Lepton flavour and lepton number violation prospects at Belle II

SUSY2019
May 20-24th, 2019
Corpus Christi, Texas, USA

Ami Rostomyan

(for the Belle II collaboration)

Belle II

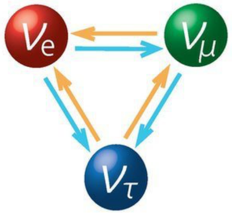
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Lepton flavour conservation

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

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



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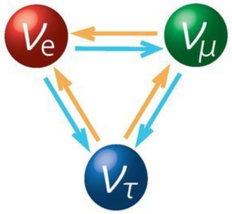

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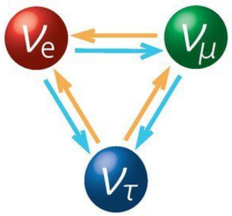

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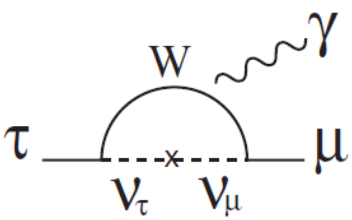
What about the charged leptons?

➡ The charged LFV processes can occur through oscillations in loops

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



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

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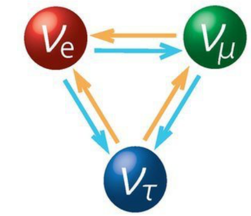

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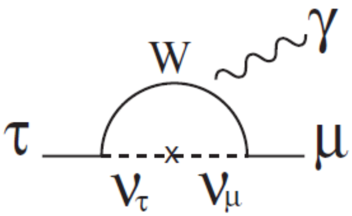

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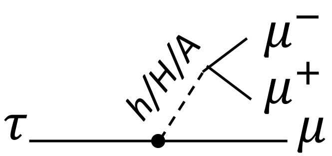
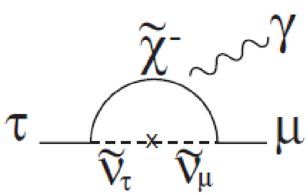
Observation of LFV will be a clear signature of the NP!

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





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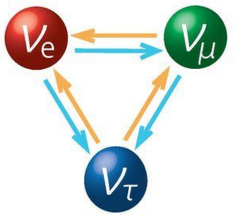

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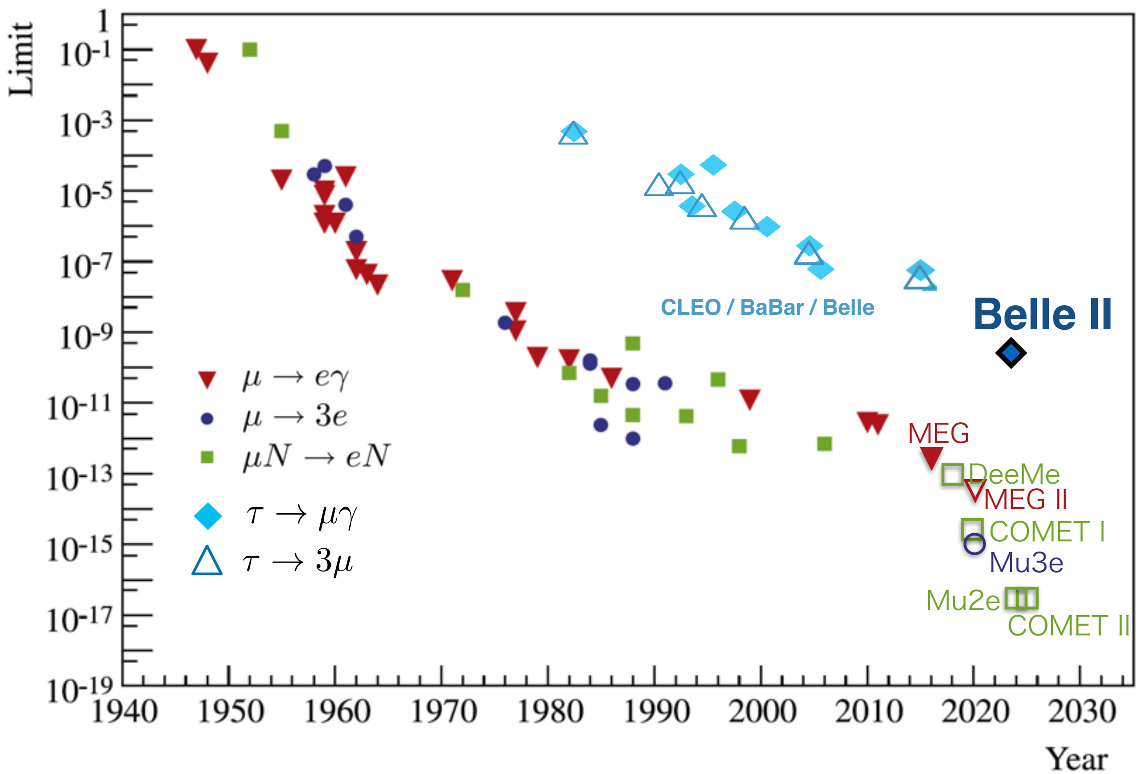

No success in searches so far!

Lepton number conservation

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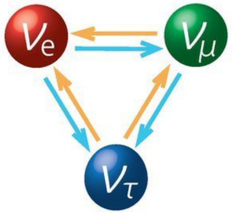

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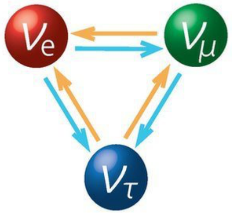

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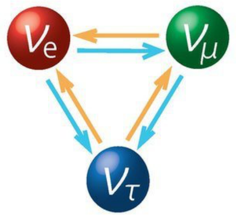

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➡ Heavily suppressed LNV τ-decay rates within the νSM

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

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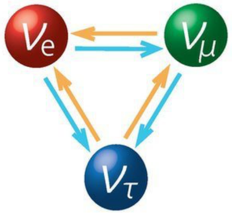

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➡ Immeasurable decay rates with high NP scale, for example in models with heavy right-handed neutrinos

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

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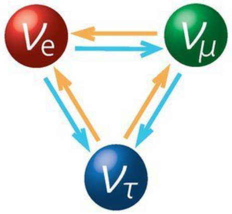

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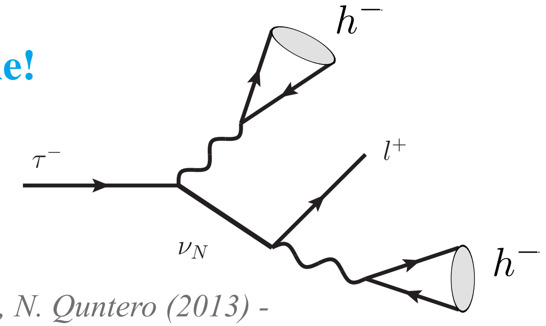
Observation of LNV will hint at light NP scale!

➡ 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) -

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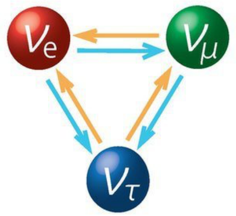

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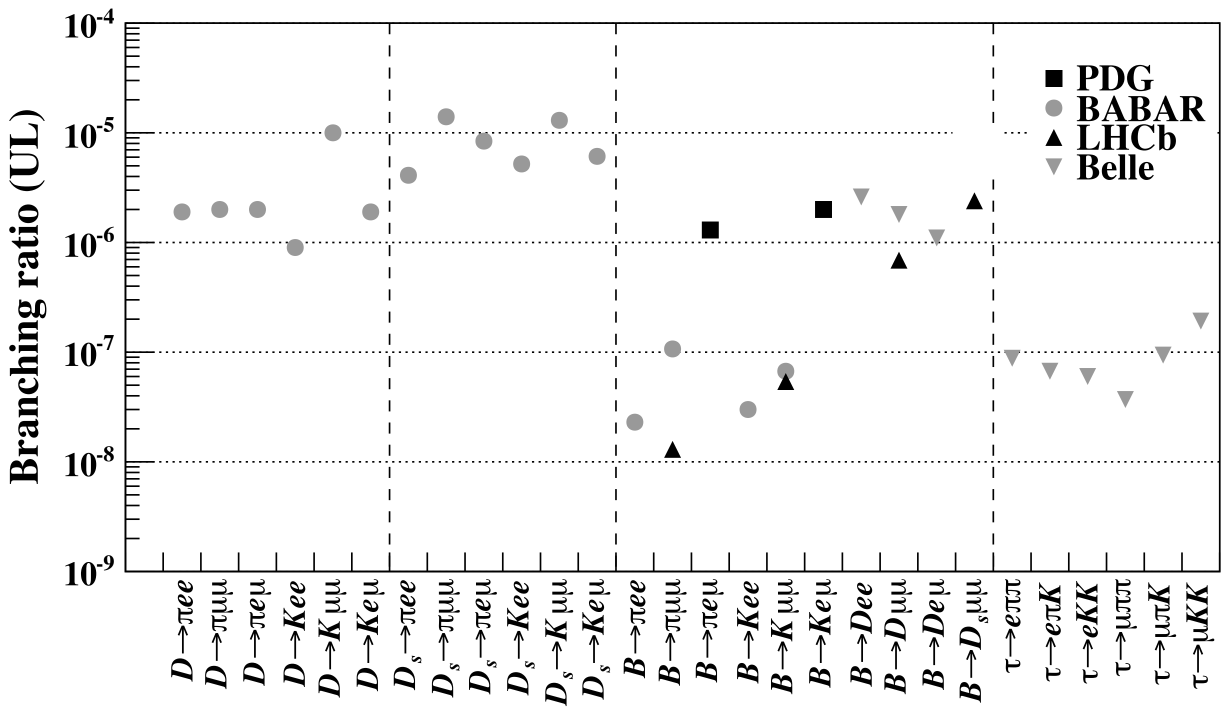
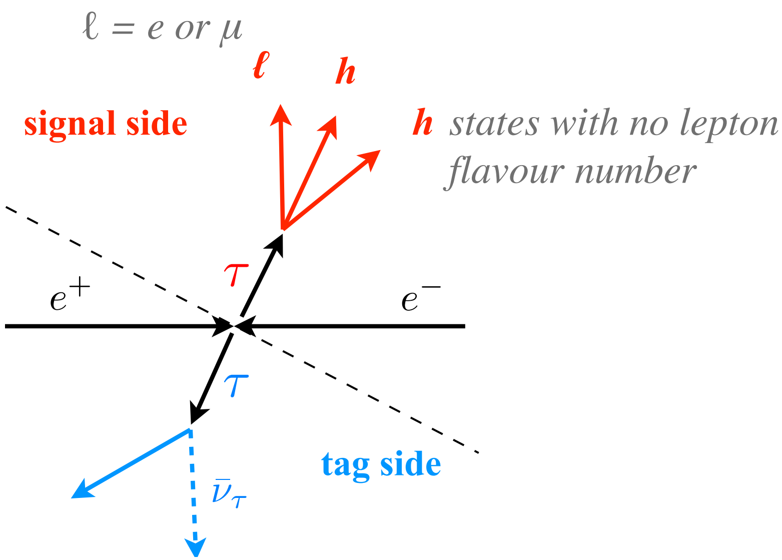


No answer yet!

The role of τ leptons in the quest

NP may favour the third generation!?

The only lepton that decays into hadrons



Test the SM in a variety of ways

- 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 ($\tau \to \ell\ell\ell$)

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

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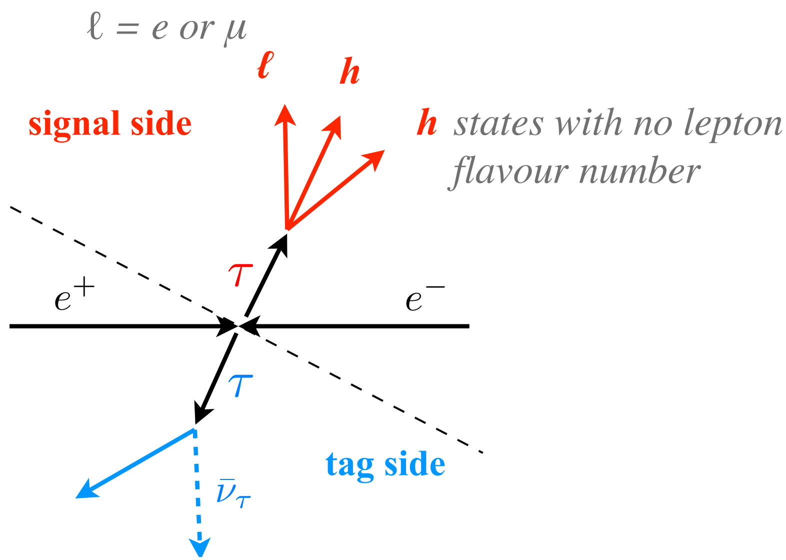
Neutrinos on the tag side



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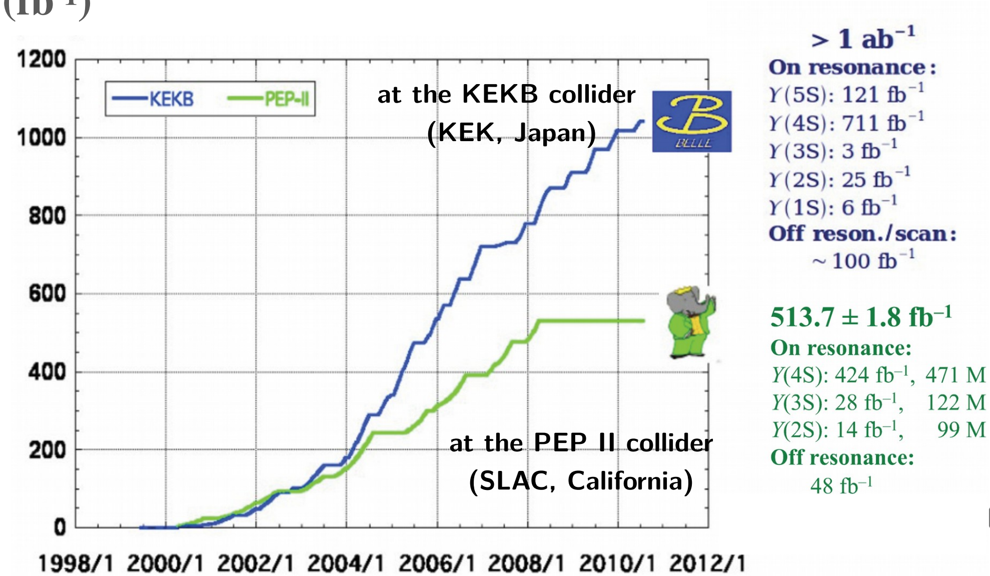
- ➡ τ → μ and τ → e: test of the lepton flavour structure

e^+e^- 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 physics

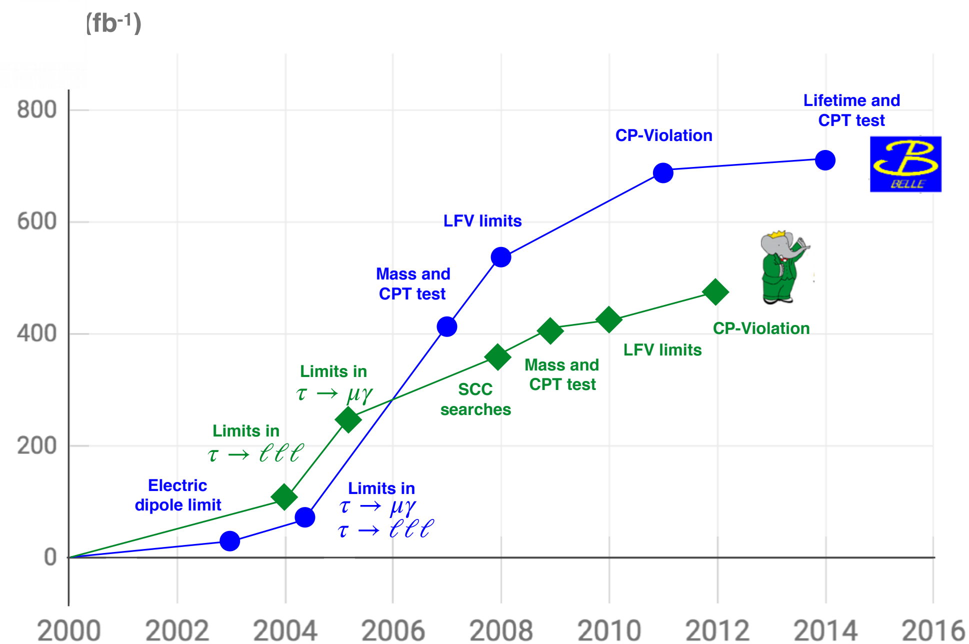
First generation of B-factories
(fb^{-1})



$\sigma(e^+e^- \to \Upsilon(4s)) = 1.05$ nb

$\sigma(e^+e^- \to \tau^+\tau^-) = 0.92$ nb

- clean environment
  - low background, high resolution
- hermetic detectors with
  - excellent PID capability
  - efficient reconstruction of π^0, η, …



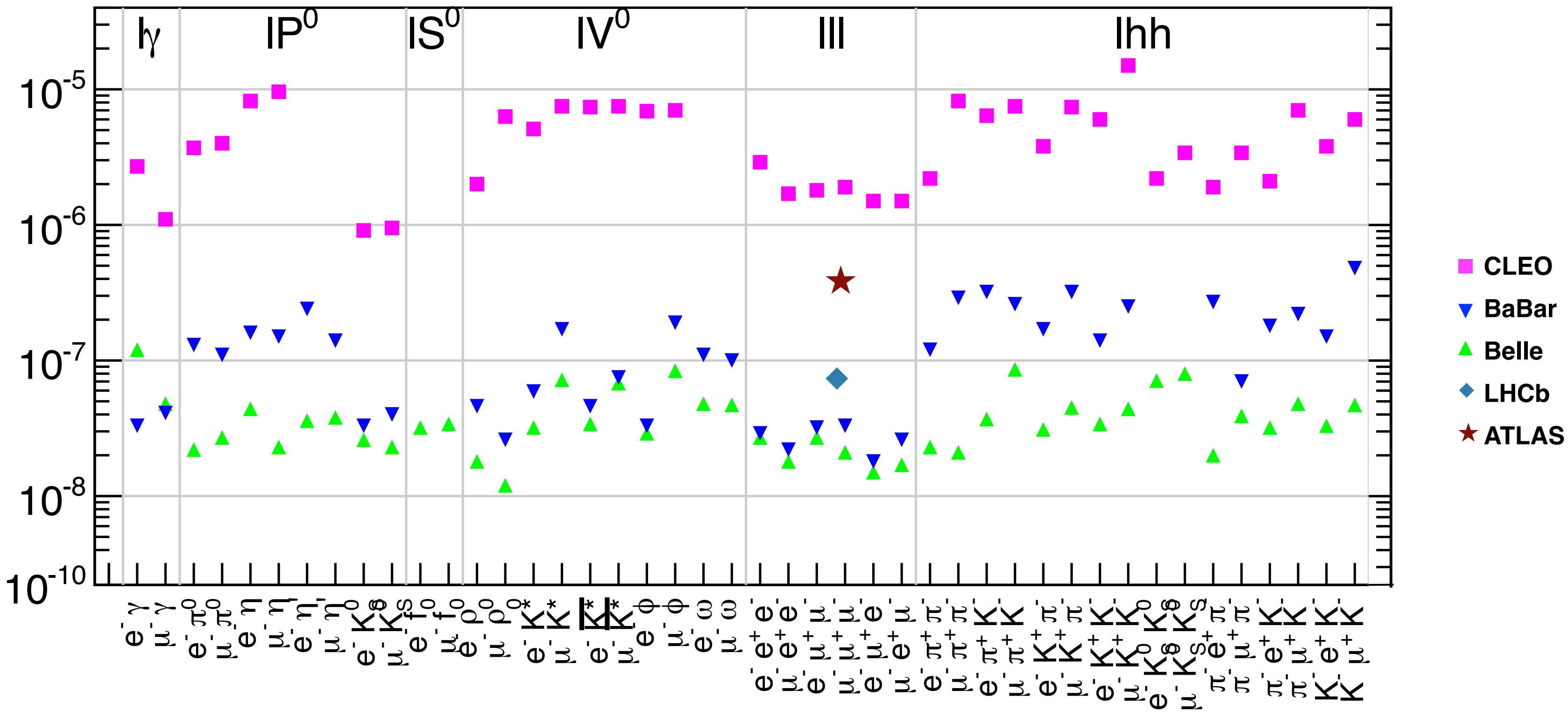
Rich physics program:

- The B-factories provided a variety of very interesting results in the last two decades.

The progress of τ LFV and LNV searches

… mostly occurred at the first generation B-factories

- ➡ immense amount of e^+e^- annihilation data
- ➡ large cross section of pairwise τ-lepton production



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

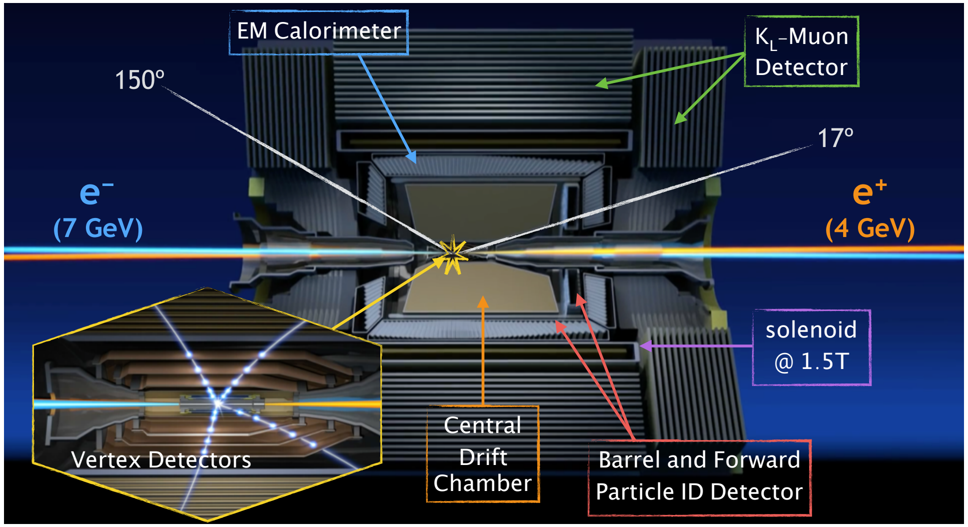
SuperKEKB – major upgrade of the KEKB

- ➡ 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

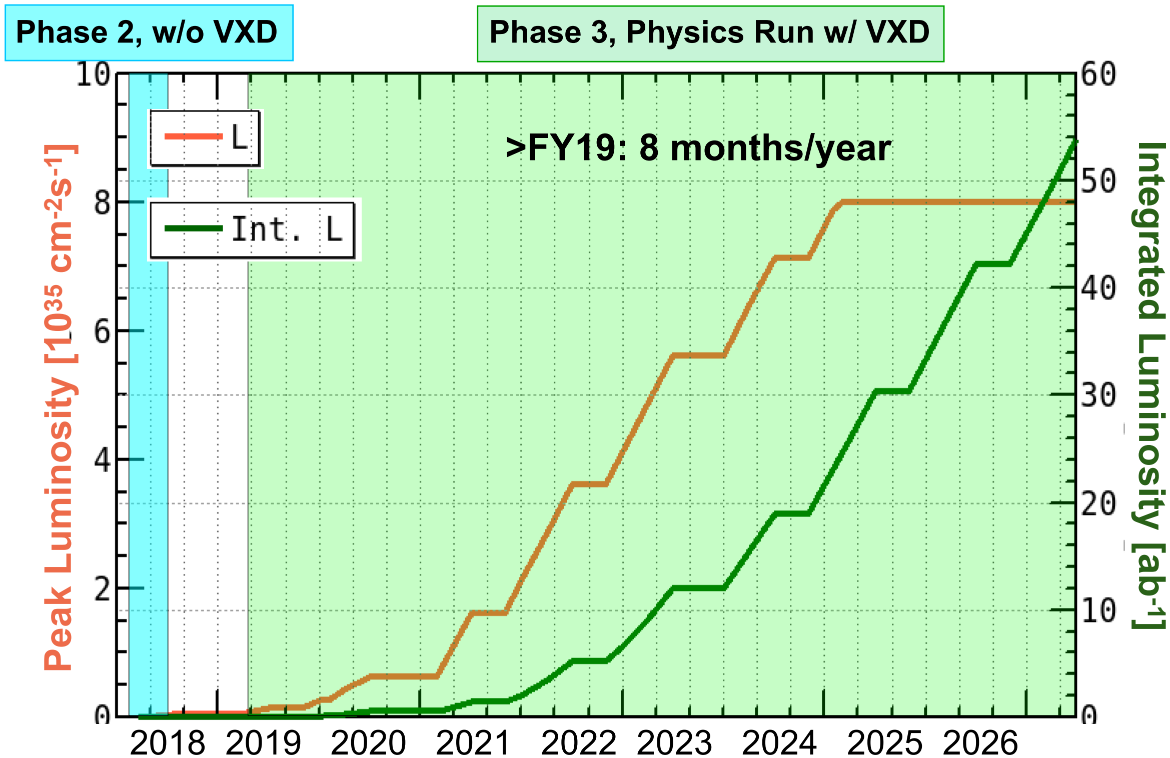
- ➡ no detector over interaction region,
- ➡ study the beam properties

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

- ➡ reached the KEK peak luminosity
- ➡ luminosity milestones:
  - $1ab^{-1}$ by the end of 2021
  - $50ab^{-1}$ by 2027

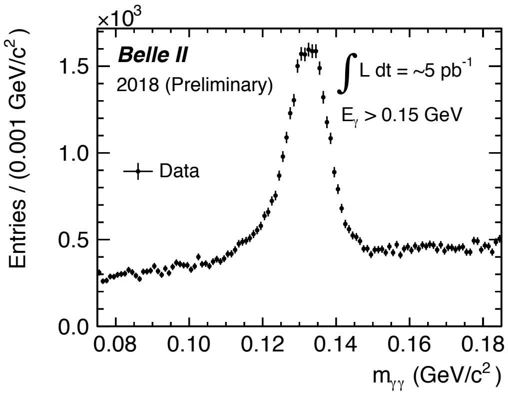


Unique environment to study τ lepton physics with high precision!

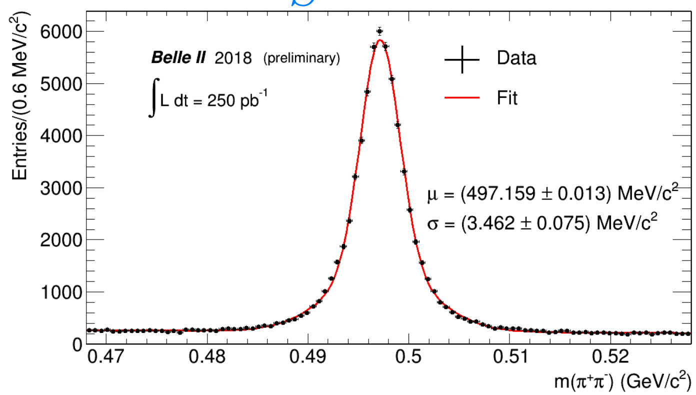
Belle II performance at Phase 2

Collected → 472 pb^{-1} of data → clear mass peaks involving charged tracks and photons

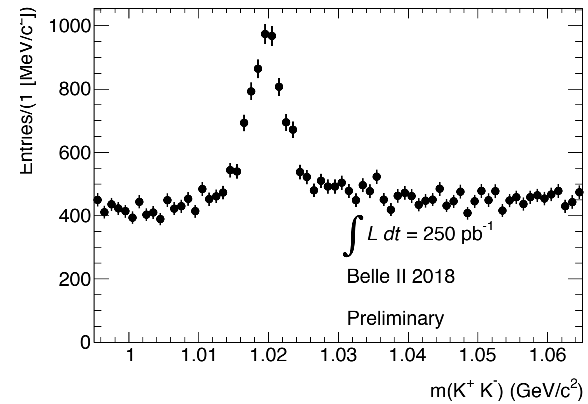
$\pi^0 \to \gamma\gamma$



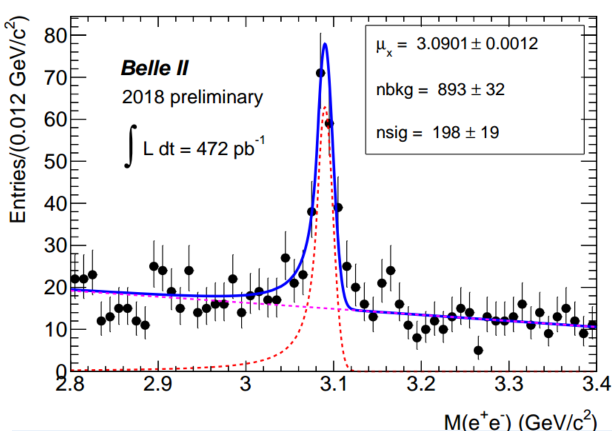
$K_S \to \pi\pi$



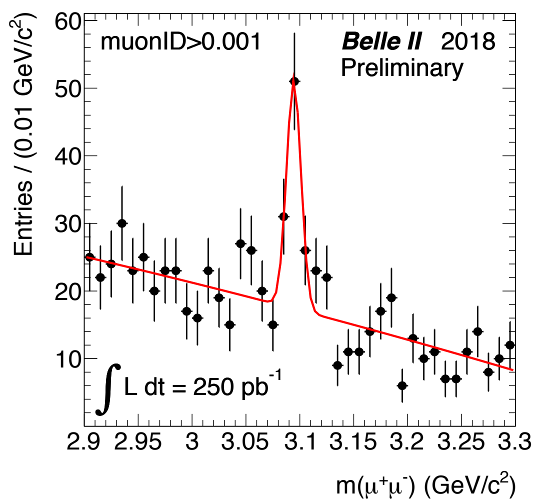
$\phi \to KK$



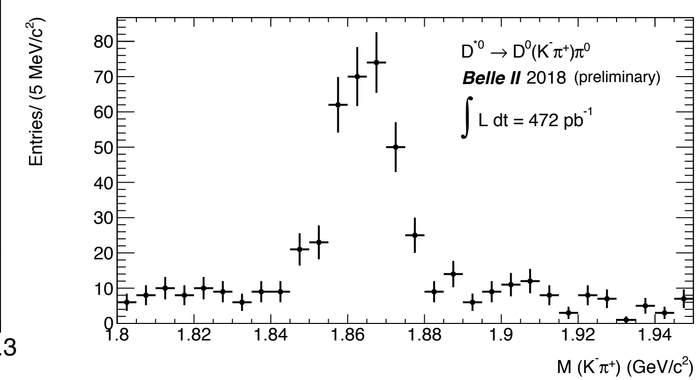
$J/\Psi \to ee$



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

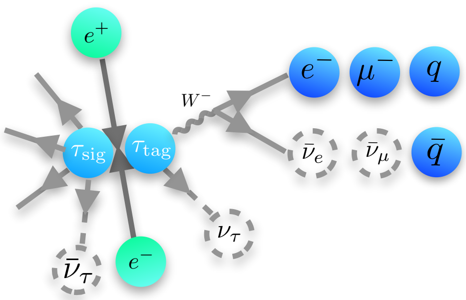


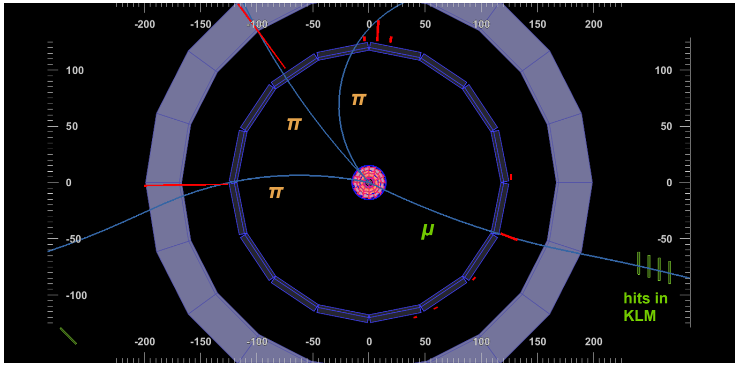
$D \to K\pi$

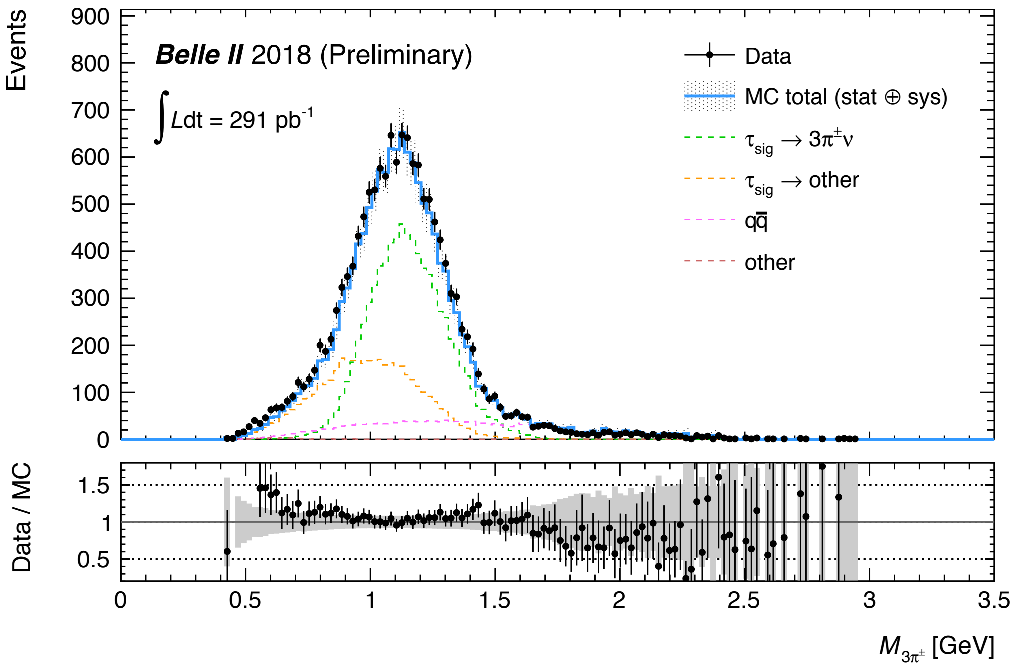


The τ leptons are also observed

Event topology to search for τ leptons





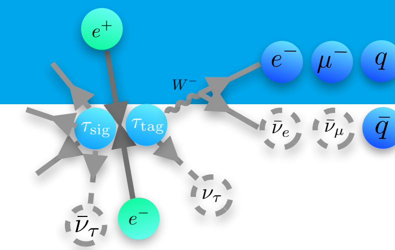


➡ after trigger and offline selections, good agreement between the data and MC

➡ clear evidence for $e^+e^- \rightarrow \tau^+\tau^-$ in the Phase 2 data

➡ demonstration of the capacity for missing energy analyses with Belle II

The τ leptons mass measurement



… cannot be measured directly

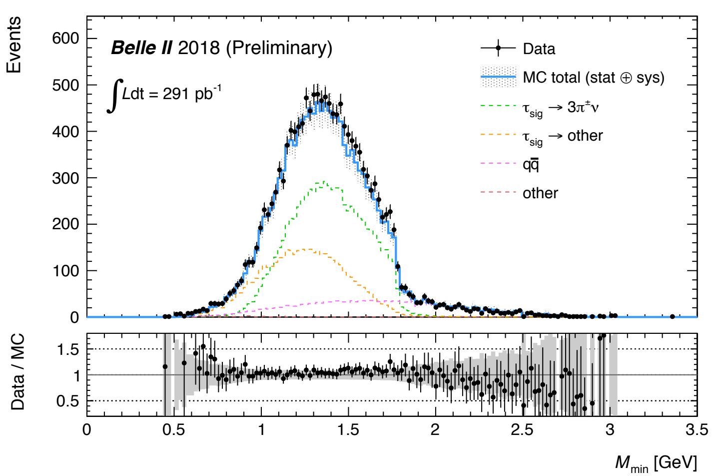
➡ the flight direction is unknown

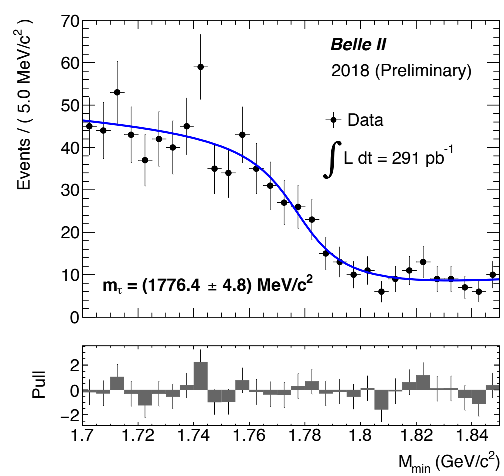
First m_τ measurement at Belle II with a pseudomass technique developed by the ARGUS:

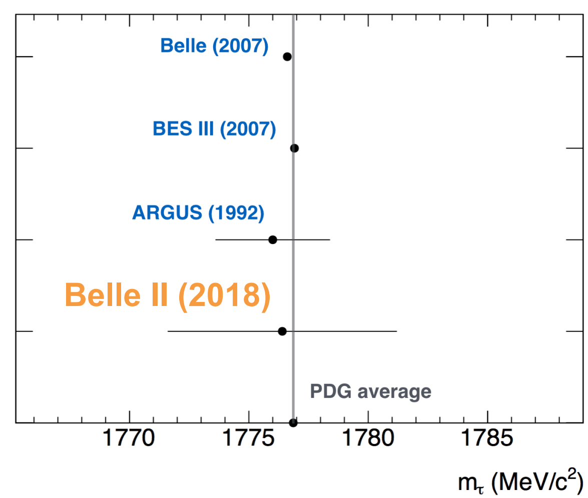
$$M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})}$$

➡ approximate the flight direction of the 3π system to be the τ one

➡ pseudomass distribution is expected to exhibit a sharp threshold behaviour in the region close to the nominal value of the τ mass



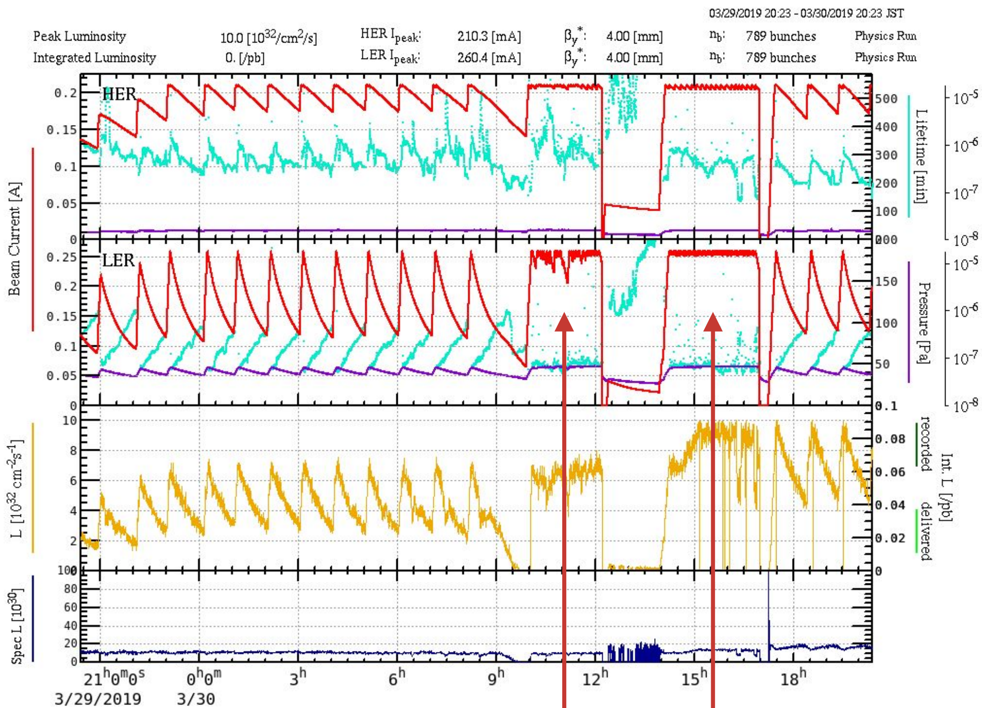




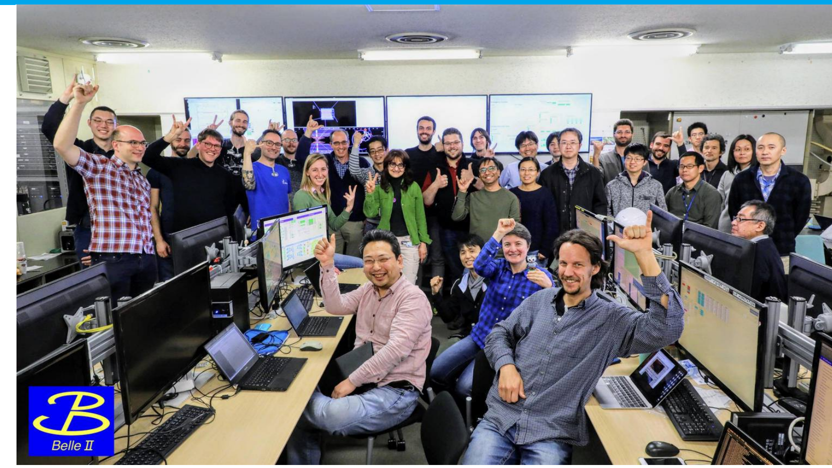
➡ good agreement with previous measurements

$m_\tau = 1776.4 \ \pm \ 4.8 \ (stat) \ MeV$

Phase 3 data taking started



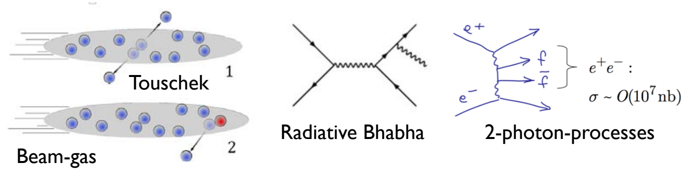
Continuous Injection
(~60% integrated luminosity increase)

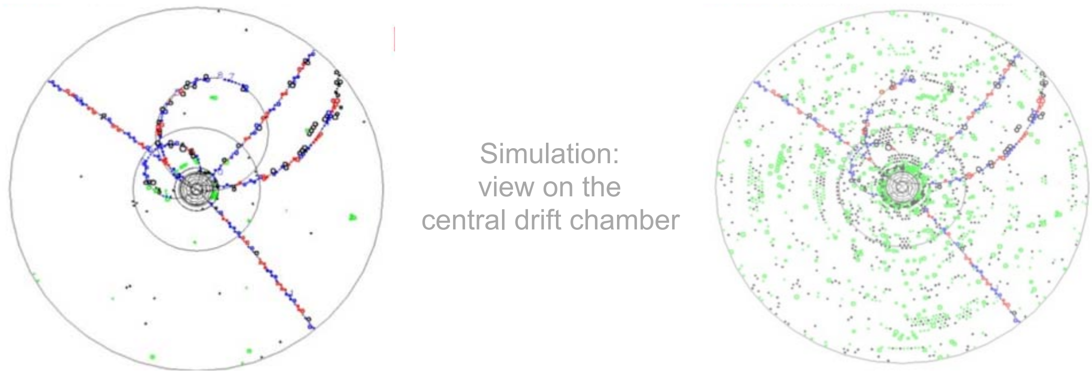


- data taking started again in March 2019
- already collected 1 fb^{-1}
  - comparable with Phase 2
- Goals:
  - ~10 fb^{-1} by July 2019
  - ~100 fb^{-1} by December 2019

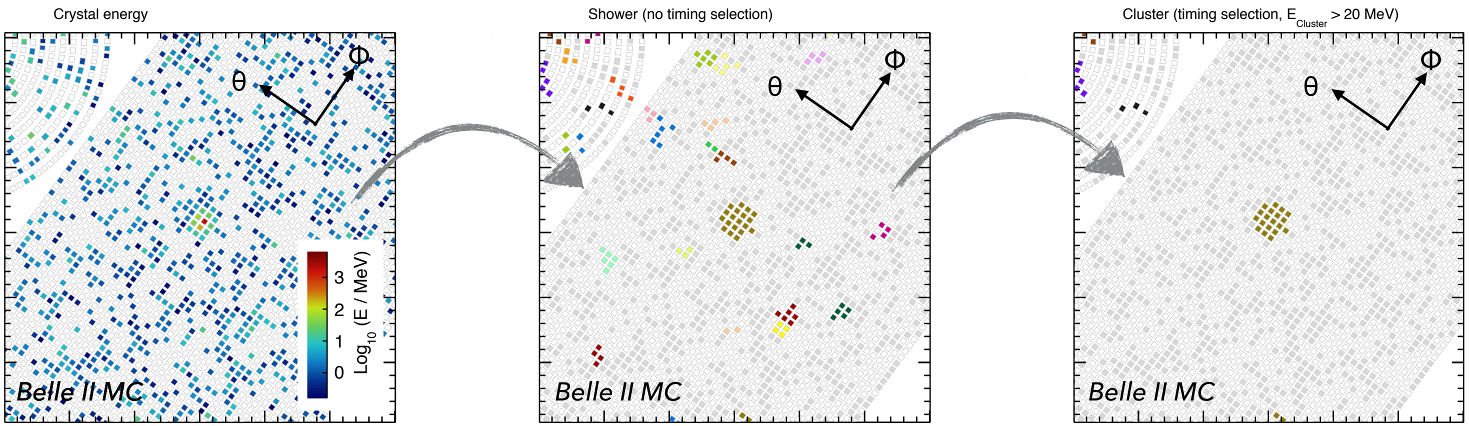
Beam background

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





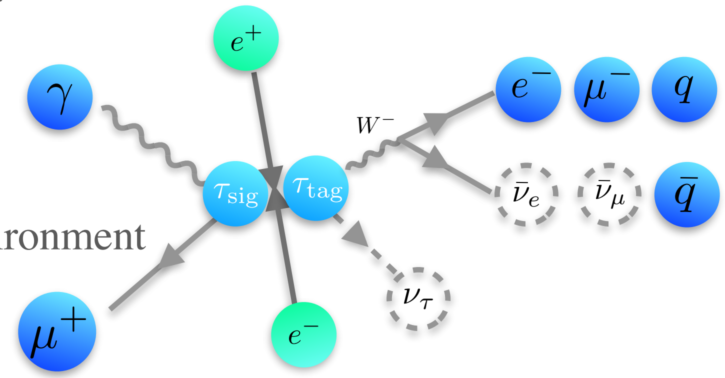
Use the timing information from calorimeter to reduce the background



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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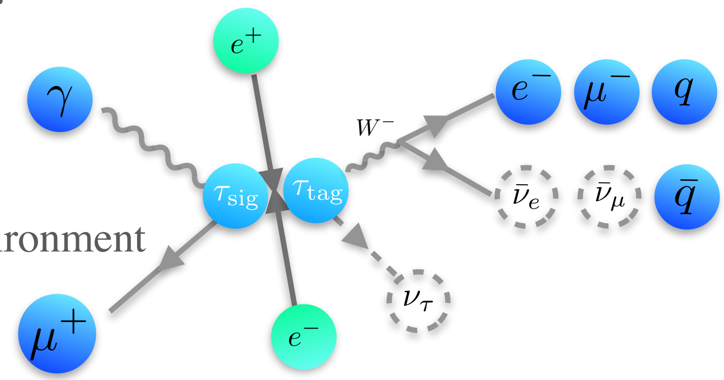
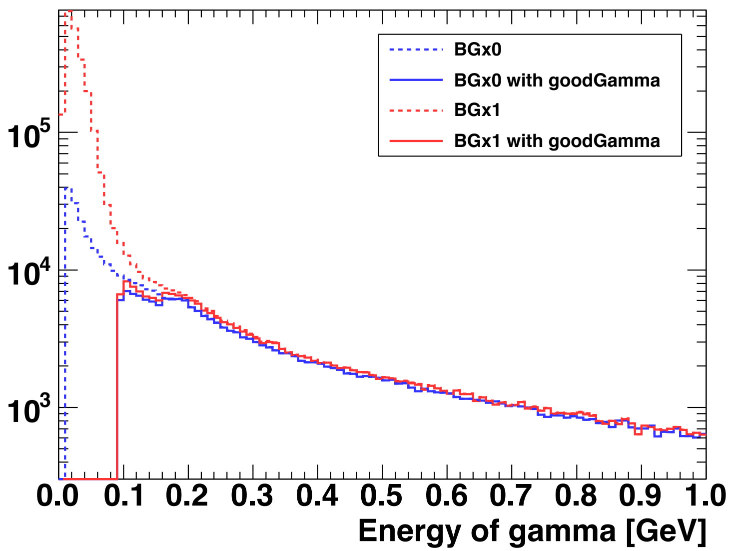
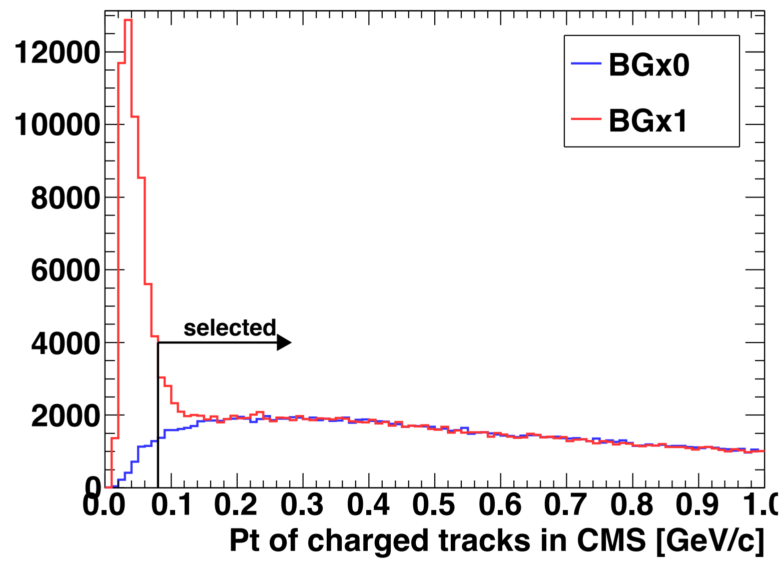


Energy-based cuts to reduce the background

- The Belle II Physics Book -
arXiv:1808.10567v2





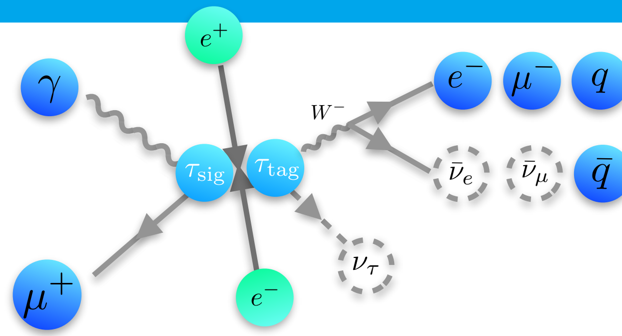
Background-free search (even with high beam BG)

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



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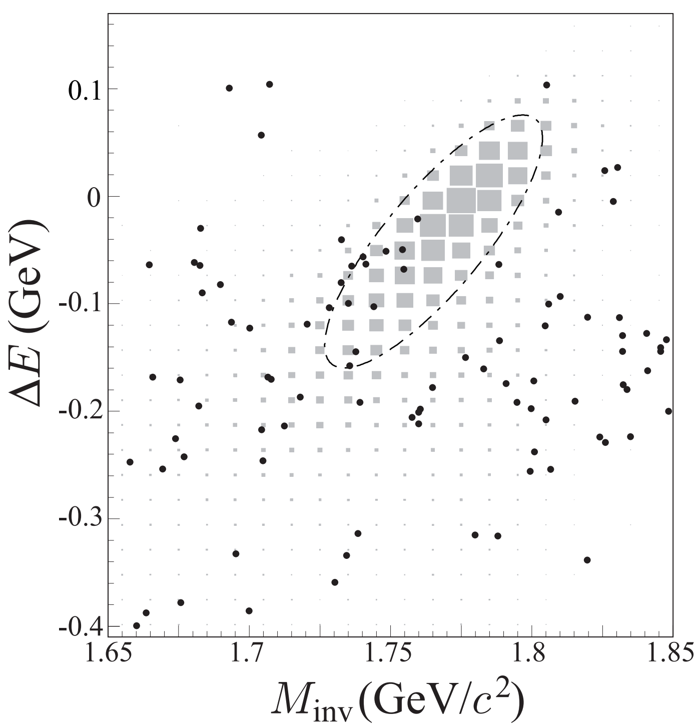
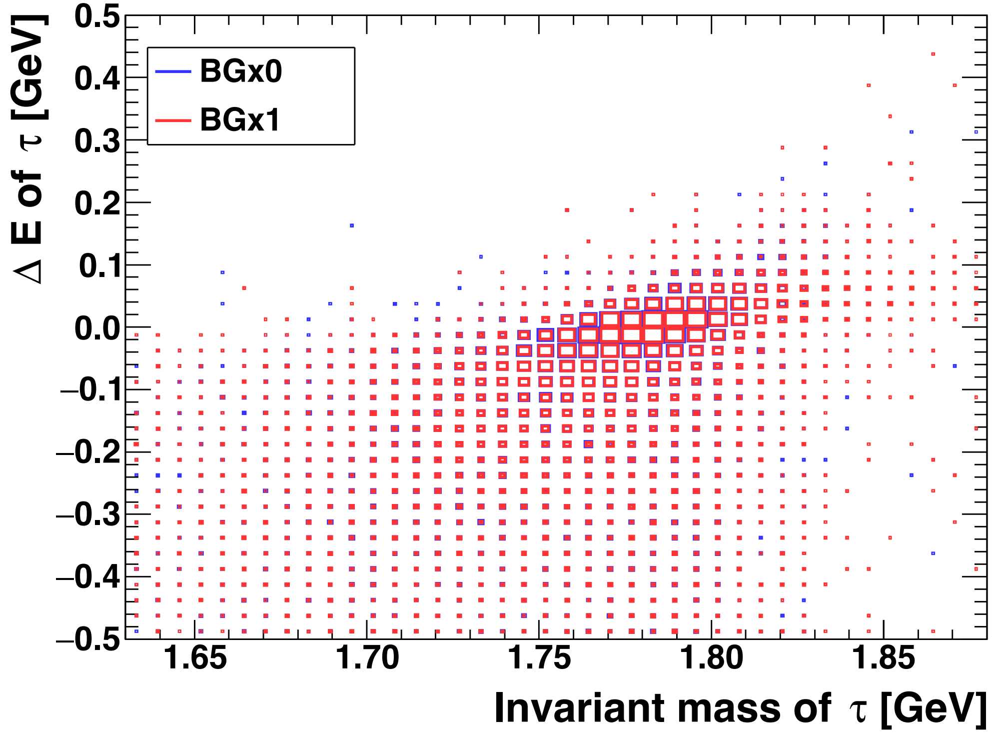
Phys. Lett., B666, 16–22 (2008)

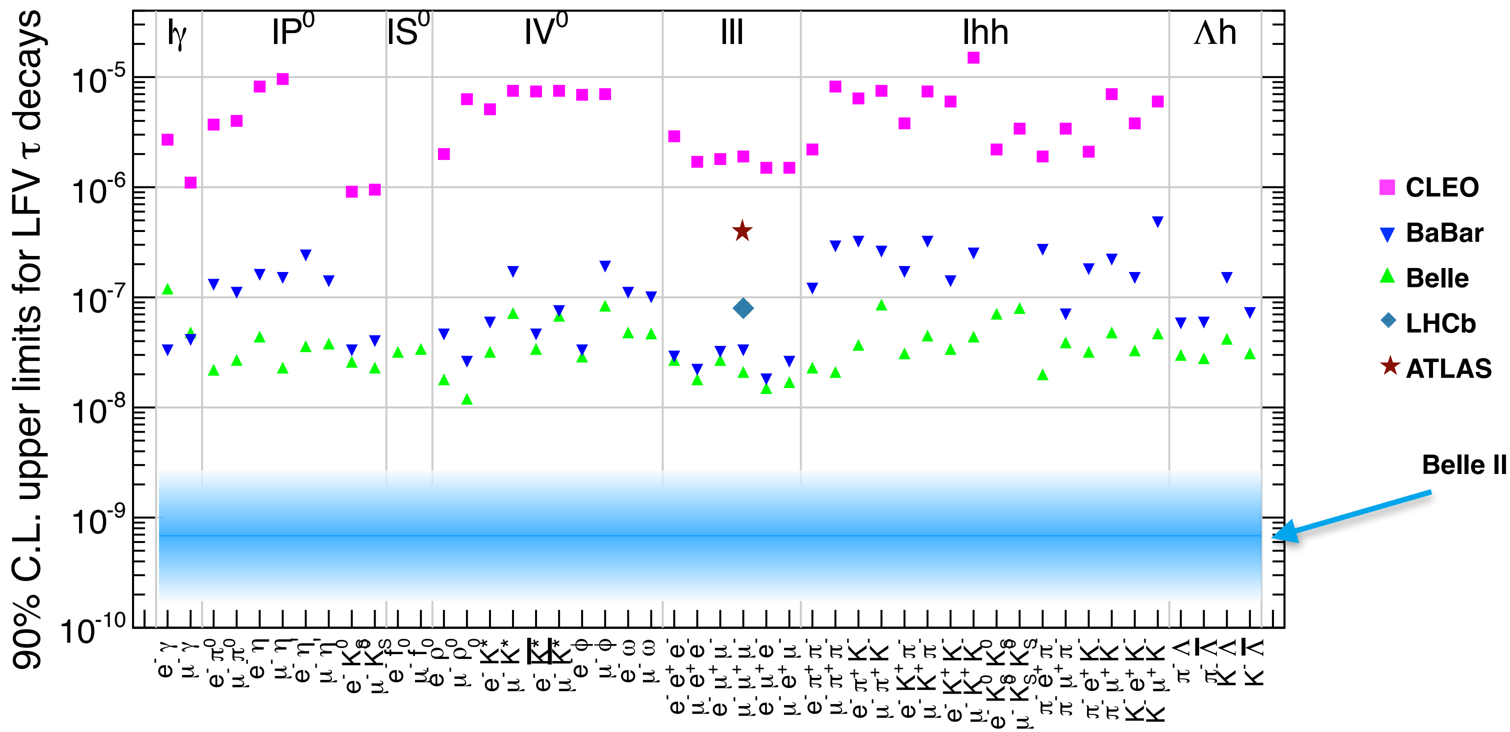




Perspectives at Belle II

LFV and LNV τ decays

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

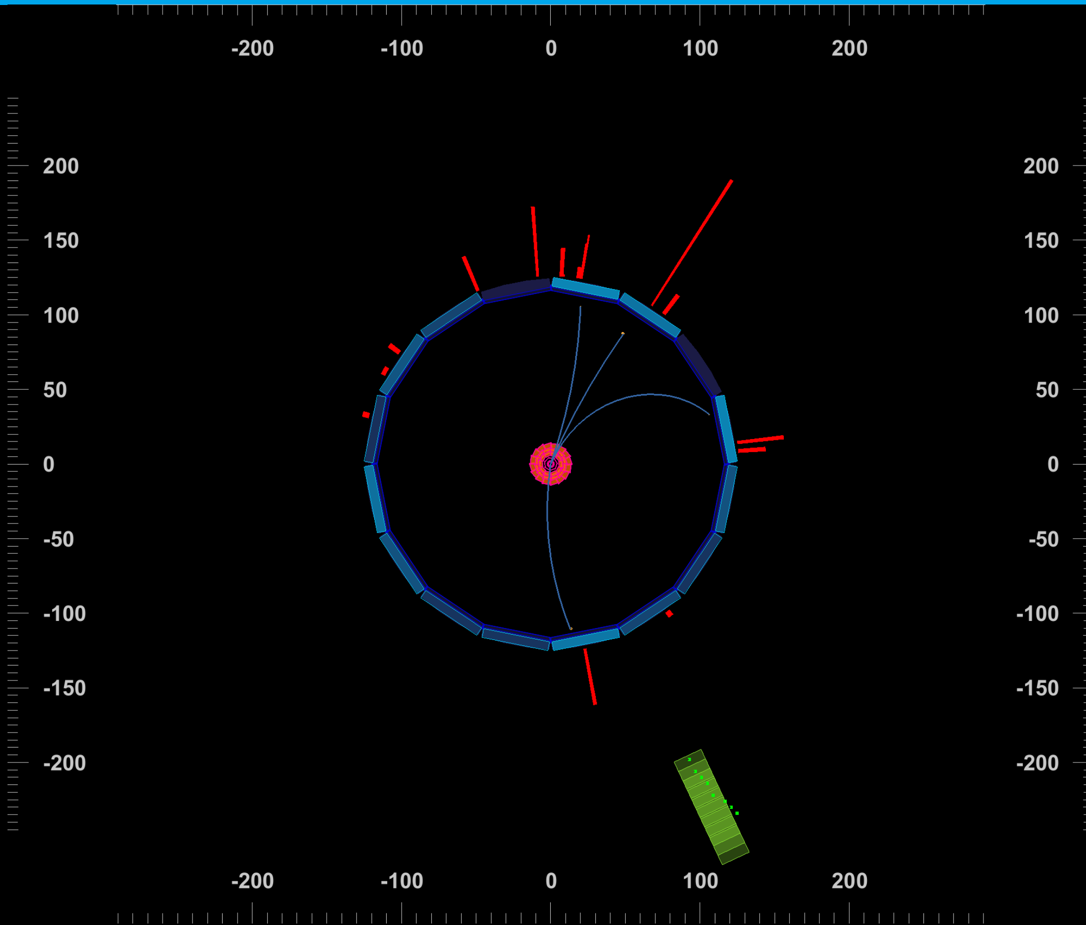


➡ Equally important is the increase of the signal detection efficiency

➡ 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

Outlook



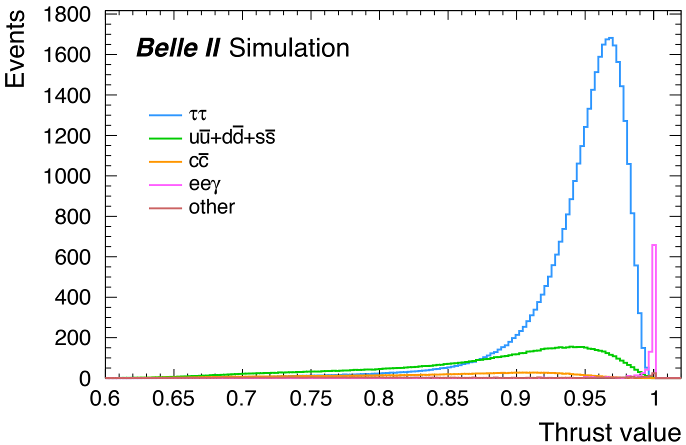
- ➡ The data with the full detector installed started in early 2019
- ➡ Belle II will probe New Physics in many channels with neutrinos in the final state
- ➡ Belle II will be the major player in τ physics in the near future
- ➡ Very exciting times are ahead!

Backups

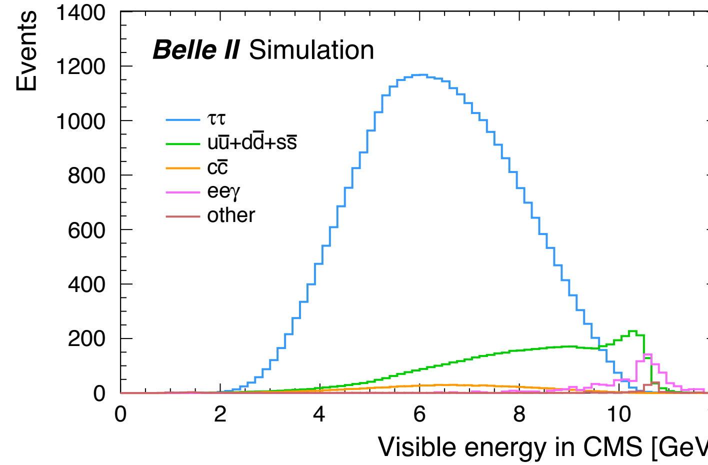
… and the τ leptons

Event topology and kinematics to observe τ leptons

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



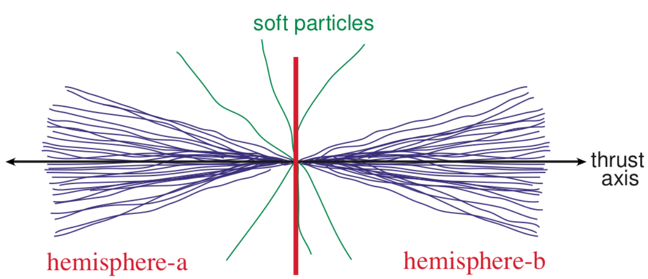
➡ undetected neutrinos in τ events

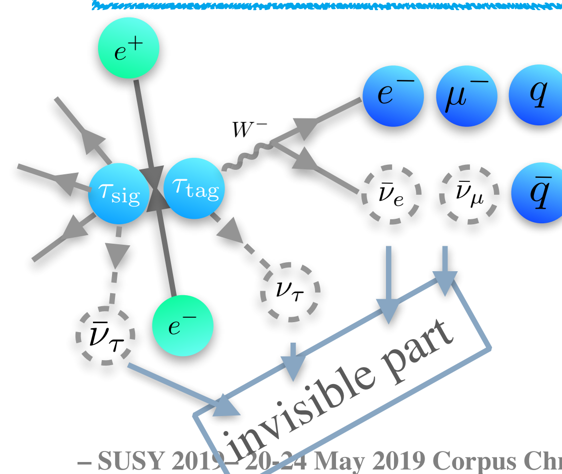


Thrust axis ($\boldsymbol{T}$) is maximising the event shape variable

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

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

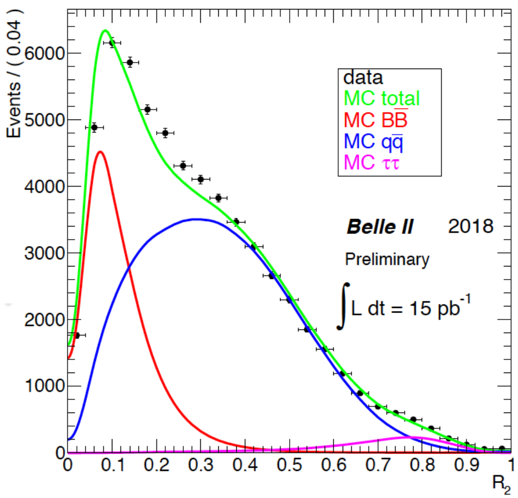




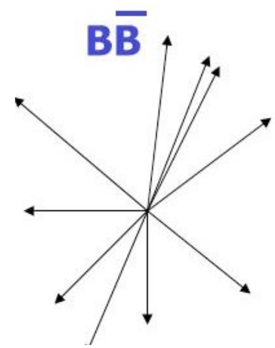
Few B mesons were also seen

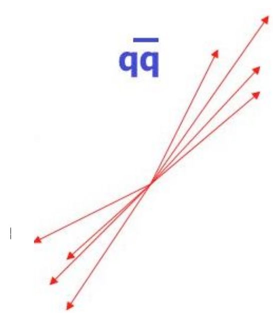
Event topology to see B mesons

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



Spherical R_2 Jet-like



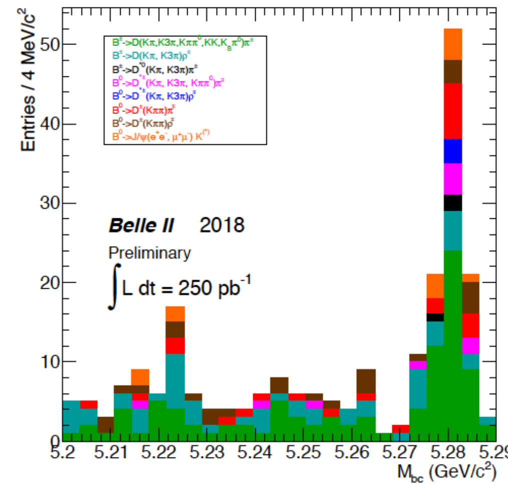


$$R_2 = \frac{H_2}{H_0}$$

momentum of particles — Legendre polynomial — angle between two particles

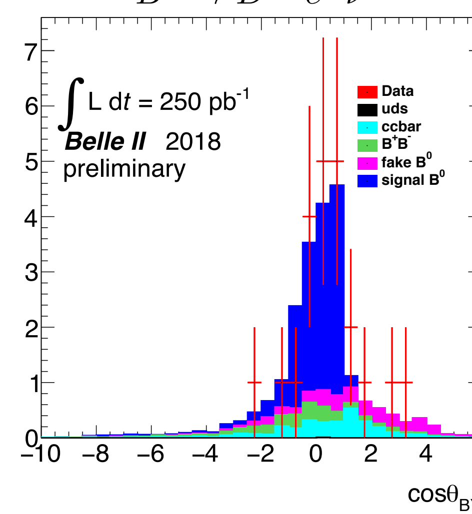
$$H_l = \sum_{ij} \frac{|p_i||p_j|}{E^2_{\text{vis}}} P_l(\cos\theta_{ij})$$

Hadronic decay modes

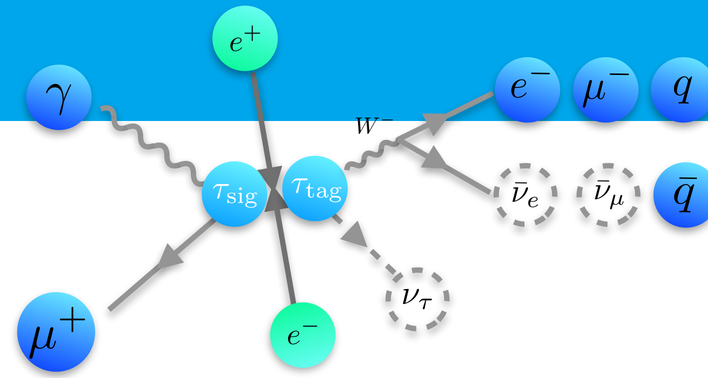


Semileptonic decay modes

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



Previous searches at Belle



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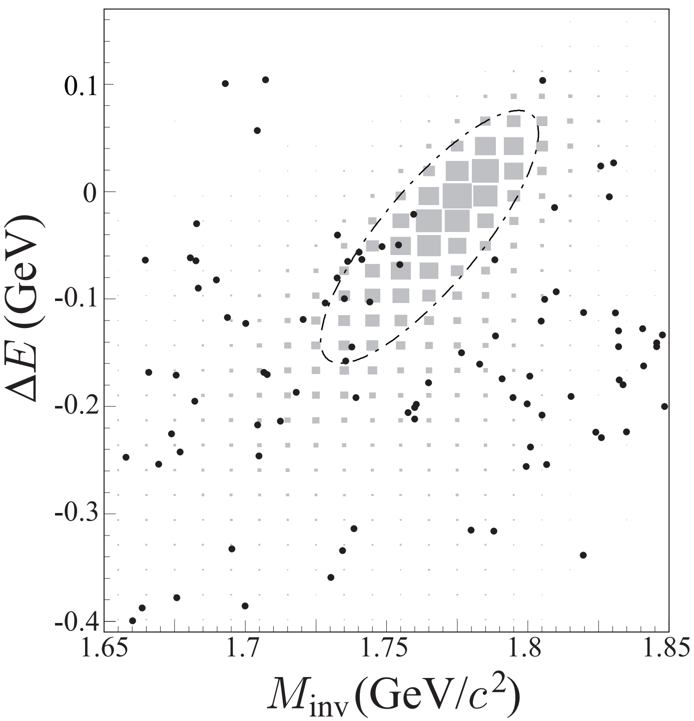

Main background sources:

➡ $\tau \rightarrow \mu\nu\nu$
➡ $\tau \rightarrow e\nu\nu$
➡ $\tau \rightarrow \pi\nu$

$\} + \gamma$

➡ $e^+e^- \rightarrow ee(\mu\mu)\ \gamma$

➡ $e^+e^- \rightarrow$ 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

➡ …

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	✓	✓	✓	✓	–	–
	O^q_V	–	–	✓ (I=1)	✓(I=0,1)	–	–
	O^q_S	–	–	✓ (I=0)	✓(I=0,1)	–	–
lepton-gluon	O_{GG}	–	–	✓	✓	–	–
	O^q_A	–	–	–	–	✓ (I=1)	✓ (I=0)
	O^q_P	–	–	–	–	✓ (I=1)	✓ (I=0)
	$O_{G\tilde{G}}$	–	–	–	–	–	✓

lepton-quark

- Celis, Cirigliano, Passemar (2014) -

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