Update on xTOP MC studies

Peter Križan for Marko Starič

J. Stefan Institute, Ljubljana

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Contents

Reminder of the MC/reconstruction

New presentations – 1D - of results shown last week

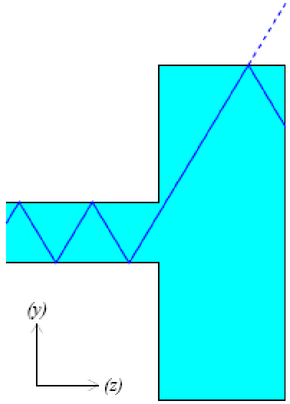
New MC results
- T0 jitter influence 10ps, 25ps, 35, 50ps
- Multialkali
- Edge roughness
- Muon/pion separation

Further steps in reconstruction code development

Study of focusing i-TOP and f-TOP

Detector configurations

- PMT: Hamamatsu SL-10 with 1×4 or 4×4 channels
- TTS: 3-gaussian (fitted Inami-san's distribution)
- QE: GaAsP with 400nm filter (sharp cutof), 35% CE
- CFD: 500ps delay, 5ns pileup time
- TDC: 10 bit, 50ps/ch, multihit (>5ns)
- 16 detector segments in ϕ at $R = 115.8$ cm
- Q-bars: 44×2 cm^2
- Focusing with spherical mirror
- i-TOP expansion volume: $\Delta z = 4.14(8.28)$ cm, 11 cm high, box-shaped



configuration	z_1	z_2	R_{mirror}	num.PMT	Δz
2-readout f-TOP	-80 cm	107 cm	500 cm	16	
	108 cm	190 cm		16	
1-readout f-TOP	-80 cm	190 cm	720 cm	16	
focusing i-TOP (1)	-80 cm	190 cm	720 cm	4×16	4.14 cm
focusing i-TOP (2)	-80 cm	190 cm	720 cm	4×16	8.28 cm

Simulation

- Pions and kaons (half-half) of both charges distributed uniformly over 4π with momenta distributed uniformly between 0 and 5 GeV/c
- 500 000 tracks/job
- Magnetic field B=1.5 T
- Background/bar/50ns: 20 hits uniformly distributed
- T_0 jitter: 10 ps (rms) or 25 ps (rms)

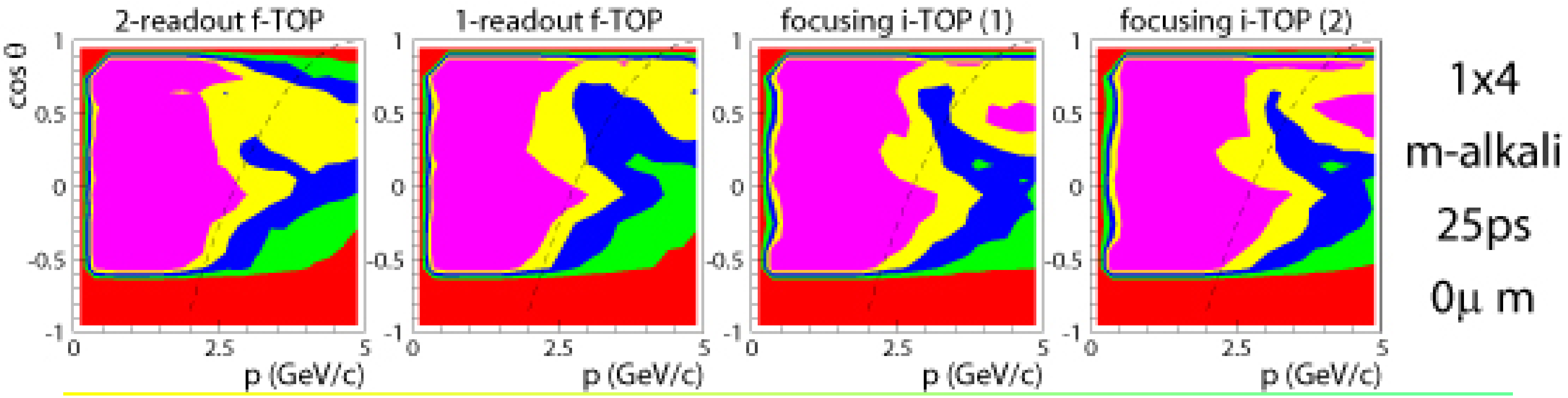
Added since last week:
- T0 jitter influence 10ps, 25ps, 35, 50ps
- Multialkali photocathode (λ>350nm)
- Edge roughness
- Muons (in addition to pions and kaons)

Simulation is a normal MC, can be replaced by any other MC input, preferably full Geant MC.
Reconstruction: important advantage: analytic likelihood function construction → very fast

Plots on the web

1) Separation power contours (1-4 sigma) in 2D, comparison of 4 different xTOP configurations (fTOP 2 read-out, fTOP 1 read-out, iTOP with 4cm long wedge (11cm high), iTOP with 8cm long wedge). The B→pipi kinematic boundary is indicated by a dashed line.

File name, example: Kpi2D-1x4-m-alkali-25ps-0um.eps = K/pi separation, SL10 with 1x4 pads, multialkali photocathode with 350nm cutoff, 25ps t0 time jitter, perfect bar edges.



Plots on the web

2) Same as 1), 1D comparison of different xTOP configurations, fix p to 2 GeV/c, 3 GeV/c, 4 GeV/c, vary theta

File name, example: Kpi1D-1x4-m-alkali-25ps-0um.eps

3) Influence of rough edges: comparison of 0 micron, 100 micron, 200 micron, 500micron wide unpolished edge

File name, example: Kpi2D-fTOP-1x4-GaAsP-25ps.ep

Impact of start time jitter, $\sigma(T_0)$

Assume four values for $\sigma(T_0)$:

10ps, 25ps, 35ps, 50ps

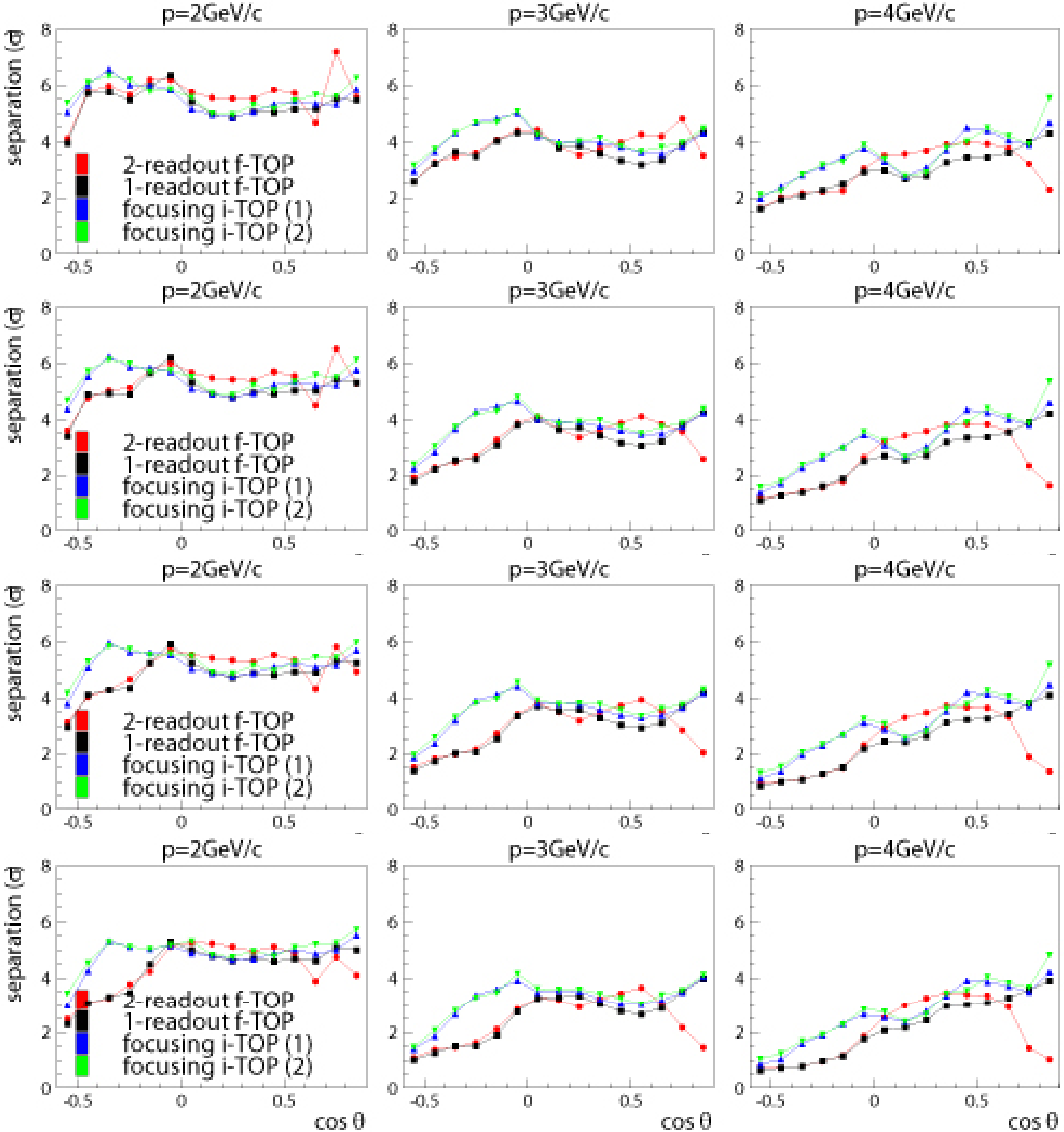
$\sigma(T_0)$

10ps

25ps

35ps

50ps



1x4 GaAsP 10ps 0μ m

1x4 GaAsP 25ps 0μ m

1x4 GaAsP 35ps 0μ m

1x4 GaAsP 50ps 0μ m

Impact of start time jitter, $\sigma(T_0)$

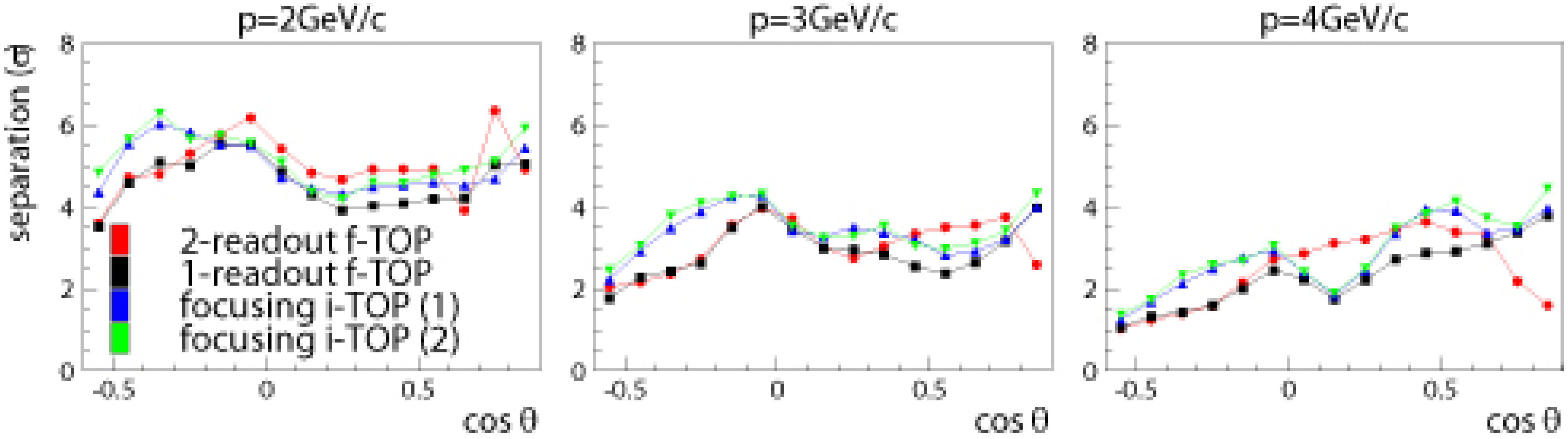
Some conclusions:

•Backward direction: iTOP better than fTOP

•High momenta, forward (cos theta > 0.7): degradation in 2 bar fTOP (~only time of flight)

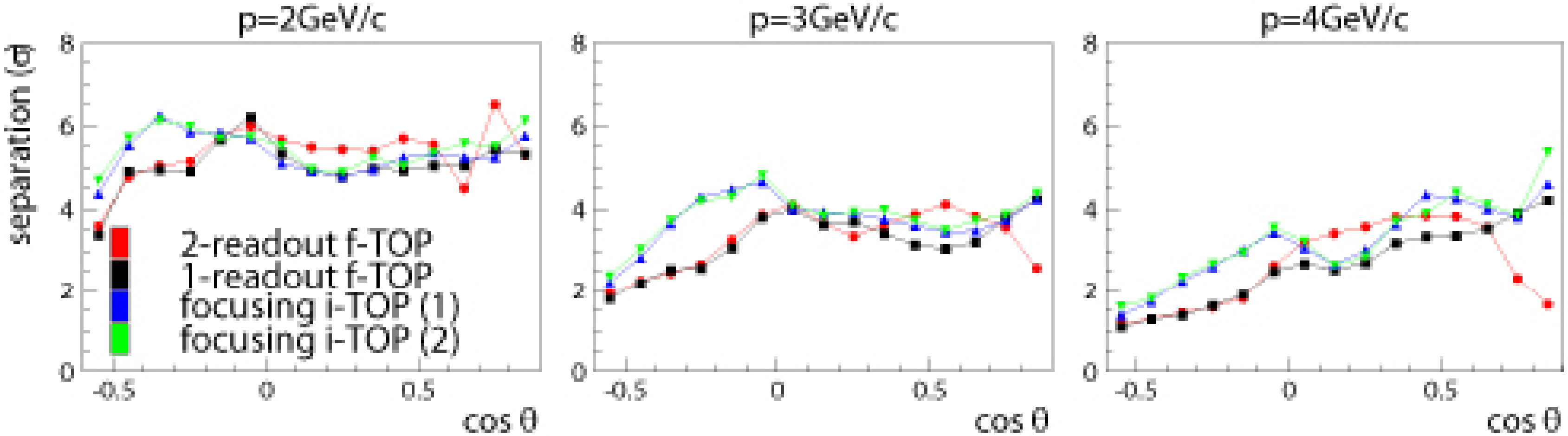
Multialkali vs GaAsP photocathode

Multi-alkali,λ>350nm



1x4
m-alkali
25ps
0μ m

GaAsP, λ>400nm

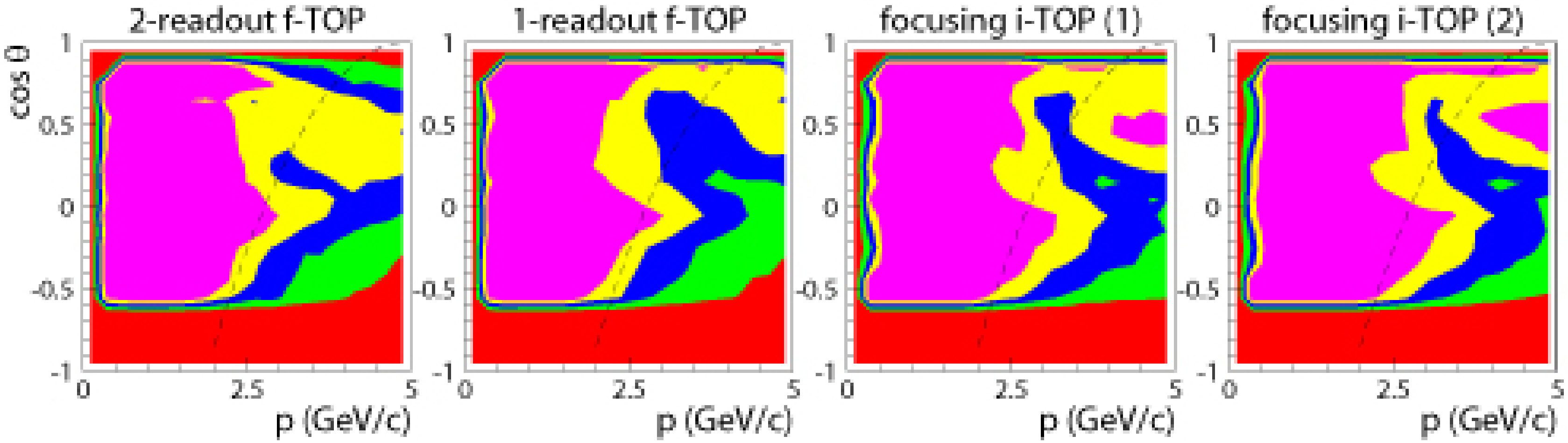


1x4
GaAsP
25ps
0μ m

Multialkali vs GaAsP photocathode

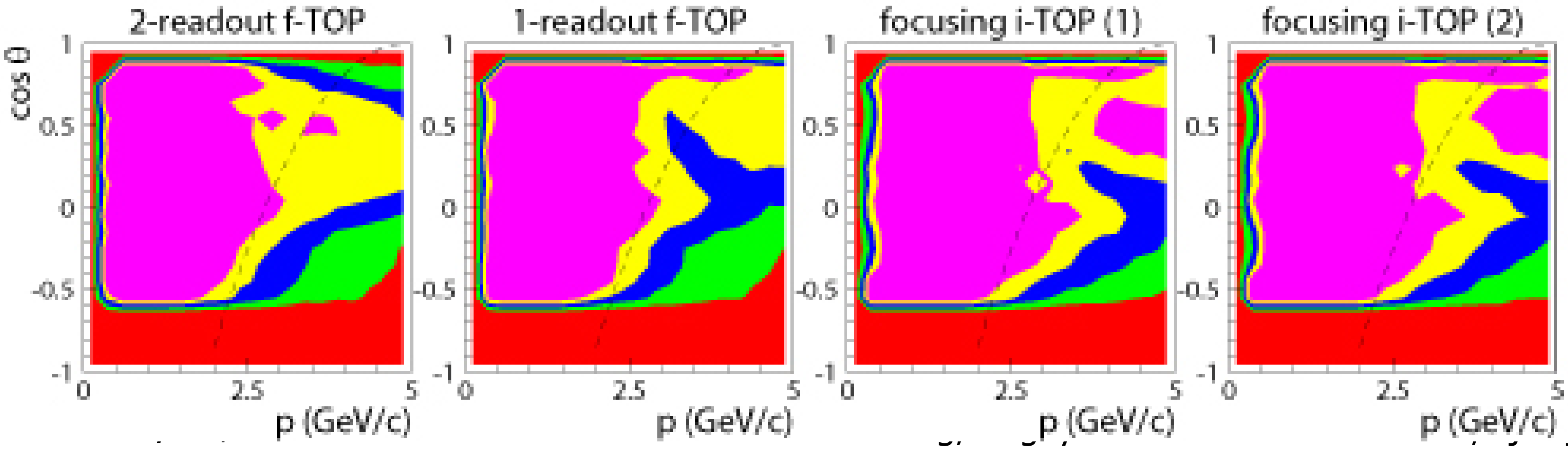
pink: 4 sigma, dashed line: B→ππ kinematic boundary

Multi-alkali, λ>350nm



1x4
m-alkali
25ps
0μ m

GaAsP, λ>400nm



1x4
GaAsP
25ps
0μ m

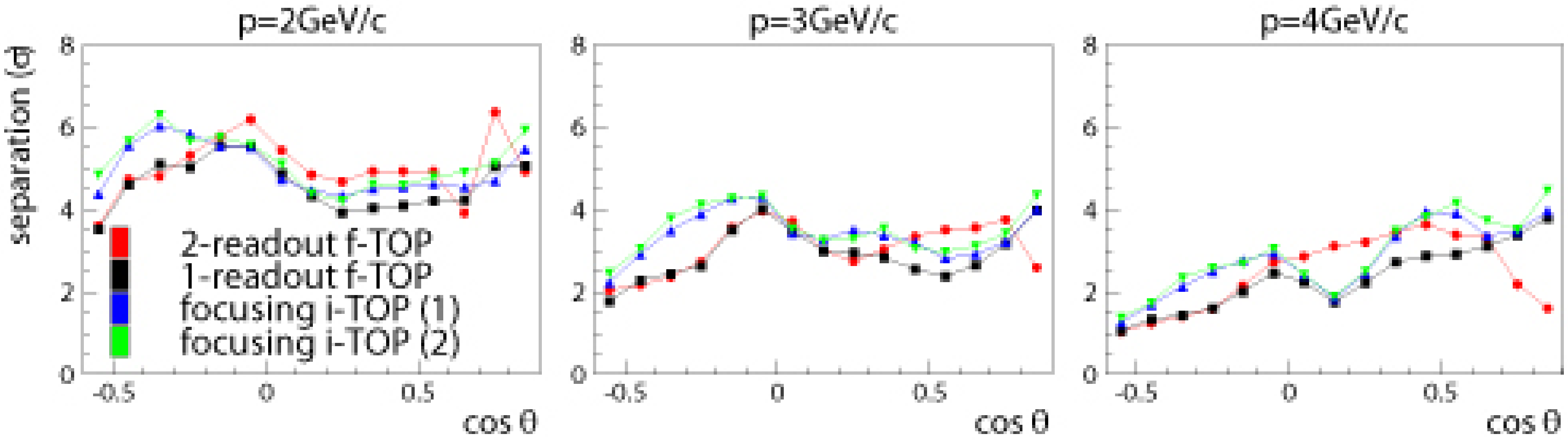
Multialkali vs GaAsP photocathode

Some conclusions:

- Multialkali separation lower by 0.5-1 sigma
- Multialkali: for 3 GeV/c tracks separation lower than 4 sigma for cos theta > 0

SL10 granularity: 1x4 vs. 4x4

1x4, multialkali



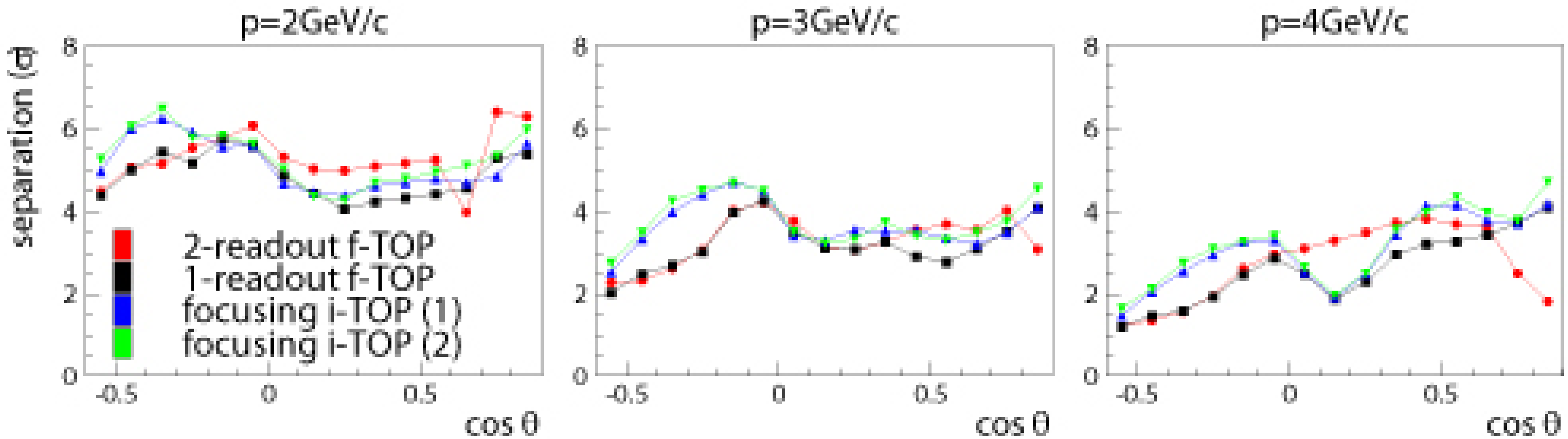
1x4

m-alkali

25ps

0μ m

4x4, multialkali



4x4

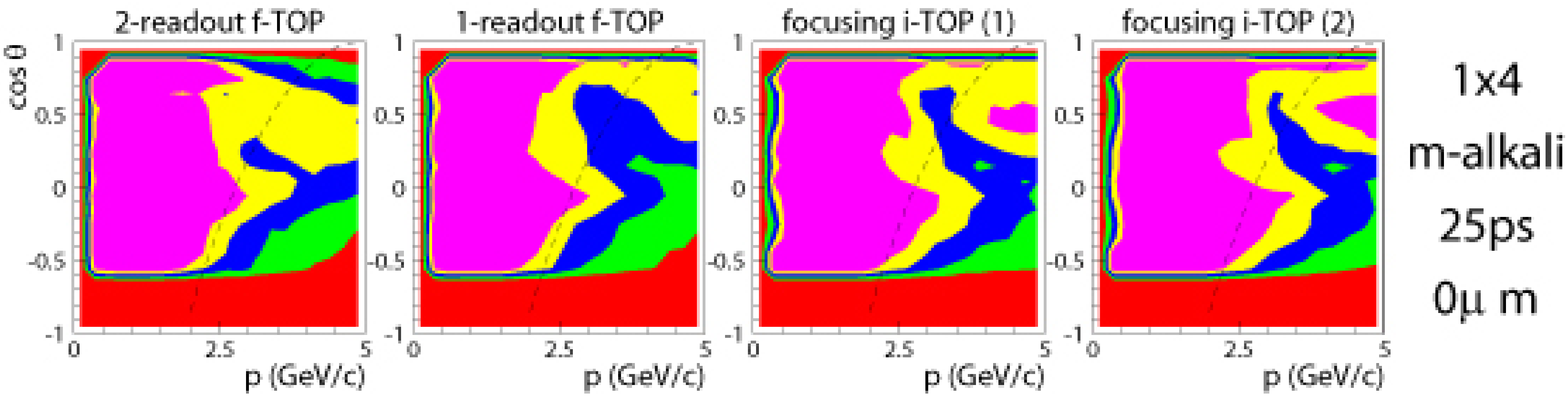
m-alkali

25ps

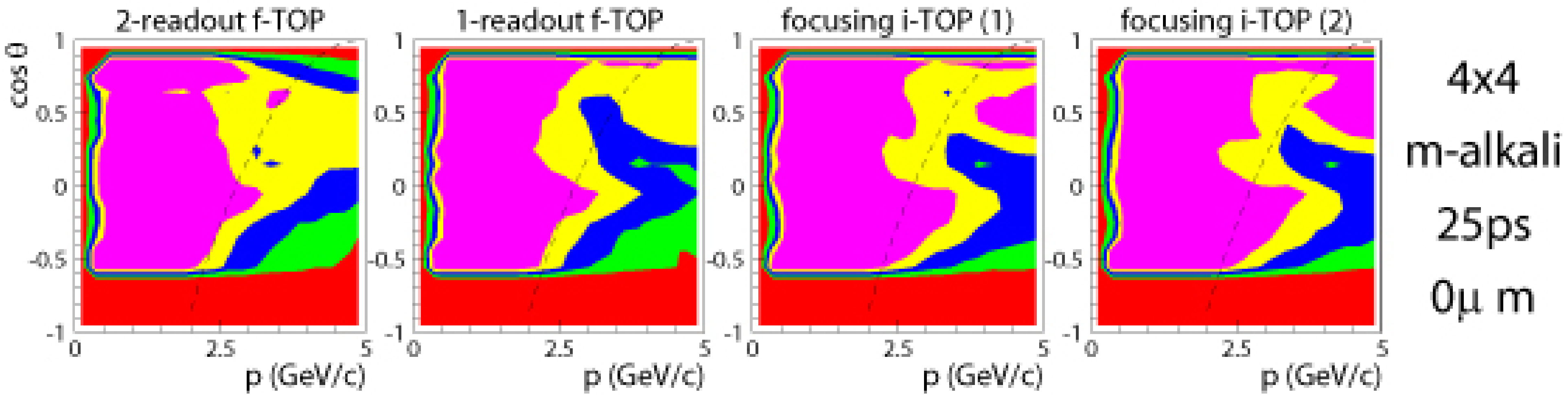
0μ m

SL10 granularity: 1x4 vs. 4x4

1x4, multialkali

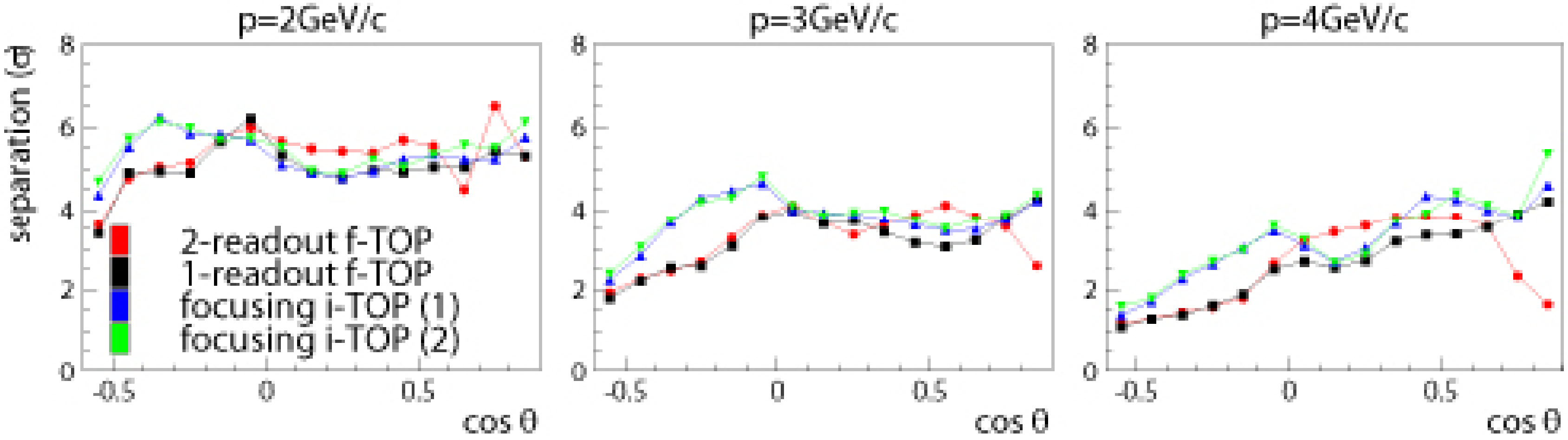


4x4, multialkali



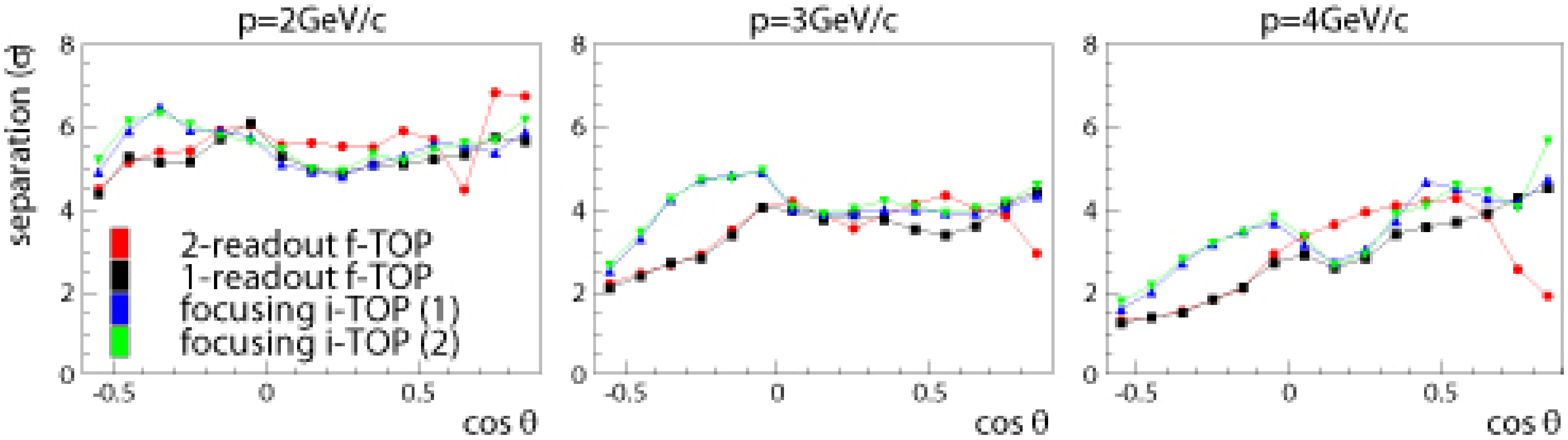
SL10 granularity: 1x4 vs. 4x4

1x4, GaAsP



1x4
GaAsP
25ps
0μ m

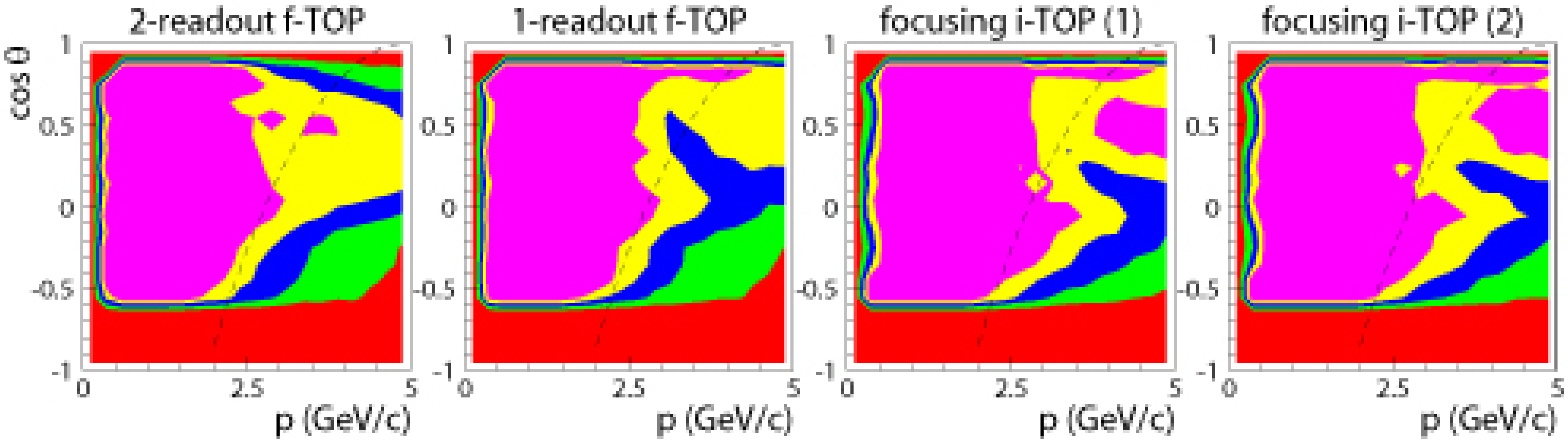
4x4, GaAsP



4x4
GaAsP
25ps
0μ m

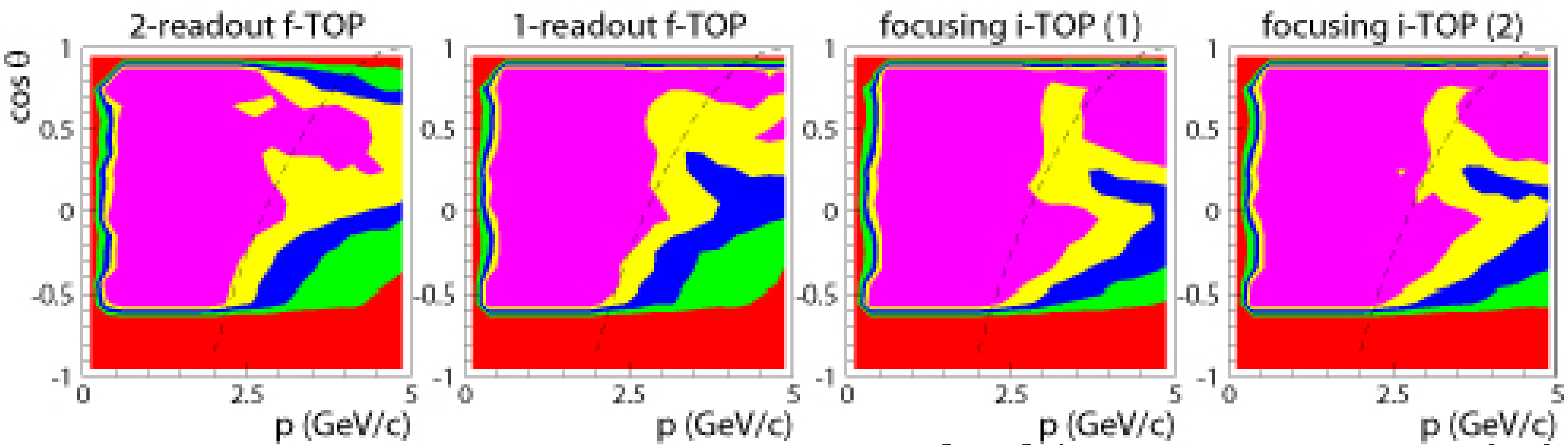
SL10 granularity: 1x4 vs. 4x4

1x4, GaAsP



1x4
GaAsP
25ps
0μ m

4x4, GaAsP



4x4
GaAsP
25ps
0μ m

SL10 granularity: 1x4 vs. 4x4

Some conclusions:

- 4x4 slightly better
- We are ‘separation hungry’

Edge roughness

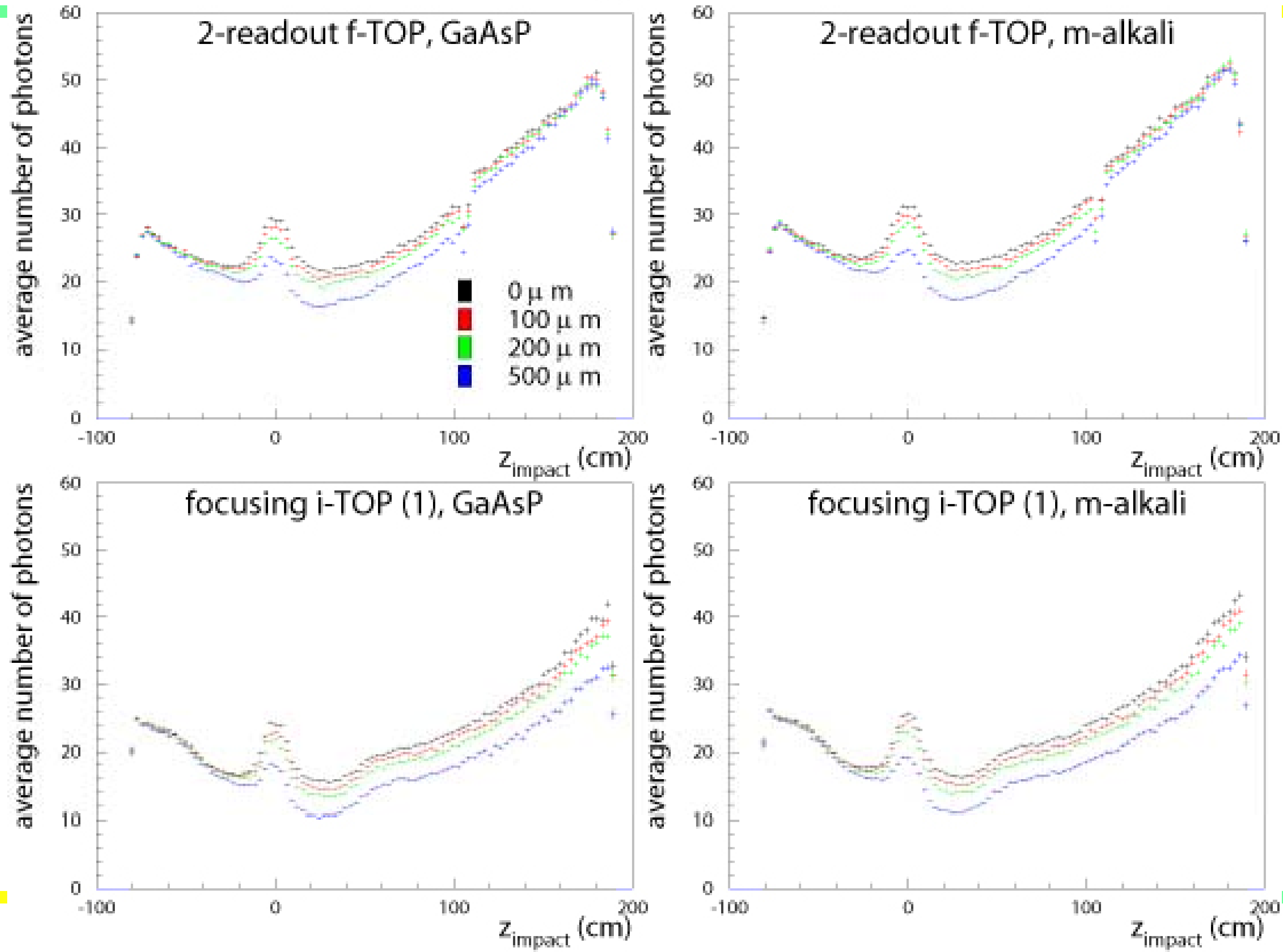
Assume polished bar except in bands next to the edges.
Assume that all light is lost that hits this region.

d: unpolished band width

In MC assume d = 0 μm, 100 μm, 200 μm, 500 μm

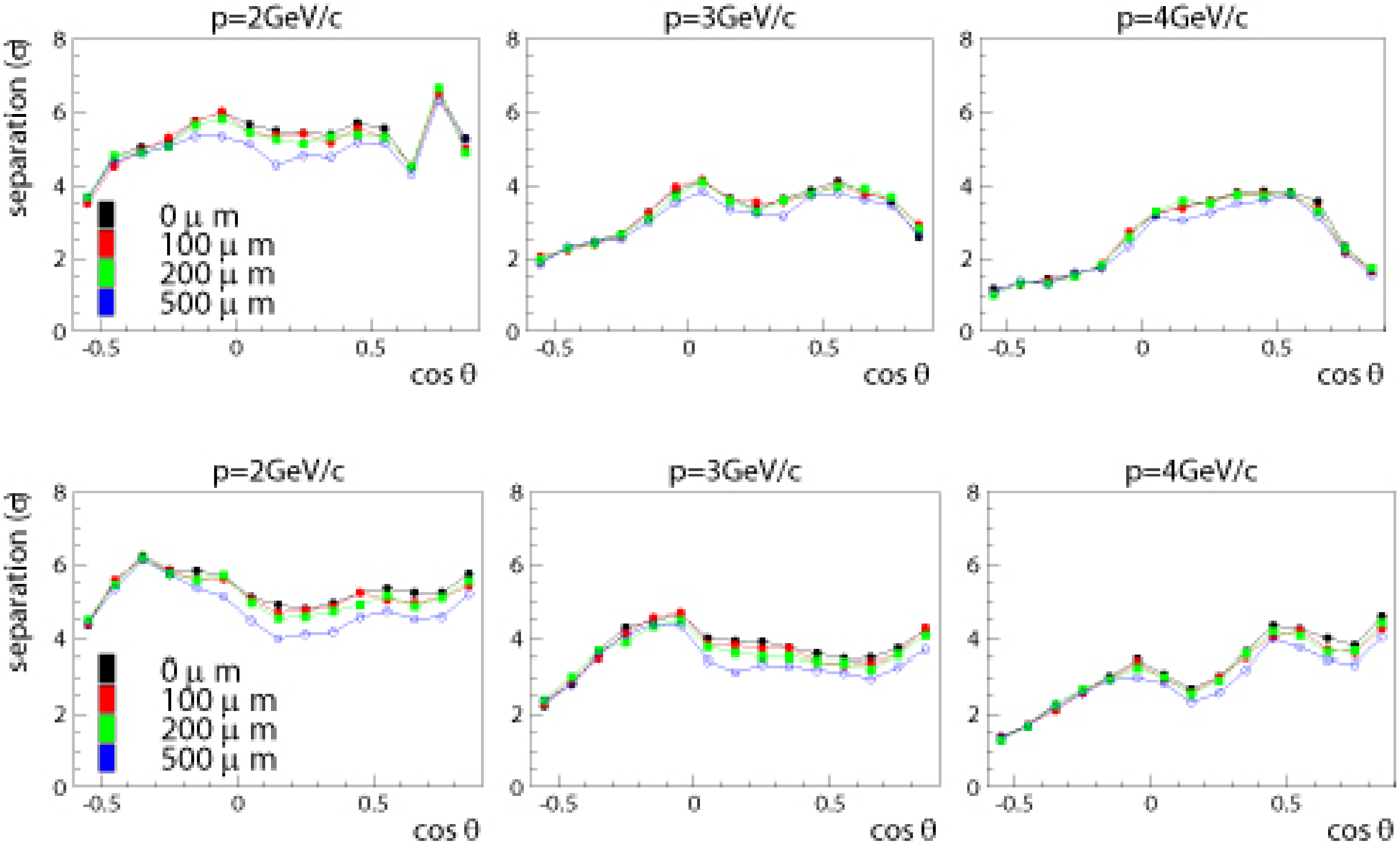
Edge roughness: number of photons vs z_{impact}

Pions, p>1 GeV/c



Edge roughness: performance vs. d

GaAsP

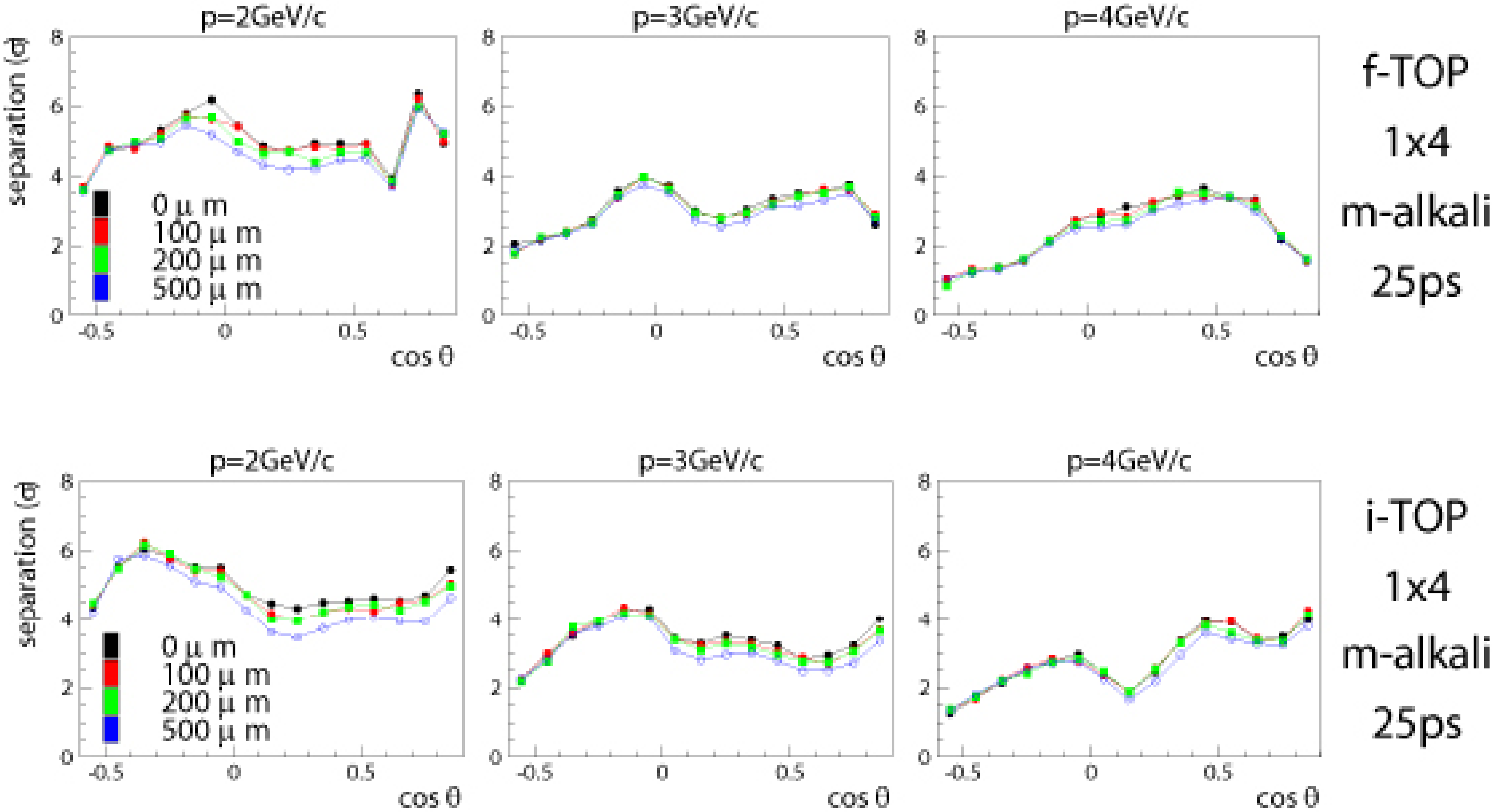


f-TOP
1x4
GaAsP
25ps

i-TOP
1x4
GaAsP
25ps

Edge roughness: performance vs. d

multialkali



Edge roughness: performance vs. d

Summary:

•up to d = 200μm no difference

•from 200μm to 500μm a step of about 1 in separation at 2 GeV/c, less at higher momenta

Muon/pion separation with xTOP?

Muon id/ fake probability at Belle

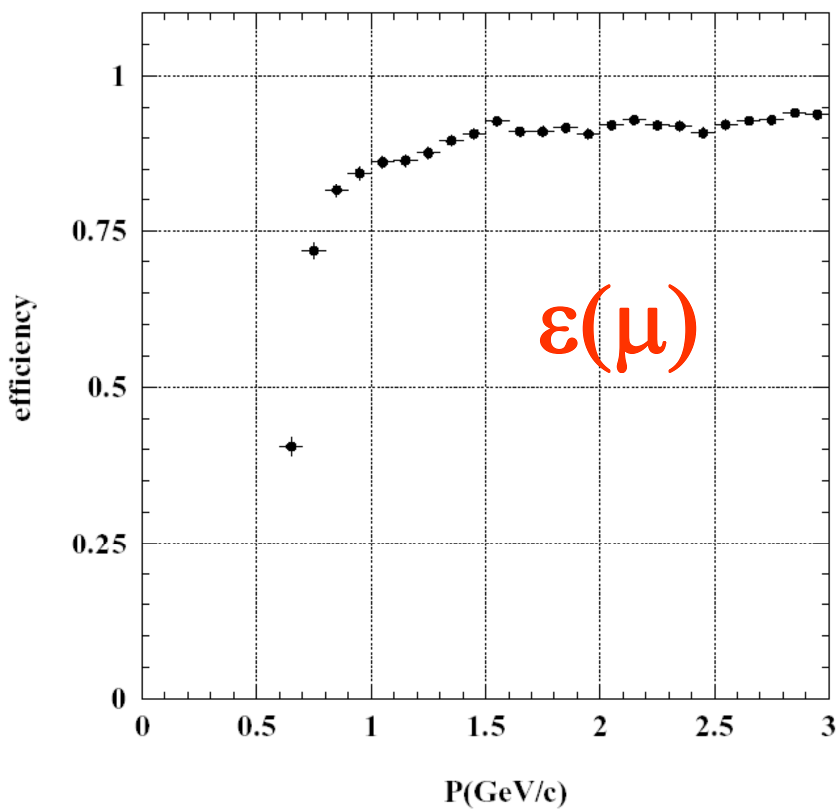


Fig. 109. Muon detection efficiency vs. momentum in KLM.

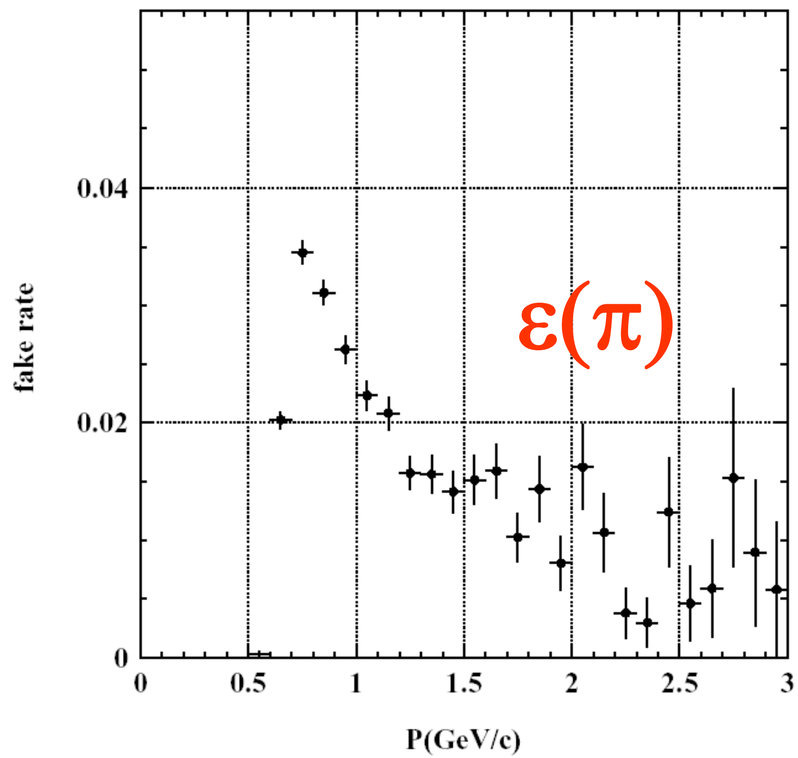


Fig. 110. Fake rate vs. momentum in KLM.

Can xTOP help? Yes

Muon/pion separation

Why could xTOP help?

$$s_{1,2} = \frac{\theta_1 - \theta_2}{\sigma_{\theta,track}} \cong \frac{1}{\sigma_{\theta,track}} \frac{1}{2\sqrt{2(n-1)}} \frac{m_2{}^2 - m_1{}^2}{p^2} \propto \frac{m_2{}^2 - m_1{}^2}{p^2}$$

Pion/kaon: sqrt($m_2^2 - m_1^2$) ~ m_K

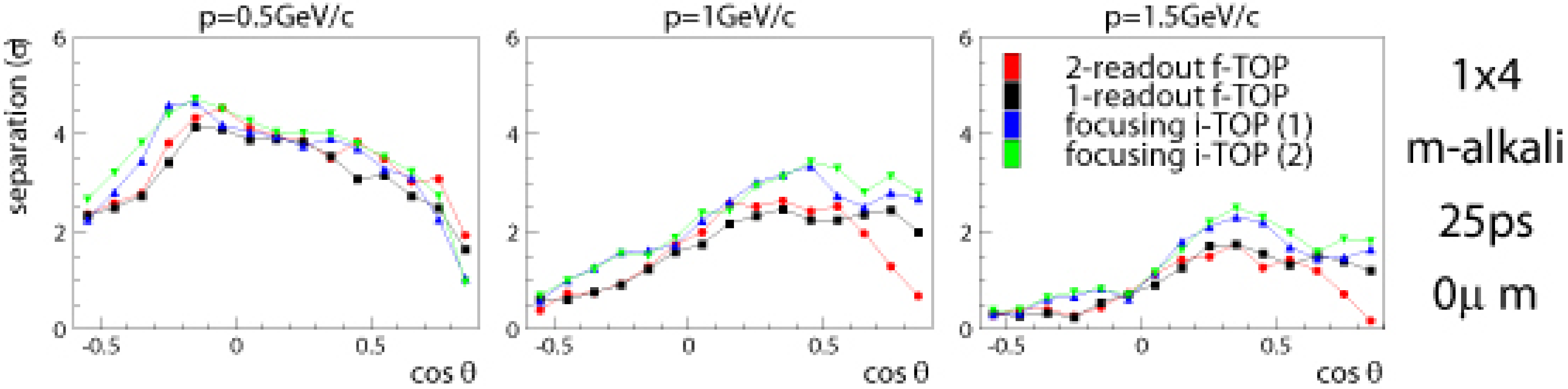
Muon/pion: sqrt($m_2^2 - m_1^2$) = 92 MeV

→ s(π/K at 4 GeV/c) ~ s(μ/π at ~0.7 GeV/c)

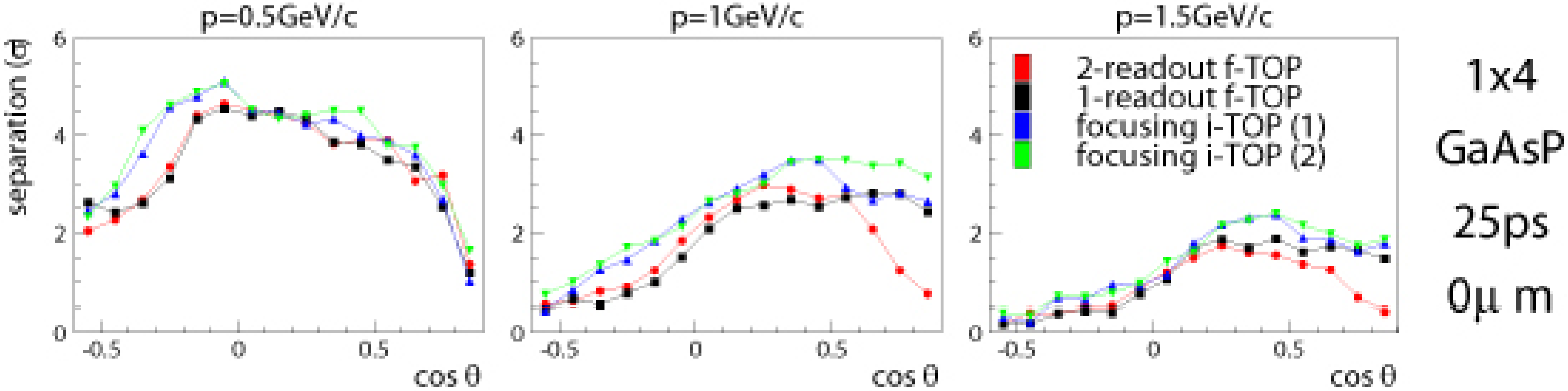
... if we assume the same σ_θ (should be slightly worse due to multiple scattering)

Muon/pion separation

multialkali

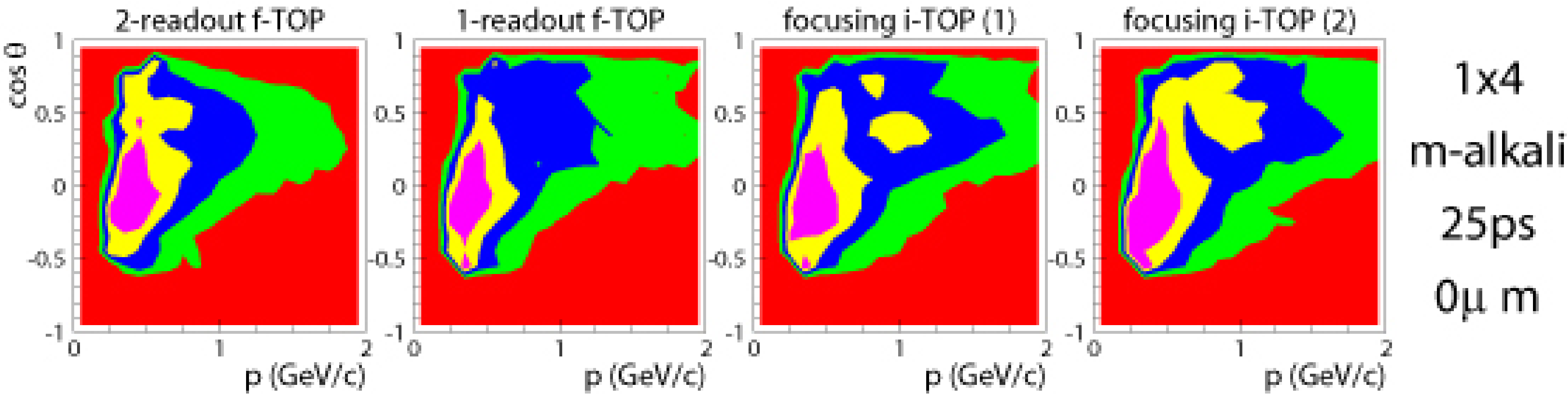


GaAsP



Muon/pion separation

multialkali

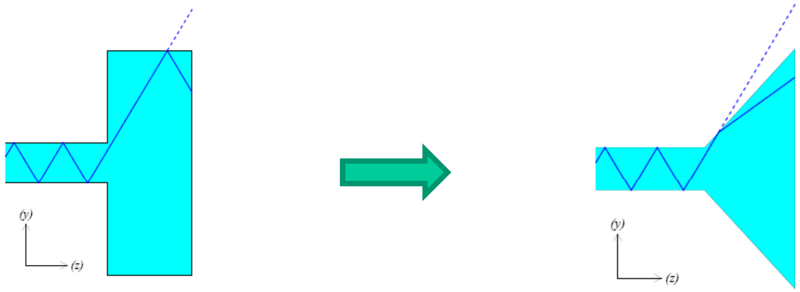


pink: 4 sigma

Next steps in the reconstruction

→ Release the new version of reconstruction with iTOP (available to the group later this week)

→ Adapt the reconstruction for the endpiece



→ Move the whole reconstruction code into C++ (autumn)

Marko would like to take the responsibility for the reconstruction code. He writes excellent, well organized code, has done a great job for the HERA-B RICH

Back-up slides

TOP MC old studies summary

Bi-alkali vs. GaAsP with filter: GaAsP with filter much better

PMT TTS: 100ps considerable degradation vs. 50ps

Multiple tracks: no effect

Tracking uncertainty: 2mrad no effect

100 bckg hits/bar: tolerable

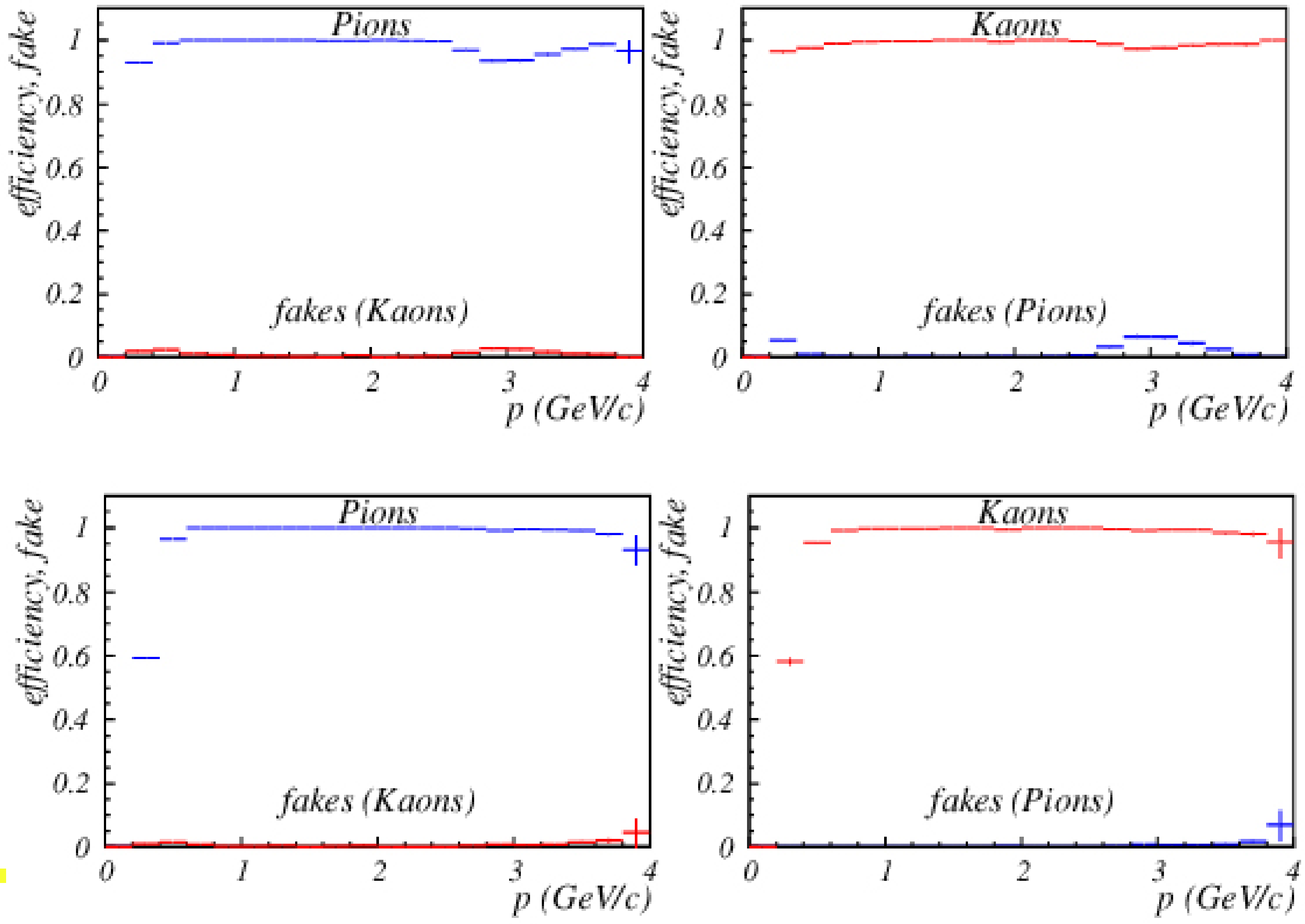
T0 start time uncertainty: 10ps little influence

Multialkali vs GaAsP photocathode

As a function of momentum (B→πK, other B generic)

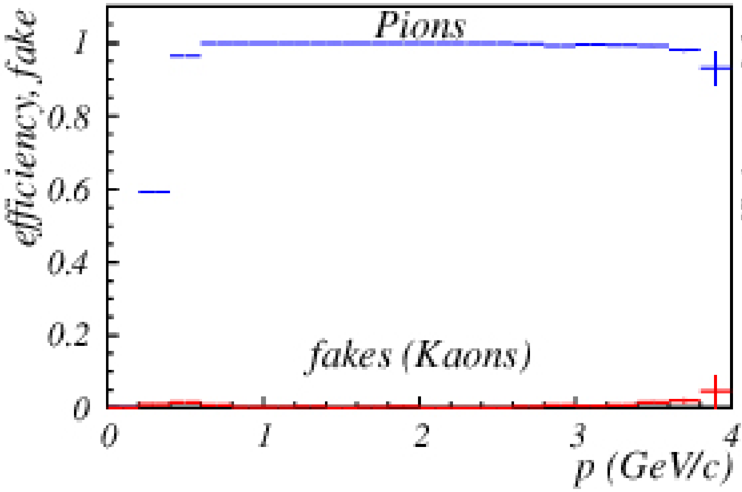
Bialkali,

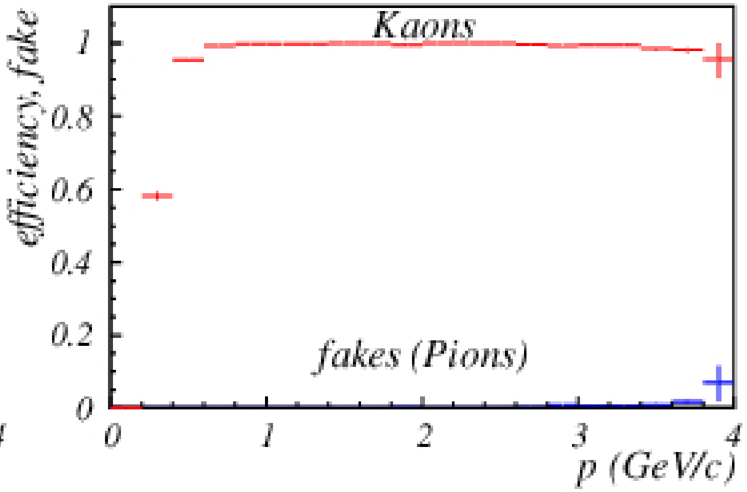
GaAsP, λ>400nm



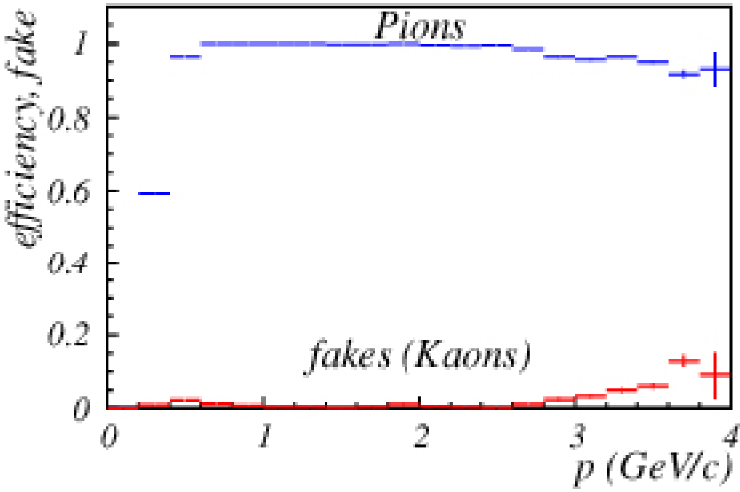
TOP: MCP PMT time resolution

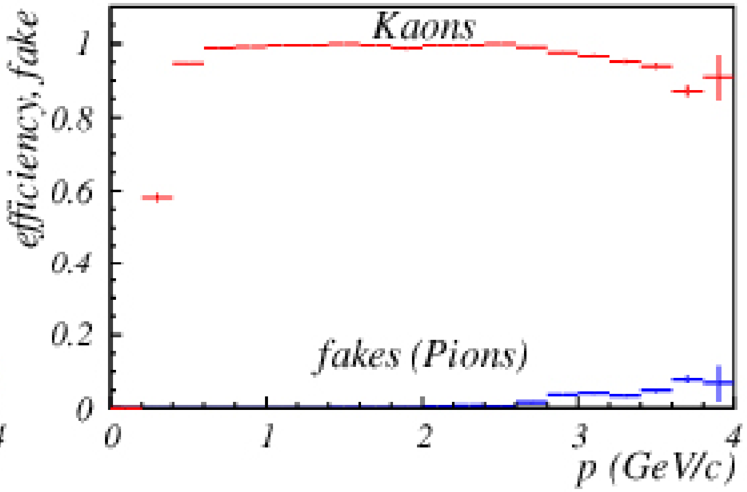
σ = 50ps





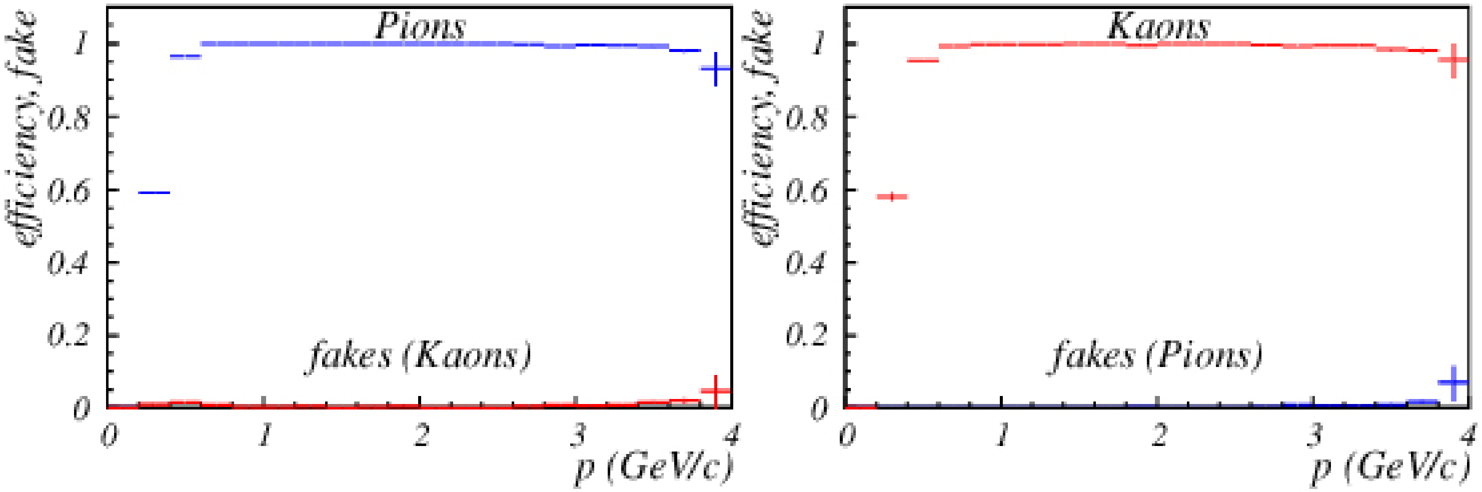
σ = 100ps



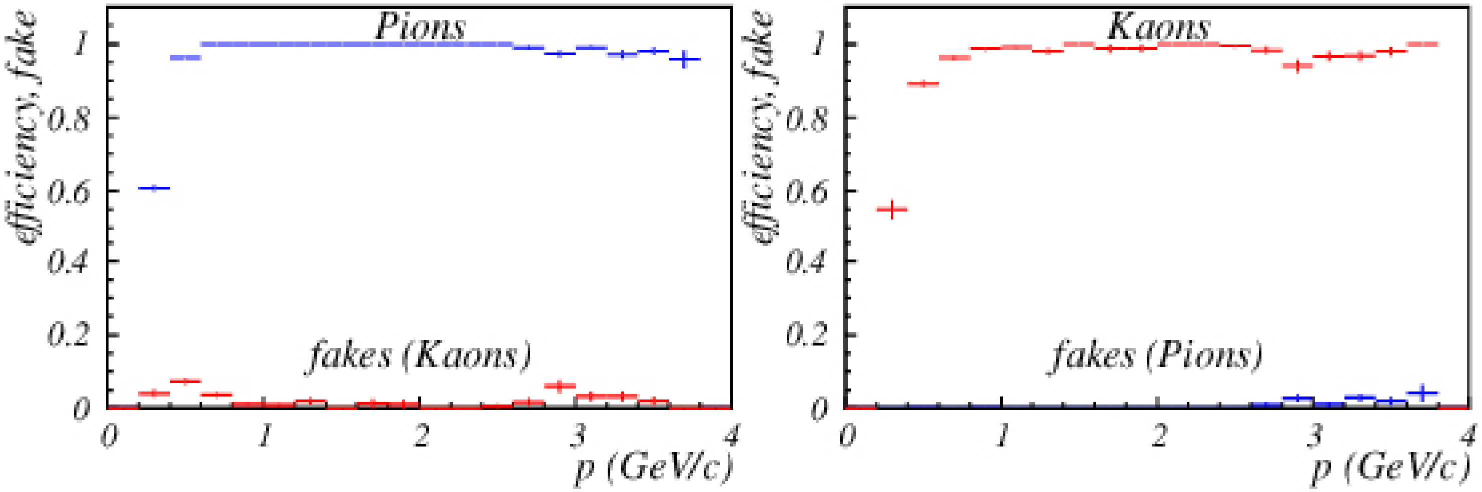


Multiple tracks per bar

Single track



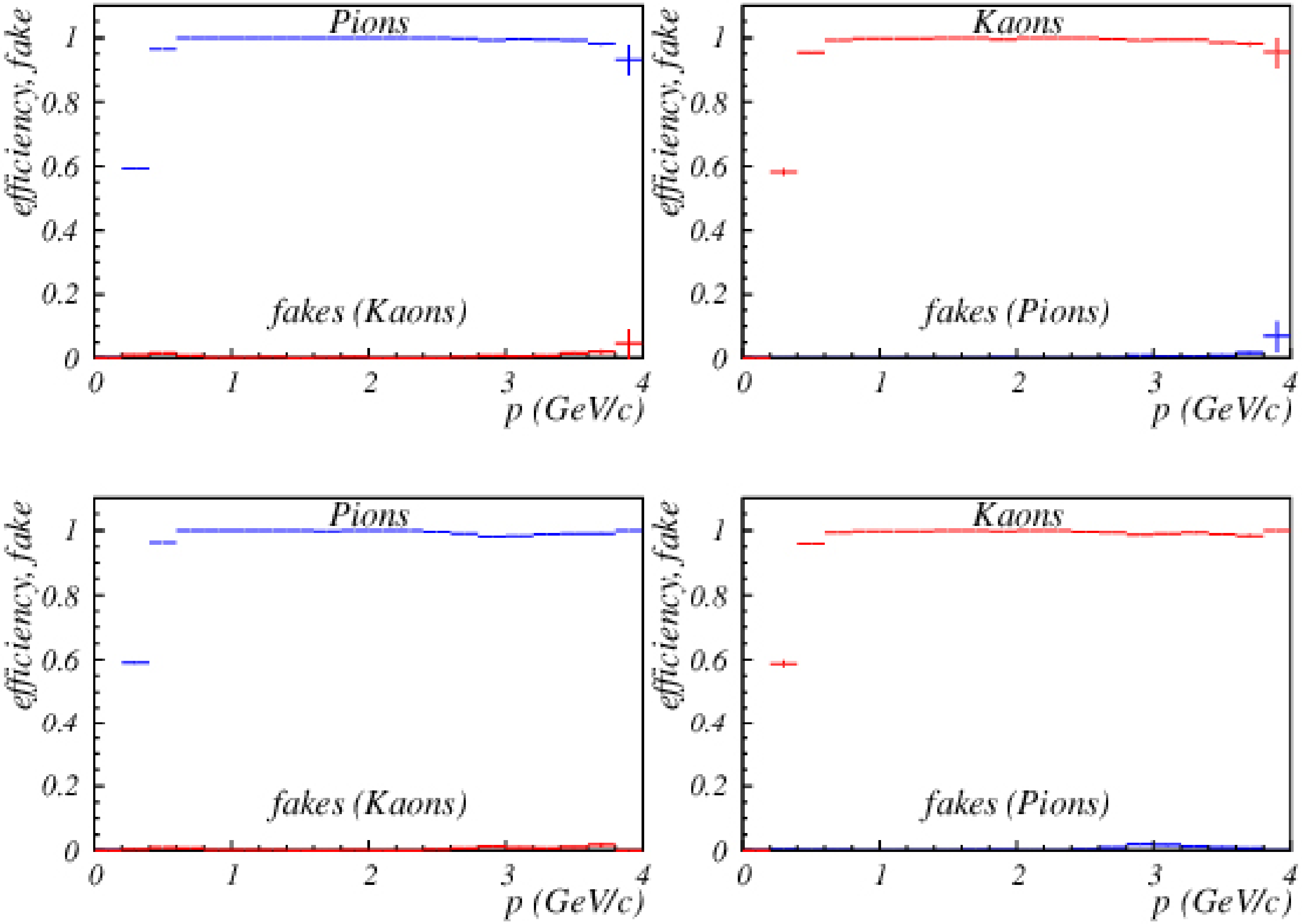
Multiple tracks



TOP: Background level

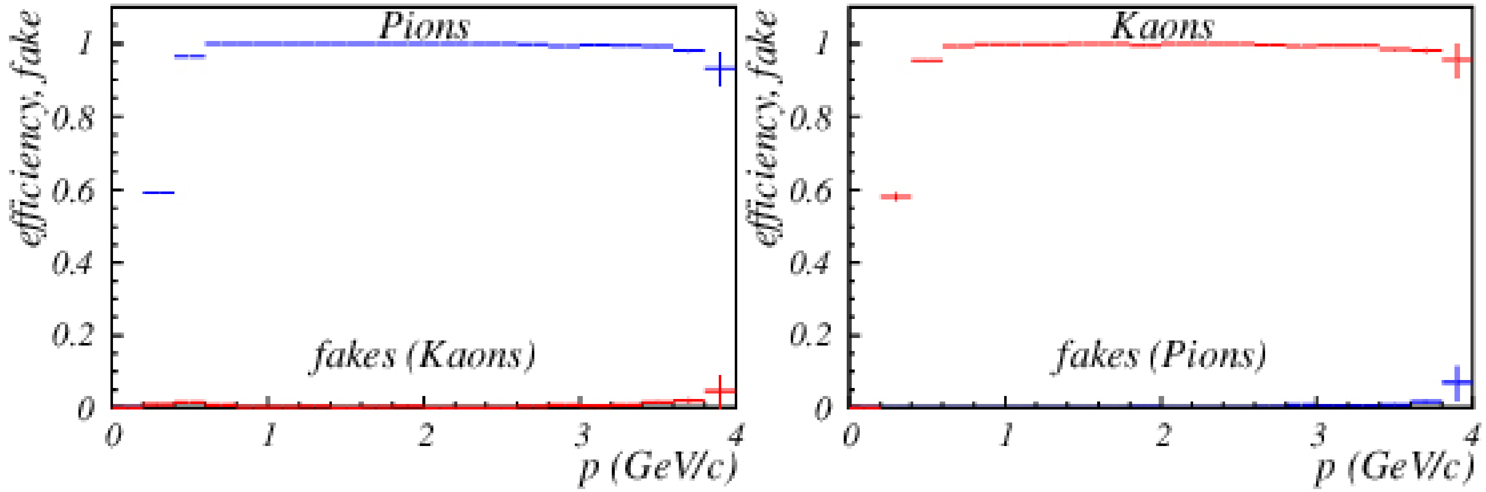
20 bckg hits/bar/50ns

100 bckg hits/bar/50ns

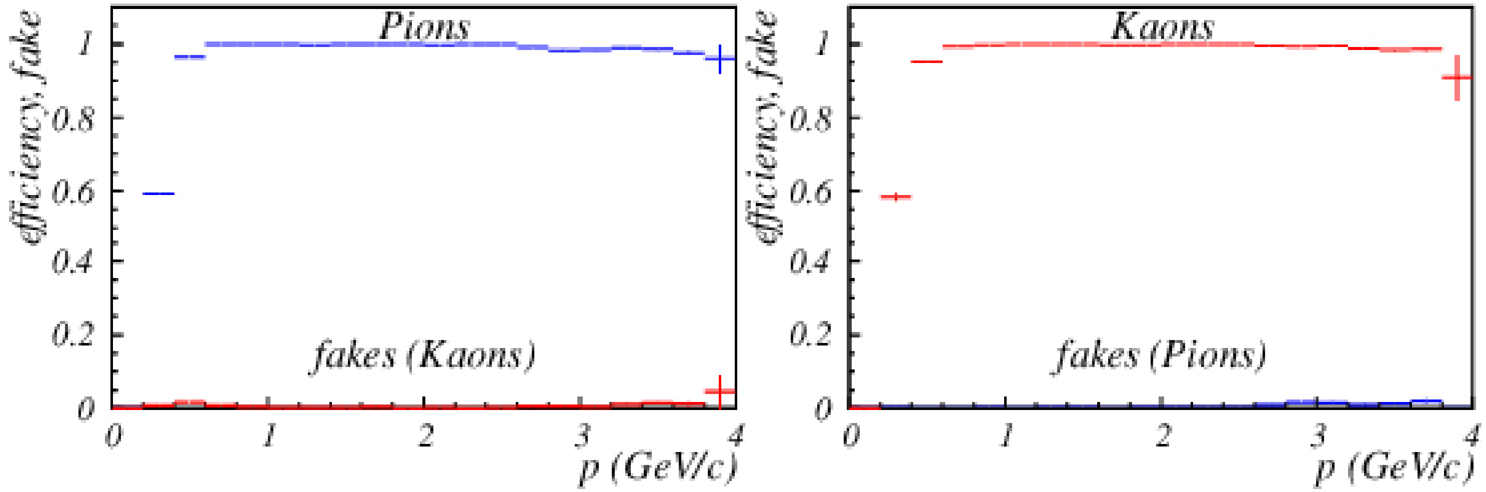


TOP: uncertainty in track parameters

No uncertainty



2 mrad uncertainty in track direction at IP

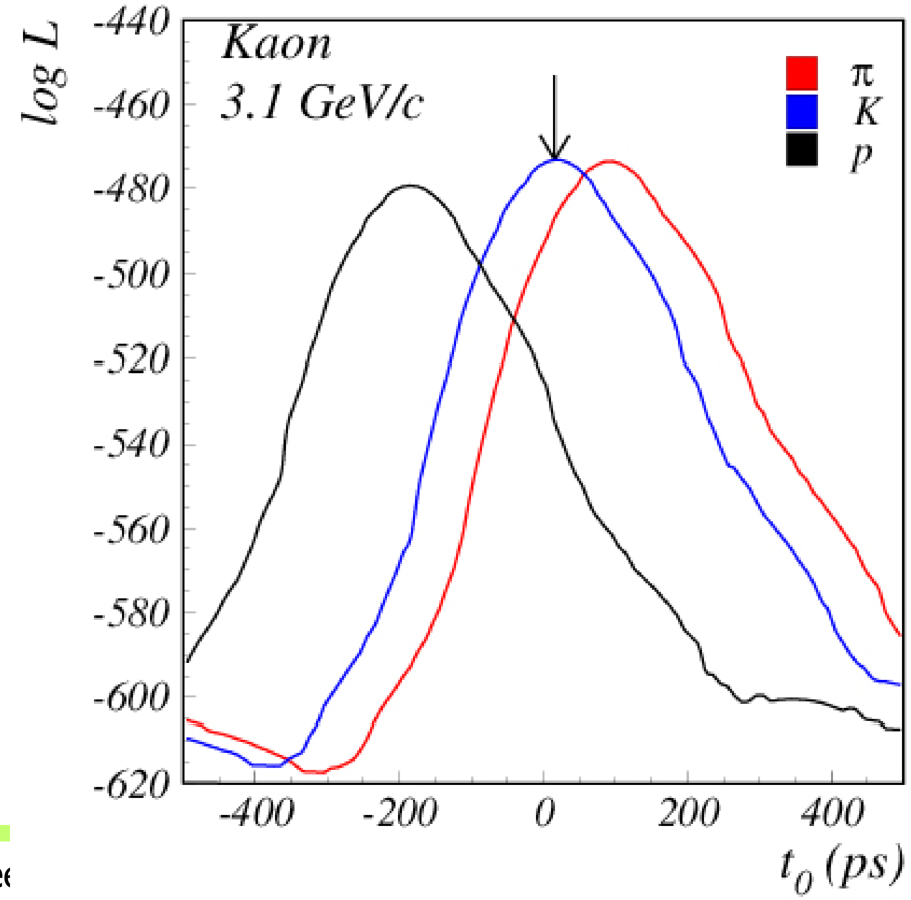


Start time T0 reconstruction

T0 uncertainty: very important
Can we determine it from the data?
In principle yes.

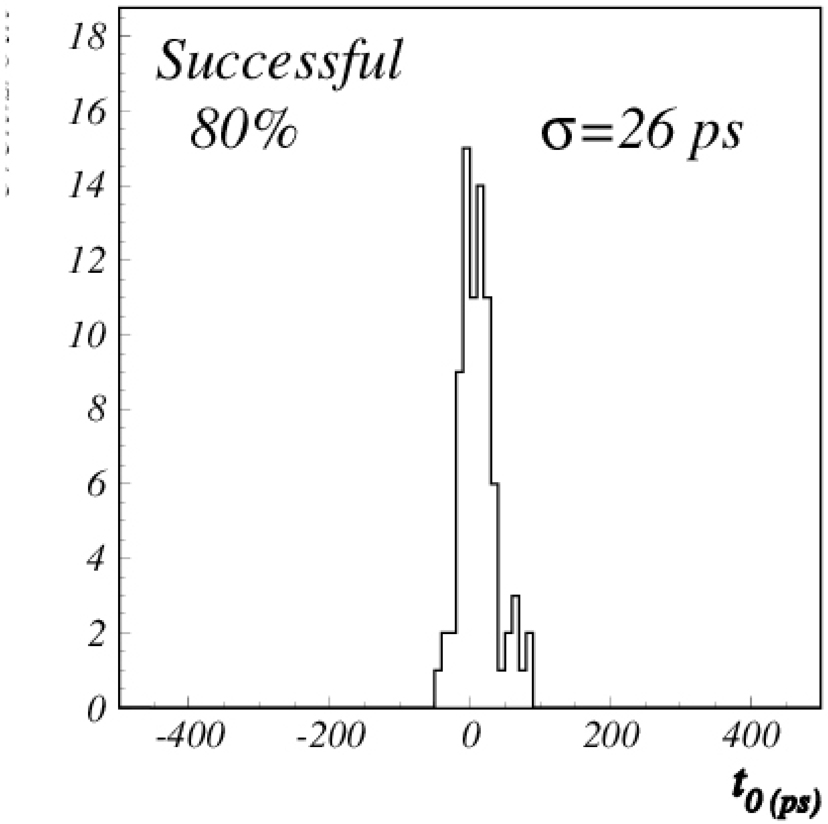
One way: determine for each track the likelihood for one of the three hypotheses as a function of T0

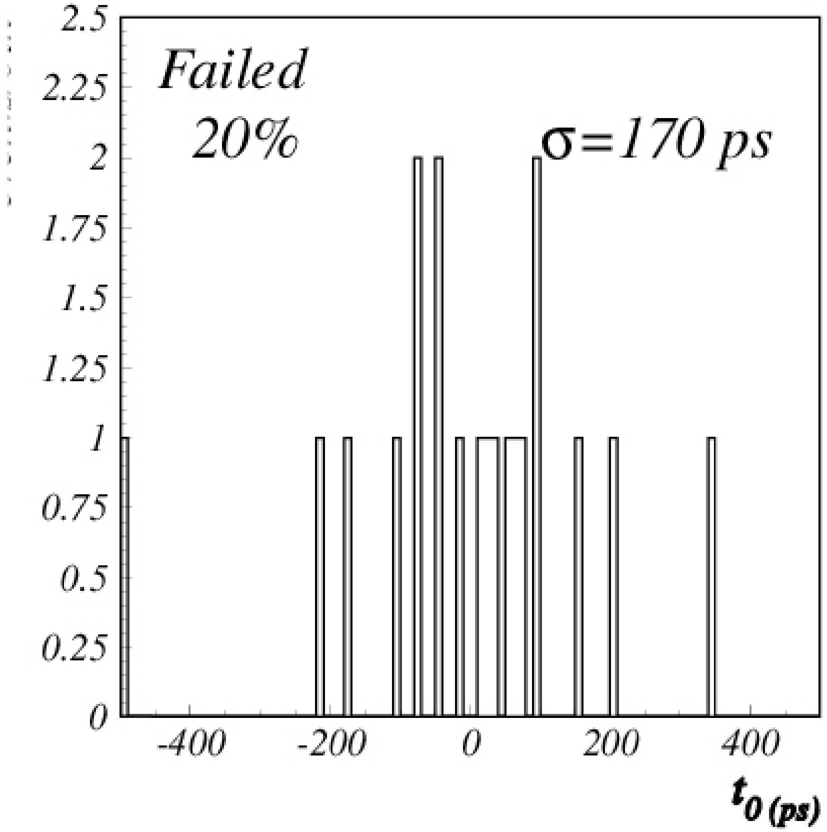
Choose the value with the highest logL



T0 reconstruction

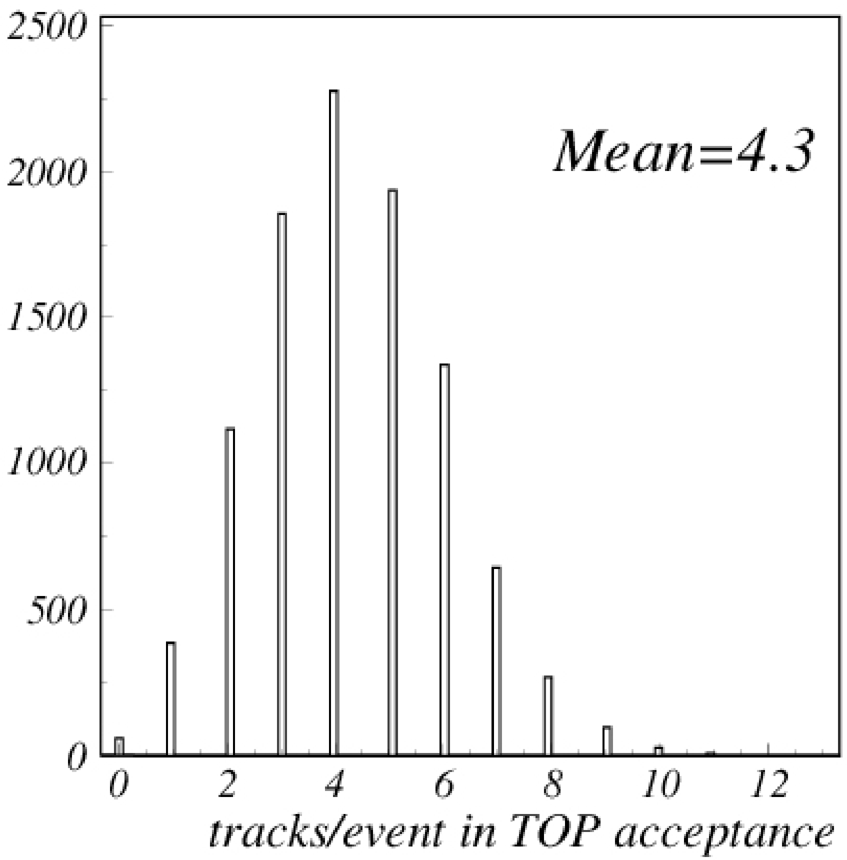
→T0 as reconstructed from single tracks.





Right hypothesis chosen (left), wrong (right)

T0 reconstruction



T0 for individual events: on average 2 time better (10-15ps).

But: problems with low multiplicity events!

Probably better: average over a larger number of events from the same bunch, compare to a reference clock (accelerator).

→ Further studies needed

TOP reconstruction: likelihood

Log likelihood probability for a given mass hyphothesis:

$$\log \mathcal{L} = \sum_{i=1}^{N} \log\left(\frac{S(x_{ch},t) + B(x_{ch},t)}{N_e}\right) + \log P_N(N_e)$$

Where

N is the measured number of photons,
$N_e = N_S^{exp} + N_B^{exp}$ is the expected number of photons (signal+background),
$S(x_{ch},t)$ is 2D distribution of signal photons,
$B(x_{ch},t)$ is 2D distribution of background photons and
$P_N(N_e)$ is the Poisson probability of mean N_e to get N photons.

Distributions S and B are normalised in the way:

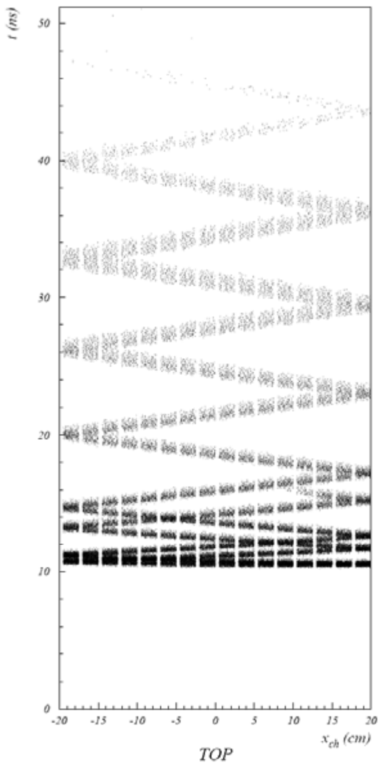
$$\sum_{x_{ch}} \int_0^{t_m} S(x_{ch},t)dt = N_S^{exp}, \qquad \sum_{x_{ch}} \int_0^{t_m} B(x_{ch},t)dt = N_B^{exp}$$

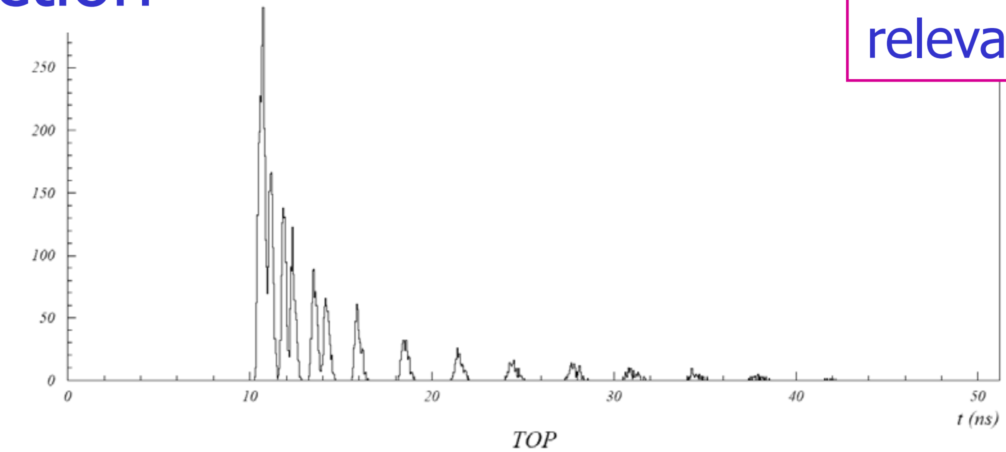
Sum runs over all channels x_{ch} and integration over full TDC range.

Note: $S(x_{ch},t)$ and N_S^{exp} are mass hypothesis dependent.

TOP reconstruction

Some of this possibly relevant for fDIRC





Signal distribution for channel x_{ch} could be parametrized as:

$$S(x_{ch}, t) = \sum_{k=1}^{m(x_{ch})} n_k(x_{ch}) g(t - t_k(x_{ch}); \sigma_k(x_{ch}))$$

Where

n_k is the number of photons in k-th peak,
$g(t - t_k; \sigma_k)$ is it's shape ($\int g(t)dt = 1$),
t_k is it's position and
σ_k is it's width (r.m.s)

- The goal: find analytical expressions for $n_k(x_{ch})$, $t_k(x_{ch})$ and $\sigma_k(x_{ch})$
- Geometric view of TOP detection: intersection of Čerenkov cone with a plane
  - $\rightarrow$ well known, quadratic equations
  - $\rightarrow$ analytical solutions should exist

→details in backup slides

Towards the analytical solution

- Coordinate system of Q-bar:

  z-axis along Q-bar, parallel to z-axis of the Belle detector

  y-axis perpendicular to Q-bar (along smallest dimension)

  origin in the centre of Q-bar

- Particle traversing the Q-bar at polar angles θ and ϕ

- Čerenkov photon emitted at point $\vec{r}_0 = (x_0, y_0, z_0)$ with polar angles θ_c and ϕ_c with respect to particle direction.

- The photon directional vector, expressed in the Q-bar system, is:

$$\vec{k} = \begin{pmatrix} k_x \\ k_y \\ k_z \end{pmatrix} = \begin{pmatrix} \cos\phi(\cos\theta\sin\theta_c\cos\phi_c + \sin\theta\cos\theta_c) - \sin\phi\sin\theta_c\sin\phi_c \\ \sin\phi(\cos\theta\sin\theta_c\cos\phi_c + \sin\theta\cos\theta_c) + \cos\phi\sin\theta_c\sin\phi_c \\ \cos\theta\cos\theta_c - \sin\theta\sin\theta_c\cos\phi_c \end{pmatrix}$$

- Photon straight line of flight: $\vec{r} = \vec{r}_0 + l\vec{k}$ (l is distance from $\vec{r}_0$ to $\vec{r}$).

- Intersection with detector plane at $z = z_D$:

$$z_D = z_0 + lk_z \quad \Rightarrow \quad l = \frac{z_D - z_0}{k_z}$$

  if length of flight $l > 0$ the intersection is in photon's forward direction and the coordinates of the photon hit are:

$$x_D = x_0 + lk_x, \quad y_D = y_0 + lk_y$$

- Time of propagation of the photon is

$$t_{TOP} = \frac{l}{v_g(\lambda)}$$

where $v_g(\lambda) = c_0/n_g(\lambda)$ is the group velocity of light in the quartz medium and $n_g(\lambda)$ the corresponding group refractive index.

- Total reflections:
Imagine the detector plane divided into cells of the size of Q-bar transverse dimensions ($a \times b$)
total reflections - the same as folding the detector plane at cell bounderies

- Number of reflections

$$n_x = \text{nint}(x_D/a)$$
$$n_y = \text{nint}(y_D/b)$$

- Coordinates at the middle cell (Q-bar exit window)

$$x = \begin{cases} x_D - an_x \,, & n_x = 0, \pm 2, \pm 4, \ldots \\ an_x - x_D \,, & n_x = \pm 1, \pm 3, \ldots \end{cases} \quad y = \begin{cases} y_D - bn_y \,, & n_y = 0, \pm 2, \pm 4, \ldots \\ bn_y - y_D \,, & n_y = \pm 1, \pm 3, \ldots \end{cases}$$

- Total reflection requirement (n is quartz refractive index):

$$|k_x| < \sqrt{1 - 1/n^2} \,, \qquad |k_y| < \sqrt{1 - 1/n^2}$$

- In summary - we've found:

$$t_{TOP}(\phi_c) = \frac{(z_D - z_0)n_g}{k_z(\phi_c)c_0} \qquad x_D(\phi_c) = x_0 + \frac{k_x(\phi_c)}{k_z(\phi_c)}(z_D - z_0)$$

$\rightarrow$ eliminate ϕ_c to get $t_{TOP}(x_D)$

TOP reconstruction

5 The analytical solution

- Detector plane coordinate of a channel x_{ch} for k-th reflection is

$$x_k = \begin{cases} ka + x_{ch} \; , & k = 0, \pm 2, \pm 4, \ldots \\ ka - x_{ch} \; , & k = \pm 1, \pm 3, \ldots \end{cases}$$

- By defining:

$$a_k = \frac{x_0 - x_k}{z_0 - z_D} \cos\theta \cos\theta_c$$

$$b_k = \frac{x_0 - x_k}{z_0 - z_D} \sin\theta \sin\theta_c$$

$$c = \cos\phi \cos\theta \sin\theta_c$$

$$d = \sin\phi \sin\theta_c$$

$$e = \cos\phi \sin\theta \cos\theta_c$$

- The cosine of ϕ_c for k-th peak in channel x_{ch} is:

$$\cos\phi_c^{(k)} = \frac{-(b_k+c)(e-a_k) \pm d\sqrt{d^2+(b_k+c)^2-(e-a_k)^2}}{(b_k+c)^2+d^2}$$

- and the peak position (using mean values for θ_c and n_g):

$$t_k = \frac{z_D - z_0}{(\cos\theta\cos\theta_c - \sin\theta\sin\theta_c\cos\phi_c^{(k)})}\frac{n_g}{c_0} + t_{TOF}$$

where t_{TOF} is the time-of-flight of a particle from the interaction point to the quartz bar, since the time is measured relative to the beam crossing time.

- Number of photons in the k-th peak:

$$n_k = N_0 l_{track}\sin^2\theta_c\frac{\Delta\phi_c^{(k)}}{2\pi}, \qquad \Delta\phi_c^{(k)} = |\phi_c(x_k+\Delta x_{ch}/2) - \phi_c(x_k - \Delta x_{ch}/2)|$$

- Width of the k-th peak due to dispersion is proportional to $t_k - t_{TOF}$:

$$\sigma_k^{disp} = (t_k - t_{TOF})\cdot\left|f(\phi_c^{(k)})\frac{1}{n}\frac{dn}{de} + \frac{1}{n_g}\frac{dn_g}{de}\right|\sigma_e$$

where

$$f(\phi_c^{(k)}) = \frac{(\cos\theta\sin\theta_c + \sin\theta\cos\theta_c\cos\phi_c^{(k)})}{(\cos\theta\cos\theta_c - \sin\theta\sin\theta_c\cos\phi_c^{(k)})}\cdot\frac{\cos\theta_c}{\sin\theta_c}$$

σ_e is the r.m.s. of the Čerenkov photon energy distribution (given by QE of PMT) and e is the photon energy.

6 Basics data for TOP used in simulation

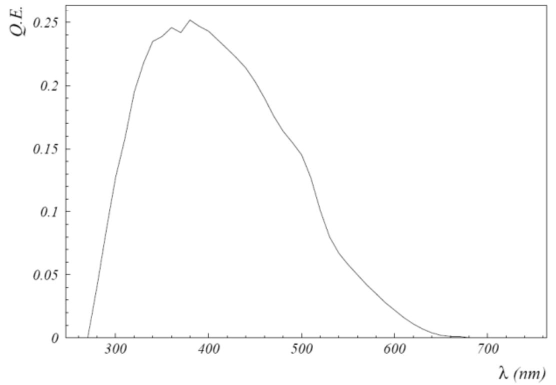
- Refractive index of quartz:

$$n(\lambda) = 1.44 + \frac{8.20nm\lambda}{\lambda - 126nm} \qquad n_g(\lambda) = \frac{n(\lambda)}{1 + \frac{\lambda}{n(\lambda)}\frac{dn}{d\lambda}}$$

- Absorption length of quartz:

$$\lambda_{abs} = 500m\left(\frac{\lambda}{442nm}\right)^4$$

- Quantum efficiency as for Hamamatsu R5900-M16
- 70% collection efficiency



- Using above data the basic TOP parameters are:

  N_0 = 105 cm^{-1}

  $< e >$ = 3.3 eV $\Rightarrow$ $< n >$ = 1.47, $< n_g >$ = 1.52

  σ_e =0.56 eV

  $\frac{1}{n}\frac{dn}{de}$ = 1.0%/eV, $\frac{1}{n_g}\frac{dn_g}{de}$ = 3.1%/eV

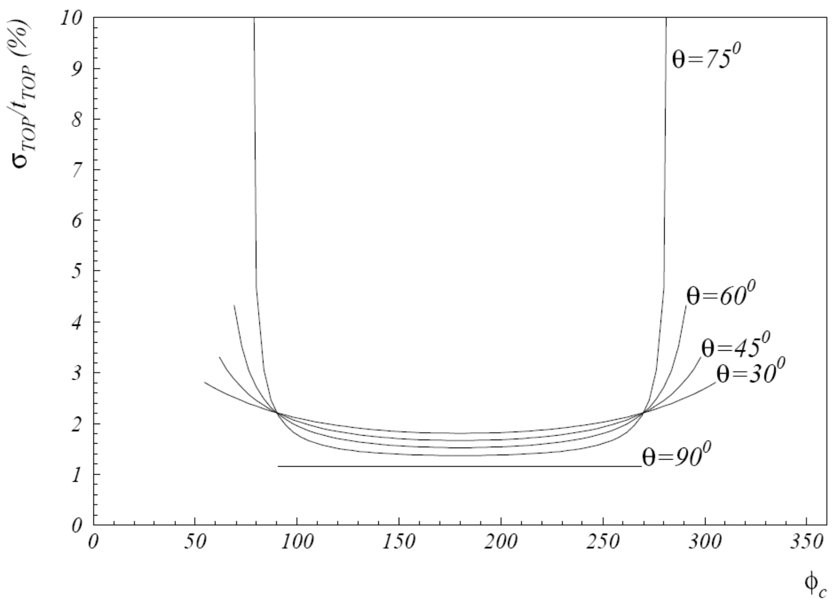
- PMT time resolution: σ_{PMT} = 50ps
- Q-bar dimensions: 40cm × 2cm × 255cm
- Coverage: Δx_{ch}=5mm, 64 active channels out of 80 per Q-bar exit window

7 TOP time resolution

Relative time resolution due to dispersion, calculated with derived formulas

$$\sigma^{disp}/t_{TOP} \approx 1\% \ - \ 2\%$$

depends on track angle θ $\longrightarrow$



Peak shape

Slightly asymmetric but could be reasonably well approximated by a Gaussian

$$g(t - t_k; \sigma_k) = \frac{n_k}{\sqrt{2\pi}\sigma_k} e^{-\frac{(t-t_k)^2}{2\sigma_k^2}}$$

with

$$\sigma_k = \sigma_k^{disp} \oplus \sigma_{PMT}$$