Particle identification (PID) and precision τ physics at Belle II

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TU WIEN TECHNISCHE UNIVERSITÄT WIEN

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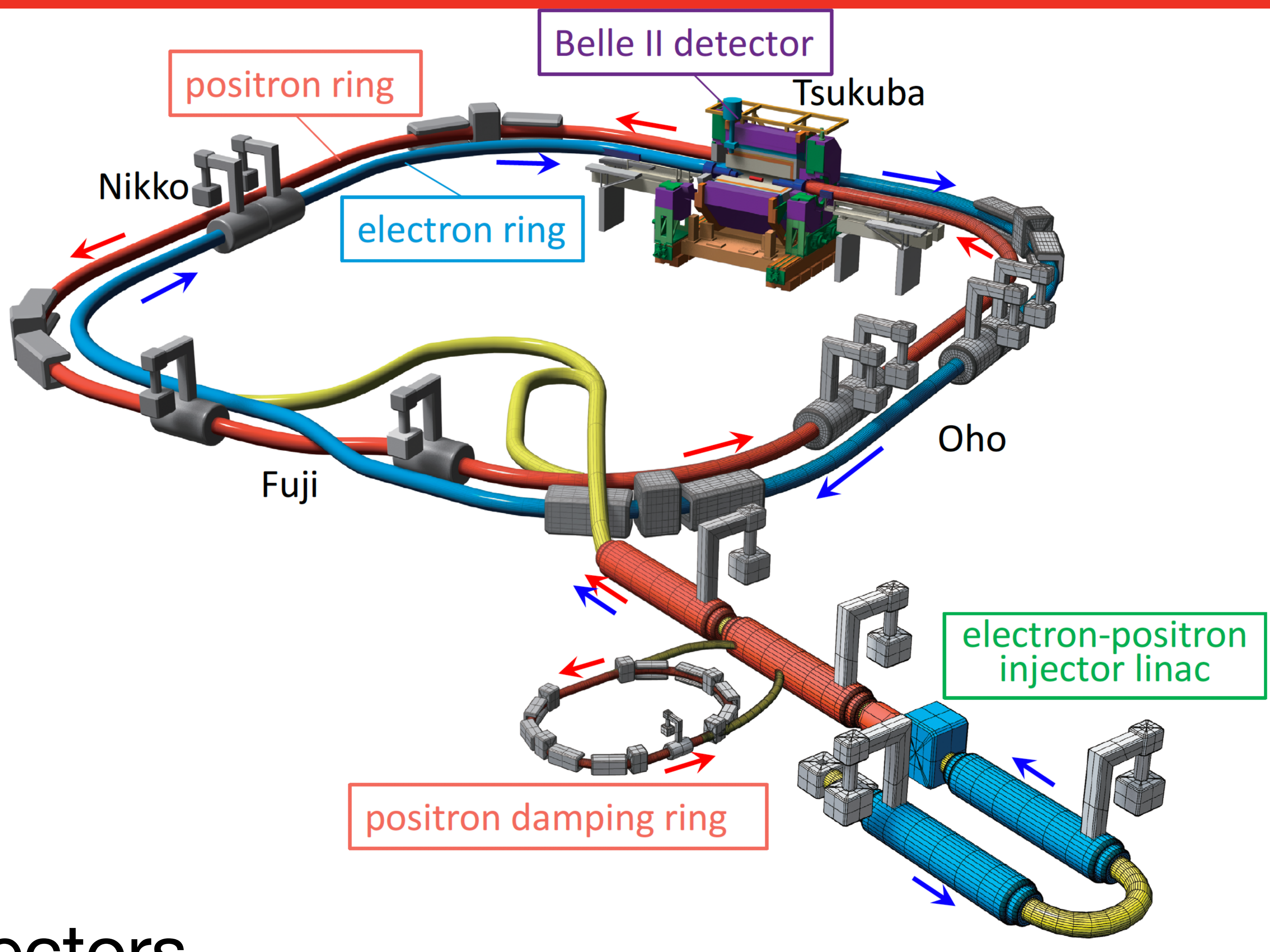
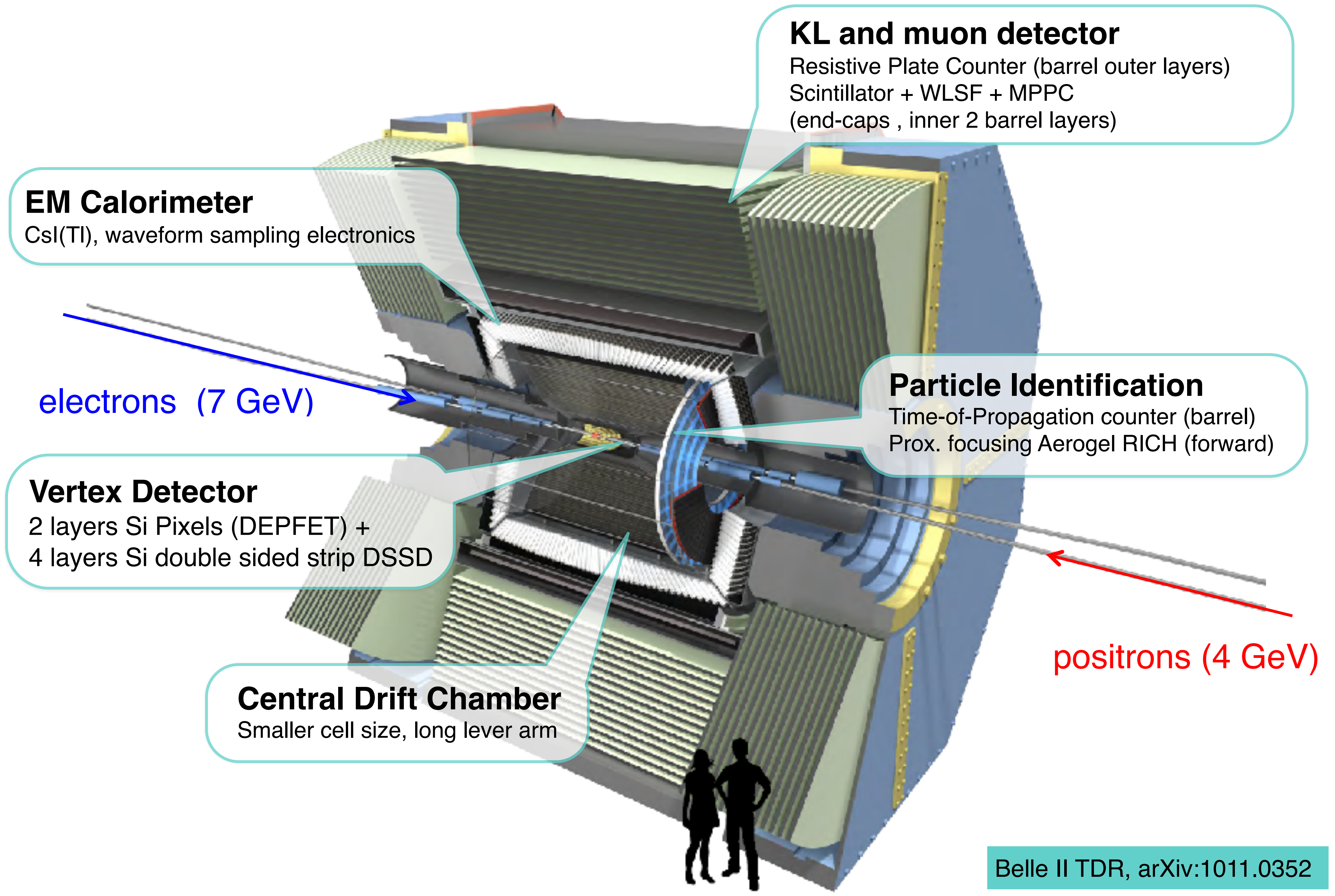
Belle II experiment

SuperKEKB accelerator

- Located at KEK in Tsukuba, Japan
- e^+ (4GeV) - e^- (7GeV) collider with $E_{CM} = \sqrt{s} = 10.58$ GeV
  - Asymmetric beam energy ⇒ boosted collision products
  - E_{CM} corresponds to mass of $\Upsilon(4S)$ resonance: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$





Belle II TDR, arXiv:1011.0352

Belle II detector

- Composed of 7 major subdetectors
- Decay vertices reconstruction: Pixelated silicon sensors (PXD) and silicon strip sensors (SVD)
- Tracking: Central drift chamber (CDC)
- h identification: Time of propagation system (TOP) and ring-imaging Cherenkov detector (ARICH)
- Energy of γ and e: Electromagnetic calorimeter (ECL)
- K_L^0 and μ identification: Chambers of the KLM

⇒ All subdetectors contribute to the particle identification (PID)

Particle identification (PID) variables

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From likelihoods to PID variables for charged particles

- In each subdetector $d \in \{\text{svd, cdc, top, arich, ecl, klm}\} \equiv D$, a likelihood $\mathscr{L}_{x,d}$ is defined for each charged stable particle hypothesis $x \in \{e, \mu, \pi, K, p, d\} \equiv X$ with a probability density function (PDF)
- Assuming independent measurements:

$$\mathscr{L}_x \equiv \prod_{d \in D} \mathscr{L}_{x,d}$$

- Likelihood ratios are used to identify candidates as a particle p
  - There exist several ways to construct ratios (i.e. denominators):
    - **Global pID**: take as denominator all possible outcomes of identification
    - **Reweighted** and **MVA pID**: improve with MVA techniques the already available likelihoods by adding weights or other parameters

Global pID:

$$p\text{ID} = \frac{\mathscr{L}_p}{\sum_{x \in X} \mathscr{L}_x} = \frac{\prod_{d \in D} \mathscr{L}_{p,d}}{\sum_{x \in X} \left(\prod_{d \in D} \mathscr{L}_{x,d}\right)} = \frac{\exp\left(\sum_{d \in D} \log \mathscr{L}_{p,d}\right)}{\sum_{x \in X} \exp\left(\sum_{d \in D} \log \mathscr{L}_{x,d}\right)}$$

Due to numerical stability, use $\log \mathscr{L}_{x,d}$

Particle identification (PID) variables

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From probability to PID variable

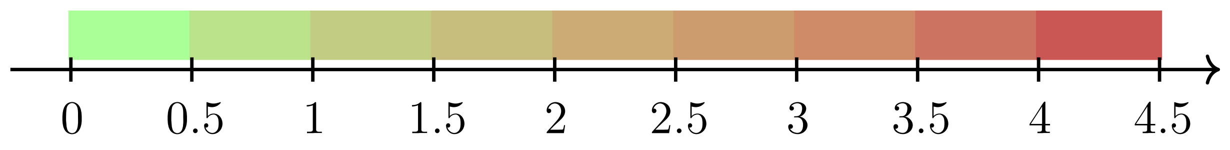
1. **Global pID**:

$$p\text{ID} = \frac{\exp(\sum_{d\in D} \log \mathscr{L}_{p,d})}{\sum_{x\in X} \exp(\sum_{d\in D} \log \mathscr{L}_{x,d})}$$

2. **Reweighted pID**: Introduction of weights $w_{x,d}$ computed with a Neural Network (NN) trained on a dataset of simulated single particles to counter-balance possible poorly calibrated detectors

$w =$

	svd	cdc	top	arich	ecl	klm
e	0.809	2.270	0.434	0.595	2.464	0.158
μ	1.363	1.958	0.429	0.611	1.962	0.483
π	1.064	1.433	0.426	0.598	2.018	0.183
K	1.793	1.908	0.422	0.605	1.663	0.219
p	1.719	1.866	0.414	0.646	1.963	0.221
d	1.265	2.026	0.381	0.693	4.085	0.149



$$p\text{ID} = \frac{\exp(\sum_{d\in D} w_{p,d} \log \mathscr{L}_{p,d})}{\sum_{x\in X} \exp(\sum_{d\in D} w_{x,d} \log \mathscr{L}_{x,d})}$$

BELLE2-NOTE-TE-2021-027

3. **MVA pID**: New method of ℓ identification based on a combination of several ECL measurements with the other subdetector likelihoods in a Boosted Decision Tree (BDT)
   - ECL PDF normally relies on E/p
     - Globally, good $e - \pi$, μ separation
     - But reduced separation power for low momentum e
   - Add shower and pulse shapes variables and define new likelihoods to compensate this reduction

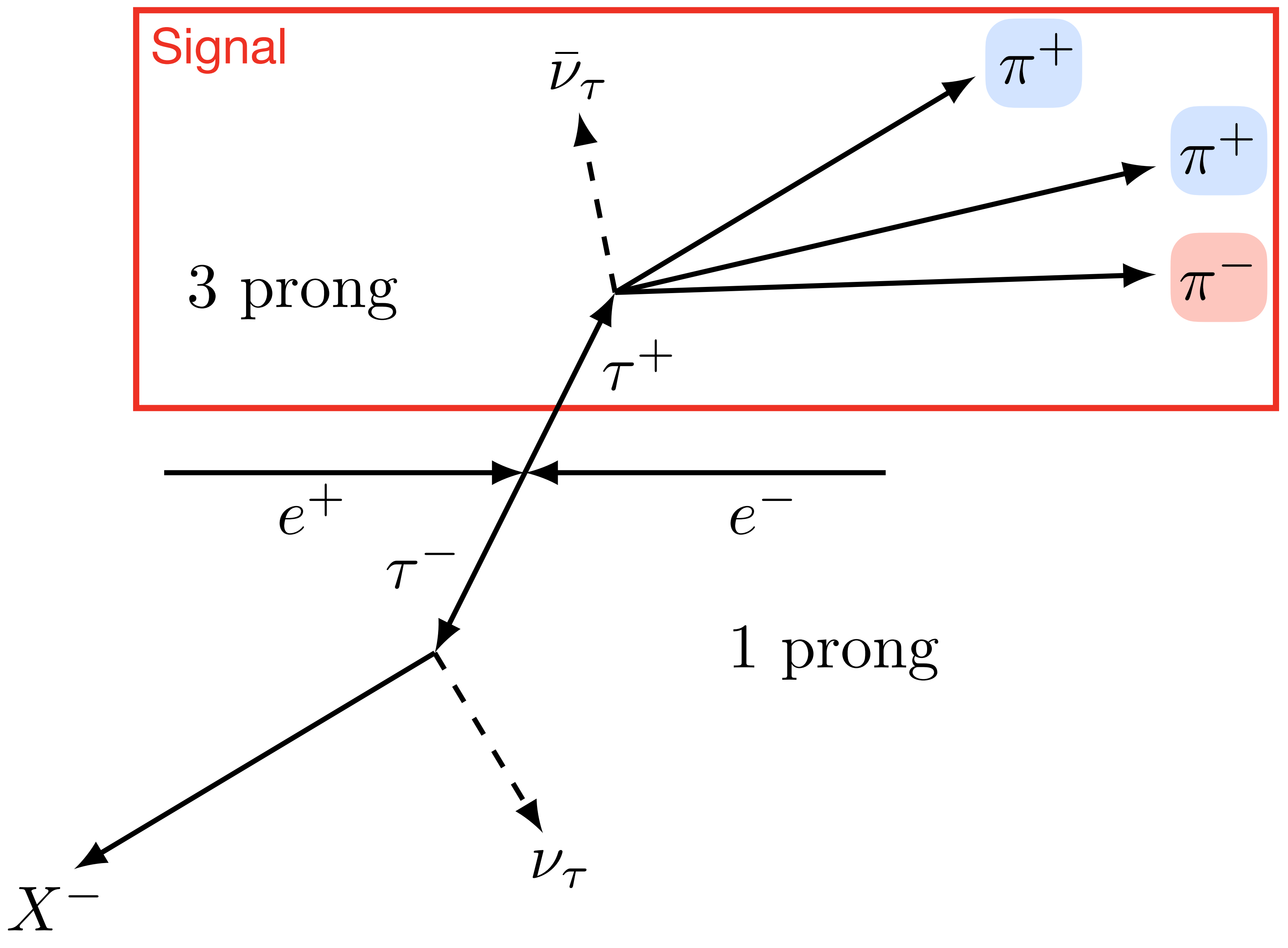
$$p\text{ID} = \frac{\exp(\sum_{d\in D} \log \mathscr{L}'_{p,d})}{\sum_{x\in X} \exp(\sum_{d\in D} \log \mathscr{L}'_{x,d})}$$

BELLE2-CONF-PH-2022-003

Performance study

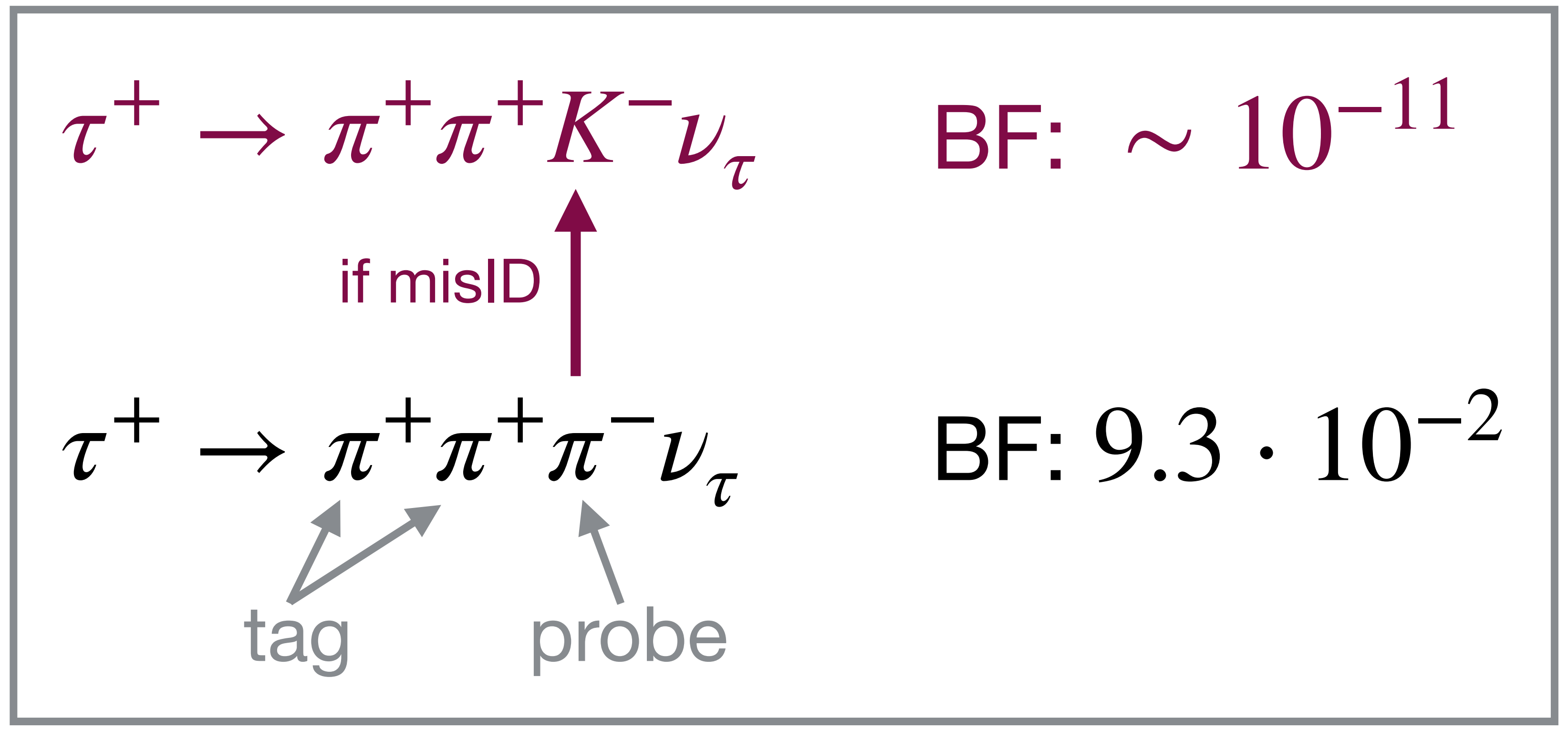
Configuration

- 3x1 prong τ decay topology with on the signal side $\tau^+ \rightarrow \pi^+\pi^+\pi^-\bar{\nu}_\tau$ and on the tag side $\tau^- \rightarrow X^-\nu_\tau$
- Use tag and probe approach on the signal side
  - Apply a tight PID cut on the tag tracks: Global πID > 0.9
  - No PID cut on probe track: defines sample
  - Truth-match the probe track as a π to evaluate purity / efficiency



Motivation

- Use the fact that $\tau^+ \rightarrow \pi^+\pi^+K^-\nu_\tau$ is highly suppressed
  - Forbidden at tree level
  - Low background due to misidentification of the probe track



Selection

- Apply a cut-based selection optimised with a FOM to select signal
- Obtained a purity of $98.23\ \%$ with an efficiency of $4.04\ \%$

BELLE2-NOTE-PH-2022-049

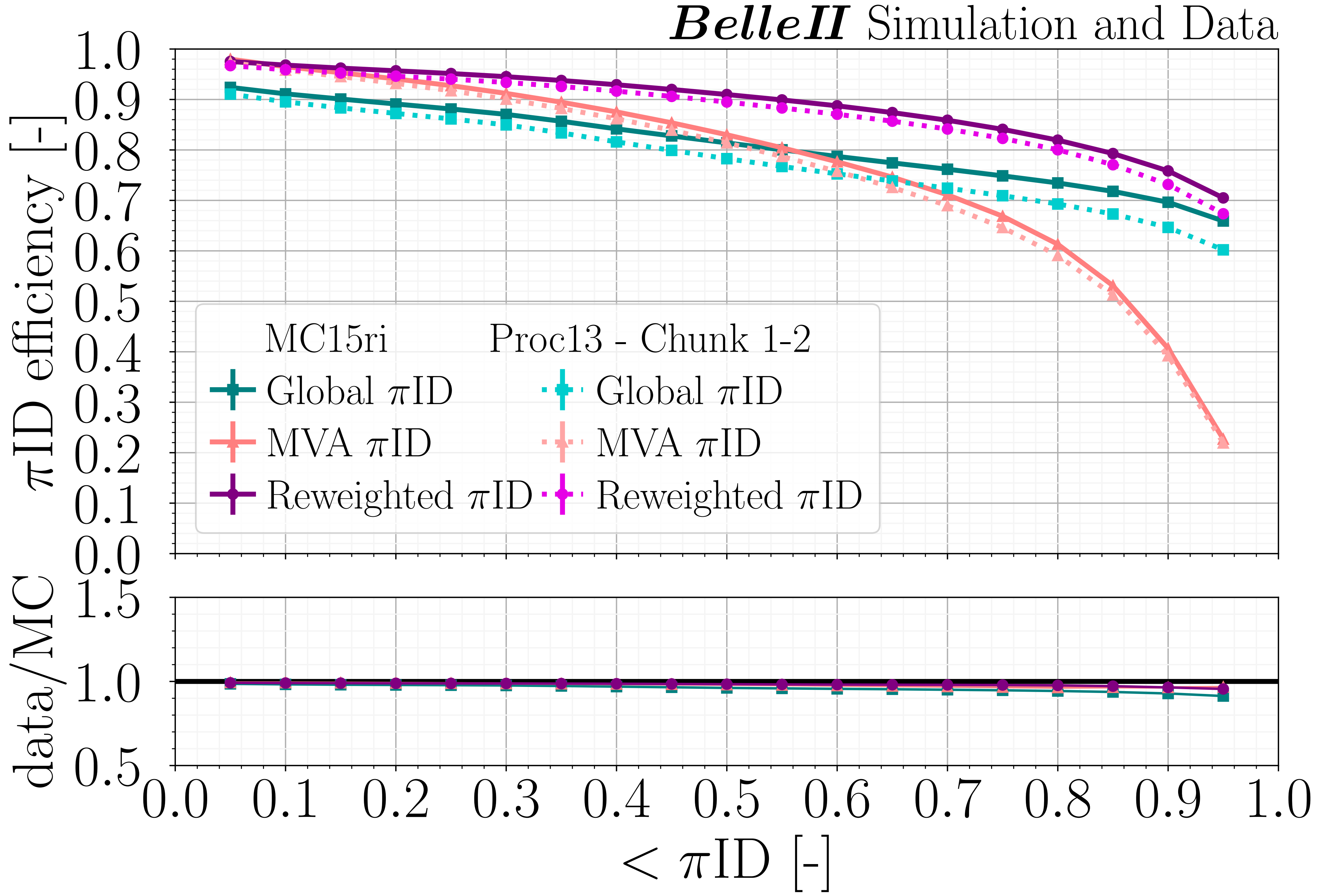
Results

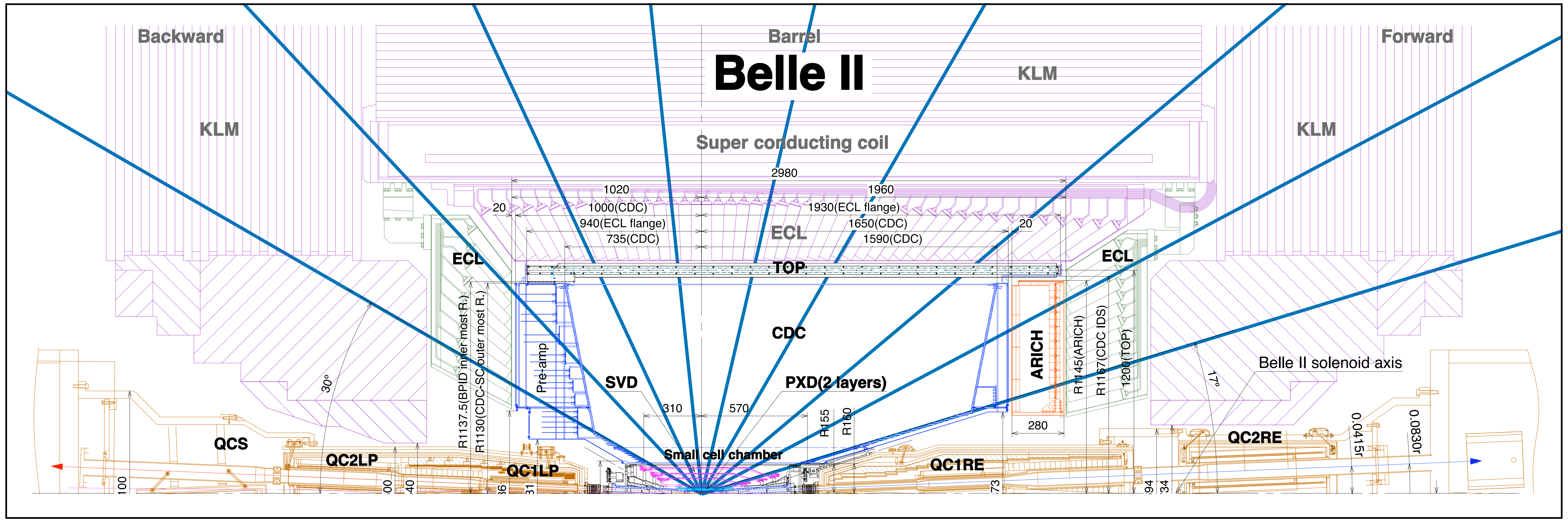
Performance

- πID efficiency computed for simulation and data on the whole spectrum of p and $\cos\theta$ as

$$\frac{N^{<\pi ID}}{N^{tot}}$$

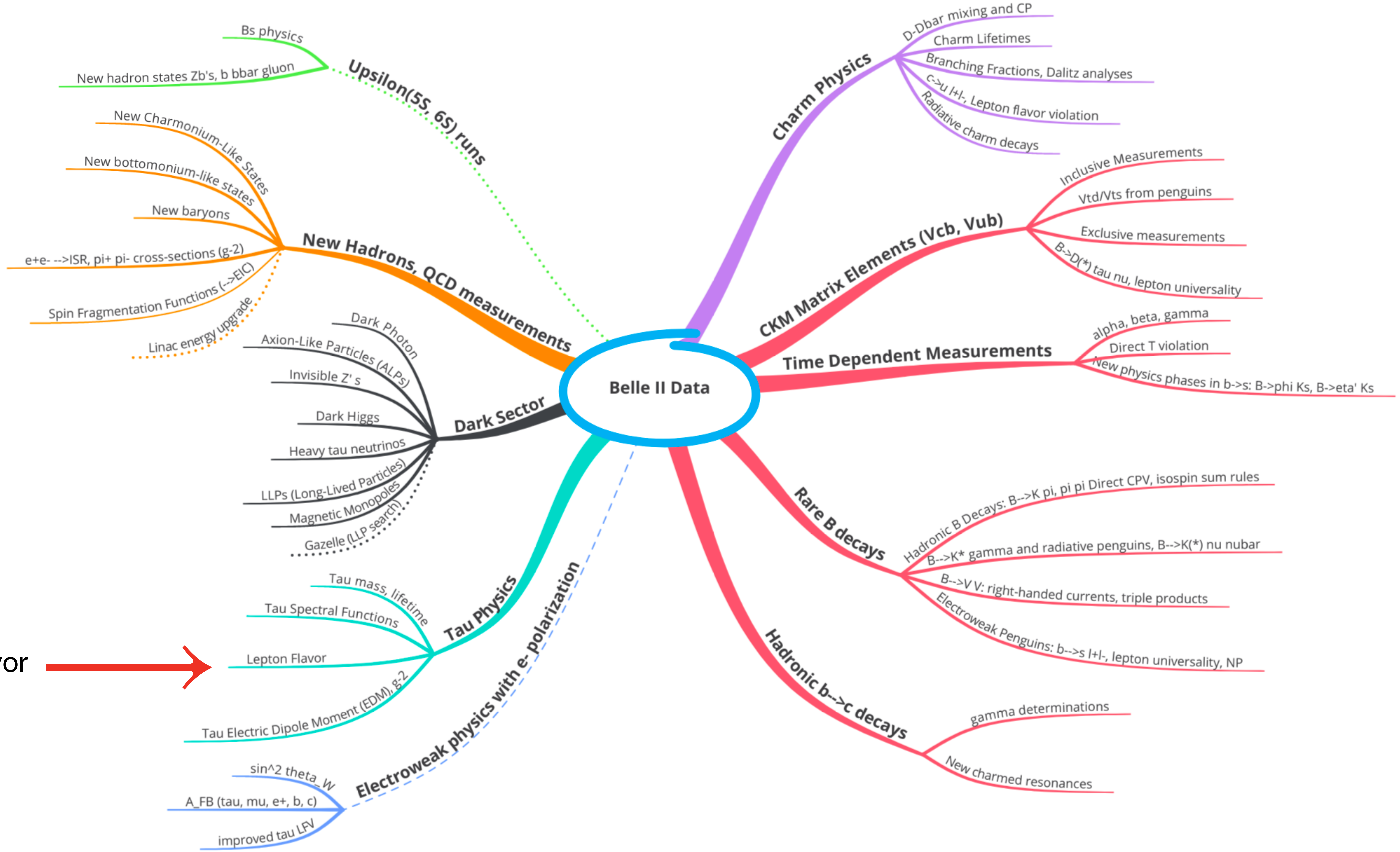
- Reweighted πID shows the best performance
  - Outperforms Global πID and MVA πID
- Small discrepancies between simulation and data
  - Results in smaller correction factors ⇒ smaller systematics





- Get correction factors in bins of $p \in$ [0.5, 4.5] GeV and $\cos\theta \in$ [-0.886, 0.956] (≡ [17, 150]°)
  - Compute associated
    - statistical uncertainties
    - systematics uncertainties
  - Provide analysts with correction tables

Belle II activities and τ physics



Lepton Flavor

Lepton flavour universality (LFU)

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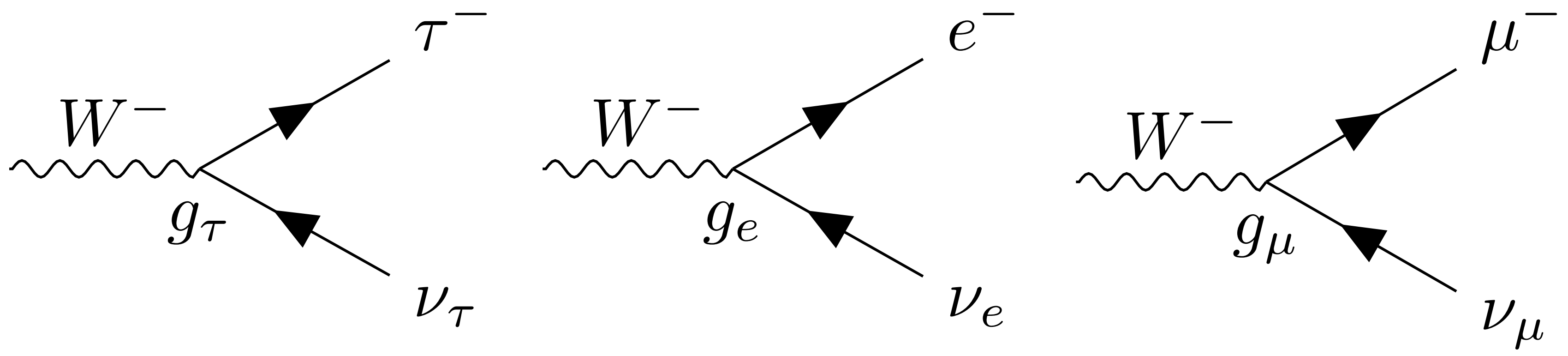
LFU

- Couplings of leptons to W boson is flavour independent, i.e. $g_e = g_\mu = g_\tau$



Anomalies in quark sector

- $R(D) - R(D^*)$ plane $\sim 3.9\sigma$
- $R(K)$ $\sim 3.1\sigma$
- $P5'$ in $B \to K^* \mu\mu$ $\sim 3.4\sigma$

Anomalies in lepton sector

- $(g-2)_\mu \sim 4.2\sigma$
- $(g-2)_e \sim 2.5\sigma$

and more…

$\Rightarrow$ Hint of new fundamental interaction that violates LFU?

LFU in τ decays

- Test of $\mu - e$ universality:

$$\left(\frac{g_\mu}{g_e}\right)^2_\tau = \underbrace{\frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}}_{R_\mu} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}$$

where $f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log(x)$

Phys. Rev. D 13, 771 (1976)

- If LFU holds: $g_e = g_\mu \Rightarrow R_\mu = 0.972564$
- HFLAV 2022: $(g_\mu/g_e)_\tau = 1.0019 \pm 0.0014$

Lepton flavour universality (LFU)

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Best measurements

- BaBar, 2010 (3x1 prong, 467fb^{-1})
  - $R_\mu = 0.9796 \pm 0.0016$ (stat.) $\pm\, 0.0036$ (syst.) $= 0.9796 \pm 0.0040$
- CLEO, 1997 (1x1 prong, 3.6fb^{-1})
  - $R_\mu = 0.9777 \pm 0.0063$ (stat.) $\pm\, 0.0087$ (syst.) $= 0.9777 \pm 0.0110$
- Systematically limited measurements

BaBar

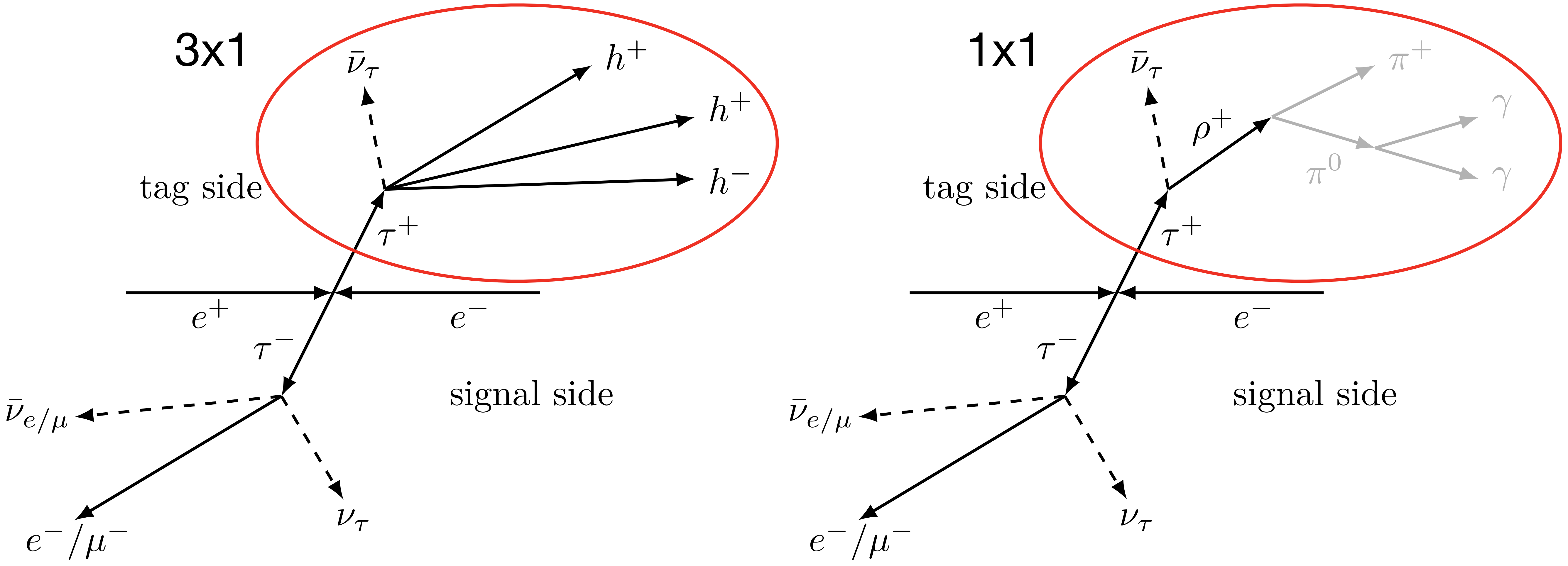
	μ
Particle ID	0.32
Detector response	0.08
Backgrounds	0.08
Trigger	0.10
$\pi^-\pi^-\pi^+$ modelling	0.01
Radiation	0.04
$\mathcal{B}(\tau^- \to \pi^-\pi^-\pi^+\nu_\tau)$	0.05
$\mathcal{L}\sigma_{e^+e^-\to\tau^+\tau^-}$	0.02

CLEO

Source	$\mathcal{B}_\mu/\mathcal{B}_e$
Acceptance ($\mathcal{A}$)	0.56
Trigger ($\mathcal{T}$)	0.51
Background (f)	0.32
Particle Id ($\mathcal{P}$)	0.36

Measurement at Belle II

- Use both 3x1 and 1x1 prong τ decay topologies



- Fixed selection of events targeting a high purity p_ℓ
  - 1x1: p_e= 98%, p_μ = 96% with 10% signal efficiency
  - 3x1: p_e= 99.5%, p_μ = 96% with 19% signal efficiency
- Evaluation of the systematics is ongoing
  - Preliminary results showed in October during B2GM

$\Rightarrow$ Stay tuned!

Summary

Particle identification (PID)

- All subdetectors contribute to the particle identification (PID)
  - Performance of the detector will influence the quality of the particle identification
- Ratios of (log-)likelihoods $\mathscr{L}_x$ are used to identify candidates as a long lived charged particle p
  - Several ratios can be defined and lead to different performances
- Necessary to aim at the best performance in terms of efficiency but not only that
  - Smaller discrepancy yields smaller systematics which could represent a key element in a precision measurement

Lepton flavour universality (LFU) in τ decays

- Over the past few years, several results in the quark sector, e.g. $b \to s\ell\ell$ (loop-level) or $b \to c\ell\nu_\ell$ (tree-level) and in the lepton sector seem to point to a coherent pattern of anomalies
  - Could be a hint of new fundamental interaction that violates LFU
- Performing a $\mu - e$ universality test is one to test the LFU prediction
- Belle II aims at providing a result using both 3x1 and 1x1 prong decay topologies
  - Finishing the evaluation of systematics for the 1x1, and starting it for the 3x1

Thank you!

Backup Slides

Event selection

Preselection

- Trigger: lml (0, 1, 2, 4, 6, 7, 8, 9, 10)
- Tag track hID: pionID > 0.9 and nCDCHits > 20

Signal and background events

- Sig: $\tau \to \pi\pi\pi\nu_\tau \Leftrightarrow$ truth-matching probe track in $\tau\tau$ sample as π
- Bkg: all other events

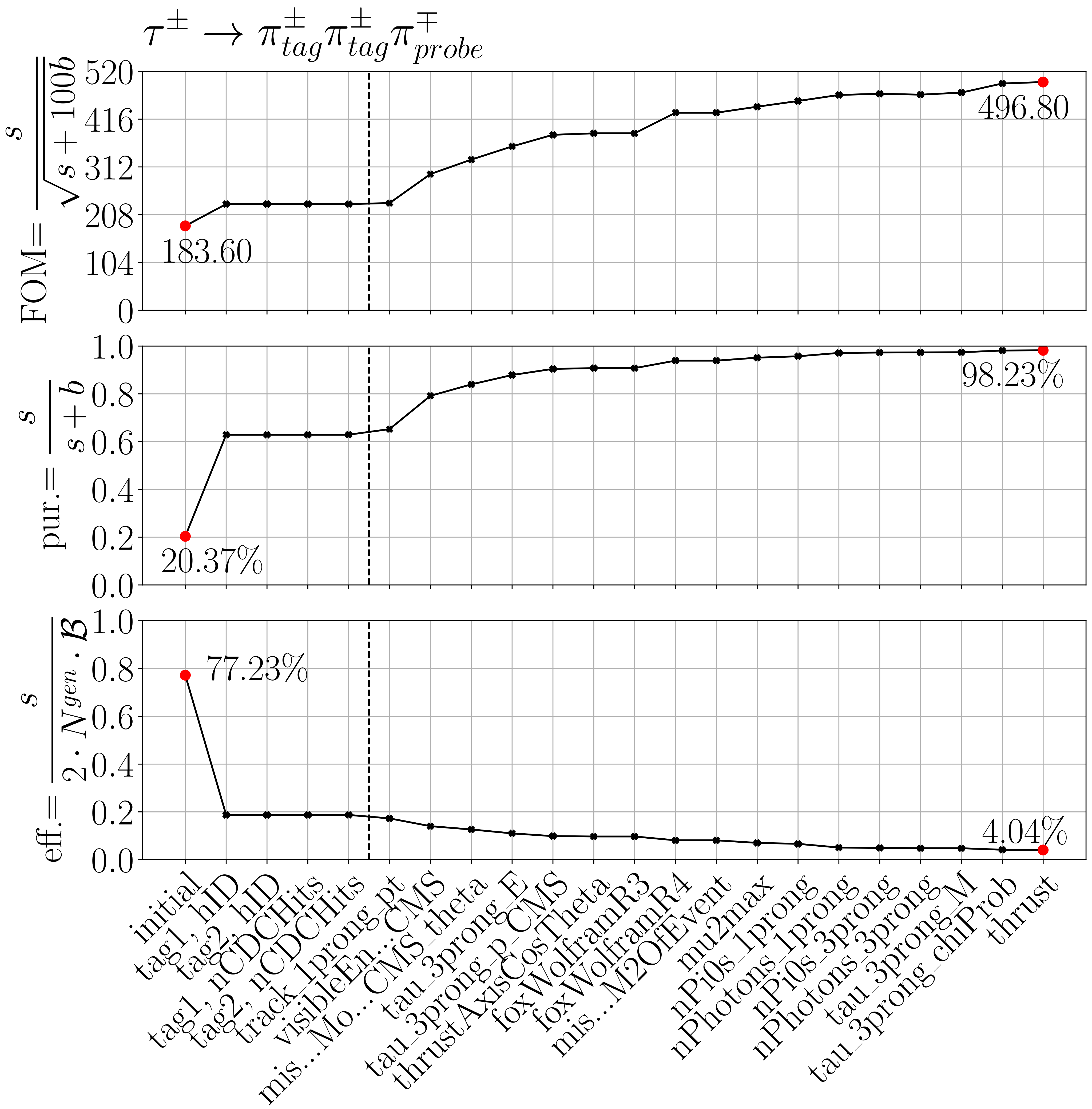
Definitions

$$\text{FOM} = \frac{s}{\sqrt{s+xb}}, \quad \text{pur} = \frac{s}{s+b}, \quad \text{eff} = \frac{s}{2 \cdot N^{gen} \cdot \mathscr{B}_{3p}}$$

- $N^{gen} = 91'900'000$ and $\mathscr{B}_{3p} = 9.31 \cdot 10^{-2}$

Cuts

- Applied one after the other, defined by maximizing FOM (pur)
- First assessed "by eye", $x = 100$
- Tuned by finding best FOM in the range neighbourhood, $x = 200$



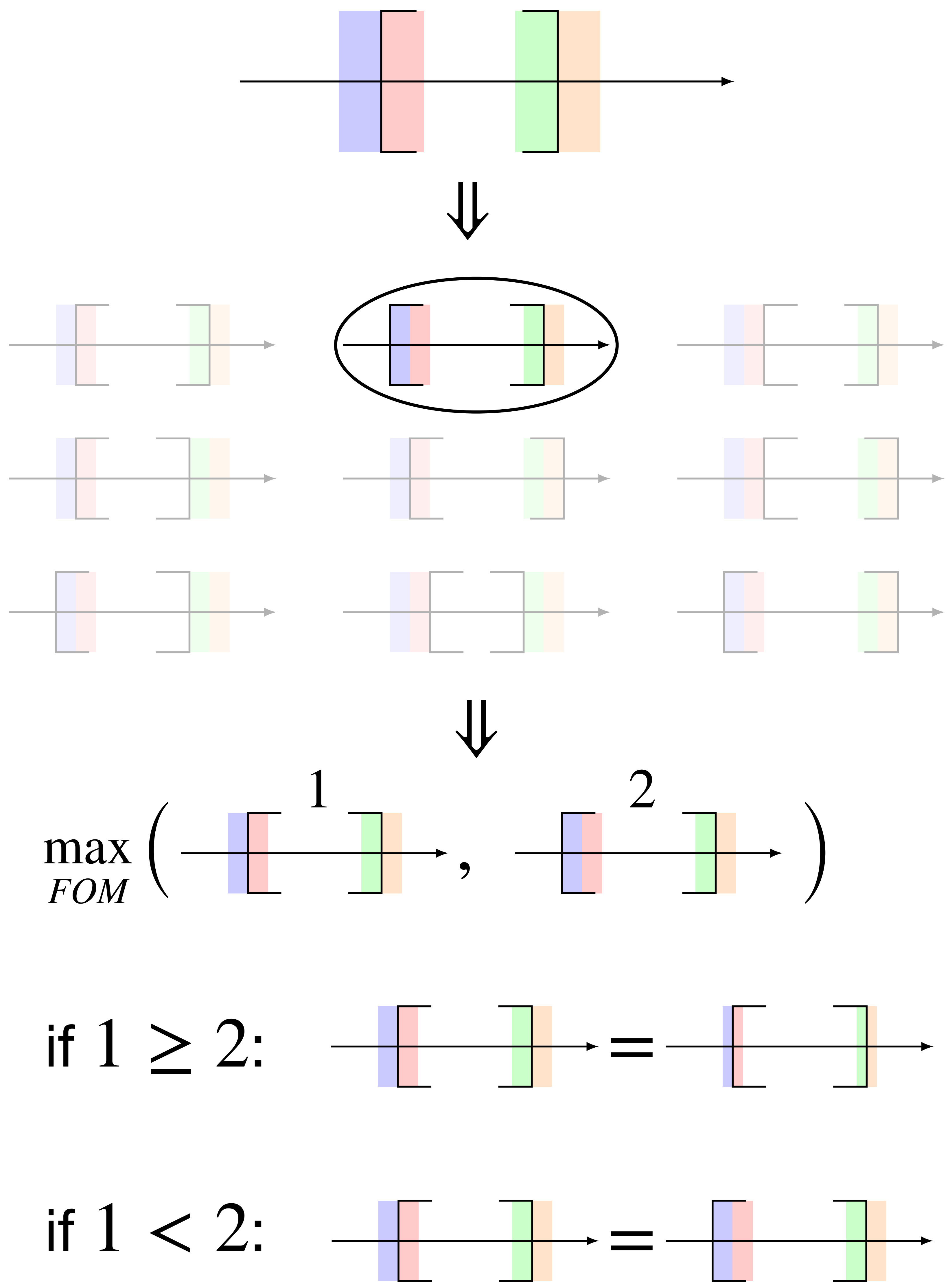
Result

- Purity of $98.23\ \%$, efficiency of $4.04\ \%$ (MVA selection: Purity of $98.03\ \%$, efficiency of $5.65\ \%$)

Event selection

Principle

- Refine cuts by looking at FOM in the neighbourhood of both sides iteratively
  - Compute 9 possibilities of an initial range, using a width set manually
  - Select the range that yields the best FOM
  - Define two cases depending on the initial and new FOM:
    - if the new FOM is lower than the one obtained initially, go back to first step, but try with a smaller width.
    - if the new FOM is higher than the one obtained initially, replace the initial range by this new range, and go back to the first step.
  - Stop the iterative process once a certain width is reached



Event selection

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Cuts without optimisation

	Feature	Cut
1	1prong p_t	$\in [0.3, 5.4]$
2	E_{vis}^{CMS}	$\in [2.3, 9.2]$
3	$\theta_{p_{miss}^{CMS}}$	$\in [0.44, 2.7]$
4	3prong E	$\in [2.48, 6.4]$
5	3prong p^{CMS}	$\in [2.48, 5.1]$
6	$\cos\theta_{\hat{t}}$	$\in [-0.46, 0.88]$
7	FoxWolfram R_3	$\in [0, 0.9]$
8	FoxWolfram R_4	$\in [0.32, 0.97]$
9	M_{miss}^2	$\in [-46.8, 52]$
10	1prong μ_{max}^2	$\in [0, 10]$
11	1prong $n\pi^0$	$= 0$
12	1prong $n\gamma$	≤ 1
13	3prong $n\pi^0$	$= 0$
14	3prong $n\gamma$	≤ 1
15	3prong M	$\in [0, 1.7]$
16	3prong χ_{prob}	$\in [0, 1]$
17	thrust	$\in [0.9, 1]$

Cuts with optimisation

	Feature	Cut
1	1prong p_t	$\in [0.3101, 5.31]$
2	E_{vis}^{CMS}	$\in [2.4101, 8.3001]$
3	$\theta_{p_{miss}^{CMS}}$	$\in [0.55101, 2.6]$
4	3prong E	$\in [2.481, 6.511]$
5	3prong p^{CMS}	$\in [2.489, 5.101]$
6	$\cos\theta_{\hat{t}}$	$\in [-0.47, 0.881001]$
7	FoxWolfram R_3	$\in [0, 0.9]$
8	FoxWolfram R_4	$\in [0.308999, 0.98]$
9	M_{miss}^2	$\in [-47.8, 53.0]$
10	1prong μ_{max}^2	$\in [0.00999, 10]$
11	1prong $n\pi^0$	≤ 1
12	1prong $n\gamma$	$= 0$
13	3prong $n\pi^0$	≤ 1
14	3prong $n\gamma$	≤ 2
15	3prong M	$\in [0, 1.5901]$
16	3prong χ_{prob}	$\in [0.00999, 0.99999]$
17	thrust	$\in [0.90901, 1]$