Tau LFV at Belle II

Francesco Tenchini
on behalf of the Belle II Collaboration
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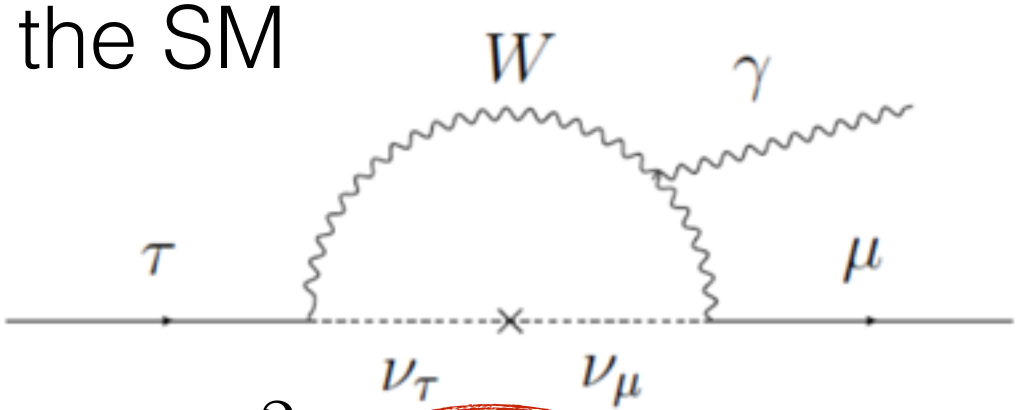
Outline

- Theoretical motivations for τ LFV searches
- SuperKEKB and Belle II
- τLF(U)V at Belle II
  - $\tau \rightarrow \mu\, \gamma$
  - $B^+ \rightarrow K^+ \tau l$
- Conclusions and Outlook

Motivation for τ LFV searches

- Lepton flavour is conserved in the Standard Model (accidental symmetry)
- Neutrino oscillations
  → first sign of neutral LFV beyond the SM
- Also generates charged LFV, but at a non measurable level:



$$\mathcal{B}_{\nu SM}(\tau \to \mu\gamma) = \frac{3\alpha}{32\pi}\left|U^*_{\tau i}U_{\mu i}\frac{\Delta m^2_{3i}}{m^2_W}\right|^2 < 10^{-40}$$

→ Powerful probe for new physics

LFV: Beyond the Standard Model

- Predicted in many theoretical models $\mathcal{O}\left(10^{-7} \sim 10^{-10}\right)$

Model	**Reference**	**$\tau \to \mu\gamma$**	**$\tau \to \mu\mu\mu$**
SM+ ν oscillations	EPJ C8 (1999) 513	10^{-40}	10^{-14}
SM+ heavy Maj ν_R	PRD 66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z’	PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66 (2002) 115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566 (2003) 217	10^{-10}	10^{-7}

- Sensitivity of various channels to cLFV is model-dependent → discriminate theories by comparing branching ratios and spectra across multiple modes

Effective Field Theory Approach

- Model-independent approach with an effective Lagrangian:

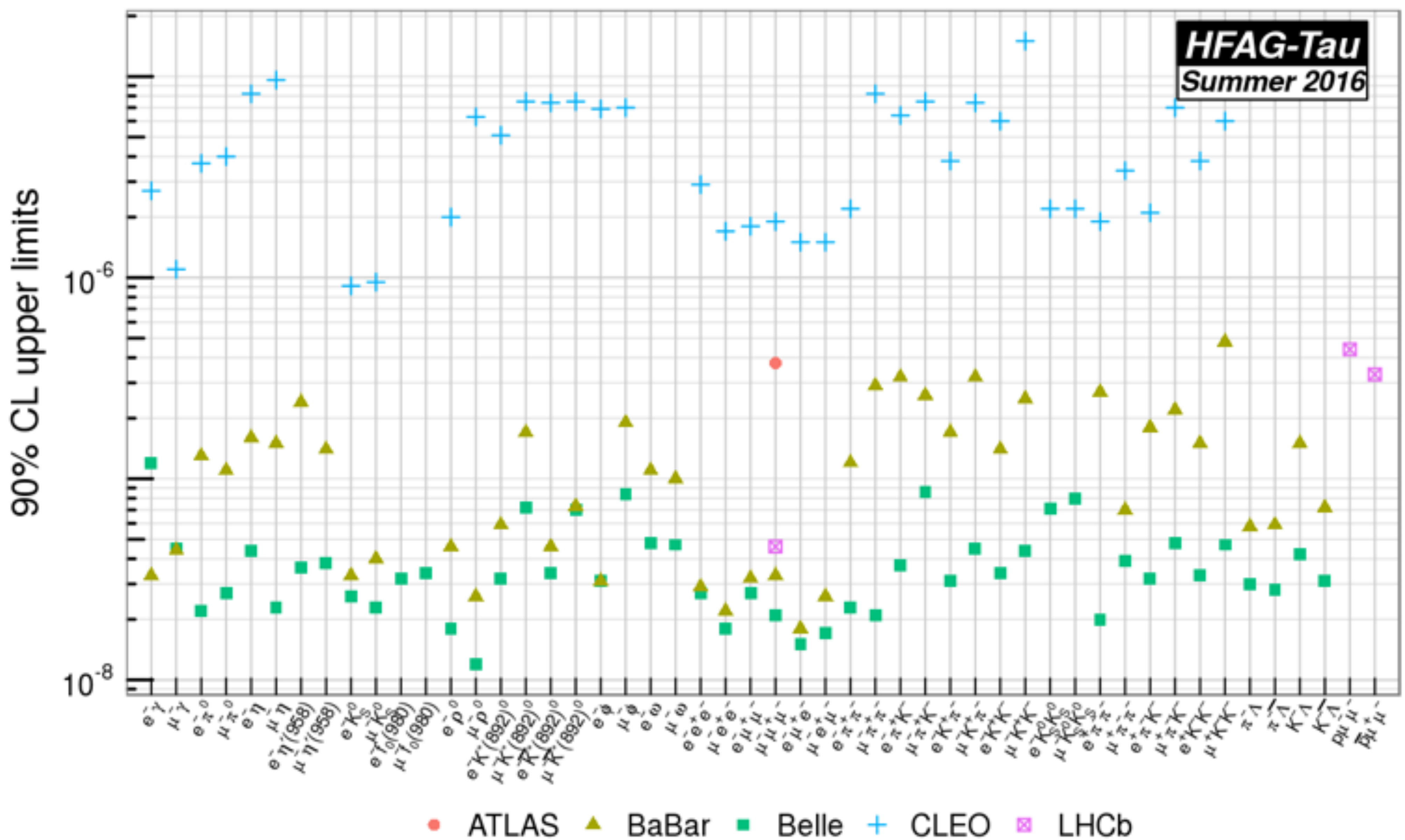
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

		$\tau \to 3\mu$	$\tau \to \mu\gamma$	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K\bar{K}$	$\tau \to \mu\pi$	$\tau \to \mu\eta^{(\prime)}$
4-lepton	$\mathrm{O}^{4\ell}_{\mathrm{S,V}}$	✓	–	–	–	–	–
dipole	O_{D}	✓	✓	✓	✓	–	–
lepton-quark	$\mathrm{O}^{\mathrm{q}}_{\mathrm{V}}$	–	–	✓ (I=1)	✓(I=0,1)	–	–
	$\mathrm{O}^{\mathrm{q}}_{\mathrm{S}}$	–	–	✓ (I=0)	✓(I=0,1)	–	–
lepton-gluon	O_{GG}	–	–	✓	✓	–	–
	$\mathrm{O}^{\mathrm{q}}_{\mathrm{A}}$	–	–	–	–	✓ (I=1)	✓ (I=0)
	$\mathrm{O}^{\mathrm{q}}_{\mathrm{P}}$	–	–	–	–	✓ (I=1)	✓ (I=0)
	$\mathrm{O}_{\mathrm{G\tilde{G}}}$	–	–	–	–	–	✓

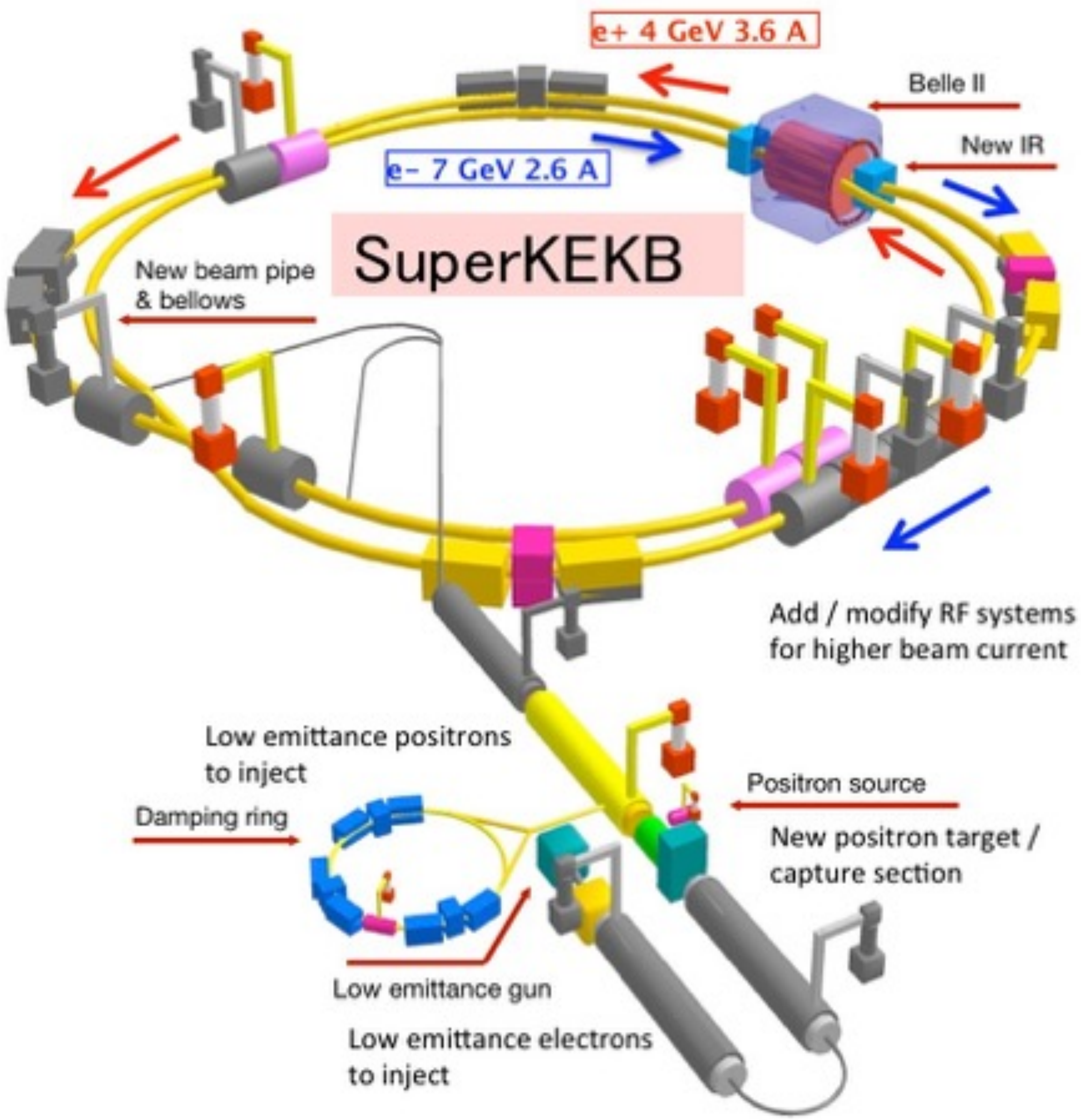
Celis, Cirigliano, Passemar (2014)

τ LFV at B Factories

- Large τ-pair production cross section at Υ(4S) (σ~0.9 nb)
- Can probe a large variety of modes



SuperKEKB and Belle II

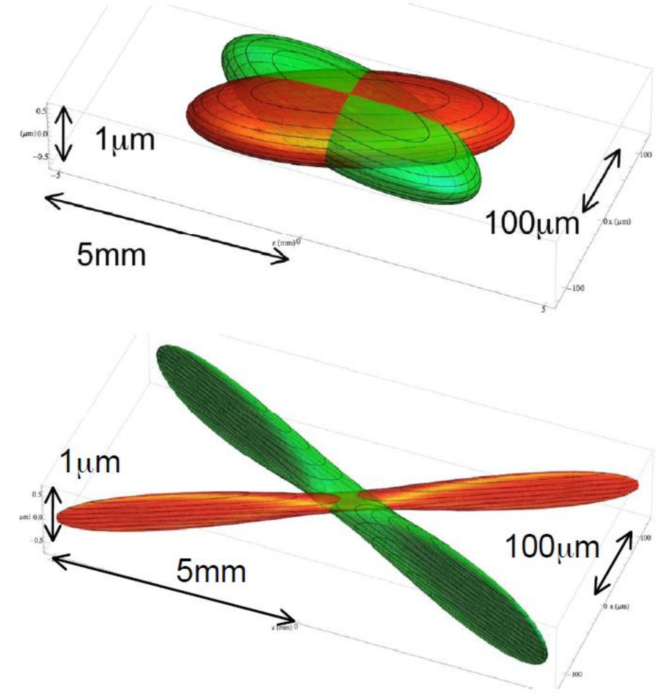


KEKB → SuperKEKB (x40 luminosity)

- Smaller interaction point
- Increased current

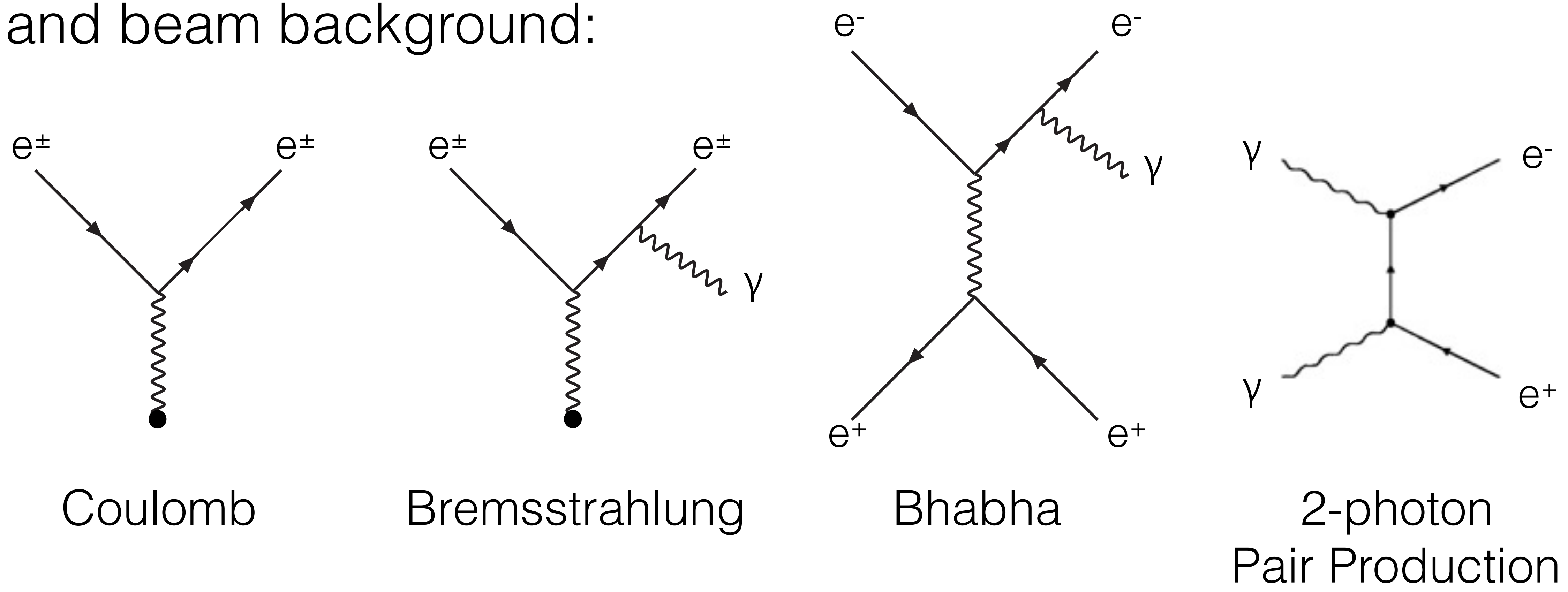
Belle → Belle II (x50 int. luminosity)

First beams & commissioning in 2016



Beam Background

- With the upgraded accelerator come increased event rates and beam background:

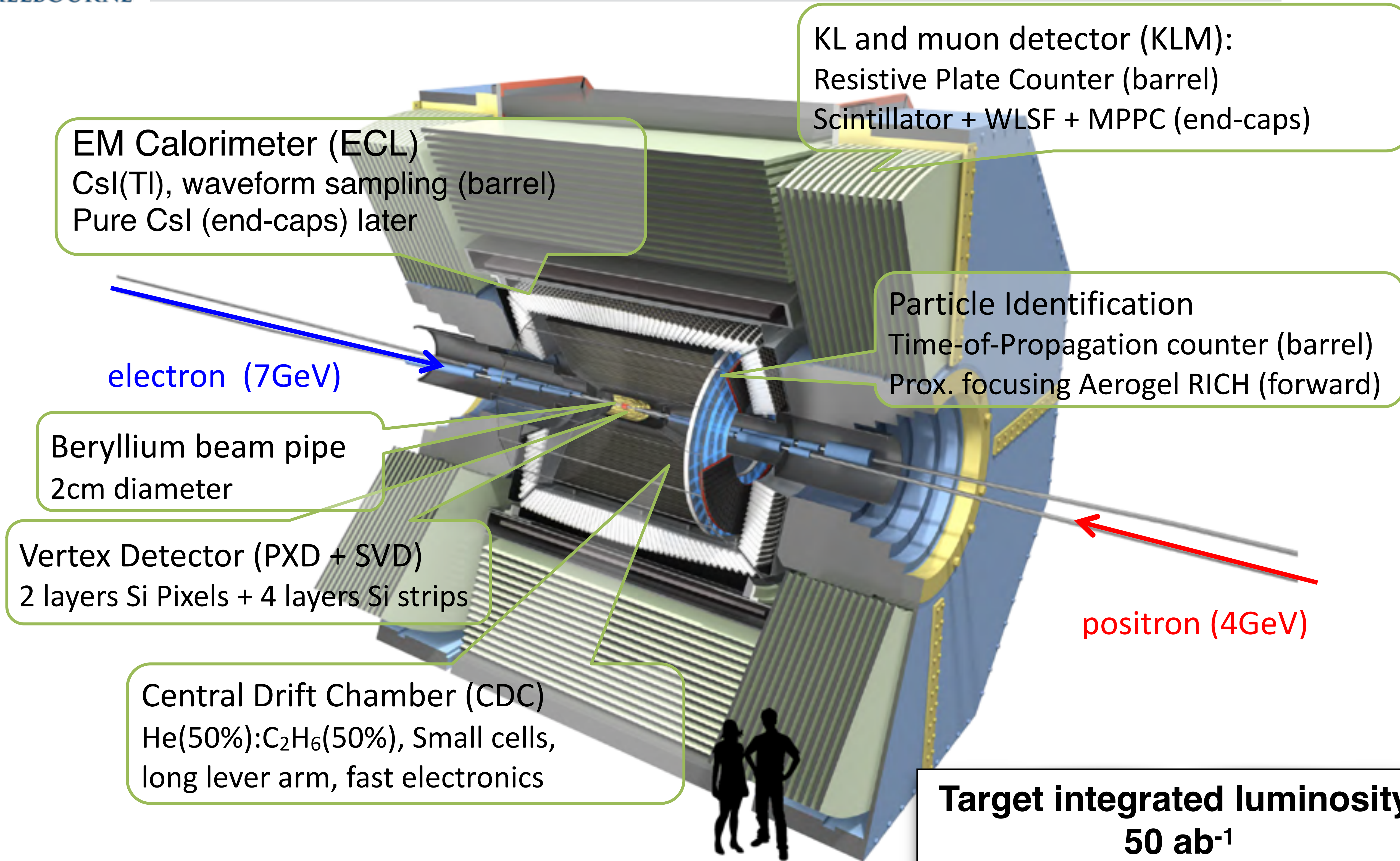


… and *intra-beam* (Touschek) scattering

- Affects detector design and resolutions
  — Pileup from charged showers
  — Shift of calorimeter energies

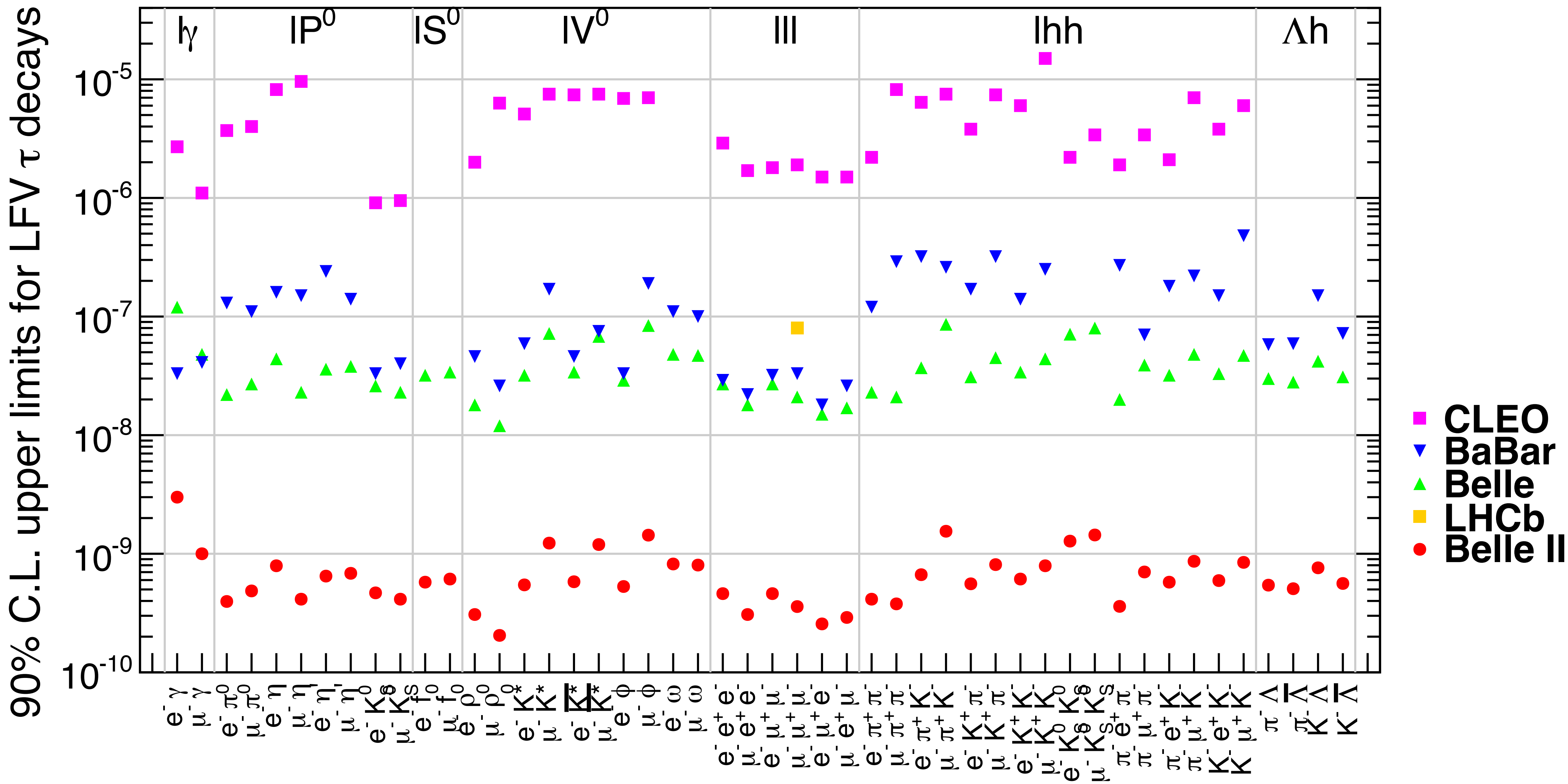
(4)

The Belle II Detector



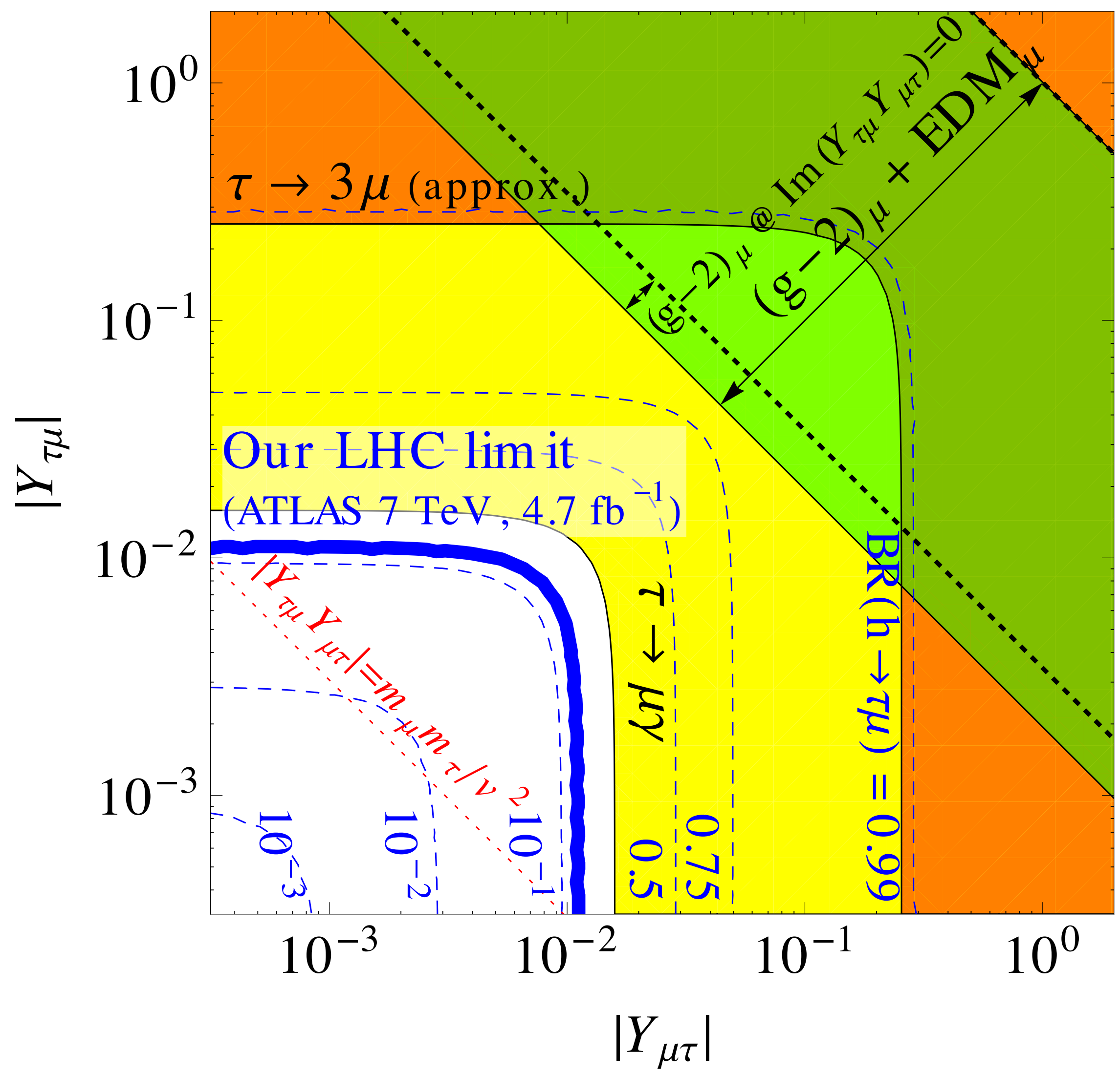
Target integrated luminosity: 50 ab^{-1}

τ LFV projections for Belle II



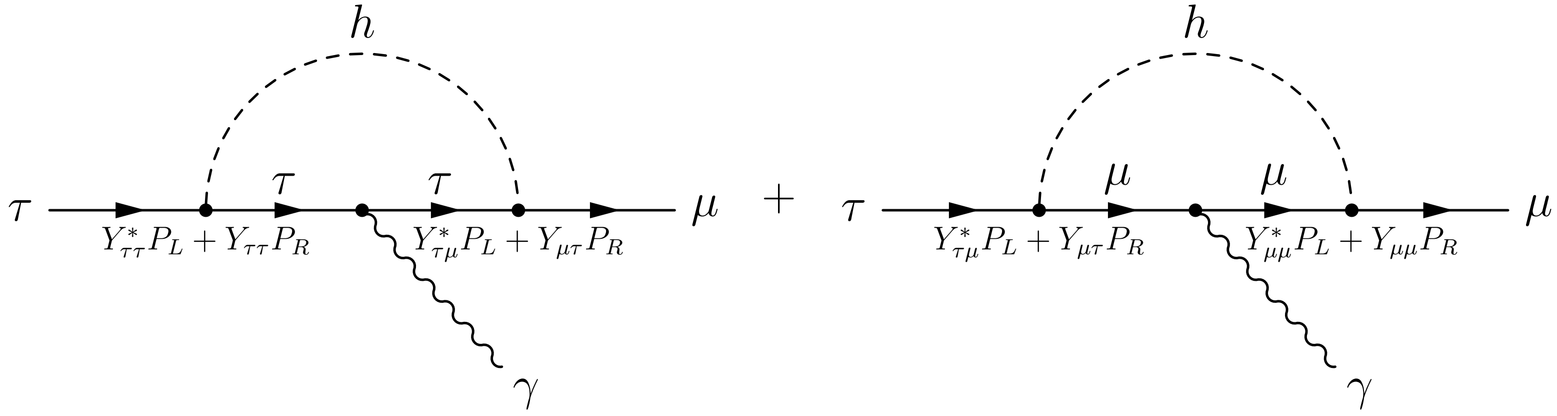
Extrapolation of existing results to 50 ab^{-1}
(in the no-background hypothesis)

Constraints from High Energy



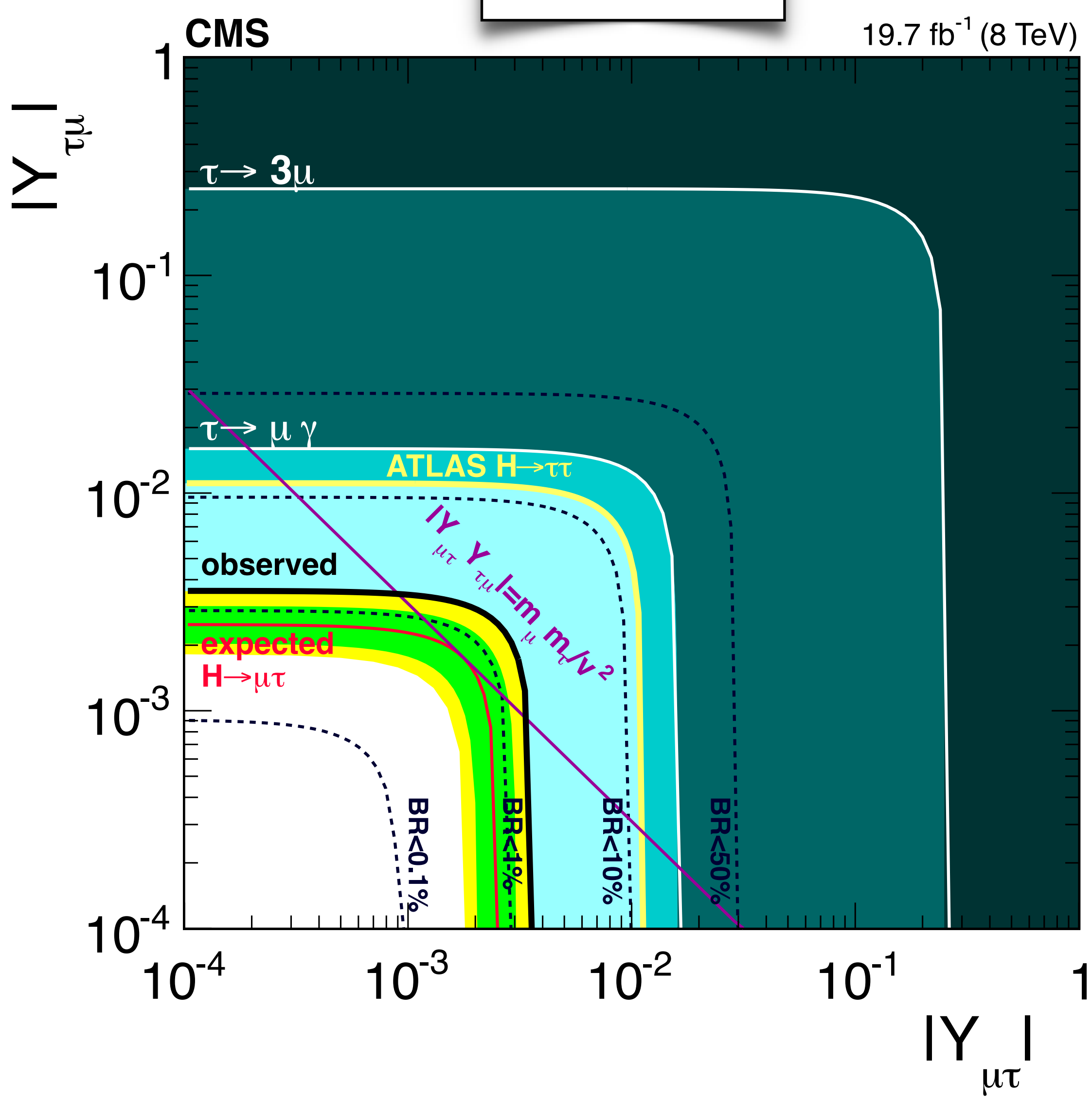
Harnik, Kopp, Zupan (2012)

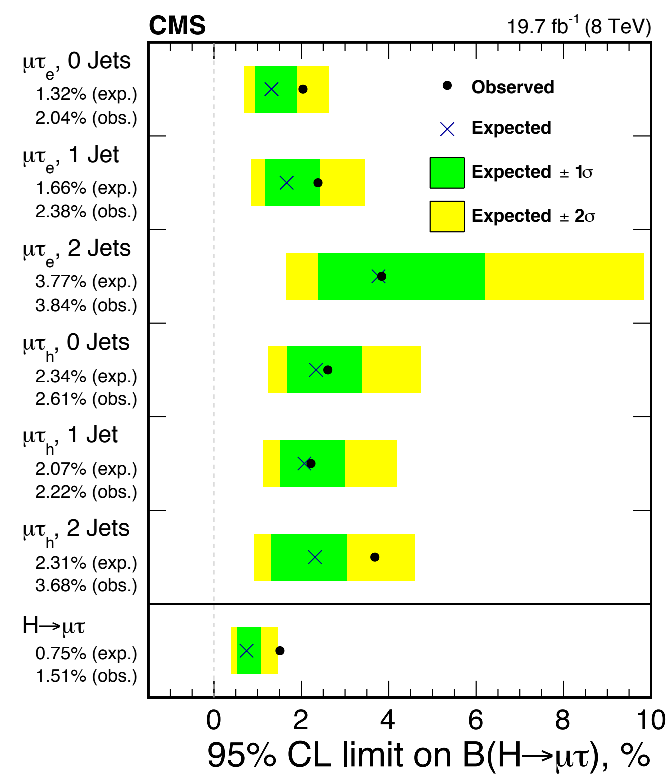
- $B(h \to \tau\mu) = (0.77 \pm 0.66)\%$ by recasting existing ATLAS $h \to \tau\tau$ results
- Implied limit on $Y_{\tau\mu}$ coupling
- Contributes to LQ, LL and (at loop level) dipole modes:

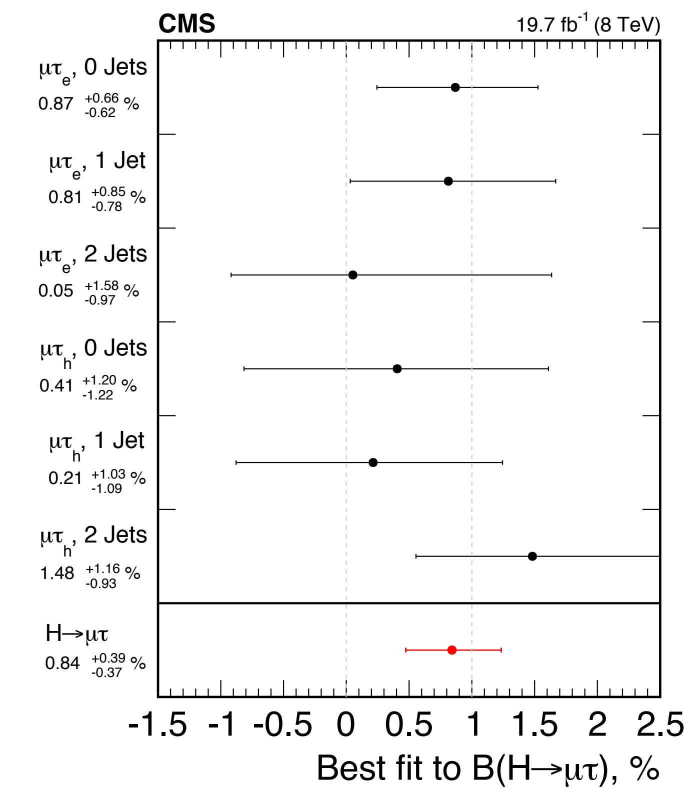


Constraints from High Energy

CMS bound







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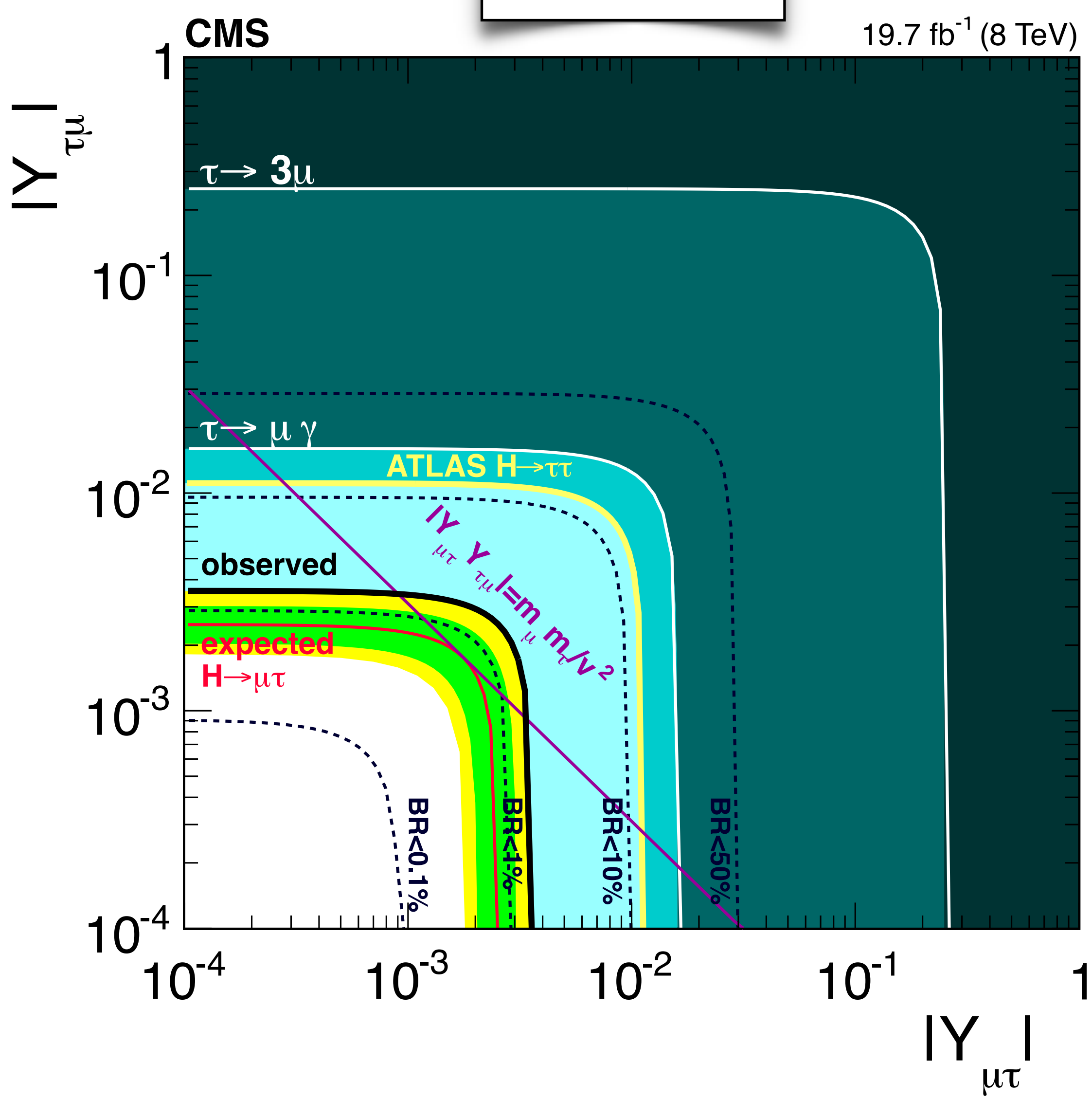
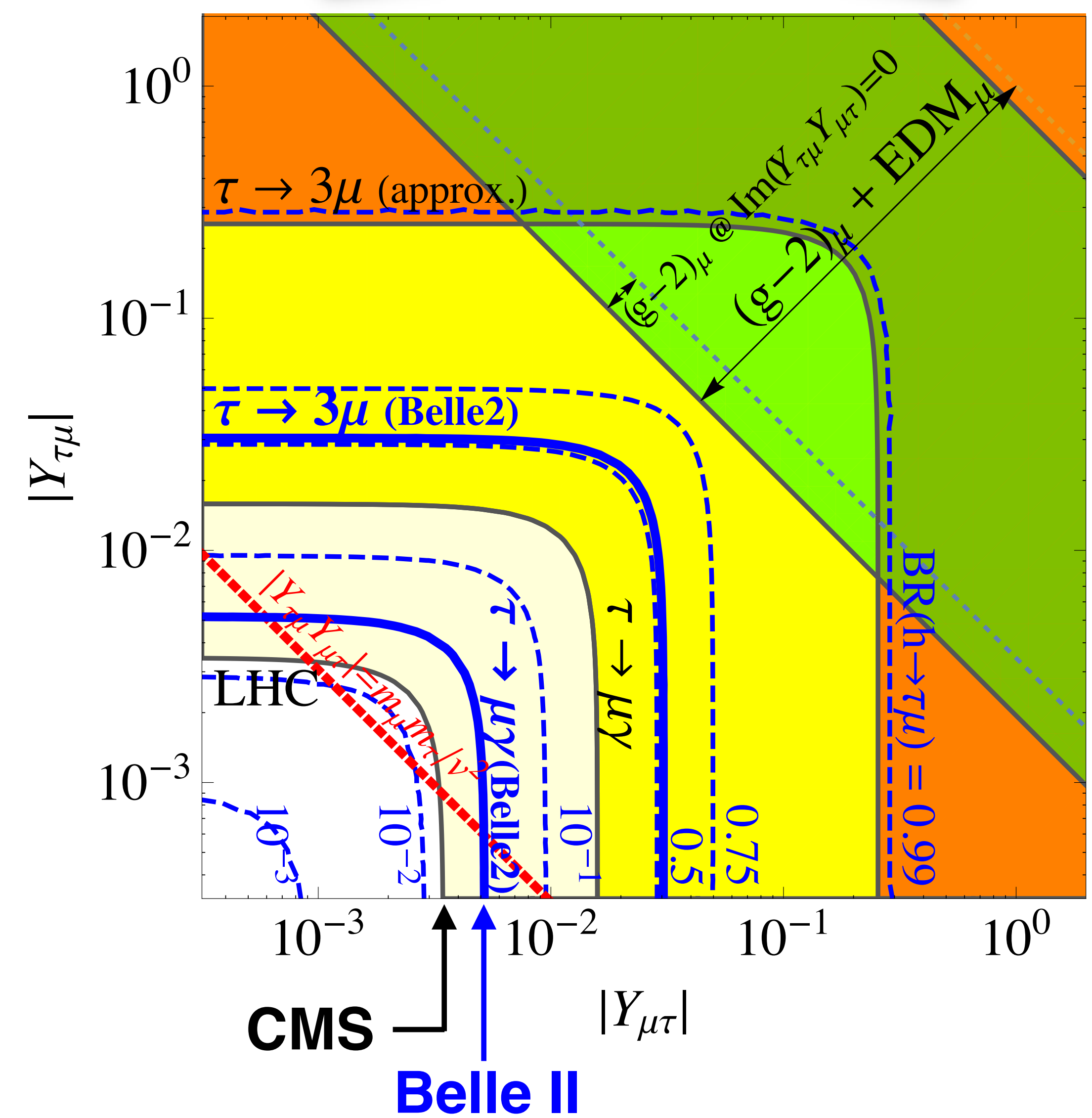
- CMS best fit $B(h \to \tau\mu) = (0.84^{+0.39}_{-0.37})\%$ → 2.4σ excess
- Sensitivity UL: $B_{95}(h \to \tau\mu) < 1.51\%$

Constraints from High Energy

CMS bound



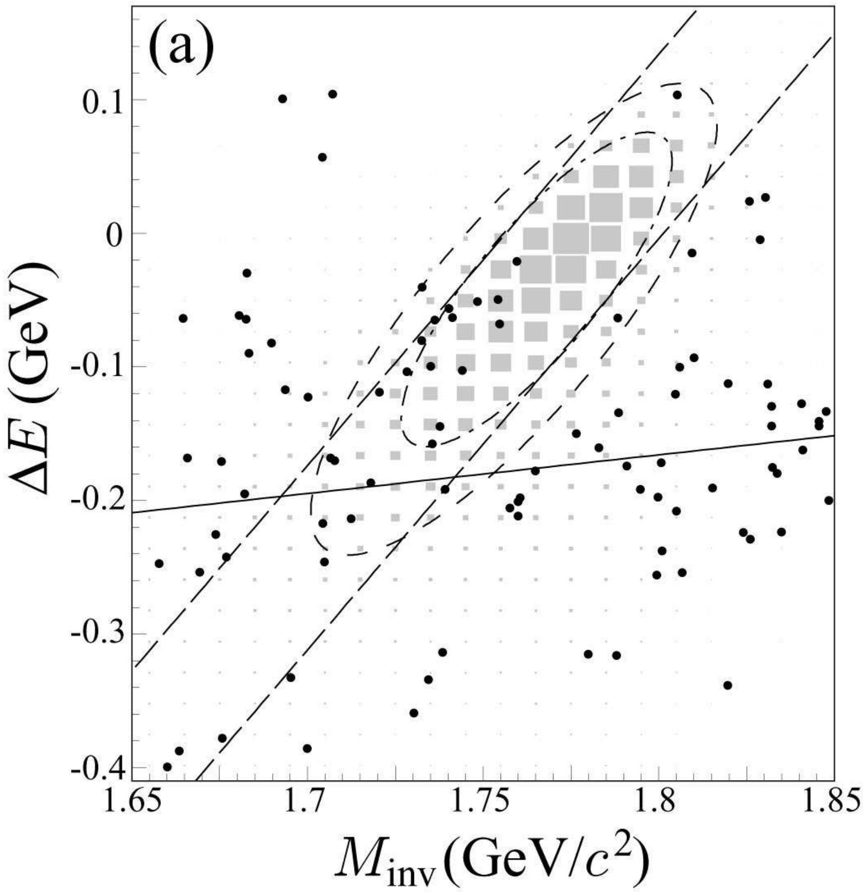
Updated plot by J. Zupan



LFV Yukawa coupling tested by both LHC and Belle II

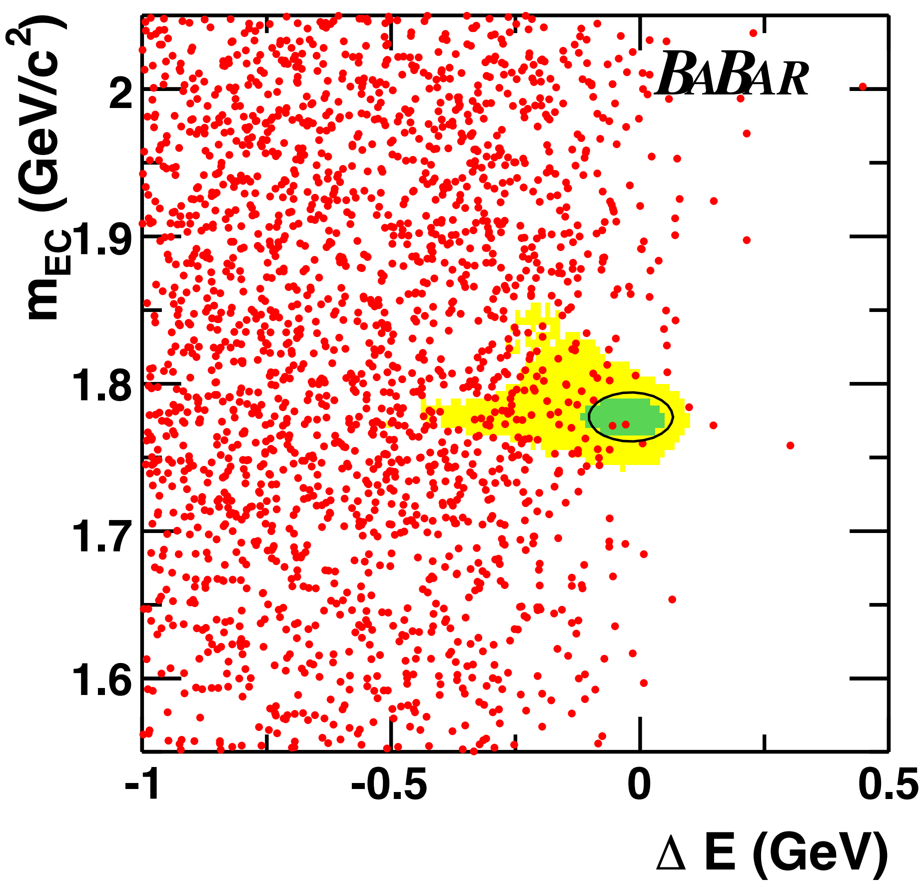
Past searches for $\tau \to \mu\gamma$

- Blinding box approach with BG evaluated outside the signal region
- Observables space: — $\mathbf{\Delta E} = E_{CM}^{(\mu+\gamma)} + E_{beam}/2$ (expected $\Delta E = 0$)
  — Signal-side $\mathbf{m_{inv}}$ (expected $m_{inv} = m_\tau = 1.777$ GeV/c^2)
- Signal regions after BG rejection cuts — data (points) and signal MC (shaded):



Belle

$B_{90}(\tau \to \mu\gamma) < 4.5 \times 10^{-8}$ (535 fb^{-1})

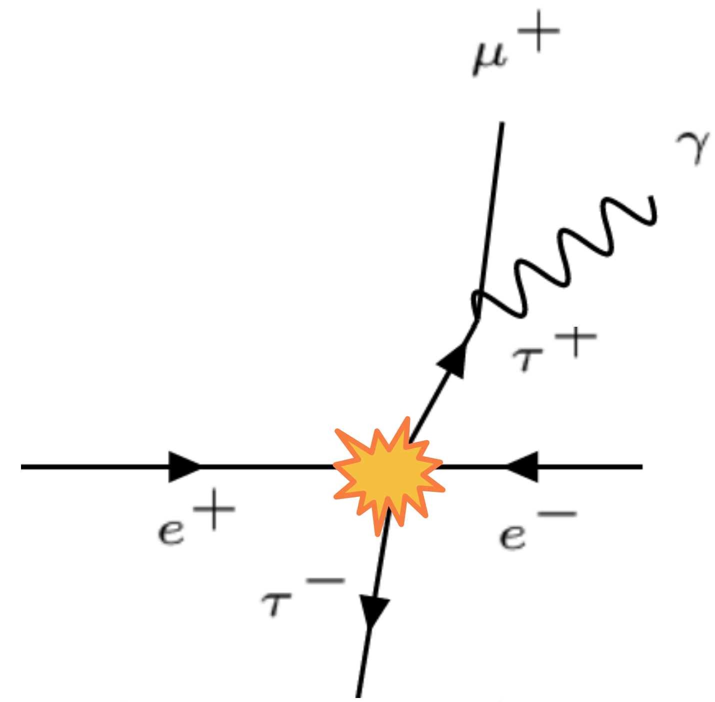


BaBar

$B_{90}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$ (515 fb^{-1})

τ→μγ at Belle II

- Sensitivity study using Belle II MC

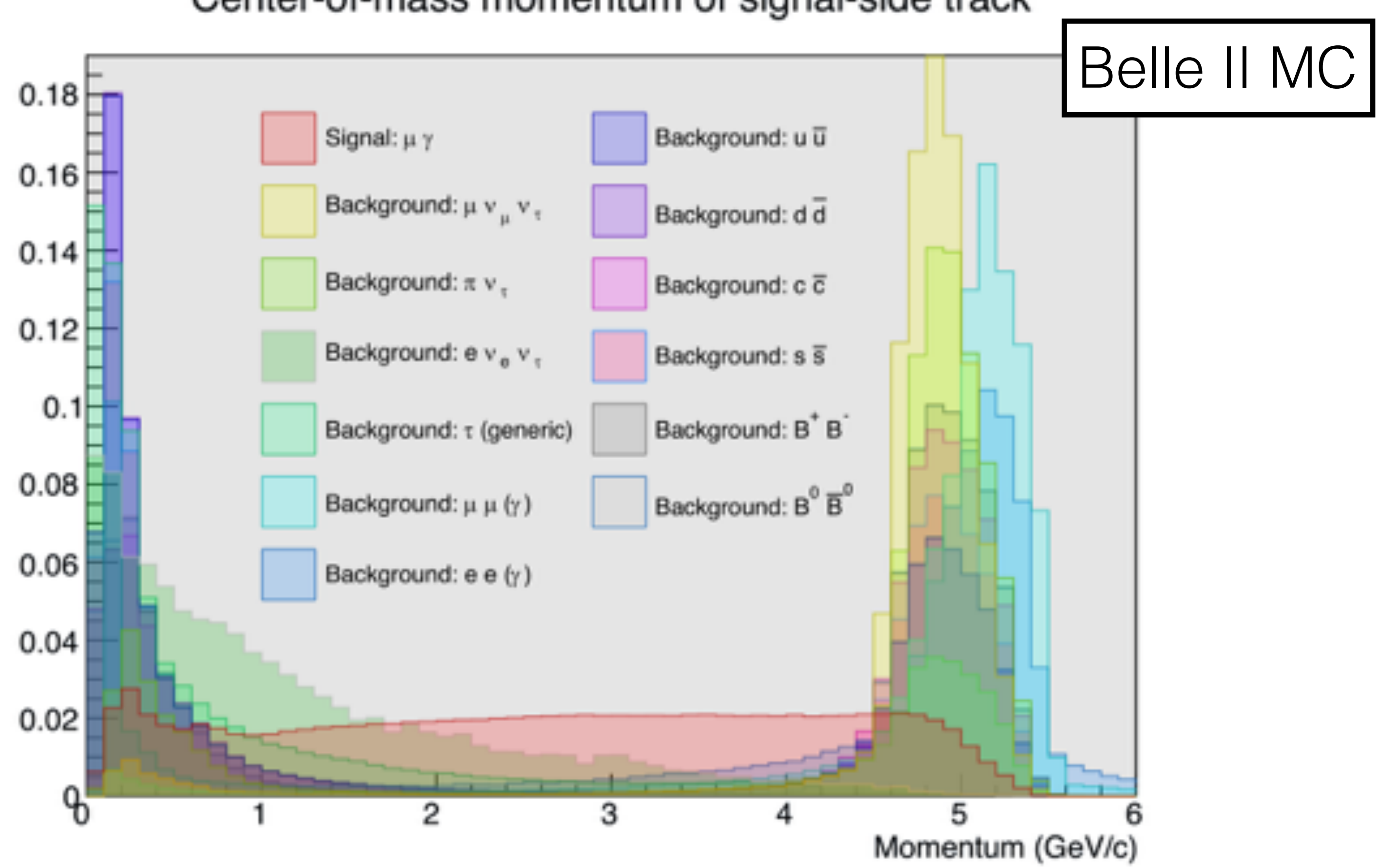


- Event signature:
  - signal τ: μ track + γ
  - tag τ: generic (non-μ)

- Background:
  - τ → μνν
  - τ → eνν
  - τ → πν

  } + γ

  - ee → ee/μμ (γ)
  - ee → hadronic



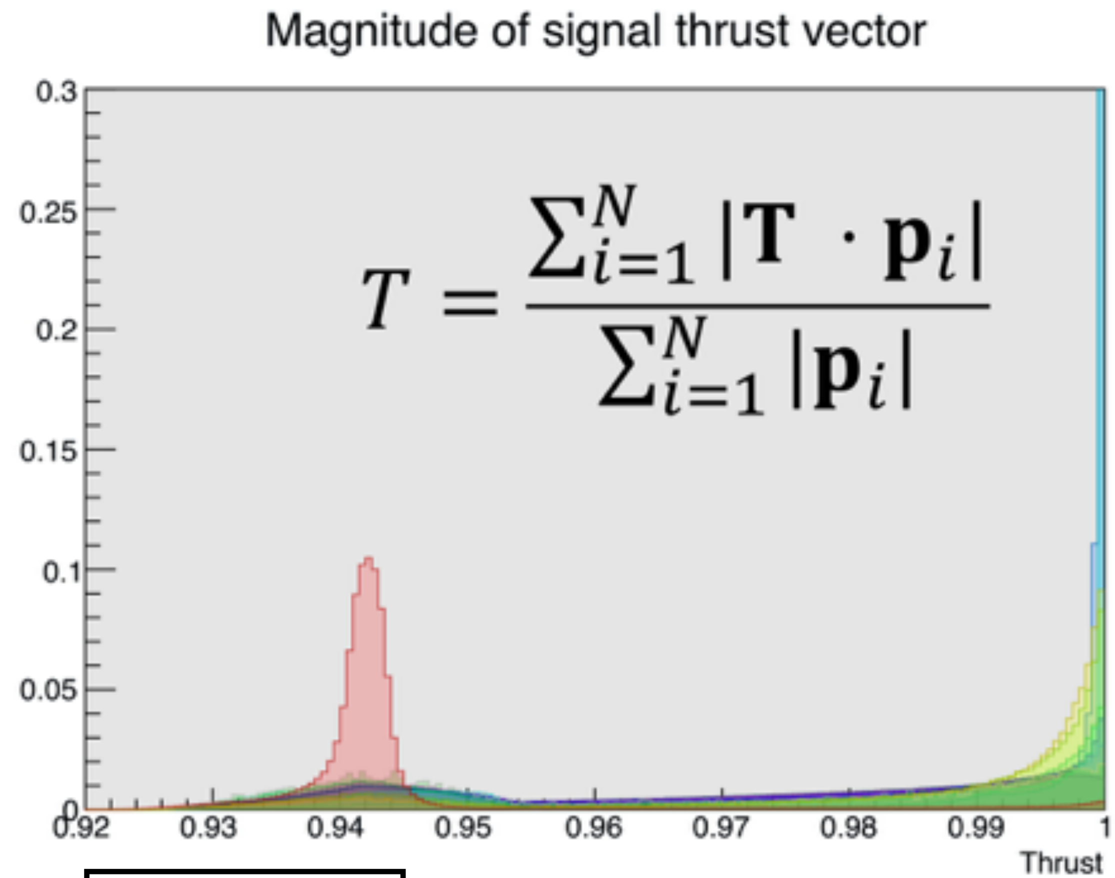
Signal Selection

- Belle II MC normalised to $1ab^{-1}$ for comparison with Belle.
- <u>Beam background is incorporated</u>
- Observables for background rejection:

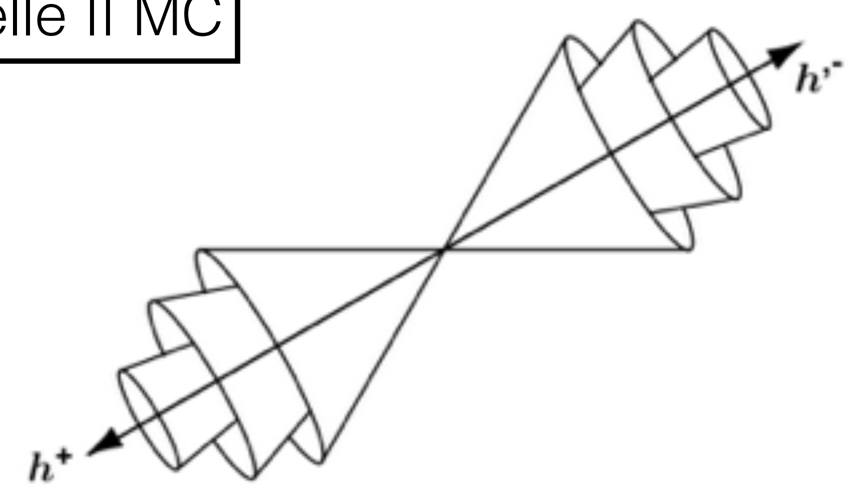
  — four-momentum,

  — angular distribution,

  — event topology and shape (thrust vector magnitude, momentum flow, Fox-Wolfram moments, …)



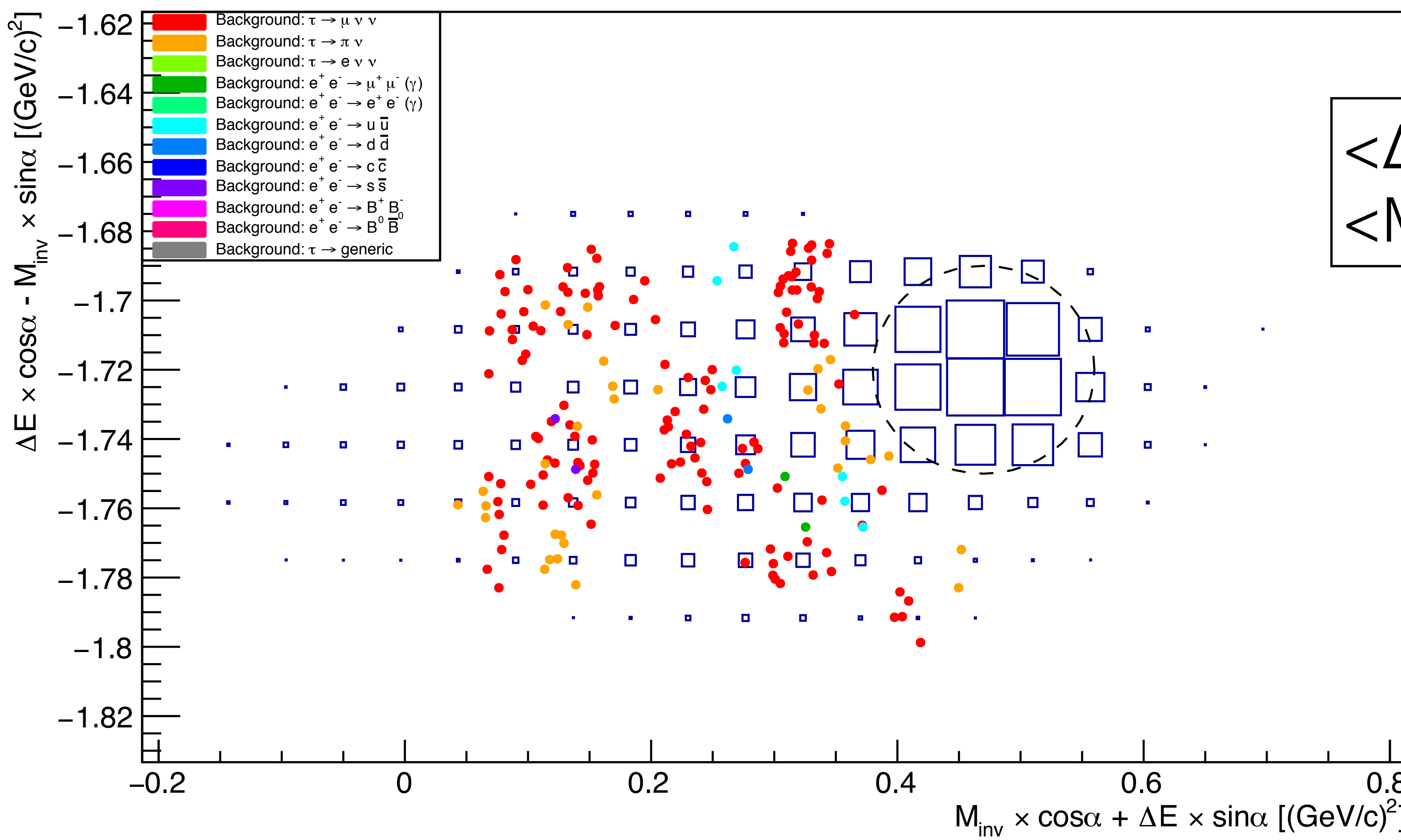
Belle II MC



Momentum Flow Cones

Results

Rotated signal region with $\tau \to \mu\gamma$ MC



$\langle \Delta E \rangle \approx 47$MeV
$\langle M_{inv} \rangle \approx 1.79$GeV

Study elliptical signal region around mean:

— Signal efficiency $\boldsymbol{\varepsilon_{signal} = 4.59\%}$

— No background → $n_{BG} < 2.30$ at 90% CL (Poisson)

Sensitivity Comparison

	Belle (535 fb^{-1})	Belle II (1 ab^{-1})
$\mathcal{L}$ (cm^2/s)	2.11 x 10^{34}	80 x 10^{34}
ε_{signal}	5.09%	4.59%
n_{BG}	10	-
$B_{90}(\tau \to \mu\gamma)$	**4.5 x10^{-8}**	**2.726 x10^{-8}**

→

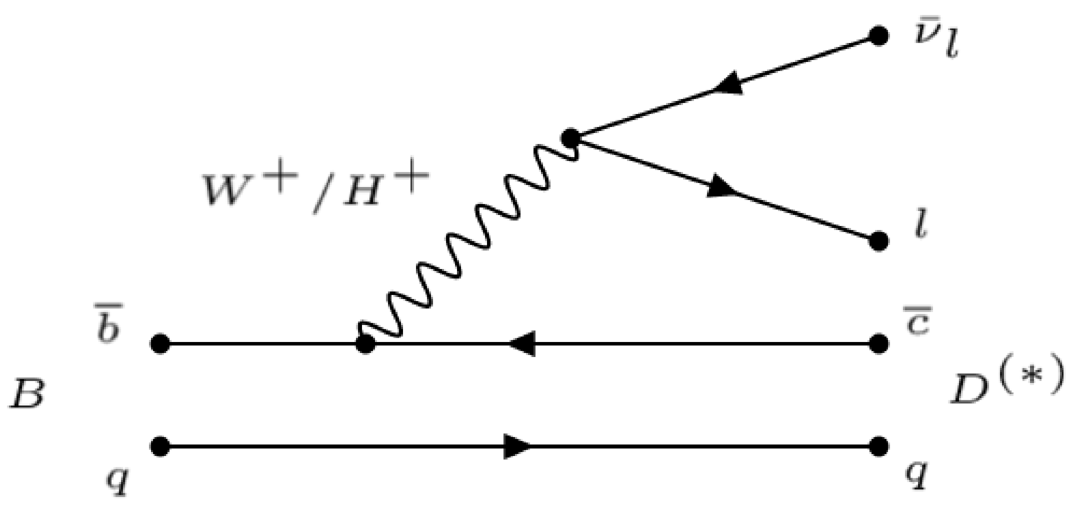
Belle II (50 ab^{-1})
5.452 x10^{-10}

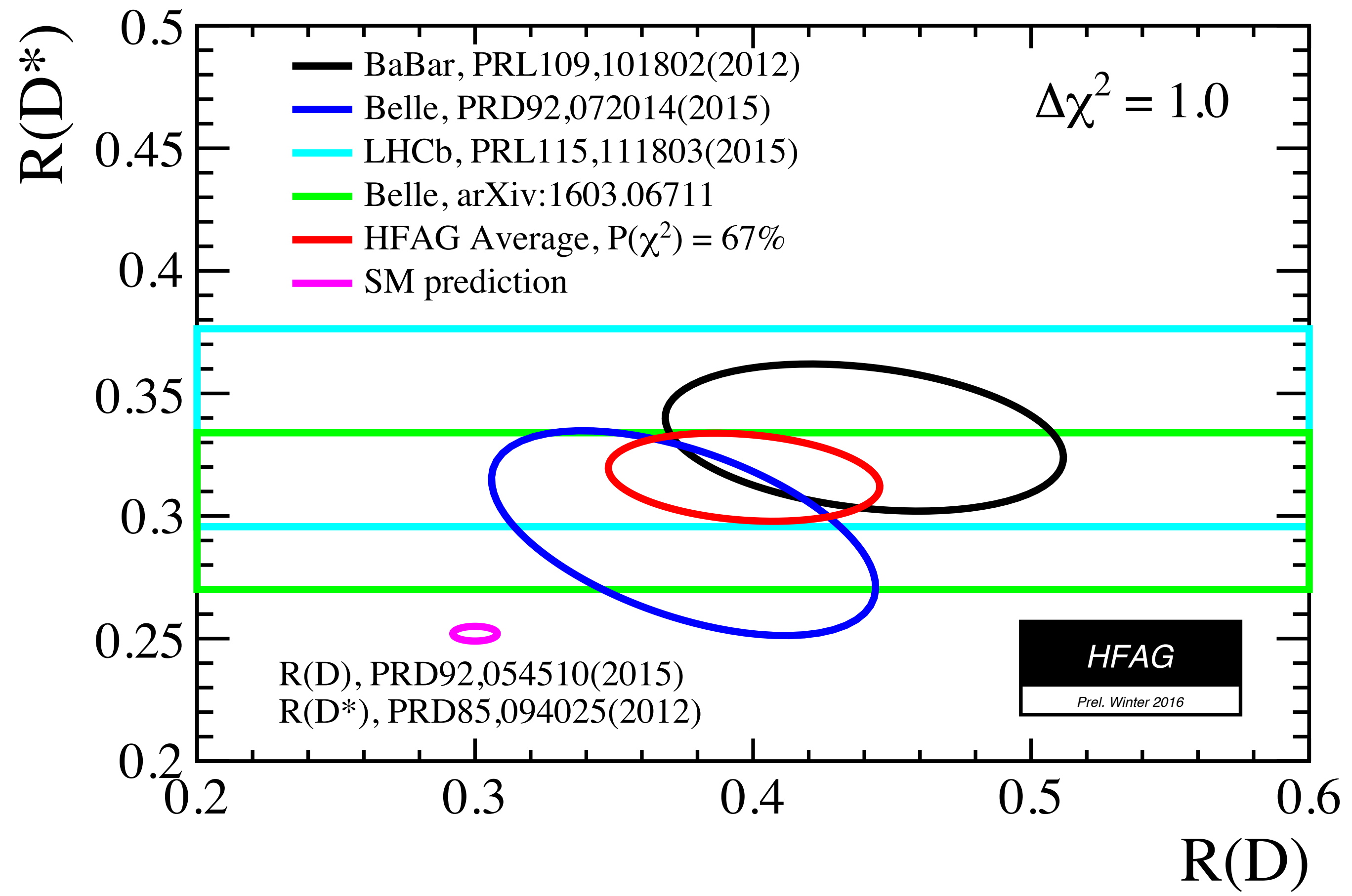
- First τ LFV sensitivity study at Belle II
- Background-free search (even with high beam BG)
- Sensitivity comparable with Belle
- Naive extrapolation to 50 ab^{-1}

τ LFUV

- The SM is built with the assumption of universality
- Measurements of R(D$^{(*)}$) show a 4σ deviation from SM predictions
- Sensitive to NP couplings with Higgs-like particles
- Interesting to study τ LF(U)V

$$R(D^{(*)}) = \frac{BR\left(\bar{B}\to D^{(*)}\tau^-\bar{\nu}_\tau\right)}{BR\left(\bar{B}\to D^{(*)}\ell^-\bar{\nu}_\ell\right)}$$



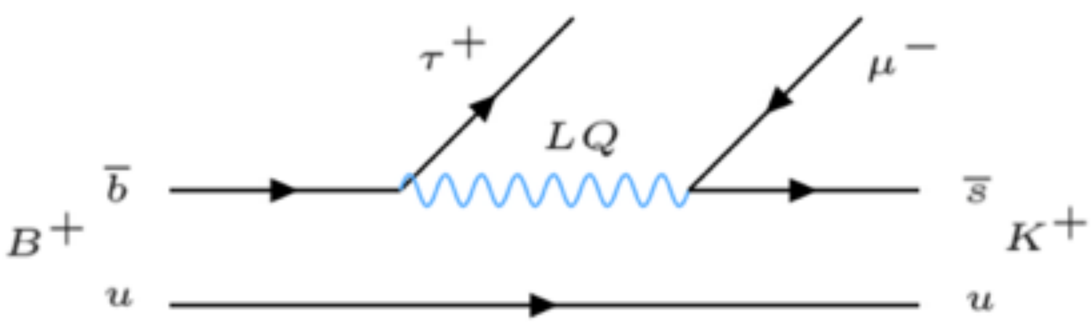


τ LFUV in b→s

- b→s transitions are penguin/box suppressed
- Signs of deviations have been found there in the past; e.g. at LHCb:

$$R(K) = \frac{Br(B^+ \to K^+\mu^+\mu^-)}{Br(B^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074}(stat.) \pm 0.036(sys.)$$

- Processes such as $B^+ \to K^+\tau l$ sensitive to NP contributions, e.g. Leptoquarks



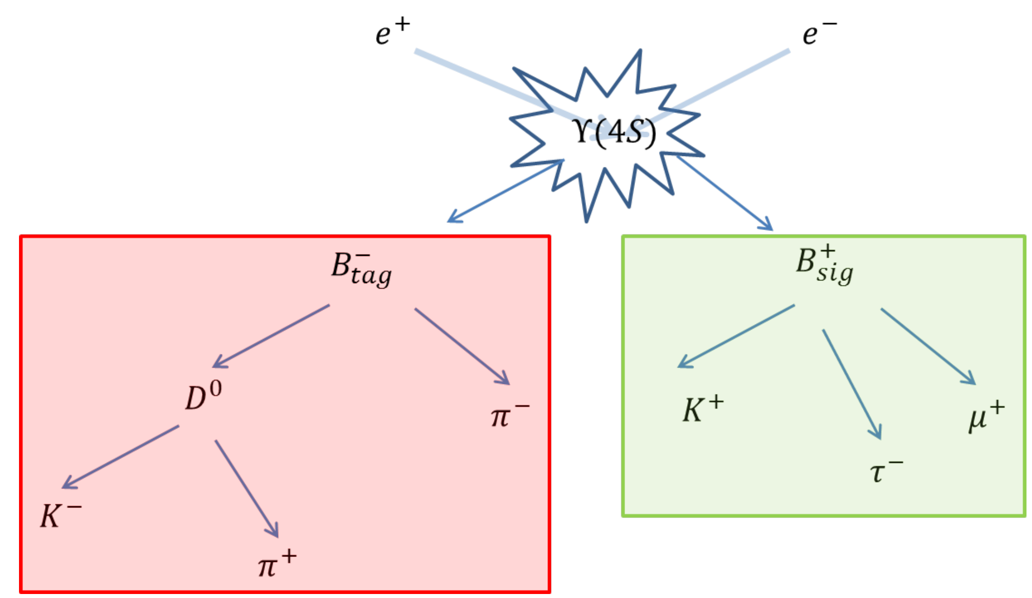
- If such a state mediating the transition existed, we could observe it at Belle II

	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K\bar{K}$
$O^{4\ell}_{S,V}$	–	–
O_D	✓	✓
O^q_V	✓ (I=1)	✓(I=0,1)
O^q_S	✓ (I=0)	✓(I=0,1)
O_{GG}	✓	✓
O^q_A	–	–
O^q_P	–	–
$O_{G\tilde{G}}$	–	–

$B^+ \to K^+\tau l$ in Belle II

- Feasibility study based on cut and count approach
- Past search on 429 fb^{-1} BaBar data (PRD 86, 012004 (2012))

Mode	$\mathcal{B}(B \to h\tau\ell)$ $(\times 10^{-5})$ central value	90% C.L. UL
$B^+ \to K^+\tau\mu$	$0.0\,^{+2.7}_{-1.4}$	< 4.8
$B^+ \to K^+\tau e$	$-0.6\,^{+1.7}_{-1.4}$	< 3.0
$B^+ \to \pi^+\tau\mu$	$0.5\,^{+3.8}_{-3.2}$	< 7.2
$B^+ \to \pi^+\tau e$	$2.3\,^{+2.8}_{-1.7}$	< 7.5



- Simulated signal events:
  - Bsig: $B^+ \to K^+\tau^\pm l^\mp$
  - Btag: generic
- Background events: $B\bar{B}/q\bar{q}$ generic MC

Generated MC

MC	σ $[nb]$	N_{events}	$\mathcal{L}_{int}$
B^+B^-	0.55	100×10^6	180 fb^{-1}
$B^0\bar{B}^0$	0.55	100×10^6	180 fb^{-1}
$u\bar{u}$	1.61	50×10^6	31 fb^{-1}
$d\bar{d}$	0.40	50×10^6	130 fb^{-1}
$s\bar{s}$	0.38	50×10^6	130 fb^{-1}
$c\bar{c}$	1.30	50×10^6	38 fb^{-1}

Selection and Outlook

Tag B

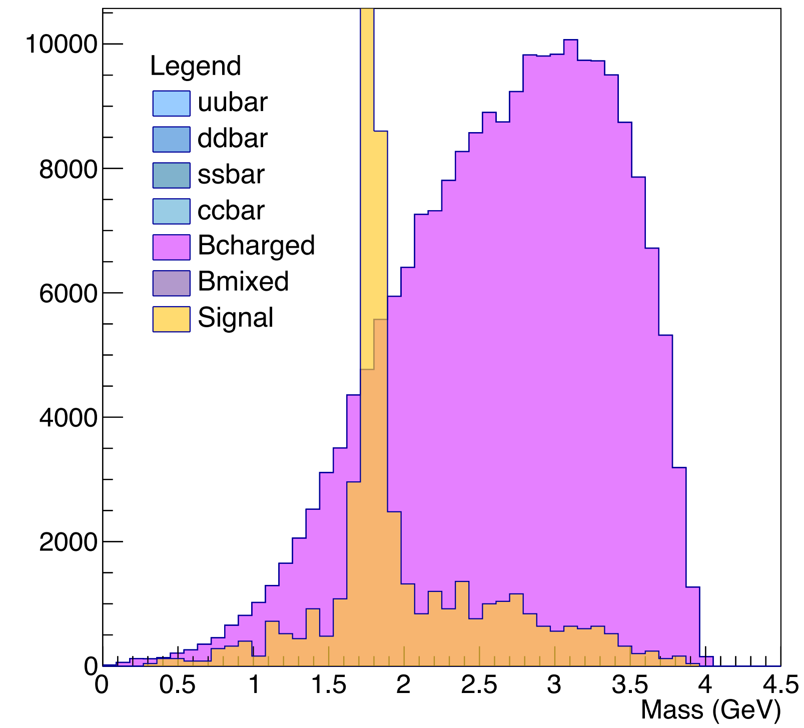
- Fully reconstruct tag side in the B → D^0X_{had} modes with a multivariate classifier (ε_{tag}=0.83%)
- Keep the one with the highest MVA likelihood.

Signal B

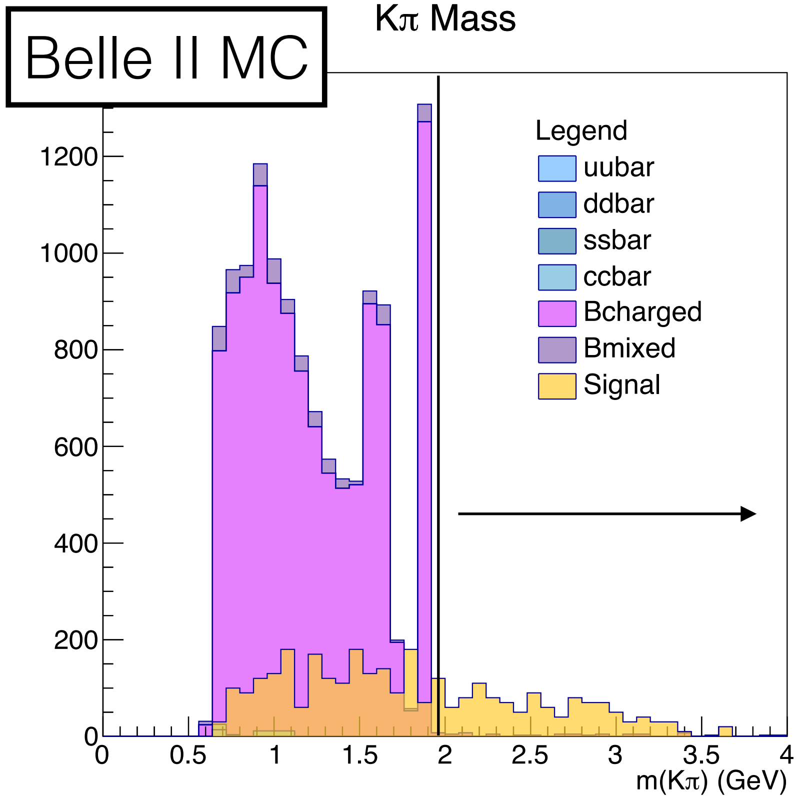
- B_{sig} from rest of the event after tag-side reconstruction.
- Signal region around reconstructed m_τ peak.
- Reject background with cuts on:
  m(Kπ), event shape variables, vertex fit quality…

Available data set is **x100** of BaBar (2012)
→ potential **x10** improvement (assumes dominant BG)

Indirect Tau Mass



Kπ Mass



Summary

- τLFV is a powerful tool to search for new physics.
- Belle II will effectively probe a wide set of decay channels.

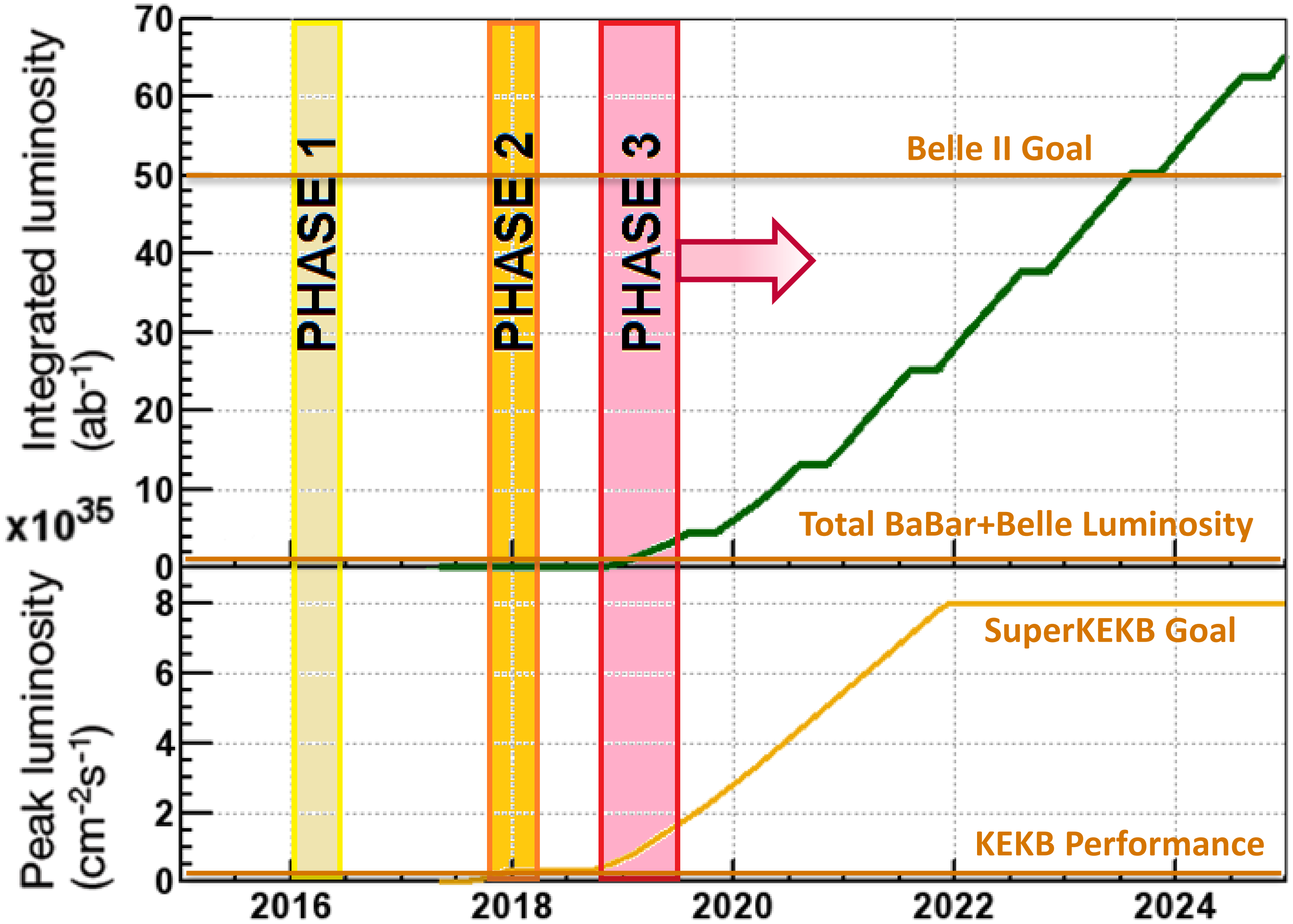
- Preliminary study for $\tau \to \mu\gamma$:
  - — $B_{90}(\tau \to \mu\gamma) < 2.726\text{x}10^{-8}$ estimated sensitivity at 1 ab^{-1}
  - — effectively rejects beam BG (comparable to Belle).
  - — Naive extrapolation: $B_{90}(\tau \to \mu\gamma) < 5.452\text{x}10^{-10}$ at 50 ab^{-1}

- LFUV feasibility study for $B^+ \to K^+\tau l$ with a fully reconstructed tag using a multivariate classifier.
  - — Potential x10 sensitivity improvement of previous result.

BACKUP

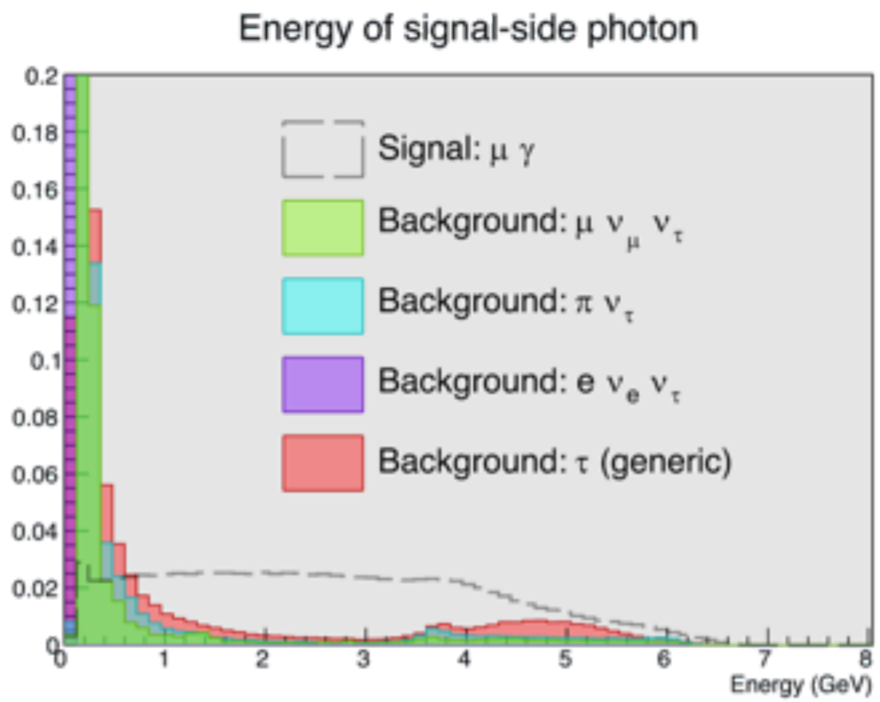
Belle II Schedule

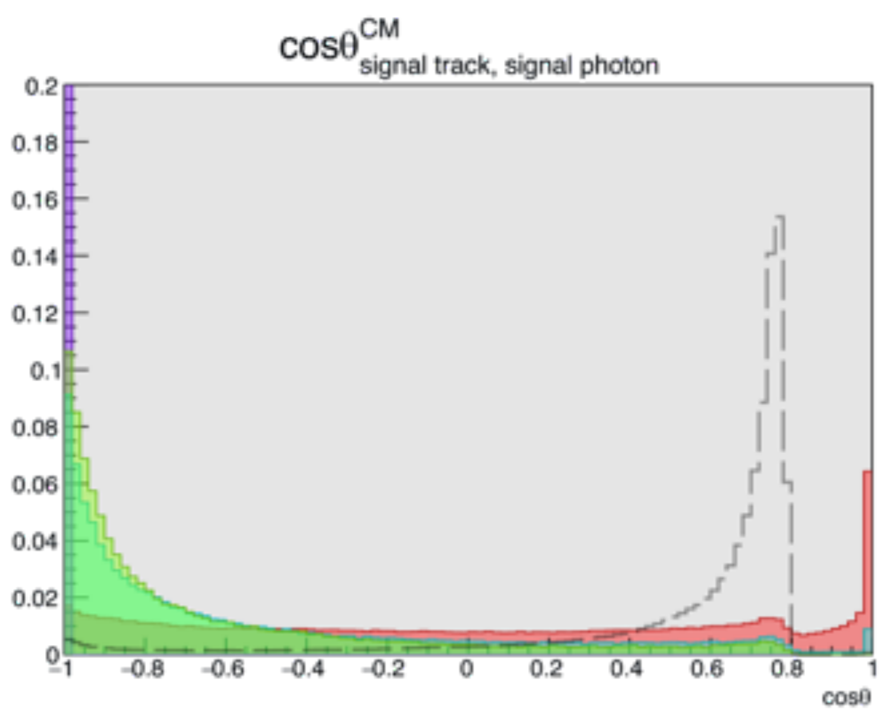
- Phase 1 (2016, complete):
  - Accelerator commissioning
  - No detector
- Phase 2 (start of 2018):
  - Partial detector
  - Background studies
  - First physics
- Phase 3 (end of 2018):
  - Full detector
  - Belle II run



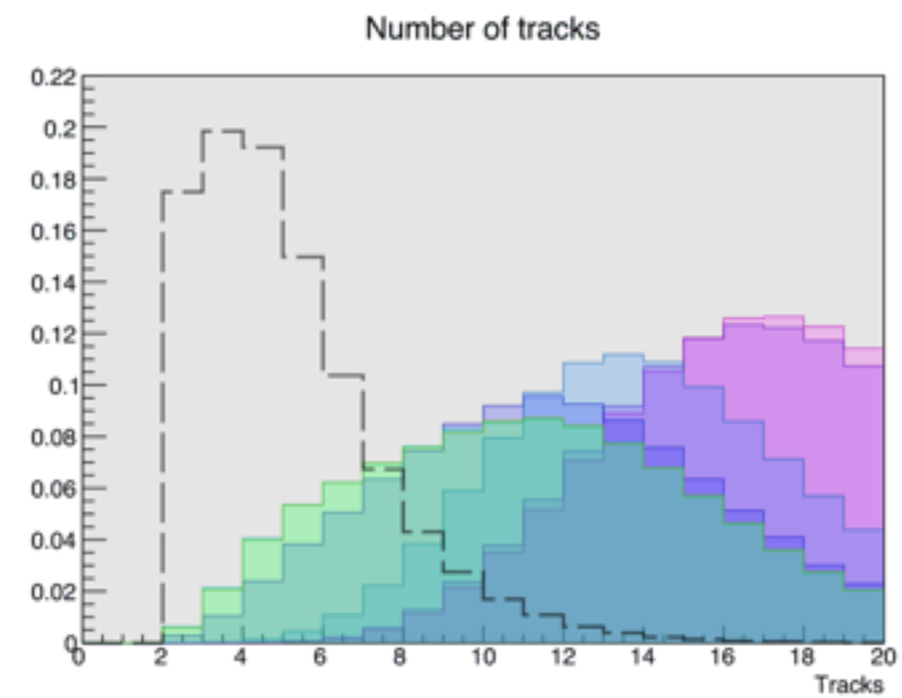
Background Rejection

τ → lνν

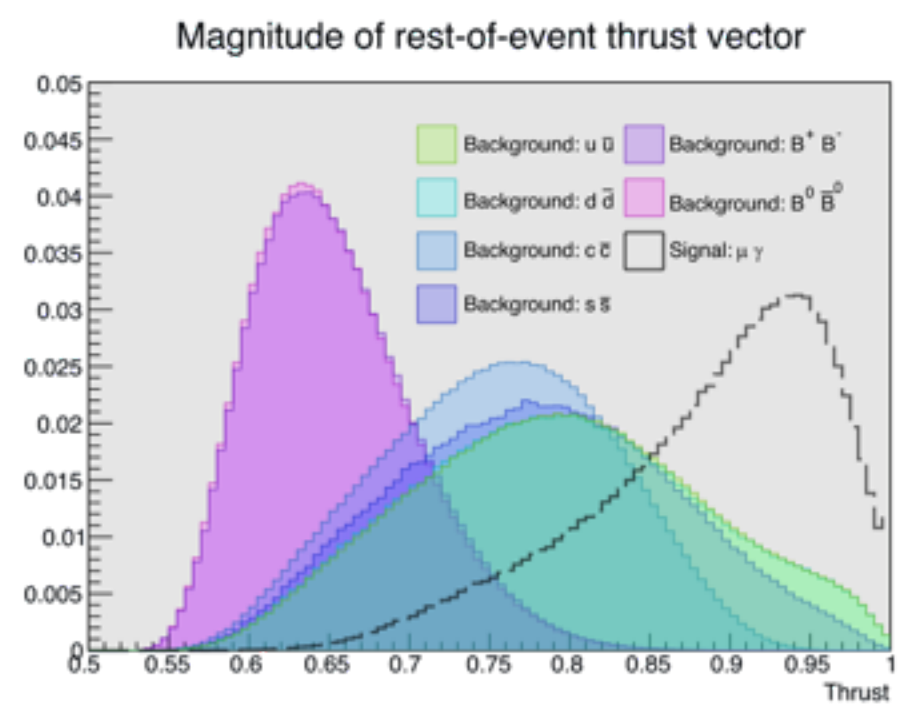




τ → hadronic

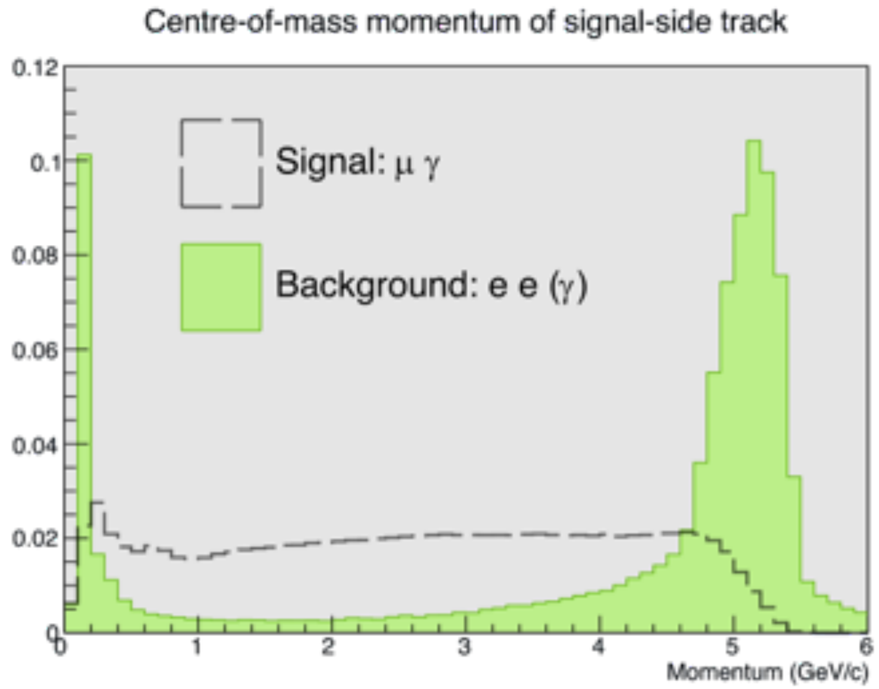


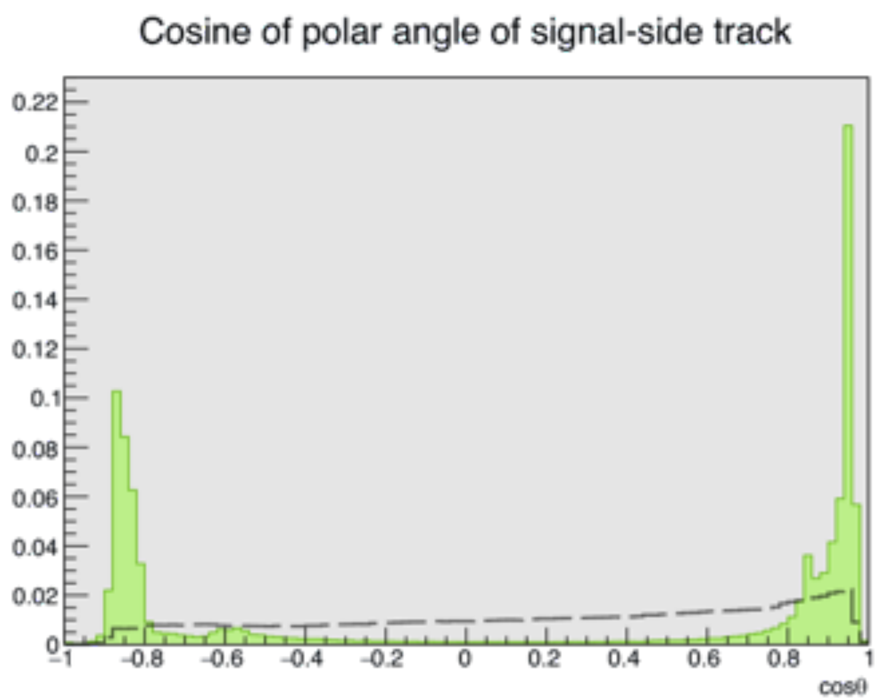
Belle II MC



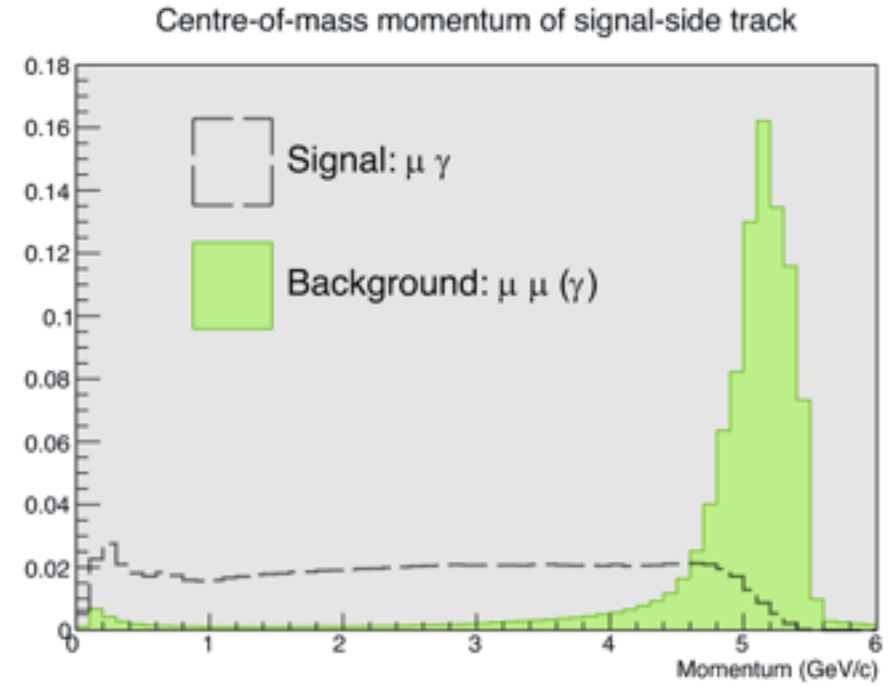
Background Rejection

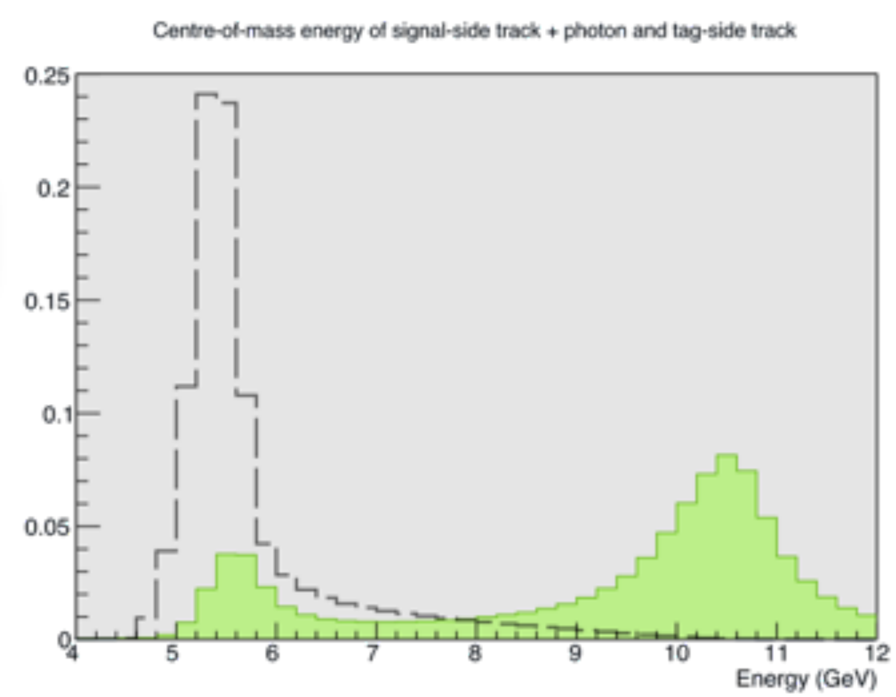
ee → ee





ee → μμ





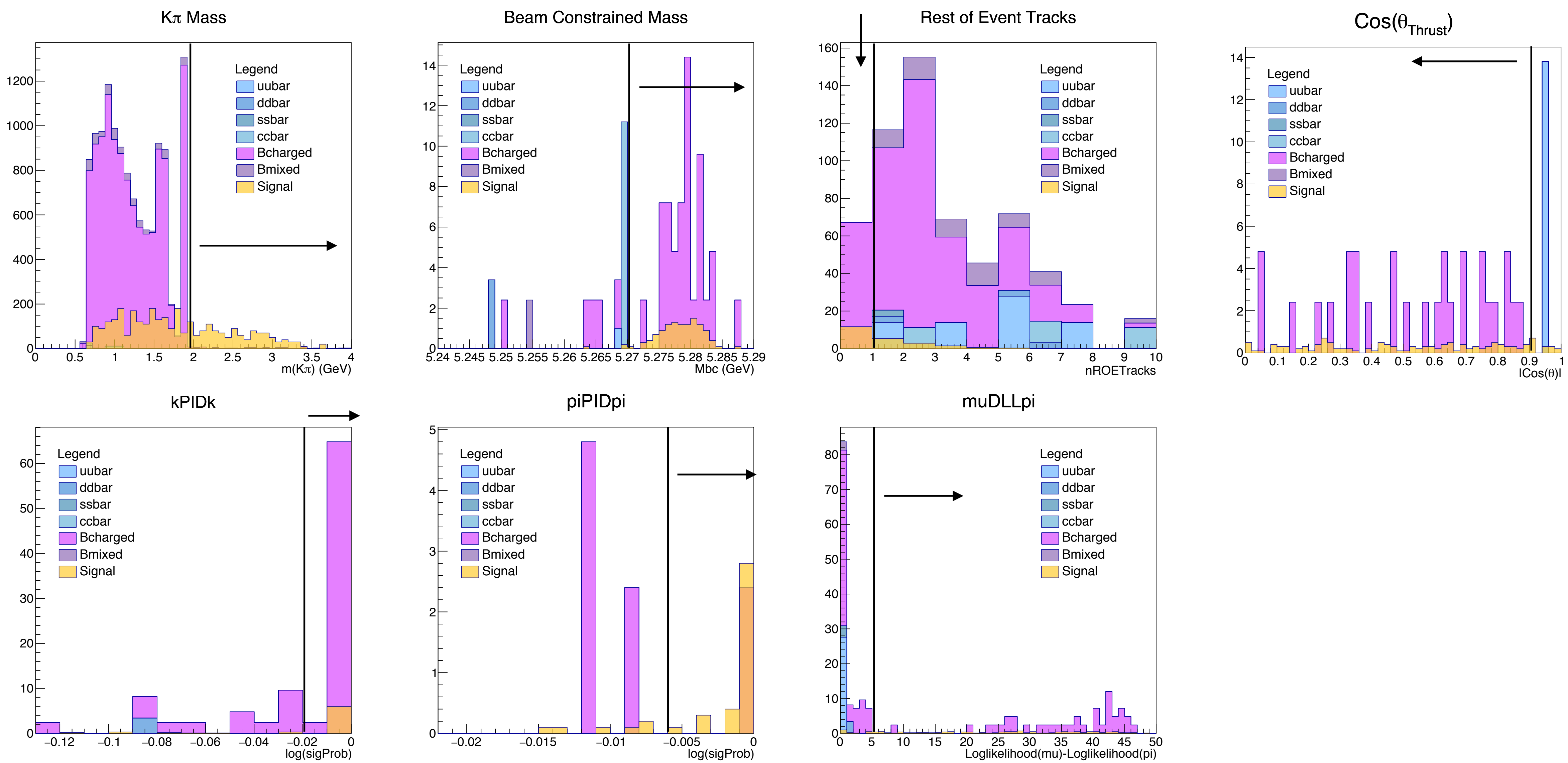
Belle II MC

$\tau \rightarrow \mu\gamma$: After Selection

Event type	Events projected (scaled to $1ab^{-1}$)	After selection (scaled to $1ab^{-1}$)	Signal Efficiency
$\tau^{\pm}\rightarrow\mu^{\pm}\gamma$	**83**	**6**	**7.23%**
$\tau^{\pm}\rightarrow\mu^{\pm}\nu_{\tau}\nu_{\mu}$	159,997,900	163	
$\tau^{\pm}\rightarrow\pi^{\pm}\nu_{\tau}$	334,056,500	40	
$\tau^{\pm}\rightarrow e^{\pm}\nu_{\tau}\nu_{e}$	163,857,700	0	
$e^{+}e^{-}\rightarrow\mu^{+}\mu^{-}(\gamma)$	1,148,000,000	15	
$e^{+}e^{-}\rightarrow e^{+}e^{-}(\gamma)$	300,000,000,000	0	
$e^{+}e^{-}\rightarrow B^{+}B^{-}$	550,000,000	0	Tot. background events (for $1ab^{-1}$)
$e^{+}e^{-}\rightarrow B^{0}\overline{B}^{0}$	550,000,000	0	
$e^{+}e^{-}\rightarrow q\overline{q}$	3,690,000,000	15	**233**

Sample N-1 plots

$B^+ \rightarrow K^+\tau^-(n\pi^0\pi^-)\mu^+$



Impact of each selection after applying the rest of the cuts