Search for Structure Dependent Components of Radiation in $K^+ \to \pi^0 e^+ \nu\gamma$ decay

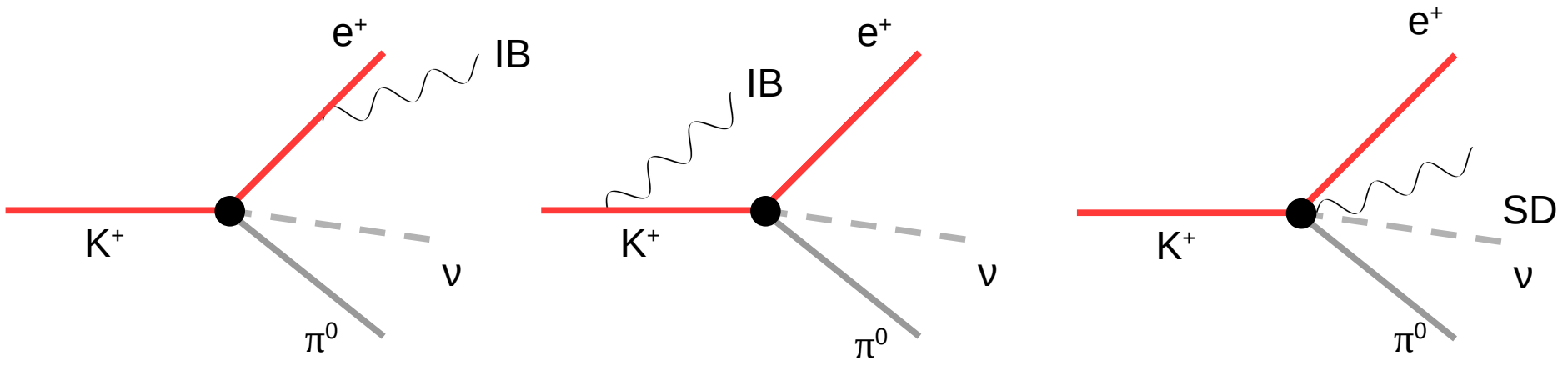
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on behalf of OKA collaboration

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Radiative Decay = Internal Bremsstrahlung (IB) + Structure Dependent (SD)



Only the SD part contains genuinely new information on the photon coupling to intermediate hadronic states and can potentially reveal

new physics

Small: SD ~ 1% BR

Calculated with Chiral Perturbation Theory ChPT

J. Bijnens, G. Ecker, J. Gasser. The DAΦNE Physics Handbook 26 Nov 1992, pp.145-183}

Current upper limit $K^+ \to \pi^0 e^+ \nu\gamma$ $BR_{SD} < 5.3 \times 10^{-5}$ *(PDG)*

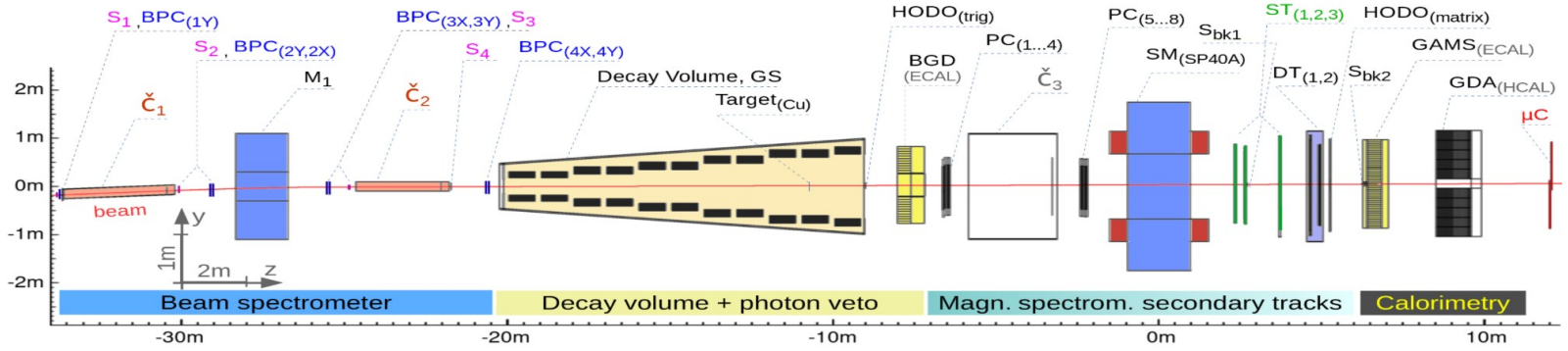
We can improve considerably Expected $\sim 3 \times 10^{-6}$

$BR_{SD} < 5.3 \times 10^{-5}$ obtained from 1-d distribution of ~ 200 decay events

V.N. Bolotov et al. Sov. J. Nucl.Phys. 44 (1986), pp.108-116

We have 15 times more

OKA detector



1. Beam spectrometer: 1mm pitch BPC ~1500 channels; Sc and C counters
2. Decay volume with Veto system:
   L=11m; Veto: 670 Lead-Scintillator sandwiches 20* (5mm Sc+1.5 mmPb), WLS readout
3. PC's, ST's and DT's for magnetic spectrometer:
   ~5000 ch. PC (2 mm pitch) + 1300 DT (1 and 3 cm)
4. Pad(Matrix) Hodoscope ~300 ch. WLS+SiPM readout
5. Magnet: aperture 200*140 cm^2
6. Gamma detectors: GAMS2000, BGD EM cal. ~ 4000 LG.
7. Muon identification: GDA-100 HCAL + 4 muon counters (μC) behind
8. For some runs Cu target inside decay volume was used: Ø=8 cm, t=2mm and C3 big Cerenkov counter

The main triggers	$S_1 \cdot S_2 \cdot S_3 \cdot \overline{C_1} \cdot C_2 \cdot \overline{S_{bk}} \cdot \left(\Sigma_{GAMS} > 2.5\,GeV\right) \cup \left(2 \leqslant MH \leqslant 4\right)$
Prescaled triggers	$S_1 \cdot S_2 \cdot S_3 \cdot C_1 \cdot C_2 \cdot S_{bk}/10$ $\quad S_1 \cdot S_2 \cdot S_3 \cdot C_1 \cdot C_2 \cdot S_{bk} \cdot \mu C\,/4$

Runs 2012, 2013 3.65×10^9 decays, 8×10^8 with 1 track

Backgrounds to $\pi^0 e^+ \nu\gamma$

- $\pi^0 e^+ \nu$: e^+ radiates easily on air and detectors
- $\pi^+ \pi^0 \pi^0$: π^+ misidentified as e^+, 1 missing γ
- $\pi^+ \pi^0$: π^+ misidentified as e^+, 1 fake γ

Other backgrounds are negligibly small

Event selection

IB-part diverges ~ 1/ω, we normalize to

$K^+ \to \pi^0 e^+ \nu\gamma$ in limited phase space: $(E^*_\gamma > 30$ MeV, $\Theta^*_{e\gamma} > 20^0)$.

SD suffers little from this restriction.

General criteria:

- Single track identified as e^+
- Angle between K^+ and e^+ $\Theta > 2$ mrad, track-to-track distance <1 см to suppress beam
- Vertex within Decay Volume
- 1 track segment downstream magnet
- 3 γ > 1 GeV, 0.12 GeV < m_{12} < 0.15 GeV, E_3 > 1.5 GeV

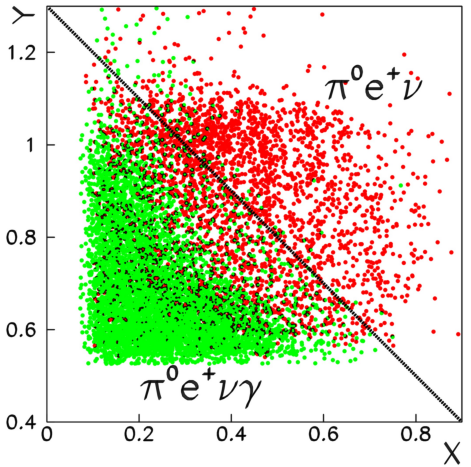
Event selection

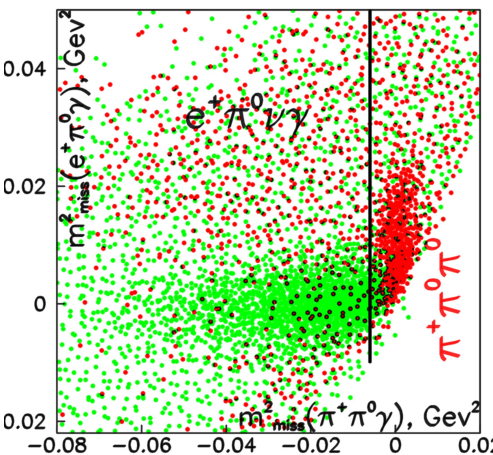
Cuts against specific backgrounds:

- $\Theta_{e\gamma} > 15$ mrad against $\pi^0 e^+ \nu$
- Dalitz: x+y < 1.3 against $\pi^0 e^+ \nu$
- Missing mass to $(\pi^+\pi^0\gamma)$: $m^2_{miss}(\pi^+\pi^0\gamma) < -0.006$ GeV^2

against $\pi^+\pi^0\pi^0$

- Energy balance: $E_{beam} - E_{e+} - E_{\pi 0} - E_{\gamma} > 1$ GeV against $\pi^+\pi^0$





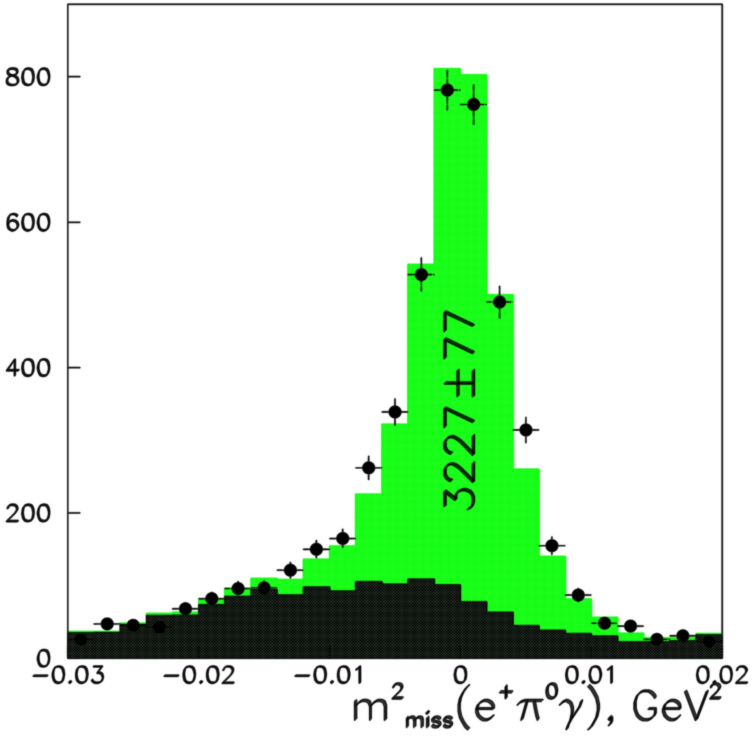
Background subtraction

Fit:

$$n(x^2) = s \times MC_{signal}(x^2) + b \times MC_{bkg}(x^2)$$

s,b — free parameters

$$x^2 = m^2_{miss}(e^+\pi^0\gamma)$$



Where to look for SD?

At large E^*_γ, $\Theta^*_{e\gamma}$. How large, numerically?

$$T \sim (\hat{V}^+_{\mu\nu} - A^+_{\mu\nu})\bar{u}(p_\nu)\gamma^\nu(1-\gamma_5)v(p_e) +$$
$$+ F^+_\nu \bar{u}(p_\nu)\gamma^\nu(1-\gamma_5)\left[\frac{p_\mu}{pq} - \frac{2p_{e\mu} + \hat{q}\gamma_\mu}{2p_e q}\right]v(p_e)$$

F_ν^+ - bremmstrahlung (IB)
$A_{\mu\nu}^+$ - *chiral axial anomaly* (AA)
$V_{\mu\nu}^+$ - mix of SD and IB
Functions of momenta invariants

Subroutine calculating $|T|^2$ and SD, AA contributions to $O(p^4)$ ChPT at any point of phase space. Implemented per

J. Bijnens, G. Ecker, J. Gasser. The DAΦNE Physics Handbook 26 Nov 1992, pp.145-183

Divide phase space into domains and calculate SD/IB in every domain

Kinematics

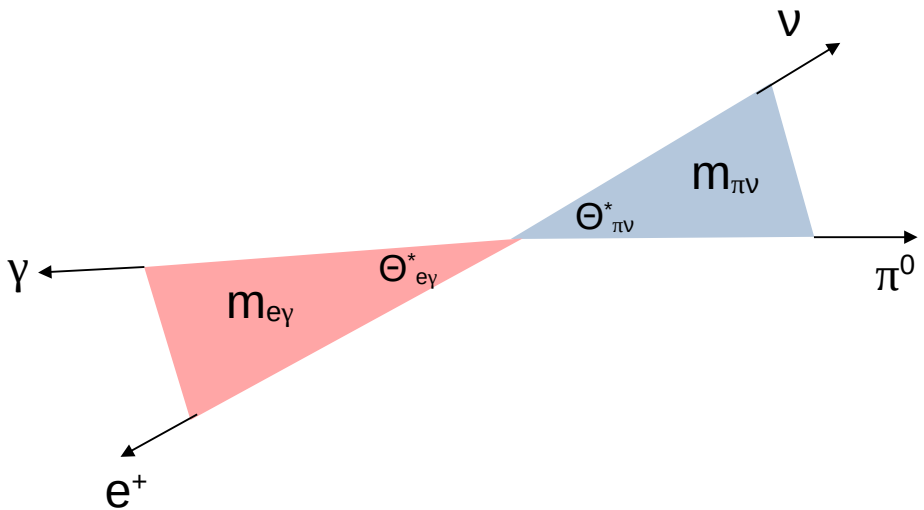
Kinematics defined by 5 variables:

J. Bijnens, G. Ecker, J. Gasser. The DAΦNE Physics Handbook 26 Nov 1992, pp.145-183}
B. Kubis et al. arXiv:hep-ph/0611366v1 29 Nov 2006

We managed to go with 4

$|T|^2$ independent from angle between planes

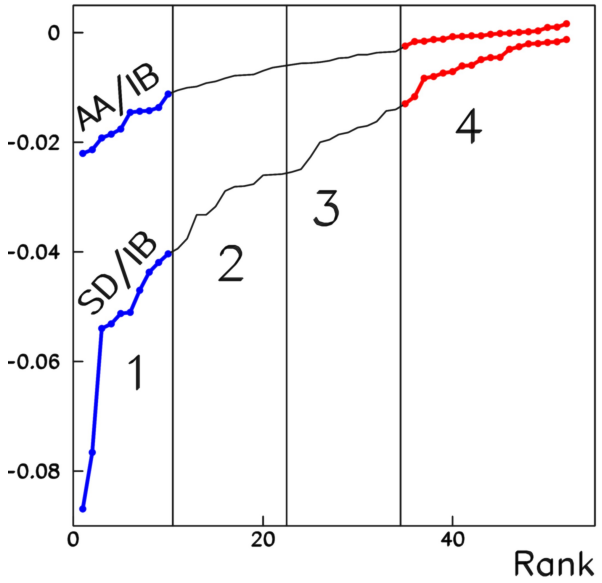
Simulation of 10^8 events

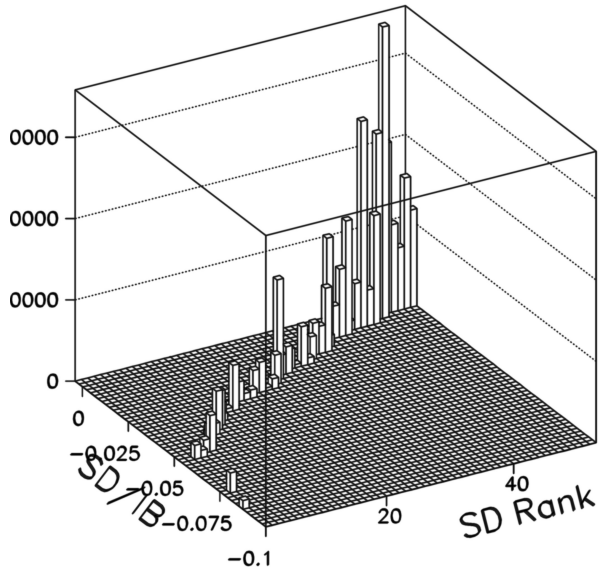


Phase space partition

52 domains ranked per their SD/IB or AA/IB: rich SD (AA) first

SD, AA contributions - predominantly negative, interference





$$\frac{BR(K^+ \to \pi^0 e^+ \nu\gamma)_{SD}}{BR(K^+ \to \pi^0 e^+ \nu\gamma)} = -0.01,$$

$$\frac{BR(K^+ \to \pi^0 e^+ \nu\gamma)_{AA}}{BR(K^+ \to \pi^0 e^+ \nu\gamma)} = -0.0015$$

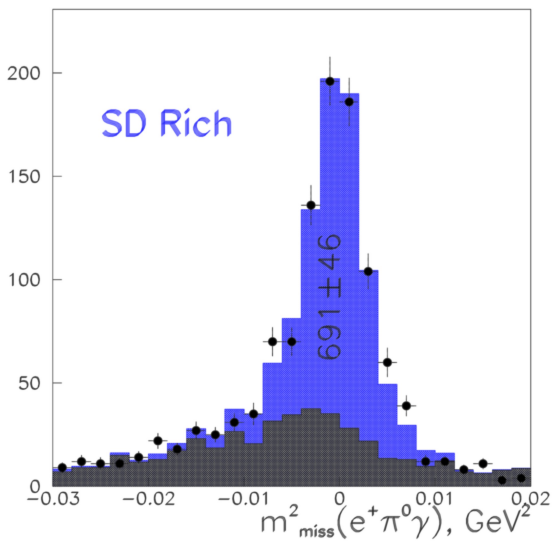
Calculation of SD contribution
Method 1: 2 bins

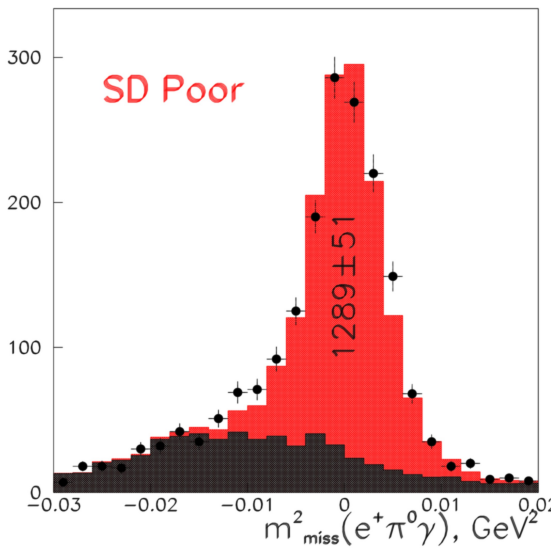
Domains combined into bins: 1 — SD rich, 4 — SD poor

$$n_i = \alpha(IB_i + \beta \times SD_i) \quad i=1,4$$

n_i — from missing mass fit,
IB_i, SD_i — from MC

β — free parameter to compare with β = 1 per ChPT





$$\beta = \frac{IB_1 n_4 - IB_4 n_1}{SD_4 n_1 - SD_1 n_4}$$

σ_β: error propagation

Bins 1,4 chosen to minimize σ_β -> min

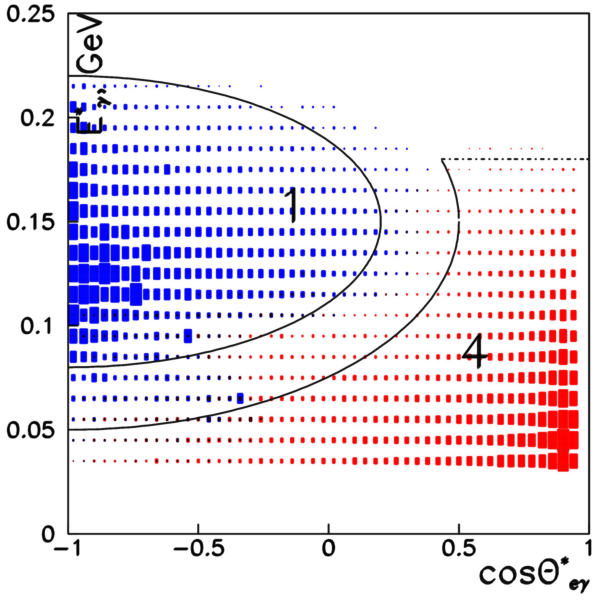
Calculation of SD contribution
Method 2: $(\Theta^*_{e\gamma}, E^*_{\gamma})$-plane

It turns out that 1 (SD-rich) and 4 (SD-poor) separated well on $(\Theta^*_{e\gamma}, E^*_{\gamma})$-plane =>

No need of domains anymore

Bins 1 and 4 re-defined on $(\Theta^*_{e\gamma}, E^*_{\gamma})$-plane,

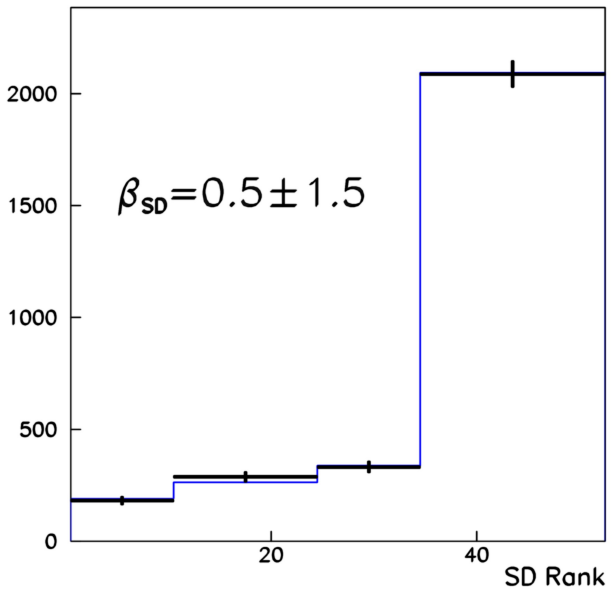
$$\beta = \frac{IB_1 n_4 - IB_4 n_1}{SD_4 n_1 - SD_1 n_4}$$

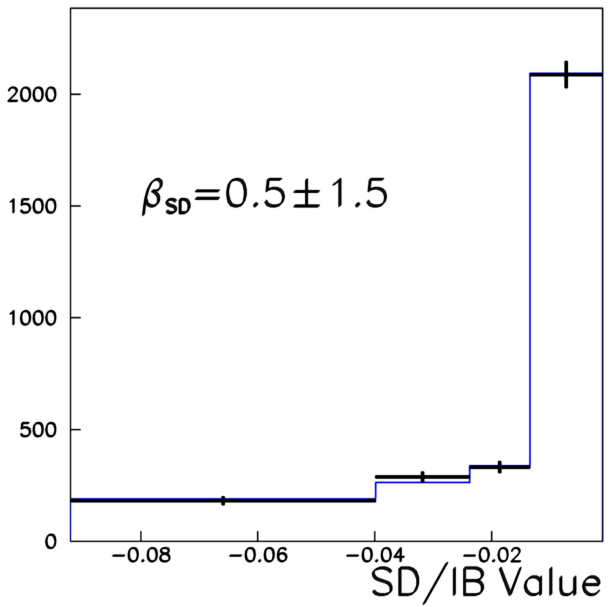


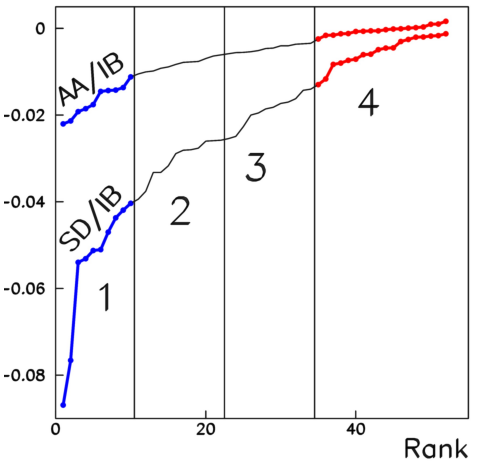
Calculation of SD contribution
Method 3: 4bins

Bins 2, 3 added to analysis thus embracing all available phase space

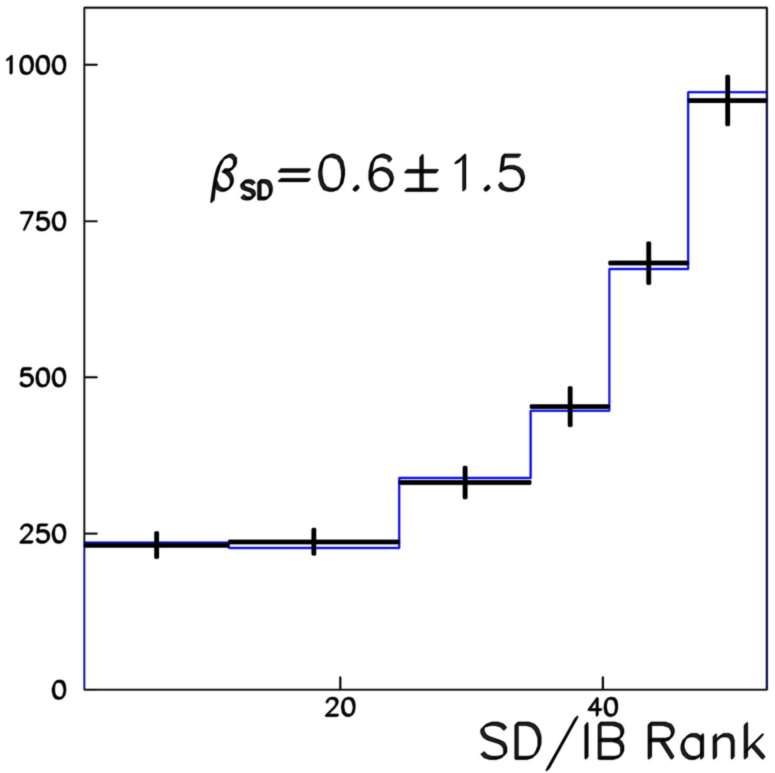
$$\mathscr{L} = \sum_{i=1}^{4} \frac{[\alpha(IB_i + \beta SD_i) - n_i]^2}{\sigma_i^2} \rightarrow min$$

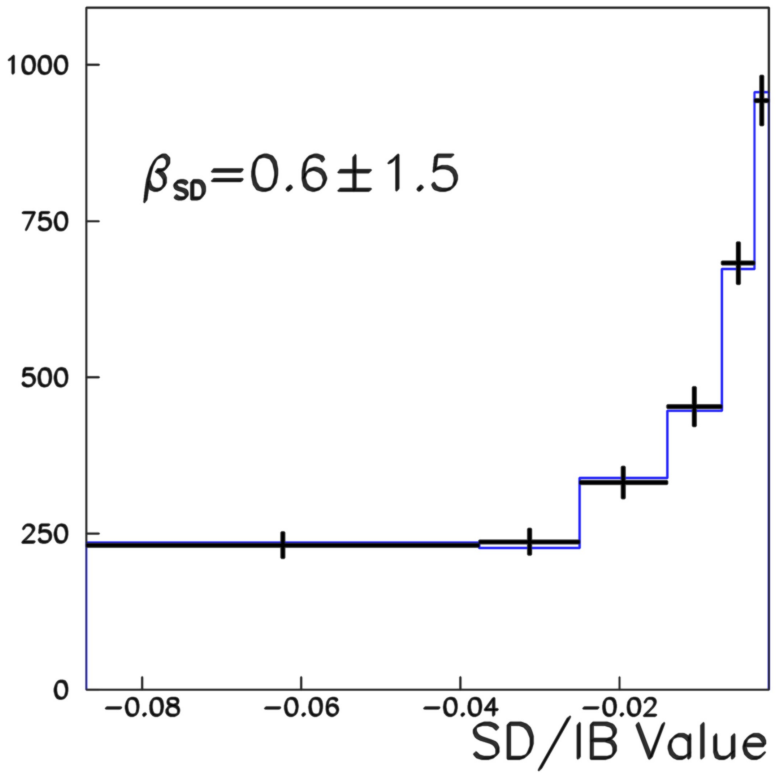






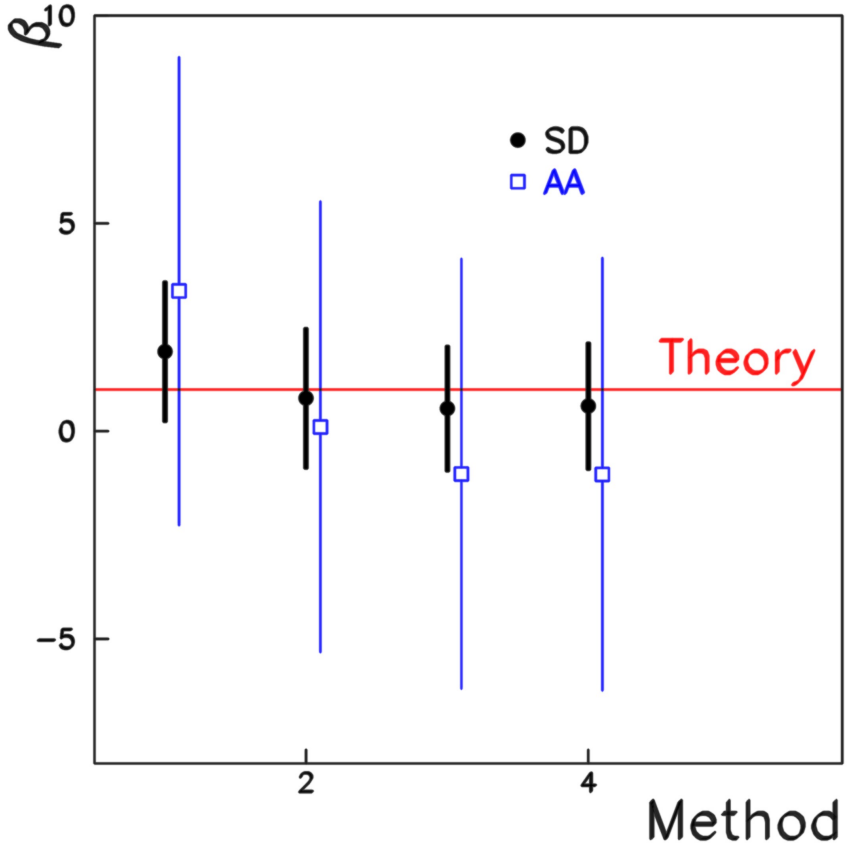
Calculation of SD contribution
Method 4: 6 bins





Results

Method		β_{SD}	β_{AA}
1	2 bins	1.9±1.7	3.4±5.6
2	$(\cos\Theta^*_{e\gamma}, E^*_{\gamma})$	0.8±1.7	0.1±5.4
3	4 bins	0.5±1.5	-1±5.2
4	6 bins	0.6±1.5	-1±5.2



Results

$\beta_{SD} = 0.9 \pm 1.6$ Errors don't let to claim

$\beta_{AA} = 0.2 \pm 5.4$ observation

Upper limits 90% CL:

$$\frac{BR(K^+ \to \pi^0 e^+ \nu\gamma)_{SD}}{BR(K^+ \to \pi^0 e^+ \nu\gamma)} = \left[\frac{BR(K^+ \to \pi^0 e^+ \nu\gamma)_{SD}}{BR(K^+ \to \pi^0 e^+ \nu\gamma)}\right]_{ChPT} \times \beta_{SD} = 0.01 \times \beta_{SD}$$

$\beta_{SD} < 3$ $BR(K^+ \to \pi^0 e^+ \nu\gamma)_{SD} < 10^{-5}$ $< 5.3 \times 10^{-5}$ PDG

$\beta_{AA} < 7.1$ $BR(K^+ \to \pi^0 e^+ \nu\gamma)_{AA} < 3.1 \times 10^{-6}$ First time

Compare $BR(K^+ \to \pi^0 e^+ \nu\gamma) = 3.09 \times 10^{-4}$ $(E^*_\gamma > 30$ MeV, $\Theta^*_{e\gamma} > 20^0)$

Conclusions

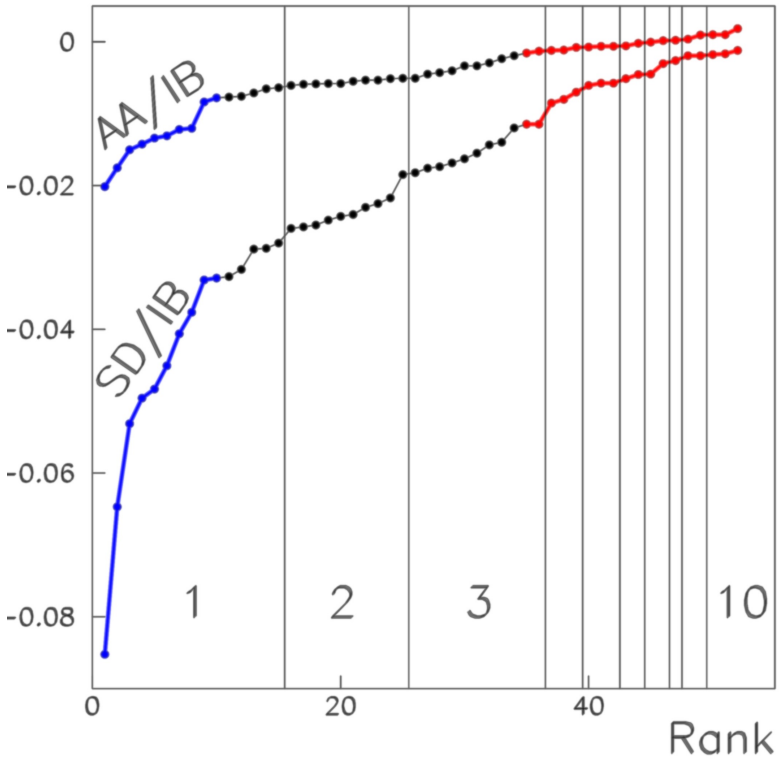
- ~3000 events of $K^+ \to \pi^0 e^+ \nu\gamma$ — decay ($E^*_\gamma > 30$ MeV, $\Theta^*_{e\gamma} > 20^0$) analysed
- Search for ***Structure-Dependent*** component (SD) performed:

$BR(K^+ \to \pi^0 e^+ \nu\gamma)_{SD} < 10^{-5}$, 5 times lower than PDG

- First search for ***Chiral Axial Anomaly*** (AA) attemped:

$BR(K^+ \to \pi^0 e^+ \nu\gamma)_{AA} < 3.1 \times 10^{-6}$

- Results agree with ChPT but errors don't let to claim observation of neither SD nor AA


0
-0.02
-0.04
-0.06
-0.08
AA/IB
SD/IB
1
2
3
10
0
20
40
Rank