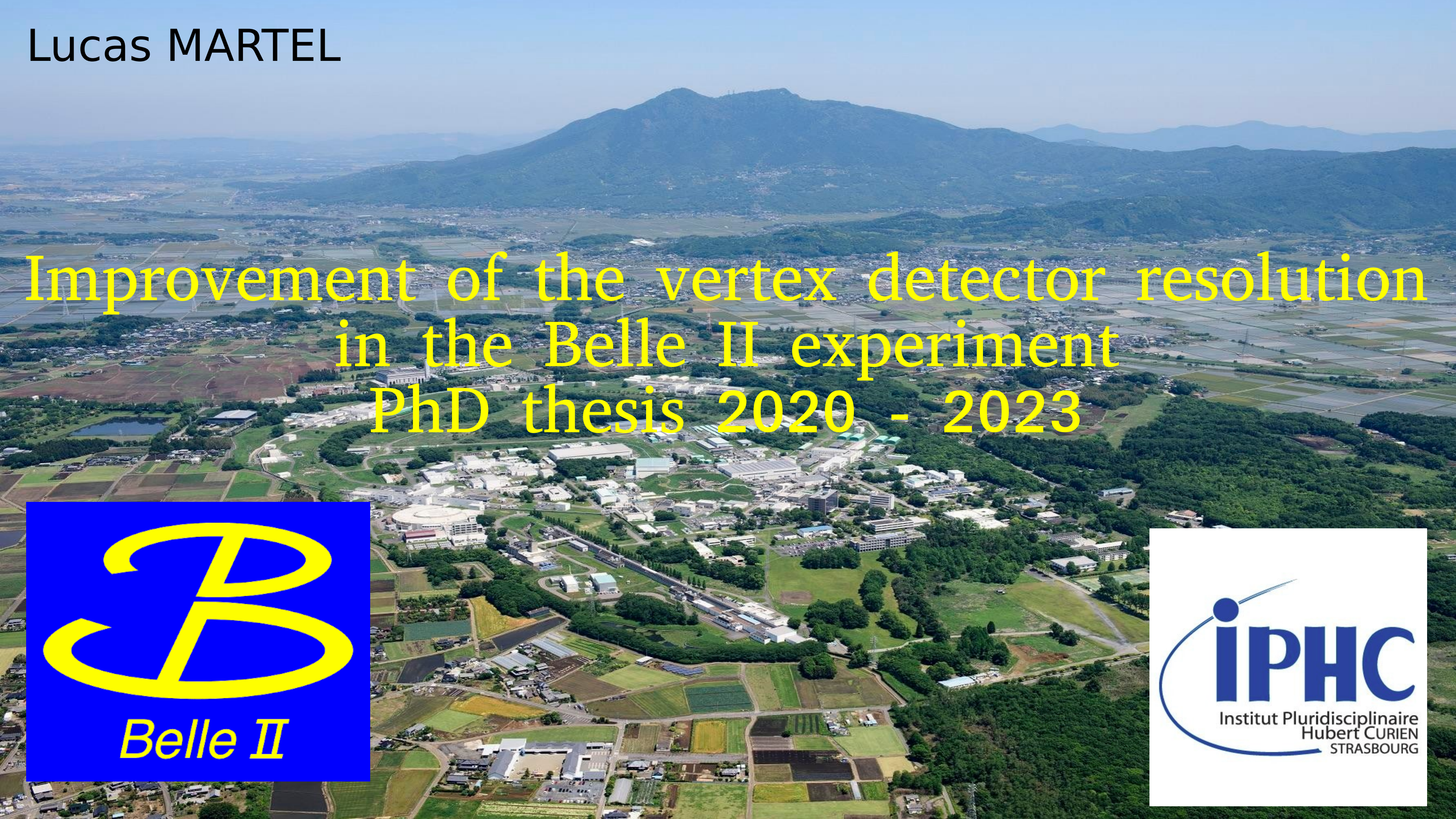


Lucas MARTEL

Improvement of the vertex detector resolution in the Belle II experiment

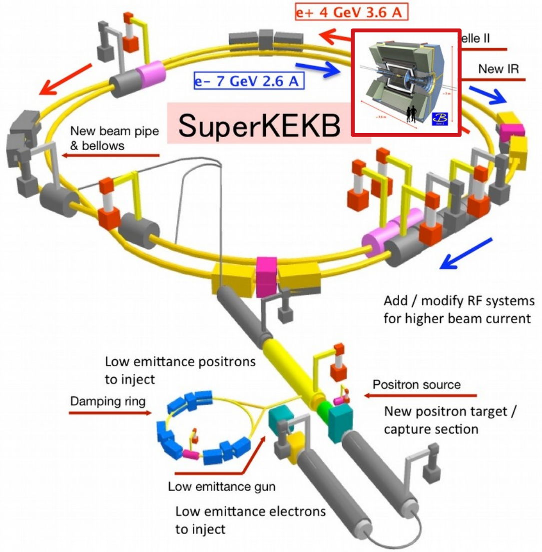
PhD thesis 2020 - 2023

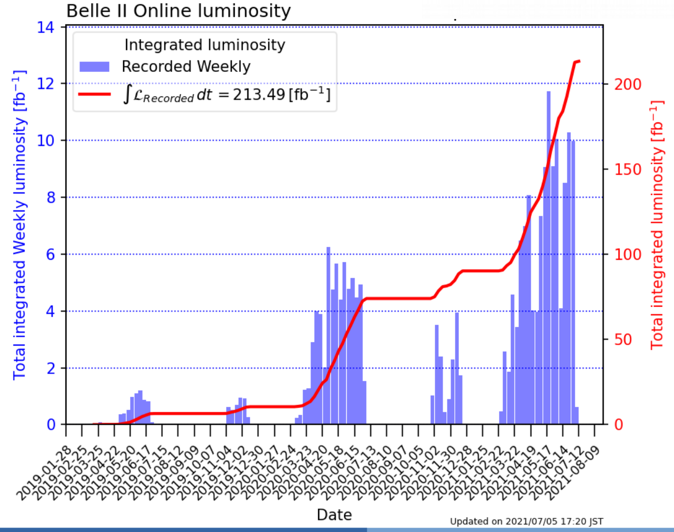
Belle II

IPHC
Institut Pluridisciplinaire
Hubert CURIEN
STRASBOURG

The Belle II experiment

- International collaboration based in Japan
- Data taking since 2019
- Comprised of asymmetric e+e- SuperKEKB collider (10,58 GeV) and Belle II detector
- Highest instantaneous luminosity in the world (> 3 x 10^{34} $cm^{-2}s^{-1}$), 200fb^{-1} of data collected in first two years of running
- Main targets: Discovery of BSM physics
- Strengths: rare and partially invisible decays + precision measurements





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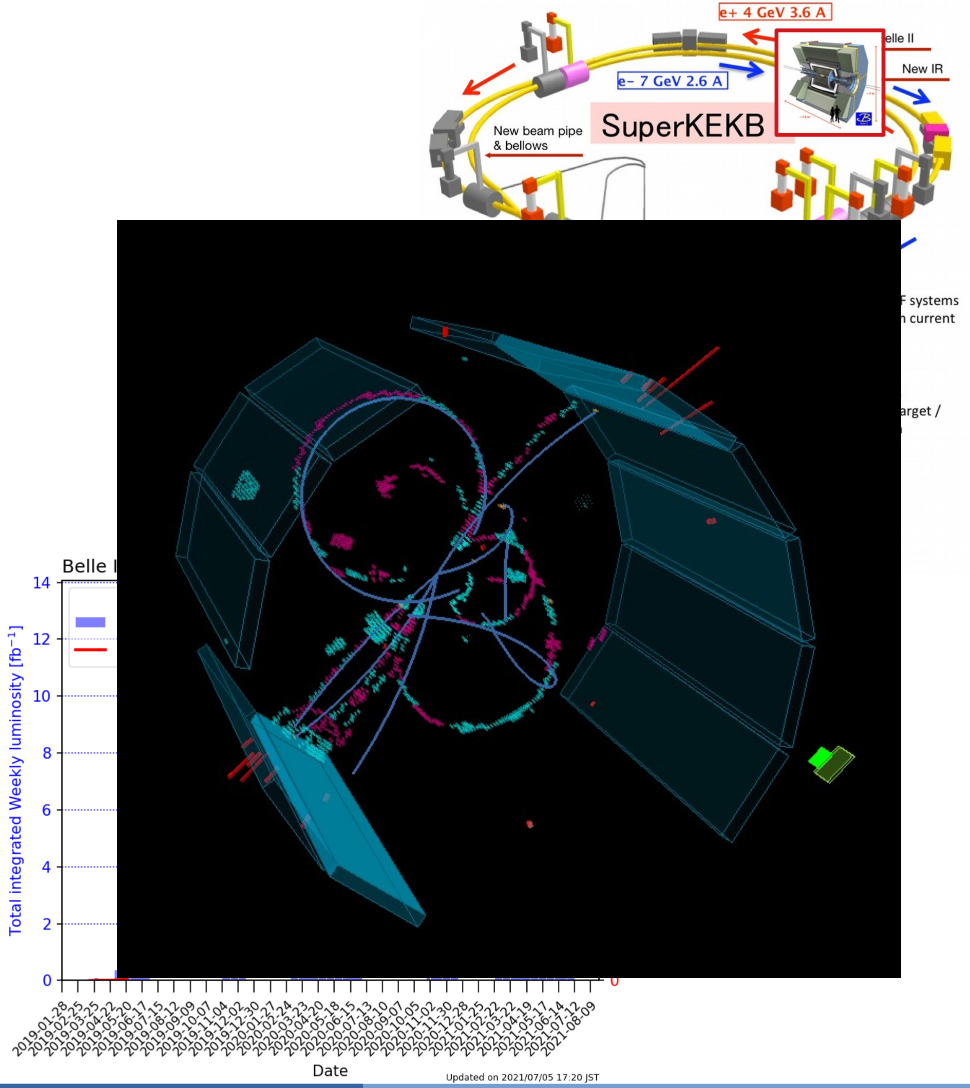
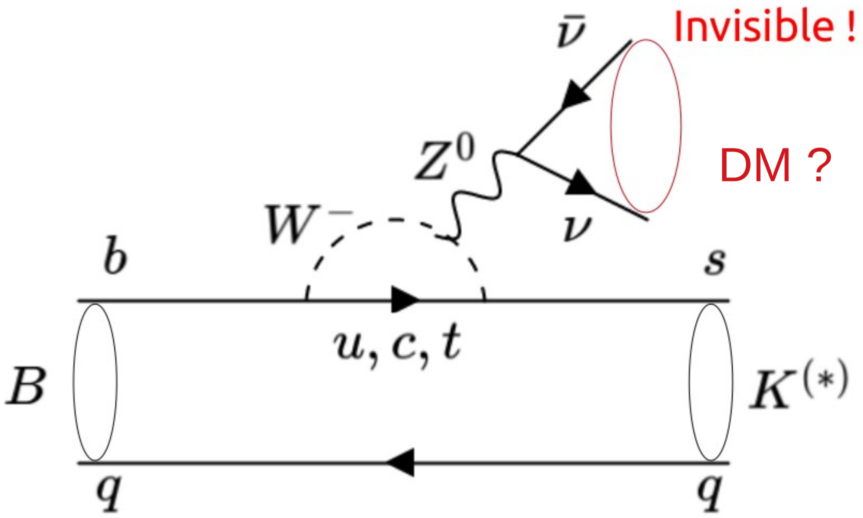


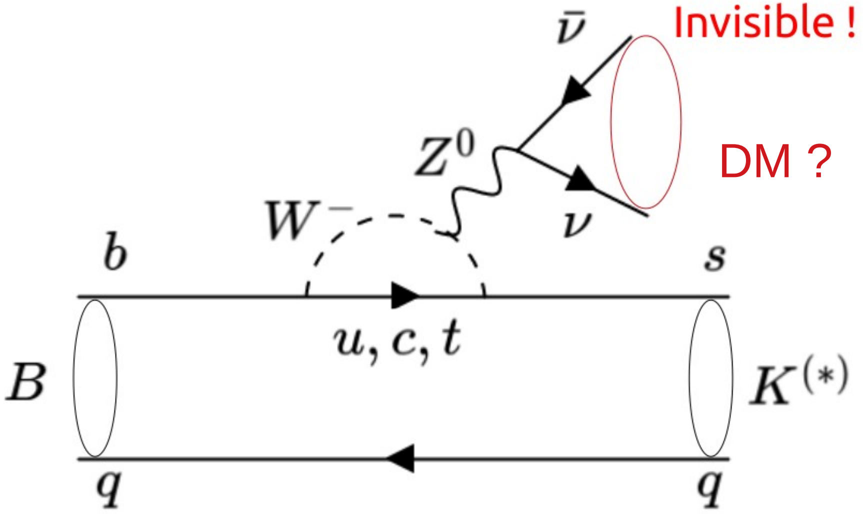
Search for $B \to K^{(*)}\nu\bar{\nu}$ decays

$B \to K^{(*)}\nu\bar{\nu}$ decays :

- Never been observed
- Partially invisible final state
- Rare : $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu}) \sim 10^{-6}$
- Good probe for BSM physics



Search for $B \to K^{(*)}\nu\bar{\nu}$ decays

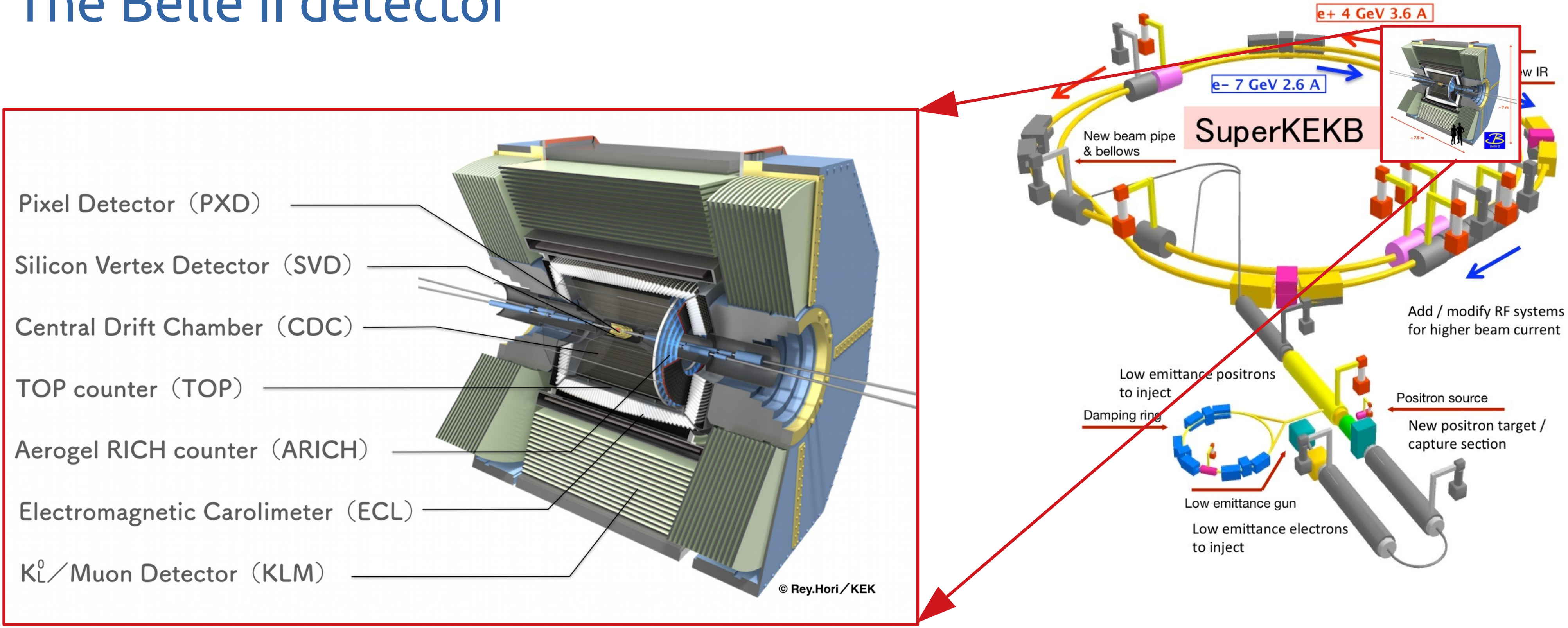


$B \to K^{(*)}\nu\bar{\nu}$ decays :

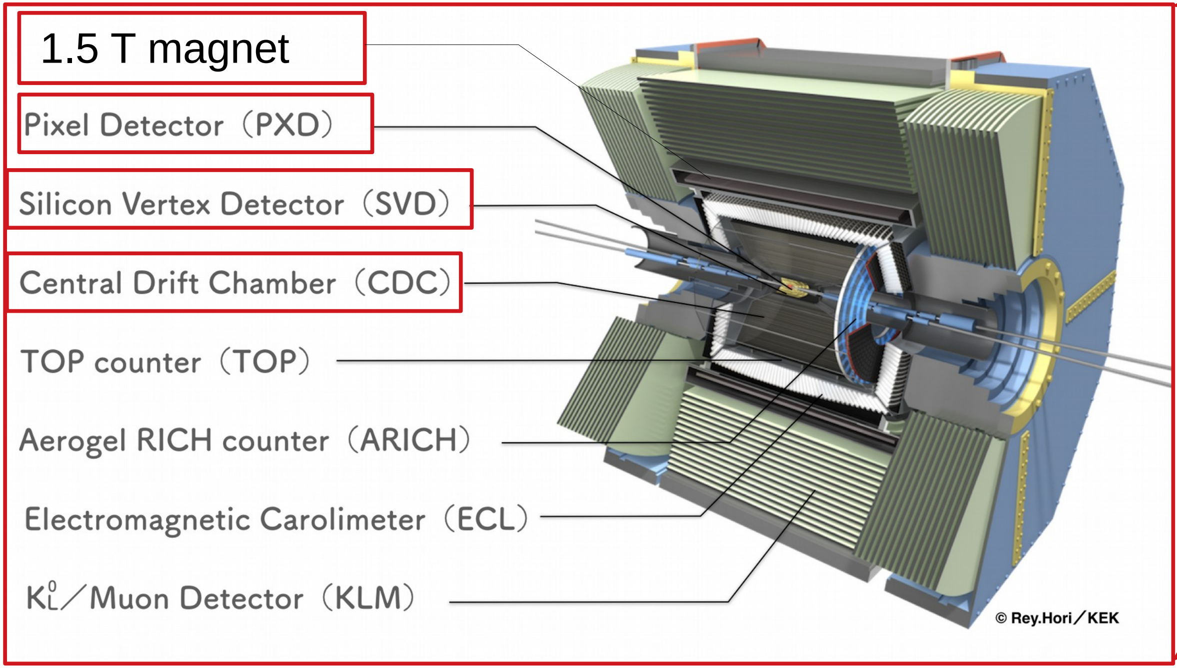
- Never been observed
- Partially invisible final state
- Rare : $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu}) \sim 10^{-5}$
- Good probe for BSM physics

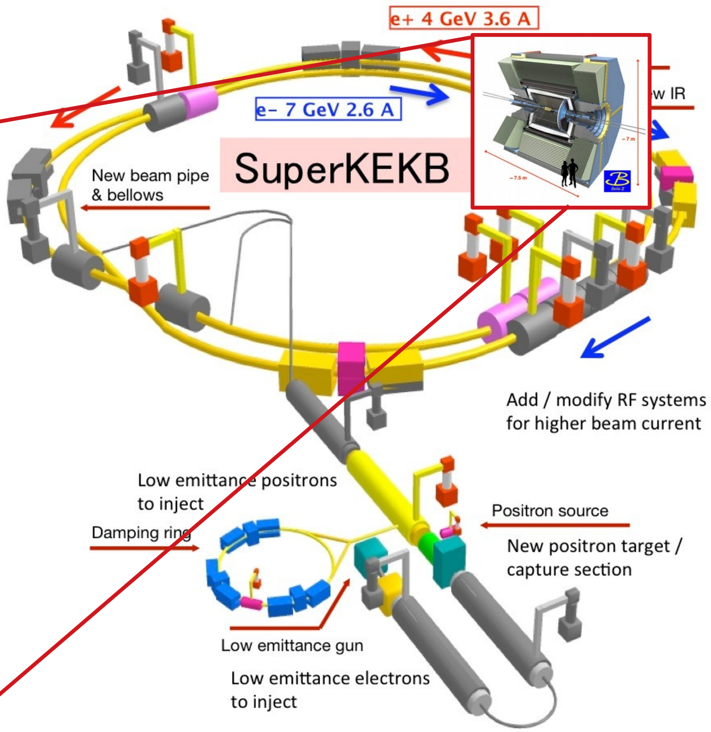
→ Search for rare decays needs the best **reconstruction efficiency** possible

The Belle II detector



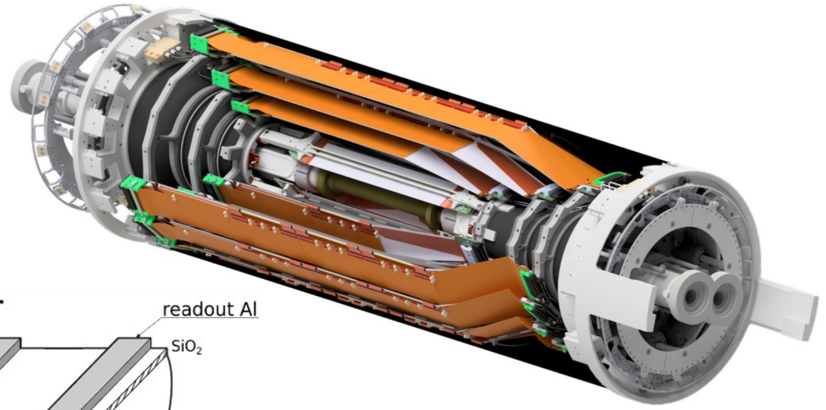
The Belle II detector - Tracking

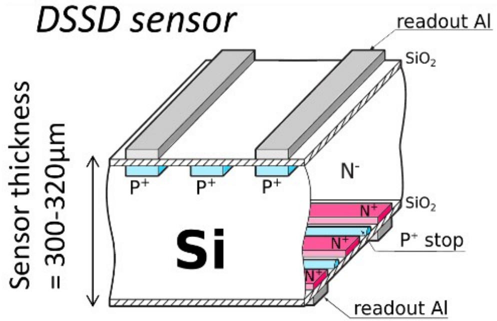




Silicon vertex detector (SVD)

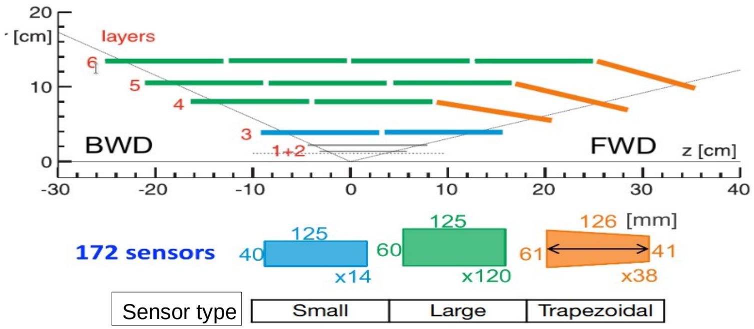
- 4 Concentric layers of detectors
- Double Sided Silicon strip Detectors
  → two sides (p/U - n/V)
- Electronic readout: APV 25 chips
- Goal of SVD: giving 3D position, hit time and deposited charge from charged particles (for tracking (vertexing), PID, PXD data reduction..)

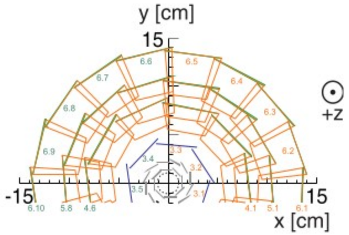




Distance between strips :
50 – 240 μm

Sensors	Small	Large	Trapezoidal
strips p	768	768	768
pitch p	50 μm	75 μm	50-75 μm
strips n	768	512	512
pitch n	160 μm	240 μm	240 μm
thickness	320 μm	320 μm	300 μm





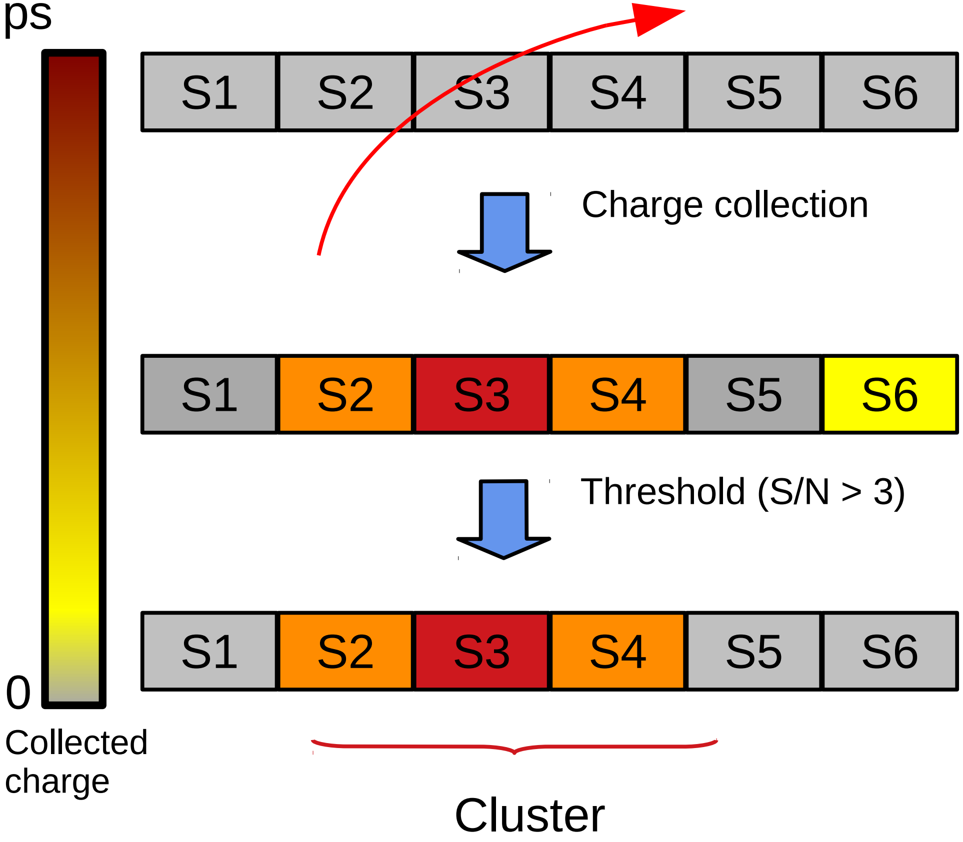
Cluster reconstruction

- The SVD cluster provides information on charged particles, extracted from a set a retained fired strips

- Strip retained if S/N > 3

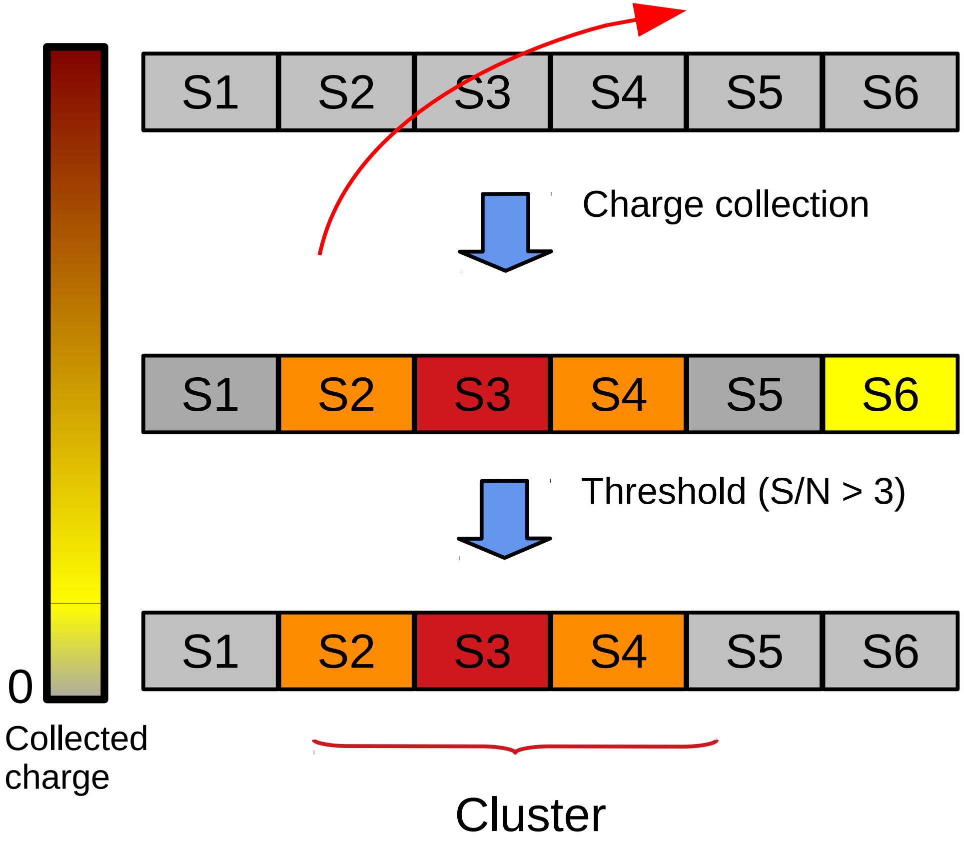
- For each strips, access to :
  - Deposited charge
  - Noise
  - Gain

- Set of retained strips → **Cluster**



Cluster reconstruction

- For each cluster, computation of:
  - Charge S_{cl}
  - Position x_{cl}
  - Time t_{cl}
- For a cluster made of n strips
- $S_{cl} = \Sigma S_i$
- $x_{cl} = \Sigma x_i S_i / \Sigma s_i$ (Center of gravity)
- $t_{cl} = \Sigma t_i S_i / \Sigma s_i$ (Center of gravity)



Estimation of cluster position resolution

- To compute the resolution σ_{cl} we need:
  - **Residuals**
  - Error on the **unbiased track intercept position** σ_t

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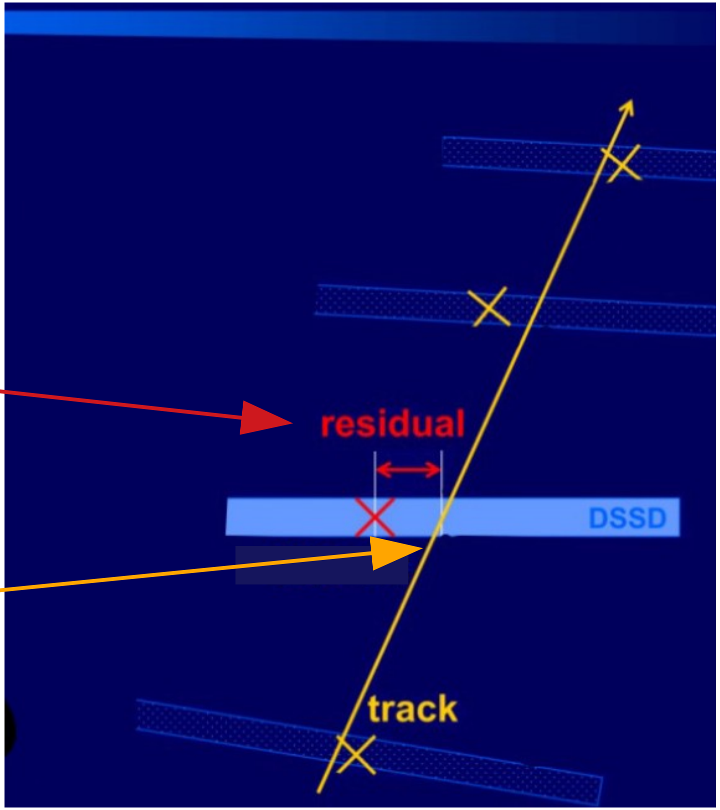


Estimation of cluster position resolution

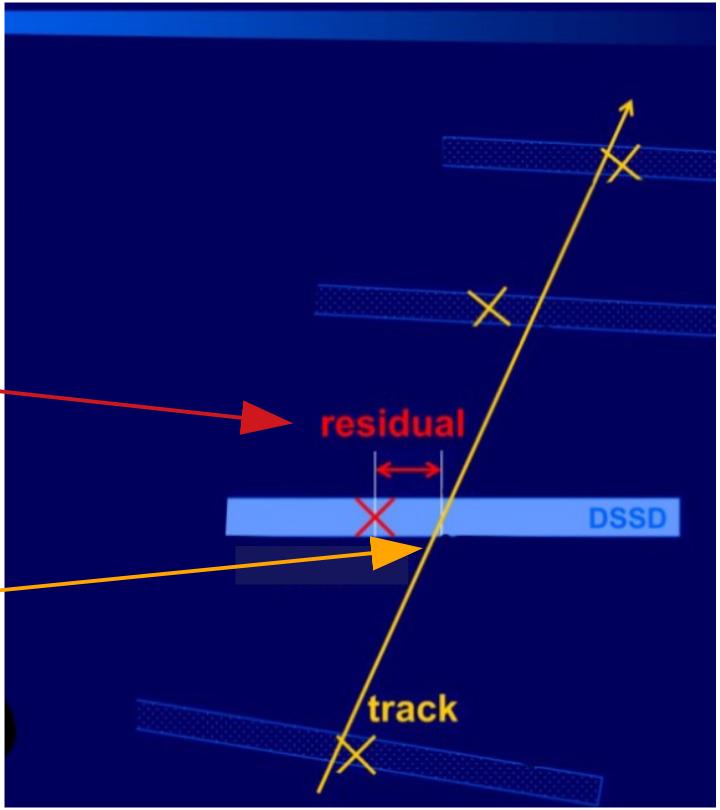
- To compute the resolution σ_{cl} we need:
  - **Residuals**

    measured **cluster position - unbiased track intercept position**

  - Error on the **unbiased track intercept position** σ_t

    Track is fitted while excluding the cluster on the sensor under study.
    The **unbiased track intercept position** is the position where this track crosses the sensor.

$$\sigma_{cl}^2 = < res^2 - \sigma_t^2 >$$



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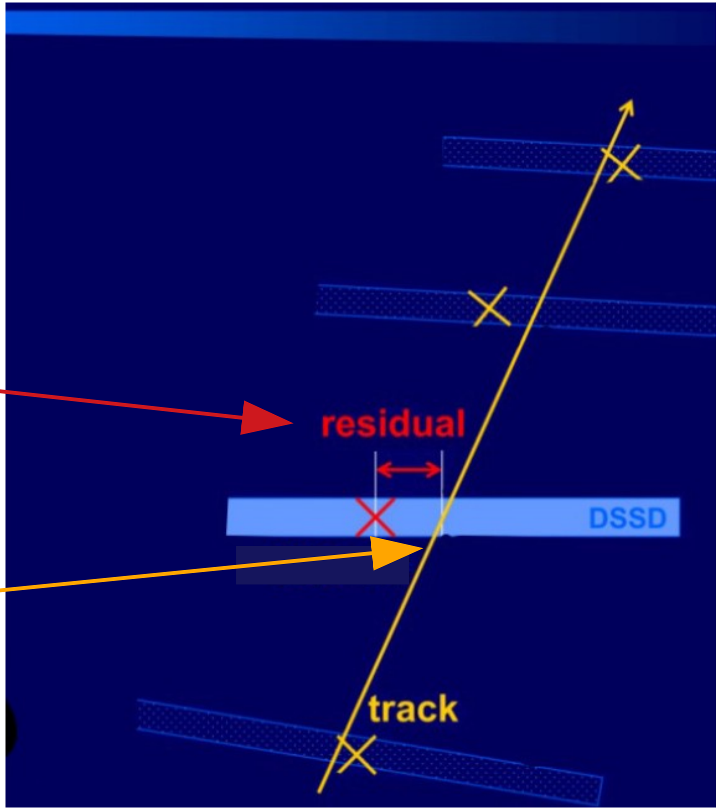
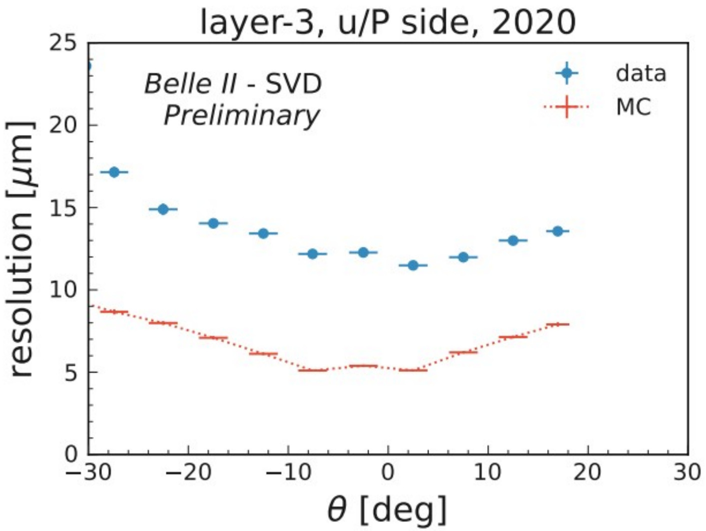


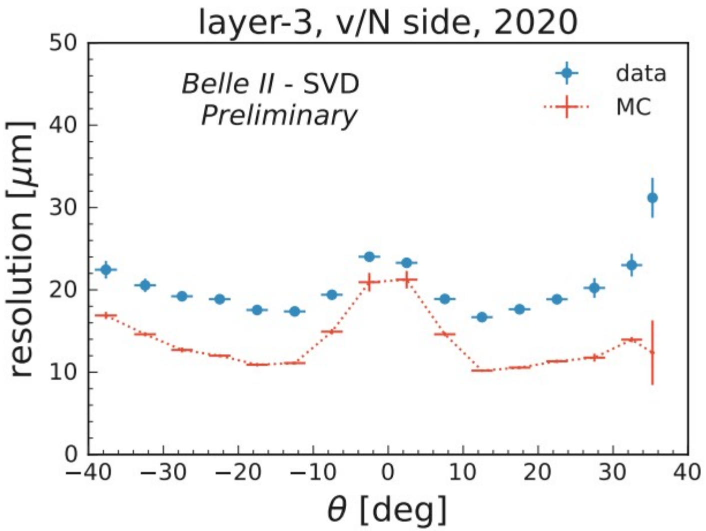
Good cluster position resolution :

➡ **Improved quality of tracks and vertices**
Correct track extrapolation uncertainty

Issues with cluster position resolution

- Resolution estimated in data (~16 fb^{-1} dimuon events) and Monte-Carlo simulation (500k dimuon events)

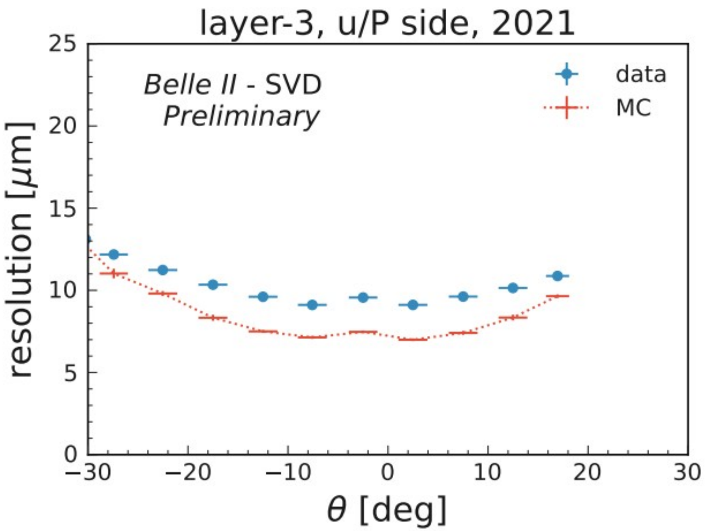


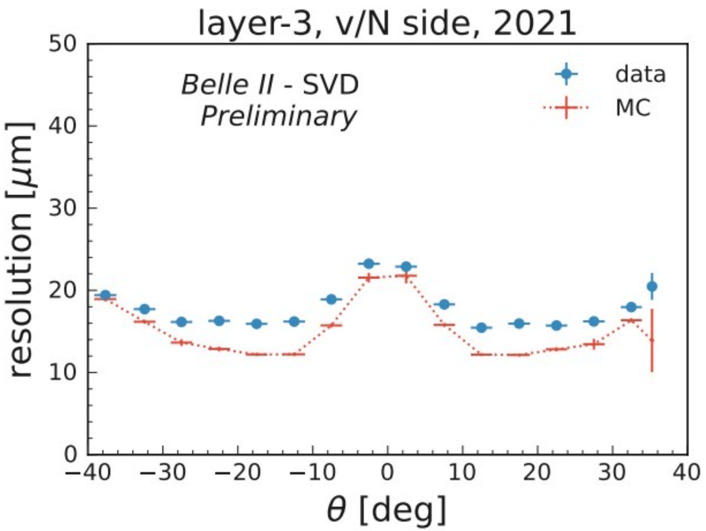


- Discrepancies between data and MC (~ 5 - 8µm) → Issues with reconstruction performance + optimistic Monte-Carlo

Issues with cluster position resolution

- Resolution estimated in data (~16 fb^{-1} dimuon events) and Monte-Carlo simulation (500k dimuon events) + improvements on reconstruction and simulation



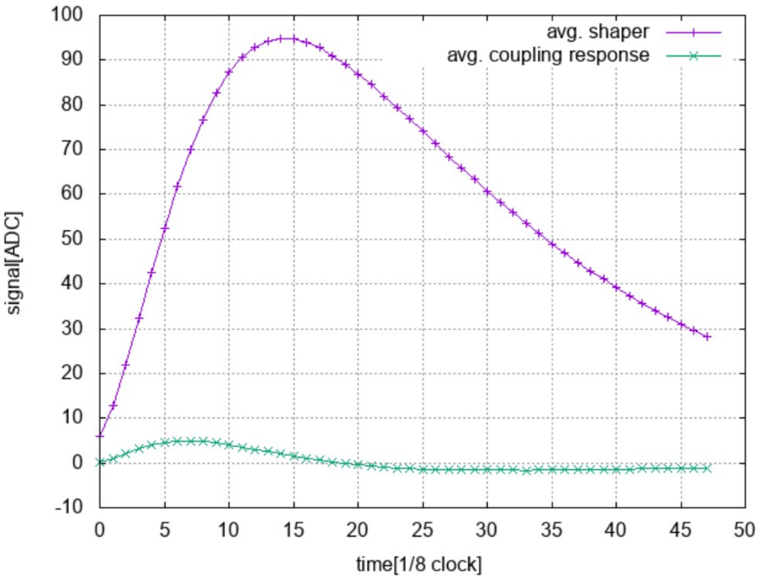


- Overall better agreement between MC and data. But still ~ 1 - 5 µm gap.
- Some tuning necessary → trying to understand and correct smaller effects.

Electronic channel couplings and resolution

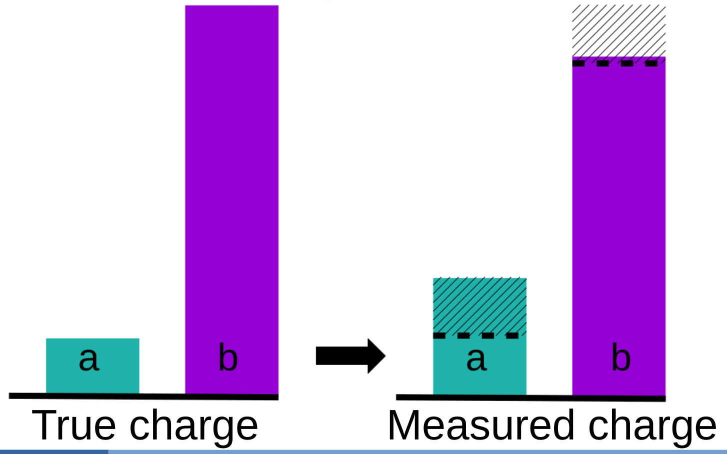
- A signal is injected on a given strip, the waveform of the adjacent APV channel is also checked

- A small signal on the adjacent APV channel is observed with lower time ~7/8 APV clock = 27ns



- Expected effect on strip charges :

charge(a) = $\text{charge}_{\text{real}}$ (a) + 0.06 * charge(b)



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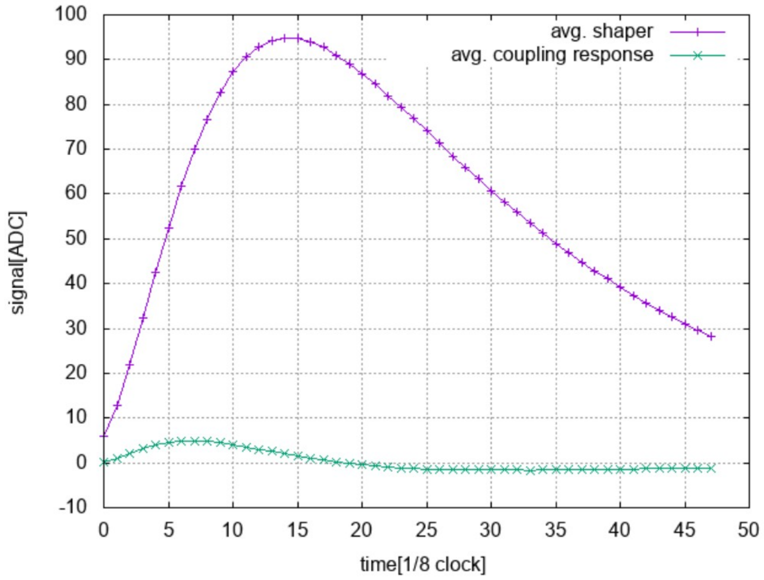

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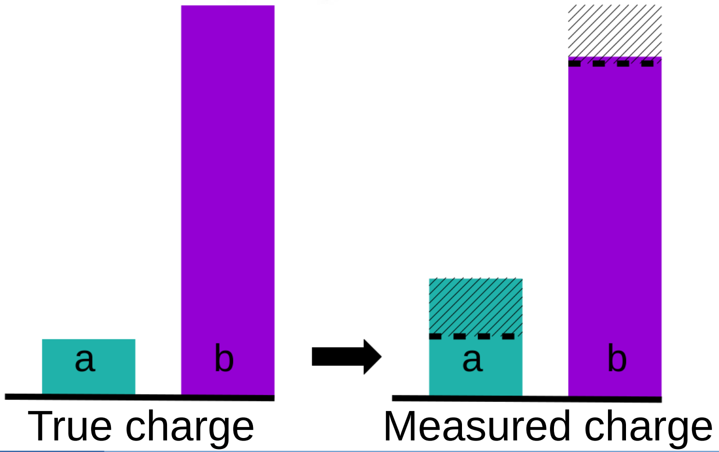
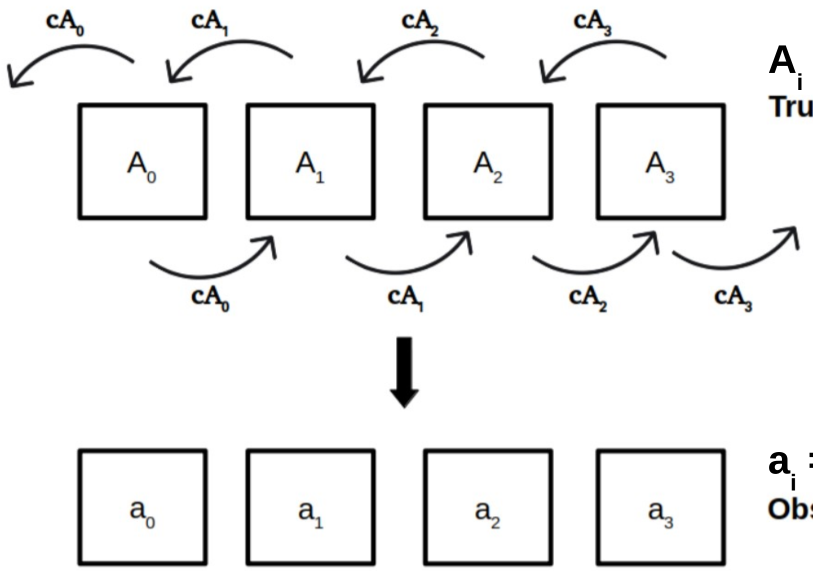
charge(a) = $\text{charge}_{\text{real}}$ (a) + 0.06 * charge(b)

Charge used to compute position : impact on resolution !



Cluster unfolding method

Example for a cluster of 4 strips



A_i =
True charges

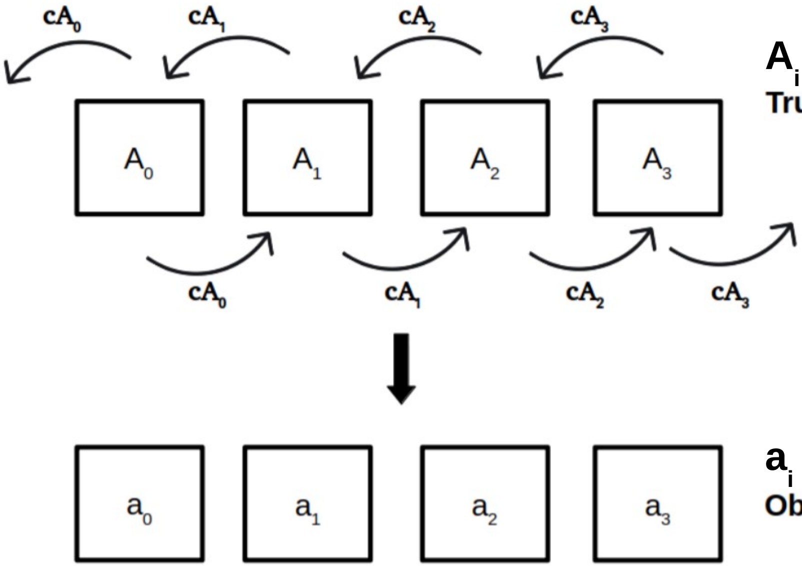
a_i =
Observed charges

In the end, the observed charges follow :

$a_i = (1\text{-}2c)A_i + c(A_{i-1} + A_{i+1})$

From the observations on electronics, c value expected to be ~ 0.06

Cluster unfolding method



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From the observations on electronics, c value expected to be ~ 0.06

Example for a cluster of 4 strips

To correct this effect, we propose to "unfold" the cluster charges :

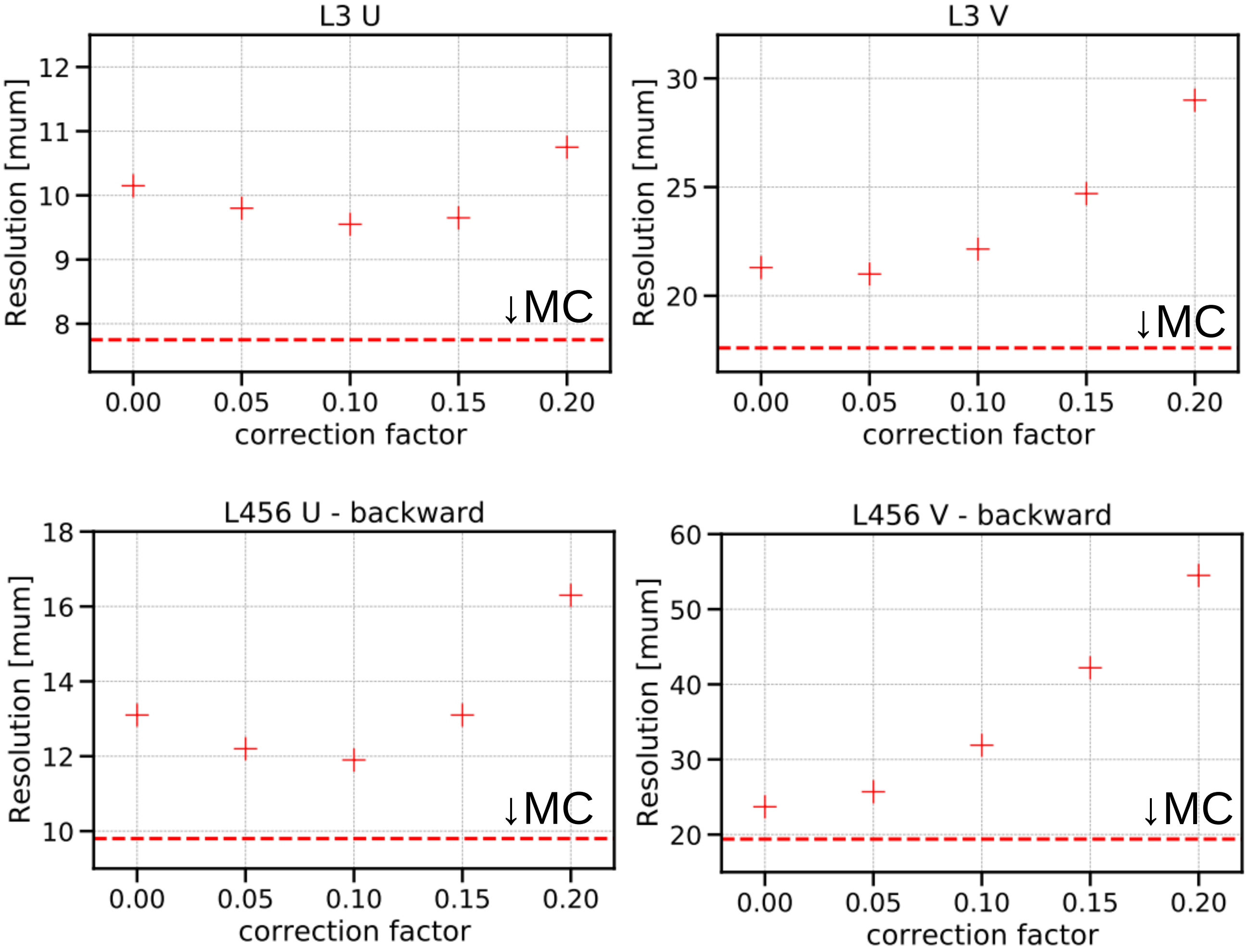
$$\begin{pmatrix} 1-2c & c & 0 & 0 \\ c & 1-2c & c & \\ 0 & c & 1-2c & c \\ 0 & 0 & c & 1-2c \end{pmatrix} \underbrace{\begin{pmatrix} A_1 \\ A_2 \\ A_3 \\ A_3 \end{pmatrix}}_{\text{True}} = \underbrace{\begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_3 \end{pmatrix}}_{\text{Obs}}$$

Unfold by inversion :

$$\underbrace{\begin{pmatrix} A_1 \\ A_2 \\ A_3 \\ A_3 \end{pmatrix}}_{\text{True}} = M^{-1} \underbrace{\begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_3 \end{pmatrix}}_{\text{Obs}}$$

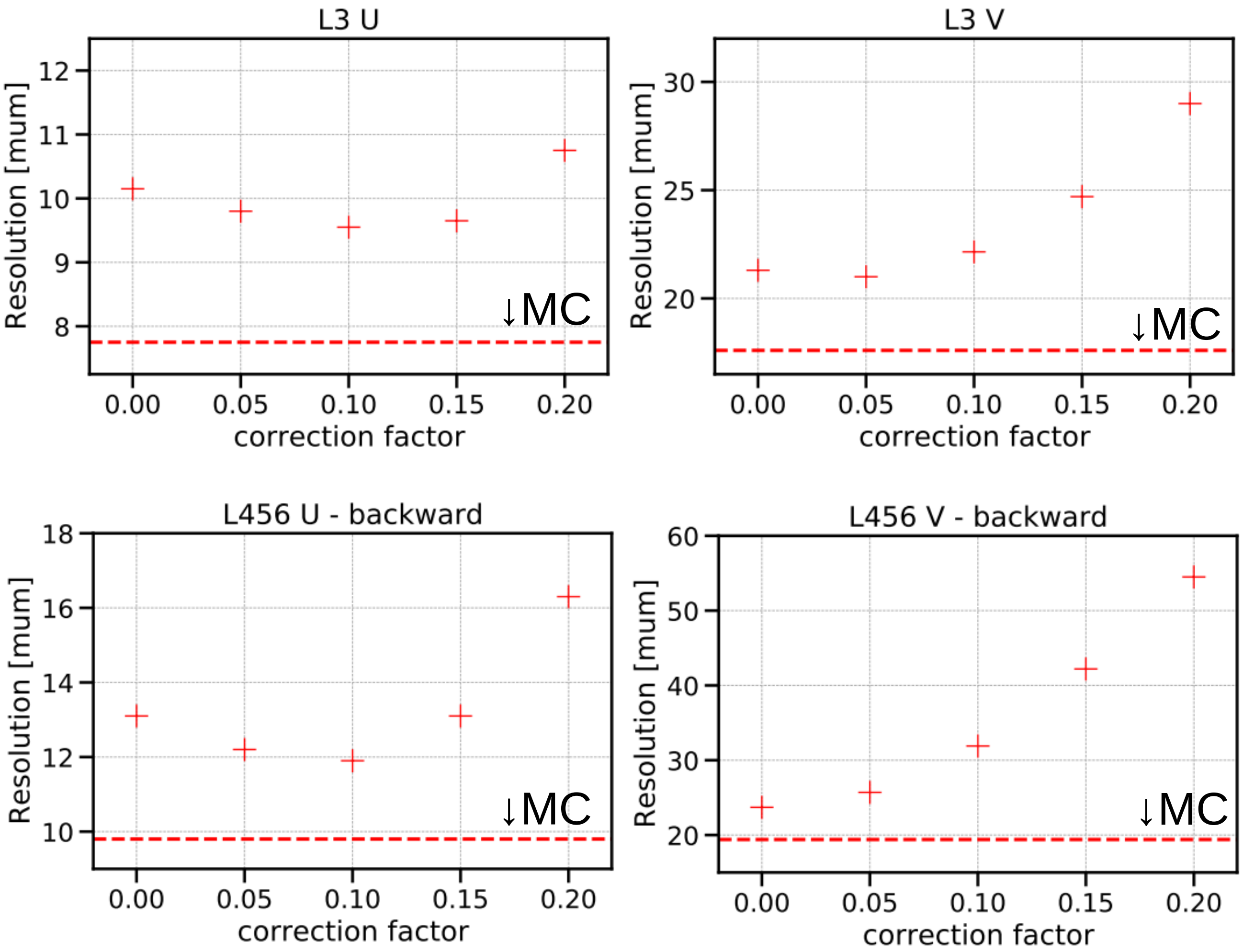
Cluster unfolding method – estimation of best correction factor

- The resolution is computed for each type of sensor for different values of **c** ranging from **0** to **0.2**

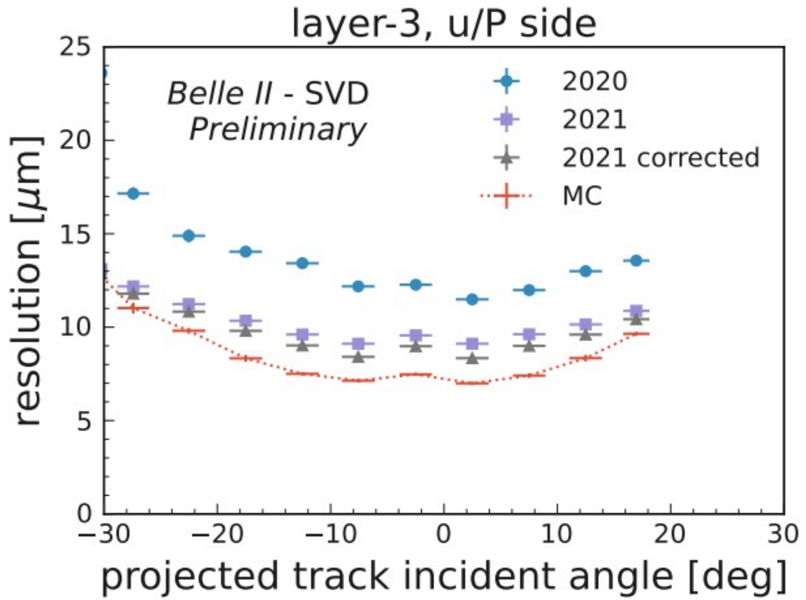


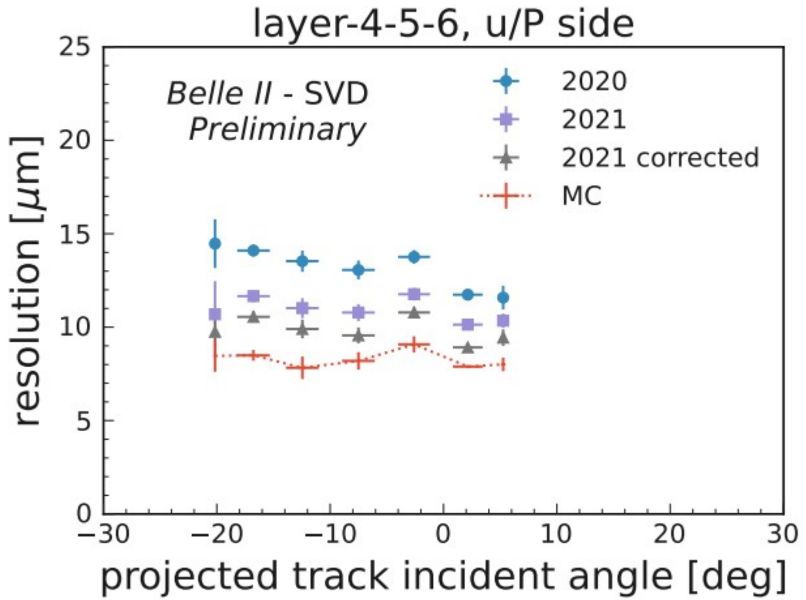
Cluster unfolding method – estimation of best correction factor

- The resolution is computed for each type of sensor for different values of **c** ranging from **0** to **0.2**
- The unfolding method does not improve the resolution on V-side sensors
- However, **U-side** sensors do benefit from the method, with an optimal gain with **c = 0.1** for all type of sensors



Takeaway





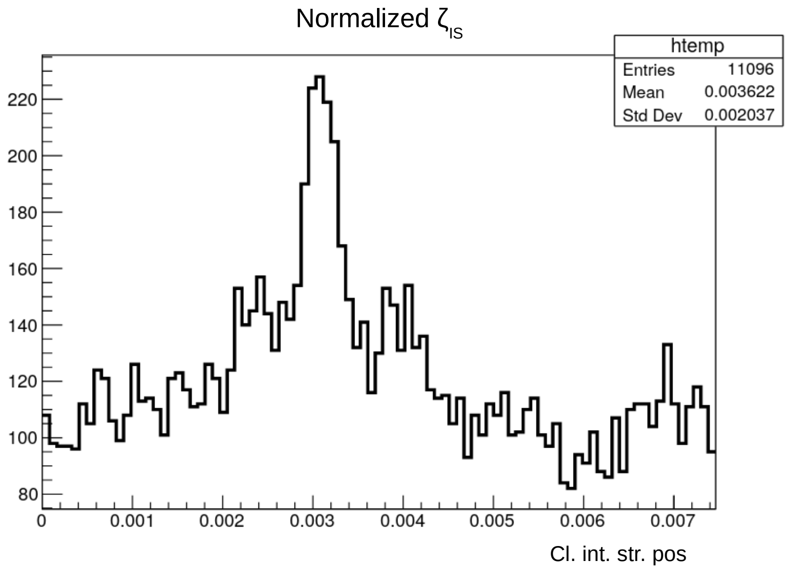
- Improvements seen on U-side sensors with cluster unfolding method (~20 – 30% of the remaining gap between data and MC)
- Unfolding implemented in the Belle II analysis software
- Some work still needed to squash the remaining discrepancies between data and MC

Thank you for listening

Backup

Cluster interstrip position distribution

- Corresponds to the computed position of the cluster within the central strip
- Defined as $\zeta_{IS} = x_{cl}$ mod(pitch)



Expected to be uniform on an evenly irradiated sensor

Cluster interstrip position distribution

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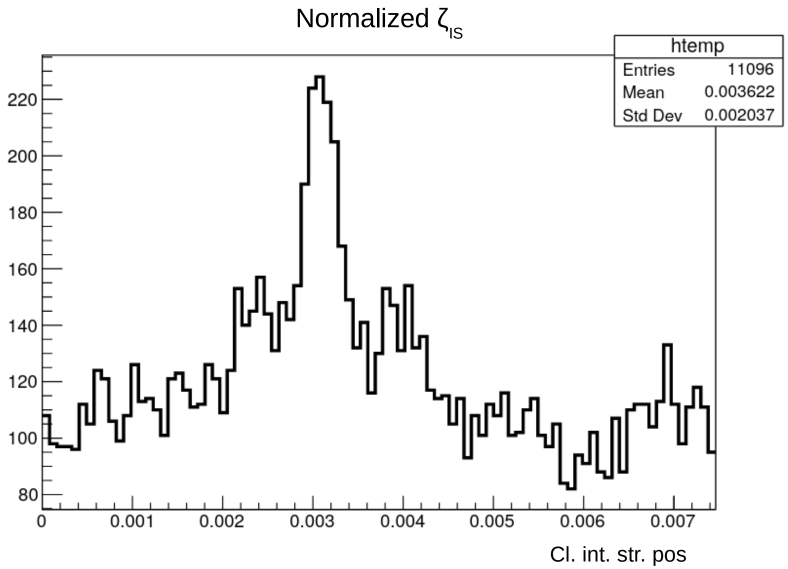

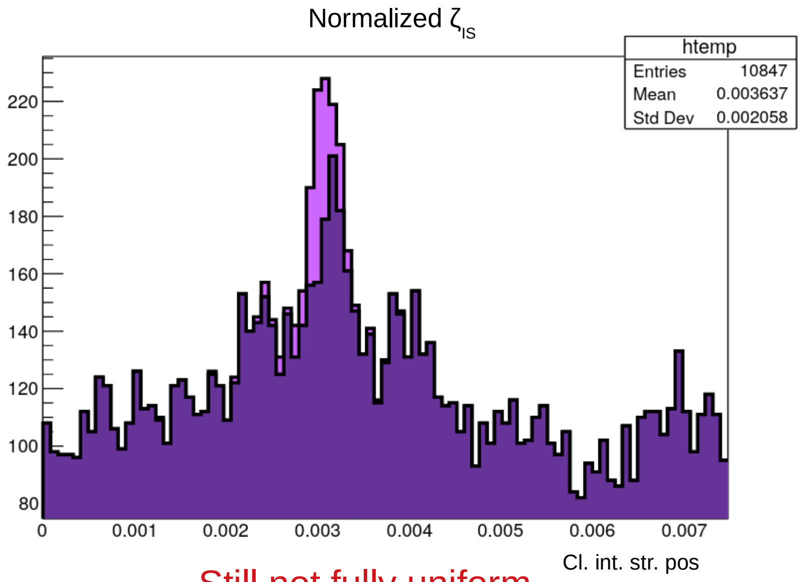

Still not fully uniform

Expected to be uniform on an evenly irradiated sensor
When taking into account clusters of size > 1

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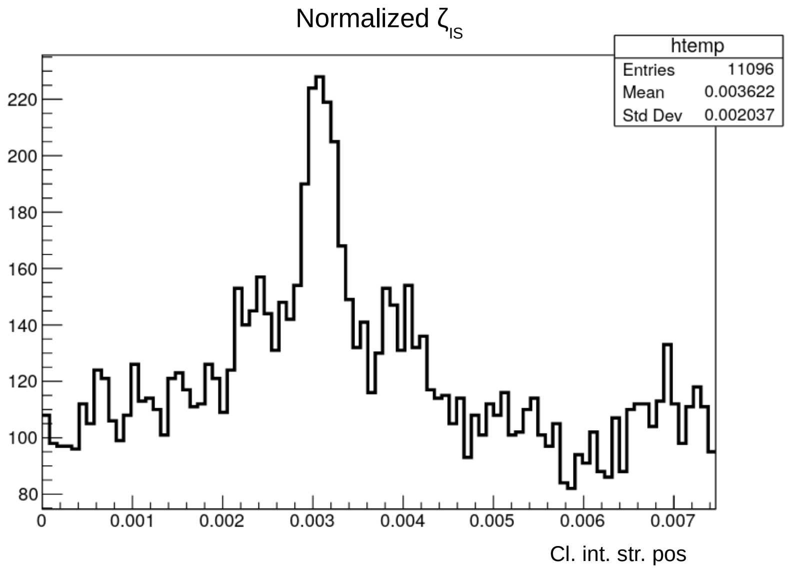
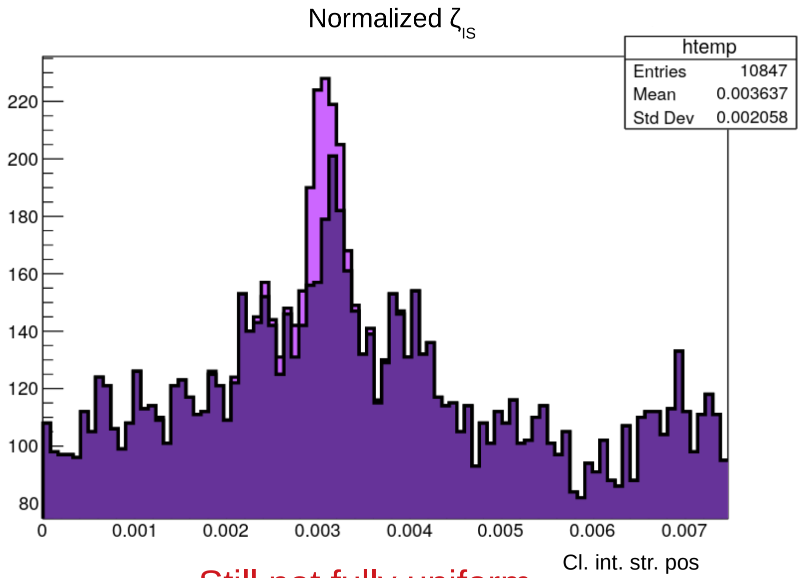




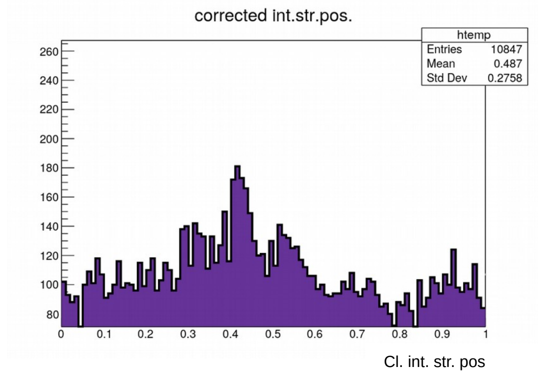
Expected to be uniform on an evenly irradiated sensor
When taking into account clusters of size > 1

Still not fully uniform

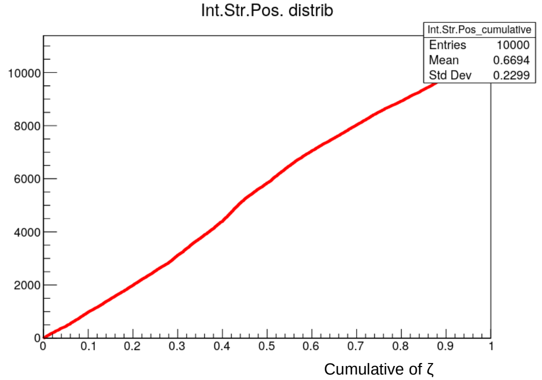
Idea : correct this distribution, use the corrected values of ζ_{IS} to recompute the cluster position ==> could impact resolution

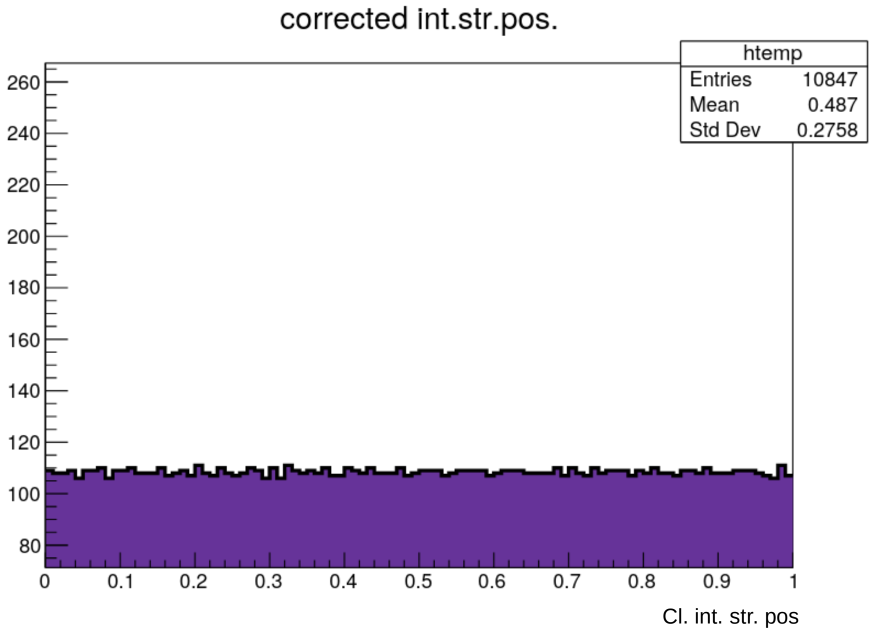
η correction method

- We define the η correction function : $F(\zeta_{IS} = \zeta) = \int_0^{\zeta} P(\zeta_{IS}) d\zeta_{IS}$
- Then we can compute the η-corrected cluster position : $x_\eta = x_{S0} + p * F(\zeta_{IS})$



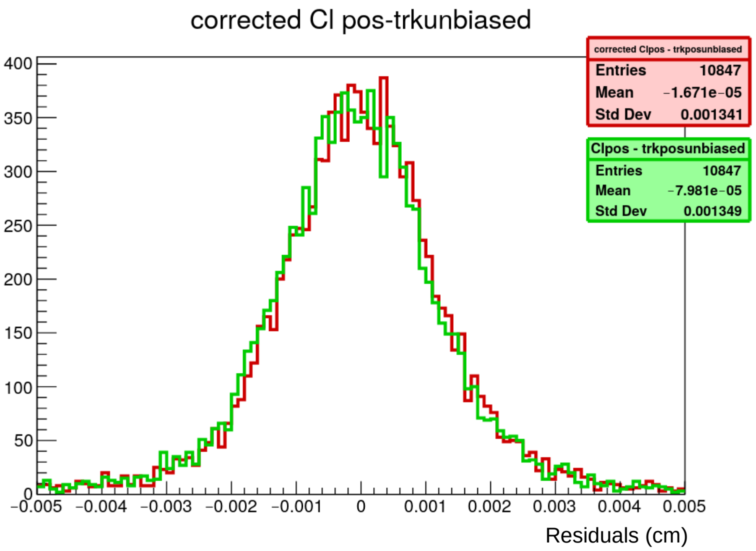
+



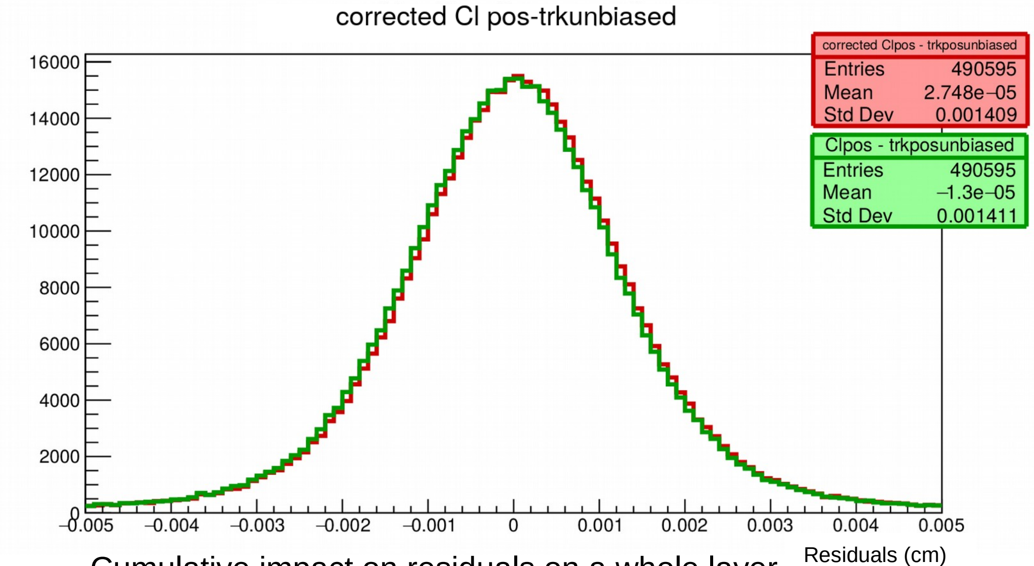


η correction method – impact on residuals

- We compute the residuals using the corrected cluster position and compare the distribution to the original one



Impact on residuals for a given sensor



Cumulative impact on residuals on a whole layer

- In the end, the correction does not have any noticeable effect on the residuals distribution

Estimation of cluster position resolution

- We define the quantity σ^2_{cl} as : $\sigma^2_{cl} = < res^2 - \sigma^2_t > = < res^2 > - < \sigma^2_t >$

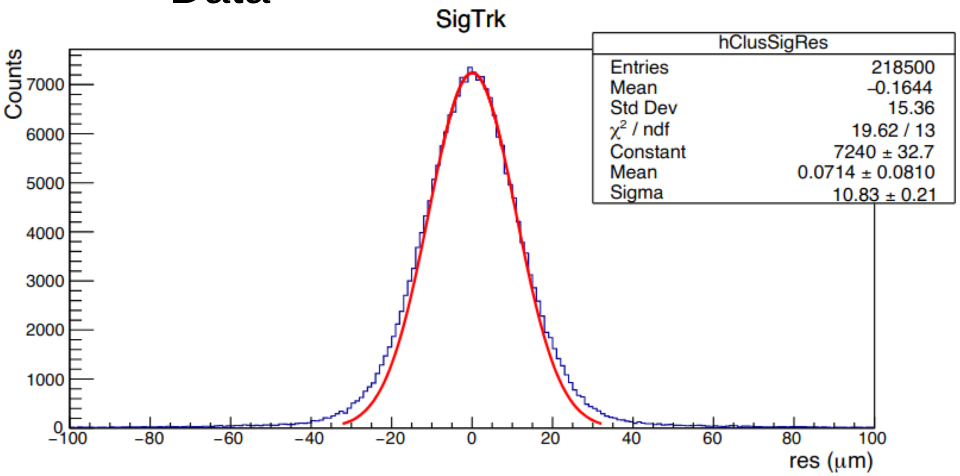
  $= \text{mean}(\text{res})^2 - \text{mean}(\sigma_t)^2 - \text{std.dev}(\sigma_t)^2$

- Since the distributions are not perfectly gaussian use instead :
  - mean(x) ≈ median(x)
  - Std.dev(x) ≈ mad(x) ≡ 1.4826*median(|x - median(x)|)

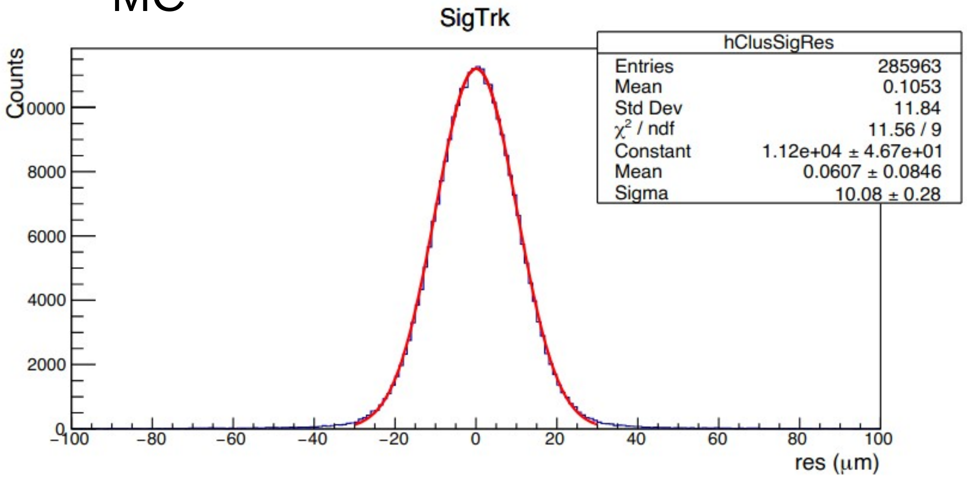
- Then $\sigma^2_{cl} = \text{mad}(\text{res})^2 - \text{median}(\sigma_t)^2 - \text{mad}(\sigma_t)^2$

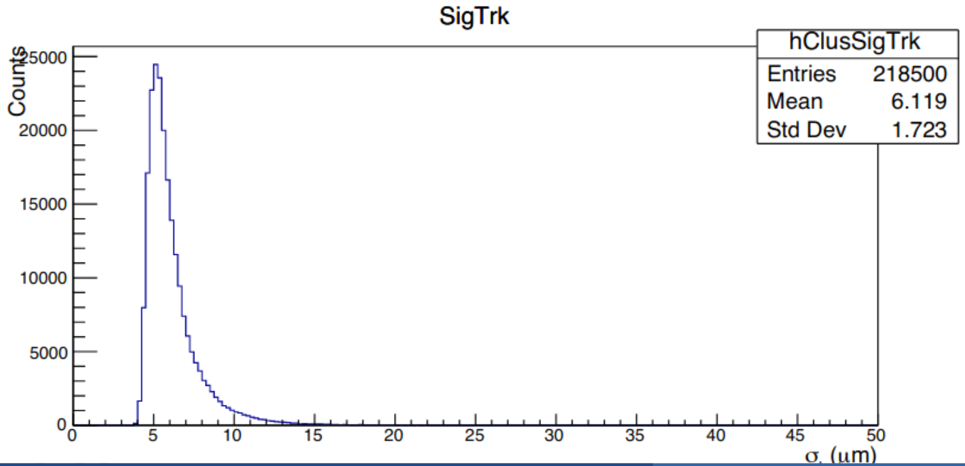
Estimation of cluster position resolution

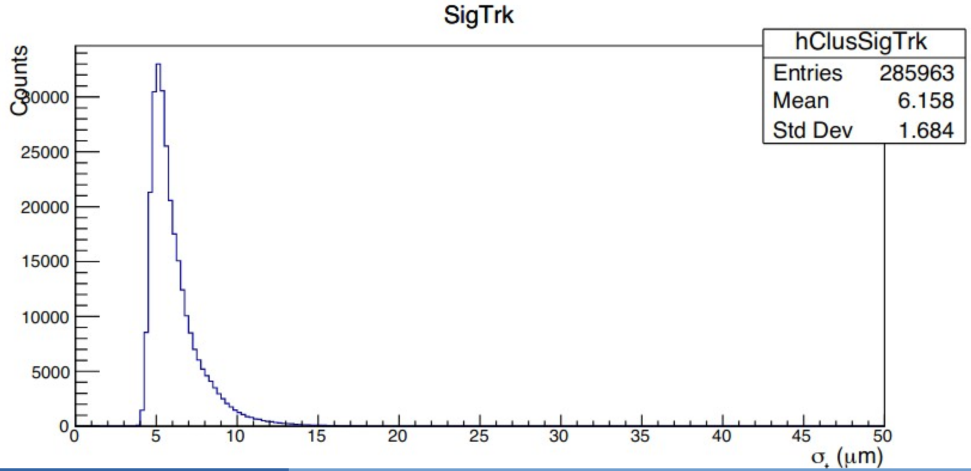
Data



MC







Estimation of cluster position resolution - Overlaps

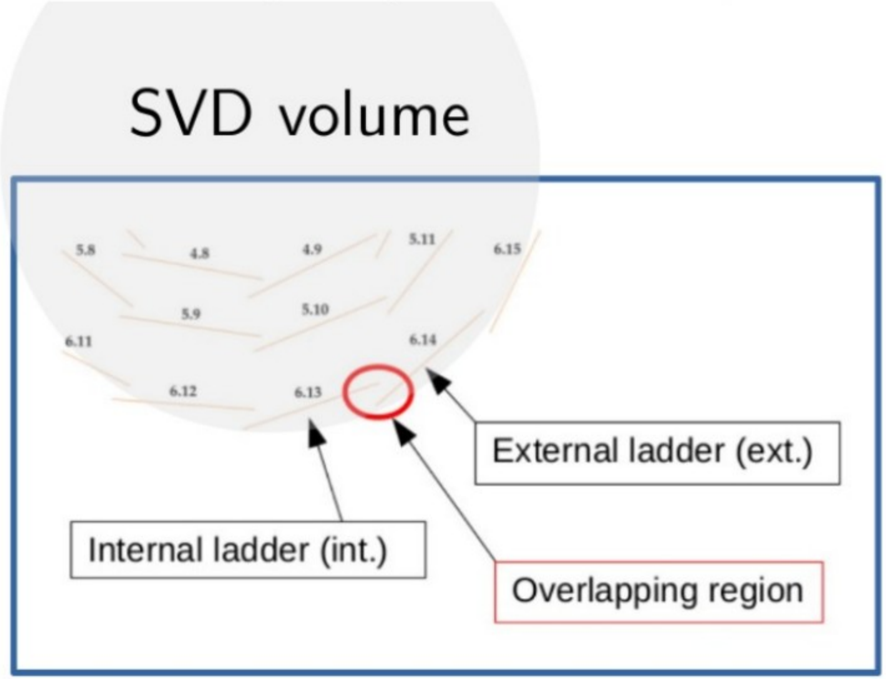
- A new strategy to compute cluster position resolutions has been devised exploiting the **SVD Overlaps** method inherited from CMS, here paper and slides.

PROS:

- Marginally sensitive to Coulomb scattering effect due to the reduced radial distance between overlapping sensors
- Can exploit any kind of tracks
- Double residuals technique may help decoupling resolutions from error on the intercept

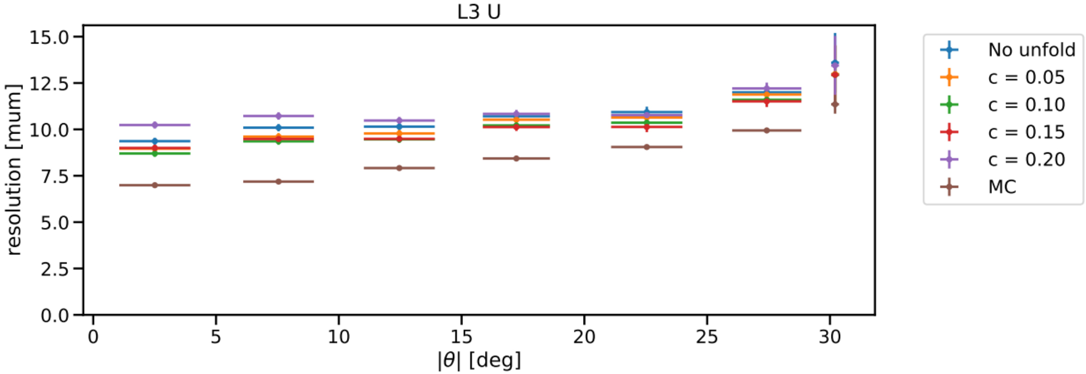
CONS:

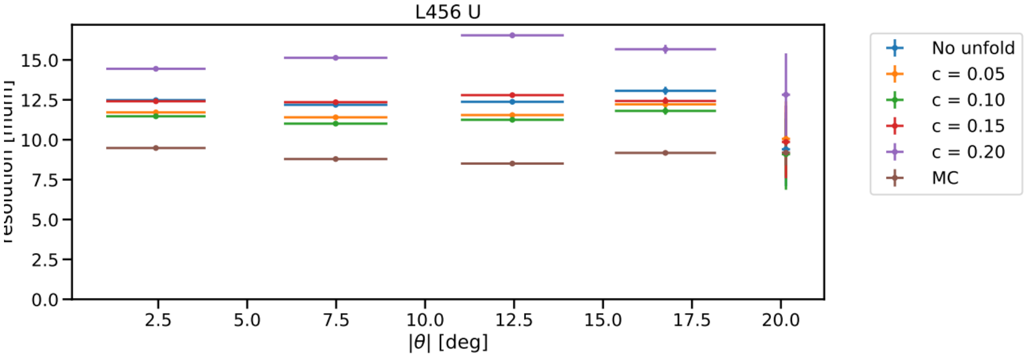
- U-side is the **most critical side for resolutions, but also the most challenging due to the reduced overlap region in u-direction and limited statistics.**

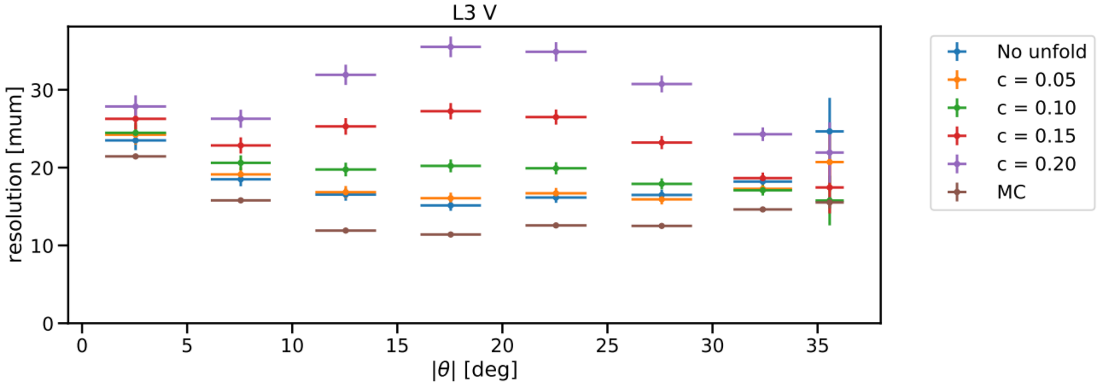


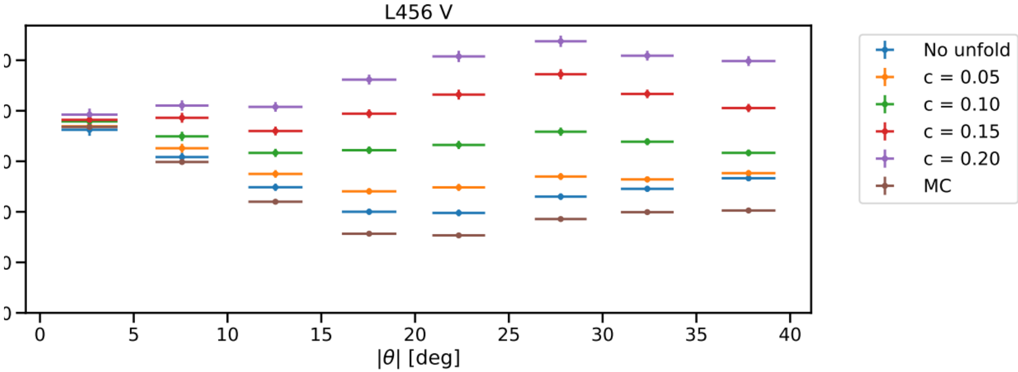
Cluster unfolding method – estimation of best correction factor

- The resolution is computed for each type of sensor for different values of **c** ranging from **0** to **0.2**

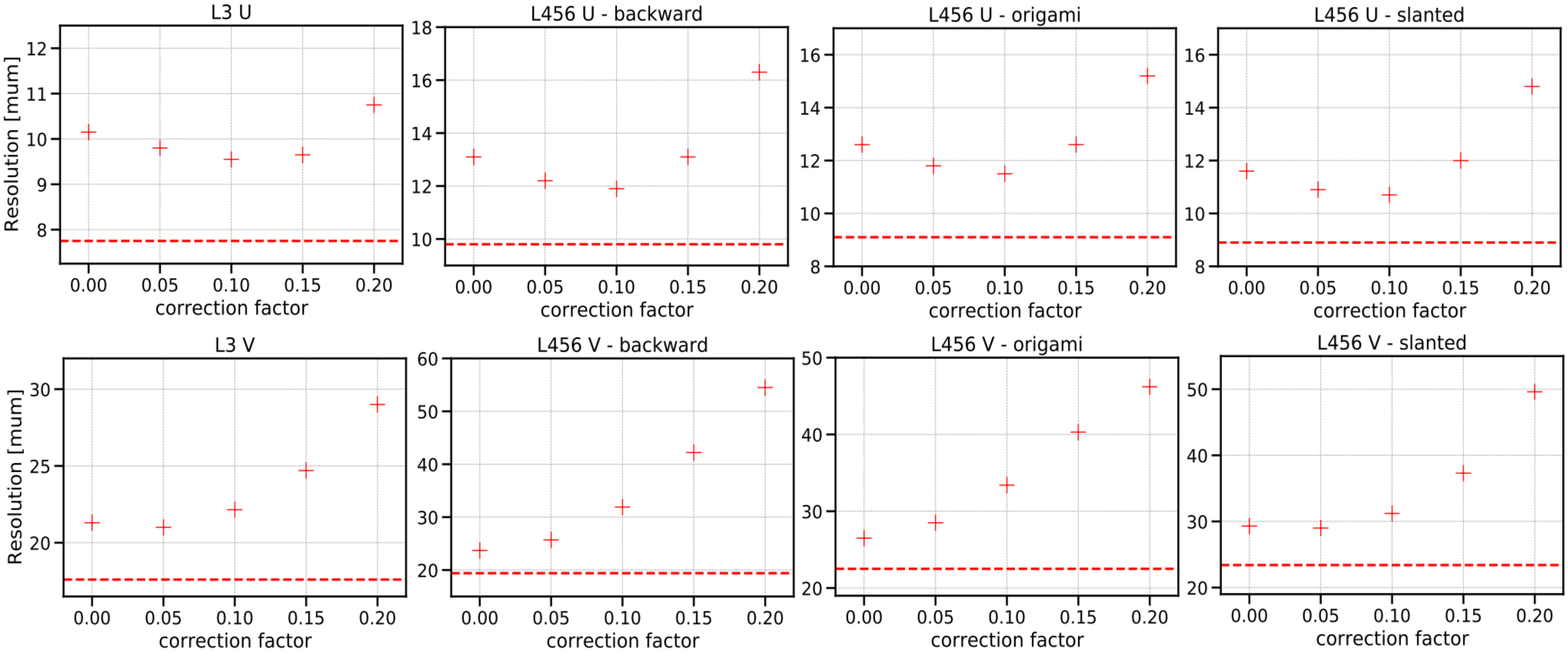








Cluster unfolding method – estimation of best correction factor



Cluster unfolding method – estimation of best correction factor

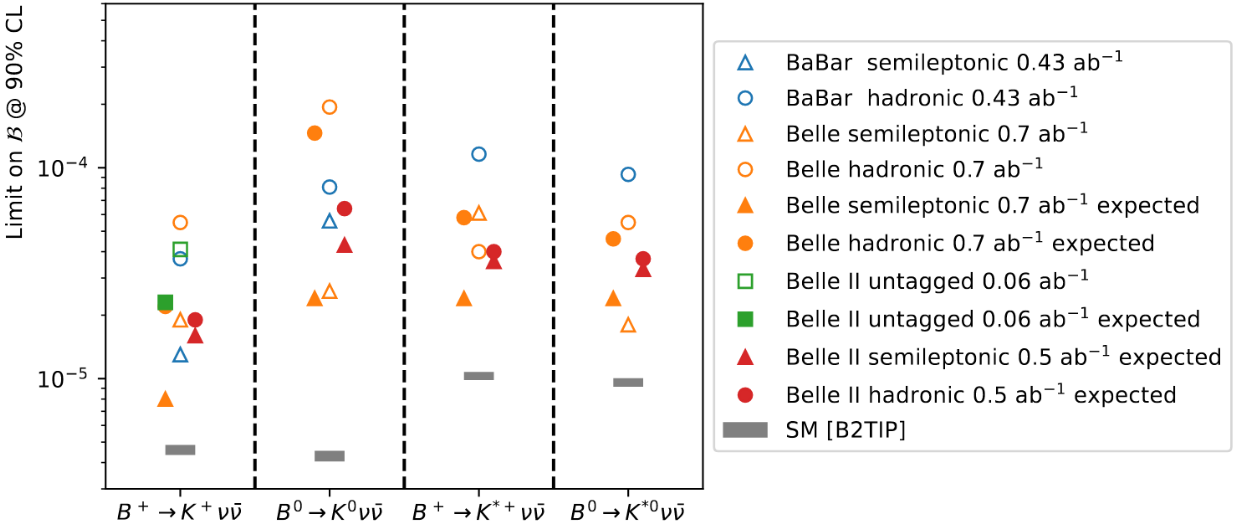
- The resolution is computed for each type of sensor for different values of **c** ranging from **0** to **0.2**
- The unfolding method does not improve the resolution on V-side sensors
- However, **U-side** sensors do benefit from the method, with an optimal gain with **c = 0.1** for all type of sensors

Sensors - U side	c = 0	c = 0.05	c = 0.1	c = 0.15	c = 0.20	MC
L3.1	9.6	9.3	9.1	9.3	10.7	7.2
L3.2	10.7	10.3	10	10	10.8	8.3
L456 backward	13.1	12.2	11.9	13.1	16.3	9.8
L456 origami	12.6	11.8	11.5	12.6	15.2	9.1
l456 slanted	11.6	10.9	10.7	12	14.8	8.9

original corrected goal

Sensors - V side	c = 0	c = 0.05	c = 0.1	c = 0.15	c = 0.20	MC
L3.1	25.1	24.5	24.8	25.6	27.8	21.1
L3.2	17.5	17.5	19.5	23.8	30.2	14.1
L456 backward	23.7	25.7	31.9	42.2	54.5	19.4
L456 origami	26.5	28.5	33.4	40.3	46.2	22.5
l456 slanted	29.3	29	31.2	37.3	49.6	23.4

Setting limits on $\mathcal{B}$



- Projections using MC
- Hadronic tagging already competitive, more work needed on SL

Limit set with the untagged analysis (on 63fb^{-1}) compared to Belle/Babar