Report on hardware tests and MC studies in Ljubljana

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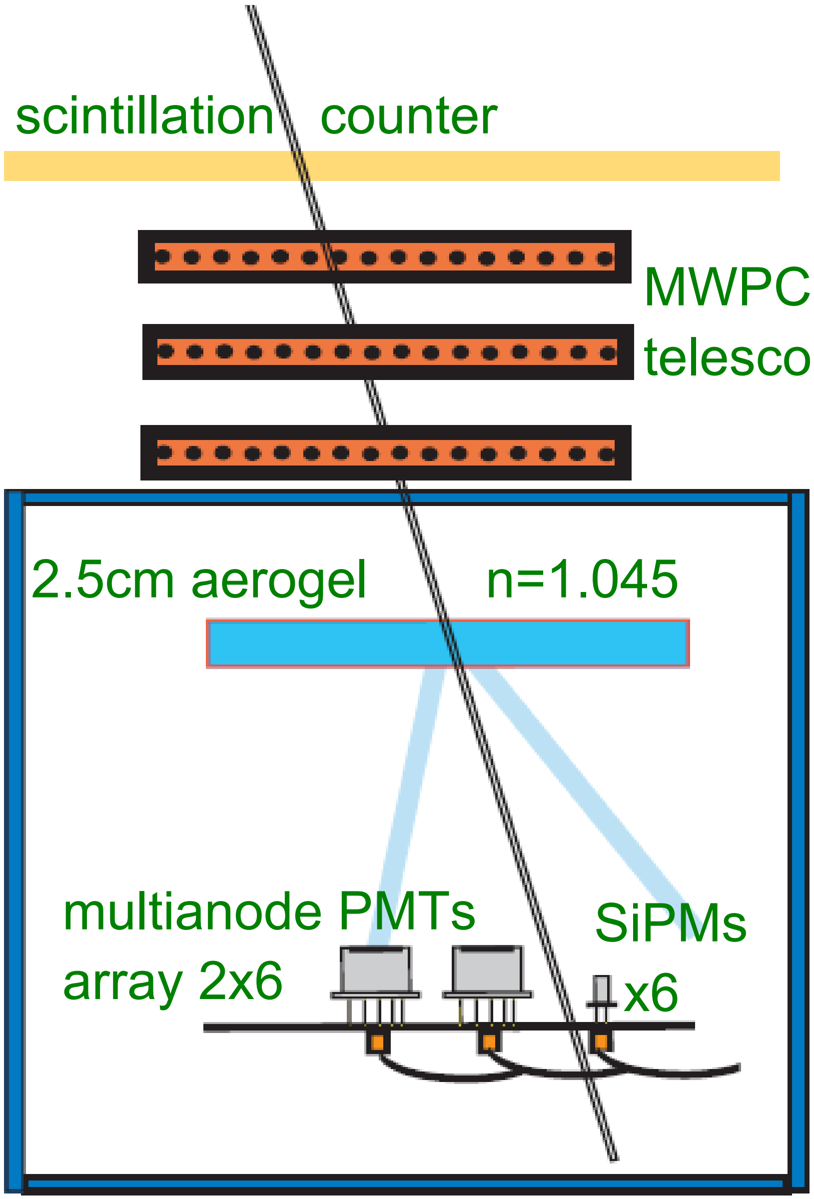
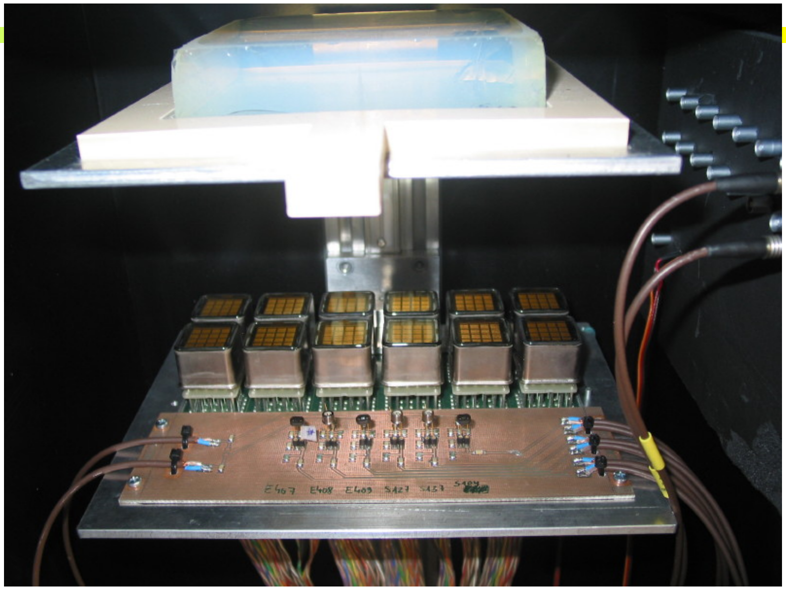
Hardware activities

Photon detectors for the forward device
- MCP PMTs: fast
- SiPMs: small, detector can be made very thin

MC studies
- Aerogel RICH
- Barrel PID device

SIPMs: Cosmic test setup



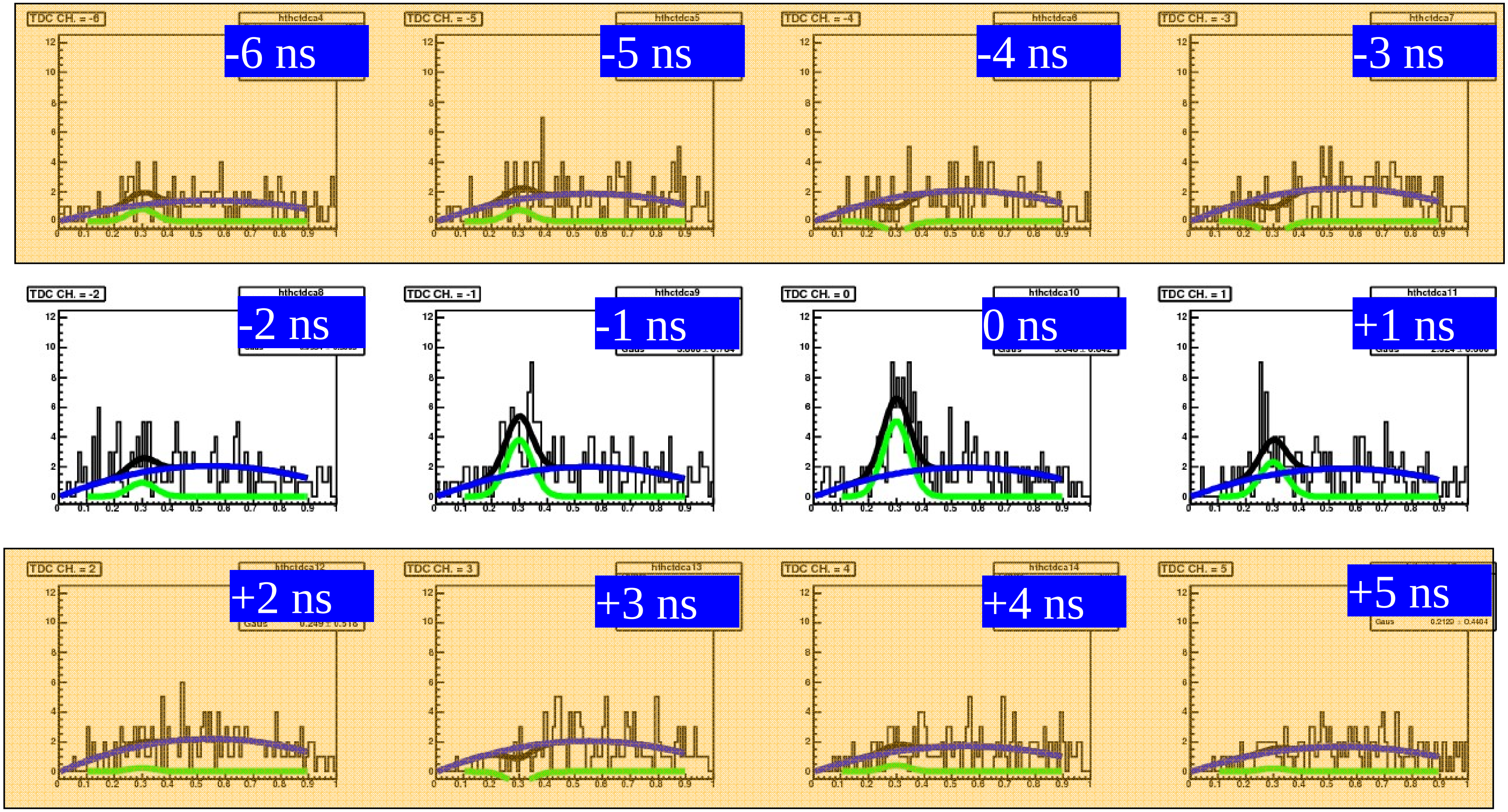


- 6 Hamamatsu SiPMs (=MPPC) of type 100U (10x10 pixels with 100μm pitch), background ~400kHz

- signals amplified (ORTEC FTA820),
- discriminated (EG&G CF8000) and
- read by multihit TDC (CAEN V673A) with 1 ns / channel

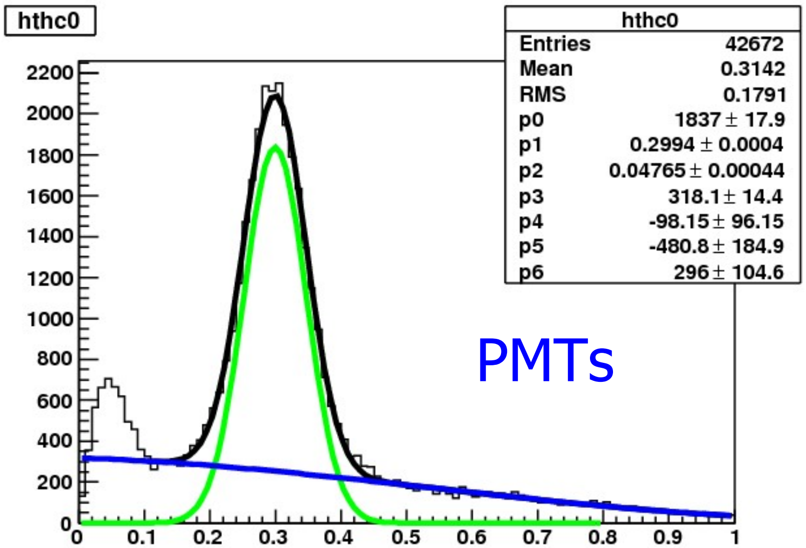
To be published in NIM A in ~3 weeks

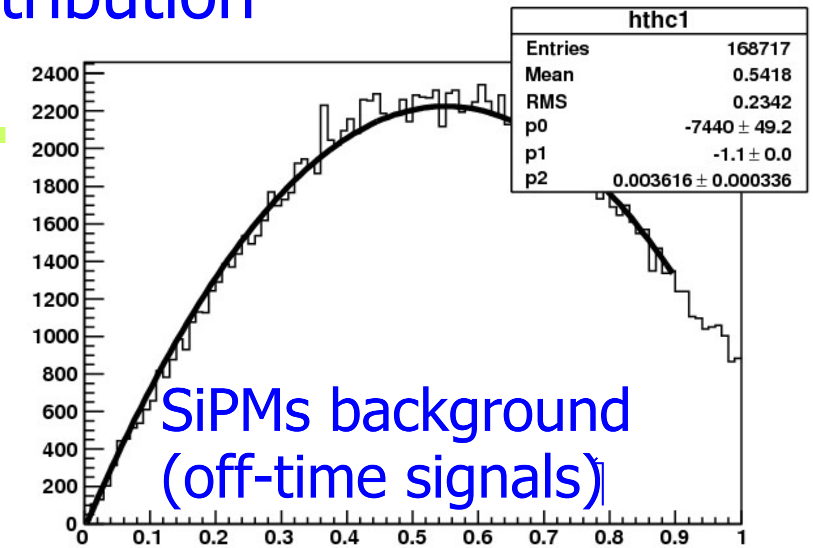
SiPM: Cherenkov angle distributions for 1ns time windows

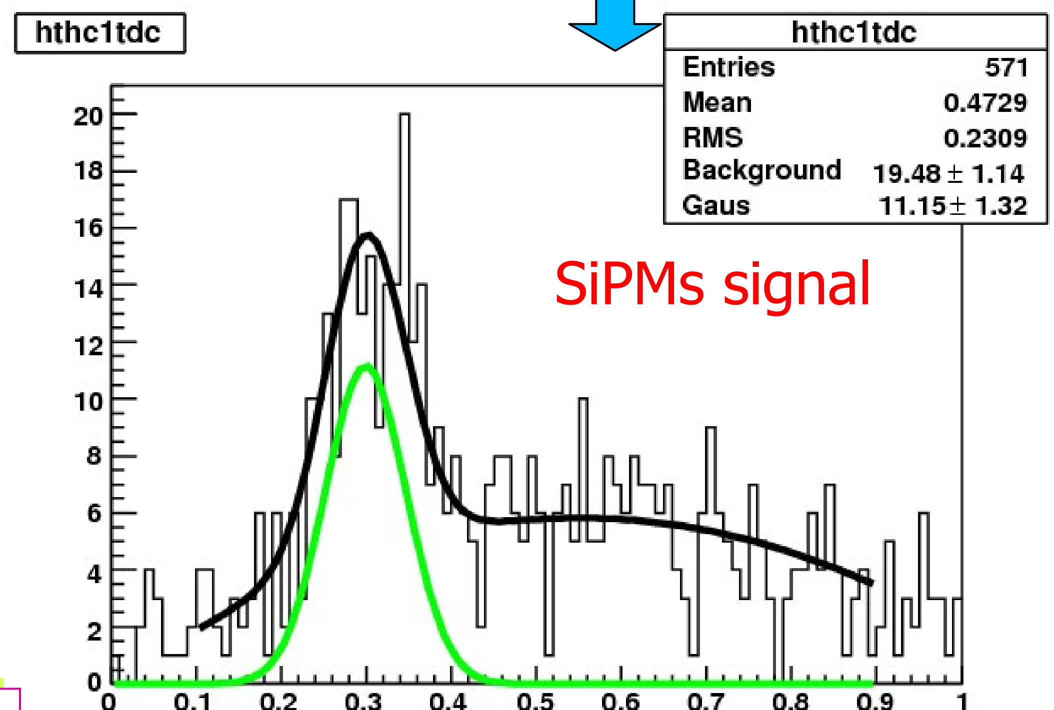


Cherenkov photons appear in the expected time windows →
First Cherenkov photons observed with SiPMs!

SiPM Cherenkov angle distribution







Fit function is a combination of

- a background (quadratic) and
- a signal (Gaussian).

Only scale parameters are free

→ SiPMs give 5 x more photons than PMTs per photon detector area – in agreement with expectations

To be published in NIM A in ~3 weeks

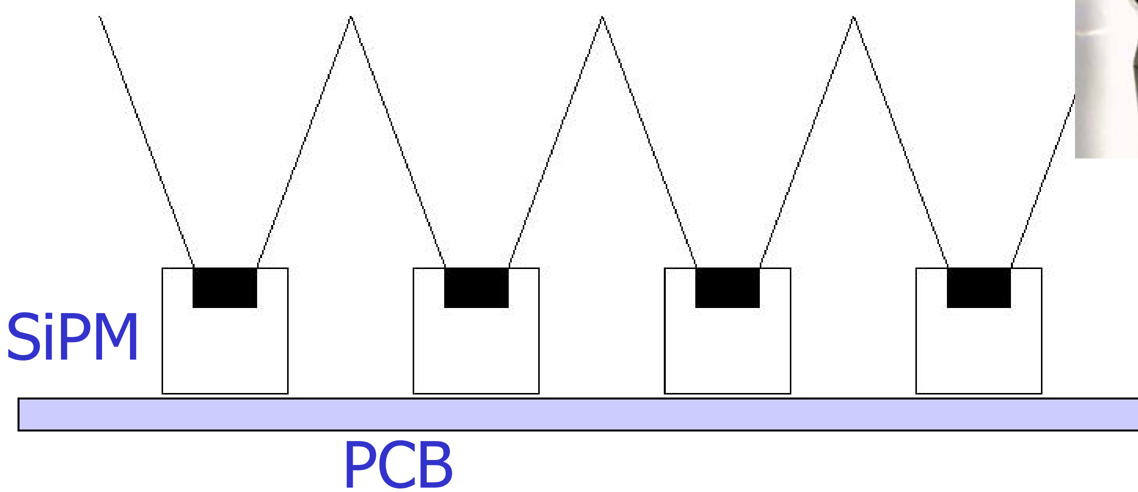
SIPMs: improving signal/noise

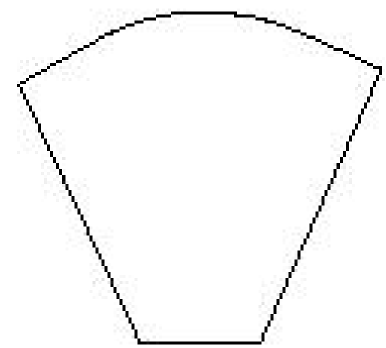
Improve the signal to noise ratio:

•Reduce the noise by a narrow (few ns) time window

•Increase the number of signal hits per single sensor by using light collectors and by adjusting the pad size to the ring thickness

Light collector with reflective walls

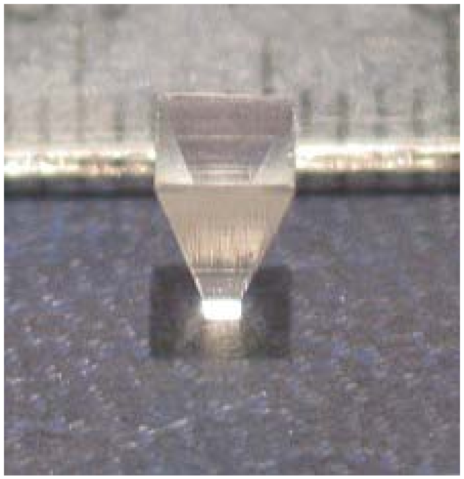


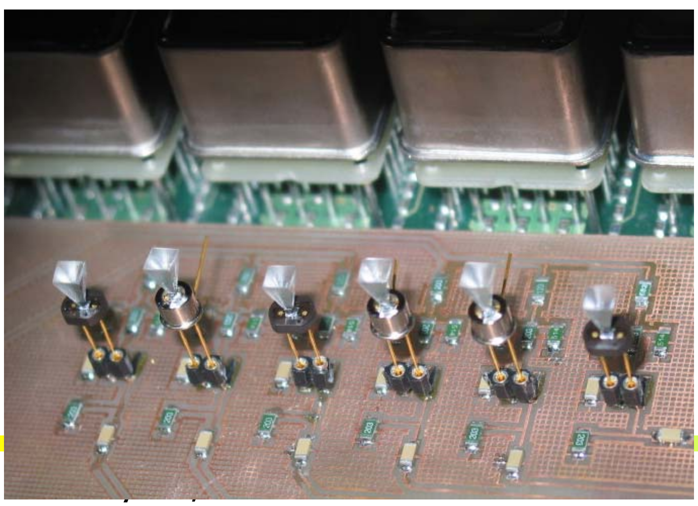


or combine a lens and mirror walls

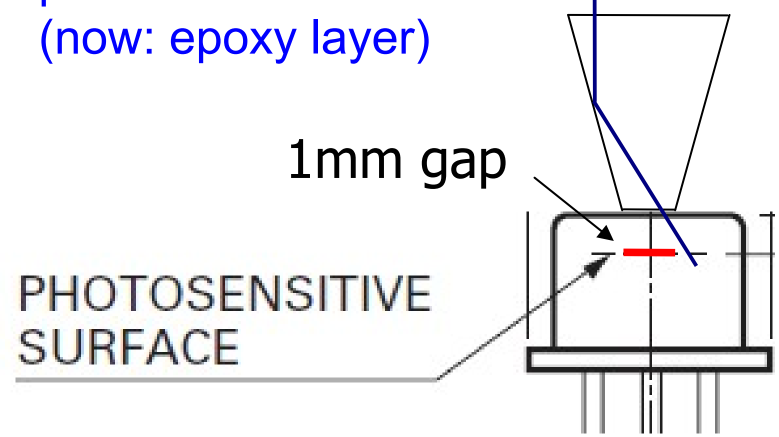
Light collection: improve signal to noise ratio

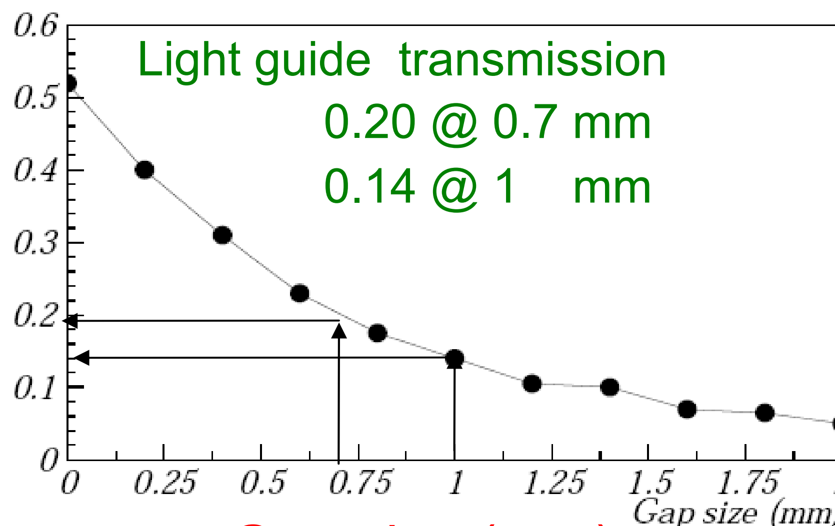
Machined from a plastic plate (HERA-B RICH lens material).





Light guide should be as close as possible to the SiPM surface (now: epoxy layer)



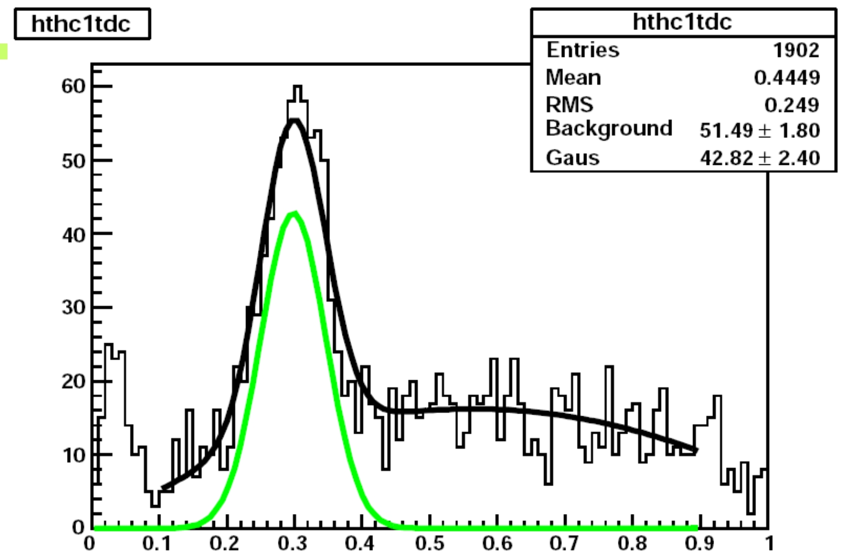


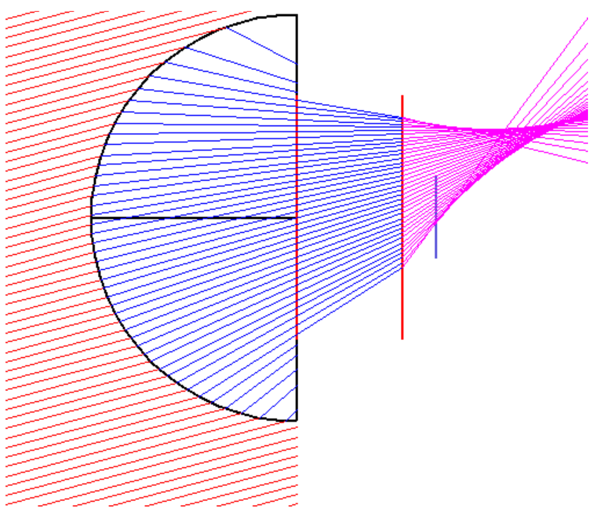
Gap size (mm)

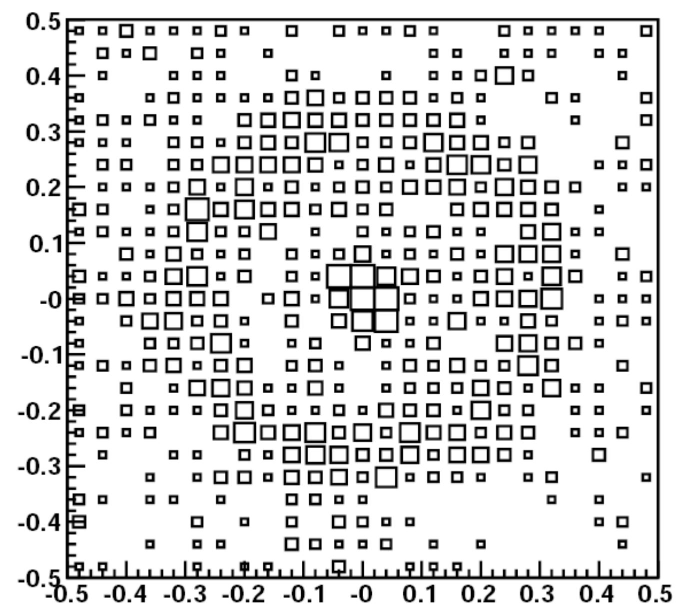
Cherenkov photons with light collectors

First attempt: use the top of a blue LED

- in agreement with the expectations
- Further improvements possible by
  - reducing the epoxy protective layer
  - using better light collector

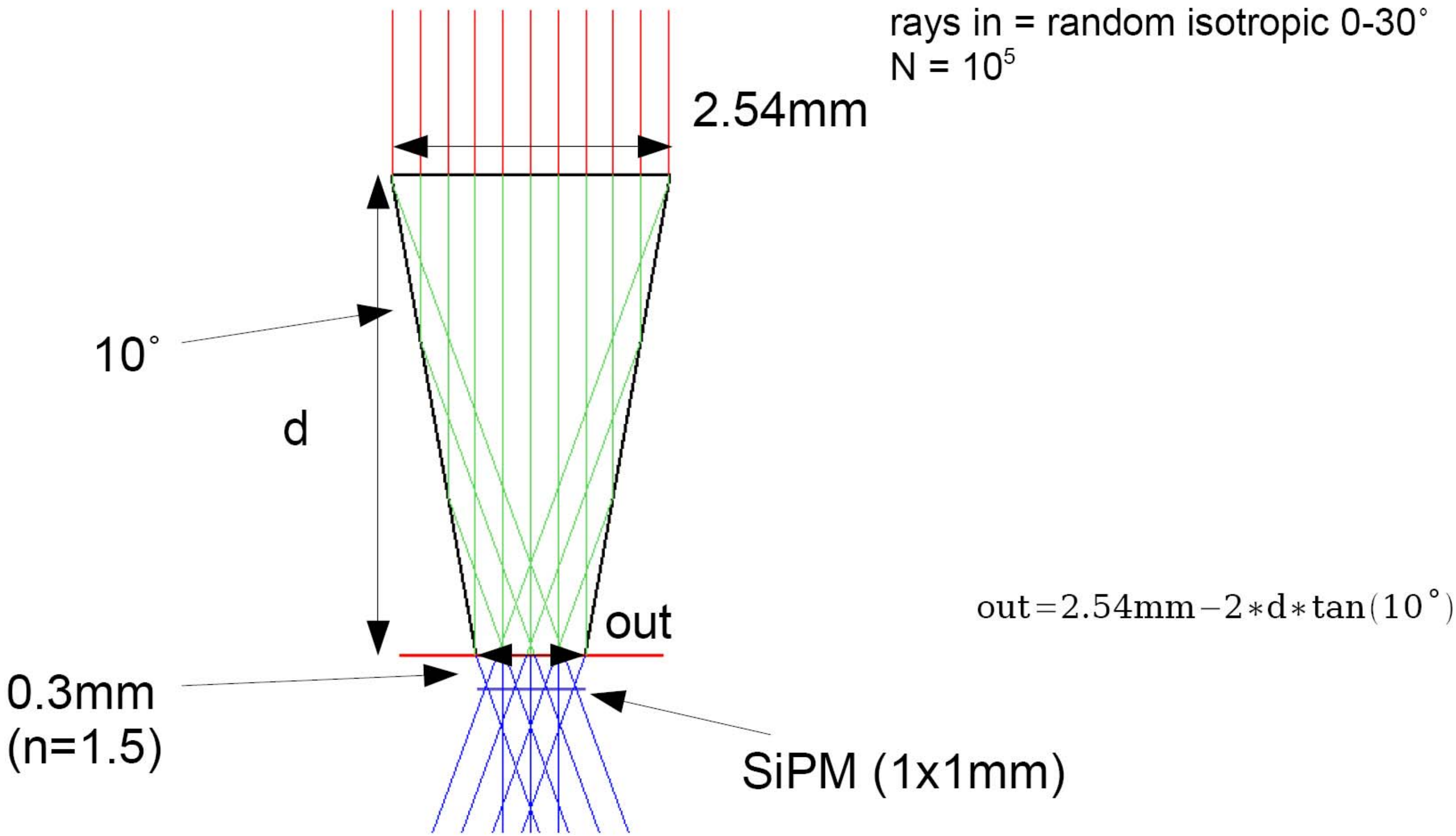




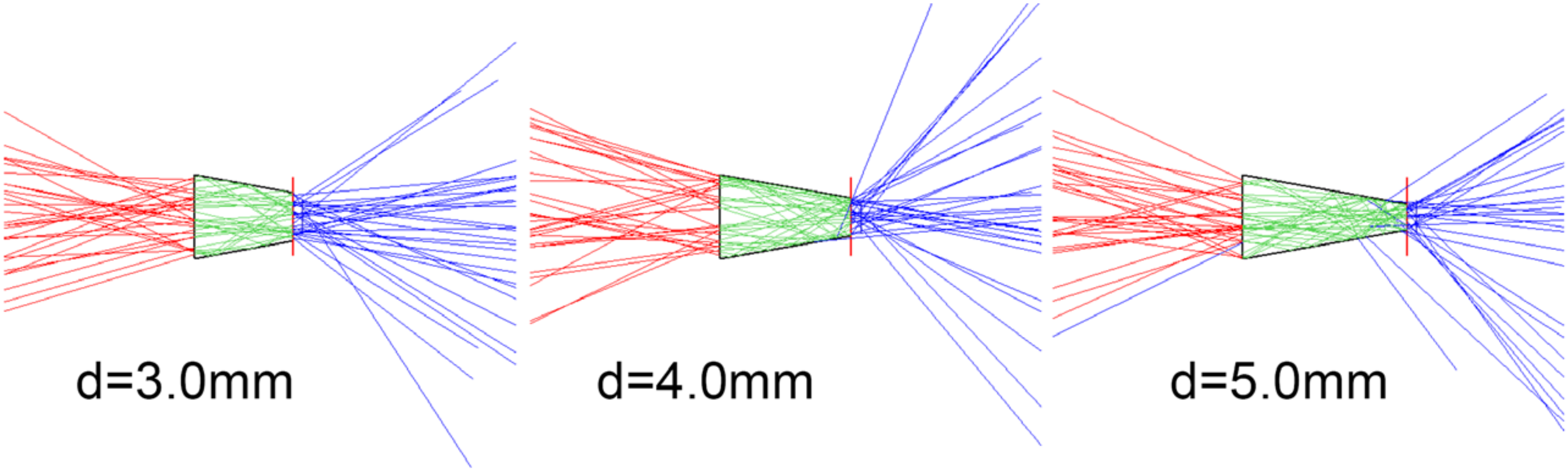


Light guide geometry optimisation

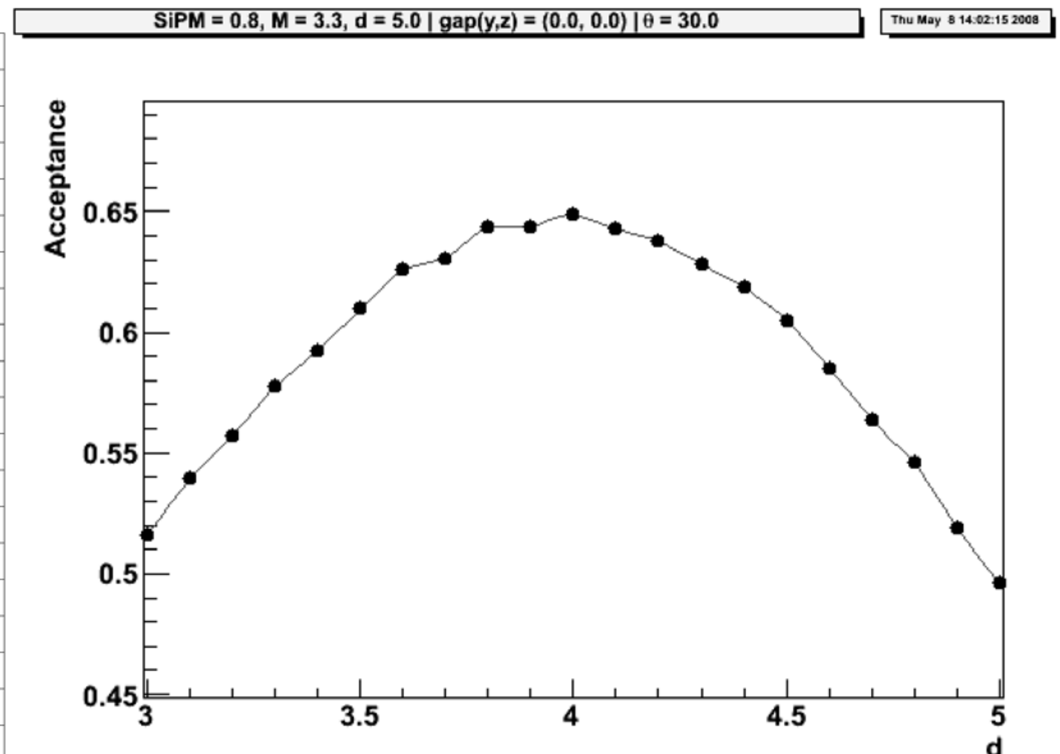
Light Guide Acceptance / (d and out)



Light guide geometry optimisation

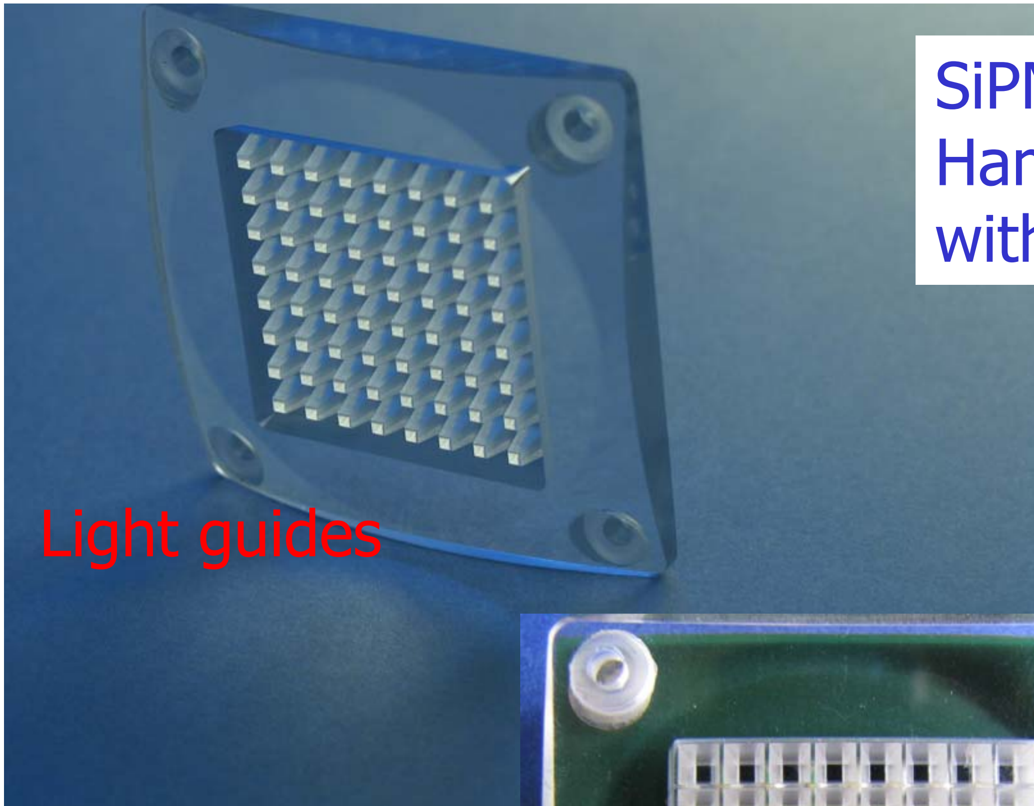


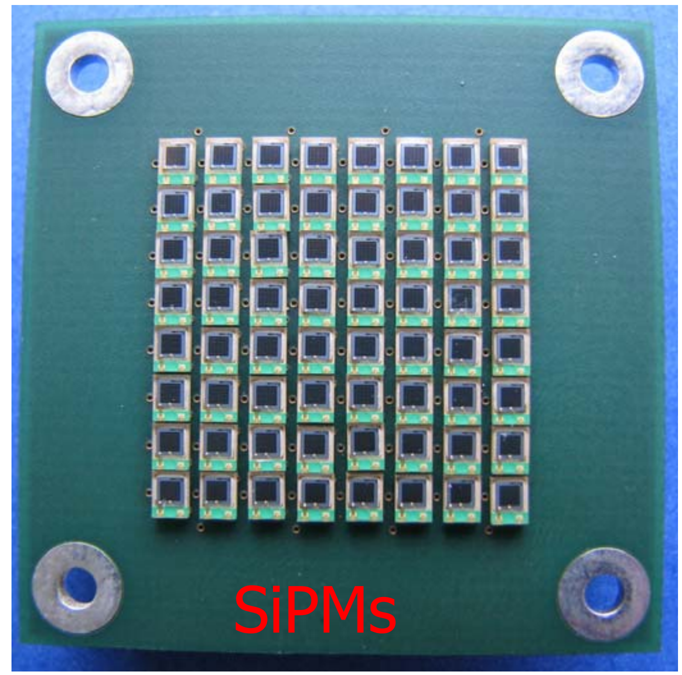
d (mm)	out (mm)	accept. (%)
3.0	1.48	51.6
3.1	1.45	54.0
3.2	1.41	55.7
3.3	1.38	57.8
3.4	1.34	59.2
3.5	1.31	61.0
3.6	1.27	62.6
3.7	1.24	63.1
3.8	1.20	64.4
3.9	1.16	64.4
4.0	**1.13**	**64.9**
4.1	1.09	64.3
4.2	1.06	63.8
4.3	1.02	62.8
4.4	0.99	61.8
4.5	0.95	60.5
4.6	0.92	58.5
4.7	0.88	56.4
4.8	0.85	54.6
4.9	0.81	51.9



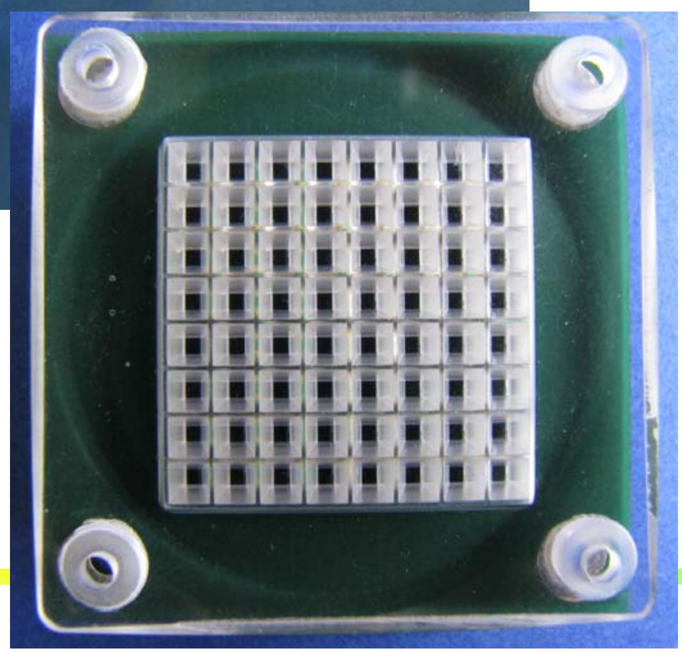
Detector module – final version for beam tests next week at KEK

SiPMs: array of 8x8 SMD mount Hamamatsu S10362-11-100P with 0.3mm protective layer





2cm



SiPMs + light guides

MC studies

Barrel device

- Simple MC of Time-Of-Propagation counter
- Reconstruction and likelihood function construction
- Could be adapted to the focusing DIRC needs

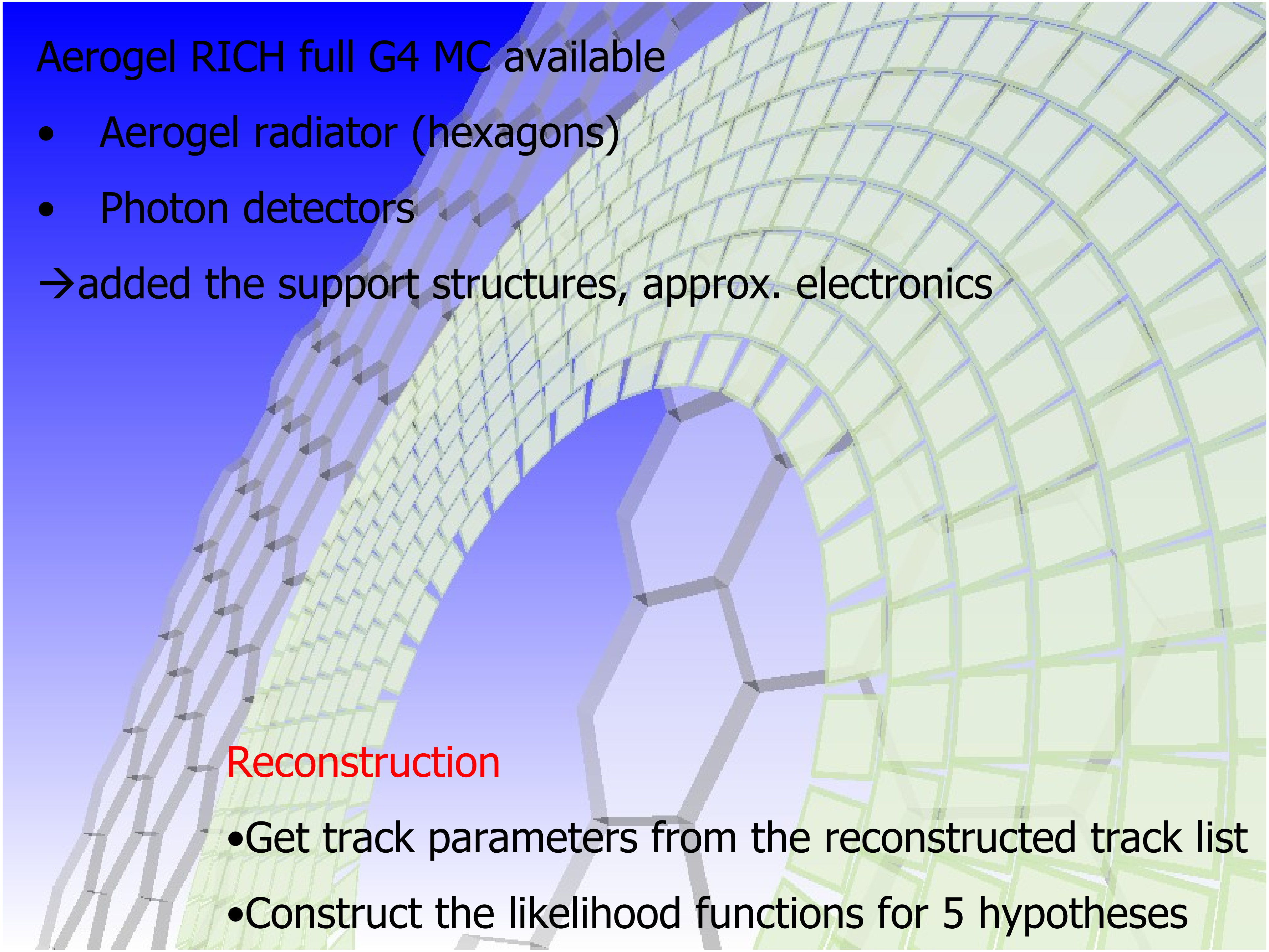
Forward RICH

- Full Geant4 MC
- Reconstruction

Aerogel RICH full G4 MC available

- Aerogel radiator (hexagons)
- Photon detectors

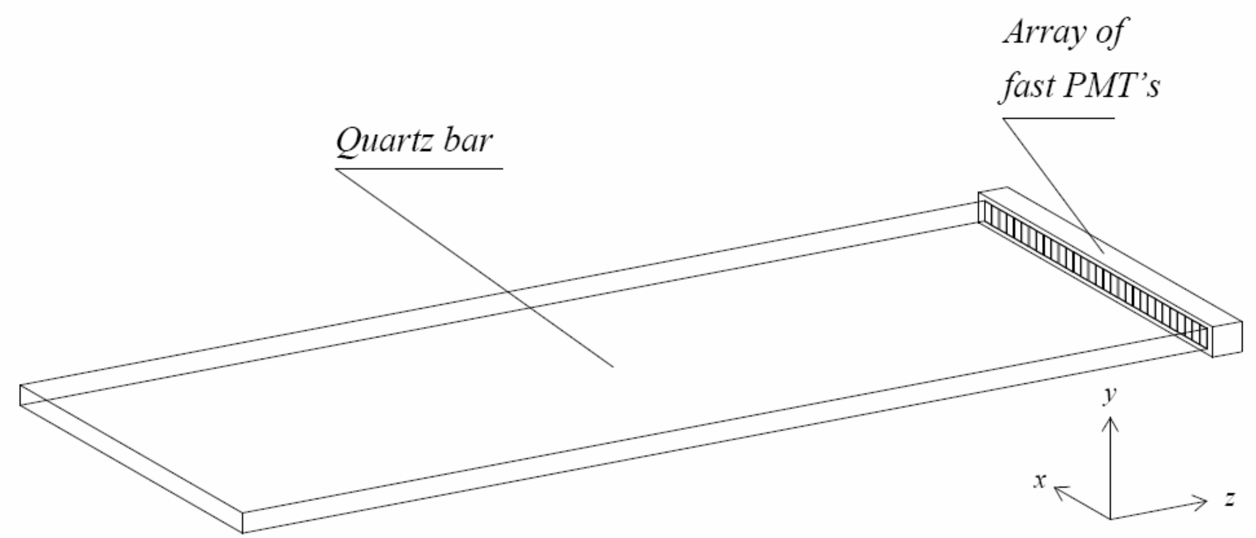
→added the support structures, approx. electronics

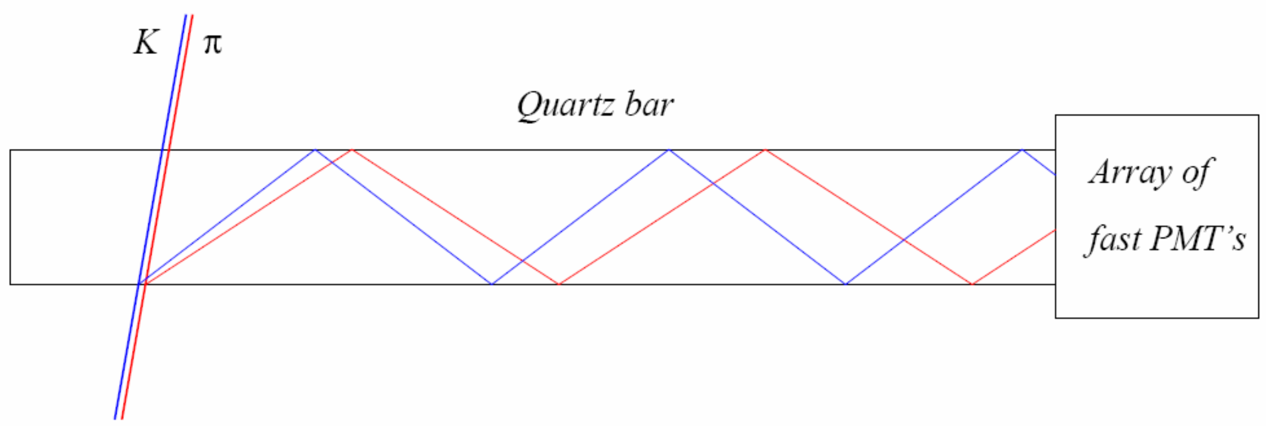


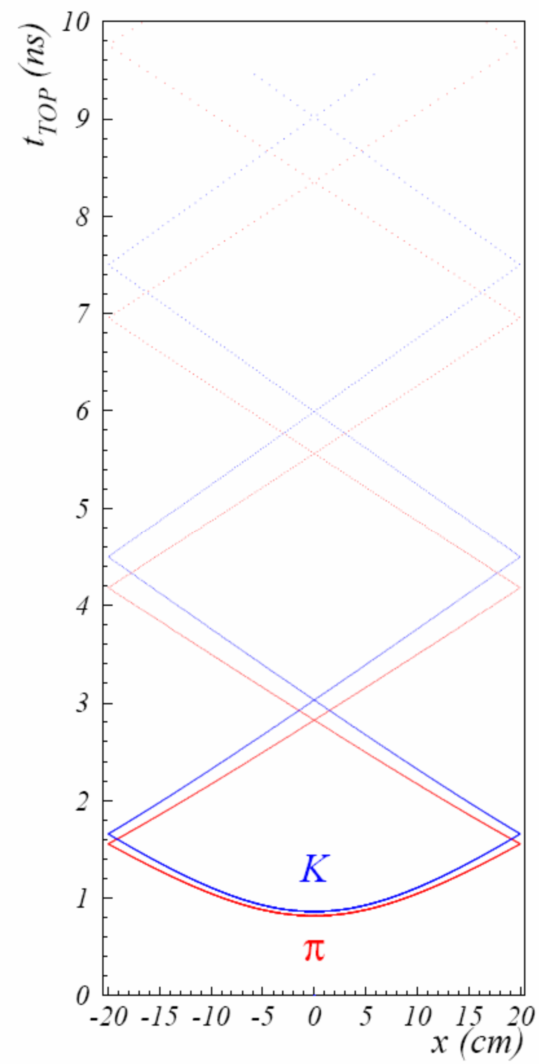
Reconstruction

- Get track parameters from the reconstructed track list
- Construct the likelihood functions for 5 hypotheses

TOP simulation and reconstruction







TOP simulation and reconstruction

Simulation: not Geant

- Input: particles from a MC generator, propagate to TOP
- Cherenkov photons: propagated along the bar $40x2x255cm^3$
- PMT response (assume GaAsP or bi-alkali, 50ps TTS)
- Uncorrelated background: 20 hits/bar side/50ns

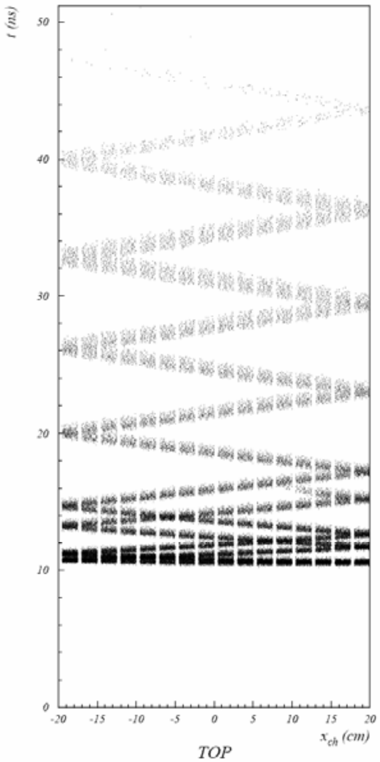
Reconstruction:

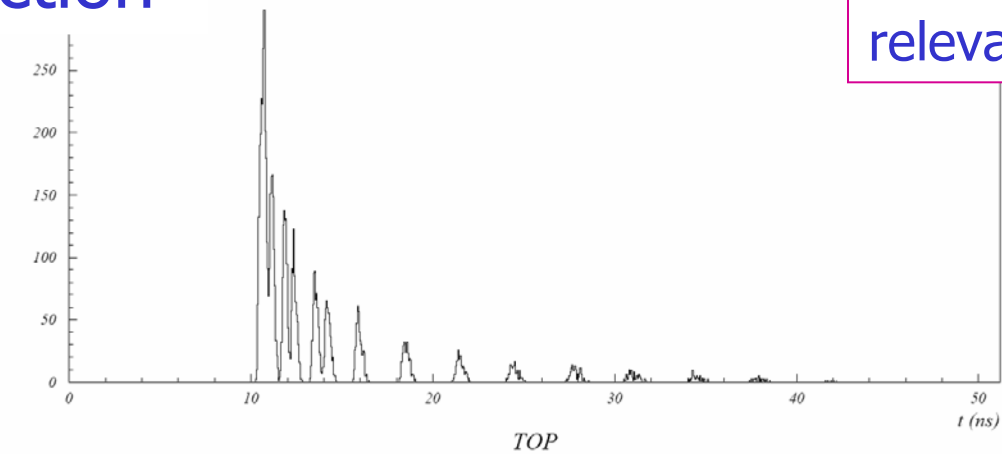
- Extended max. likelihood, with analytically derived likelihood function (as presented at RICH07, to be published in NIMA)

→details in backup slides

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)

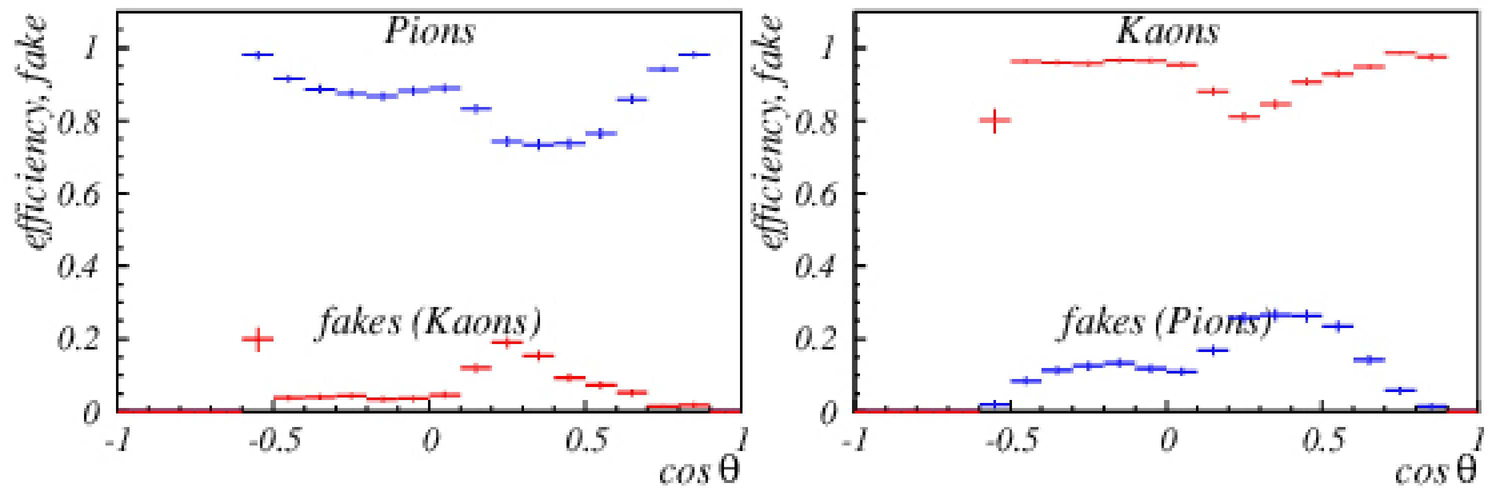
- The goal: find analytical expressions for $n_k(x_{ch})$, $t_k(x_{ch})$ and $\sigma_k(x_{ch})$
- Geometric view of TOP detection: intersection of Čerenkov cone with a plane
  - → well known, quadratic equations
  - → analytical solutions should exist

→details in backup slides

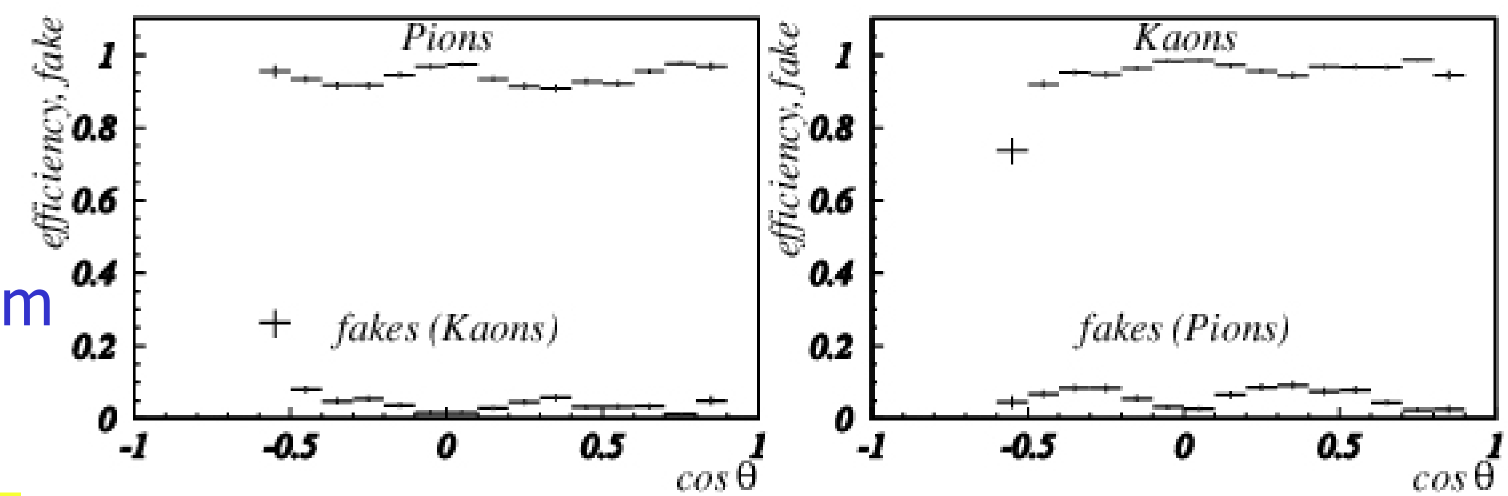
TOP: biakali vs GaAsP photocathode

For 4GeV/c tracks vs lab theta

Bi-alkali



GaAsP
with λ>400nm

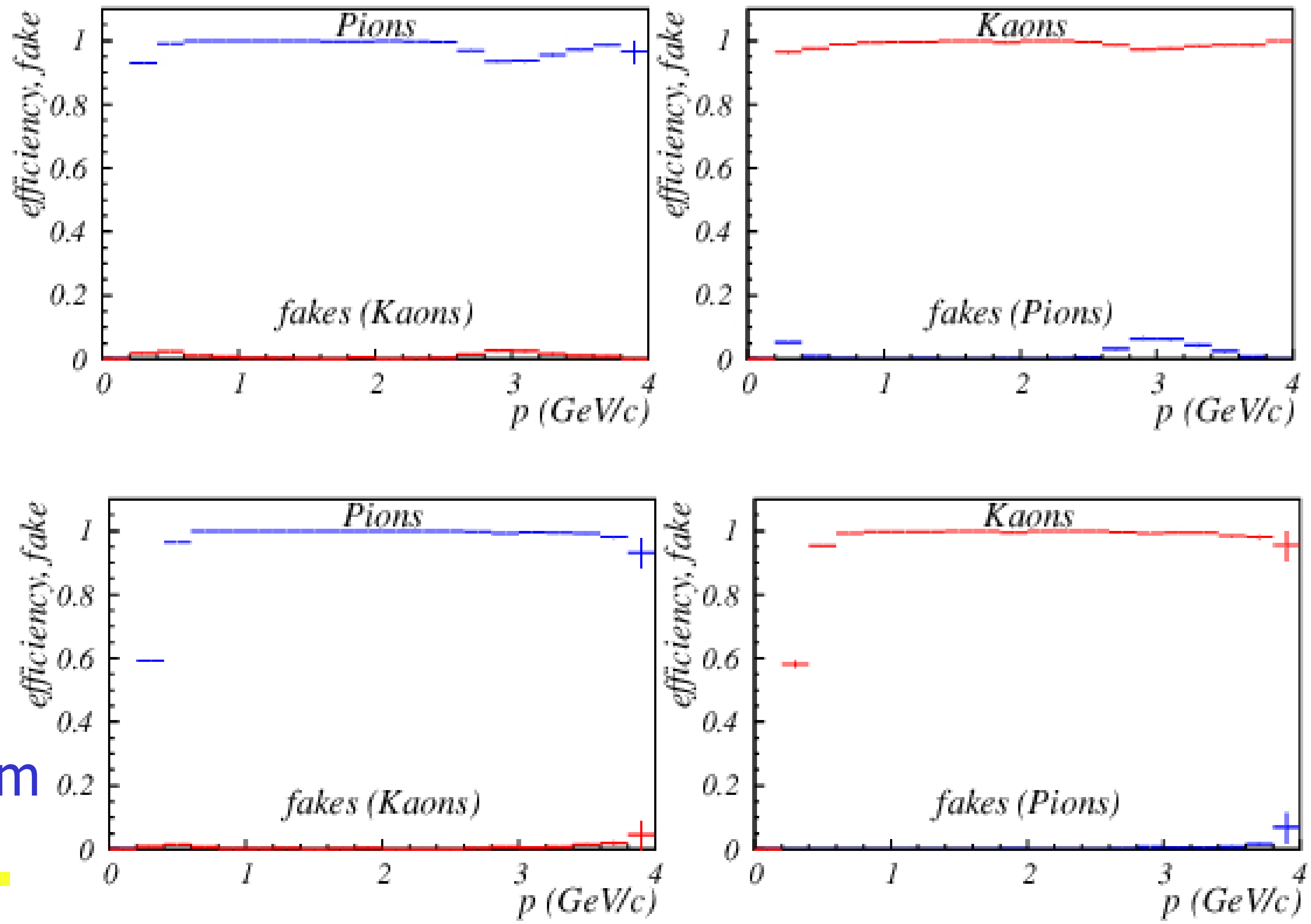


TOP: biakali vs GaAsP photocathode

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

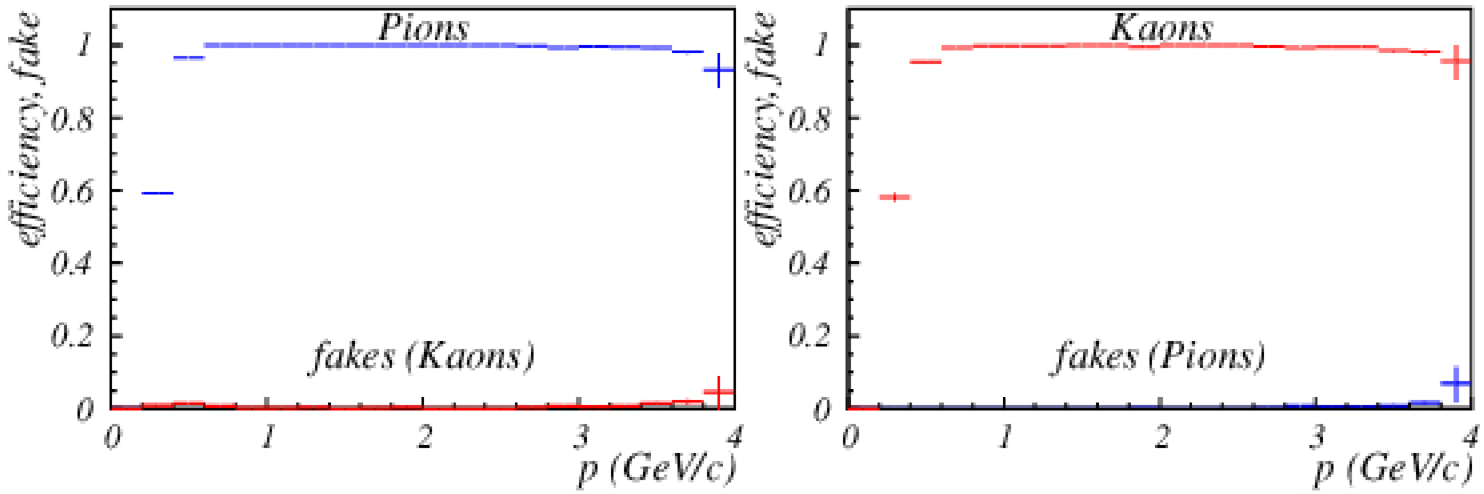
Bi-alkali

GaAsP
with λ>400nm

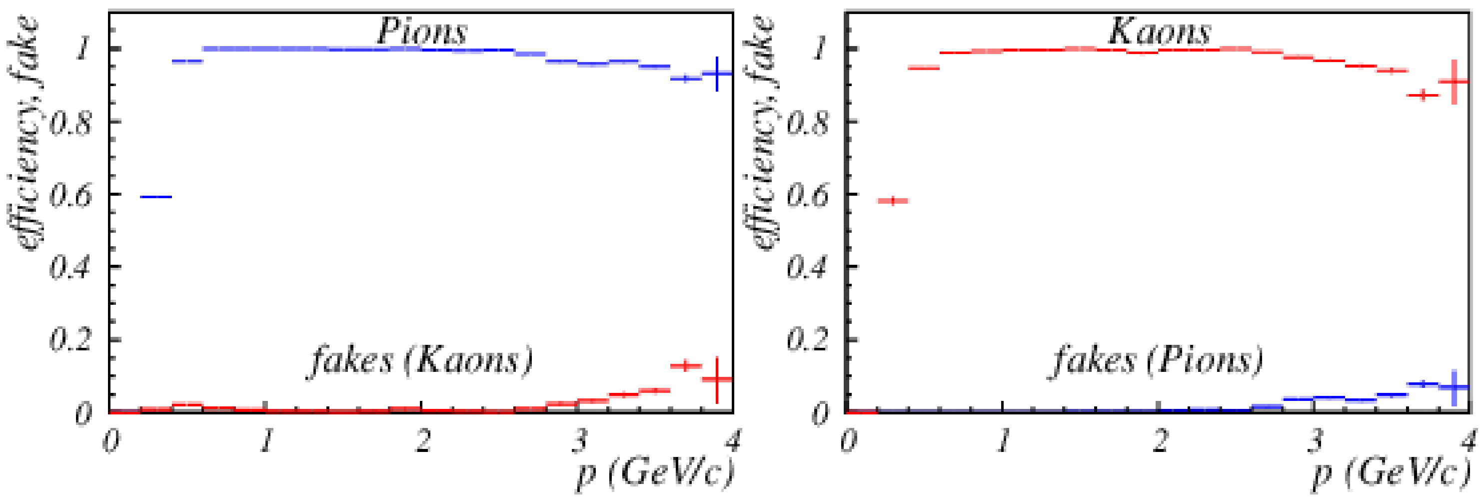


TOP: MCP PMT time resolution

σ = 50ps



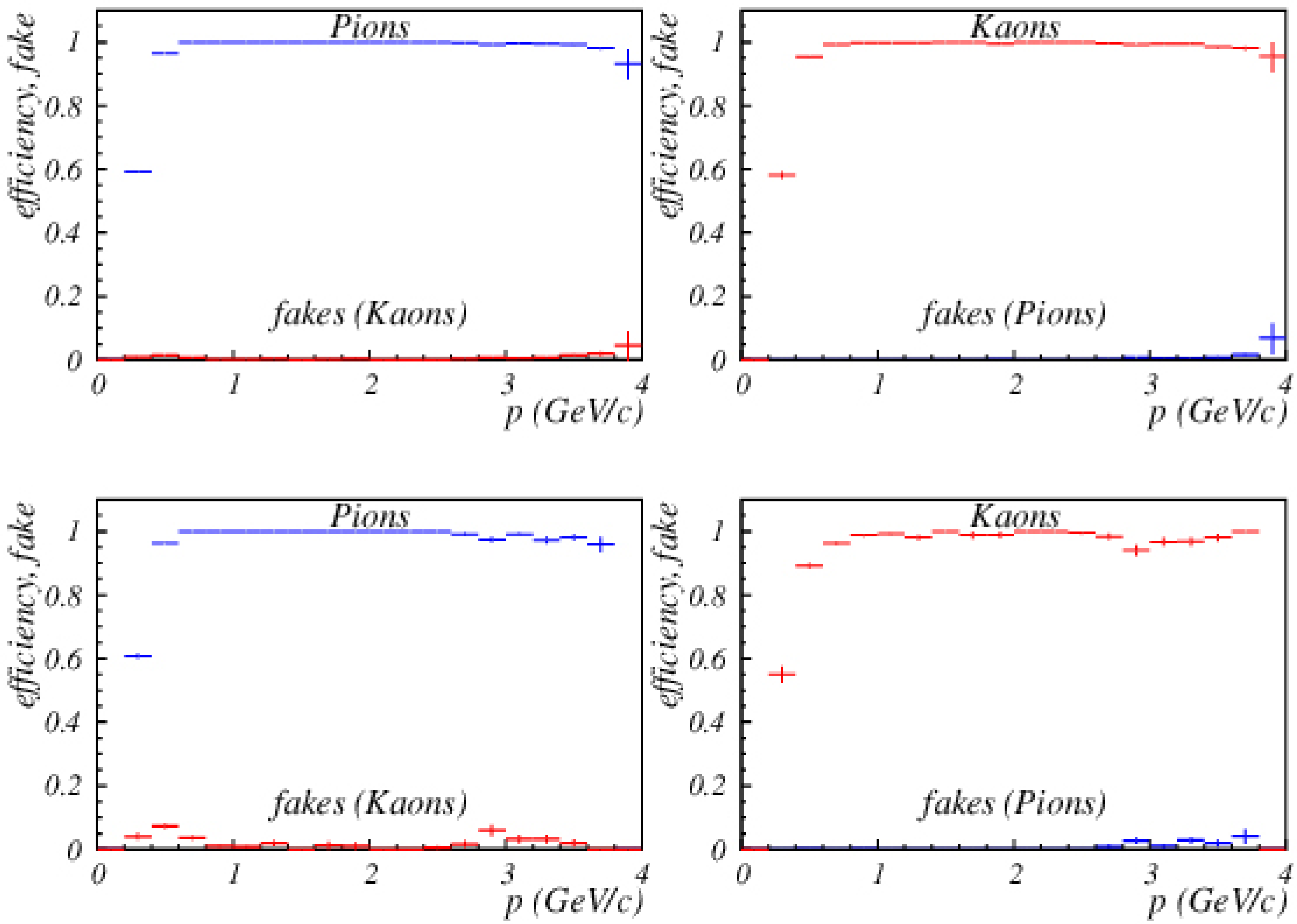
σ = 100ps



Multiple tracks per bar

Single track

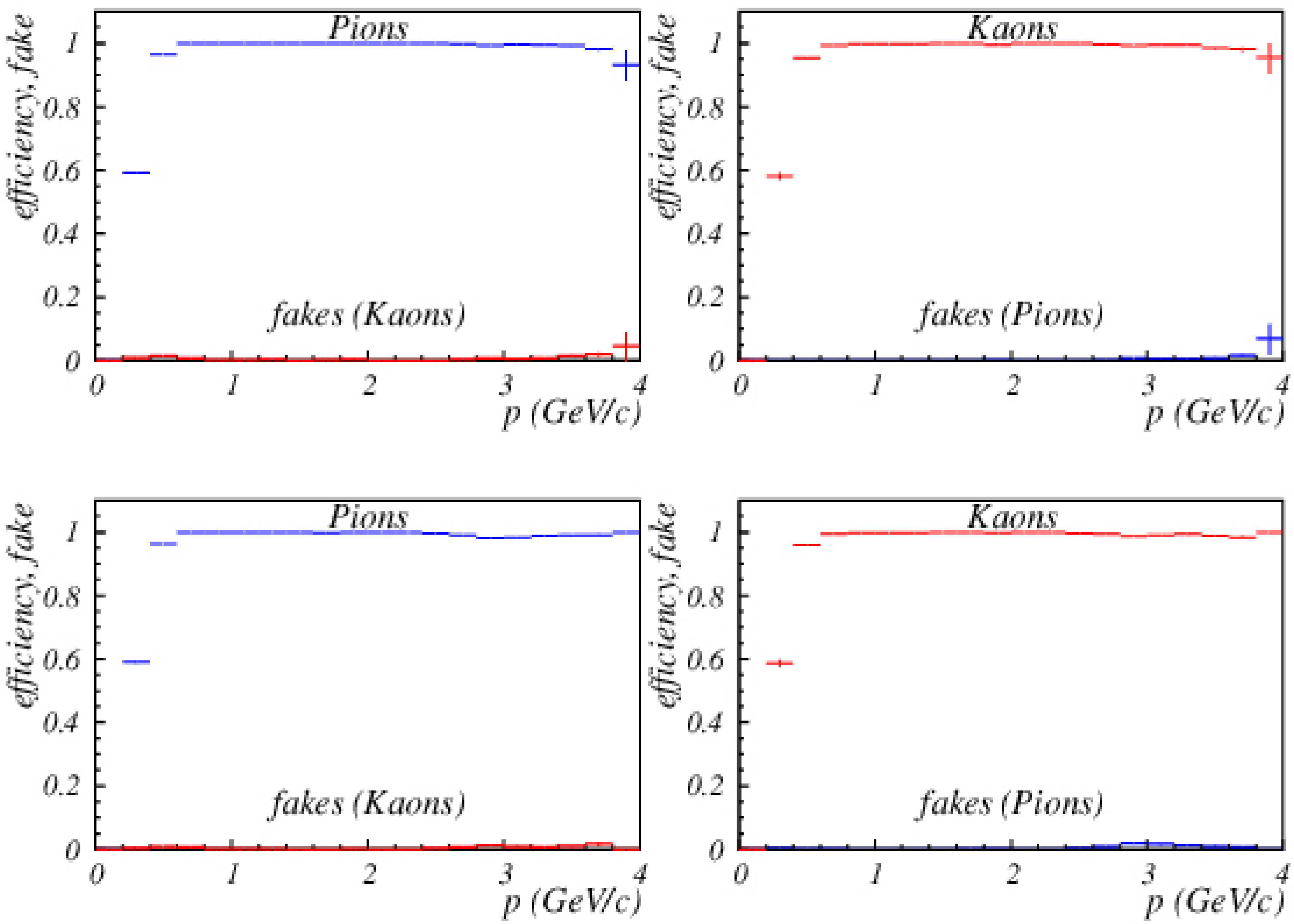
Multiple tracks



TOP: Background level

20 bckg hits/bar/50ns

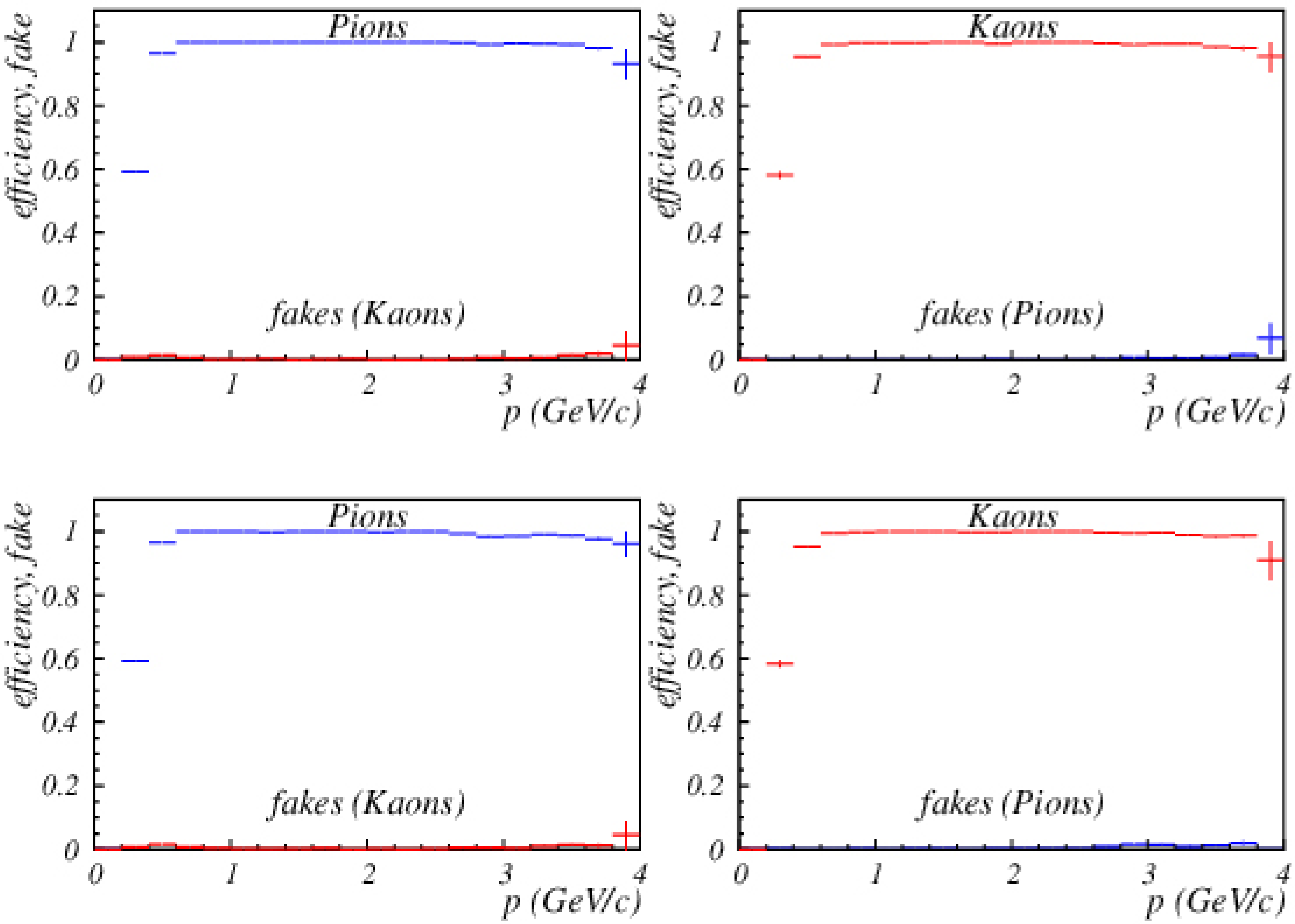
100 bckg hits/bar/50ns



TOP: uncertainty in track parameters

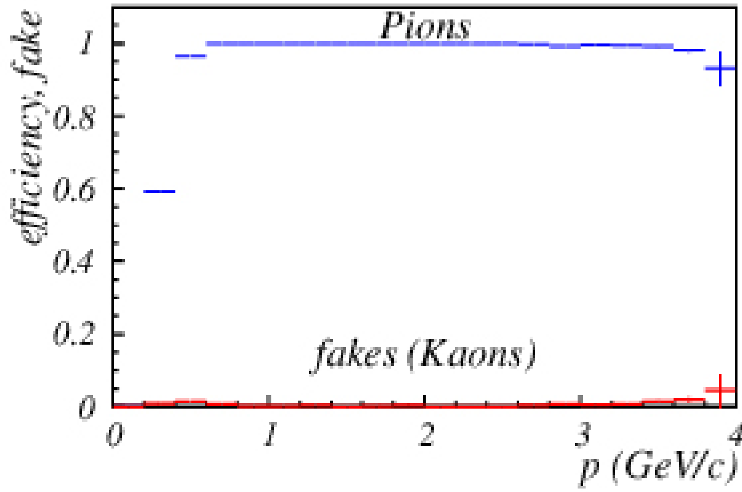
No uncertainty

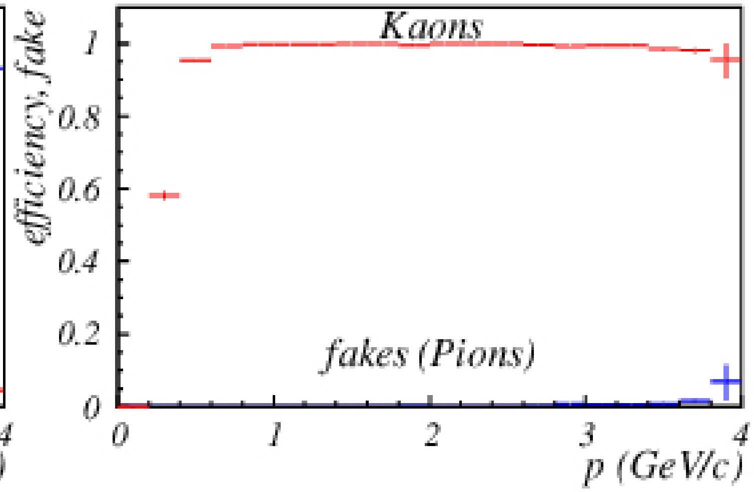
2 mrad uncertainty in track direction at IP



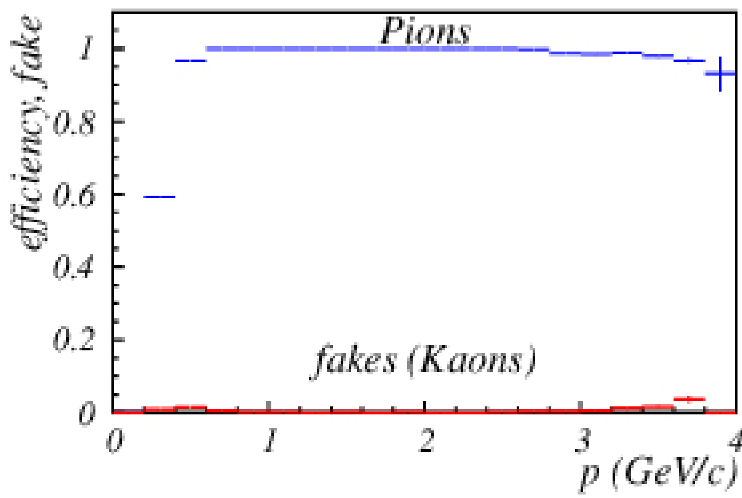
TOP: uncertainty in start time T0

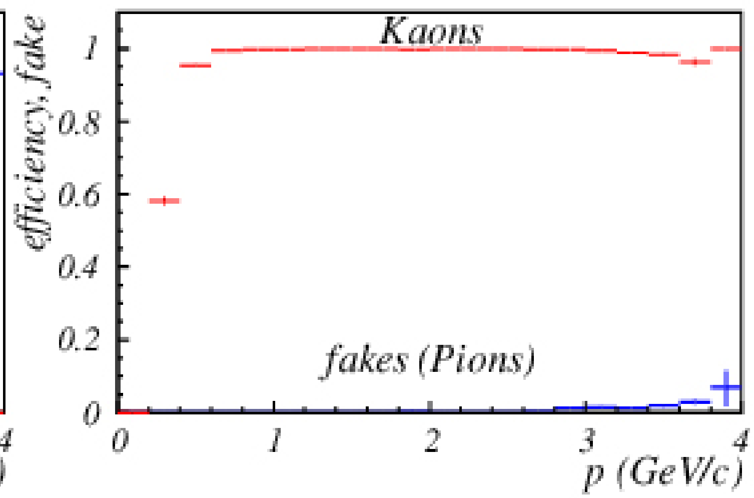
σ(T0) = 0





σ(T0)=10ps





TOP MC 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

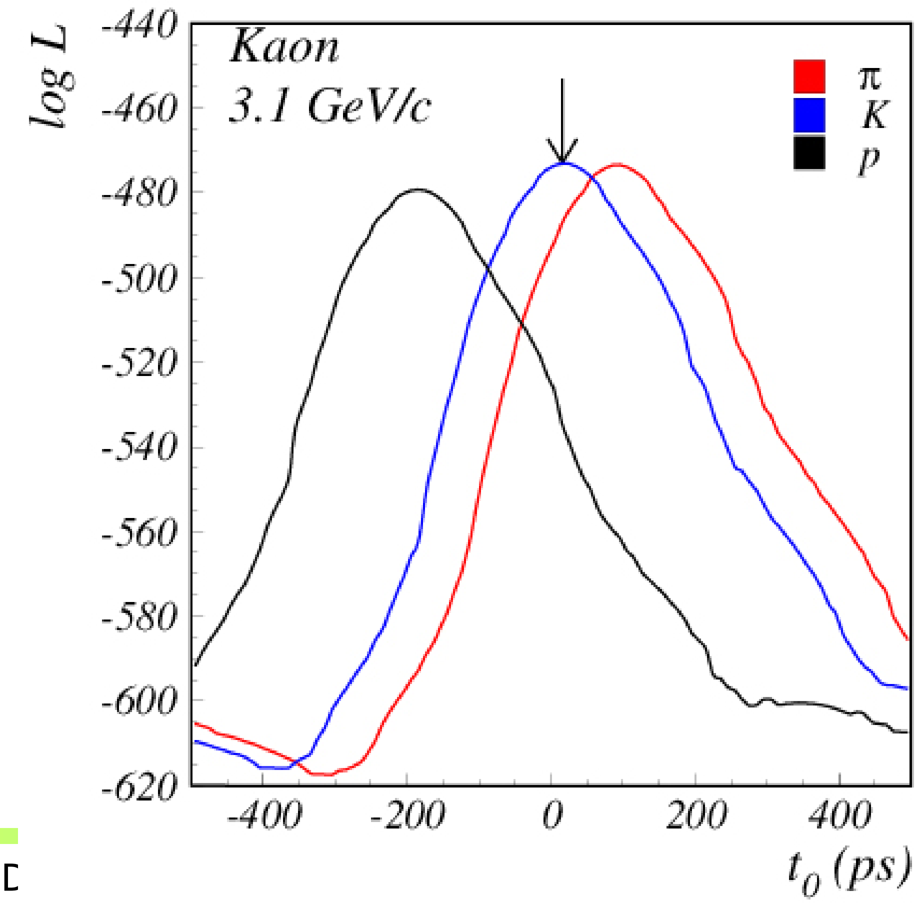
T0 start time uncertainty: 10ps little influence

Start time T0 reconstruction

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

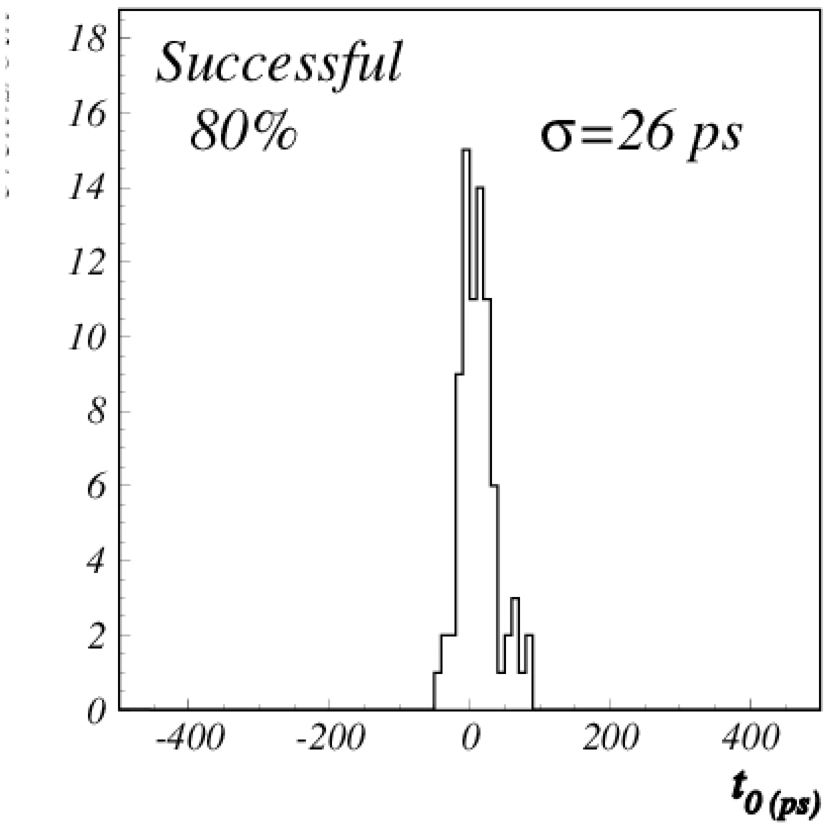
One way: determine for each track the likelihood for one of the three hypotheses as a function of T0

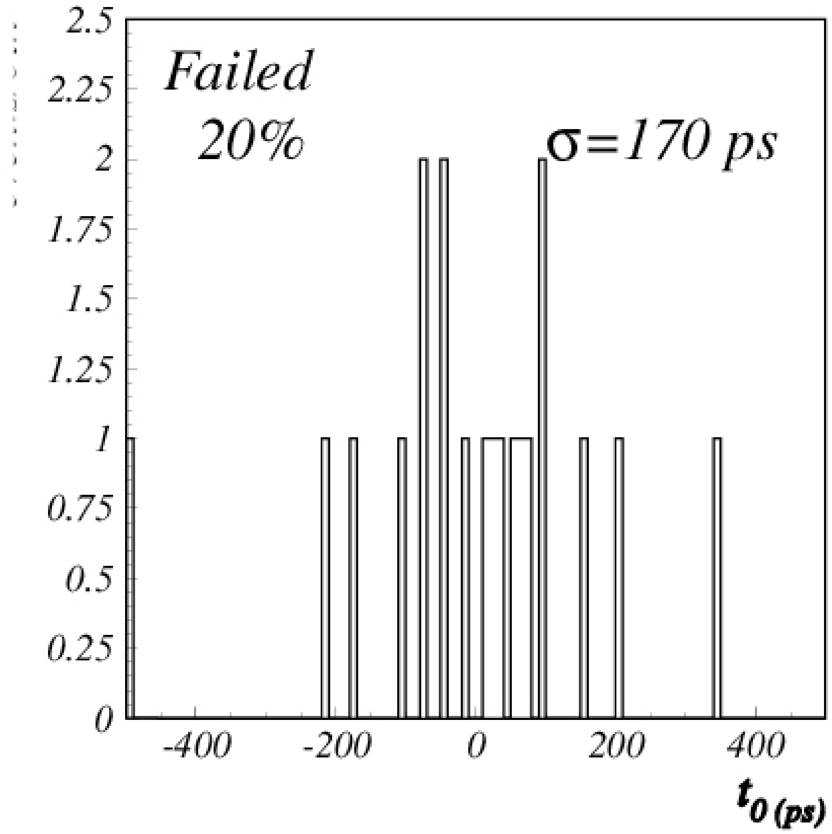
Choose the value with the highest logL



T0 reconstruction

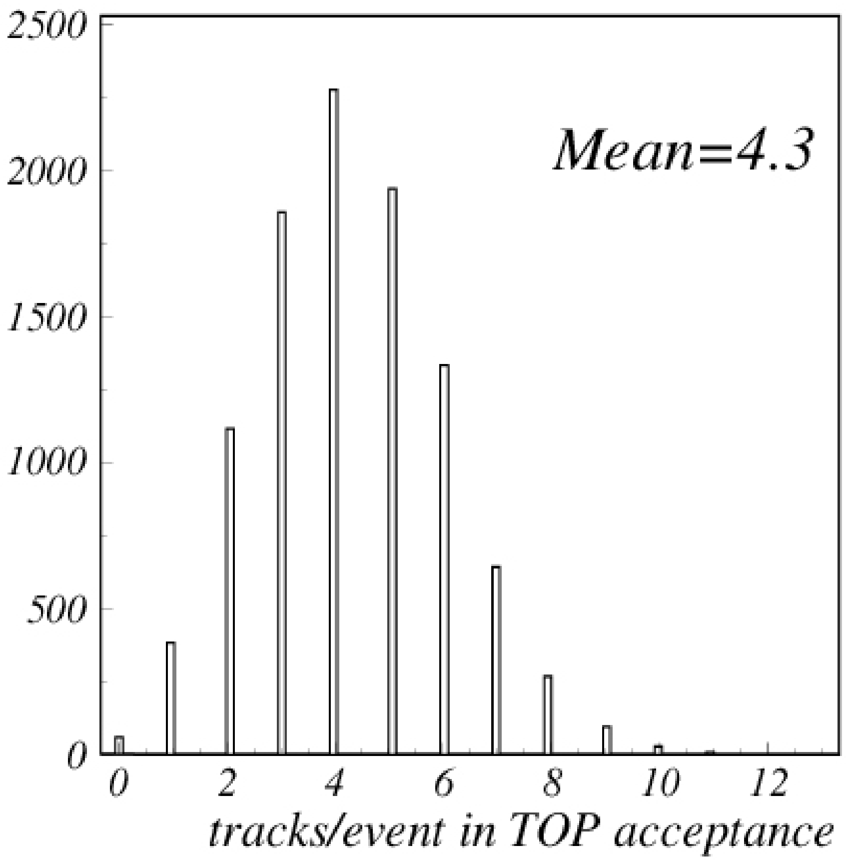
→T0 as reconstructed from single tracks.





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

Next steps

Photon detector tests: establish which type survives in the detector, and is affordable; test the read-out options

→ Beam (June and November?) and bench (MCP agenig) tests in the next half a year

→ Tests of electronics (wave sampling – Gary Varner)

→ SiPM radiation hardness: measure neutron flux inside Belle (going on), mount a few SiPMs in the spectrometer (to be done in summer)

MC:

→ Refine the description for the forward device

→ Work on the reconstruction for the full Geant MC of the barrel device (if time available...)

Back-up slides

TOP reconstruction: likelihood

Log likelihood probability for a given mass hyphothesis:

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

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:

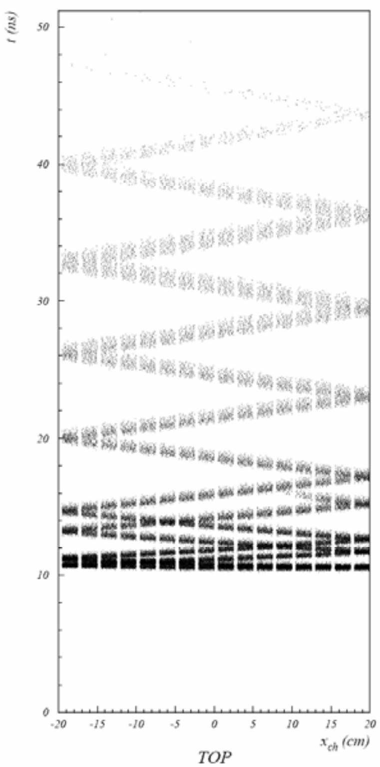
$$\sum_{x_{ch}} \int_0^{t_m} S(x_{ch}, t)dt = N_S^{exp}, \qquad \sum_{x_{ch}} \int_0^{t_m} B(x_{ch}, t)dt = N_B^{exp}$$

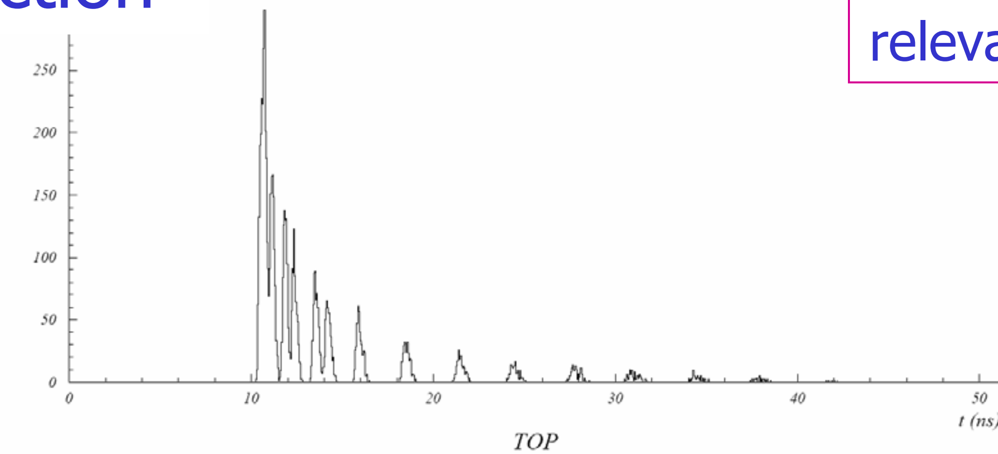
Sum runs over all channels x_{ch} and integration over full TDC range.

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

TOP reconstruction

Some of this possibly relevant for fDIRC





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- 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
  - → well known, quadratic equations
  - → 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

$$n_x = \mathrm{nint}(x_D/a)$$

$$n_y = \mathrm{nint}(y_D/b)$$

- 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):

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

- 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:

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

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

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

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

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

- 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.

TOP MC

6 Basics data for TOP used in simulation

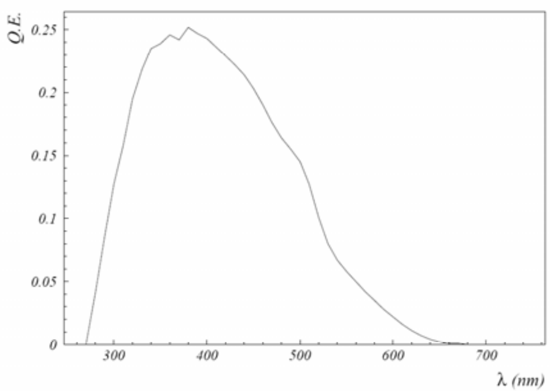
- Refractive index of quartz:

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

- 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, $\quad \frac{1}{n_g}\frac{dn_g}{de}$ = 3.1%/eV

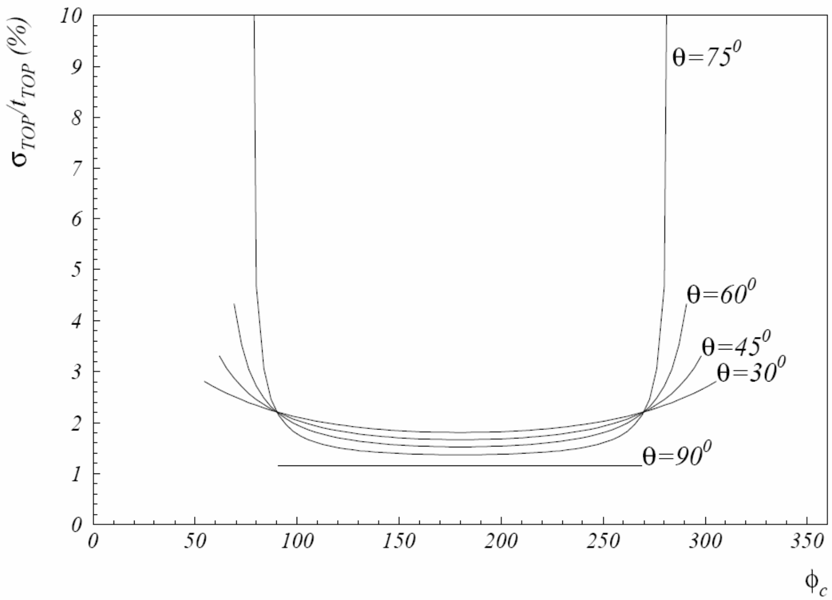
- PMT time resolution: σ_{PMT} = 50ps
- Q-bar dimensions: 40cm × 2cm × 255cm
- Coverage: Δx_{ch}=5mm, 64 active channels out of 80 per Q-bar exit window

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

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