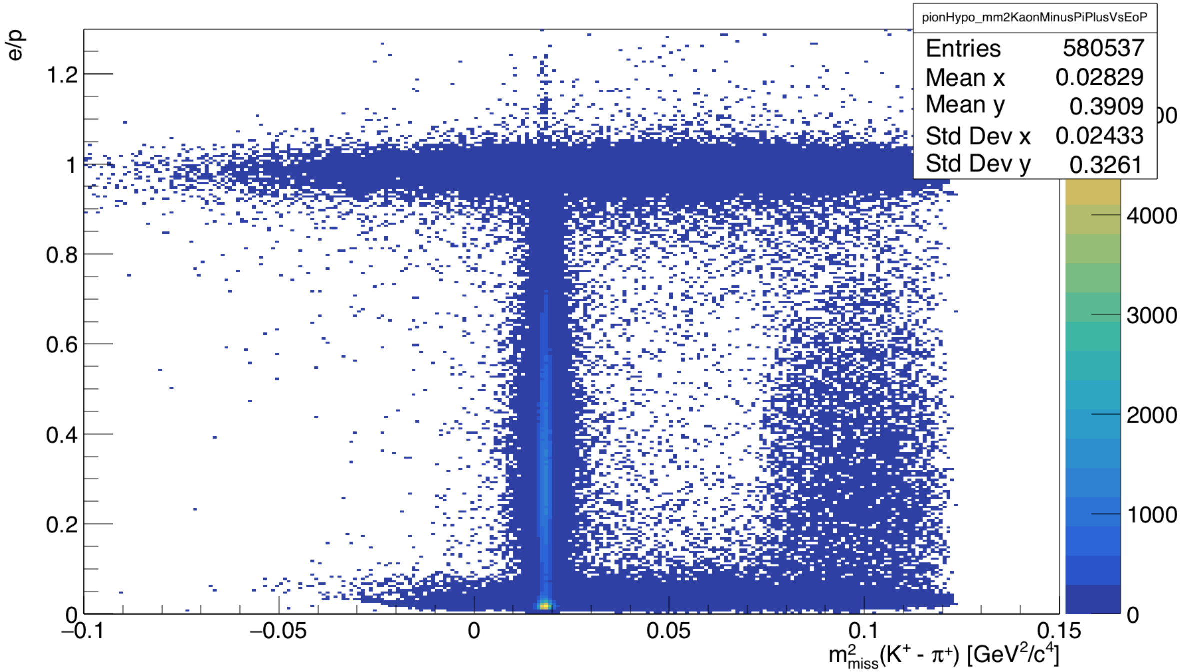
$K_{\mu 3}$ sample



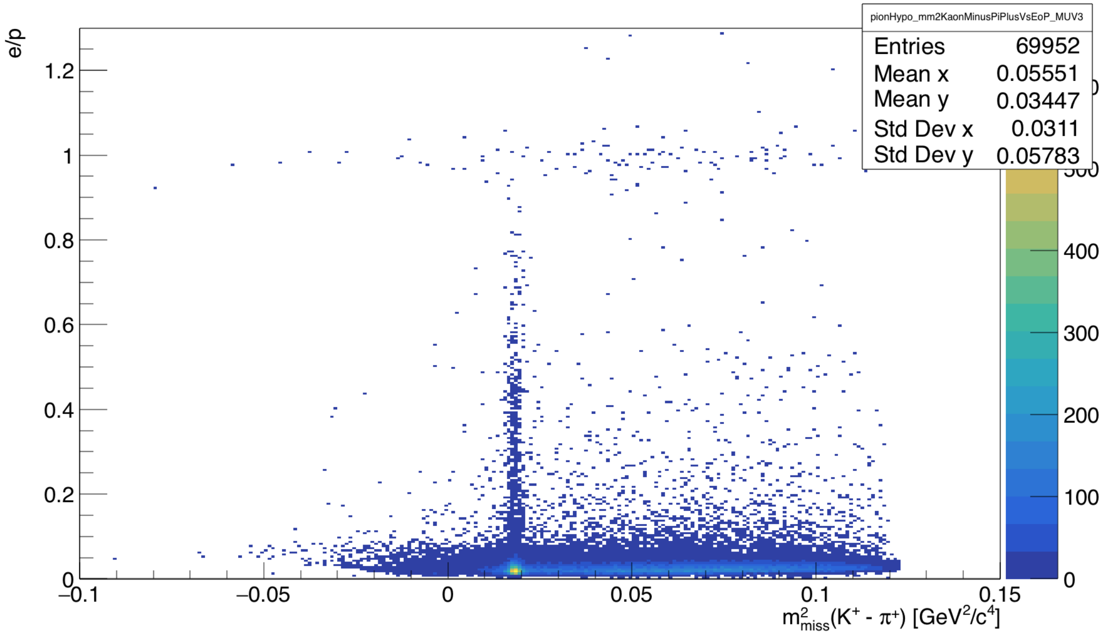
$K_{2\pi}$ sample



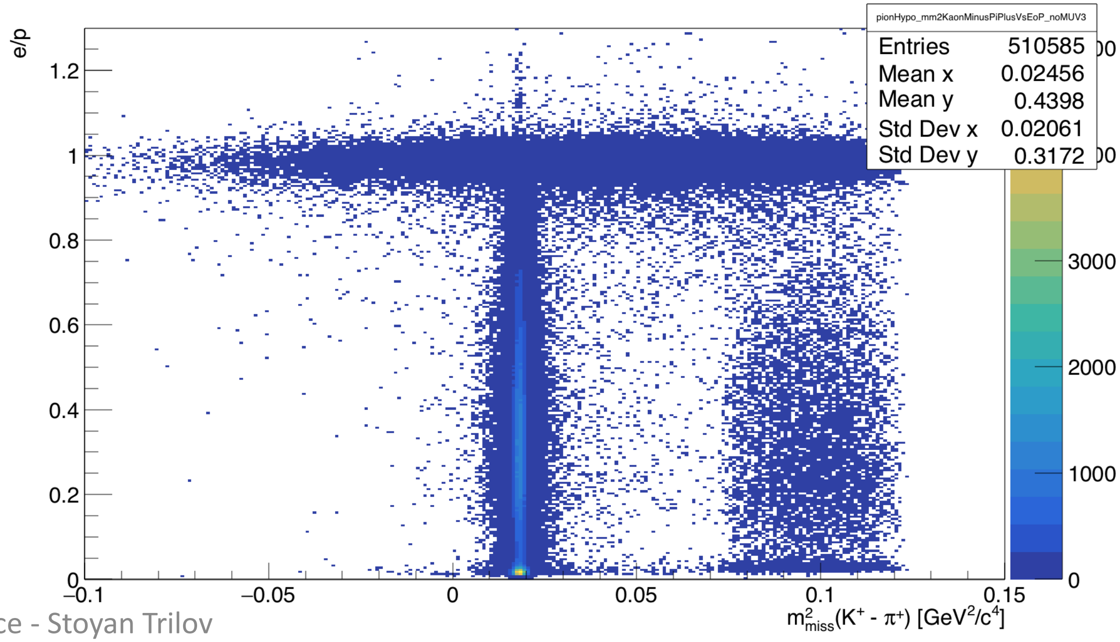
$m^2_{miss}(\pi^+)$ vs e/p: Data



MUV in +ve ID



MUV in veto



After π^0 tagging and photon veto

Conclusion and next steps

- Conclusion
  - NA62 allows a unique opportunity to measure K_{l3} branching fractions and form factors
  - Reduction of systematics possible due to momentum measurement of incoming and outgoing particles
- Next steps
  - Data/MC studies
  - Explore different combination of cuts/detectors – optimise
  - Non-cut approaches
    - Build a likelihood based on 2 or more variables
    - BDT

Spares

Form factor previous results II

Parameterisations:

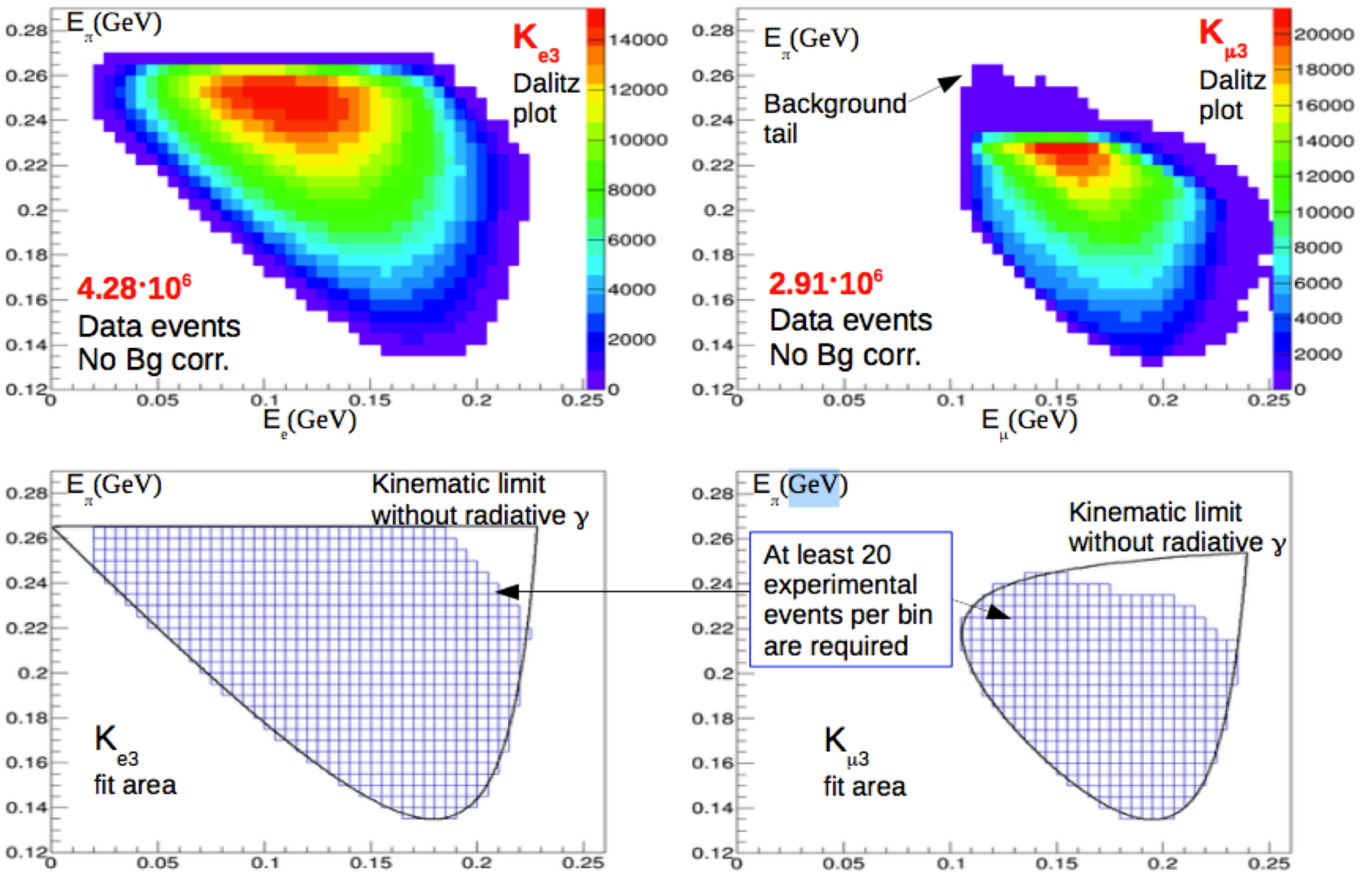
Linear: $\widetilde{f_{+,0}} = 1 + \lambda_{+,0}\left(\frac{t}{m_{\pi^+}^2}\right)$

Quadratic: $\widetilde{f_{+,0}} = 1 + \lambda'_{+,0}\left(\frac{t}{m_{\pi^+}^2}\right) + \lambda''_{+,0}\left(\frac{t}{m_{\pi^+}^2}\right)$

Pole: $\widetilde{f_+} = \frac{m_V^2}{m_V^2 - t}, \widetilde{f_0} = \frac{m_S^2}{m_S^2 - t}$

- Assumes the exchange of vector and scalar resonances K^+ with spin-parity 1⁻/0⁺ and masses m_V/m_S
- $f_+(t)$ described by $K^*(892)$, for $f_0(t)$ no obvious dominance is seen

See Shkarovskiy talk at ICPPA 2017



Form factor previous results

	Quadratic parametrisation (10^{-3})			Pole parametrisation (MeV)		Dispersive parametrisation (10^{-3})	
	$\lambda_{+}^{'}$	$\lambda_{+}^{''}$	$\lambda_{0}^{'}$	M_{V}	M_{S}	Λ_{+}	ln[C]
Central value	23.35	1.73	14.90	894.3	1185.5	22.67	189.12
Statistical error	0.75	0.29	0.55	3.2	16.6	0.18	4.91
Systematic error	1.23	0.41	0.80	5.4	35.3	0.55	11.09
Total error	1.44	0.50	0.97	6.3	35.5	0.58	12.13

See Shkarovskiy talk at ICPPA 2017

V_{us} uncertainty breakdown

Mode	$V_{us} f_{+}(0)$	% error	BR	τ	Δ	I
K_{e3}	0.2171(8)	0.36	0.27	0.06	0.22	0.05
$K_{\mu 3}$	0.2170(11)	0.51	0.45	0.06	0.22	0.06

Uncertainty sources:

- branching ratio measurements (BR)
- lifetime measurements (τ)
- long-distance radiative and isospin-breaking corrections (Δ)
- phase-space integrals from form-factor parameters (*I*)

M. Moulson, Experimental determination of V_{us} from kaon decays, CKM 2016 Proceedings