The RICH and Related Physics Topics

• $\mathcal{CP}$, B-mesons, and LHCb
• A Case for Particle ID
• The RICH System
• The Parts to Build a RICH
• RICH - Physics
• Conclusion

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13 - 20 2000
Why CP violation?

- Possible that CP is partly due to New Physics. ($K^0$-system not conclusive)

- CP is likely to be sensitive to small effects due to New Physics, e.g. new particles involved in mixing, etc.

- No CP $\rightarrow$ no matter in the universe $\rightarrow$ no us. (Sakharov)
  Cosmology suggests we need more CP than the SM can provide.

Excellent place to look for New Physics!
Standard Model $\mathbb{CP}$ - and why use B’s

In SM: $\mathbb{CP}$ due to complex phase in CKM matrix $V_{mn}$, where $V_{ud} \propto \text{Amplitude}(u \to d)$, $V_{ud}^* \propto \text{Amplitude}(\bar{u} \to \bar{d})$ etc.

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
1 & \lambda & \lambda^3 \\
\lambda & 1 & \lambda^2 \\
\lambda^3 & \lambda^2 & 1
\end{pmatrix}
\begin{pmatrix}
1 & 1 & e^{-i\gamma} \\
1 & 1 & 1 \\
e^{-i\beta} & 1 & 1
\end{pmatrix}
\]

- Both, $\beta$ and $\gamma$, accessible in $B_d^0$ system!
- $\beta$ from $B_d^0$ mixing (involving $b \to t \to d$)
- $\gamma$ from $b \to u$ transitions in $B_d^0$ and $B_s^0$ decays
- at $0(\lambda^4)$ another complex phase appears: $V_{ts} \propto e^{i\delta\gamma} \to B_s^0$ mixing angle

$B_d^0 = d\bar{b}$

$B_s^0 = s\bar{b}$
- why b at LHC?

at LHCb interaction point: \( \mathcal{L} = 2 \cdot 10^{32} \text{cm}^{-1}\text{s}^{-1} \)
for 14 TeV p-p collisions \( \sigma_{b\bar{b}} \approx 500 \mu\text{barn} \)

- \(10^{12}b\bar{b}\) pairs per year!
- \(\sim 10^4\) more than in \(e^+e^-\) colliders.
- need them: typical B.R. for CP-sensitive channels: \(10^{-5}\)
- Get all types of \(B^0\)
  not only \(B^0_d\), but also plenty of \(B^0_s\) and all other flavours.
Amongst the work left to do for LHCb in 2005

- Use huge statistics to improve existing measurements of $\sin(2\beta)$:
  - World in 2005 (after 6 years of B-factories) $\sigma_{\sin 2\beta} \approx 0.02$
  - LHCb after 1 year: $\sigma_{\sin 2\beta} \approx 0.02$

- Measure $\gamma$ in many different ways, some more and some less susceptible to New Physics, using both, $B^0_s$ and $B^0_d$ decays.

- Explore the $B^0_s$ sector with high statistics ($\delta\gamma, \Delta m_s, ...$)

- There's is plenty more: rare B-decays, $B^\pm$, $B^\pm_c$, $\Lambda_b$, ...

**CP Measurement for Decays to CP-Eigenstates**

The phases in the CKM matrix appear in the interference between two decay paths.

They can be measured via the *time-dependent* asymmetry between $B^0_d \rightarrow \pi^+\pi^-$ and $\bar{B}^0_d \rightarrow \pi^+\pi^-$

$$A_{\pi\pi}(\tau) = \frac{\Gamma(B^0_d \rightarrow \pi^+\pi^-) - \Gamma(\bar{B}^0_d \rightarrow \pi^+\pi^-)}{\Gamma(B^0_d \rightarrow \pi^+\pi^-) + \Gamma(\bar{B}^0_d \rightarrow \pi^+\pi^-)} = \sin(2(\beta + \gamma)) \cdot \sin(\Delta m \tau)$$

$B^0_d$ and $\bar{B}^0_d$ are the flavours at creation, $\tau$ the decay-eigentime since creation, $\Delta m$ the mass difference between the two $B^0_d$ mass-eigenstates, $B^0_H, B^0_L$. In practice, complications (and interesting Physics) arise from penguin diagrams.
The Principle

Need to know:

- Decay products $\rightarrow$ Particle ID
- Decay time $\rightarrow$ Decay distance
- at $\tau_B = 0$: $B^0$ or $\bar{B}^0 \rightarrow$ Tagging $\rightarrow$ Particle ID

Compare time dependent decay rates, e.g.

$$\Gamma(B^0 \rightarrow \pi^+\pi^-)(\tau)$$

and its CP conjugate:

$$\Gamma(\bar{B}^0 \rightarrow \pi^+\pi^-)(\tau)$$
The need for particle ID

Some channels that are sensitive to $\gamma$

<table>
<thead>
<tr>
<th>Channel</th>
<th>SM</th>
<th>NP</th>
<th>$K/\pi$-sep.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_{d} \rightarrow D^*\pi(a_1)$</td>
<td>$\checkmark$</td>
<td></td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$B^0_{s} \rightarrow D_sK$</td>
<td>$\checkmark$</td>
<td>$\checkmark \checkmark$</td>
<td></td>
</tr>
<tr>
<td>$B^0_{d} \rightarrow \pi\pi$</td>
<td>$\checkmark$</td>
<td></td>
<td>$\checkmark \checkmark$</td>
</tr>
<tr>
<td>$B^0_{s} \rightarrow KK$</td>
<td>$\checkmark$</td>
<td></td>
<td>$\checkmark \checkmark$</td>
</tr>
<tr>
<td>$B^0_{d} \rightarrow \pi\pi$</td>
<td>$\checkmark$</td>
<td></td>
<td>$\checkmark \checkmark$</td>
</tr>
<tr>
<td>$B^0_{s} \rightarrow K\pi$</td>
<td>$\checkmark$</td>
<td></td>
<td>$\checkmark \checkmark$</td>
</tr>
</tbody>
</table>

- LHCb can measure $\gamma$ in many different ways
- Many interesting channels are themselves bg to topologically similar ones.
- Typical B.R. $\sim 10^{-5}$
- Rely heavily on $K/\pi$ separation (RICH)

$K/\pi$ separation is also crucial for the “opposite-side Kaon tag” to tag the flavour of the $B^0$ at production. More later.
The Need For Particle ID

$B_d^0 \rightarrow \pi\pi$

$B_s^0 \rightarrow D_s K$

Invariant mass [ GeV/c^2 ]

Events / 20 MeV/c^2

No RICH

$B_d \rightarrow \pi\pi$

$B_d \rightarrow \pi K$

$B_s \rightarrow \pi K$

$B_s \rightarrow KK$

$\Lambda_b \rightarrow p K$

$\Lambda_b \rightarrow p\pi$

$B_s \rightarrow D_s K$

$B_s \rightarrow D_s \pi$
LHCb Detector

is a dedicated B-physics detector at the LHC

- Dedicated B-trigger (inc. hadron trigger)
- Excellent proper time resolution
- Particle identification (RICH)
LHCb RICH schedule

- May 1995: LHCb-Letter of Intent
- February 1998: LHCb-Technical Proposal


- July 2003: Alignment system complete
- July 2004: RICH construction finished
- July 2005: RICH is installed. Ready for data taking 1/7/2005
Both, the $b$, and the $\bar{b}$ go nearly in the same direction, close to the beam axis → a forward spectrometer gets both $b$ (crucial for tagging)
The RICH system

Ring Imaging CHerenkov detector: Particle ID, tells $\pi^\pm$ from $K^\pm$

- $\sigma^\text{single} = \text{emission pt error} \oplus \text{chrom. dispersion} \oplus \text{tracking} \oplus \text{photodetector granularity}$

- $N_{ph} = \frac{370}{\text{eV cm}} \int \sin^2 \theta R_{\text{mirr}} \epsilon_A Q_{\text{eff}}(E) \, dE$

- need to balance the two. E.g. accepting a wider range of $\gamma$-energies increases $N_{ph}$, but worsens $\sigma^\text{chrom}_\theta$

Last but not least: RICH must be paid for, fit into the LHCb detector and add as little material as possible
What do we want from the RICH?

Particle ID over a momentum range from 1 – 150 GeV

- To cover $p = 1 – 150$ GeV, the LHCb RICH employs three radiator s in two RICH detectors.

(a) $B \rightarrow \pi\pi$ decay

(b) tagging kaons

polar angle vs $p$ for all tracks in $B^0_d \rightarrow \pi\pi$ events

Number of tracks

Momentum (GeV/c)

0 100 200 300
0 50 100 150 200
0 20 40 60 80
0 5 10 15 20

RICH-1

RICH-2

0 50 100 150 200
0 100 200

14
2 radiators in RICH 1

- 5 cm aerogel ($<\text{obs.}\gamma> \sim 6.6/\text{ring}$)
- fine mix of a solid and a gas
- structure $<< \lambda_{\text{photon}}$
- can fine-tune $n$. choose: $n=1.03$
- reduce bg from Rayleigh scattering: filter absorbs $\lambda < 350\text{ nm}$
- 85 cm of $\text{C}_4\text{F}_{10}$ ($<\text{obs.}\gamma> \sim 33/\text{ring}$)
- $n=1.0014$

With both radiators, RICH 1 covers momenta from $\sim 1\text{ GeV}$ to $\sim 70\text{ GeV}$
Rings in RICH 1

\[ p_{\text{min}} \propto \frac{1}{\sqrt{n^2 - 1}}, \quad p_{\text{max}} \propto \sqrt{\frac{1}{\sigma_\theta \sqrt{n - 1}}} \]

\( \theta_c(p) \) for pions and kaons

Pattern recognition in RICH 1
RICH 2 to extend $K/\pi$ sep. to $p = 150$ GeV reduce $n$ and $\sigma_\theta$ by building a huge detector filled with CF$_4$

to extend momentum range...

- reduce $n : 1.0014 \rightarrow 1.0005$
- reduce $\sigma_\theta$
  - smaller dispersion: $\sigma_{\theta}^{\text{chrom}} : 0.8 \text{ mrad} \rightarrow 0.4 \text{ mrad}$
  - larger focal length
    $0.85 \text{ m} \rightarrow 4 \text{ m}$
    $\sigma_{\theta}^{\text{pix}} : 0.8 \text{ mrad} \rightarrow 0.2 \text{ mrad}$
    $\rightarrow \sigma_{\theta}^{\text{total}} : 1.5 \text{ mrad} \rightarrow 0.6 \text{ mrad}$

with 167 cm of CF$_4$ see 18 ph/ring

To keep a compact design, flat mirrors reflect the photons onto the photo-detector plane. The angular acceptance is reduced to 120 mrad.
# Mirrors and Alignment

<table>
<thead>
<tr>
<th></th>
<th>RICH 1</th>
<th>RICH 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>area covered by</td>
<td>16 rectangles</td>
<td>56 hexagons</td>
</tr>
<tr>
<td>spherical area</td>
<td>2.7 m²</td>
<td>9.2 m²</td>
</tr>
</tbody>
</table>

- **Material**: 6 mm glass, coated with 900 nm Al, over-coated with 200 nm quartz.  
  **Reflectivity**: $\sim 90\%$

- **Alignment**:
  - **first**: in-situ survey of all positions to $< 0.5 \text{ mrad}$ in RICH 1, $0.1 \text{ mrad}$ in RICH 2
  - **laser system** to monitor changes in time.
  - **then use** $\beta = 1$ tacks for final precision ($< 0.1 \text{ mrad}$)
Photo Detectors for the RICH

Requirements

They must be...

- Sensitive & efficient
  (expect to see only 6.6ph/ring from aerogel)
- Fast (1 bunch-crossing every 25 ns)
- Precise (pixel size 2.5 mm)
- Affordable: cover 2.6 m² with photo detectors

They'll have to cope with...

- Up to 3 kRad/year
- Magnetic fringe field of 20 – 30 Gauss
The Pixel HPD

- multi-alkali photo cathode on quartz window $\int Q_{\text{eff}}(E) dE = 0.77 \text{eV}$
- Si detector: $\sim 90\%$ efficient (expected)
- X-focusing $e^-$-optics map $\varnothing 75 \text{mm}$ cathode onto $\varnothing 15 \text{mm}$ on Si sensor.
- 1024 square pixels $0.5 \times 0.5 \text{mm}^2$ on Si $\Leftrightarrow 2.5 \times 2.5 \text{mm}^2$ on cathode
- Internal binary read-out (rad-hard, $\tau_p = 25 \text{ns}$)
- $\mu$ metal shielding against stray-fields
Cathode dispersion of radiators

\[ \int Q_{\text{eff}}(E) \, dE = 0.77 \text{eV} \]
Tube Dimensions

Tube with magnetic shielding  Stacked tubes (87 mm between centers)

Active area fraction $= 0.907 \times (75/87)^2 = 0.67$
Simulated Mean Occupancies/Channel

*RICH 1*

< 8%

Rarely more than one photon/pixel ⇒ binary readout OK

*RICH 2*

< 1%
RICH prototype with 61 pixel Si sensor

photon yield found: 7.7/tube(evt), expected: 7.8/tube(evt)
Magnetic Field tests
Image of cross with and without field (30 G)

Full-scale prototype tubes (but: with phosphor-cathode and CCD detector) with $\mu$ metal shielding were exposed fields up to 30 G
- image remains on Si detector
- point spread function barely effected
- distortion can be corrected off-line.
\( \pi/K \) sep at 50 GeV in RICH 2 prototype

Cherenkov angle distribution obtained with the full-scale RICH-2 prototype (equipped with the smaller 61-pixel HPD from DEP, pixel size 2 mm) beam momentum = 50 GeV
Kaon Tag equivalent to a gain in statistics of factor $3\frac{1}{2}$

- Efficiency $\epsilon = 31.2\%$
- Misstag rate $\omega = 31.0\%$
- Statistically equiv to
  \[ P = \epsilon (1 - 2\omega)^2 = 4.5\% \]
  perfectly tagged events.
- Before kaon tag: $P \approx 1.8\%$
- All tags combined: $P \approx 6.2\%$

Compare Performance with RICH/with perfect part. ID:
RICH $P = 4.5\%$ Perf. $P = 6.6\%$
$B^0_d \rightarrow \pi\pi$

With RICH:
- Signal/two-body bg = 15
- S/B (inc. combinatorics) > 1
- event yield (rec & tagged) 4.9 $k$/year
\[ \beta + \gamma \] from \[ B^0_d \rightarrow \pi\pi \]

Tree diagram

Without penguin contributions:
\[ A^{\text{no peng}}_{\pi\pi} (\tau) = D \cdot A^{\text{mix}} \sin (\Delta m\tau) \]
with \[ D = \frac{1-2\omega}{1+B/S} \]
and \[ A^{\text{mix}} = \sin (2(\beta + \gamma)) \]

With penguins:
\[ A_{\pi\pi} (\tau) = D \left( A^{\text{dir}} \cos (\Delta m\tau) + A^{\text{mix}} \sin (\Delta m\tau) \right) \]

Can measure \( A^{\text{dir}} \) and \( A^{\text{mix}} \) very well:
\( \sigma_{A^{\text{dir}}}, \sigma_{A^{\text{mix}}} < 0.1 \) after 1 year

Interpreting this in terms of \( \beta + \gamma \) is difficult because of the unknown penguin contributions.
\[ \beta + \gamma \text{ from } B^0_d \rightarrow \pi\pi \text{ and } B^0_s \rightarrow KK \]

Assuming U-spin symmetry for the strong interaction, a combined analysis \( B^0_d \rightarrow \pi\pi \) and \( B^0_s \rightarrow KK \) allow simultaneous extraction of \( \beta \), \( \gamma \) and the penguin contributions

- No problem from FSI effects
- Penguins are not a problem, but part of the measured parameters (\( \rightarrow \) sensitive to New Physics)
- Exploits LHCb’s high sensitivity in \( B^0_d \rightarrow \pi\pi \) as well as its \( B^0_s \) physics potential
- Effects of U-spin assumption need to be quantified
\[ \beta + \gamma \text{ from } B_{d}^{0} \rightarrow \pi\pi \text{ and } B_{s}^{0} \rightarrow KK \]

From 3.6k \( B_{s}^{0} \rightarrow KK \) reconstructed and tagged evts/year, for \( \Delta m_{s} = 20 \text{ps}^{-1} \)

- \( \sigma_{A_{\text{dir}}} \), \( \sigma_{A_{\text{mix}}} = 0.1 \) after 1 year

Combined with \( B_{d}^{0} \rightarrow \pi\pi \), this translates to:

- \( \sigma_{\beta+\gamma} \approx 5^\circ \) after 1 year
$B_s^0 \rightarrow D_s K$

**No RICH**

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>5.2</td>
<td>10000</td>
</tr>
<tr>
<td>5.25</td>
<td>8000</td>
</tr>
<tr>
<td>5.3</td>
<td>6000</td>
</tr>
<tr>
<td>5.35</td>
<td>4000</td>
</tr>
<tr>
<td>5.4</td>
<td>2000</td>
</tr>
<tr>
<td>5.45</td>
<td>1000</td>
</tr>
<tr>
<td>5.5</td>
<td>500</td>
</tr>
<tr>
<td>5.55</td>
<td>200</td>
</tr>
<tr>
<td>5.6</td>
<td>100</td>
</tr>
<tr>
<td>5.65</td>
<td>50</td>
</tr>
<tr>
<td>5.7</td>
<td>20</td>
</tr>
</tbody>
</table>

**With RICH**

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>5.1</td>
<td>1400</td>
</tr>
<tr>
<td>5.2</td>
<td>1200</td>
</tr>
<tr>
<td>5.3</td>
<td>1000</td>
</tr>
<tr>
<td>5.4</td>
<td>800</td>
</tr>
<tr>
<td>5.5</td>
<td>600</td>
</tr>
<tr>
<td>5.6</td>
<td>400</td>
</tr>
</tbody>
</table>

2.1 k evts/year, S/B=1.3
Extracting $\gamma$ from $B_s^0 \rightarrow D_s K$

- $D_s K$ is not a CP eigenstate - need to measure 2 asymmetries:
  
  $$A_{D_s K^+}(\tau) = \frac{\Gamma(B_d^0 \rightarrow D_s^- K^+)-\Gamma(B_d^0 \rightarrow D_s^+ K^+)}{\Gamma(B_d^0 \rightarrow D_s^- K^+)+\Gamma(B_d^0 \rightarrow D_s^+ K^+)}$$
  
  and CP-conjugate

- Can extract both, CP phase ($-2\delta\gamma + \gamma$) and possible strong interaction phase.

- $B_s$ mixing ($2\delta\gamma$), including possible new physics effects, from $B_s^0 \rightarrow J/\psi \phi$

- No Penguins

- theoretically clean channel - benchmark SM-$\gamma$ measurement.

- $\sigma_\gamma \approx 6^\circ - 13^\circ$ after 1 year
Conclusion

• The LHC is going to provide an enormous number of $b\bar{b}$ pairs
• LHCb is being built to exploit this for a large variety of B-physics measurements, probing the SM
• For high precision $\bar{C}P$ measurements in many different channels, particle ID, esp. $K/\pi$ separation, is essential.
• The LHCb RICH-system will provide $K/\pi$ sep for $p = 1 - 150$ GeV
What follows are back-up slides
Photo Detector Backup Option

Multi Anode Photomultiplier tubes have been shown to fulfill the RICH requirements and are being maintained as a back-up option.

lens system
testbeam data
An alternative way to cope with penguins is to use $B_d^0 \rightarrow \rho \pi$ decays:

$$B_d^0 \rightarrow \rho^+ \pi^-$$

$$B_d^0 \rightarrow \rho^- \pi^+ \rightarrow \pi^+ \pi^- \pi^0$$

extract $\beta + \gamma$, penguin and tree terms separately

- $\sigma_{\beta+\gamma} \sim 5^\circ$ after 1 year
$K/\pi$ separation as function of $p$

$\Delta \sigma (\pi - K)$

Log momentum

$\Delta \sigma (\pi - K)$

Momentum [GeV/c]

$\sigma$–separation of $\pi$ and $K$ hypothesis for true pions in triggered and accepted signal events; $\Delta \sigma = \sqrt{2\Delta \ln \mathcal{L}}$

$> 2\sigma$ separation: 1 – 150 GeV

$> 3\sigma$ separation: 2 – 100 GeV
Material Budget

Contributions (expressed in fractions of a radiation length) to the material in RICH 1 and RICH 2, which fall within the LHCb acceptance

<table>
<thead>
<tr>
<th>Item</th>
<th>RICH 1</th>
<th>RICH 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entrance window</td>
<td>0.001</td>
<td>0.014</td>
</tr>
<tr>
<td>Aerogel</td>
<td>0.033</td>
<td></td>
</tr>
<tr>
<td>Gas radiator</td>
<td>0.024</td>
<td>0.017</td>
</tr>
<tr>
<td>Mirror</td>
<td>0.046</td>
<td>0.046</td>
</tr>
<tr>
<td>Mirror support</td>
<td>0.030</td>
<td>0.033</td>
</tr>
<tr>
<td>Exit window</td>
<td>0.006</td>
<td>0.014</td>
</tr>
<tr>
<td>Total ($X_0$)</td>
<td>0.140</td>
<td>0.124</td>
</tr>
</tbody>
</table>
## Radiators

<table>
<thead>
<tr>
<th>Material</th>
<th>CF$_4$</th>
<th>C$<em>4$F$</em>{10}$</th>
<th>Aerogel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$ [cm]</td>
<td>167</td>
<td>85</td>
<td>5</td>
</tr>
<tr>
<td>$n$</td>
<td>1.0005</td>
<td>1.0014</td>
<td>1.03</td>
</tr>
<tr>
<td>$\theta_{\text{max}}$ [mrad]</td>
<td>32</td>
<td>53</td>
<td>242</td>
</tr>
<tr>
<td>$p_{\text{thresh}}(\pi)$ [GeV]</td>
<td>4.4</td>
<td>2.6</td>
<td>0.6</td>
</tr>
<tr>
<td>$p_{\text{thresh}}(K)$ [GeV]</td>
<td>15.6</td>
<td>9.3</td>
<td>2.0</td>
</tr>
<tr>
<td>$\sigma_{\text{emission}}$ [mrad]</td>
<td>0.31</td>
<td>0.74</td>
<td>0.60</td>
</tr>
<tr>
<td>$\sigma_{\text{chromatic}}$ [mrad]</td>
<td>0.42</td>
<td>0.81</td>
<td>1.61</td>
</tr>
<tr>
<td>$\sigma_{\text{pixel}}$ [mrad]</td>
<td>0.18</td>
<td>0.83</td>
<td>0.78</td>
</tr>
<tr>
<td>$\sigma_{\text{track}}$ [mrad]</td>
<td>0.20</td>
<td>0.42</td>
<td>0.26</td>
</tr>
<tr>
<td>$\sigma_{\text{total}}$ [mrad]</td>
<td>0.58</td>
<td>1.45</td>
<td>2.00</td>
</tr>
<tr>
<td>$N_{\text{pe}}$</td>
<td>18.4</td>
<td>32.7</td>
<td>6.6</td>
</tr>
</tbody>
</table>
Charged Particles

Data

MC
Charged Particles

Av. Hits/evt for 120 GeV pions, entering the 61 pixel prototype [here] at 135°

- Typically 25 – 35% of a tube must be masked off.
- Expect to discriminate from Cherenkov hits by the distinctive event shapes.
- 10 – 15% of all hits originate from such events.
Limits on Momentum Coverage

- Lower limit depends on \( n \):
  \[
  \cos(\theta_c) = \frac{1}{n} \sqrt{1 + \left(\frac{m}{p}\right)^2} \geq 1
  \]

- Upper limit due to:
  \[
  \Delta \theta_c \approx \sqrt{\frac{1}{8n(n-1)} \cdot \frac{\Delta(m^2)}{p^2}} \quad \text{(large } p)\]

\[
 p_{\text{min}} \propto \frac{1}{\sqrt{n^2 - 1}}, \quad p_{\text{max}} \propto \sqrt{\frac{1}{\sigma \theta \sqrt{n - 1}}}
\]

To cover \( p = 1 - 150 \text{ GeV} \), the LHCb RICH employs three radiators in two RICH detectors.
2 RICH detectors

**RICH 1 (before magnet)**
- 2 radiators to cover $p = 1 - 70$ GeV
- ID for prts at polar angles up to 300 mrad

**RICH 2 (after magnet)**
- 1 radiator, bigger, better $\theta_c$ resolution, covers $p = 10 - 150$ GeV
- polar angles up to 120 mrad
Momenta and Polar Angles Covered by the RICHES

Polar angle vs momentum for all tracks in $B^0_d \rightarrow \pi^+\pi^-$ events. Despite the reduced angular acceptance, RICH 2 covers the vast majority of events with $p > 70 \text{ GeV}$.
Extracting $\beta$ from $B_d^0 \rightarrow J/\psi K_s^0$

Get $\beta$ from interference between two decay-paths.

Phase difference is $2\beta$
New Physics in $\beta$

Perhaps $B^0_d \to J/\psi K^0_s$ does not measure the SM $\beta$:

$$\begin{array}{c}
\bar{b} \\
\text{new} \\
\text{FCNC} \\
d \\
\end{array} \quad \begin{array}{c}
\bar{d} \\
\text{new} \\
\text{FCNC} \\
b \\
\end{array}$$

$$\begin{array}{c}
\bar{B} \\
\end{array} \propto e^{-2i(\beta + \phi_{\text{new}})} \begin{array}{c}
\bar{B} \\
\end{array}$$

but some new angle $\beta_{J/\psi K_s} = \beta + \phi_{\text{new}}$

it will measure the $B$-mixing angle in any case.
Kaon Tag

Guess the flavour of the $B^0$ at creation by the flavour of the other $\overline{B^0}$ at decay.

- **lepton tag**: Use $b \rightarrow l^-, \nu_l, c$
- **Kaon tag**: Use $b \rightarrow c \rightarrow s$
- **strategy**: Find high $p_t$ lepton or Kaon
- **Kaon tag** only possible with $K/\pi$ separation.
3 Radiators in 2 RICH Detectors

- To cover $p = 1 - 150$ GeV, the LHCb RICH employs three radiators in two RICH detectors.

polar angle vs $p$ for all tracks in $B^0_d \rightarrow \pi\pi$ events