Standard model tests in modes with neutrinos

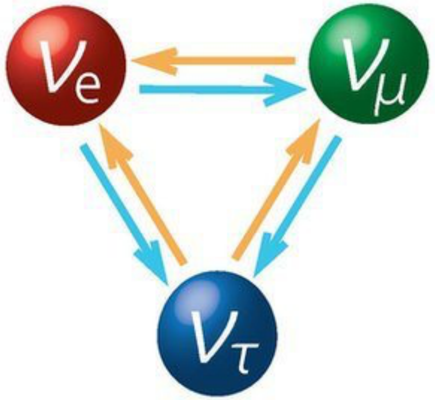
Towards the Ultimate Precision in Flavour Physics

Simon Wehle
Warwick, 18.04.2018

Motivation

Standard model tests in modes with neutrinos

- Decays involving neutrinos can be sensitive to a variety of new physics models
- Experimentally extremely challenging
- We can learn lot about the origin of flavour



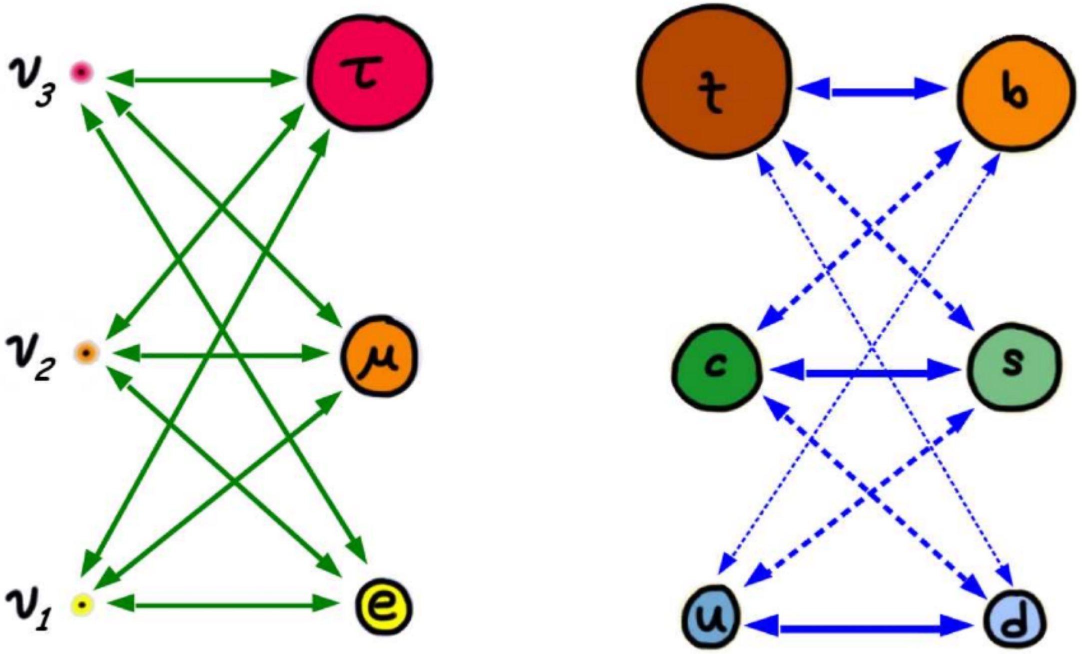
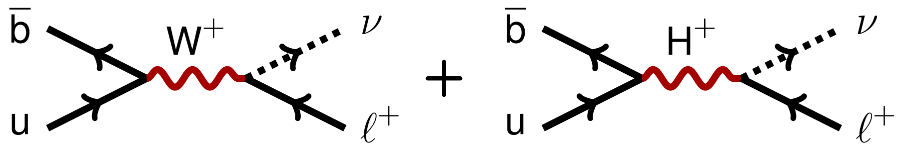


Illustration: W. Altmannshofer

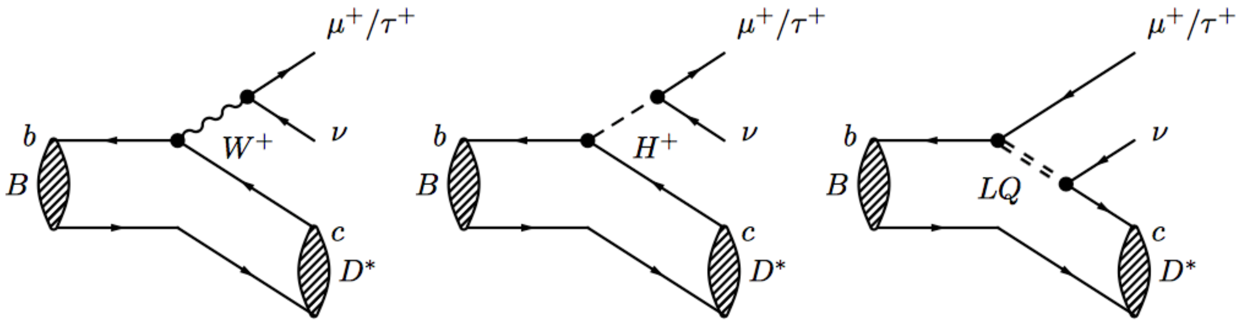
Standard model tests in modes with neutrinos

Overview of the topics in this talk

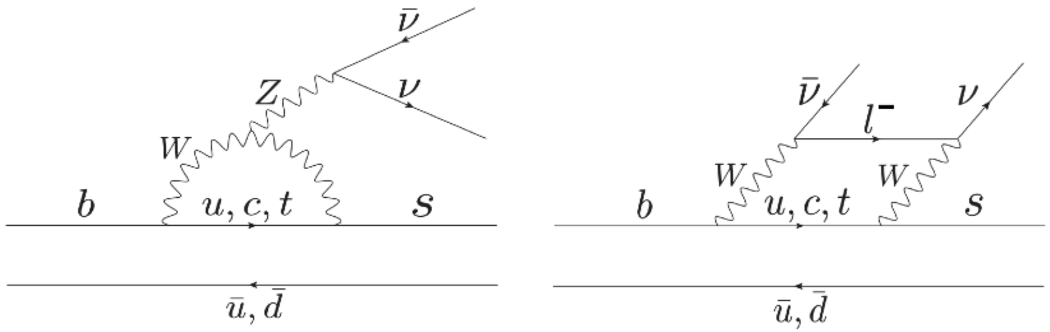
- Leptonic B decays



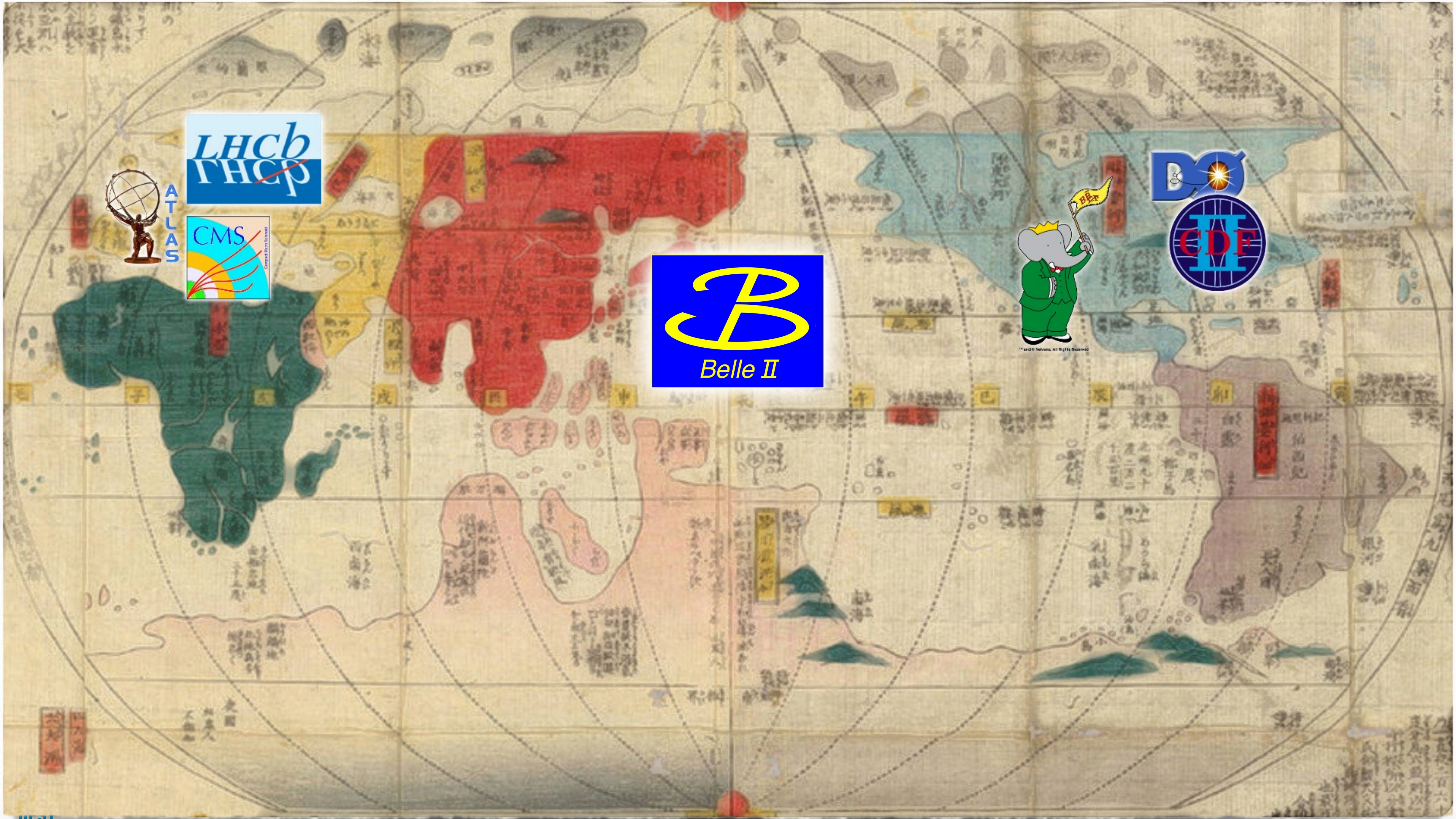
- Semileptonic B decays



- Missing Energy Channels:
  - $B \to K^{(*)}\nu\nu$
  - $B \to \nu\nu$



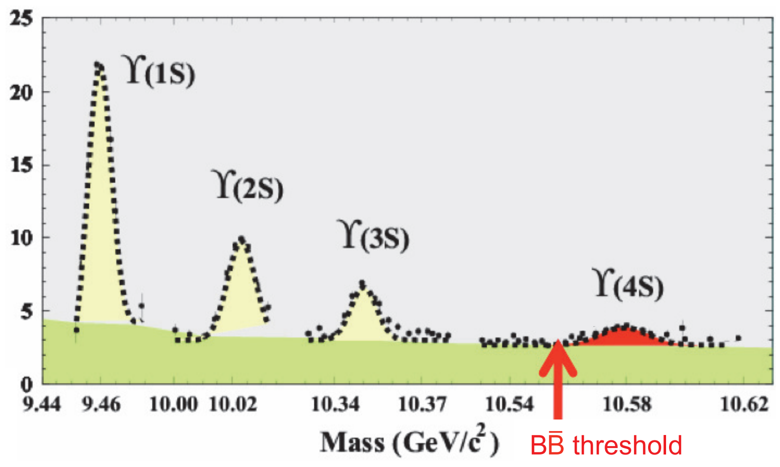
- How Belle II is ideal to challenge these decays

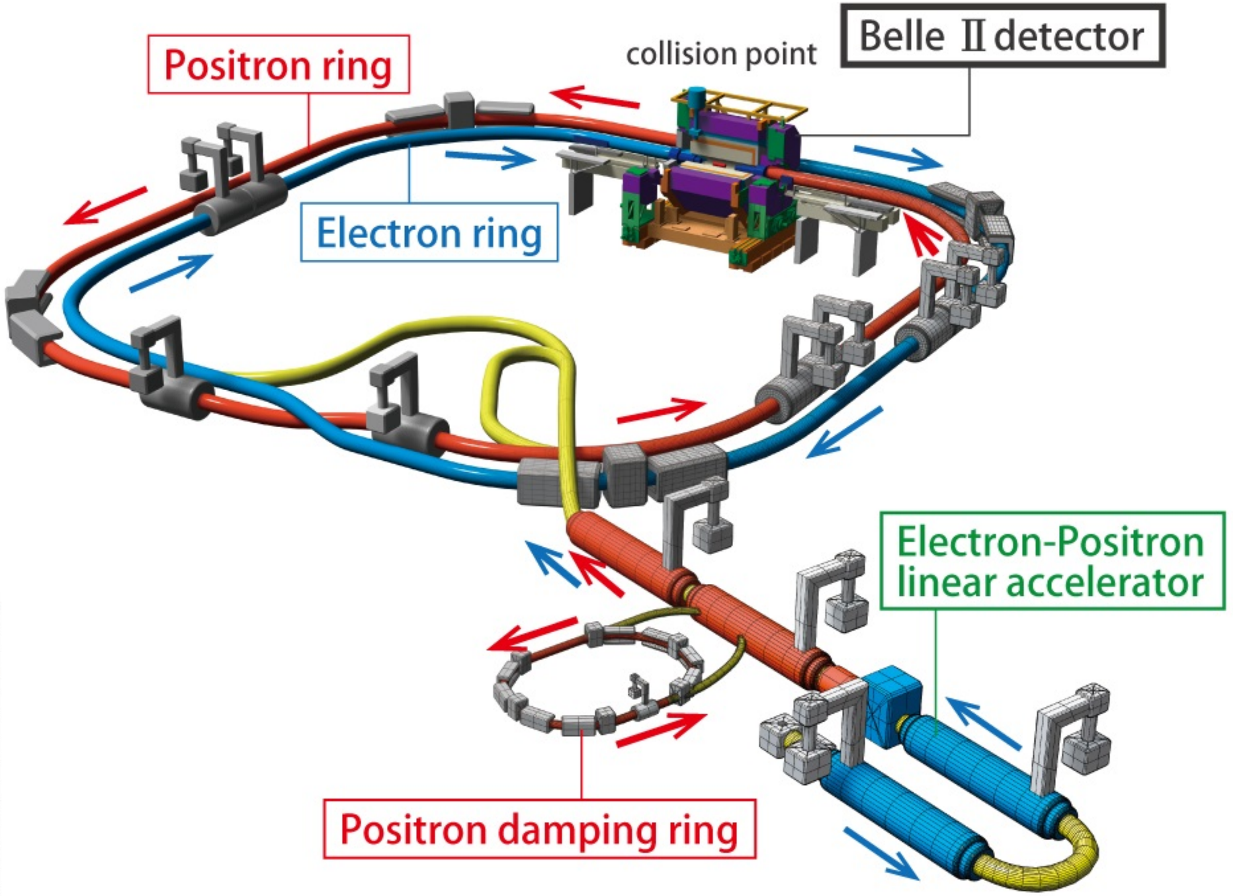

LHCb
ATLAS
CMS
Belle II
DØ
CDF

Experimental Setup for Belle II

The Challenges

- Electron positron collider are an ideal setup for missing energy channels
  - Initial state precisely known
  - Negligible pileup
- Neutrino energy can be determined precisely

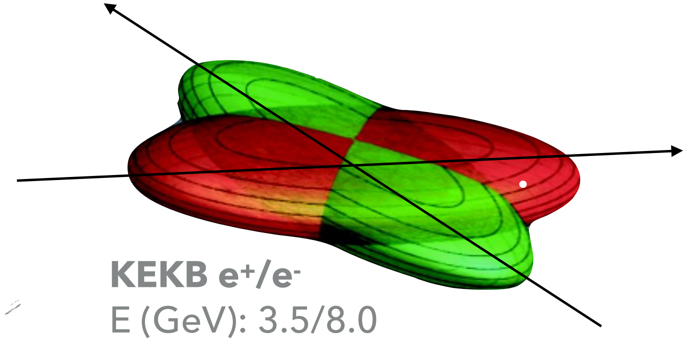




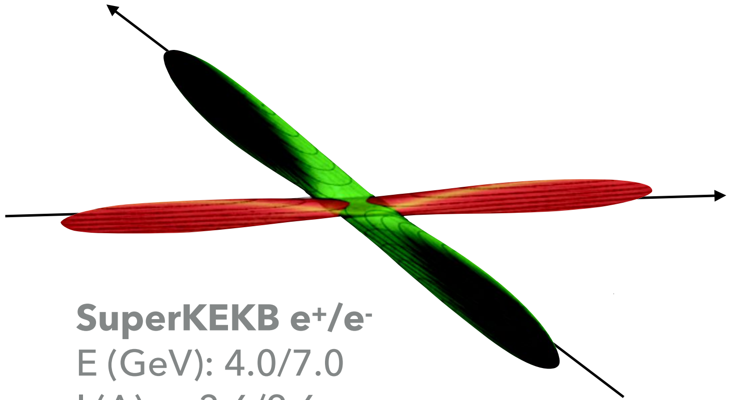
40 x Belle Luminosity

Experimental Setup for Belle II

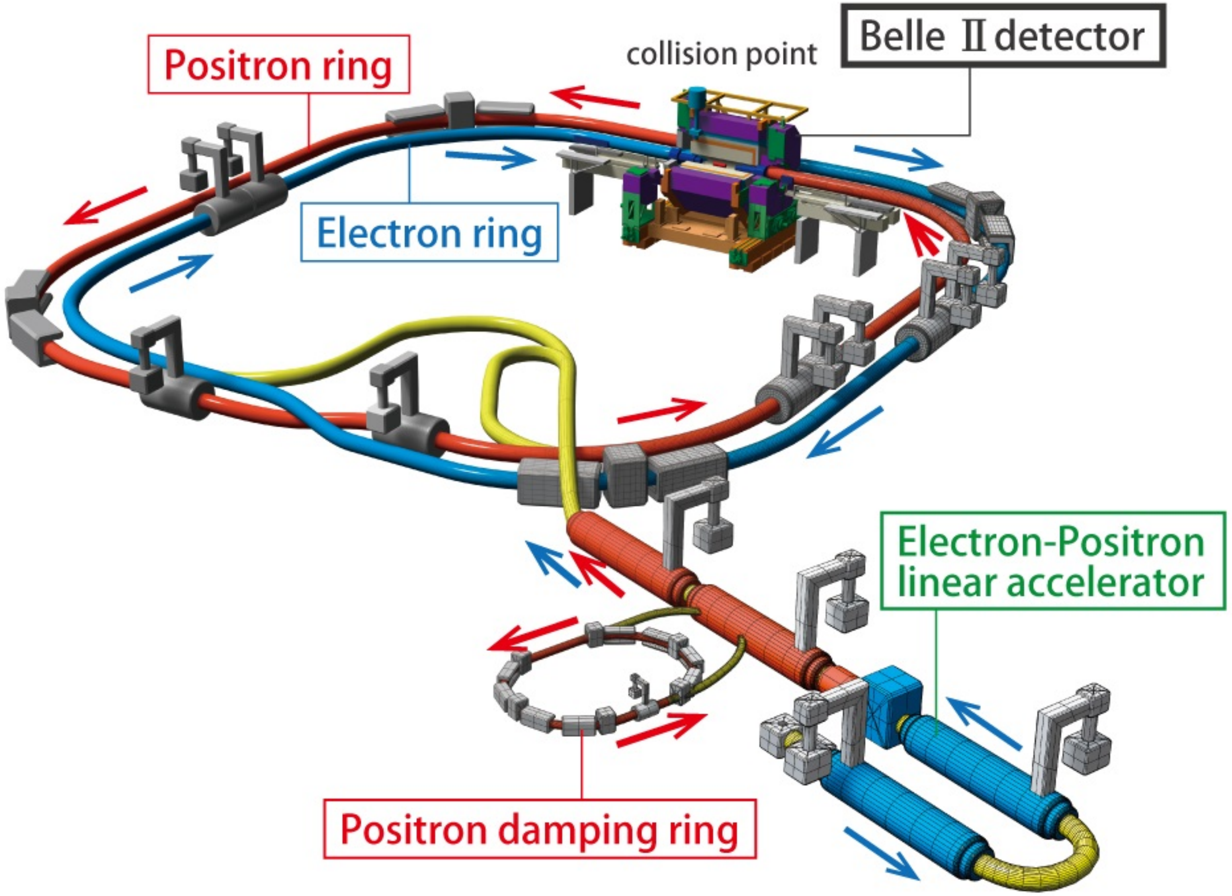
The Challenges



KEKB e+/e-
E (GeV): 3.5/8.0
I (A): ~ 1.6/1.2
β^*_y (mm): ~5.9/5.9
Crossing angle (mrad): 22



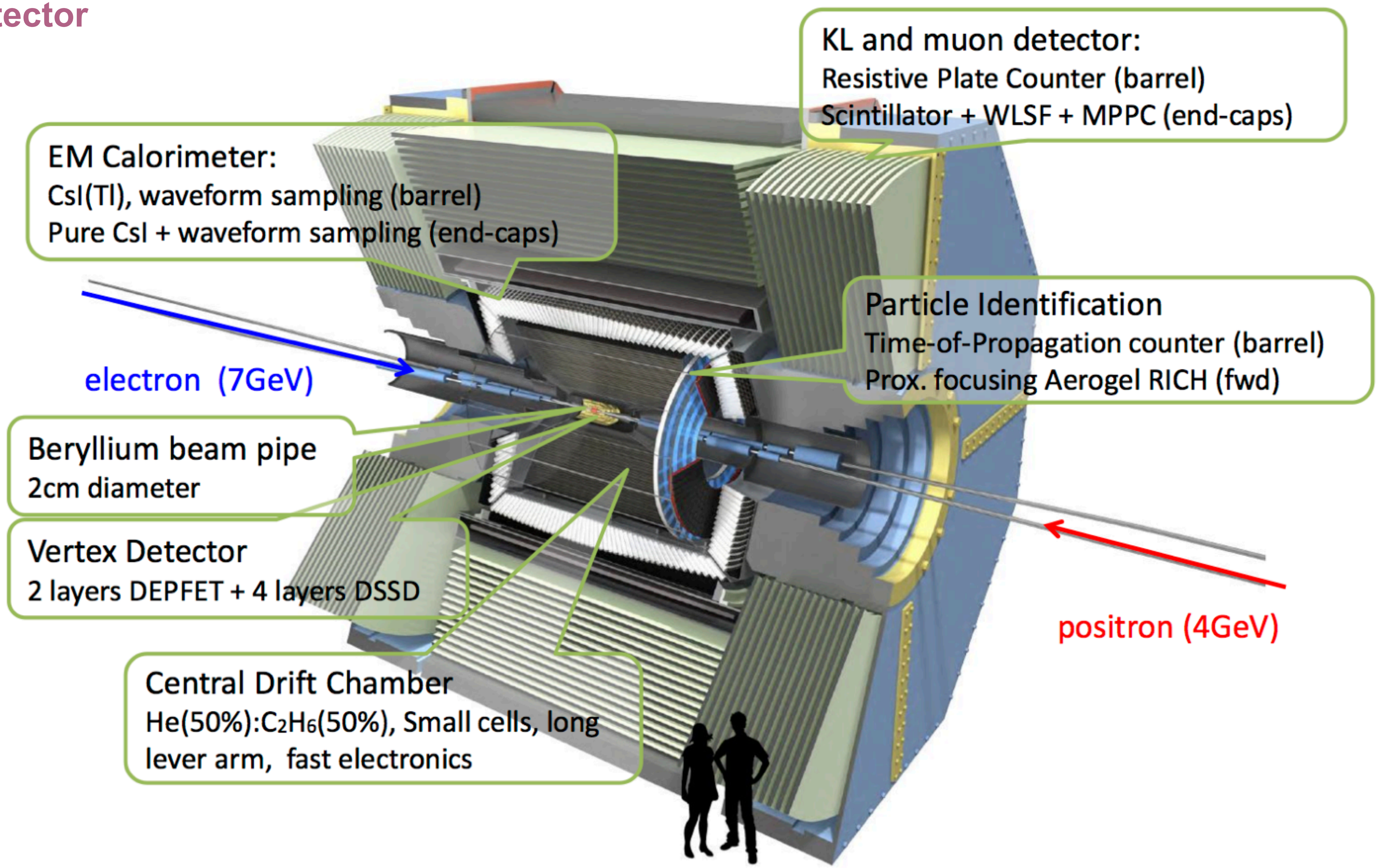
SuperKEKB e+/e-
E (GeV): 4.0/7.0
I (A): ~ 3.6/2.6
β^*_y (mm): ~0.27/0.3
Crossing angle (mrad): 83



40 x Belle Luminosity

Experimental Setup for Belle II

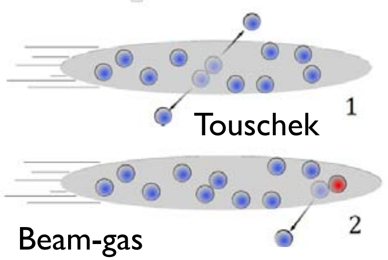
The Belle II detector

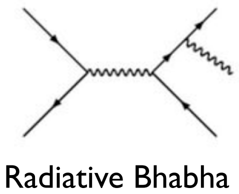


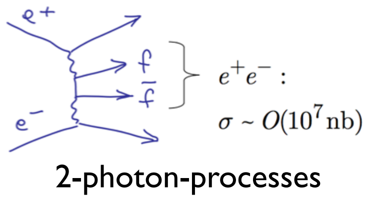
Beam Background

Challenge for the experiment

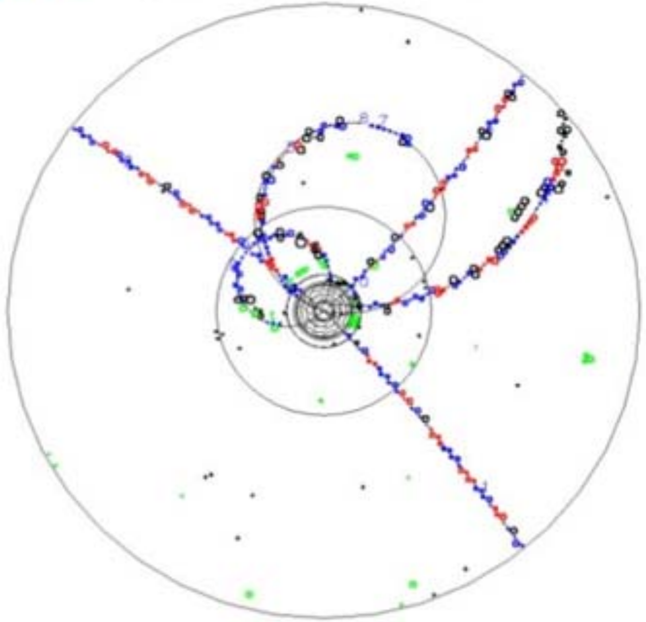
- 40 times higher luminosity comes at the cost of higher machine induced backgrounds





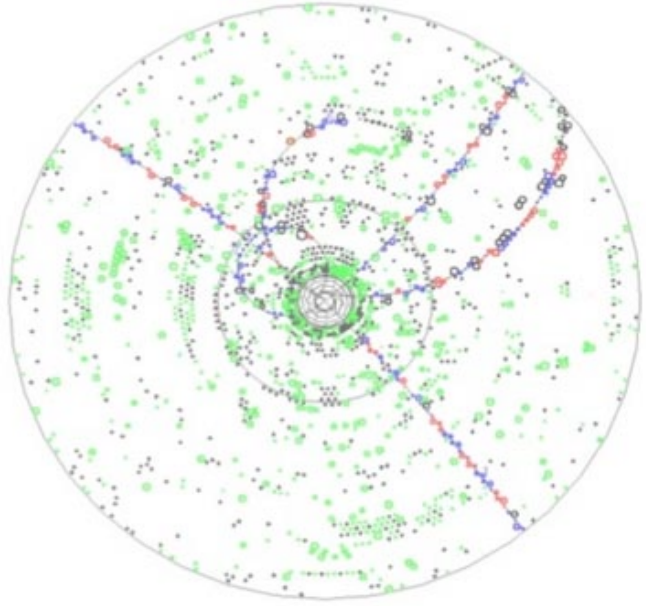


Belle



Simulation:
view on the
central drift chamber

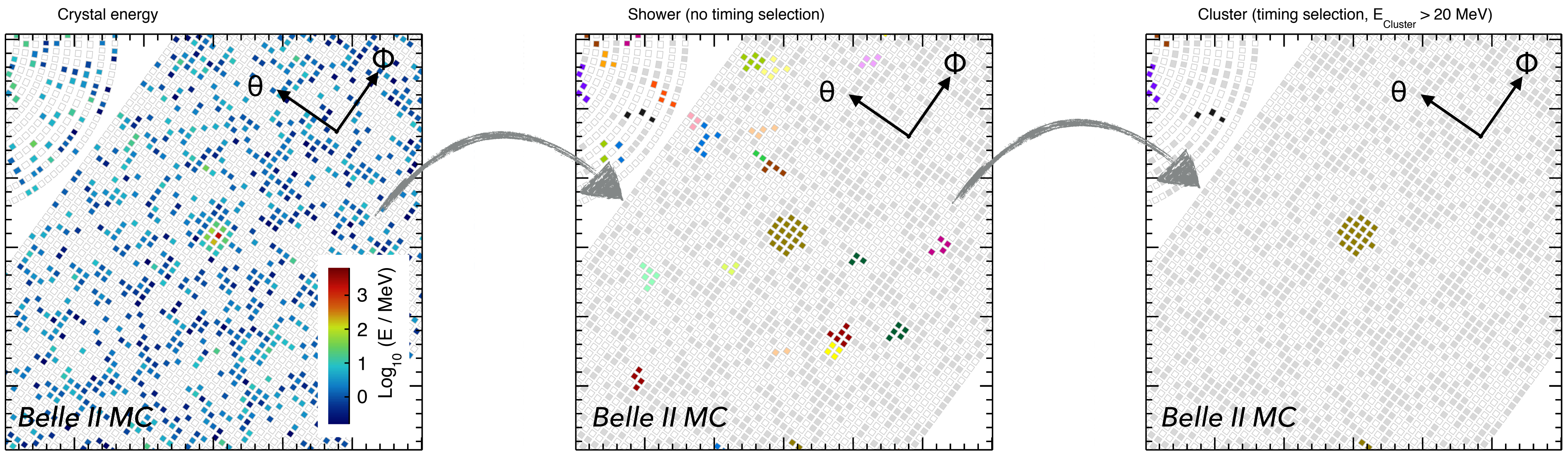
Belle II



Beam Background

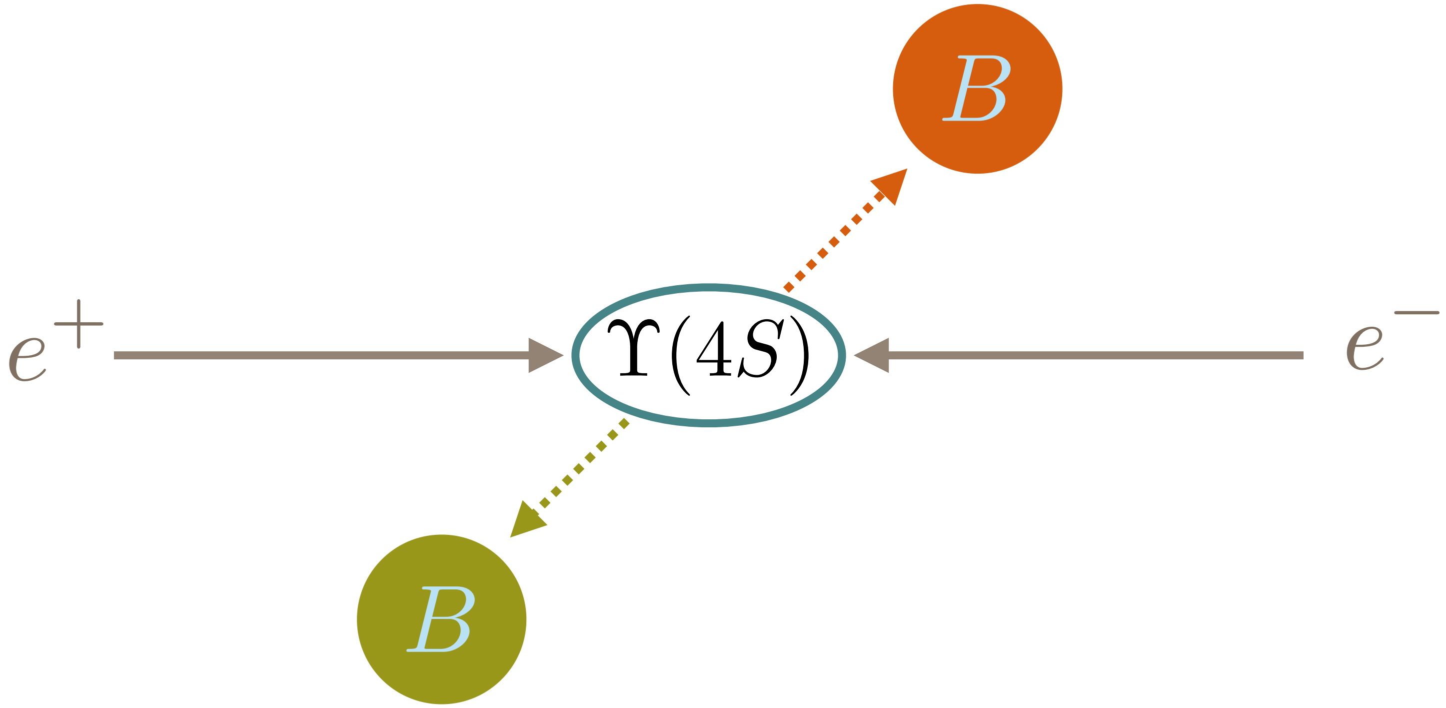
Challenge for the experiment

- Belle II can use timing information of the calorimeter to reduce background



Experimental Setup for Belle II

Advantages at e^+e^- colliders



Experimental Setup for Belle II

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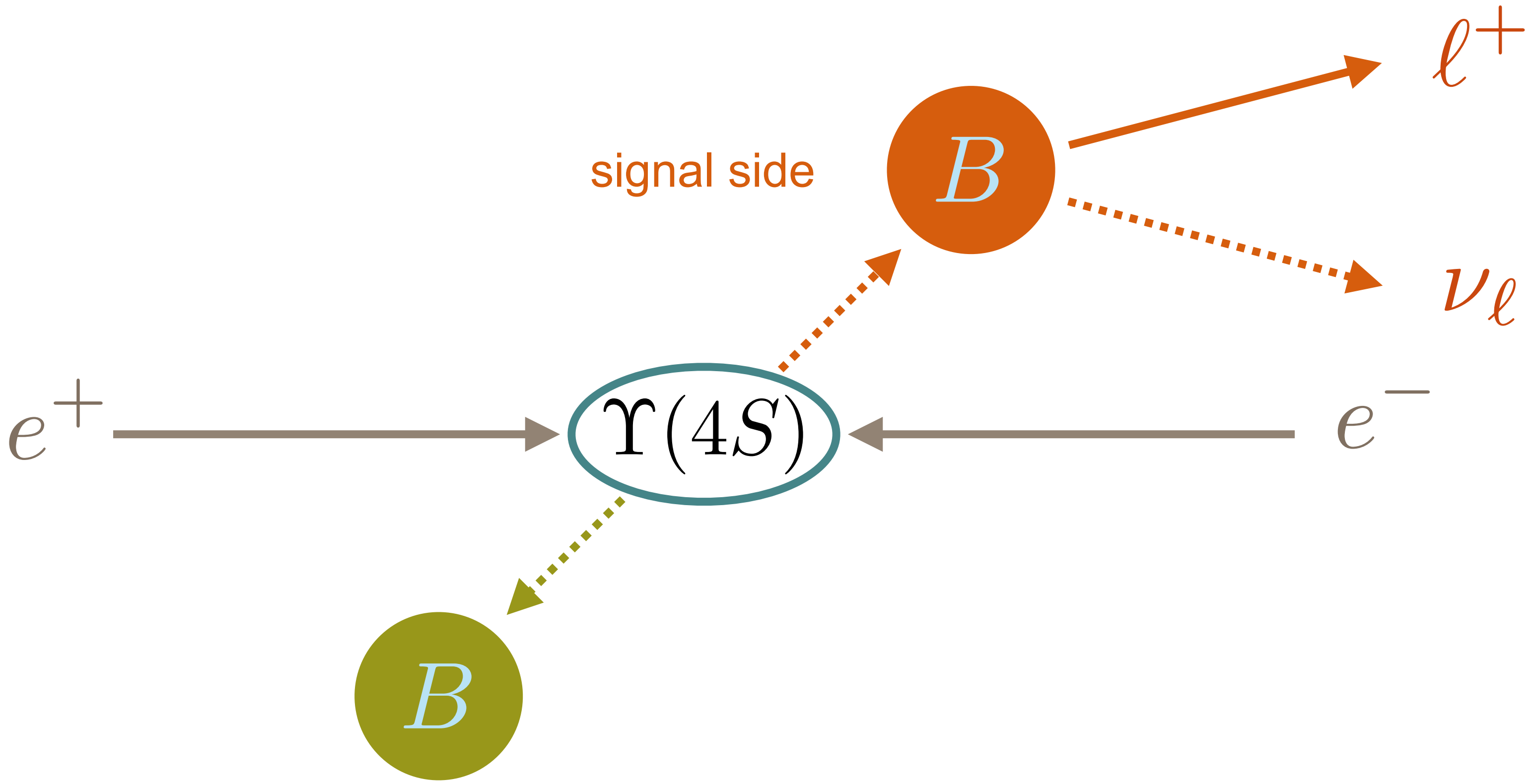

Experimental Setup for Belle II

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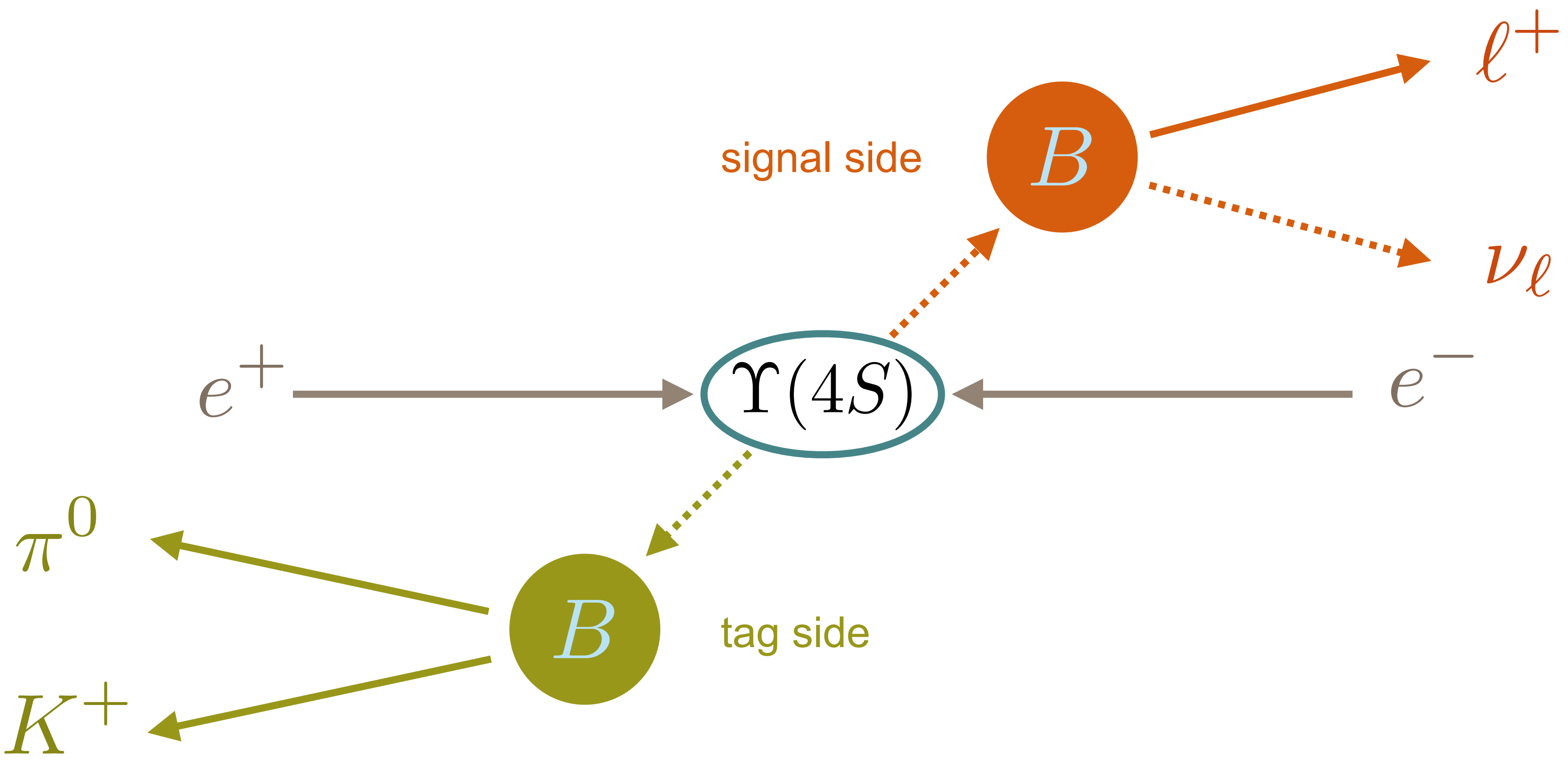
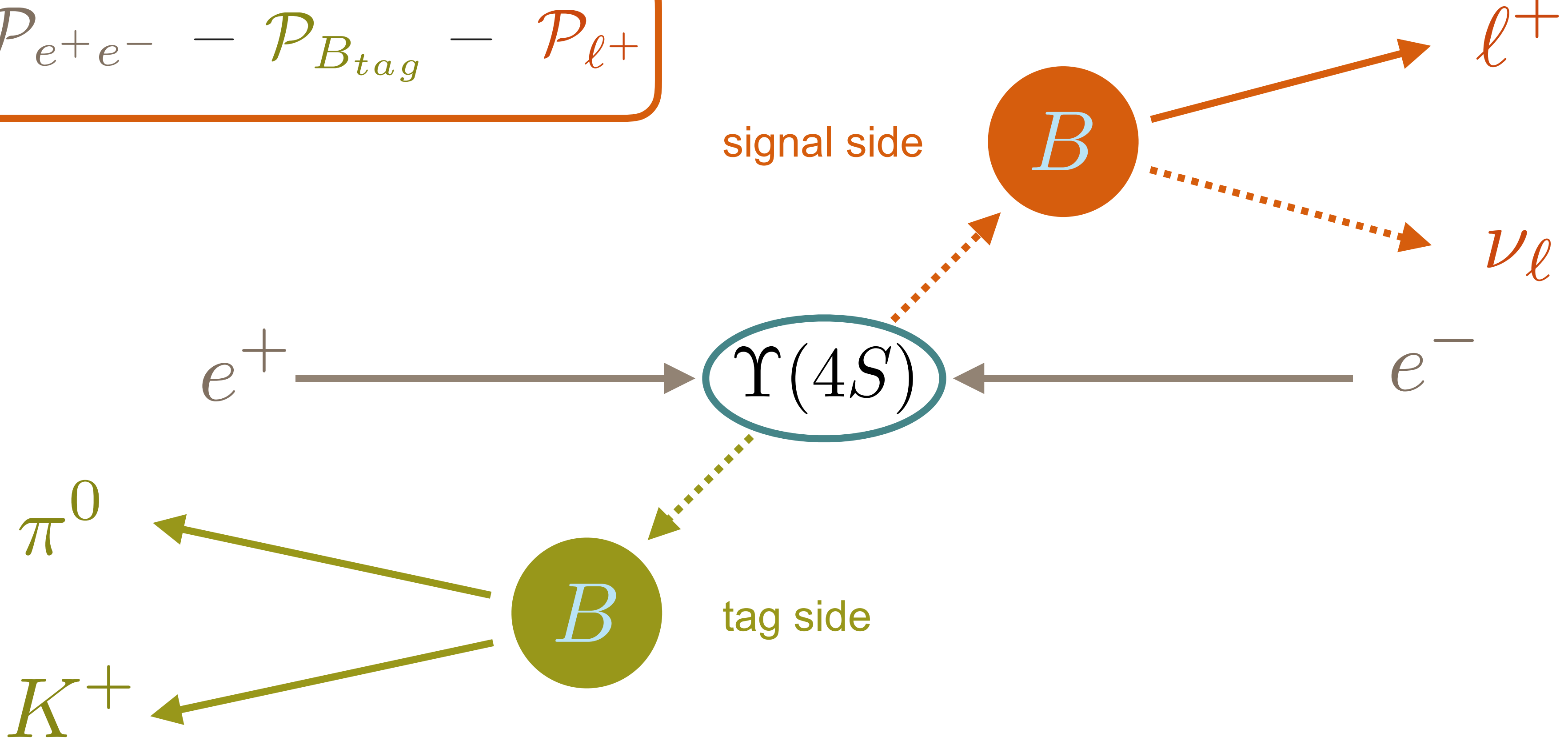


Experimental Setup for Belle II

Advantages at e^+e^- colliders

$$\mathcal{P}_{\nu_\ell} = \mathcal{P}_{e^+e^-} - \mathcal{P}_{B_{tag}} - \mathcal{P}_{\ell^+}$$



Experimental Setup for Belle II

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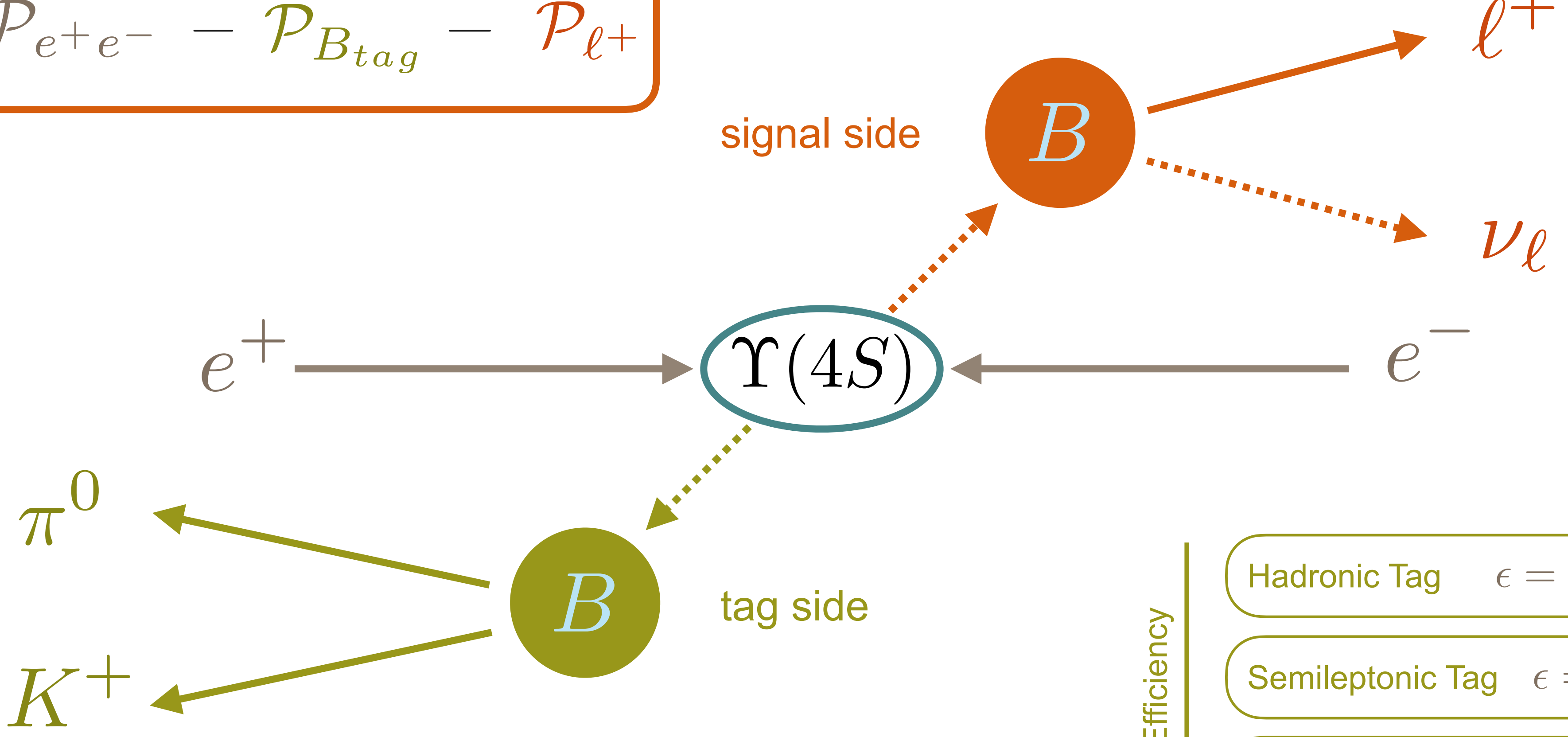
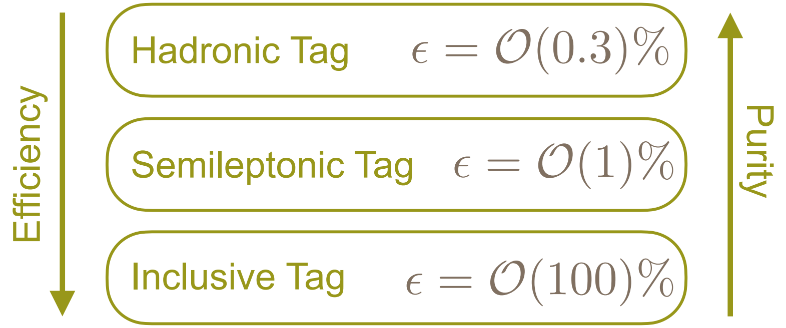




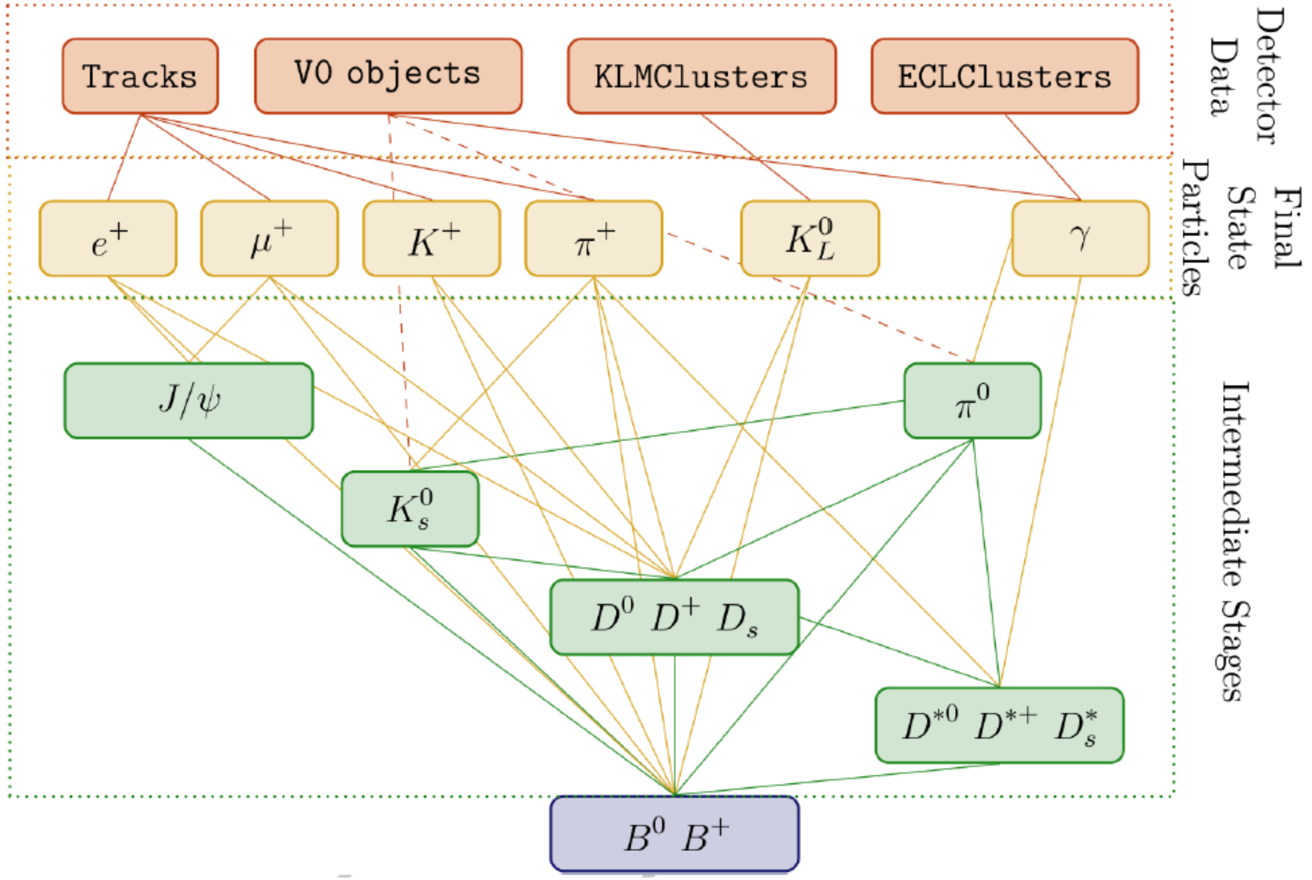
Missing Energy Channels

Full Event Interpretation (FEI)

- Hierarchical approach
  - Multivariate classifier for each state
  - Gather all information in the signal probability
- FEI can provide hadronic and semileptonic final states

Maximum reconstruction efficiency

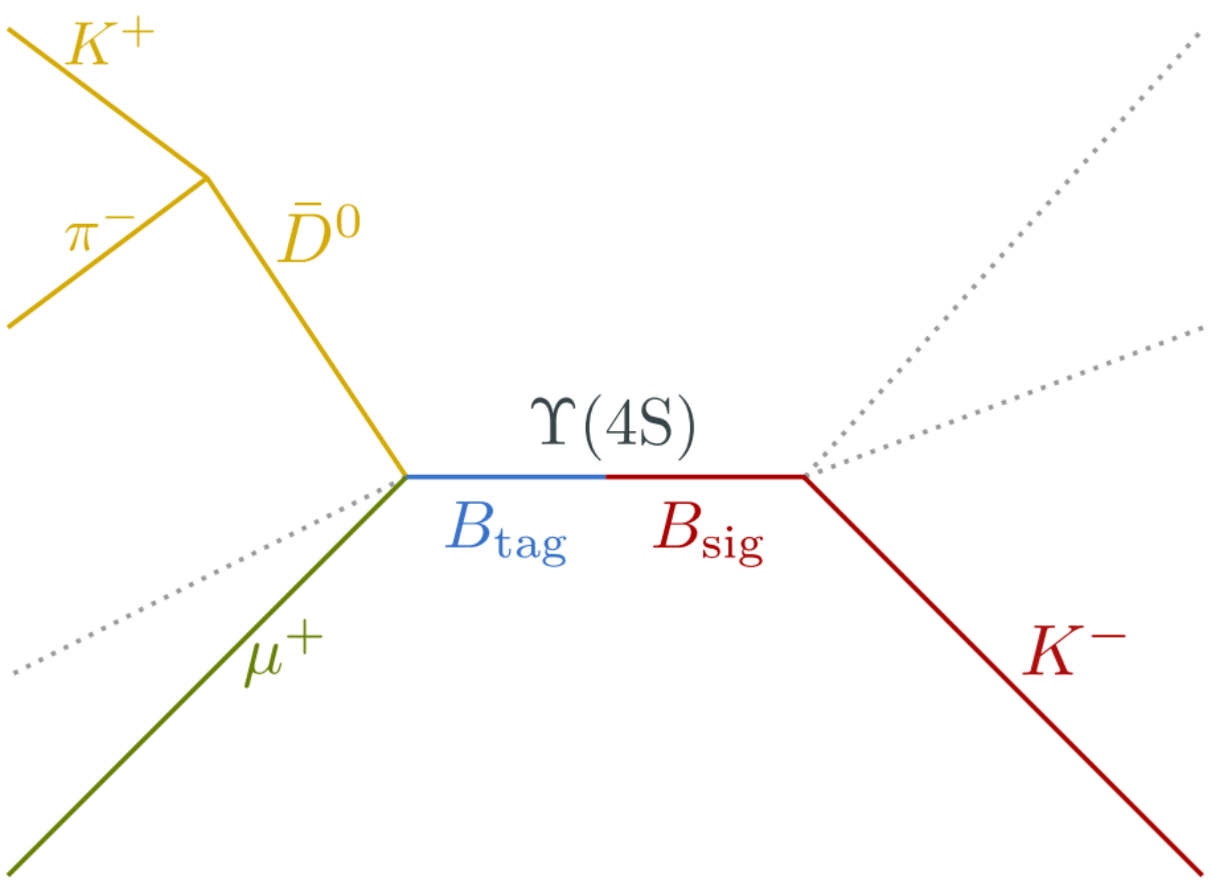
Tag	FR @ Belle	FEI @ Belle	FEI @ Belle II
Hadronic B^+	0.28 %	0.49 %	0.61 %
Semileptonic B^+	0.67 %	1.42 %	1.45 %
Hadronic B^0	0.18 %	0.33%	0.34 %
Semileptonic B^0	0.63 %	1.33%	1.25 %



Missing Energy Channels

Full Event Interpretation

1. Reconstruct Tag side B meson
2. Reconstruct Signal Side particles
3. Remove associated energy from calorimeter



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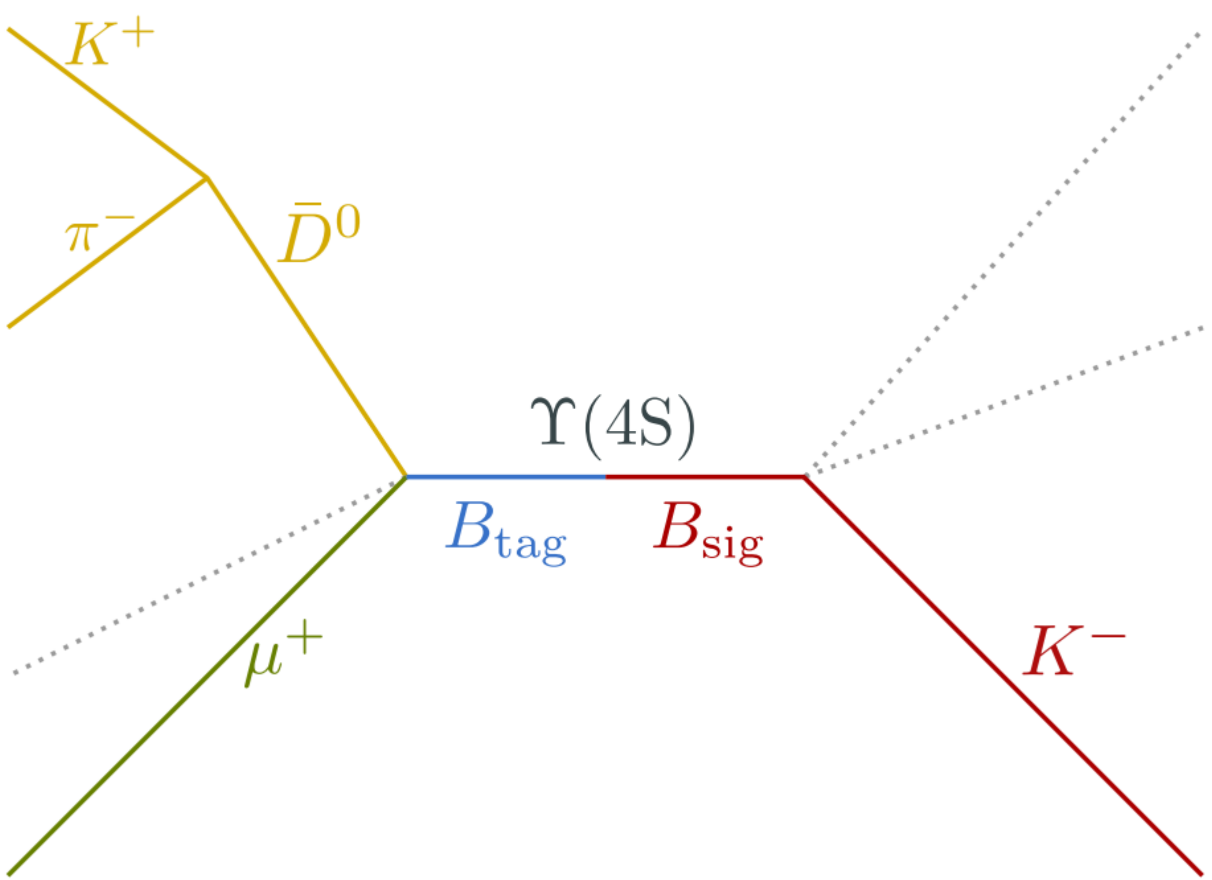
➟ Extra Energy ECL



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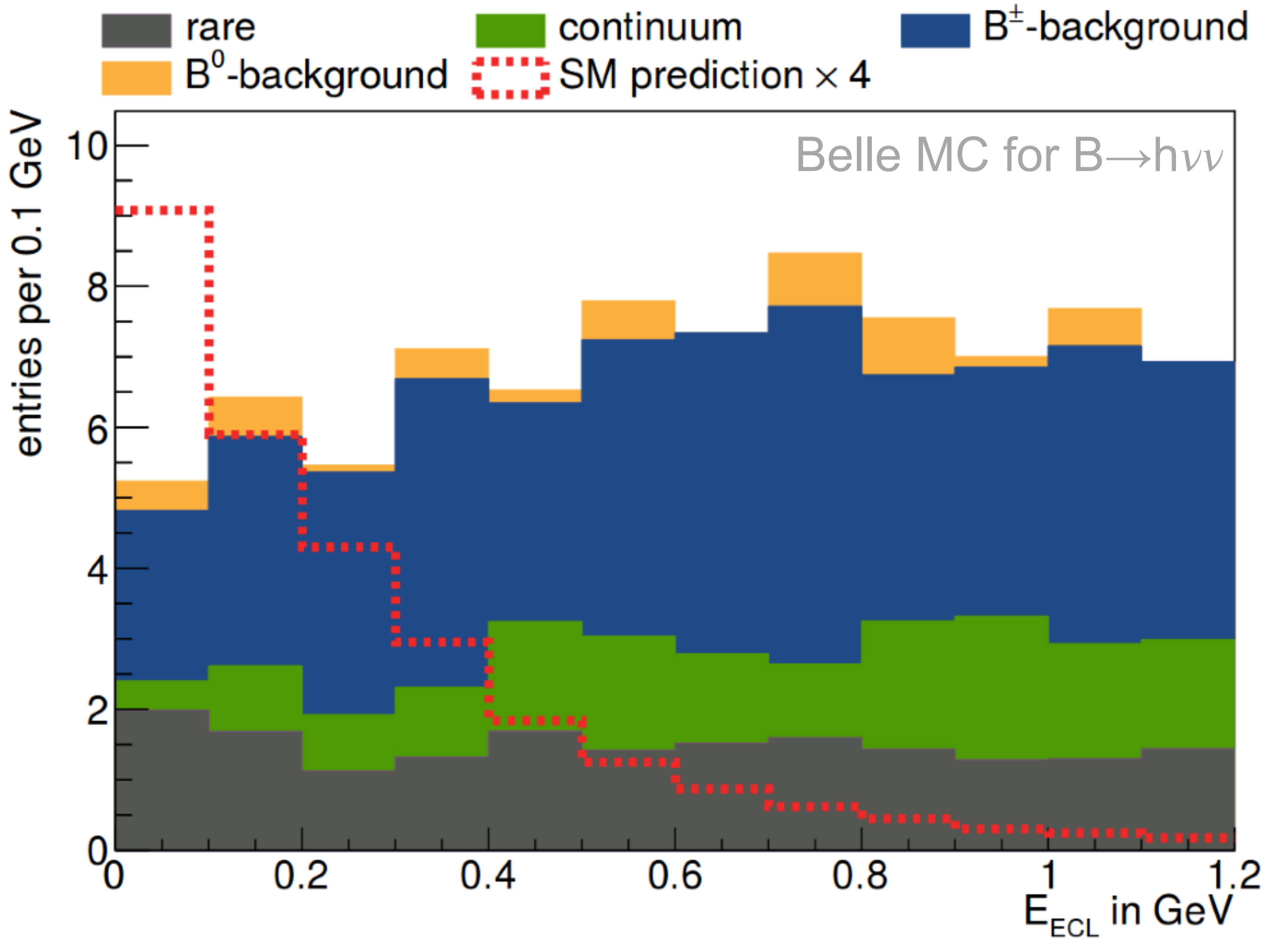
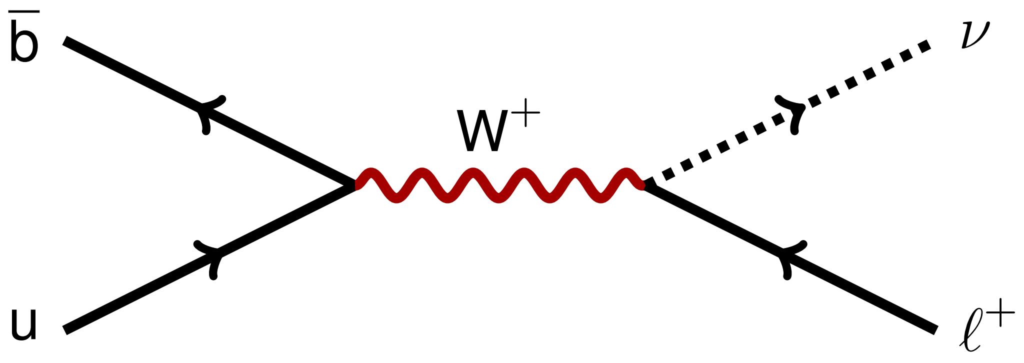


Leptonic B decays

Modes with high missing energy



$$\mathcal{B}\left(B^+ \to \ell^+ \nu\right)_{\mathrm{SM}} = \frac{G_F^2 M_B M_\ell^2}{8\pi}\left(1 - \frac{M_\ell^2}{M_B^2}\right)^2 f_B{}^2 |V_{ub}|^2 \tau_B$$

- Direct access to V_{ub}
- Can challenge lepton flavour universality
- Can probe charged higgs

	SM Prediction	**PDG 2016**
$\mathcal{B}\left(B^+ \to e^+ \nu_e\right)$	$(1.09 \pm 0.21) \cdot 10^{-11}$	$< 9.8 \cdot 10^{-7}$ CL=90%
$\mathcal{B}\left(B^+ \to \mu^+ \nu_\mu\right)$	$(4.65 \pm 0.91) \cdot 10^{-7}$	$< 1.0 \cdot 10^{-6}$ CL=90%
$\mathcal{B}\left(B^+ \to \tau^+ \nu_\tau\right)$	$(1.03 \pm 0.2) \cdot 10^{-4}$	$(1.06 \pm 0.20) \cdot 10^{-4}$

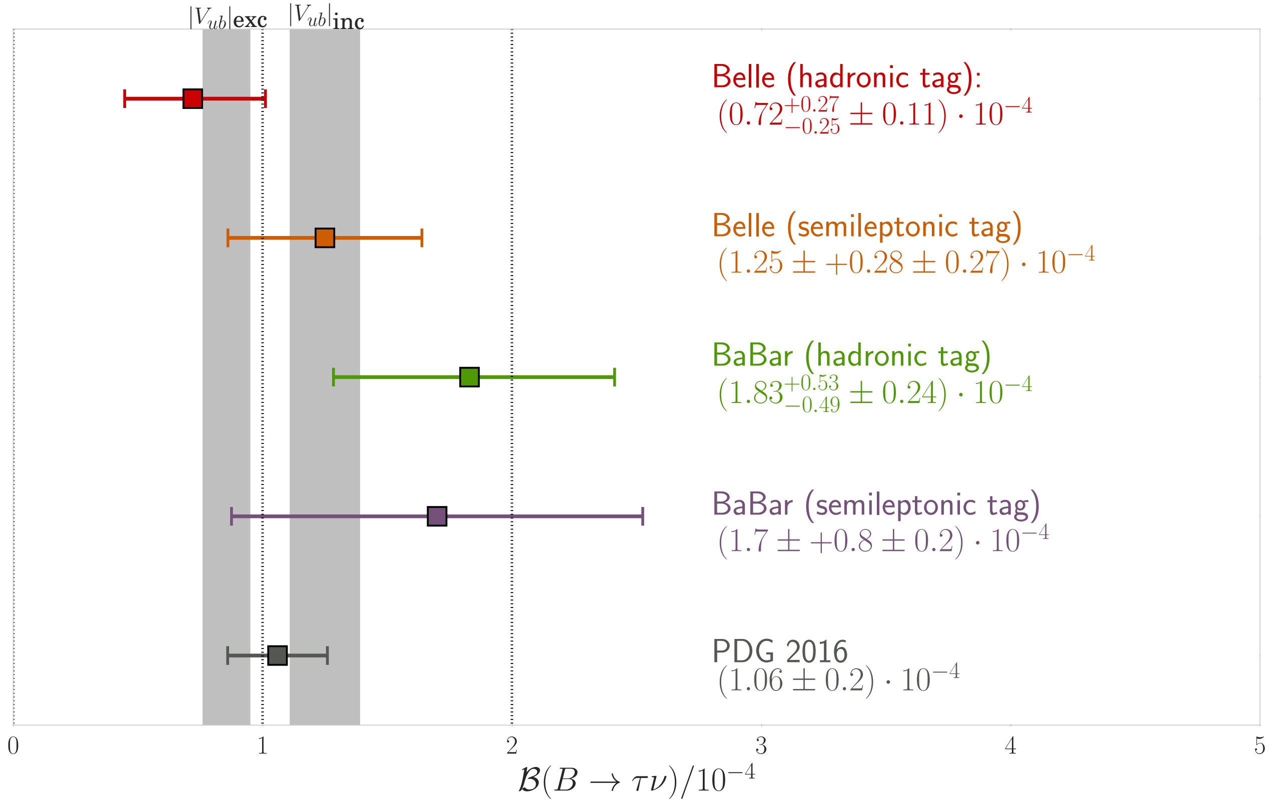
Leptonic B decays

The tau mode - Overview of recent measurements

- Always at leas two neutrinos in the decay
- Signature: 1 track + invisible

$$B^+ \to \tau^+ \nu_\tau$$
$$\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$$

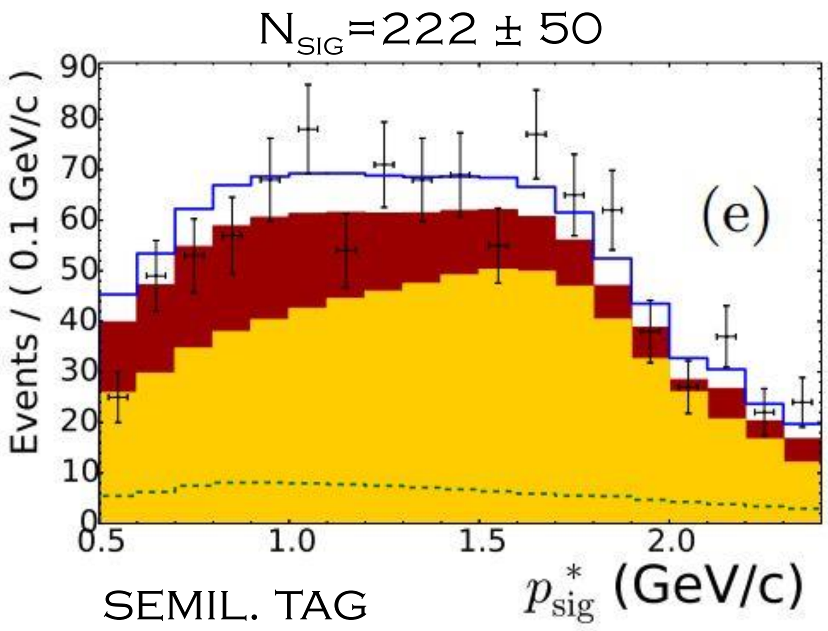
$\tau \to \ell \nu\nu$, $\tau \to \pi\nu\nu$, $\tau \to \rho\nu\nu$, $\tau \to a_1\nu\nu$



Leptonic B decays

The tau mode

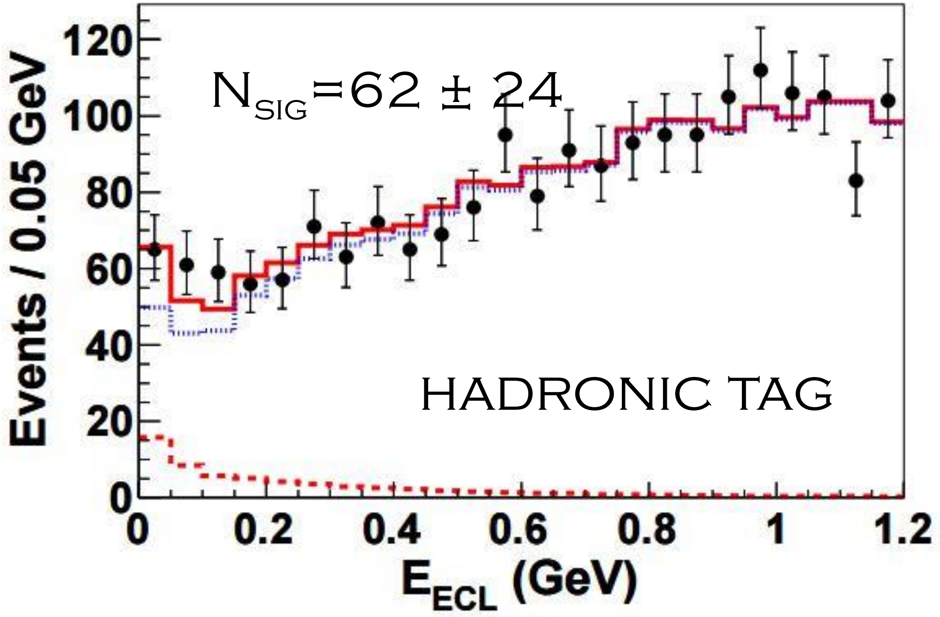
- Belle measured tau mode with semileptonic and hadronic tagging
- Tau decay modes deliver independent statistical subsamples



Belle, arXiv:1503.05613, 700 fb-1

$$\tau^- \to e^- \bar{\nu}_e \nu_\tau$$
$$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$$
$$\tau^- \to \pi^- \nu_\tau$$
$$\tau^- \to \pi^- \pi^0 \nu_\tau$$

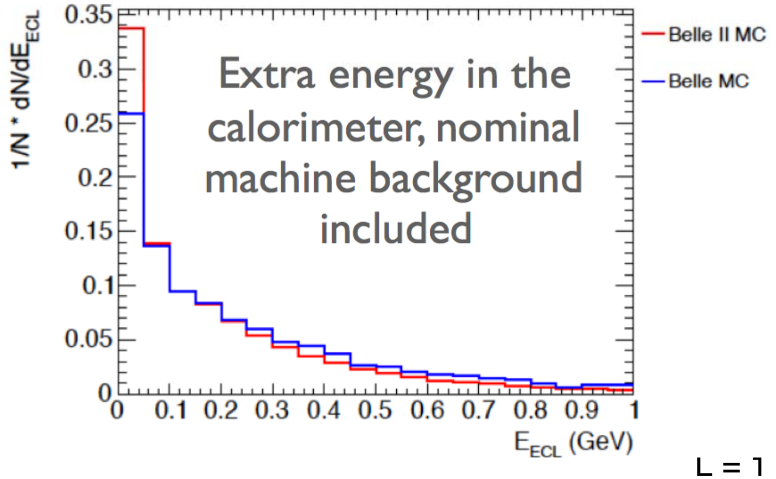
Belle, PRL110, 131801 (2013), 700 fb-1

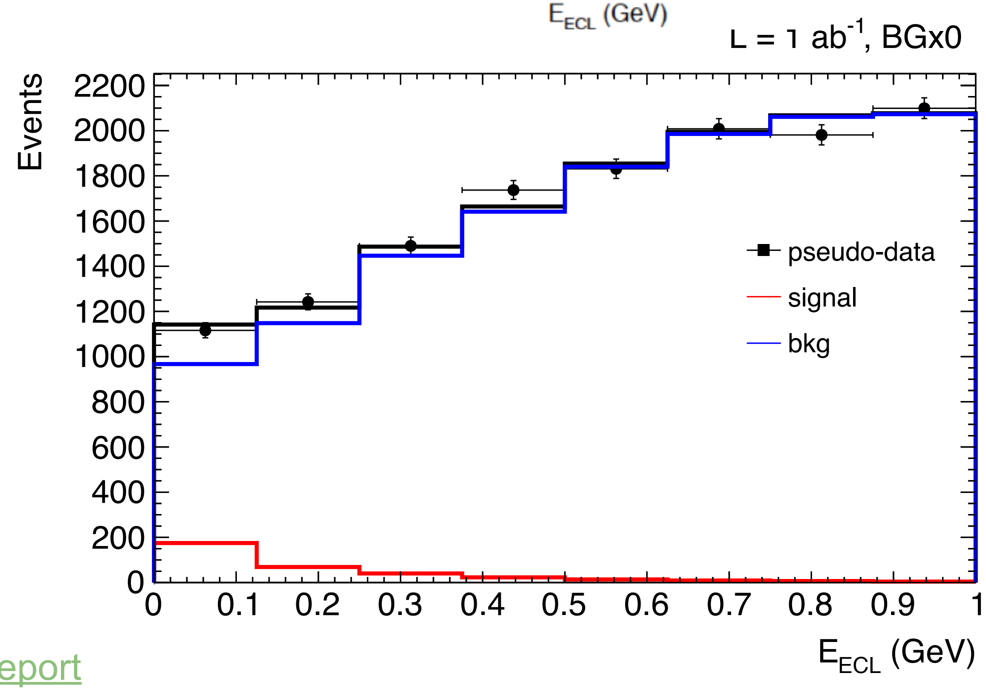


Leptonic B decays

The tau mode

- Belle II can measure the tau mode with approx. 10% uncertainty at 5ab-5
- Better resolution, more sensitive to beam background





	Integrated Luminosity (ab^{-1})	1	5	50
hadronic tag	statistical uncertainty (%)	29.2	13.0	4.1
	systematic uncertainty (%)	12.6	6.8	4.6
	total uncertainty (%)	31.6	14.7	6.2
semileptonic tag	statistical uncertainty (%)	19.0	8.5	2.7
	systematic uncertainty (%)	17.9	8.7	4.5
	total uncertainty (%)	26.1	12.2	5.3

see B2TIP report

Leptonic B decays

The muon mode

μ

- The current status:

Table 4: The results of searches for the decay $B^- \to \mu^- \bar{\nu}_\mu$.

Experiment	Upper limit @ 90% C.L.	Comment
Belle [22]	2.7×10^{-6}	Fully reconstructed hadronic tag, 711 fb^{-1}
Belle [15]	1.7×10^{-6}	Untagged analysis, 253 fb^{-1}
BaBar [16]	1.0×10^{-6}	Untagged analysis, 468×10^6 $B\overline{B}$ pairs

- Analysis can be performed with and without tagging
- New result from Belle untagged

Leptonic B decays

The muon mode - recent Belle Measurement

- Latest Belle measurement:
- Fit ratio of:

$$R = N_{B\to\mu\bar{\nu}_\mu} / N_{B\to\pi\mu\bar{\nu}_\mu}$$

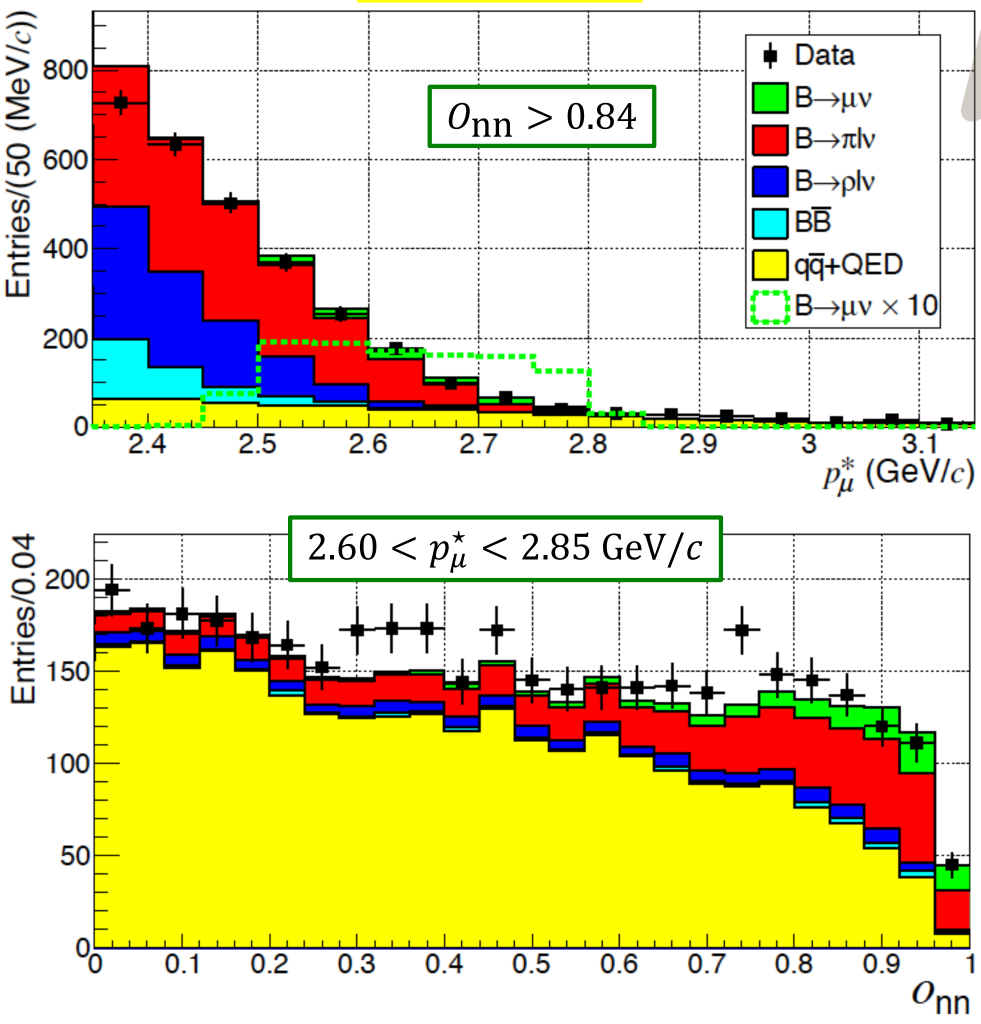
- Resulting in:

$$N_{B\to\mu\bar{\nu}_\mu} = 195 \pm 67$$

$$\mathcal{B}(B \to \mu\bar{\nu}_\mu) =$$
$$(6.46 \pm 2.22_{\mathrm{stat}} \pm 1.6_{\mathrm{syst}}) \times 10^{-7}$$

SM: $(3.46 \pm 0.28) \times 10^{-7}$

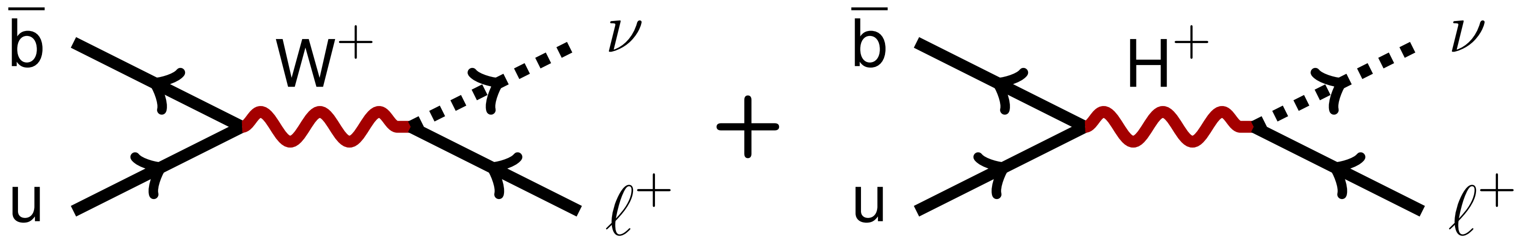
arXiv:1712.04123



Submitted to PRL

Leptonic B decays

Tight constraints on charged higgs



$$\mathcal{B}\left(\mathrm{B}^+ \to \ell^+ \nu\right)_{\mathrm{2HDM}} = \mathcal{B}\left(\mathrm{B}^+ \to \ell^+ \nu\right)_{\mathrm{SM}} \cdot \left(1 - \frac{M_\mathrm{B}^2 \tan^2\beta}{M_{\mathrm{H}^+}^2}\right)^2$$

Already tightly constrained by weak radiative B meson decays

$$M_{\mathrm{H}^+} > 580\ \mathrm{GeV}$$

Steinhauser, https://arxiv.org/pdf/1702.04571.pdf

Leptonic B decays

Belle II future

- Sensitivity to NP, ratios cancel uncertainties from f_B an V_{ub}:

$$R_{\rm ps} = \frac{\tau_{B^0}}{\tau_{B^-}} \frac{\mathcal{B}(B^-\to\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0\to\pi^+\ell^-\bar{\nu}_\ell)}\,, \quad R_{\rm pl} = \frac{\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^- \to \mu^-\bar{\nu}_\mu)}\,.$$

- There is much room for new physics:

$$R_{\rm ps}^{\rm NP} = (0.539 \pm 0.043)\left|1 + r_{\rm NP}^\tau\right|^2 \qquad R_{\rm ps}^{\rm exp} = 0.73 \pm 0.14$$

$$\left|1 + r_{\rm NP}^\tau\right| = 1.16 \pm 0.11$$

Leptonic B decays

Belle II future

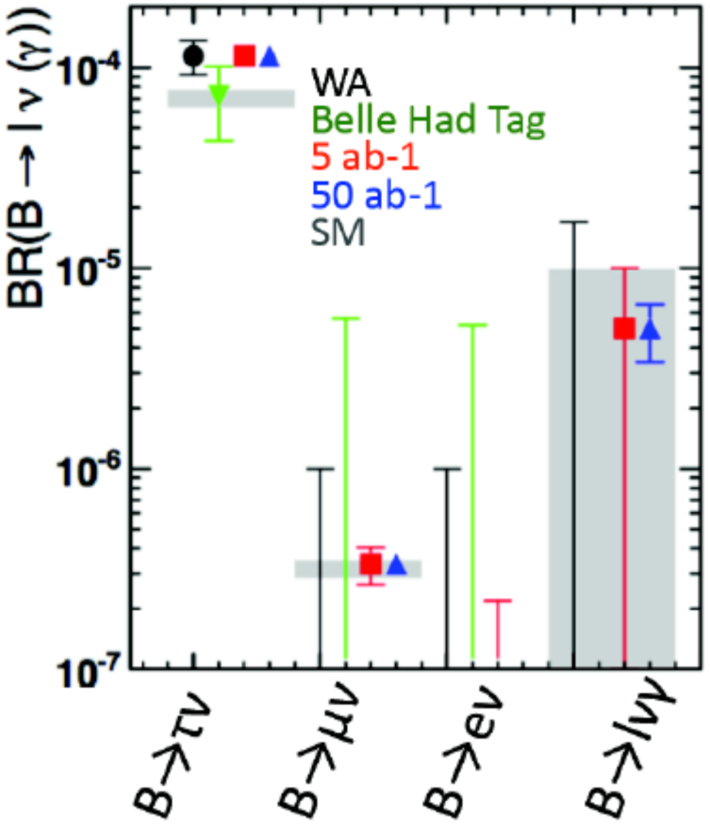
- Projections for Belle II for $B\rightarrow\ell\nu$

ℓ	$\mathcal{B}_{\rm SM}$	711 fb^{-1}	5 ab^{-1}	50 ab^{-1}
τ	$(7.71 \pm 0.62) \times 10^{-5}$	61179 ± 5031	430231 ± 35378	4302312 ± 353781
μ	$(3.46 \pm 0.28) \times 10^{-7}$	275 ± 23	1933 ± 159	19333 ± 1590
e	$(0.811 \pm 0.065) \times 10^{-11}$	0.0064 ± 0.0005	0.0453 ± 0.0037	0.4526 ± 0.0372

- Belle II projections for the branching ratio ratios:

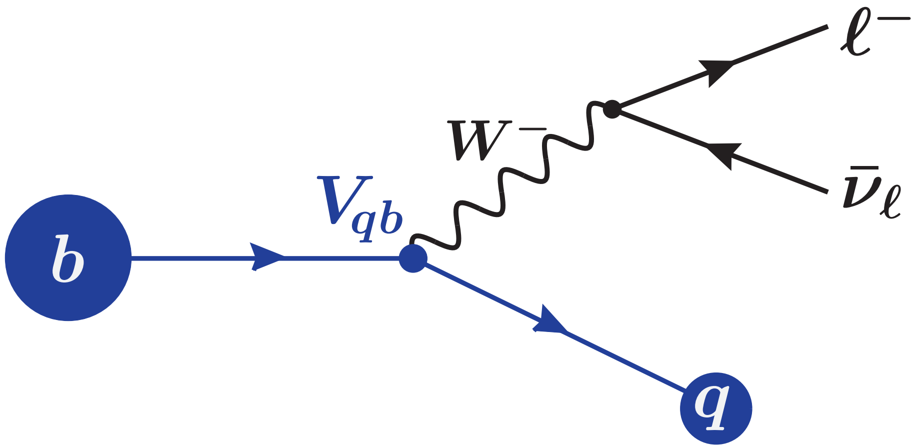
$$R_{\rm ps}^{5\,\mathrm{ab}^{-1}} = 0.54 \pm 0.11\,, \quad R_{\rm ps}^{50\,\mathrm{ab}^{-1}} = 0.54 \pm 0.04\,,$$
$$R_{\rm pl}^{5\,\mathrm{ab}^{-1}} = 222 \pm 76\,, \quad R_{\rm pl}^{50\,\mathrm{ab}^{-1}} = 222 \pm 26\,.$$

see B2TIP report



Semileptonic B decays

Will the hints for new physics persist?



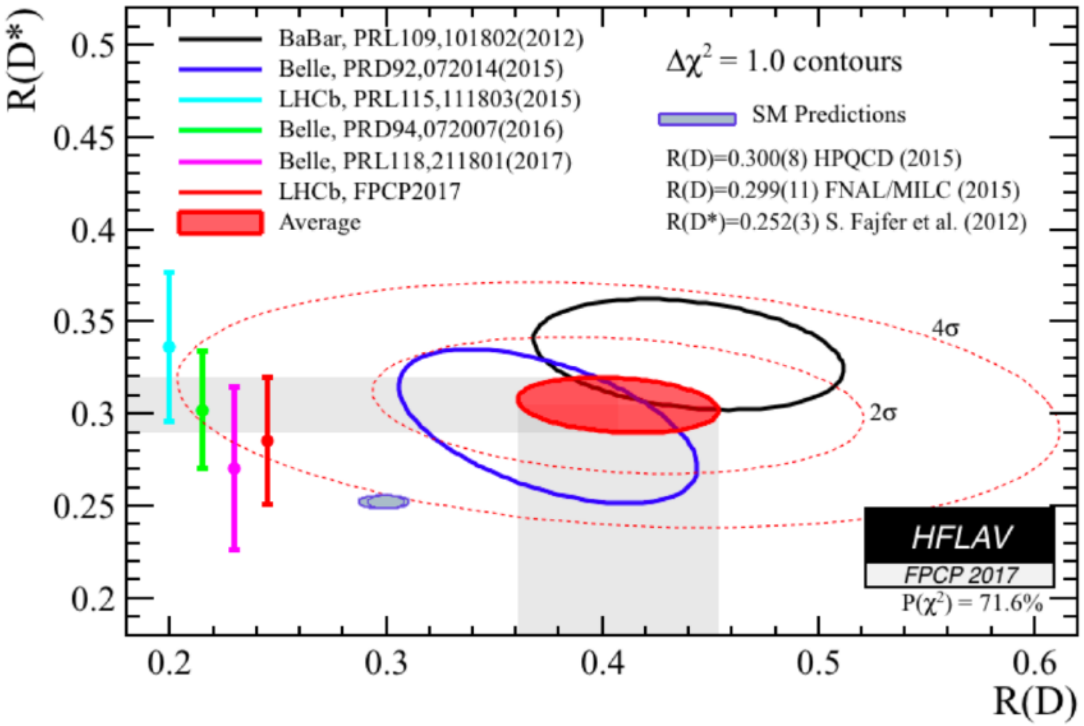
$$R = \frac{b \to q\,\tau\bar{\nu}_\tau}{b \to q\,\ell\bar{\nu}_\ell}$$

$\ell = e, \mu$

Semitauonic decays

Measurement of R_{D^*}

- Combination of data from LHCb, BaBar and Belle
  - Measurement of $R_{D(*)}$ shows hints for new physics with **~4**σ
- Many statistically independent approaches:
  - 3 tagging methods (hadronic, semileptonic, inclusive)
  - Signal modes ($\tau \rightarrow l\nu\nu$, $\tau \rightarrow h\nu$)
- Belle II should confirm/deny this anomaly already with $5ab^{-1}$



Prediction for Belle II:

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

Semitauonic decays

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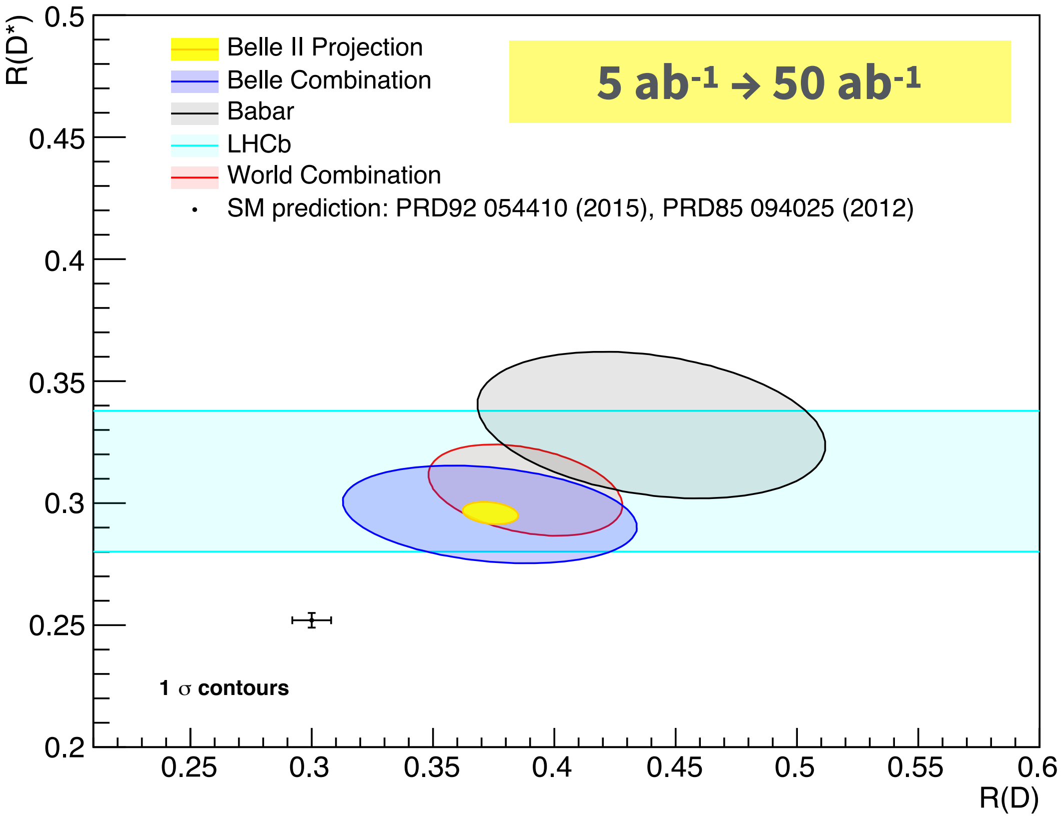

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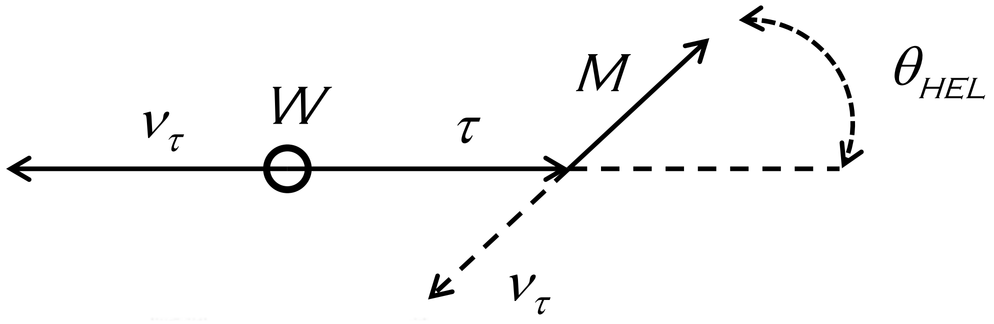
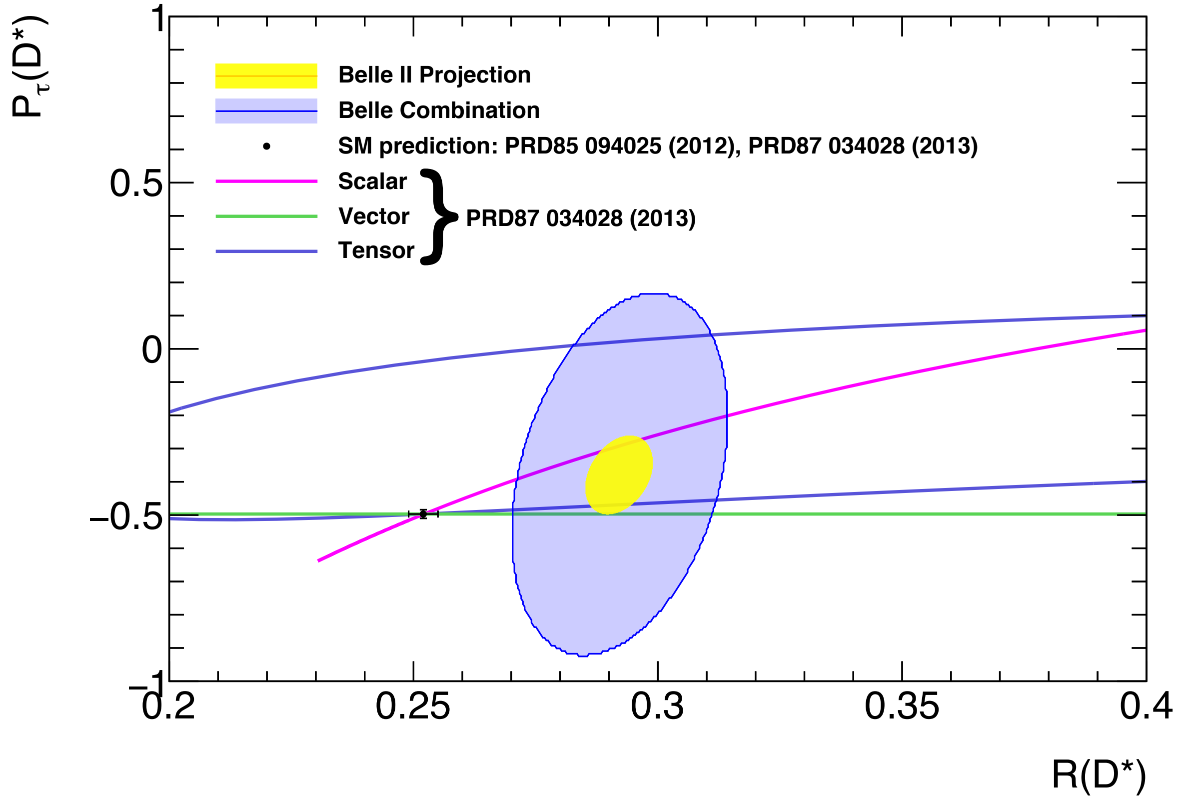
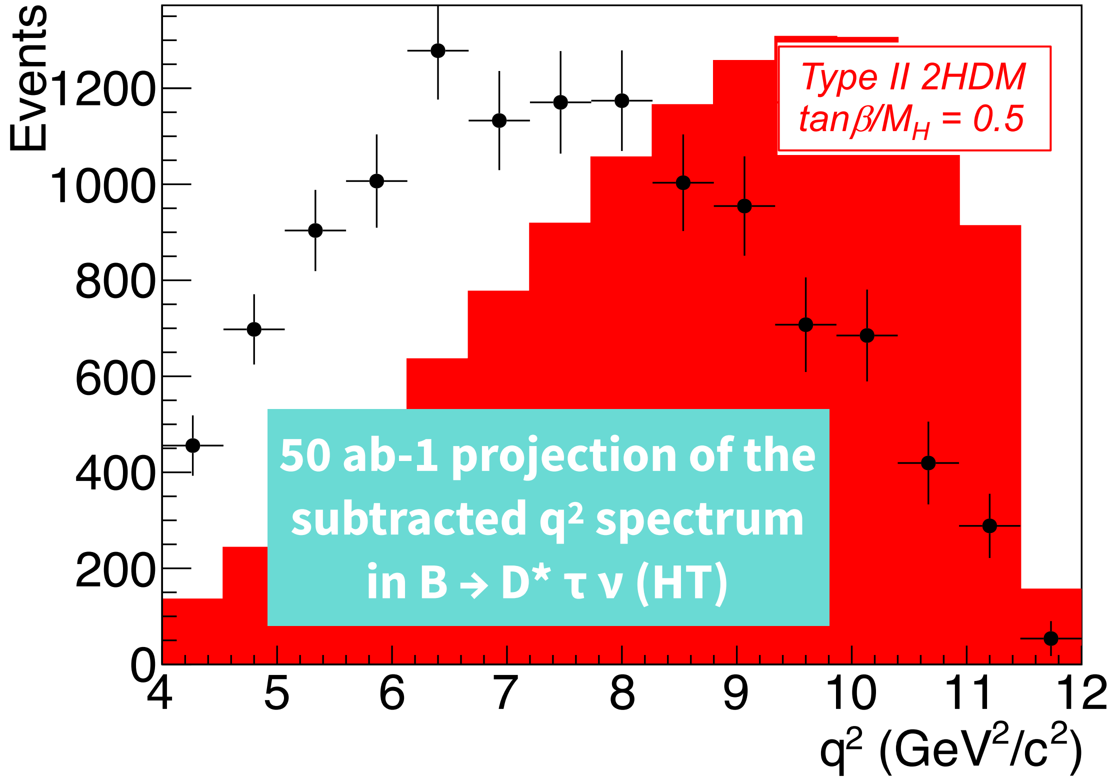
Semitauonic decays

Measurement of R_{D^*}

- Also tau polarisation sensitive to NP







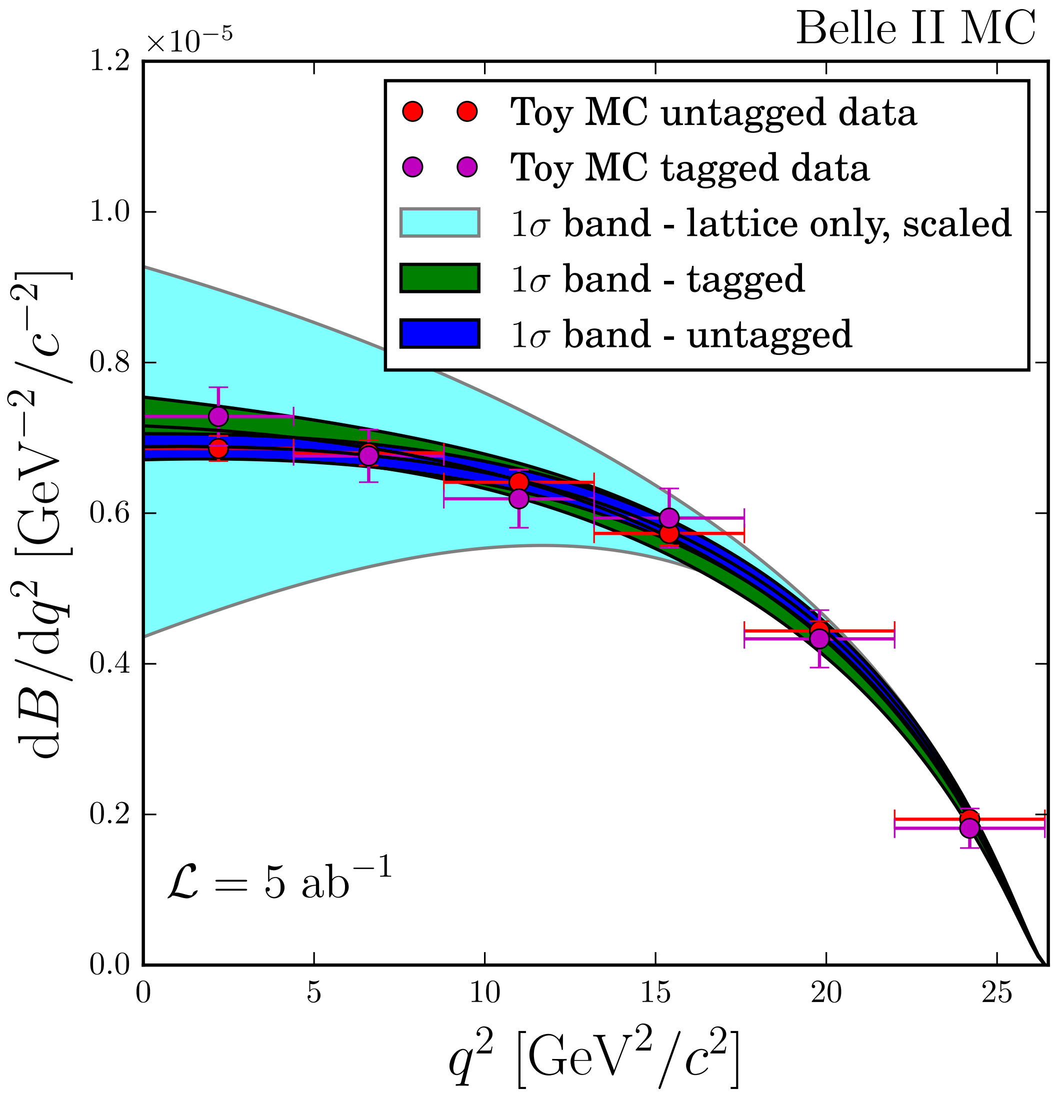
Semileptonic B decays

Challenging $|V_{ub}|$

- $|V_{ub}|$ should be measured with ~1-2% accuracy with B→$\pi\ell\nu$ (based on Belle II full sim.)
- Y(5S) runs also enable B_s→K$\ell\nu$

Belle II Physics Book

L [ab^{-1}]		σ V_{ub} [%]
1	tagged	6.2
	untagged	3.6
5	**tagged**	**3.2**
	untagged	**2.1**
	leptonic	**5**
50	tagged	1.7
	untagged	1.3
	leptonic	1.5 - 2



Semitauonic decays

More interesting ratios

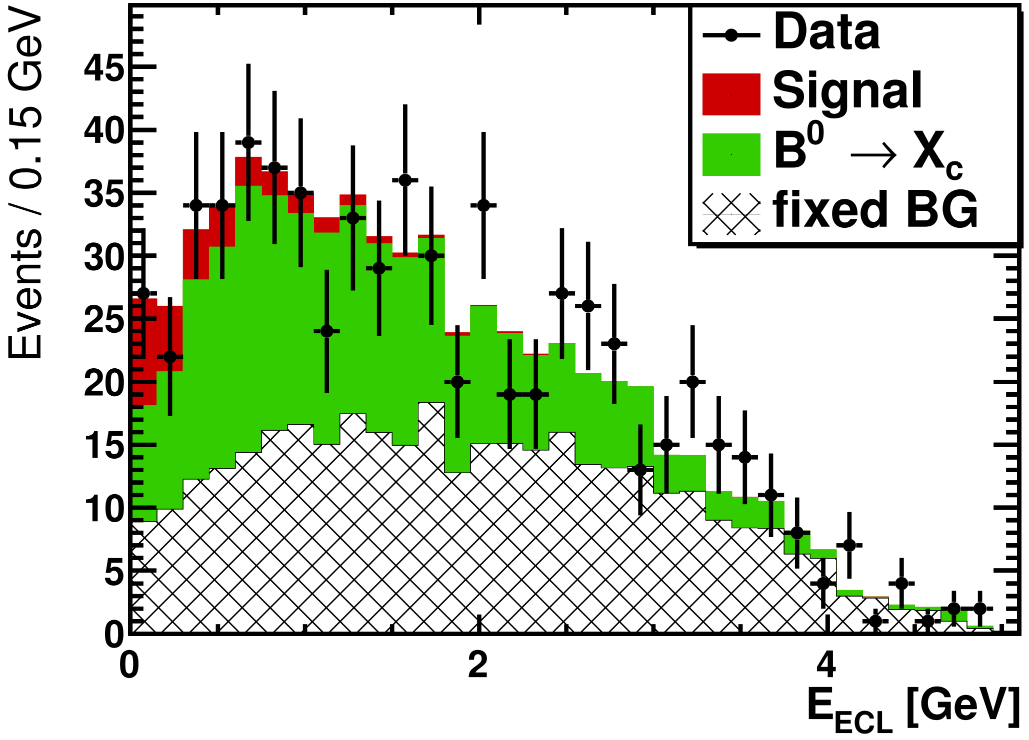
- Belle I measurement
  - using hadronic tagging
  - 1D likelihood fit to E_{ECL}

$$R(\pi) = \frac{\mathcal{B}(B \to \pi\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to \pi\ell\bar{\nu}_\ell)}$$

$$R(\pi) = 1.05 \pm 0.51$$

$$R(\pi)_{SM} = 0.641 \pm 0.016$$

$\tau \to \ell\nu\nu,\ \tau \to \pi\nu\nu, \tau \to \rho\nu\nu, \tau \to a_1\nu\nu$



Phys. Rev. D 93, 032007 (2016)

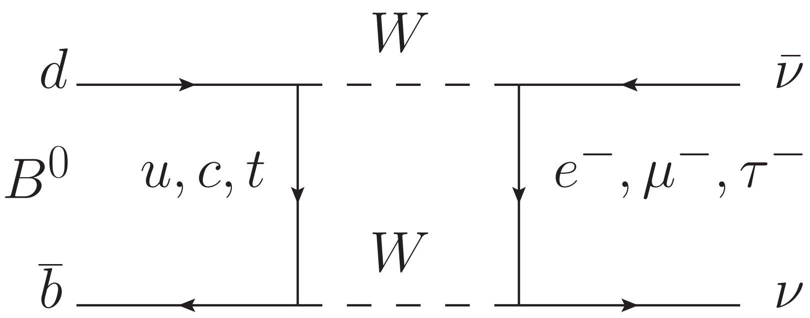
Belle II

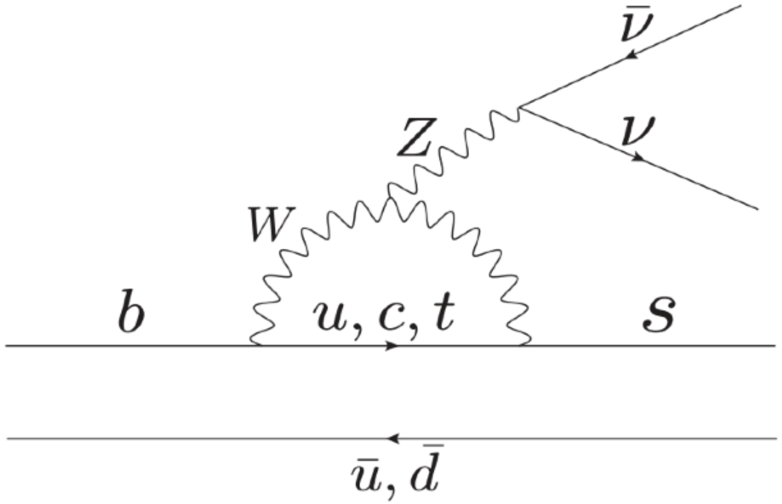
$$R_\pi^{5\,\mathrm{ab}^{-1}} = 0.64 \pm 0.23\,,$$

$$R_\pi^{50\,\mathrm{ab}^{-1}} = 0.64 \pm 0.09\,.$$

B→Kvv and Missing Energy Channels

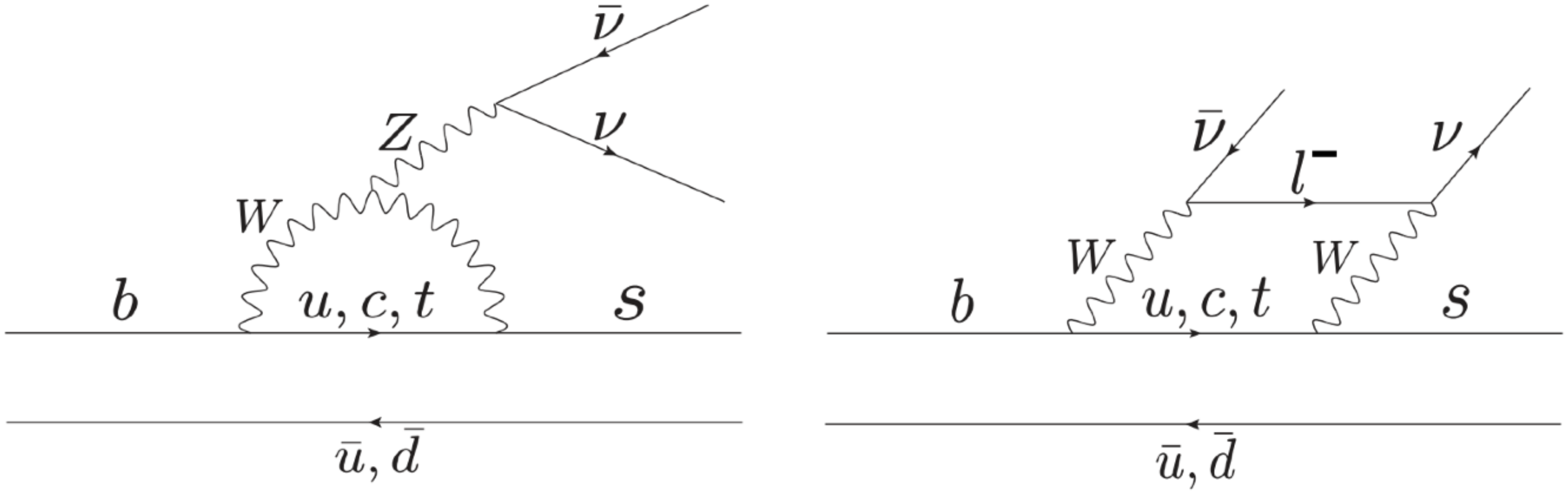
Golden modes for Belle II





Search for B $\rightarrow$ $h^{(*)}\nu\nu$

Challenges



- Sensitive to similar NP as tension in C9:
  - b⟶s transition shows signs of NP
- Theoretically very clean (no charm loops)

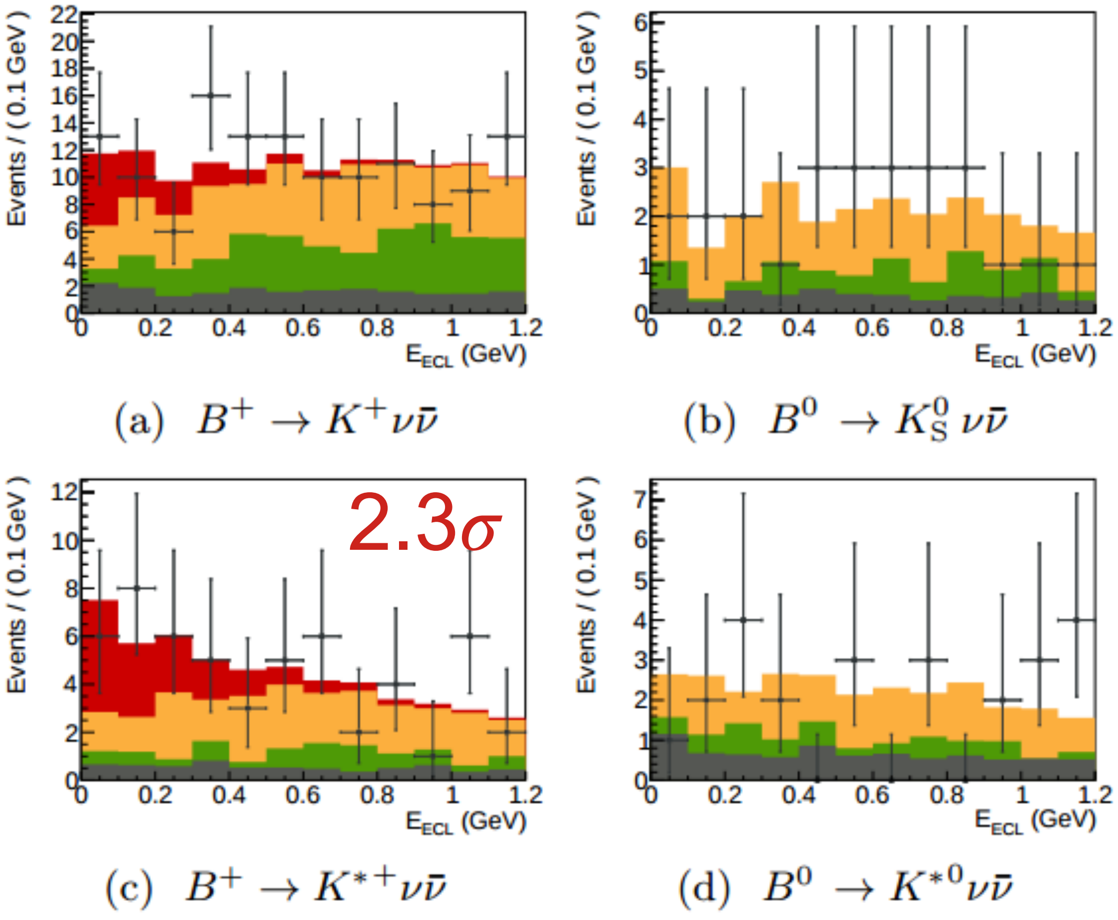
$$h^{(*)} = K^+, K^0_S, K^{*+}(K^0_S\pi^+, K^+\pi^0), K^{*0}(K^+\pi^-), \pi^+, \pi^0, \rho^+, \rho^0$$

Search for B → h$^{(*)}$νν

Golden mode for Belle II

- Recent Belle measurement
- Signal extraction via template histogram fit
  - Signal, b->c, continuum, light quark pairs

Channel	Observed signal yield	Significance
$K^+\nu\bar{\nu}$	$17.7 \pm 9.1 \pm 3.4$	$1.9\,\sigma$
$K^0_S\,\nu\bar{\nu}$	$0.6 \pm 4.2 \pm 1.4$	$0.0\,\sigma$
$K^{*+}\nu\bar{\nu}$	$16.2 \pm 7.4 \pm 1.8$	$2.3\,\sigma$
$K^{*0}\nu\bar{\nu}$	$-2.0 \pm 3.6 \pm 1.8$	$0.0\,\sigma$
$\pi^+\nu\bar{\nu}$	$5.6 \pm 15.1 \pm 5.9$	$0.0\,\sigma$
$\pi^0\nu\bar{\nu}$	$0.2 \pm 5.6 \pm 1.6$	$0.0\,\sigma$
$\rho^+\nu\bar{\nu}$	$6.2 \pm 12.3 \pm 2.4$	$0.3\,\sigma$
$\rho^0\nu\bar{\nu}$	$11.9 \pm 9.0 \pm 3.6$	$1.2\,\sigma$



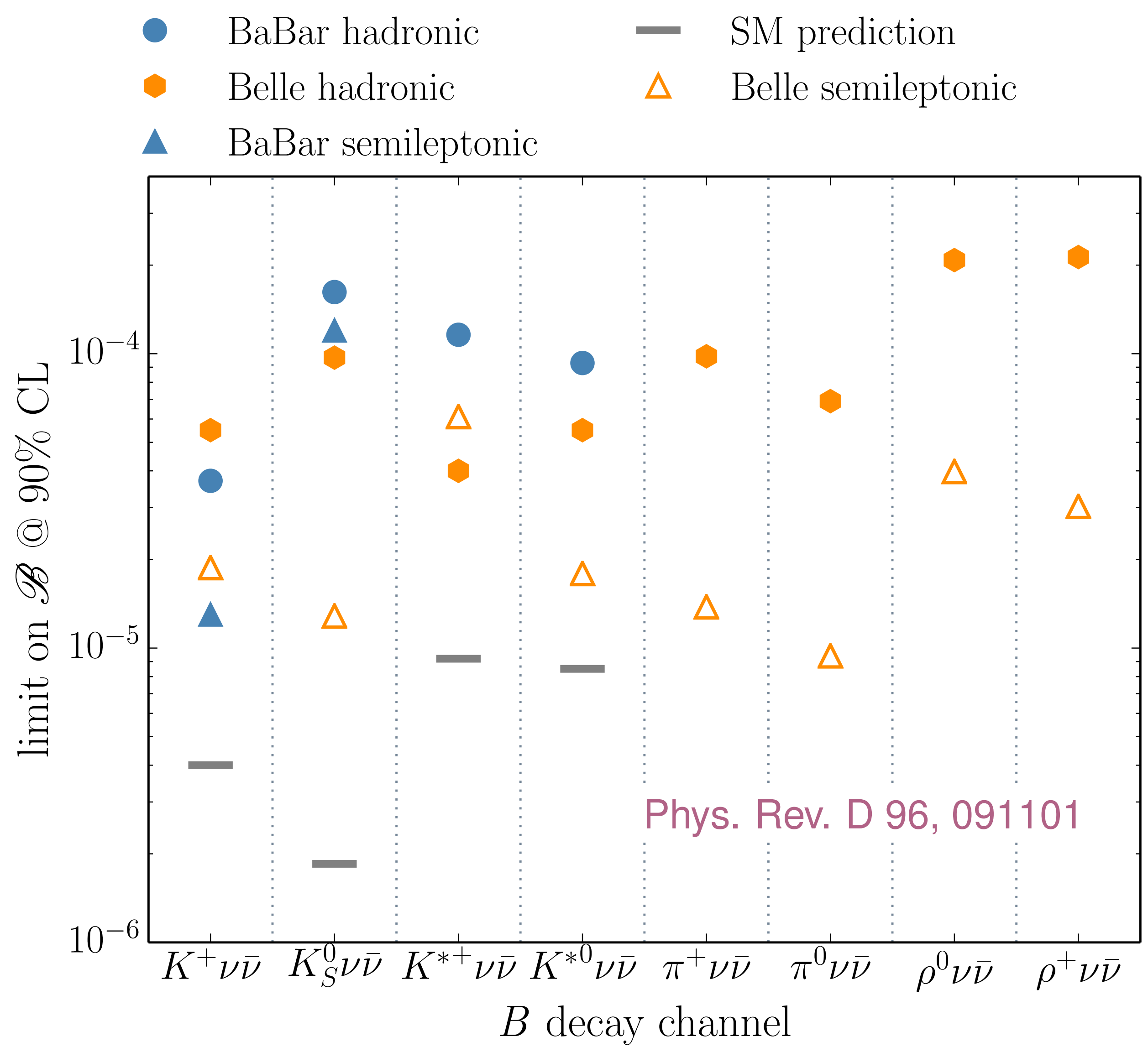
(a) $B^+ \to K^+\nu\bar{\nu}$ (b) $B^0 \to K^0_S\,\nu\bar{\nu}$ (c) $B^+ \to K^{*+}\nu\bar{\nu}$ (d) $B^0 \to K^{*0}\nu\bar{\nu}$

PRD 96, 091101 (2017)

Search for B → $h^{(*)}\nu\nu$

Golden mode for Belle II

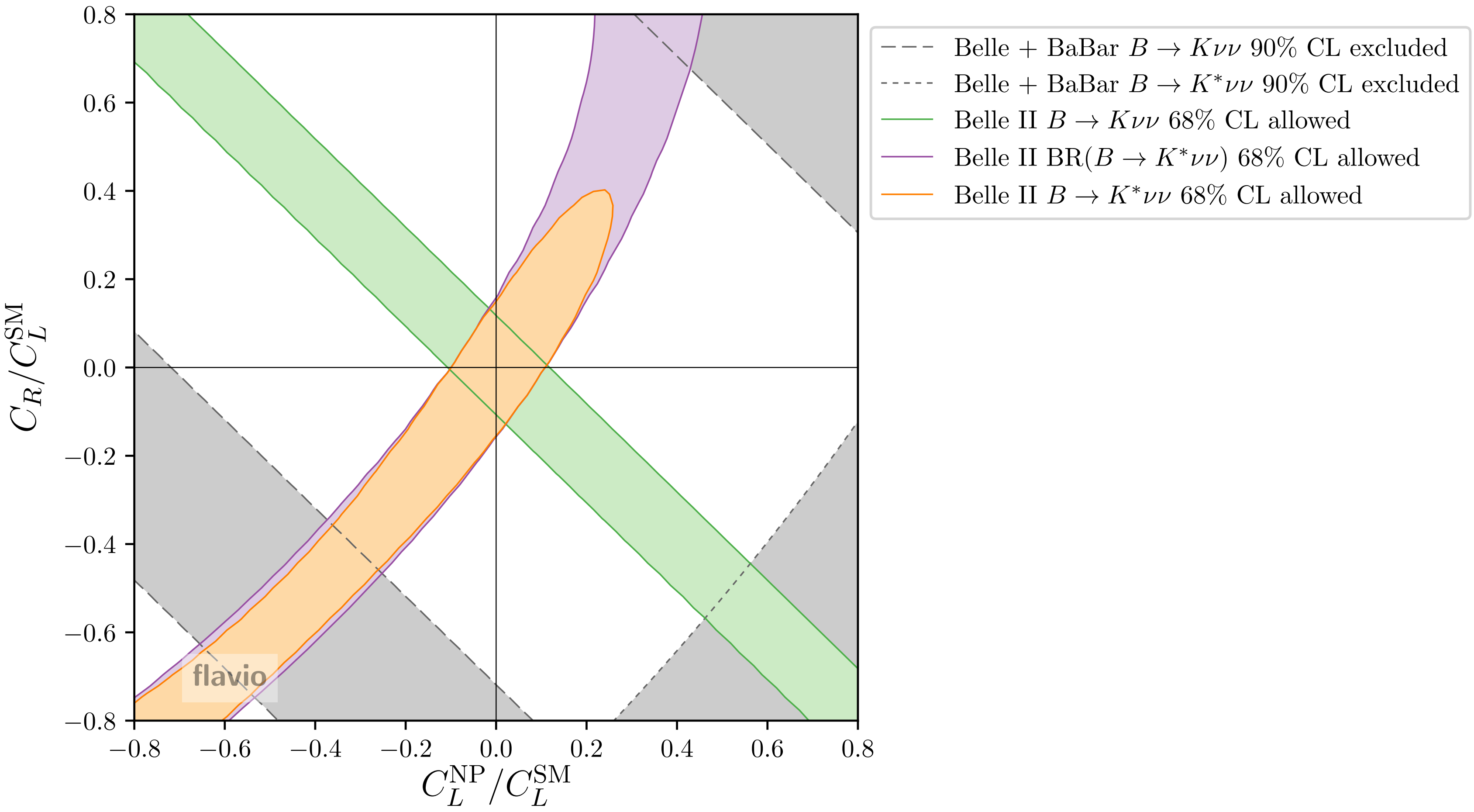
- Belle measurement sets strongest limits with in most channels
- Belle II will be able to measure branching ratios for B → $K^{(*)}\nu\nu$
- Belle II can measure the K* polarisation fraction F_L



Search for B → $h^{(*)}\nu\nu$

Golden mode for Belle II

- Effective field theory → constrain new physics across measurements



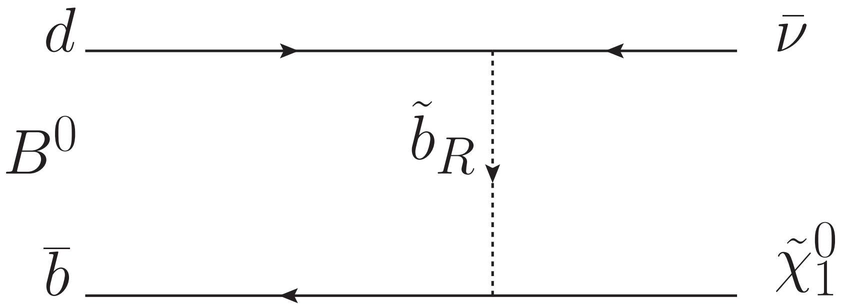
Search for B → h$^{(*)}$νν and B to invisible

Challenges

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+ \nu\bar{\nu})$	$< 450\%$	30%	11%
$\mathrm{Br}(B^0 \to K^{*0} \nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\mathrm{Br}(B^+ \to K^{*+} \nu\bar{\nu})$	$< 420\%$	25%	9.3%
$F_L(B^0 \to K^{*0} \nu\bar{\nu})$	–	–	0.079
$F_L(B^+ \to K^{*+} \nu\bar{\nu})$	–	–	0.077
$\mathrm{Br}(B^0 \to \nu\bar{\nu}) \times 10^6$	< 14	< 5.0	< 1.5
$\mathrm{Br}(B_s \to \nu\bar{\nu}) \times 10^5$	< 9.7	< 1.1	–

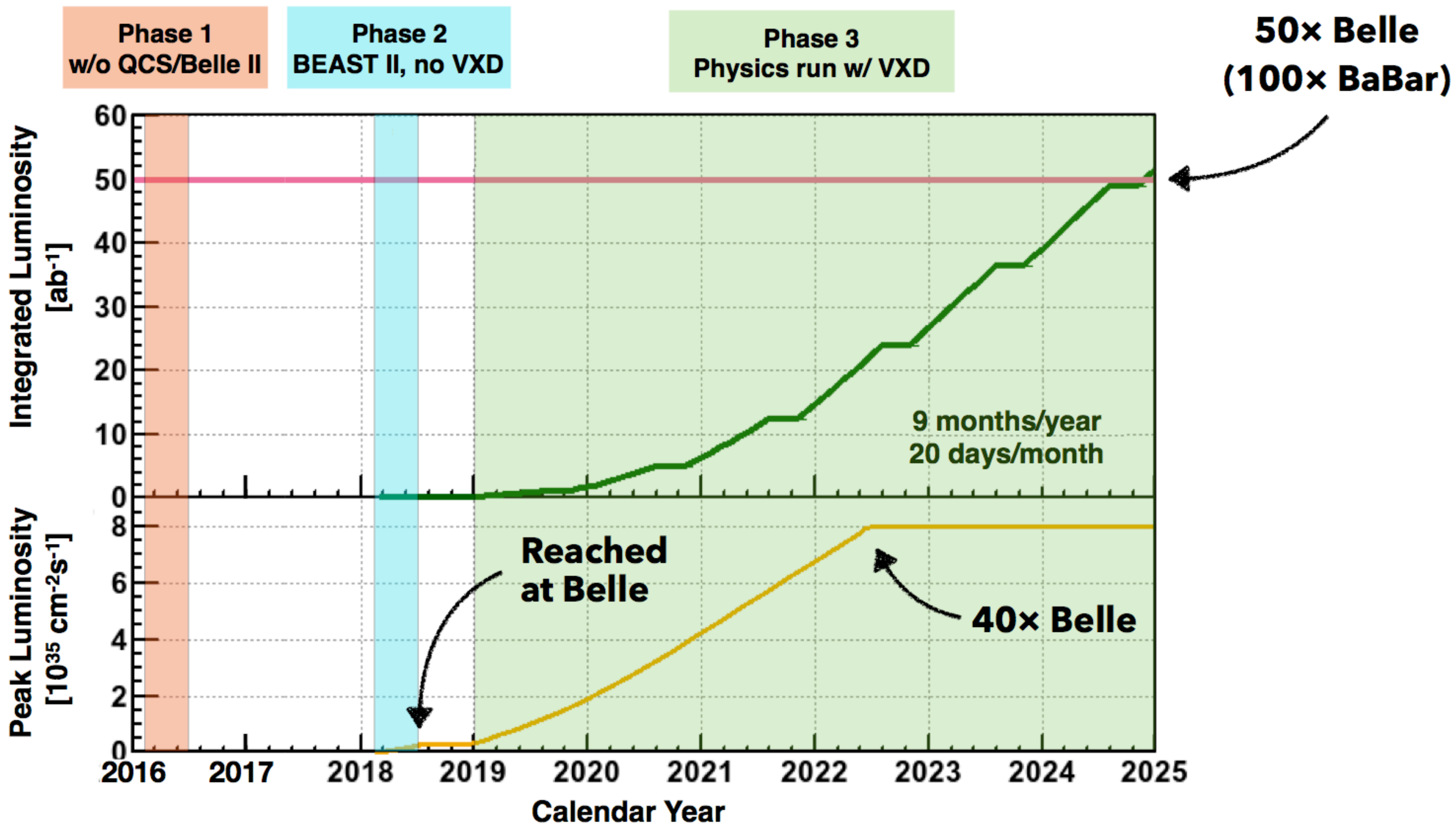
see B2TIP report

- Belle II can probe invisible decays of B mesons
  - Irreducible background from possible dark matter candidates
  - Same effects correlated to B → K$^{(*)}$νν
  - Can be constrained by B → K$^{(*)}$J/ψ



Plans For Belle II

First collisions very soon soon!



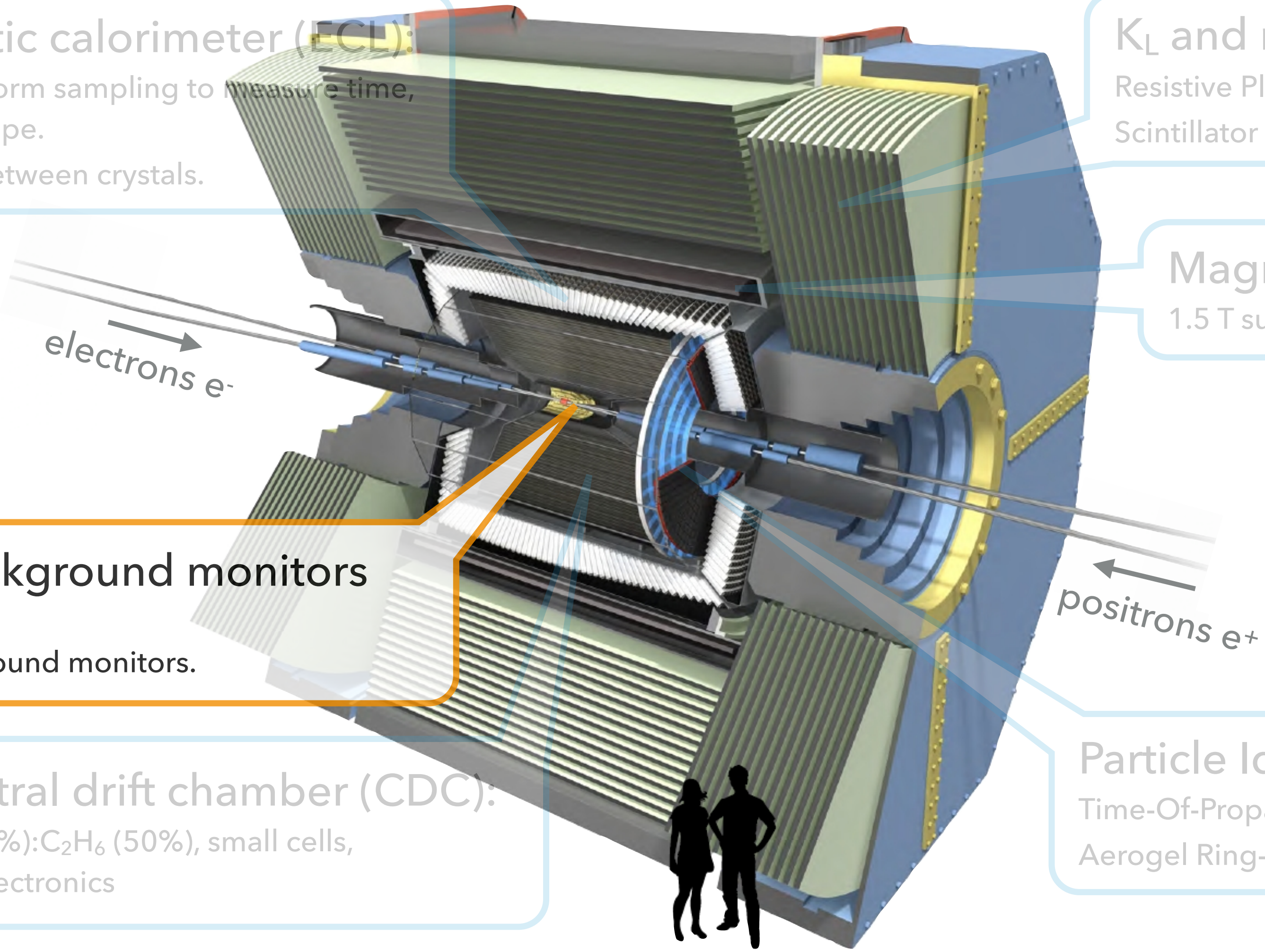
Belle II detector during Phase 2 (2018)

Running without vertex detector

Electromagnetic calorimeter (ECL):
CsI(Tl) crystals, waveform sampling to measure time, energy, and pulse-shape.
No projective gaps between crystals.

K_L and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

Magnet:
1.5 T superconducting



BEAST II background monitors
1/8 PXD, 1/16 SVD
Additional background monitors.

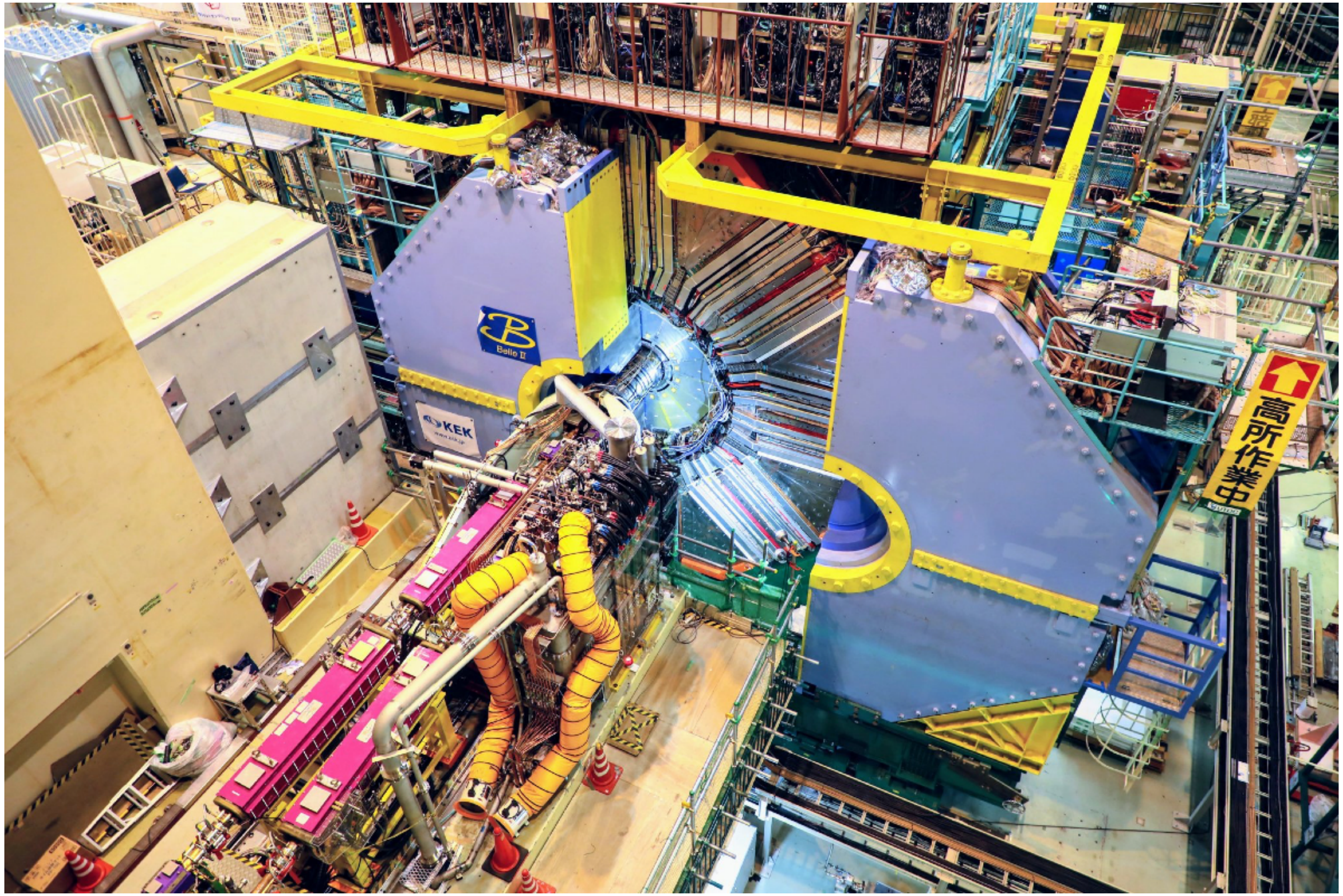
Trigger:
Hardware: < 8 kHz
no software trigger

Central drift chamber (CDC):
He(50%):C_2H_6 (50%), small cells,
fast electronics

Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

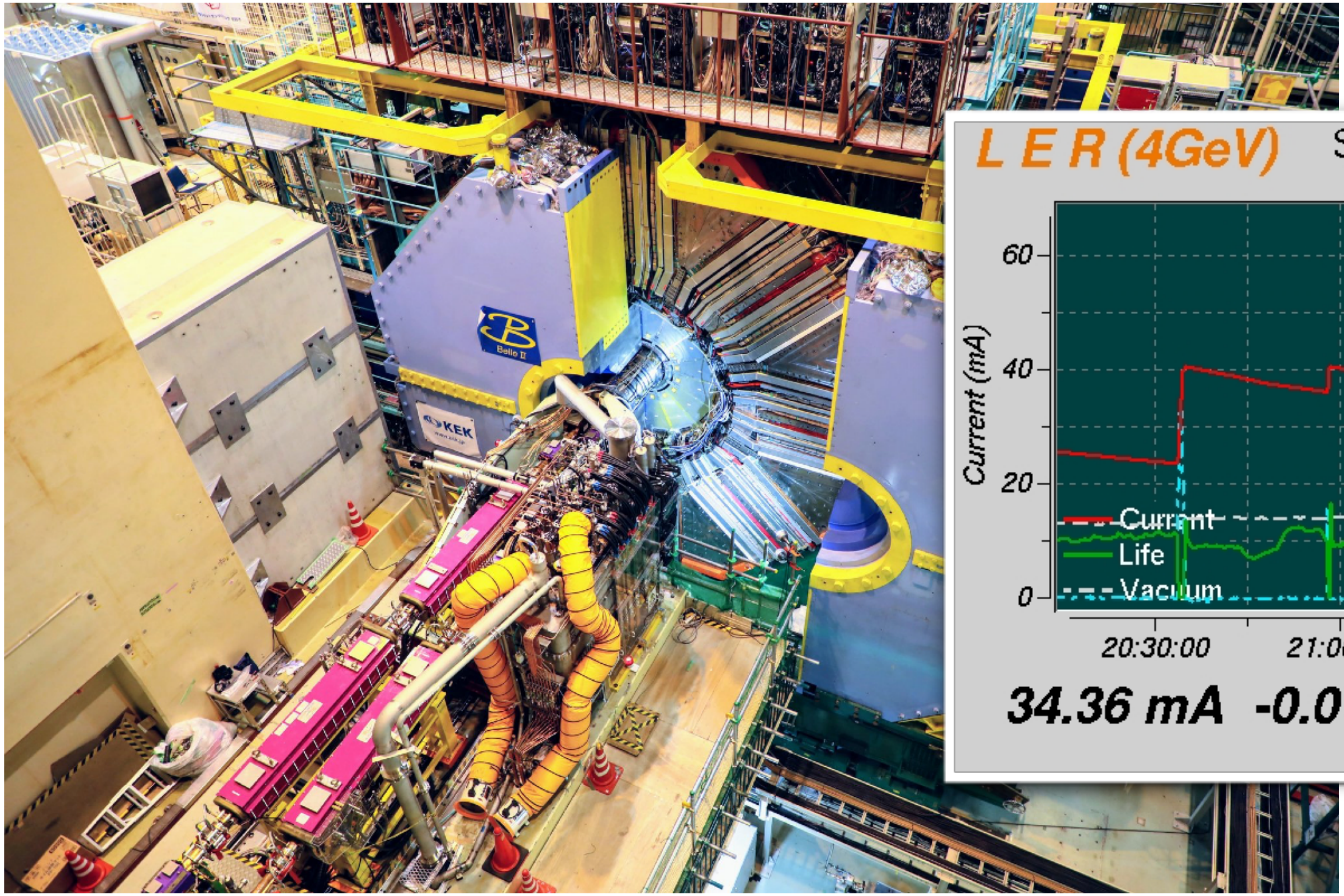
Plans For Belle II

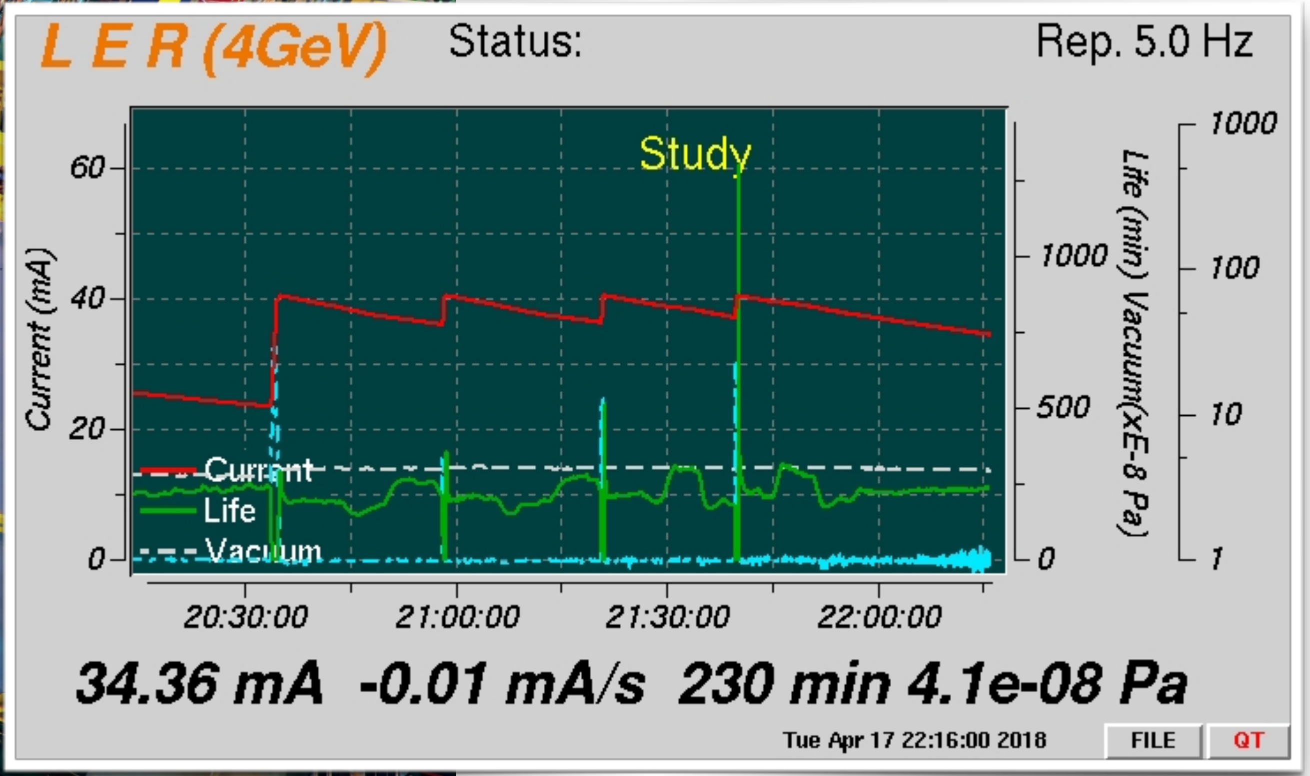
First beams in LER and HER - First positron beam!



Plans For Belle II

First beams in LER and HER - First positron beam!

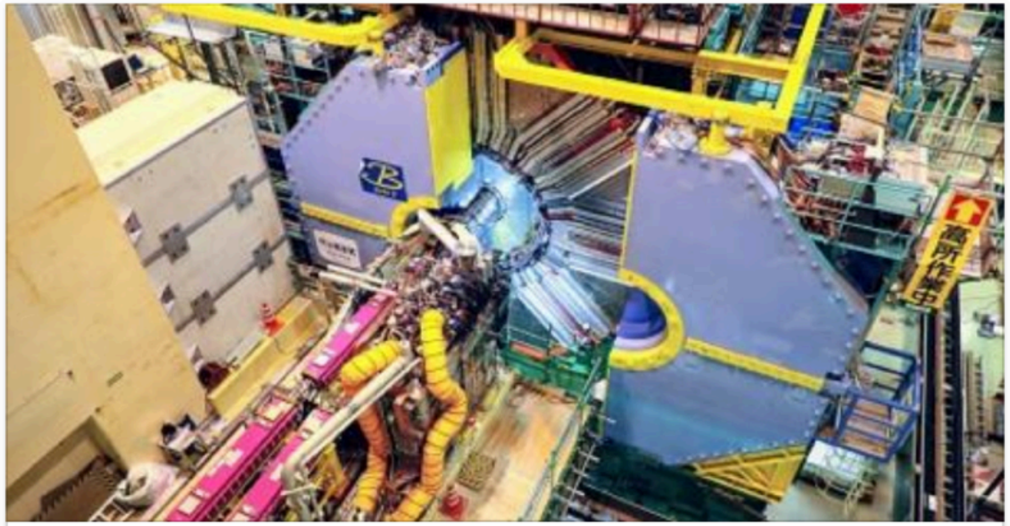




Conclusions

And Outlook

- Belle II will be able to probe new physics scenarios in many channels with neutrinos in the final state
- First data will be taken soon
- Exciting times are ahead!



【世界最強加速器SuperKEKB】電子と陽電子の初衝突の瞬間を見守ろう KEK×niconico

世界最強の粒子加速器「SuperKEKB」本格始動。ファースト・コリジョン（初の粒子衝突

LIVE.NICOVIDEO.JP

Conclusions

And Outlook

- Belle II will be able to probe new physics scenarios in many channels with neutrinos in the final state
- First data will be taken soon
- Exciting times are ahead!

First collisions planned for Friday, April 20th at 12:00

Thank you very much!

Contact

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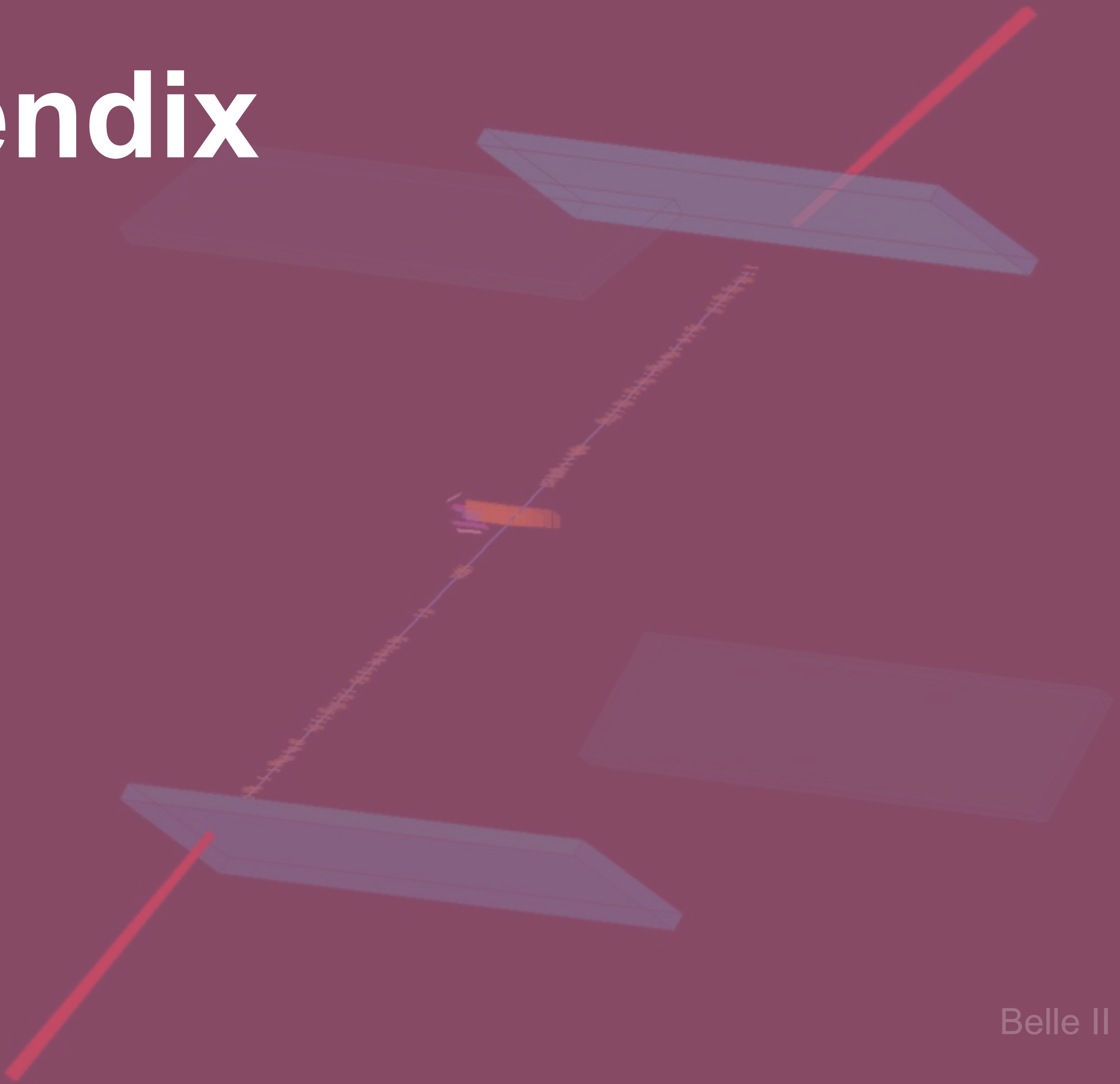
+49 (0)40-8998-4789

Appendix

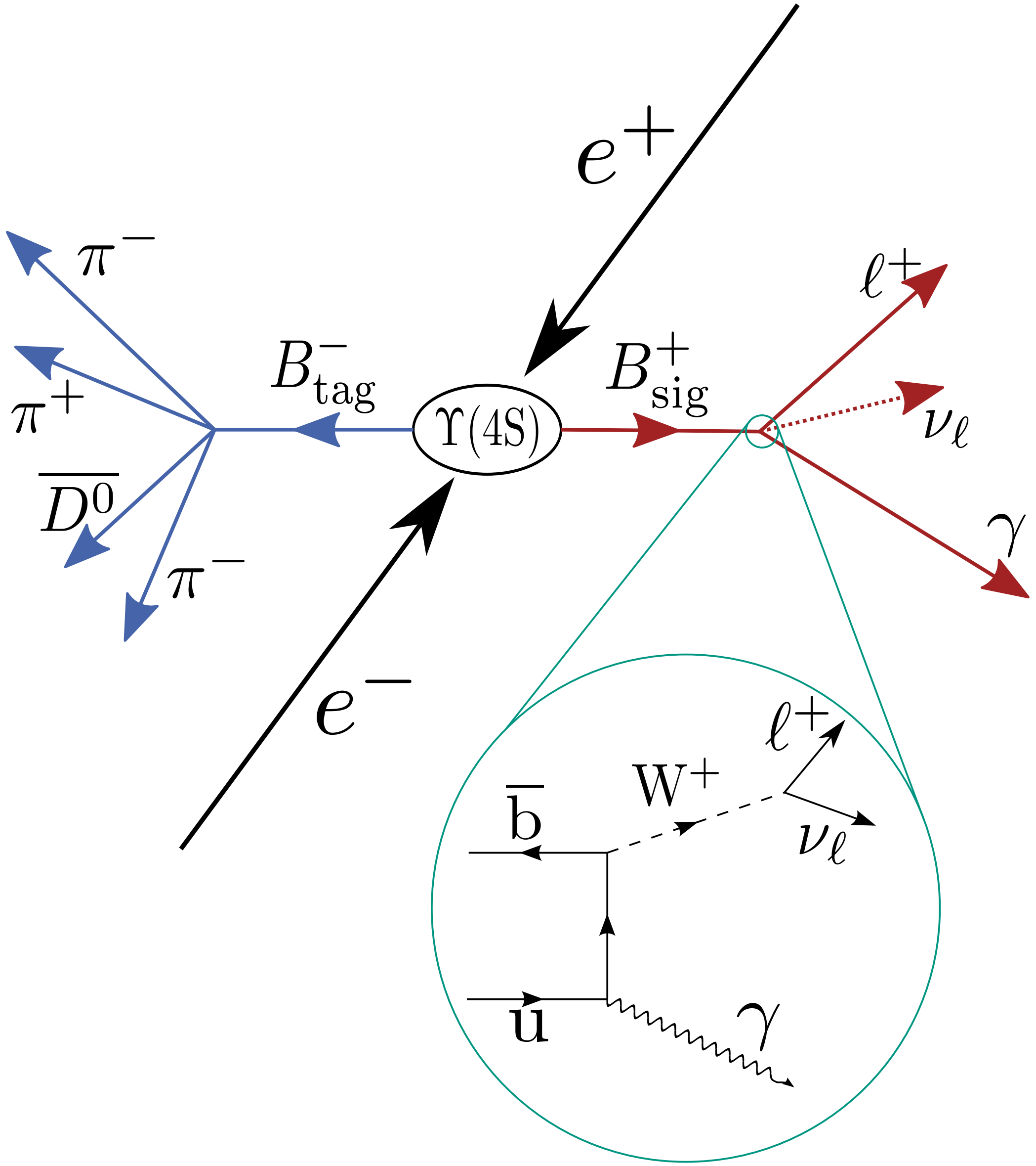


Belle II comics run, 18.02.2018

Leptonic radiative B decays

Important probe

- The decay $B^+ \to \ell^+ \nu \gamma$ allows to probe the first inverse moment λ_B of the Light-Cone Distribution Amplitude (LCDA) of the B meson.
- Important input for QCD factorisation necessary for theory predictions of non-leptonic B meson decays



Leptonic radiative B decays

Important probe

- Belle I measurement on full dataset:

Belle Result (A. Heller)

Upper Limits:

$\mathcal{B}(B^+ \to e^+\nu_e\gamma) < 6.1 \cdot 10^{-6}$

$\mathcal{B}(B^+ \to \mu^+\nu_\mu\gamma) < 3.4 \cdot 10^{-6}$

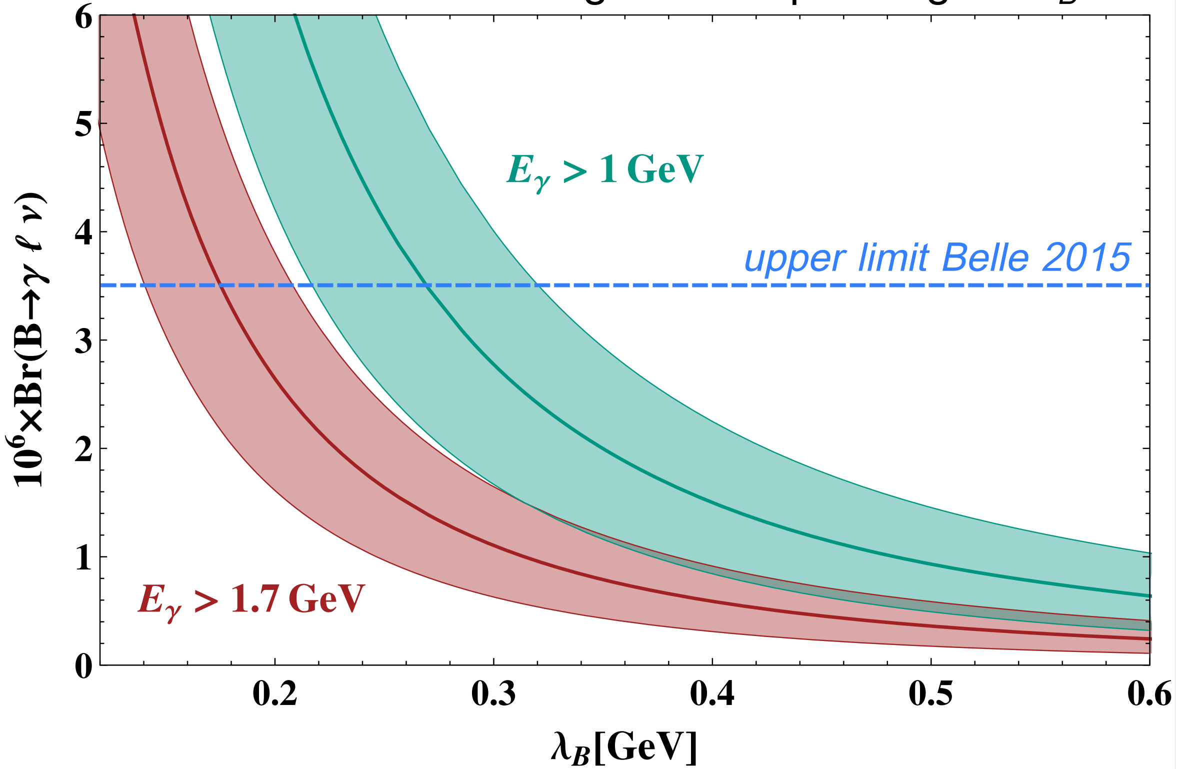
$\mathcal{B}(B^+ \to \ell^+\nu_\ell\gamma) < 3.5 \cdot 10^{-6}$

$\lambda_B > 238\,\mathrm{MeV}$ (90%C.L.)

Expected Statistical Error for $\mathcal{B}(B^+ \to \ell^+\nu_\ell\gamma) = 5.0 \times 10^{-6}$

Belle Improv. Analysis	Belle II $5ab^{-1}$	Belle II $50ab^{-1}$
+1.2	+0.46	+0.14
-1.32	-0.50	-0.16

Theoretical Branching Ratio depending on λ_B



M. Beneke and J. Rohrwild (2011)

From Moriz Gelb, Cracow EPIPHANY Conference on Advances in Heavy Flavour Physics