Summary of the
Detector Working Group Sessions

Detector Summary

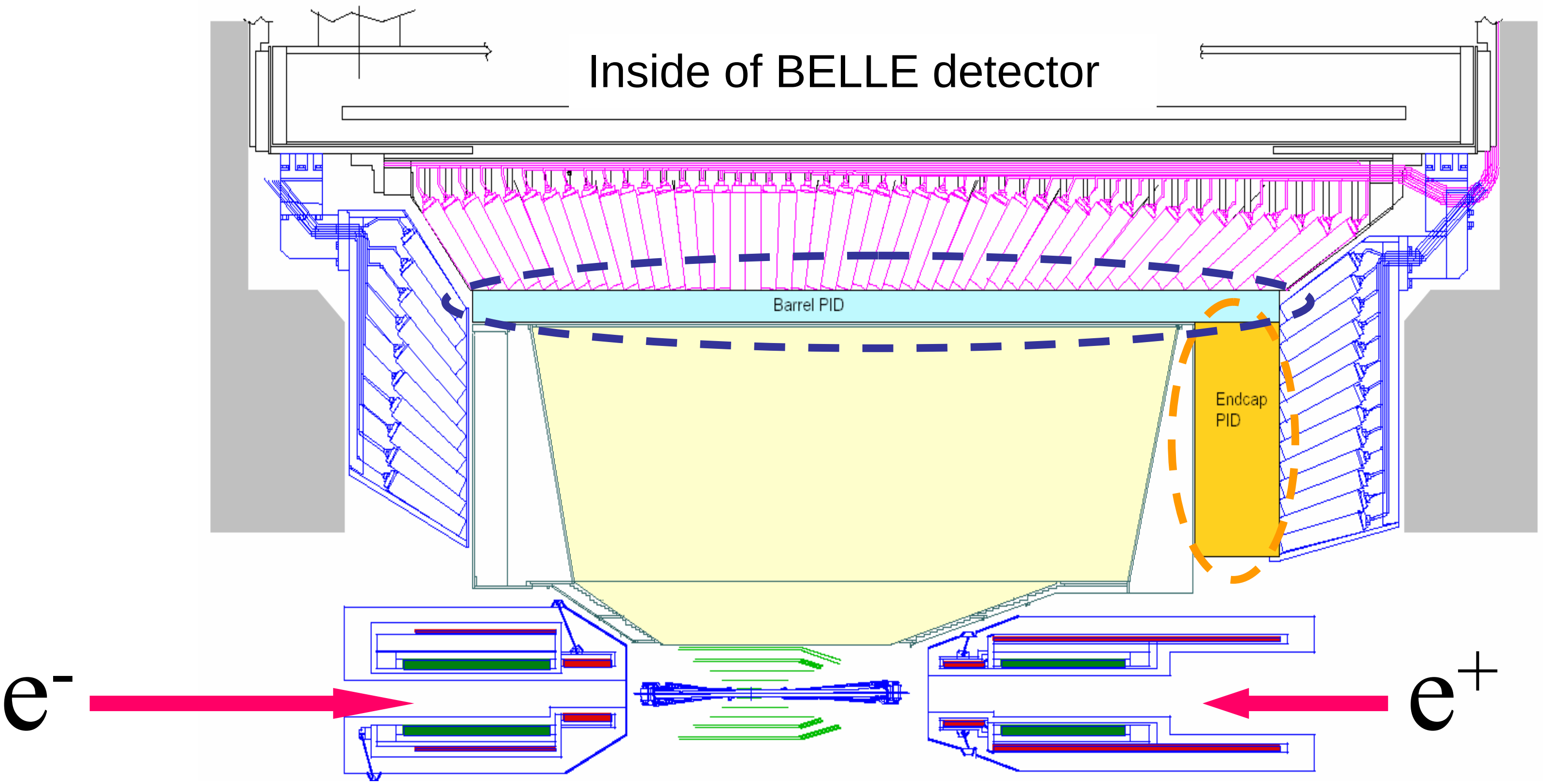
- Critical Issues
  - Boost
  - Beampipe radius & cooling
  - Beam Background environment
- Physics Opportunities
  - Tau-Charm operation
  - B_s Production
  - Polarization
- Design Issues
  - Forward PID
  - Backward EMC & PID
  - Reuse of BABAR or BELLE
- Detector R&D

What we heard at this meeting

- PID
  - Mazuka and Va’vra
- Vertex Detector
  - Neri (simulations)
  - Forti (MAPS)
- Backgrounds
  - Weaver, Paolini and Calderini
- Tracking Chamber
  - Boyarski
- Physics Issues

PID

Upgrading BELLE Detector
Two new particle ID devices, both RICHes



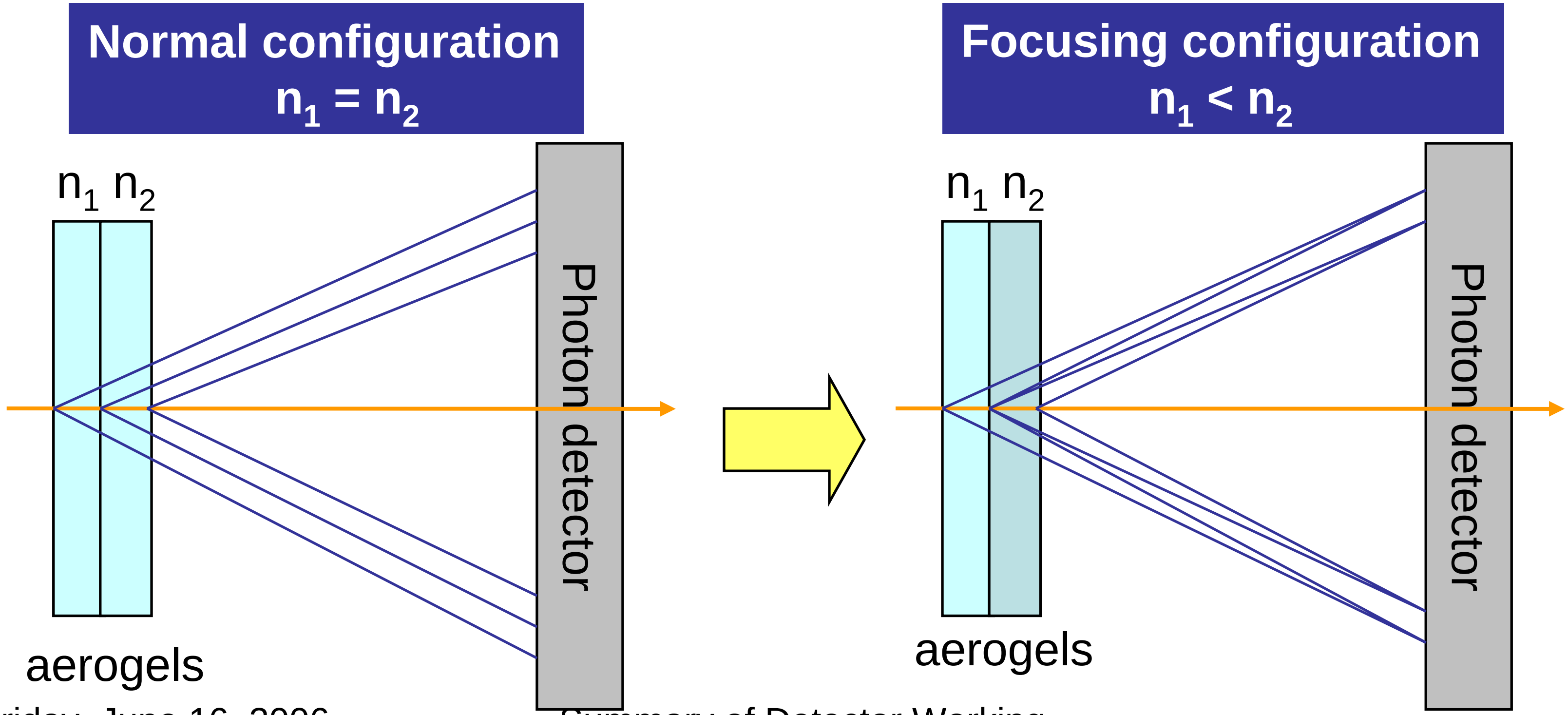
Endcap: **Proximity Focusing Aerogel RICH(A-RICH)**

Barrel: **Time of Propagation Counter(TOP)**

Focusing configuration

How to increase the number of photons without degrading the resolution?

Use radiator with gradually increasing refractive index in down stream direction



Normal configuration
$n_1 = n_2$

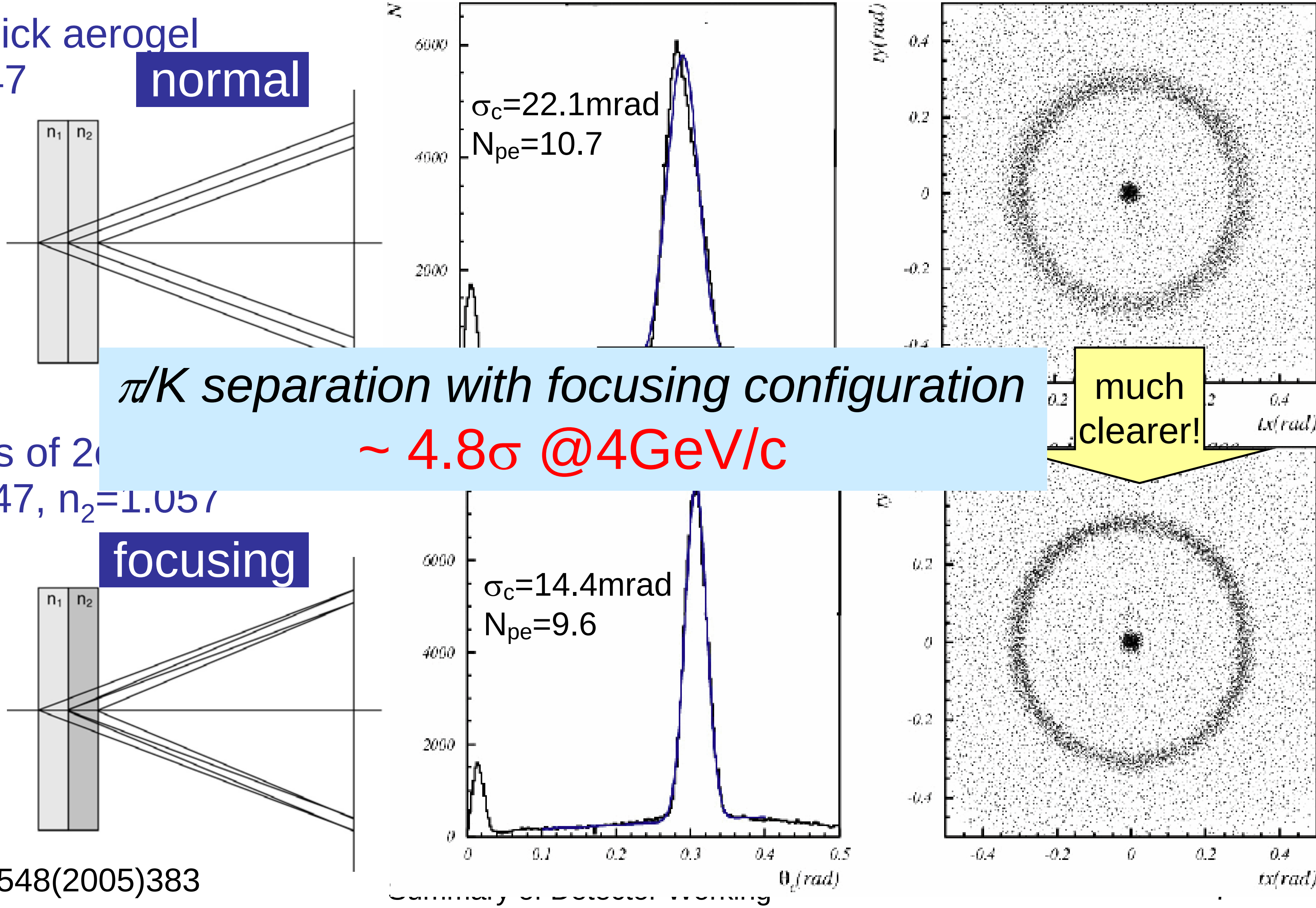
Focusing configuration
$n_1 < n_2$

Results of focusing configuration

A-RICH

4cm thick aerogel
n=1.047

2 layers of 2
n_1=1.047, n_2=1.057



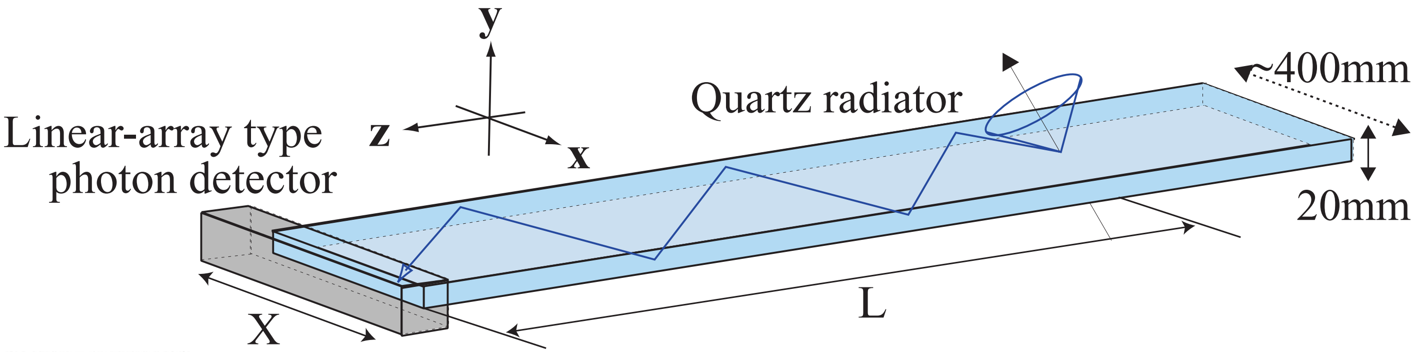
π/K separation with focusing configuration

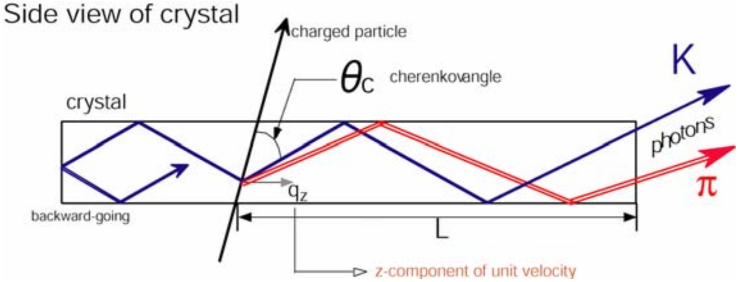
~ 4.8σ @4GeV/c

NIM A548(2005)383

Barrel: TOP counter

Cherenkov ring imaging is used as timing information





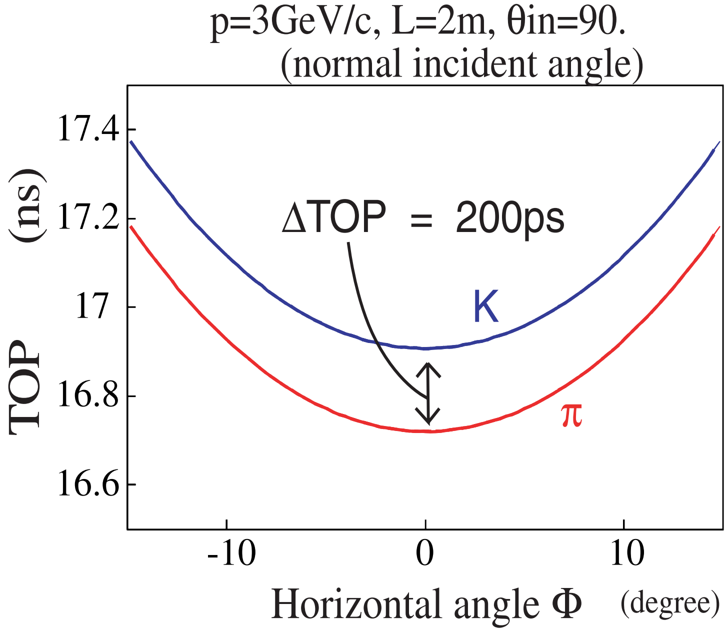
$$cos\theta_c = \frac{1}{n(\lambda)\beta}$$

Difference of path length

→ Difference of time of propagation (TOP)

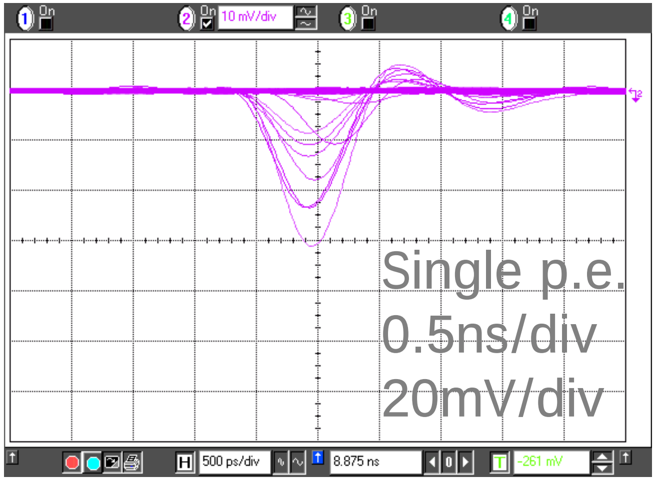
(+ TOF from IP)

With precise time resolution (σ~40ps)

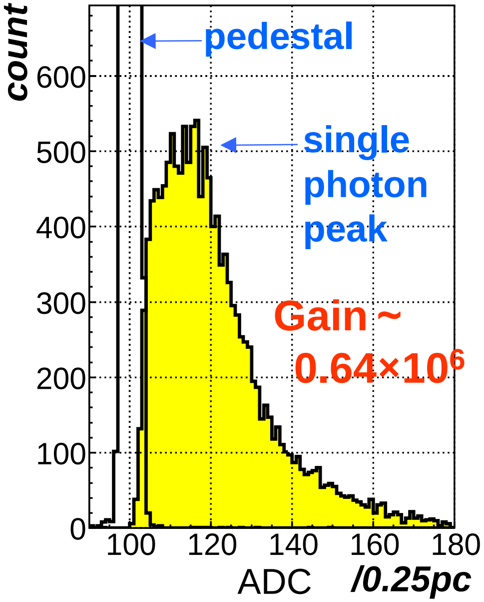


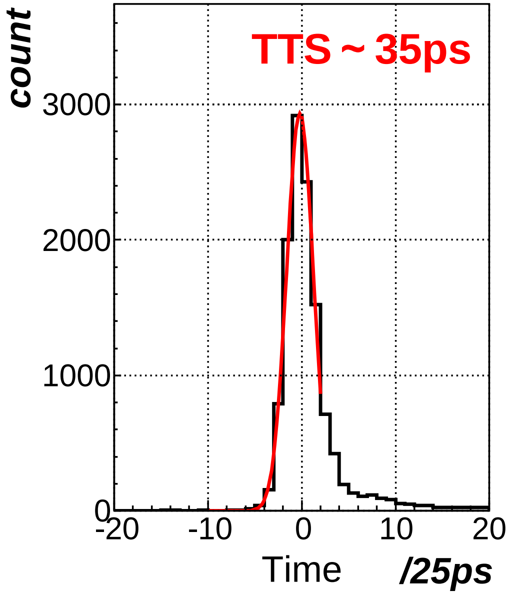
GaAsP MCP-PMT performance

- Wave form, ADC and TDC distributions



Single p.e.
0.5ns/div
20mV/div





- Enough gain(~10^6) to detect single p.e.
- Good time resolution (TTS~35ps) for single p.e.
- Next
  - Check the performance in detail
  - Life time of GaAsP photo-cathode tube

Summary

We are studying new types of RICH for super KEKB

Aerogel RICH counter for endcap

- Test the focusing configurations
  - We studied about optimal parameters
- More studies: RICH with TOF (using MCP-PMT)
  - Extend PID ability into low momentum region

TOP counter for barrel

- M ps)
- A
- M
  - It will reduce the effect of chromatic dispersion

Both RICHes(A-RICH, TOP) look very promising

π/K separation can be over 4σ @4GeV/c

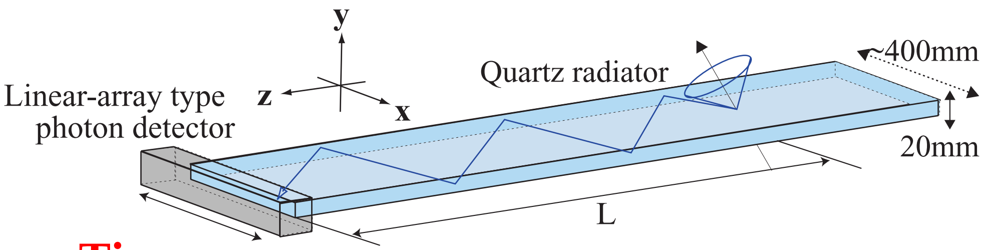
But there is still a lot of work to be done!

Improvements compared to BaBar DIRC

- Timing resolution improved from σ ~1.7ns -> σ ≤150ps
- Time resolution at this level can help the Cherenkov angle determination for photon path lengths Lpath ≥ 2-3m
- Time can be used to correct the chromatic broadening
- Better timing improves the background rejection
- Smaller pixel sizes allow smaller detector design, which also reduces sensitivity to the background
- Mirror eliminates effect of the bar thickness

Examples of two “DIRC-like” detectors

TOP counter (Nagoya):



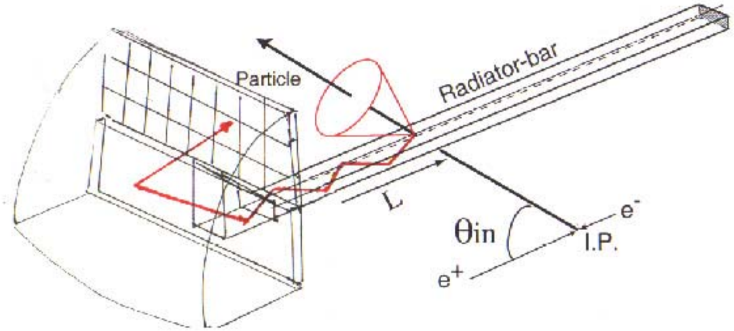
x, Time

- **2D imaging:**

  a) x-coordinate

  b) TOP (σ ≤ 70ps).

Focusing DIRC prototype (SLAC):



x, y, Time

- **3D imaging:**

  a) x-coordinate

  b) y-coordinate

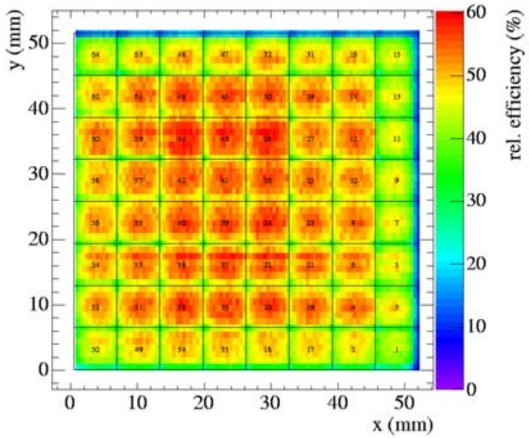
  c) TOP (σ ≤ 150ps).

Photon detectors in the prototype (σ~70-150ps)

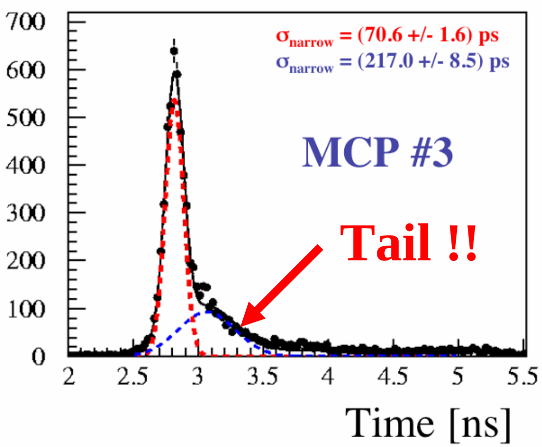
Burle MCP PMT (64 pixels):

PiLas single pe calibration:

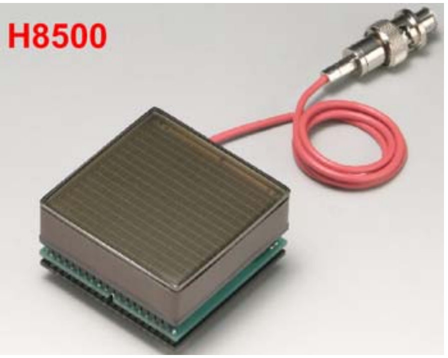
Efficiency w.r.t. Photonis PMT, MCP #15, blue, 2.4kV, 20040607



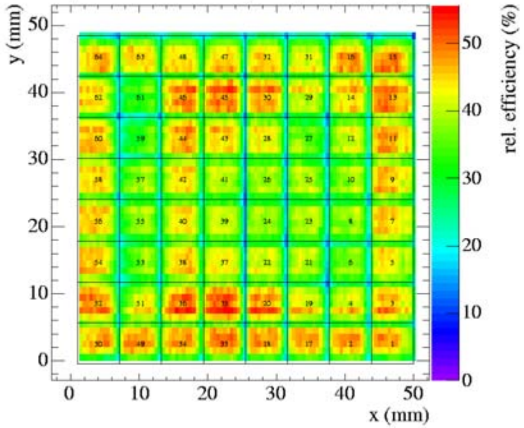
Burle 85011-501 MCP-PMT:



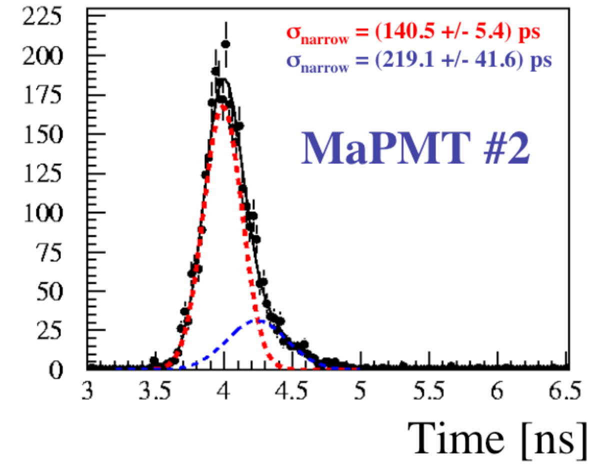
Hamamatsu MaPMT (64 pixels):



Efficiency w.r.t. Photonis PMT, FP #2, blue, 0.9kV, 20040708

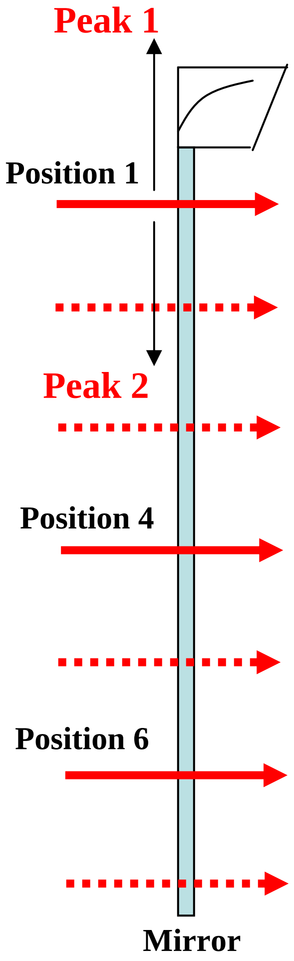


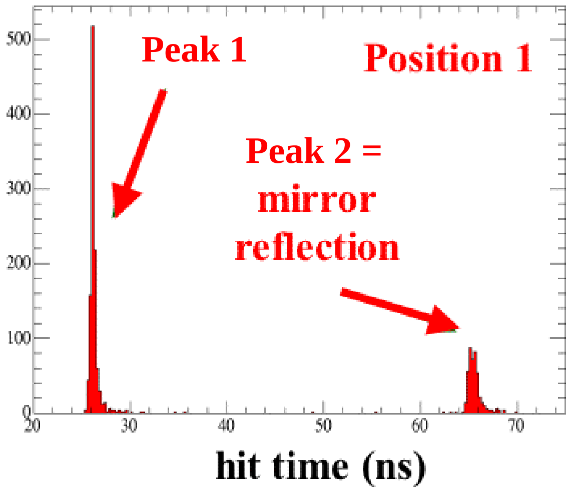
Hamamatsu Flat Panel H8500 PMT:

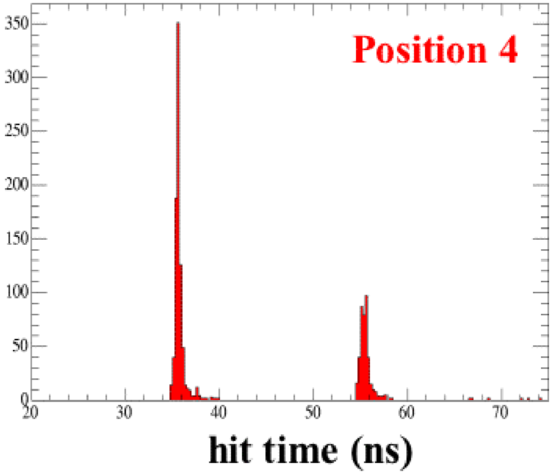


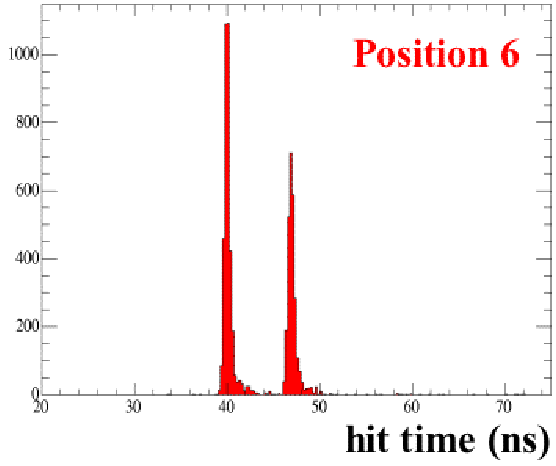
Cherenkov ring in the time domain

Pixel #25, Slot #4



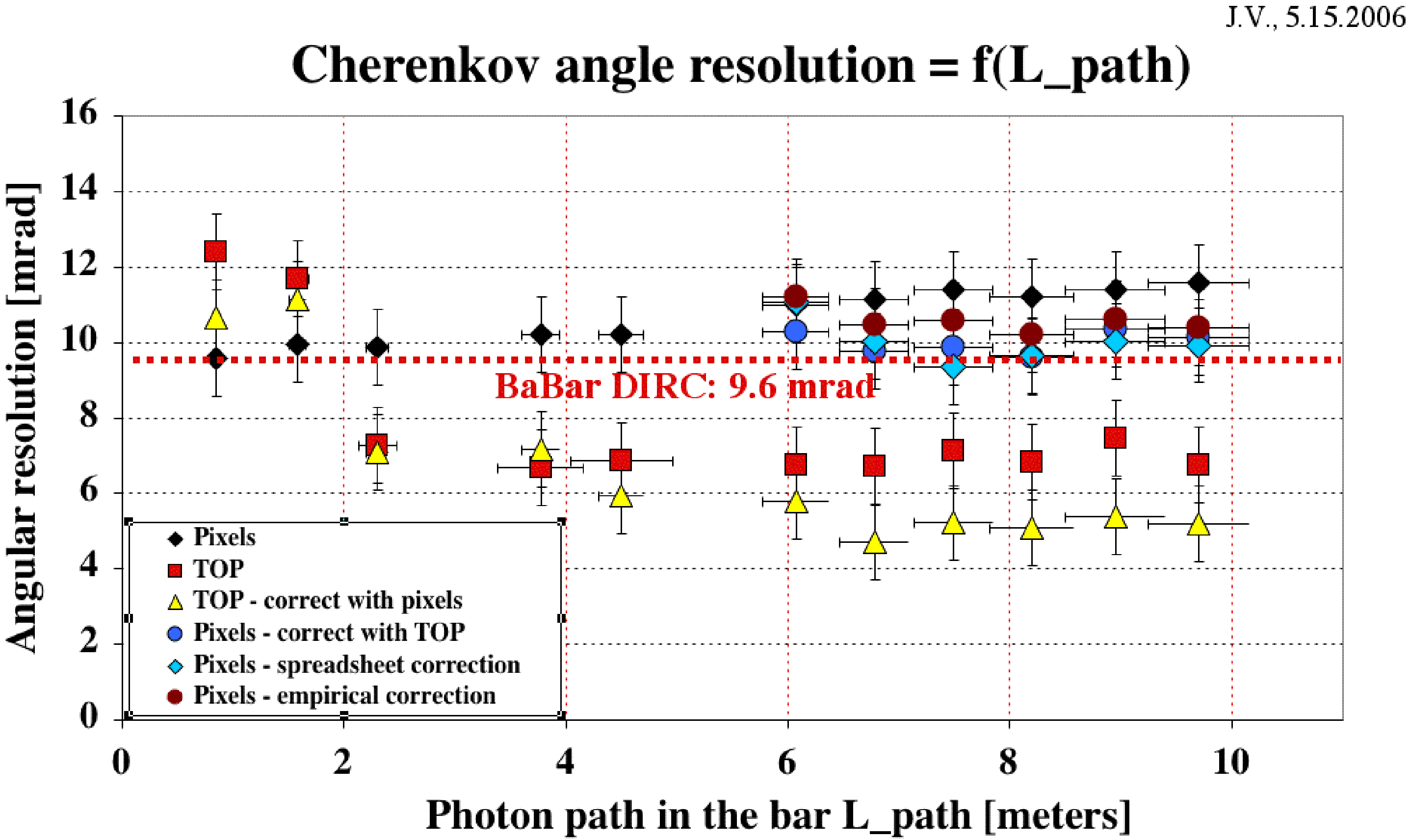






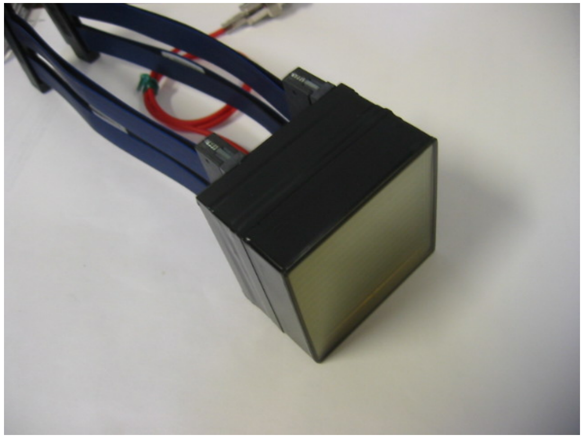
- Two peaks correspond to forward and backward part of the Cherenkov ring.

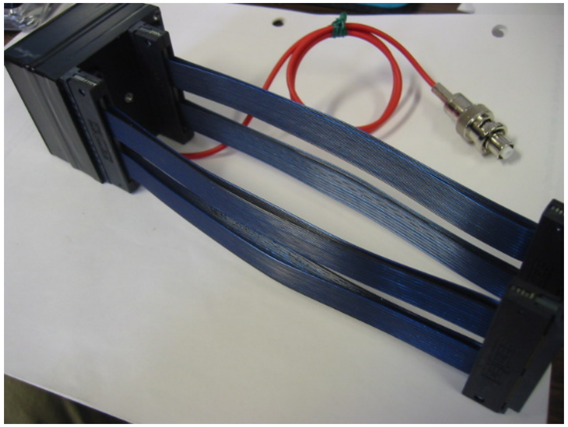
Status of chromatic corrections - preliminary



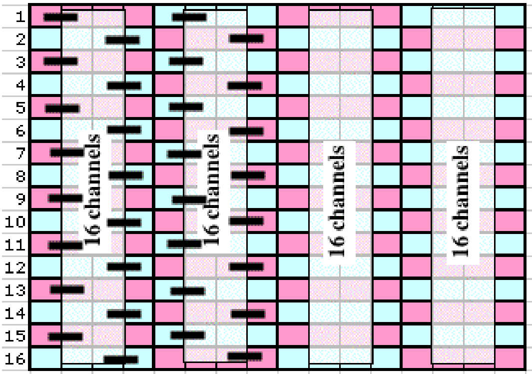
- A slight improvement of ~1-2 mrads for long Lpath.
- Apply the chromatic correction to longer photon paths only

New 256-pixel Hamamatsu MaPMT H-9500

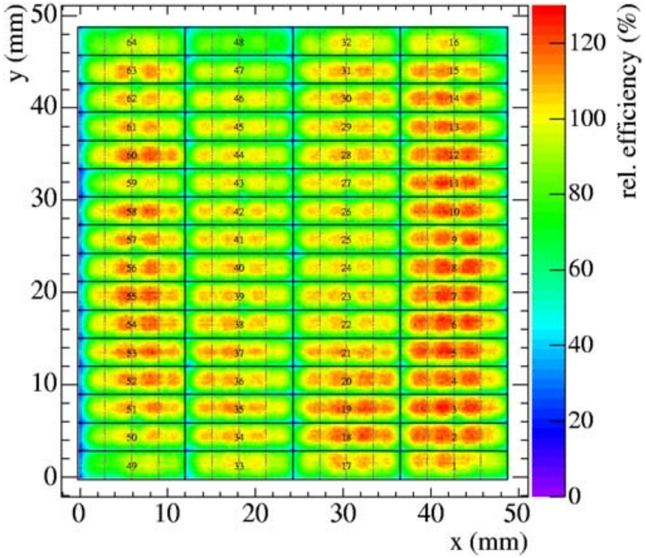




We made a small adaptor board to connect pads in the following way:



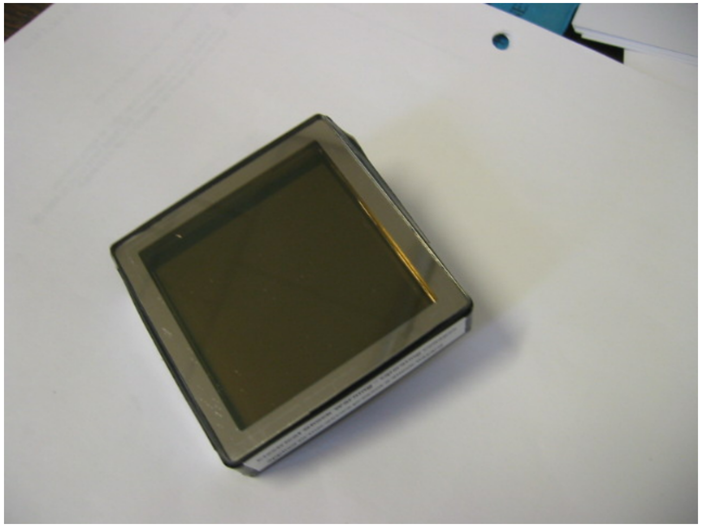
2D scan:

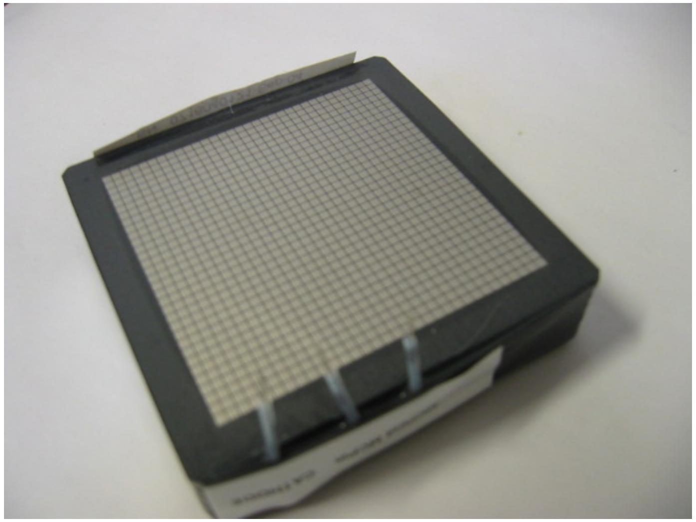


- 256 pixels (16 x 16 pattern).
- Pixel size: 2.8 mmx2.8 mm; pitch 3.04 mm
- 12 stage MaPMT, gain ~10^6, bialkali QE.
- Typical timing resolution σ ~ 220 ps.
- Charge sharing important

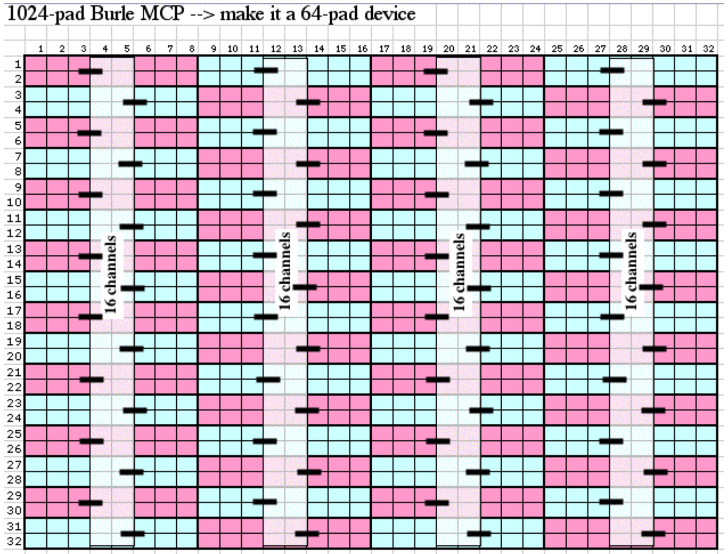
- **Large rectangular pad: 1x4 little ones**
- **This tube was now installed to slot 3**

"Open area" 1024-pixel Burle MCP 85021-600





Burle will connect pads as follows:



- **Large rectangular pad: 2x8 little ones**
- **Small margin around boundary**
- Nominally 1024 pixels (32 x 32 pattern)
- Pixel size: ~1.4mm x 1.4mm
- Pitch: 1.6 mm
- **This tube will be in slot 4 in next run**

VERTEX DETECTOR WORK

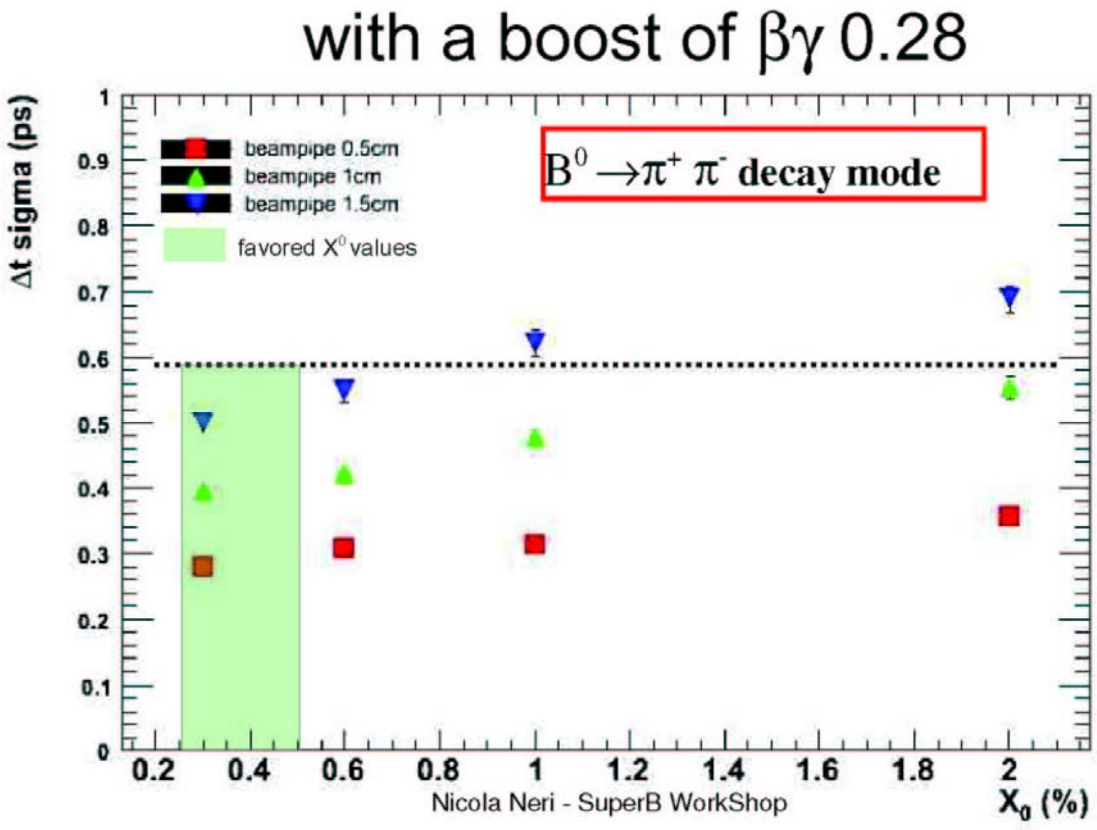
Nicola Neri’s simulation of vertexing,

and

Francesco Forti’s MAPS report.

For comparison:

BaBar:	R= 27.9 mm (32mm Layer1)	**SuperB**	R=10 mm
Total material	1.1% X0		0.48% X0

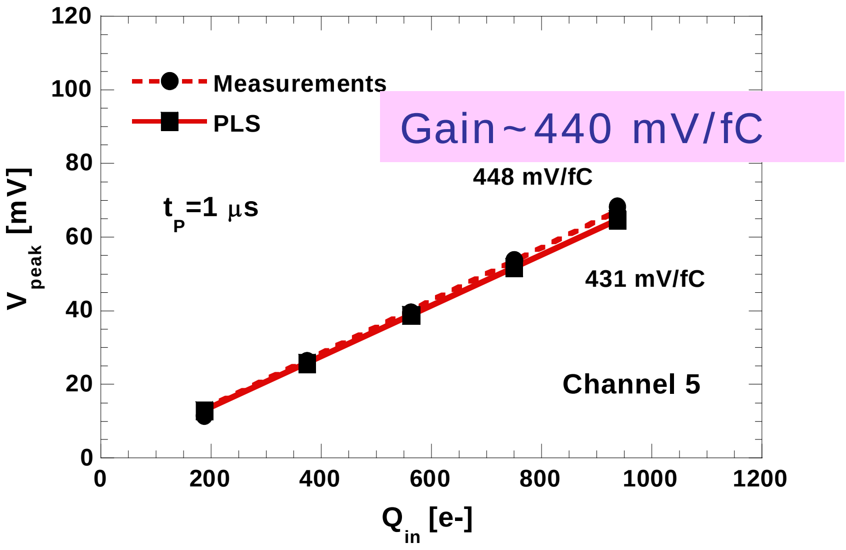


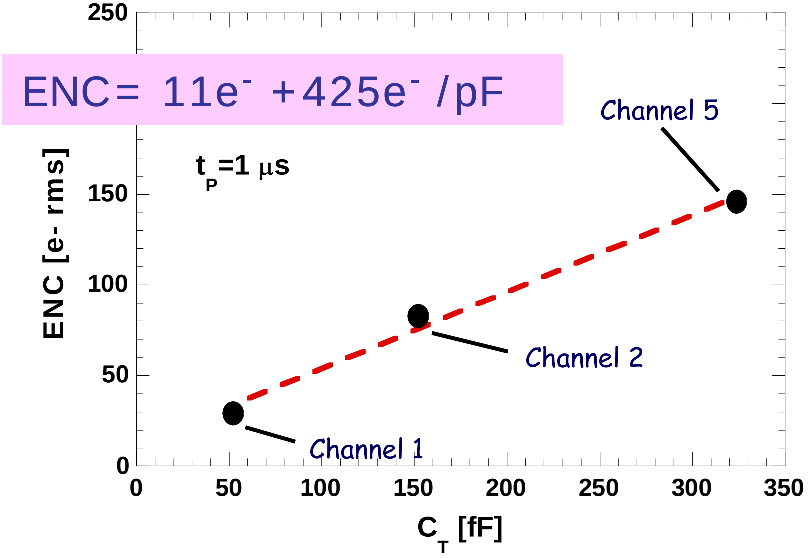
Outline

- Introduction: standard MAPS for vertex detectors in HEP
- The new features of our MAPS:
  - deep n-well collecting electrode
  - signal processing at pixel level
- The characterization of the 1st prototype “Apsel0”:
  - Front-End Electronics
  - Sensor response to:
    - soft X-rays from ^{55}Fe
    - β-rays from ^{90}Sr/^{90}Y
- 2nd prototype “Apsel1”:
  - FEE improvements
  - Single channel response to ionizing radiation
  - Test on the matrix
- Next submission: “Apsel2”
- Conclusions

Gain & Noise Measurements

- Charge sensitivity and Equivalent Noise Charge measured in the three channels with integrated injection capacitance C_{inj}
- Good agreement (~10%) with the post layout simulation results (PLS)





- Equivalent Noise Charge is linear with C_{Tot}

$C_{Tot}=C_D+C_F+C_{inj}+C_{in}$

C_D = detector capacitance(~270fF ch.5, C_D^{MIM}=100fF)

C_F = preamplifier feedback capacitance (8 fF)

C_{inj}= test inj. Capacitance (30 fF)

C_{in} = preamplifier input capacitance (14 fF)

$$ENC = C_T \sqrt{S_W \frac{A_1}{t_p} + A_2 A_f}$$

dominant contribution

S_W=series white noise spectral density

A_f=1/f noise power coeff., A_1, A_2=shaping coeff.

- Sensor capacitance higher than initially expected: noise performance greatly affected. Room for improvement in next chip submission

Conclusions (I)

- A novel kind of CMOS MAPS (deep N-well MAPS) has been designed and fabricated in a 130 nm CMOS technology:
  - A deep n-well used as the sensitive electrode
  - The standard readout channel for capacitive detectors used to amplify the charge signal and extract digital information
- The first prototype, apsel0, was tested and demonstrated that the sensor has the capability of detecting ionizing radiation.
- In the new chip, apsel1, noise and gain issues (present in apsel0) have been correctly addressed.
- Single pixel measurements confirm the observation of soft X and β rays
- The 8x8 (simple) matrix has been successfully readout

Conclusions (II)

- Still ongoing analysis of the response to radioactive sources from the pixel matrix
- Next submission (Aug. 06) focused on:
  - Cure the threshold dispersion
  - More diagnostic features on pixel matrix
  - Test digital blocks toward data sparsification
- Our final goal: to develop a matrix with sparsified readout suitable to be used in a trigger (L1) system based on associative memories.

The SLIM5 collaboration (Silicon with Low Interaction with Material – CSN5 INFN)

S. Bettarini[1,2], A. Bardi[1,2], G. Batignani[1,2], F. Bosi[1,2], G. Calderini[1,2], R. Cenci[1,2], M. Dell'Orso[1,2], F. Forti[1,2], P.Giannetti[1,2] , M. A. Giorgi[1,2], A. Lusiani[2,3], G. Marchiori[1,2], F. Morsani[2], N. Neri[2], E. Paoloni[1,2], G. Rizzo[1,2] , J. Walsh[2],

C. Andreoli[4,5], E. Pozzati[4,5],L. Ratti[4,5], V. Speziali[4,5],

M. Manghisoni[5,6], V. Re[5,6], G. Traversi[5,6],

L. Bosisio[7], G. Giacomini[7], L. Lanceri[7], I. Rachevskaia[7], L. Vitale[7],

M. Bruschi[8], B. Giacobbe[8], N. Semprini[8], R. Spighi[8], M. Villa[8], A. Zoccoli[8],

D. Gamba[9], G. Giraudo[9], P. Mereu[9],

G.F. Dalla Betta[10] , G. Soncini[10] , G. Fontana[10] , L. Pancheri[10] ,

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[7] INFN Trieste and Università degli Studi di Trieste

[8] INFN Bologna and Università degli Studi di Bologna

[9] INFN Torino and Università degli Studi di Torino

[10] Università degli Studi di Trento and INFN Padova

[11] Università degli Studi di Modena e Reggio Emilia and INFN Padova

4 Workpackages:

.1 MAPS and Front End Electronics

.2 Detectors on high-resistivity Silicon

.3 Trigger / DAQ

.4 Mechanics/Integration/Test-Beam

Beam Pipe and Backgrounds

A design of a new beam pipe from Pisa

and

several reports on background studies.

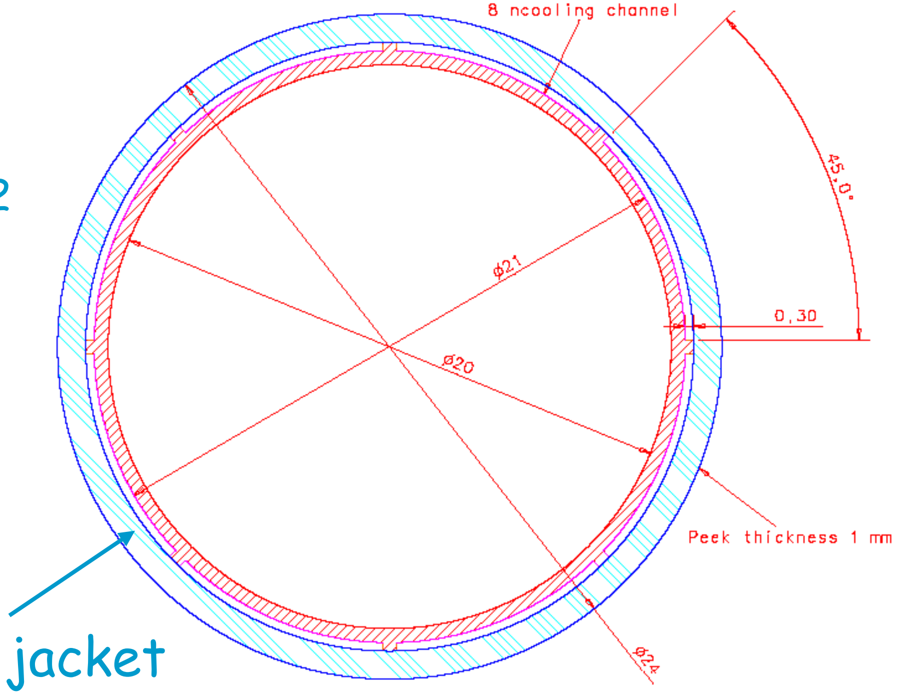
A possible design

Pipe Inner Radius 1 cm

"Uniform" Water Jacket
(8 flat channels)

Single channel area = 2.35 mm^2
Channel width = 300 um

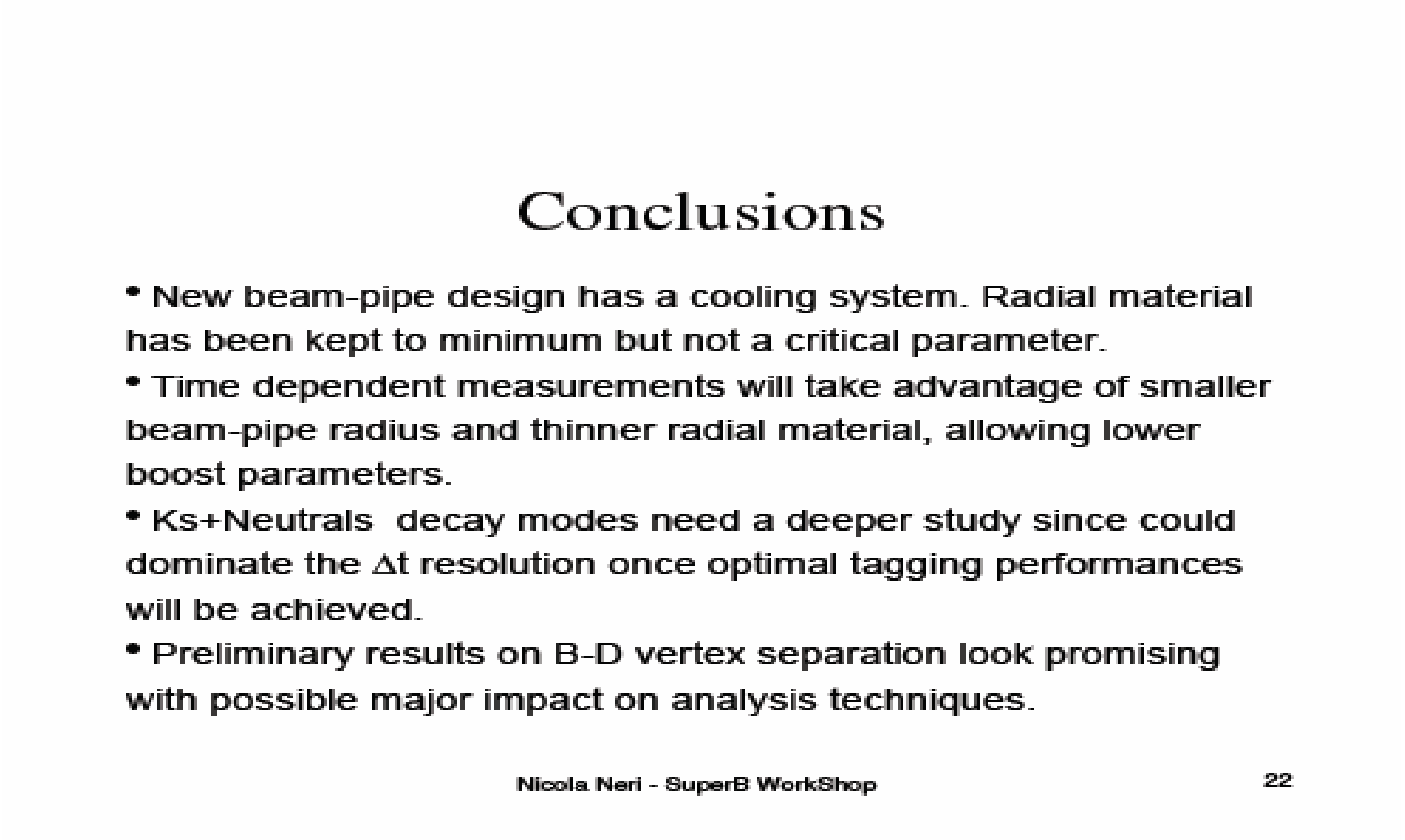
To dissipate 1KW with water specific heat and thermal conductivity



Peek (plastic) jacket

Flow: 4.2 m/s (OK)

Requires channel 1-side coating
to prevent erosion
(7um Ni and/or BerylCoatD)



Conclusions

- New beam-pipe design has a cooling system. Radial material has been kept to minimum but not a critical parameter.
- Time dependent measurements will take advantage of smaller beam-pipe radius and thinner radial material, allowing lower boost parameters.
- Ks+Neutrals decay modes need a deeper study since could dominate the Δt resolution once optimal tagging performances will be achieved.
- Preliminary results on B-D vertex separation look promising with possible major impact on analysis techniques.

Nicola Neri - SuperB WorkShop 22

Backgrounds

- In general, we believe that the backgrounds at Super B are likely to be not much worse than we live with today.

- But with a x100 increase in luminosity we need to work hard on evaluating this, and be wary of new sources.

- Mike Sullivan, with his old tried-and-true tools, and Evgeni Paoloni and Giovani Calderini, with interesting new tools, are making good progress.

  Need to coordinate their work, and bring it to closure.

- We had a nice report in the parallel session from Weaver on detailed measurement of PEP II beam properties, and quantitative attempts to measure beam correlations. Could be helpful in helping a quantitative description of beam-beam effects and understanding backgrounds.

Tracking Chambers

- There is a lot of work going on by Belle at KEK

Adam Boyarski presented a thorough study of aging in the BaBarChamber, with quantitative modeling

Boyarski's exeprience :-

1. A water additive can keep a drift chamber alive at very high rates, but water does not prevent film growth.
2. Oxygen can clean cathodes and anodes.
3. The breakdown mechanism in chambers with no additives is due to high E-fields from charge accumulation in thin films on cathodes and Fowler-Nordheim field emission.
4. Cathode aging can be modeled.

Physics

There has been broad, and rather universal, agreement on the powerful physics reach of a 10**36 cm**-2 sec*-1 luminosity B Factory.

We heard many new talks at this meeting, making essentially the same story. This is NOT our problem.

Charm/Tau Task Force

David Hitlin is leading a small group looking at physics at lower energy running – charm and tau physics at around 4 Gev.

Their report is due out in a few weeks, and will probably recognize the potential importance of incorporating polarisation rotators for study of polarised tau decays.

What is needed for the Fall INFN Report

- Energy Asymmetry
- Beam pipe radius
- Beam pipe design
- Backgrounds
- Trigger and DAQ
- PID
- Calorimeter
- R&D
- Polarized Beam

Re-use of Detectors

When we talk about trying to reuse either of the two B Factory detectors, as we consider getting ready to do SuperB physics, I suggest that we might not confine our eager, lustful eyes only to these two devices – by the time we are ready for that decision, there will be other detectors (paid for by federal funds) that may offer some attractive advantages –

like CLEO, DO or CDF.

SuperB R&D

- We need to consider when is the right time to set up a formal structure to guide the R&D activities. This probably needs to wait until there is a real project, being discussed by world agencies – and it should probably be arranged to have ‘local agencies’ fund ‘local activities’.

Next Meeting

We still have a lot of work to do.

We will meet again in the fall – let’s try to work towards some closure on the issues that need answers before we can write the report that INFN needs.

Summary from Oide's talk at 2005 2nd Hawaii SuperBF Workshop

- Present design of SuperKEKB hits fundamental limits in the beam-beam effect and the bunch length (HOM & CSR).

- Higher current is the only way to increase the luminosity.

- Many technical and cost issues are expected with a new RF system.

HIGH CURRENT and HIGH BACKGROUND IS A BIG ISSUE FOR :

DETECTOR DESIGN

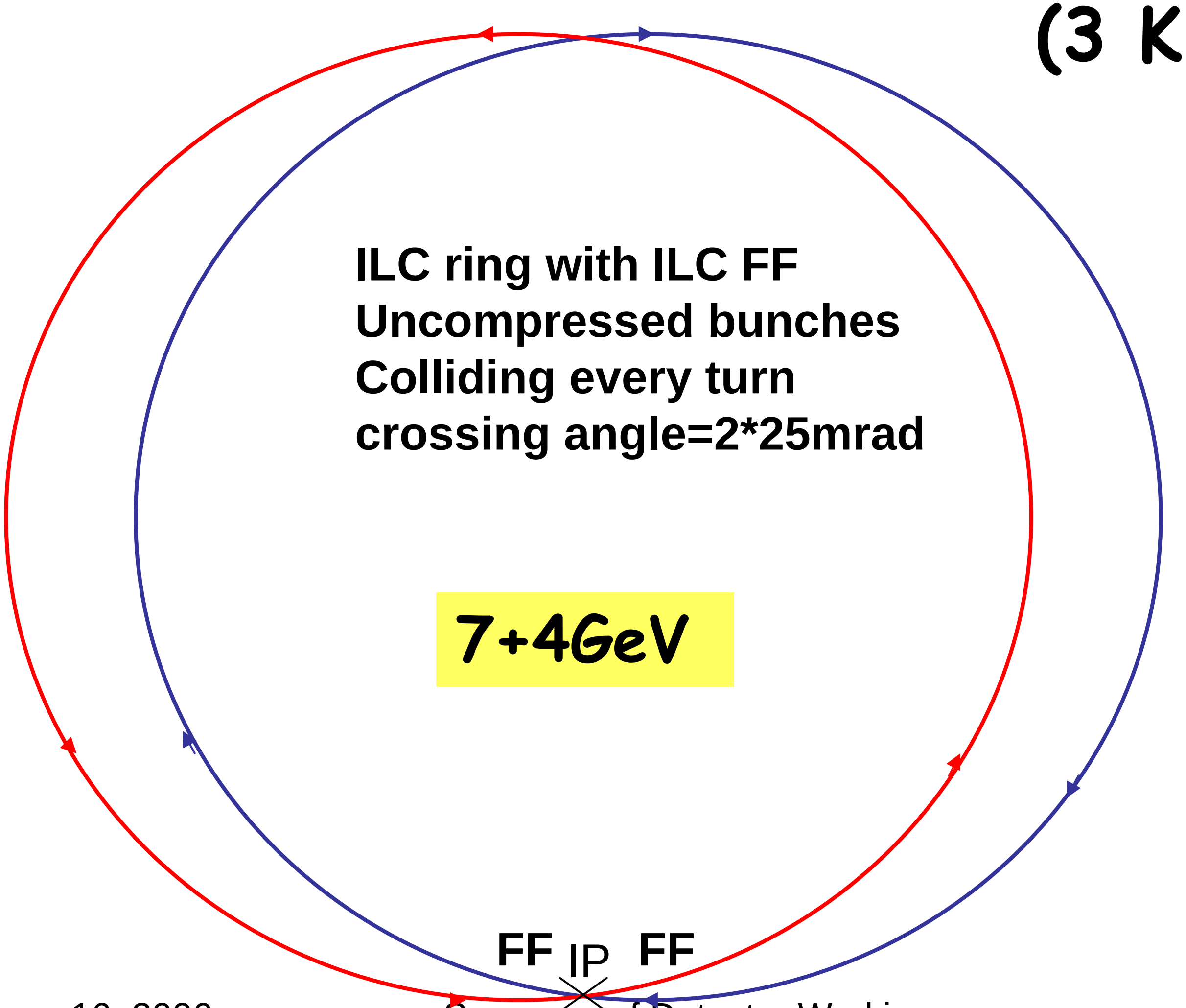
WALL POWER NEEDED

- **We need a completely different collider scheme.....**

Solution

Synergy with ILC + CRAB WAIST

(3 Km/ 6Km)



ILC ring with ILC FF
Uncompressed bunches
Colliding every turn
crossing angle=2*25mrad

7+4GeV

BKGD expected lower than in BaBar at PEPII.

1.0 cm Beam pipe possible inside SVT

Detector comments

Background should be lower than in Babar. Occupancy would be OK in Vertex Detector even with a smaller radius beam pipe. (from 3cm of Babar down to 1.cm). Simulations are currently run for interaction region and Bgkd.

Apparatus would be more hermetic than Babar and Belle (7+4 GeV).

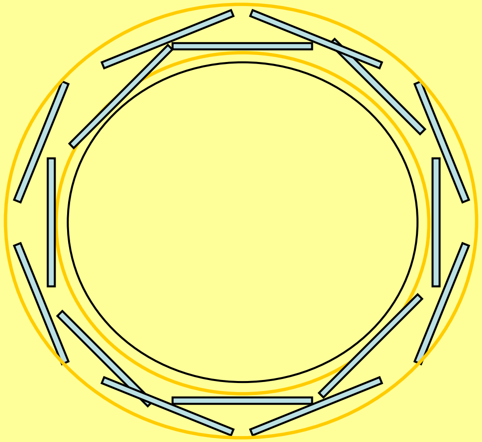
Detectors don’t require a major R&D

PID would be needed also in forward/backward direction.

By reducing Lorentz boost higher resolution vertex is needed (MAPS?)

R&D on EMC (Babar Caltech..)

R&D on PID (Babar: Slac) (Belle :KeK ,Lubijana



x5 scale with 10mm radius BP, 6mm pixel chip

R&D on Maps within Belle (Hawaii group)and Babar (Pisa+Slac)

- Two monolithic active pixel layers glued on beam pipe
  - Since active region is only ~10μm, silicon can be thinned down to ~50μm.Good resolution O(5μm).
  - Improves pattern recognition robustness and safety against background

Goals

Preliminary evaluation of need for special runs on tau and charm Evaluation of needs for special runs symmetric, at c.m. energies even lower than 10 GeV.

Evaluation of benefits with one polarized beam

Better definition of a single machine design

fix one minimum circumference of the machine

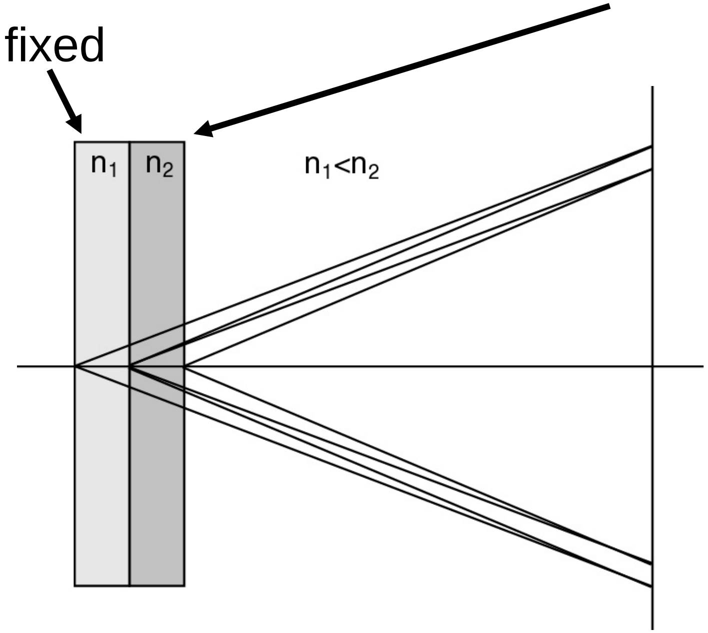
Study of the interaction region and Background

Beam pipe preliminary design

(to move on to a realistic design of vertex-tracker with an adequate R&D)

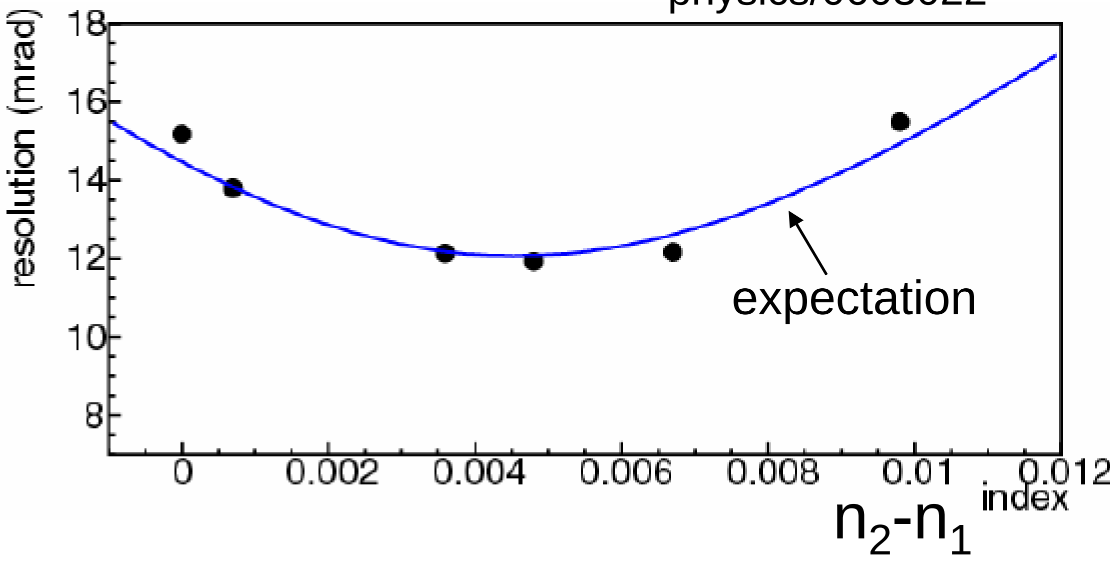
Optimization of dual radiator indices

Upstream aerogel: n_1=1.045
Downstream aerogel: n_2 is changed



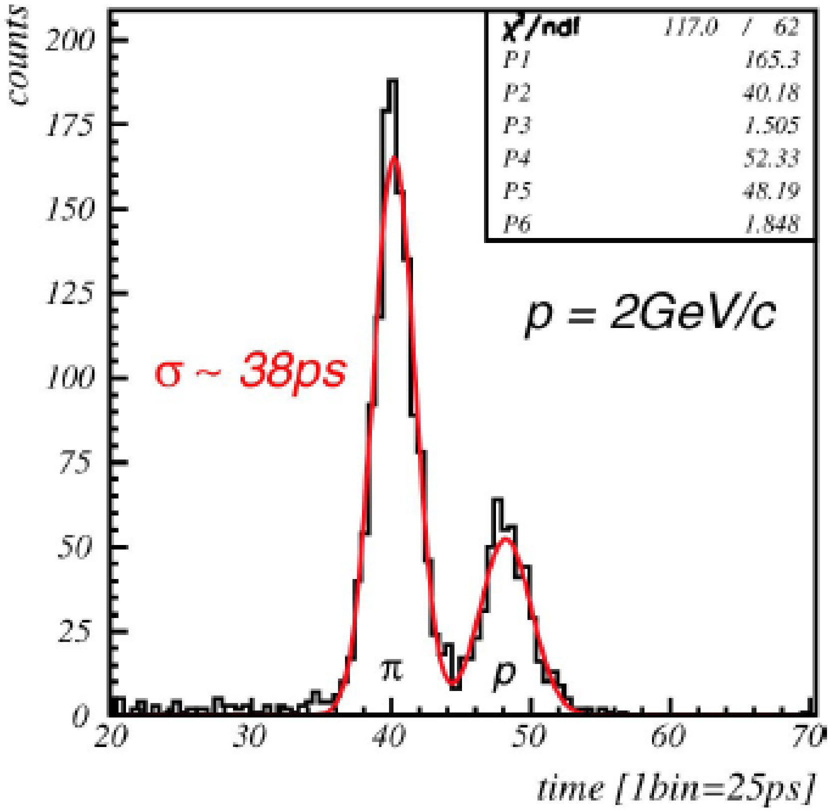
Data points: Dec. 2005 beam test

physics/0603022



- Measured resolution is in good agreement with expectation
- Wide minimum region allows some tolerances(~0.003) in aerogel production

A-RICH with TOF PID at low momentum



TOF test with pions and protons at 2GeV/c

Photons from PMT window

π/p are well separated

Even in distance between start counter and MCP-PMT is 65cm, instead of 2.0m in Belle

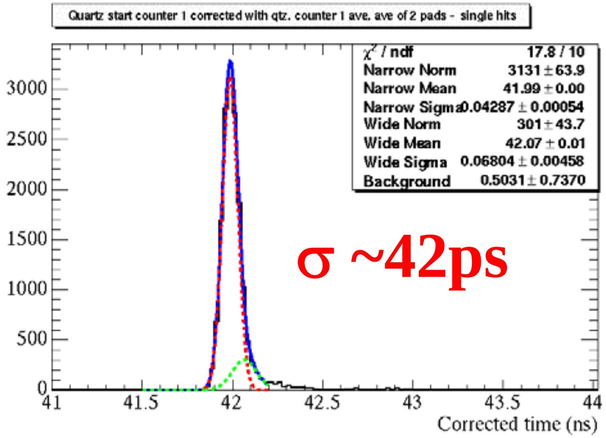
At this test, π/p separation with MCP-PMT

S_{TOF} ~ 4.8σ @2GeV/c

A-RICH with TOF using MCP-PMT looks very promising

1. Start counter 1 - Double-quartz counter

Average of 2 pads:

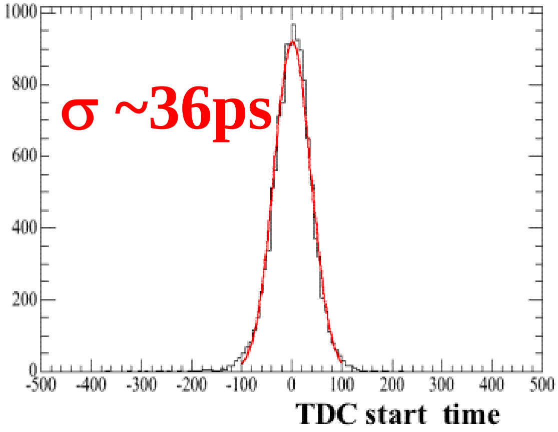


σ ~42ps

4-pad Burle MCP-PMT:

Local START Counters:

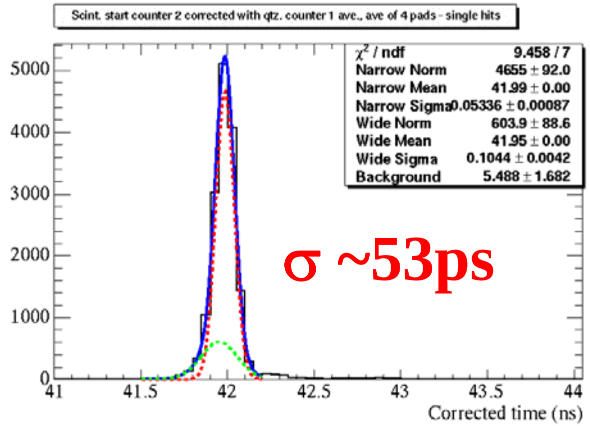
3. Overall average of Start 1, Start 2 and Quantacon counters:



σ ~36ps

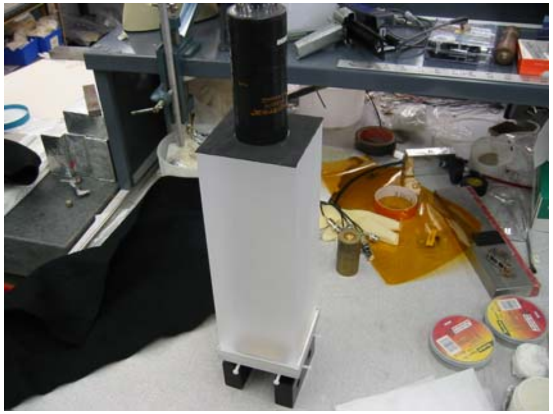
2. Start counter 2 - Scintillator counter

Average of 4 pads:



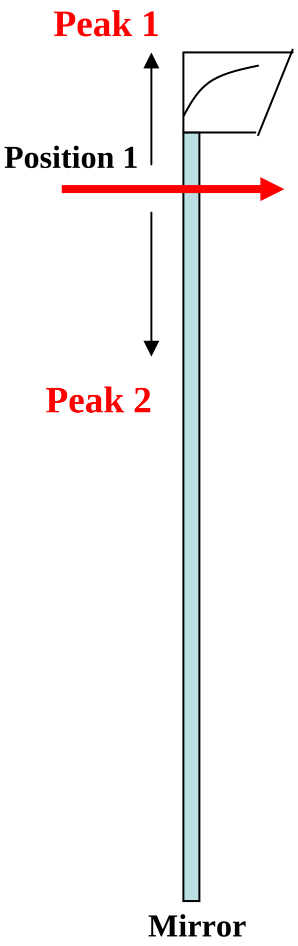
σ ~53ps

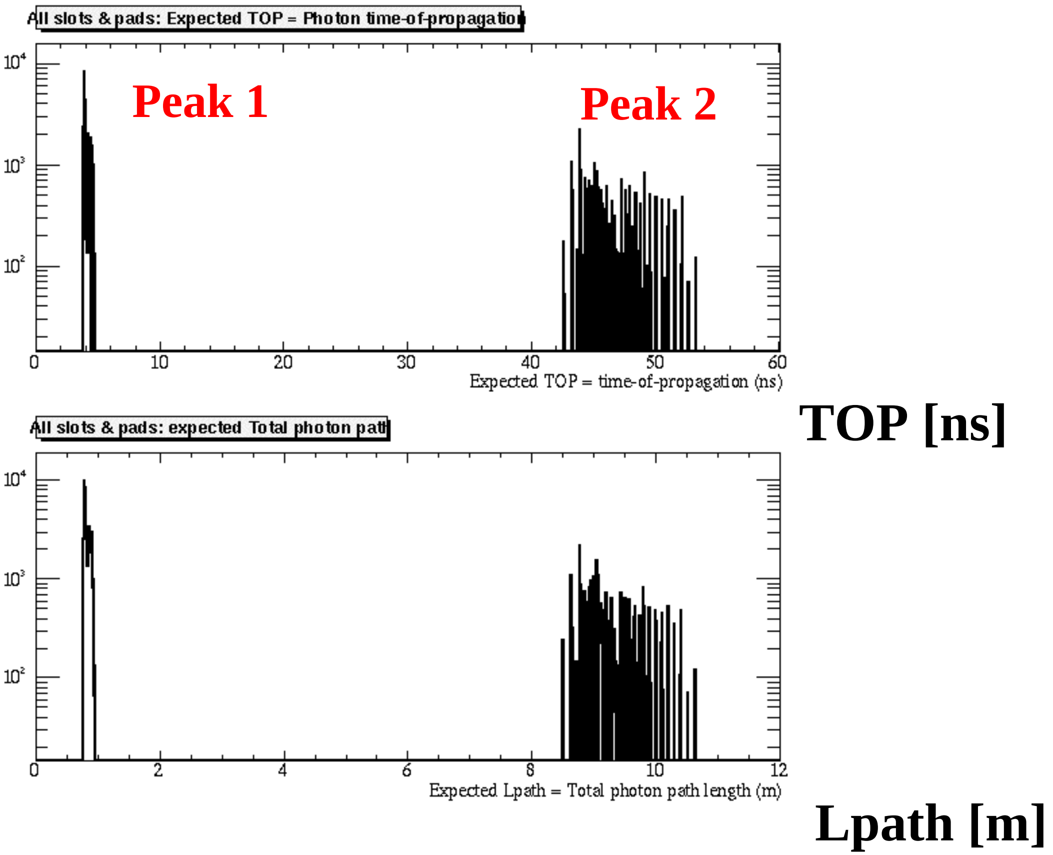
4-pad Burle MCP-PMT :



- **Corrections: ADC, hodoscope position and timing drifts.**

Typical distribution of TOP and Lpath





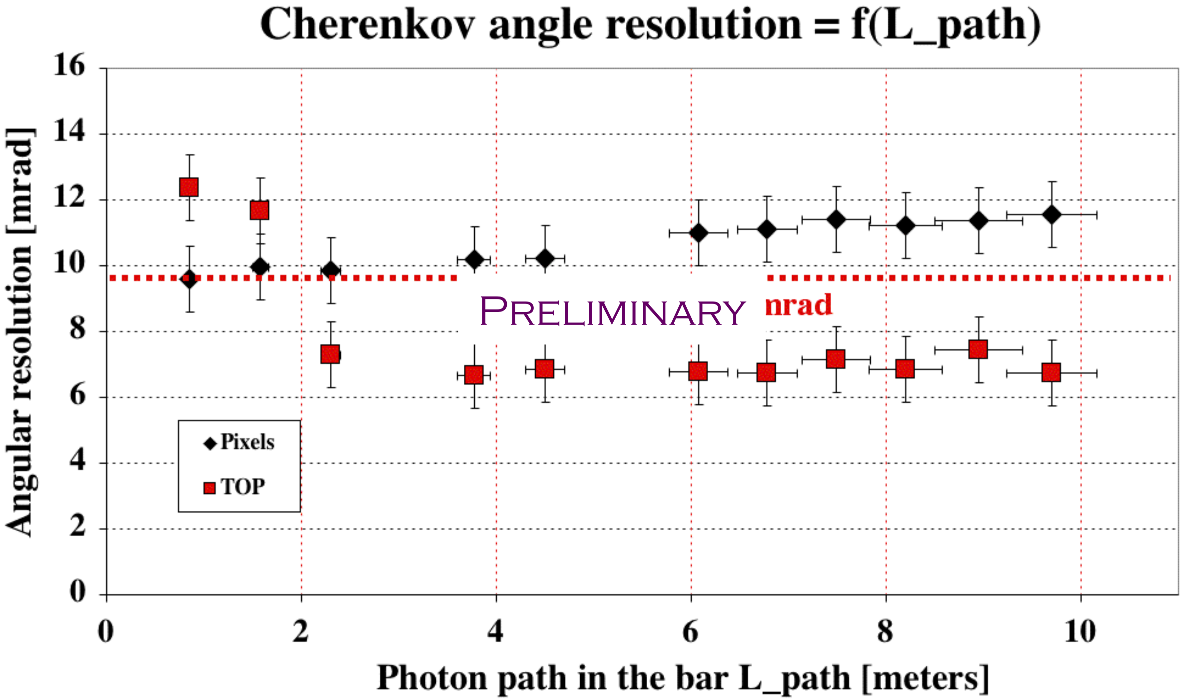
- **Measured TOP and calculated photon path length Lpath**
- **Integrate over all slots & pixels**

Summary of preliminary results:

Θ_c resolution from pixels is 10-12 mrad.

Θ_c resolution from time of propagation (TOP) improves rapidly with path length, reaches plateau at ~7mrad after 3-4 meters photon path in bar.

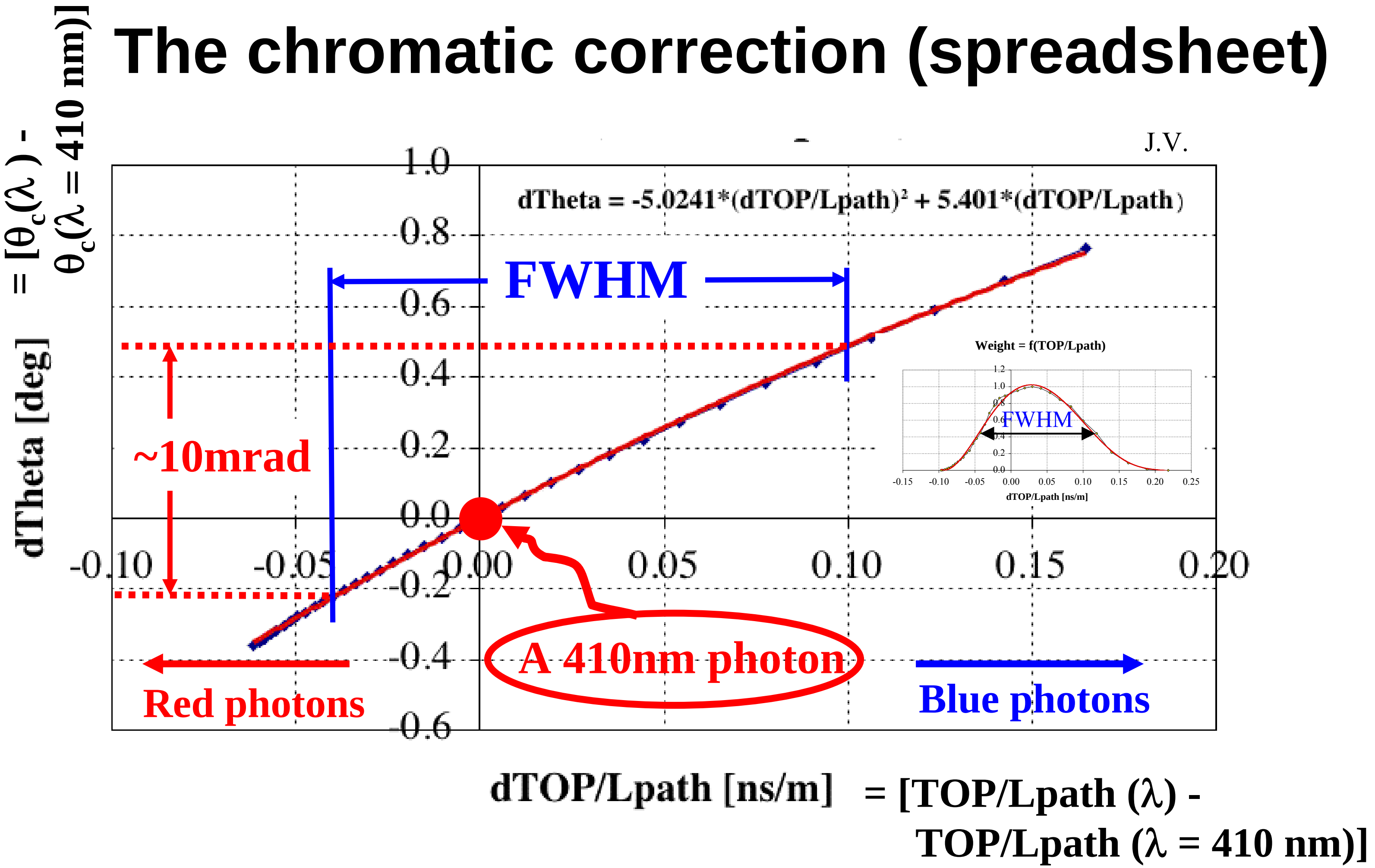
J.V., 5.12.2006



Comments: a) The present TOP-based analysis assumes β = 1,

b) In the final analysis we will combine pixels & time into a maximum likelihood analysis.

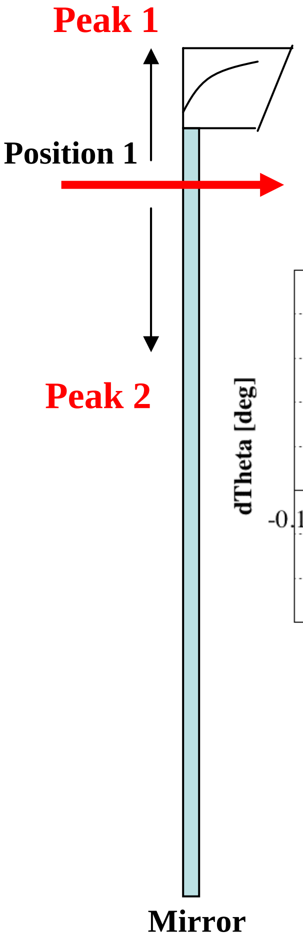
The chromatic correction (spreadsheet)



- An average photon with a color of λ ~410 nm arrives at "0 ns offset" in dTOP/Lpath space. A photon of different color, arrives either early or late.
- The overall expected effect is small, only FWHM ~10mrad, or σ ~ 4 mrads.

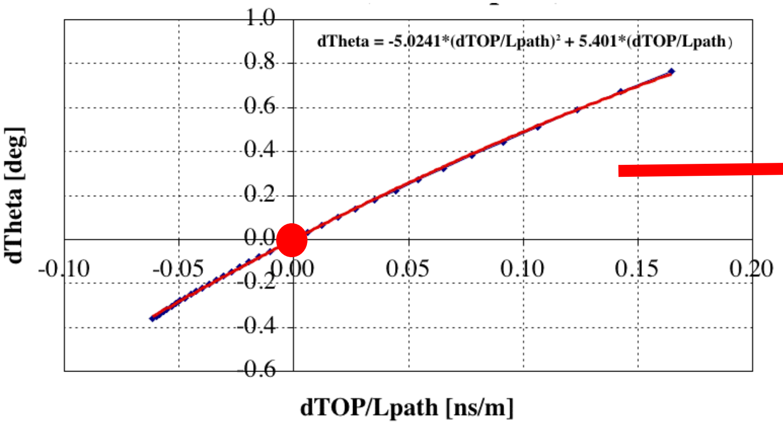
Method #1: Spreadsheet calculation of $d\theta_c$ vs d(TOP/Lpath).

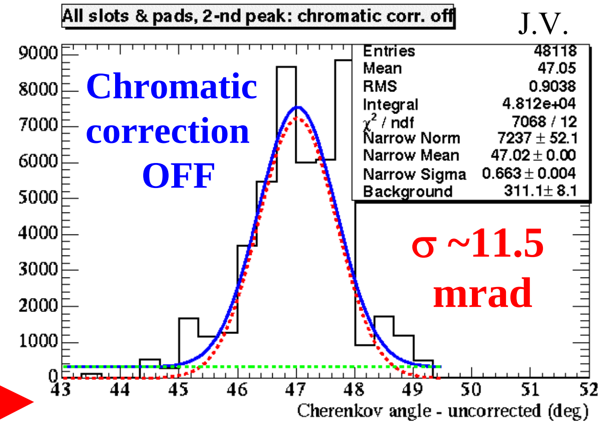
All slots, all pads, position 1, Peak 2 only:

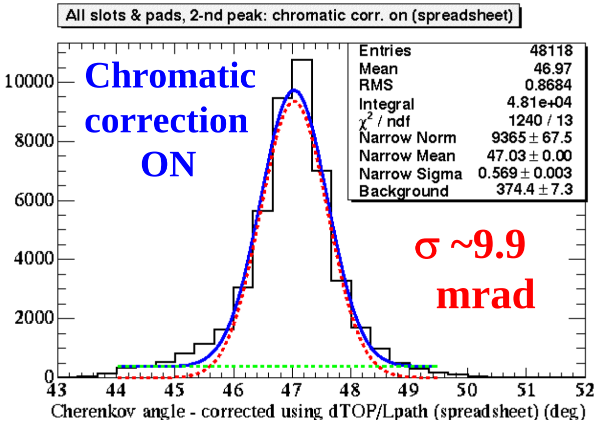


PRELIMINARY

Spreadsheet:



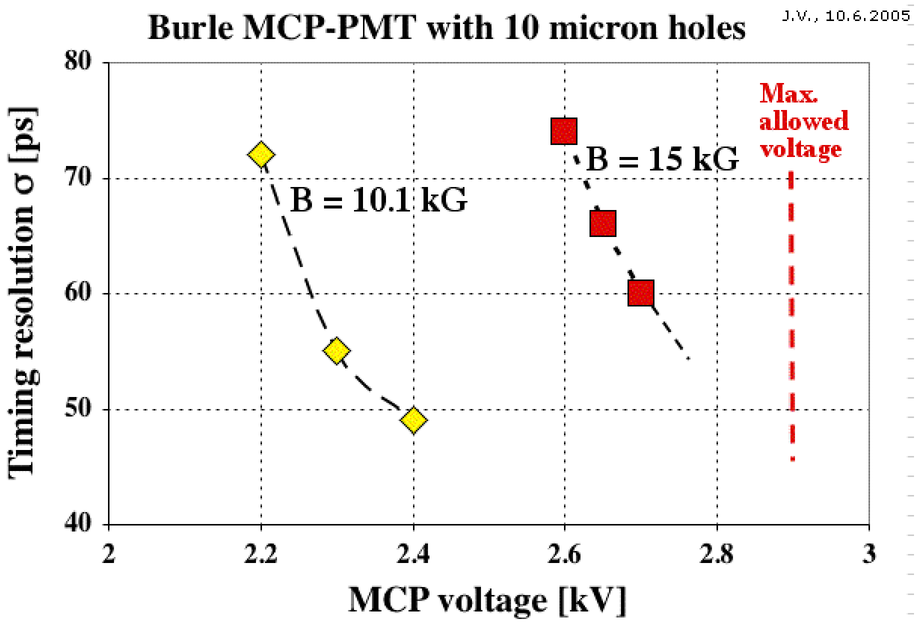




Cher. Angle (pixel) [deg]

- **An improvement of ~1.5 mrads.**

Timing results at B = 15 kG

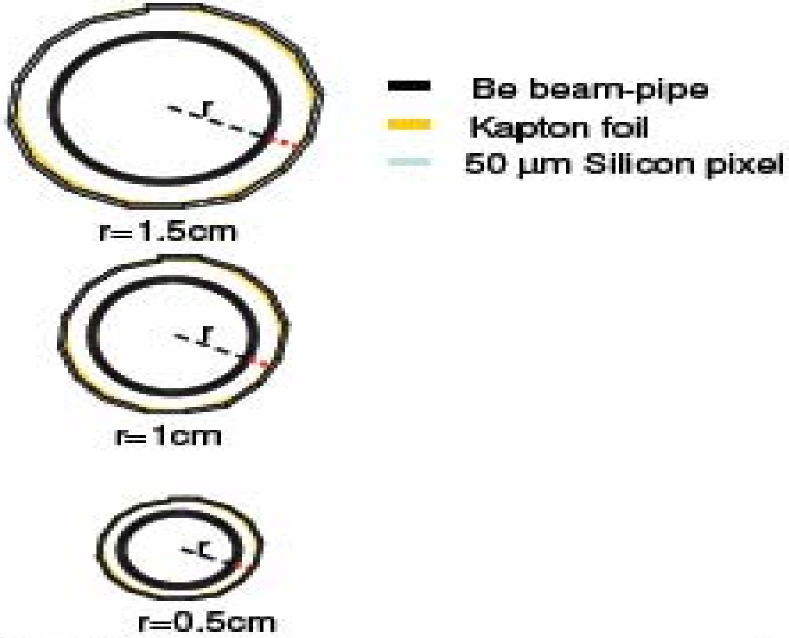


- Single photoelectrons
- 10μm hole 4-pad MCP-PMT
- Ortec VT-120A amp

- It is possible to reach a resolution of σ ~50ps at 15kG.

Beam-pipe scenarios

- conservative scenario:
  - beam pipe radius 1.5cm
  - hit resolution z,ϕ side = 10 μm
  - Radial material = 0.50%X_0
- most likely scenario:
  - beam pipe radius 1.0cm
  - hit resolution z,ϕ side = 10 μm
  - Radial material = 0.39% X_0
- aggressive scenario:
  - beam pipe radius 0.5cm
  - hit resolution z,ϕ side = 5 μm
  - Radial material = 0.24%X_0

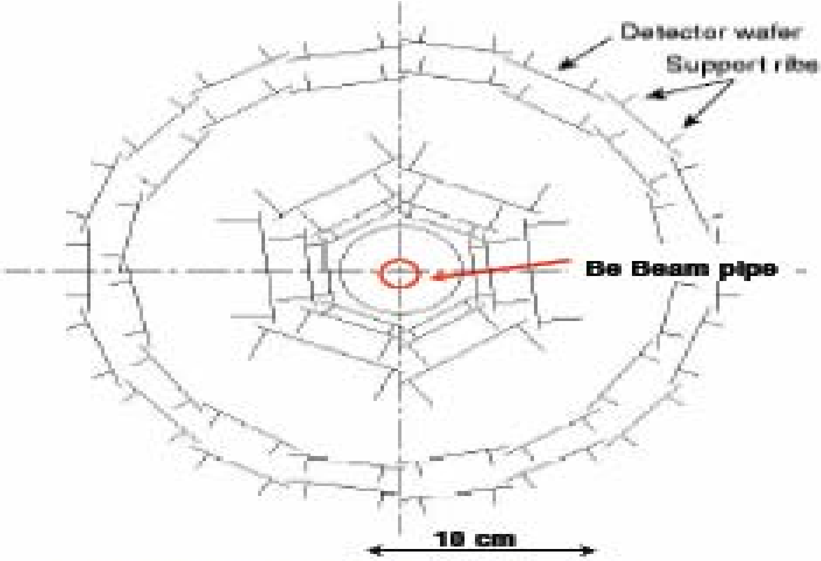


SuperB SVT Geometry

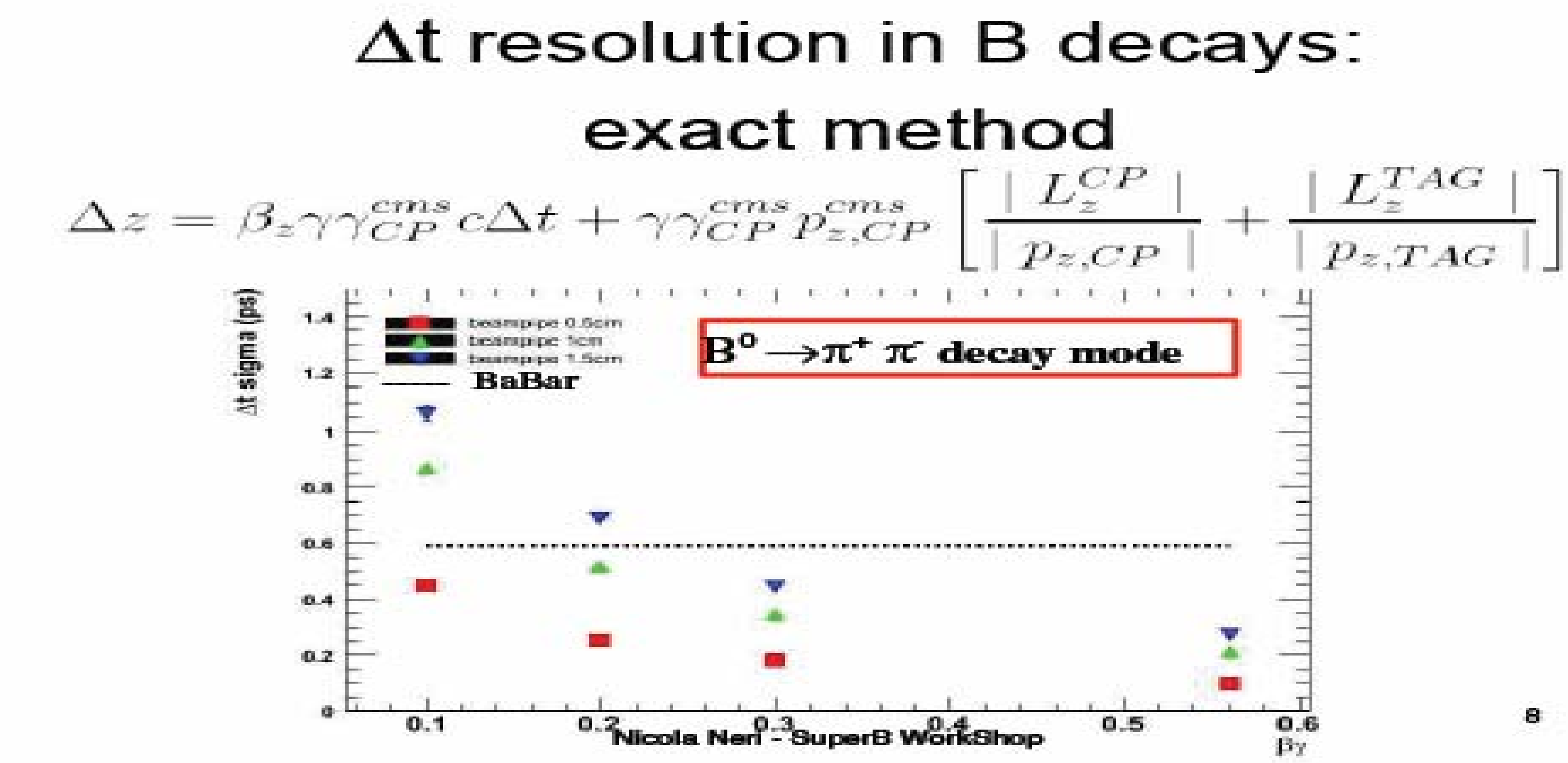
ADDED

Layer	Radius
0	1.05 cm
1	3.3 cm
2	4.0 cm
3	5.9 cm
4	9.1 to 12.7 cm
5	11.4 to 14.6 cm

- Added layer0
- Reduced beam-pipe radius 2.5→1cm
- Reduce Be thickness 1.3→0.6mm
- 4 µm Au foil before layer0



(Arched wedge wafers not shown)



Δt resolution in B decays: exact method

$$\Delta z = \beta_z\gamma\gamma_{CP}^{cms}\, c\Delta t + \gamma\gamma_{CP}^{cms}\, p_{z,CP}^{cms}\left[\frac{|\, L_z^{CP}\, |}{|\, p_{z,CP}\, |} + \frac{|\, L_z^{TAG}\, |}{|\, p_{z,TAG}\, |}\right]$$

Nicola Neri - SuperB WorkShop

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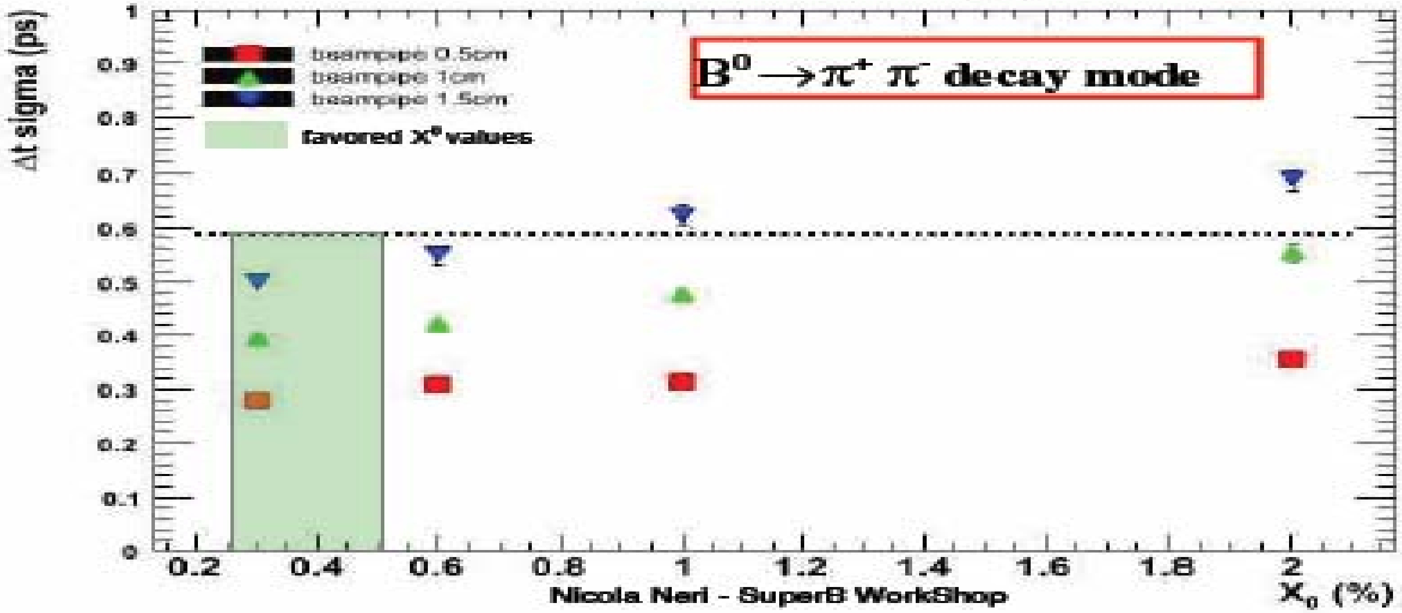
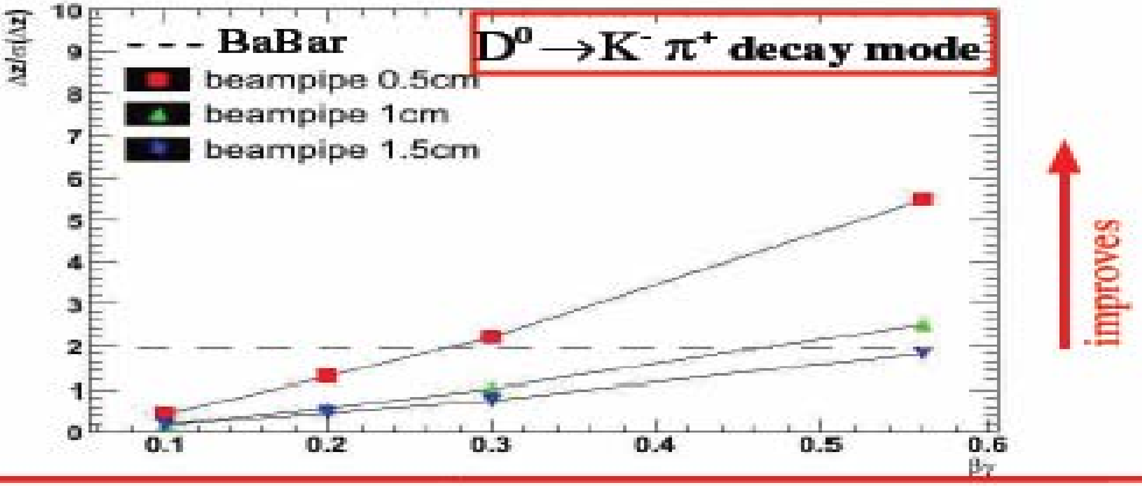
Δt resolution in B decays *vs* X_0(%) with a boost of $\beta\gamma$ 0.28



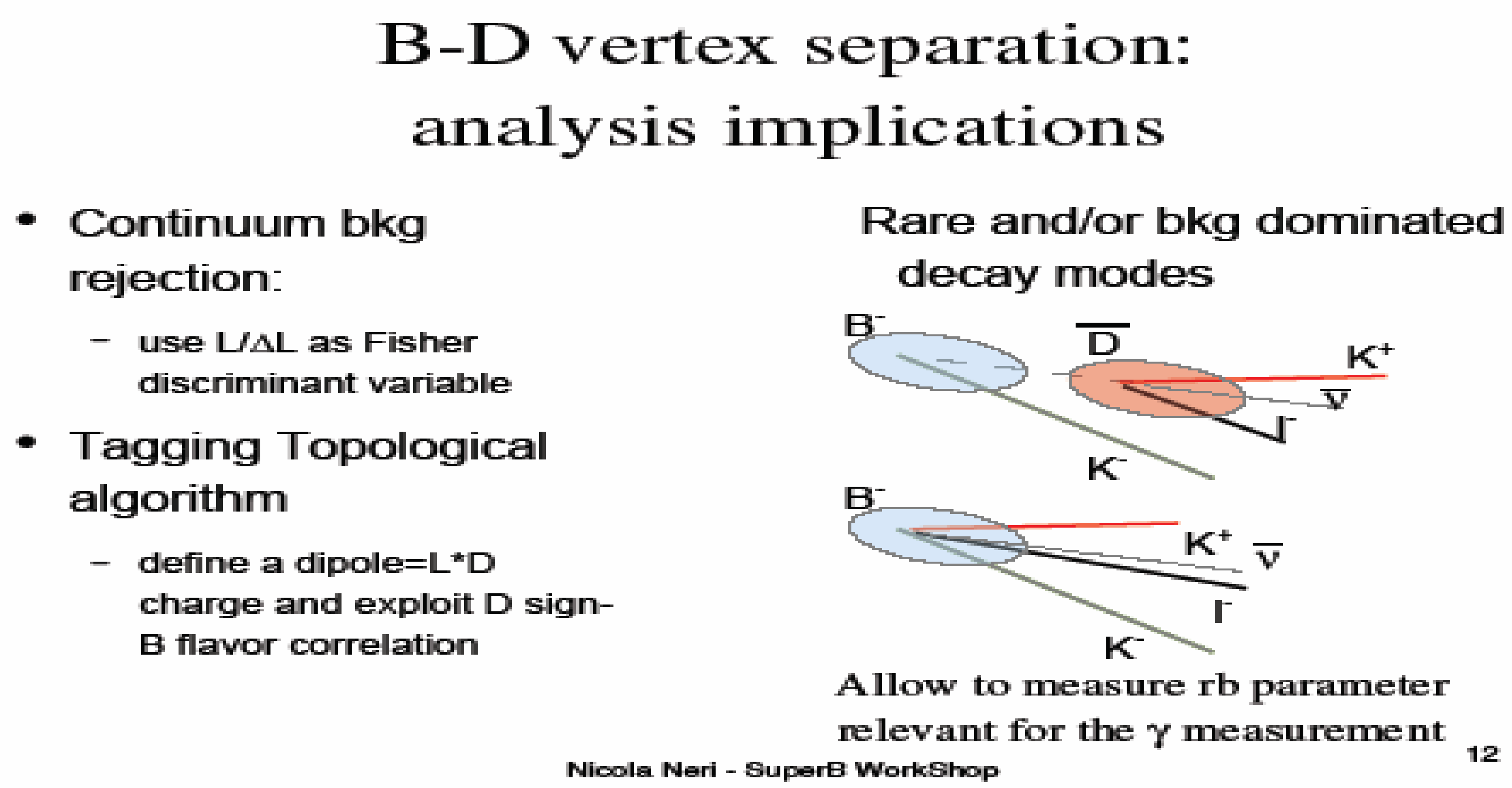
Δz resolution in D decays at Ψ_{3770}

Assume $\sigma(Tag)=\sigma(Vtx)$: low track multiplicity, no charm bias in Tag vtx



$D^0 \rightarrow K^- \pi^+$ decay mode

D lifetime 0.4 ps, for B it is 1.5 ps ⇒ Smaller Δz significance.
Layer0 at 0.5cm and reduction of the radial material is important.



B-D vertex separation: analysis implications

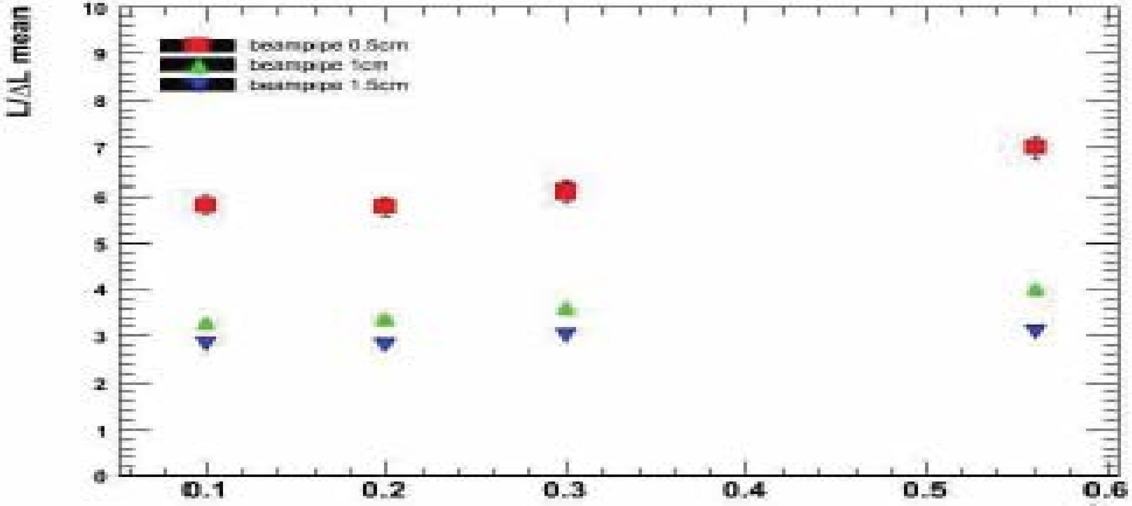
- Continuum bkg rejection:
  - use L/ΔL as Fisher discriminant variable
- Tagging Topological algorithm
  - define a dipole=L*D charge and exploit D sign-B flavor correlation

Rare and/or bkg dominated decay modes

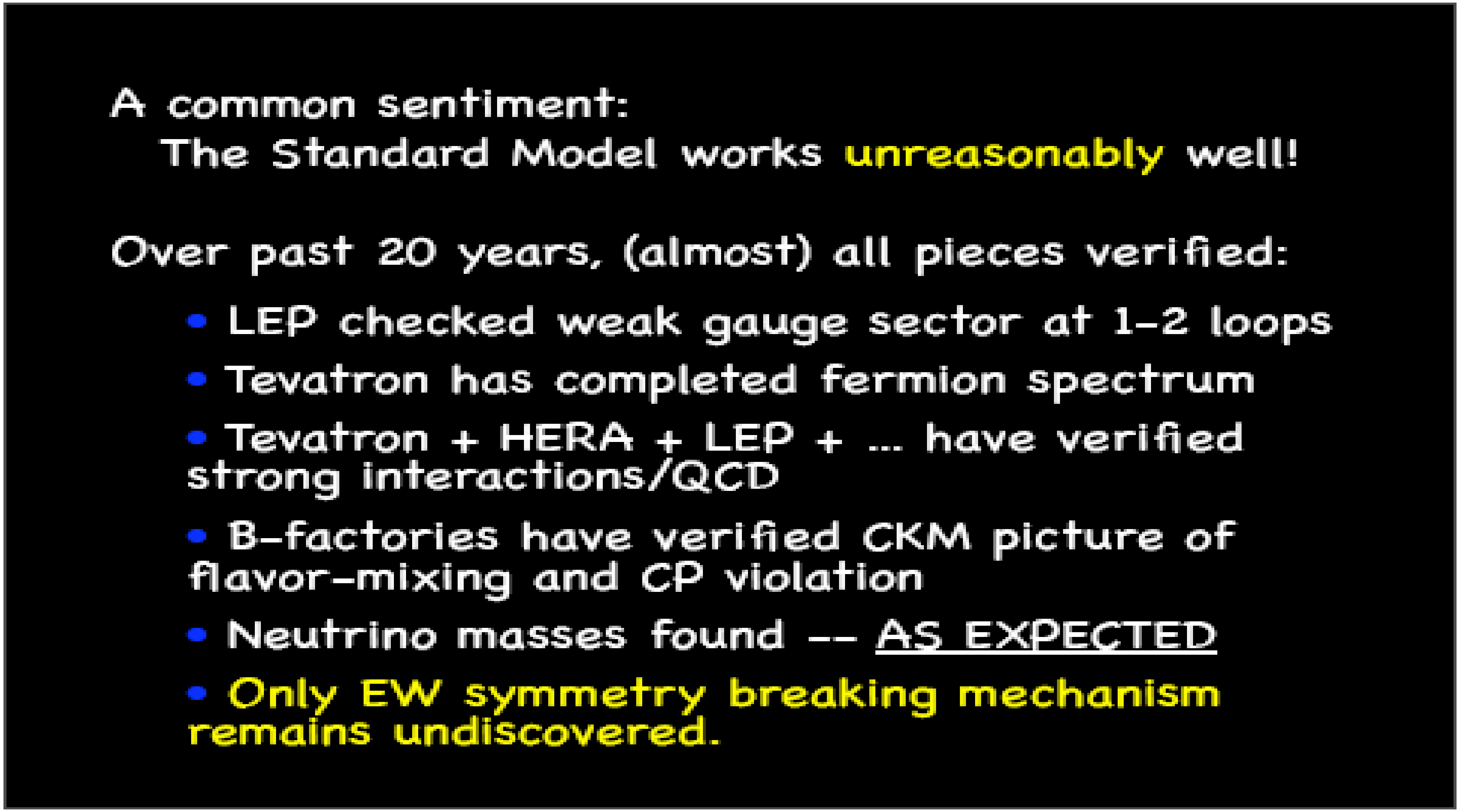
Allow to measure rb parameter relevant for the γ measurement

Nicola Neri - SuperB WorkShop

L/ΔL: small dependence on boost



The significance of L for B→DX signal events becomes linear with the boost of CM when the βγ of the CM dominates wrt to the βγ from the B decay.



A common sentiment:

The Standard Model works unreasonably well!

Over past 20 years, (almost) all pieces verified:

- LEP checked weak gauge sector at 1-2 loops
- Tevatron has completed fermion spectrum
- Tevatron + HERA + LEP + ... have verified strong interactions/QCD
- B-factories have verified CKM picture of flavor-mixing and CP violation
- Neutrino masses found -- AS EXPECTED
- Only EW symmetry breaking mechanism remains undiscovered.

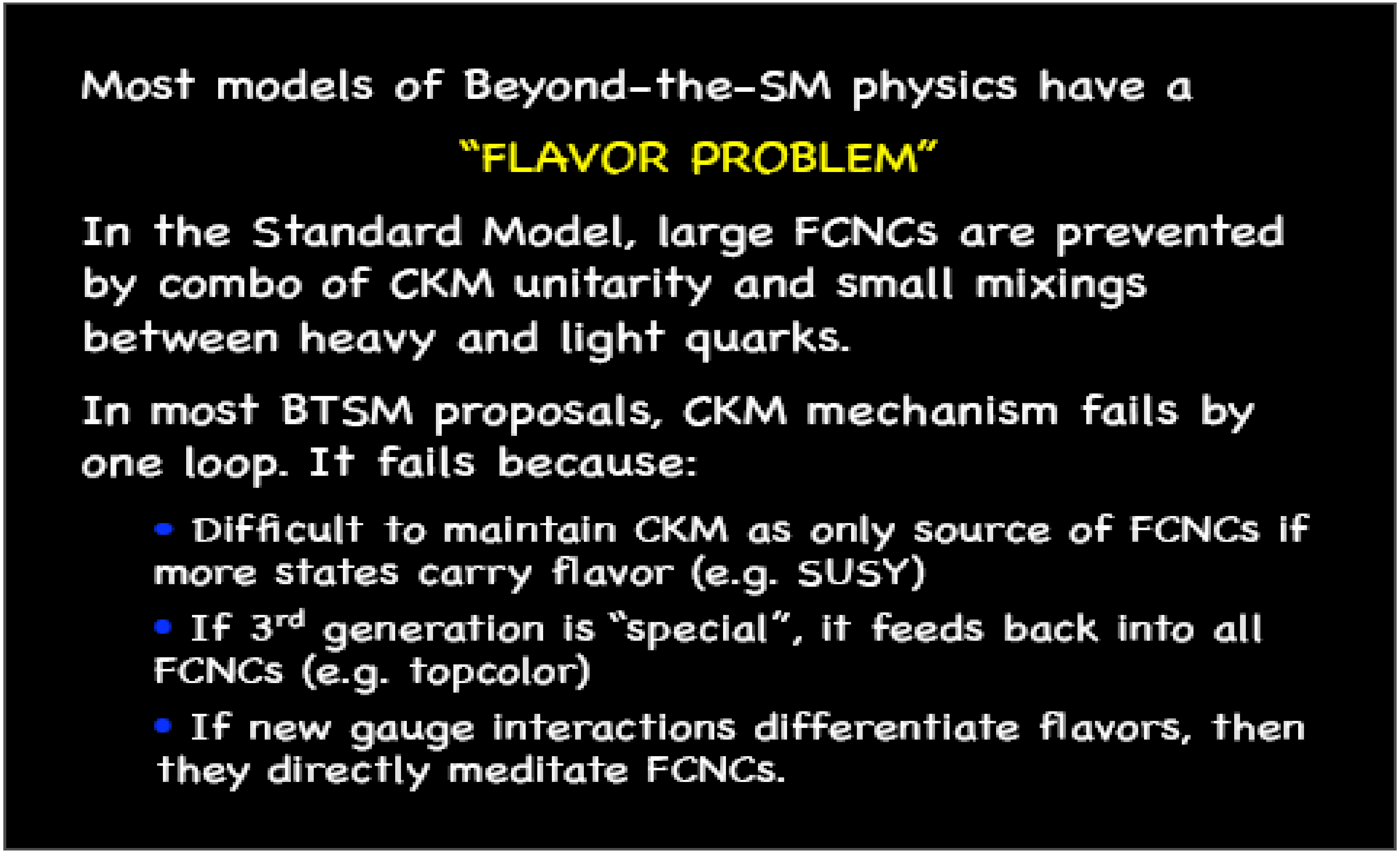
So arguments for SuperB factories based on

- Deciphering the 3 generation riddle
- Determining dynamics leading to CKM structure
- Discovering ultimate source of CPV

will go unheeded by many physicists.

Theorists' view: We are used to "decoupling" flavor physics from new physics that solves hierarchy problem. We generally don't expect non-trivial flavor dynamics anywhere near weak scale.

Flavor measurements are useful constraints on new physics, but are unlikely to teach us much about new physics once it is found. (E.g. LHC Theory Initiative)



Most models of Beyond-the-SM physics have a

"FLAVOR PROBLEM"

In the Standard Model, large FCNCs are prevented by combo of CKM unitarity and small mixings between heavy and light quarks.

In most BTSM proposals, CKM mechanism fails by one loop. It fails because:

- Difficult to maintain CKM as only source of FCNCs if more states carry flavor (e.g. SUSY)
- If 3rd generation is "special", it feeds back into all FCNCs (e.g. topcolor)
- If new gauge interactions differentiate flavors, then they directly meditate FCNCs.

But there's more: A SuperB factory is really a Super-Flavor factory. Will produce around 10^{10} τ-pairs!

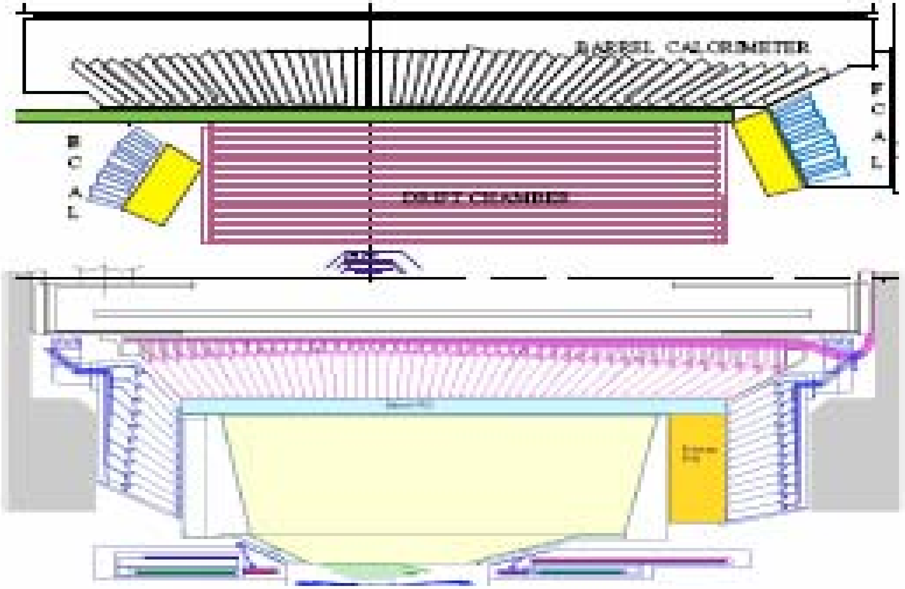
Lots of interesting New Physics in τ-sector, thanks to neutrino mixing results.

Reminder:

- In neutrino sector, large mixings occur between ν_μ and ν_τ, and between ν_μ and ν_e.
- This νLFV translates into cLFV in SM, but with amplitudes $\propto (m_\nu/m_W)^2$. Will never be seen!
- New Physics model often have more direct ways to turn νLFV into cLFV.

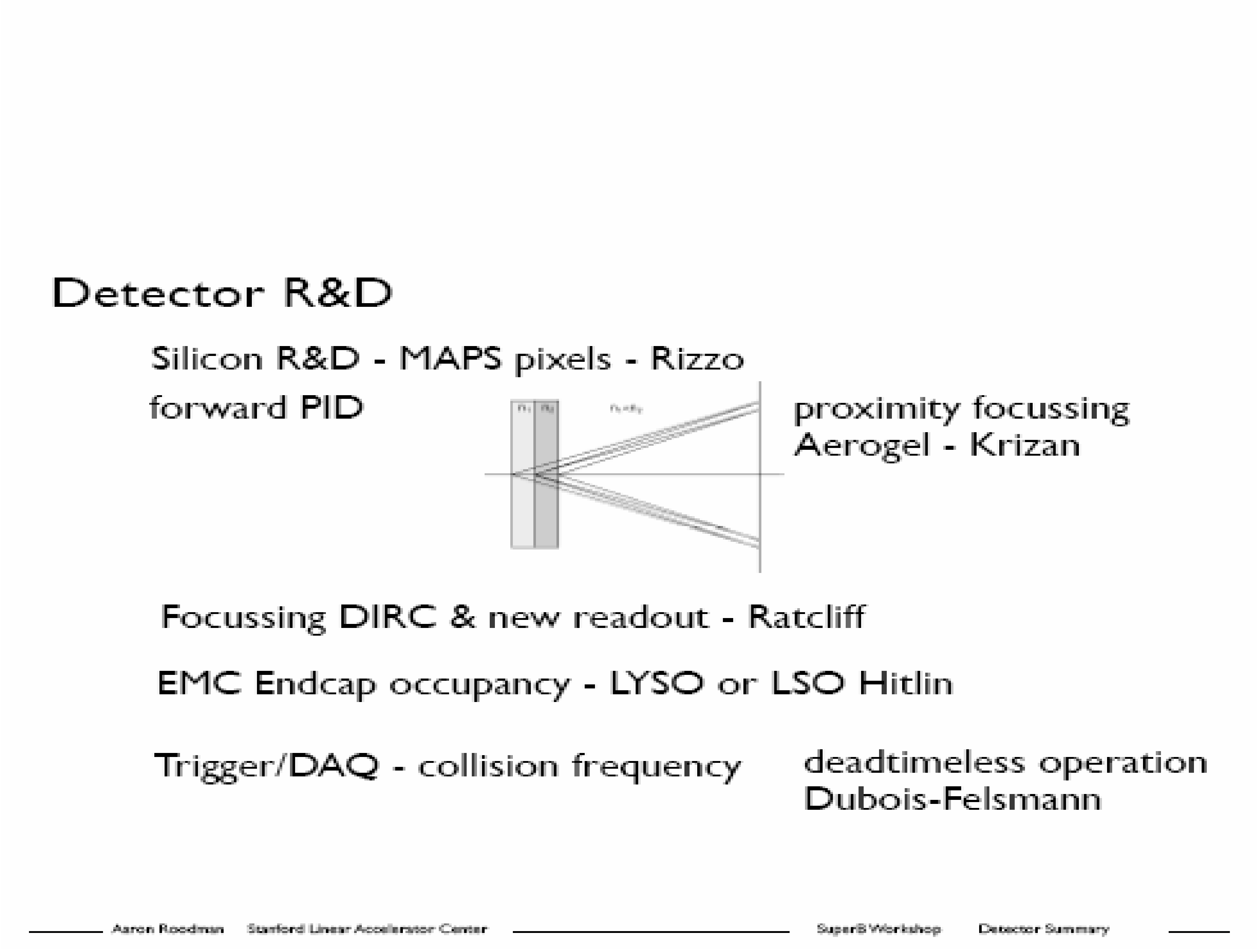
Design Issues

Either BABAR or BELLE could be the basis of a SuperB detector



BELLE causes problem for DIRC

lower boost means backwards detectors more important



Detector R&D

Silicon R&D - MAPS pixels - Rizzo

forward PID

proximity focussing
Aerogel - Krizan

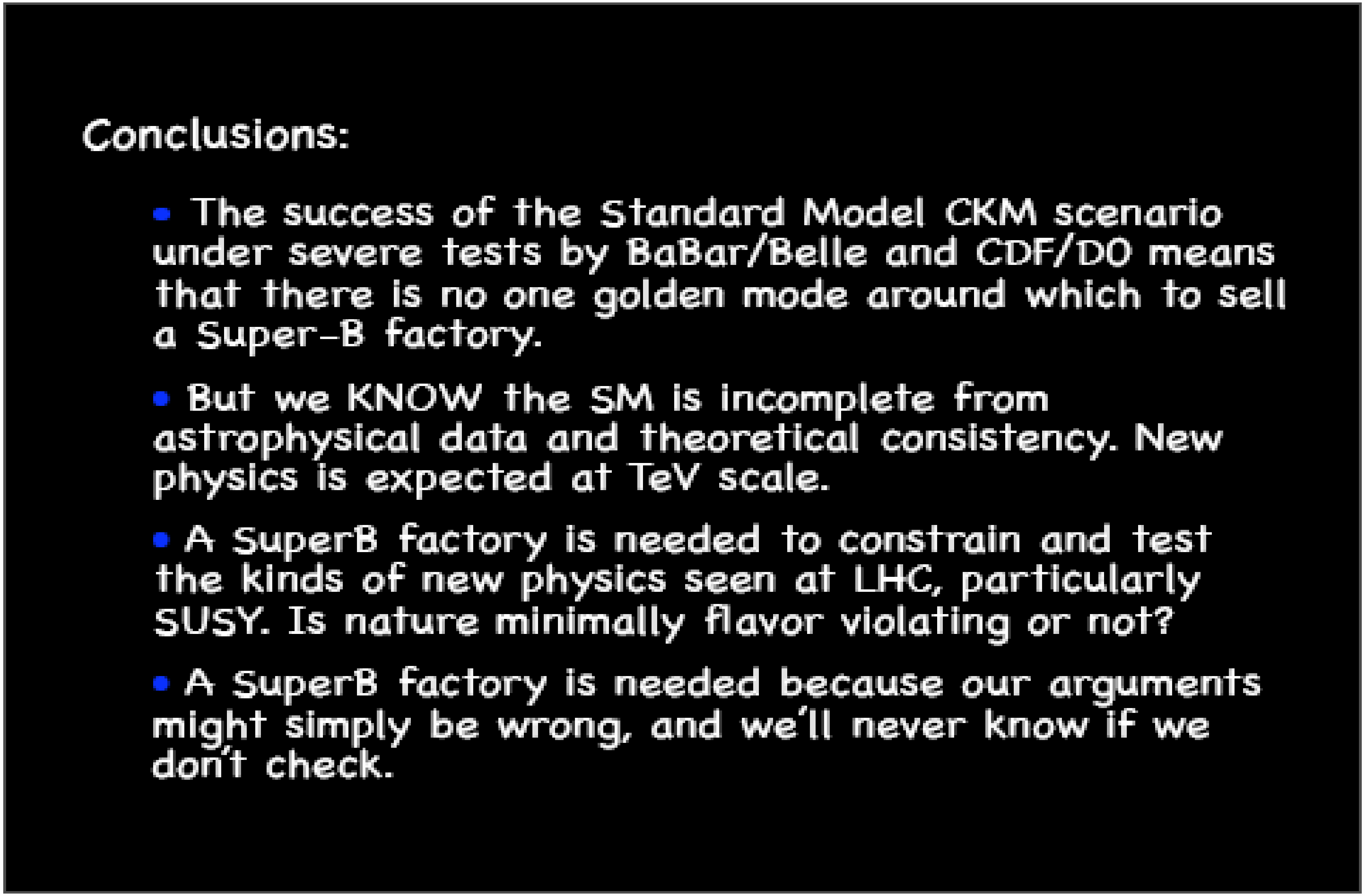
Focussing DIRC & new readout - Ratcliff

EMC Endcap occupancy - LYSO or LSO Hitlin

Trigger/DAQ - collision frequency

deadtimeless operation
Dubois-Felsmann

Aaron Roodman Stanford Linear Accelerator Center SuperB Workshop Detector Summary



Conclusions:

- The success of the Standard Model CKM scenario under severe tests by BaBar/Belle and CDF/D0 means that there is no one golden mode around which to sell a Super-B factory.
- But we KNOW the SM is incomplete from astrophysical data and theoretical consistency. New physics is expected at TeV scale.
- A SuperB factory is needed to constrain and test the kinds of new physics seen at LHC, particularly SUSY. Is nature minimally flavor violating or not?
- A SuperB factory is needed because our arguments might simply be wrong, and we'll never know if we don't check.

Outline of Summary Detector Working Group Sessions

David WGS Leith,
Professor and
Emeritus Director of Research
Steering Committee Meeting
Friday, June 16, 2006

Summary

1. A water additive can keep a drift chamber alive at very high rates, but water does not prevent film growth.
2. Oxygen can clean cathodes and anodes.
3. The breakdown mechanism in chambers with no additives is due to high E-fields from charge accumulation in thin films on cathodes and Fowler-Nordheim field emission.
4. Cathode aging can be modeled.

Adam presented a thorough study of aging in the

BaBar Chamber, and quantitative modeling.