Particle Identification at the FCC-ee

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FCC-France Workshop

Outline

Current baseline designs for FCC-ee experiments do not include a dedicated detector for hadron identification (henceforth referred to as PID), although IDEA drift chamber may have strong capabilities in this area.

In this brief talk will cover:

- Requirements, especially on momentum range (focus on B physics at the Z^0)
- Candidate technologies
- Conclusions

Spoiler alert: no entirely satisfactory solution is yet evident, but the main challenges can at least be identified.

Requirements

Applications of PID in Z^0 physics

Let's focus on the Z^0, where requirements are most clearly defined.

A good PID system, if available, would be exploited in many measurements, *e.g.*

- Complementary / redundant info to ECAL in searches for LFV Z decays;
- Separating π/K in tau final states;
- Help in flavour-tagging jets;
- Studies of particle production.

But in b physics and spectroscopy PID is *essential* !

PID requirements in b-physics & hadron spectroscopy

Hadron identification essential for a large set of flavour physics measurements.

- Distinguishing between same topology final-states.
- Kaons for *flavour tagging* (*i.e*. $B^0_{(s)}$ or $B^0_{(s)}$ bar) in time-dependent CPV studies.
- Suppressing combinatorics.
- K or proton identification for exotic spectroscopy studies.

Experiments have often 'got by' & produced very nice results without a dedicated PID detector (*e.g.* ALEPH, CDF, ATLAS/CMS), but essential for precise & transformative measurements, so mandatory at CLEO, Belle(II), BaBar & LHCb.

Requirements on PID for b physics

Take as example decay $B_s \rightarrow D_s K$: interesting in itself as a powerful mode for measuring Unitarity Triangle γ, but also representative of many other channels.

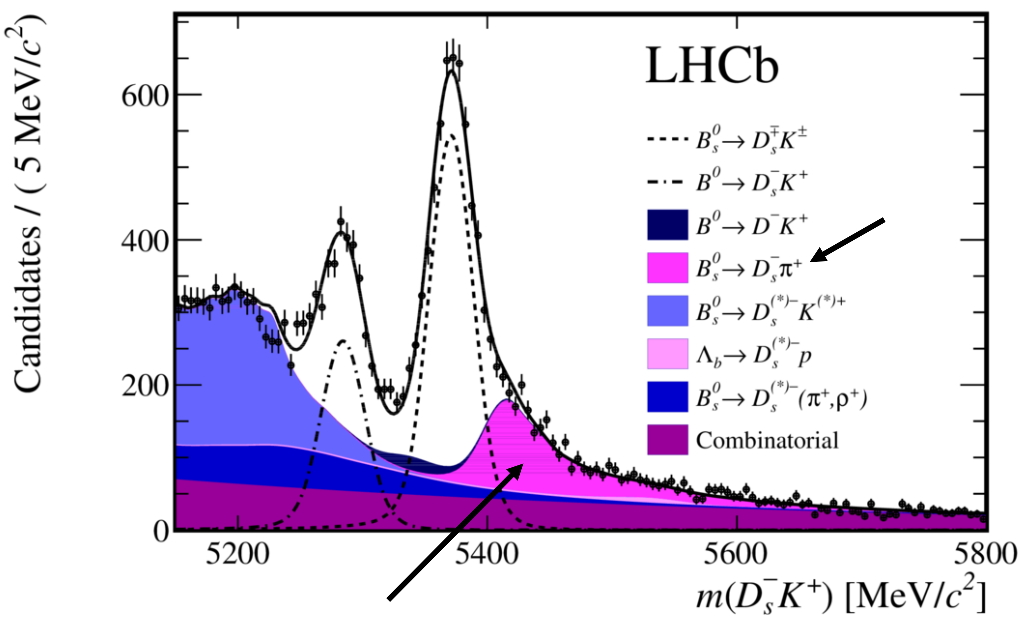
Suffers from an order-of-magnitude higher same-topology background of $B_s \rightarrow D_s \pi$. Significant help comes from mass resolution, which separates peaks.

LHCb, after PID cuts.

(mass resolution on signal is ~15 MeV/c^2.)

Residual $D_s \pi$ background lies at higher masses.

Note that some background with missing particles, *e.g.* from D_s^* or ρ^+, will always contaminate signal region.



[LHCb, JHEP 05 (2015) 019]

w/o RICH this would be x10 signal

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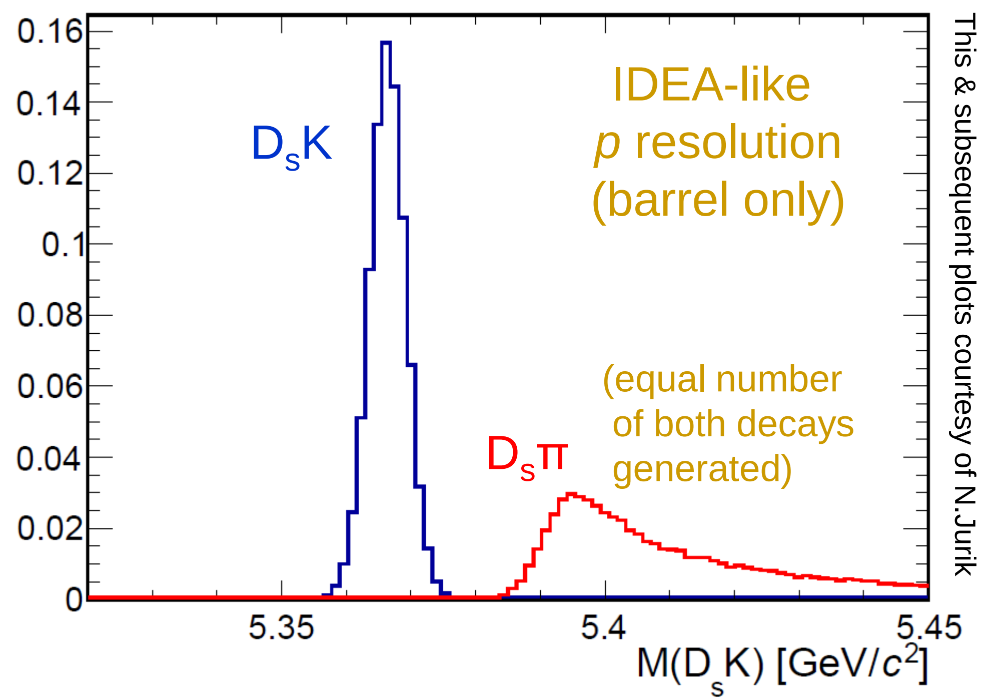
Mass resolution should be very good at FCC-ee.

Result of simple attempt to simulate expected *p* resolution of IDEA in barrel region.

Looks very promising (but again, do not forget additional backgrounds that will *always* appear under peak).



Requirements on PID for b physics

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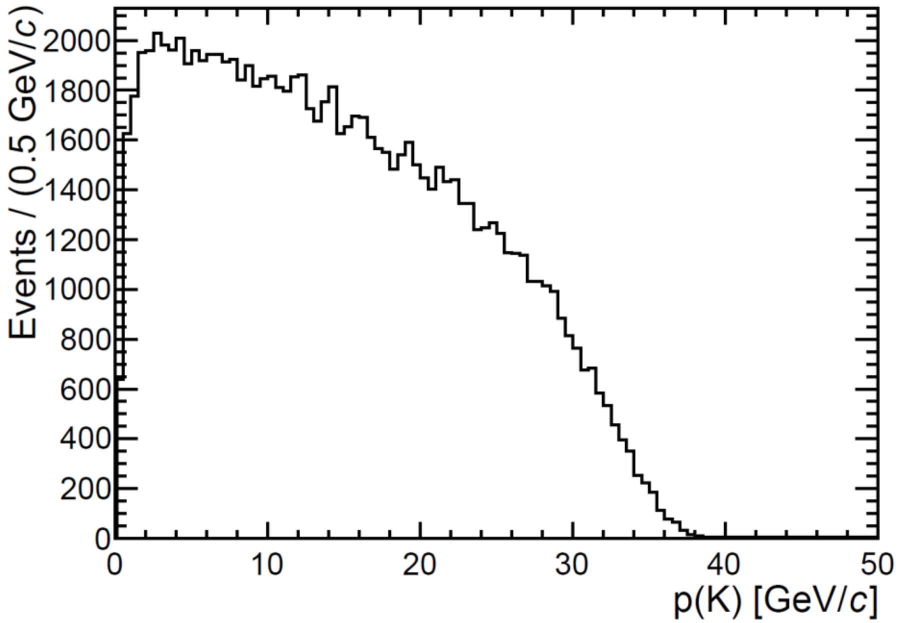
Suffers from an order-of-magnitude higher same-topology background of $B_s \to D_s \pi$.
Separating $B_s \to D_s K$ vs $B_s \to D_s \pi$ with PID depends on *p*-spectrum of bachelor K/π.

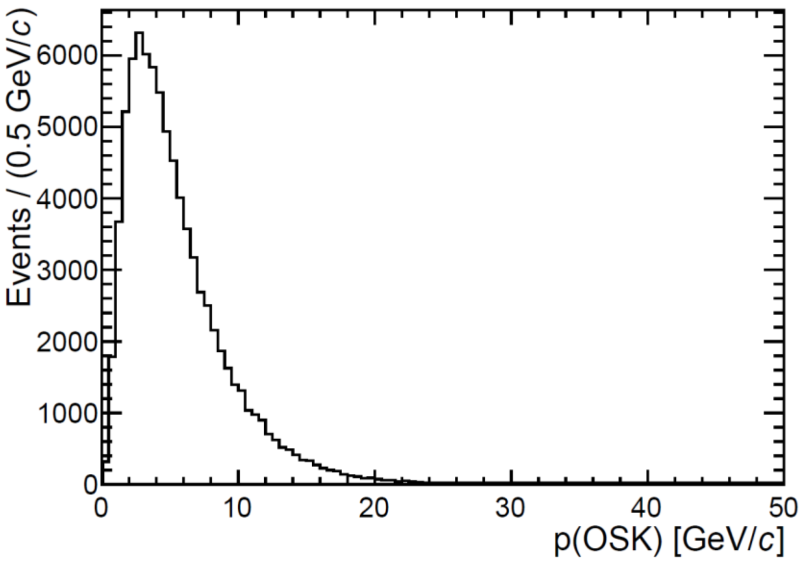


In an ideal world then we would like PID up to 30-40 GeV/*c*. This very challenging for a RICH detector in constraints that exist. Coverage up to ~20 GeV/c still useful.

Requirements on PID for b physics

Take as example decay $B_s \to D_s K$: interesting in itself as a powerful mode for measuring Unitarity Triangle γ, but also representative of many other channels.

Spectrum of kaons for 'opposite side' tagging from $b \to c \to s$ decay chain. These have very high weight in determining initial flavour of B_s prior to oscillation. Vital input in time-dependent CP-violation measurements.

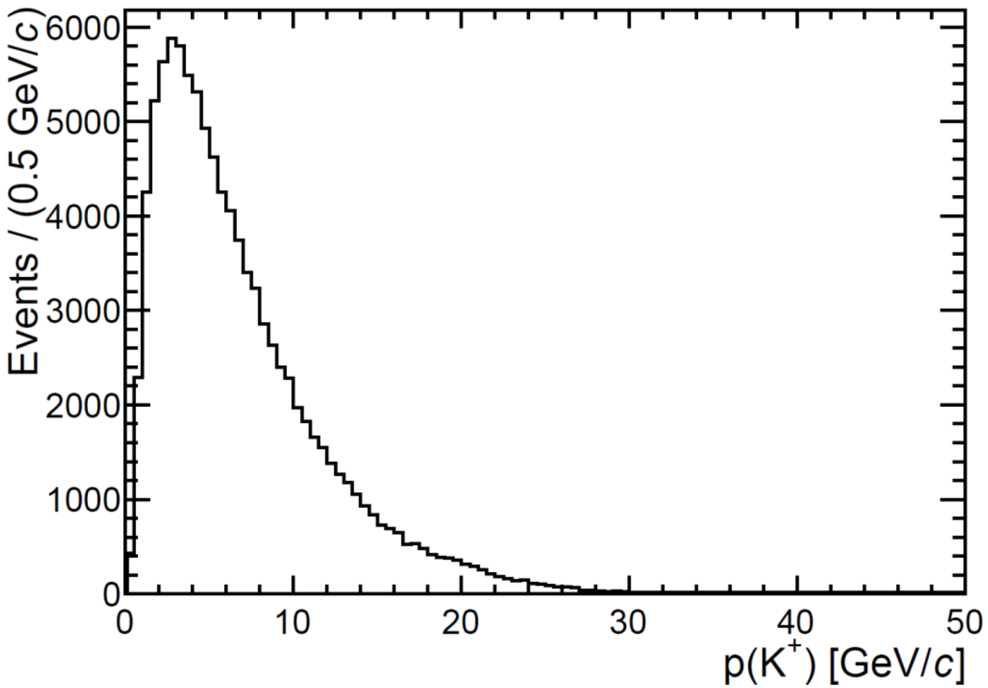


Most of action lies below 10 GeV/*c*. (Story will be even truer for 'same side' kaons.)

Requirements on PID for b physics

Take as example decay $B_s \to D_s K$: interesting in itself as a powerful mode for measuring Unitarity Triangle γ, but also representative of many other channels.

Kaons from $D_s \to KK\pi$ decays (here demands on π/K separation less stringent):



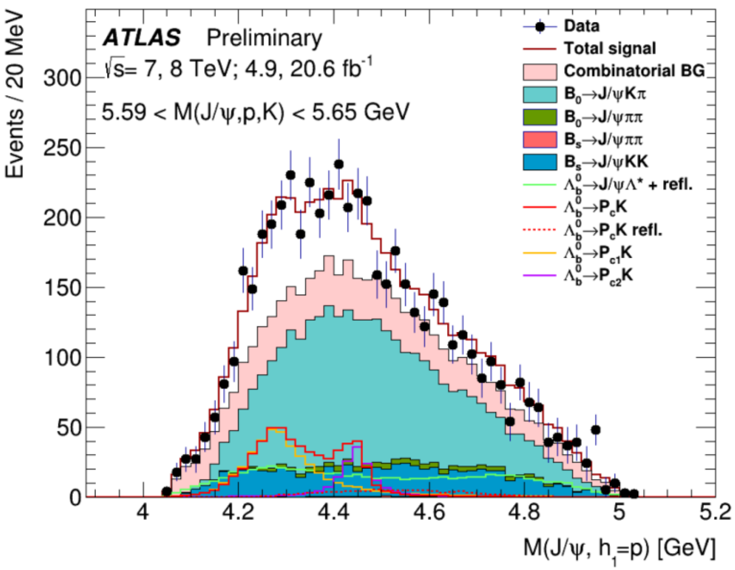
Requirements on PID for spectroscopy

Hadron identification extremely powerful tool in hadron spectroscopy studies.

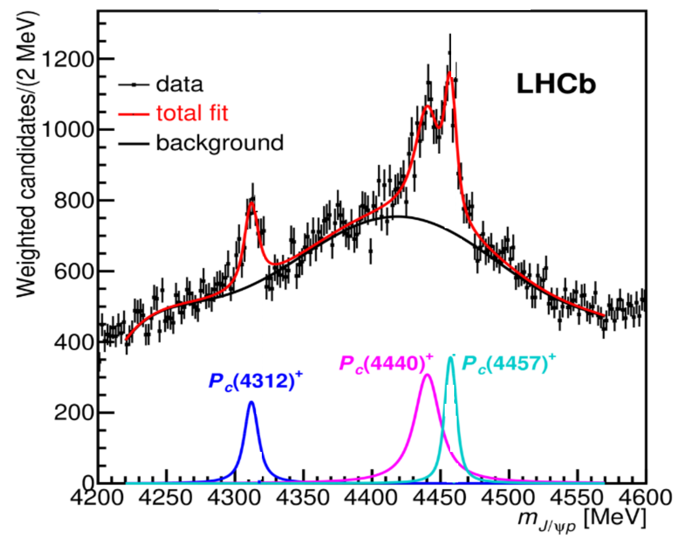
e.g. proton identification for pentaquark search in $\Lambda_b \to J/\Psi pK$

Without PID

[ATLAS-CONF-2019-048]



With PID ~ no background



[LHCb, PRL 122 (2019) 222001]

Typically the hadron of interest appears in a multi-body decay, so is not too hard.

Requirements on PID for spectroscopy

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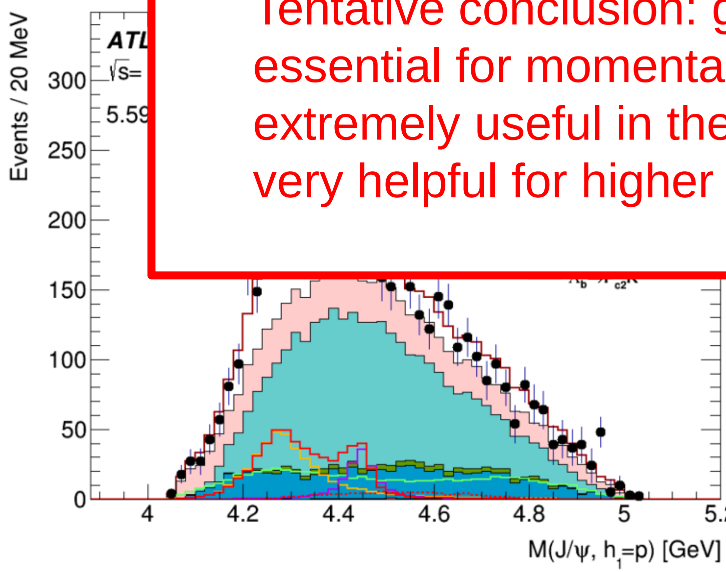
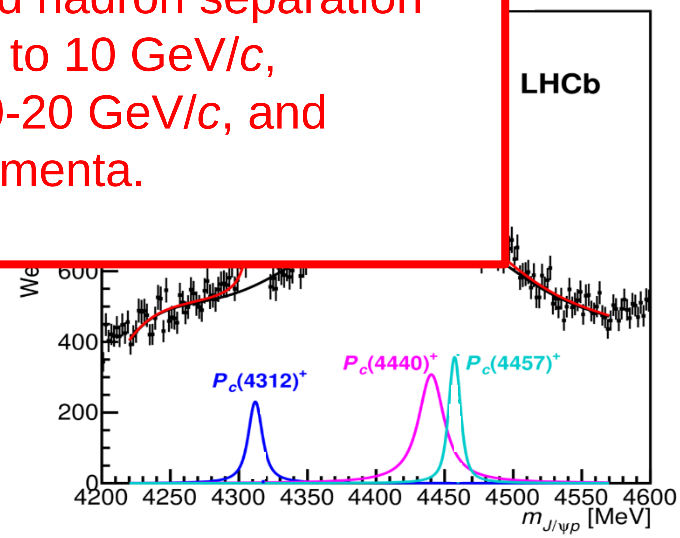
Wi ... ground

Tentative conclusion: good hadron separation essential for momenta up to 10 GeV/*c*, extremely useful in the 10-20 GeV/*c*, and very helpful for higher momenta.

[ATLAS-CONF-2019-048]





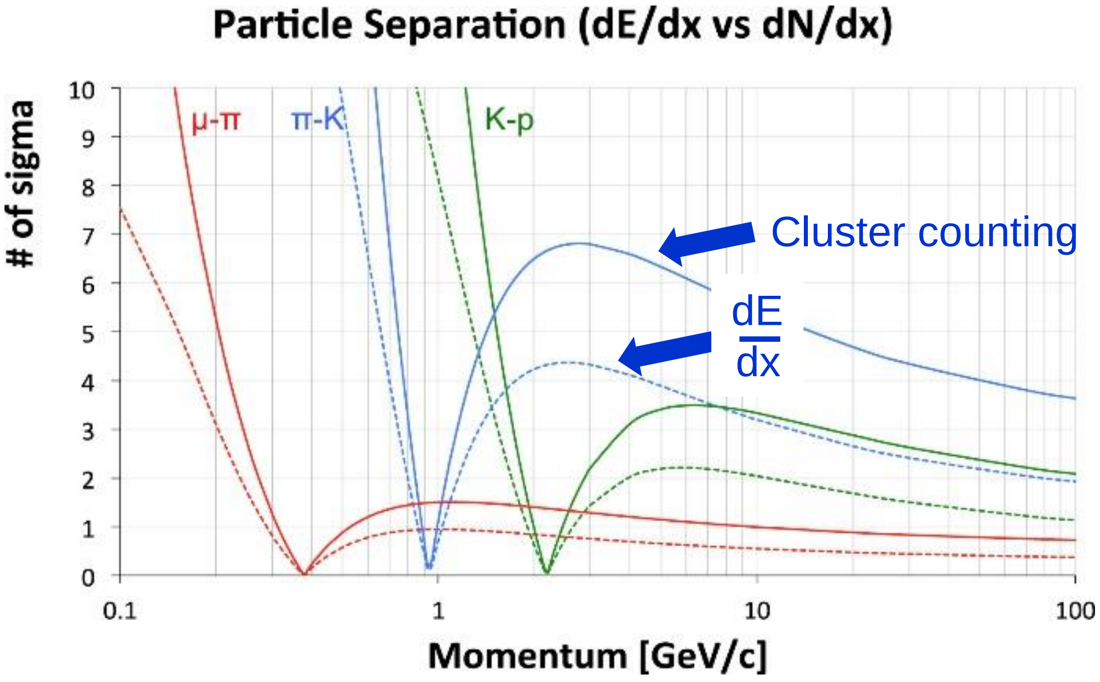
[LHCb, PRL 122 (2019) 222001]

Typically the hadron of interest appears in a multi-body decay, so is not too hard.

Candidate technologies

PID through cluster counting

dE/dx is limited to low momentum PID. However better separation is feasible If one can count the actual ionisation clusters. This is proposed for the IDEA drift chamber, [Chiarello *et al.*, NIM A 936 (2019) 503], which builds on experience from KLOE & MEG2.



Word of warning – not from a full simulation !

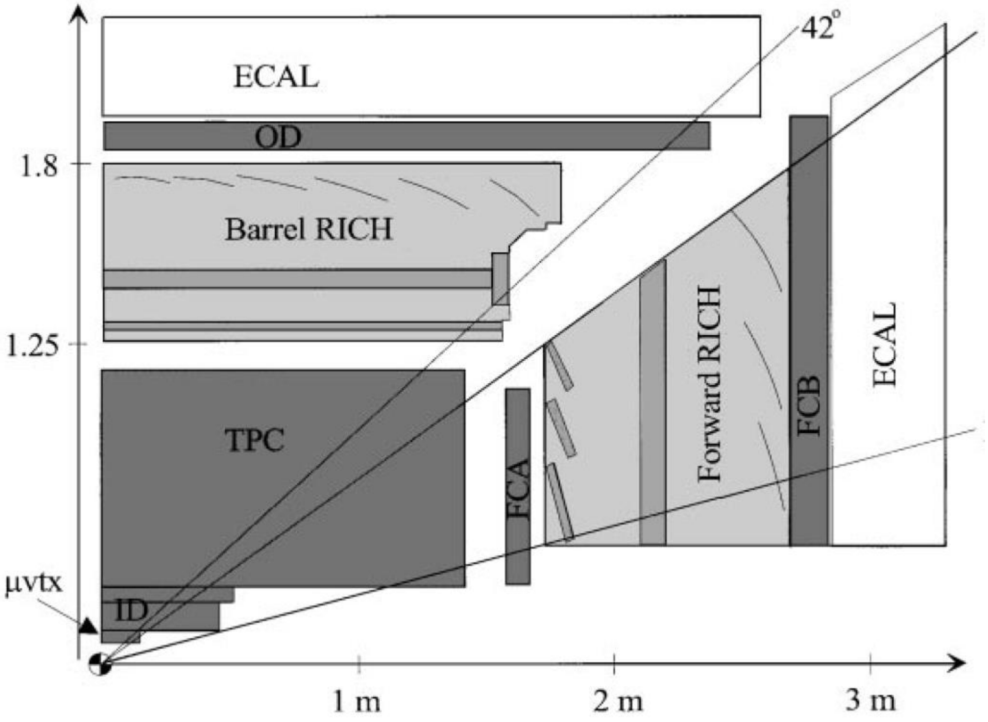
Also note that any dE/dx-like PID has an annoying blind spot for π/K separation at low p.

If this works well, it will be extremely powerful ! But experiments with Si-based tracking systems (*e.g.* CLD) would need another solution if they require PID.

RICH solution

RICH can (in principle) provide good PID over a wide momentum range.

Main challenge is space – only previously attempted in cylindrical detector at DELPHI & SLD.   Ingenious but very demanding designs, squeezed into ~60 cm.

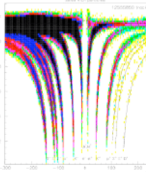


Consequences: restriction on tracking volume and impact on ECAL performance.

Google readily throws up common opinion on DELPHI / SLD RICH adventure

SLD CRID at SLAC !

how not to do RICH PID



- Alternative design
  - TMAE wire chambers to detect UV Cherenkov photons.
- In this case (and some, but not all, others) dozens of people spent a dozen years and a dozen M$ for very small gains.
- **KISS**
  - pay for photodetectors that work
- This lesson was learned
  - the DIRC at Babar works well

SLAC-PUB 59
November 199
(I)

Performance of the SLD Barrel CRID During the 1992 Physics Data Run*

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[i]Department of Physics, Colorado State University, Fort Collins, CO 80523, USA

No PID performance curves ever shown

Google readily throws up common opinion on DELPHI / SLD RICH adventure

SLD CRID at SLAC !

Harsh, and does not reflect extreme challenge of what was being attempted.

how not to do RICH PID

Alternative design
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In this case (and some, but not all, others) dozens of people spent a dozen years and a dozen M$ for very small gains.

KISS
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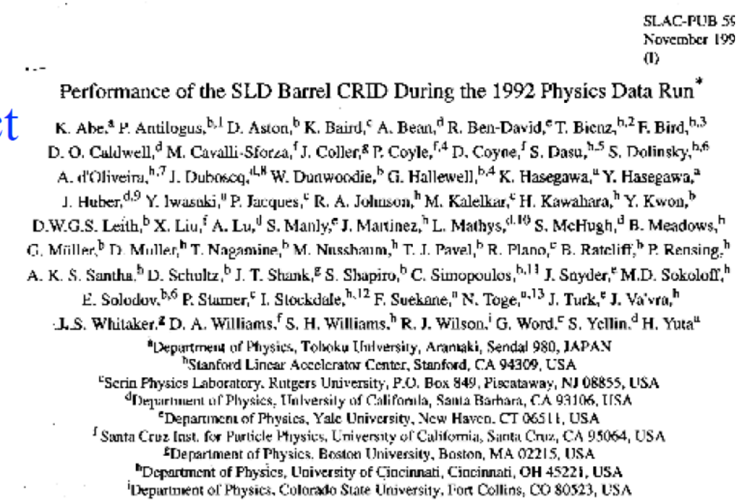

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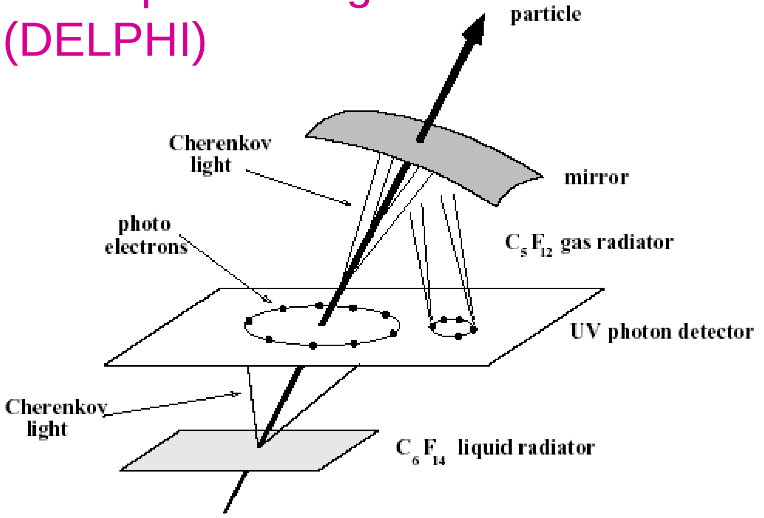
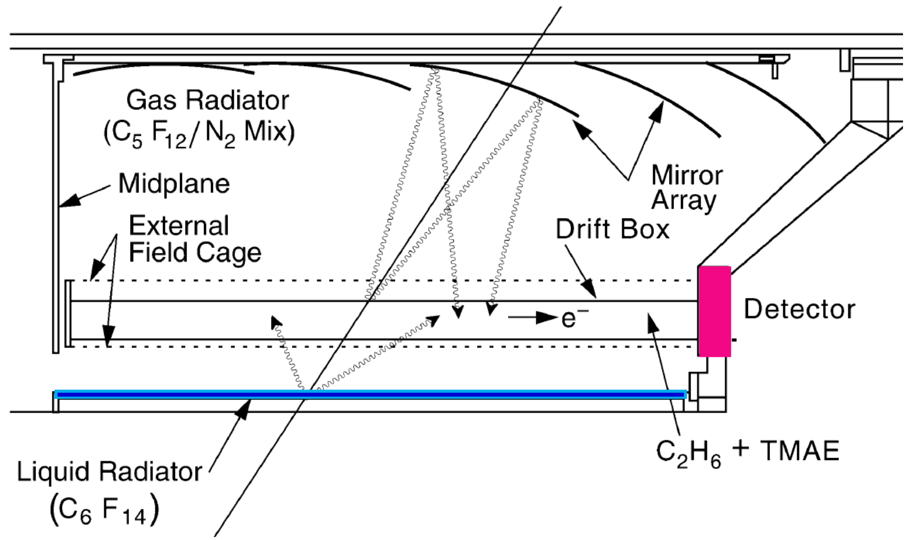
No PID performance curves ever shown

DELPHI and SLD RICH systems

Conceptual design (DELPHI)



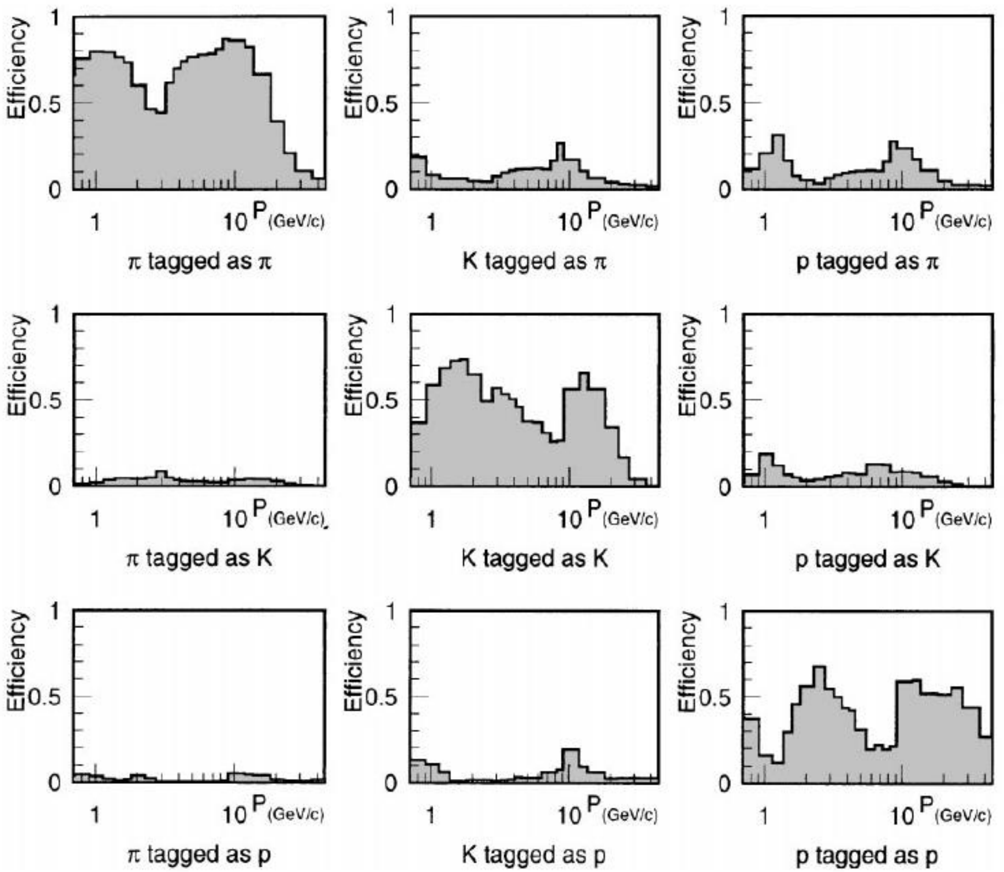
SLD barrel CRID



Highly challenging and delicate systems, similar in design for both:

- Liquid / gas / gas (C_6F_{14} / TMAE / C_5F_{12}) together in tight, inaccessible volume – plumbing nightmare. All kept at 40^o to avoid C_5F_{12} condensation.
- Photoconverter gas TMAE (Tetrakis diMethylAmine Ethylene) the substance from hell ("it it glows you're screwed, if it doesn't glow you're screwed" – SLD CRID group's "Laws of TMAEDYNAMICS").
- Long TPC-like drift distances for the photoelectrons – sensitive to distortions.

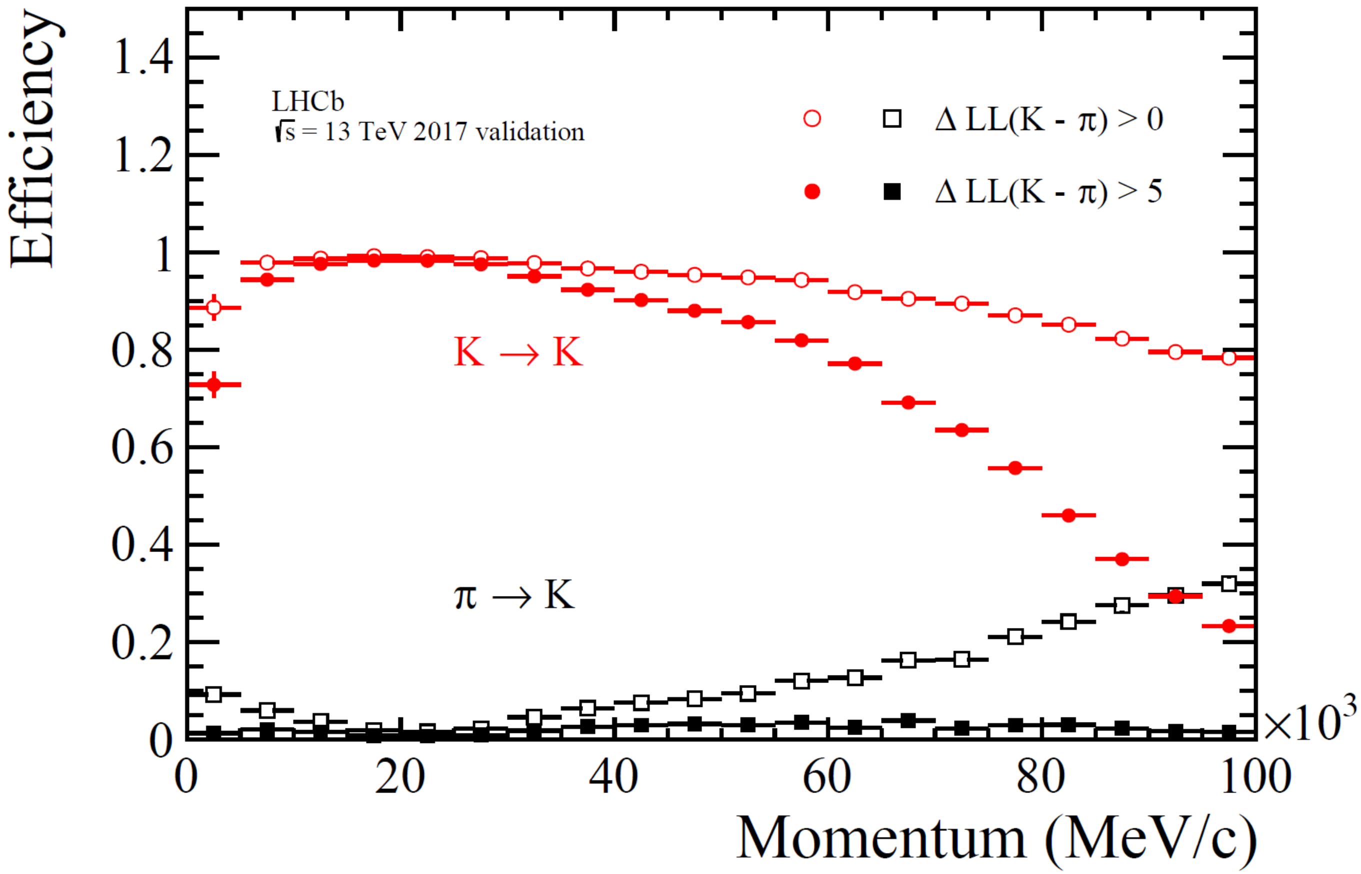
Efficiency matrix of DELPHI RICH



[Battaglia and Kluit, NIM A 433 (1999) 252]

Kaon id efficiencies generally < 50%, and range limited to p < 20 GeV/*c* .

To be compared with…



…but LHCb has much more space to play with, plus 20 years of RICH know-how.

Photo-detector options

Challenges of FCC-ee different to those in hadronic environment. ‘Simple’ events, no demands on fast timing or radiation hardness, but efficiency at a premium.

Technology	**B-field response**	**QE range**	**Cost**	**Comments**
MAPMT	X	λ > 200 – 200 nm	$$	B-field shielding a showstopper
MCP	✓		$$$	Excellent time resolution – not essential for FCC-ee RICH ?
SiPM	✓		$$($)	High dark count – requires cooling; radiation tolerance – not an issue at FCC-ee
Gaseous / CsI	✓	λ < 200 nm	$	Low number of photo-electrons (in CF4 ~ 5 / m, *c.f.* 3x higher with MaPMTs)

- Area to be covered ~5m x 2π x 2m > 50 m^2. Suggests cost of <$ 0.2M per m^2, which is currently only feasible for gaseous option.
- Interesting to monitor noise and cost evolution of SiPM. Indeed, R&D proceeding in most areas (*e.g.* ‘windowless RICH’, SiPMs, LAPPDs). motivated by future LHCb upgrades and electron-ion collider.

Radiators and related parameters

Hard to find single radiator to cover full momentum range of interest. Two popular cases for recent experiments are C_4F_{10} (lowish p) and CF4 (higher p).

C_4F_{10} (n = 1.0015, θ_max: 55 mrad)

- π threshold : 2.5 GeV/c
- K threshold : 9.0 GeV/c
- n_det.ph.s (β=1) / 1m : ~ 20
- To exploit PID up to 50 GeV/c : σ_C_ph < 1.5 mrad (vis. range)

No positive id at low p but π/K separation still possible through veto mode operation

Indicative # assuming HPD / SiPM / MaPMT photo-detector

CF_4 (n = 1.0005, θ_max: 32 mrad)

- π threshold : 4.4 GeV/c
- K threshold : 15.6 GeV/c
- n_det.ph.s (β=1) / 1m : ~ 10
- to exploit PID up > 60 GeV/c : σ_C_ph < 0.7 mrad

Screenshot from Silvia Dalla Torre

For an FCC-ee detector, one could compromise on C_4F_{10} alone, and work on optimising resolution to push the upper π/K separation bound. However….

Radiators and related parameters

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Indic
assu
HPD
SiPM
MaP
phot
dete

Flurocarbons are eco-unfriendly, and are unlikely to be an acceptable option for use in next generation of experiments.

Alternative required !

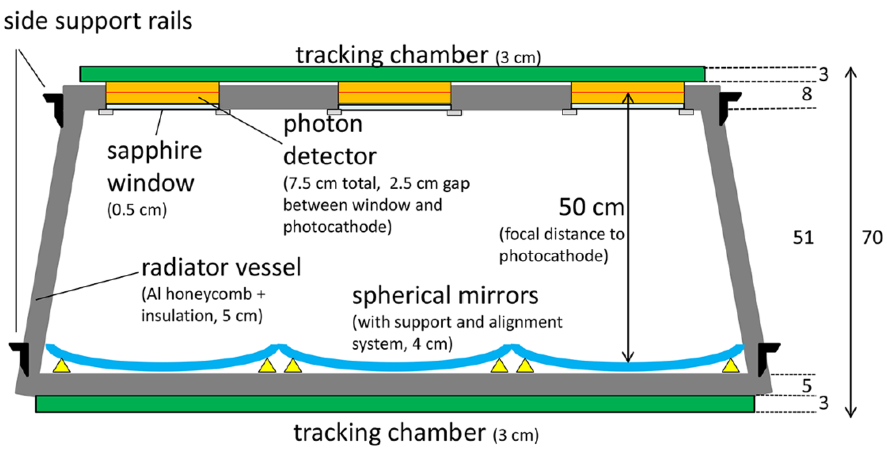
- to exploit PID up > 60 GeV/c : σ_C_ph < 0.7 mrad

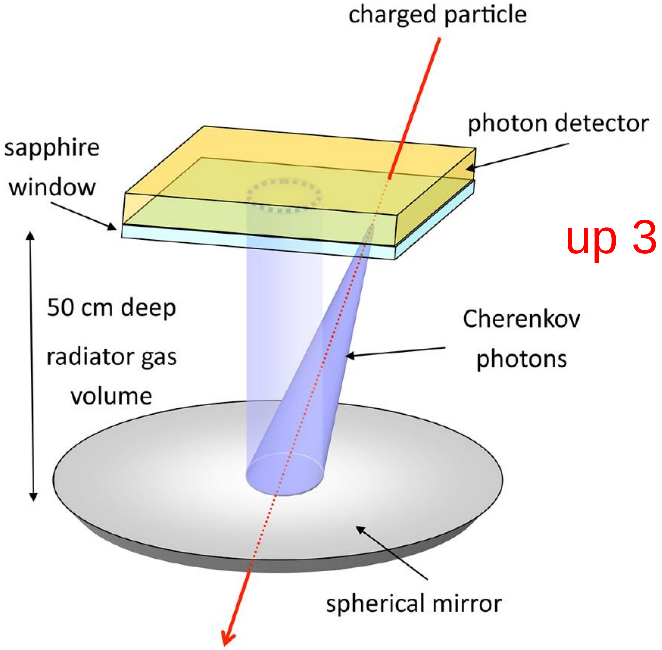
For an FCC-ee detector, one could compromise on C_4F_{10} alone, and work on optimising resolution to push the upper π/K separation bound. However….

Other possibilities

Refractive index and number of photons can be tuned by pressure in radiator.

Idea was proposed, but not implemented, as a part of ALICE upgrade, with intention of extending PID range to 5-25 GeV [Acconcia. *et al*, EPC 129 (2014) 129].





up 3.5 bar

Reasonably compact, but comes with overheads
e.g. extra material, and in this case need to heat radiator to prevent condensation.

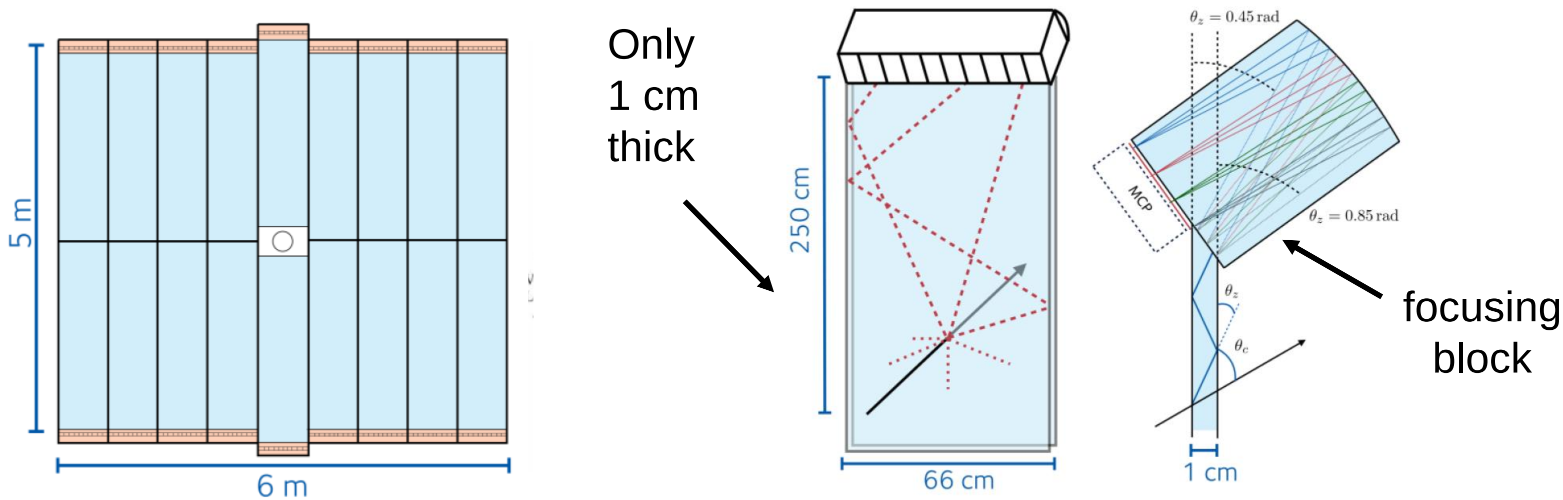
TORCH solution

[Charles & Forty, NIM A 639 (2011) 173]

An alternative solution that takes up much less space that a RICH is a DIRC-like solution, *i.e.* benefit from total-Internal-reflection of Cherenkov light in thin quartz bar.

Measure either Cherenkov angle (DIRC*) or time of propagation in radiator (Belle II TOP**). TORCH does both, also benefitting from time-of-flight to radiator.

Possible upgrade project for LHCb – here a planar detector, ~9.5 m from IP



Pixelated MCPs with ~70 ps / photon, giving 10-15 ps per track with 30 p.e.s.

In this configuration obtain 3σ π/K separation up to 10 GeV.

* I.Adam *et al.*, NIM A 538 (2005) 281
** U. Tamponi, arXiv:1811.04532

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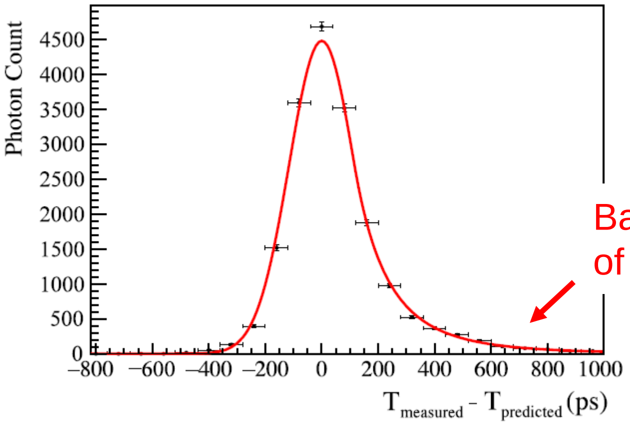
R&D involving CERN, Oxford, Bristol, Edinburgh, Bath and Photek (industry).

Work ongoing on prototypes, development of MCPs and read-out electronics.

Quartz plate for prototype.



[Bhasin *et al.*, NIM A 961 (2020) 163671]

Single photon resol^{n} measured in test beam. After subtraction of timing ref. obtain σ ≈ 100 ps.

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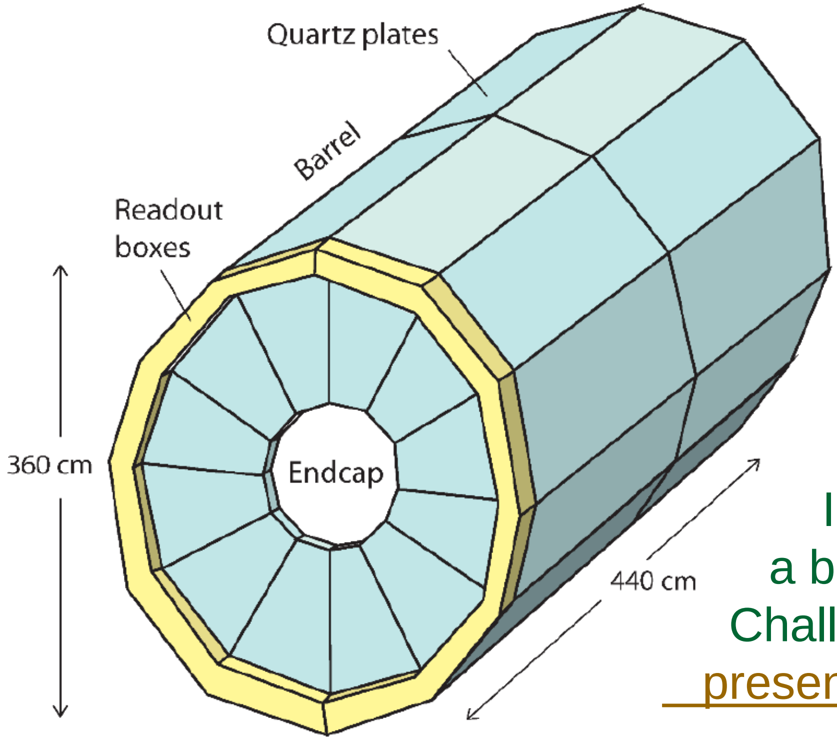
TORCH at FCC-ee

TORCH can be adopted to cylindrical detector design (R. Forty – strawman layout).



Looks elegant and *is* very thin.

However focusing block and photodetectors will introduce dead Space into overlap region.

Radiator closer to IP than in LHCb.
Reduced lever arm for TOF component.

In order to keep 10 GeV π/K separation (or do a bit better) must improve granularity + time res^{n}. Challenging, but not impossible (see M. van Dijk presentation at January FCC workshop, CERN).

Attractive concept, but will not provide high momentum PID.

Conclusions

Hadron identification would be a very welcome attribute at the FCC-ee.

For b physics and hadron spectroscopy it is essential.

The critical range is 1-10 GeV/*c*, with coverage at higer momenta highly desirable.

On paper, cluster counting looks very powerful. Watch with interest.

The RICH solution is robust and performant, but it requires space,
and would have significant consequences for overall experiment design.

New generation PID detectors, such as TORCH, appear an elegant solution,
but will struggle to cover much of the momentum range of interest.

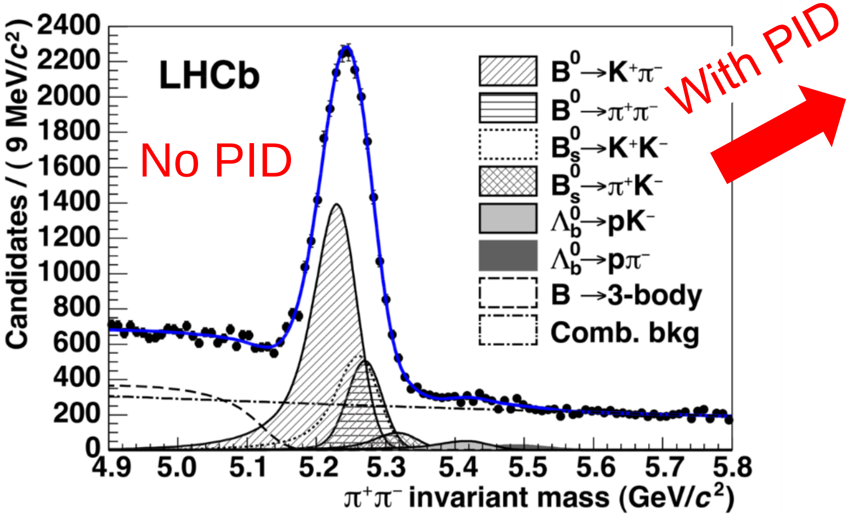
The PID community has been alerted to the challenge. Good ideas welcome !

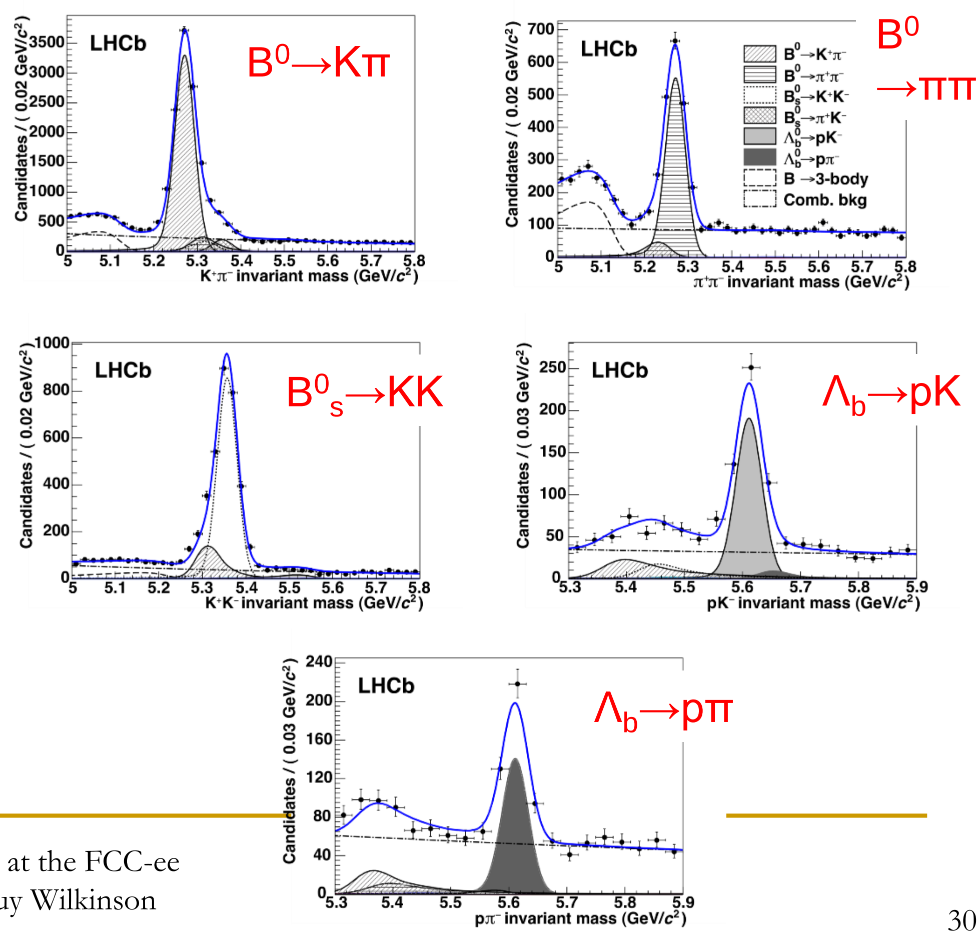
Backups

PID requirements in b-physics & hadron spectroscopy

Hadron identification essential for a large set of flavour physics measurements.

- Distinguishing between same topology final-states.





[LHCb, JHEP 10 (2012) 37]

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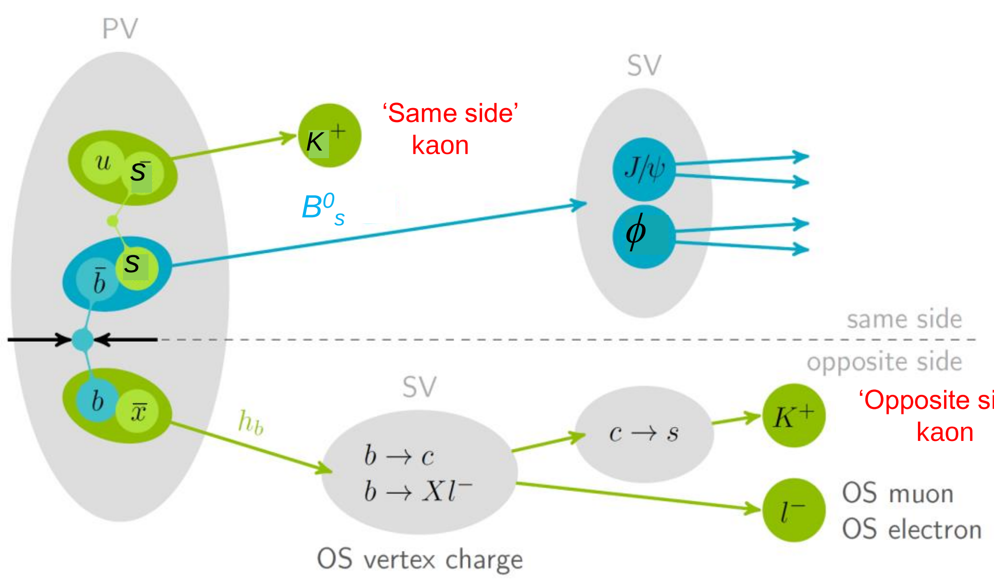
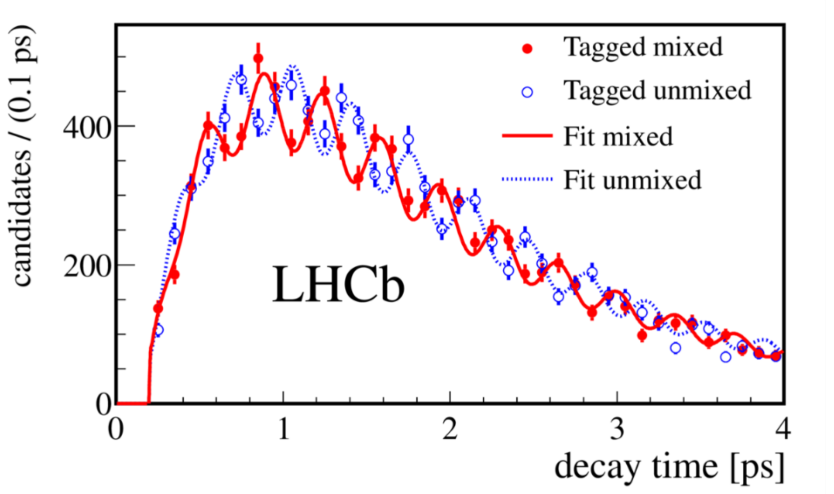


PID requirements in b-physics & hadron spectroscopy

Hadron identification essential for a large set of flavour physics measurements.

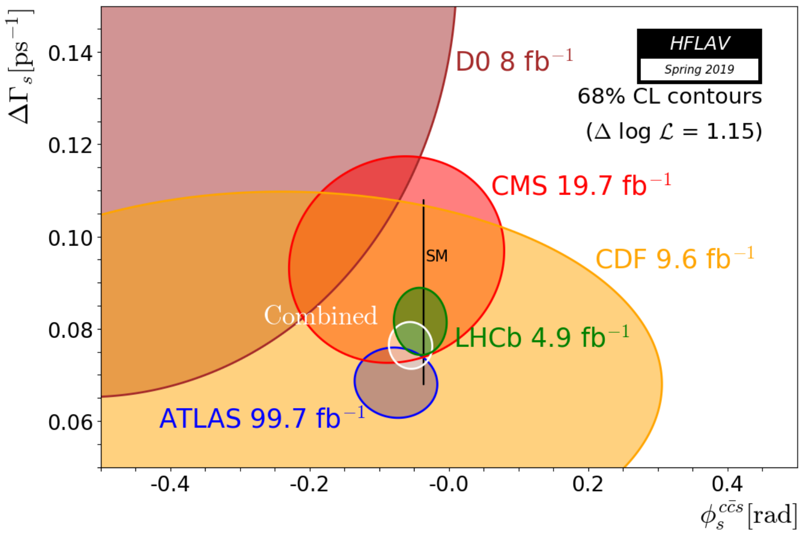
- Kaons for *flavour tagging* (*i.e*. $B^0_{(s)}$ or $B^0_{(s)}$ bar) in time-dependent CPV studies.

e.g. for B_s mixing measurements…



[LHCb, NJC 15 (2013) 053021]

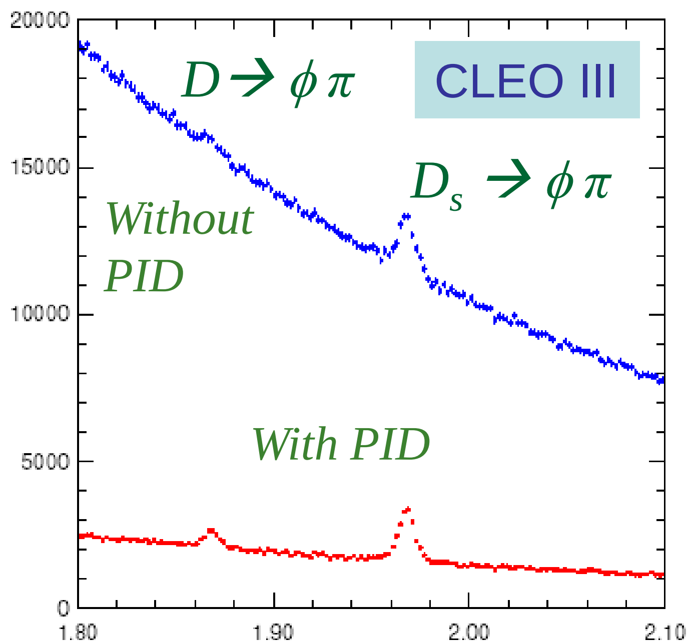
…& CPV ϕ_s measurements (where FCC-ee can make impact)

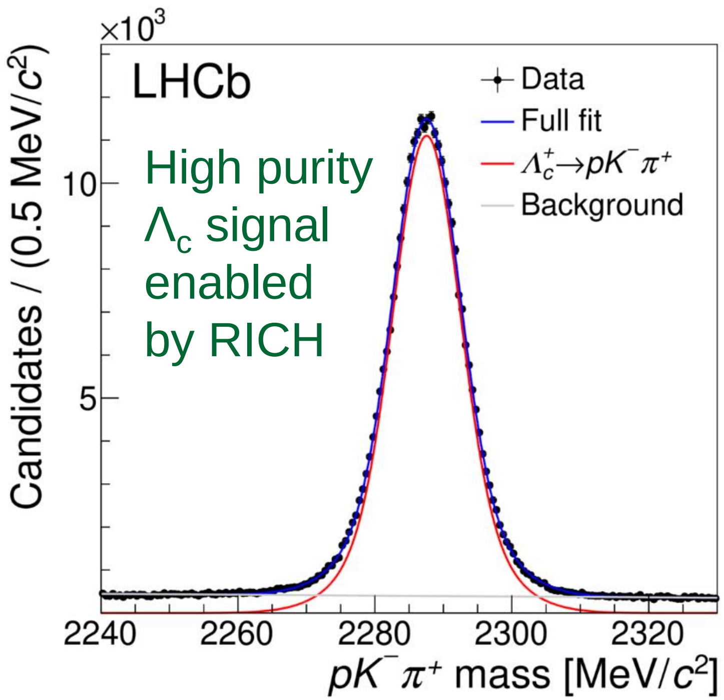


PID requirements in b-physics & hadron spectroscopy

Hadron identification essential for a large set of flavour physics measurements.

- Suppressing combinatorics.





[LHCb, PRD 100 (2019) 032001]