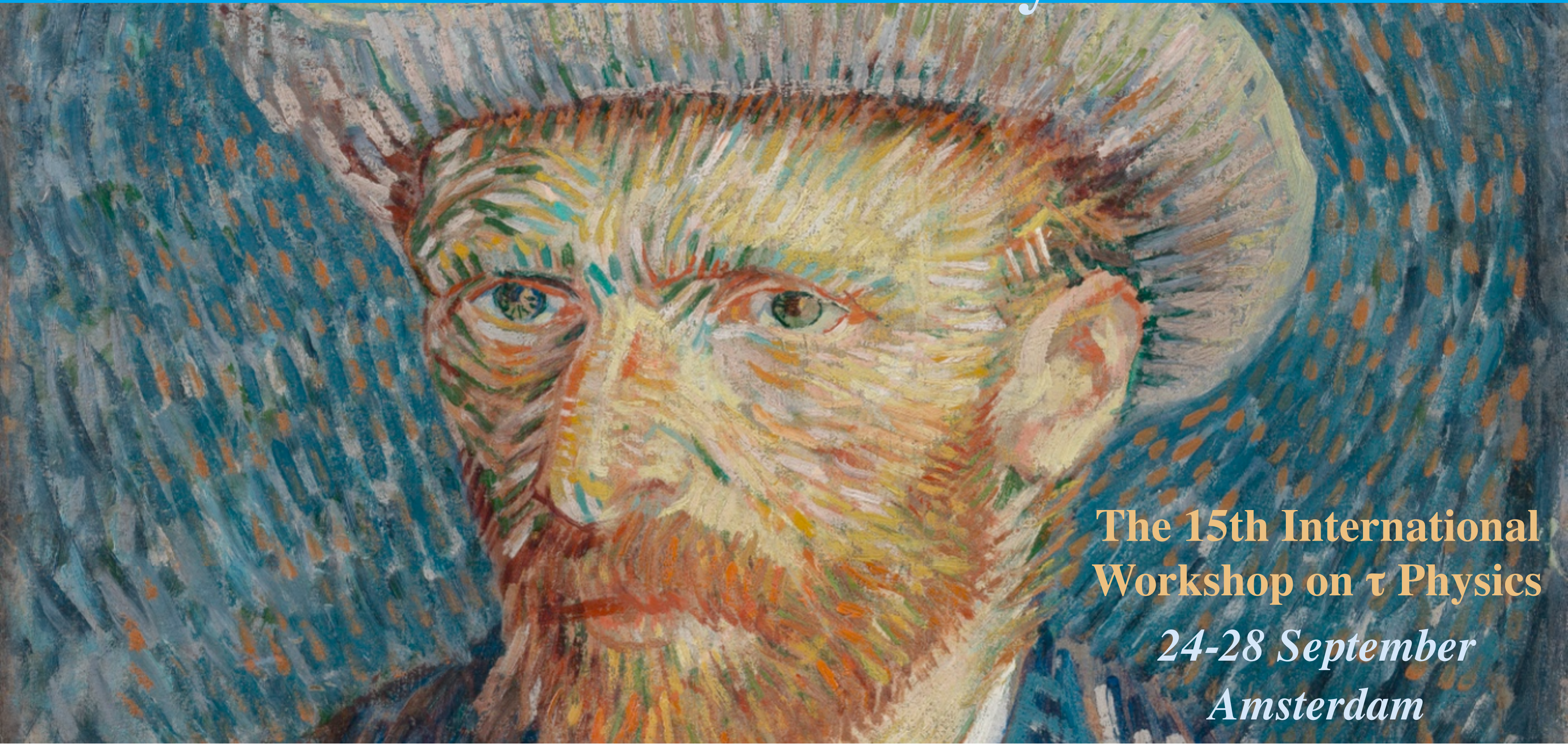
# Tests of Lepton Flavour- / Number- ~~Conservation~~ *Violation* and ~~Universality~~ *Non-universality* at Belle II



**The 15th International Workshop on $\tau$ Physics**

*24-28 September*

*Amsterdam*


**Ami Rostomyan**

**(for the Belle II collaboration)**

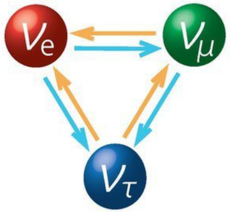
HELMHOLTZ ASSOCIATION

DESY

# Lepton flavour conservation

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

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

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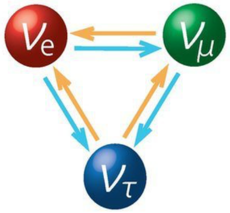

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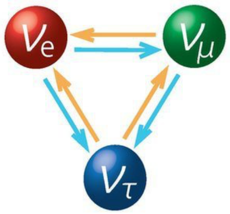


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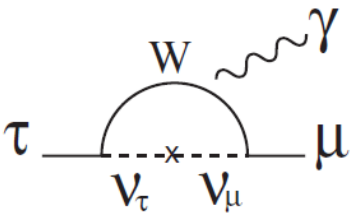
➡ The charged LFV processes can occur through oscillations in loops

➡ Immeasurable small rates ($10^{-54}$-$10^{-49}$) for all the LFV $\mu$ and $\tau$ decays




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

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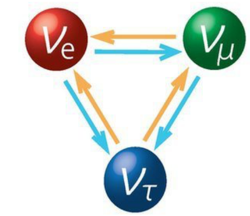


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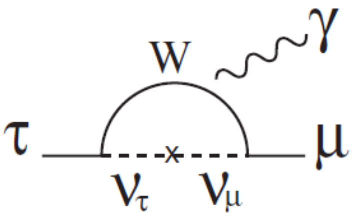


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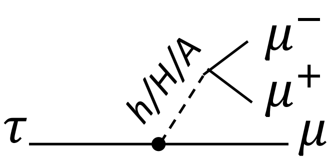
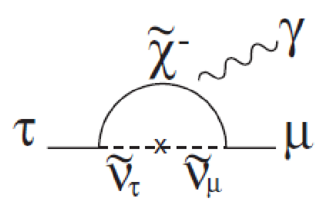
**Observation of LFV will be a clear signature of the NP!**

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



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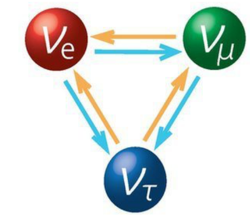


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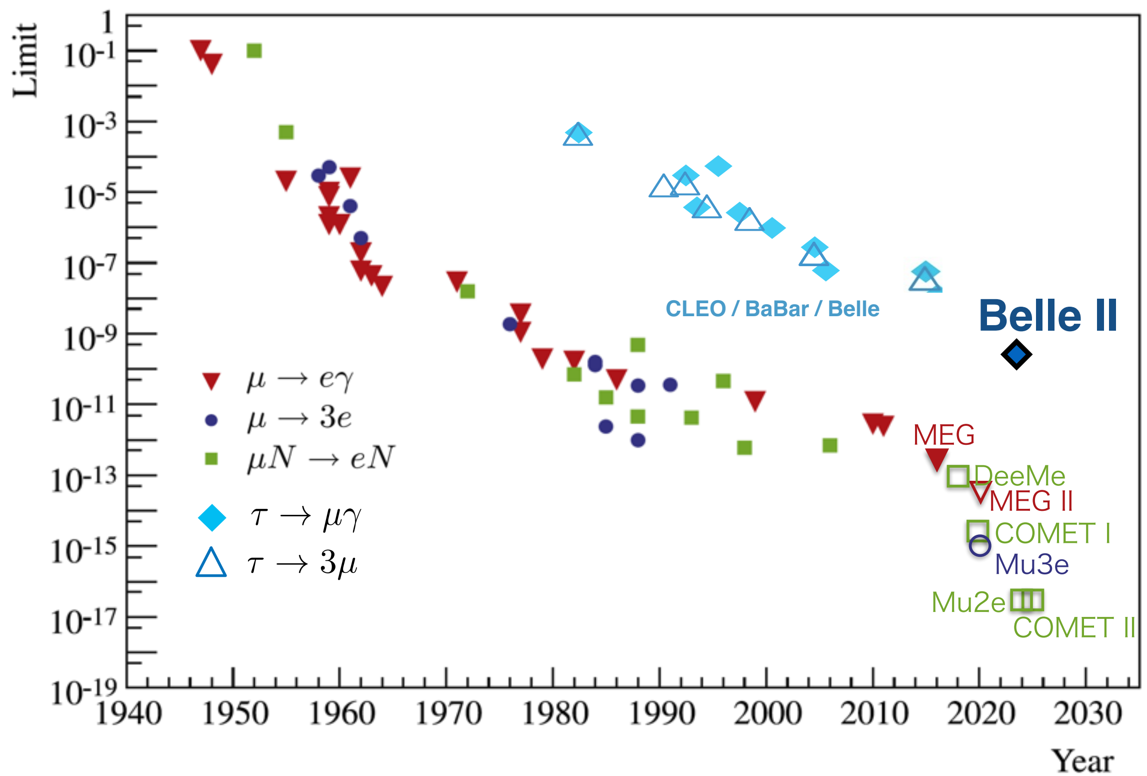


**No success in searches so far!**

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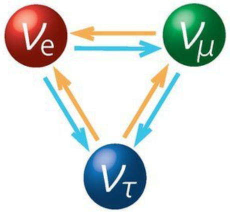


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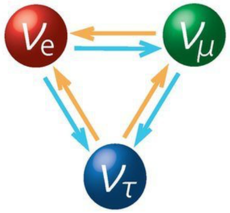


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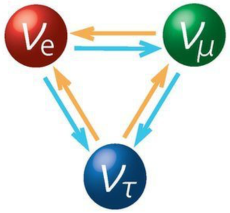

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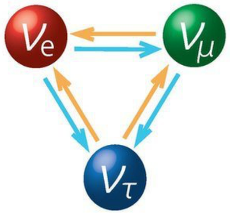


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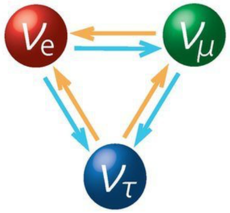


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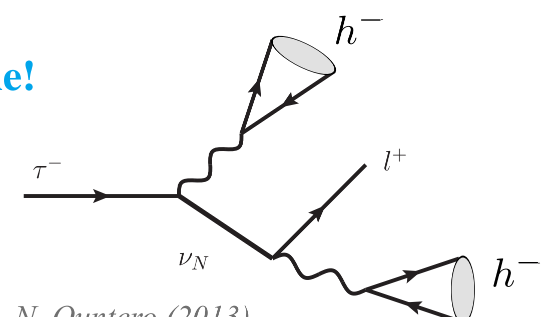
**Observation of LNV will hint at light NP scale!**




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

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

➡ Significant enhancement of the τ decay rates

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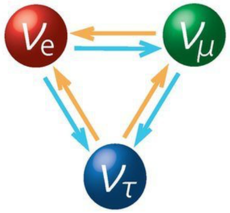


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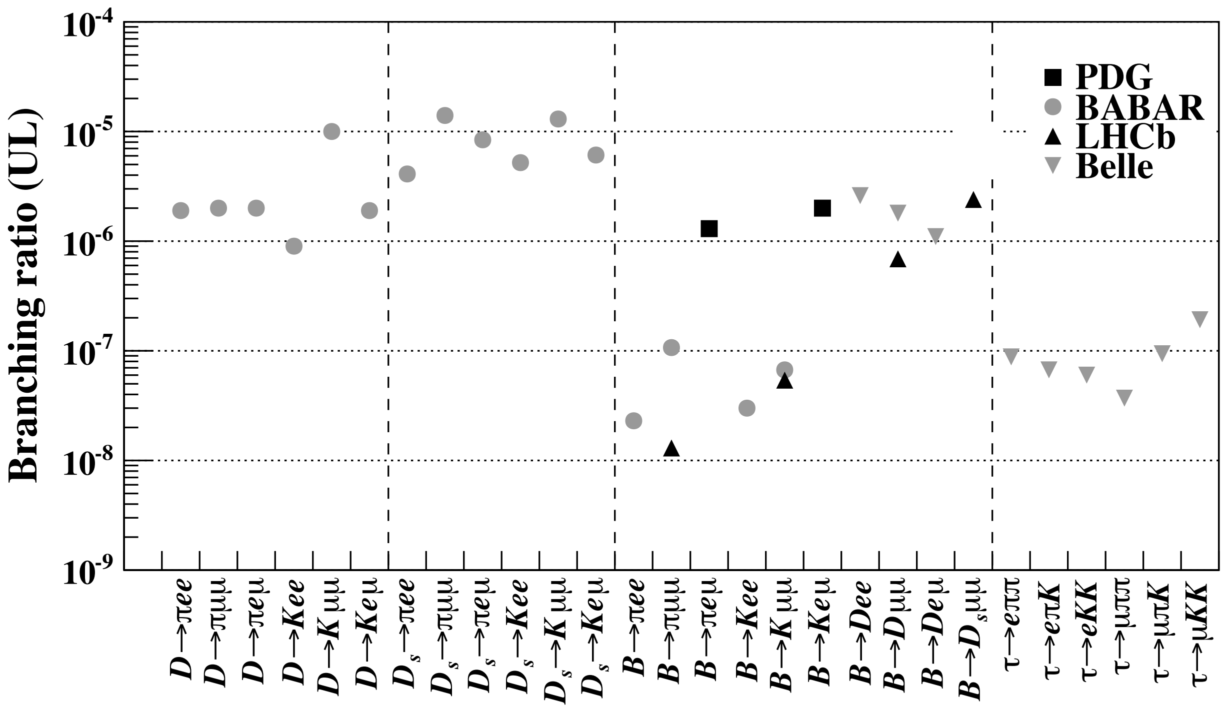
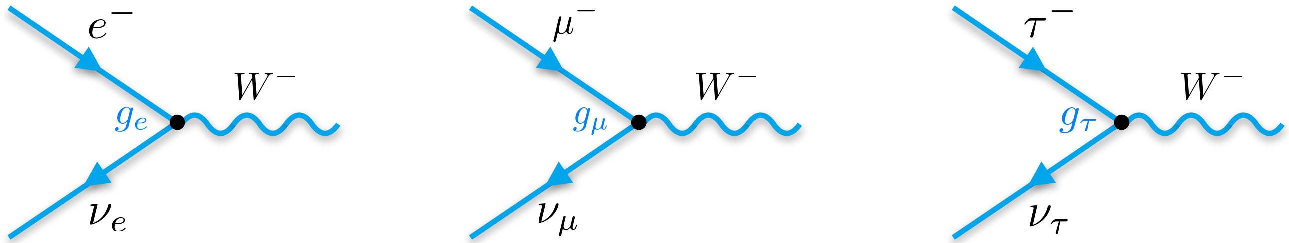



**No answer yet!**

# Lepton universality

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

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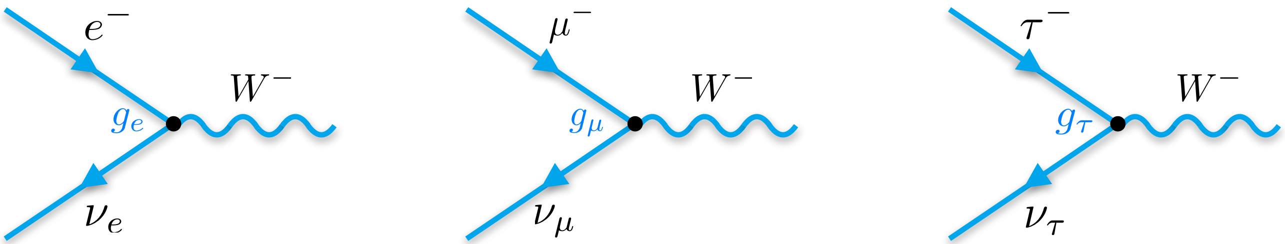


**Identical decays involving electrons, muon or taus**

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

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

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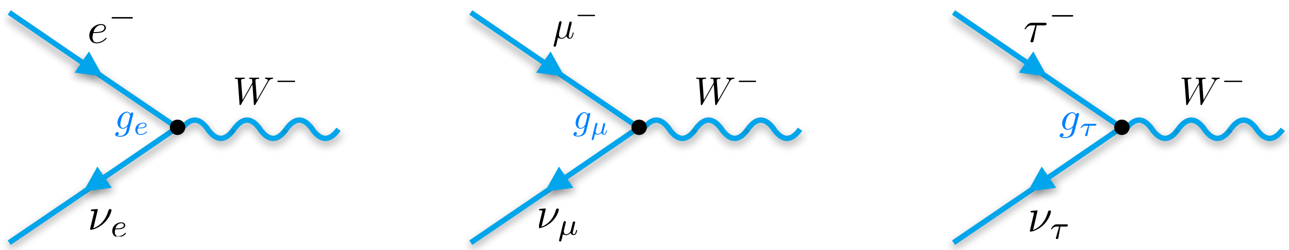


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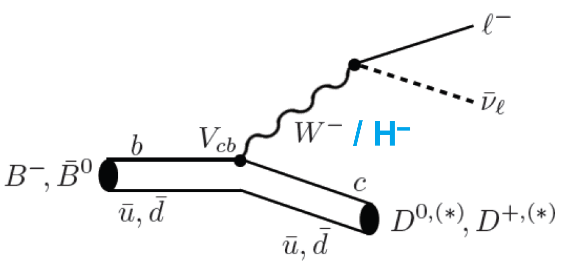
**Discovery of lepton flavour non-universality is a key signature of NP!**



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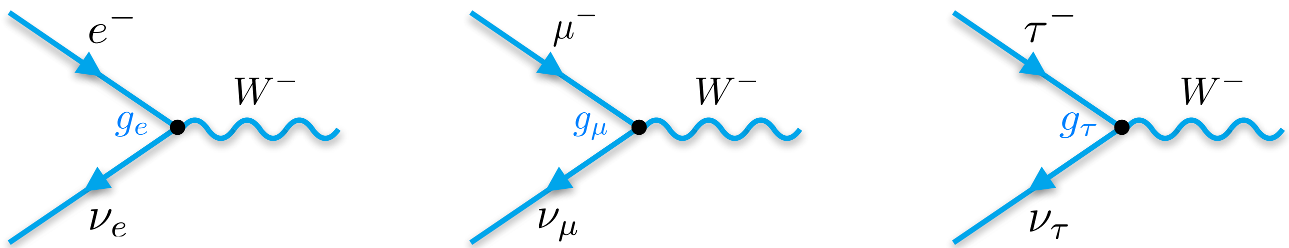


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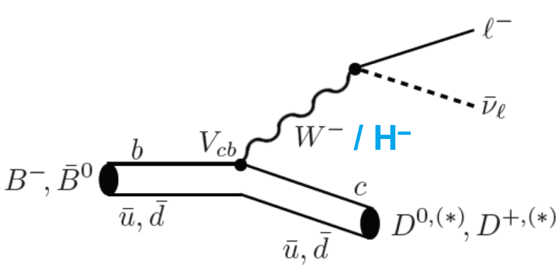


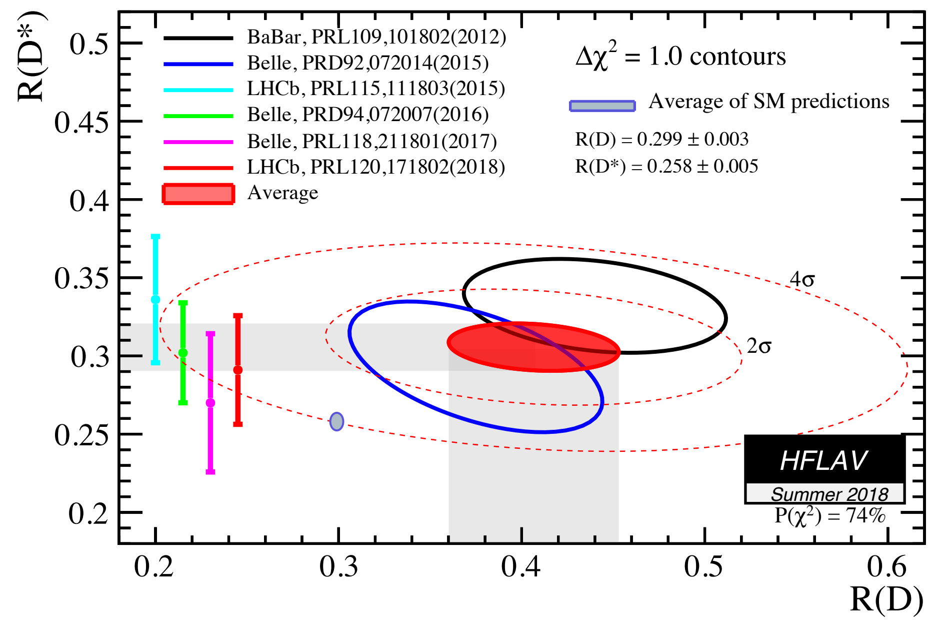


**Hint for NP with ~4σ**

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**NP may favour the third generation!?**

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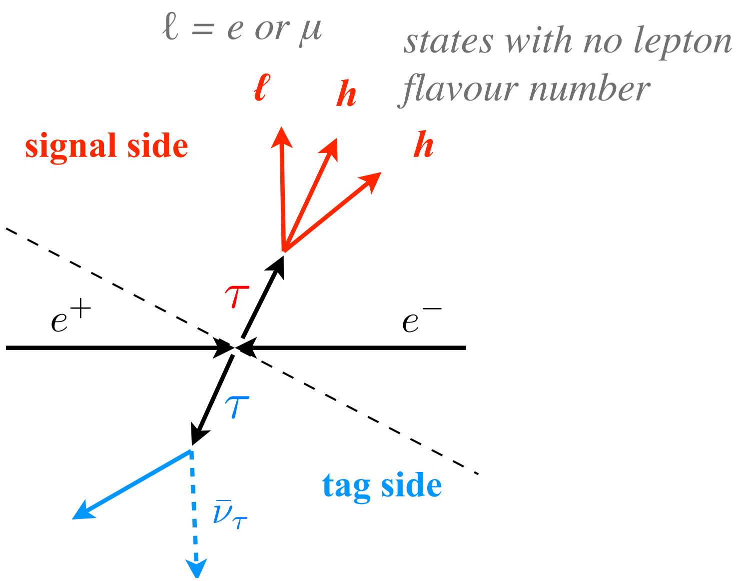
**The only lepton that decays into hadrons**




- ➡ a large variety of **LFV** and **<u>LNV</u> semi-leptonic** decays ($\tau \to \ell h(h)$), in addition to radiative ($\tau \to \ell\gamma$) and leptonic decays ($\tau \to \ell\ell\ell$)
- ➡ $\tau \to \mu$ and $\tau \to e$: test of the lepton flavour structure

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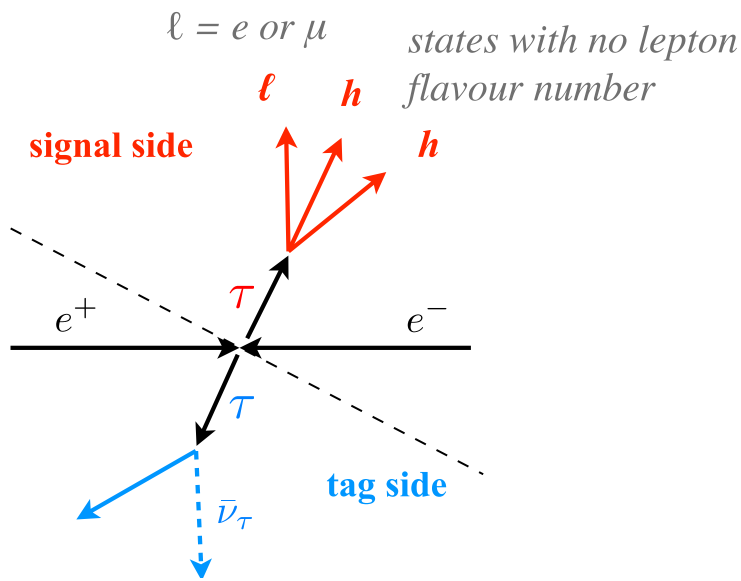


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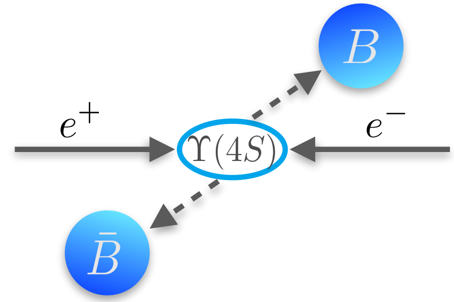
## B mesons decay into e, μ, τ leptons

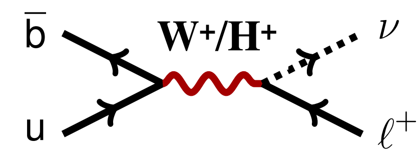



➡ modes used to test the lepton flavour universality

**TREE**

$B \to \ell\nu$

$B \to D^*\ell\nu$

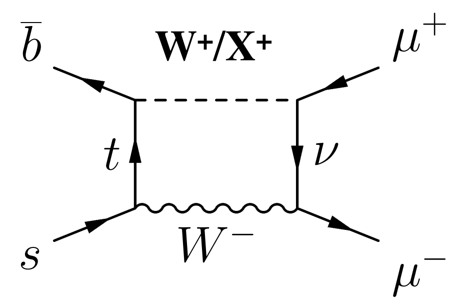



**LOOP**

$B \to \ell\ell$

$B_s \to \ell\ell$

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



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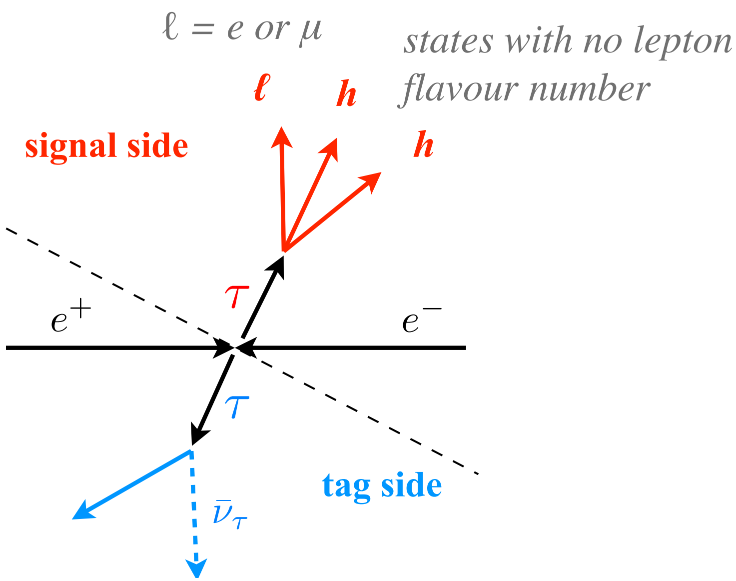


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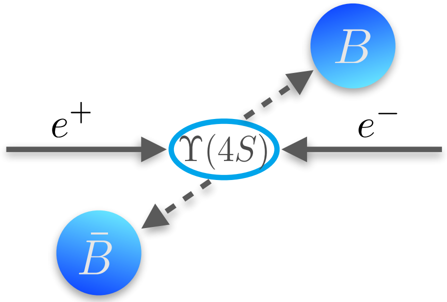


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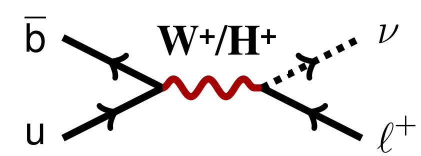


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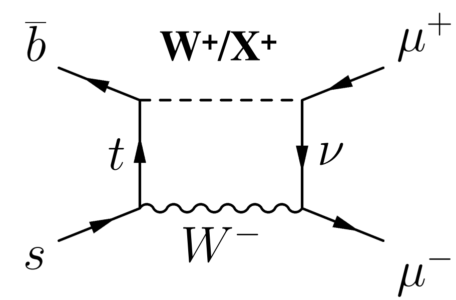
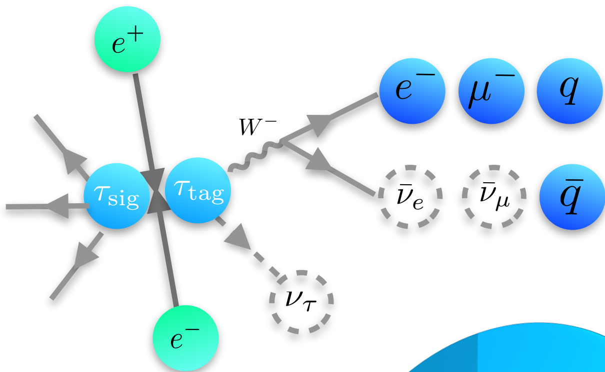
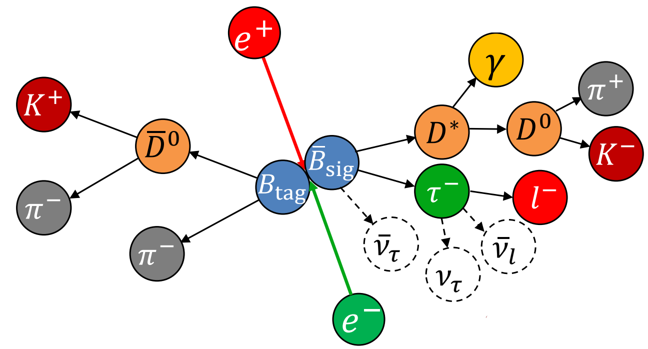


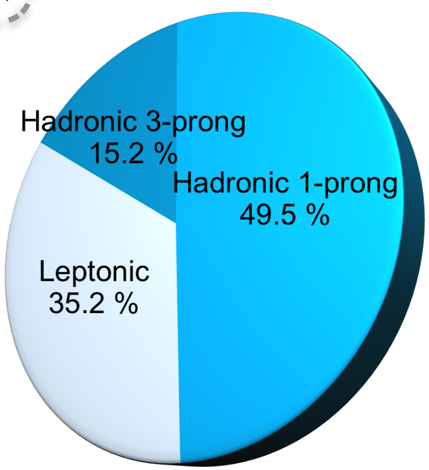

**Test the SM in a variety of ways**

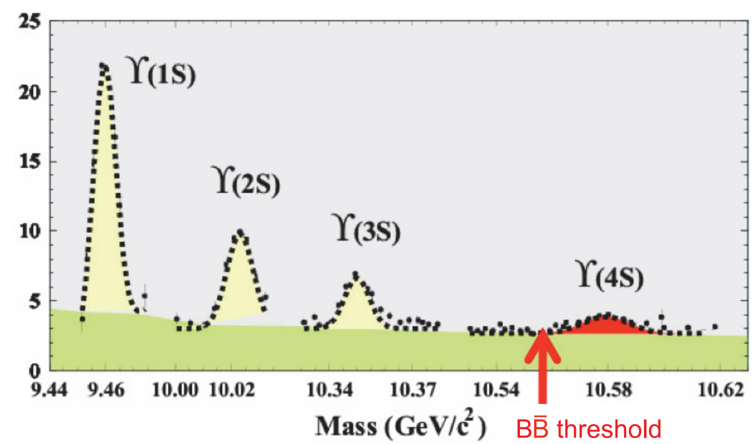
# Neutrinos on the tag or signal side

## Not possible to fully reconstruct the full event




## 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 $\tau$-lepton production (X-section = 0.9 nb for $e^+e^- \to \tau^+\tau^-$ at 10.58 GeV

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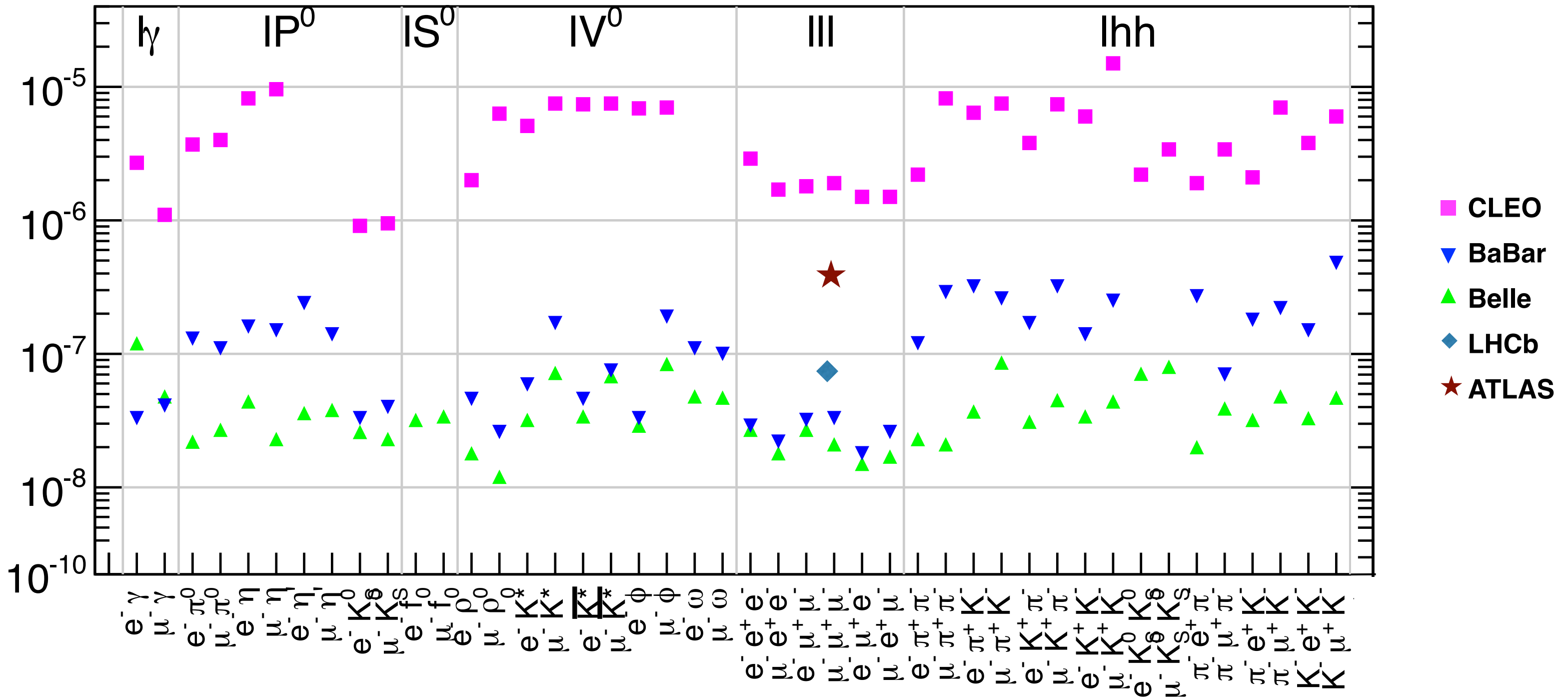



**The upper limits reached for τ decays approached the regions sensitive to NP.**

# Belle II @ SuperKEKB

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

*Tsukuba, Japan*

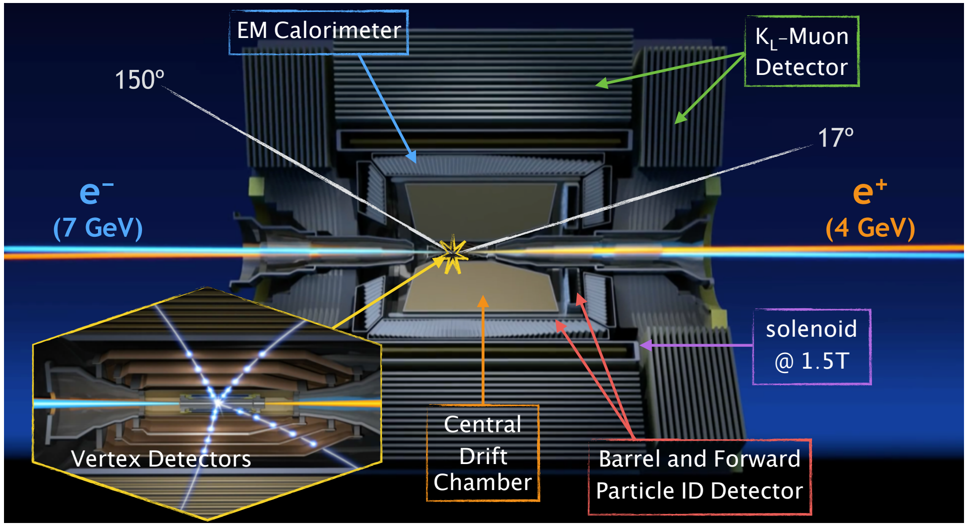

**SuperKEKB** – major upgrade of the KEKB

- ➡ 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**



# Plans for Belle II

## Phase 1: first beams

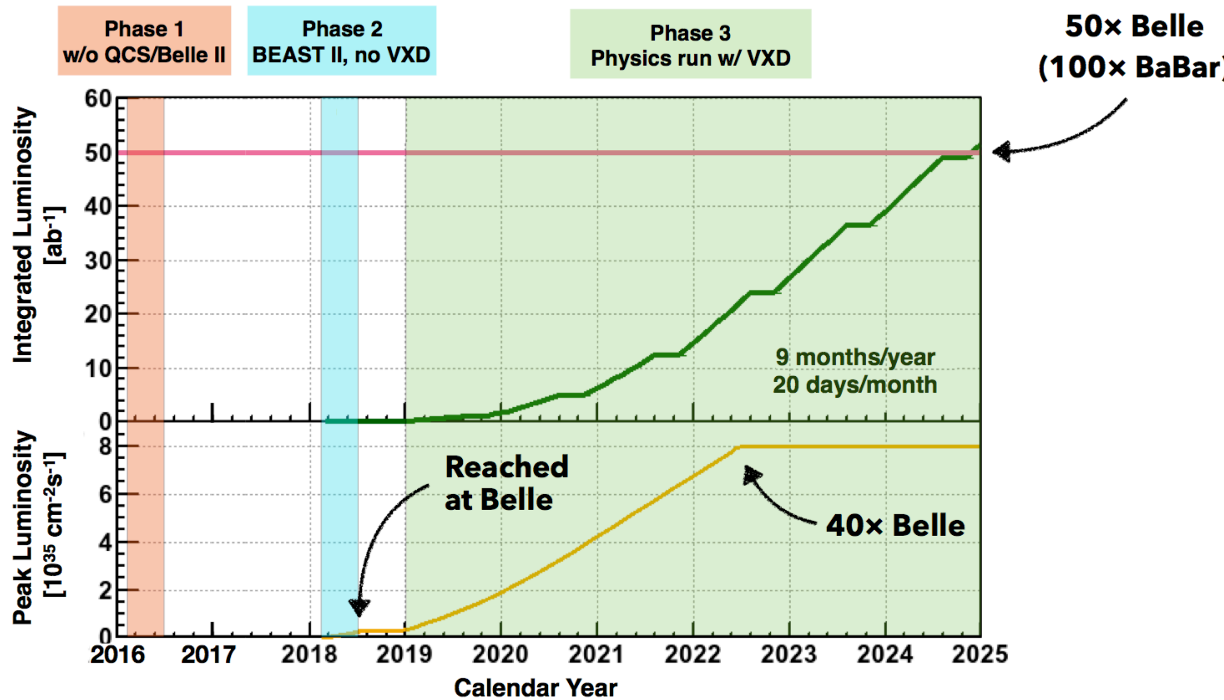
- no detector over interaction region,
- study the beam properties

## Phase 2: first collisions

- no PXD detector
- instead BEAST II (radiation monitoring system)
- understand backgrounds
- establish nano-beam scheme

## 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 Michel's presentation**

# Plans for Belle II

## Phase 1: first beams

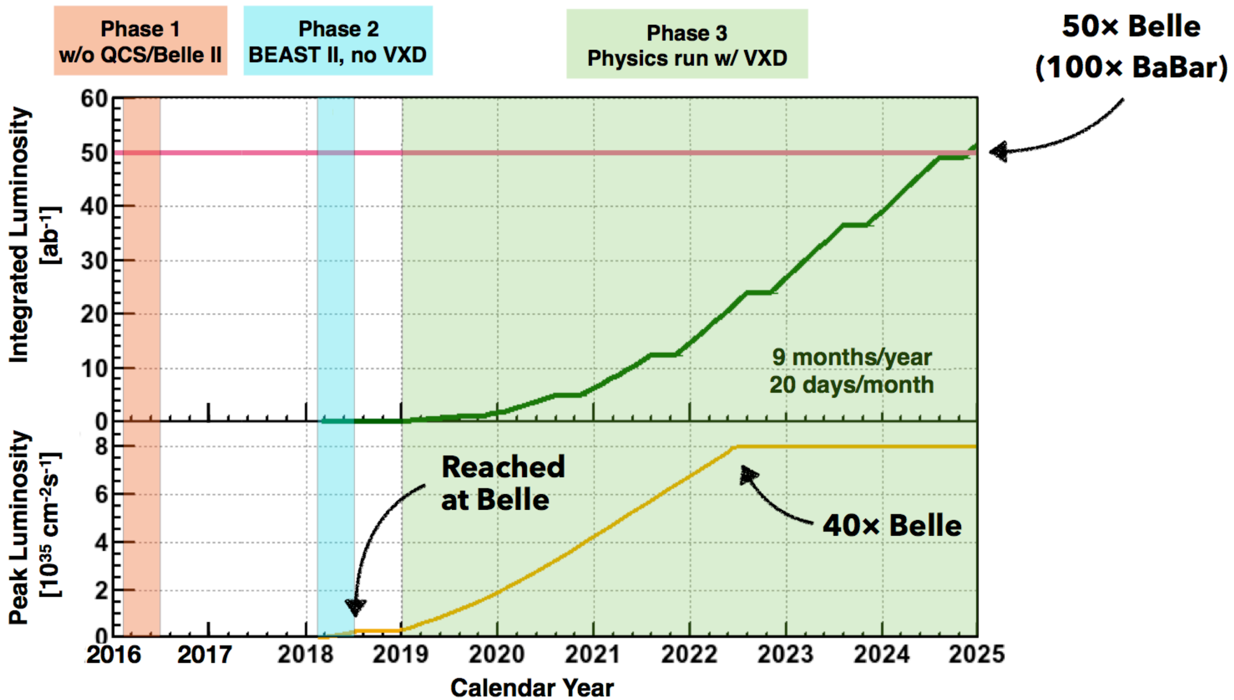
- no detector over interaction region,
- study the beam properties

## Phase 2: first collisions

- no PXD detector
- instead BEAST II (radiation monitoring system)
- understand backgrounds
- establish nano-beam scheme

## Phase 3: first physics with full detector

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

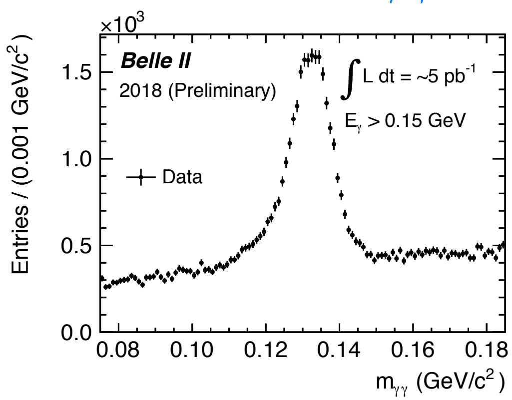



**More details are given in Michel's presentation**

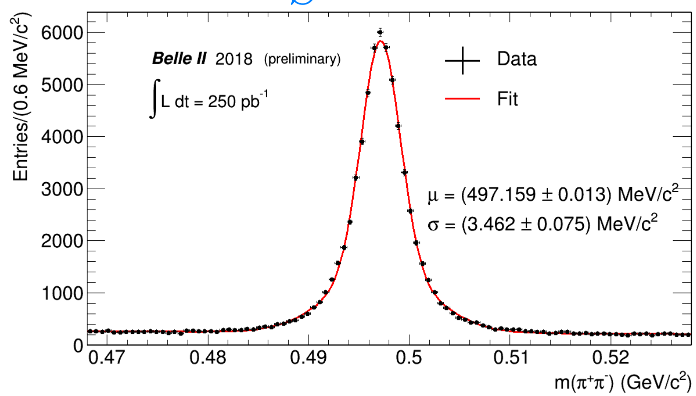
# Belle II performance at Phase II

## Clear mass peaks for charged tracks and photons

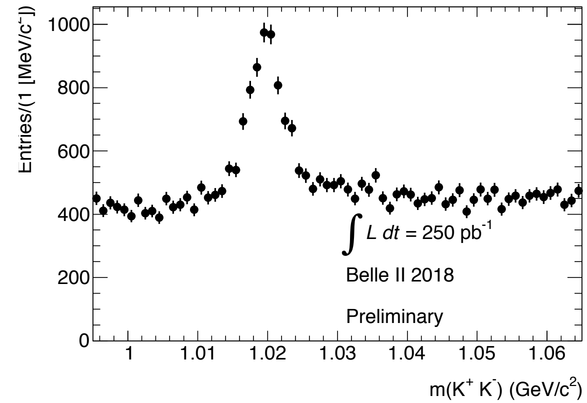
$\pi^0 \to \gamma\gamma$



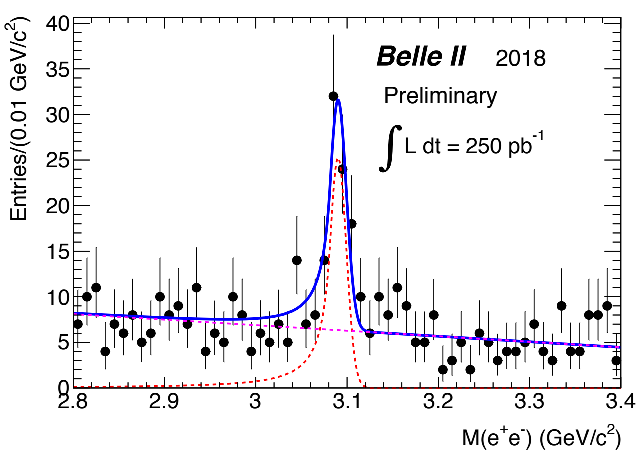

$K_S \to \pi\pi$



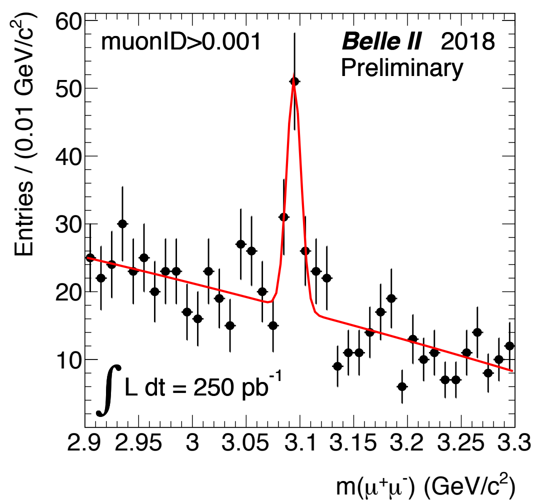

$\phi \to KK$



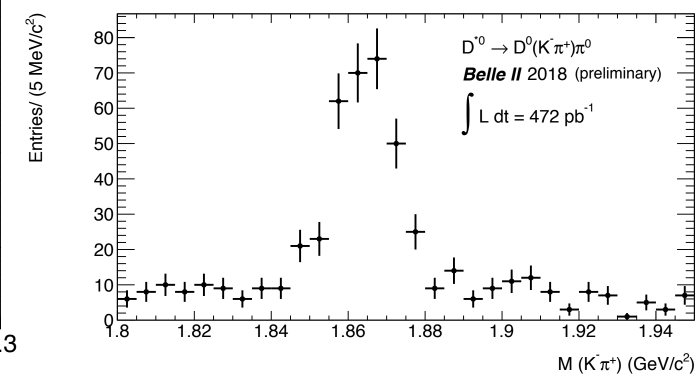

$J/\Psi \to ee$




$J/\Psi \to \mu\mu$



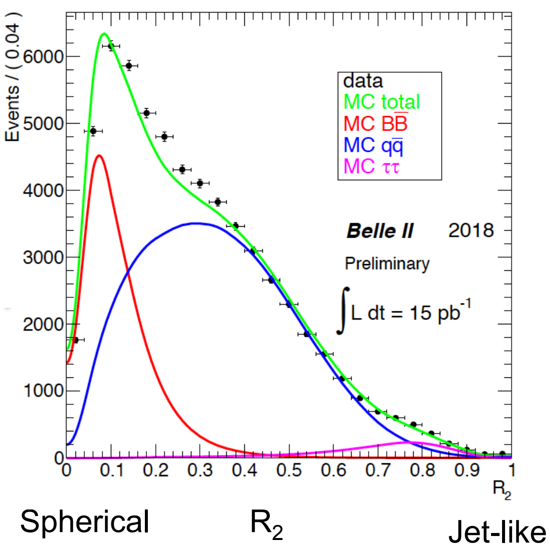

$D \to K\pi$



# Few B mesons were also seen

## Event topology to see B mesons

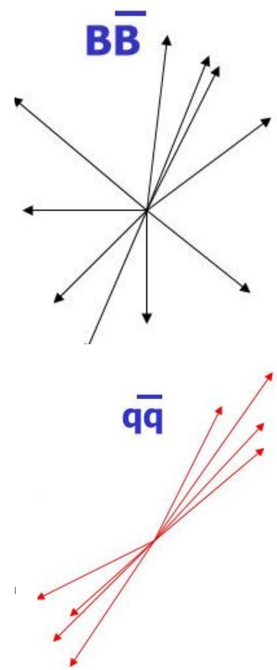
- Beam collisions just above BB threshold
- B pairs produced at rest in the CMS
- Recording B pairs with ~99% efficiency



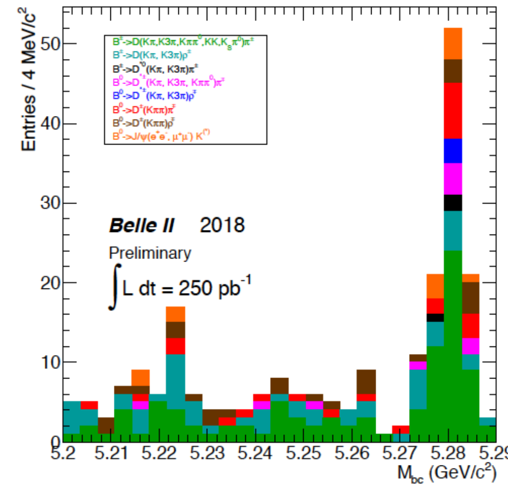

$$R_2 = \frac{H_2}{H_0}$$

momentum of particles — Legendre polynomial — angle between two particles

$$H_l = \sum_{ij} \frac{|p_i||p_j|}{E^2_{\text{vis}}} P_l(\cos\theta_{ij})$$

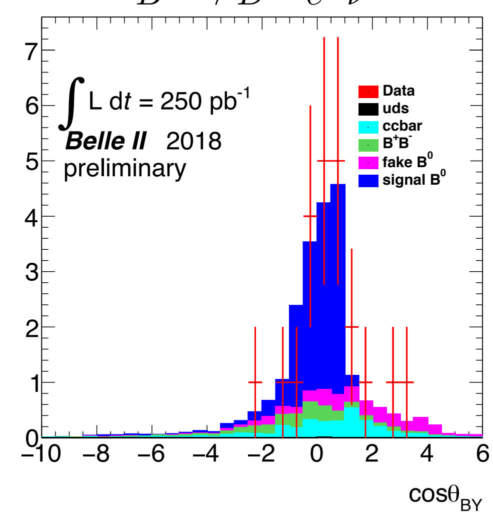



## Hadronic decay modes




## Semileptonic decay modes

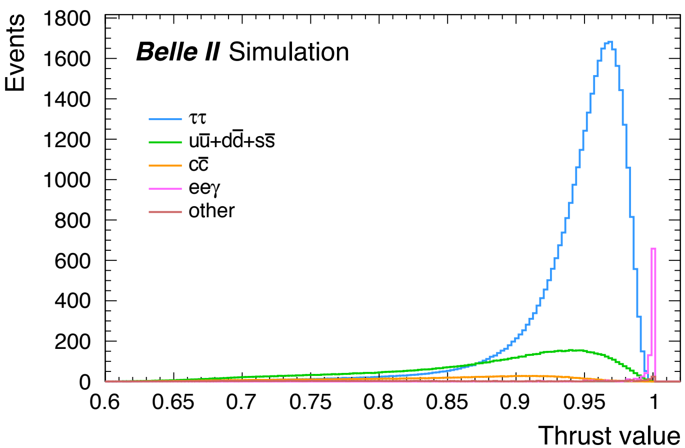
$$\bar{B}^0 \to D^{*+} e^- \bar{\nu}$$



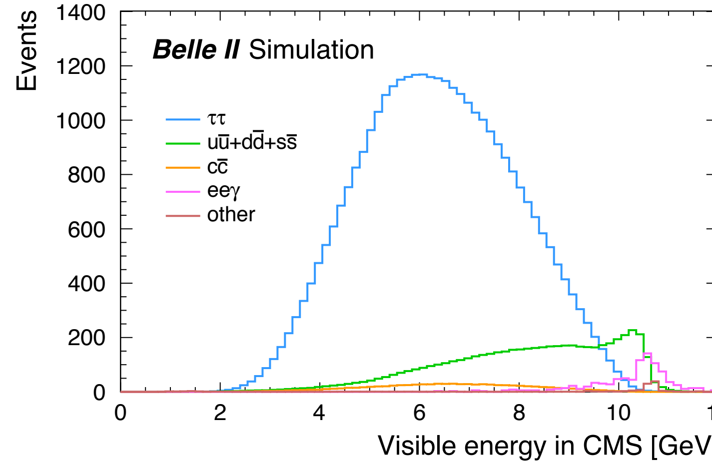
# … and the τ leptons

## Event topology and kinematics to observe τ leptons

➡ relatively mild deviation of the τ decay particles from the primary trajectory



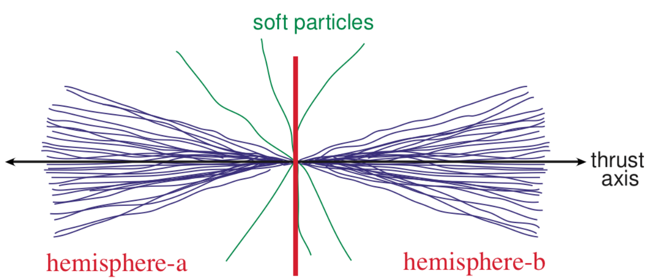

➡ undetected neutrinos in τ events

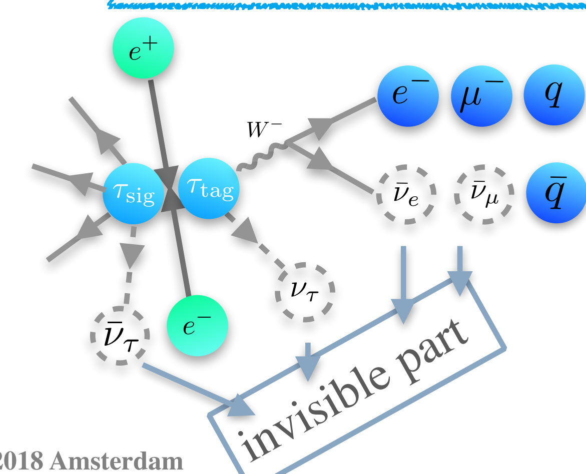



Thrust axis ($\boldsymbol{T}$) is maximising the event shape variable

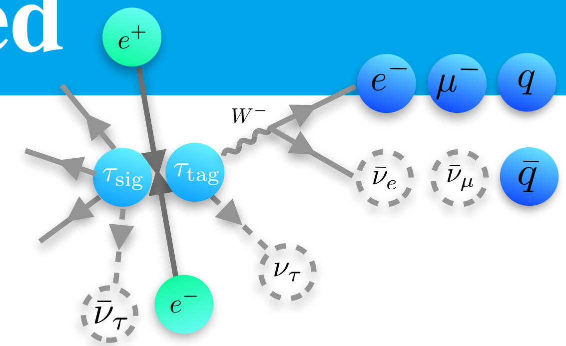
$$\text{thrust value} = \sum_h \frac{\vec{p}_h \cdot \hat{T}}{|p_h|}$$

$$\text{visible energy} = \sum_h E_h$$

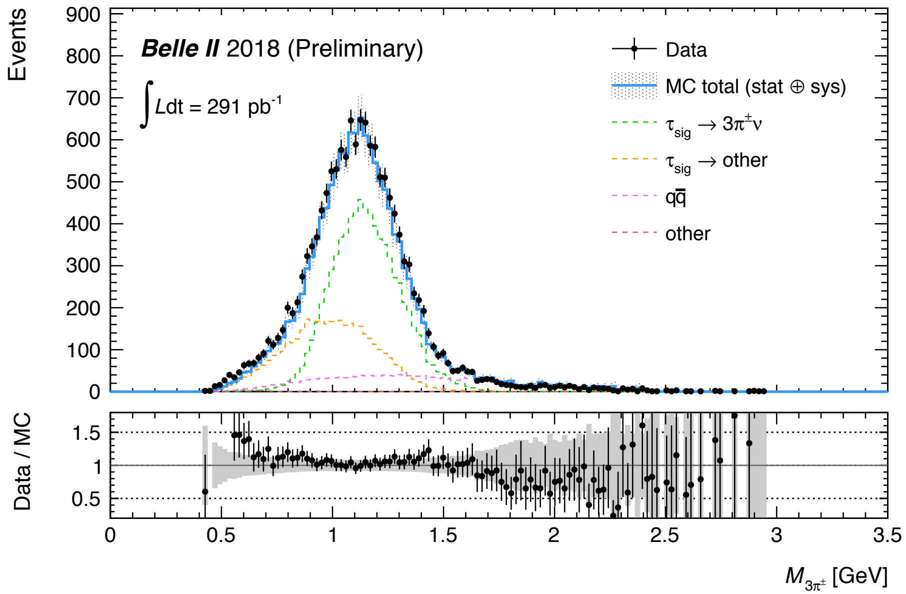


# The τ leptons are also observed




## Event topology to see τ leptons

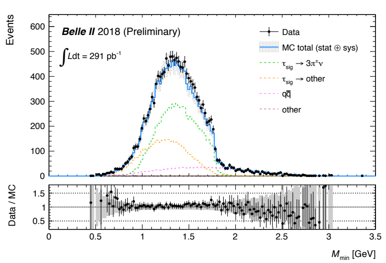



**More details are given in Michel's presentation**

### Measurement of $\tau$ mass

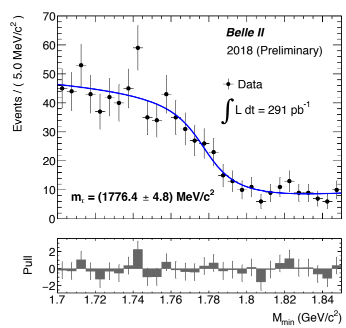
- Measured in the decay mode $\tau \rightarrow 3\pi\nu$, using a pseudomass technique developed by the ARGUS collaboration:
- $M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})}$
- The distribution of the pseudomass is fitted to a empirical edge function.
- A first measurement of $m_\tau$ at Belle II is performed using the data collected during the Phase II.

$M_{min}$ distribution @ 291 pb$^{-1}$:




Michel H. Villanueva 13

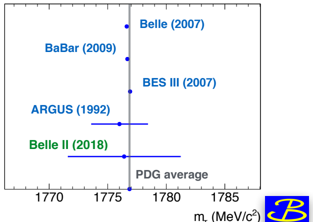
### Measurement of $\tau$ mass




Our result, obtained from Belle II early data

**$m_\tau$ = (1776.4 ± 4.8 (stat)) MeV/c$^2$**

Is consistent with previous experimental results.

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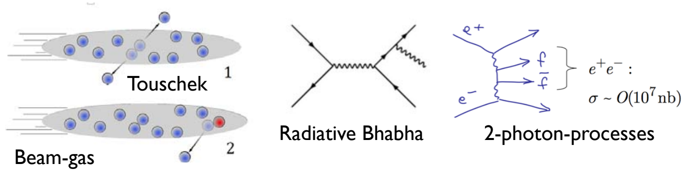
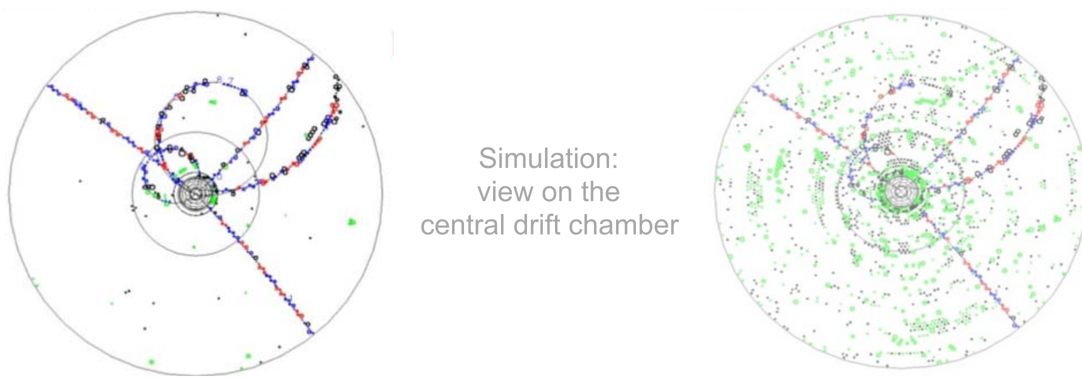
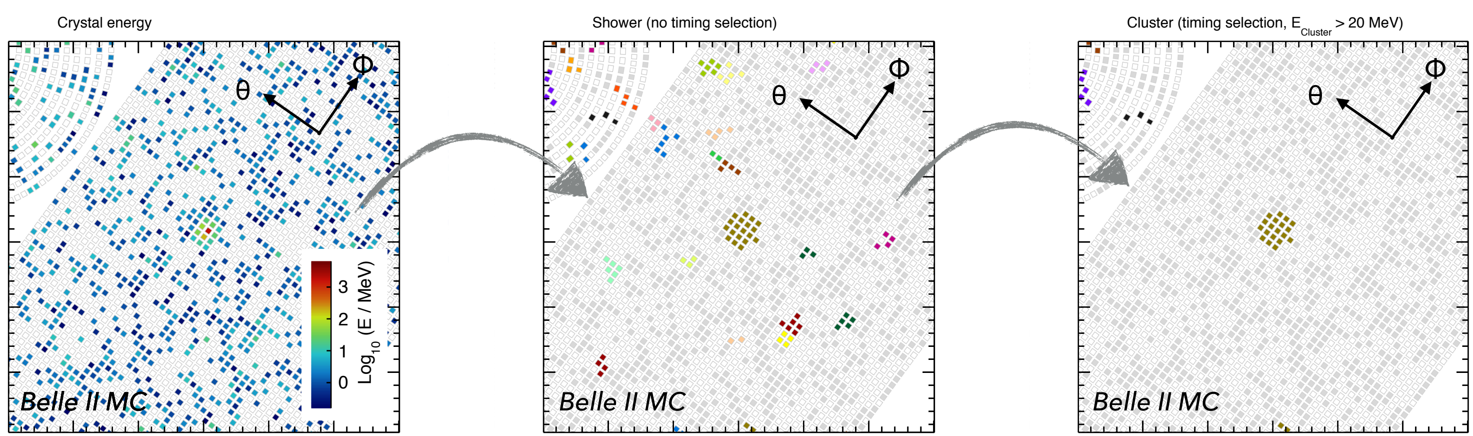
# Beam background

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



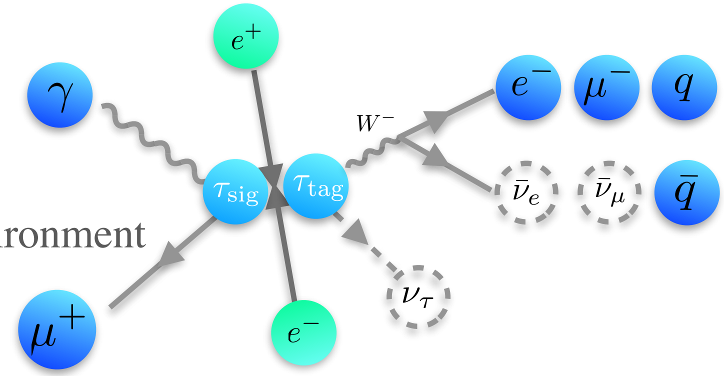

## Use the timing information from calorimeter to reduce the background



# 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



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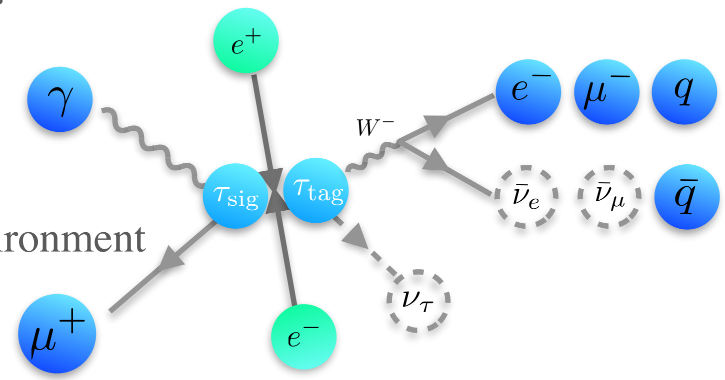
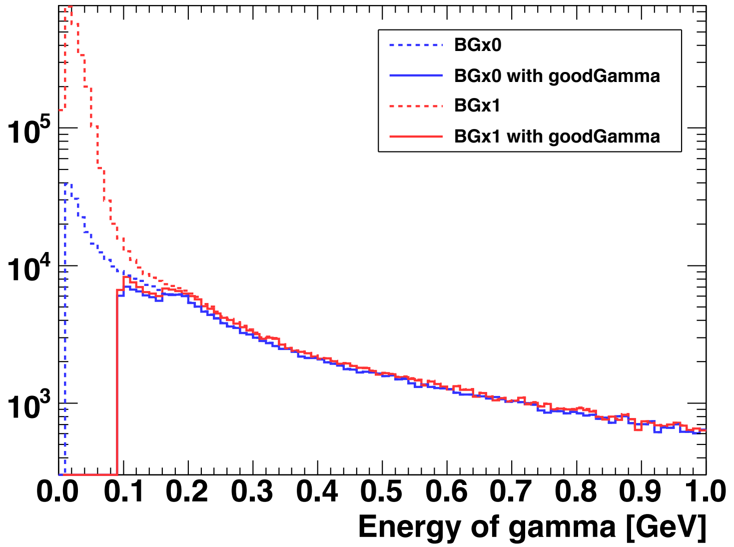
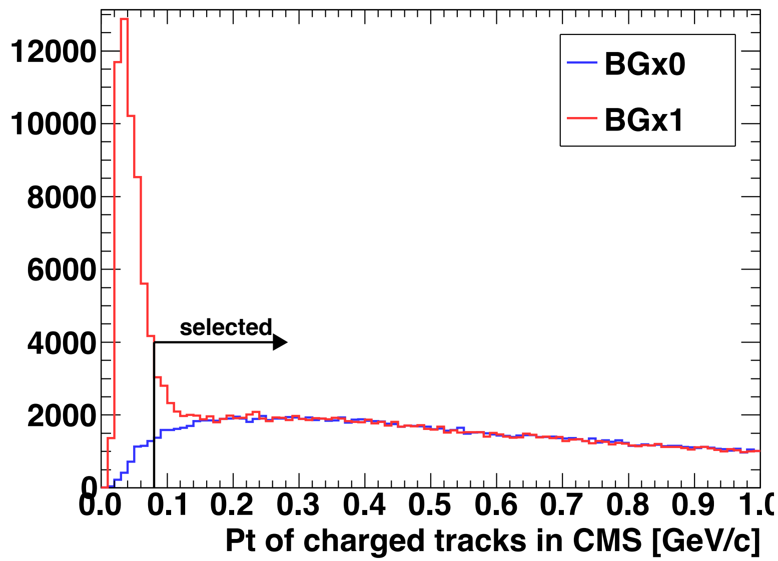



**Energy-based cuts to reduce the background**

*- The Belle II Physics Book -*
*arXiv:1808.10567v2*



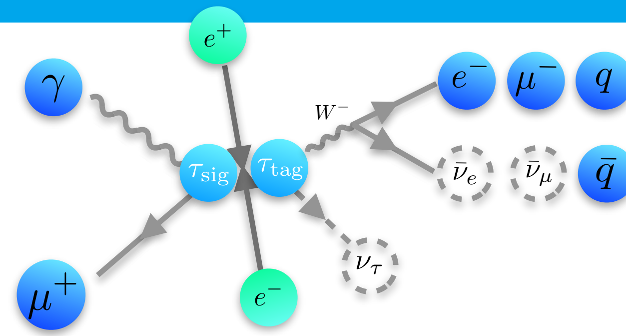




**Background-free search (even with high beam BG)**

# Previous searches at Belle and Belle II

**Two independent variables:**

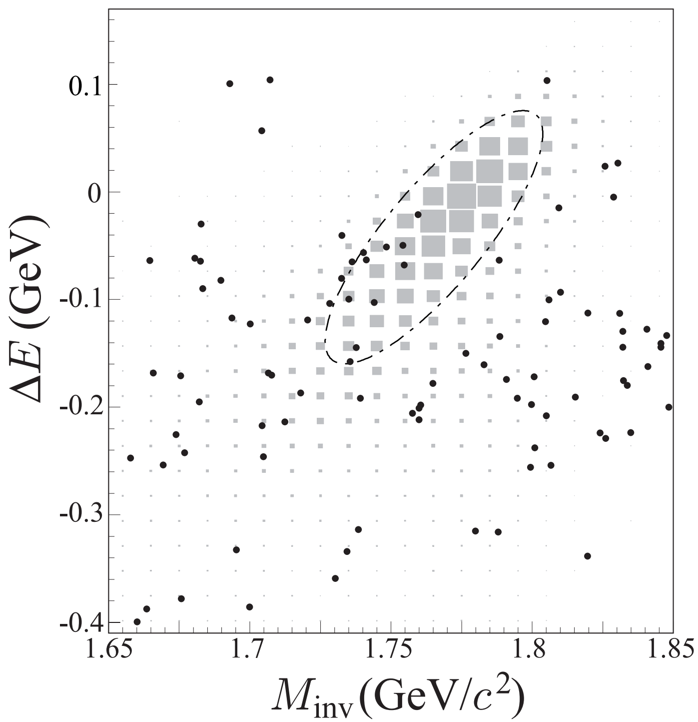
$$\Delta E = E^{\mathrm{CM}}_{\mu\gamma} - E^{\mathrm{CM}}_{\mathrm{beam}} \qquad M_{\mu\gamma} = \sqrt{E^2_{\mu\gamma} - P^2_{\mu\gamma}}$$

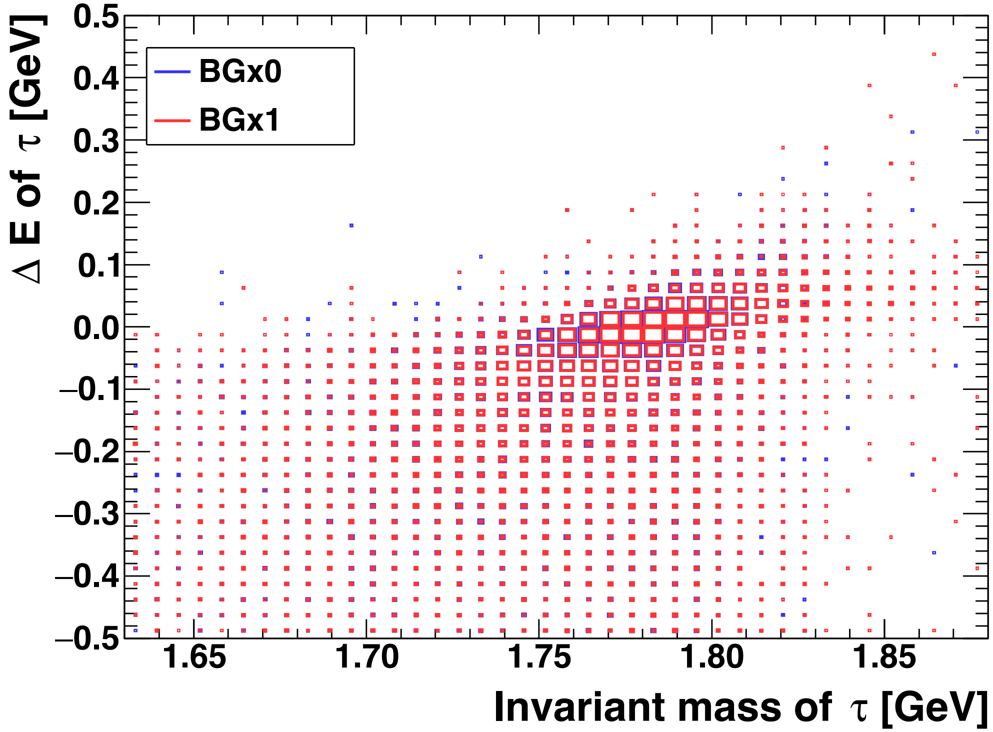



➡ For signal → ΔE close to 0 and $M_{\mu\gamma}$ close to τ mass

*- The Belle II Physics Book -*
*arXiv:1808.10567v2*

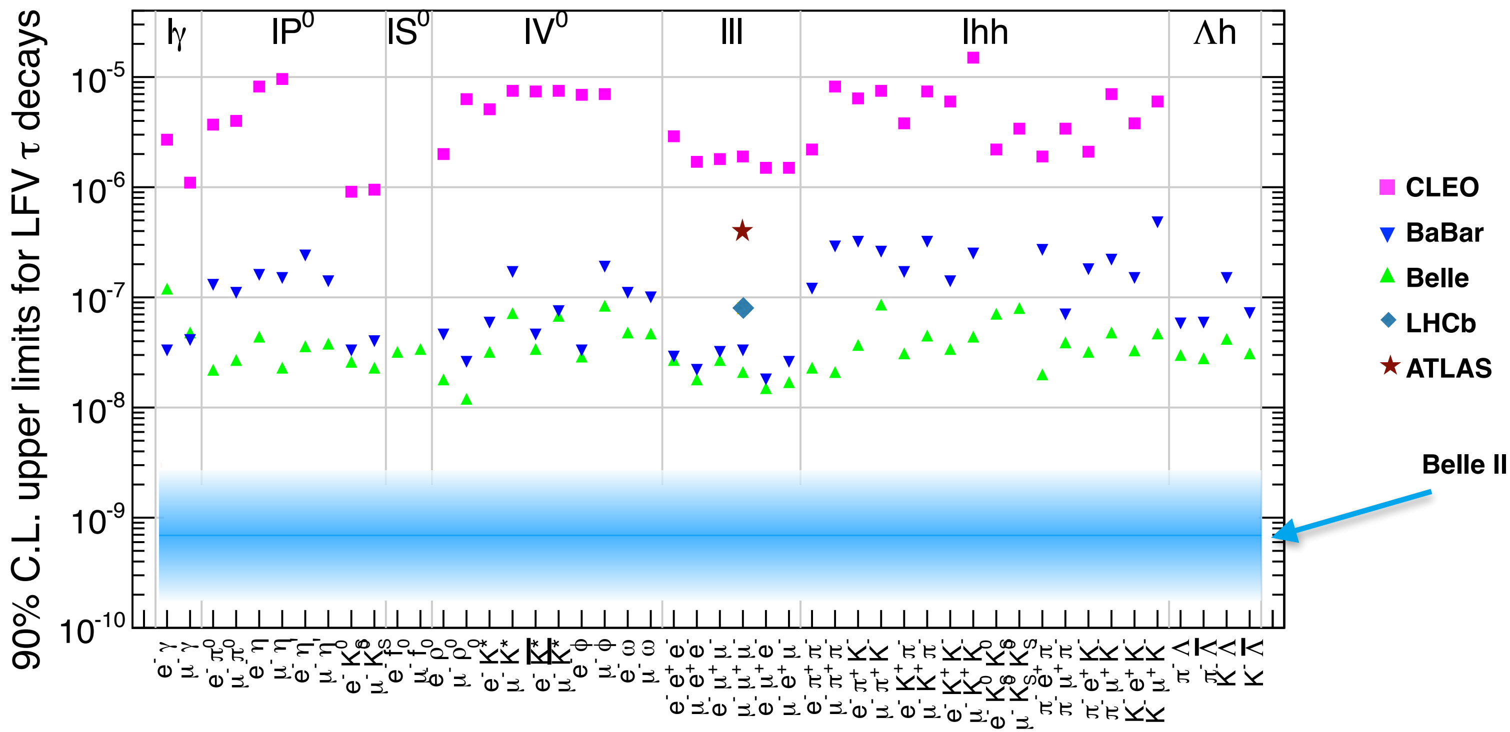
*Phys. Lett., B666, 16–22 (2008)*



## LFV and LNV τ decays

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




➡ Equally important is the increase of the signal detection efficiency

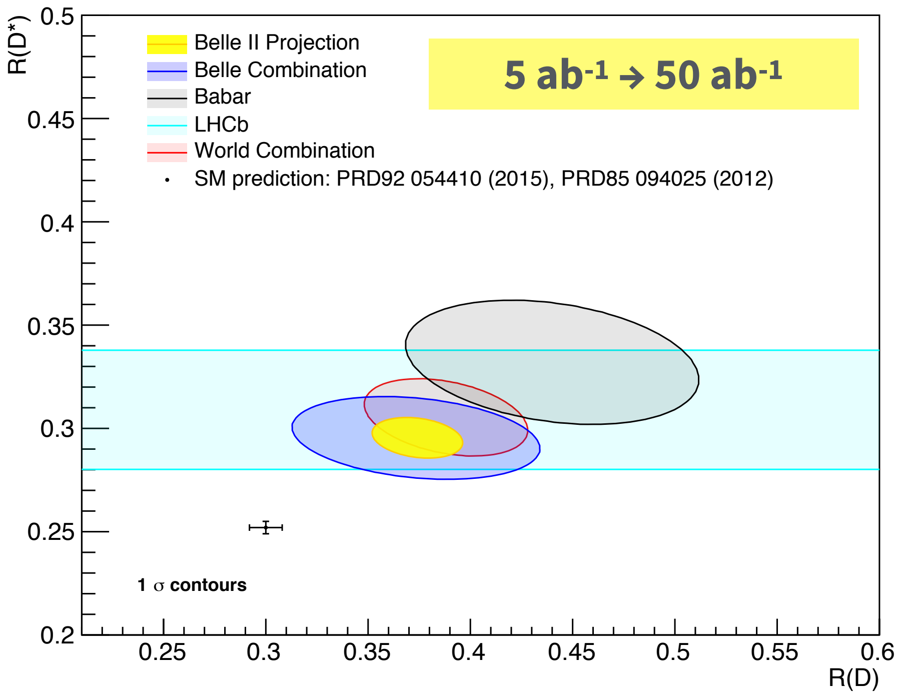
- ➡ high trigger efficiencies; improvements in the vertex reconstruction, charged track and neutral-meson reconstructions, particle identification, refinements in the analysis techniques…

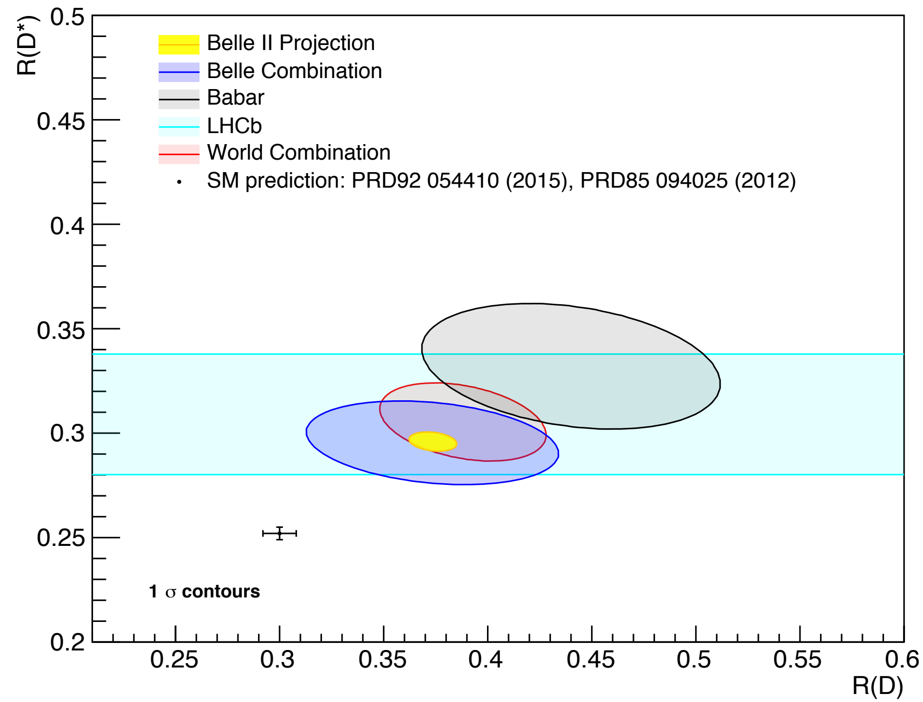
**The searches at Belle II will push the current bounds further by more than one order of magnitude**

# 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)



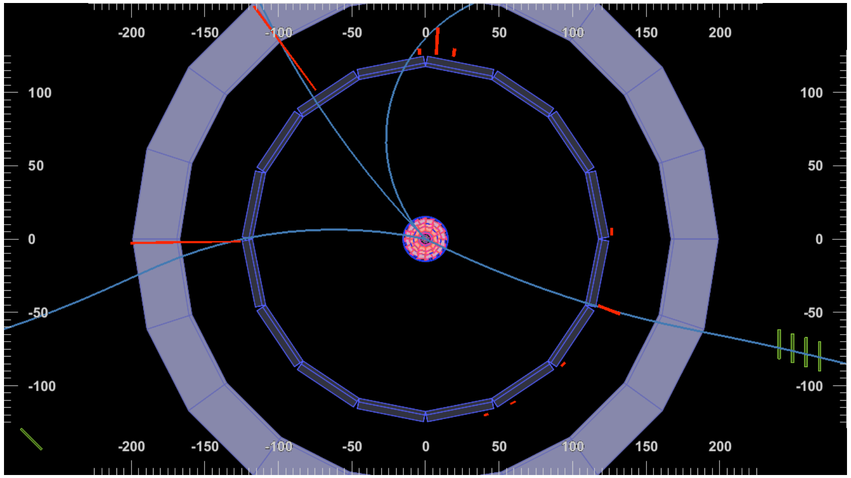



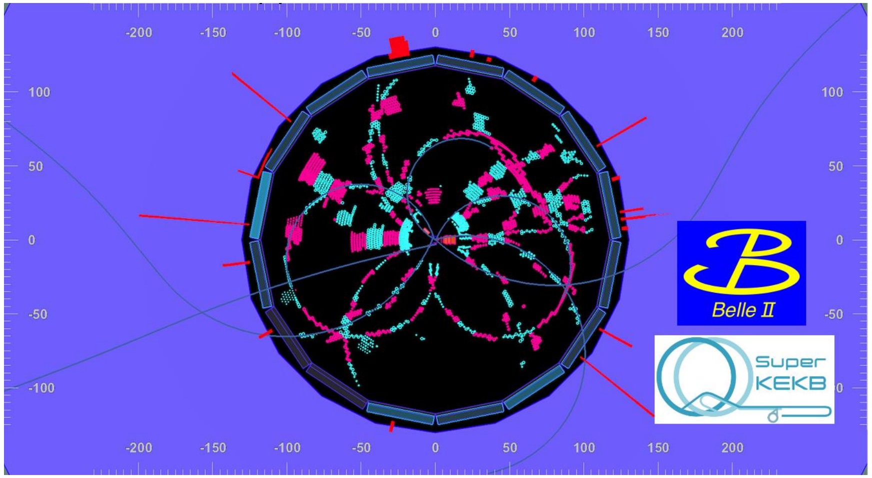

- ➡ Current experimental results limited by statistics
- ➡ $1ab^{-1}$ (KEKB) → $50ab^{-1}$ (SuperKEKB)
- ➡ LHCb experiment continues in parallel

**BelleII can confirm/deny this anomaly**

# Outlook

- ➡ SuperKEKB has completed the commissioning phase
- ➡ Phase 2 data is available already and is delivering results






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

# Backups