

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

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on behalf of OKA collaboration*

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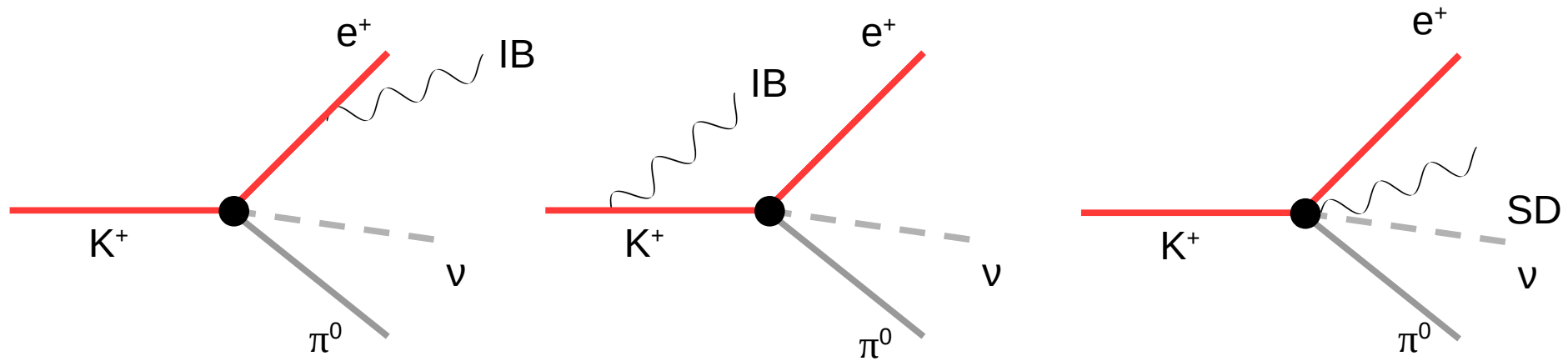
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# Radiative Decay = Internal Bremsstrahlung (IB) + Structure Dependent (SD)



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

Small: SD  $\sim$  1% BR

*Calculated with Chiral Perturbation Theory ChPT*

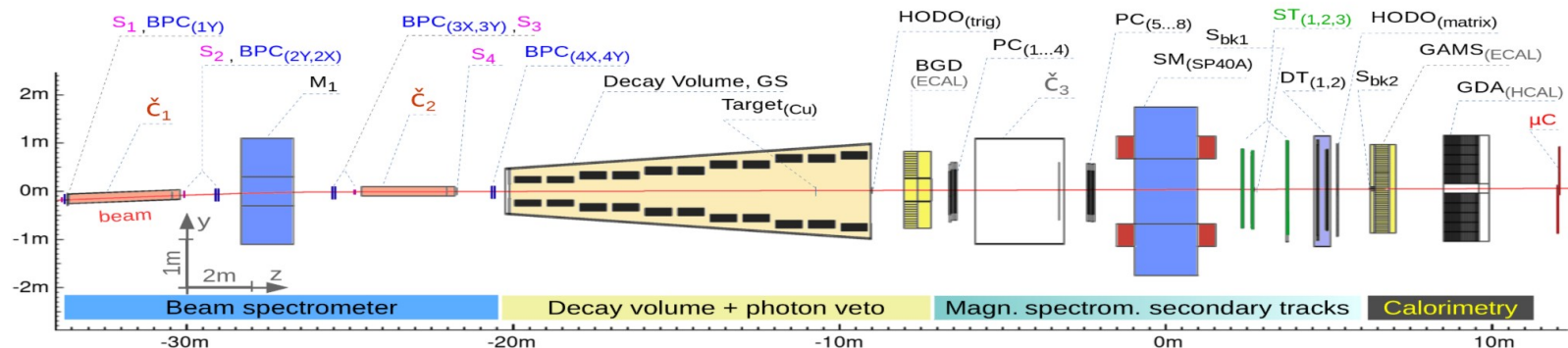
*J. Bijnens, G. Ecker, J. Gasser. The DAΦNE Physics Handbook 26 Nov 1992, pp.145-183*

|                                                                              |                                      |
|------------------------------------------------------------------------------|--------------------------------------|
| <b>Current upper limit <math>K^+ \rightarrow \pi^0 e^+ \nu \gamma</math></b> | $BR_{SD} < 5.3 \times 10^{-5}$ (PDG) |
| <b>We can improve considerably</b>                                           | Expected $\sim 3 \times 10^{-6}$     |

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

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

**We have 15 times more**



1. **Beam spectrometer:** 1mm pitch BPC ~1500 channels; Sc and Č 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<sup>2</sup>
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

$$S_1 \cdot S_2 \cdot S_3 \cdot \overline{C_1} \cdot C_2 \cdot \overline{S_{bk}} \cdot (\Sigma_{GAMS} > 2.5 \text{ GeV}) \cup (2 \leq MH \leq 4)$$

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      3.65x10<sup>9</sup> decays,    8x10<sup>8</sup> with 1 track

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

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

Other backgrounds are negligibly small

# Event selection

IB-part diverges  $\sim 1/\omega$ , we normalize to

$K^+ \rightarrow \pi^0 e^+ \nu \gamma$  in limited phase space:  $(E_\gamma^* > 30 \text{ MeV}, \Theta_{e\gamma}^* > 20^\circ)$ .

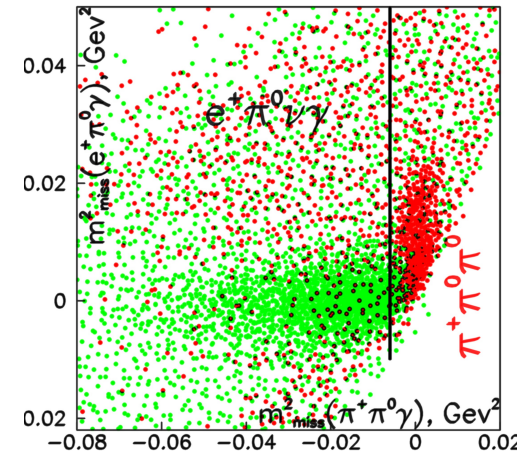
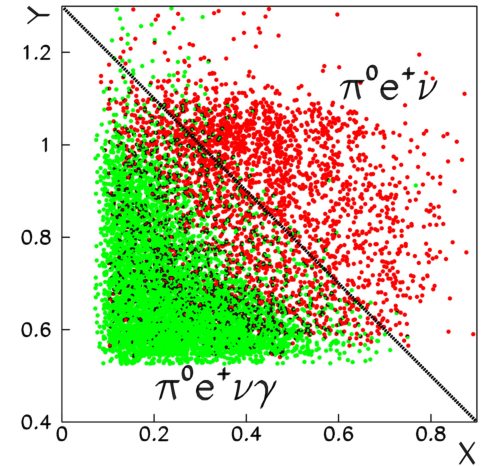
SD suffers little from this restriction.

## General criteria:

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

## 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  $(\pi^+ \pi^0 \gamma)$ :  $m_{\text{miss}}^2(\pi^+ \pi^0 \gamma) < -0.006 \text{ GeV}^2$   
against  $\pi^+ \pi^0 \pi^0$
- Energy balance:  $E_{\text{beam}} - E_{e^+} - E_{\pi^0} - E_{\gamma} > 1 \text{ GeV}$  against  $\pi^+ \pi^0$



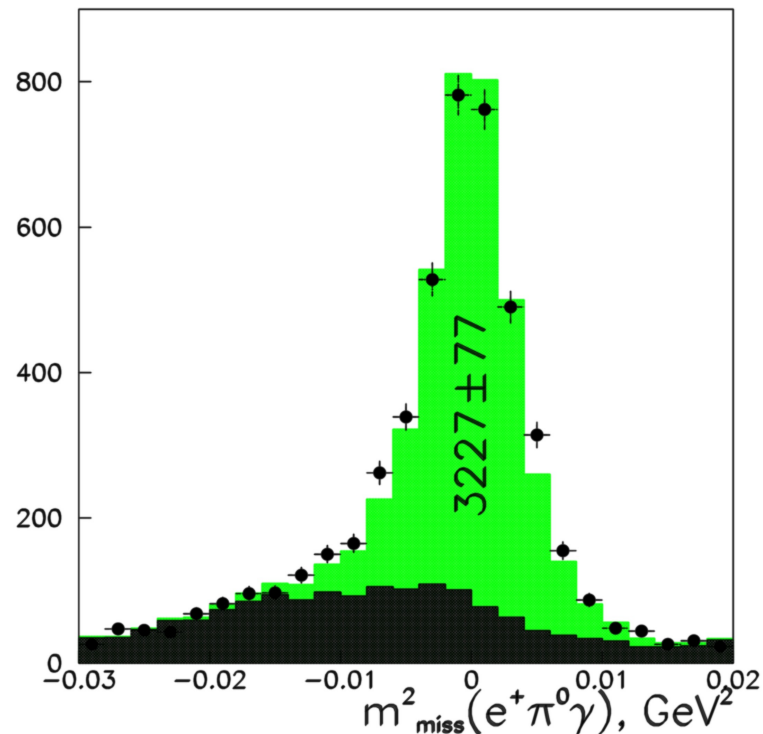
# Background subtraction

Fit:

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

$s, b$  — free parameters

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



# Where to look for SD?

At large  $E_\gamma^*$ ,  $\Theta_{e\gamma}^*$ . **How large, numerically?**

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

$F_\nu^+$  - bremsstrahlung (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:

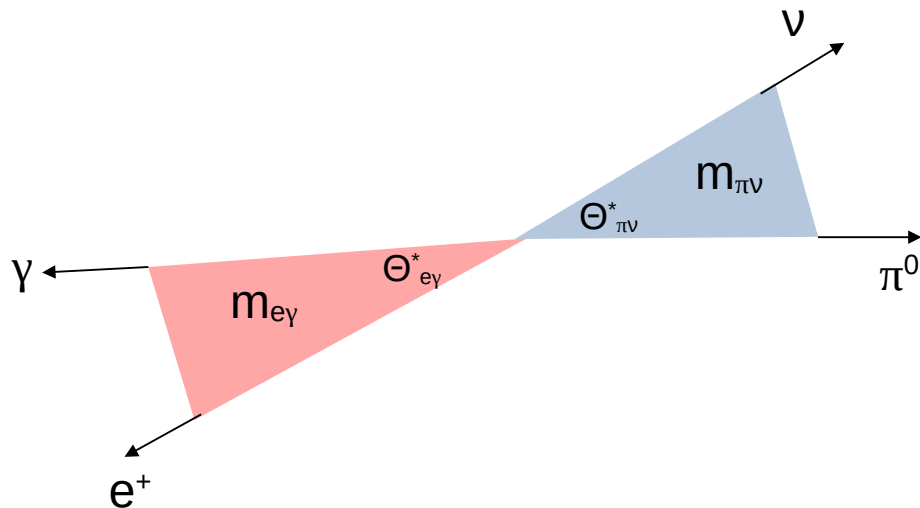
J. Bijnens, G. Ecker, J. Gasser. The DAΦNE Physics Handbook 26 Nov 1992,  
pp.145-183}

B. Kubis et al. arXiv:hep-ph/0611366v1 29 Nov 2006

We managed to go with 4

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

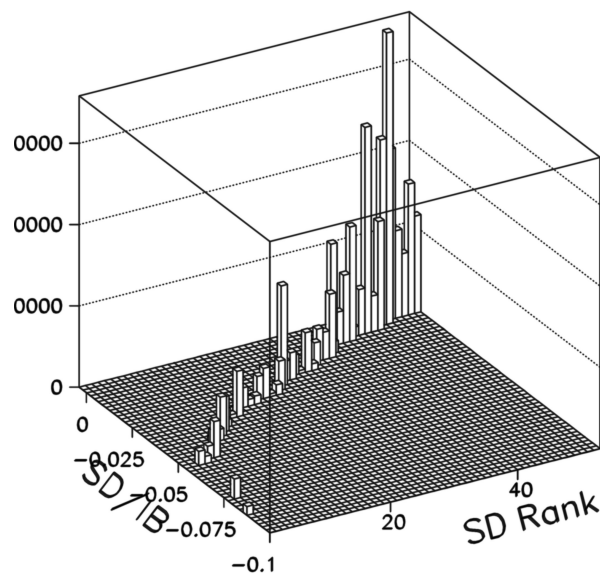
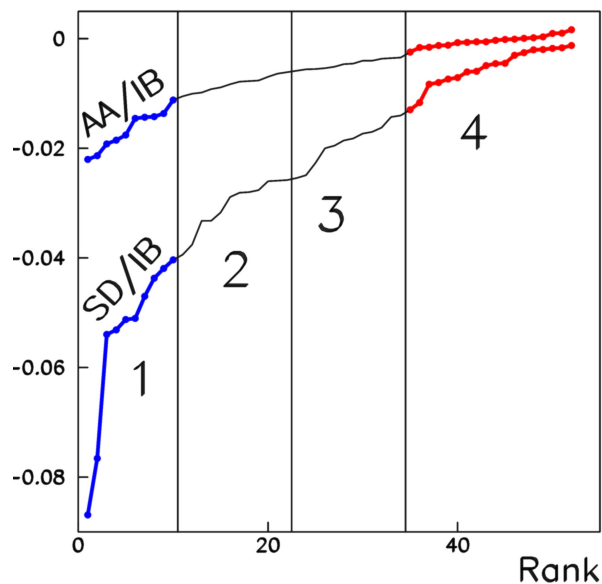
Simulation of  $10^8$  events



# Phase space partition

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

SD, AA contributions - predominantly **negative**, interference



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

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

# Calculation of SD contribution

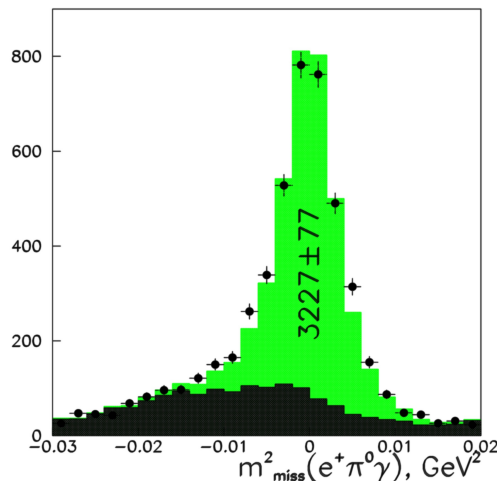
## Method 1: 2 bins

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

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

$\beta$  — free parameter to compare with  $\beta = 1$  per ChPT

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



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

$\sigma_\beta$ : error propagation

Bins 1,4 chosen to minimize  $\sigma_\beta \rightarrow \text{min}$

# Calculation of SD contribution

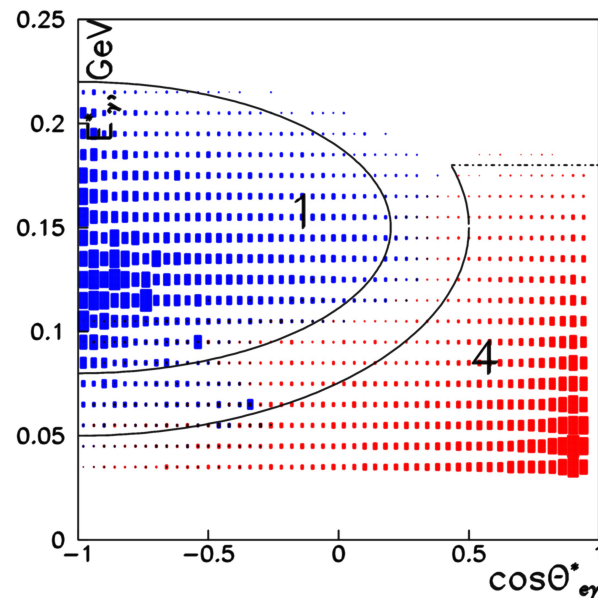
## Method 2: $(\Theta_{e\gamma}^*, E_\gamma^*)$ -plane

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,

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

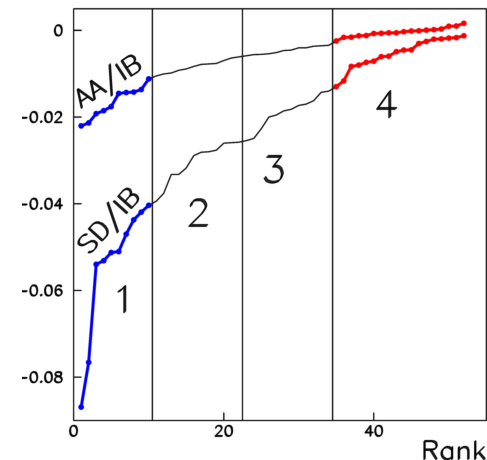
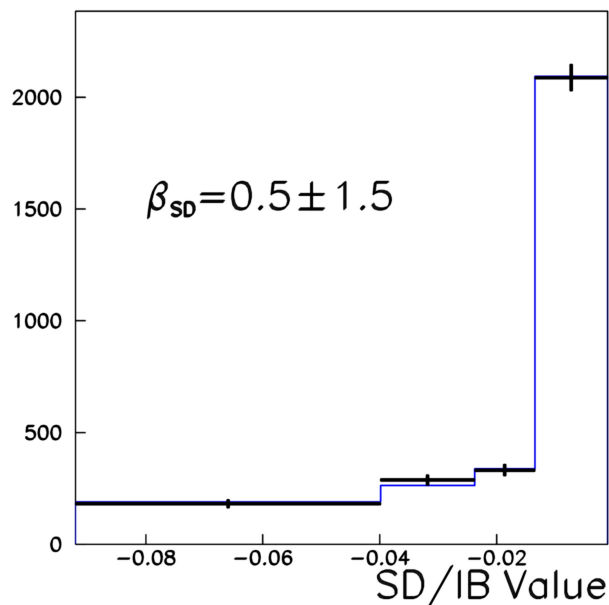
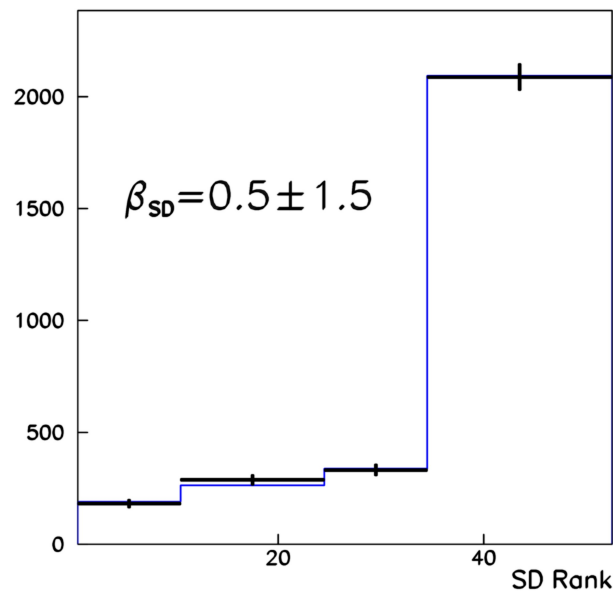


# Calculation of SD contribution

## Method 3: 4bins

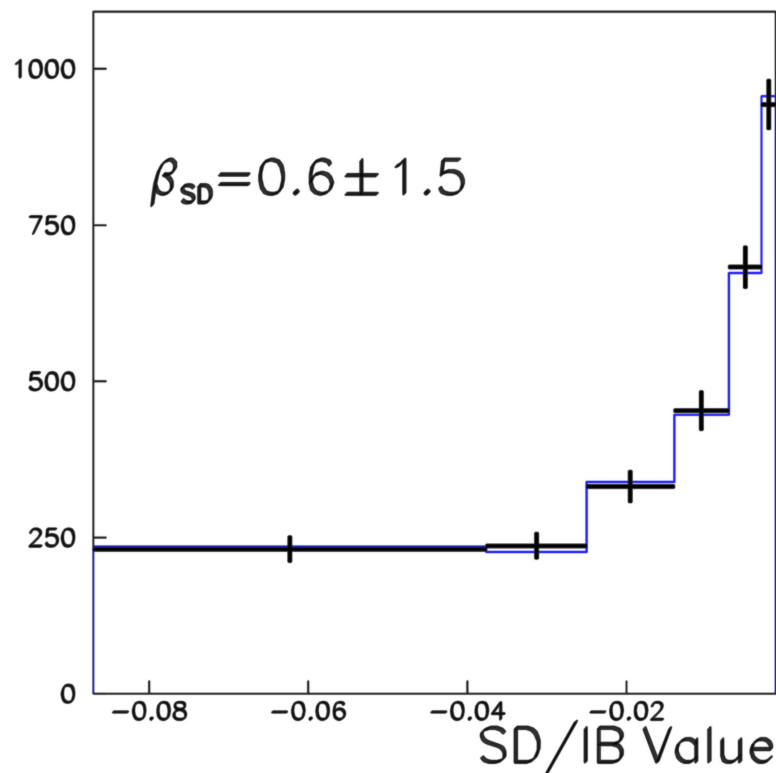
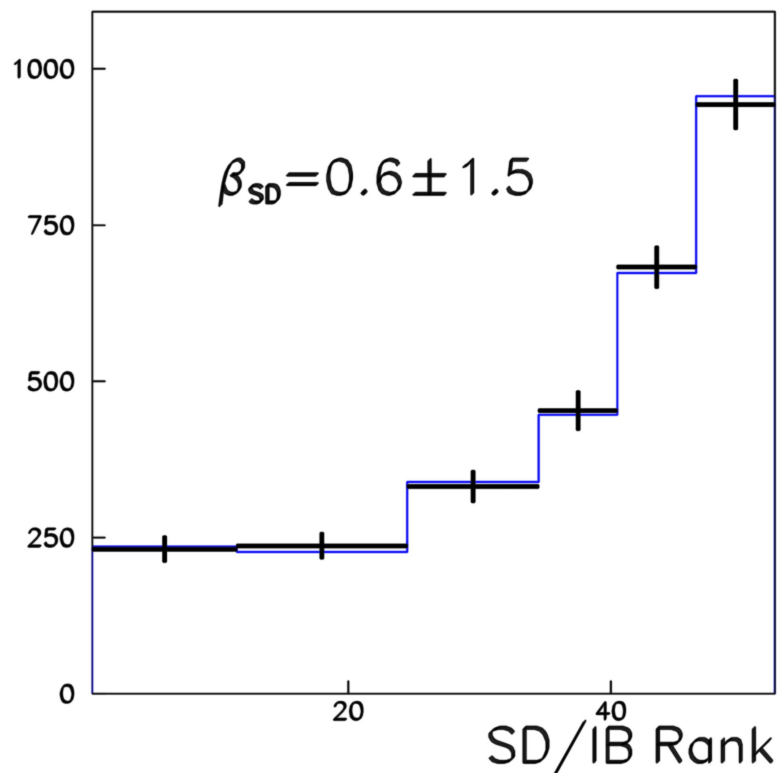
Bins 2, 3 added to analysis thus embracing all available phase space

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



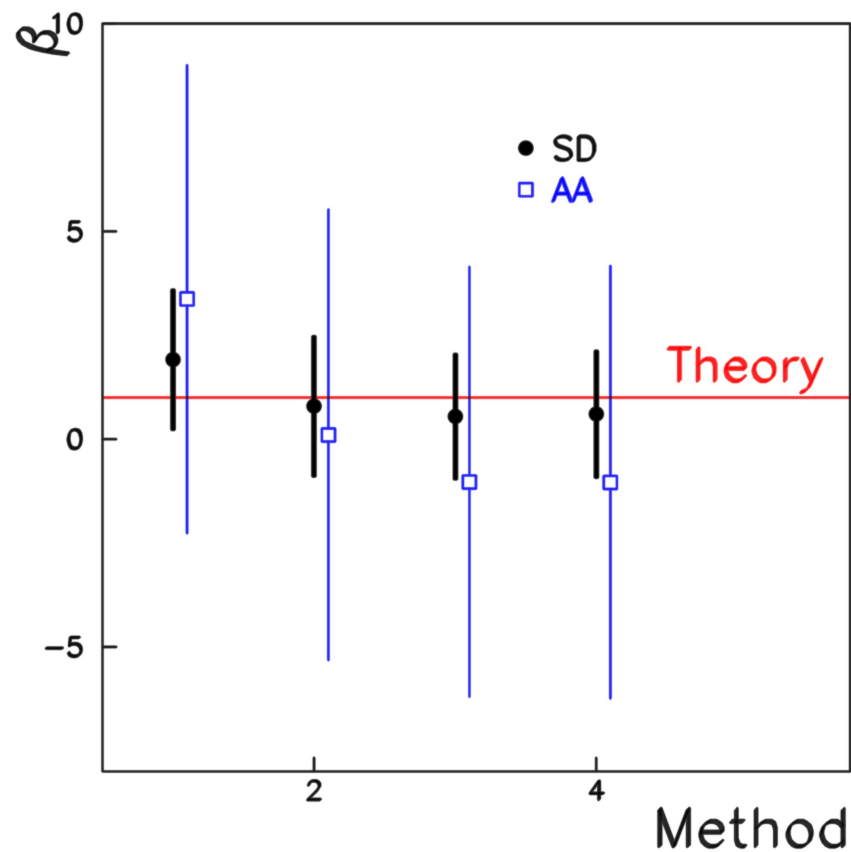
# Calculation of SD contribution

## Method 4: 6 bins



# Results

| Method |                                          | $\beta_{SD}$  | $\beta_{AA}$  |
|--------|------------------------------------------|---------------|---------------|
| 1      | 2 bins                                   | $1.9 \pm 1.7$ | $3.4 \pm 5.6$ |
| 2      | $(\cos\Theta_{e\gamma}^*, E_{\gamma}^*)$ | $0.8 \pm 1.7$ | $0.1 \pm 5.4$ |
| 3      | 4 bins                                   | $0.5 \pm 1.5$ | $-1 \pm 5.2$  |
| 4      | 6 bins                                   | $0.6 \pm 1.5$ | $-1 \pm 5.2$  |



# 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:

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

$$\beta_{SD} < 3 \quad BR(K^+ \rightarrow \pi^0 e^+ \nu \gamma)_{SD} < 10^{-5}$$

$< 5.3 \times 10^{-5}$  PDG

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

First time

Compare  $BR(K^+ \rightarrow \pi^0 e^+ \nu \gamma) = 3.09 \times 10^{-4}$  ( $E_\gamma^* > 30$  MeV,  $\Theta_{e\gamma}^* > 20^\circ$ )

# Conclusions

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

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

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

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

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

