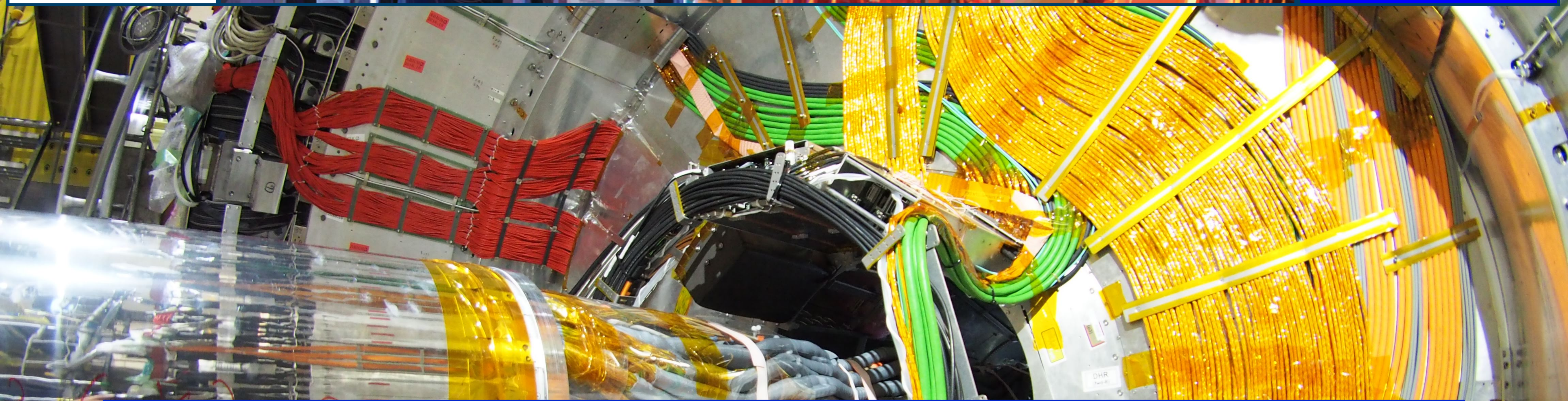
THE UNIVERSITY OF MELBOURNE

ICHEP 2020 | PRAGUE

Belle II



Leptonic and semileptonic decays with taus at the Belle II experiment

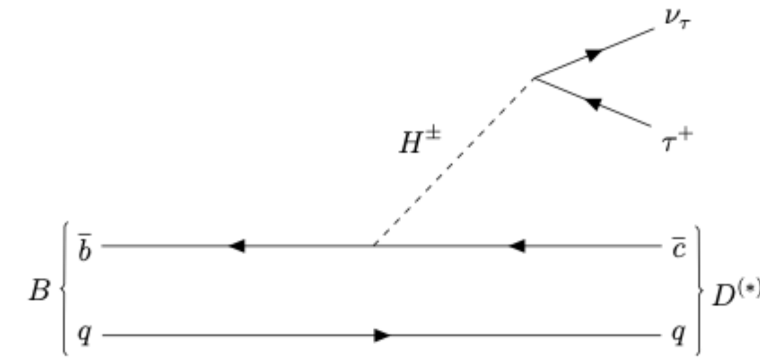
Marco Milesi, on behalf of the Belle II collaboration

School of Physics - The University of Melbourne

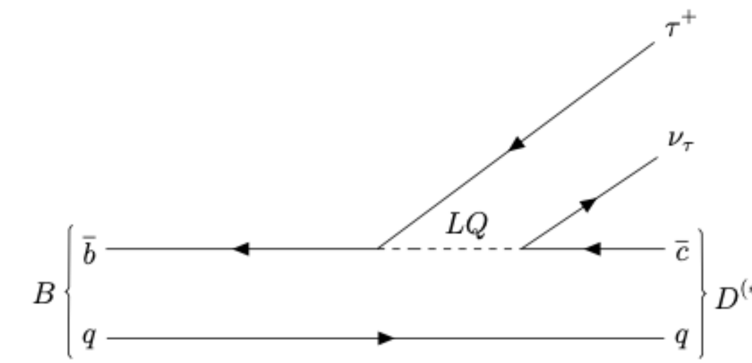
ICHEP 2020, Prague, July, 31st 2020

Motivation for $B \to \tau\nu, B \to (X)\tau\nu$

1. Powerful test for lepton flavour universality violation $\rightarrow$ $b \rightarrow c\tau\bar{\nu}$ portal to new physics:

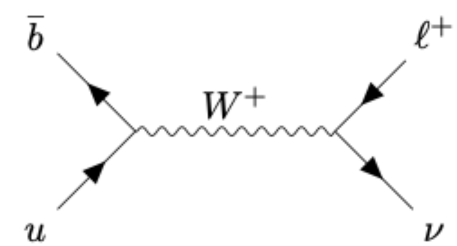


- Two-Higgs doublet models (stronger coupling to τ leptons).

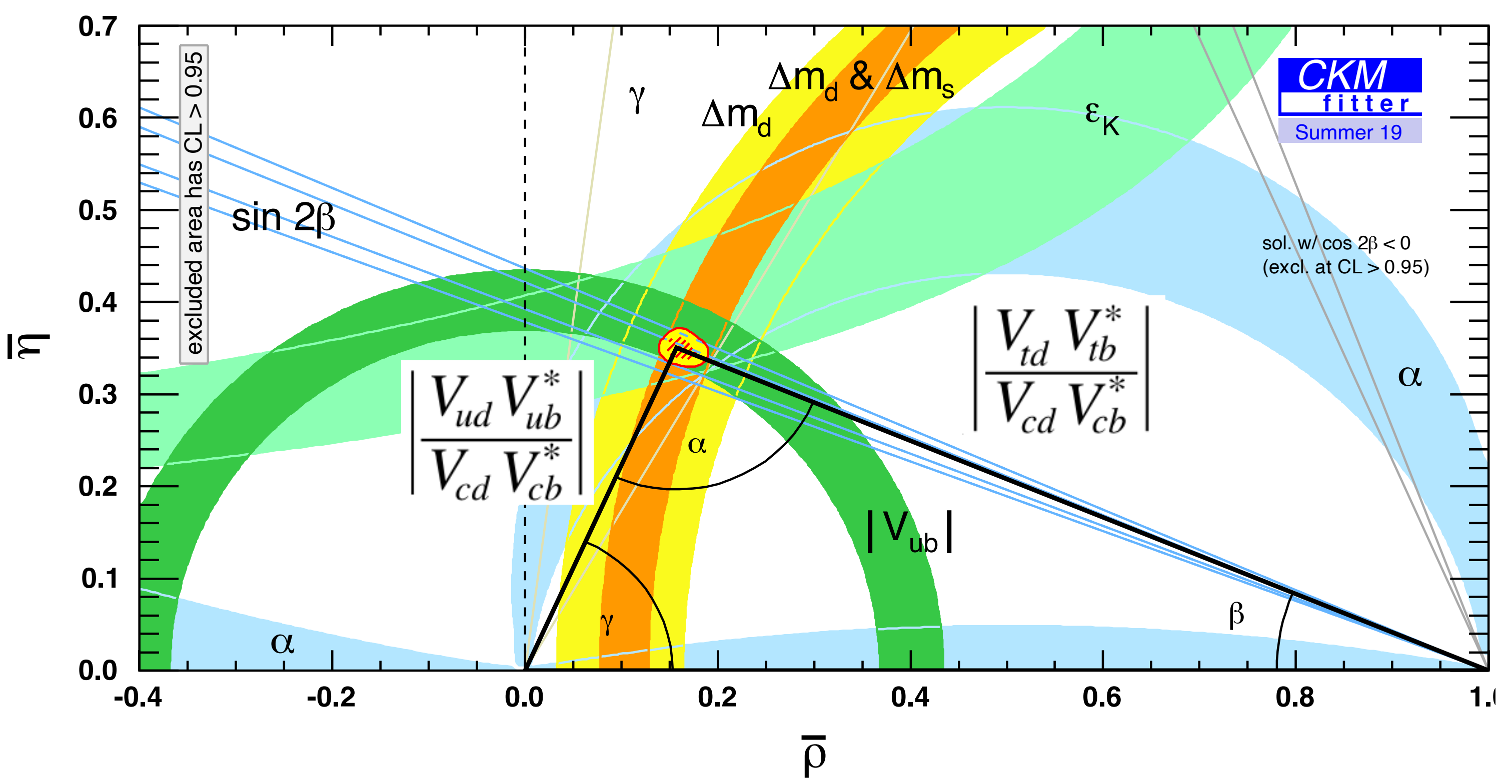


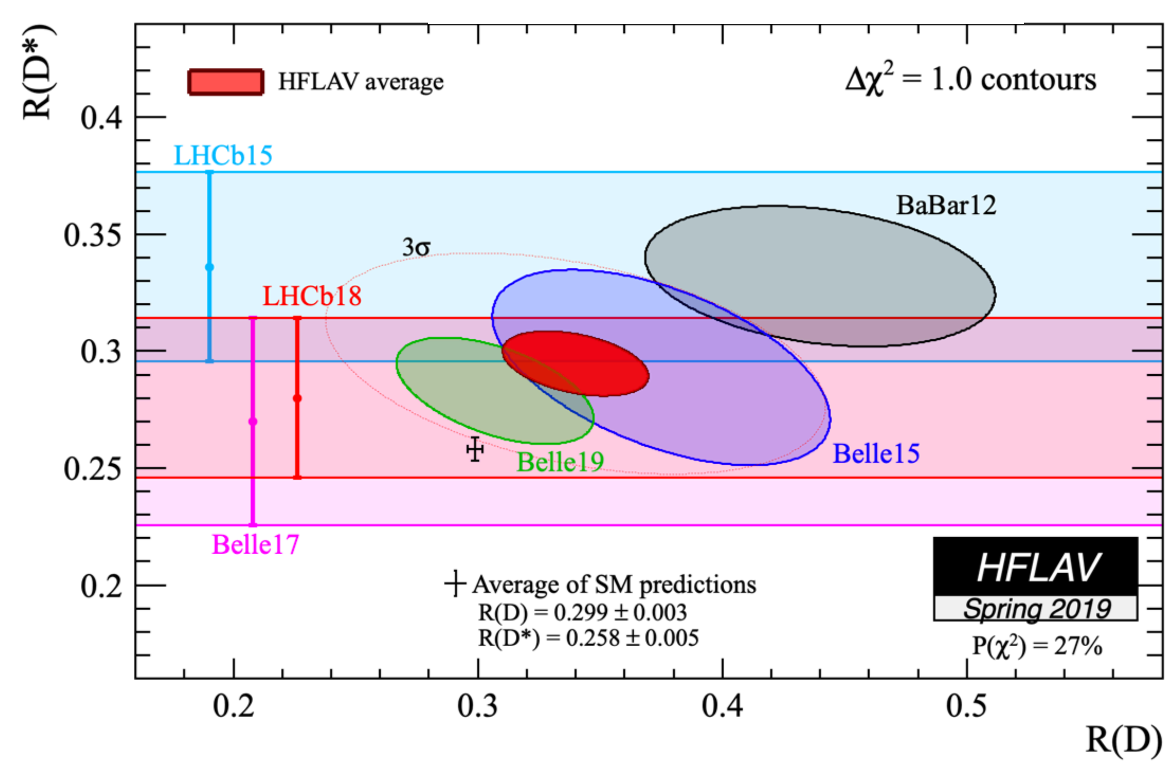
- Leptoquarks.

2. Complementary measurements of V_{ub} to light lepton ($\ell = e, \mu$) semileptonic channels $\rightarrow$ input to CKM global fits.

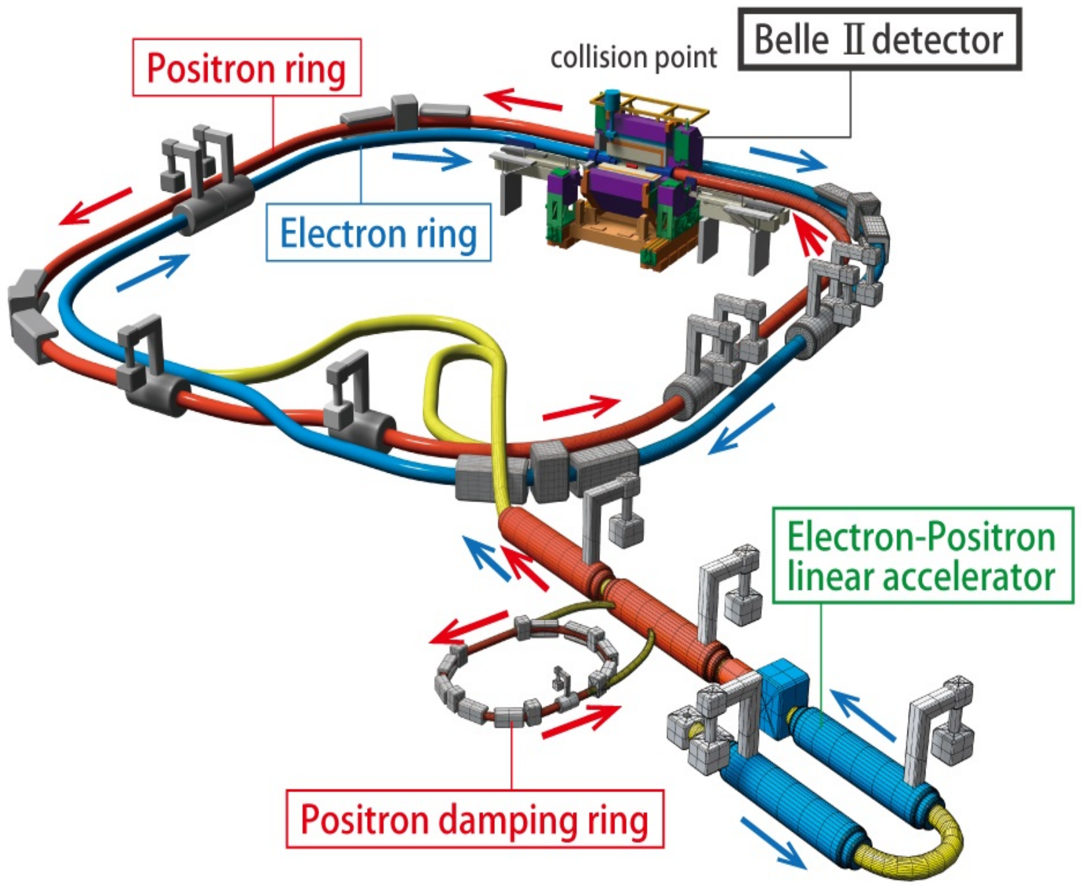


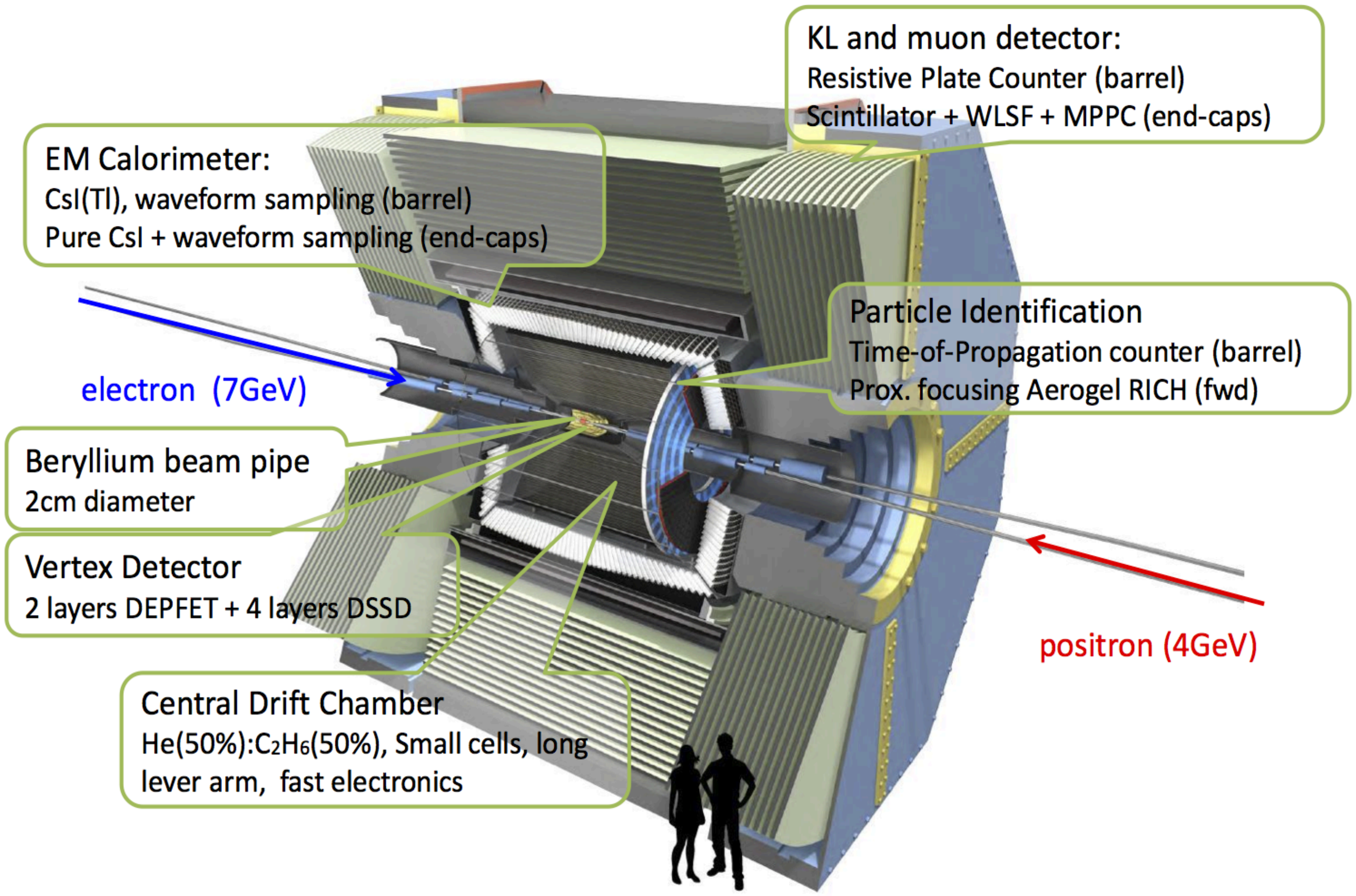
$$R(D^{(*)}) = \frac{\mathcal{B}\left(B \rightarrow D^{(*)}\tau\nu\right)}{\mathcal{B}\left(B \rightarrow D^{(*)}\ell\nu\right)}$$





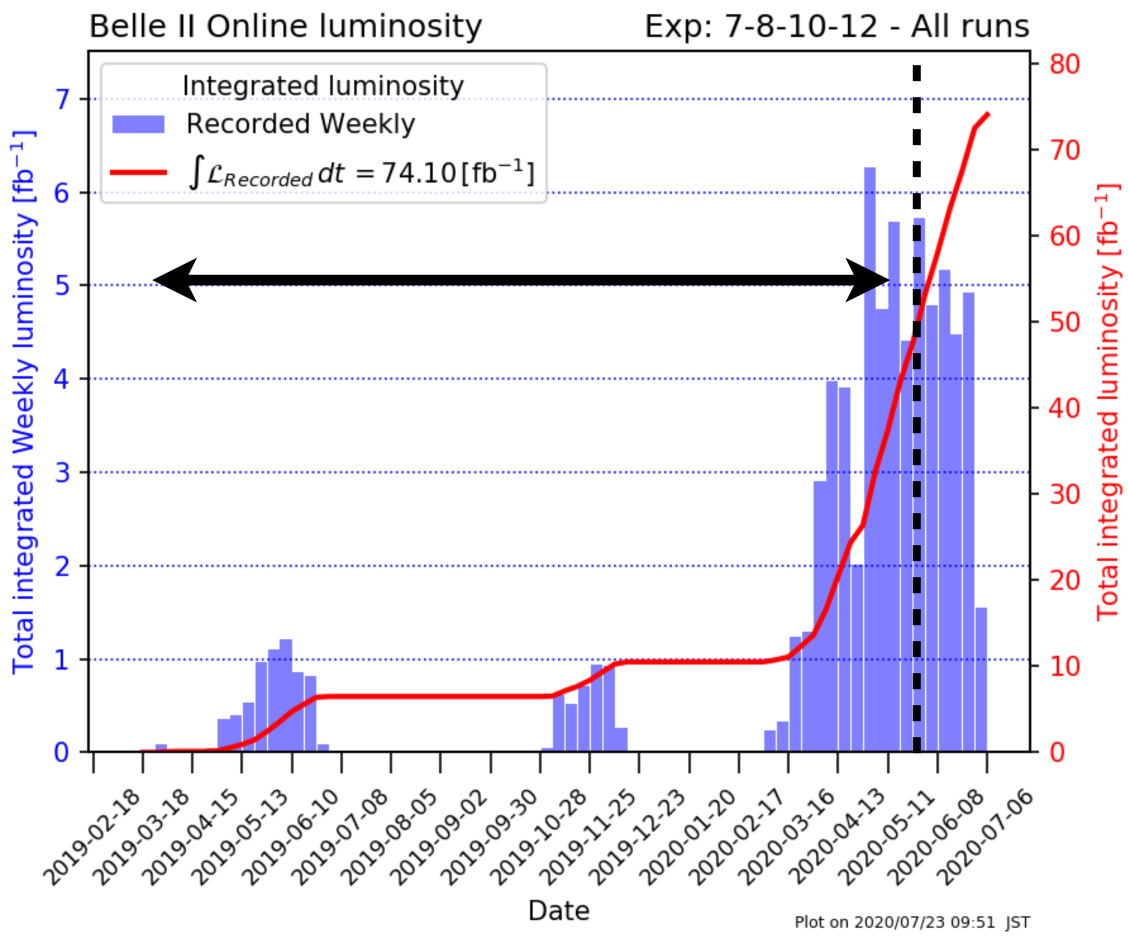
SuperKEKB and the Belle II detector

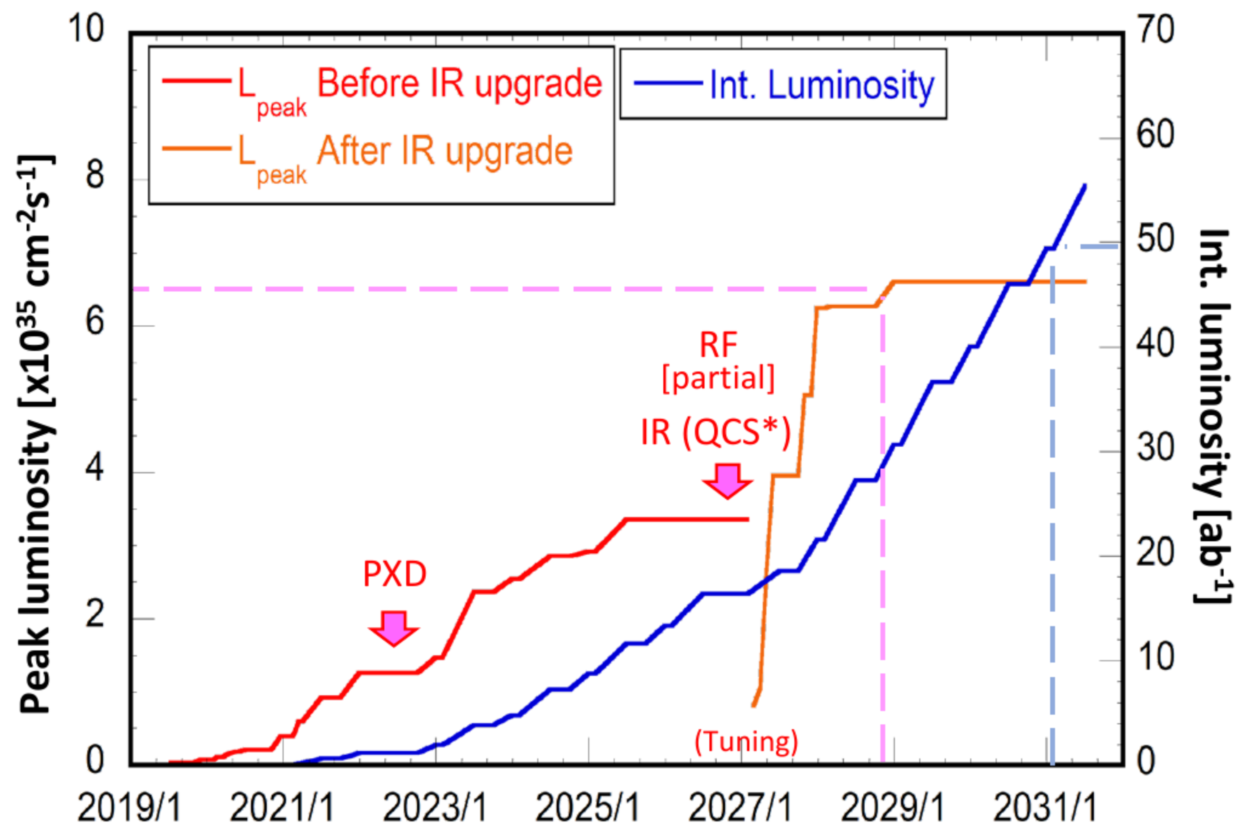




- *SuperKEKB*: 40x higher instantaneous luminosity than KEKB $\rightarrow \mathscr{L} = 6 \times 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- *Belle II*: major upgrade of Belle detector to cope with harsher beam background conditions.
- Improvements in reconstruction algorithm, esp. tracking, vertexing and particle identification.

Current Belle II dataset and projected luminosity





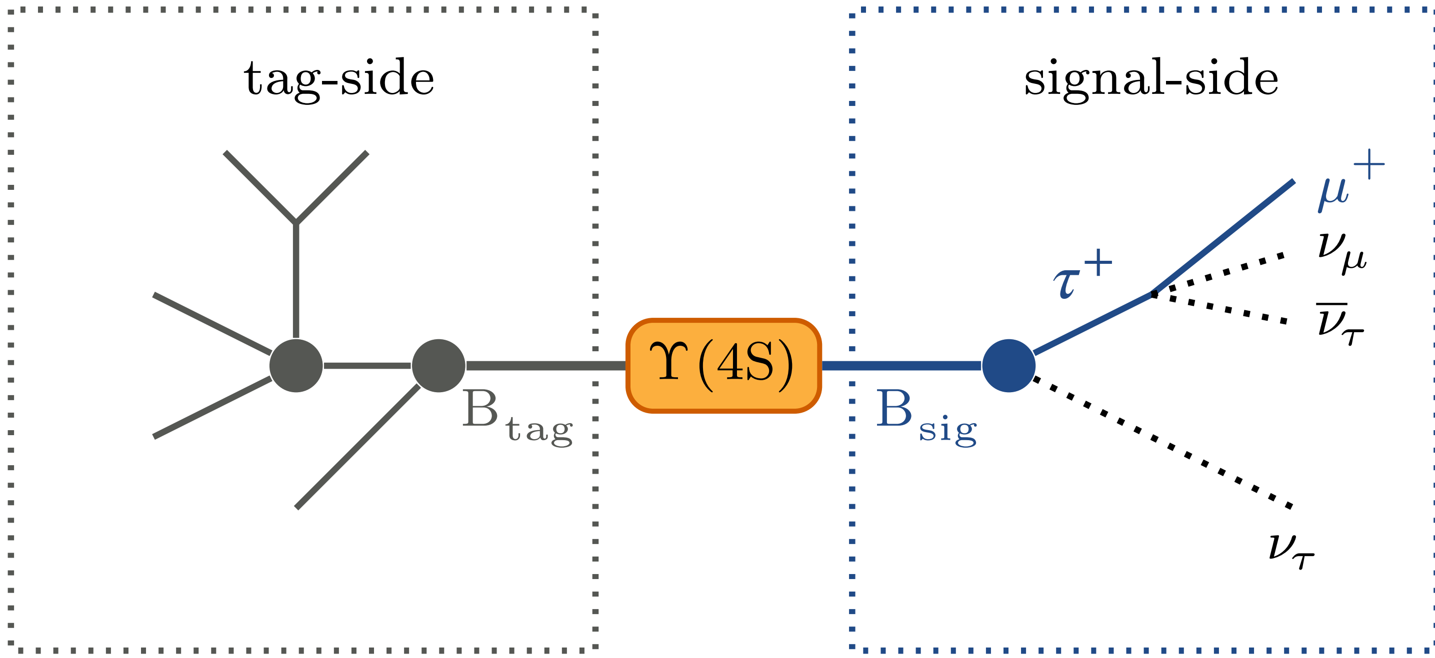
ICHEP 2020 dataset: $\int \mathscr{L} dt = 34.6\ \mathrm{fb}^{-1}$

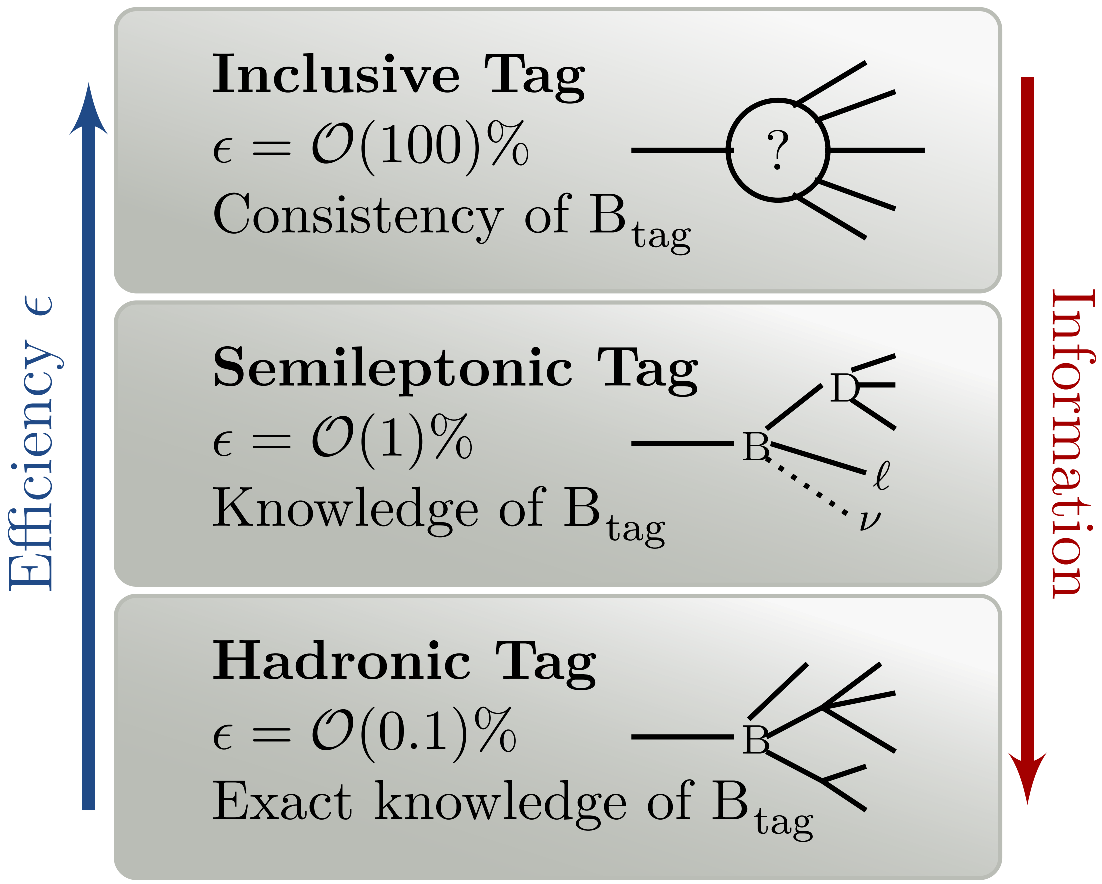
- Present data sample too limited for performing B (semi)tauonic physics measurements.

  $\rightarrow$ Studied data/MC comparisons to demonstrate understanding of detector performance.

- Expecting first measurements with τ's with $\mathcal{O}(200\ \mathrm{fb}^{-1})$ in 2021.

Event reconstruction strategy





- Exploit flavour and kinematic constraints on "signal" B system by *tagging* the other.

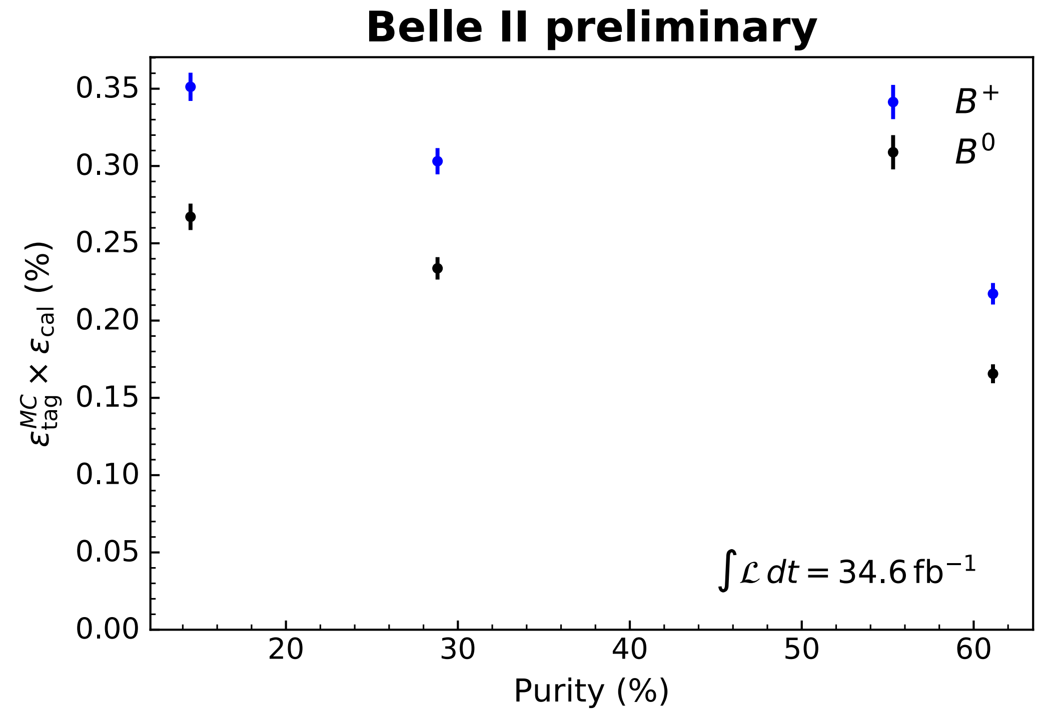
$* \rightarrow$ C.M. frame

$$M_{bc} = \sqrt{\left(\frac{\sqrt{s}}{2}\right)^2 - p^{*2}_{B_{tag}}} = \sqrt{E^{*2}_{beam} - p^{*2}_{B_{tag}}} \qquad \Delta E = E^*_{B_{tag}} - E^*_{beam}$$

- B_{sig} most often reconstructed through leptonic decays of the τ ($\mathscr{B}(\tau \to \ell\nu\nu) \approx 34\,\%$) to further minimise background.

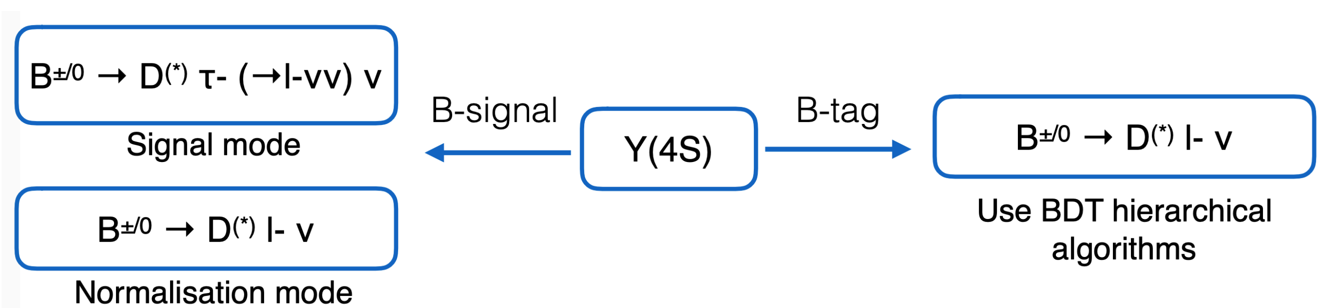
Full Event Interpretation algorithm for B_{tag} reconstruction

- Full Event Interpretation (FEI) algorithm developed in Belle II software → $\mathcal{O}(200)$ BDT classifiers trained on $\mathcal{O}(10{,}000)$ B decay channels to identifiy the B_{tag}



W. Sutcliffe's talk

- FEI successfully exploited in $R(D^{(*)})$ "semileptonic tag" analysis on Belle data analysed with the Belle II software.

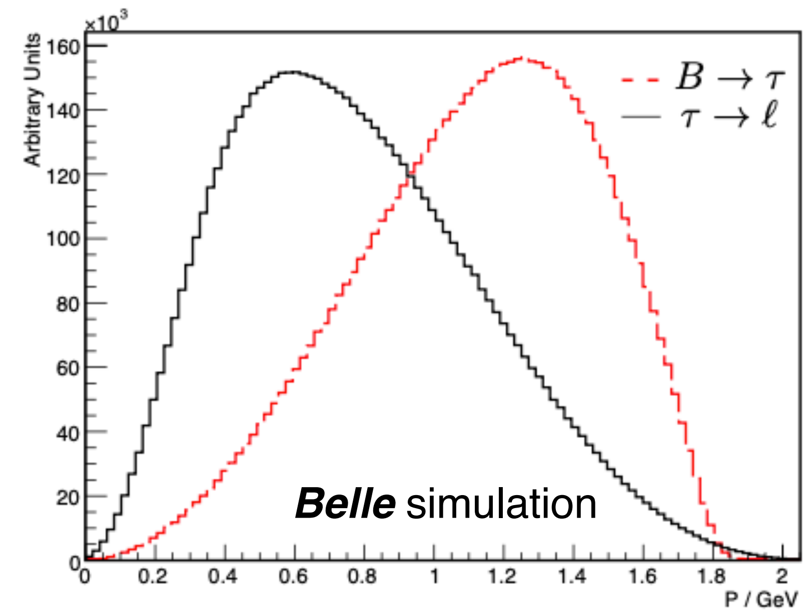


G. Caria *et al.* (Belle Collaboration), Phys. Rev. Lett. **124**, 161803

Experiment	Tag method	τ mode	R(D)	R(D*)	
Babar '12	Hadronic	ℓ ν ν	**0.440 ± 0.058 ± 0.042**	0.332 ± 0.024 ± 0.018	
Belle '15	Hadronic	ℓ ν ν	**0.375 ± 0.064 ± 0.026**	0.293 ± 0.038 ± 0.015	
LHCb '15	-	ℓ ν ν	-	0.336 ± 0.027 ± 0.030	
Belle '16	Semileptonic	ℓ ν ν	-	0.302 ± 0.030 ± 0.011	B^0
Belle '17	Hadronic	π ν, ρ ν	-	0.270 ± 0.035 ± 0.027	
LHCb '18	-	π π π ν	-	0.291 ± 0.019 ± 0.029	
Belle '19	**Semileptonic**	**ℓ ν ν**	**0.307 ± 0.037 ± 0.016**	**0.283 ± 0.018 ± 0.014**	B^0, B^+
Average (2018)	-	-	*0.407 ± 0.039 ± 0.024*	*0.306 ± 0.013 ± 0.007*	
Average (2019)	-	-	**0.340 ± 0.027 ± 0.013**	**0.295 ± 0.011 ± 0.008**	
SM			0.299 ± 0.003	0.258 ± 0.005	

Relevant observables for B decays with τ's

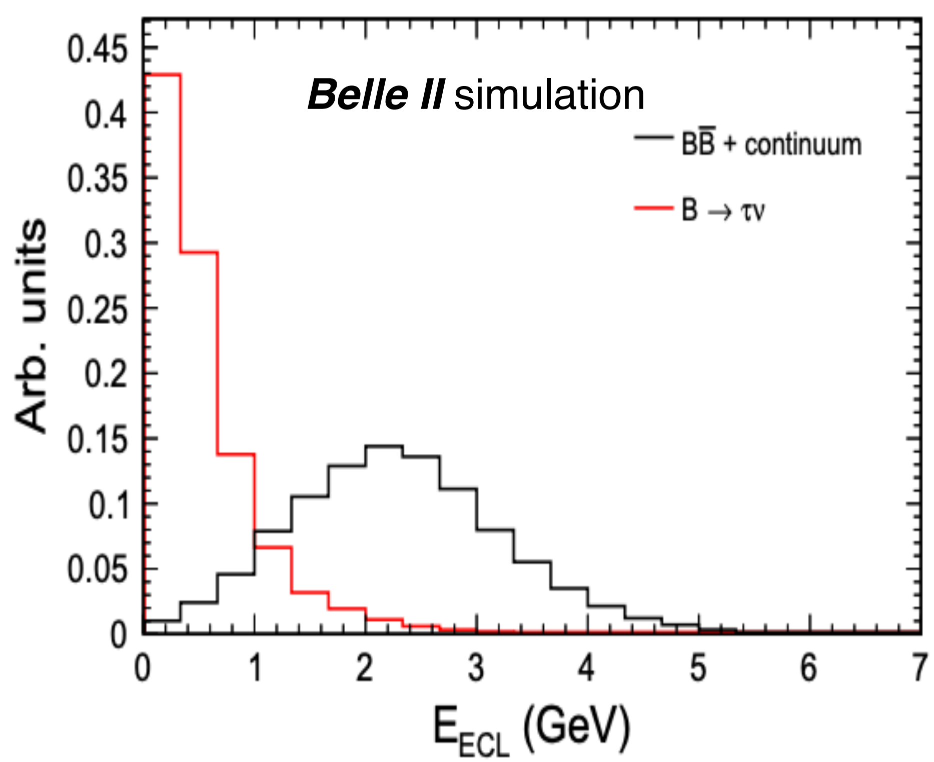
- p_ℓ^* (in B_{sig} r.f.)$\rightarrow$ crucially dependent on good lepton identification performance.
    - Challenging due to low momentum of lepton daughters.



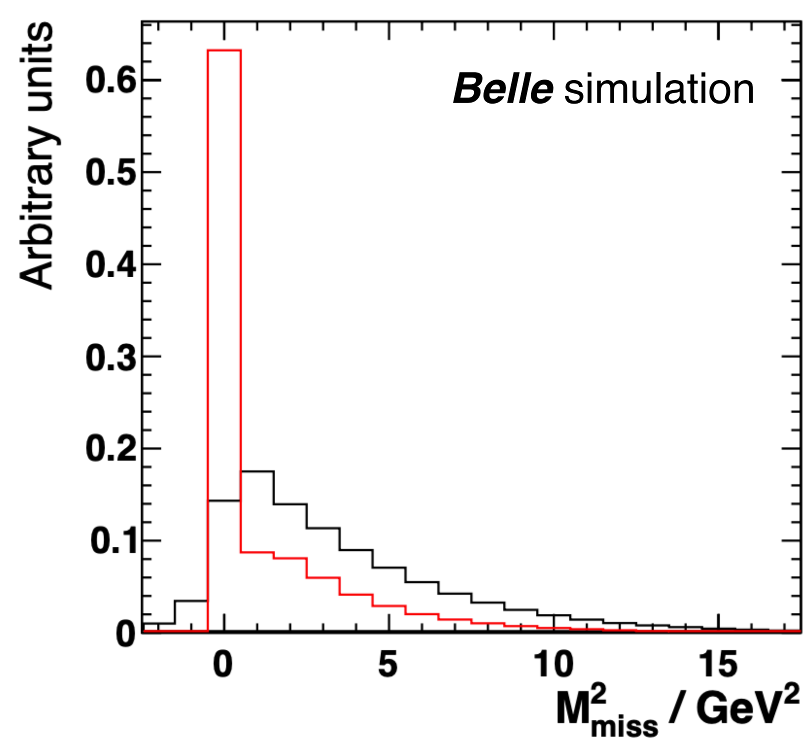
- m^2_{miss} $\rightarrow$ separates signal from $B \rightarrow X\ell\nu$, pure hadronic final states.

- E_{ECL} $\rightarrow$ energy in the calorimeter of neutral particles not used in the reconstruction of the signal or tag.

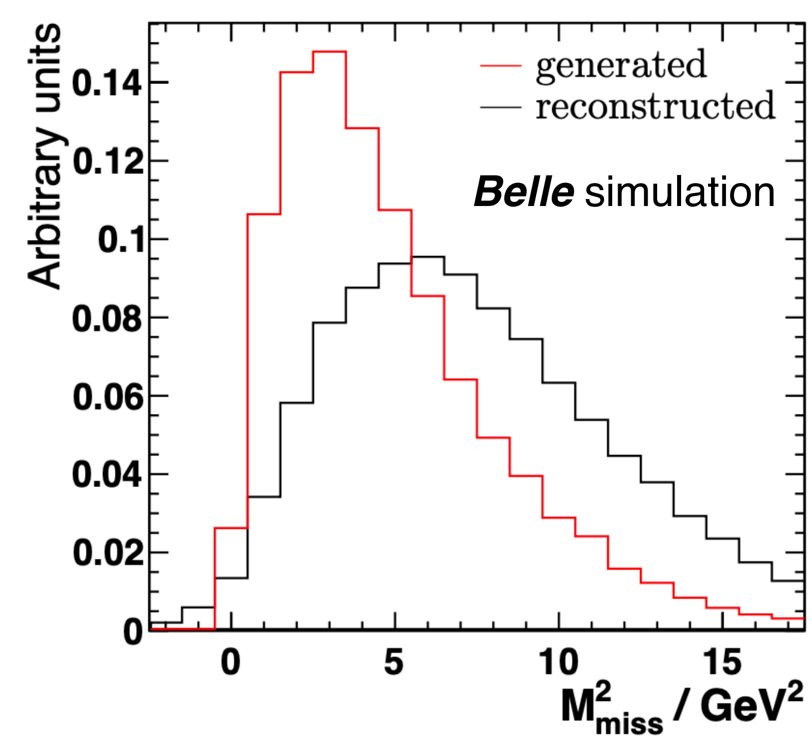
$B \rightarrow \tau\nu$ (*MC reco only*)



$B \rightarrow X\ell\nu$



$B \rightarrow X\tau\nu$



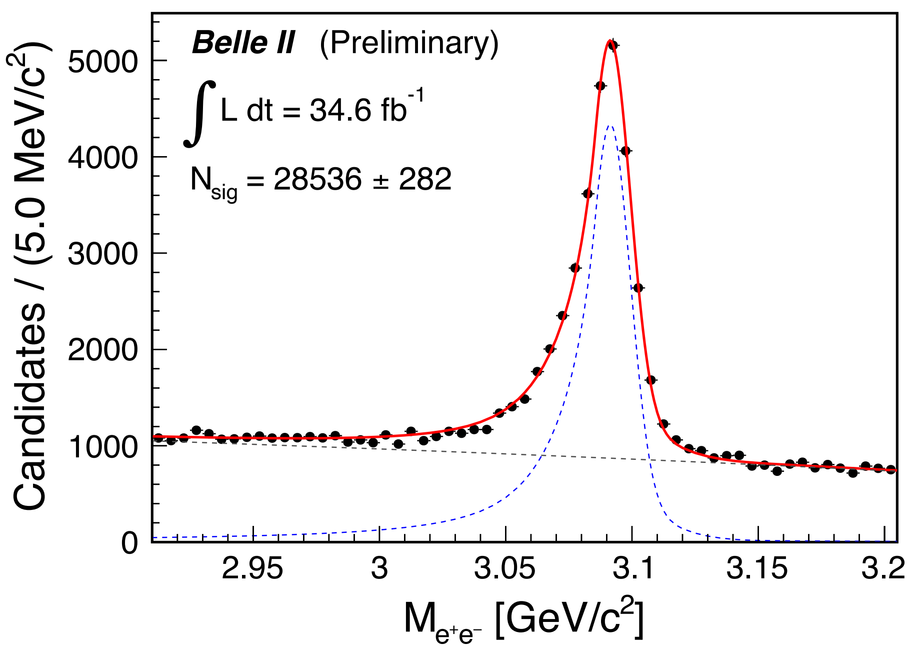
Lepton identification performance in 2020 data

- Lepton identification & hadron mis-id performance in simulation calibrated to data using several "standard candles" to cover broad p range.

Likelihood ratio (w/ inputs from all sub-detectors)

$$\ell\text{ID} = \frac{\mathcal{L}_\ell}{\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p}.$$

$J/\psi \to e^+e^-$

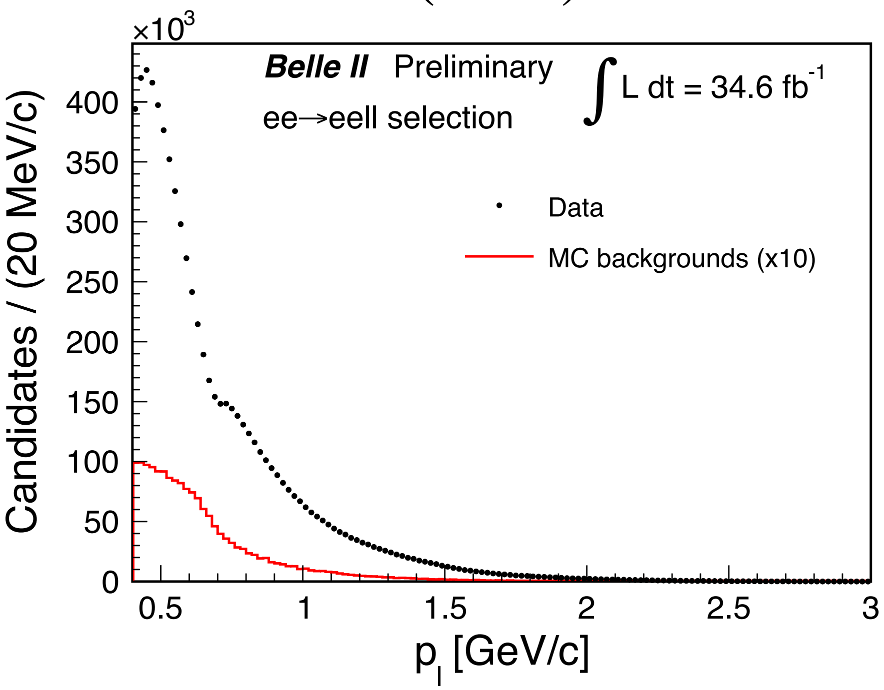


NEW!

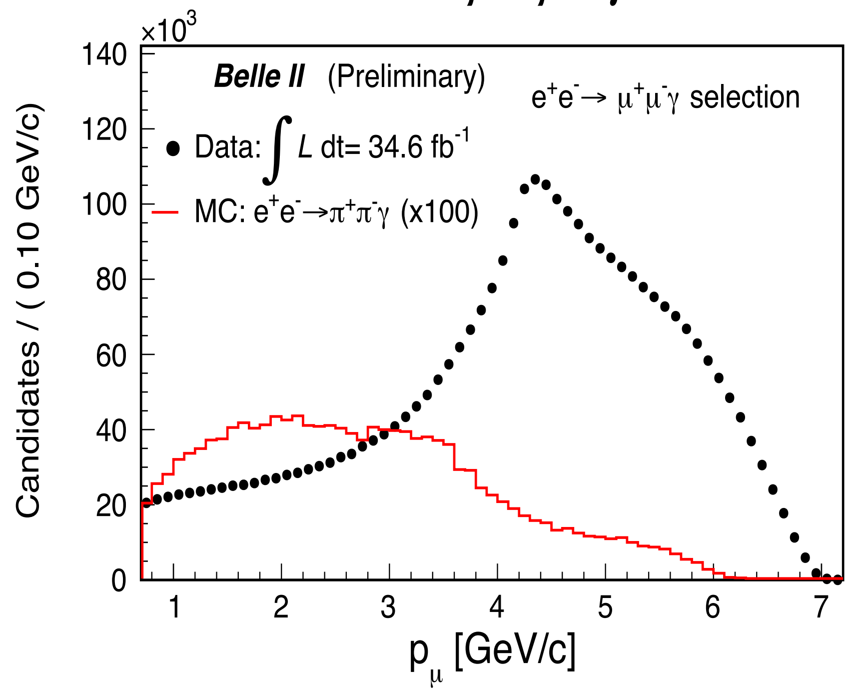
BELLE2-NOTE-PL-2020-027

Lepton ID efficiency (ℓ=e,μ)	Hadron mis-id.
$J/\psi \to \ell\ell$	$K_S \to \pi\pi$
$ee \to ee\ell\ell$	$ee \to \tau(1\text{-}p)\tau(3\text{-}p)$
$ee \to ee(\gamma)$	$D^{*+} \to D^0(K^-\pi^+)\pi^+$
$ee \to \mu\mu\gamma$	$D^{*+} \to D^0(K^-\pi^+)\pi^+$

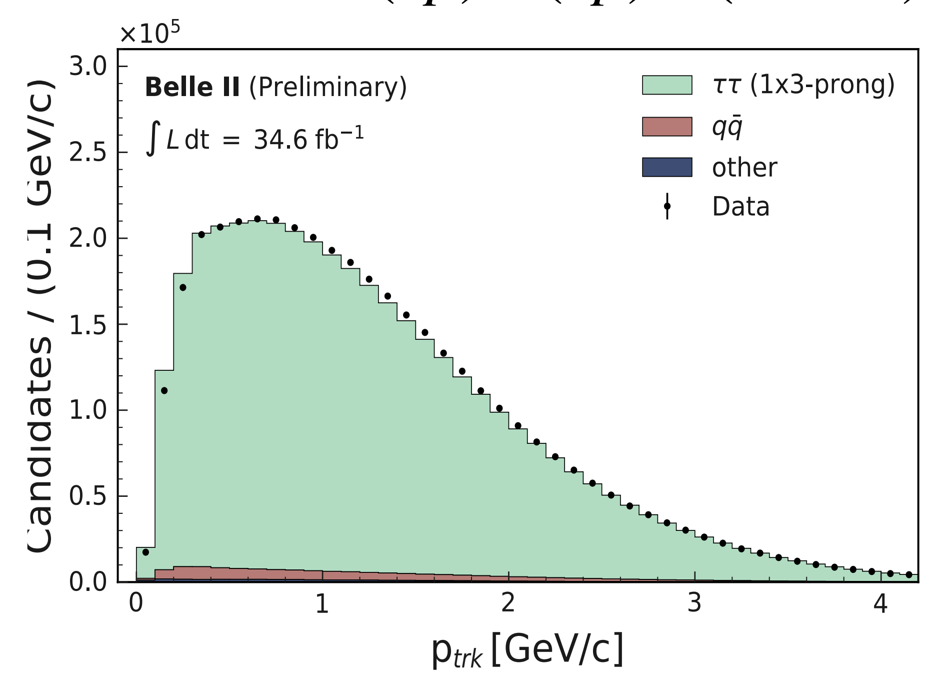
$e^+e^- \to (e^+e^-)e^+e^-$



$e^+e^- \to \mu^+\mu^-\gamma$



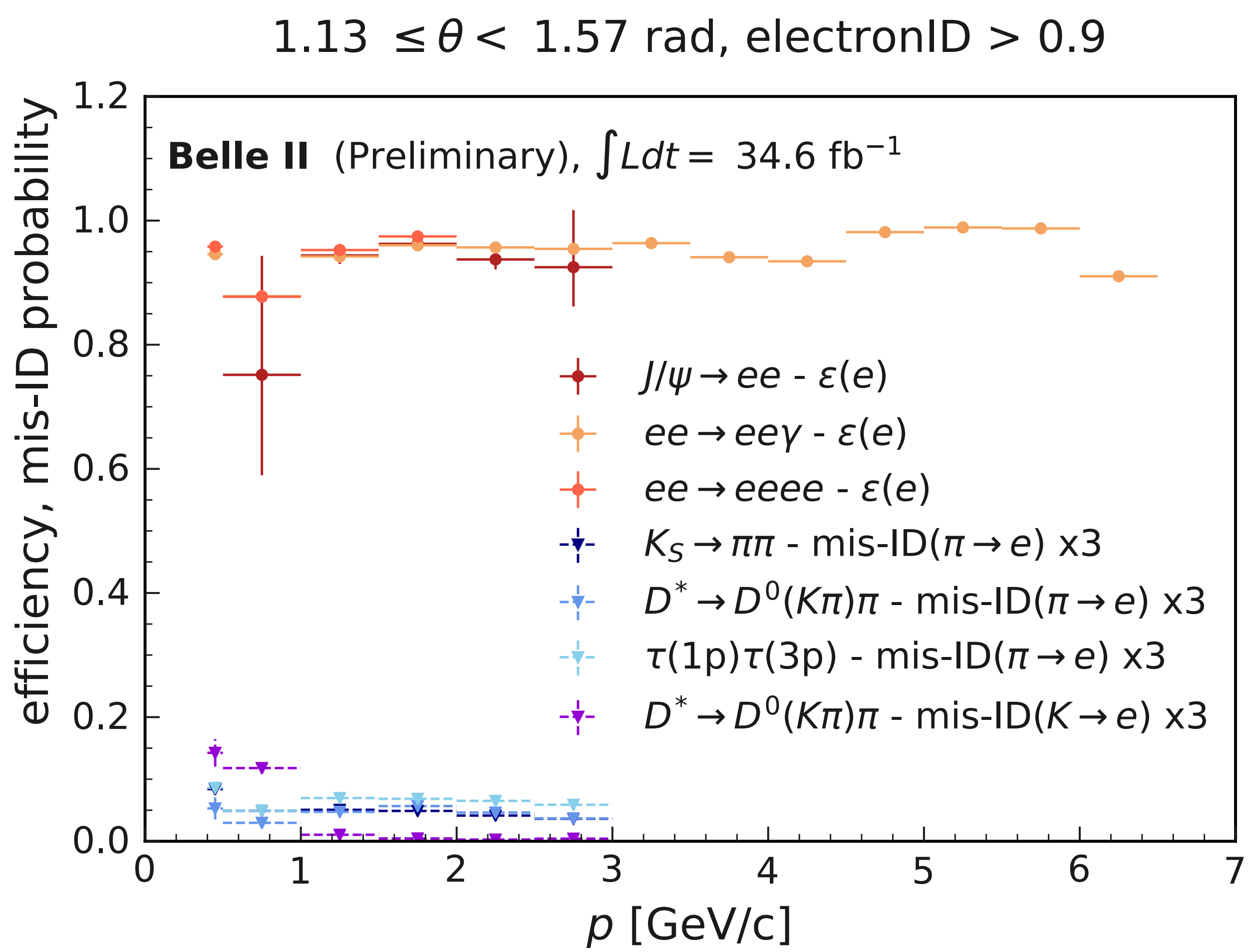
$e^+e^- \to \tau^+(1p)\tau^-(3p) \quad (\pi \to \ell)$



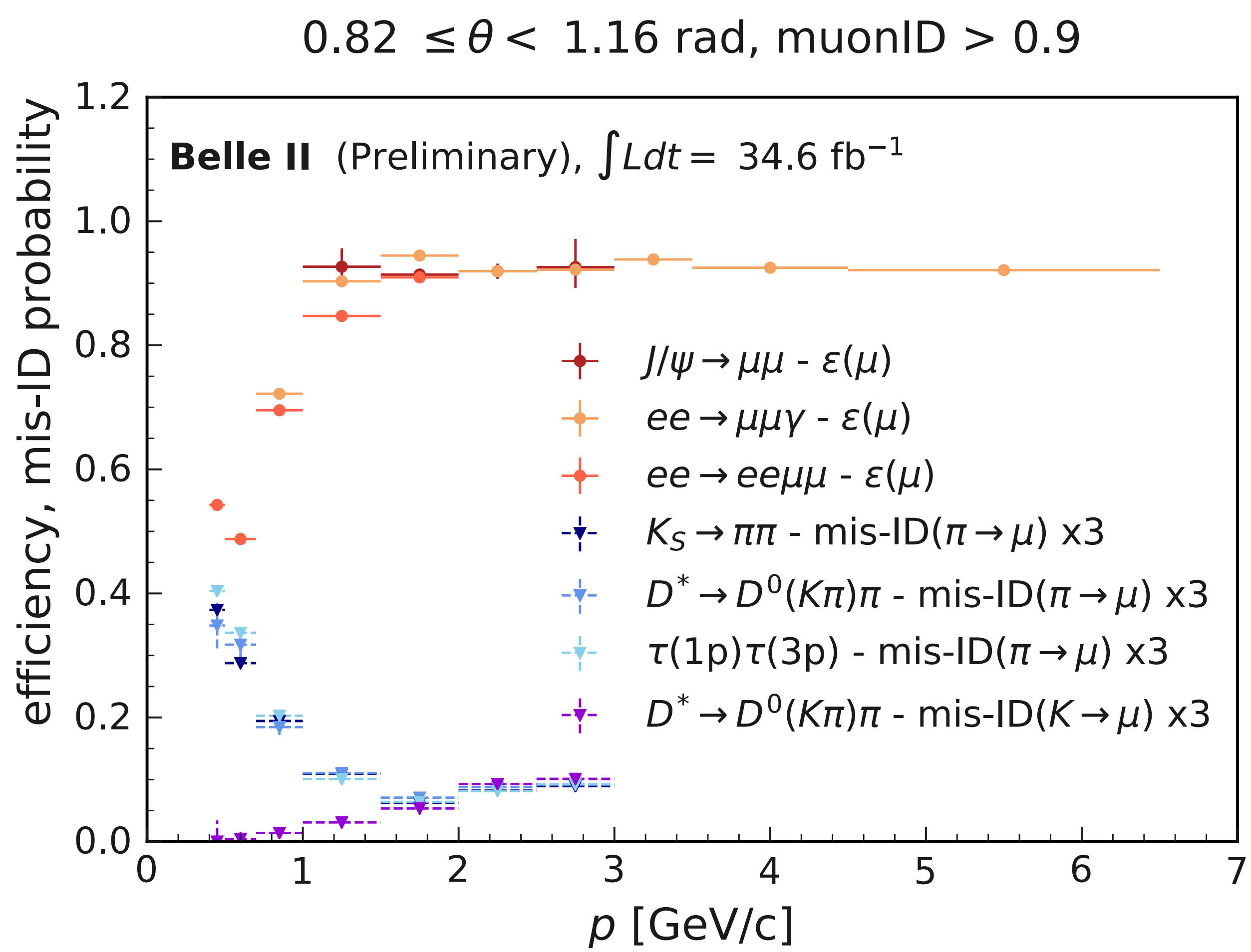
Lepton identification performance in 2020 data

- Results for a representative bin in the detector "barrel" region.

Electrons



Muons

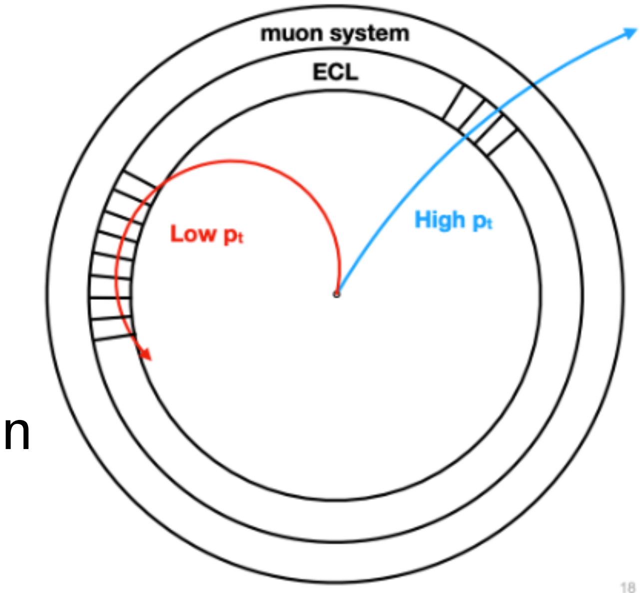


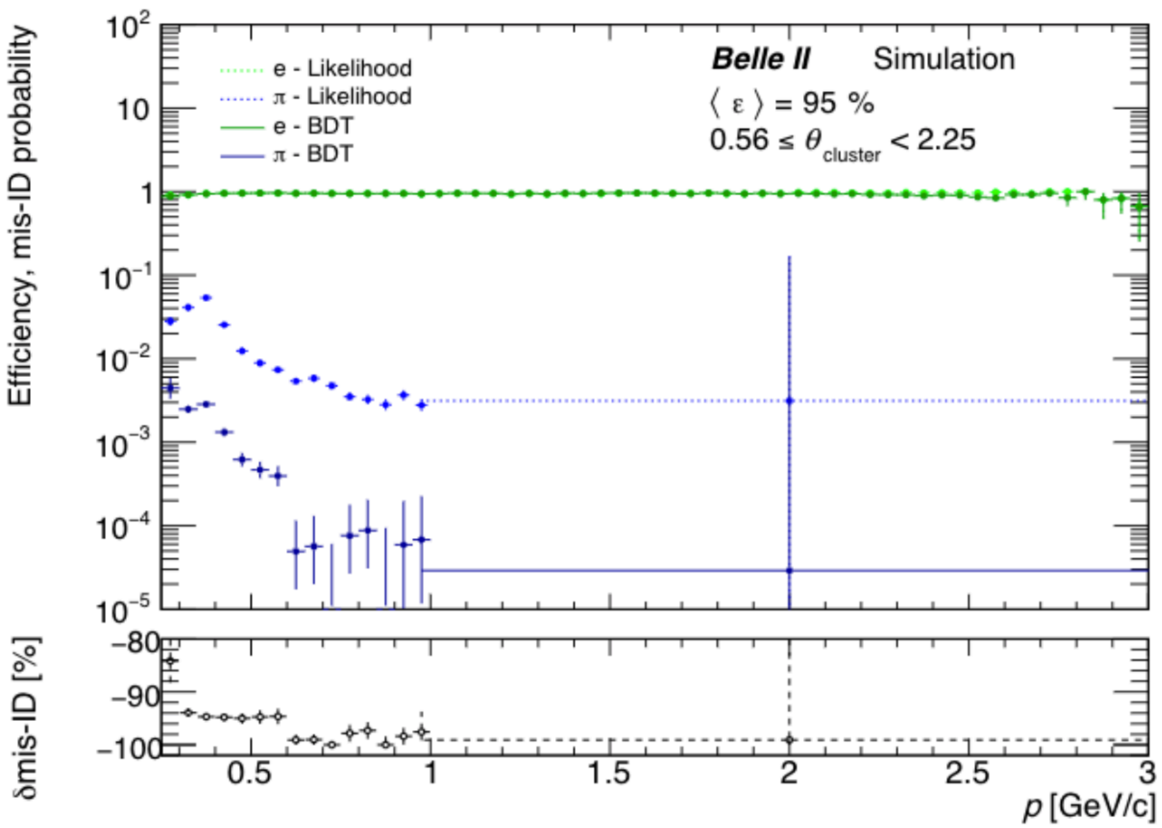
- e, $\mathscr{L}_{ratio} > 0.9$, $p > 1$ GeV/c $\to$ ⟨efficiency⟩ of 94% for 2% pion mis-id probability.
- μ, $\mathscr{L}_{ratio} > 0.9$, $p > 1$ GeV/c $\to$ ⟨efficiency⟩ of 90% for 4% pion mis-id probability.

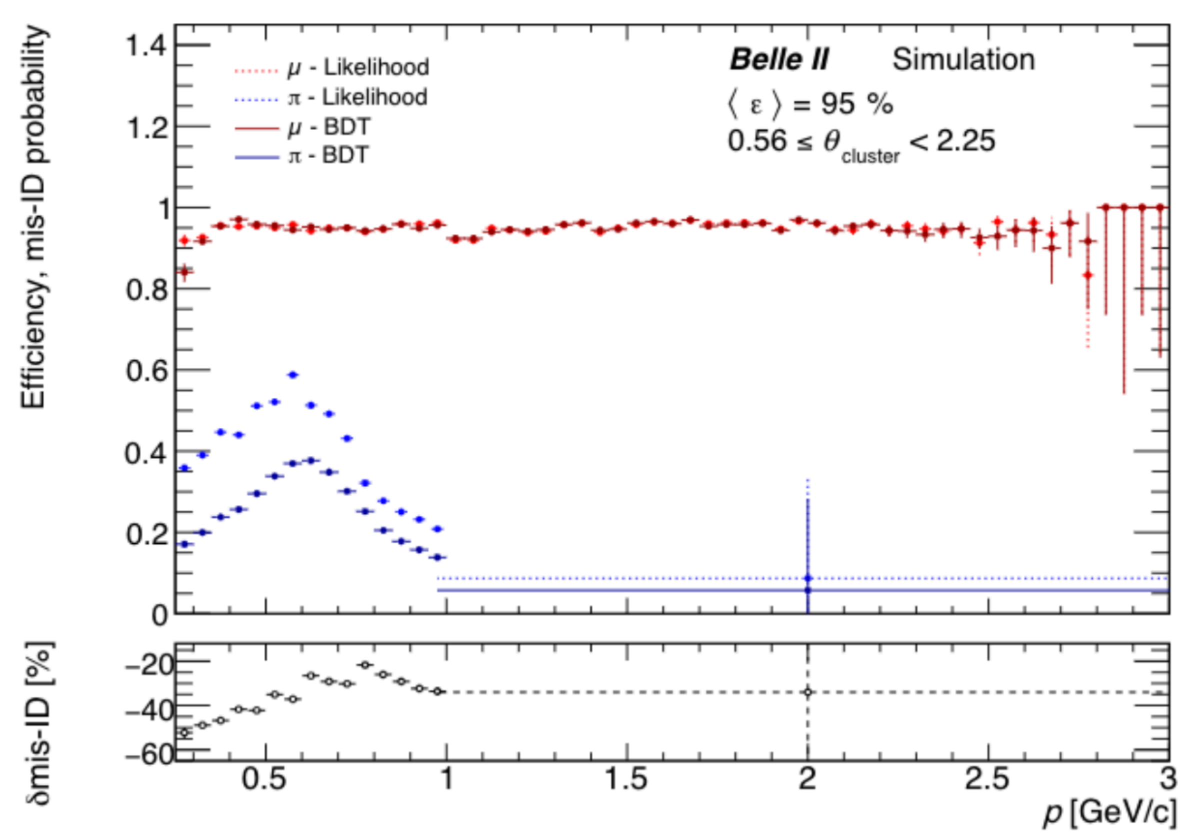
Upgrades to lepton identification using the ECL

- At low momentum, limit in KLM acceptance and large energy losses for electrons before the ECL make lepton identification a challenge.

$\rightarrow$ Combine several calorimetric observables (lateral shower shapes, extrapolated track depth in the ECL...) in a BDT to improve lepton-hadron separation.





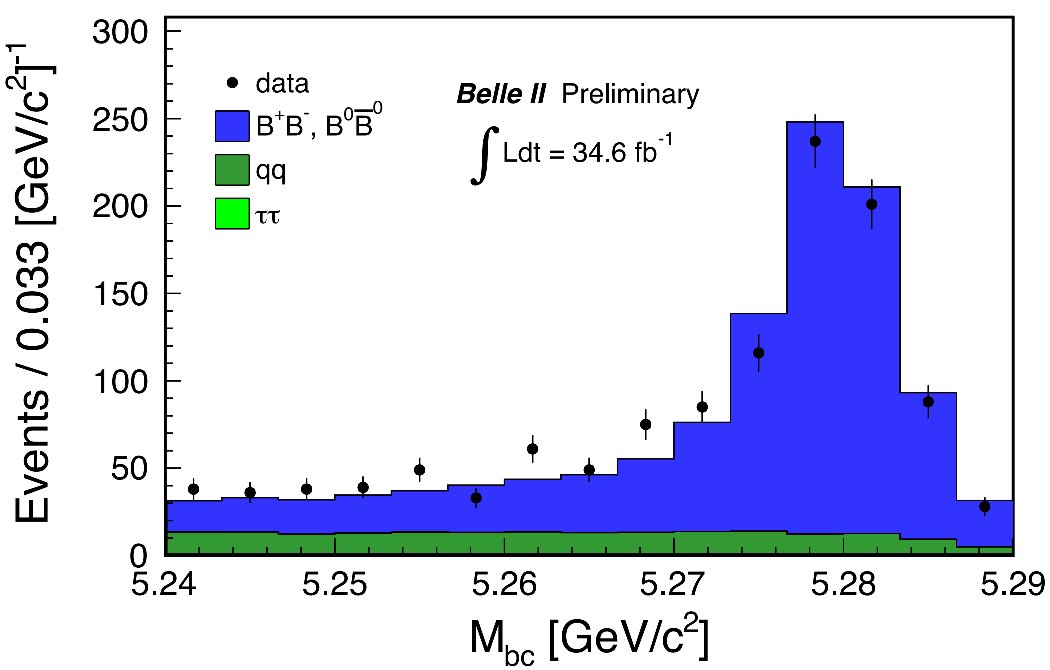


- Factor 10 reduction in $\pi - e$ fake rate, and a factor 2 in $\pi - \mu$ fake rate for $p < 1$ GeV/c (MC)

Full leptonic $B^- \to \tau^-(\to e^-\bar{\nu}_e\nu_\tau)\bar{\nu}_\tau$ - Preliminary results

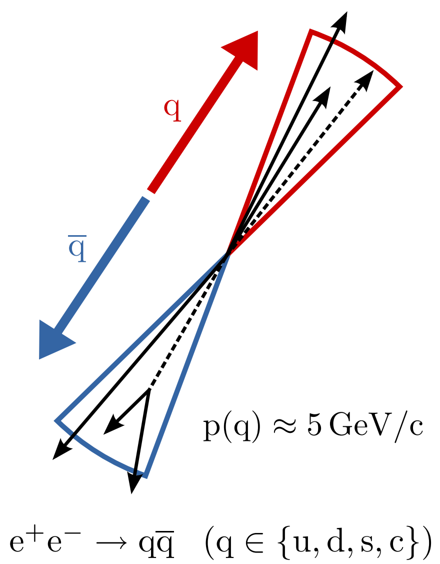
- First pure tauonic result of Belle II → test-bench for event reconstruction capability.
- Only $\tau \to e\nu_e\nu_\tau$ channel considered. Use hadronic FEI tagging.

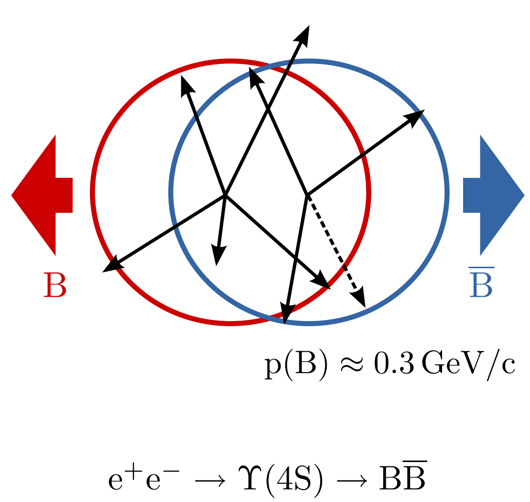
NEW! BELLE2-NOTE-PL-2020-023

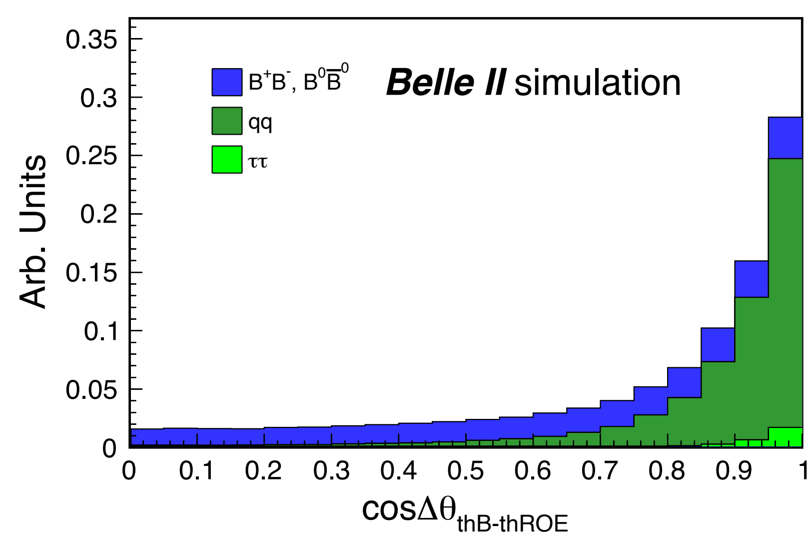


≈50% purity for correctly reconstructed B_{tag} candidates estimated from fit to M_{bc}

Event preselection + tag selection	Description
$\lvert d_0\rvert < 0.5$ cm, $\lvert z_0\rvert < 2$ cm, $p > 0.1$ GeV/c, $N_{trk} \geq 3$	track preselection
$E_{cluster} > 100$ MeV, $0.29 < \theta_{cluster} < 2.61$ rad, $N_{cluster} \geq 3$	ECL cluster preselection
$2 < E_{ECL}(tot) < 7$ GeV, $E_{vis} > 4$ GeV	total energy in event
$\log_{10}(p_{FEI}) > -2$	FEI sig. prob. cut for B_{tag}
$\cos\Delta\theta_{thrust} < 0.8$	continuum supression [*]
$M_{bc} > 5.27$ GeV/c^2	selection on B_{tag} M_{bc}

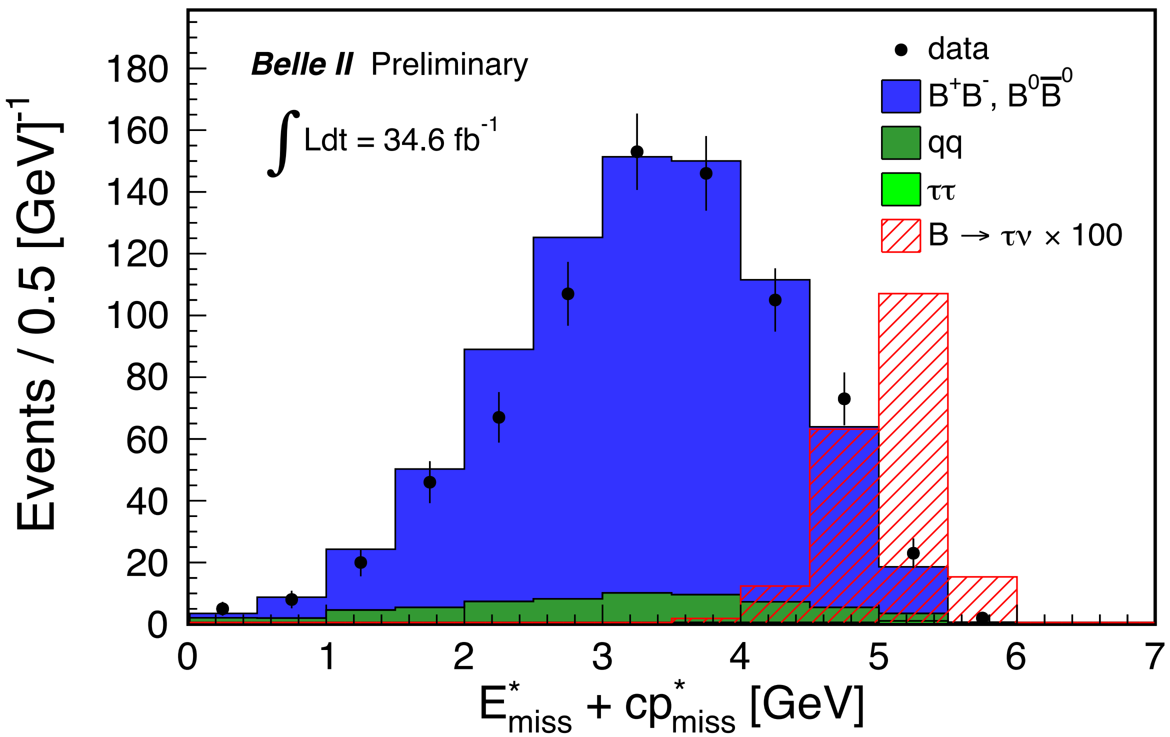


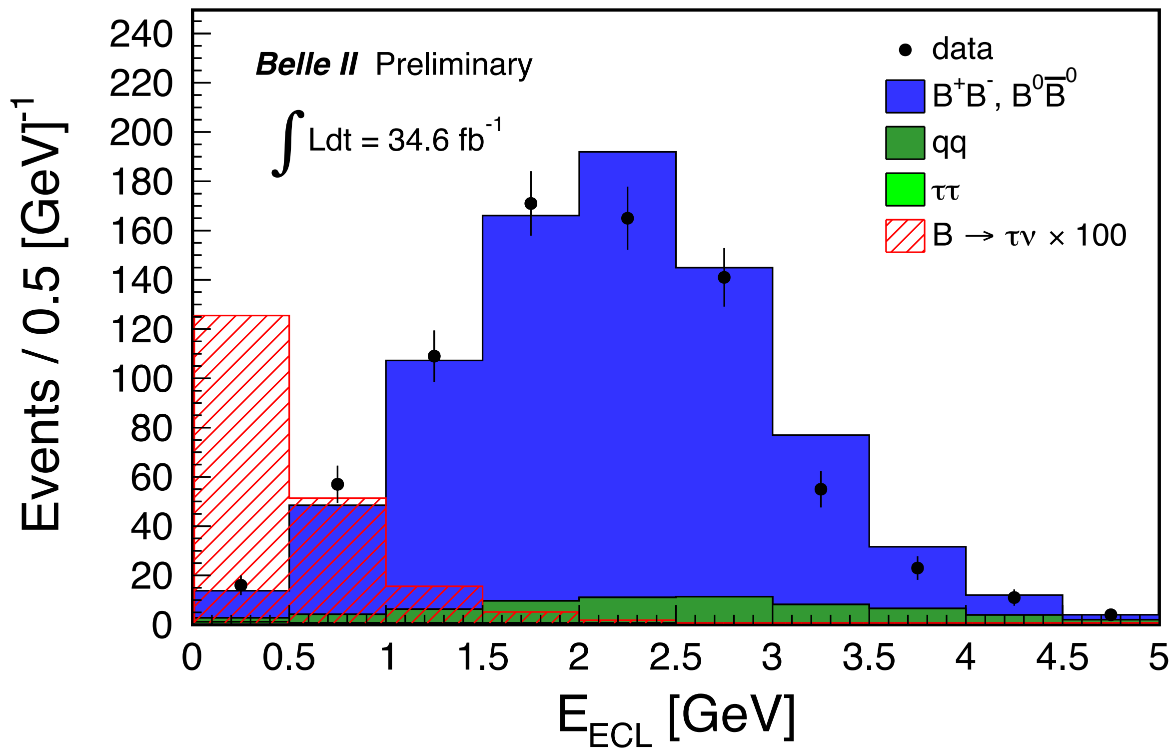




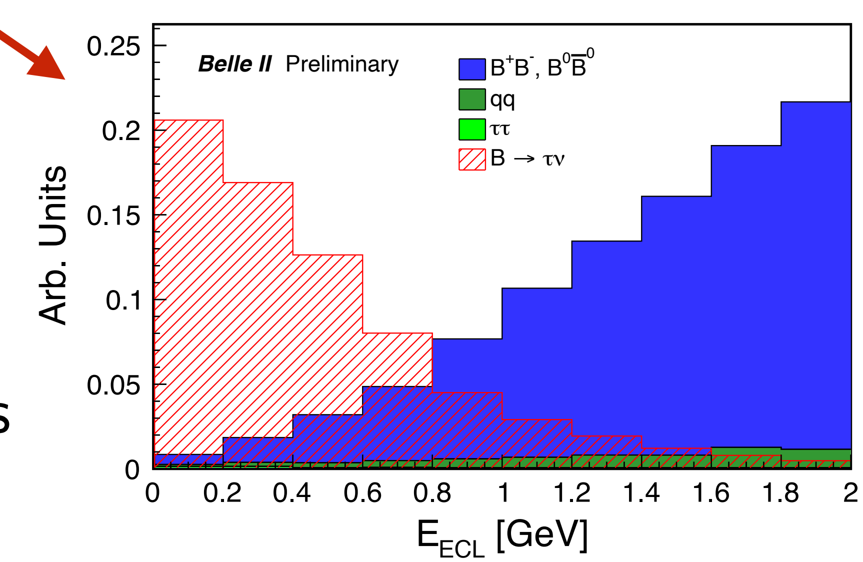
[*] angle between thrust axes of B_{tag} and the "rest of the event"

Full leptonic $B^- \to \tau^-(\to e^-\bar{\nu}_e\nu_\tau)\bar{\nu}_\tau$ - Preliminary results





- Selection on electron candidates: $p_e > 0.5$ GeV/c, electronID > 0.9.



- E_{ECL}, $E^*_{miss} + cp^*_{miss}$ (*: c.m. frame)
  - Fair modelling of background in the signal-enriched regions with the available statistics.

$\rightarrow$ demonstrate potential for observation of $B \to \tau\nu$ with larger dataset.

- Tail in E_{ECL} distribution:
  - Background $(B, q\bar{q}) \to$ mis-assigned K_L's and γ's.
  - Signal $\to$ resolution effects, *beam background*.

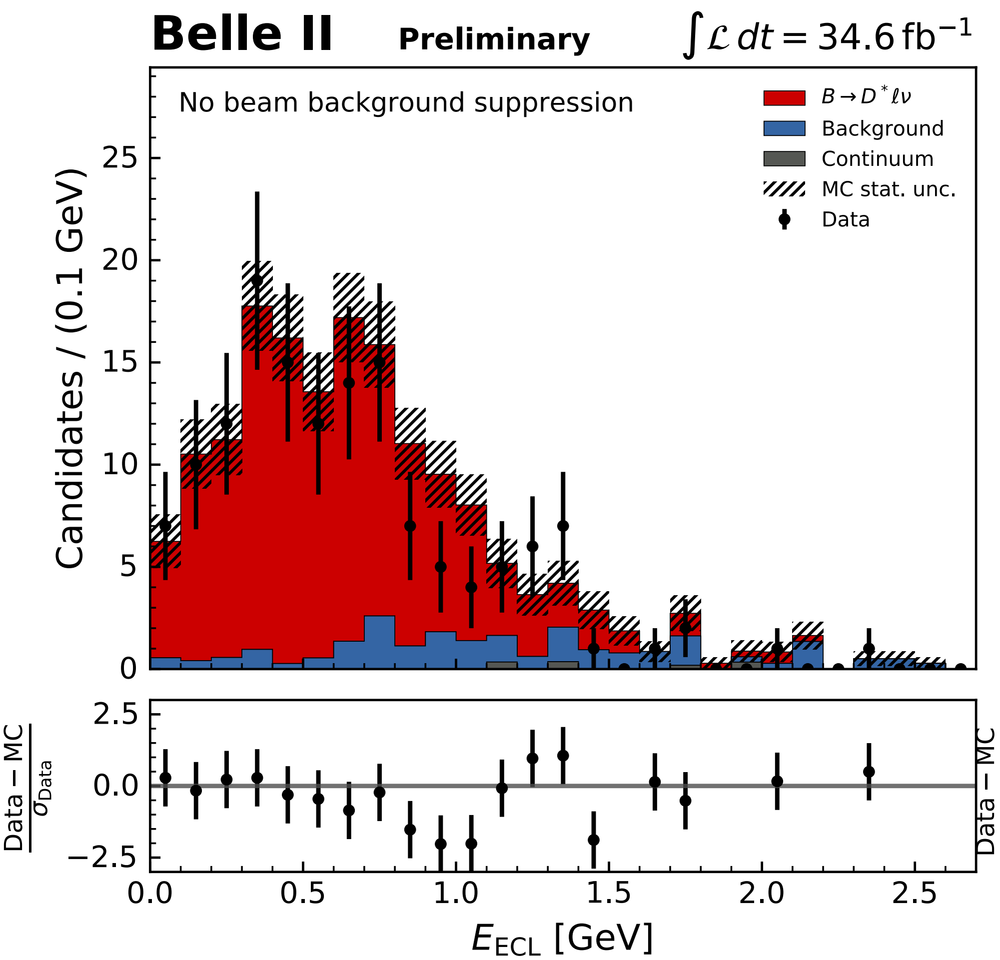
R. Cheaib's talk

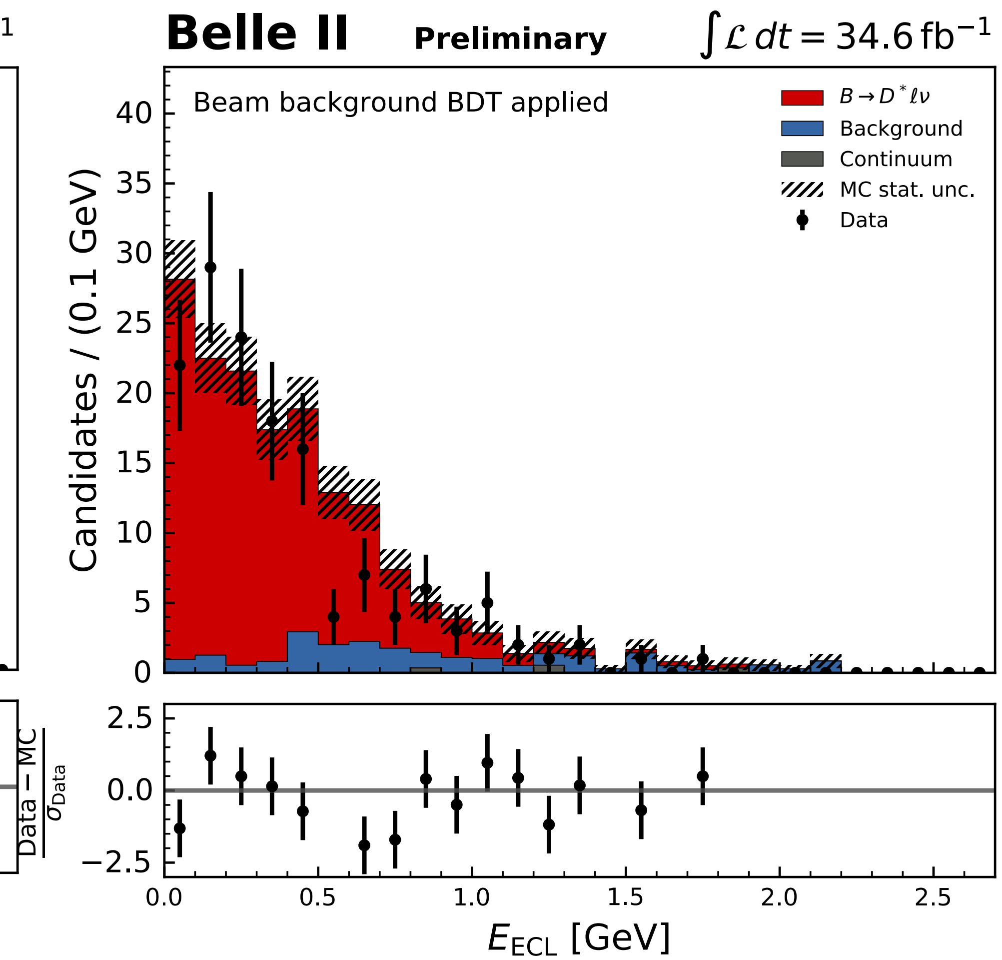
NEW!

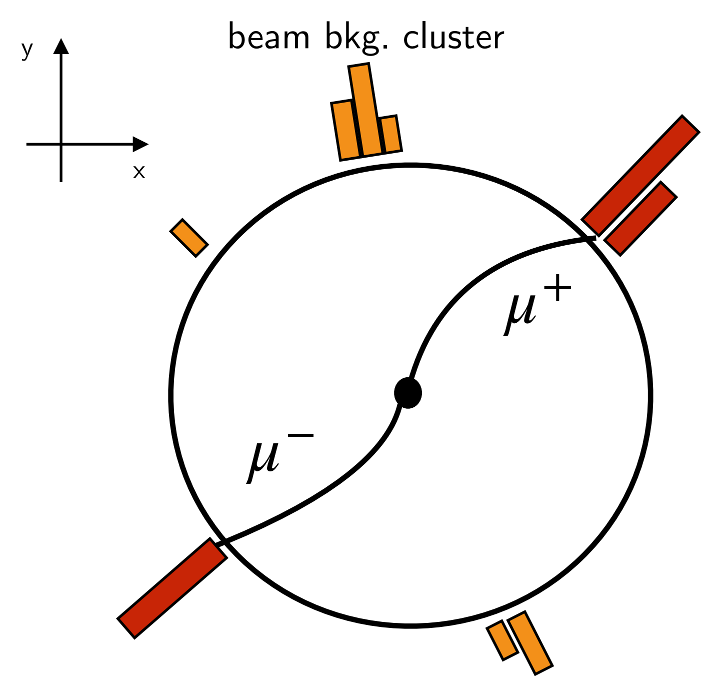
BELLE2-CONF-PH-2020-023

- BDT developed to reduce beam background neutrals on E_{ECL} in the $\bar{B}^0 \to D^{*+}\ell^-\nu$ analysis, based on 6 calorimetric clusters shower shapes and angular positions ($E_{cluster} > 100$ MeV).

- Algorithm trained on $e^+e^- \to \mu^+\mu^-$ control sample.







Prospects for (semi)leptonic B decays with τ leptons

- $B \to \tau\nu$:
  - expecting 5σ observation with 2.6 ab^{-1}
  - $\mathscr{B}(B \to \tau\nu)$ tot. uncertainty of (10%) with 5 ab^{-1}
- $B \to D^{(*)}\tau\nu$ $(R(D^{(*)}))$:
  - $\mathscr{O}(5\%)$ precision (tot. uncertainty) with 5 ab^{-1}

The Belle II Physics Book, PTEP 2019 no. 12, 123C01

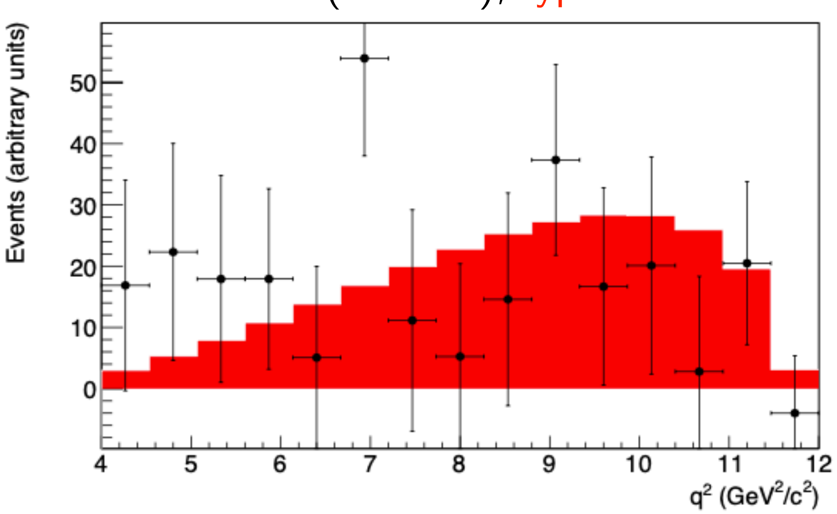
	Integrated Luminosity (ab^{-1})	1	5	50
hadronic tag	statistical uncertainty (%)	29	13	4
	systematic uncertainty (%)	13	7	5
	total uncertainty (%)	32	15	6
semileptonic tag	statistical uncertainty (%)	19	8	3
	systematic uncertainty (%)	18	9	5
	total uncertainty (%)	26	12	5

- Measure observables sensitive to NP effects in $b \to c\tau\nu$:
  - Polarisations: $P_\tau(D^{(*)}) = \dfrac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$, $P_{D^*} = \dfrac{\Gamma_L}{\Gamma_L + \Gamma_T}$
  - Kinematic distributions (q^2, p_ℓ)

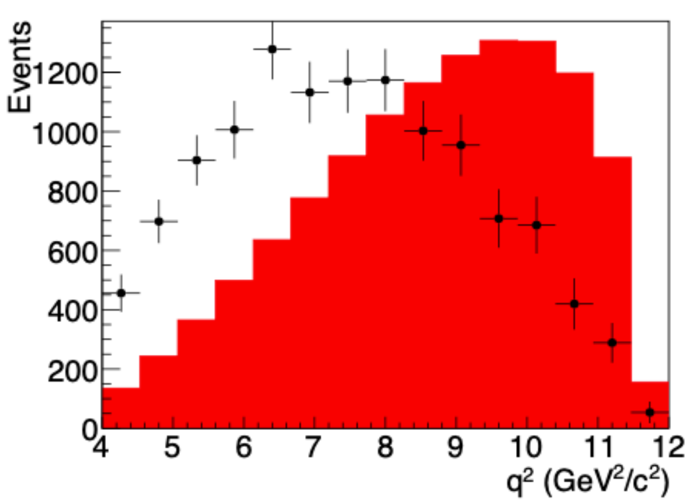
	5 ab^{-1}	50 ab^{-1}
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

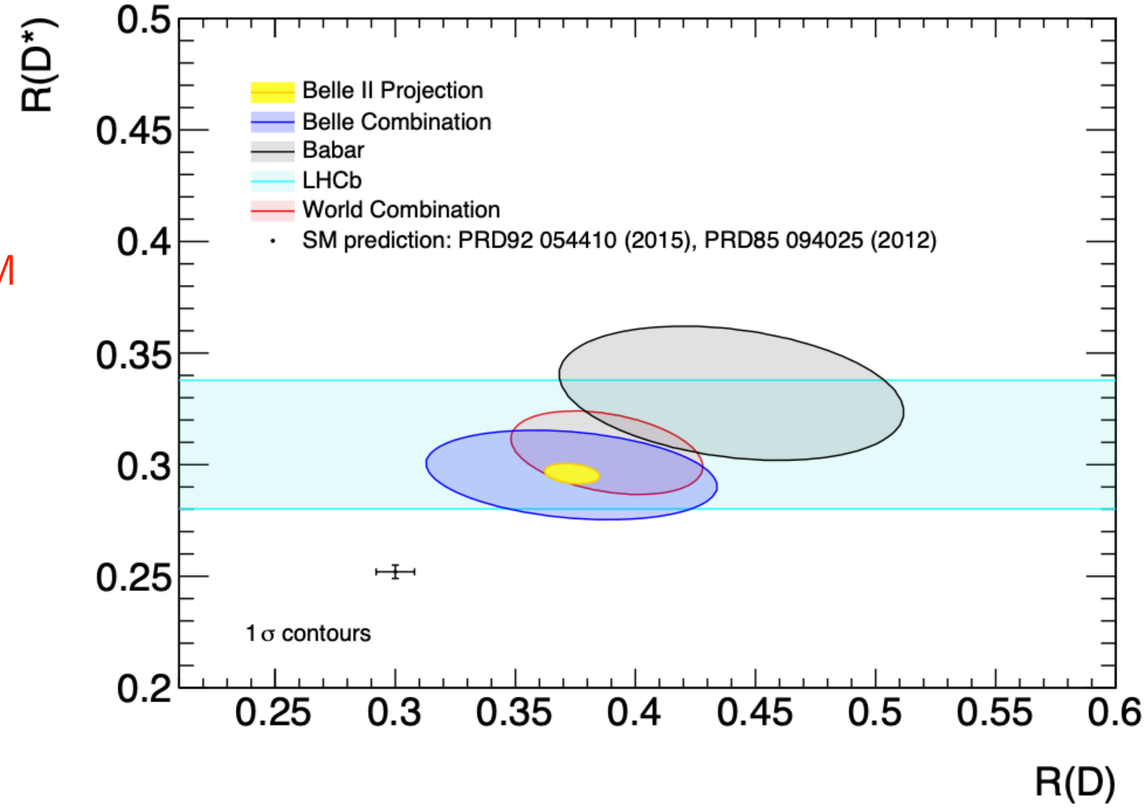
$B \to D\tau(\to \ell\nu\nu)\nu$, q^2 distribution

Belle data (711 fb^{-1}), type II 2HDM



Belle II (SM, 50 ab^{-1}), type II 2HDM



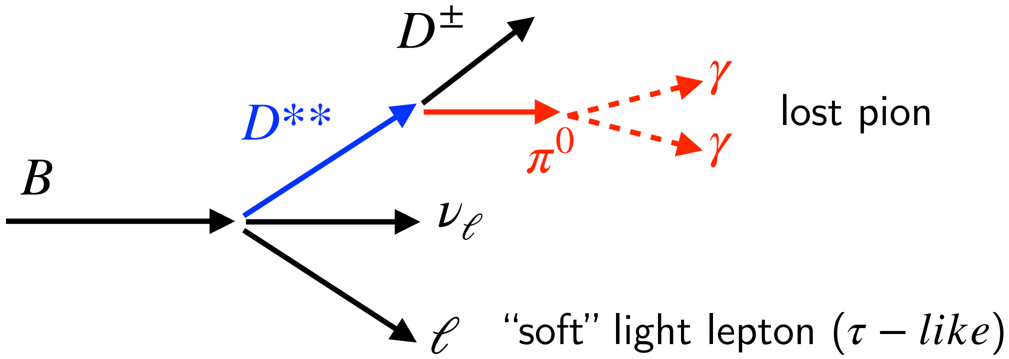


Experimental challenges

- Background from $B \to D^{**}\ell\nu_\ell$:

  $\to$ Measure branching ratios with higher precision.

  $\to$ (For exclusive analyses) improve π^0 reconstruction efficiency.



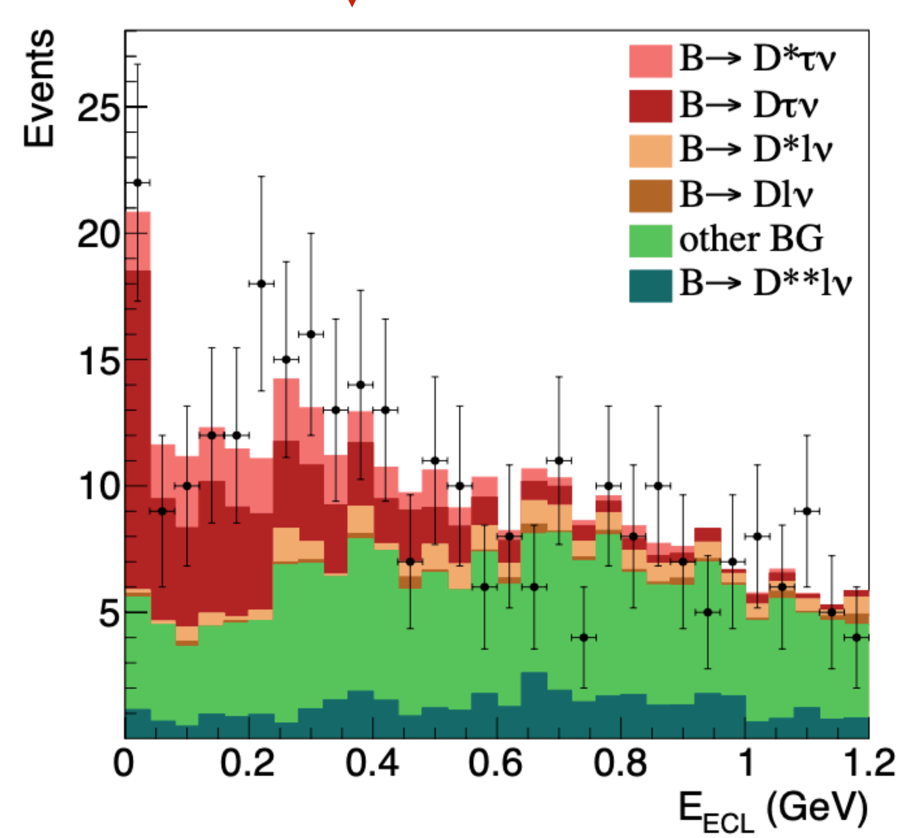
Source	Belle (Had, ℓ^-) R_D	Belle (Had, ℓ^-) R_{D^*}	Belle (SL, ℓ^-) R_{D^*}	Belle (Had, h^-) R_{D^*}
MC statistics	4.4%	3.6%	2.5%	$^{+4.0}_{-2.9}$%
$B \to D^{**}\ell\nu_\ell$	4.4%	3.4%	$^{+1.0}_{-1.7}$%	2.3%
Hadronic B	0.1%	0.1%	1.1%	$^{+7.3}_{-6.5}$%
Other sources	3.4%	1.6%	$^{+1.8}_{-1.4}$%	5.0%
Total	7.1%	5.2%	$^{+3.4}_{-3.5}$%	$^{+10.0}_{-9.0}$%

- Fake lepton suppression at low momenta, and improved LID calibration.

- Furthermore, for *inclusive* $B \to X\tau\nu$ analysis:

  $\to$ Handle background from leptonic charm decays $B \to D \to \ell$

  $\to$ large background yield implies *all* MC processes' $\mathcal{B}$'s must be measured with high precision.



Belle hadronic tag $B \to D\tau\nu$ ($\tau \to \ell\nu_\ell\nu_\tau$) analysis, $M^2_{miss} > 2.0$ GeV^2/c^4
Phys. Rev., D92(7), 072014 (2015)

Conclusions

- Belle II operations are in full swing, with $\approx 70\ \mathrm{fb}^{-1}$ of data collected to date.

- First analyses on B (semi)leptonic decays with tau leptons successfully test improved techniques for event reconstruction (FEI).

- Preliminary studies of lepton identication in multiple channels show good performance, and exciting new developments will soon be tested in physics analyses.

- More intriguing results on B tauonic final states are on the way for 2021.