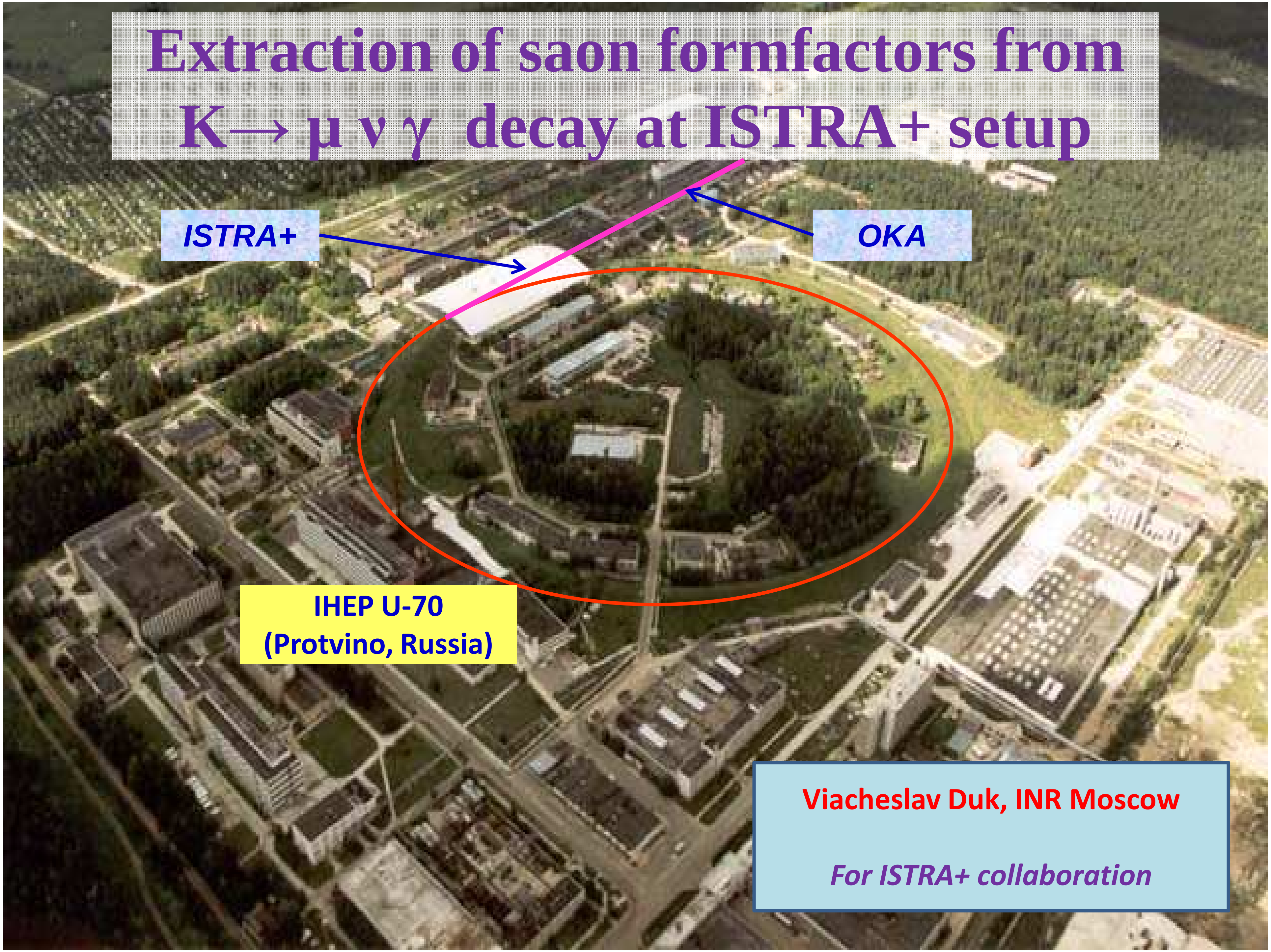
Extraction of saon formfactors from $K \to \mu \nu \gamma$ decay at ISTRA+ setup



Viacheslav Duk, INR Moscow

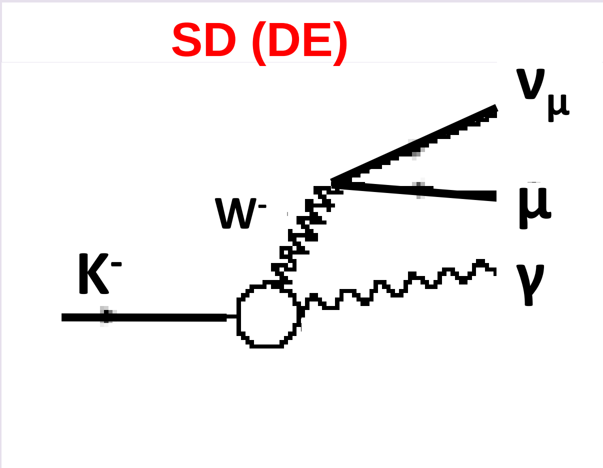
For ISTRA+ collaboration

Outline

- $K \to \mu \nu \gamma$ decay
- ISTRA+ experiment
- Event selection
- Background rejection
- Signal extraction
- Spectrum fitting
- Results
- Conclusions

$K \rightarrow \mu \nu \gamma$ decay: motivation

photon emitted from the vertex (SD or DE) → Probing electroweak structure of kaon → Testing predictions of ChPT, LFQM, …



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

$\Gamma=\Gamma_{IB}+\Gamma_{SD}+\Gamma_{INT}$

K→μνγ theory: differential decay rate

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

3 main terms:
IB – dominant
SD±, INT± - most interesting (→ F_V , F_A)

Kinematical variables:
$x=2*E_\gamma(cm)/M_k$
$y=2*E_\mu(cm)/M_k$

$$f_{IB}(x,y) = \left[\frac{1-y+r}{x^2(x+y-1-r)}\right] \times \left[x^2 + 2(1-x)(1-r) - \frac{2xr(1-r)}{x+y-1-r}\right],$$

$$f_{SD+} = [x+y-1-r][(x+y-1)(1-x)-r],$$

$$f_{SD-} = [1-y+r][(1-x)(1-y)+r],$$

$$f_{INT+} = \left[\frac{1-y+r}{x(x+y-1-r)}\right][(1-x)(1-x-y)+r],$$

$$f_{INT-} = \left[\frac{1-y+r}{x(x+y-1-r)}\right][x^2-(1-x)(1-x-y)-r],$$

$$r = \left[\frac{M_\mu}{M_K}\right]^2,$$

$$A_{IB} = \Gamma_{K_{\mu 2}} \frac{\alpha}{2\pi} \frac{1}{(1-r)^2},$$

$$A_{SD} = \Gamma_{K_{\mu 2}} \frac{\alpha}{8\pi} \frac{1}{r(1-r)^2} \left[\frac{M_K}{F_K}\right]^2,$$

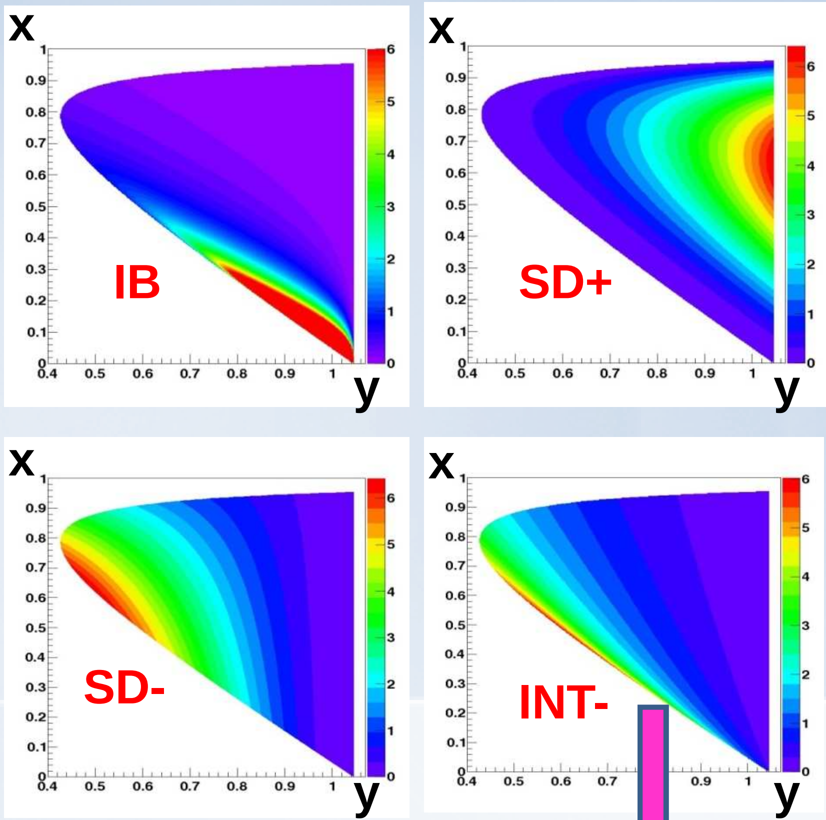
$$A_{INT} = \Gamma_{K_{\mu 2}} \frac{\alpha}{2\pi} \frac{1}{(1-r)^2} \frac{M_K}{F_K}.$$

K→μνγ theory: differential decay rate

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

3 main terms:
IB – dominant
SD±, INT± - most interesting (→ F_V , F_A)

Kinematical variables:
$x=2*E_{\gamma}(cm)/M_k$
$y=2*E_{\mu}(cm)/M_k$



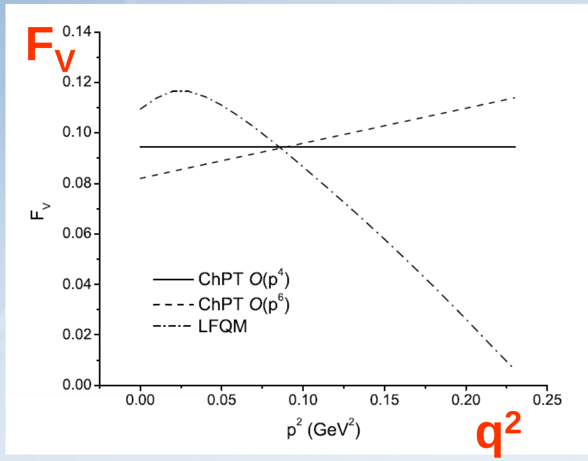
Our strategy:
Focusing on INT- region

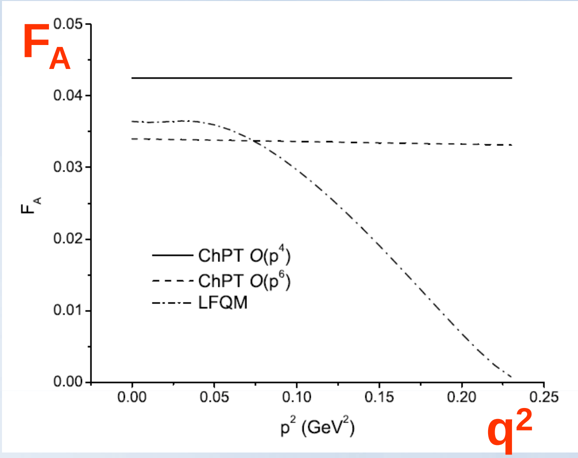
K→μνγ theory: formfactors

ChPT O(p⁴):
F_V , F_A constant

ChPT O(p⁶):
F_V , F_A linear functions of q^2

LFQM:
F_V , F_A depend on q^2 in a complicated way





$$q^2 = (P_K - P_\gamma)^2 = M_k^2 * (1-x)$$

ChPT O(p⁴)
F_V = 0.0945
F_A= 0.0425
F_V+F_A= 0.137
F_V-F_A= 0.052

ChPT O(p⁶)
$F_V=F_V(0) * [1+\lambda*(1-x)]$
$F_V(0)$= 0.082
λ = 0.4
$F_A \approx$ 0.034

$K \to \mu\nu\gamma$: main experimental results

experiment	collaboration	year	cuts	results
Barmin et al	ITEP	1988	$P_\mu < 231.5$ MeV/c	BR(IB)
Demidov et al	ITEP	1990	$P_\mu < 231.5$ MeV/c	BR(IB)
Akiba et al	E104 (KEK)	1985	$214.5 < P_\mu < 231.5$ MeV/c	BR(IB)
Adler et al	E787 (BNL)	2000	$P_\mu > 218.4$ MeV/c $E_\gamma > 90$ MeV	$\lvert F_V + F_A \rvert$, BR(SD+)

Formfactors:

E787(BNL) Phys.Rev.Lett.85(2000)2256 ($K \to \mu\nu\gamma$)

$|F_V+F_A|=0.165 \pm 0.013$; $-0.04<F_V-F_A<0.24$

E865(BNL) Phys.Rev.Lett.89(2002)061803 ($K \to e\nu e^+e^-$, $K \to \mu\nu e^+e^-$)

$F_V+F_A=0.147 \pm 0.026$; $F_V-F_A=0.077 \pm 0.028$

ISTRA+ collaboration

- Institute for High Energy Physics, Protvino (**IHEP**)
- Institute for Nuclear Resaerch, Moscow (**INR**)
- Joint Institute for Nuclear Research, Dubna (**JINR**)

ISTRA+: from $\pi \rightarrow e \nu \gamma$ to $K \rightarrow \mu \nu \gamma$

1990

Study of $\pi \rightarrow e \nu \gamma$ decay: measuring F_V, $\gamma = F_A/F_V$, F_T

2003-2007

$K \rightarrow e\nu\pi^0$, **$K \rightarrow \mu\nu\pi^0$**: high statisitics, formfactor measurements.
Phys.Lett.B589(2004)111, Phys.Lett.B581(2004)31
$K \rightarrow \pi^- \pi^0\pi^0$: dalitz plot slope measurement.
Phys.Lett.B567(2003)159
$K \rightarrow \pi^- \pi^0 P$: search for light pseudoscalar sgoldstino.
Phys.Lett.B602(2004)149
$K \rightarrow e\nu\pi^0$: BR and V_{us} measurement. arXiv:0704.2052 [hep-ex]
$K \rightarrow e\nu\pi^0\gamma$: T-odd correlation. Phys.Atom.Nucl.70:734-740,2007
$K \rightarrow \mu\nu\pi^0\gamma$: first observation of the decay, T-odd correlation.
Phys.Atom.Nucl.70:29-34,2007

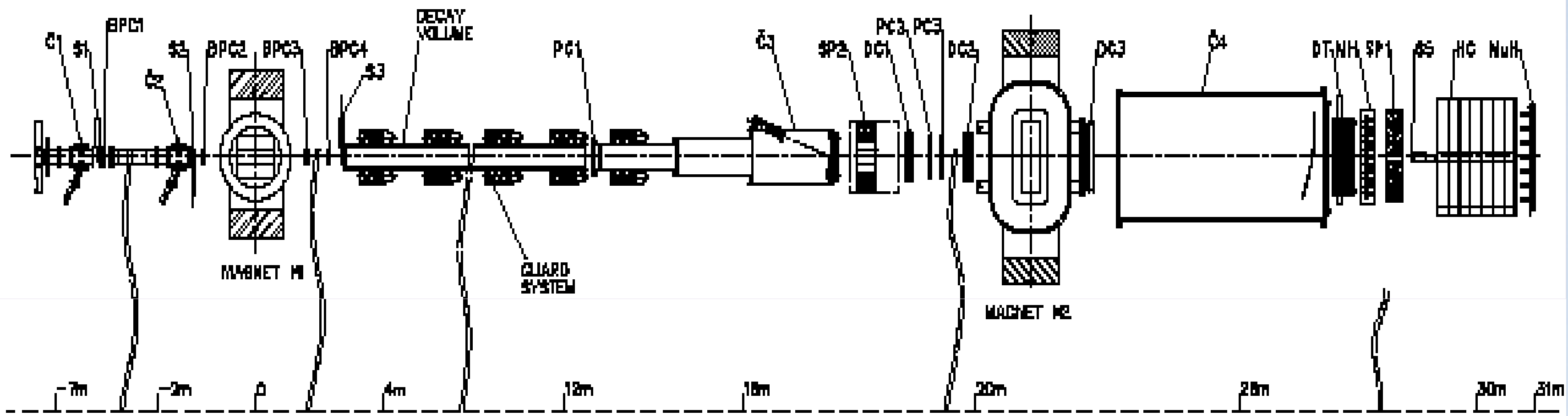
2010

Study of $K \rightarrow \mu \nu \gamma$ decay: measuring $F_V - F_A$

> 2010

ISTRA+ ⇒ OKA, see next talk by A.Khudyakov

ISTRA+ setup

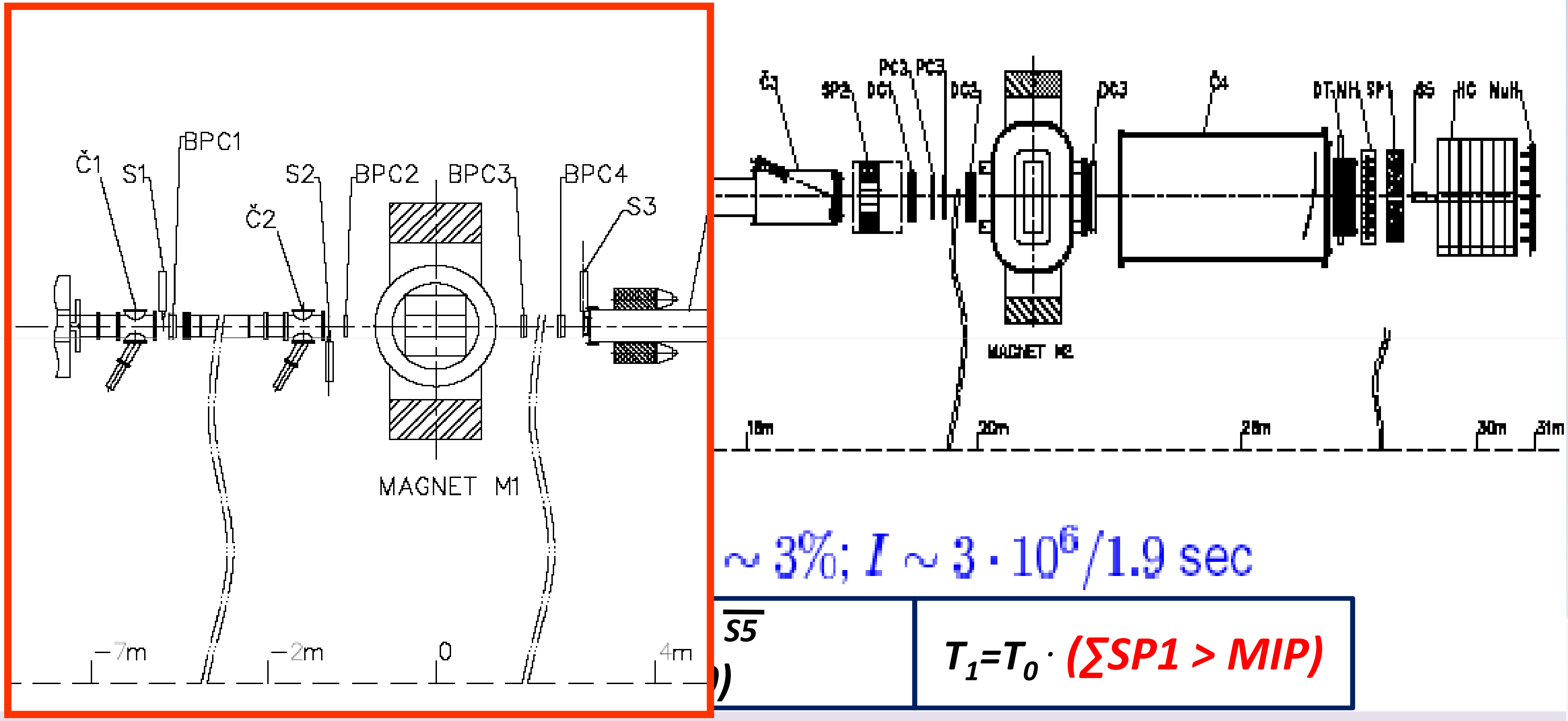


$p \sim -25$ GeV ; $\Delta p/p \sim 1.5\%$; $K^- \sim 3\%$; $I \sim 3 \cdot 10^6/1.9$ sec

$T_0 = S1 \cdot S2 \cdot S3 \cdot S4 \cdot C0 \cdot C1 \cdot C2 \cdot \overline{S5}$ *(prescaled by a factor of ~10)*	$T_1 = T_0 \cdot (\sum SP1 > MIP)$

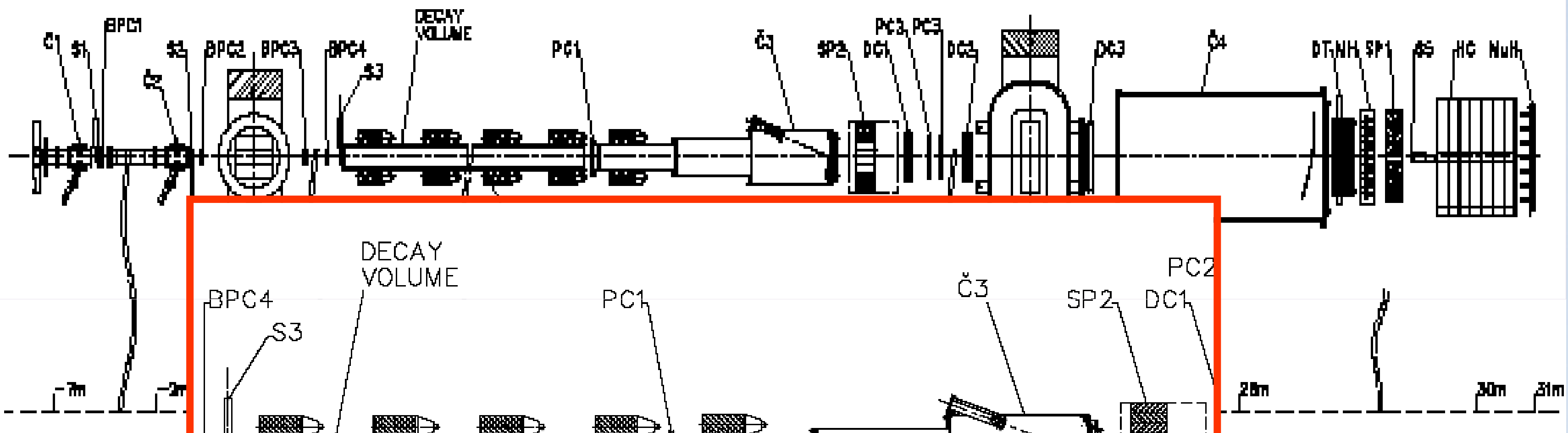
C1-C4 – thresh. cherenkov counters; S1-S5 – scintillation counters; PC1-PC3 – proportional chambers; SP2 – veto calorimeter; SP1 – lead-glass calorimeter; DC – drift chambers; DT-drift tubes; MH – matrix scintilation godoscope

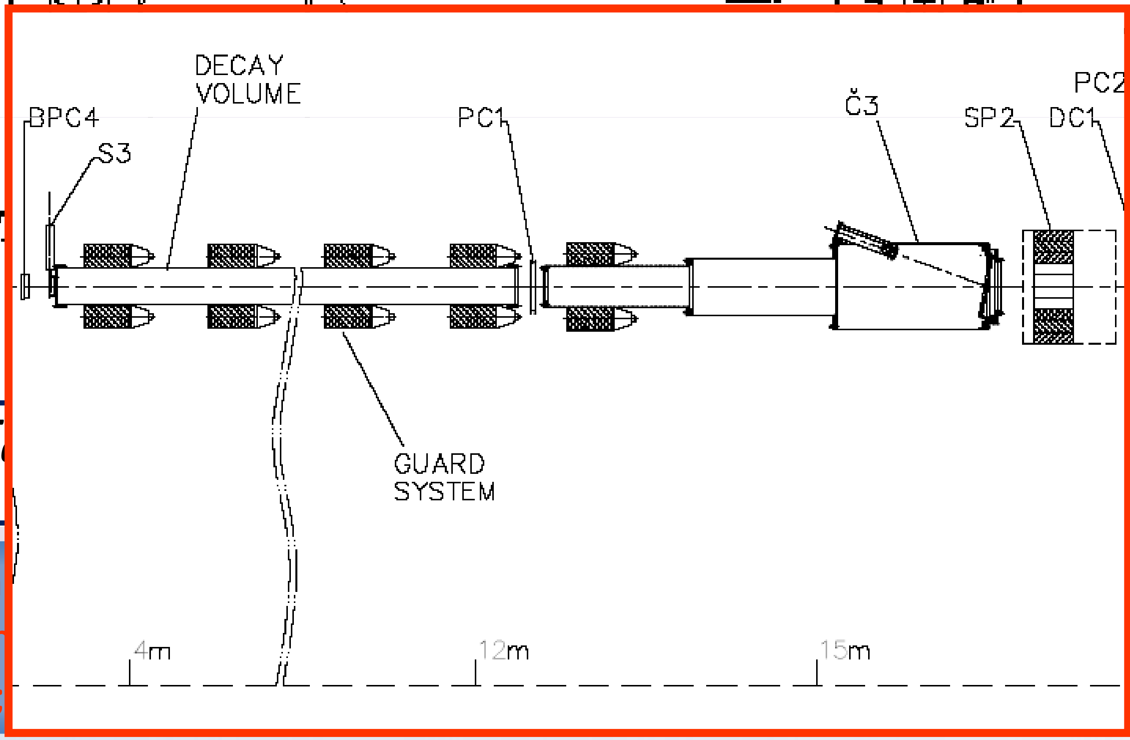
ISTRA+ setup: beam part



C1-C4 – thresh. cherenkov counters; S1-S5 – scintillation counters; PC1-PC3 – proportional chambers; SP2 – veto calorimeter; SP1 – lead-glass calorimeter; DC – drift chambers; DT-drift tubes; MH – matrix scintilation godoscope

ISTRA+ setup: decay volume



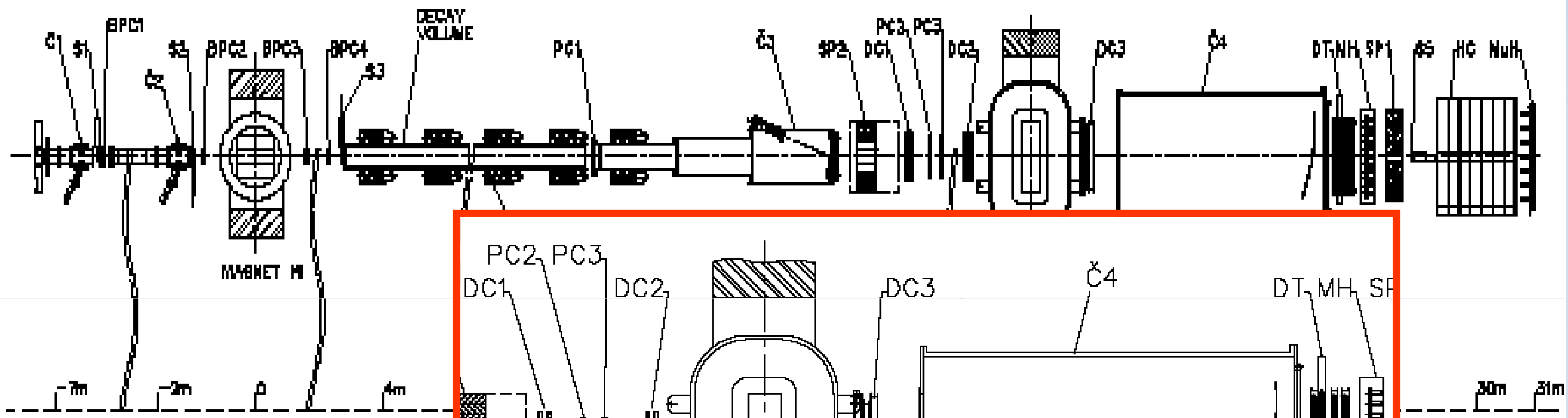


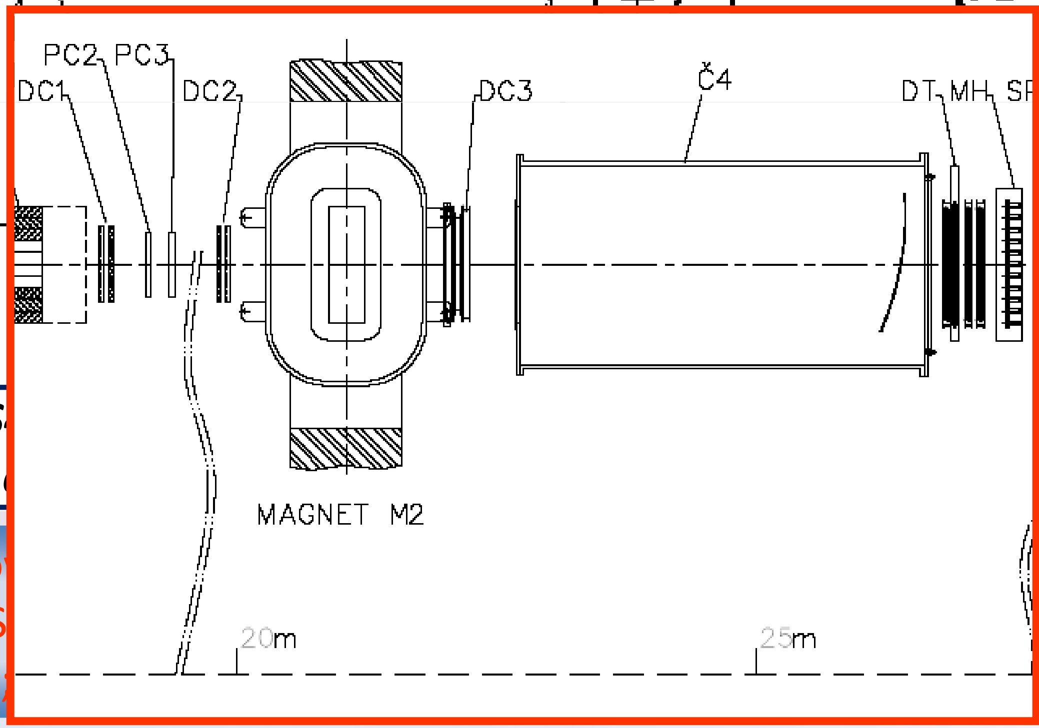
$p \sim -25$ … ec

T… MIP)

C1-C4 – th… C1-PC3 – proportion… rimeter; DC – drift chambers;

ISTRA+ setup:
magnetic spectrometer





$p \sim -25$ GeV ; $\Delta p/p$

T_0=S1 · S2 · S3 · S

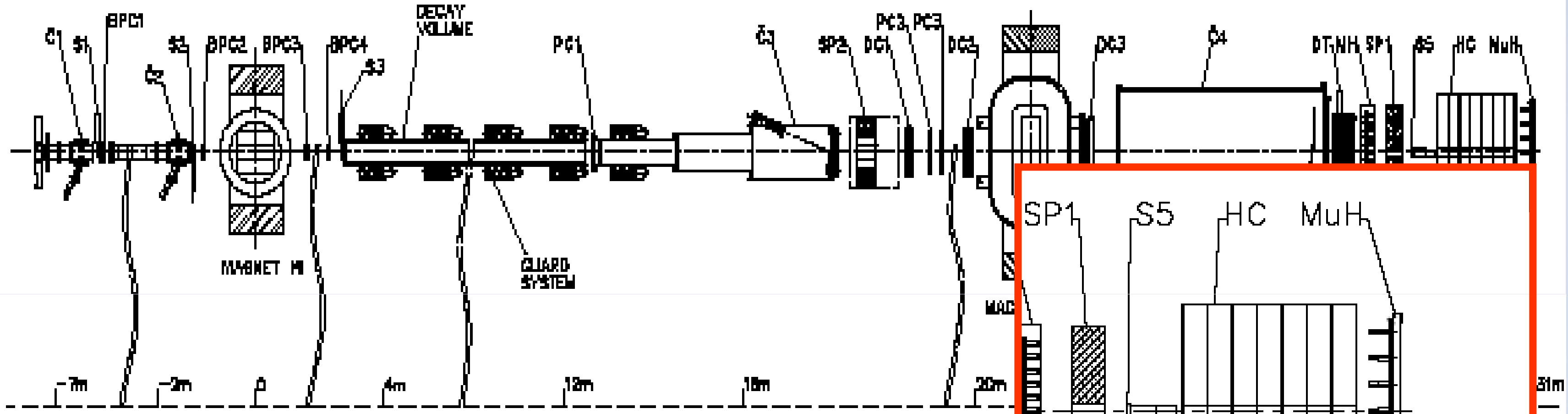
(prescaled by

C1-C4 – thresh. cherenko

proportional chambers; S … C – drift

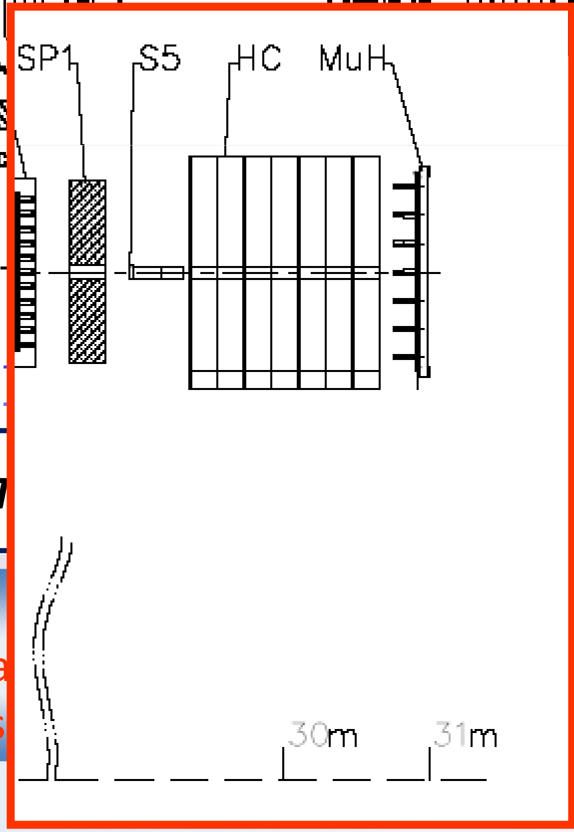
chambers; DT-drift tubes;

ISTRA+ setup: ECAL, HCAL



$p \sim -25$ GeV ; $\Delta p/p \sim 1.5\%$; $K^- \sim 3\%$; $I \sim 3 \cdot$

$T_0 = S1 \cdot S2 \cdot S3 \cdot S4 \cdot C0 \cdot C1 \cdot C2 \cdot \overline{S5}$ *(prescaled by a factor of ~10)*	$T_1 = T$



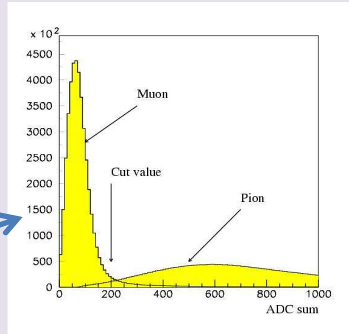
C1-C4 – thresh. cherenkov counters; S1-S5 – scintillation
proportional chambers; SP2 – veto calorimeter; SP1 – lea
chambers; DT-drift tubes; MH – matrix scintilation godos

Event selection

- **Track** requirements (one primary track, one secondary track, cuts on track quality)
- **Veto** requirements (no signals above threshold)
- **Vertex** requirements (400 < z < 1600 cm, cut on vertex fit probability)
- **Particle ID** :

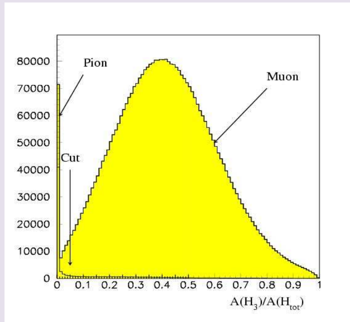
Photon: isolated shower in ECAL

Muon: 1) ADC sum in HCAL < 200



2) relative energy deposition in

last 3 layers of HCAL > 0.05



Trigger efficiency ε for photon

Data structure:

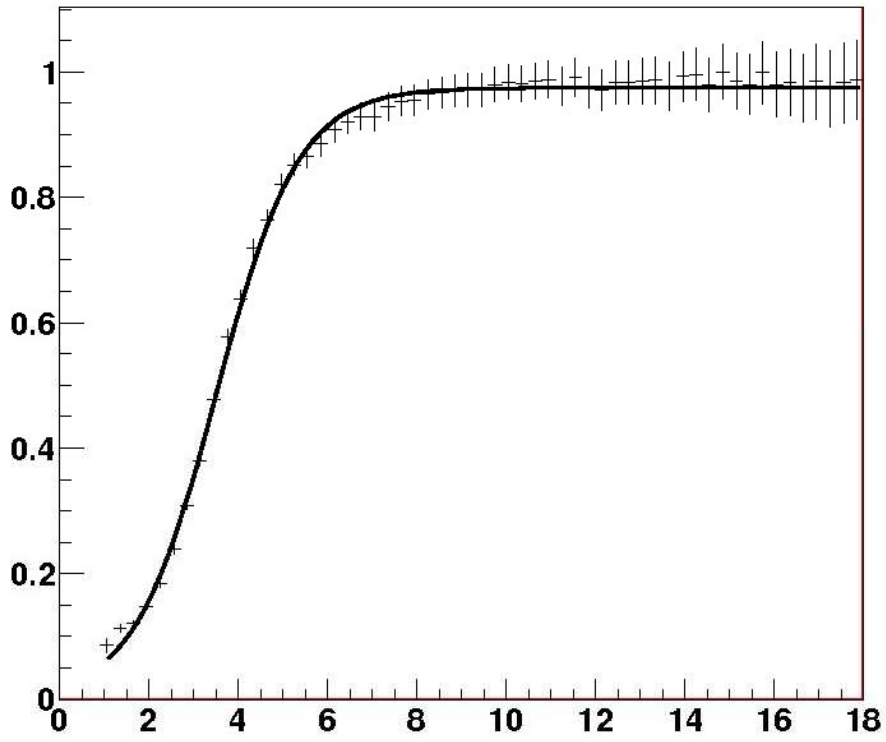
T_0 trigger: ~10%

$T_1 = T_0 \cdot$ (∑ECAL > MIP) : ~90%

Trigger efficiency:

$\varepsilon = T_0 * T_1 / T_0$

Data with T_1 are weighted by $1/\varepsilon$



Energy deposition in ECAL, GeV

Background rejection and signal observation

- Main background:
- $K \to \mu\, \nu\, \pi^0$ (Kμ3)

with 1 gamma lost (from $\pi^0 \to \gamma\gamma$)

- $K \to \pi\, \pi^0$ (Kπ2)

with 1 gamma lost (from $\pi^0 \to \gamma\gamma$) and π misidentification

- Signal observation:

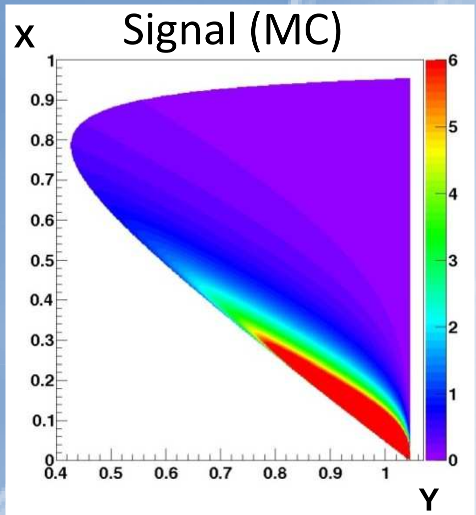
$M(\mu\, \nu\, \gamma) = \sqrt{(P_\mu + P_\nu + P_\gamma)^2}$ where

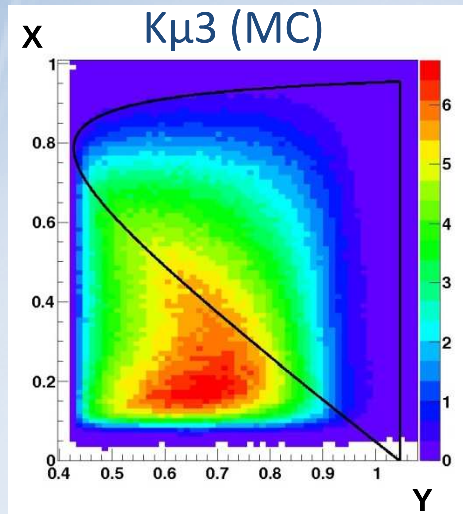
$\vec{p}_\nu = \vec{p}_K - \vec{p}_\mu - \vec{p}_\gamma$; $E_\nu = |\vec{p}_\nu|$

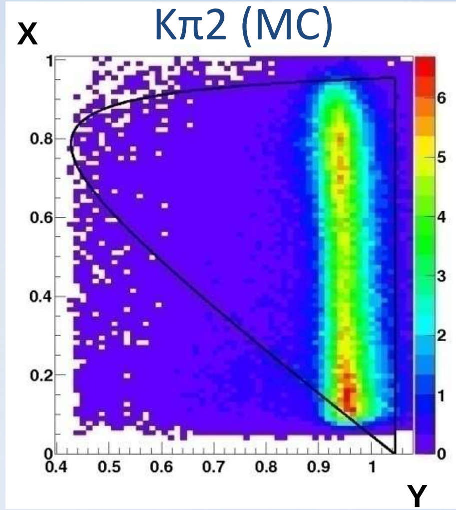
$M(\mu\nu\gamma)$ peaks at $M_K = 0.494$ GeV for signal

Background rejection procedure: scanning over (x,y) Dalits-plot and looking for a peak in $M(\mu\nu\gamma)$

Background rejection: (x,y) Dalits plot





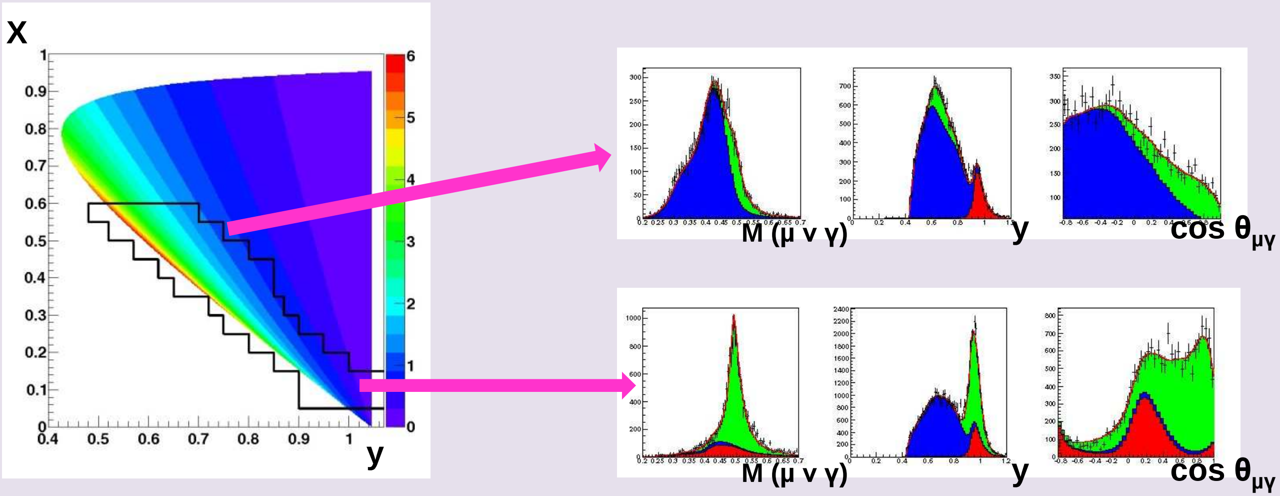


Previous experiments: looking for signal near y kinematical border

ISTRA+: looking for signal near E_ν kinematical border

Signal extraction

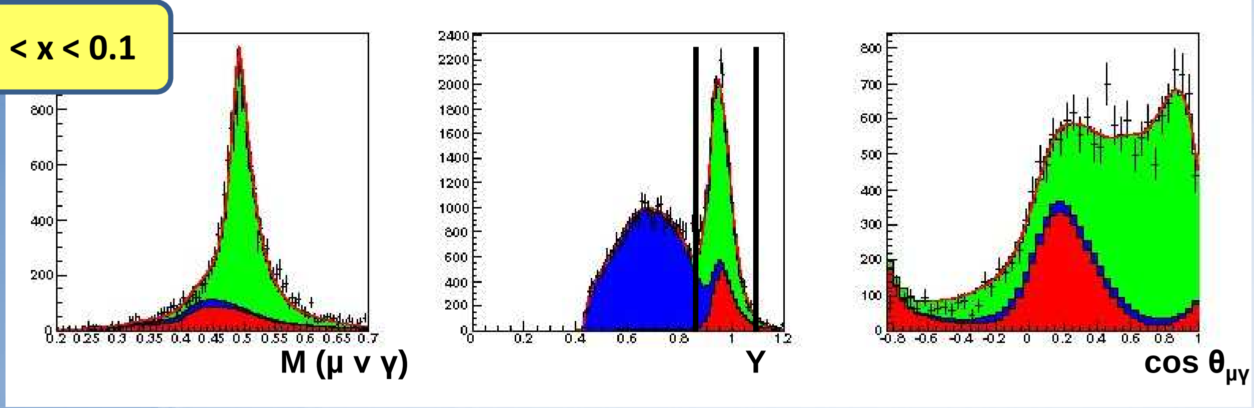
- (x,y) dalits-plot is divided into stripes with $\delta x=0.05$ width (x-stripes)
- Optimal cut on y is put in each x-stripe
- Simultaneous fit of $M(\mu\,\nu\,\gamma)$, y and $\cos\theta_{\mu\gamma}$ is done in x-stripes



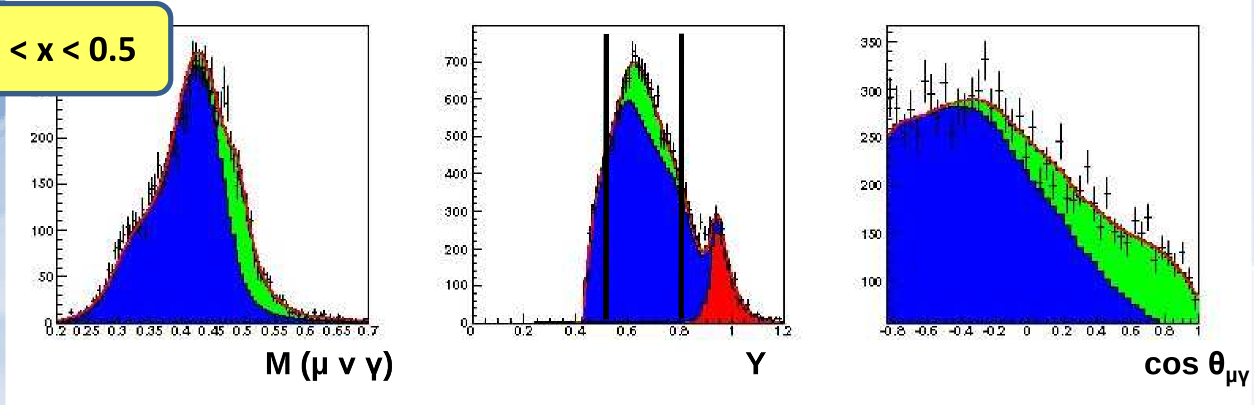
~22K events extracted

Signal extraction: simultaneous fit in x-stripes

0.05 < x < 0.1



0.45 < x < 0.5

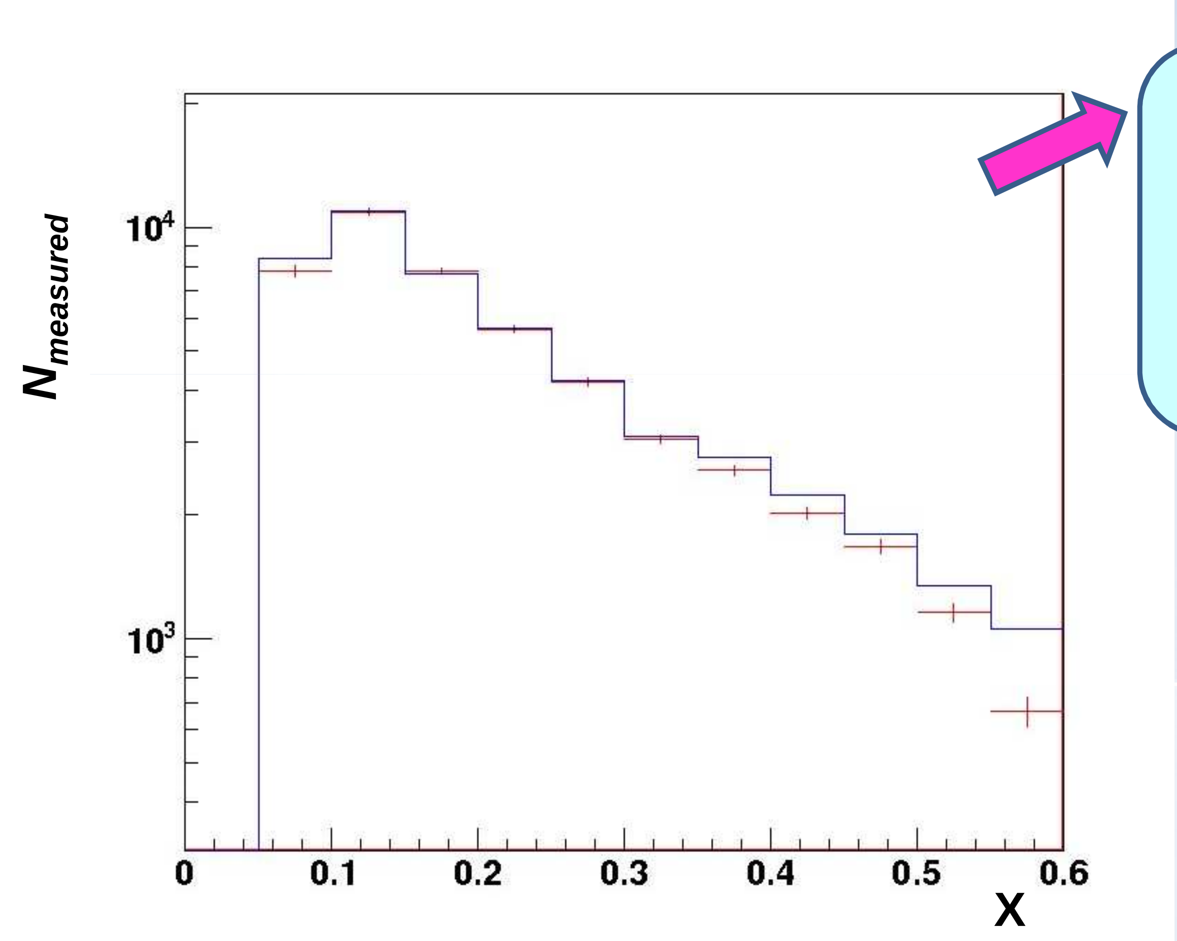


fitting M(μ ν γ) alone is not sufficient (signal and background are similar)

Signal and background shapes taken from MC

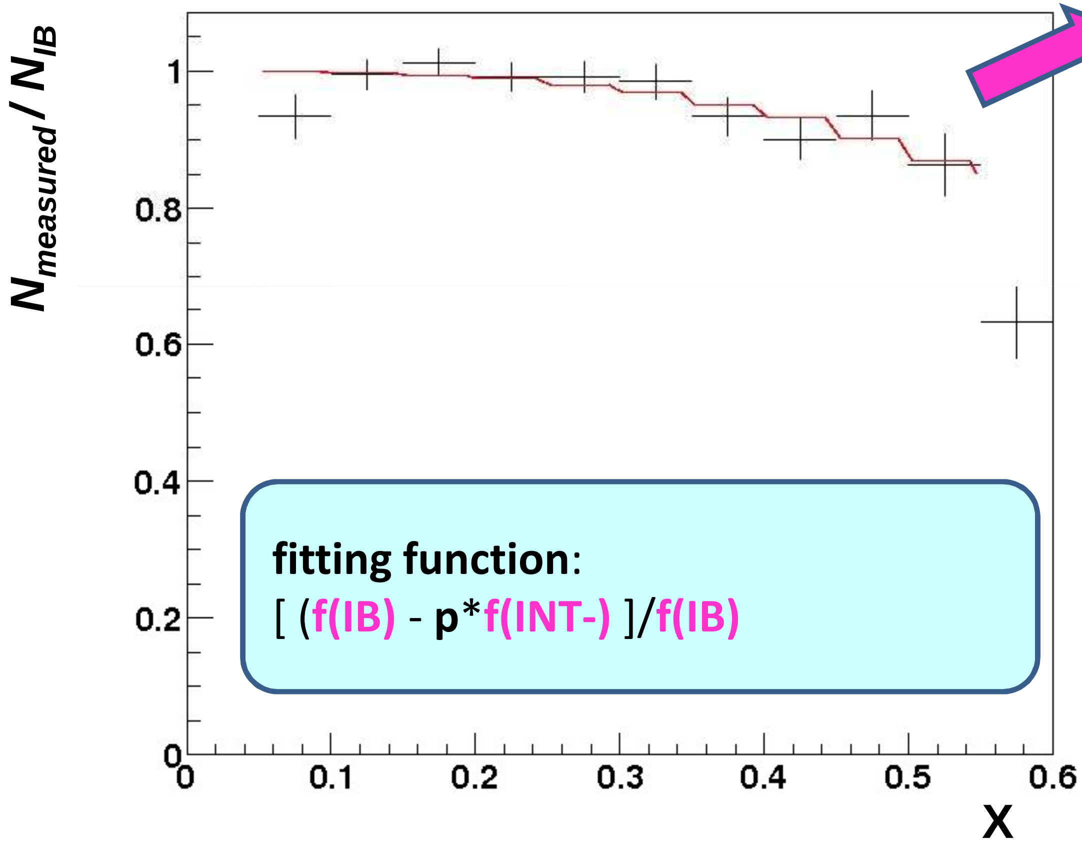
green – signal, blue – Kμ3, red – Kπ2

final x-spectrum



- $N_{measured}$ taken from fits in x-stripes
- blue histogram – IB
- lack of events for large x due to INT- term
- Negative sign of **INT-** clearly seen

Spectrum fitting: x normalized on IB



fitting function:
[(f(IB) - **p***f(INT-)]/f(IB)

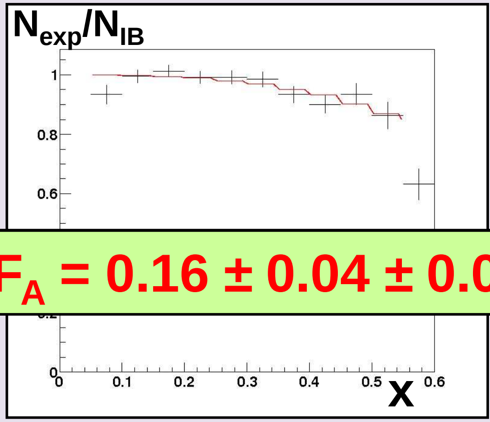
- $N_{measured}$ taken from fits in x-stripes
- N_{IB} taken from MC
- for IB only $N_{measured} / N_{IB}$=1
- Negative sign of **INT-** clearly seen
- **~4%** effect of **INT-**

Final result:

$$F_V - F_A = 0.16 \pm 0.04 \pm 0.05$$

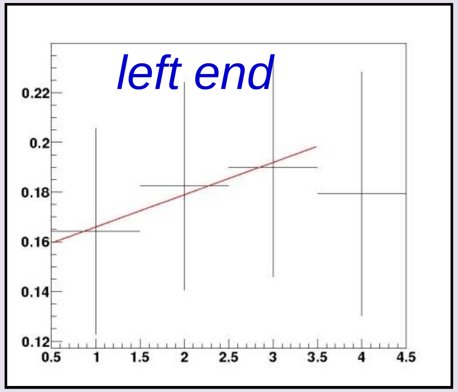
F_V-F_A: systematic error

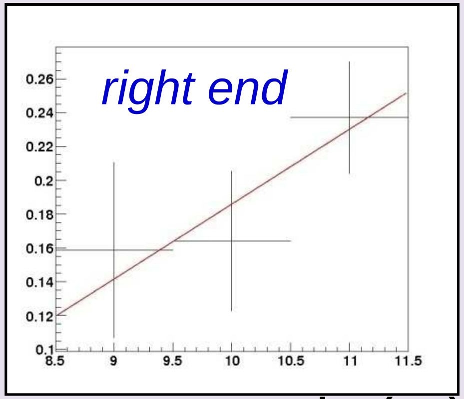
Systematic error	value
cut on x	$3.1*10^{-2}$
cut on y	-
cut on z	$2.3*10^{-2}$
fit systematics	$3.2*10^{-2}$
total	**$5.0*10^{-2}$**



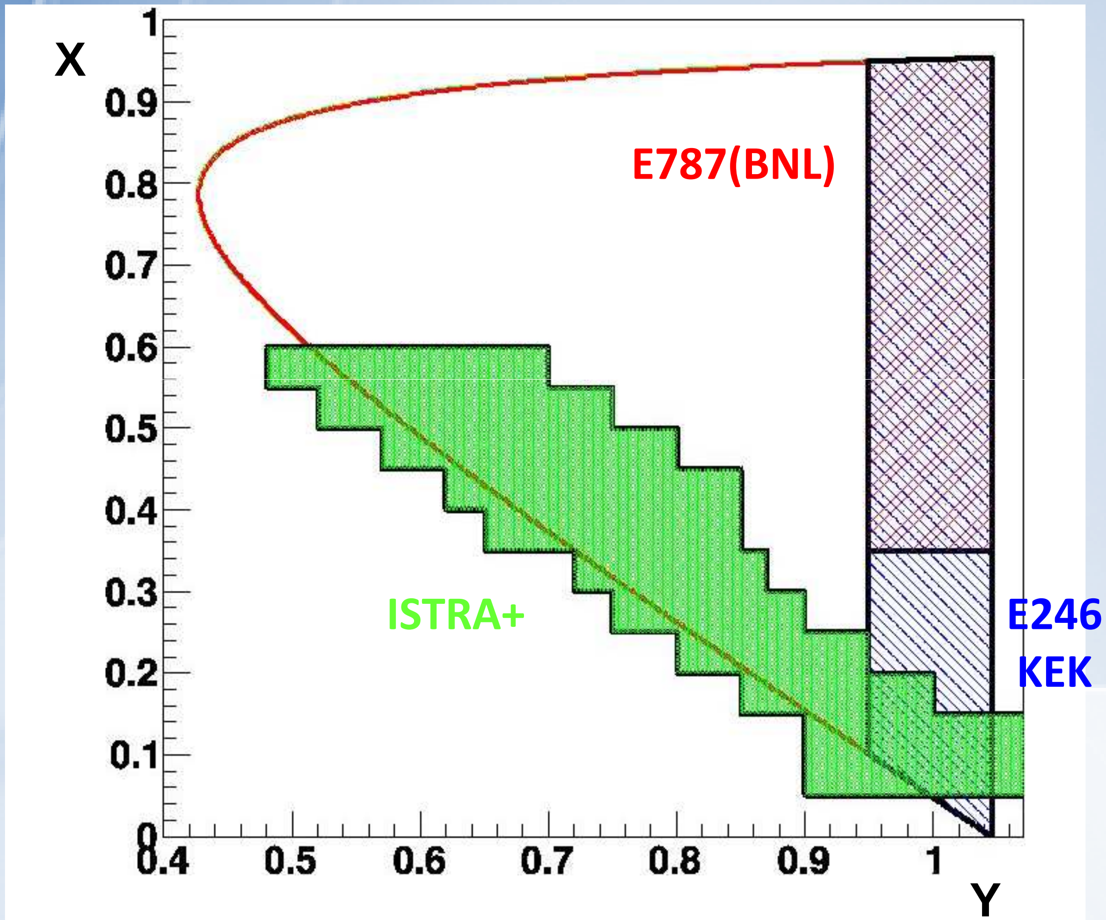
$F_V - F_A = 0.16 \pm 0.04 \pm 0.05$

x-systematics





ISTRA+ kinematical region: complementary with previous experiments



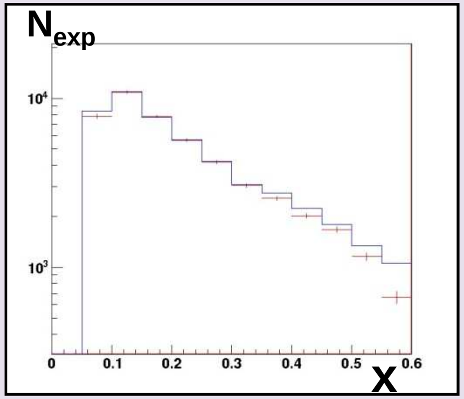
F_V-F_A: comparison with ChPT $O(p^4)$

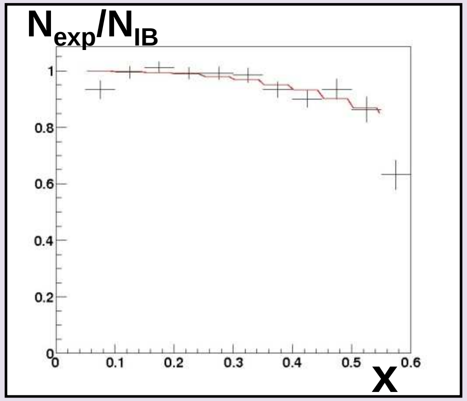
$F_V - F_A = 0.16 \pm 0.04(stat) \pm 0.05(syst)$

$\chi^2/ndf = 7.7 / 8$

ChPT $O(p^4)$

$F_V - F_A = 0.052$





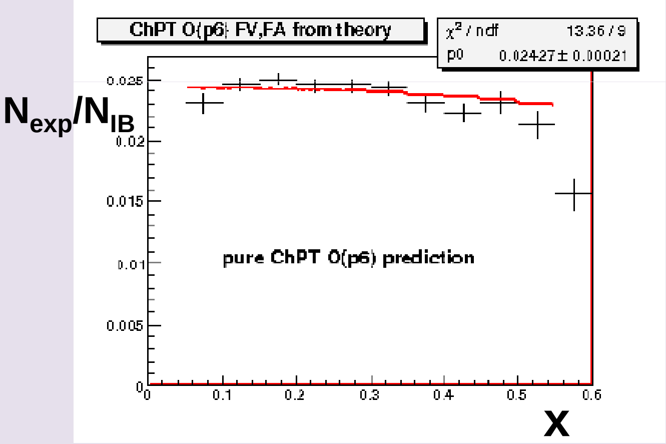
1.7σ above ChPT $O(p^4)$

F_V-F_A: comparison with ChPT $O(p^6)$

F_V , F_A taken from theory

pure ChPT $O(p^6)$

$\chi^2/ndf = 13.4 / 9$



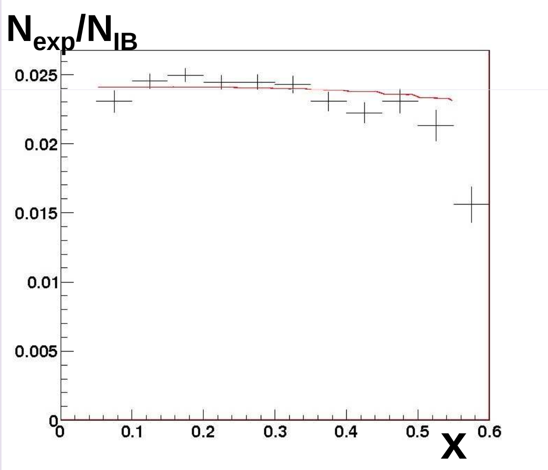
1σ from χ^2=1

F_V-F_A: comparison with LFQM

F_V , F_A taken from theory

pure LFQM

$\chi^2/ndf = 15.8 / 9$



1.6σ from χ^2=1

F_V-F_A: comparison with ChPT $O(p^6)$

ChPT $O(p^6)$

$F_V = F_V(0) * [1 + \lambda(1-x)]$

$F_V(0) = 0.082$

$F_A \approx 0.034$

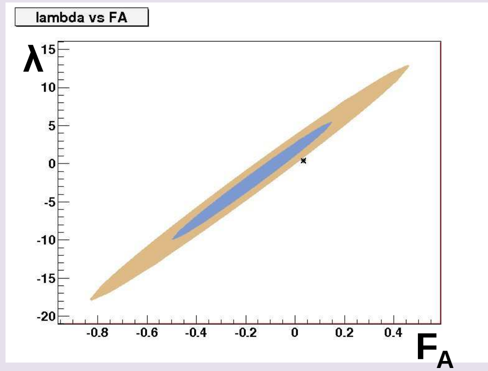
$\lambda = 0.4$

ISTRA+

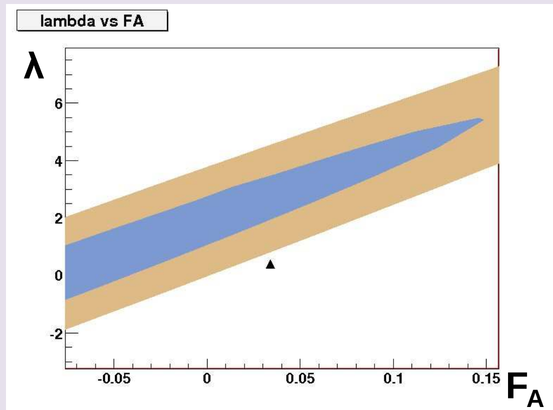
$F_V(0)$ from theory

$F_A = -0.17 \pm 0.32$

$\lambda = -2.1 \pm 7.7$



$\chi^2/ndf = 7.6 / 8$



F_A and λ : strong correlation

ISTRA+ result:
complementary with previous experiments

experiment	collaboration	year	cuts	results
Barmin et al	ITEP	1988	P_μ < 231.5 MeV/c	BR(IB)
Demidov et al	ITEP	1990	P_μ < 231.5 MeV/c	BR(IB)
Akiba et al	E104 (KEK)	1985	214.5 < P_μ < 231.5 MeV/c	BR(IB)
Adler et al	E787 (BNL)	2000	P_μ > 218.4 MeV/c E_γ > 90 MeV	$\lvert F_V + F_A \rvert$
Akimenko et al	**ISTRA+**	**2010**	**E_γ < 136 MeV (x<0.55)**	**$F_V - F_A$**

E787: 2800 events

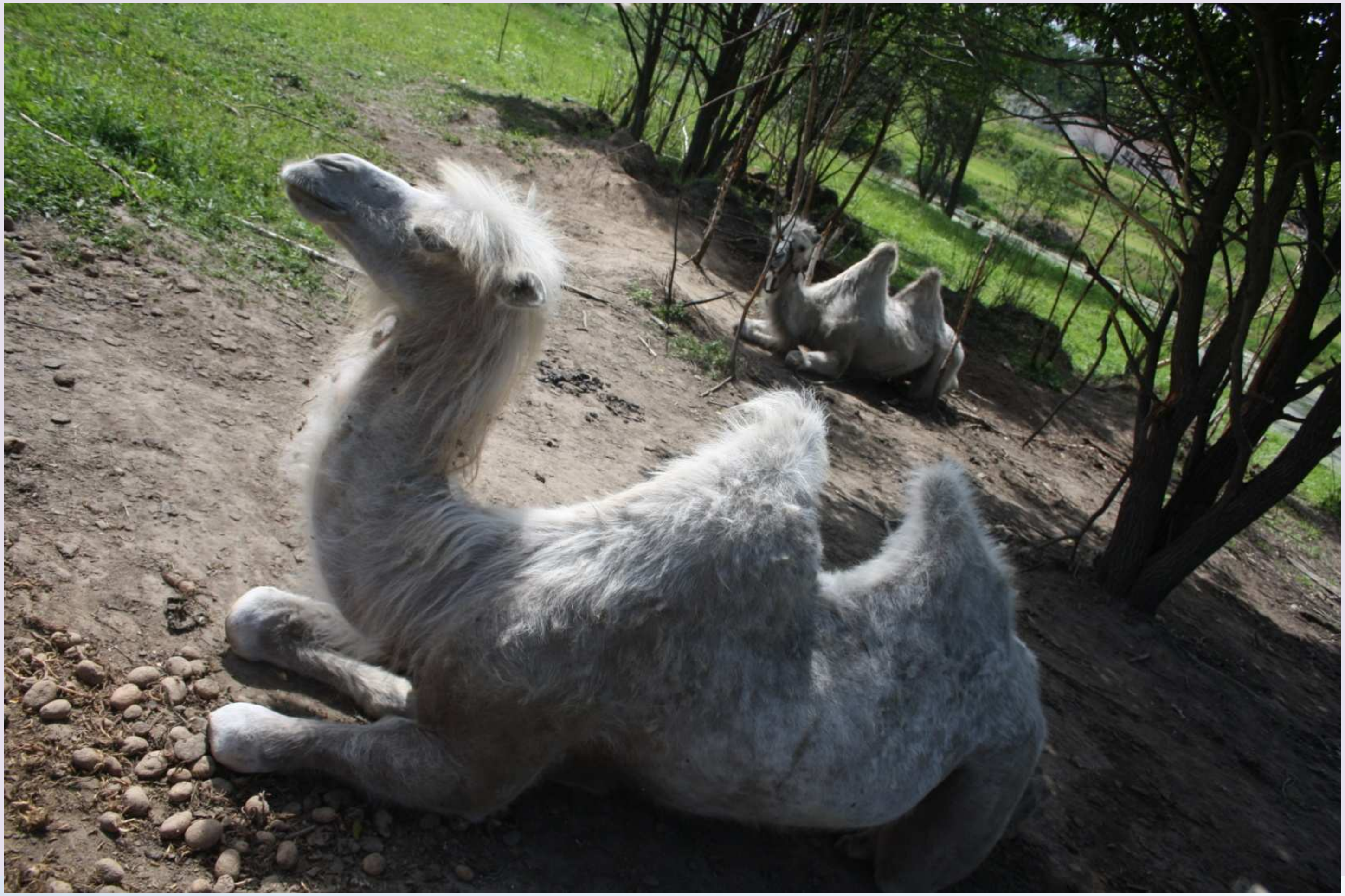
ISTRA+: 22000 events

~8 times larger statistics

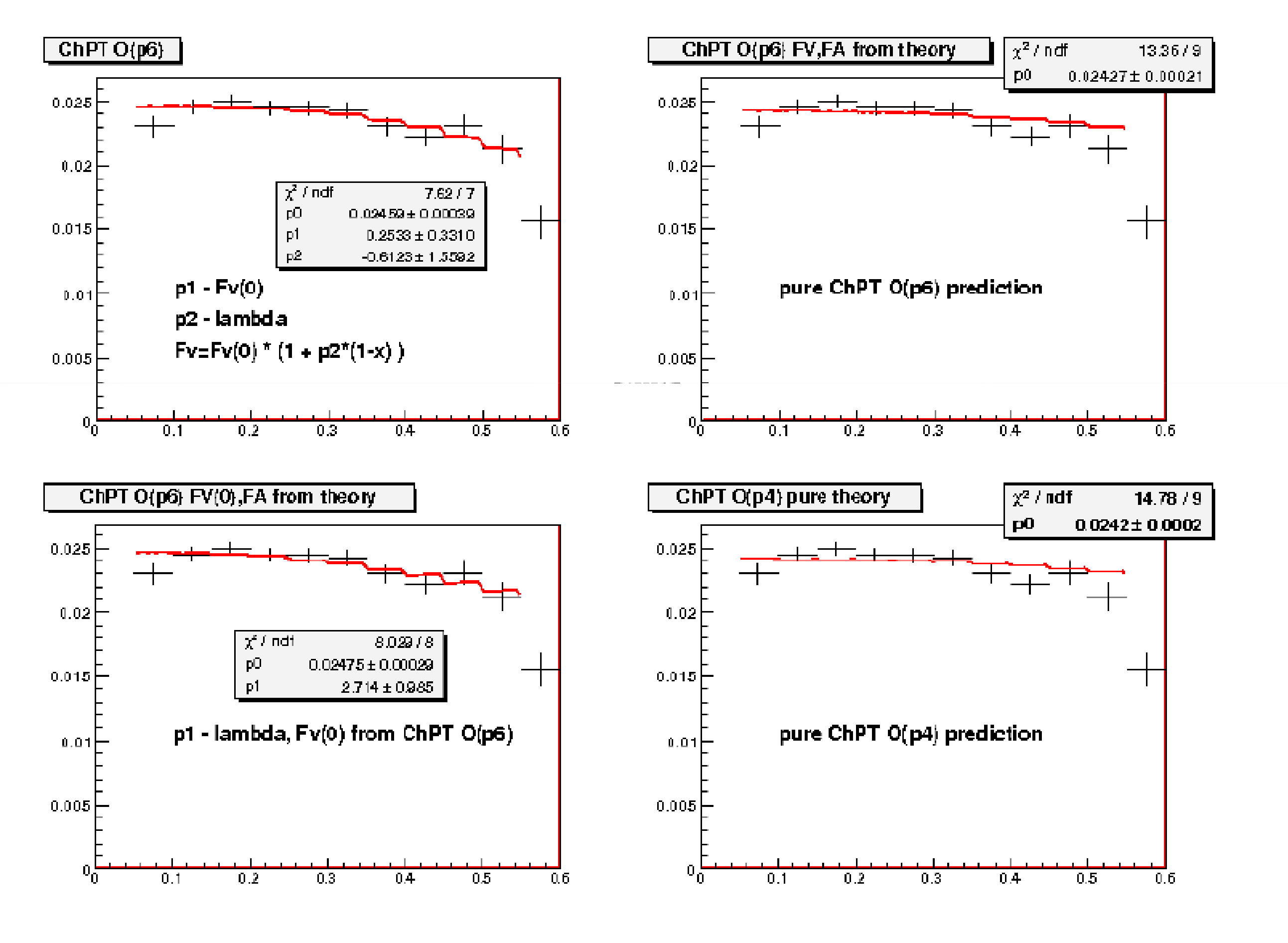
conclusion

- The K→ μ ν γ decay is observed at ISTRA+ setup in a new kinematical region
- The event number observed is 22K (the largest statistics in the world)
- First measurement of INT- term gives **F_V-F_A= 0.16 ± 0.04(stat) ± 0.05(syst)**
- The sign of INT- is negative

THANK YOU!!!



ChPT $O(p^6)$: additional fits



Decay amplitude : general formulae

$$
\begin{aligned}
M &= M_{IB} + M_{SD}, \\
M_{IB} &= ie\frac{G_F}{\sqrt{2}} sin\theta_c F_K m_e \epsilon^*_\alpha K^\alpha, \\
M_{SD} &= -ie\frac{G_F}{\sqrt{2}} sin\theta_c \epsilon^*_\mu L_\nu H^{\mu\nu},
\end{aligned}
$$

$$
\begin{aligned}
\langle 0|\bar{s}\gamma^\mu\gamma_5 u|K^+(p_K)\rangle &= -iF_K p_K^\mu, \\
\langle\gamma(q)|\bar{u}\gamma^\mu\gamma_5 s|K(p_K)\rangle &= e\frac{F_A}{m_K}\left[(p\cdot q)\epsilon^{*\mu} - (\epsilon^*\cdot p)q^\mu\right], \\
\langle\gamma(q)|\bar{u}\gamma^\mu s|K(p_K)\rangle &= ie\frac{F_V}{m_K}\varepsilon^{\mu\alpha\beta\nu}\epsilon_{*\alpha} q_\beta p_\nu ,
\end{aligned}
$$

$$
\begin{aligned}
K^\alpha &= \bar{u}(p_\nu)(1+\gamma_5)\left(\frac{p_K^\alpha}{p_K\cdot q} - \frac{2p_e^\alpha + \not{q}\gamma^\alpha}{2p_e\cdot q}\right)v(p_e), \\
L_\nu &= \bar{u}(p_\nu)\gamma_\nu(1-\gamma_5)v(p_e), \\
H^{\mu\nu} &= \frac{F_A}{m_K}(-g^{\mu\nu}p_K\cdot q + p_K^\mu q^\nu) + i\frac{F_V}{m_K}\epsilon^{\mu\nu\alpha\beta}q_\alpha p_{K\beta} ,
\end{aligned}
$$

formfactors in ChPT O(p^6) : general formulae

$$
\begin{aligned}
F_V(p^2) = \frac{m_K}{4\sqrt{2}\pi^2 F_K}\Bigg\{ & 1 - \frac{256}{3}\pi^2 m_K^2 C_7^r + 256\pi^2(m_K^2 - m_\pi^2)C_{11}^r + \frac{64}{3}\pi^2 p^2 C_{22}^r \\
& - \frac{1}{16\pi^2(\sqrt{2}F_K)^2}\Bigg[\frac{3}{2}m_\eta^2 \ln\left(\frac{m_\eta^2}{\mu^2}\right) + \frac{7}{2}m_\pi^2 \ln\left(\frac{m_\pi^2}{\mu^2}\right) + 3m_K^2 \ln\left(\frac{m_K^2}{\mu^2}\right) \\
& - 2\int \left[x m_\pi^2 + (1-x)m_K^2 - x(1-x)p^2\right] \ln\left(\frac{x m_\pi^2 + (1-x)m_K^2 - x(1-x)p^2}{\mu^2}\right) dx \\
& - 2\int \left[x m_\eta^2 + (1-x)m_K^2 - x(1-x)p^2\right] \ln\left(\frac{x m_\eta^2 + (1-x)m_K^2 - x(1-x)p^2}{\mu^2}\right) dx \\
& - 4\int m_\pi^2 \ln\left(\frac{m_\pi^2}{\mu^2}\right) dx\Bigg]\Bigg\}, \qquad (9)
\end{aligned}
$$

$$
\begin{aligned}
F_A(p^2) = & \frac{4\sqrt{2}m_K}{F_K}(L_9^r + L_{10}^r) + \frac{m_K}{6F_K^3(2\pi)^8}[142.65(m_K^2 - p^2) - 198.3] \\
& - \frac{m_K}{4\sqrt{2}F_K^3\pi^2}\Bigg\{(4L_3^r + 7L_9^r + 7L_{10}^r)m_\pi^2 \ln\left(\frac{m_\pi^2}{m_\rho^2}\right) + 3\,(L_9^r + L_{10}^r)m_\eta^2 \ln\left(\frac{m_\eta^2}{m_\rho^2}\right) \\
& +2\,(8L_1^r - 4L_2^r + 4L_3^r + 7L_9^r + 7L_{10}^r)m_K^2 \ln\left(\frac{m_K^2}{m_\rho^2}\right)\Bigg\} \\
& - \frac{4\sqrt{2}m_K}{3F_K^3}\Big\{2m_\pi^2(18y_{18}^r - 2y_{81}^r - 6y_{82}^r + 2y_{83}^r + 3y_{84}^r - y_{85}^r + 6y_{103}^r) \\
& +2m_K^2(18y_{17}^r + 36y_{18}^r - 4y_{81}^r - 12y_{82}^r + 4y_{83}^r + 6y_{84}^r + 4y_{85}^r - 3y_{100}^r \\
& +6y_{102}^r + 12y_{103}^r - 6y_{104}^r + 3y_{109}^r) + \frac{3}{2}(m_K^2 - p^2)(2y_{100}^r - 4y_{109}^r + y_{110}^r)\Big\}, \qquad (10)
\end{aligned}
$$

ChPT O(p^4) value

One-loop diagrams in ChPT O(p^6)

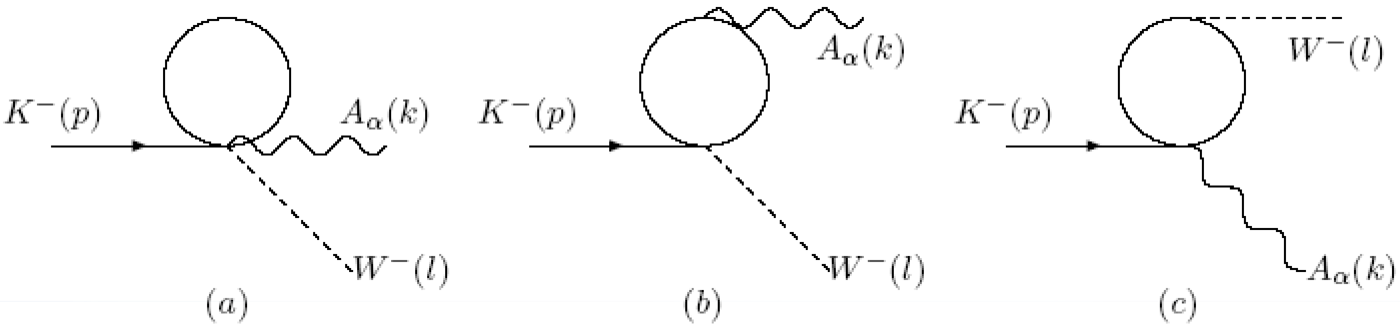


Figure 1: One-loop diagrams that contribute to F_V in $P_{\ell 2\gamma}$