TORCH

A proposed particle ID subsystem for the LHCb upgrade using time-of-flight information from Cherenkov light.

Mat Charles (Oxford)
Roger Forty (CERN)

Part I
Cherenkov TOF at 10 GeV: Why and how?

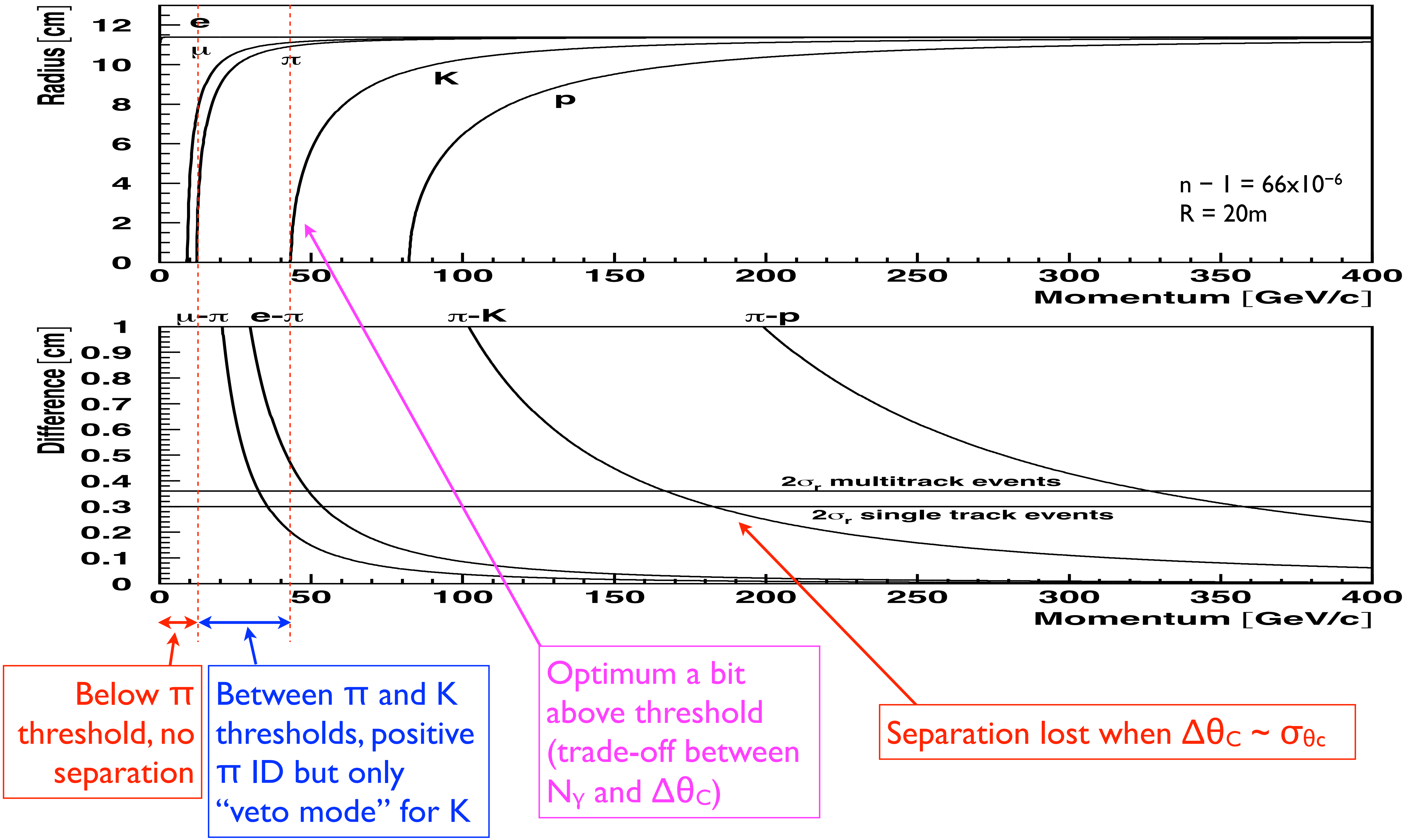
Already introduced by Jerry Va'vra. Key points:

- Measure θ_C to correct for dispersion
- Adapted to LHCb's forward geometry

RICH K/π separation by momentum range

Performance follows a simple pattern.

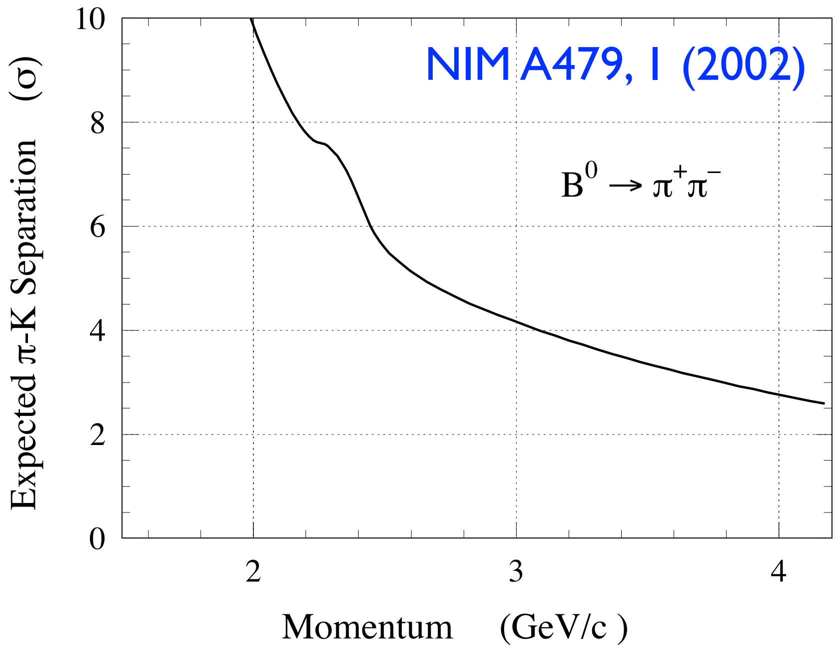
Here's an example stolen from Jurgen's talk:



RICH K/π separation by momentum range

... so momentum range dictates choice of radiator.

At low p, have many solid/liquid radiators, e.g. BABAR DIRC:



Fused silica:
mean n = 1.473
π threshold ~ 130 MeV/c
K threshold ~ 460 MeV/c

Separation not so good beyond about 4 GeV/c

At medium & high p, have many inert gases to choose from, e.g.

Gas	n−1 (visible @ STP)	π threshold	K threshold
N_2	300×10^{-6}	5.7 GeV/c	20 GeV/c
CF_4	500×10^{-6}	4.4 GeV/c	15.6 GeV/c
C_4F_{10}	1400×10^{-6}	2.6 GeV/c	9.3 GeV/c
C_5F_{12}	1700×10^{-6}	2.4 GeV/c	8.5 GeV/c

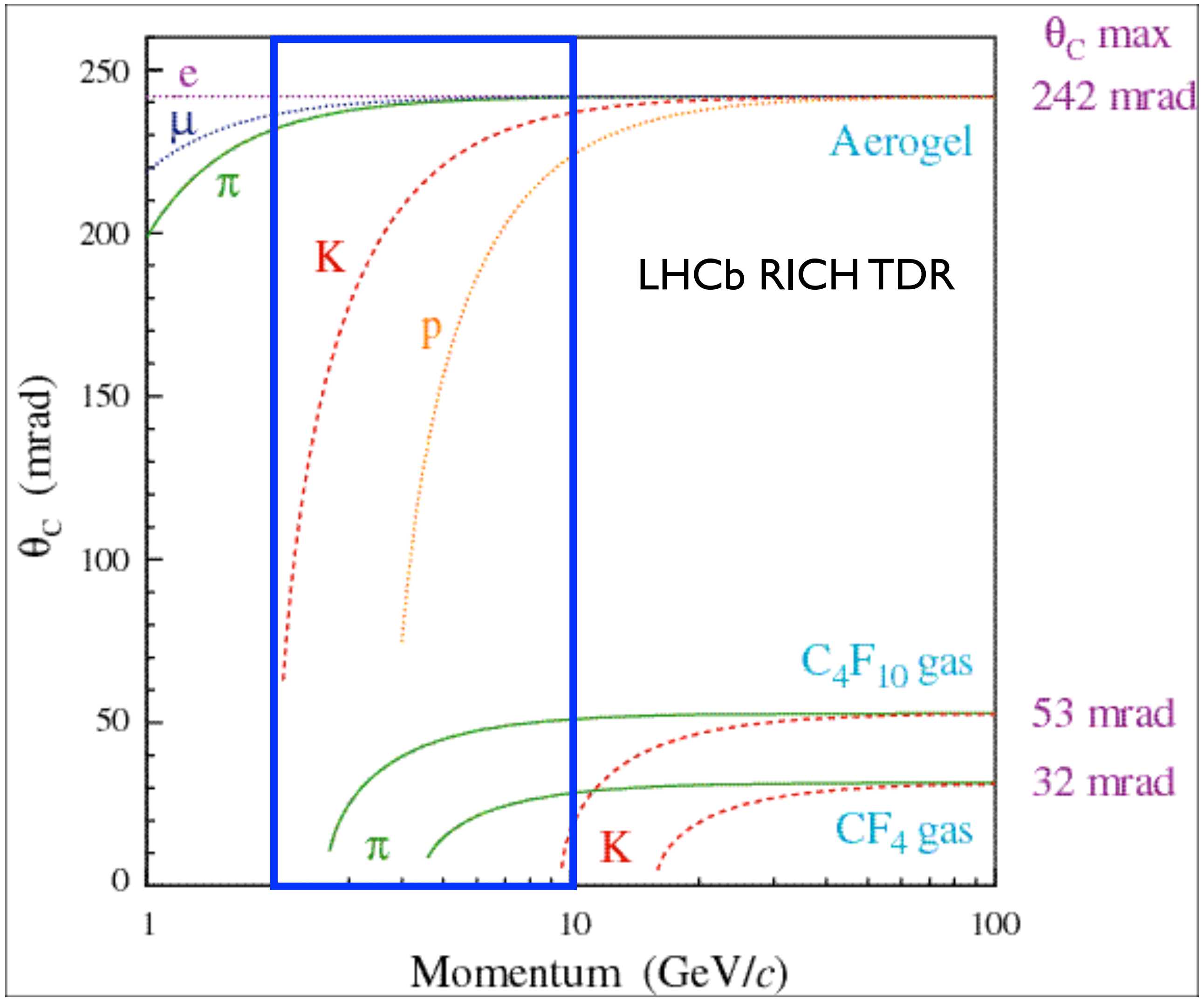
But what about the gap inbetween: 4 - 9 GeV/c?

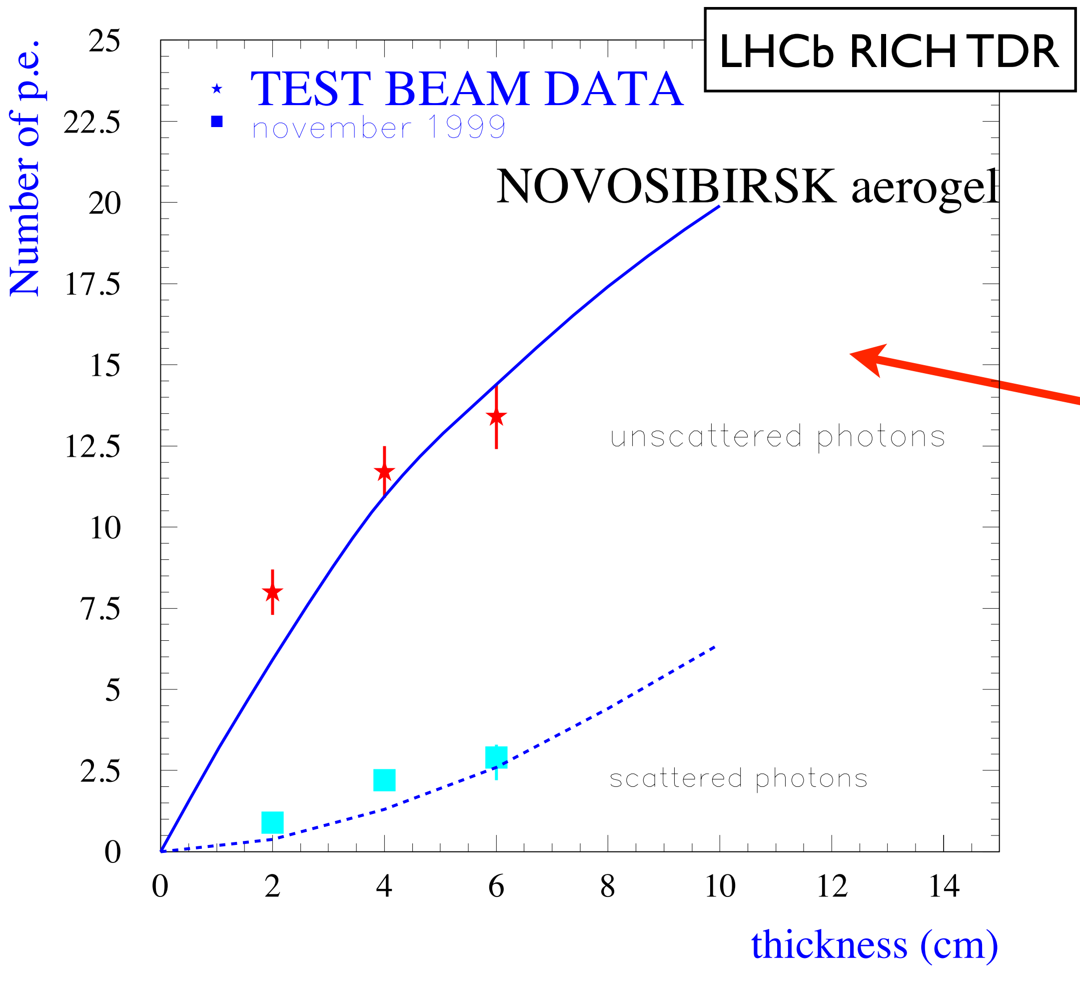
RICH K/π separation by momentum range

One option: aerogel

In LHCb RICH1, $n \approx 1.029$ (in air) to 1.037 (in C_4F_{10})

Kaon threshold in our aerogel ~ 1.8 to 2.0 GeV/c.





Blue: simulation for C=0.005 μm/cm and n=1.034

But Rayleigh scattering limits

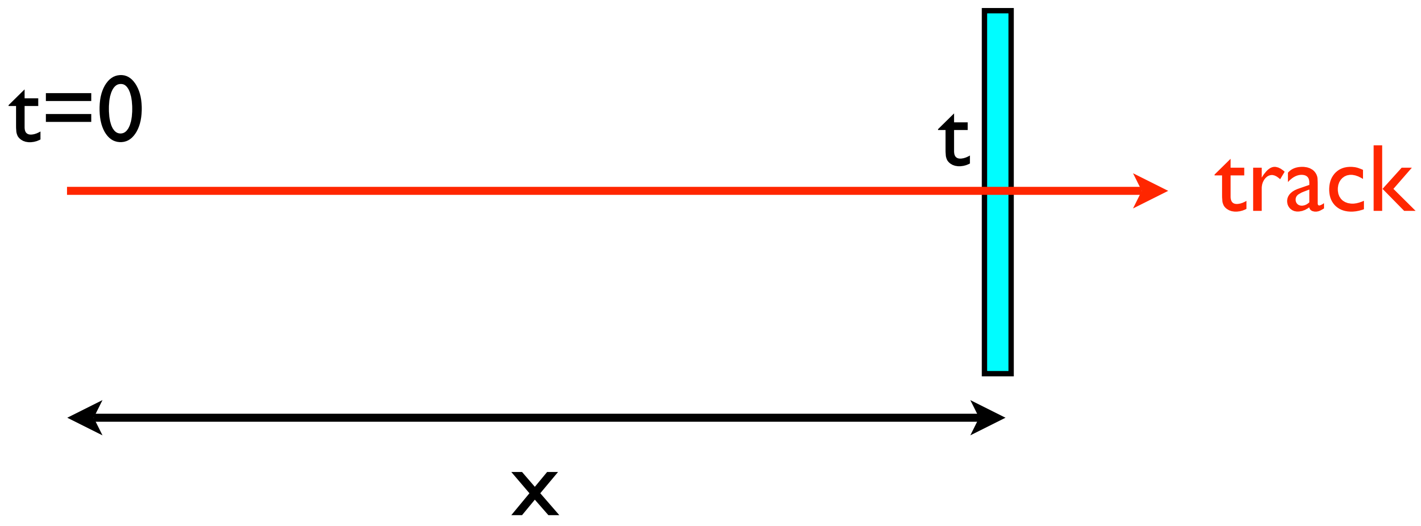
- useful length of radiator
- wavelength range

... and hence photon yield.

Workable -- but what other options are there?

Poster by Young-Min Kim

K/π separation with time of flight



$$t = \frac{x}{c}\sqrt{1+\left(\frac{m}{p}\right)^2} \approx \frac{x}{c}\left[1+\frac{1}{2}\left(\frac{m}{p}\right)^2\right] \quad \Rightarrow t_K - t_\pi \approx \frac{x}{c}\frac{1}{2p^2}\left[m_K^2 - m_\pi^2\right]$$

So if you want 3σ separation, you need:

$$\sigma_t < \frac{1}{3}\frac{x}{c}\frac{1}{2p^2}\left[m_K^2 - m_\pi^2\right]$$

linear in x... but quadratic in p

For p=10 GeV/c and x=10m, this means σ_t < 12.5 ps
Need a fast response time -- Cherenkov photons fit the bill.

Caveat: This neglects an important performance-improving effect.

K/π separation with time of flight

How deep should we make our Cherenkov radiator?

- per-photon emission point uncertainty = $d / (c\sqrt{12})$
- photon yield $\approx d\, N_0 \langle \sin^2\theta_C \rangle$
- rest of per-photon uncertainty is, let's say, $\sigma_\gamma = 70$ ps
- optimum from simple calculus: $d = (\sigma_\gamma\, c\, \sqrt{12}) \approx 7$ cm

Taking $N_0 = 100\ \text{cm}^{-1}$, $n=1.5$, $\beta \approx 1$:

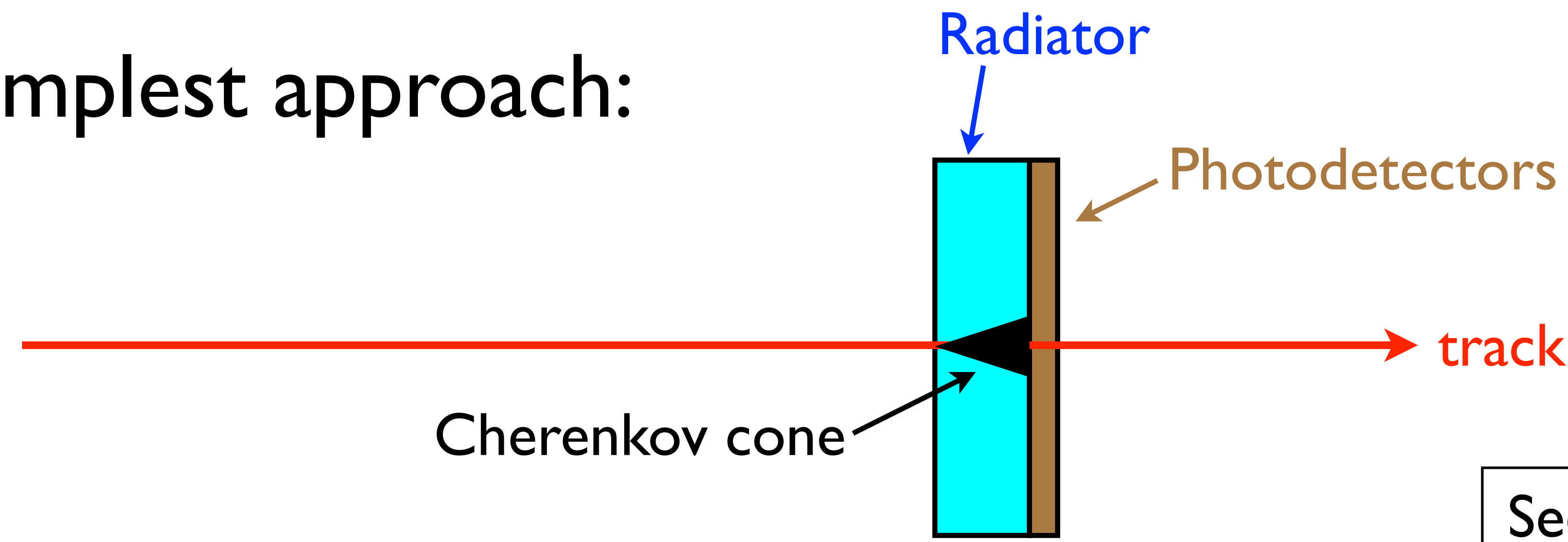
- overall uncertainty $\approx$ 4.9 ps for d=7 cm
- overall uncertainty $\approx$ 9.4 ps for d=1 cm

... so if driven just by performance, would want quartz plate several cm deep. In practice, cost & material is an issue $\Rightarrow$ 1-2 cm.

Caveat: This neglects an important performance-improving effect.

Layout of Cherenkov ToF detector

Simplest approach:



See work done by Henry Frisch et al. (Chicago/ANL/FNAL/SLAC)

Elegant in its simplicity:

- Optics simple; photons easy to collect
- No pattern recognition required

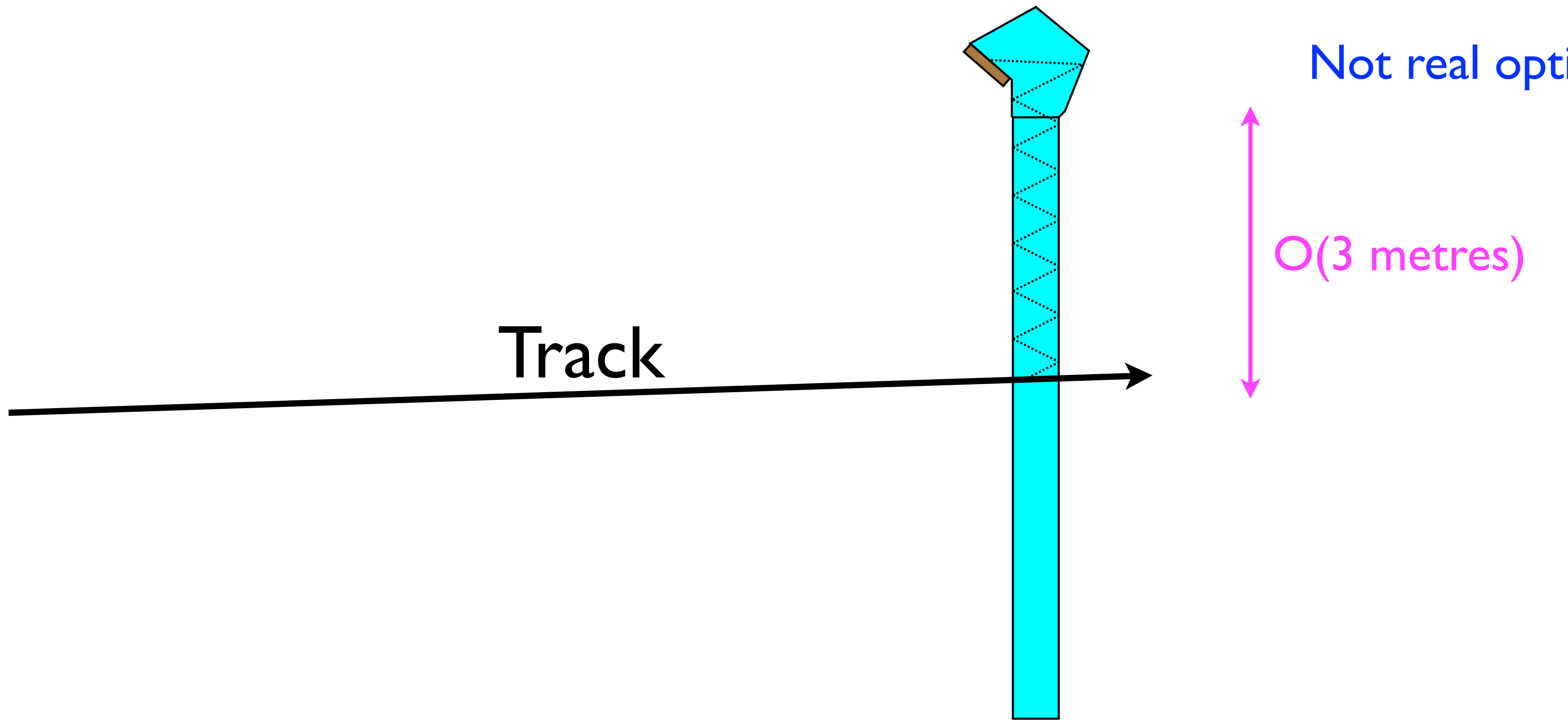
... but some major drawbacks:

- Potentially large active area to instrument.
  - ... remembering that we want to put this far downstream for lever arm
  - e.g. LHCb acceptance: (2 x 300 mrad) x (2 x 250 mrad) at 12m ⇒ 42m^2
- Very demanding on photodetectors (and electronics)
  - Will get pounded by particles -- must be radiation hard (for LHC)
  - Minimal dead area, since blob will be tightly focused

This is a neat design... but not what I'm going to talk about.

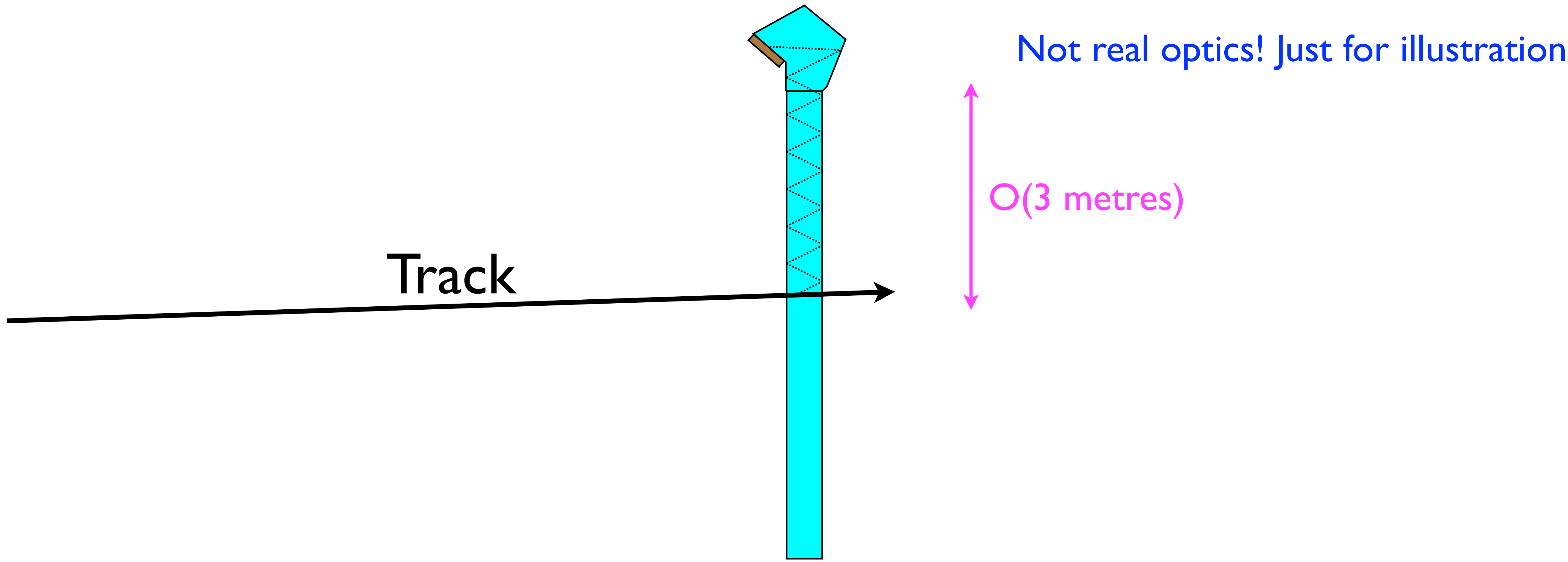
Layout of Cherenkov ToF detector

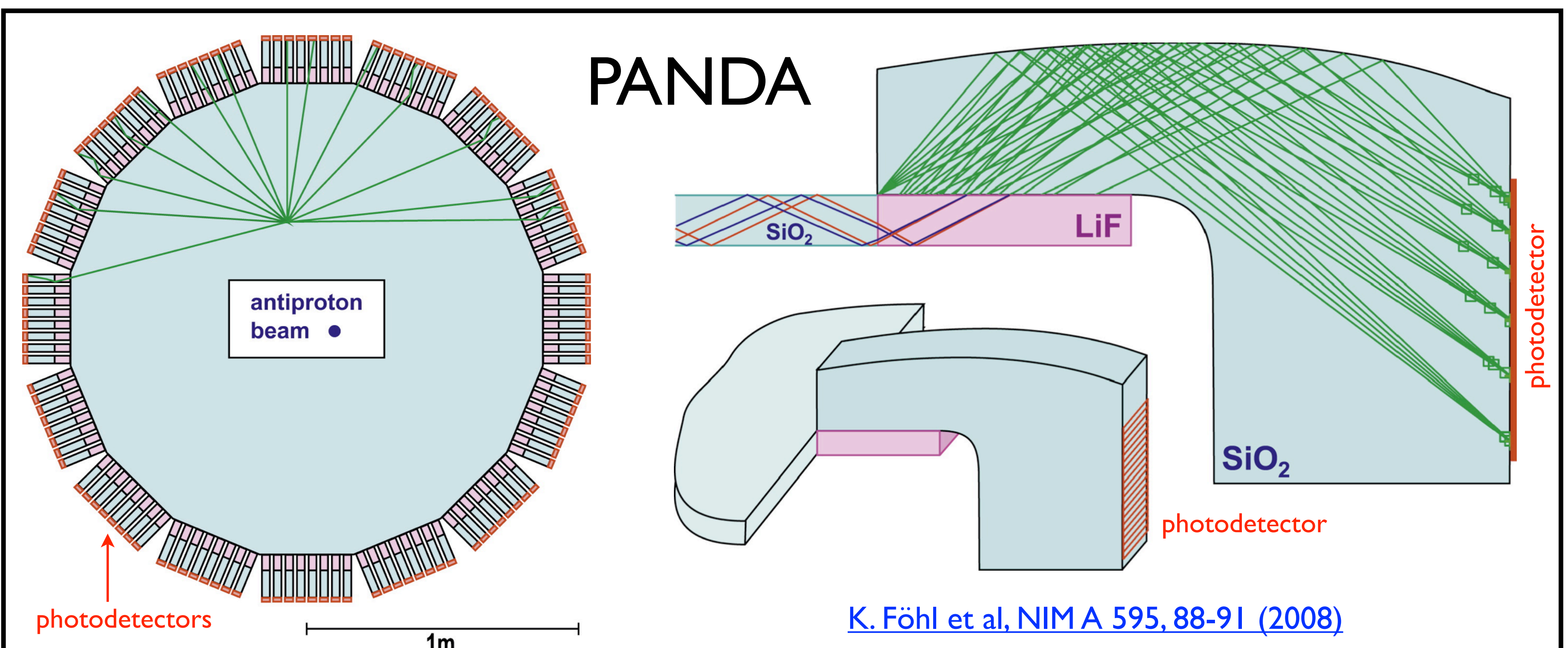
Instead, use TIR to pipe photons outside detector acceptance:



Layout of Cherenkov ToF detector

Instead, use TIR to pipe photons outside detector acceptance:



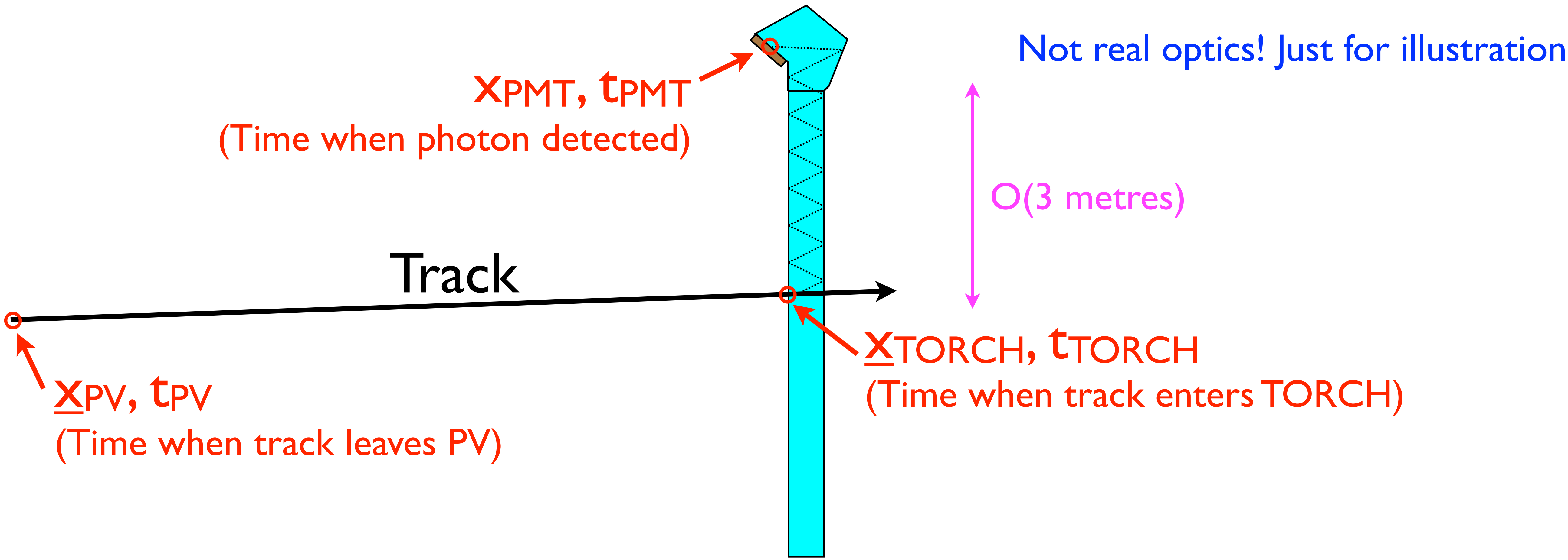


K. Föhl et al, NIM A 595, 88-91 (2008)

This should look familiar! But different focusing.

Layout of Cherenkov ToF detector

Instead, use TIR to pipe photons outside detector acceptance:



what we want

Time of flight of track = $(t_{TORCH} - t_{PV}) = |\underline{x}_{TORCH} - \underline{x}_{PV}| \,/\, \beta c$

Time of propagation of photon in quartz = $(t_{PMT} - t_{TORCH})$ = (path length) (n_g/c)

have to reconstruct this

danger: chromatic dispersion

Chromatic dispersion

How big is chromatic dispersion?

- Photon has to travel through several metres of quartz: O(20 ns)
- Over useful range of λ, n_g easily varies 10%
- => Dispersion causes uncertainty of O(ns). Way too much!

Strategy: measure direction and path length of photon in quartz

- Path length obviously necessary to get time of propagation
- Direction so that we can get $\cos\theta_C = \text{dir}_{\text{track}} \cdot \text{dir}_{\text{photon}}$
- ... and hence $1 / \beta n$
- ... and hence n (given mass hypothesis and track momentum)
- ... and hence n_g
- ... and hence time of propagation of photon (given path length)

Therefore: Measure 2 angles and time for each photon.

Chromatic dispersion

How big is chromatic dispersion?

- Photon has to travel through several … O(20 ns)
- Over useful range of λ, n_g easily …
- => Dispersion causes uncert…

Wait a minute! Isn't the mass what you're trying to measure?

Strategy: measure direction and …

- Path length obviously necessary to ge…
- Direction so that we can get $\cos\theta_C$ …
- … and hence $1 / \beta n$
- … and hence n (given mass hypothesis and track momentum)
- … and hence n_g
- … and hence time of propagation of photon (given path length)

Therefore: **Measure 2 angles and time for each photon.**

Nature is very kind to us

Look at it like hypothesis-testing:

- You assume a mass
- You do the reconstruction, including using the mass to get n_g
- You see if measured track ToF using photons, $t_{TORCH}-t_{PV}$, is consistent with expectation of $|\underline{x}_{TORCH}-\underline{x}_{PV}|/\beta c$

If you assume wrong mass, the calculation of n_g comes out wrong, biasing t_{TORCH} -- and the sign is helpful.

ToP is a big effect! Can help as much as ToF of track itself:

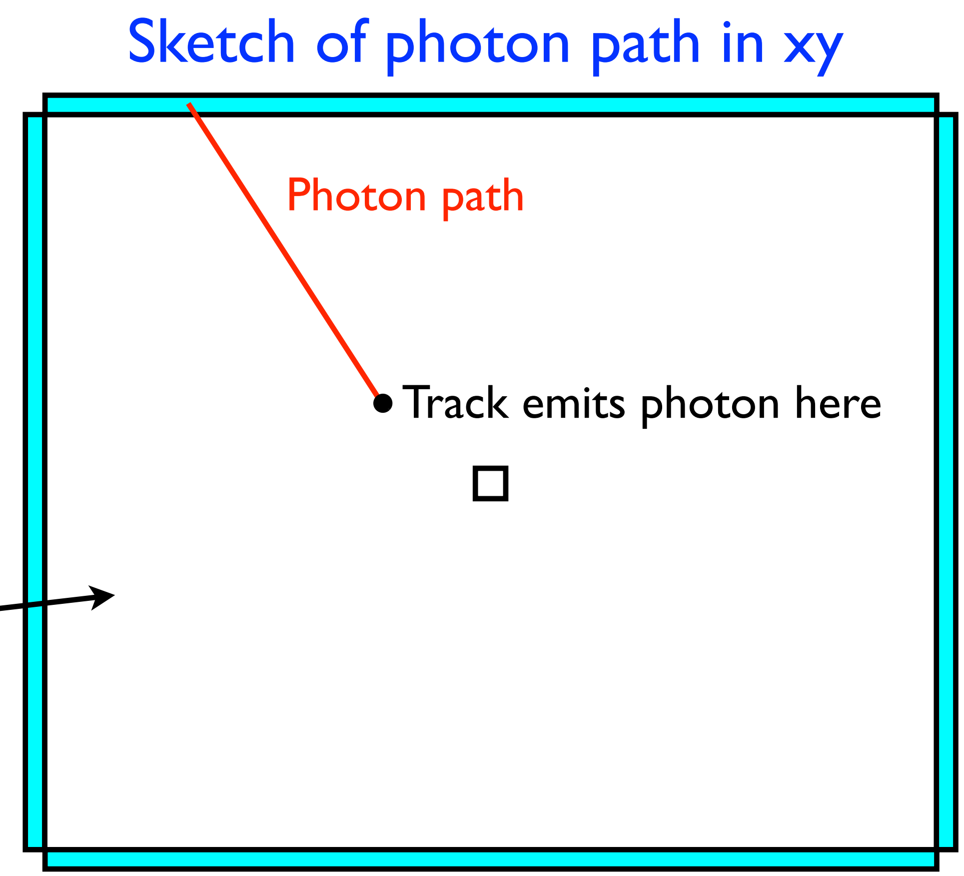
- n is wrong by same factor as track ToF ($\beta_{wrong}/\beta_{true}$)
- n_g is wrong by an even bigger factor (dispersion relation)
- Proportional to [path length of photon in quartz x n_g/c]

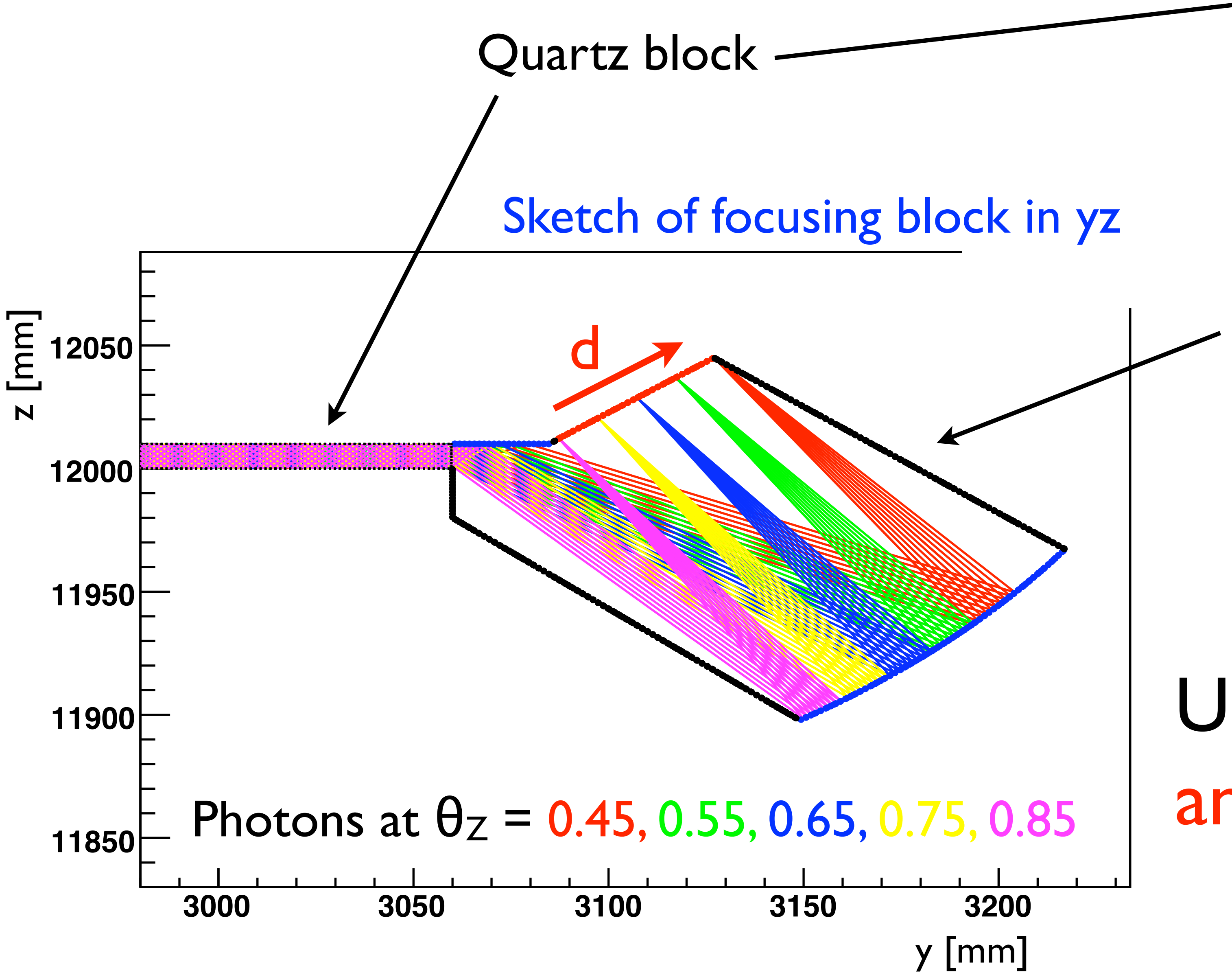
Quartz acts like extra track path length, only better by factor > n_g!
TIR bounces help too.

Time of flight of track = $(t_{TORCH} - t_{PV}) = |\underline{x}_{TORCH}-\underline{x}_{PV}| / \beta c$
Time of propagation of photon in quartz = $(t_{PMT} - t_{TORCH})$ = (path length) (n_g/c)

Measure 2 angles for each photon

Easy to measure angle in transverse plane (xy) with photodetectors around edges of quartz block.



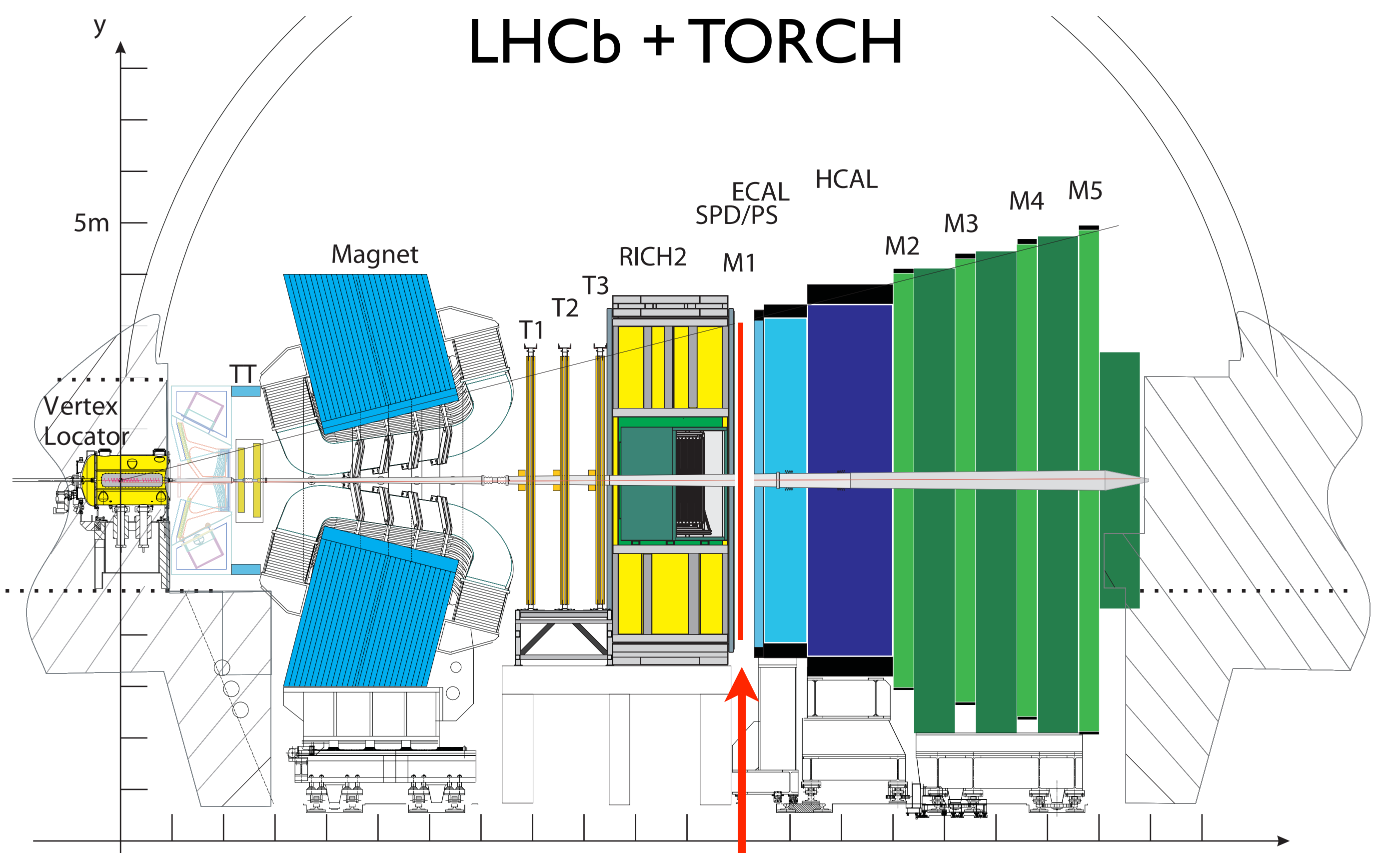


Use focusing block to measure angle in xz/yz plane (θ_z).

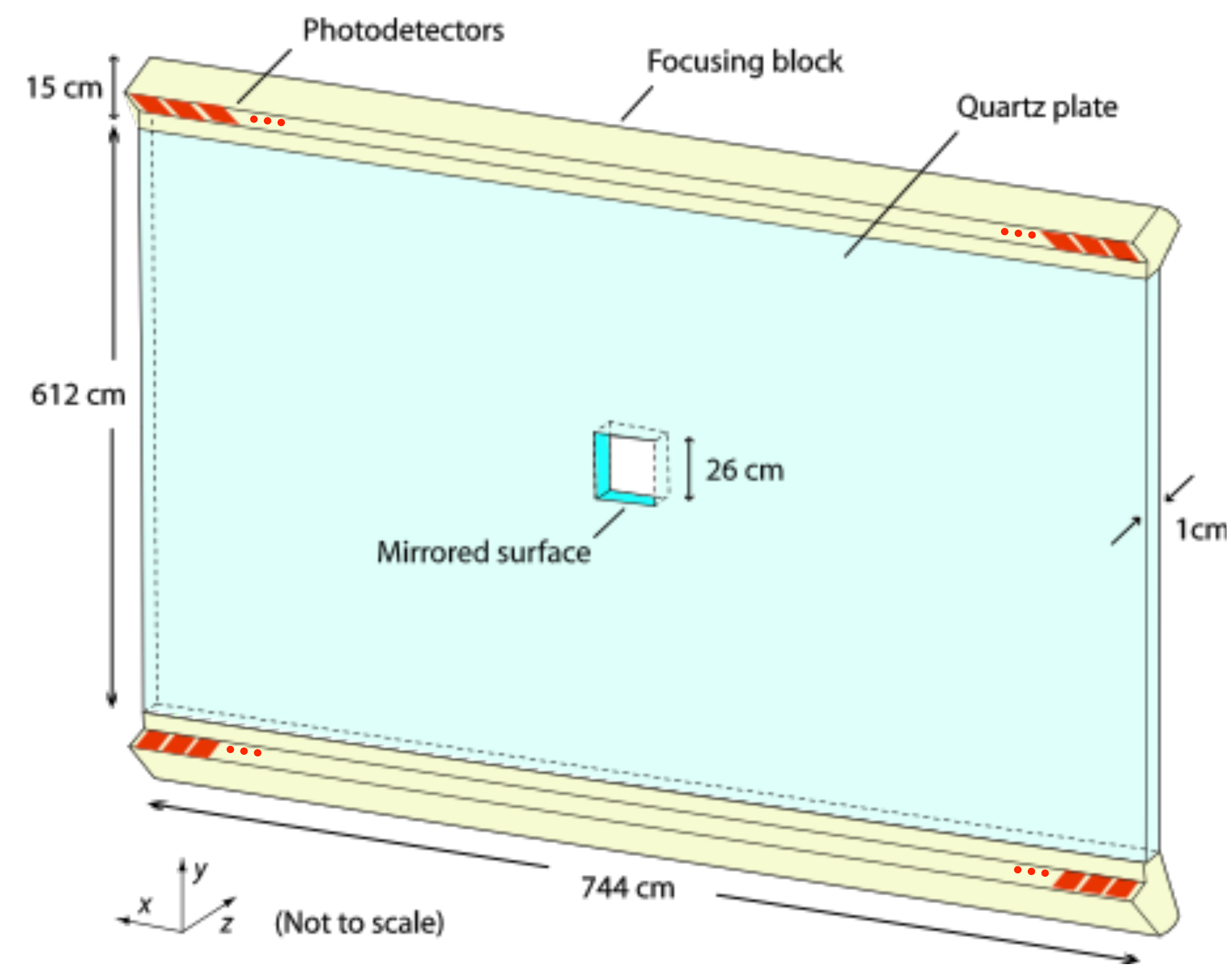
Part II
Application to the LHCb upgrade

Caution: using standalone (toy) MC for ray-tracing and photodetector response.

Current design

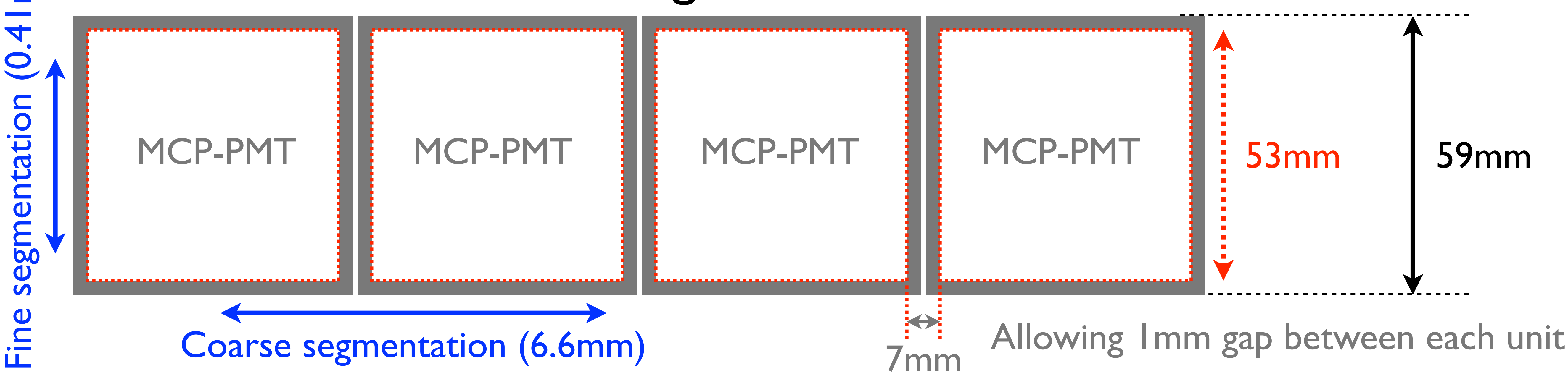


1cm-thick quartz plate at z=12m



Sides are instrumented too (not shown)

Photodetectors tiled along each side:

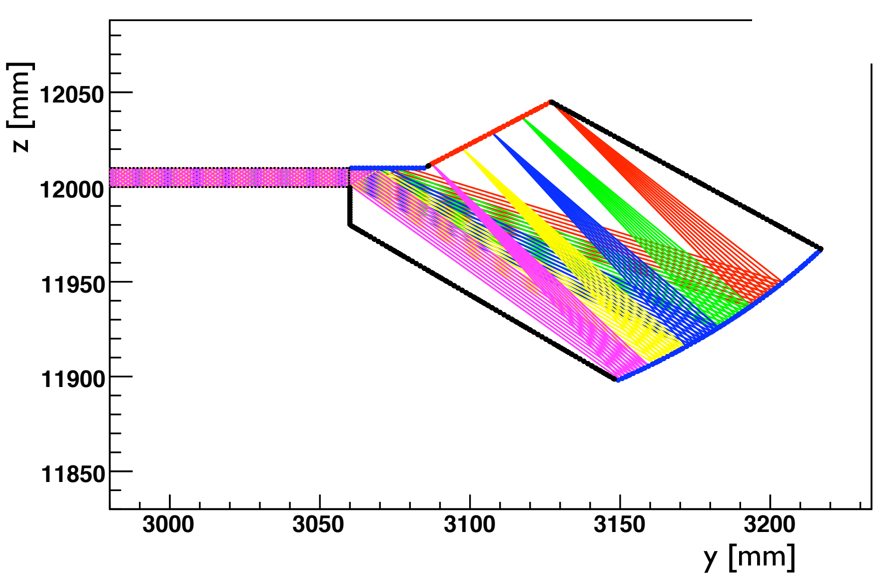


Photodetectors and optics

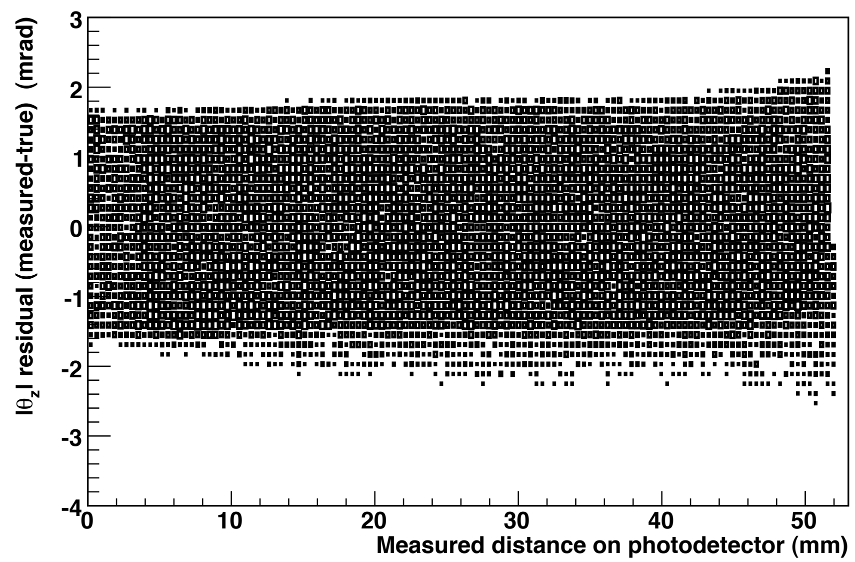
Simulated photodetector:

- Loosely based on Photonis XP85022 MCP-PMT
- ... but instead of 32x32 segmentation, simulate 8x128
  - Coarse segmentation to measure angle in xy plane
  - Fine segmentation to measure θ_z
- 20ps resolution (not critical -- other effects dominate)

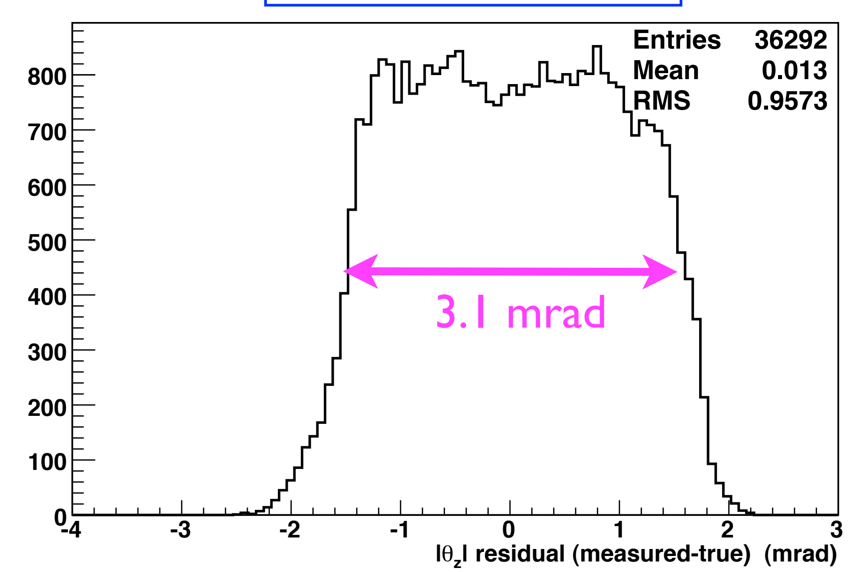
Stand-off optics



Residuals of $|\theta_Z|$ vs distance



Residuals of $|\theta_Z|$



"Top hat" expected from pixellation:
0.4 rad / 128 channels = 3.1 mrad

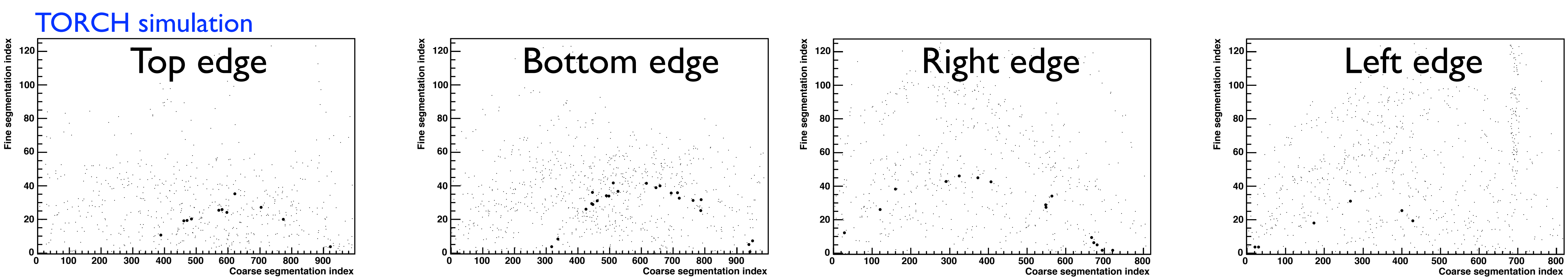
- Per-photon resolution on time of propagation in quartz: 70 ps (dominated by reconstruction, esp. θ_z measurement)

Pattern recognition

- Broadly, three problems:
  1) Given a track, which photons come from it?
  2) Given a PV with many tracks, when was the PV time (t_{PV})?
  3) Given a track and t_{PV}, which mass hypothesis is it most consistent with?

Pattern recognition

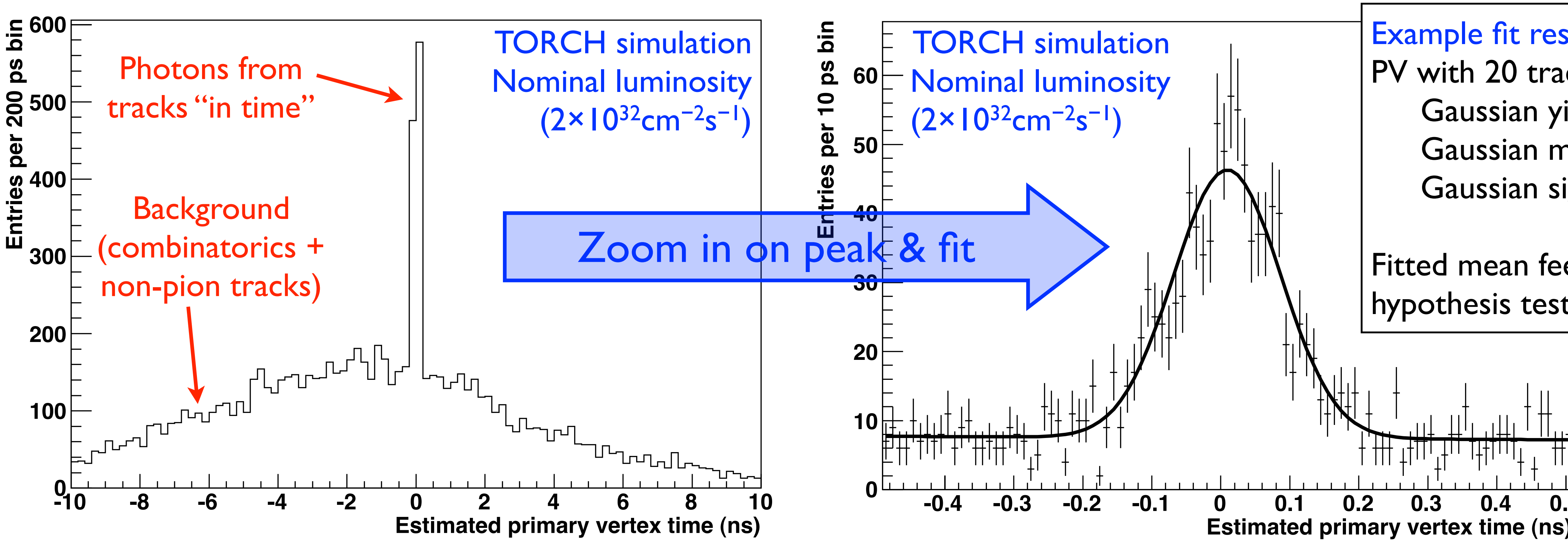
- Broadly, three problems:
  1) Given a track, which photons come from it?
  2) Given a PV with many tracks, when was the PV time (t_{PV})?
  3) Given a track and t_{PV}, which mass hypothesis is it most consistent with?
- First item is geometrical:
  - Photodetector is sensitive to a limited range of E_γ only...
  - ... hence to a limited range of n only (from properties of quartz)...
  - ... hence to a limited range of θ_C only (from $\cos\theta_C = 1/\beta n$).
  - So photons can only land in particular regions of the photodetector planes:



Example event: Photons from one track are picked out and form arcs in the 2D channel index plane.

Pattern recognition

- Broadly, three problems:
  1) Given a track, which photons come from it?
  2) Given a PV with many tracks, when was the PV time (t_{PV})?
  3) Given a track and t_{PV}, which mass hypothesis is it most consistent with?
- Use TORCH itself to get PV timing:
  - Each PV produces many tracks, most of which are pions. For each track:
    - Compute time of flight of track from PV to TORCH (from tracking info)
    - Do per-photon measure of when track reaches TORCH (from PMT timing & photon reco)
    - Subtract off to get per-photon estimates of when track left PV
  - Real pions (and high-momentum e/μ/K/p) will form a peak -- find & fit it.



Example fit result from first event's PV with 20 tracks (of which 13 π):

Gaussian yield = 760 ± 40

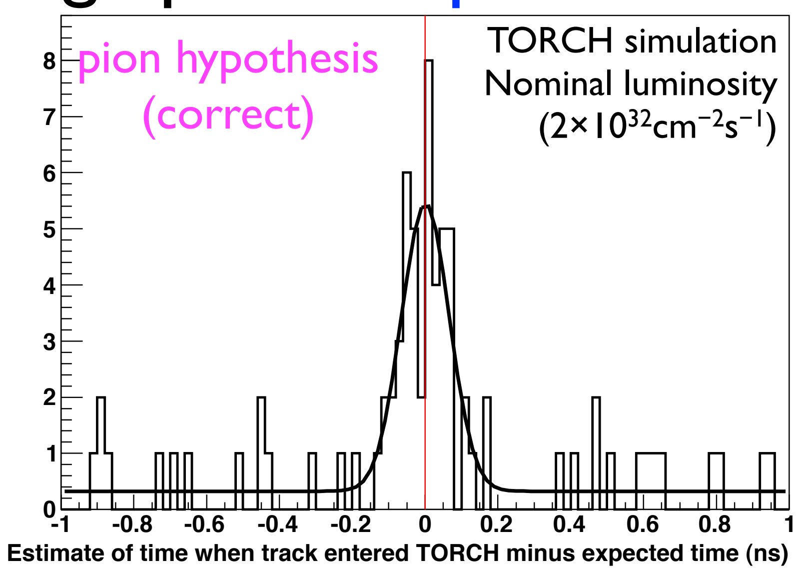
Gaussian mean = 9.4 ± 3.9 ps

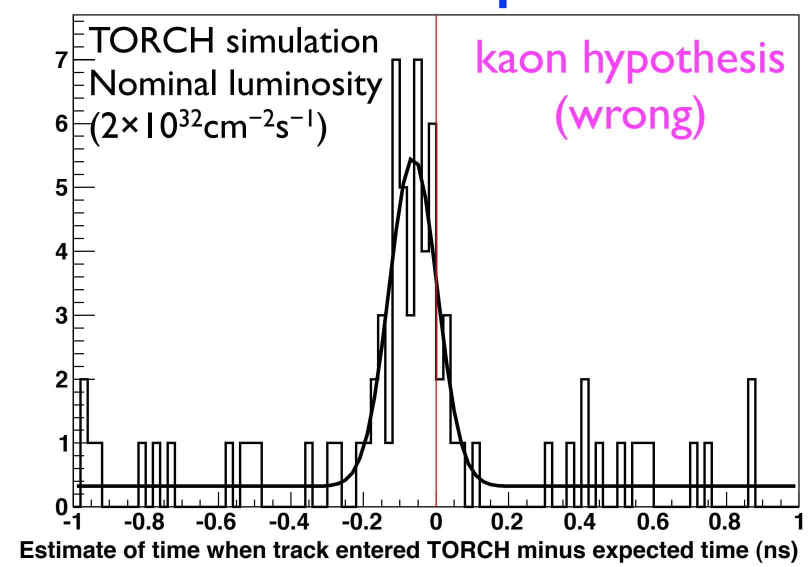
Gaussian sigma = 78 ± 4 ps

Fitted mean feeds directly into PID hypothesis testing (next slide).

Pattern recognition

- Broadly, three problems:
  1) Given a track, which photons come from it?
  2) Given a PV with many tracks, when was the PV time (t_{PV})?
  3) Given a track and t_{PV}, which mass hypothesis is it most consistent with?
  - At high p, fit ToF peak and compare mean to expectation (sensitive)





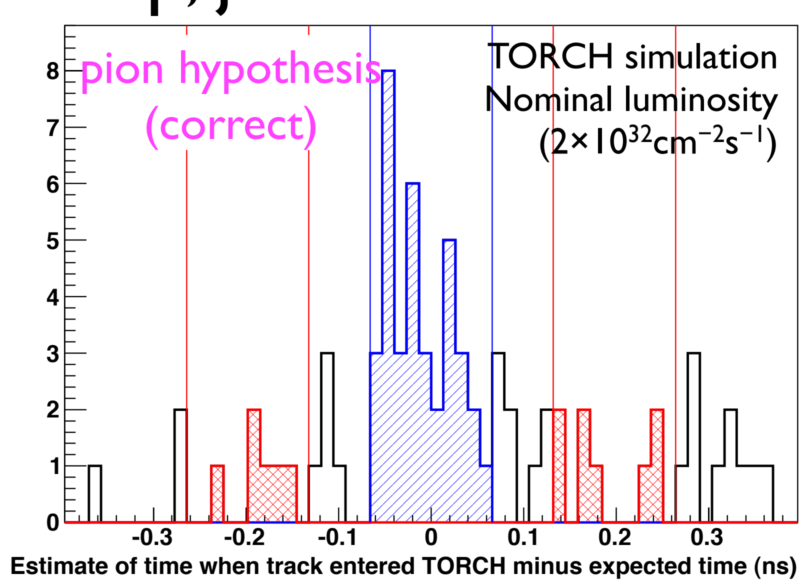
Pion track with p=14 GeV/c

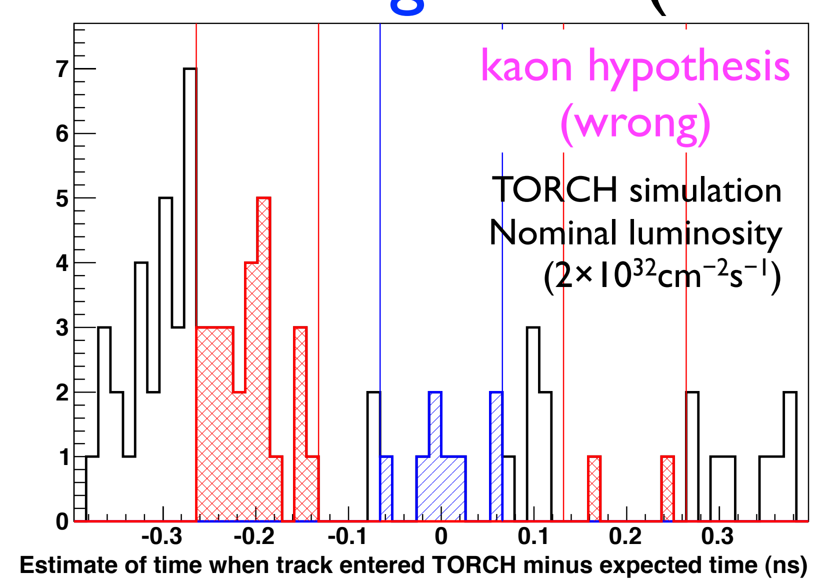
Red line: expectation given mass hypothesis

Problem at low p: wrong-hypothesis peak is far away, smeared, and hard to find.

  - At low p, just look for an excess above background (robust)

Beware different x-axis scale!

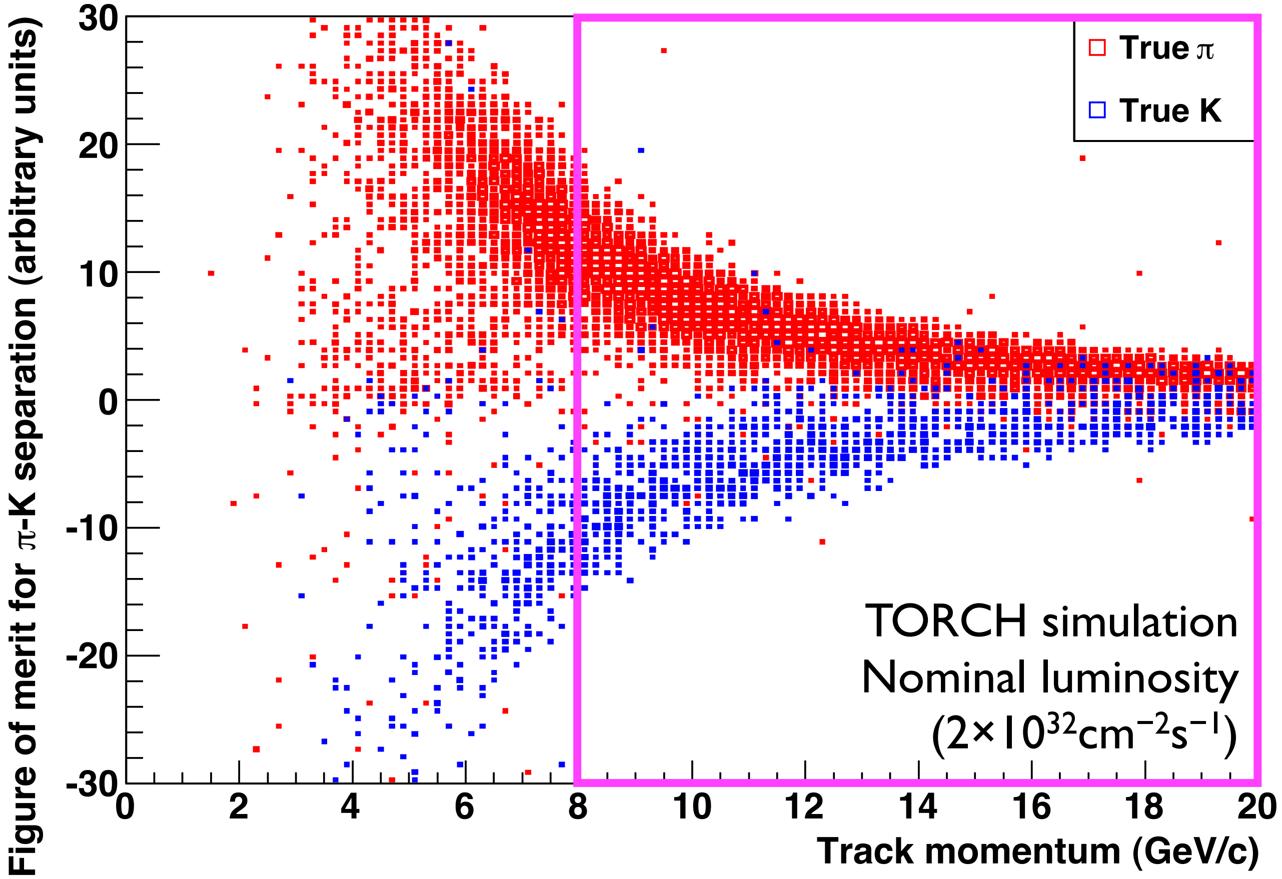




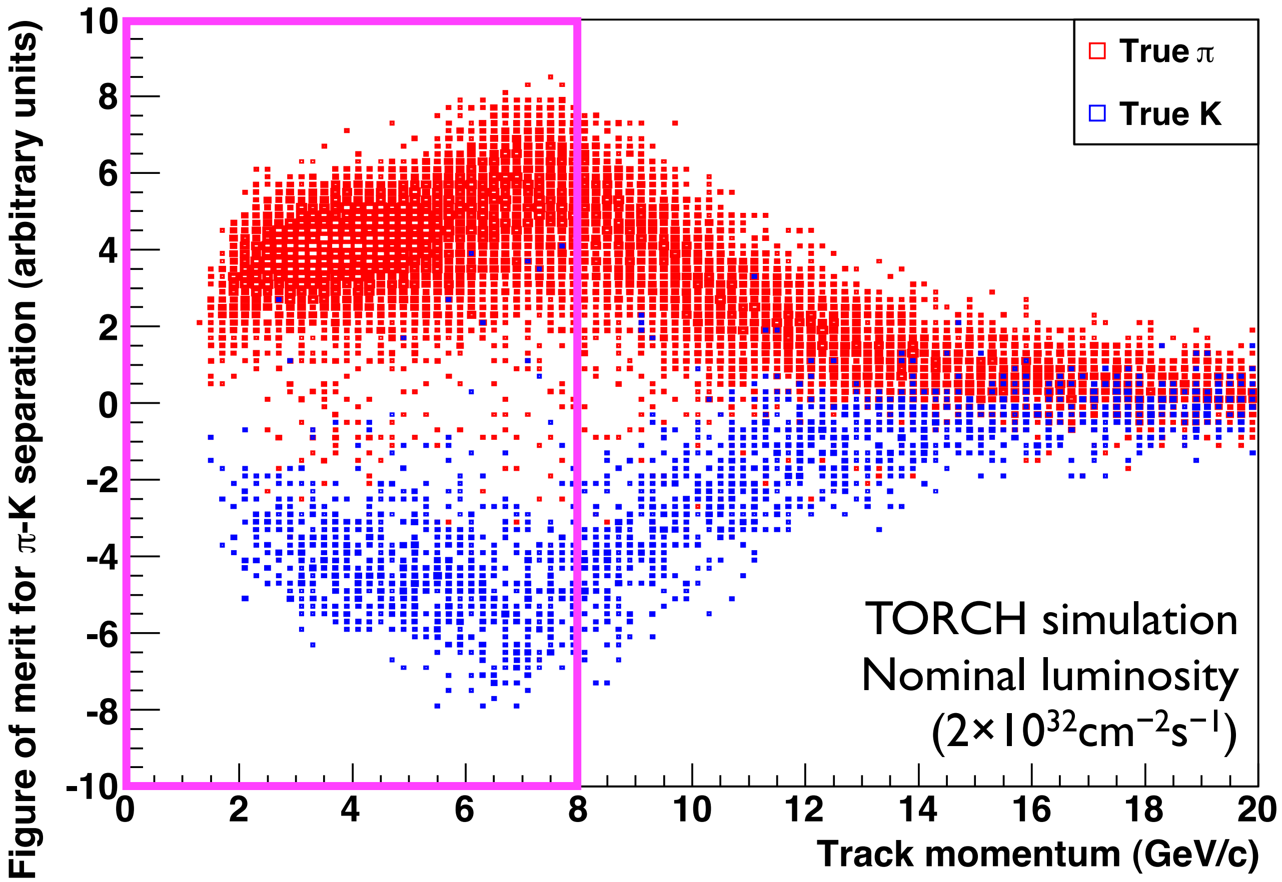
Pion track with p=7 GeV/c

Blue: signal box
Red: sidebands
Compute sideband-subtracted signal yield.

Simulated PID performance



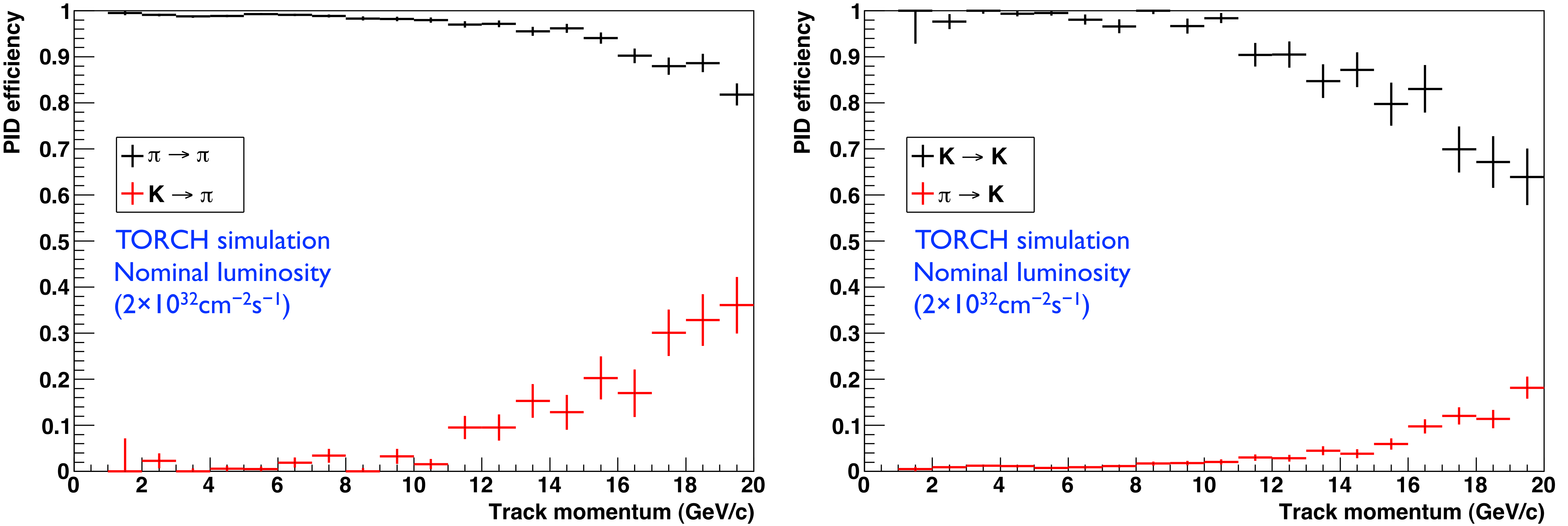
Fitting method used when possible for p > 8 GeV/c



Sideband subtraction method used for p < 8 GeV/c (and also if fit fails for p>8 GeV/c)

Simulated PID performance

Using only tracks that are matched to a primary vertex:

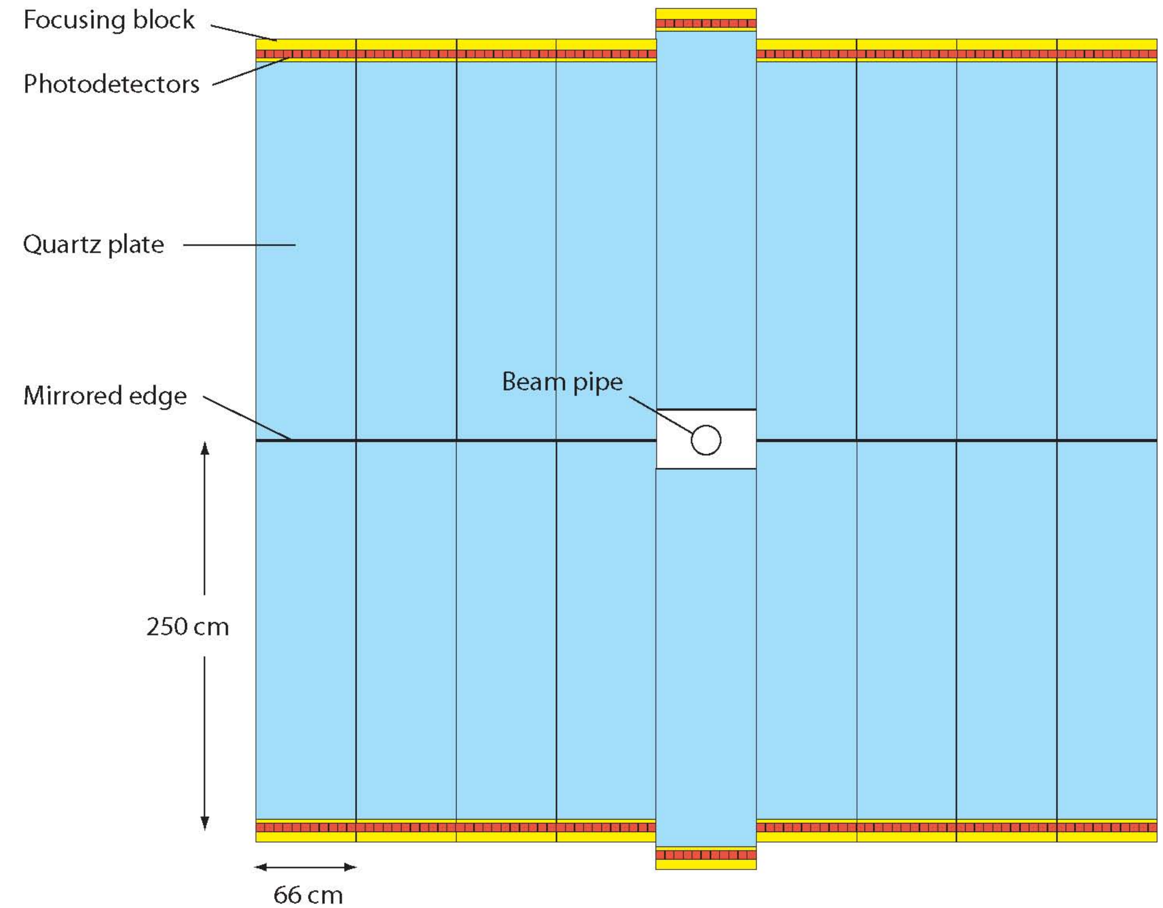


- This looks pretty healthy, especially below 10 GeV/c.
- Caveat: Does not include all backgrounds yet!
- In real life, would use something smarter for pattern recognition (e.g. global likelihood as used for current RICHes)

What comes next

Preliminary hardware tests

- Working on getting hold of some test photodetectors.
- Bench tests of photodetectors, timing, basic optics.



Modular TORCH

Making design more realistic

- Investigating smaller "modular TORCH"
- Work beginning on readout electronics.

Physics studies

- Main driver for low-momentum PID is B-tagging.
- Quantify how much physics performance TORCH buys.
- Now have signal MC in hand to study this...

More stuff

The LHCb upgrade

- Nominal LHC luminosity at LHCb is 2×10^{32} cm^{-2}s^{-1}
  - (... lower than ATLAS & CMS: 10^{34} cm^{-2}s^{-1})
- Hope to collect O(10 fb^{-1}) in next O(5 years)
- Plan for staged upgrade from O(2016) for higher rates
  - Upgrade detector, electronics, trigger & DAQ
  - Current RICH electronics limited to 1MHz (need 40MHz)
  - ... so current HPD photodetectors will have to be scrapped.
- Baseline is to maintain current RICH1+RICH2 layout...
- ... but some things might push us to change it:
  - If RICH1 aerogel performance degrades for high-luminosity running (occupancy & photon yield issues);

See poster by Young Min Kim

  - If LHCb needs to reduce the upstream material for high-luminosity running.
- Caveat: All this depends on funding & on LHC schedule.

Photodetectors

Based on Burle-Photonis XP85022 micro-channel plate PMT with 32x32 channels

That model might not be suitable for a real detector, but we've assumed it for performance studies...

Inactive border: 3mm on each side

Active area: 53mm x 53mm

Fine segmentation: 128 columns in 53mm (0.41mm cell width)

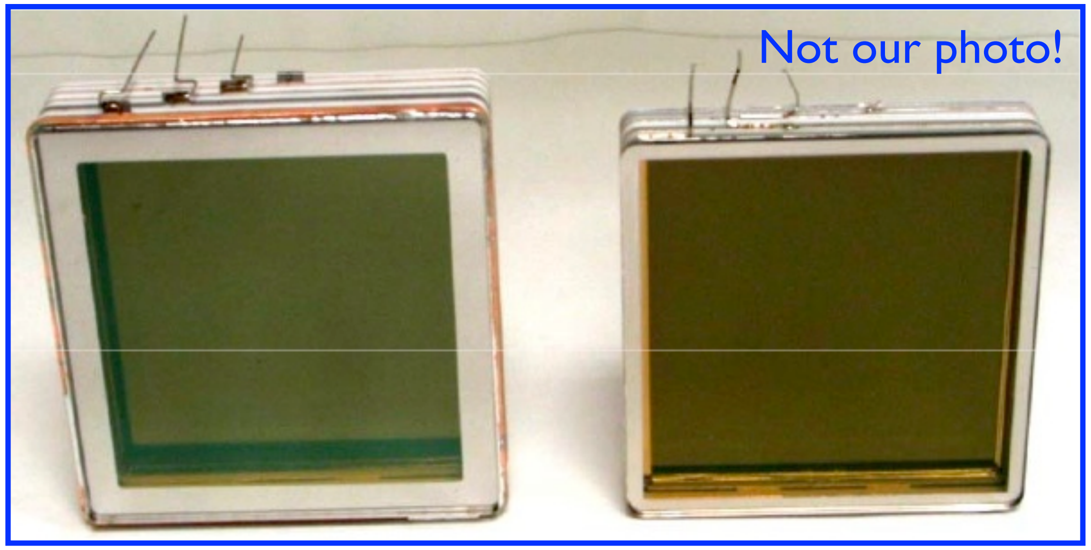
Coarse segmentation: 8 rows in 53mm (6.6mm cell height)

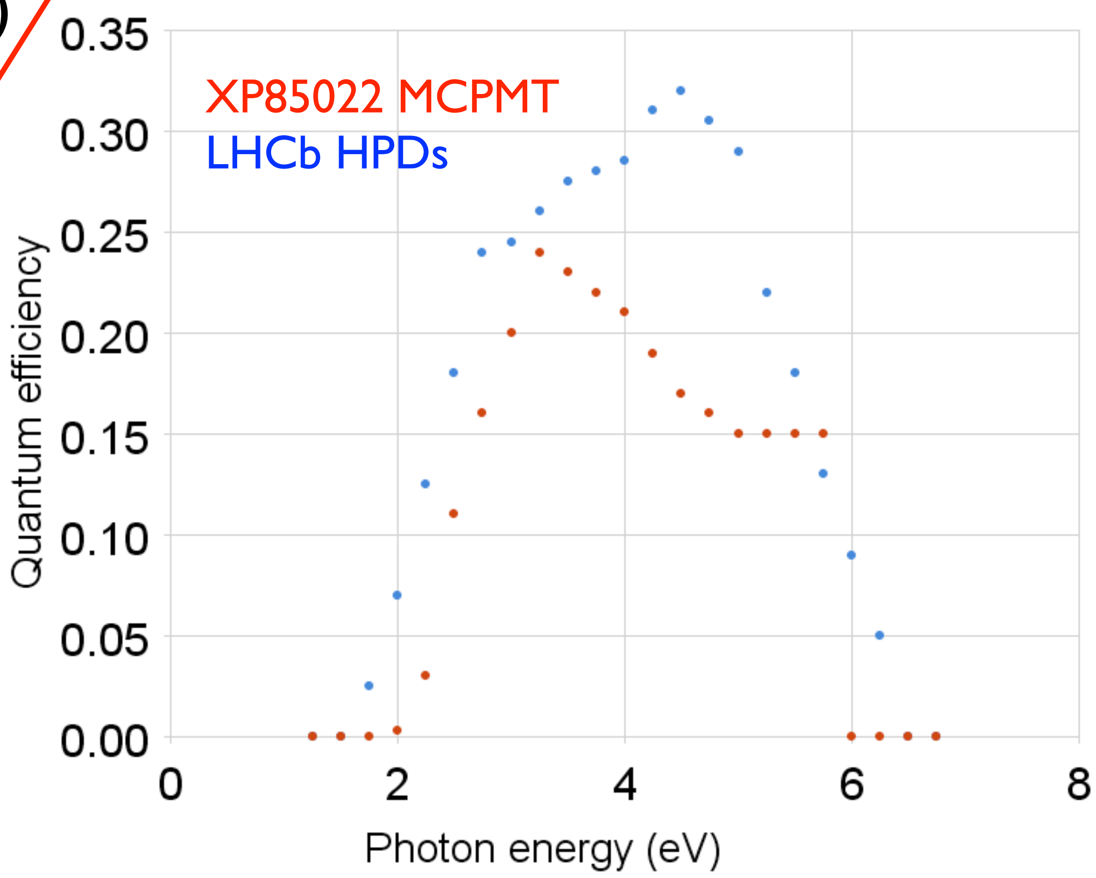
Photoelectron detection efficiency taken to be 65%

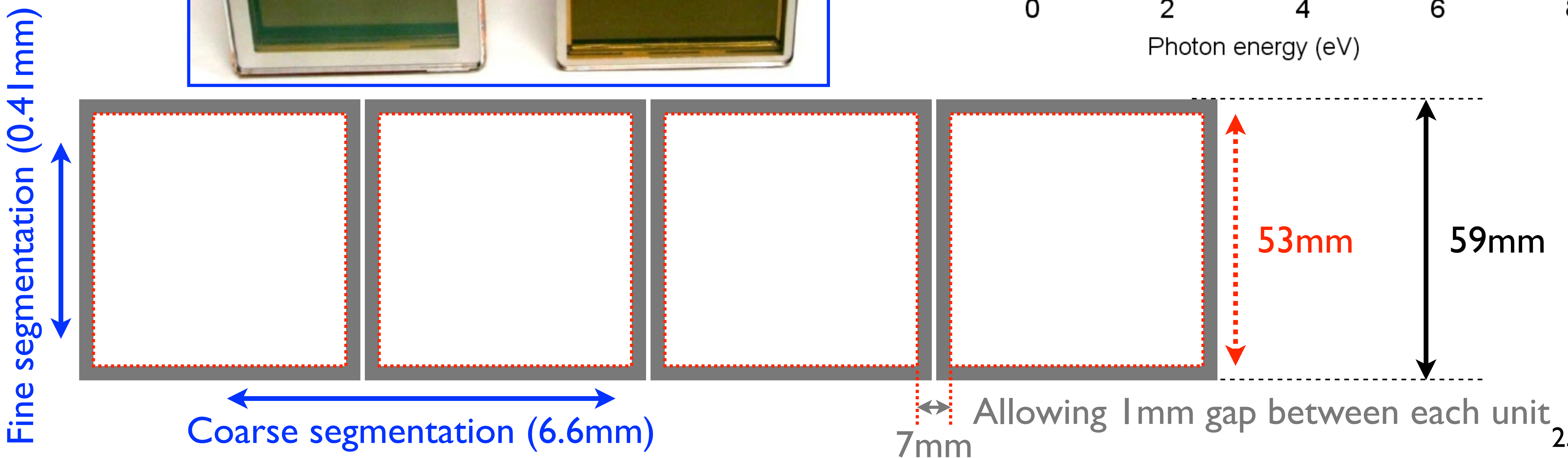
Intrinsic time resolution assumed Gaussian with σ = 20 ps

About 450 units required to instrument all four sides.

Our assumptions about what's feasible (not from spec)







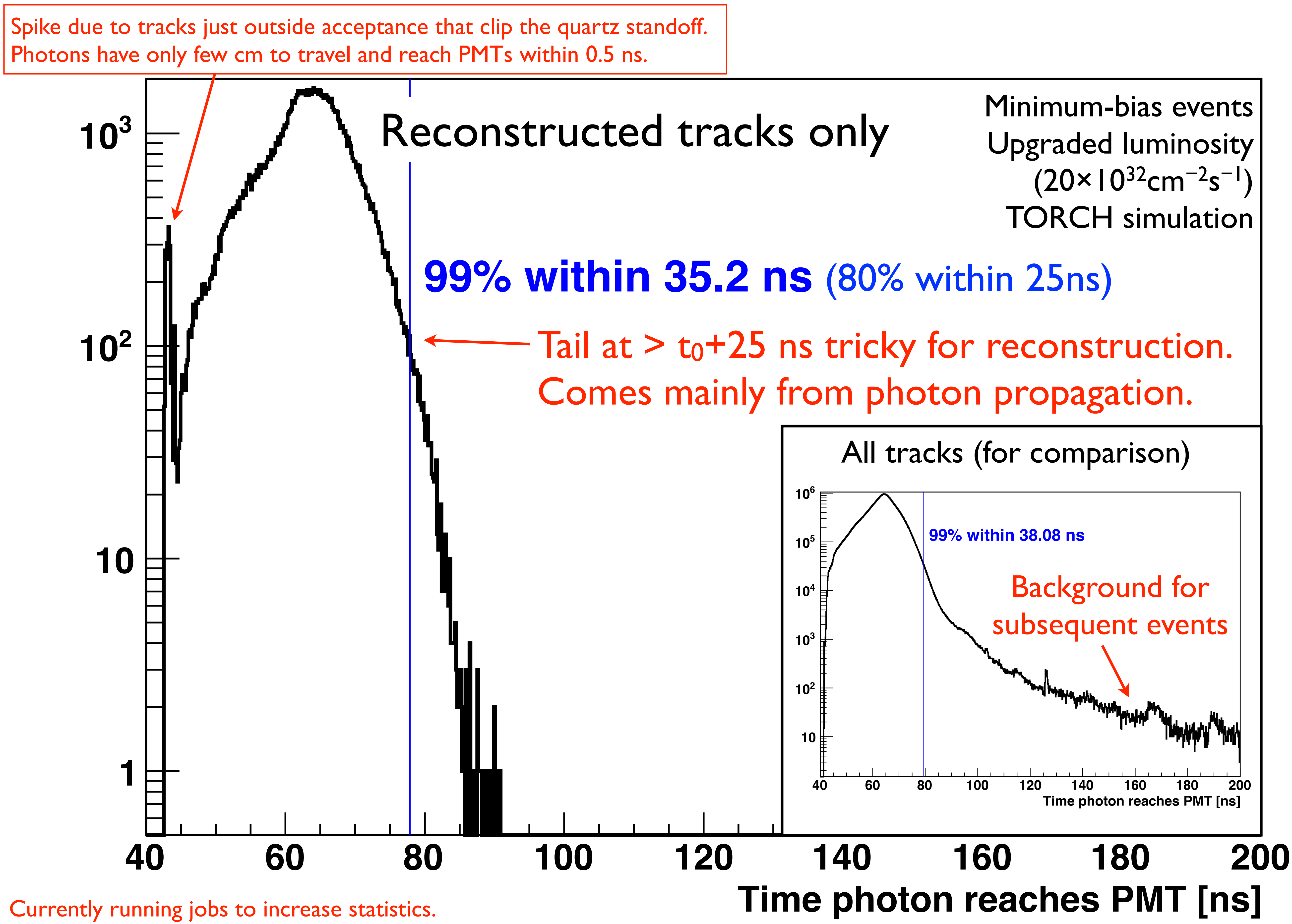
Interlude: TORCH simulation

- Our philosophy for designing & benchmarking the TORCH:
  1) Start with unrealistic assumptions & simulation
  2) Does it work under these conditions?
  3) If so, make things more realistic & go back to step 2.
- How we simulate events right now:
  - Start with full GEANT4 LHCb Monte Carlo, without TORCH
  - Record all charged particles that reach the TORCH plane (z=12m)
  - Feed those charged particles into stand-alone ray-tracing simulation that knows about the TORCH layout and photodetectors but nothing else.
  - Record the hits and try to reconstruct what happened.
  - Assign PID for reconstructed tracks.
- Ultimately, want to move to GEANT4 throughout.
  - Extract more timing information
  - ... in particular propagation of tracks through magnetic field and on to TORCH
  - Some background sources not picked up now (e.g. EM showers from photons inside TORCH; backscatter from calorimeters)
  - ... but this depends on having a reasonably stable design.

Practical considerstions

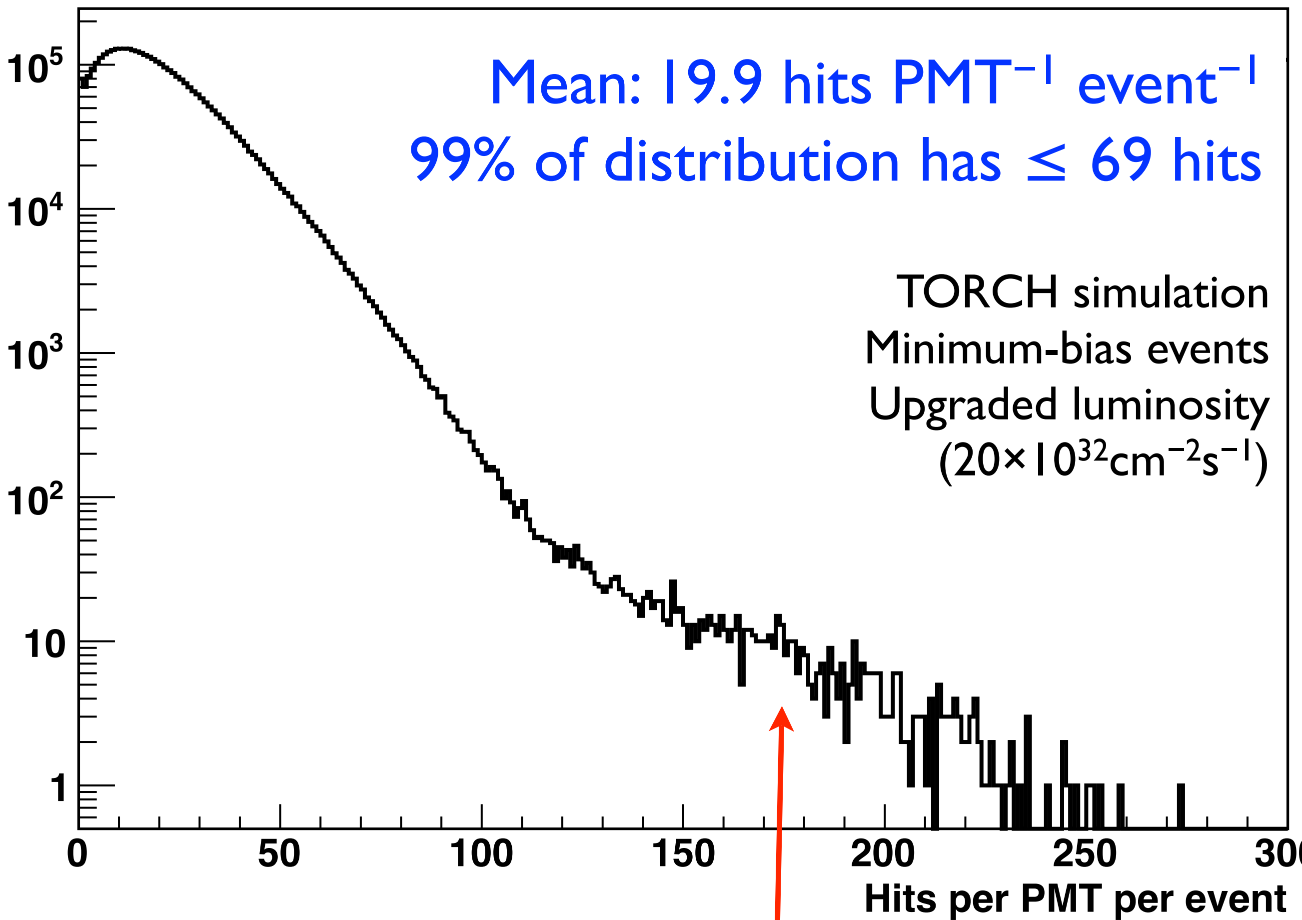
- This is all very nice -- but could it be built?
- Starting to look into practical feasibility:
  - Layout of electronics
  - Occupancy/rate in photodetectors
    - ... to understand demands on readout system
    - ... to understand limits on charge supply from PMT
  - Photon arrival times
    - How much doesn't fit within a 25ns window?
- Just started rethinking the quartz layout
  - Big rectangle: Issues of manufacturing, mechanical engineering, optical coupling between plates, etc.
  - Instead: modular, interchangeable blocks of about 0.7m x 2.5m
  - Instrument only top & bottom surfaces (not sides)
  - Thicker quartz to bump photon yield back up

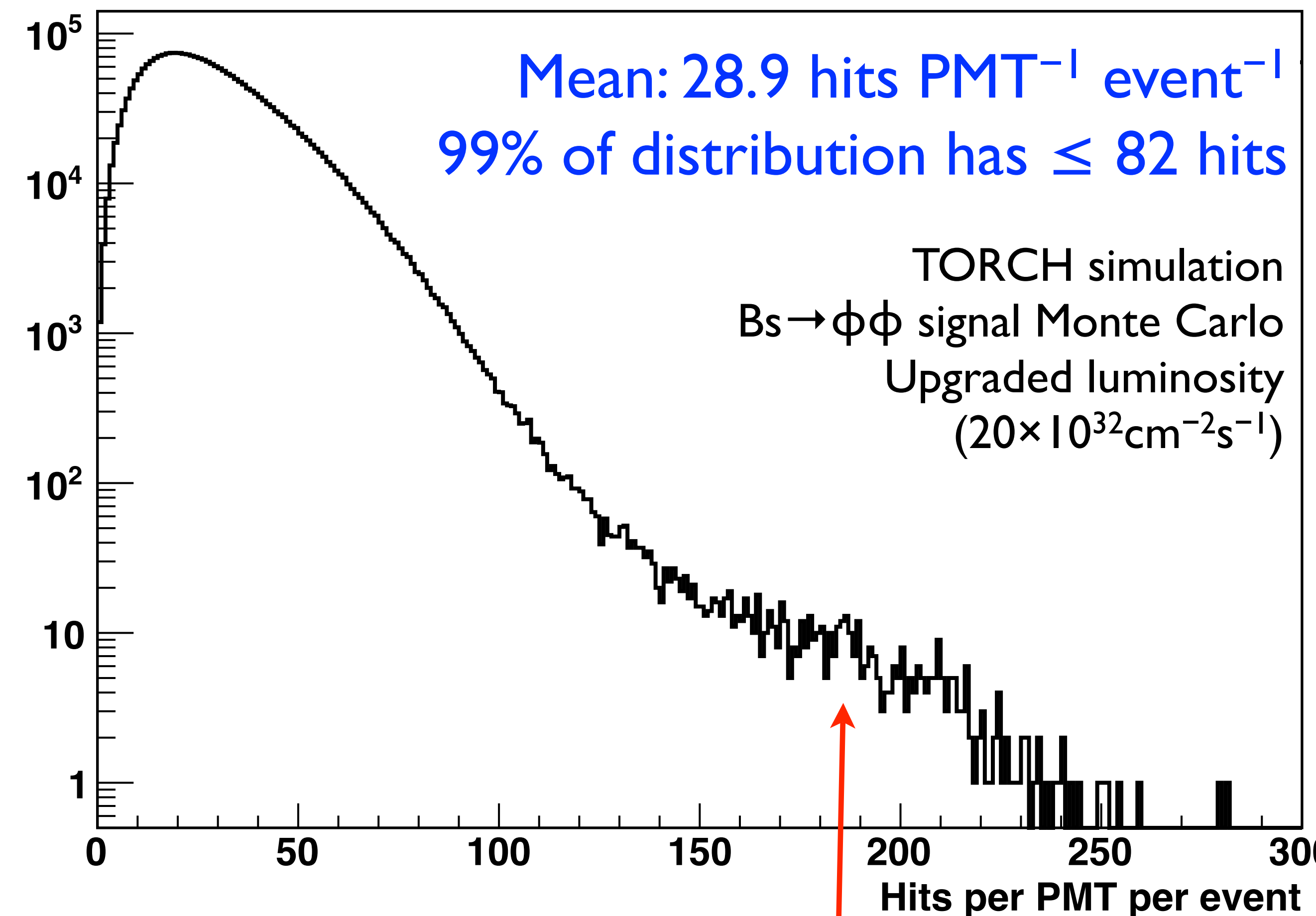
Time distribution of hits



Currently running jobs to increase statistics.

Occupancy

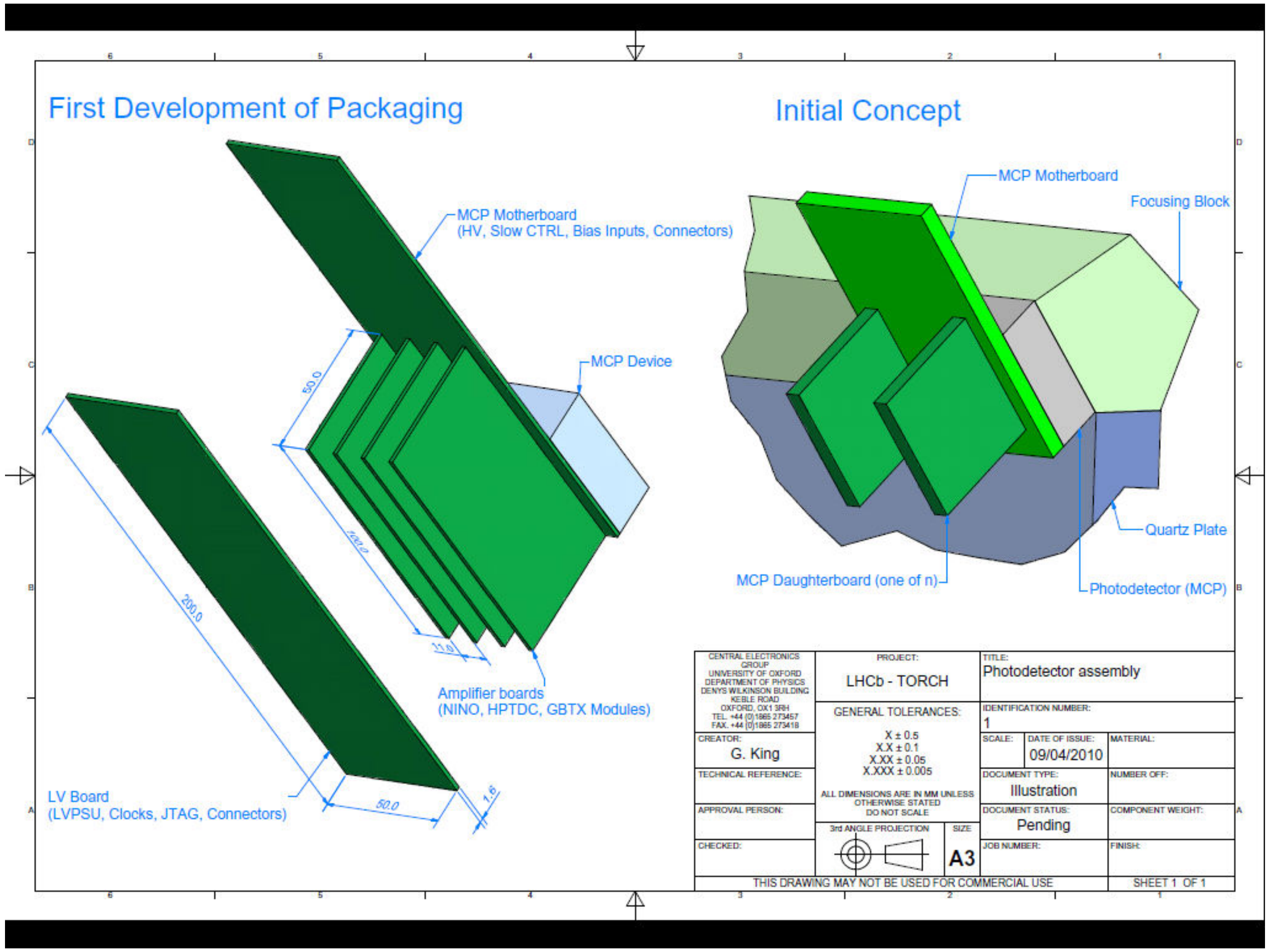




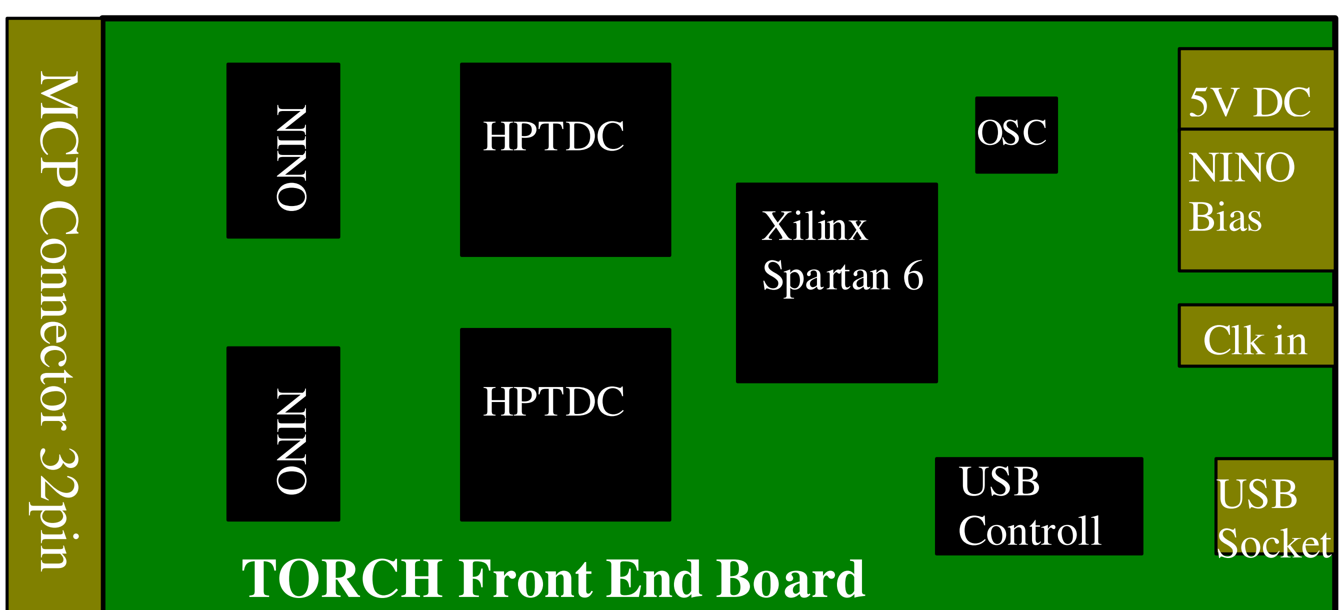
Tail from pathological events when track enters standoff block, lights up PMT.

- Assuming 19 bits per hit (10 for channel, 9 for time*), get per-PMT sustained rate of 11 Gb s^{-1} for lumi20.
- Similar calculation can give expected rate of photoelectrons detected (very roughly 3×10^6 cm^{-2} s^{-1} at this luminosity).
- For gain of 10^5, implies about 0.5 C cm^{-2} year^{-1} integrated charge.
- Caution: Background model incomplete.

Mechanical & Electronic design

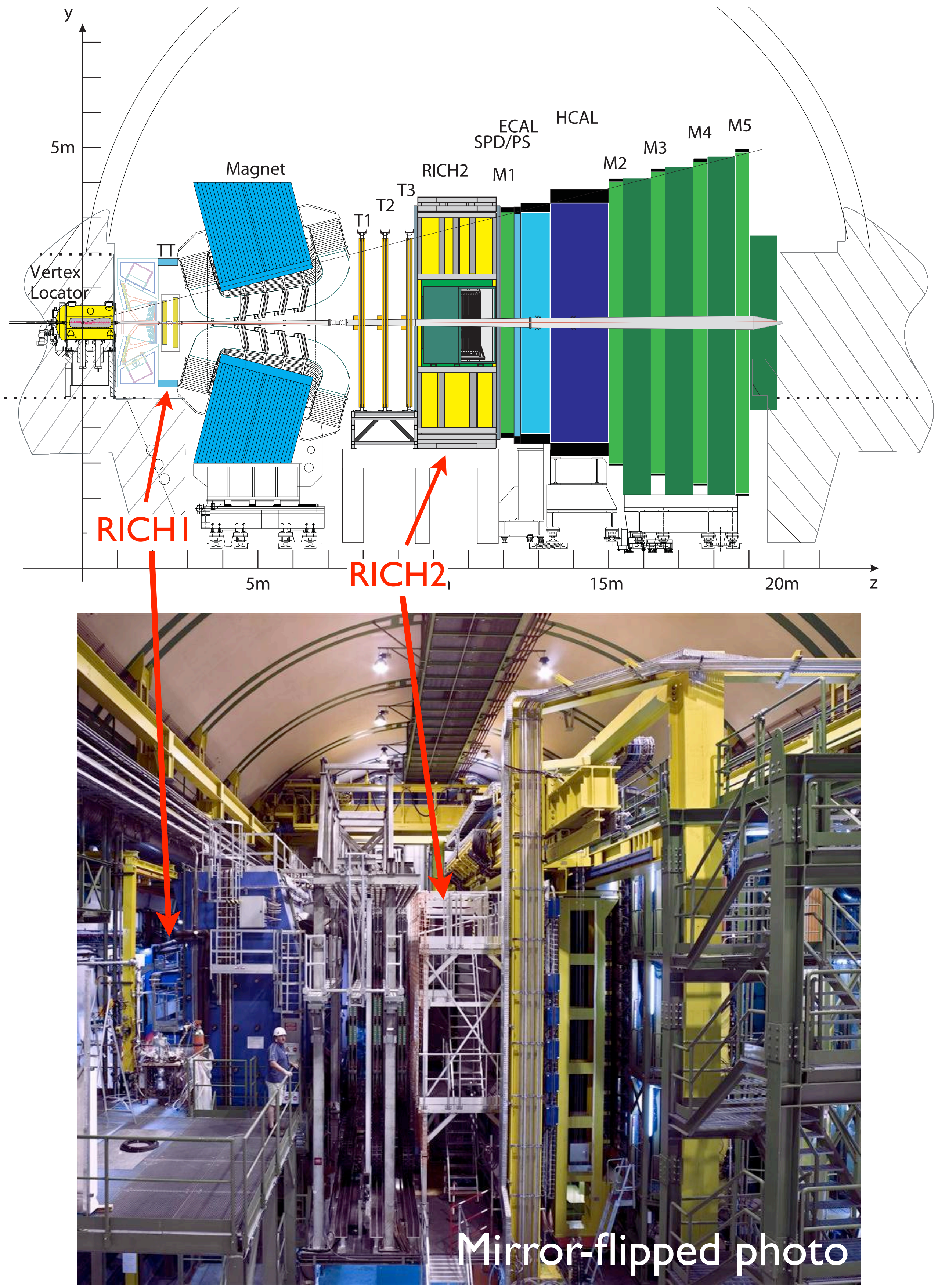


- Still at the conceptual stage...
- ... but we are hoping to start bench tests with MCP-PMTs soon.

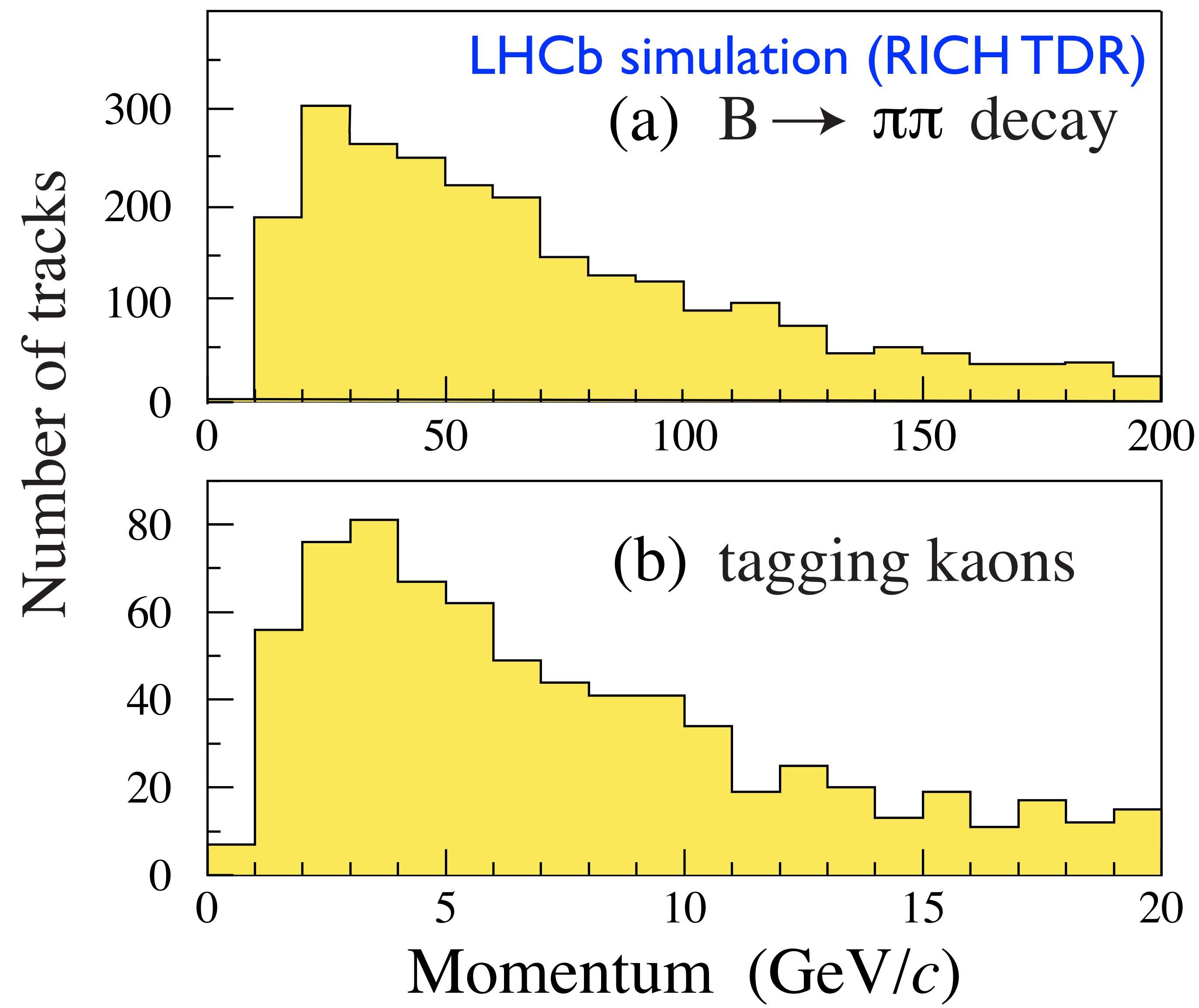


2 x 8-channel NINO
2 x 8-channel HPTDC
Small FPGA

The LHCb RICH systems



Have to cover wide range of momentum...



... especially for tagging, where most of the action is below 10 GeV/c.

Optics 101

Phase velocity: How fast a wavefront moves in a medium

- v=c/n -- this defines the refractive index n.

Group velocity: How fast a wavepacket -- in this case a photon -- moves

- $v_g = c/n_g$ -- defines group velocity refractive index n_g similarly (sloppy notation...)

In a dispersive medium, n and n_g differ and are functions of wavelength.

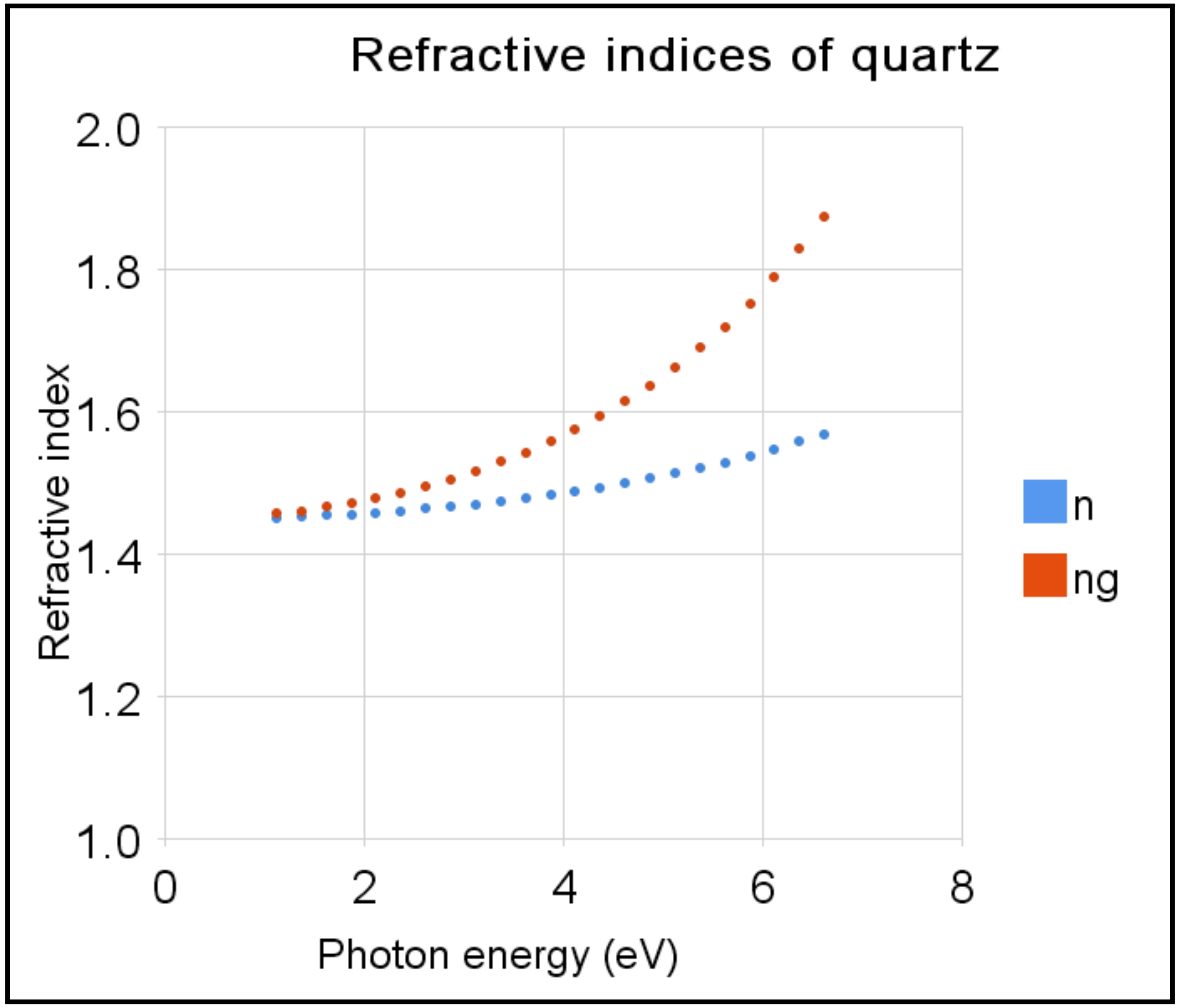
$$n_g = n - \lambda \frac{dn}{d\lambda},$$

For charged particle above threshold with speed βc, Cherenkov light emitted at:

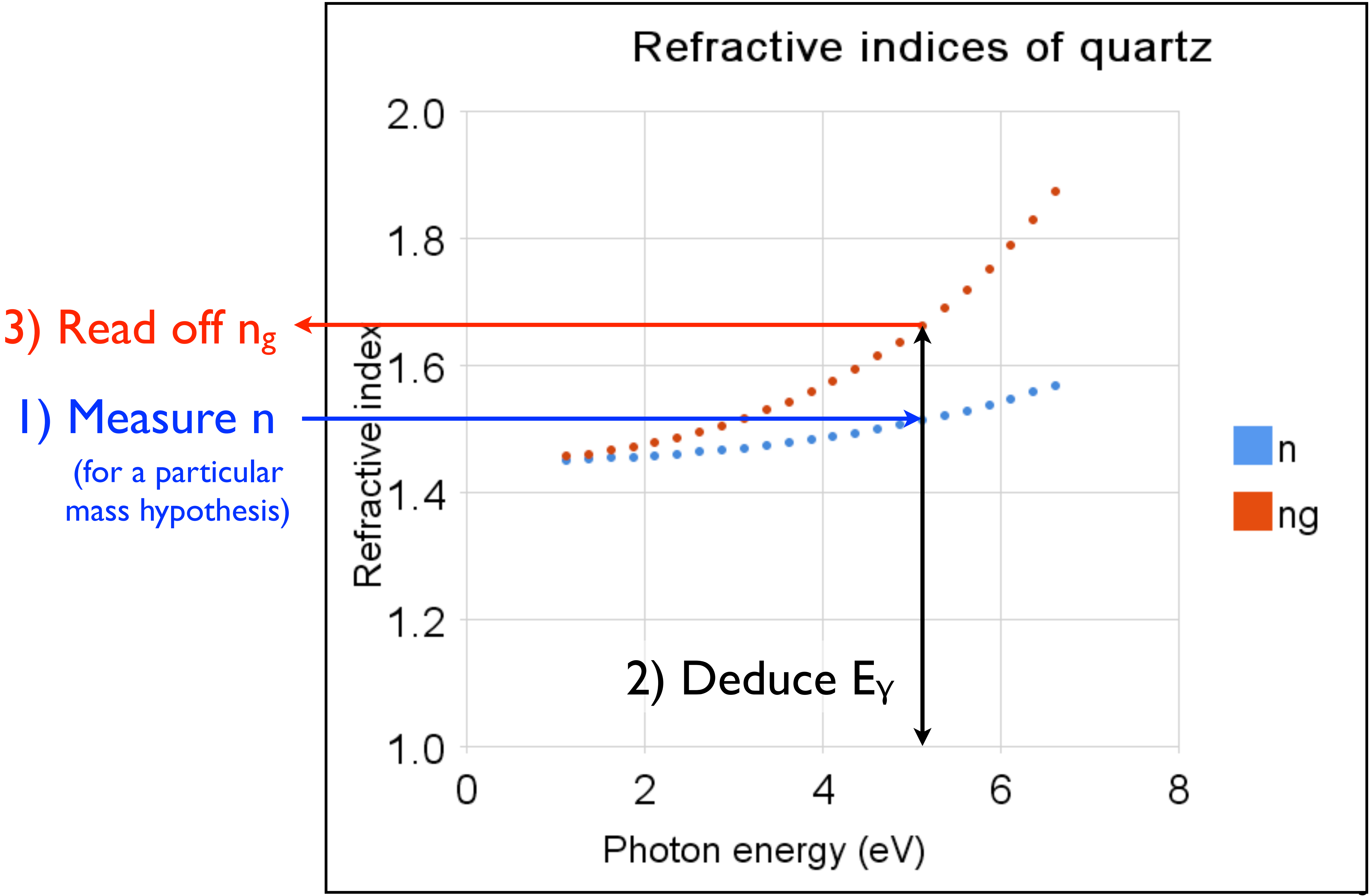
$\cos(\theta_c) = 1 / \beta n$

Since n depends on E_γ, photons with different energy will be emitted at different θ_c.

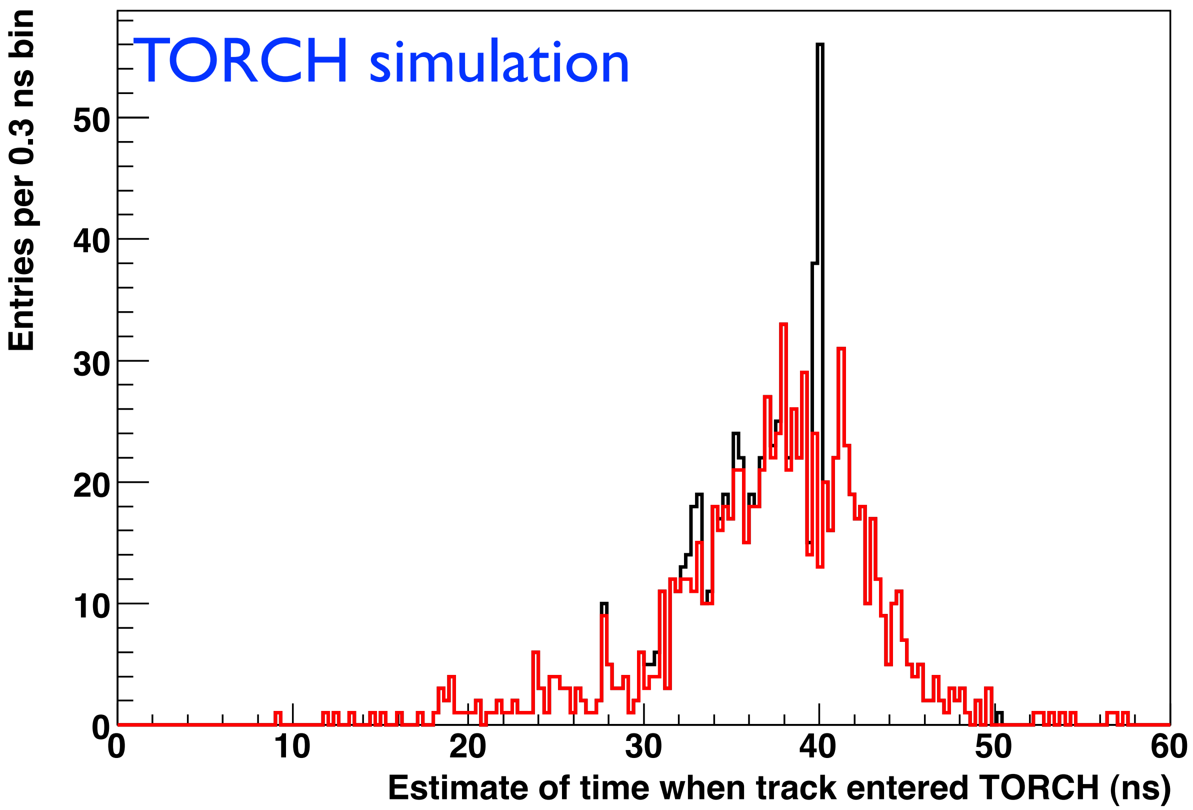
TORCH idea: if you measure θ_c, you can figure out the photon energy without measuring it -- and hence get v_g.



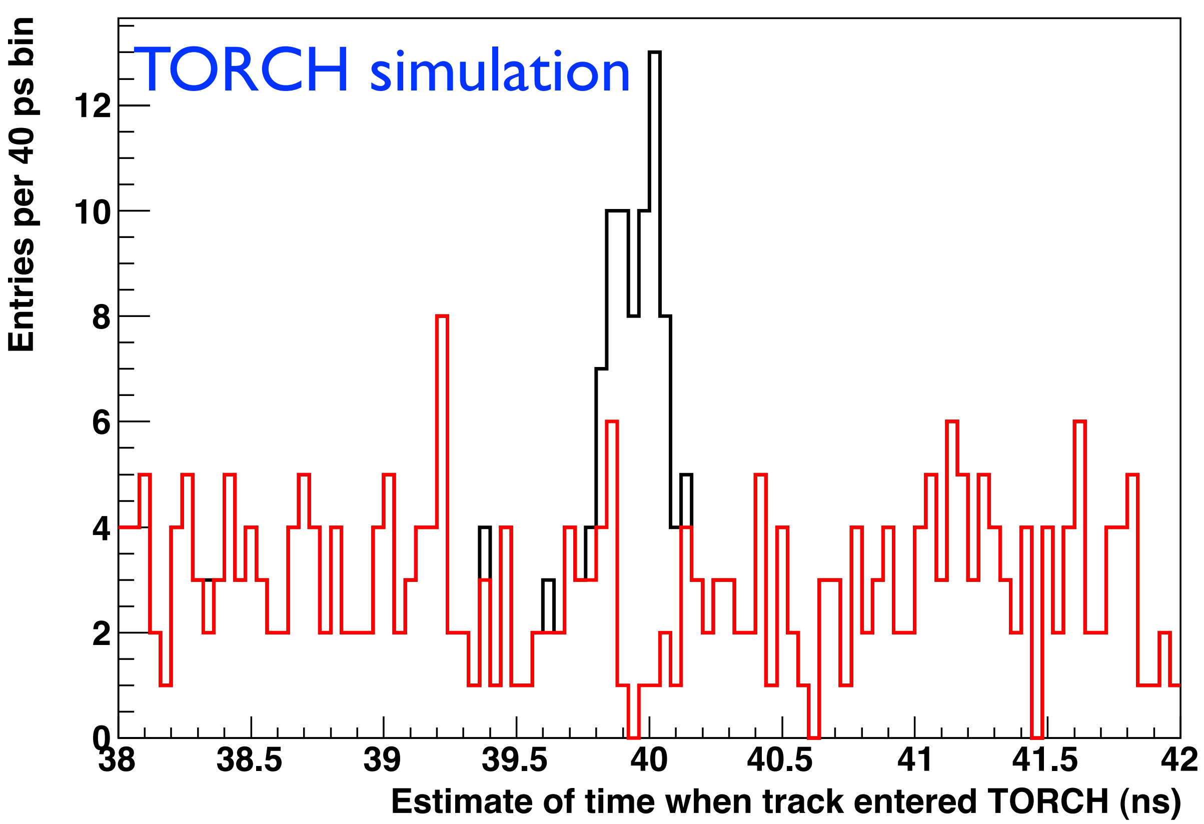
TORCH idea: if you measure θ_c, you can figure out the photon energy without measuring it -- and hence get v_g.



Example timing plots



Big-scale plot illustrating that photons from the same track form an obvious peak above background.



Zoomed plot of same track.

You could fit this to get the time when the track entered the TORCH (but in practice we wait to gather more information first).