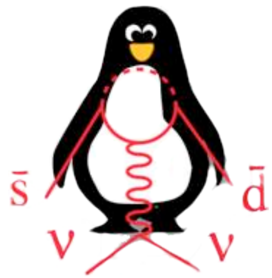
Study of the $K^+ \to e^+ \nu \gamma$ decay in the NA62 experiment at CERN



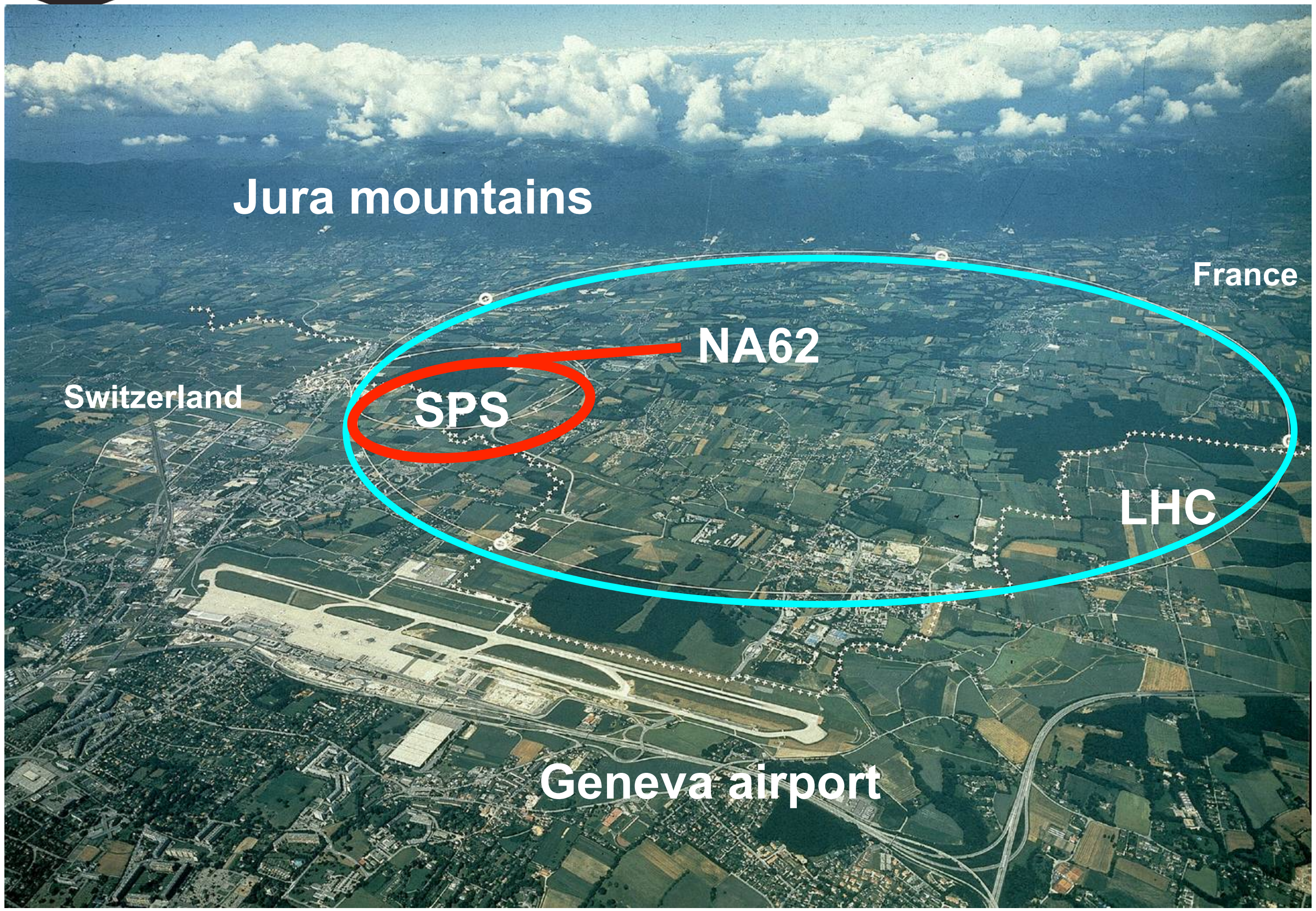
Angela Romano

University of Birmingham

IoP Joint HEPP and APP Meeting 2012
Queen Mary, University of London

- The NA62 collaboration at CERN SPS;
- Kaon leptonic radiative decay: $K^+ \to e^+ \nu \gamma$ ($K_{e2\gamma}$);
- Conclusions.

NA62 experiment at CERN SPS



NA62 (R_K phase)

2007: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$

2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$

(PLB 698 (2011) 105)

Data taking:
- 4 months in 2007
- 2 weeks in 2008: for systematic studies

NA62 ($K^+ \to \pi^+ \nu\bar{\nu}$)

2008 - 2013: design & construction

Start in 2014: $K^+ \to \pi^+ \nu\bar{\nu}$ data taking

The NA62 Collaboration:

Birmingham, **Bristol**, CERN, Dubna, **Glasgow**, Fairfax, Ferrara, Florence, Frascati, IHEP Protvino, INR Moscow, **Liverpool**, Louvain, Mainz, Merced, Naples, Perugia, Pisa, Rome I, Rome II, Saclay, San Luis Potosí, SLAC, Sofia, TRIUMF, Turin.

NA62 (R_K phase) Detector

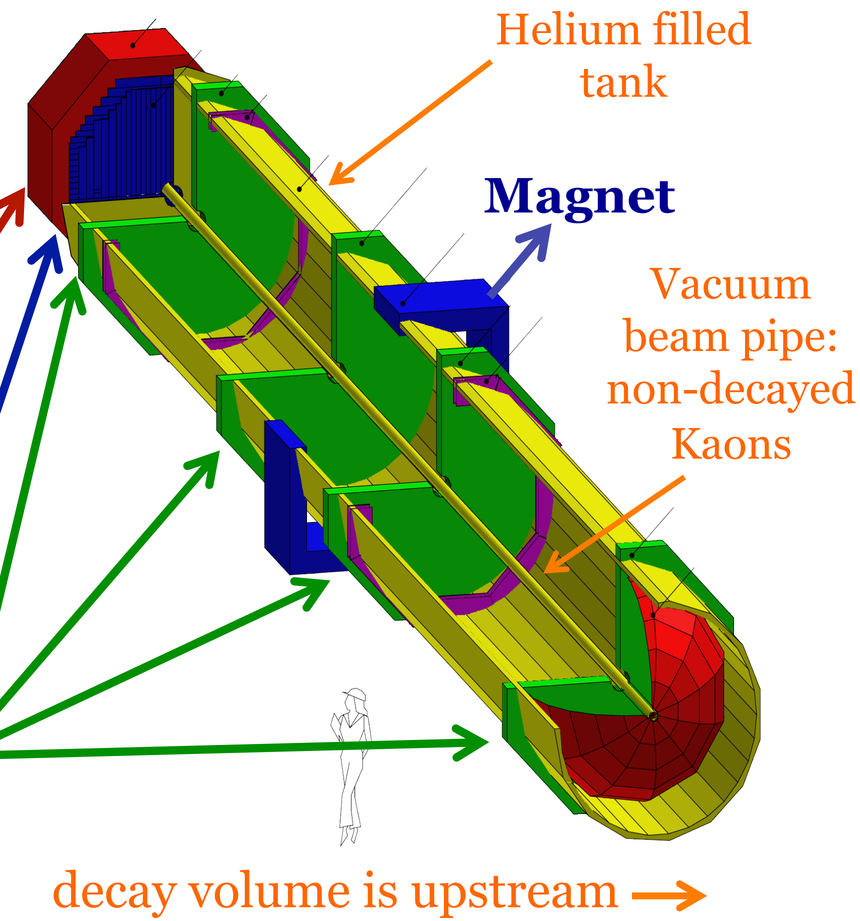
Primary SPS protons (400 GeV/c) ~ **10^{12} per SPS spill**;
Unseparated secondary beam (74 GeV/c): **π/K ~ 10**;
~ 1M kaons per SPS spill;
~ **18%** of kaons decaying in 114m long vacuum tank (decay volume);

<u>Main subdetectors</u>
<u>from its predecessor NA48</u>:

Liquid Krypton EM calorimeter (LKr):
High granularity, quasi-homogeneous;
$\sigma_E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ [GeV]
$\sigma_x=\sigma_y=4.2/\sqrt{E} + 0.6$mm (1.5mm@10GeV)

Hodoscope:
fast trigger, precise time measurement (150ps)

Spectrometer (4 DCHs + Magnet):
4 views/DCH ⇒ high efficiency;
$\sigma_p/p = 0.48\% + 0.009\%\cdot p$ [GeV/c]



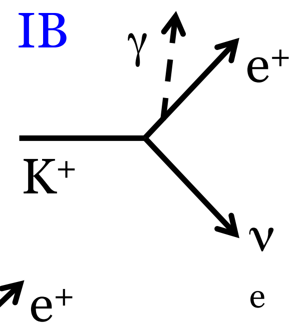
Kaon Leptonic Radiative decay:

$K^+ \to e^+ \nu \gamma$ ($K^+_{e2\gamma}$)

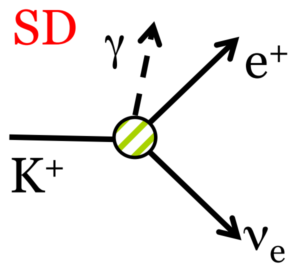
$K^{+}_{e2\gamma}$: Theory

Amplitude M of the decay $K^{+}_{e2\gamma}$ written in terms of three contributions:

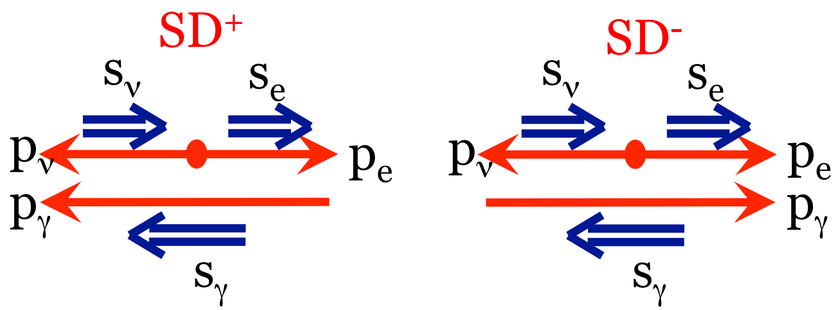
$M = M_{IB} + M_{SD} + M_{INT}$



1. "Inner Bremsstrahlung" (IB) component
   - Photon emitted by e⁺ (external leg);
   - <u>Helicity suppressed</u> (e^+=R, ν=L for m_e->0);
   - α and **(V-A)** structure as in K_{e2};



2. "Structure Dependent" ($SD^{\pm}$) components
   - Photon emitted at the K^+ decay vertex;
   - Two non-interfering contributions: positive & negative γ helicity;
   - <u>No helicity suppressed</u>;
   - **(V±A)** structures contributing;



3. Interference ($INT^{\pm}$) components
   - IB & $SD^{\pm}$ interfering contributions;
   - $M_{INT} \propto (m_e/m_K)^2$;
   - Negligible due to the small electron mass;

$K^+_{e2\gamma}$(SD) : Kinematics

$$\rho(x,y) = \frac{d^2\Gamma(K^+_{e2\gamma})}{dxdy} = \underbrace{\rho_{IB}(x,y)}_{\text{helicity suppressed}} + \boxed{\rho_{SD^\pm}(x,y)} + \underbrace{\rho_{INT^\pm}(x,y)}_{\text{negligible}}$$

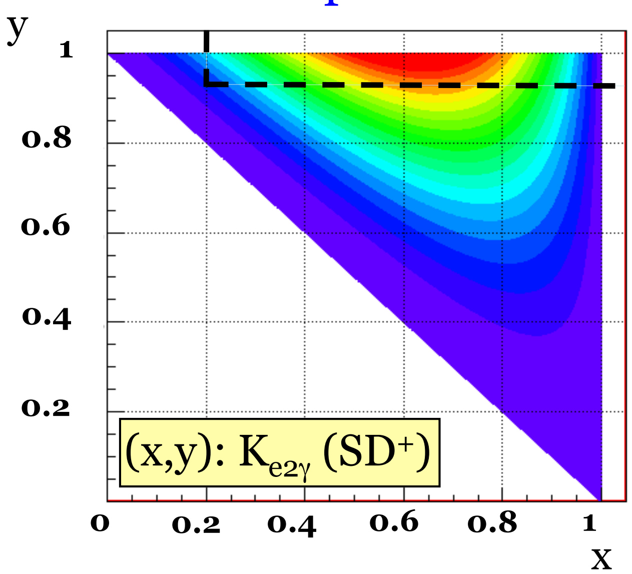
$$x = \frac{2E^*(\gamma)}{M_K}; \qquad y = \frac{2E^*(e)}{M_K};$$

⇨ $E^*(e)$, $E^*(\gamma)$: electron and photon energy in K^+ rest frame

$$\boxed{\rho_{SD^\pm}(x,y)} = \frac{G_F^2 |V_{us}|^2 \alpha}{64\pi^2} M_K^5 [(V+A)^2 f_{SD^+}(x,y) + (V-A)^2 f_{SD^-}(x,y)]$$

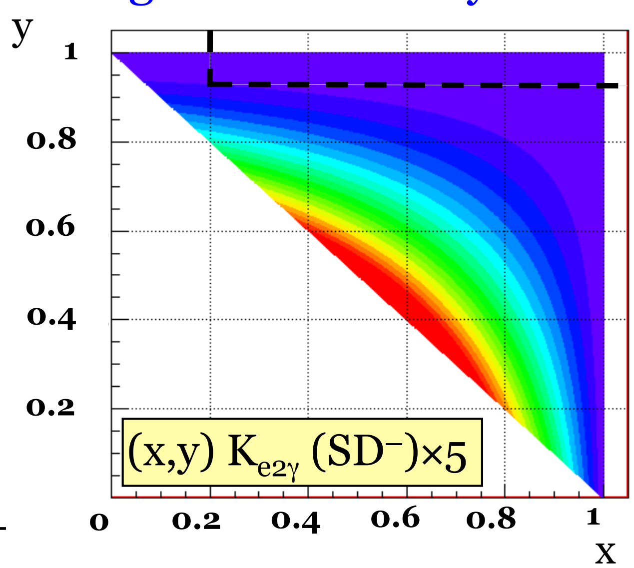
V, A: model-dependent vector and axial-vector effective couplings

SD⁻ component is smaller and beyond the kinematical region of the analysis



$$f_{SD^+}(x,y) = (1-x)(x+y-1)^2$$

$$f_{SD^-}(x,y) = (1-x)(1-y)^2$$



$K^{+}_{e2\gamma}$ (SD⁺): Motivation & Goal

- SM Test to the Next-to-Leading Order (NLO) in chiral expansions (ChPT $O(p^4)$, ChPT $O(p^6)$) ; (NPB396 (1993) 81)
- Model independent extractions of theoretical Form Factors (FFs);
- Independent measurement with a different technique wrt the one performed by KLOE; (EPJC64 (2009) 627)
- "Key" ingredient for the estimate of the R_K background; (PLB B698 (2011) 105)

<u>Analysis Goals</u>:

1. Model-independent Decay rate $d^2\Gamma/dxdy$ & Branching Ratio BR($K^{+}_{e2\gamma}$) in the kinematic region of interest;
2. Parameters of the model: SD^{+} Form Factors; (precision test for ChPT $O(p^6)$);

$K^{+}_{e2\gamma}(SD^{+})$: Experimental Status & Background

KLOE result (PDG 2010):

- ✓ N_{evt}=1484 (10MeV < E*(γ) < 250MeV, p*(e) > 200 MeV/c)
- ✓ $\Gamma(K_{e2\gamma})/\Gamma(K_{\mu 2}) = (1.438 \pm 0.066_{stat} \pm 0.013_{syst})\times 10^{-5}$
- ✓ $|V+A| = 0.125 \pm 0.007_{stat} \pm 0.001_{syst}$

KLOE measurement of V+A leads to
$BR(SD^{+}$, full phase space$) = (1.37\pm0.06)\times 10^{-5}$
(EPJC64 (2009) 627)

Main Backgrounds:

- ✓ $K^{+}\to e^{+}\pi^{0}\nu$ (K_{e3}) decay: $\Gamma(K_{e3})/\Gamma(K_{e2\gamma}) \sim 3000$;

  K_{e3} can mimic $K_{e2\gamma}$ decay if the positron is energetic and one photon from the $\pi^{0}\to\gamma\gamma$ decay is undetected;
- ✓ $K^{+}\to\pi^{+}\pi^{0}$ ($K_{2\pi}$) decay: $\Gamma(K_{2\pi})/\Gamma(K_{e2\gamma}) \sim 12000$;

  $K_{2\pi}$ can mimic $K_{e2\gamma}$ decay if the pion is mis-ID as a positron ($\sim10^{-3}$ probability) and one photon from the $\pi^{0}\to\gamma\gamma$ decay is undetected;

$K^+ \to e^+\nu\gamma$ (SD^+)

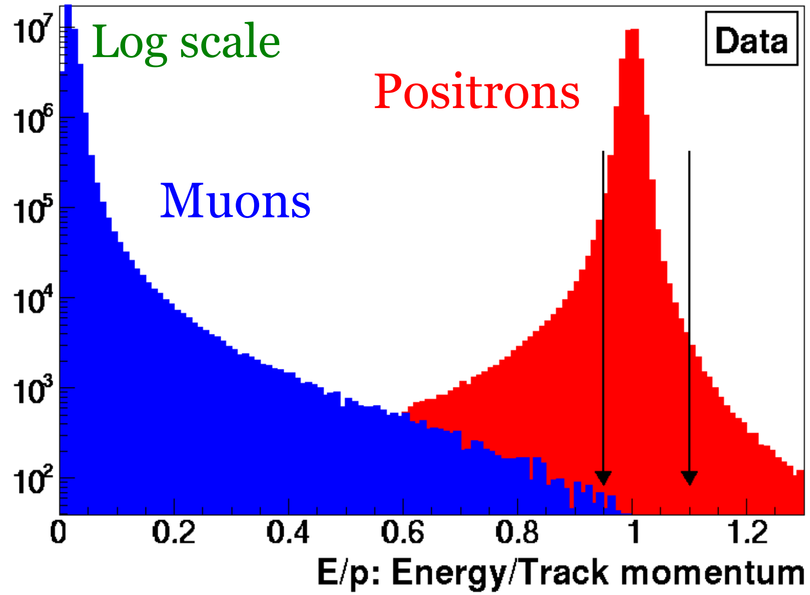
Analysis Strategy

$K^+_{e2\gamma}$ (SD⁺) : Event Selection

Positron Selection:

Common part with Ke2:

- one reconstructed track;
- positive charge;
- geometrical acceptance cuts;
- K decay vertex: closest distance of approach between track & kaon axis;
- $0.95 < E/p < 1.10$ (positron);
- track momentum: $10GeV/c < p < 55GeV/c$

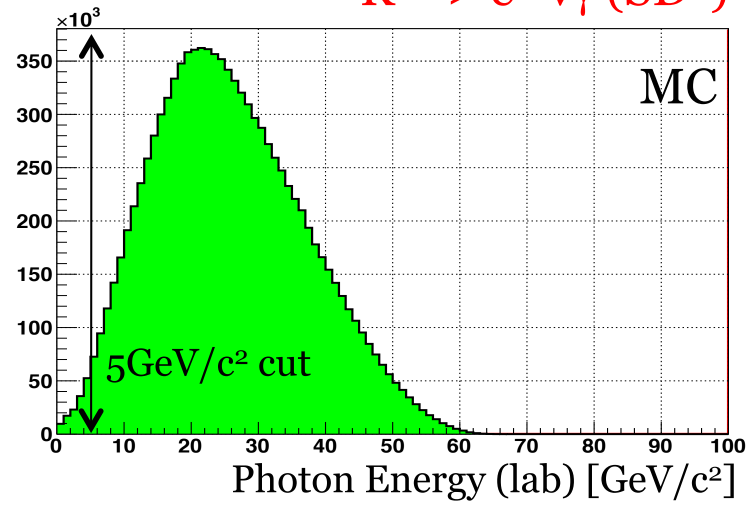


Photon Selection:

Specific part for radiative decay:

- one extra LKr energy deposition cluster;
- isolated and good;
- LKr geometrical acceptance cuts;
- in time with the track;
- photon energy: $E > 5\ GeV/c^2$

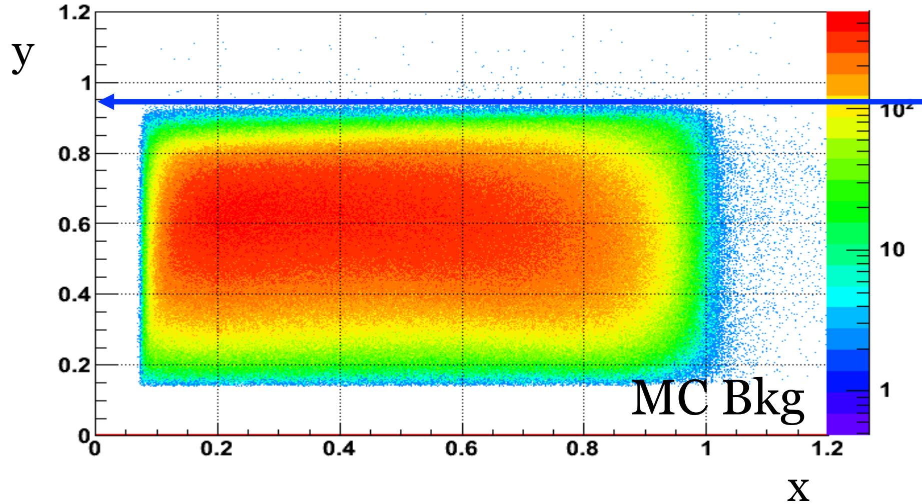
$K^+ \to e^+ \nu\gamma$ (SD⁺)



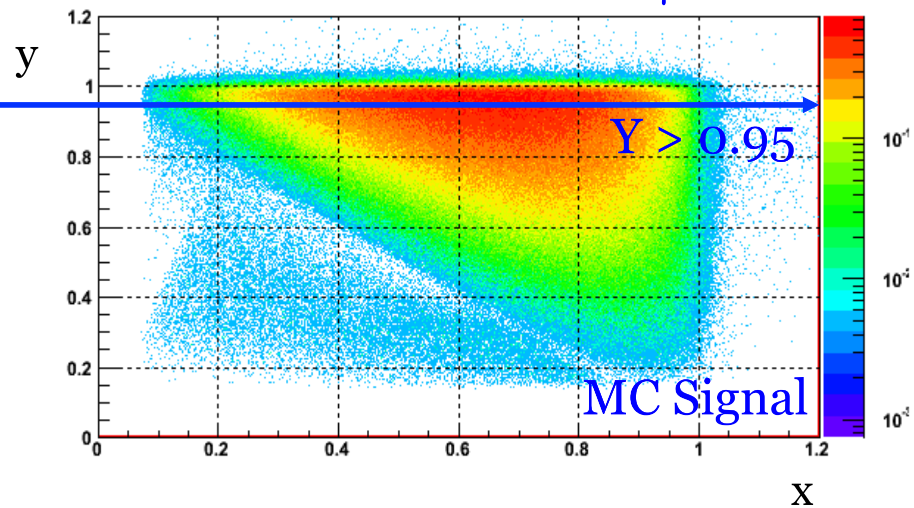
Angela Romano

Reconstructed Signal - Bkg

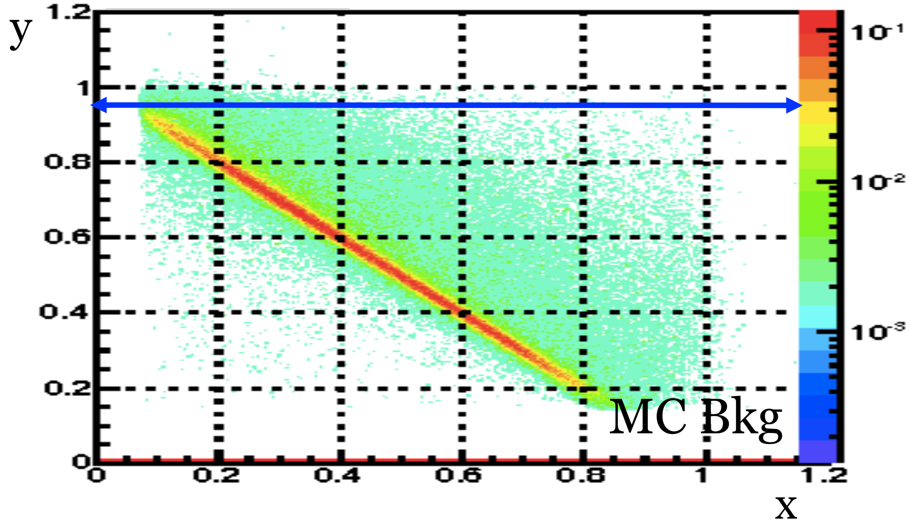
$K^+ \to e^+ \pi^0 \nu$ (K_{e3})



$K^+ \to e^+ \nu \gamma$ (SD^+) ($K_{e2\gamma}$)



$K^+ \to e^+ \nu \gamma$ (IB)

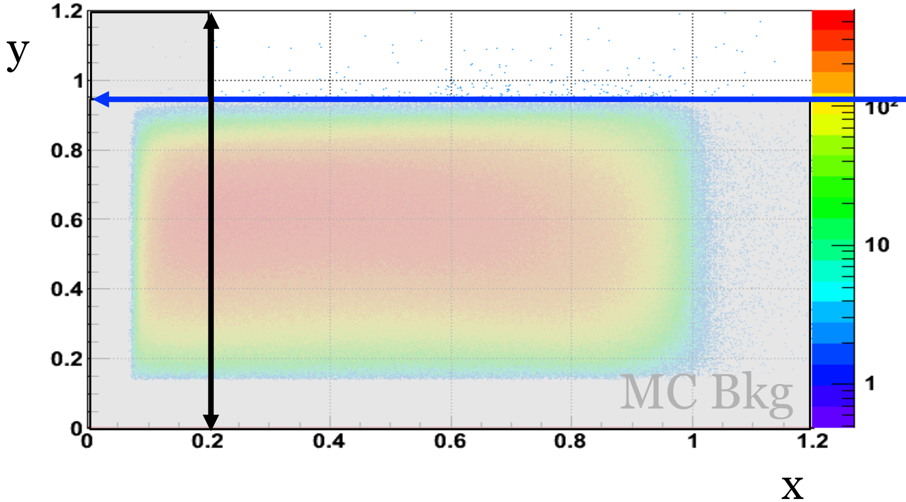


$$x = \frac{2E^*(\gamma)}{M_K}; \qquad y = \frac{2E^*(e)}{M_K};$$

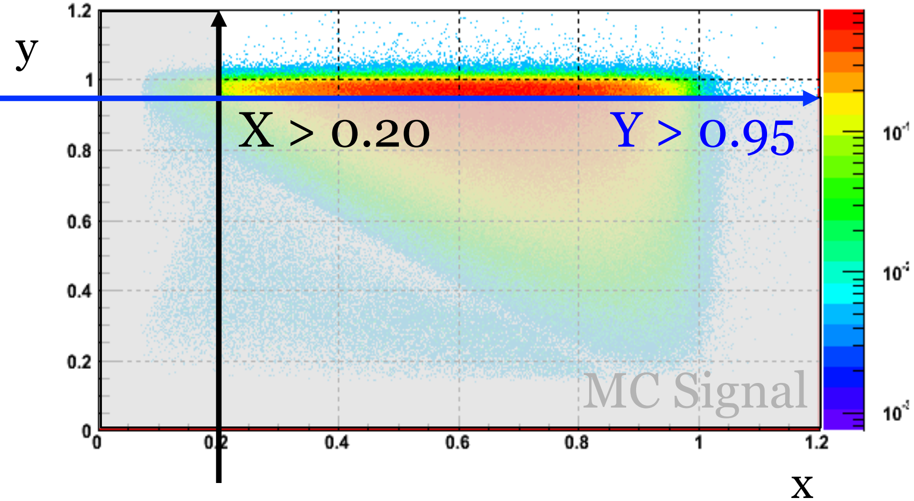
$$y^{max}_{K_{e3}} = 0.923 < y^{max}_{K_{e2\gamma}} = 1$$

Reconstructed Signal - Bkg

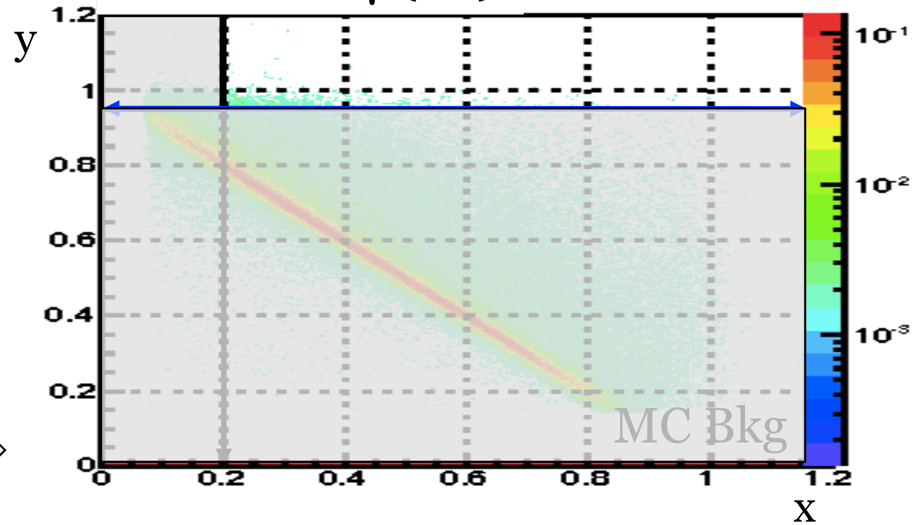
$K^+ \rightarrow e^+ \pi^0 \nu$ (K_{e3})



$K^+ \rightarrow e^+ \nu \gamma$ (SD^+) ($K_{e2\gamma}$)



$K^+ \rightarrow e^+ \nu \gamma$ (IB)



$$y^{max}_{K_{e3}} = 0.923 < y^{max}_{K_{e2\gamma}} = 1$$

$$x > 0.20; \quad y > 0.95;$$

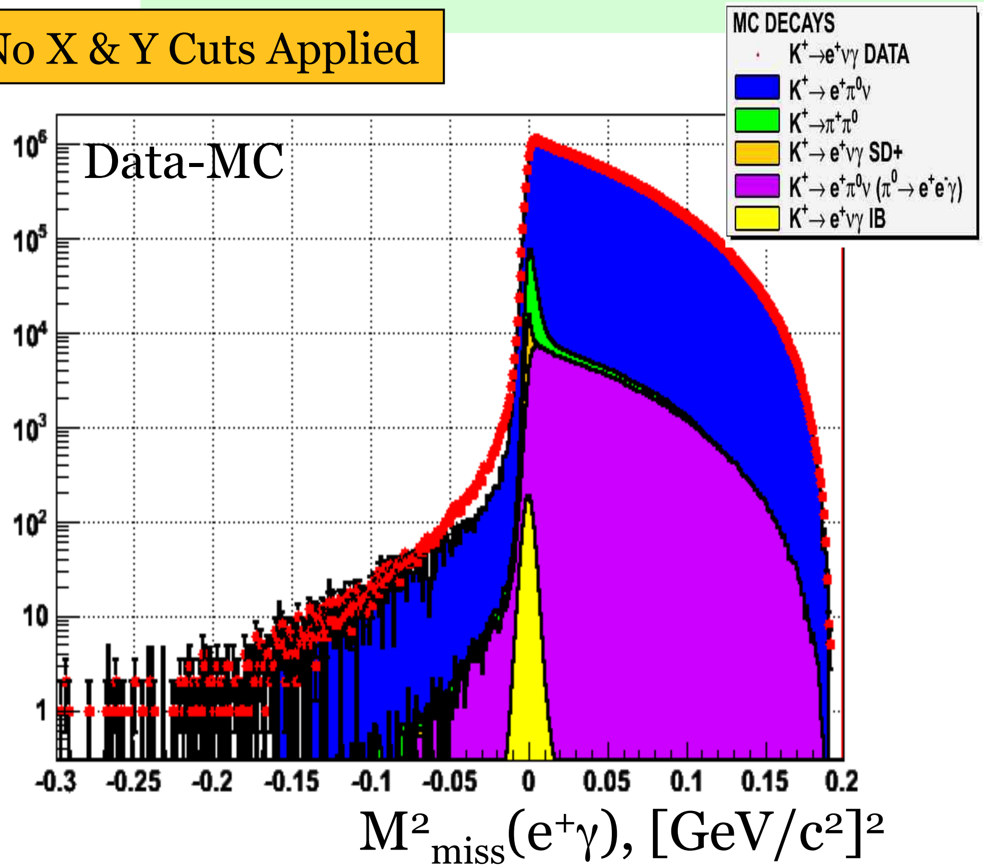
The x cut has been optimised for minor sources of background;

$K^{+}_{e2\gamma}(SD^{+})$: Partial (40%) Data Set

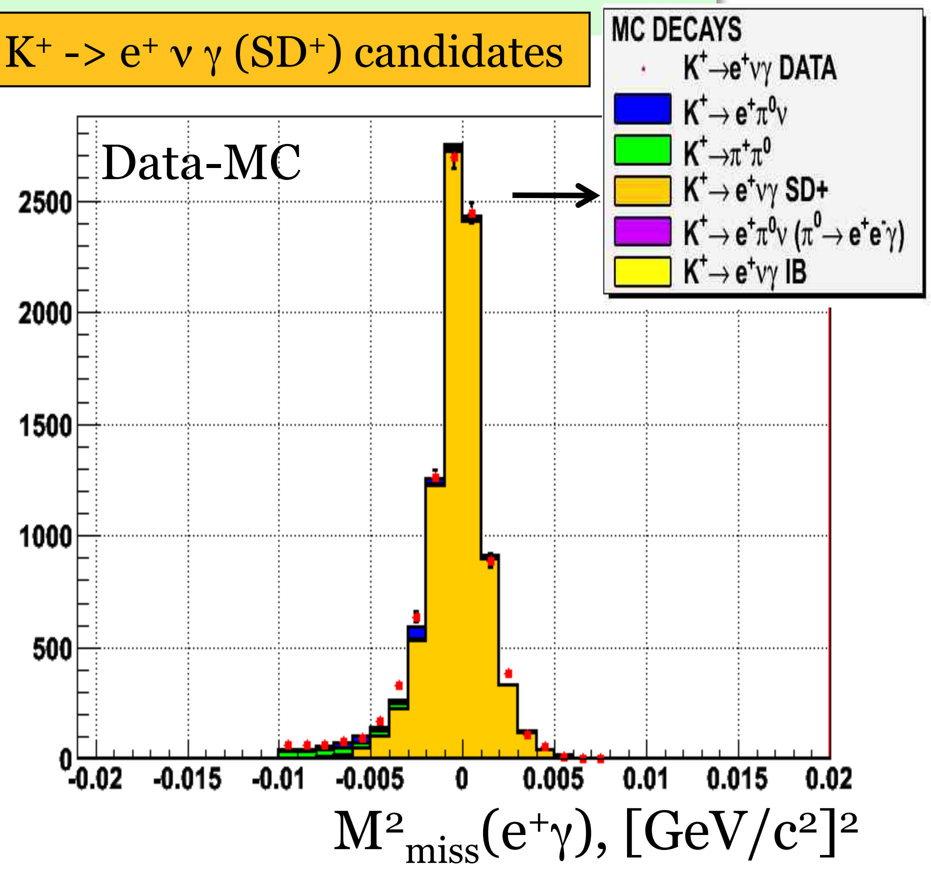
Kinematic identification:

- Three body decay: $M^2_{miss}(e^+\gamma) = |(P_{K^+} - P_{e^+} - P_{\gamma})^2| < 0.01\ GeV^2/c^4$

No X & Y Cuts Applied



K+ -> e+ ν γ (SD+) candidates



$Acc(K^{+}_{e2\gamma}) = N^{MC}_{final}(K^{+}_{e2\gamma})/N^{MC}_{TOT}(K^{+}_{e2\gamma})$

$Acc(K^{+}_{e2\gamma}) \sim 7\%$

~ 10k $K^{+}_{e2\gamma}(SD^{+})$ candidates

Bkg/Data ~ 5% (mainly K_{e3})

Form Factors Fit

A χ^2 fit has been performed to the measured x spectrum using the distribution expected from the ChPT models;

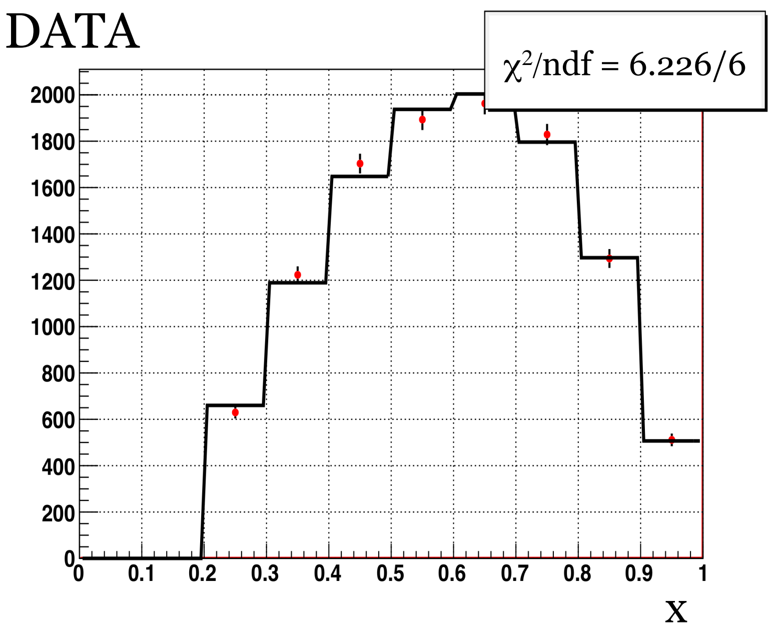
$$\frac{d^2\Gamma(K^+ \to e^+\nu\gamma)}{dxdy} = \frac{G_F^2 \sin^2\theta_c M_K^5 \alpha}{64\pi^2}(V+A)^2(1-x)(x-y-1)^2$$

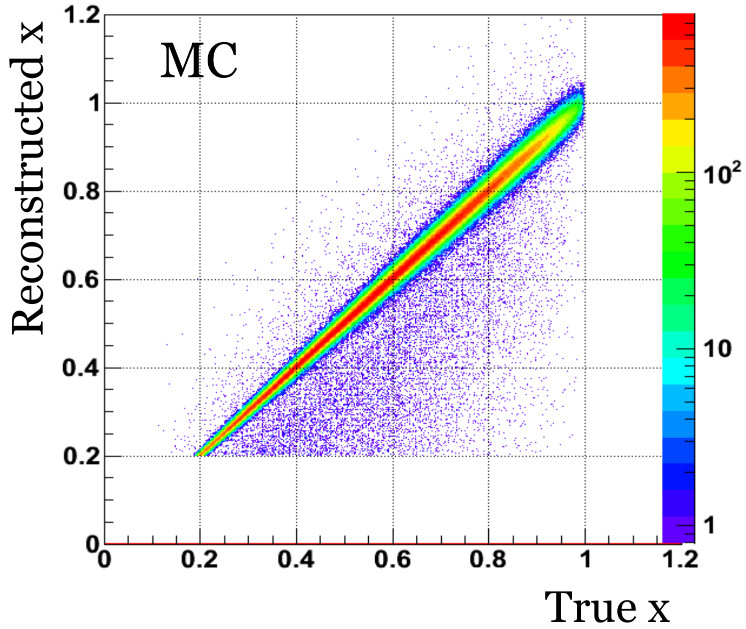
Axial and Vector effective couplings used:

$A=0.034$, as given by ChPT $O(p^6)$; (PRD77 (2008) 014004)

$V=V_0(1+\lambda(1-x))$; (EPJC64 (2009) 627)

Smearing effects due to the detector acceptance, resolution and mis-reconstruction are convoluted with the theoretical distribution;





Fit Results (40% data set)

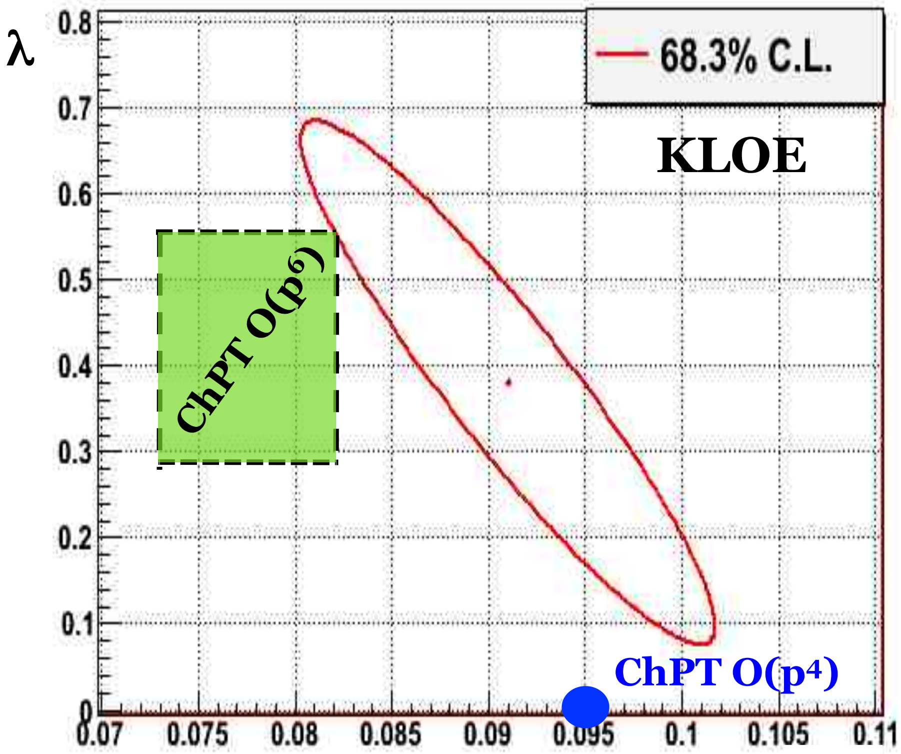
Form Factor parameters with their uncertainties and the correlation coefficient represented with the standard error ellipse (68% C.L.)

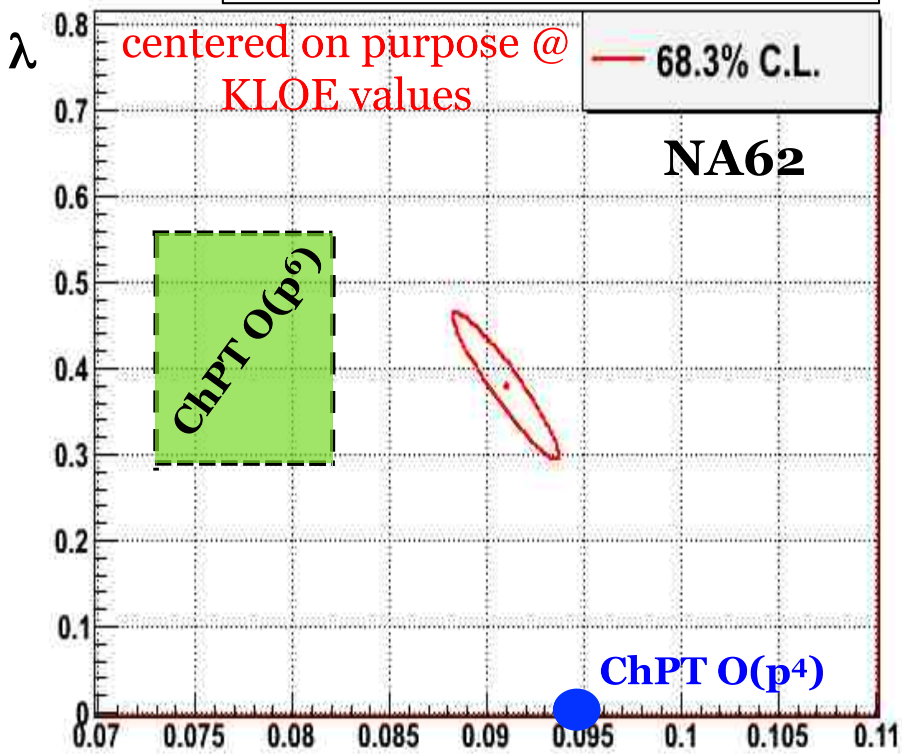
Analysis phase space region (K rest frame):

KLOE: $p_e > 200 MeV/c$, $E_\gamma > 10 MeV/c^2$;

NA62: $E_e > 235 MeV/c^2$, $E_\gamma > 50 MeV/c^2$;

NA62/KLOE statistics ~ 10
NA62/KLOE ellipse axis ~ 33%





KLOE: Dominated by stat errors V_0

(EPJC64 (2009) 627), (NPB684(2004281))

NA62: V_0

Significant systematic uncertainty expected

Conclusions

- A comprehensive study of the process $K^+ \to e^+\nu\gamma(SD^+)$ is being performed;
  - ~10k candidates, ~5% bkg contamination (40% of NA62 data set);
- Total uncertainty is dominated by the background subtraction (mainly K_{e3});
  - signal kinematic region is affected by non gaussian tails above the K_{e3} kinematic endpoint: $y^{max}_{K_{e3}} = 0.923 < y^{max}_{K_{e2\gamma}} = 1$
- Model independent BR(SD^+, NA62 phase space) can be evaluated with a ~2% precision;
- SD^+ FFs and extraction of V,A effective coupling:
  - KLOE results are in agreement with the expectations from ChPT and confirm at ~2σ the presence of a slope in V (as predicted in $O(p^6)$);
  - NA62 results will get advantages from the large data sample providing that the background is kept reasonably under control.

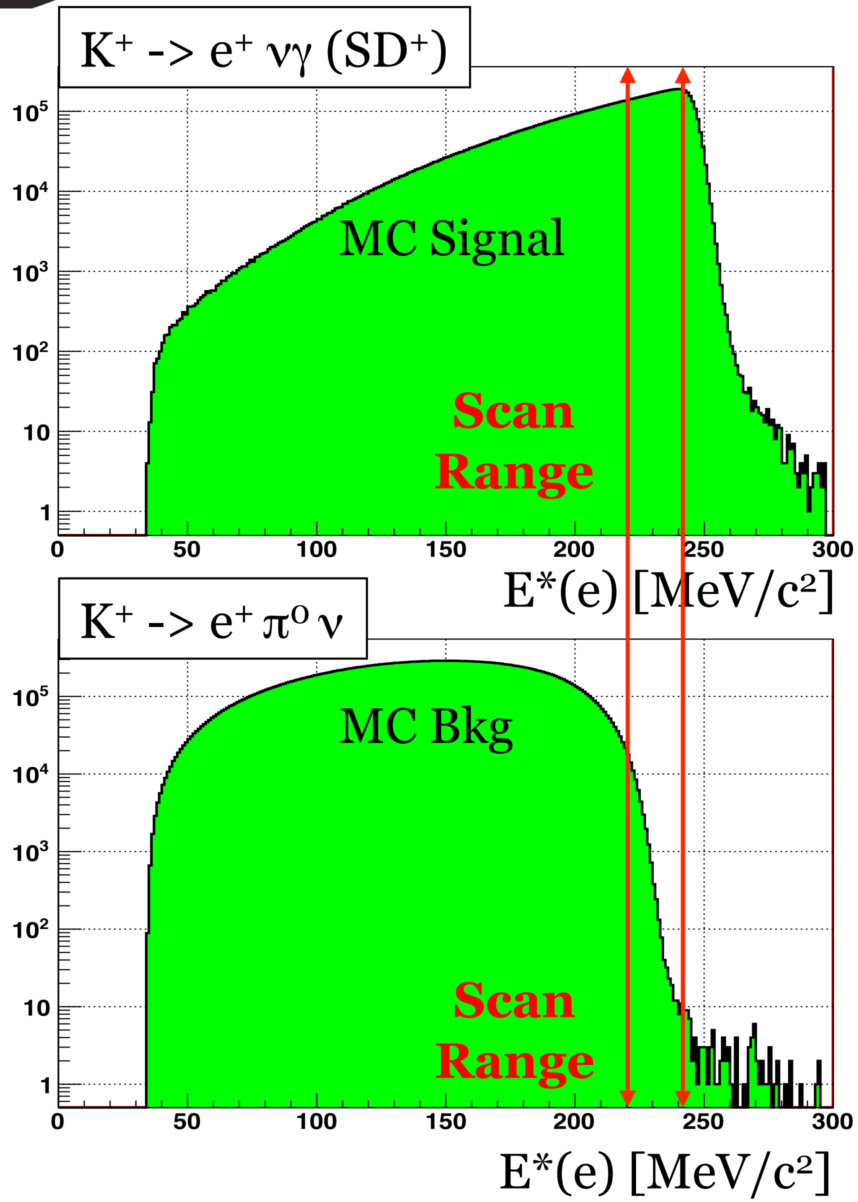
Spares

IoP Joint HEPP and APP Meeting 2012
Queen Mary, University of London

Next Steps..

- A detailed study of backgrounds to $K^+ \to e^+\nu\gamma(SD^+)$:
  - Background contamination and associated uncertainty;
- Non gaussian tails of multiple scattering of the track in the material on the beam line affecting the analysis:
  - multiple scattering being simulated with several models;
- Systematic uncertainties to be addressed:
  - Trigger efficiency for backgrounds with lost photons;
- FFs Fit optimization:
  - Fit parameters under control;
  - Stability checks wrt the variation of all analysis cuts.
- Combined analysis on the full NA62 data set;

Kaon Rest Frame Kinematics



Electron Energy in Kaon Rest Frame $E^*(e)$ [MeV/c²]

Used to reject background coming from $K^+ \to e^+ \pi^0 \nu$ decay channel.

To decide for a lower CUT value a scan of E^*_{min} was performed.

Looking at the Electron Energy distributions in the Kaon Rest the **scan range** was set between:

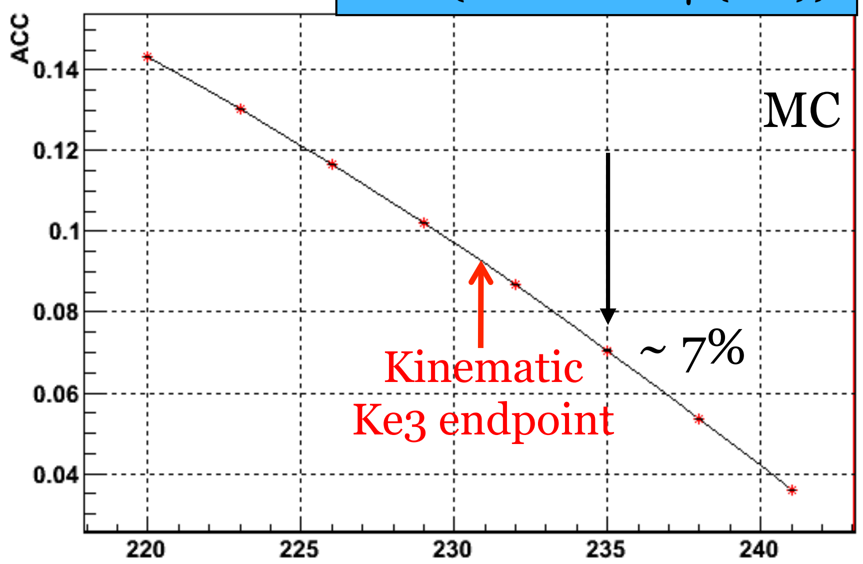
(220 < E*min(e) < 241) MeV/c²

Kaon Rest Frame Kinematics

Acceptance: Acc (i) = $N_{final}(i)/N_{TOT}(i)$ where $N_{final}(i)$ are N(i) which pass the selection

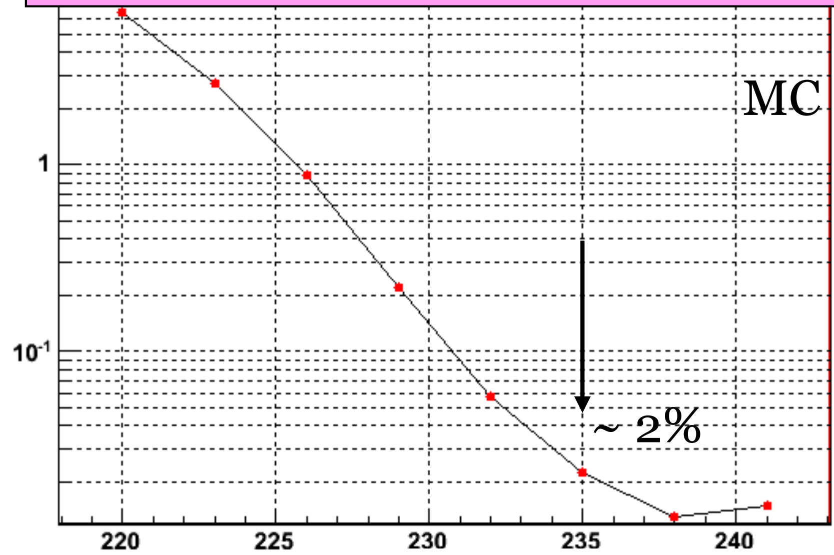
Background-Signal ratio:
$B(j)/S(i) = N_{final}(j)/N_{final}(i)$,
- j is the background channel
- i is the signal channel

Acc ($K^+ \to e^+ \nu\gamma$ (SD))



$E^*_{min}(e)$ cut [MeV/c²]

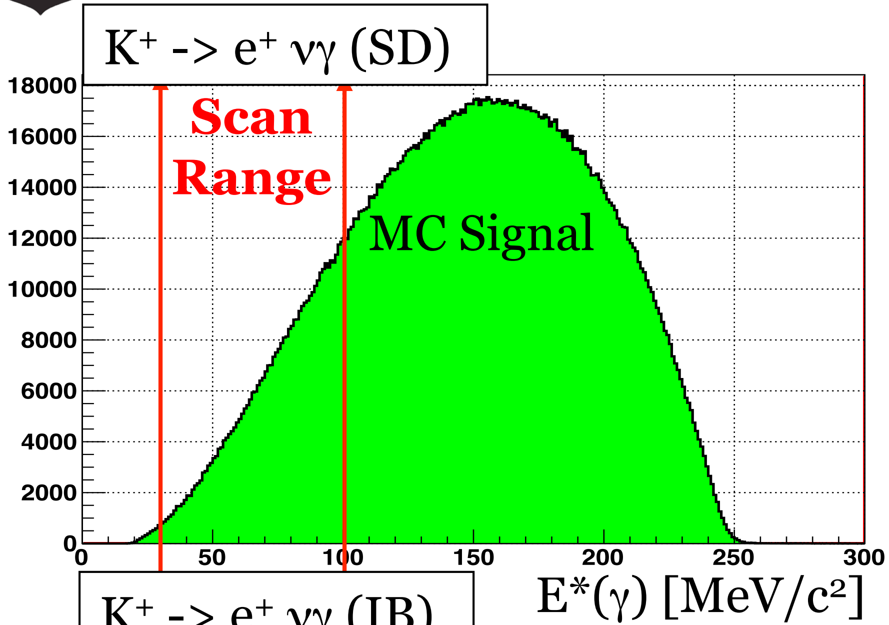
B ($K^+ \to e^+ \pi^0 \nu$)/ S($K^+ \to e^+ \nu\gamma$ (SD))

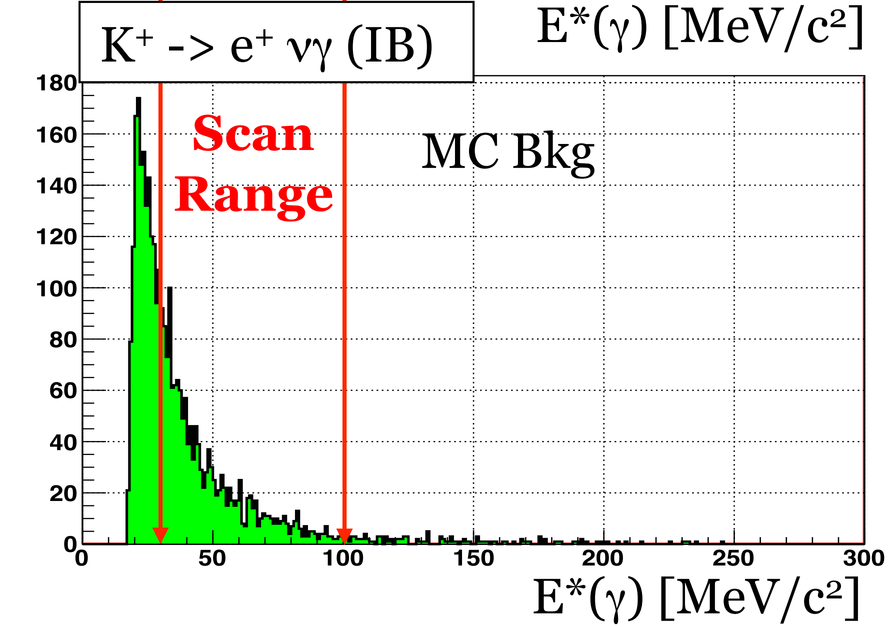


$E^*_{min}(e)$ cut [MeV/c²]

Kaon Rest Frame Electron Energy lower cut: $E^*_{min}(e) = 235$ MeV/c²

Kaon Rest Frame Kinematics





Photon Energy in Kaon Rest Frame $E^{*}(\gamma)$ [MeV/c^2]

Used to reject background coming from $K^+ \to e^+ \nu\gamma$ (IB) decay channel

To decide for a lower CUT value a scan of E^{*}_{min} was performed.

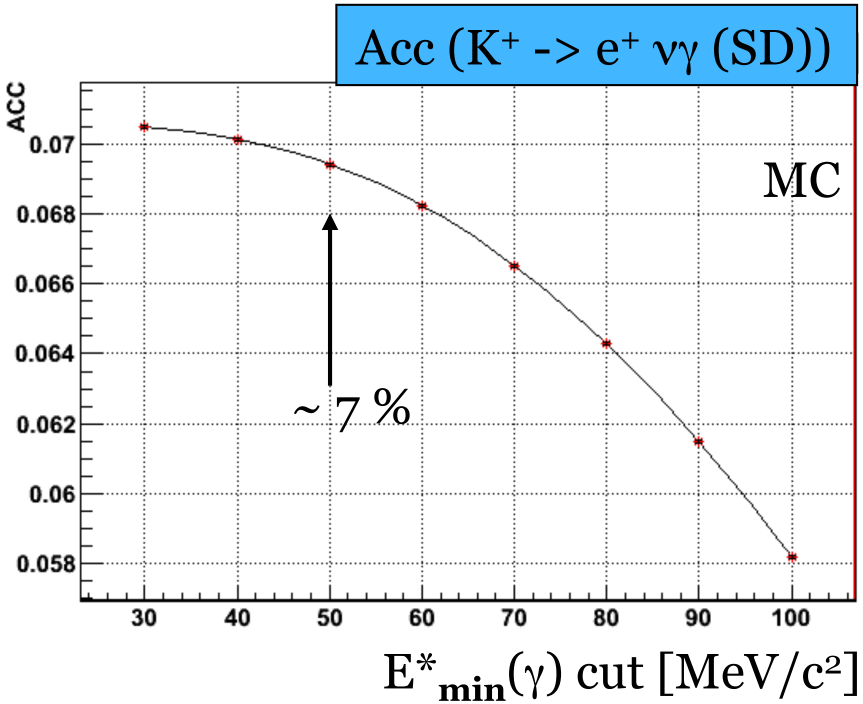
Looking at the Photon Energy distributions in the Kaon Rest Frame the **scan range** was set between:

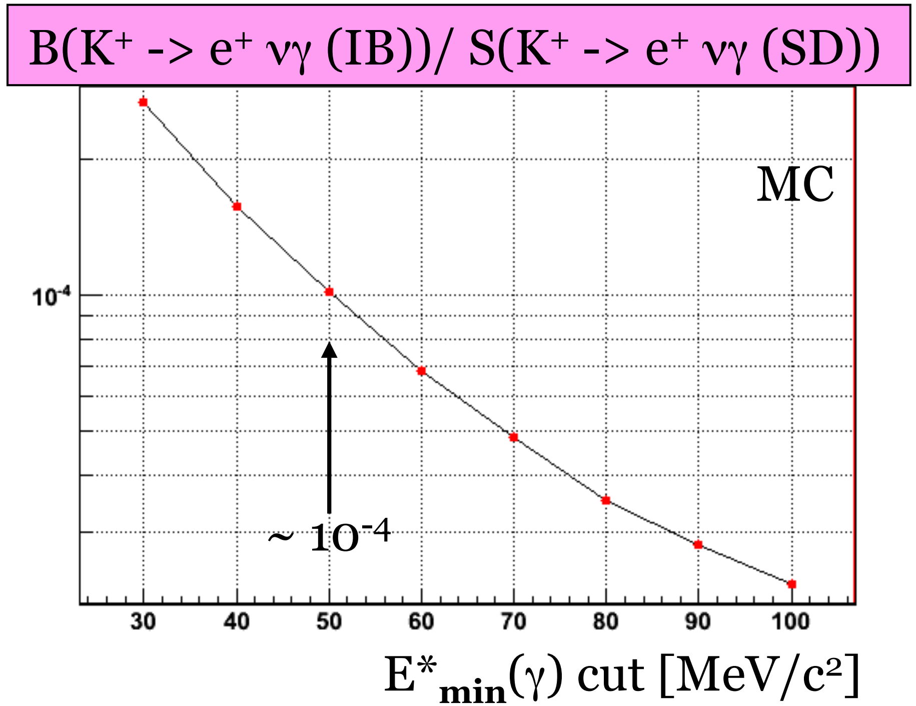
$(30 < E^{*}min(\gamma) < 100)\ MeV/c^2$

Kaon Rest Frame Kinematics

Acceptance: Acc (i) = $N_{final}(i)/N_{TOT}(i)$
where $N_{final}(i)$ are N(i) which pass the selection

Background-Signal ratio:
$B(j)/S(i) = N_{final}(j)/N_{final}(i)$,
- j is the background channel
- i is the signal channel

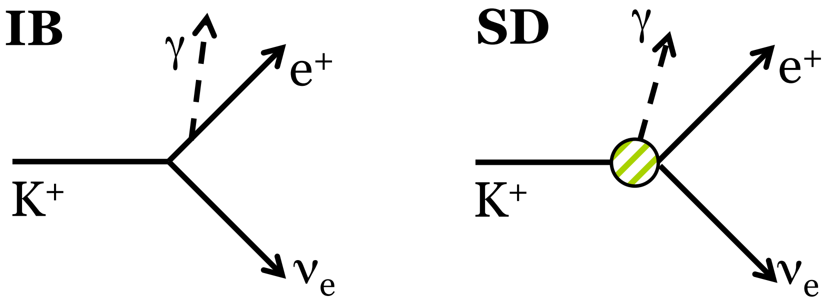




Kaon Rest Frame Photon Energy lower cut: $E^*_{min}(\gamma)$ = 50 MeV/c²

Radiative $K^+ \to e^+\nu\gamma$ process

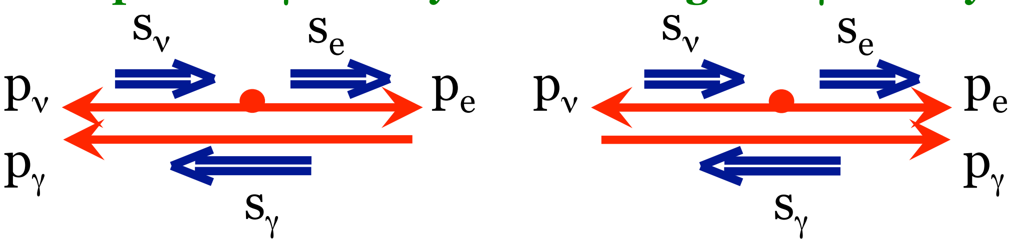
R_K is inclusive of IB radiation by definition.
SD radiation is a background. INT is negligible.



SD radiation is not helicity suppressed.
KLOE measurement of the form factor leads to
BR(SD^+, full phase space) = $(1.37\pm0.06)\times10^{-5}$.
(EPJC64 (2009) 627)

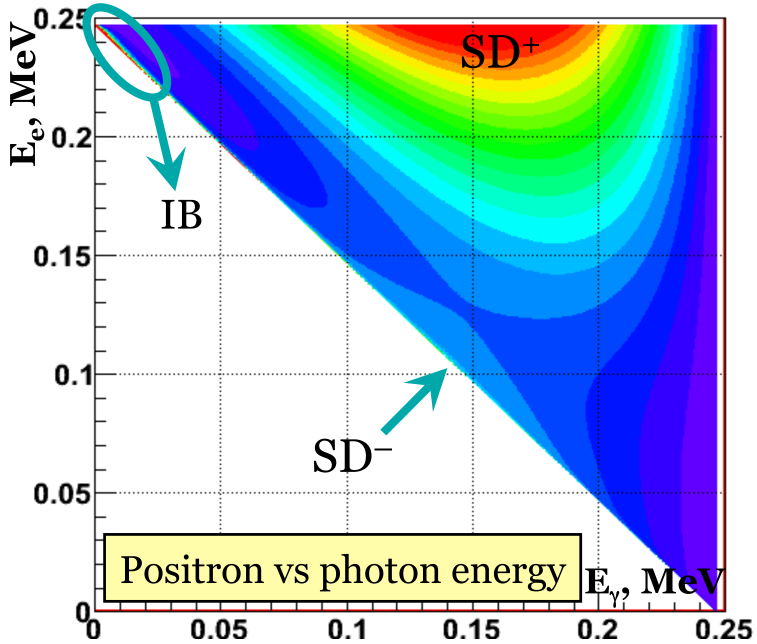
SD bkg ~4 times larger for Pb data samples than for NoPb

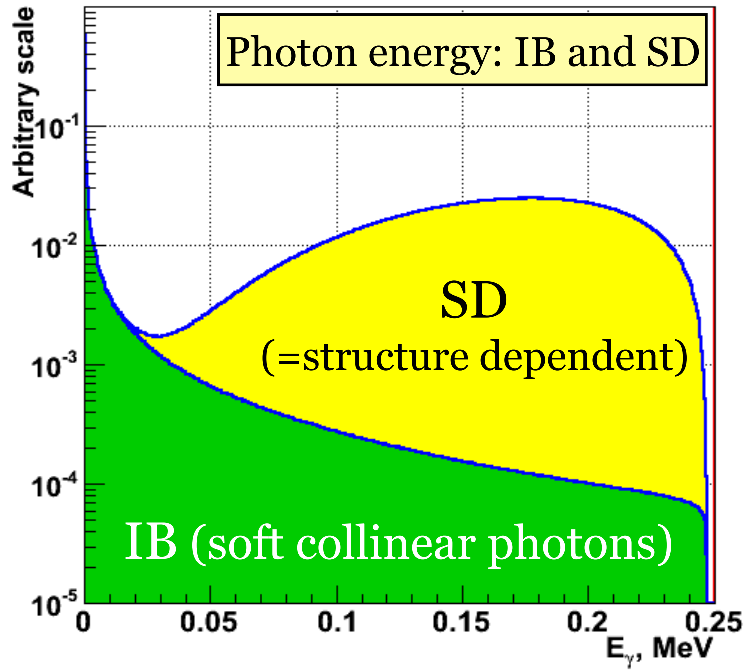
SD^+: positive γ helicity **SD^-: negative γ helicity**



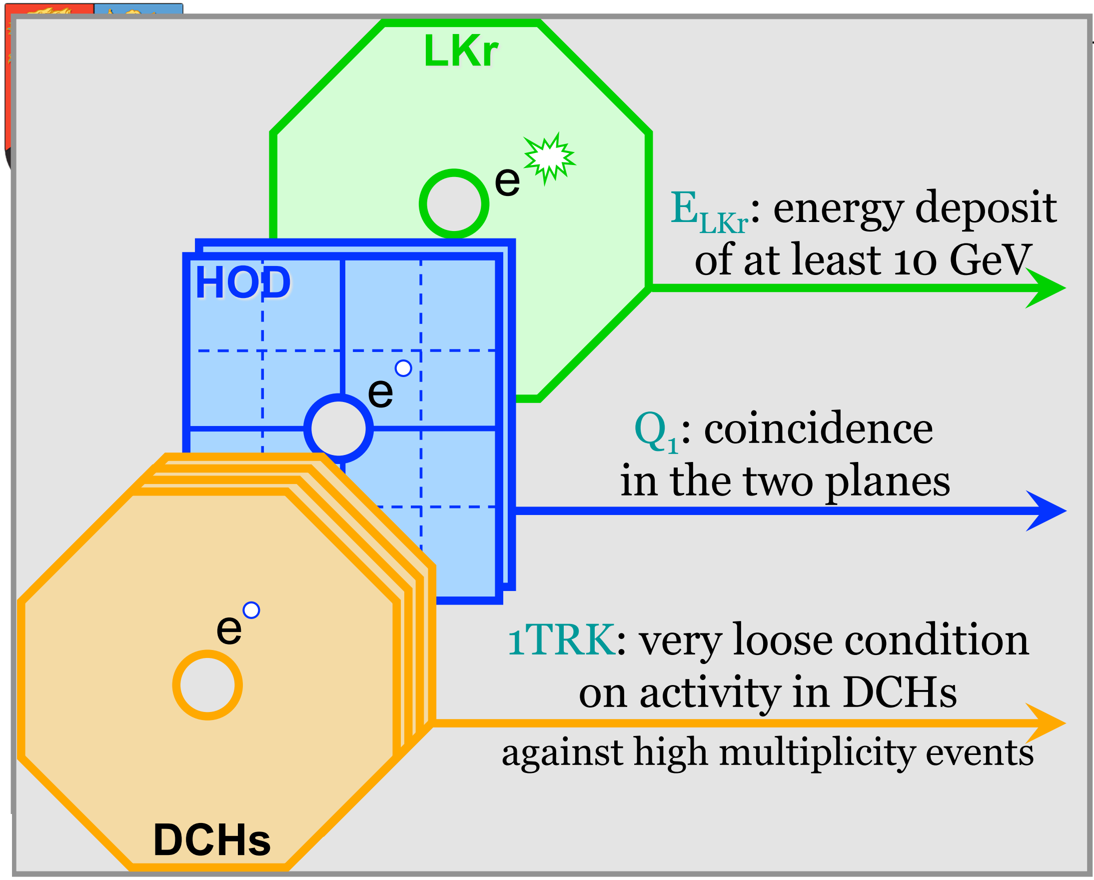
Result: $B/(S+B) = (2.60\pm0.11)\%$

BR($K_{e2\gamma}$ (SD^+)) measurement being performed with same data samples: ~10K candidates, ~5% backgrounds.





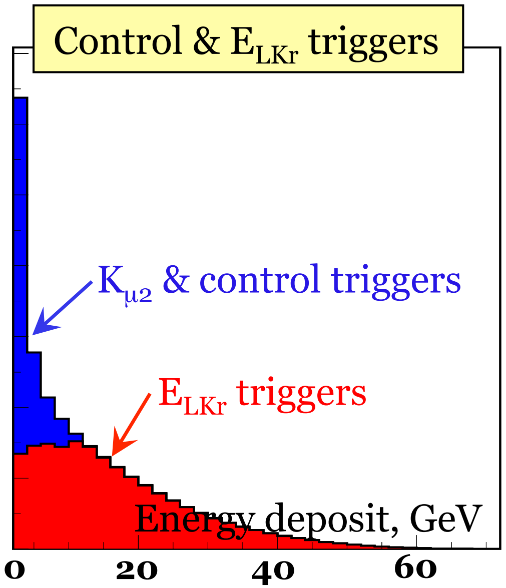
Trigger Logic

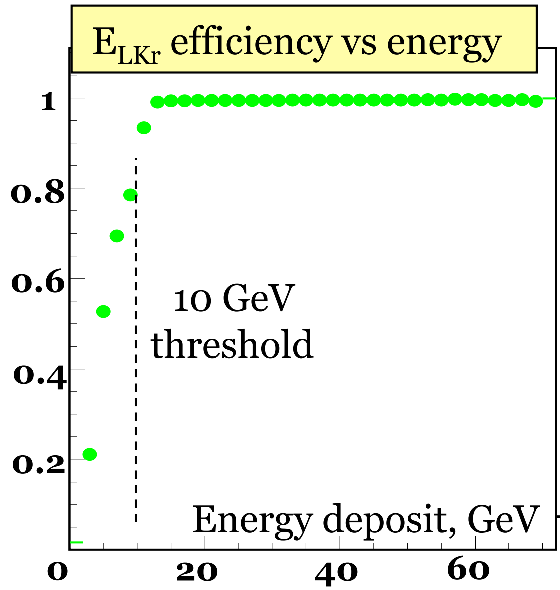


Minimum bias
(high efficiency, but low purity)
trigger configuration used

K_{e2} condition: $Q_1 \times E_{LKr} \times 1TRK$.
Purity ~10^{-5}.

$K_{\mu2}$ condition: $Q_1 \times 1TRK/D$,
downscaling (D) 150.
Purity ~2%.

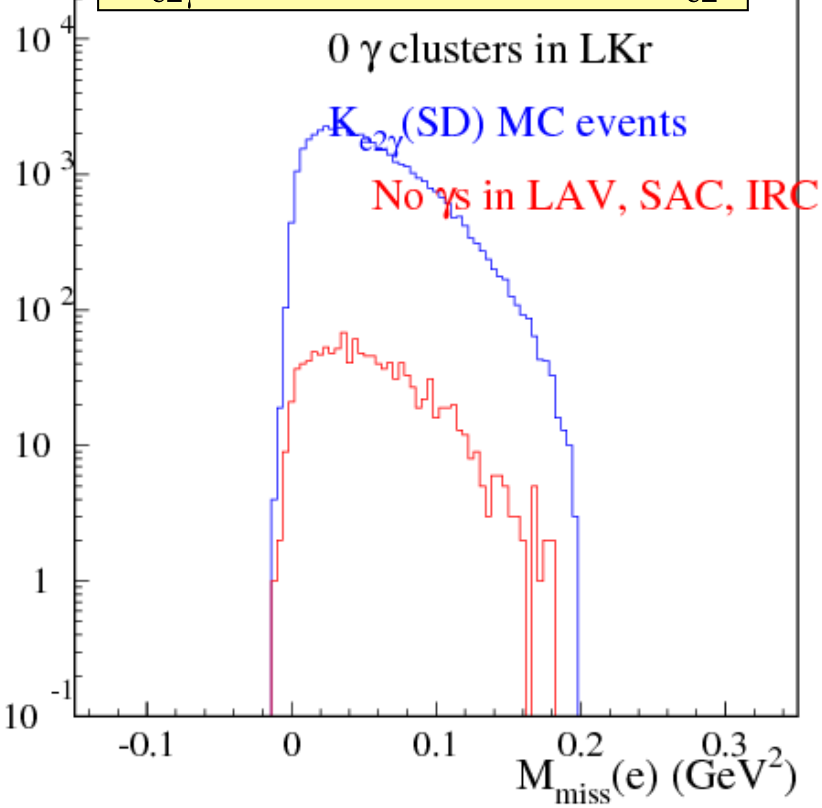




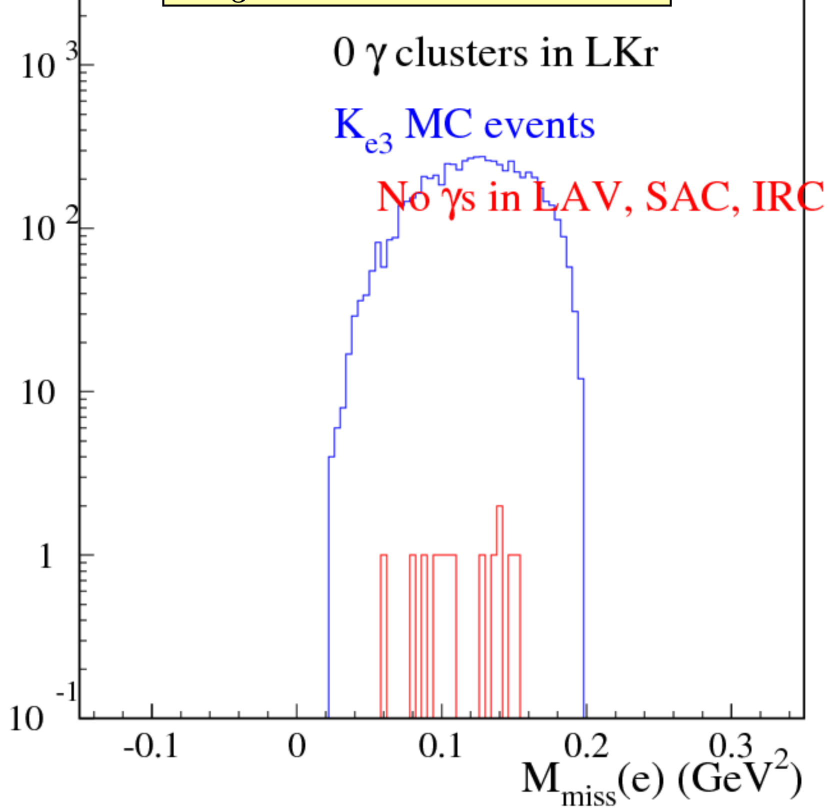
- Efficiency of K_{e2} trigger: monitored with $K_{\mu2}$ & other control triggers.
- E_{LKr} inefficiency for electrons measured to be (0.05±0.01)% for p_{track}>15 GeV/c.
- Different trigger conditions for signal and normalization!

$K_{e2\gamma}$ (SD), K_{e3} suppression

$K_{e2\gamma}$ (SD$^+$) MC selected as K_{e2}



K_{e3} MC selected as K_{e2}



$K_{e2\gamma}$ (SD$^+$) sample reduced by a factor of 35

K_{e3} sample reduced by a factor of 500

Rejection provided by the new veto detectors is excellent for K_{e2} analysis

K_{e2} sample untouched by the veto requirement