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

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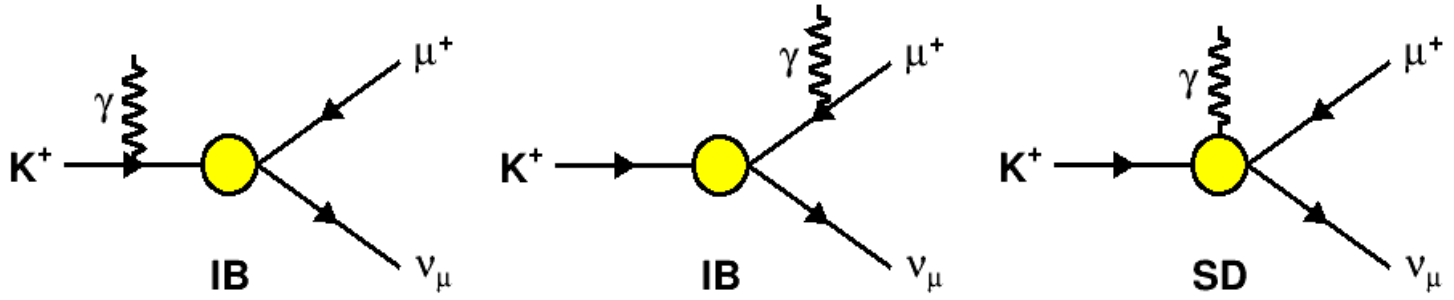
on behalf of OKA collaboration

IV Int. Conference on particle physics and astrophysics
22-26 October 2018, MEPhI, Moscow, Russia

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

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

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

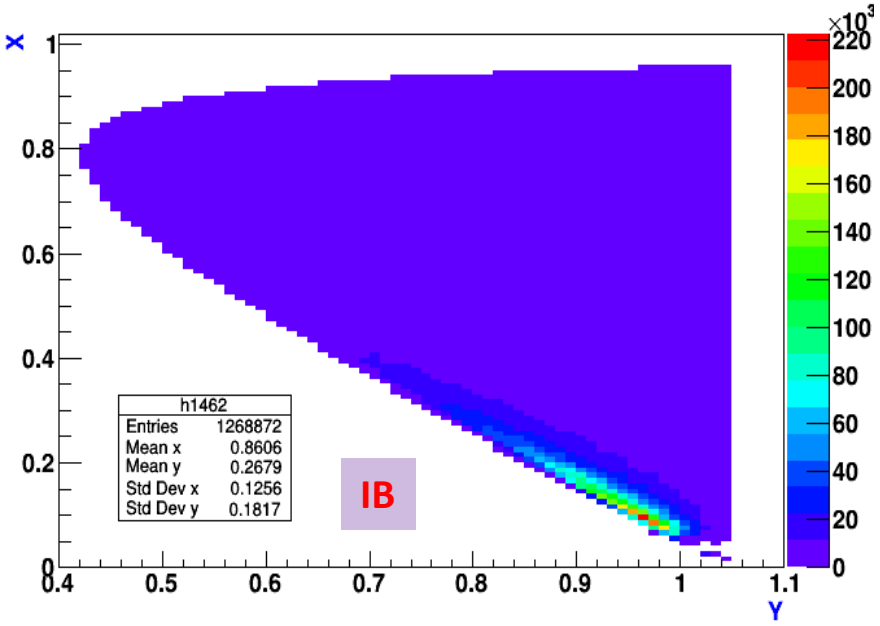
In lower order of $\chi PT\ O(p^4)$ $F_V = 0.0945$, $F_A = 0.0425$ **and** $F_V - F_A = 0.052$

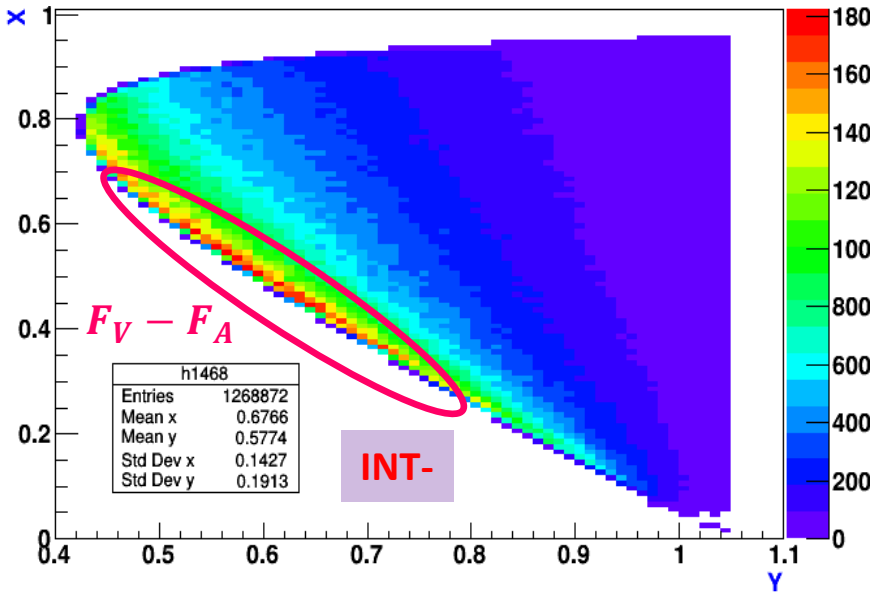
We will measure $F_V - F_A$ **difference that connects with INT-** and **SD-**.

First measurement of this difference was made by ISTRA+ (Phys.Lett. B695 (2011) 59-66)

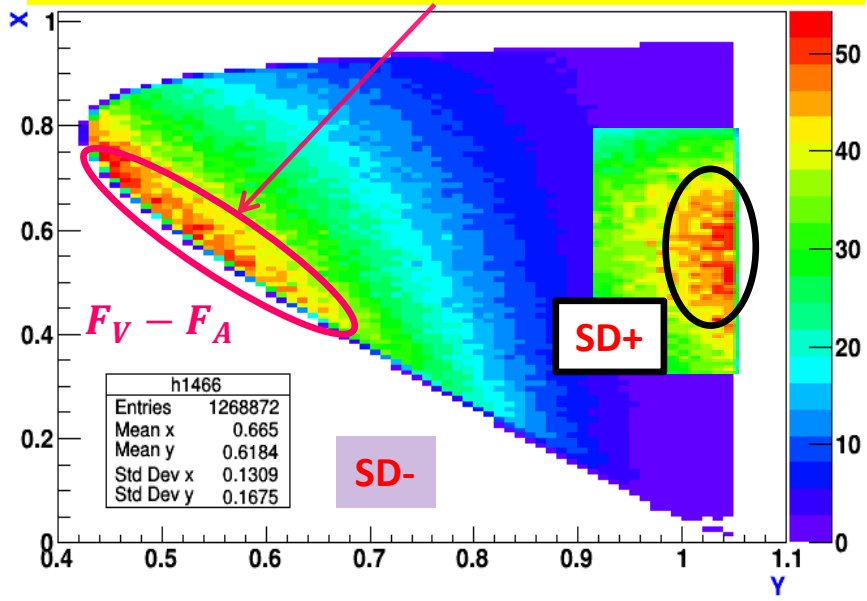
$$F_V - F_A = 0.21 \pm 0.04(stat.) \pm 0.04(syst.)$$

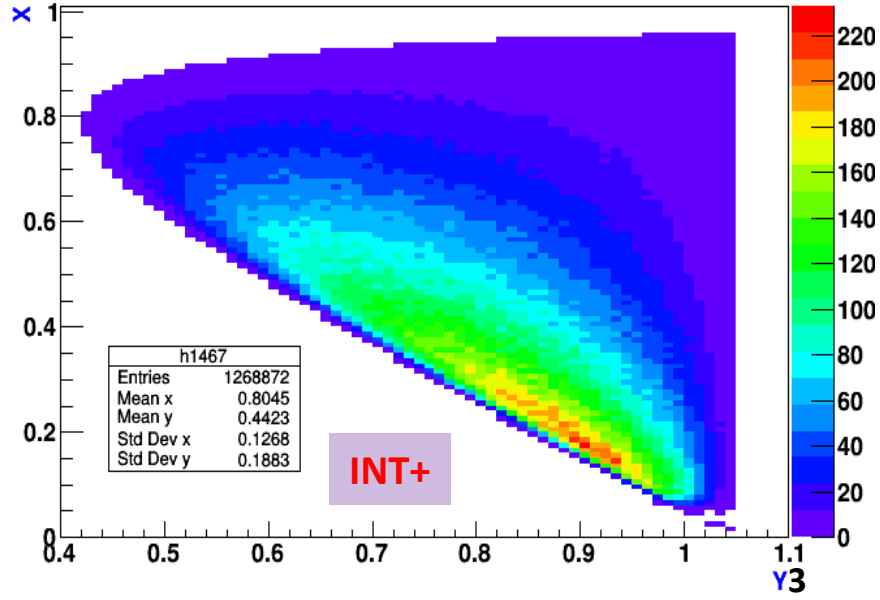
$K \to \mu\nu_\mu\gamma$ decay matrix





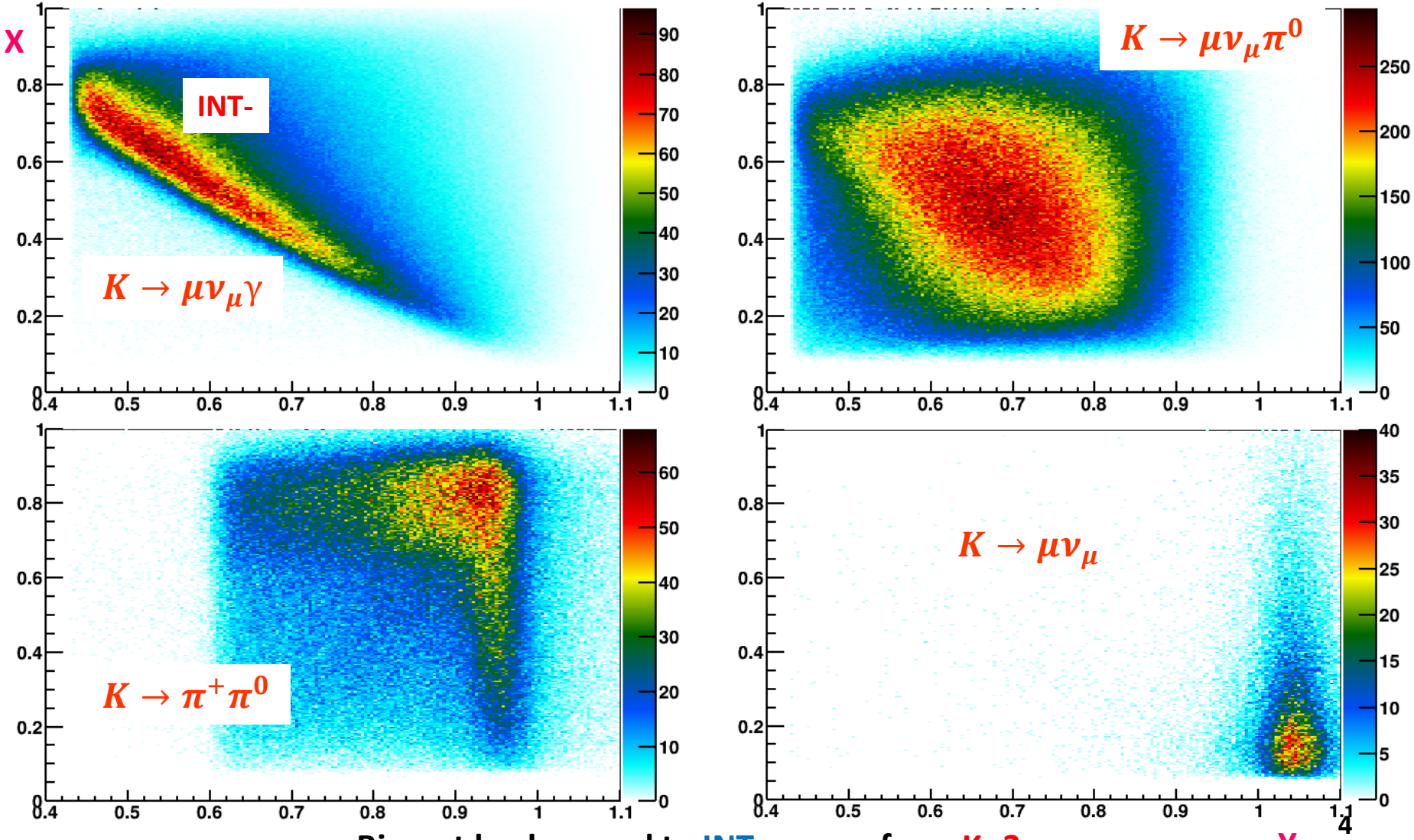
Contribution of SD- to $F_V - F_A$ is ~20 times lower





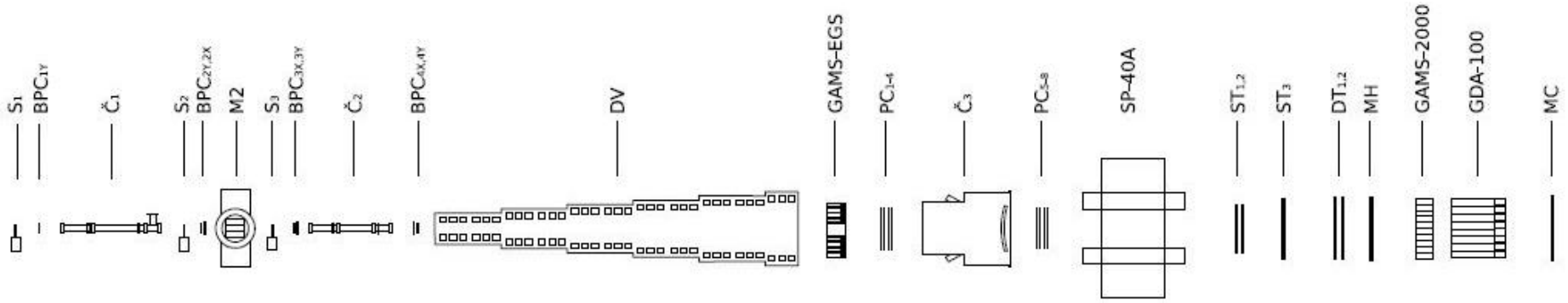
Main backgrounds

$K^+ \to \mu^+ \nu_\mu \pi^0$ (**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%)
$K^+ \to \mu^+ \nu_\mu$ 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**).

4 Triggers →

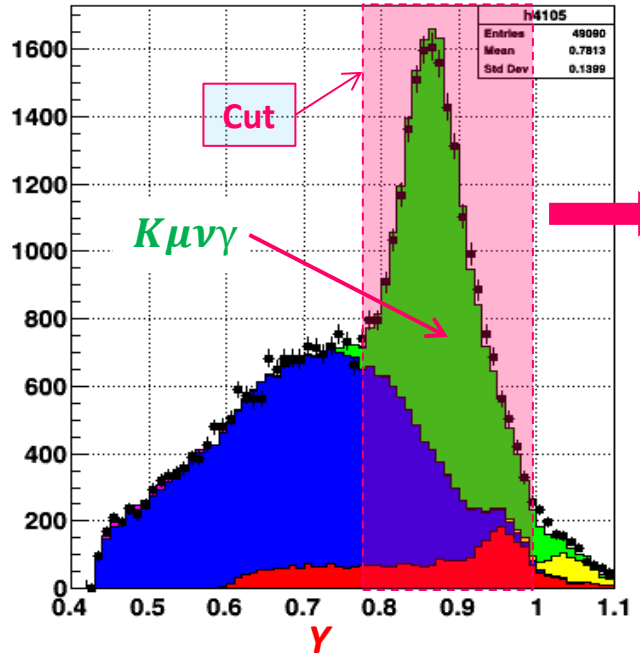
1) **Muon** - $beam * \overline{C_1} * C_2 * \overline{BK} * MC$
2) **Kaon** - $beam * \overline{C_1} * C_2 * \overline{BK}$
3) **GAMS** - $beam * \overline{C_1} * C_2 * \overline{BK} * E_{GAMS}$
4) **$2-4$ tracks** - $beam * \overline{C_1} * C_2 * \overline{BK} * MH$

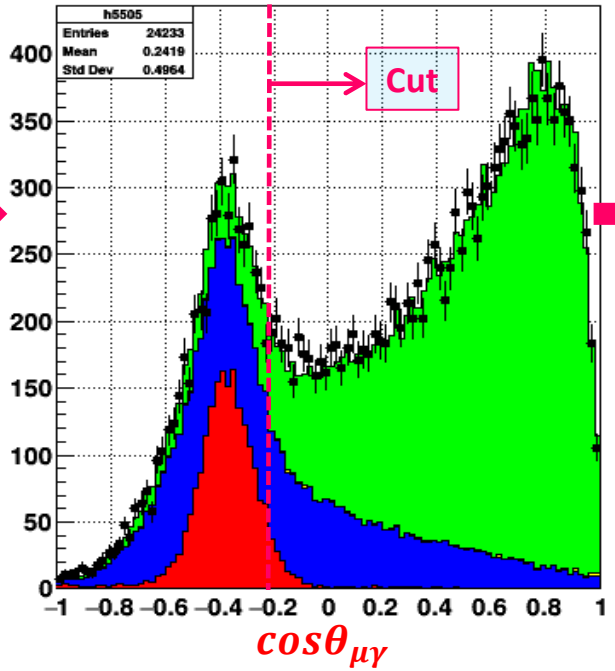
OKA beam is a RF-separated secondary beam of $\mathbf{70}\boldsymbol{GeV}$ Proton Accelerator of IHEP, Protvino.
Beam has up to **20% of kaons** with momentum $\mathbf{17.7}\boldsymbol{GeV/c}$ during **analyzed Run 14** **(November 2012).**

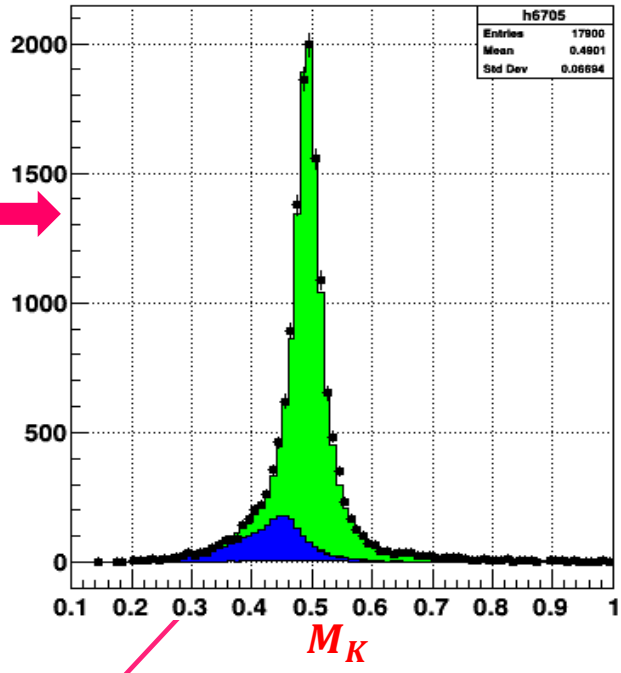
Event selection →

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

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







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

Next steps were applied for each X-stripe:

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

Lab system

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

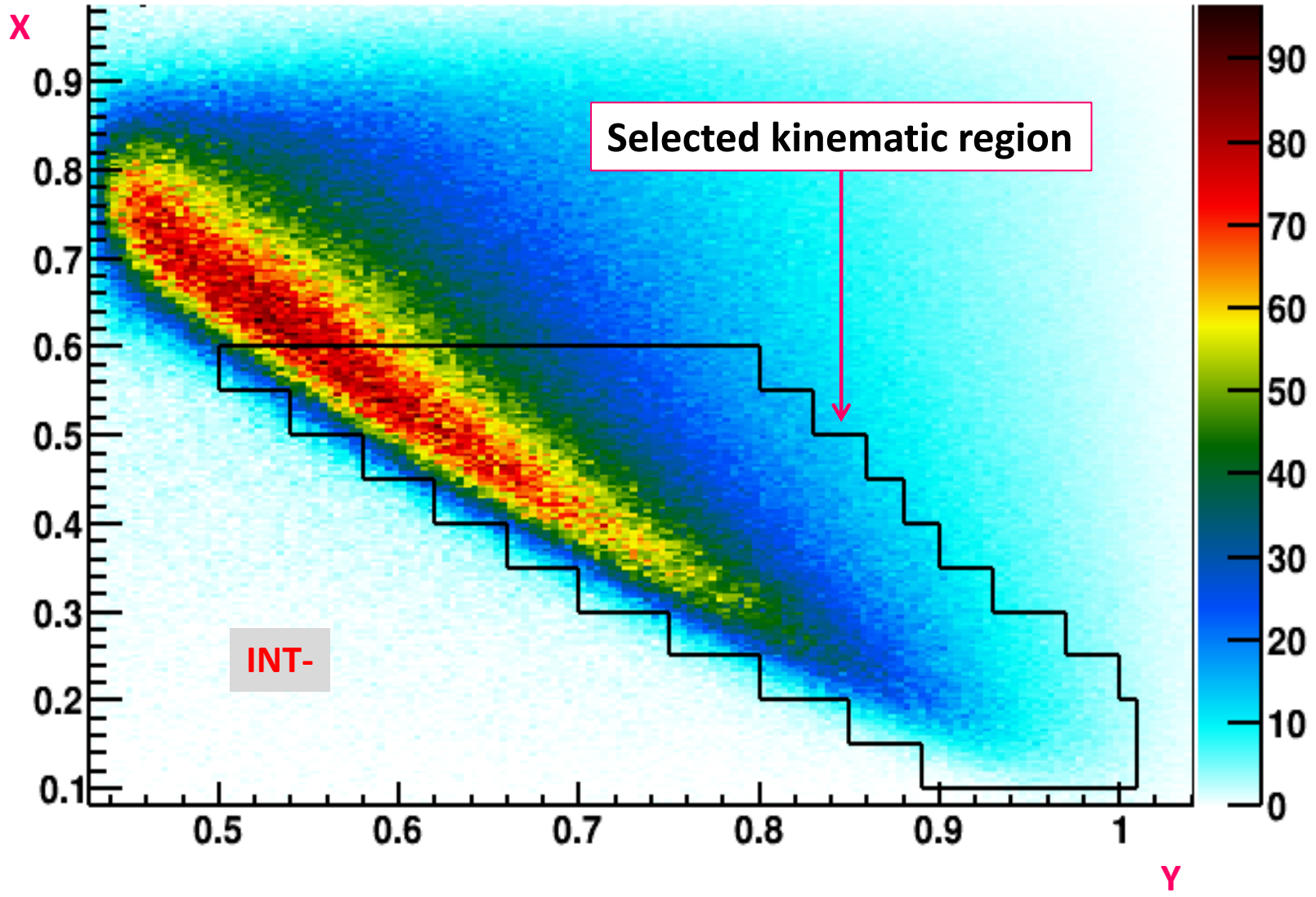
P_μ, P_ν, P_γ - 4-momentum of decay particles

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

Method was proposed by ISTRA+

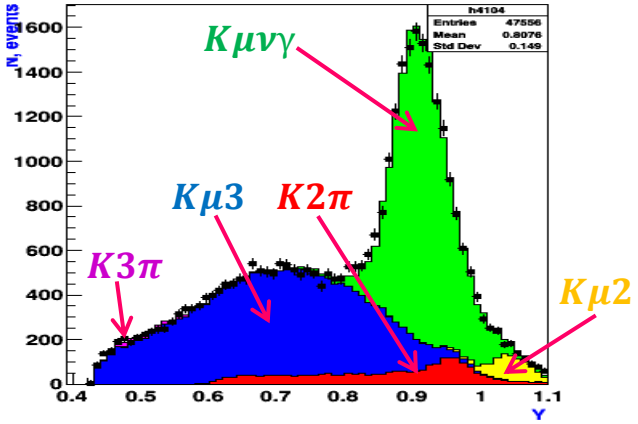
For correct estimation of statistical error σ_{exp} the errors of M_K histogram fit were used .

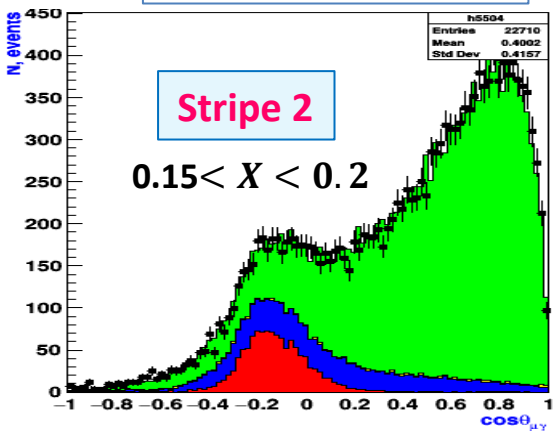
$K \to \mu\nu_\mu\gamma$ decay selection

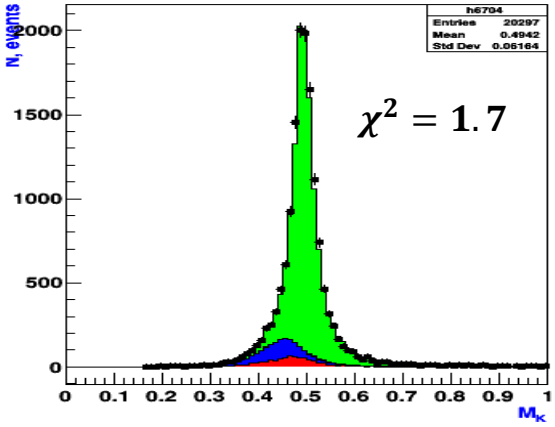


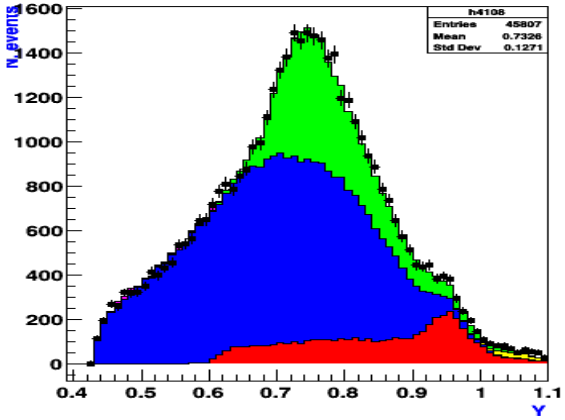
The cuts on **Y** for signal in 10 **X-stripes**.

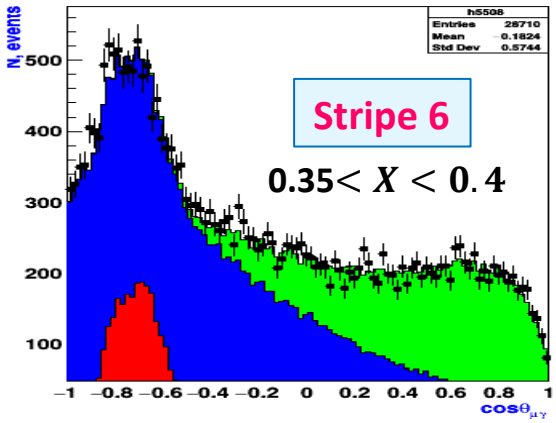
X-Stripes 2,6,10

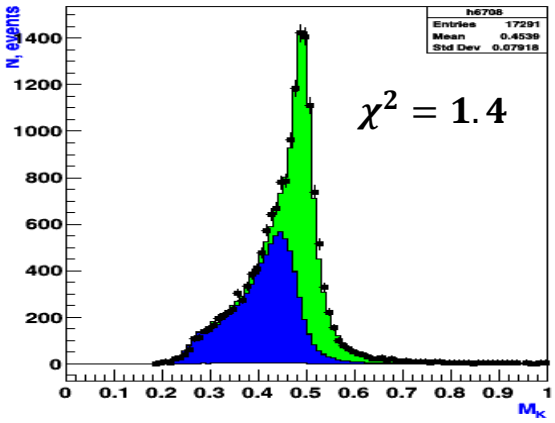


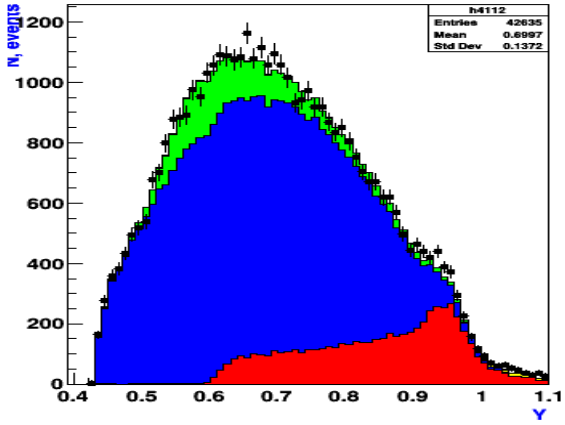


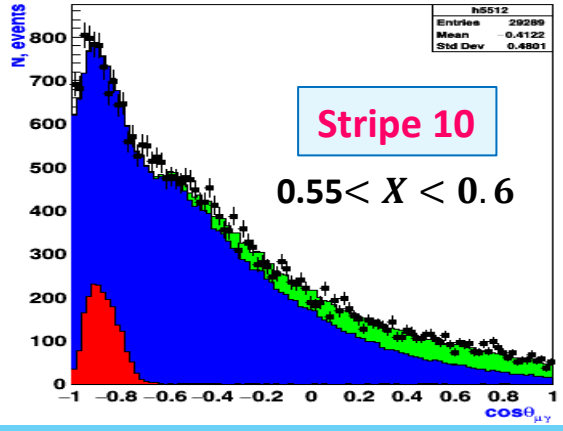


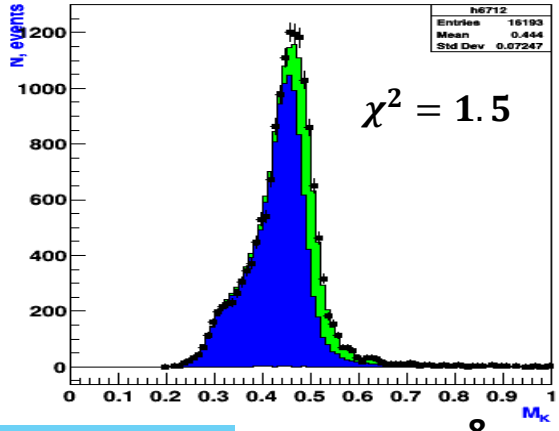












Simultaneous fit has a good agreement with $1.3 < \chi^2/NDF < 1.7$

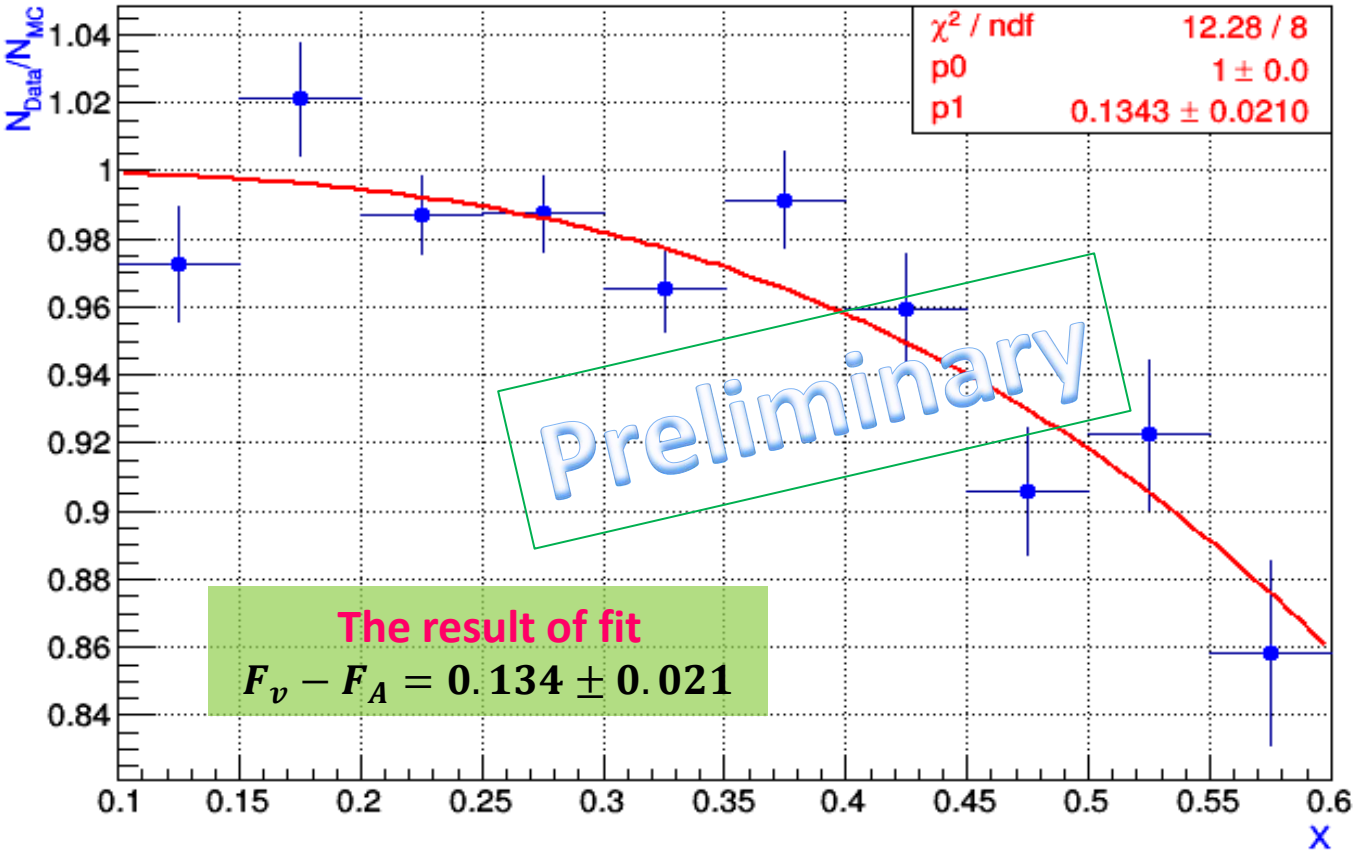
$F_v - F_A$ calculation

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 **INT-** is negligible. For large **X** we see that N_{Data} also contains negative interference term.

We fit N_{Data}/N_{IB} distribution with which is a sum of IB and **INT-**

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

$$p1 = F_v - F_A$$



The total number of selected $K \to \mu\nu\gamma$ decay events is $\sim 100K$.

Systematics

Since analysis is complicated and can depends on **width of X-stripes**, **Y** and **angle cuts** and **fit procedure** we try to estimate all possible systematics. Next possibilities are considered:

1) Non ideal description of signal and background in **MC** – $\mathbf{1.5 \times 10^{-2}}$
2) Left and right **X limits** (number of points in fit) – $\mathbf{5 \times 10^{-4}}$
3) Width of X-stripes (Δx = 0.035 and 0.07 instead 0.05) – $\mathbf{1 \times 10^{-2}}$
4) **Y limits** in X-stripes (**FWHM** instead full signal reg.) – $\mathbf{8 \times 10^{-3}}$
5) Possible contribution of **INT+** term (**E787**) – $\mathbf{1.8 \times 10^{-2}}$

The total systematics from 5 possible sources is 0.027

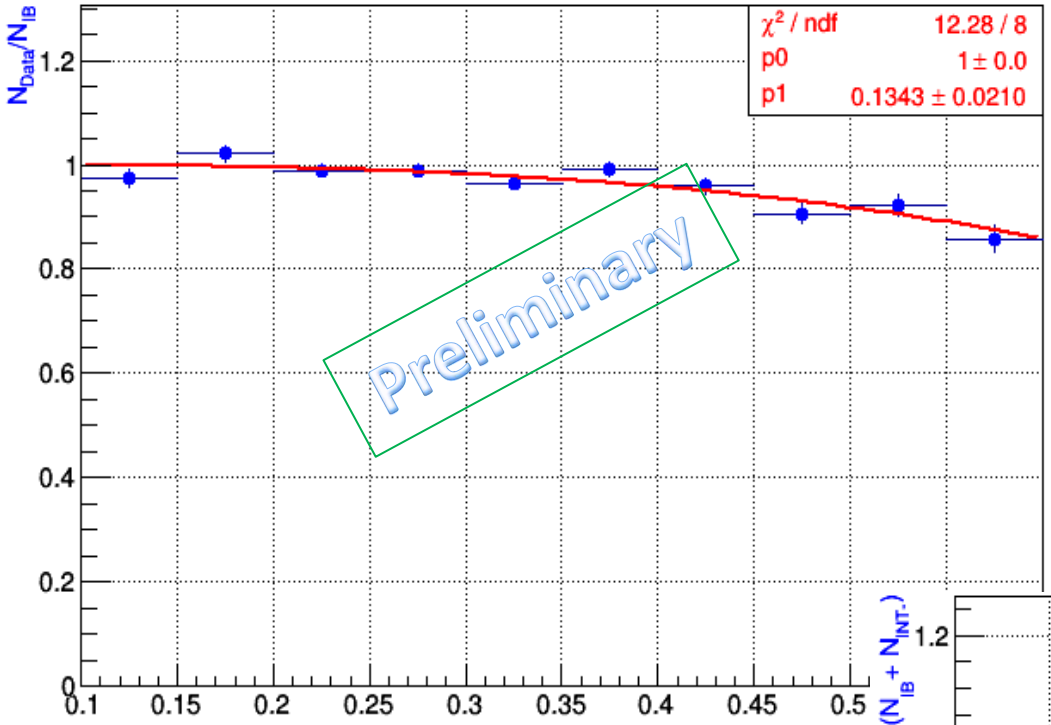
Detail description of systematics estimation procedure are presented in Backup slides.

Conclusion

1) Largest statistics about **100K** events of $K \to \mu\nu_\mu\gamma$ has been found.
2) The negative **INT−** term has been selected and $F_V - F_A$ has been measured: $F_V - F_A = 0.134 \pm 0.021(stat.) \pm 0.027(syst.)$
   The presented result is preliminary.
3) The result is **2.4σ above χPT O(p4)** prediction.
   Fresh calculation in framework of the gauged nonlocal effective chiral action (EχA) gives $F_V - F_A = 0.081$ (arXiv:1810.06815 [hep-ph], Oct 16 2018).
   Our result is 1.6σ above EχA prediction.
4) This result is comparable within the errors with similar analysis of **ISTRA+** experiment : $F_V - F_A = 0.21 \pm 0.04(stat.) \pm 0.04(syst.)$
5) **Measured stat. and syst. errors are ~2 times less than result of ISTRA+**

Backup slides

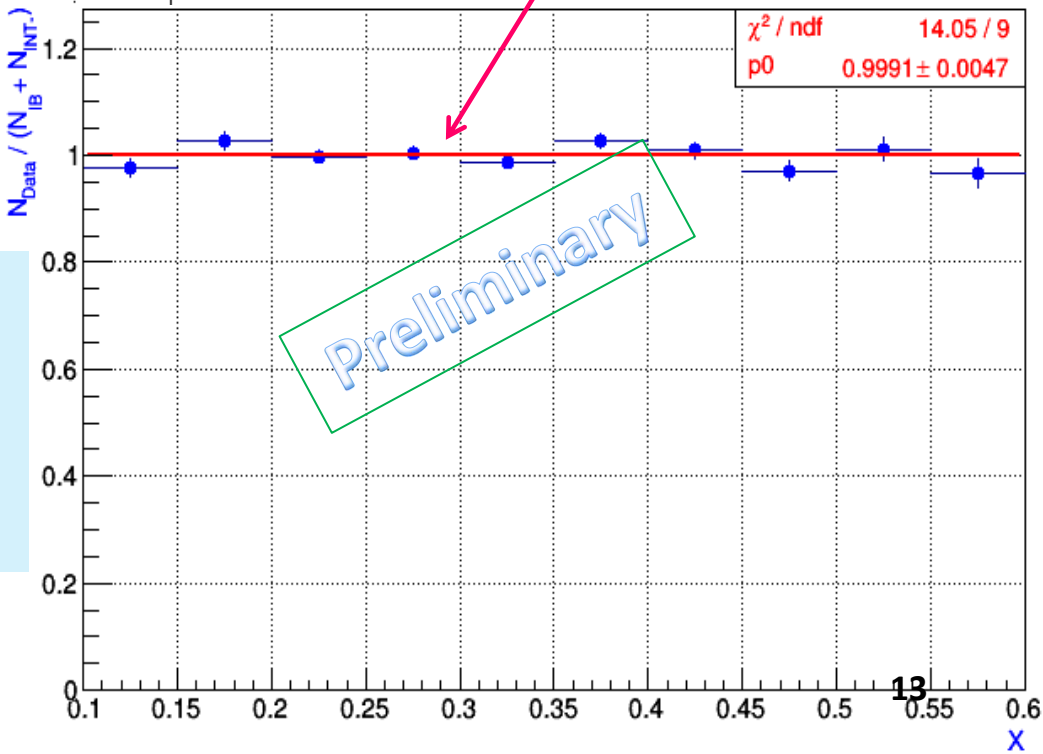
Verification *of the fit method*



Measured $p1 = F_V - F_A = 0.134$ value and normalization factor $p0 = 1$ were used to build new $\boldsymbol{p_{signal}}$ function

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

Since the $\boldsymbol{N_{Data}/(N_{IB} + N_{INT-})}$ ratio does not depend on **X** the fit procedure is correct.



For additional checking the method we fit the original plot by

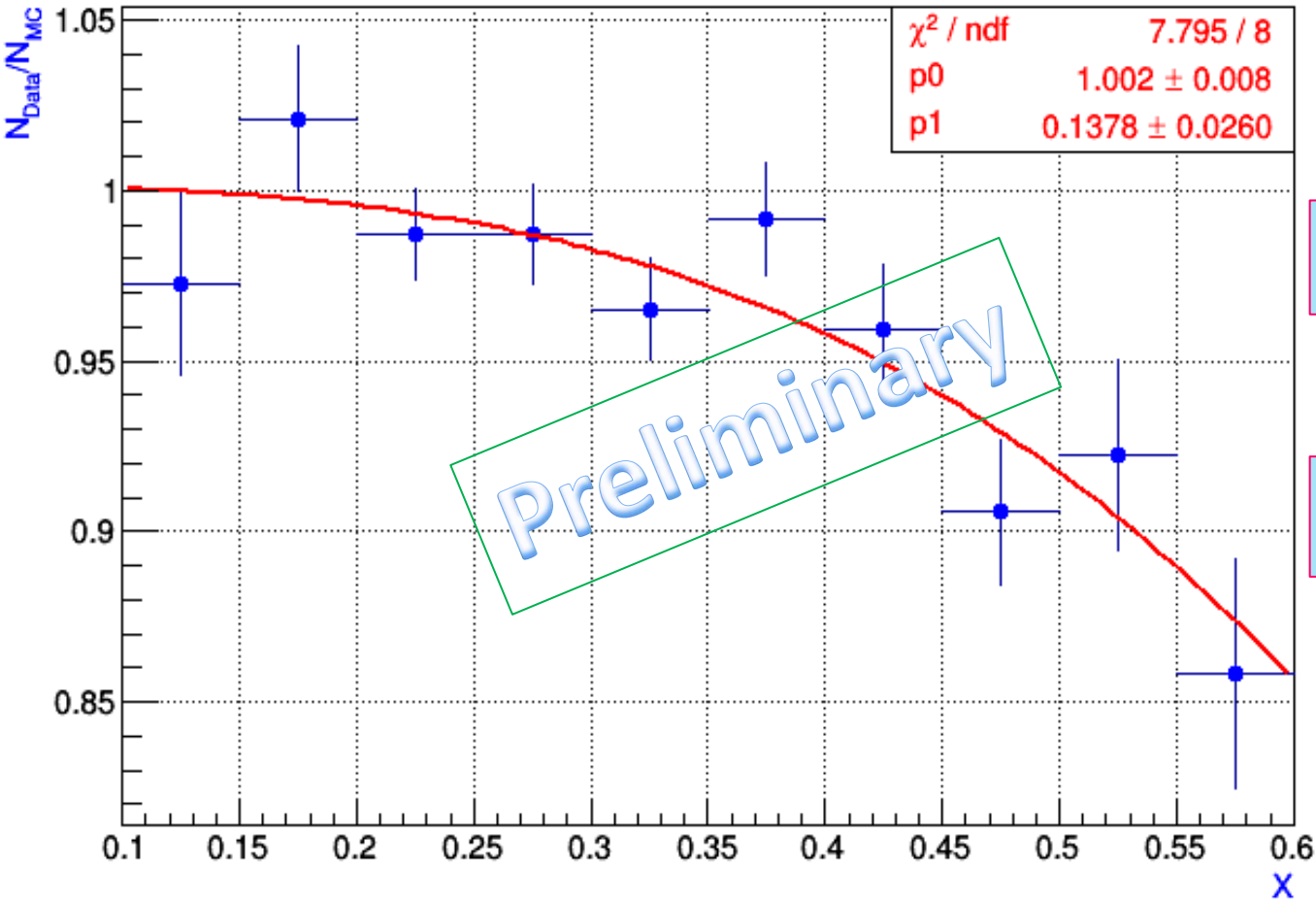
$$\boldsymbol{p_{signal}} = p0 \times (1 + (\mathbf{0.134} + p') \times f\left(\frac{N_{INT-}}{N_{IB}}\right))$$

As we could suppose possible additional term $\boldsymbol{p' = 3 \times 10^{-5}}$ is about zero.

Systematics

1) Non ideal forms of signal and background

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 = 1.54

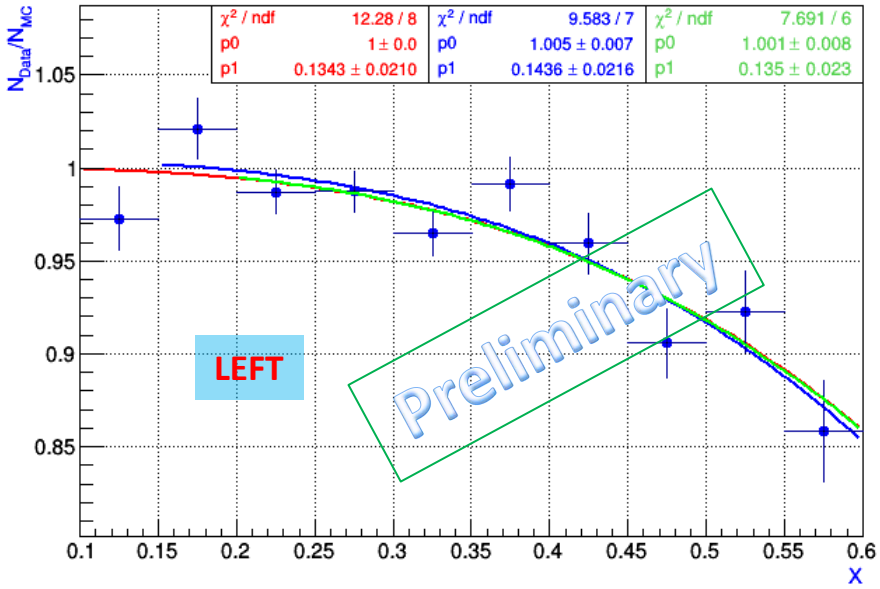
Present fit
χ^2/NDF = 0.97

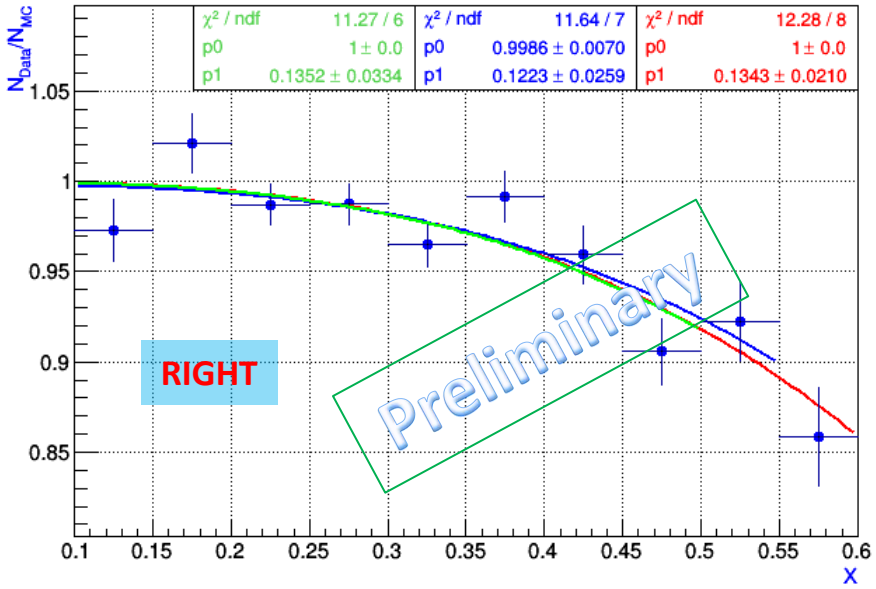
New value of $F_V - F_A$ is consistent with the main one but the fit error is larger.
We suppose σ_{form} depends as $\sigma^2{}_{fit} = \sigma^2{}_{form} + \sigma^2{}_{stat}$ and therefore

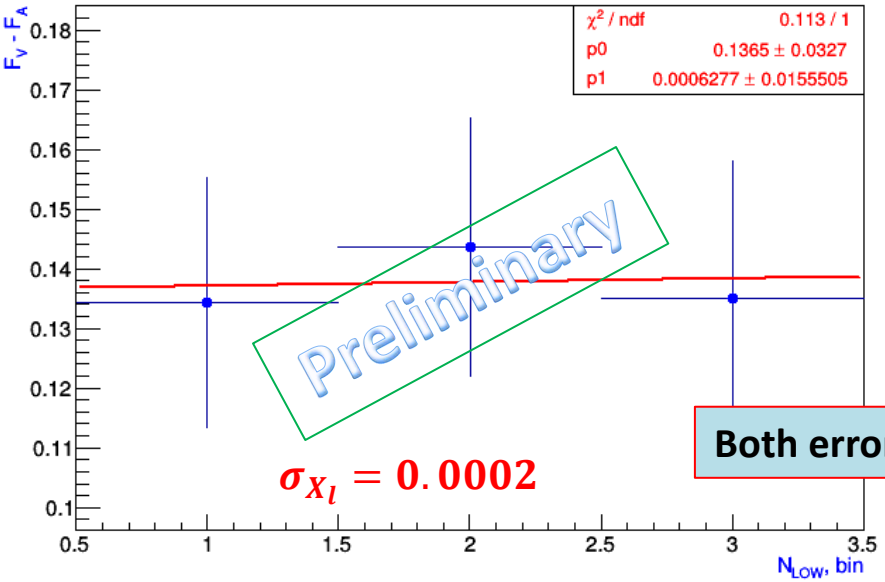
$\sigma_{stat} = 0.021$ → $\sigma_{form} = 0.0153$

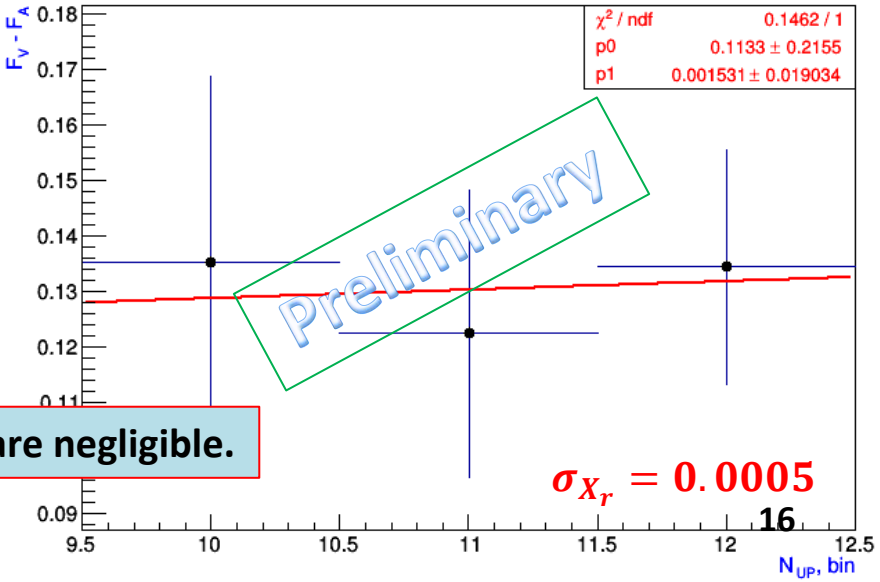
2) Left and right X limits

Dependency N_{Data}/N_{IB} on **X** was fitted by removing points at the left (right) edge.
The result points were fitted by straight line for conservative estimate of systematics.
The line slope multiplied by the resolution in **X** (from **MC**) gives systematic error.



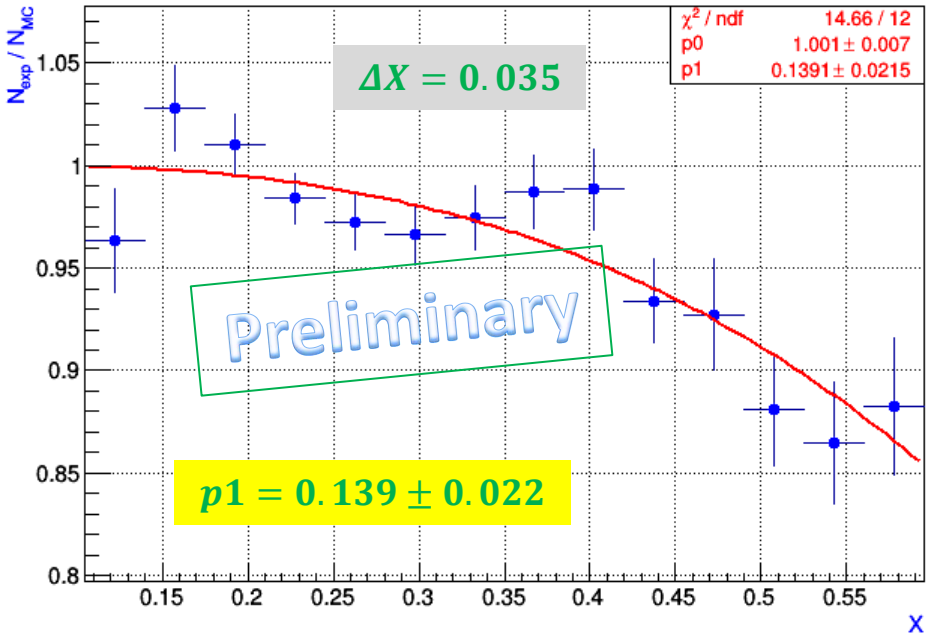


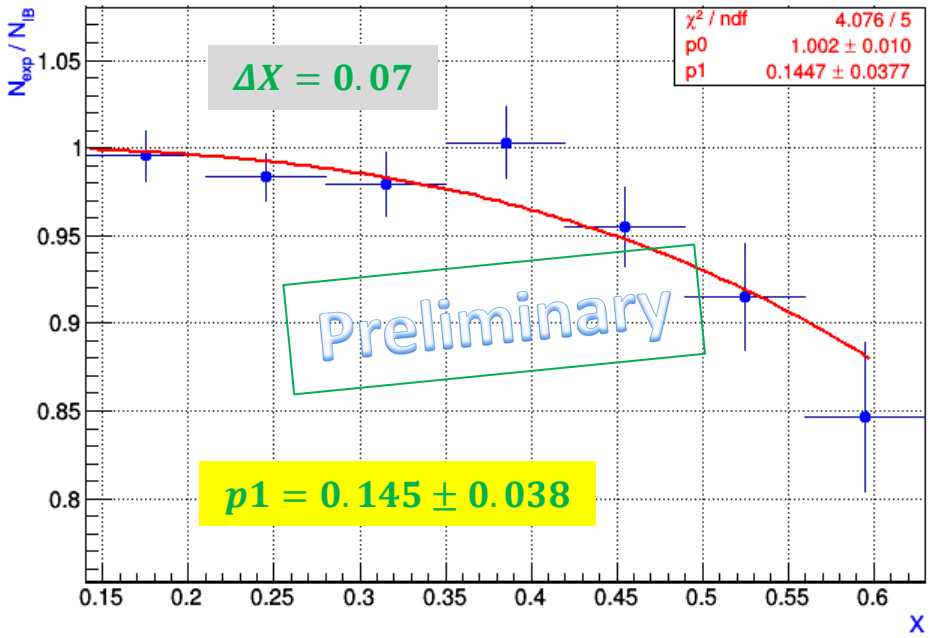


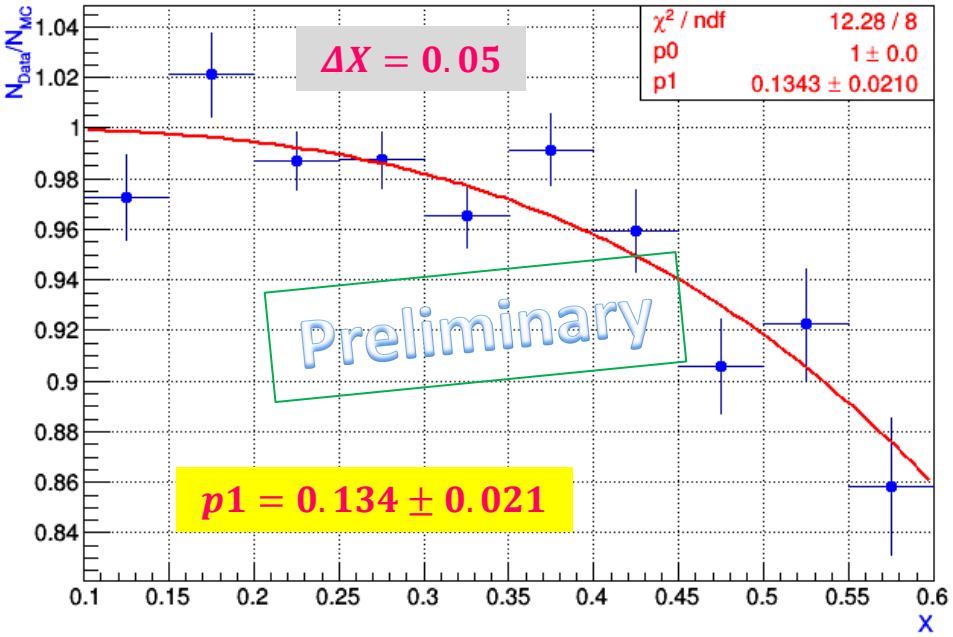


Both errors are negligible.

3) *Width of X-stripes*







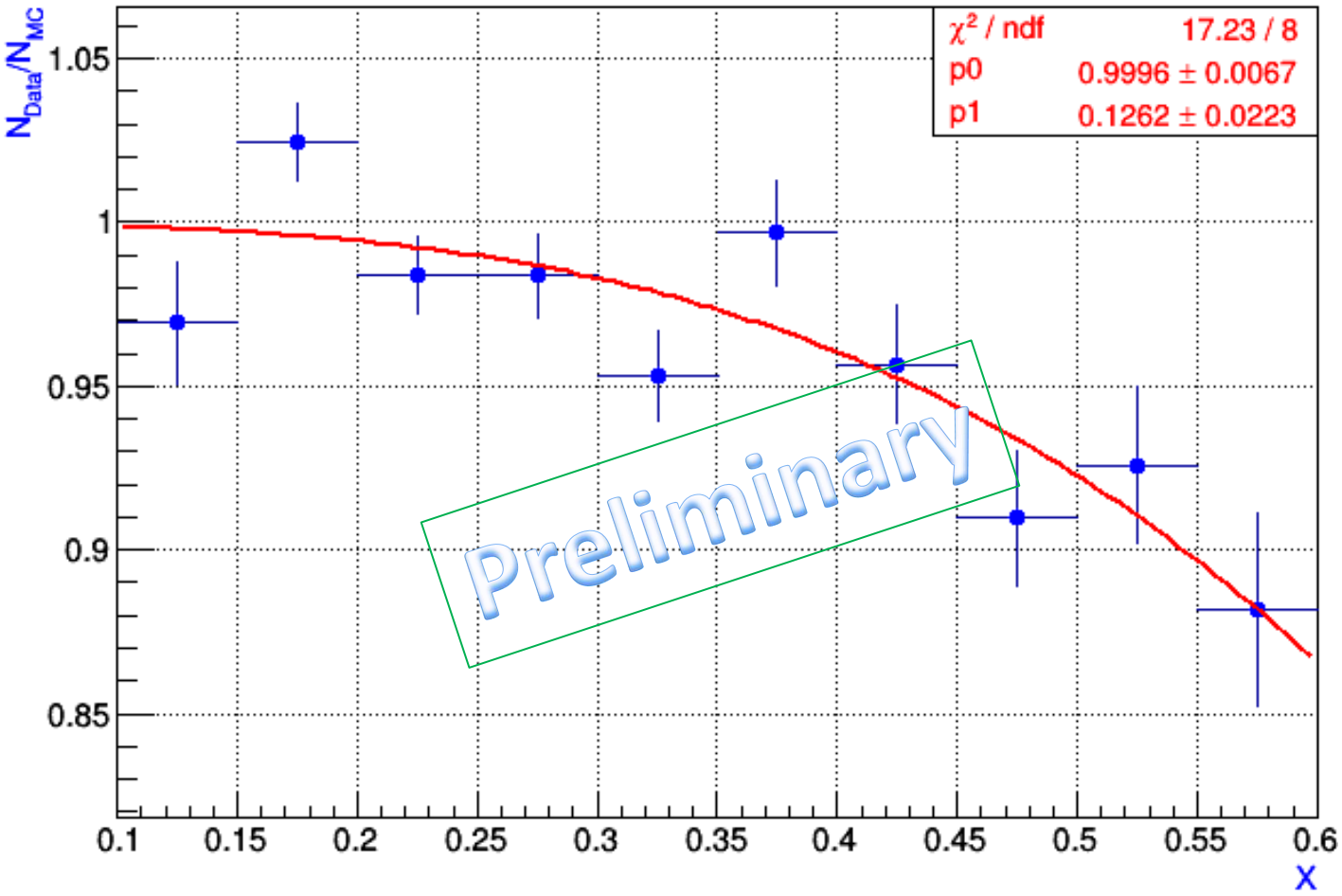
We repeated the data analysis procedure for 2 other values of **X**-binning:

- $\Delta X = 0.035$, that is the worst **X**-resolution at maximal value of **X = 0.6**;
- $\Delta X = 0.07$ **2 times higher** value.

$$\sigma_X = 0.01$$

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.

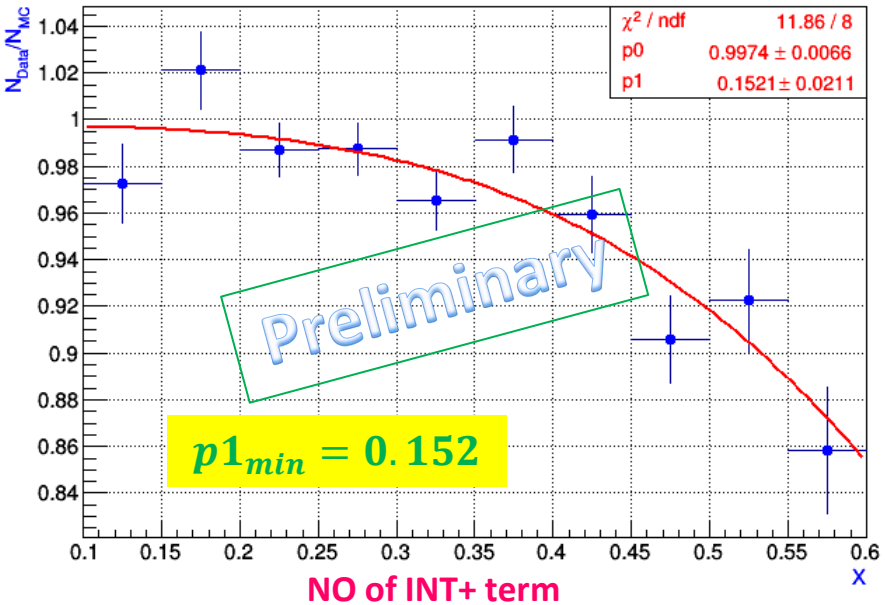


$$\sigma_X = 0.008$$

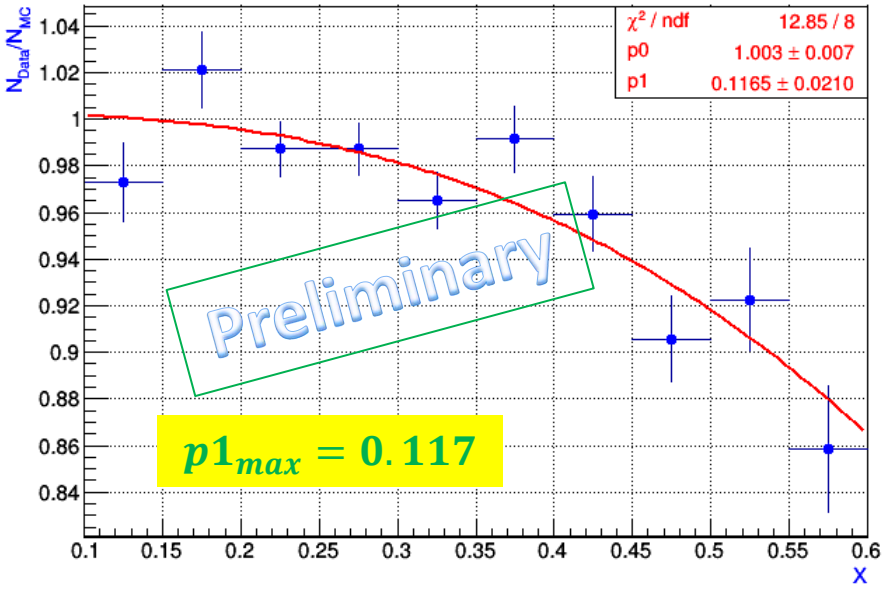
5) Possible contribution of INT+ term

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

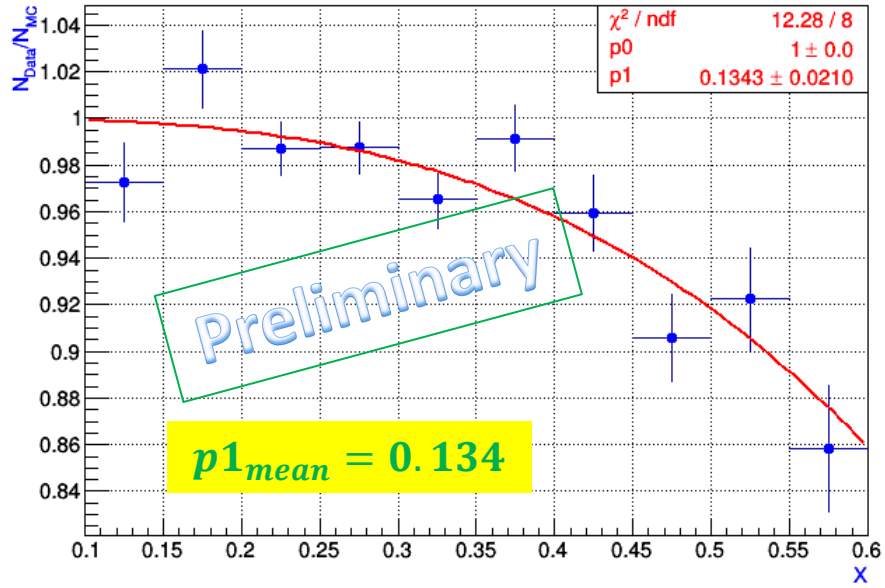
Minimum of INT+ term



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.

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