INT- contribution to form factors of $K^+ \to \mu^+ \nu_\mu \gamma$ decay in OKA experiment

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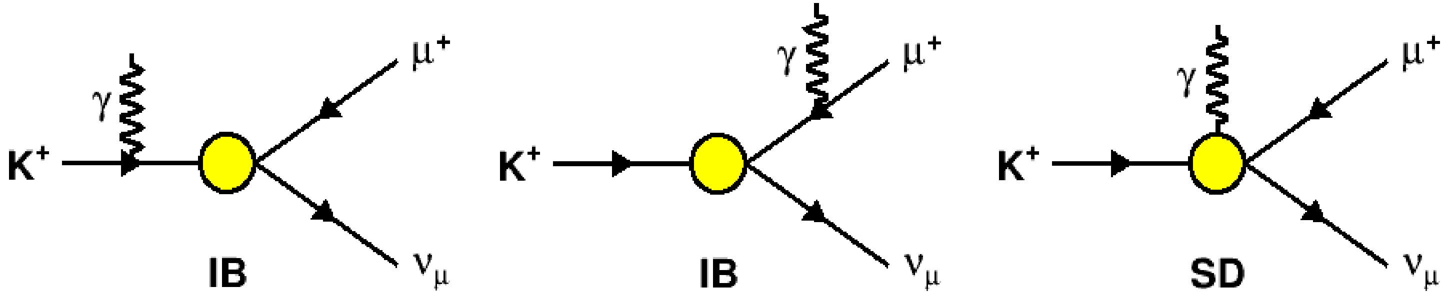
$K \to \mu\nu_\mu\gamma$ decay



IB - inner bremsstrahlung, where photon is emitted from the charged particle in the initial or final state

SD - structure-dependent radiative decay, which involves the emission of a photon from the intermediate states in the transition

INT - possible interference of **IB** and **SD**

Differential cross section in K-meson rest frame

$$\frac{d\Gamma_{K_{\mu\nu\gamma}}}{dxdy} = A_{IB} f_{IB}(x,y) + A_{SD}[(F_V+F_A)^2 f_{SD+}(x,y) + \boxed{(F_V-F_A)^2 f_{SD-}(x,y)}] - A_{INT}[(F_V+F_A) f_{INT+}(x,y) + \boxed{(F_V-F_A) f_{INT-}(x,y)}]$$

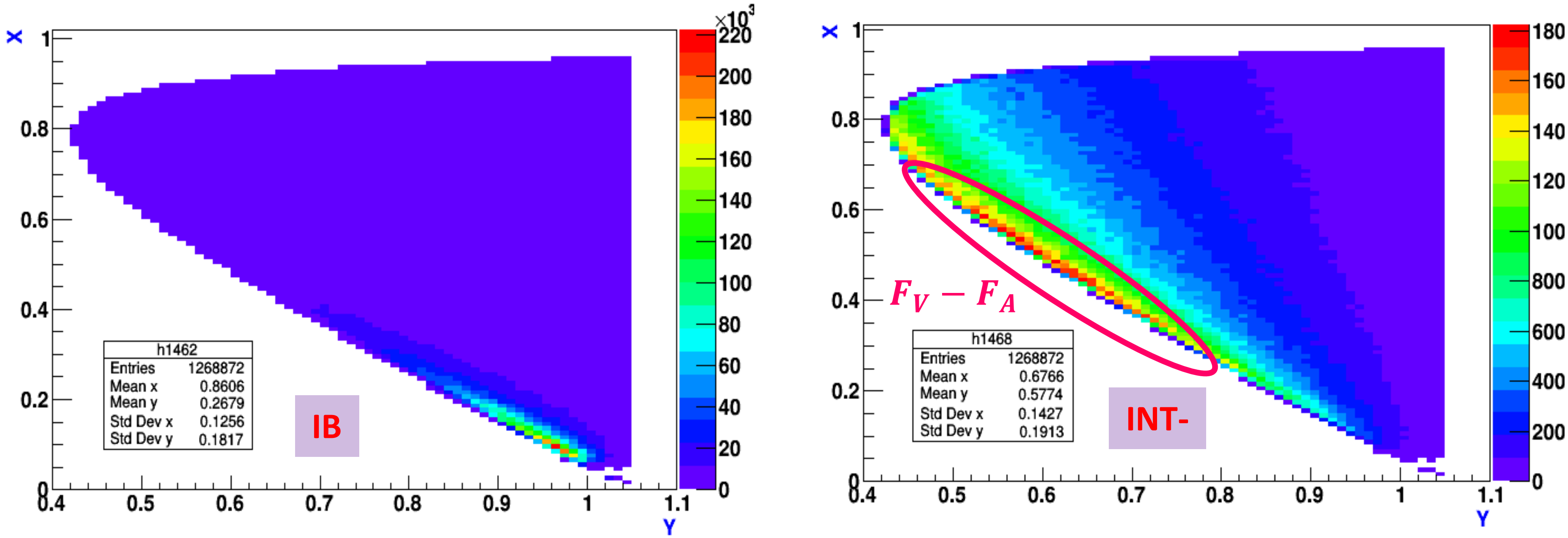
where $x = 2E_\gamma/m_K$, $y = 2E_\mu/m_K$, **c.m.s.**

In lower order of $\chi PT\ O(p^4)$ $F_V = 0.0945$, $F_A = 0.0425$ **and** $F_V - F_A = 0.052$

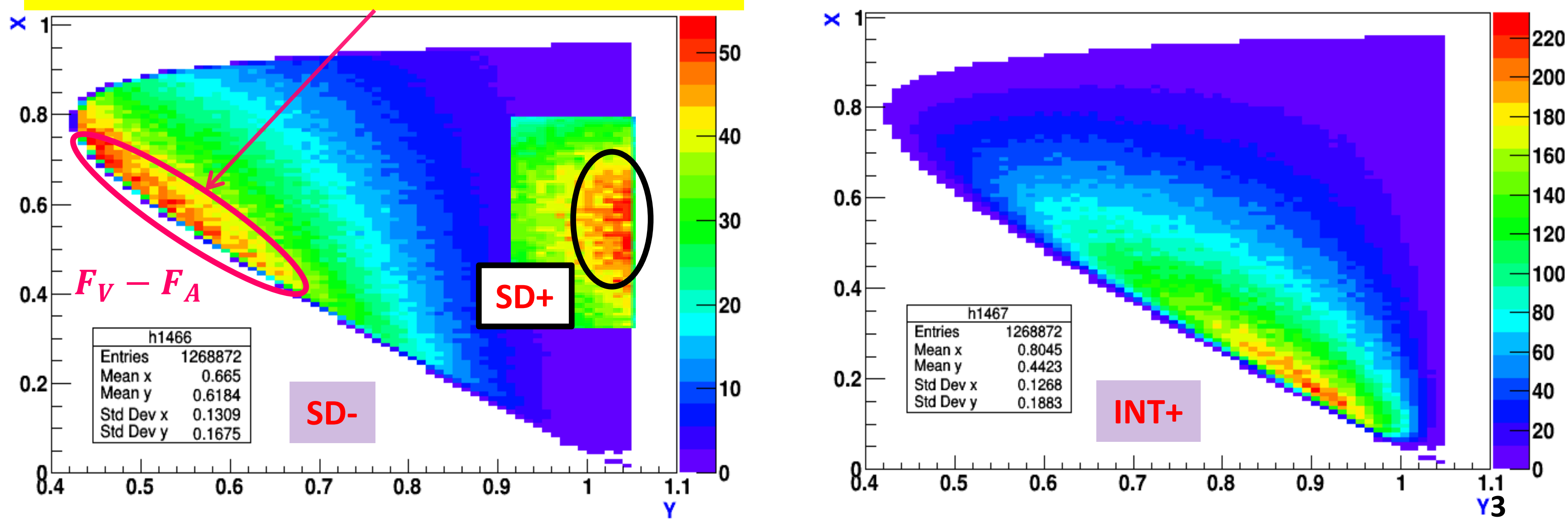
We will measure $F_V - F_A$ difference that connects with INT- and SD-.
Best measurement of this difference was made by OKA (Eur. Phys. J. C 79, 635 (2019))

$$F_V - F_A = 0.134 \pm 0.021(stat.) \pm 0.027(syst.)$$

$K \to \mu\nu_\mu\gamma$ *decay matrix*

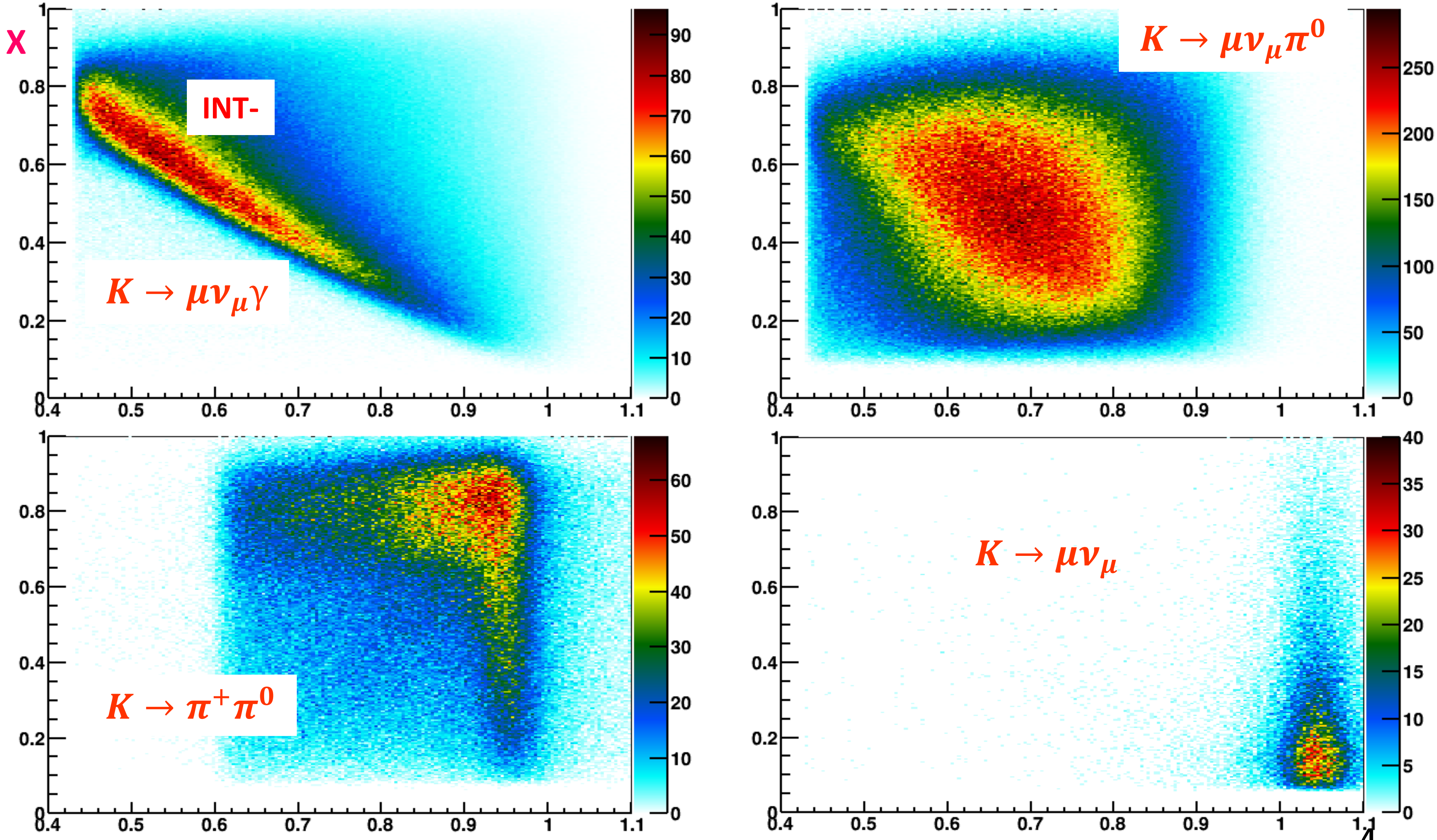


Contribution of SD- to $F_V - F_A$ is ~20 times lower



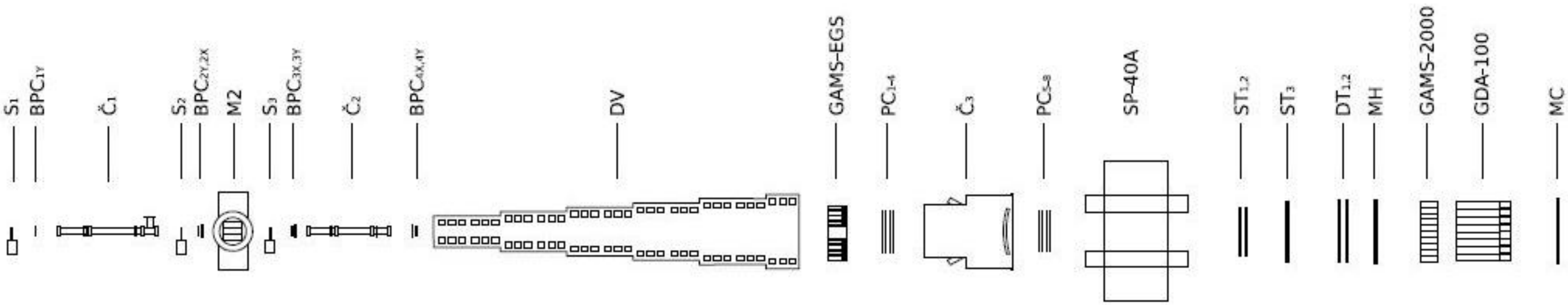
Main backgrounds

$K^+ \to \mu^+\nu_\mu\pi^0$ (**Kμ3**) with **1γ** lost from $\pi^0\to\gamma\gamma$ (Br = 3.353%)
$K^+ \to \pi^+\pi^0$ (**K2π**) with **1γ** lost from $\pi^0\to\gamma\gamma$ and **π** misidentification (Br = 20.66%)
$K^+ \to \mu^+\nu_\mu$ (**Kμ2**) with **1γ** background (Br = 63.55 %)
$K^+ \to \pi^+\pi^-\pi^+$ (**K3π**) with **1γ** background and **π** misidentification (Br = 5.58%)



Biggest background to INT- comes from Kμ3

OKA setup



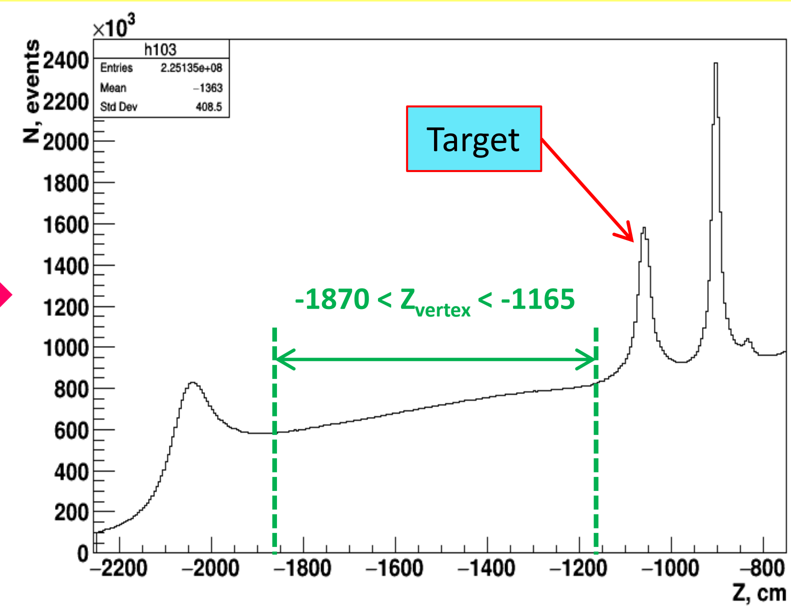
OKA setup includes

Beam spectrometer, **Decay volume** (**DV**) with **Veto** system **,** **Main magnetic spectrometer,**
2 Gamma detectors (**GAMS-2000**, **EGS**)**,** **Muon identification** (hadron calorimeter **GDA-100** and **MC**),
Matrix Hodoscope (**MH**).

OKA beam is a RF-separated secondary beam of $\boldsymbol{70GeV}$ Proton Accelerator of IHEP, Protvino.
Beam has up to **20% of kaons** with momentum $\boldsymbol{17.7GeV/c}$ during **analyzed Run 14** **(November 2012).**

<u>Event selection</u>

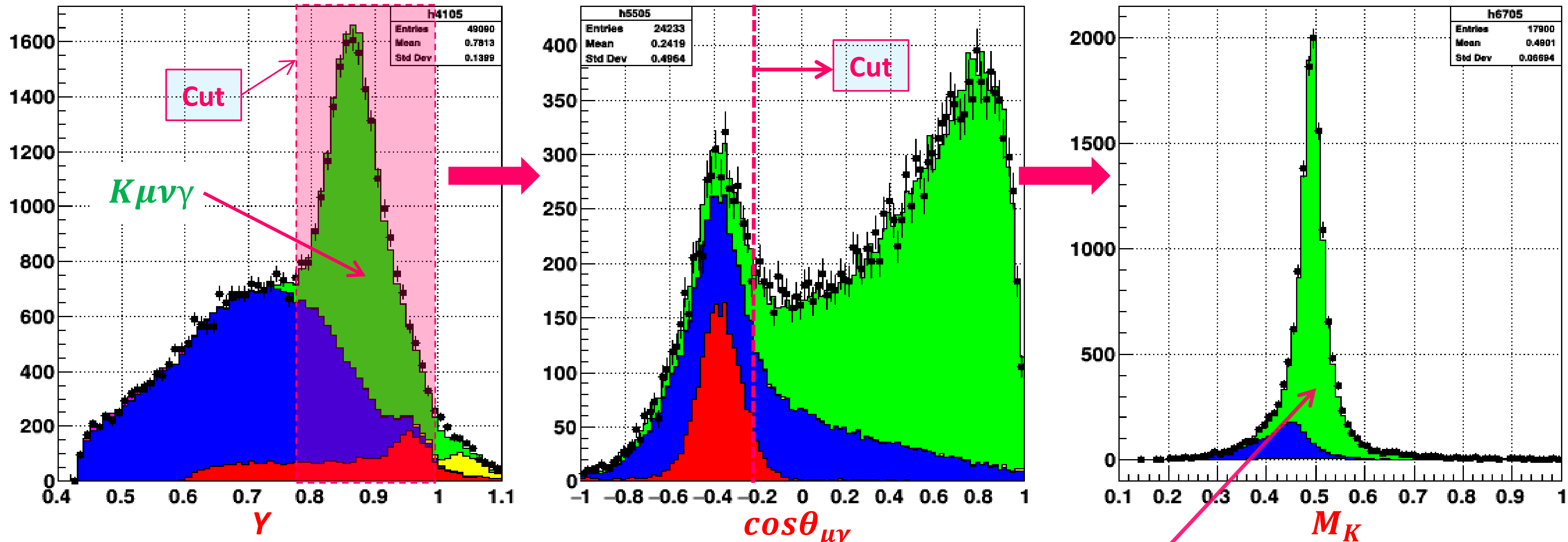
GAMS trigger - $beam * \overline{C_1} * C_2 * \overline{BK} * E_{GAMS}$
1 **Kaon** beam track
1 secondary **Muon**
1 shower in **GAMS** $> \boldsymbol{1GeV}$
Decay vertex inside decay volume **DV**



<u>Number of events (Run 14, 2012)</u>

No target - 261×10^6 - published in 1989
Target 1,2 - 243×10^6 - added to present analysis

Method of $K \to \mu\nu_\mu\gamma$ decay selection



Lab system

$$M_K{}^2 = \left(P_\mu + P_\nu + P_\gamma\right)^2$$

P_μ, P_ν, P_γ - 4-momentum of decay particles

$\overrightarrow{p_\nu} = \overrightarrow{p_K} - \overrightarrow{p_\mu} - \overrightarrow{p_\gamma}$, $E_\nu = |\overrightarrow{p_\nu}|$

1. All **x-y** kinematical region was divided into **x-stripes** with width $\boldsymbol{\Delta x = 0.05}$.

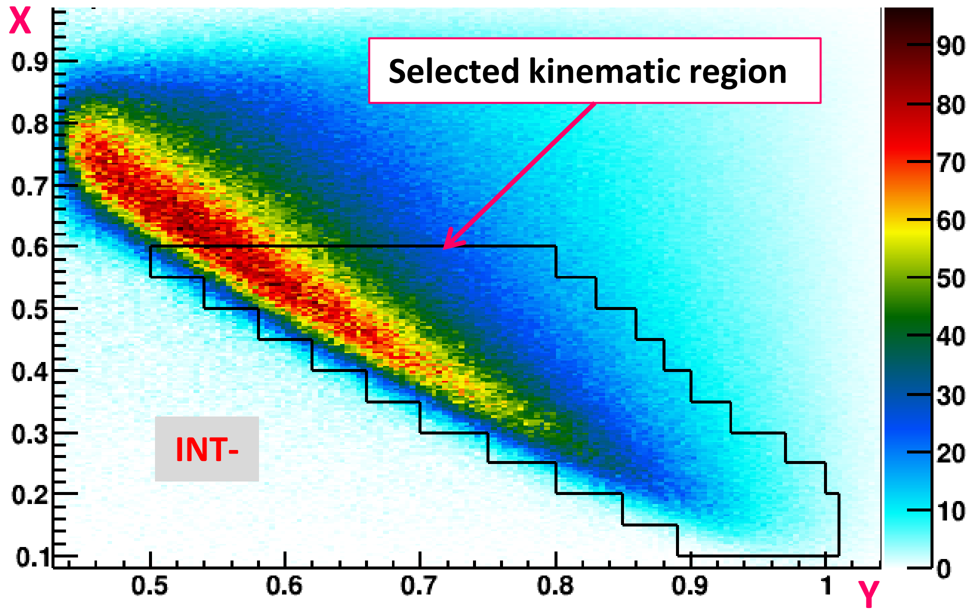
Next steps were applied for each X-stripe:

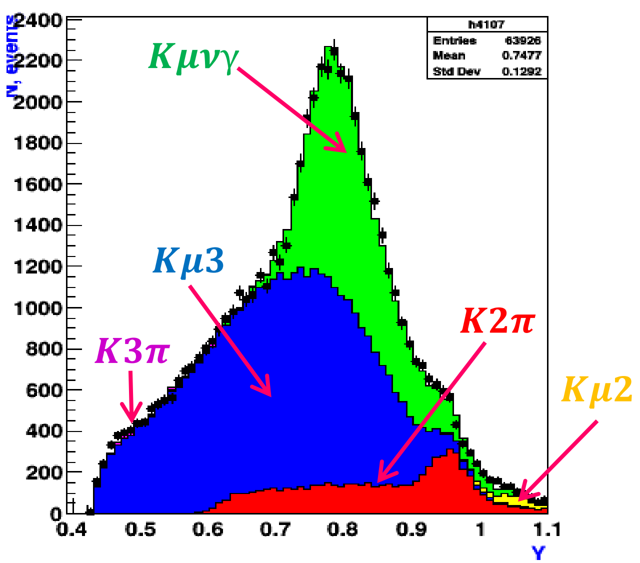
2. Apply a cut $\boldsymbol{Y_{min} < Y < Y_{max}}$ in signal region and fill $\boldsymbol{cos\theta_{\mu\gamma}}$ plot. $\boldsymbol{\theta_{\mu\gamma}}$ - angle between μ and γ in **c.m.s.**
3. Put a cut on $\boldsymbol{cos\theta_{\mu\gamma}}$ to reject background.
4. Fill $\boldsymbol{M_K}$ plot.
5. For the first iteration **IB** term was used only (Green color).
6. Simultaneous fit of all 3 histograms with **MINUIT.**

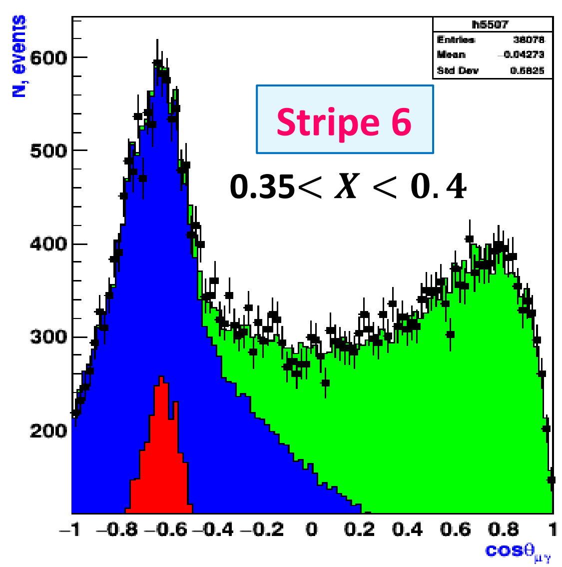
Method was proposed by ISTRA+

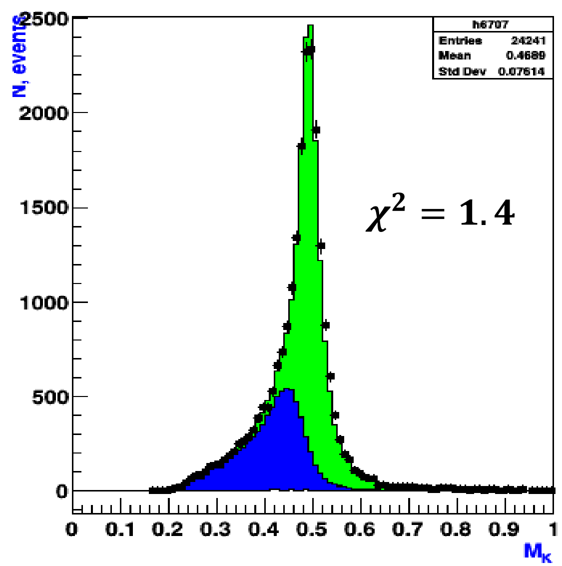
For correct estimation of statistical error $\boldsymbol{\sigma_{exp}}$ the errors of $\boldsymbol{M_K}$ histogram fit were used only.

The cuts on Y for signal in 10 X-stripes









Simultaneous fit has a good agreement with $1.3 < \chi^2/NDF < 1.7$

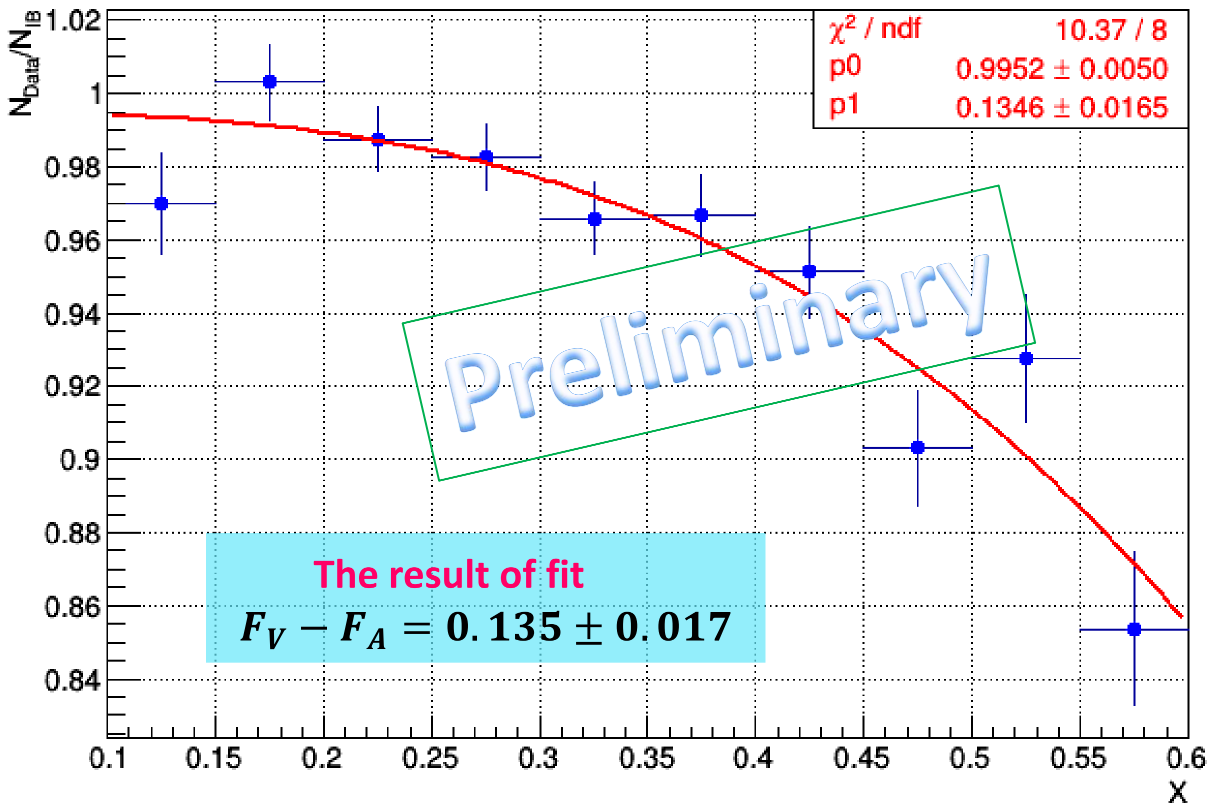
$F_v - F_A$ calculation

For each **X-stripe** we have experimental event number N_{Data} from data fitting and **IB** event number N_{IB} from **MC**. Then we plot N_{Data}/N_{IB} as a function of **X**.
For **IB** only we would have N_{Data}/N_{IB} **= 1**. For small **X IB** is dominated and I**NT-** is negligible. For large **X** this ratio also contains negative interference term.

We fit N_{Data}/N_{IB} distribution with which follows from the sum of IB and **INT-**

$$p_{signal} = p0 \times \left(1 + p1 \times f\left(\frac{N_{INT-}}{N_{IB}}\right)\right)$$

$$p1 = F_V - F_A$$



The total number of selected $K \to \mu\nu\gamma$ decay events - 144115 ± 380
Old published OKA result (Eur. Phys. J. C 79, 635 (2019)) - 95428 ± 309

Systematics

Since analysis can depends on **width of X-stripes**, **Y** and **angle** **cuts** and **fit procedure** next possible systematics is considered:

1) Non ideal description of signal and background in MC – $\mathbf{0.012}$
2) Left and right X limits (number of bins in fit) – $\mathbf{0.008}$
3) Width of X-stripes ($\Delta \boldsymbol{x}$ = 0.035 and 0.065 instead 0.05) – $\mathbf{0.005}$
4) Y limits in X-stripes (FWHM instead full signal region) – $\mathbf{0.005}$
5) Possible contribution of INT+ term (E787 result) – $\mathbf{0.018}$

The total systematics from 5 possible sources - $\mathbf{0.024}$

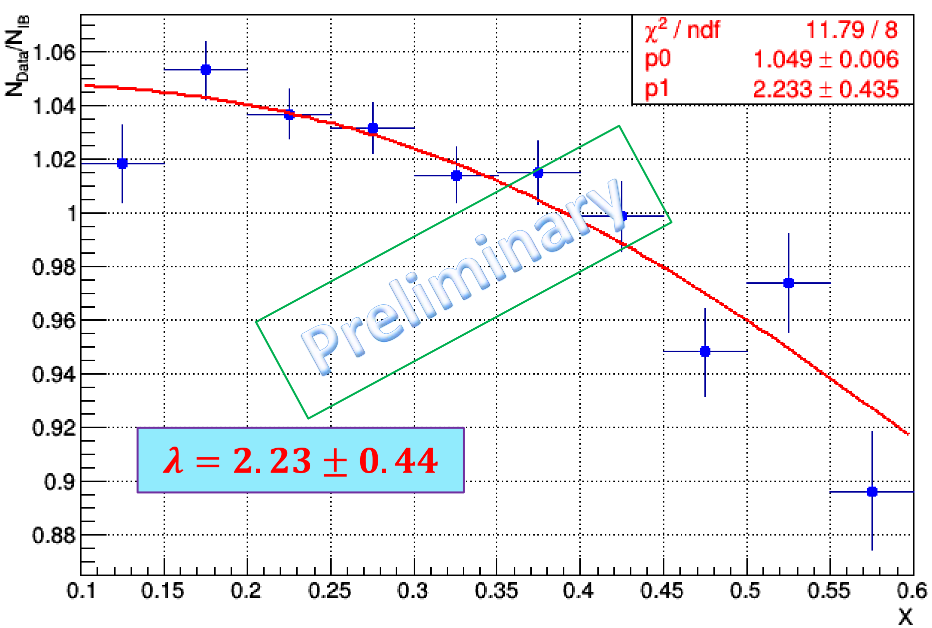
Detail description of systematics estimation procedure are presented in Backup slides.

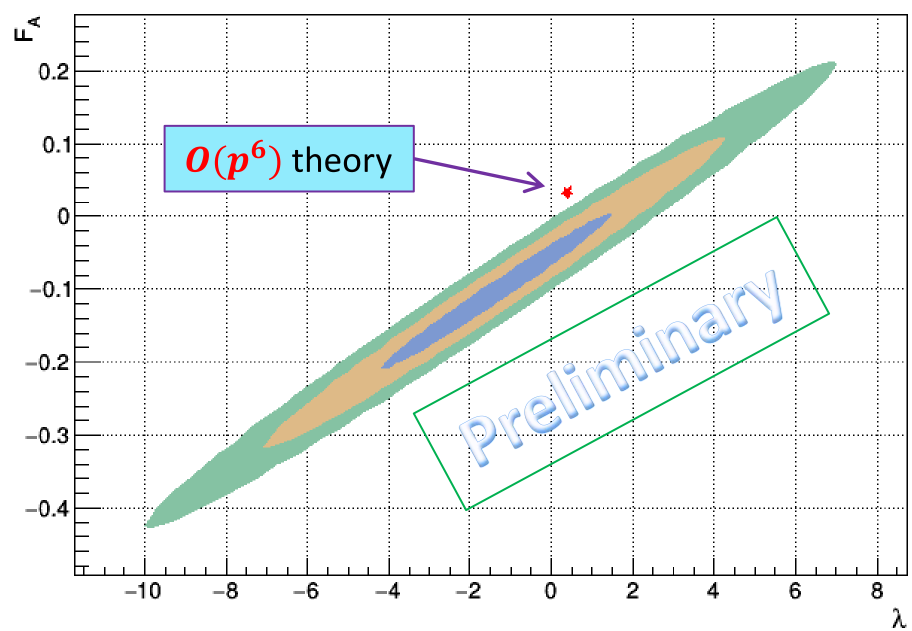
$\chi PT\ O(p^6)$

In the next order $\chi PT\ O(p^6)$ F_V linearly depends on the momentum transfer q^2 with parametrization $F_V = F_V(0)\big(1 + \lambda(1 - x)\big), F_A = const$, where $F_V(0) = 0.082$, $F_A = 0.034$, $\lambda = 0.4$.

The theoretical prediction was tested in three ways:

1) $F_V(0), F_A, \lambda$ were fixed from the theory prediction: $F_V(0) = 0.082$, $F_A = 0.034$, $\lambda = 0.4$.
   This fit has bad compliance with $\chi^2/NDF = 29.0/9$.
2) $F_V(0)$ and F_A are taken from $\chi PT\ O(p^6)$, λ is a fit parameter.
   It gives $\lambda = 2.23 \pm 0.44$ with $\chi^2/NDF = 11.8/8$. This result is 4.2σ above theory.
3) $F_V(0)$ was fixed from $\chi PT\ O(p^6)$. F_A and λ are the fit parameters.
   Fig. shows the $F_A - \lambda$ correlation. Theoretical prediction (**red star**) is out of 3σ-ellipse.





The next order of chiral theory has worse agreement although can not be excluded.

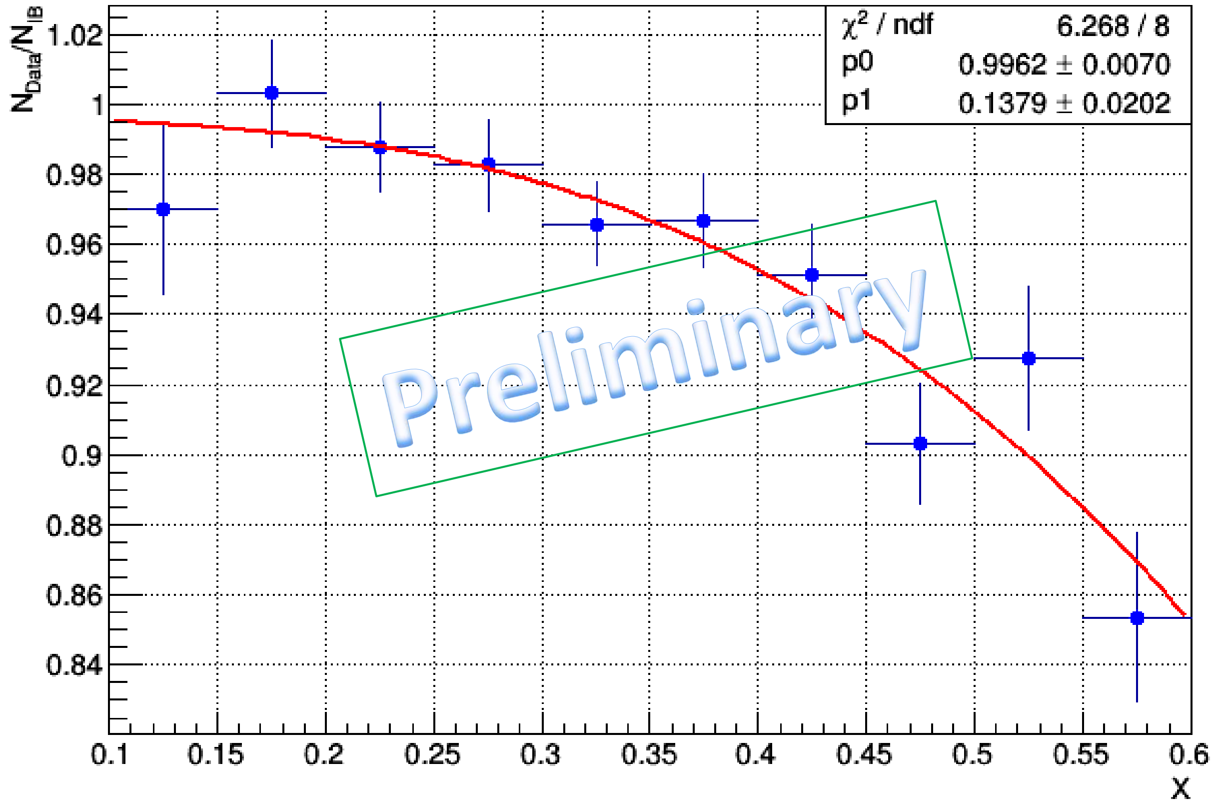
Conclusion

1) Largest statistics about **144K** events of $K \rightarrow \mu\nu_{\mu}\gamma$ decay has been collected.
2) $F_V - F_A$ difference has been measured with highest accuracy:
   $F_V - F_A = 0.135 \pm 0.017(stat.) \pm 0.024(syst.)$
3) The result is **2.9σ above χPT O(p4)** prediction or **1.9σ above** the calculation in framework of gauged nonlocal effective chiral action (EχA) ($F_V - F_A = 0.081$ **(S. Shim et al., Phys. Lett. B 795 (2019) 438**).
4) The result is very close to the last published result of **OKA** experiment:
   $F_V - F_A = 0.134 \pm 0.021(stat.) \pm 0.027(syst.)$
   but both measured errors are smaller than OLD result of OKA.
5) The next order of chiral theory has worse agreement although can not be excluded.
6) The presented results are preliminary.

Backup slides

1) *Non ideal description of signal and background in MC*

For estimation of systematic error from possible non ideal description of signal and background in **MC**, the error of each bin was scaled by $\sqrt{\chi^2/NDF}$ factor. χ^2 is obtained from simultaneous fit in each **X**-stripe.



Main fit
χ^2/NDF = 1.30

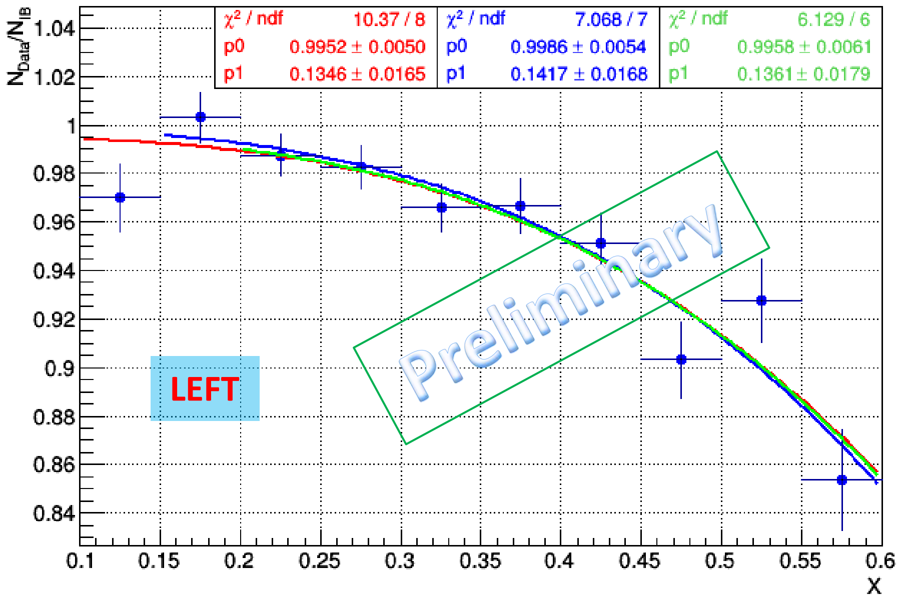
Present fit
χ^2/NDF = 0.78

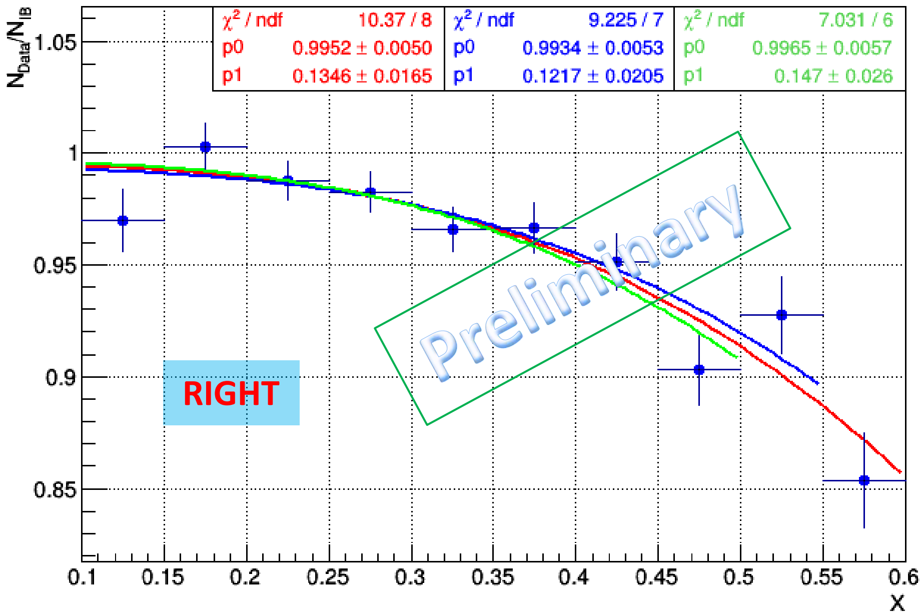
New value of $F_V - F_A$ is consistent with the main one but the fit error is larger. We suppose σ_{form} depends as $\sigma^2{}_{fit} = \sigma^2{}_{form} + \sigma^2{}_{stat}$ and therefore

$$\sigma_{stat} = 0.0202 \rightarrow \sigma_{form} = 0.0117$$

2) Left and right X limits

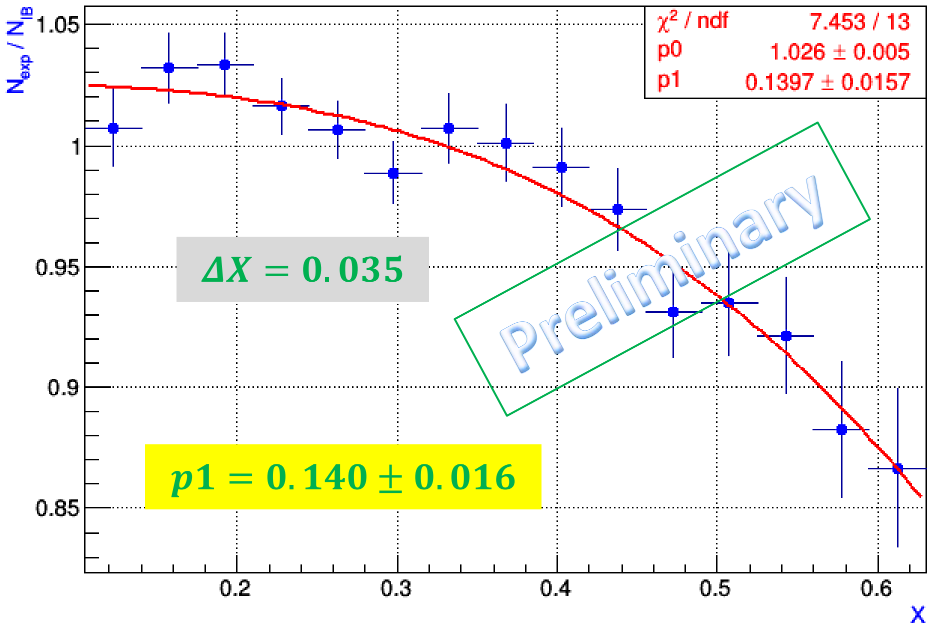
Dependency N_{Data}/N_{IB} on **X** was fitted by removing 1 or 2 points at the left (right) edge.
The average difference between the new $F_V - F_A$ values and the nominal one is taken as systematic error.

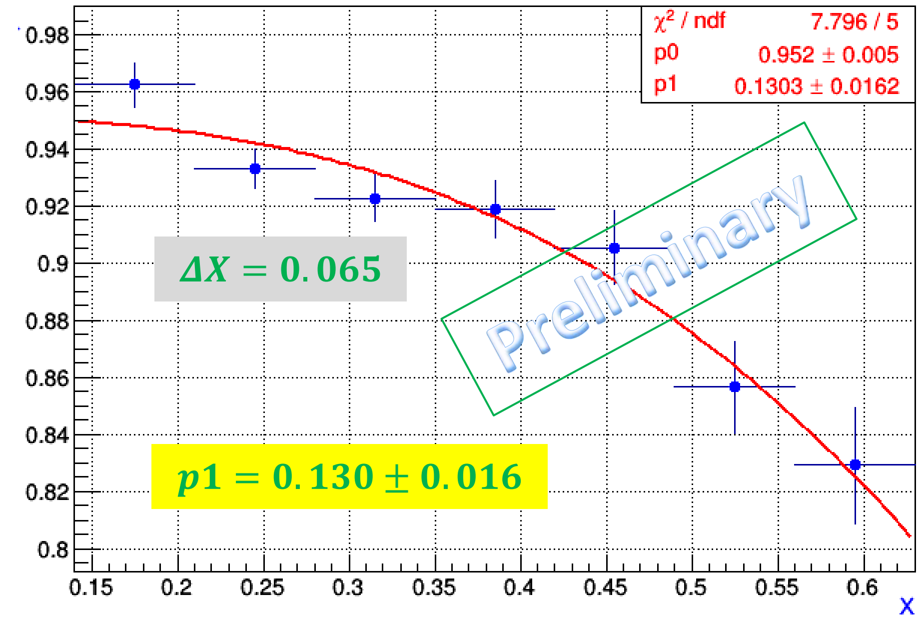


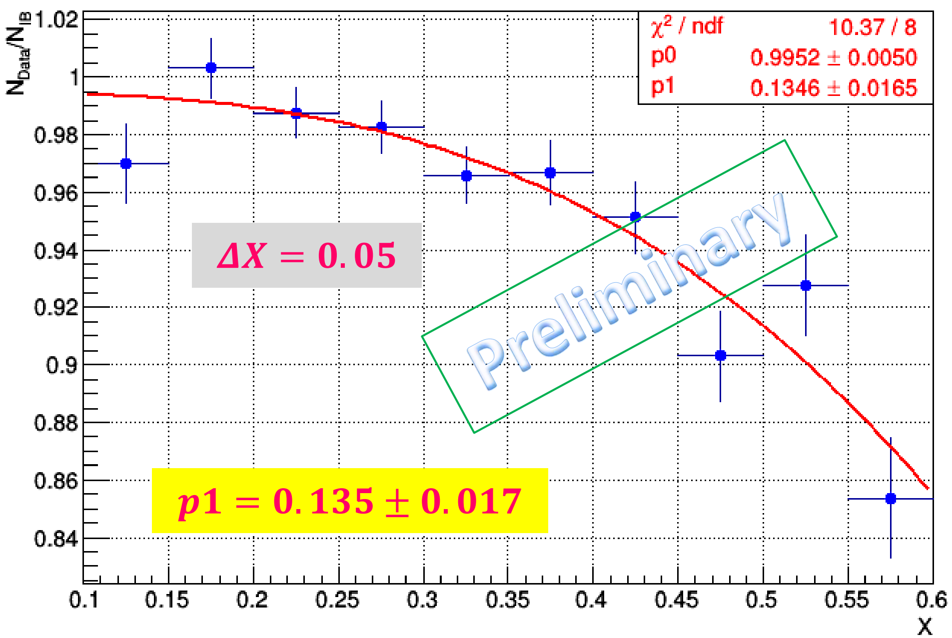


$\boldsymbol{\sigma_X = 0.008}$

3) Width of X-stripes







We repeated the data analysis procedure for 2 other values of **X**-binning:

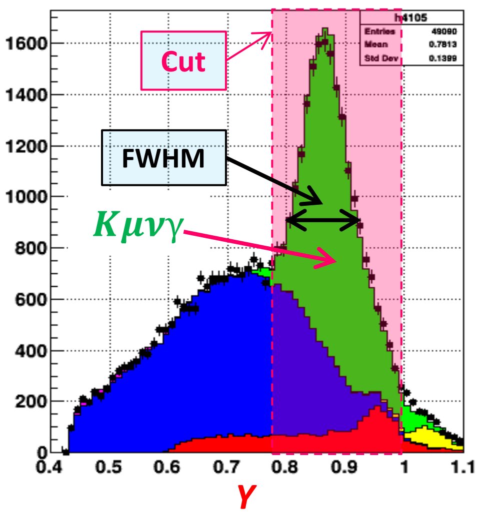
- $\boldsymbol{\Delta X = 0.035}$, that is the worst **X**-resolution at maximal value of **X = 0.6**;
- $\boldsymbol{\Delta X = 0.07 = main + 0.015}$ value.

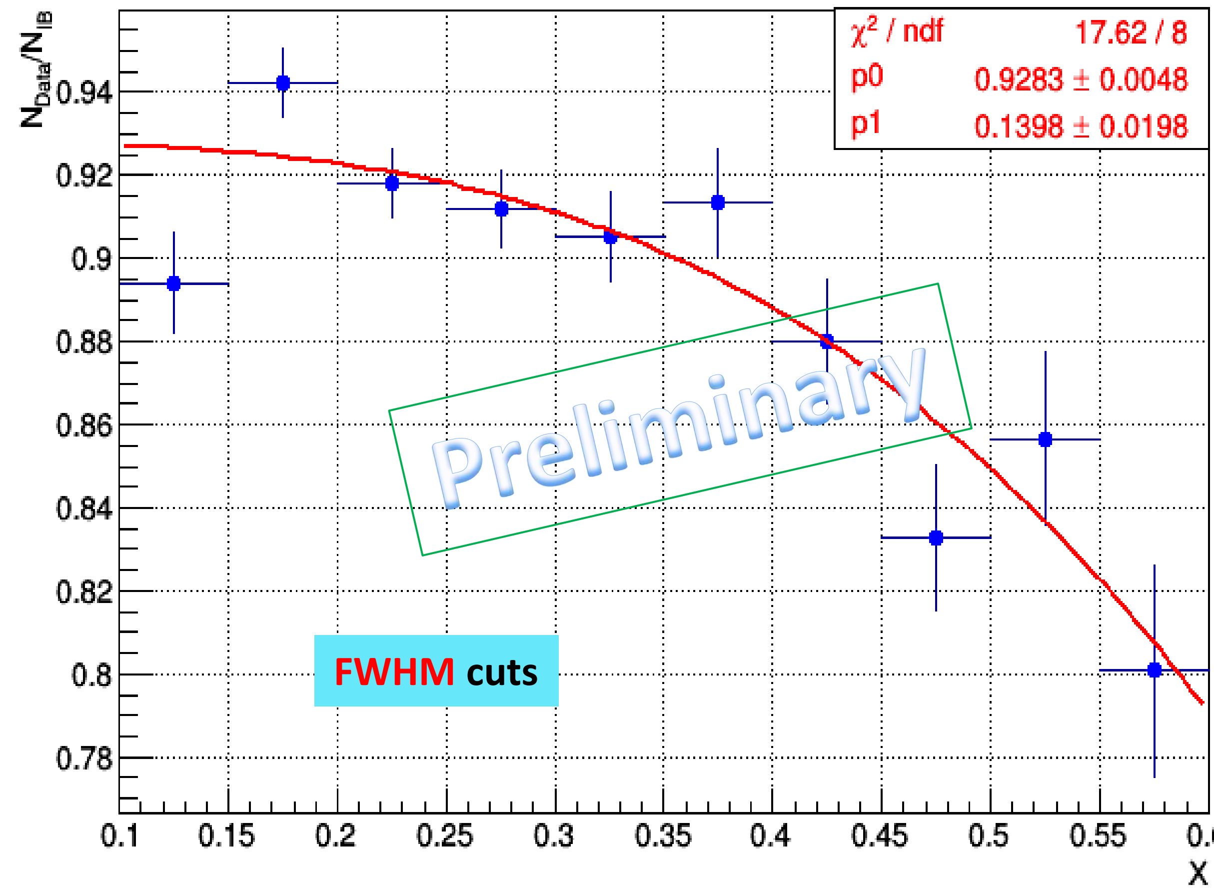
The biggest difference between new $F_V - F_A$ values and the nominal one:

$$\boldsymbol{\sigma_{\Delta X} = 0.005}$$

4) ***Y limits*** *in X-stripes*

FWHM cuts for selection of events were applied in **Y**-dependency for signal **MC**. Such cuts on **Y** are stronger than those used for main data analysis.



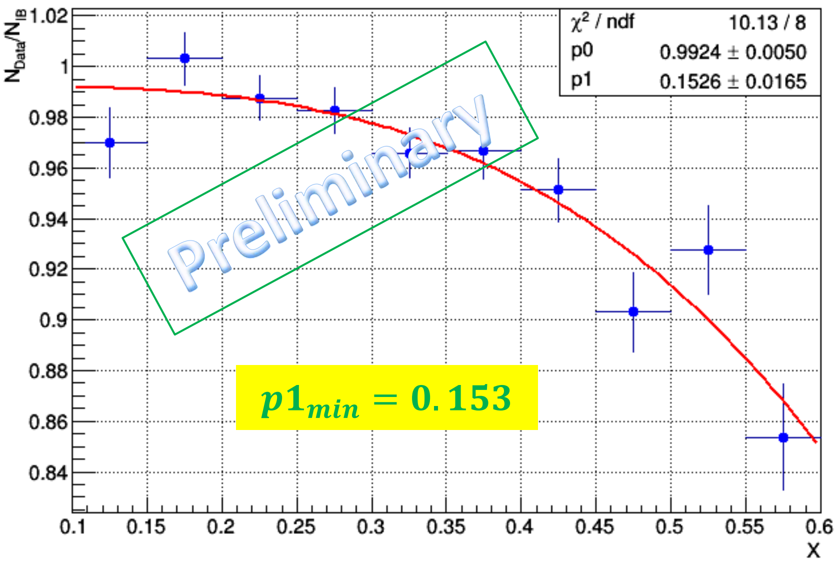


Biggest difference between new $F_V - F_A$ and nominal values: $\boldsymbol{\sigma_Y = 0.005}$

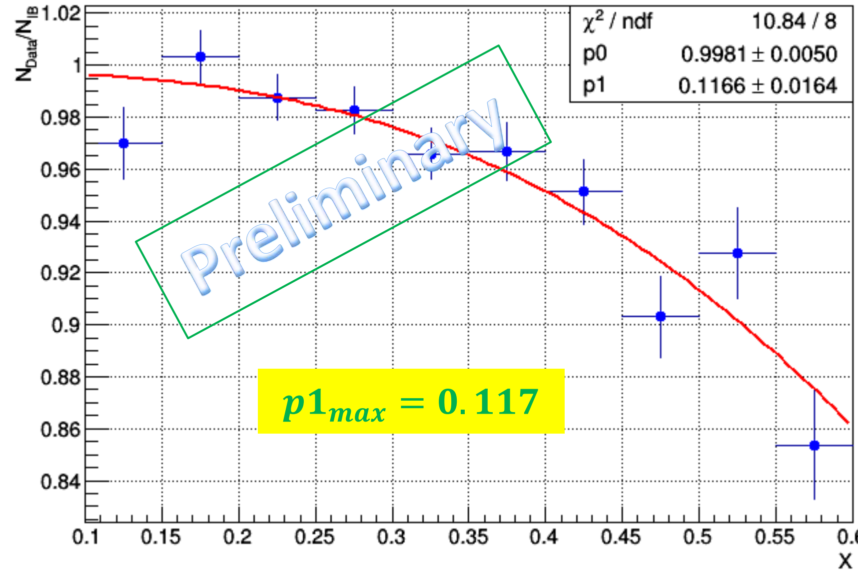
5) Possible contribution of *INT+* term

$$p_{signal} = p0 \times \left(1 + (F_V + F_A) \times f\left(\frac{N_{INT+}}{N_{IB}}\right) + \ (F_V - F_A) \times f\left(\frac{N_{INT-}}{N_{IB}}\right)\right)$$

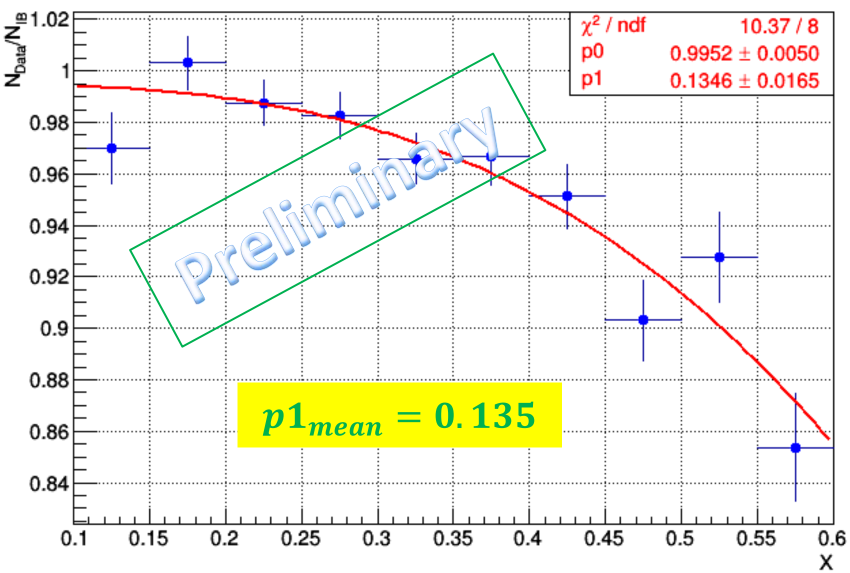
Minimum of INT+ term



Maximum of INT+ term



NO of INT+ term



$F_V + F_A$ value was measured by **E787** experiment **(Phys. Rev. Lett. 85 (2000) 2256)**.

$$|F_V + F_A| = 0.165 \pm 0.013$$

2 fits were repeated with minimal and maximal value of this measured sum.

$$\sigma_{INT+} = 0.018$$