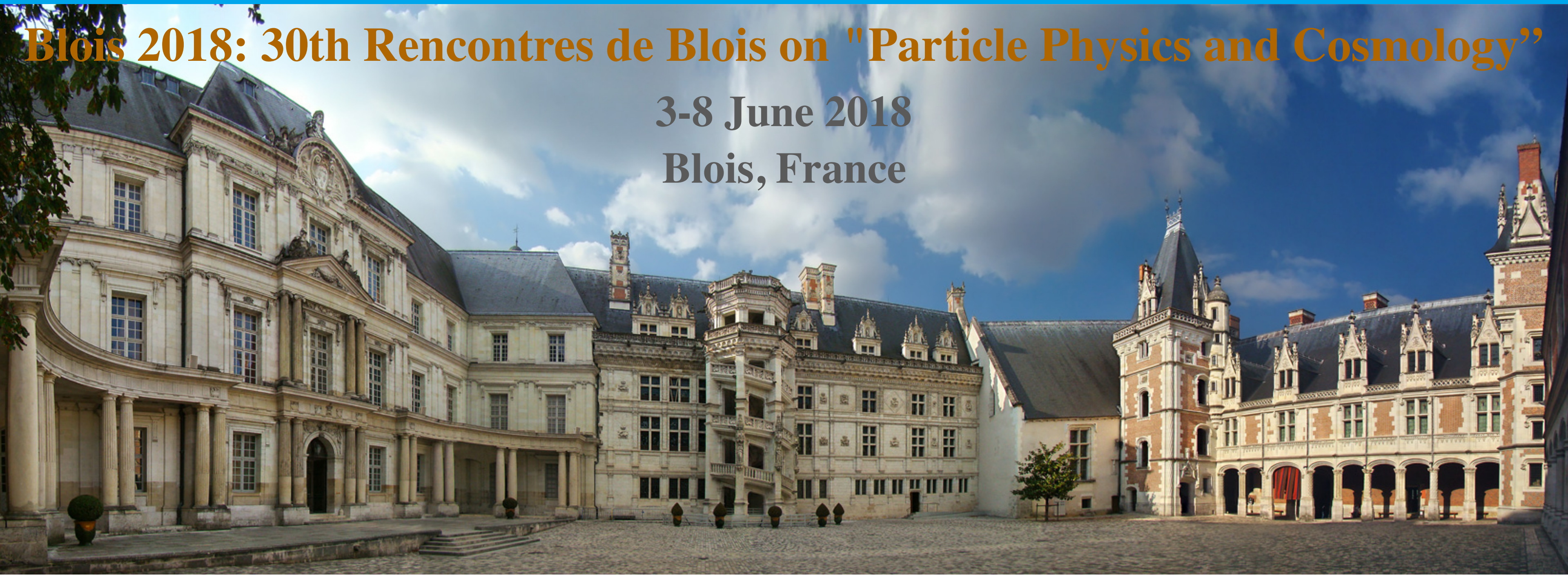
Tests of Lepton Flavour- / Number- ~~Conservation~~ *Violation* and ~~Universality~~ *Non-universality* at Belle II



Ami Rostomyan

(for the Belle II collaboration)

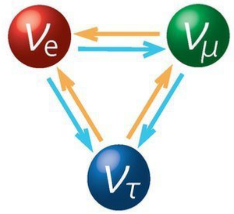
HELMHOLTZ ASSOCIATION

DESY

Lepton flavour conservation

Conservation of the individual lepton-flavour and the total lepton numbers within the SM ($m_\nu = 0$)

$$G_{SM}^{global} = U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$

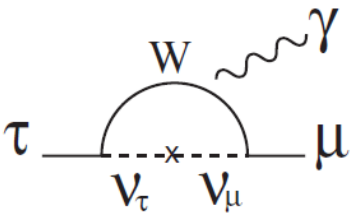


➡ The observation of neutrino oscillations as a first sign of LFV beyond the SM!

What about the charged leptons?

➡ The charged LFV processes can occur through oscillations in loops

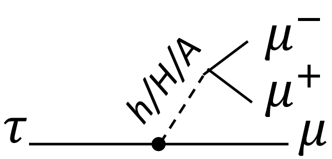
➡ Unmeasurable small rates (10^{-54}-10^{-49}) for all the LFV μ and τ decays

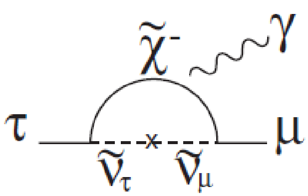


$$\mathcal{B}(\ell_1 \to \ell_2 \gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\ell_1 i} U_{\ell_2 i} \frac{\Delta m^2_{i1}}{M^2_W} \right|^2.$$

Observation of LFV will be a clear signature of the NP!

➡ Charged LFV enhanced in many NP models (10^{-10} - 10^{-7})

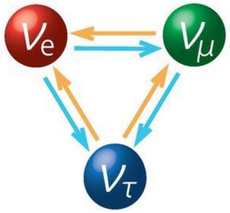




Lepton flavour conservation

Conservation of the individual lepton-flavour and the total lepton numbers within the SM ($m_\nu = 0$)

$$G_{SM}^{global} = U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$



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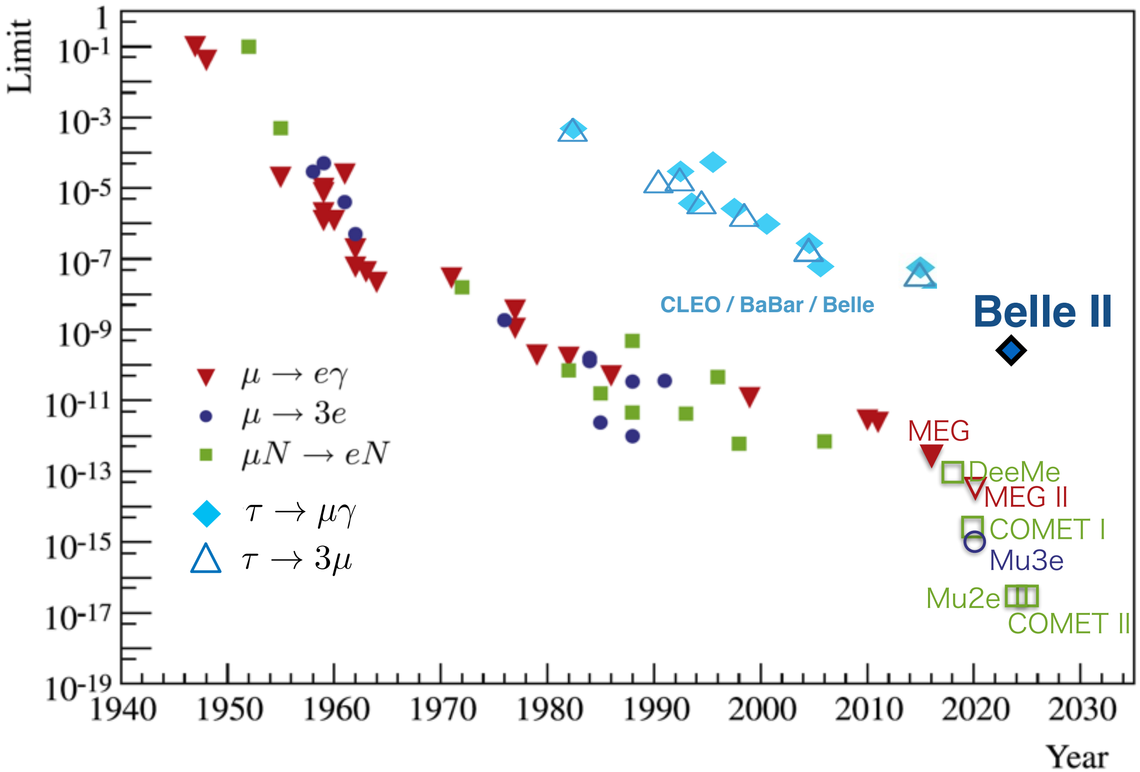
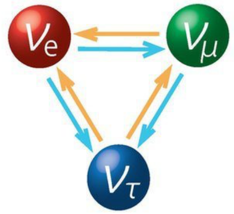


No success in searches so far!

Lepton number conservation

Within the SM ($m_\nu = 0$), conservation of the individual lepton-flavour and the total lepton numbers

$$G_{SM}^{global} = U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$



➡ The observation of neutrino oscillations as a first sign of LFV beyond the SM!

Are neutrinos Dirac ($|\Delta L| = 0$) or Majorana ($|\Delta L| = 2$) particles?

➡ Heavily suppressed LNV τ-decay rates within the νSM

$$\langle m \rangle^2_{\ell_1 \ell_2} = \left| \sum_{m=1}^{3} U_{\ell_1 m} U_{\ell_2 m} m_{\nu_m} \right|^2 ,$$

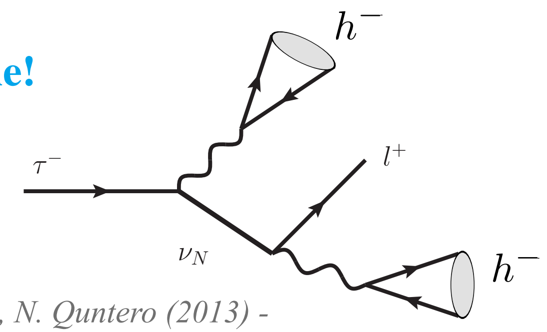
➡ Unmeasurable decay rates with high NP scale, for example in models with heavy right-handed neutrinos

$$\left| \sum_{m'=4}^{3+n} \frac{V_{\ell_1 m'} V_{\ell_2 m'}}{m_{N_{m'}}} \right|^2 ,$$

Observation of LNV will hint at light NP scale!

➡ NP models with light (0.1 - 5 GeV) right-handed Majorana neutrinos

➡ Significant enhancement of the τ decay rates



- G.L.Castro, N. Quntero (2013) -

Lepton number conservation

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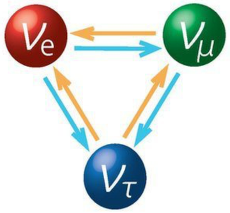

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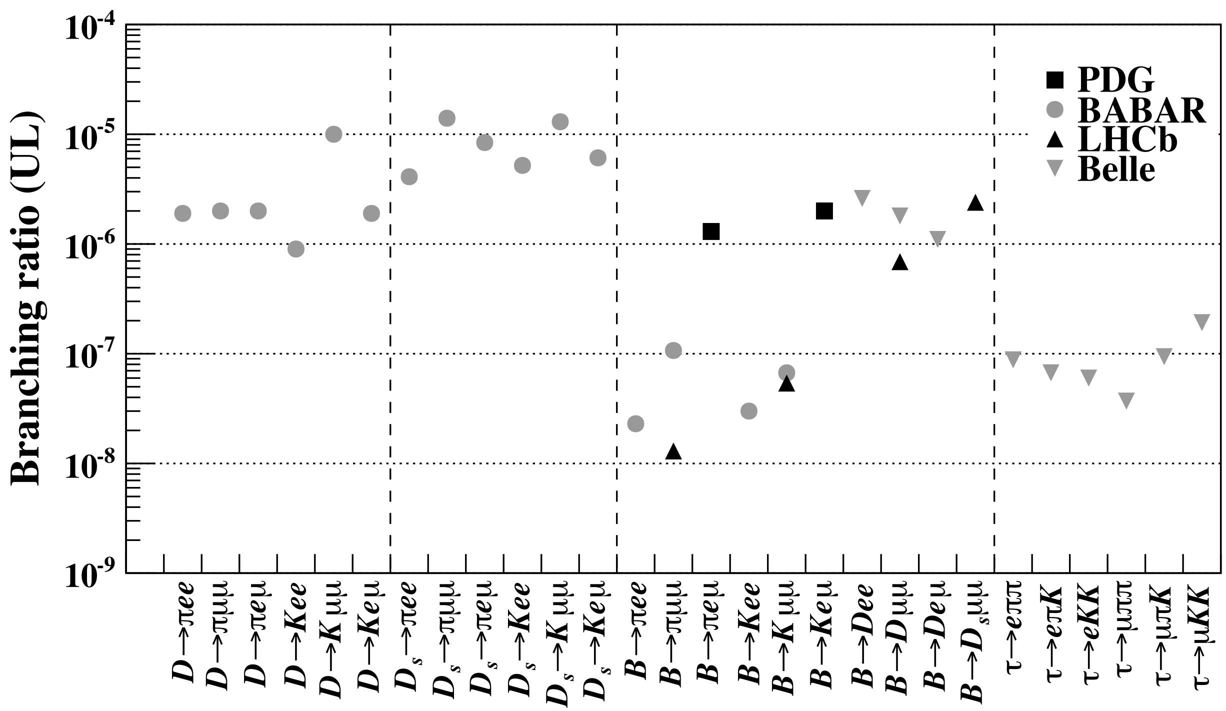
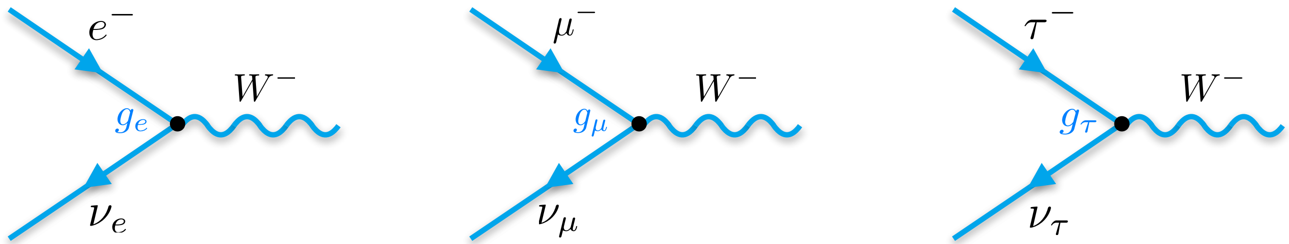


No answer yet!

Lepton universality

Within the SM, the coupling of leptons to W bosons is flavour-independent: $g_e = g_\mu = g_\tau$

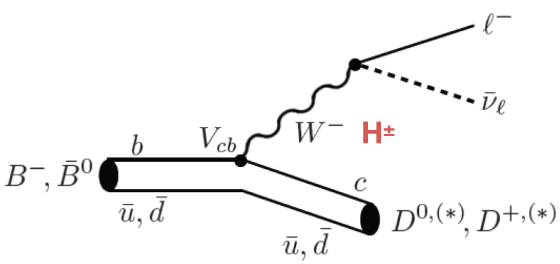


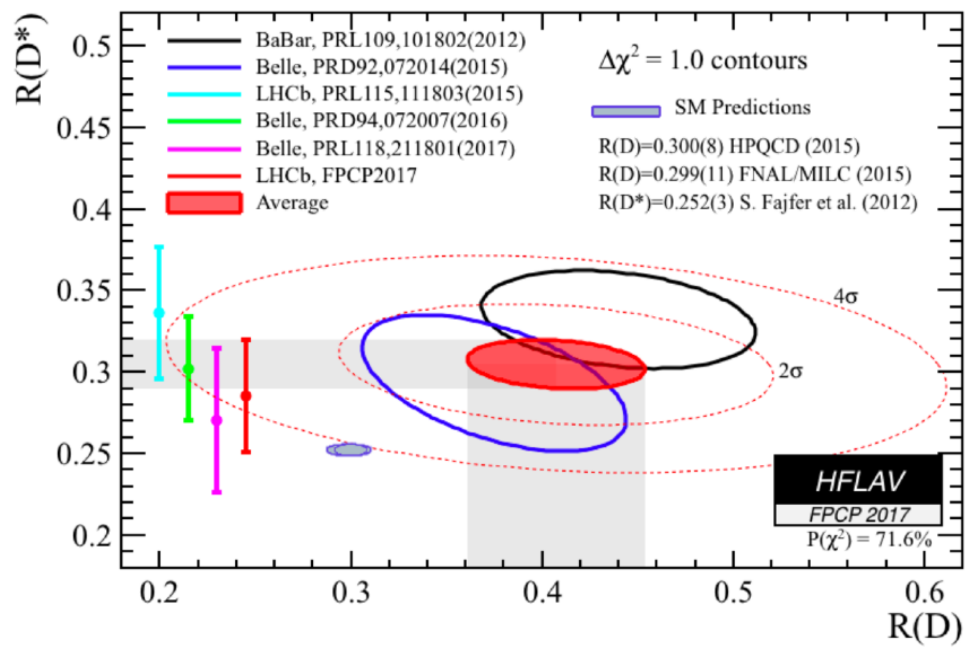
Identical decays involving electrons, muon or taus

- ➡ differences due to lepton masses
- ➡ easy to account for in predictions
- ➡ for example:

$$R(D^*) = \frac{\mathcal{BR}(B \to D^*\tau\nu)}{\mathcal{BR}(B \to D^*\ell\nu)} \quad \text{with } \ell = e, \mu$$

Discovery of lepton flavour non-universality is a key signature of NP!



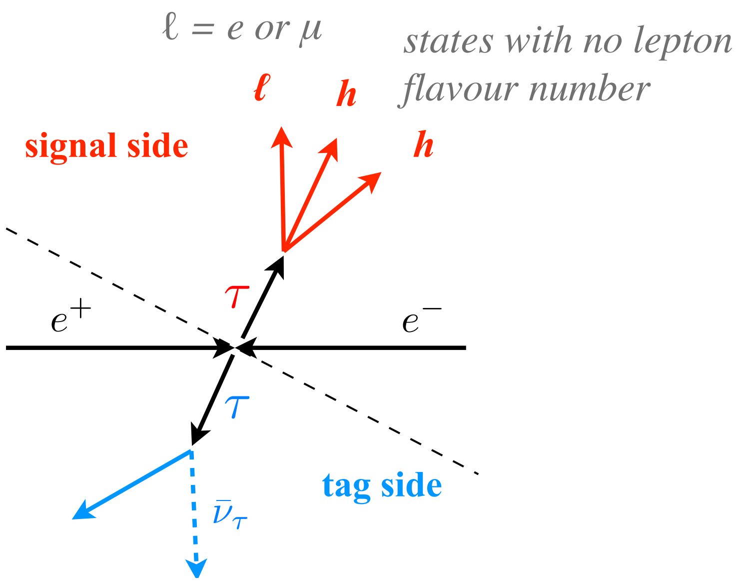


Hint for NP with ~4σ

The role of τ leptons in the quest

NP may favour the third generation!?

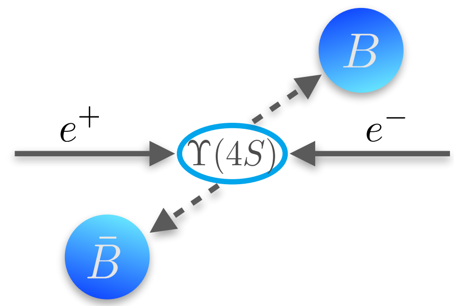
The only lepton that decays into hadrons



➡ a large variety of **LFV** and **LNV semi-leptonic** decays ($\tau \to \ell h(h)$), in addition to radiative ($\tau \to \ell\gamma$) and leptonic decays ($\tau \to \ell\ell\ell$)

➡ τ → μ and τ → e: test of the lepton flavour structure

B mesons decay into e, μ, τ leptons



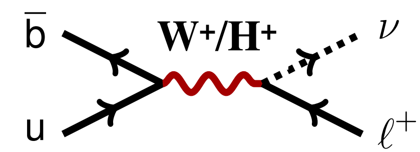
➡ modes used to test the lepton flavour universality

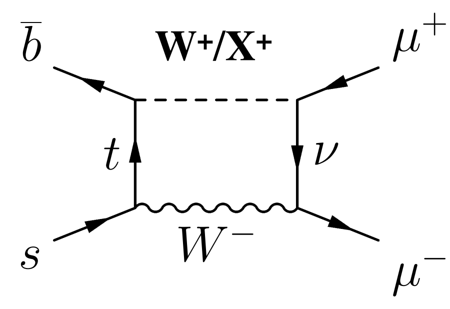
TREE

- $B \to \ell\nu$
- $B \to J/\Psi\,\ell\nu$
- $B \to D^*\ell\nu$

LOOP

- $B \to \ell\ell$
- $B_s \to \ell\ell$
- $B \to K^{(*)}\ell\ell$

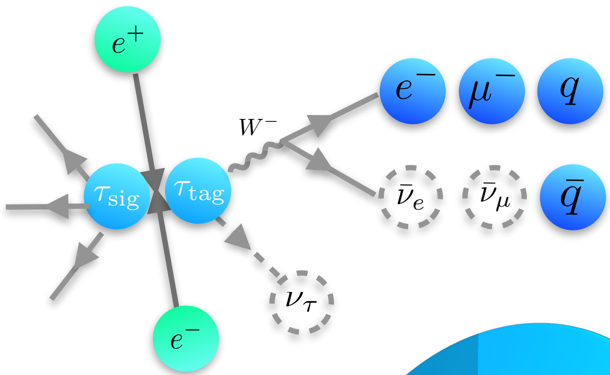


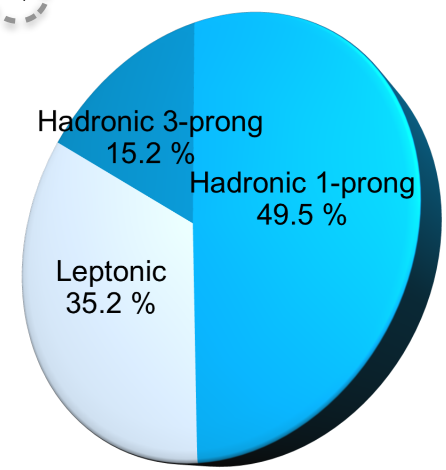


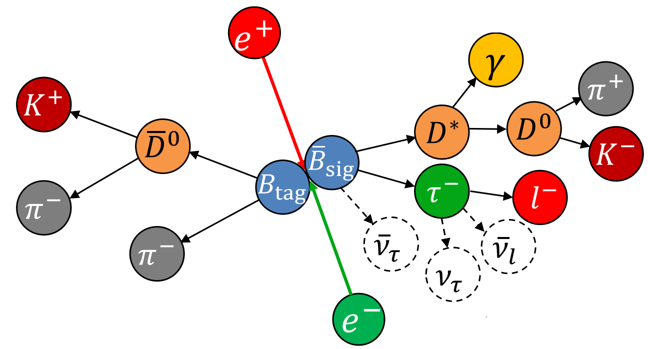
Test the SM in a variety of ways

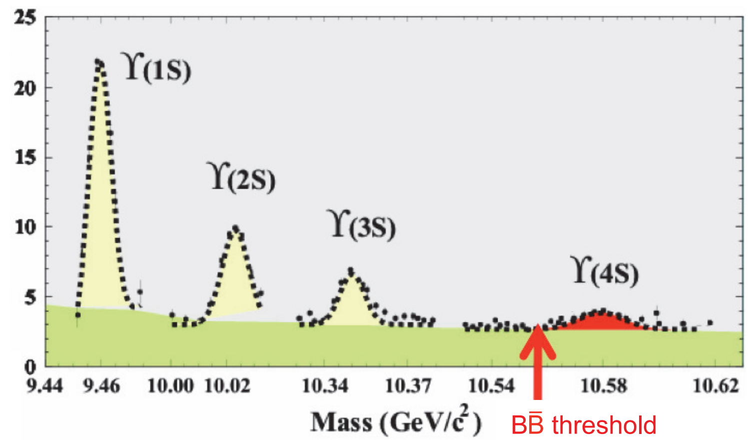
Neutrinos on the tag or signal side

Not possible to fully reconstruct the tag or the signal side









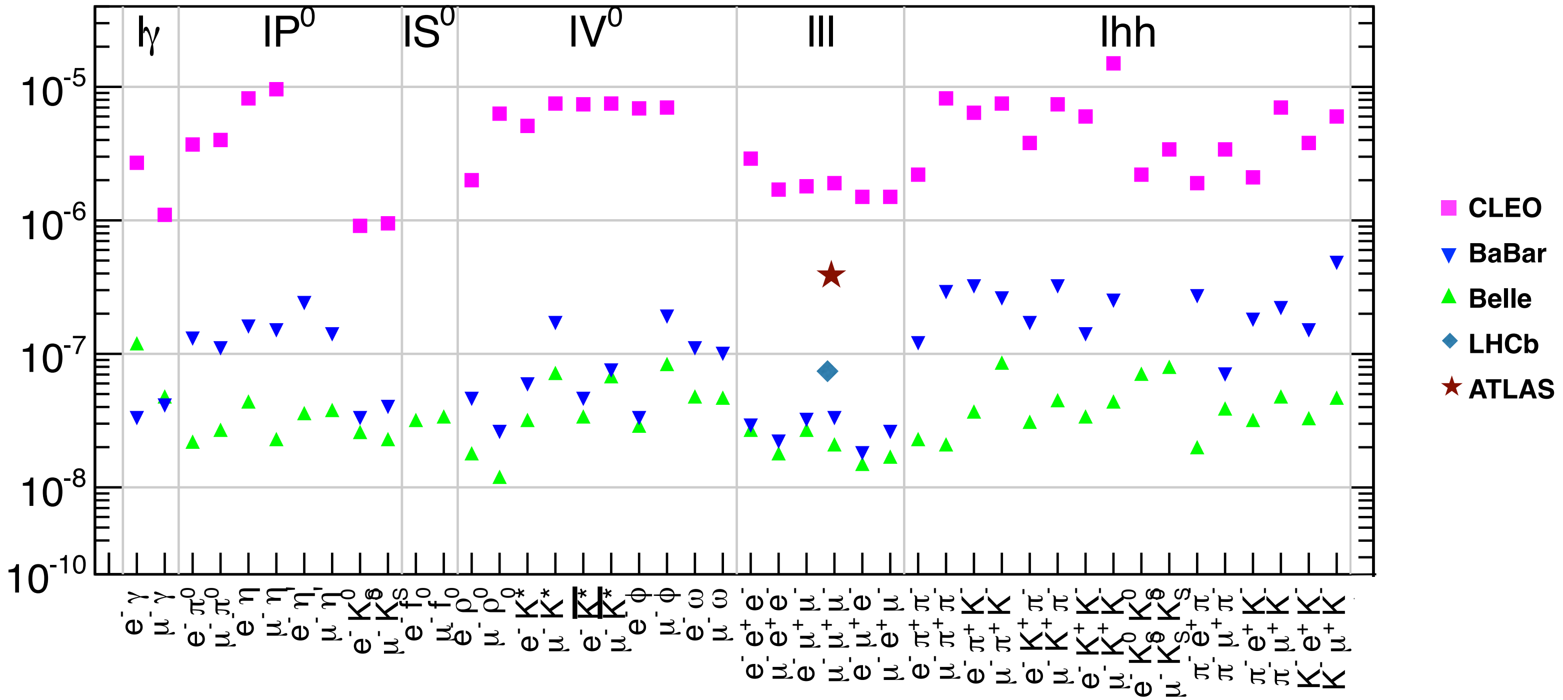
e^+e^- annihilation data is ideal for missing energy channels

- ➡ the kinematics of the initial state is precisely known
- ➡ the neutrino energy can be determined precisely

The progress of τ LFV and LNV searches

… mostly occurred at the B-factories

- immense amount of e^+e^- annihilation data (BaBar → 531 fb^{-1}, Belle → 1000 fb^{-1})
- large cross section of pairwise τ-lepton production (the X-section of $e^+e^- \to \tau^+\tau^-$ at 10.58 GeV of 0.9 nb to be compared to the $e^+e^- \to BB$ X-section of 1.2 nb)



The upper limits reached for τ decays approached the regions sensitive to NP.

Belle II @ SuperKEKB

New facility to search for physics beyond the SM by studying B, D and τ decays

Tsukuba, Japan

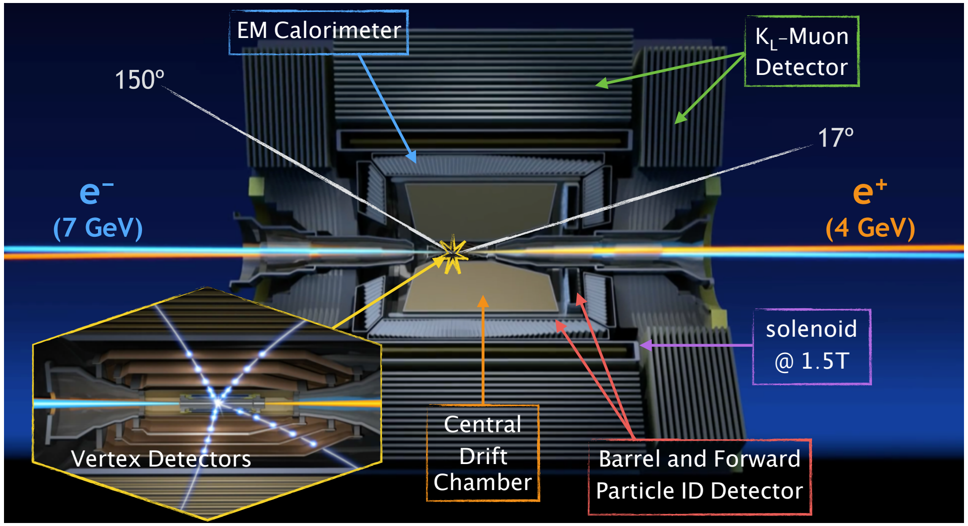
SuperKEKB – major upgrade of the KEKB

- an asymmetric electron-positron collider
- collisions near and at Υ(nS)
- smaller interaction point
- increased currents

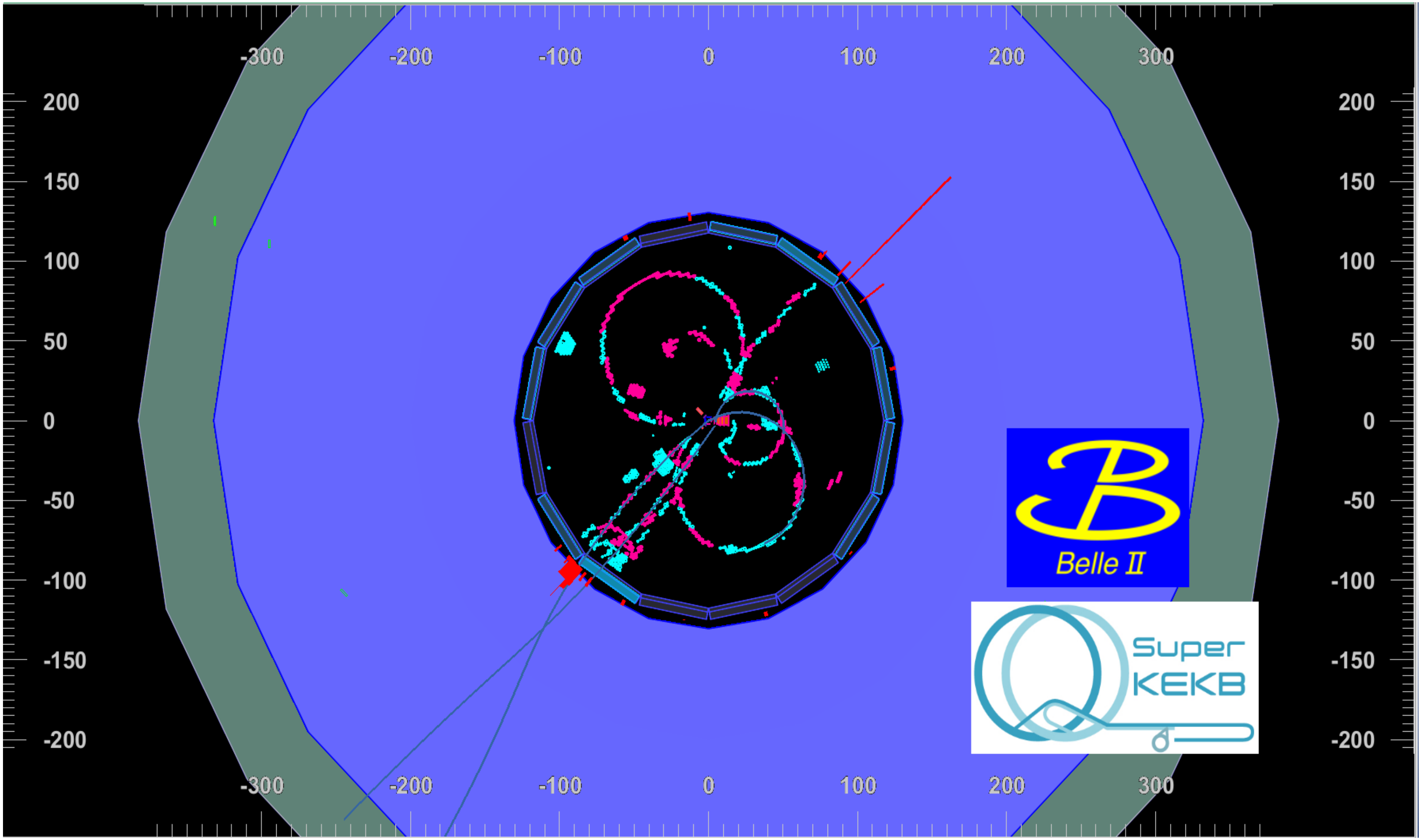
First beams and commissioning in 2016

Belle II detector – upgraded Belle detector

- improved tracking efficiency, particle identification
- smarter software and more precise algorithms
- rolled in April 2017
- **First recorded events in April 2018**

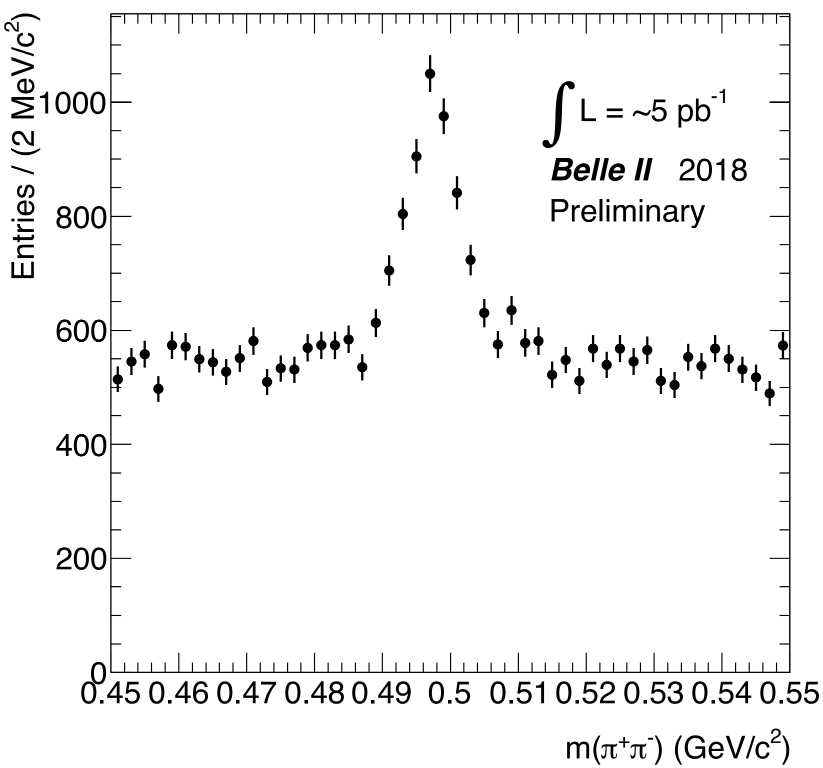


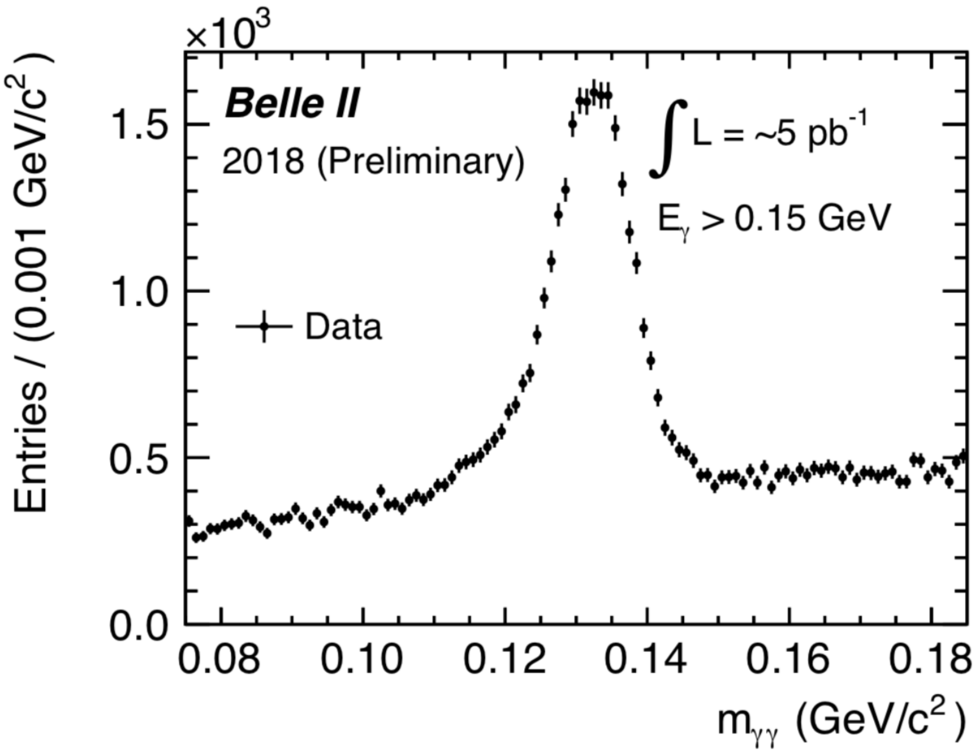
First recorded events



First collisions: first peaks

Mass peaks for charged tracks and photons





Data accumulation is on going, currently having a 46 pb^{-1} data set

Plans for Belle II

Phase 1: first beams

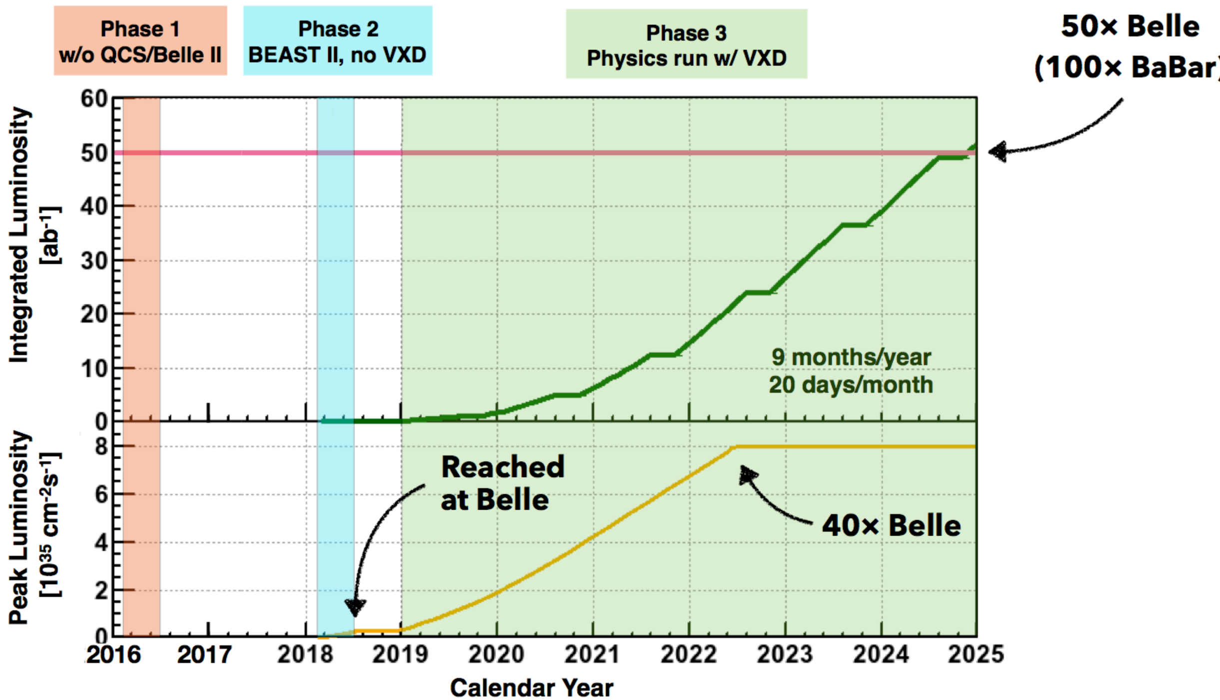
- ➡ no detector over interaction region,
- ➡ study the beam properties

Phase 2: first collisions

- ➡ no PXD detector
- ➡ instead BEAST II (radiation monitoring system)
- ➡ understand backgrounds
- ➡ establish nano-beam scheme and reach KEKB luminosity

Phase 3: first physics with full detector

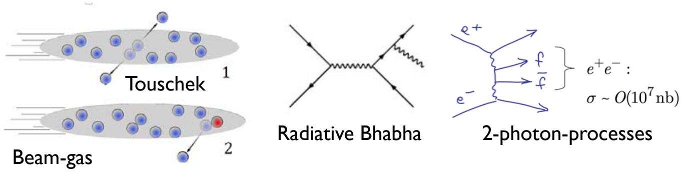
- ➡ luminosity milestones:
  - $1ab^{-1}$ after 1 year
  - $5ab^{-1}$- mid of 2020
  - $50ab^{-1}$ by 2025

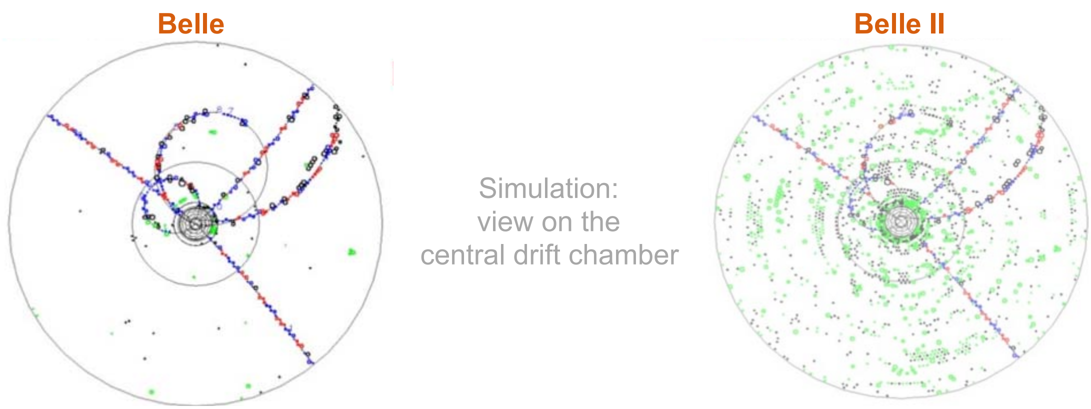


More details are given in Isabelle Ripp-Baudo's presentation

Beam background

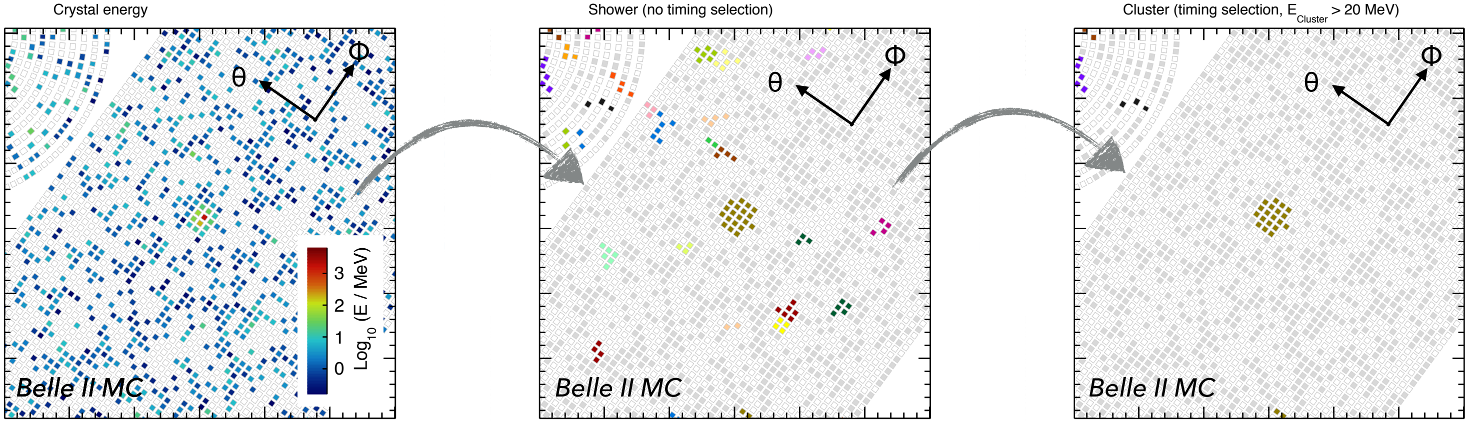
40 times higher luminosity comes at the cost of higher machine induced backgrounds





Simulation:
view on the
central drift chamber

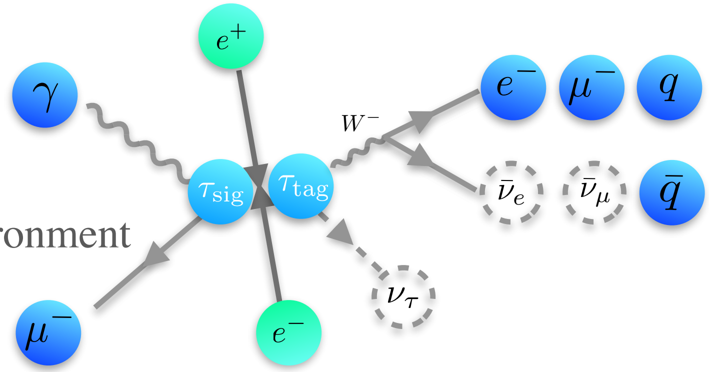
Use the timing information from calorimeter to reduce the background



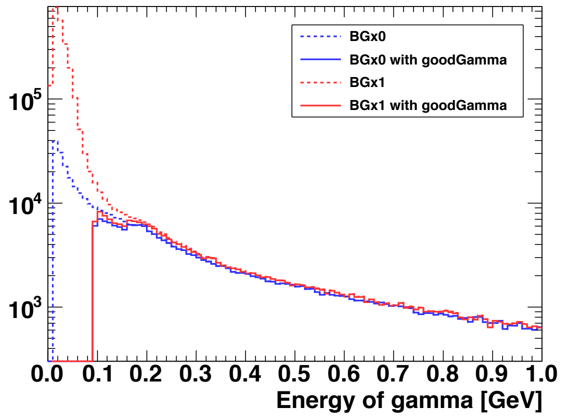
Suppression of beam background

The beam backgrounds are expected to be 10-20 higher

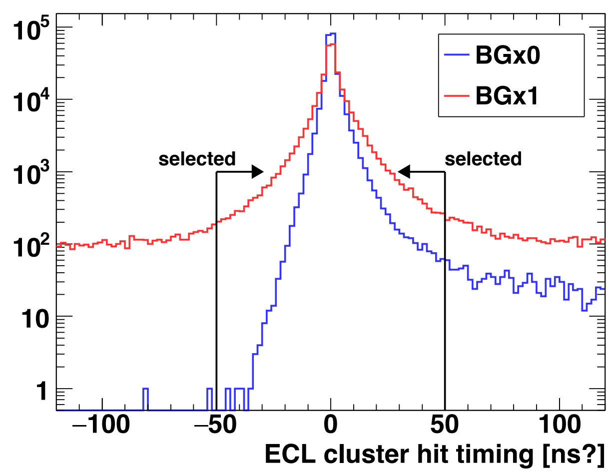
- small number of daughter particles from τ LFV decay
- τ LFV searches more complicated compared to Belle
- feasibility studies using MC samples in more contaminated environment

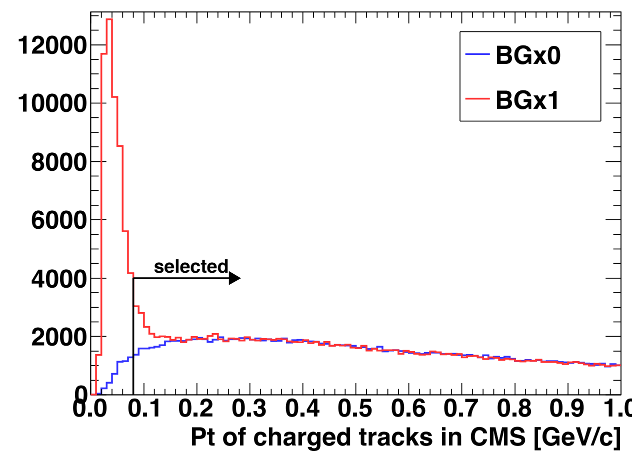


Energy-based cuts to reduce the background



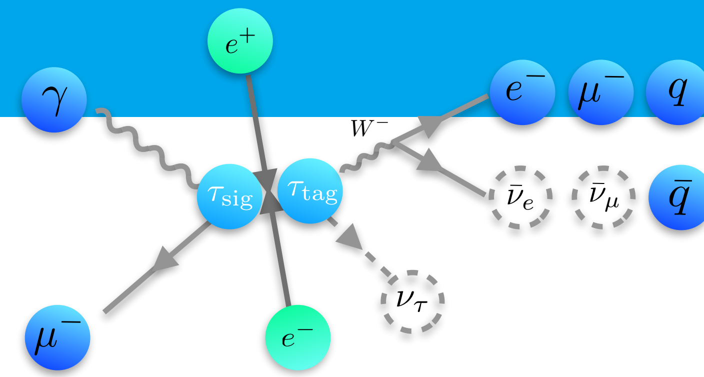
ECL cluster timing





Background-free search (even with high beam BG)

Previous searches at Belle

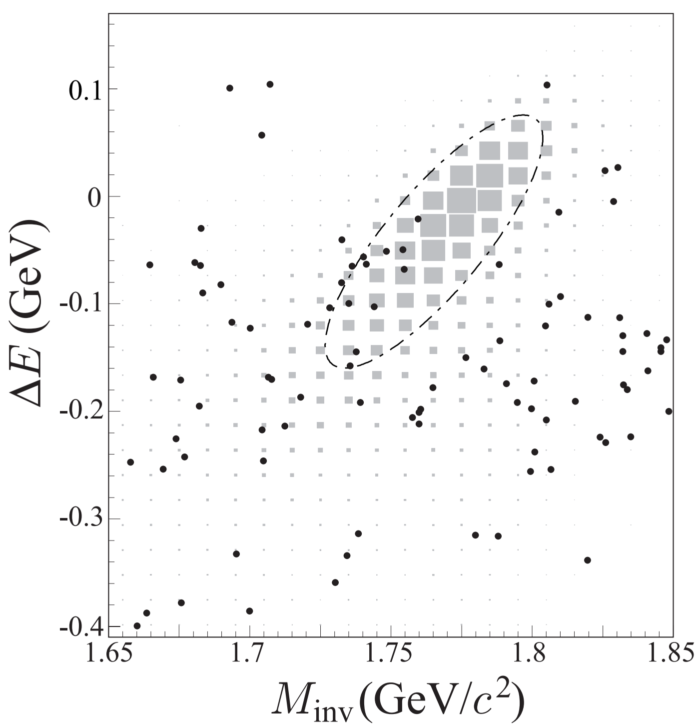


Two independent variables:

$$\Delta E = E_{\mu\gamma}^{\rm CM} - E_{\rm beam}^{\rm CM} \qquad M_{\mu\gamma} = \sqrt{E_{\mu\gamma}^2 - P_{\mu\gamma}^2}$$

➡ For signal → ΔE close to 0 and $M_{\mu\gamma}$ close to τ mass

$\tau \to \mu\gamma$



Main background sources:

- ➡ τ → μνν
- ➡ τ → eνν
- ➡ τ → πν

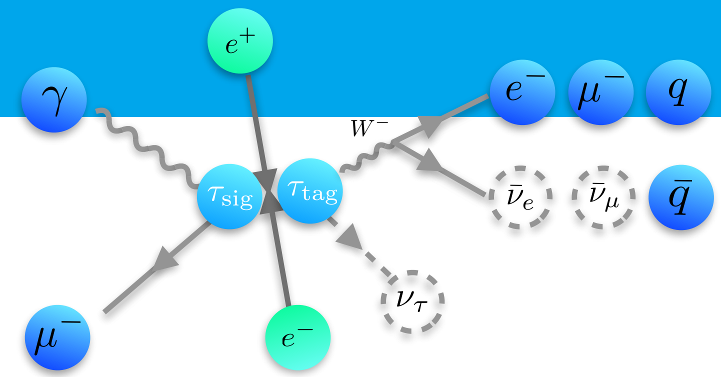
} + γ

- ➡ e^+e^- → ee(μμ) γ
- ➡ e^+e^- → continuum

Background suppression:

- ➡ event topology
- ➡ back-to-back production: thrust value close to 1
- ➡ missing momentum towards the tag hemisphereτ
- ➡ relation between the missing momentum and missing mass
- ➡ total visible energy
- ➡ …

… and at Belle II



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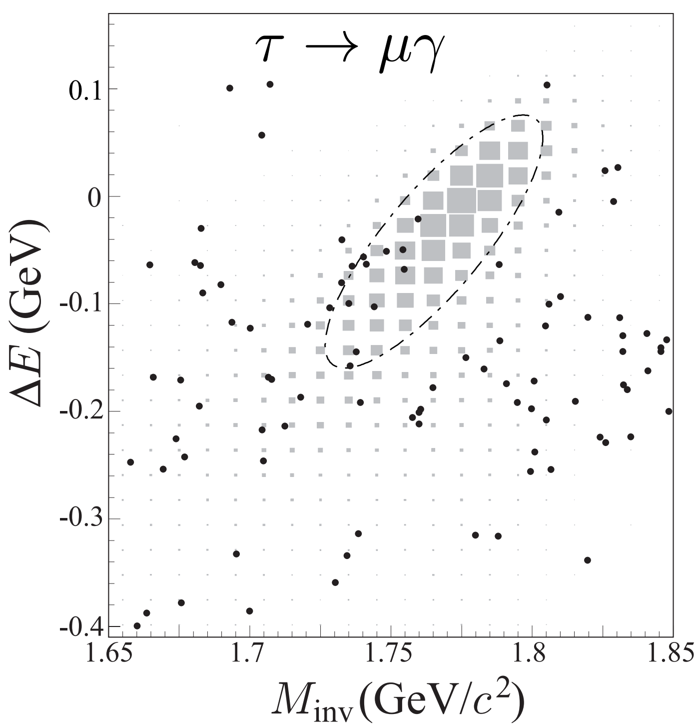
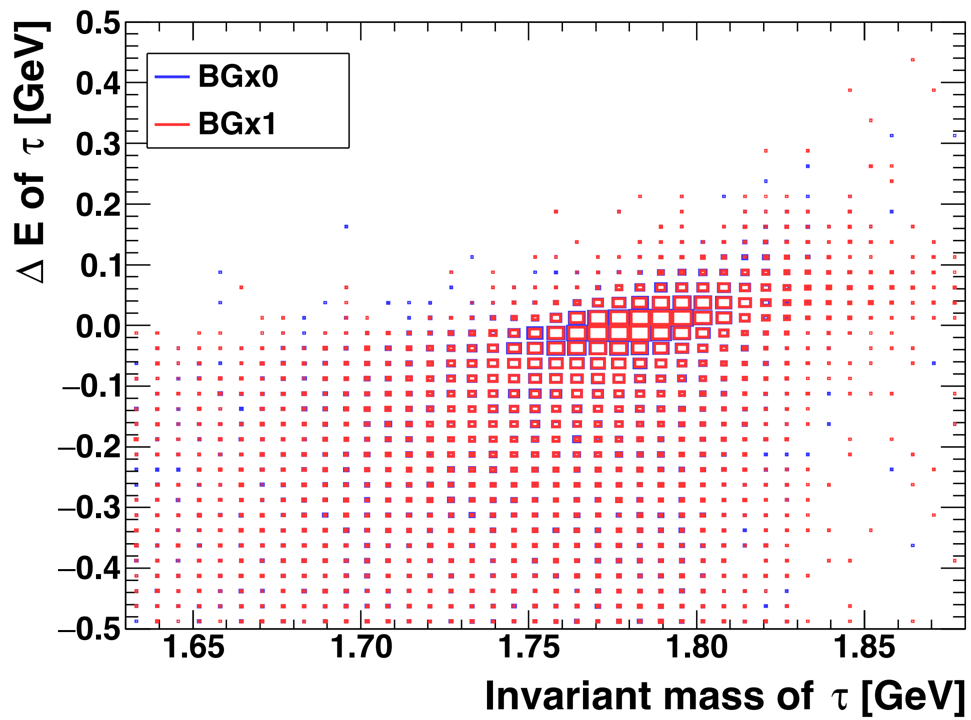
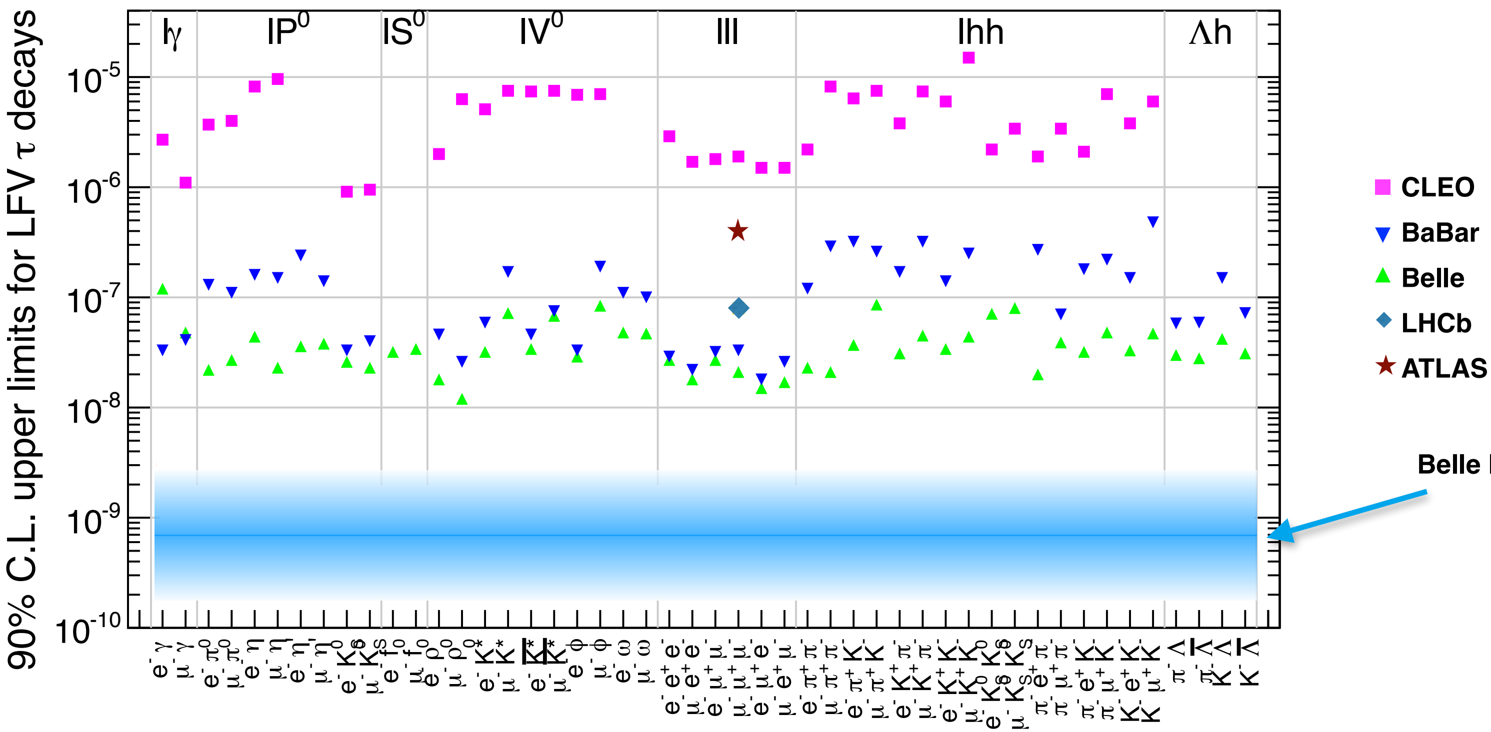




Perspectives at Belle II

LFV and LNV τ decays

➡ One of factors pushing up the sensitivity of probes is the increase of the luminosity



➡ Equally important is the increase of the signal detection efficiency

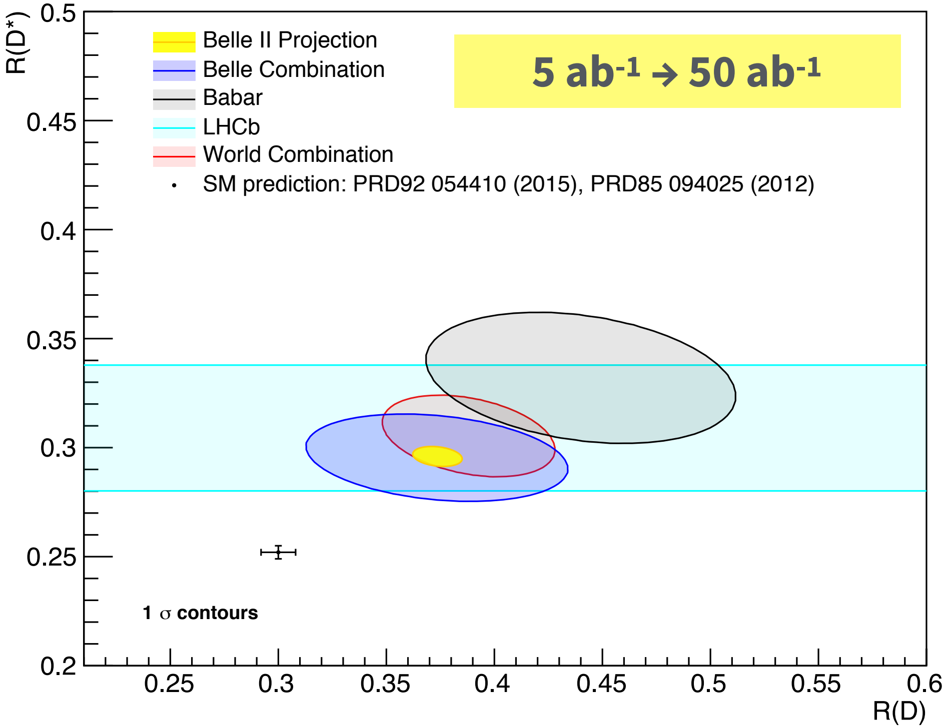
➡ high trigger efficiencies; improvements in the vertex reconstruction, charged track and neutral-meson reconstructions, particle identification, refinements in the analysis techniques…

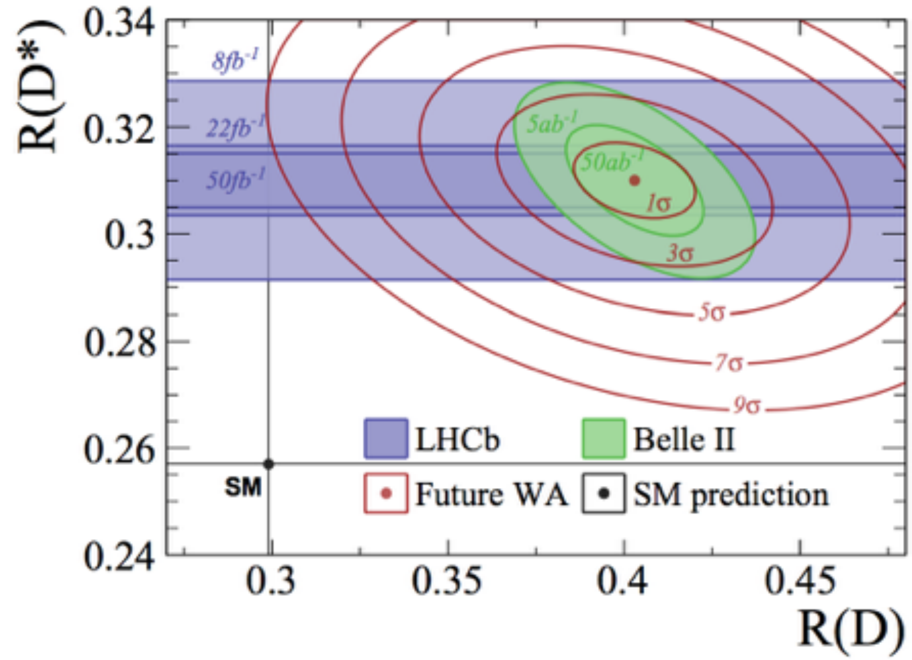
The searches at Belle II will push the current bounds further by more than one order of magnitude

Perspectives at Belle II

Semi-tauonic B decays (example)

$$R(D^{(*)}) = \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}l\nu)}$$ (l=e or μ)



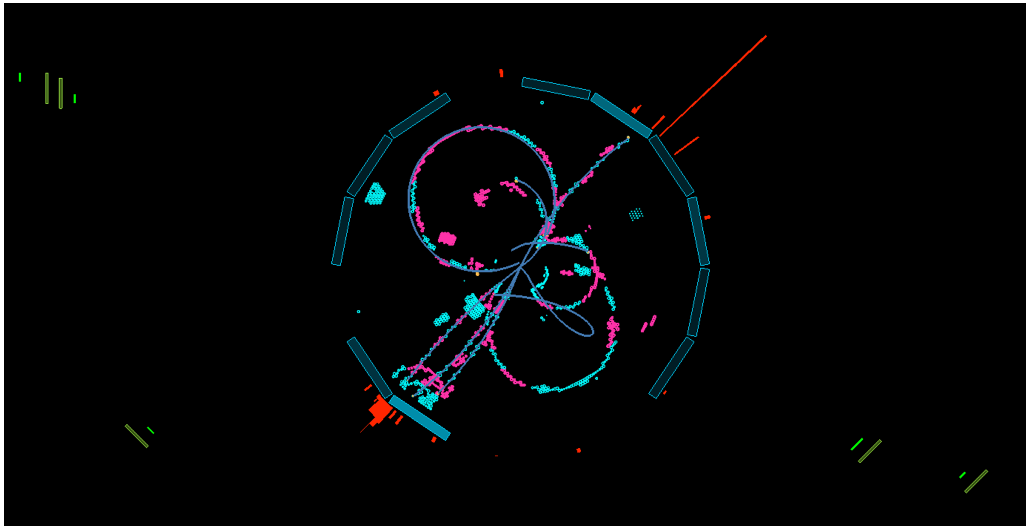


- ➡ Current experimental results limited by statistics
- ➡ 1ab^{-1} (KEKB) → 50ab^{-1} (SuperKEKB)
- ➡ LHC experiments continue in parallel

BelleII can confirm/deny this anomaly already with 5ab^{-1}

Outlook

- ➡ SuperKEKB is completing the commissioning phase and first collisions achieved
- ➡ Phase 2 data taking has been started
- ➡ First data is available already



- ➡ The data with the full detector installed will start in early 2019
- ➡ Belle II will probe the New Physics in many channels with neutrinos in the final state
- ➡ Belle II will be the major player in τ physics in the near future
- ➡ Very exciting times are ahead!

Backups

Effective field theory approach

No compelling evidence for new particles mediating LFV processes

➡ Strong experimental constraints on the scale Λ for new degrees of freedom

➡ Parameterise the LFV τ decays via the effective field theory (EFT)

➡ Their effect will show up at low energies as a series of non-renormalisable operators:

$$L = L_{SM} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

➡ Each NP model generates a specific pattern of operators

➡ Due to the variety of the hadronic final states, the semi-leptonic τ decays probe a larger set of operators

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

- Celis, Cirigliano, Passemar (2014) -

The τ decays offer an opportunity to probe the underlying NP responsible for the LFV.