Tau Lepton Physics at Belle II

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on behalf of the Belle II collaboration

International Workshop on e^+e^- Collisions from Phi to Psi

BINP, Novosibirsk, 1 March 2019

Outline

1) Overview of SuperKEKB and the Belle II experiment

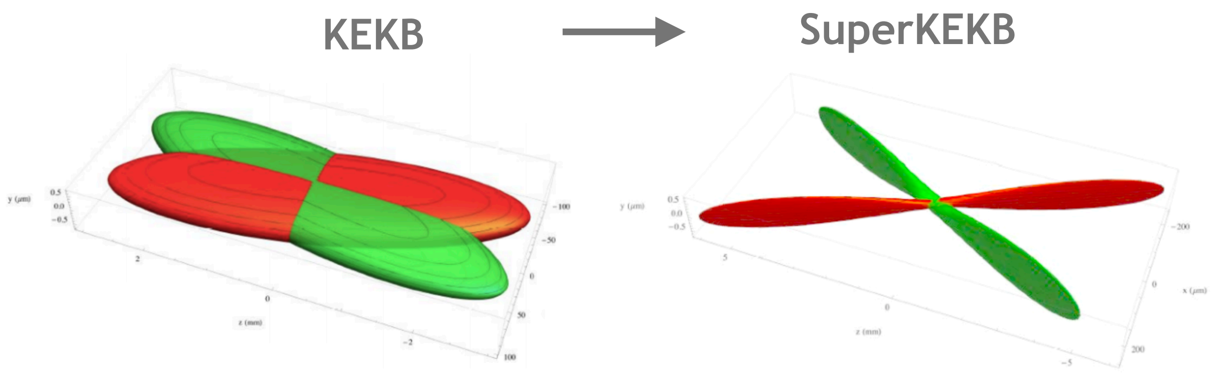
2) First τ lepton physics results using early data

3) Prospects for τ lepton physics at Belle II

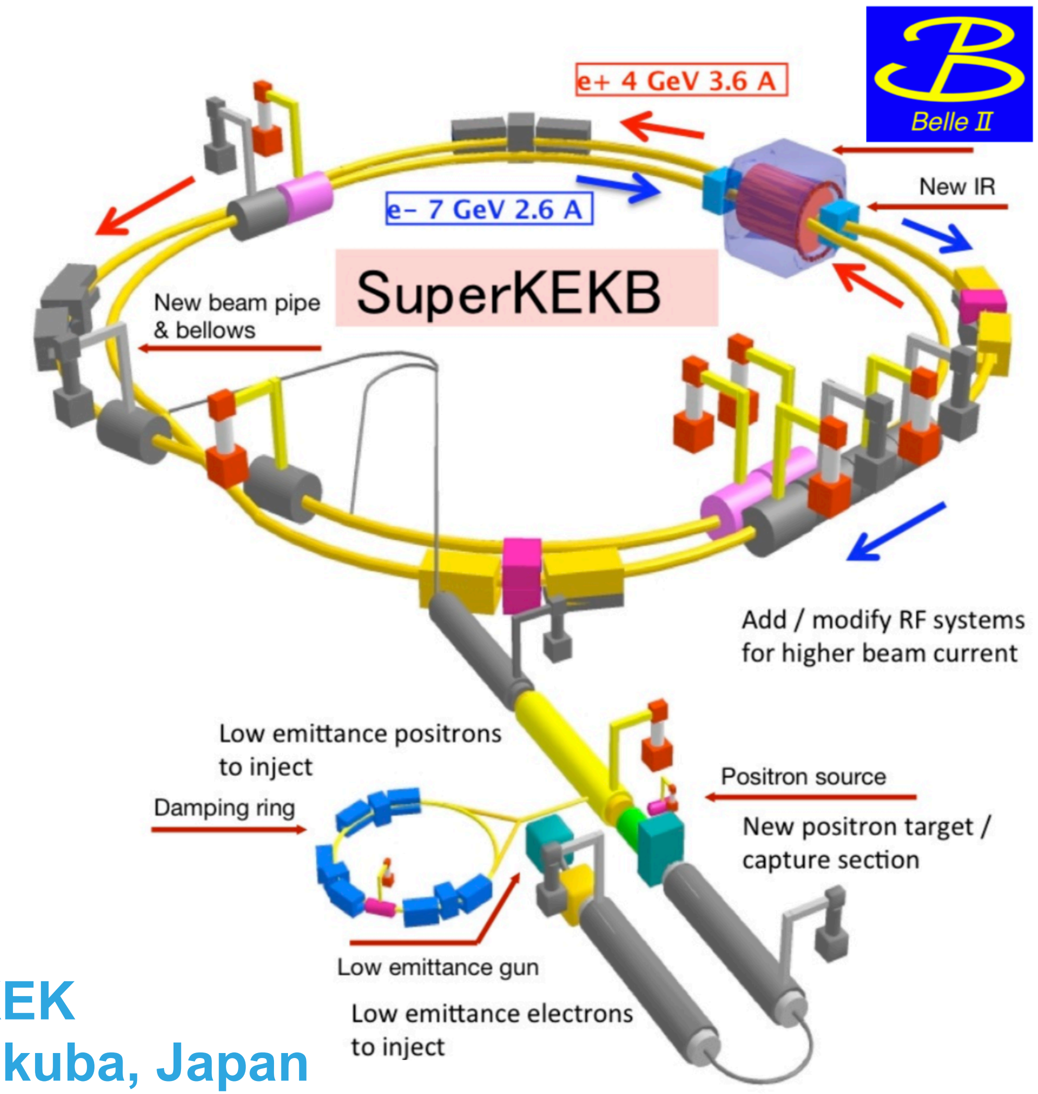
4) Summary and outlook

SuperKEKB Accelerator

- New facility to search for physics beyond the SM by studying *B*, *D* meson and τ lepton decays
- Energy asymmetric electron-positron collider (7-4 GeV)
- Higher beam currents compared to KEKB, and can achieve 50 nm vertical beam spot size at IP:



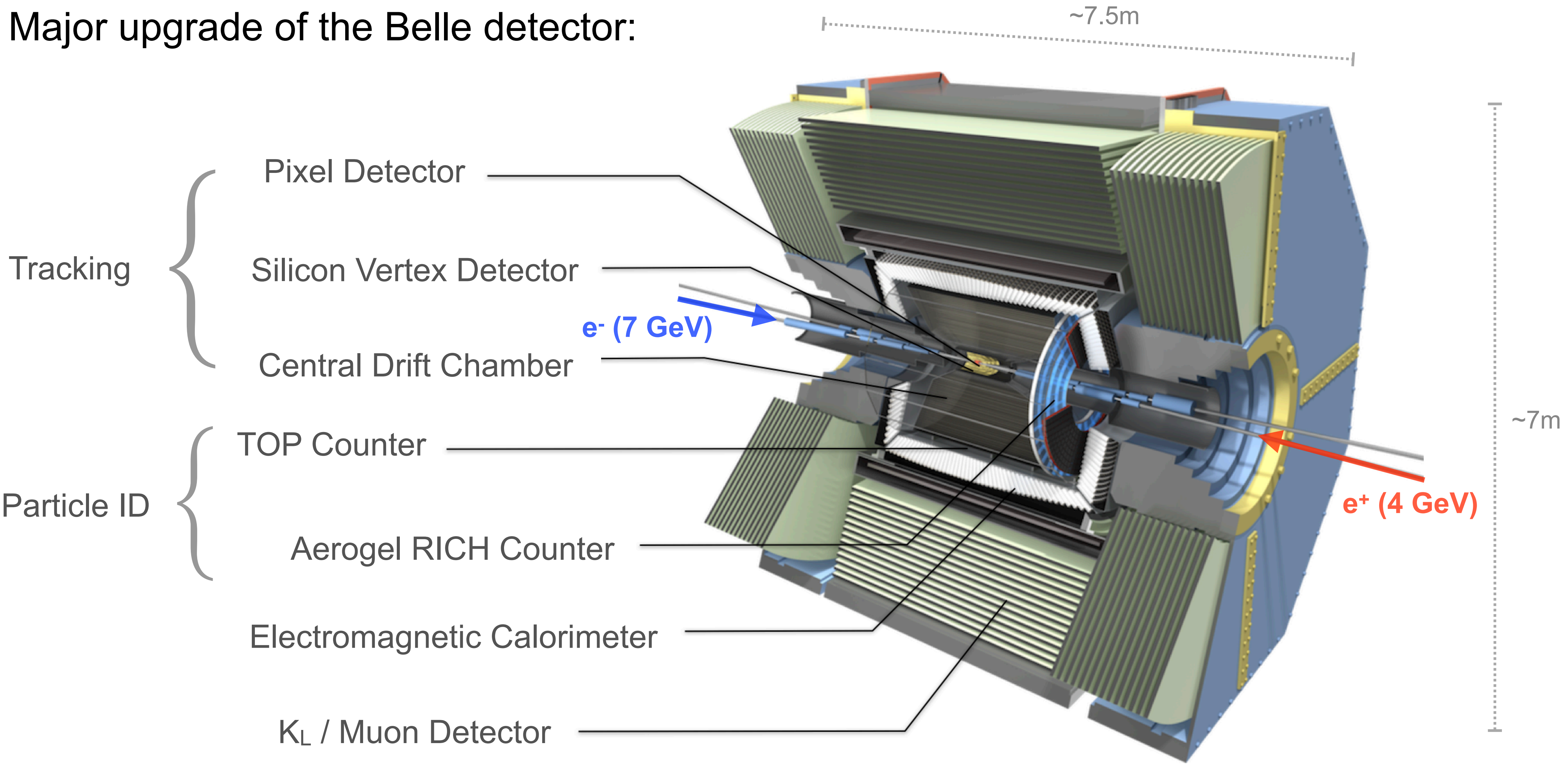
- Unprecedented design luminosity of 8.0×10^{35} $cm^{-2}s^{-1}$
- First beams and commissioning in 2016, Belle II detector rolled in 2017



@KEK
Tsukuba, Japan

Belle II Detector

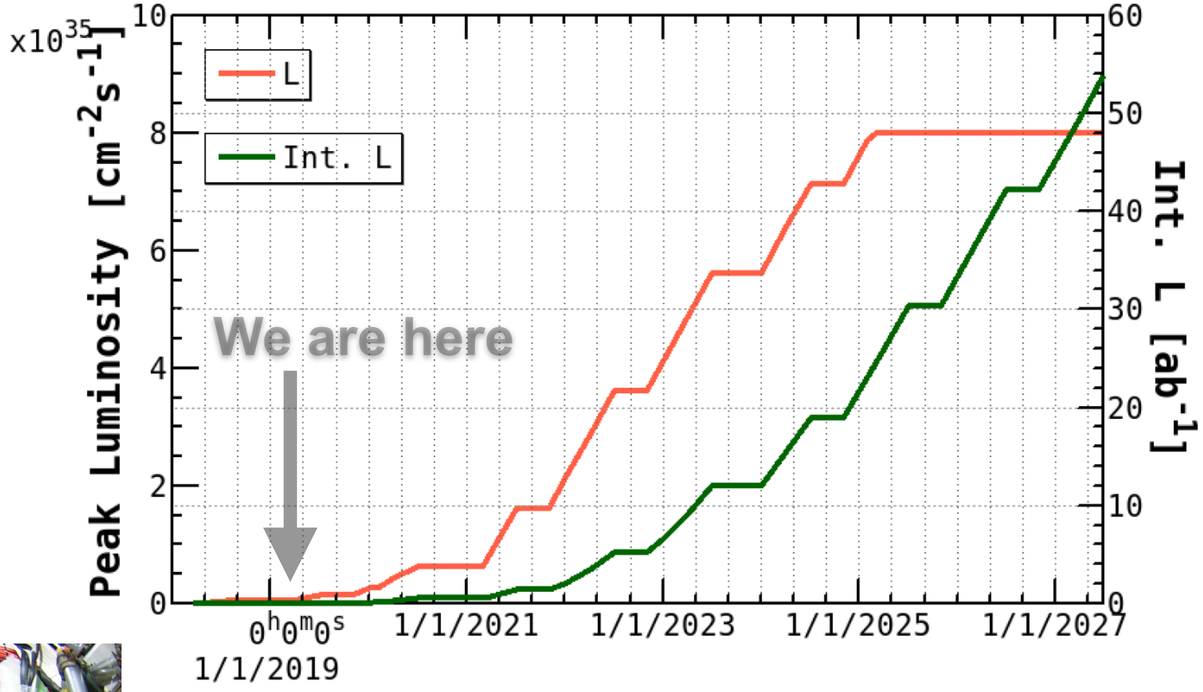
- Major upgrade of the Belle detector:



Belle II as τ-factory, and schedule

- Belle II is not only a *B*-factory, but a next-generation **τ lepton factory**
  - $\sigma(e^+e^- \to \Upsilon(4s))$ = 1.05 nb, $\sigma(e^+e^- \to \tau^+\tau^-)$ = 0.92 nb

- Over its lifetime Belle II aims to record 50 ab^{-1} of e^+e^- collision data (x50 that of Belle)
  - 4.6×10^{10} τ-pair events
  - **unique environment to study τ lepton physics with high precision!**

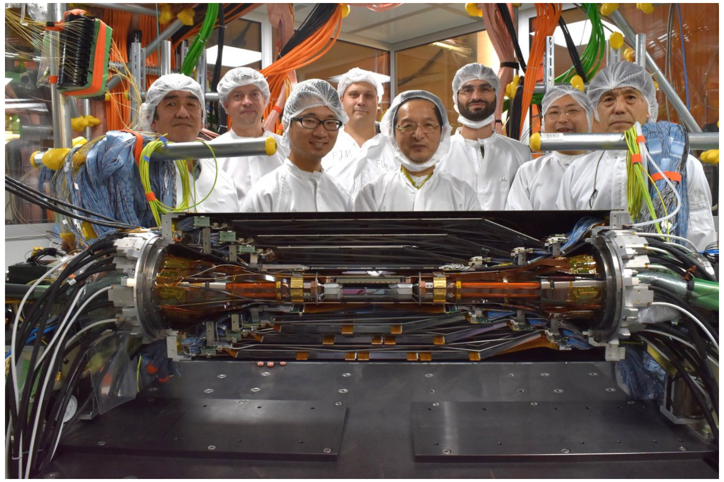


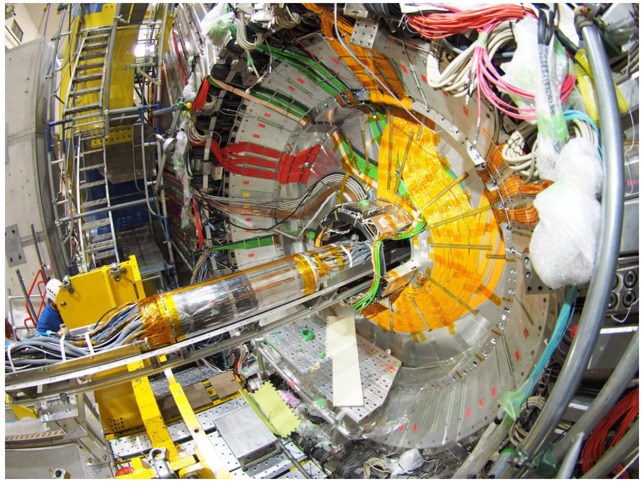
Phase II

(2018, 3 months)

Phase III

(starting later this month)

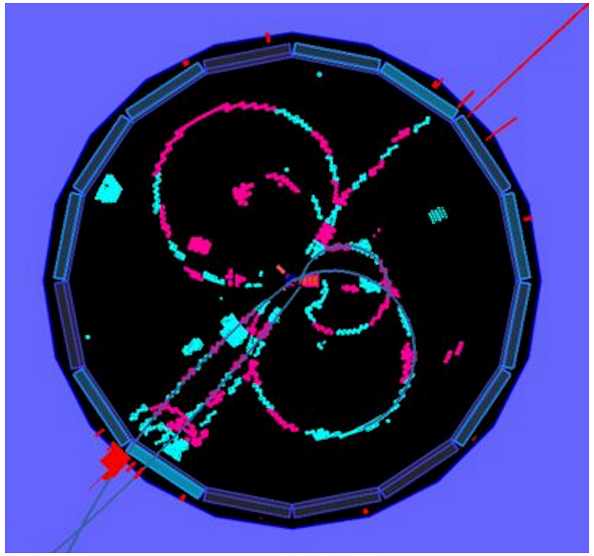


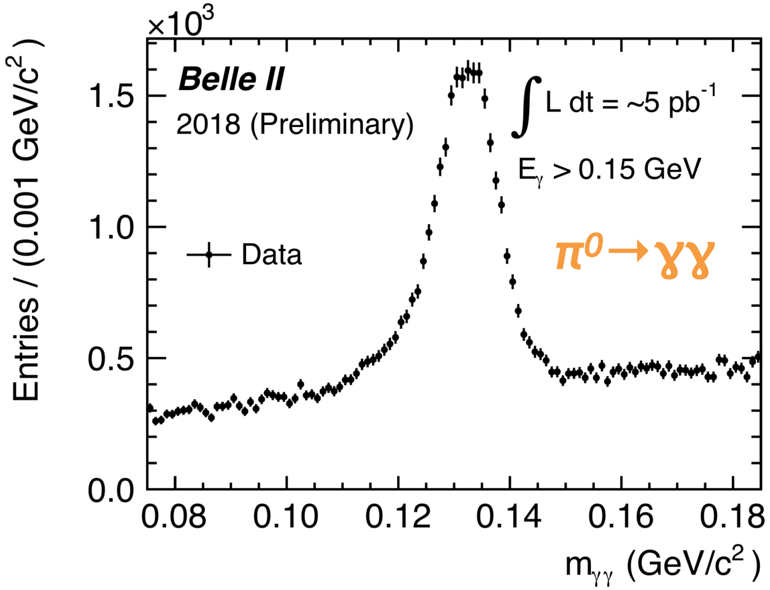


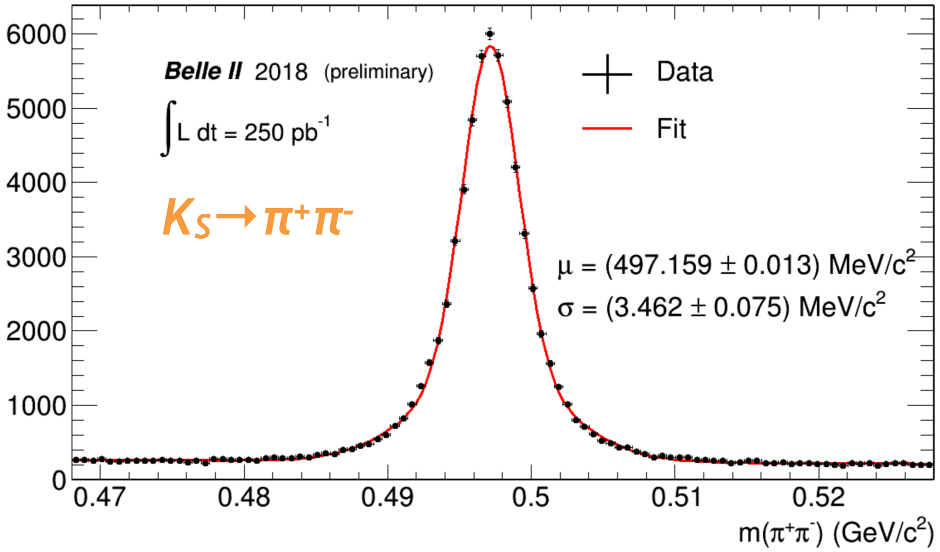
- Data taking in **Phase II** was performed with all subsystems, except full vertex detector
- VXD now installed and ready for **Phase III**

First collisions

- First collisions recorded by Belle II on 26th April 2018
- During Phase II (April-July) about **500 pb^{-1}** of data was recorded
- Good performance of the subsystems. Clear mass peaks observed from both tracks and photons.
- τ leptons also observed…

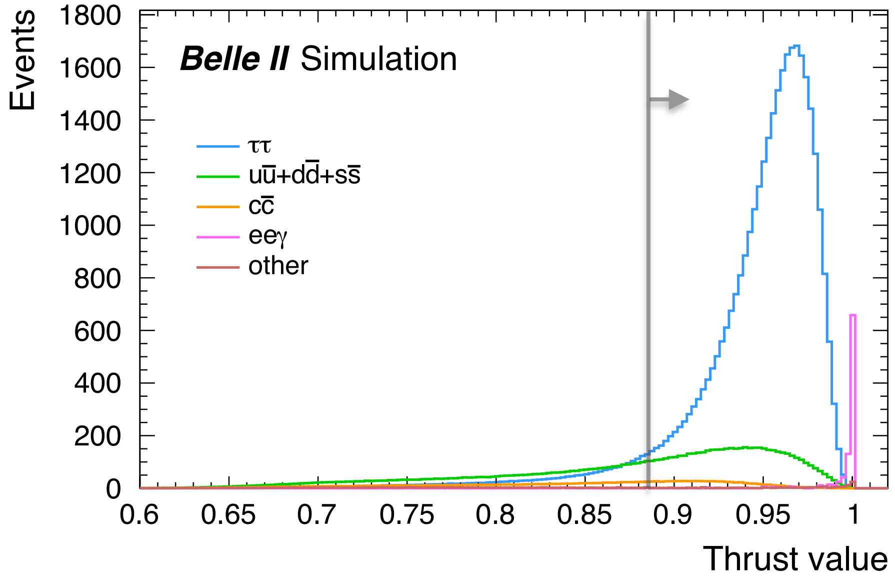


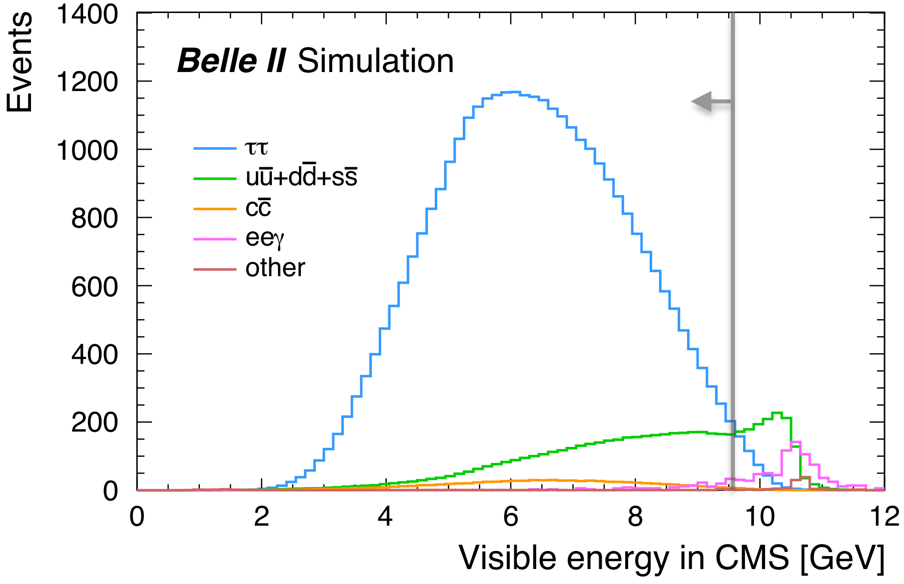


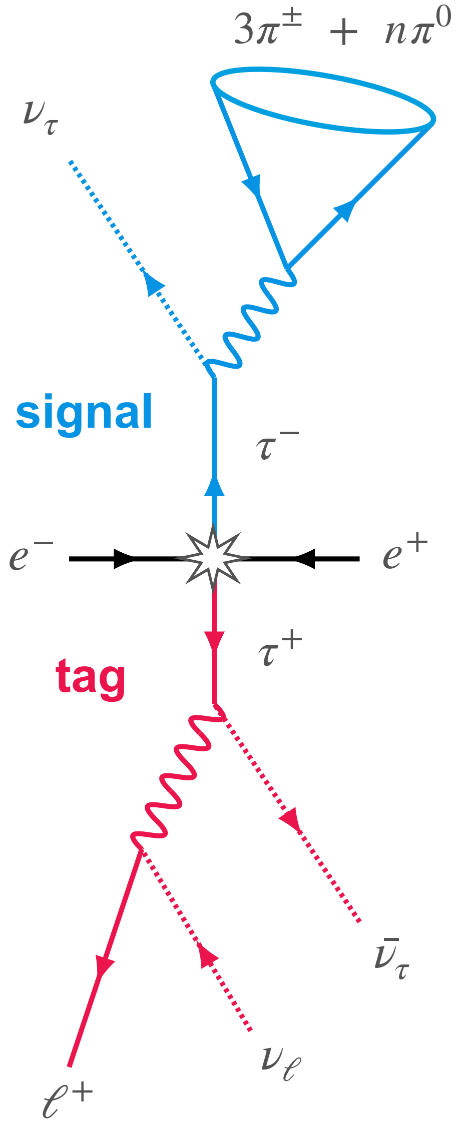


Tau leptons in early Belle II data

- Targeting $e^+e^- \to \tau^+\tau^-$ with 3-by-1 prong decay: $\tau_{tag} \to \ell^\pm \nu_\ell \bar{\nu}_\tau$ $\tau_{signal} \to 3\pi^\pm \nu_\tau + n\pi^0$
- Events required to fire CDC track trigger: 291 pb^{-1} of usable data
- Event topology and kinematic selections tailored to suppress $q\bar{q}$ and $ee\gamma$ backgrounds, driven by:
  - **thrust value** $= \sum_h \frac{\vec{p} \cdot \hat{T}}{|p_h|}$, large for the signal since both τ leptons are boosted (back-to-back)
  - **total visible energy**, bellow √s for the signal due to the three undetected neutrinos



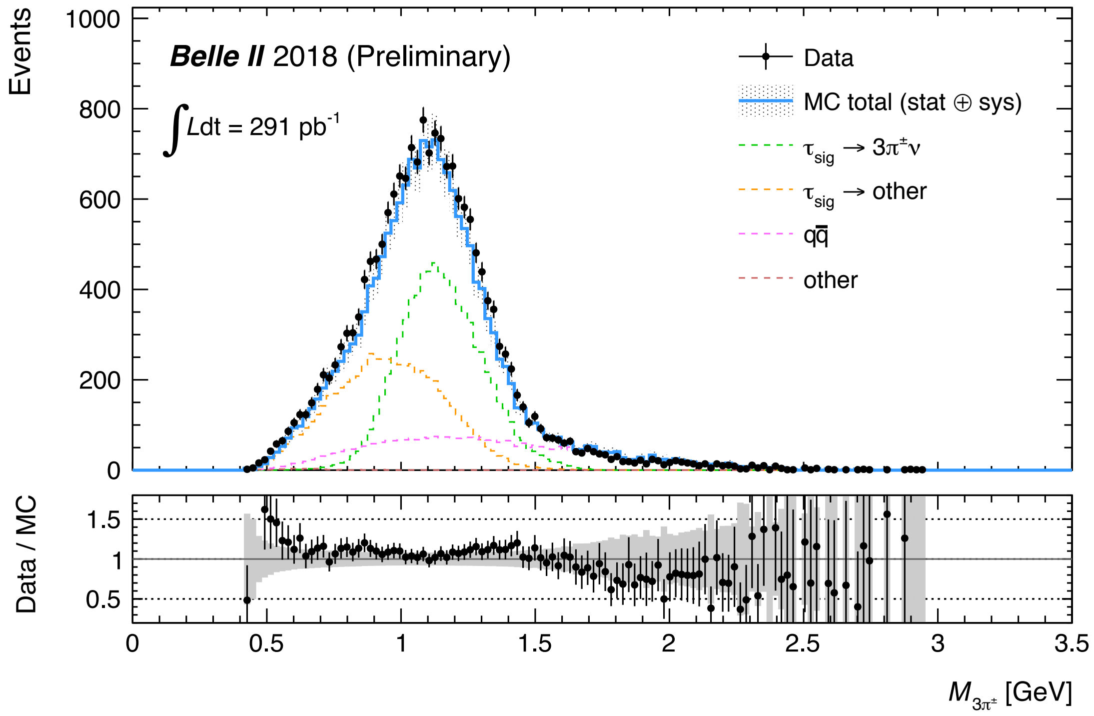




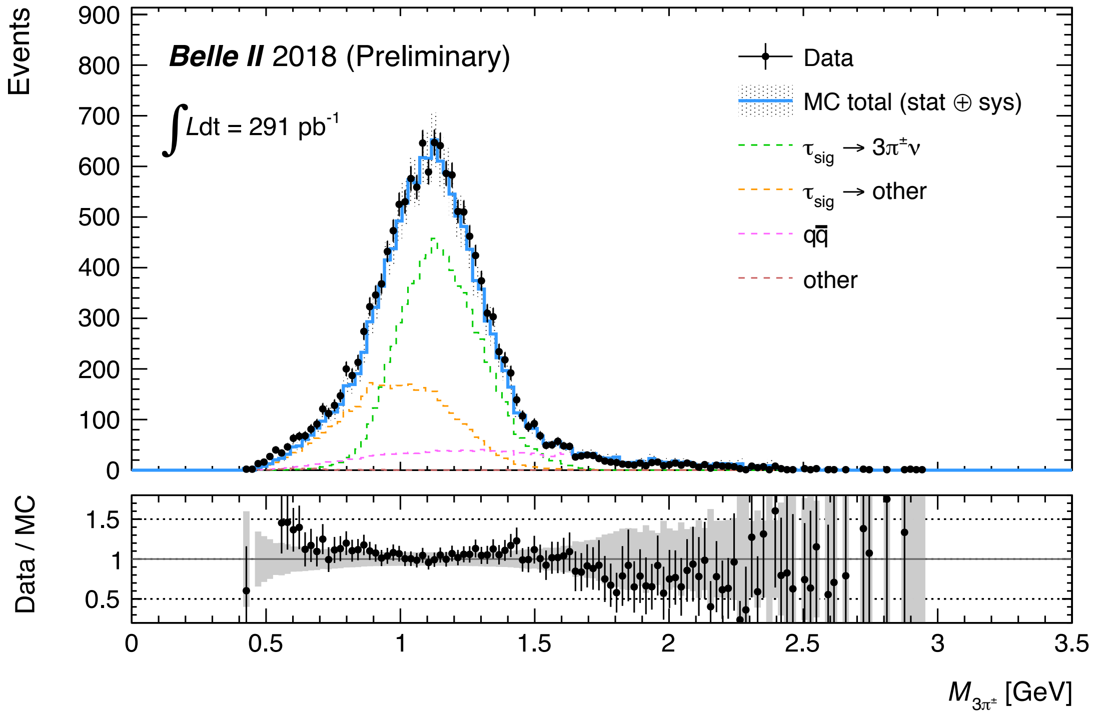
Tau leptons in early Belle II data

- After trigger + offline selections, we have agreement between the data and MC

inclusive decay: $\tau_{signal} \rightarrow 3\pi^{\pm}\nu_{\tau} + n\pi^{0}$

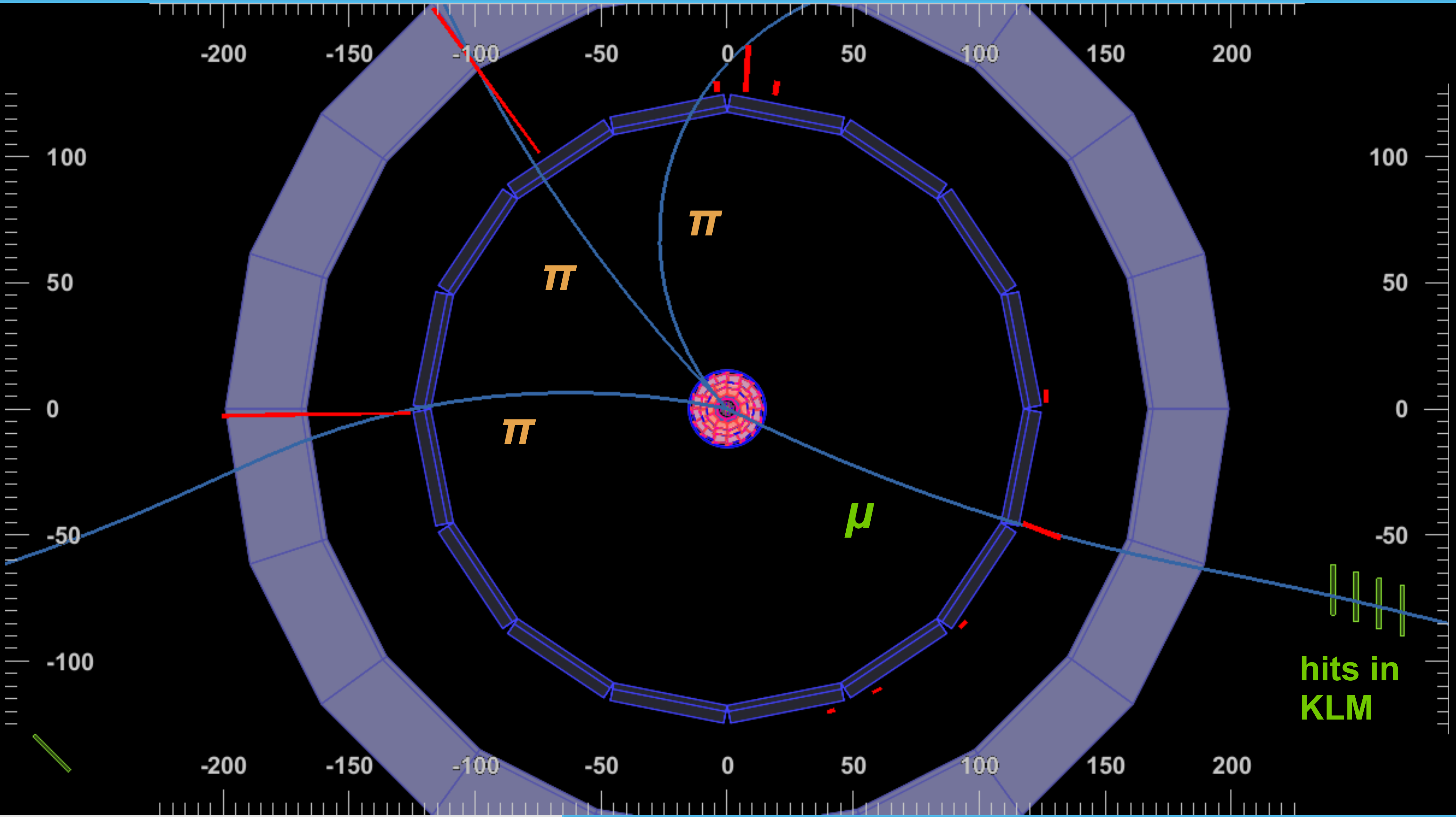


exclusive decay: $\tau_{signal} \rightarrow 3\pi^{\pm}\nu_{\tau}$



- Clear evidence for $e^{+}e^{-} \rightarrow \tau^{+}\tau^{-}$ in the Phase II data, and a demonstration of the capacity for missing energy analyses with Belle II

$e^+e^- \to \tau^+\tau^-$ event candidate



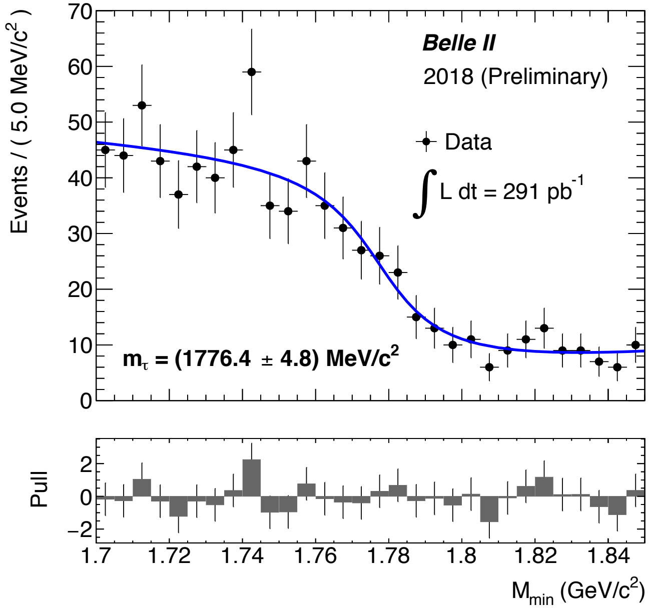
Tau lepton mass measurement

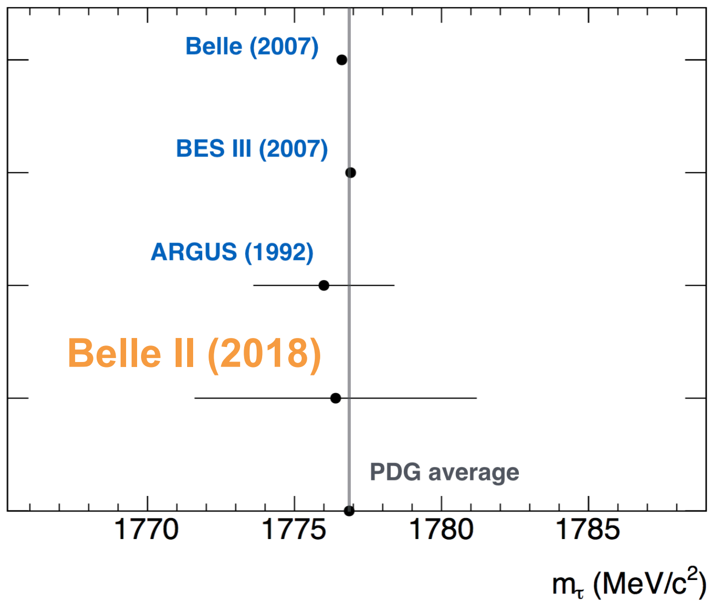
- First m_τ measurement at Belle II was performed with a pseudomass technique developed by the ARGUS collaboration:

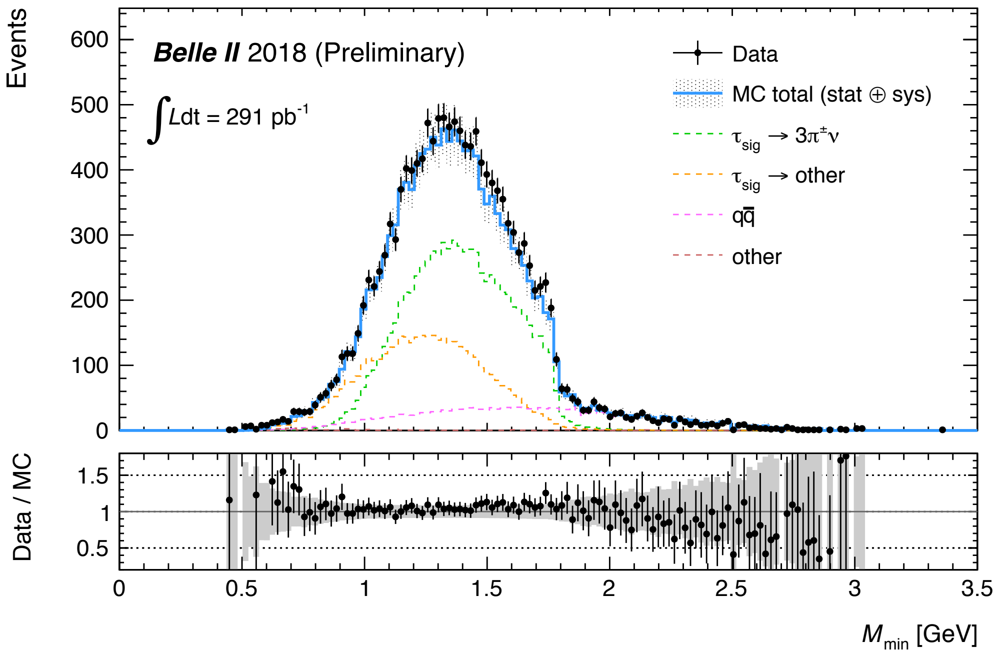
$$M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})},$$

- M_{min} distribution in the $\tau_{\text{signal}} \to 3\pi^\pm \nu_\tau$ decay channel is fitted to an empircal edge pdf (where m^* is an estimator for m_τ):

$$F(M_{min}; a, b, c, d, m^*) = (aM_{min} + b) \times tan^{-1}[(m^* - M_{min})/c] + dM_{min} + 1$$







- A fit to the pdf in the 1.7-185 GeV region yields an m_τ measurement of:

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

which is in good agreement with previous measurements.

Prospects for tau lepton physics

- The Phase III of data taking is expected to start later this month

- The huge amount of data to be delivered (50 ab^{-1}, 2019 - 2027) will enable a broad program of τ lepton physics:

arXiv:1808.10567

  - **Searches for Lepton Flavour Violation (LFV)**
  - **CP violation**
  - **Second class currents**
  - **and much more…**
    (Michel parameters, precision m_τ, electric dipole moment, …)

- A brief overview of the program is provided here.
  More info can be found in **The Belle II Physics Book**.

KEK Preprint 2018-27
BELLE2-PAPER-2018-001
FERMILAB-PUB-18-398-T
JLAB-THY-18-2780
INT-PUB-18-047
UWThPh 2018-26

The Belle II Physics Book

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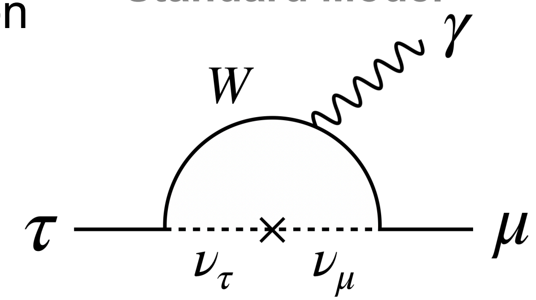
Searches for charged LFV

- LFV has been established for the neutrinos, but what about their charged partners (e, μ and τ)?

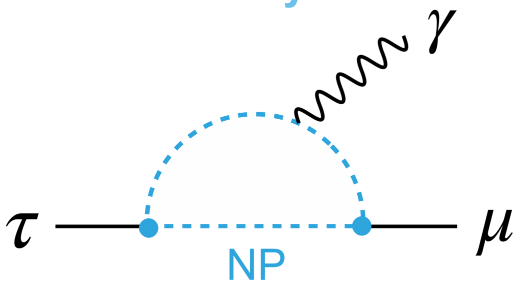
- In the SM, charged LFV decays via neutrino oscillation are highly suppressed and immeasurably small:

$$Br(\ell_1 \to \ell_2\gamma)_{SM} \propto \left(\frac{\delta m_\nu^2}{m_W^2}\right)^2 \sim 10^{-54}\text{-}10^{-49}$$

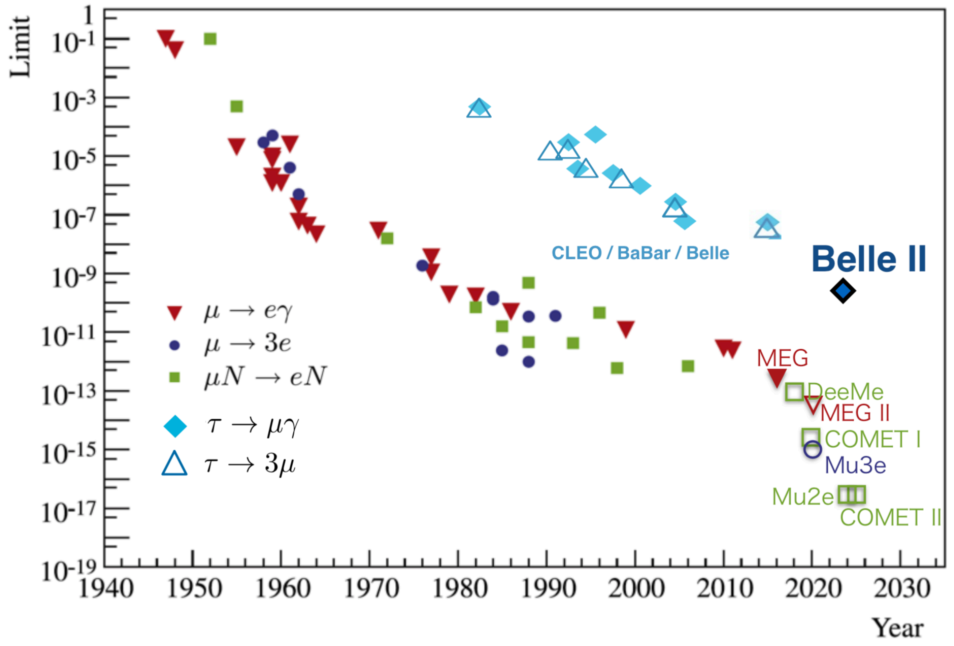
Standard Model



New Physics



- **Observation of charged LFV would be a clear signature for New Physics!**
  - *Br* enhanced in many NP models (10^{-10}-10^{-7})
  - SUSY, extended Higgs sector, seesaw, leptoquarks, non-universal Z', and many more
  - μ→e: stringent bounds exist from MEG
  - τ→μ/e: weaker bounds (Belle, BaBar and CLEO)

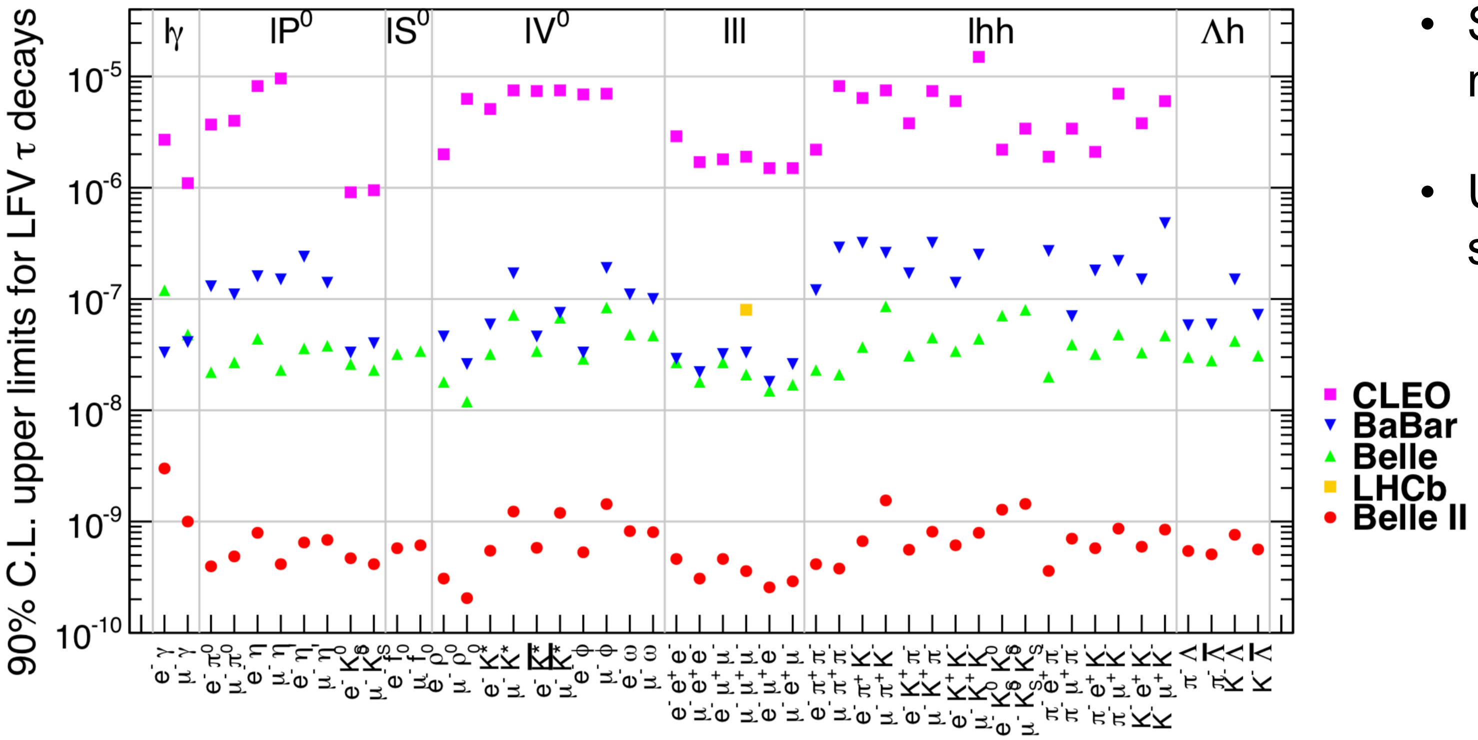


- As heaviest lepton, NP can have preferential τ LFV couplings

Prospects for τ LFV decays

- Due to their large mass, τ leptons provide a wide variety of LFV (and LNV) decay modes to study:
  - radiative: $\tau \to \ell\gamma$
  - leptonic: $\tau \to \ell\ell\ell$
  - semileptonic: $\tau \to \ell h(h)$

  - "golden channels" for discovery: $\tau\to\mu\gamma$, $\tau\to\mu\mu\mu$
  - complementary: semileptonic modes allow us to test LFV couplings b/w quarks and leptons, and better discriminate b/w NP models



- So far, searches for τ LFV decays mostly occurred at last-gen *B* factories
- Upper limits had approached the regime sensitive to NP (10^{-10}-10^{-7})

arXiv:1808.10567

Extrapolating from Belle results (50 ab^{-1}):

Belle II will push the current bounds forward by at least one order of magnitude!

CP violation in $\tau \to K_S \pi^\pm \nu_\tau + n\pi^0$

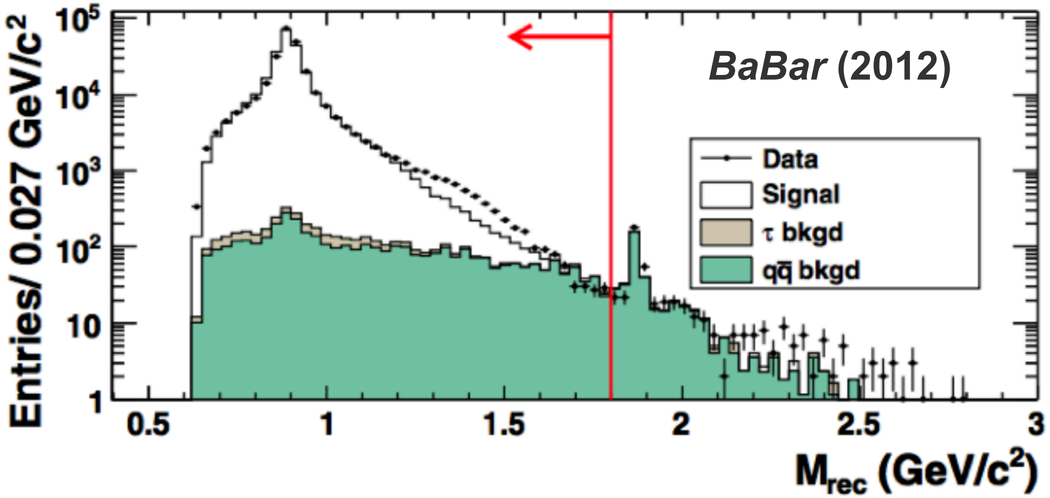
- Due to CP violation in the kaon sector, $\tau \to K_S \pi^\pm \nu_\tau$ decays in the SM have a nonzero decay-rate asymmetry:

$$A_\tau = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}$$

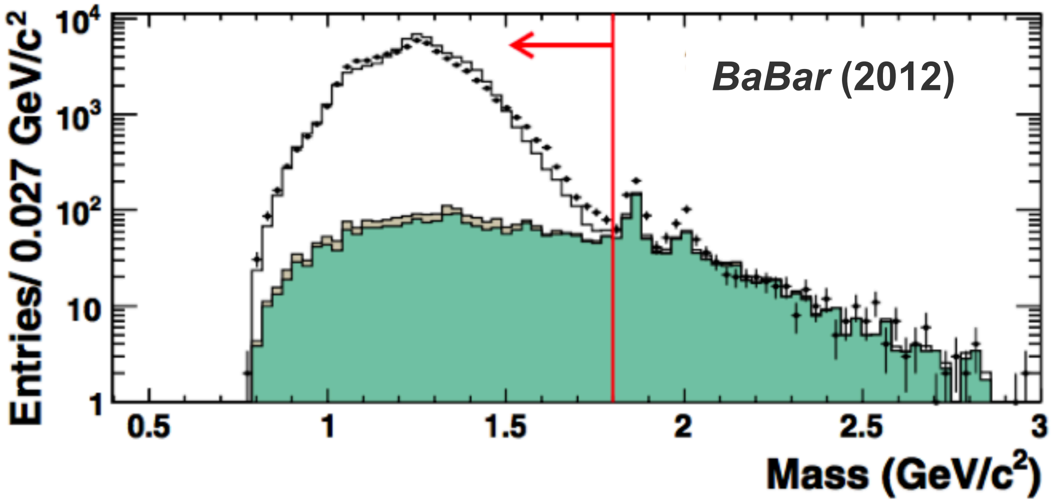
- SM prediction: $(3.6 \pm 0.1) \times 10^{-3}$
- BaBar measurement: $(-3.6 \pm 2.3 \pm 1.1) \times 10^{-3}$ **(2.8σ)**

- **An improved A_τ measurement is a priority at Belle II**

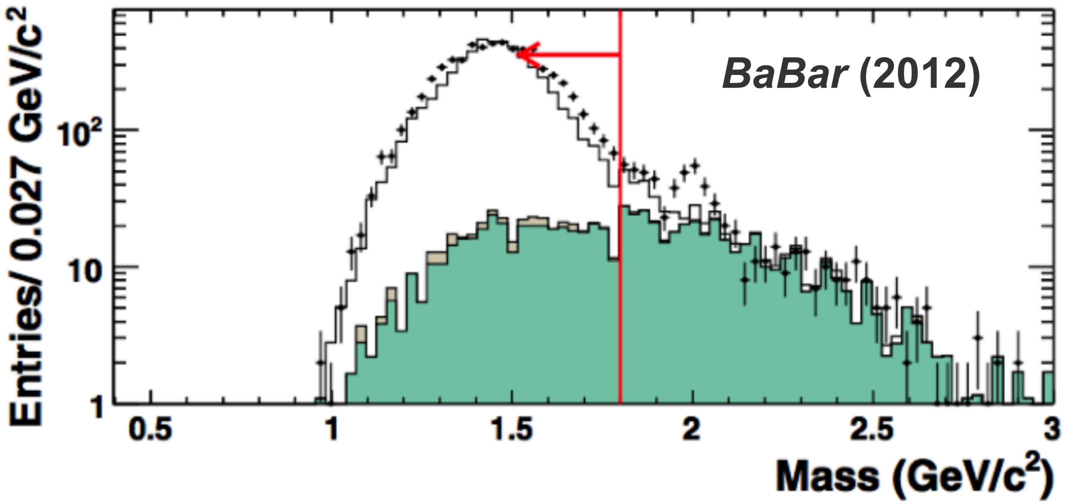
$\tau \to K_S \pi^\pm \nu_\tau$ Phys.Rev D85 (2012) 031102



$\tau \to K_S \pi^\pm \nu_\tau + \pi^0$



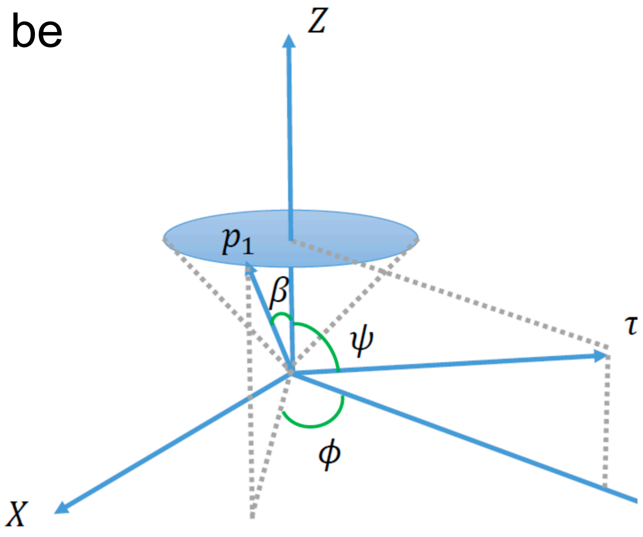
$\tau \to K_S \pi^\pm \nu_\tau + 2\pi^0$



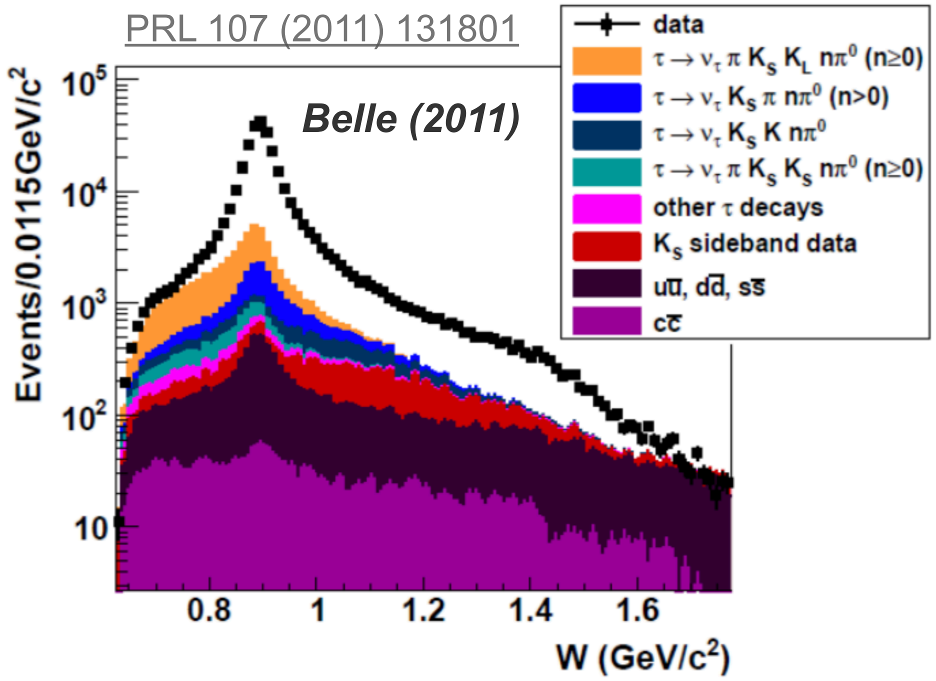
- CP violation could also arise from a charged scalar boson exchange. It would be detected as a difference in the decay angular distributions:

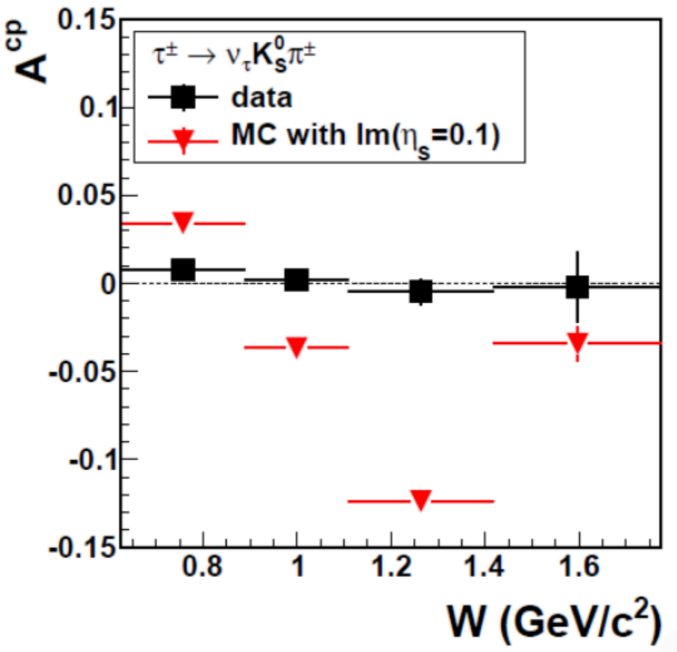
$$A_i^{CP} = \frac{\iint_{Q_{1,i}^2}^{Q_{2,i}^2} \cos\beta\cos\psi\left(\frac{d\Gamma_{\tau^-}}{d\omega} - \frac{d\Gamma_{\tau^+}}{d\omega}\right)d\omega}{\frac{1}{2}\iint_{Q_{1,i}^2}^{Q_{2,i}^2}\left(\frac{d\Gamma_{\tau^-}}{d\omega} + \frac{d\Gamma_{\tau^+}}{d\omega}\right)d\omega} \simeq \langle\cos\beta\cos\psi\rangle_{\tau^-}^i - \langle\cos\beta\cos\psi\rangle_{\tau^+}^i,$$

$$d\omega = dQ^2 d\cos\theta d\cos\beta$$



PRL 107 (2011) 131801





- With 50 ab^{-1} of data, Belle II is expected to provide a x70 more precise measurement:

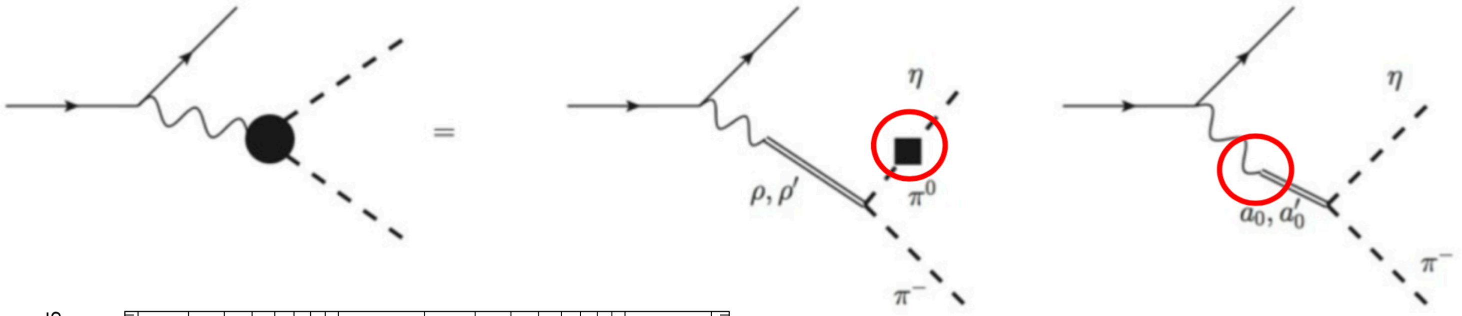
$|A_{CP}| < (0.5\text{-}3.8) \times 10^{-4}$

(assuming central value $A^{CP} = 0$)

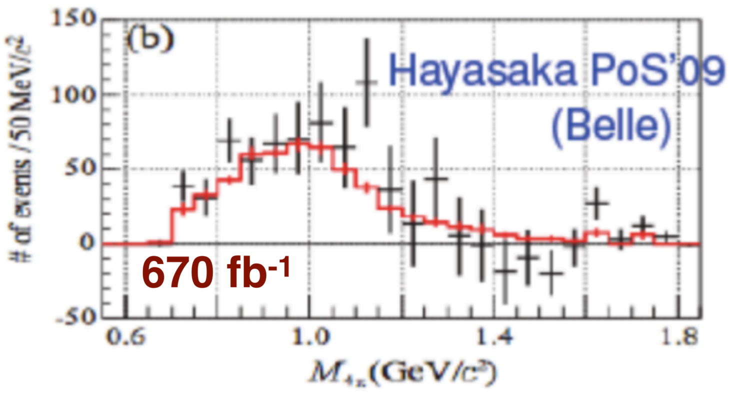
Second class currents in $\tau \to \eta\pi\nu$

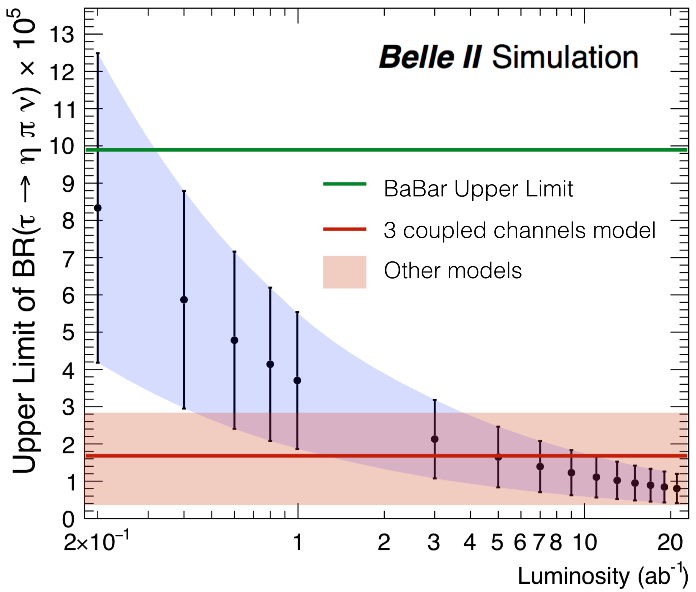
- Hadronic currents classified as first or second class according to their spin, parity and G-parity quantum numbers
  - Second Class Current (SCC): J^{PG} = 0^{+-} (a_0), 0^{-+} (η), 1^{++} (b_1), 1^{--} (ω) **⇒ yet to be observed!**

- In the SM, $\tau \to \eta\pi\nu$ decays proceed via SCCs (isospin-violating) with tiny BRs $\lesssim \mathcal{O}(10^{-5})$



- Searched for at last-gen *B* factories:
  - Belle: ***Br* < 7.3 x 10**$^{-5}$
  - BaBar: ***Br* < 9.9 x 10**$^{-5}$





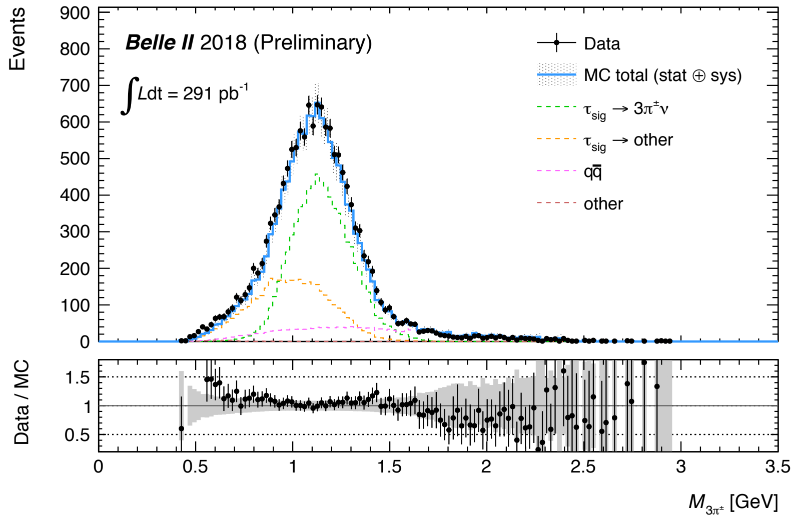
- The observation of SCC via $\tau \to \eta\pi\nu$ decay is a priority at Belle II

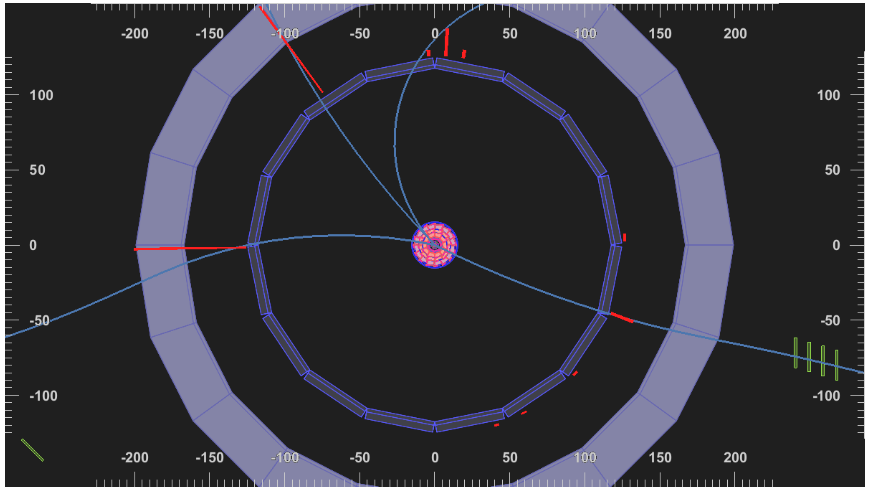
- SM predictions can be tested for the first time with the first years data taking (1 ab^{-1})

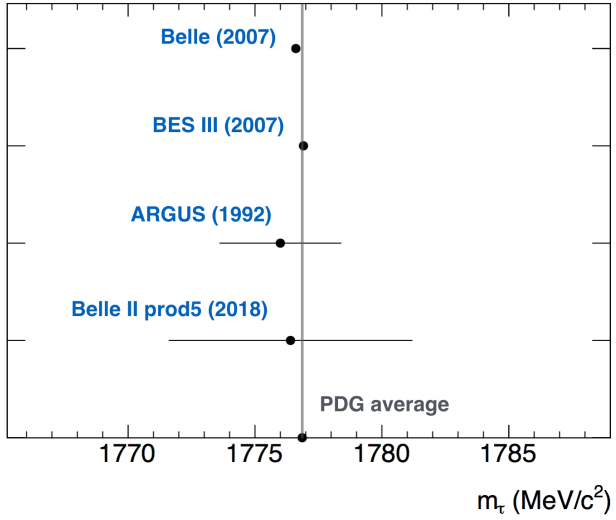
- **Clear signal could suggest New Physics!**

Outlook

- SuperKEKB has completed the commissioning phase. Phase II data is available and delivering results.







- The Phase III of data taking with the full Belle II detector installed will start later this month.

- Belle II has a broad program of τ lepton physics planned, and will be a major player in the near future.

- Exciting times ahead!

BACKUP

Tau lepton rediscovery: selections

Tracks

- p_T > 100 MeV
- |dz| < 5 cm, |dr| < 1 cm
- -0.8660 < cos(θ) < 0.9565
- E/p < 0.8

Photons

- E > 200 MeV
- nHits > 1.5
- E_9E_{25} > 0.9
- -0.8660 < cos(θ) < 0.9565

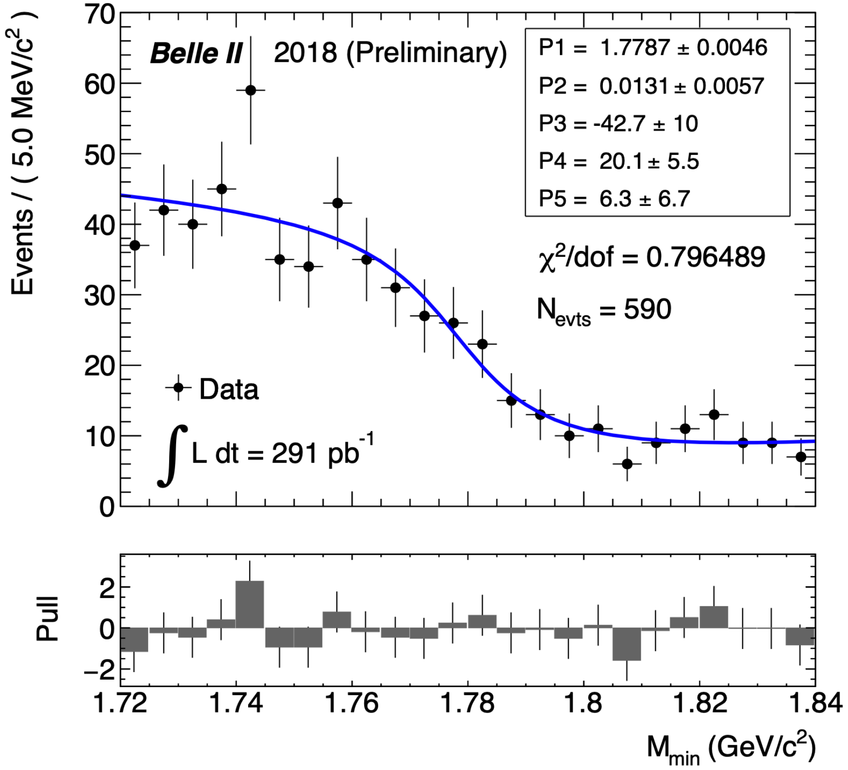
Trigger

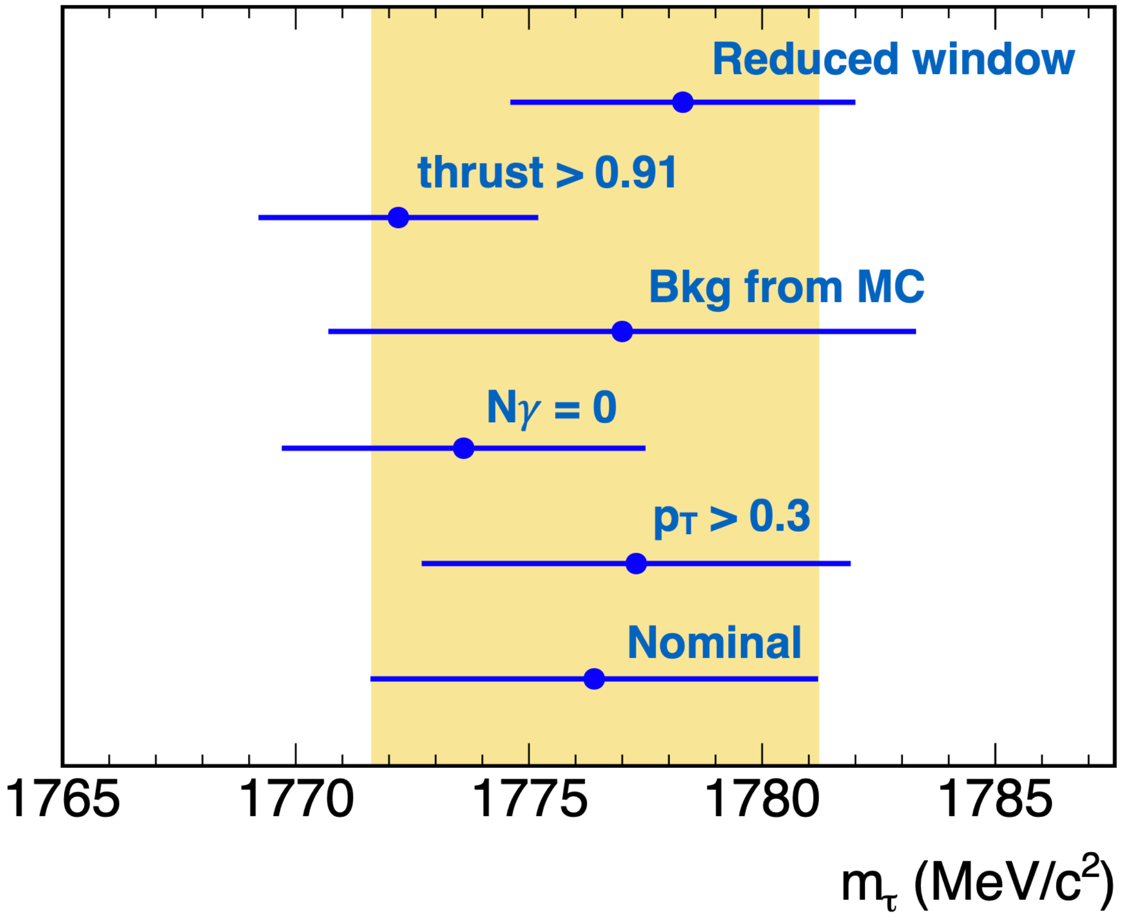
- CDC track trigger *bit 3*
  ≥3 tracks @ L1

Event Selections

- 4 tracks per event
- sum charge zero
- two hemispheres wrt thrust axis, 3 tracks on one side and 1 track in opposite
- thrustValue > 0.87
- visibleEnergyCMS < 9.7
- E_T signal at CMS < 5.29
- E_T tag at CMS < 5.29
- $\pi^0 \leq 2$, $N_\gamma \leq 5$ on tag side
- *inclusive* decay channel:
  $\pi^0 \leq 1$, $N_\gamma \leq 3$ on signal side
- *exclusive* decay channel
  π^0-veto, $N_\gamma \leq 1$ on signal side

Tau mass cross checks





- Reduced mass window:

m_τ = (1777.3 ± 4.6) MeV

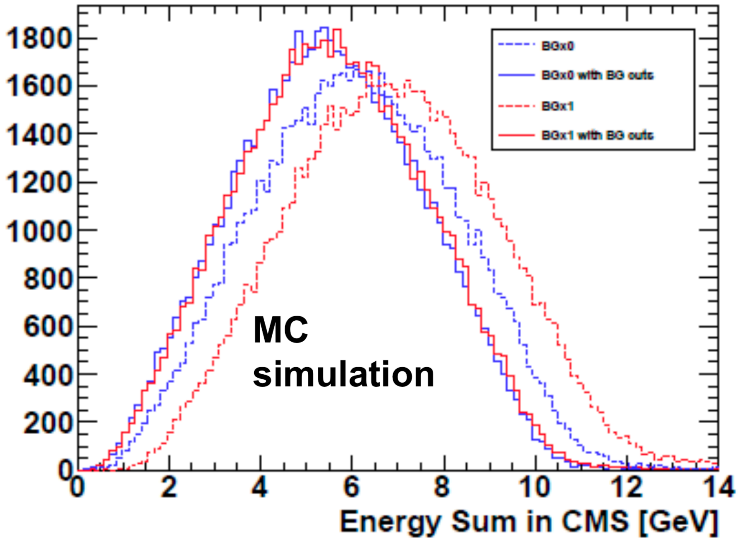
Beam background

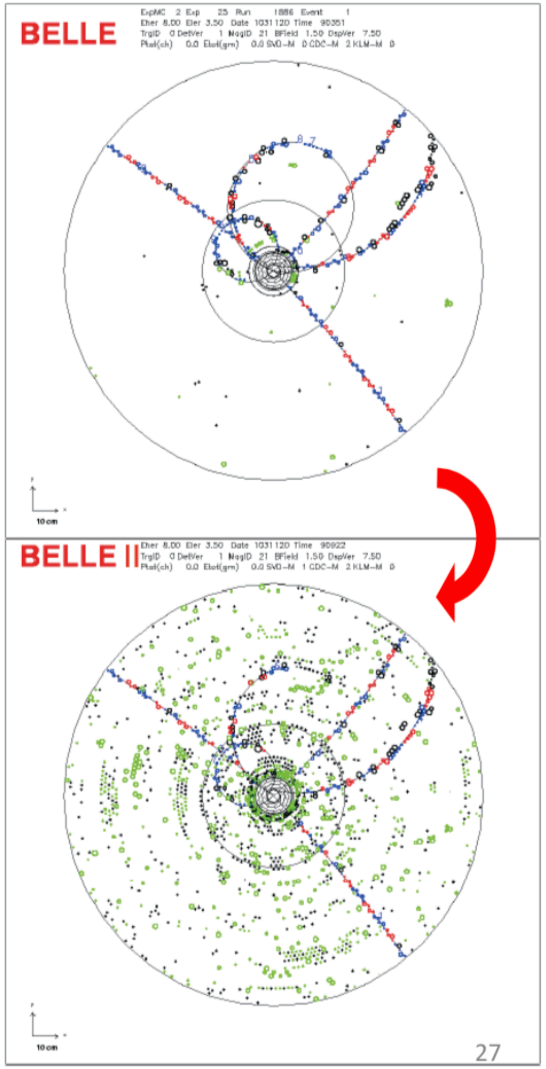
- 40 times higher luminosity comes at the cost of higher beam related backgrounds
  - expect 20 higher than at Belle

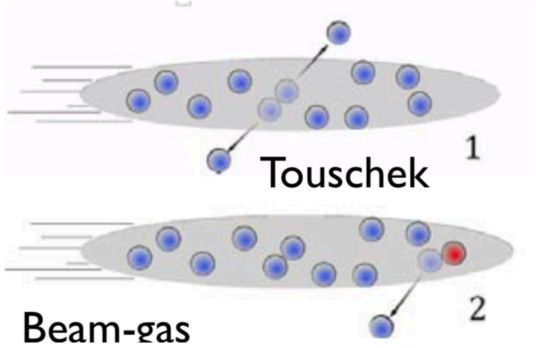
- **Understanding the beam background is essential for τ physics in Belle II!**

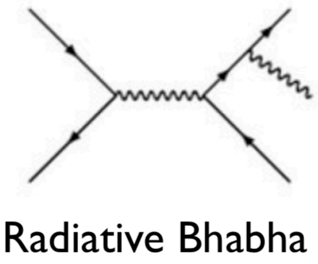
- Beam bkg is controllable in an event by imposing track selections and using timing information from calorimeter

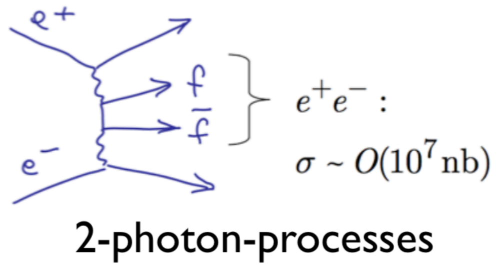
arXiv:1808.10567v2







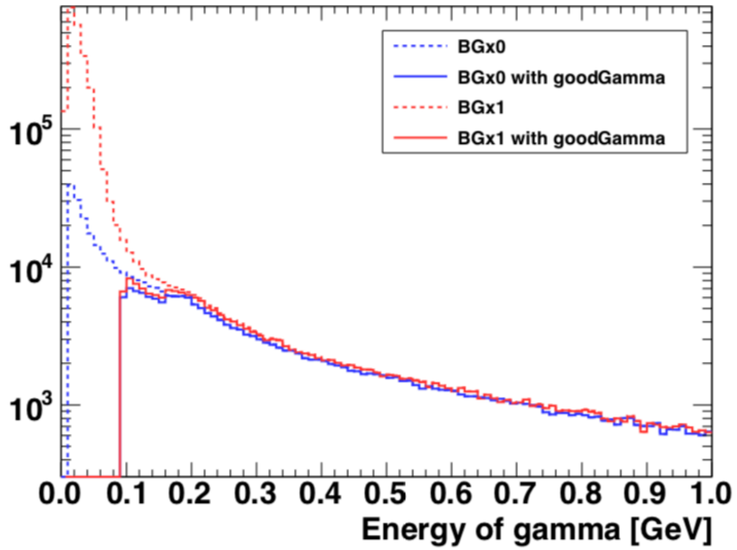




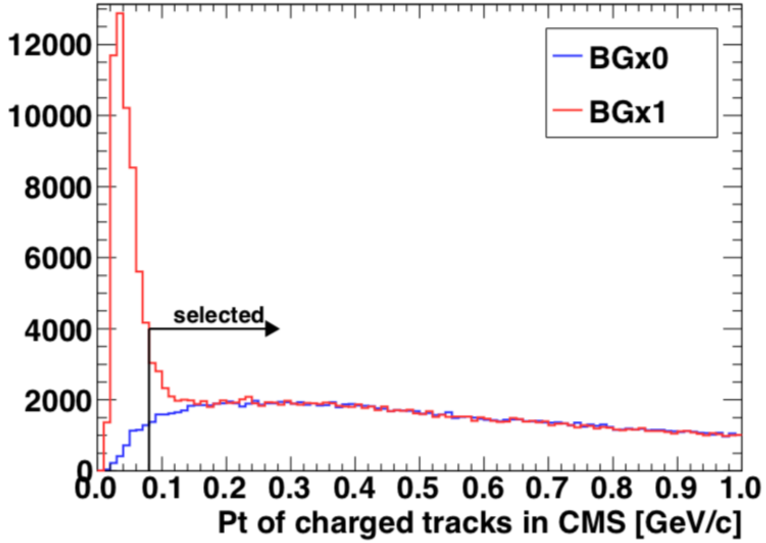
Beam background reduction

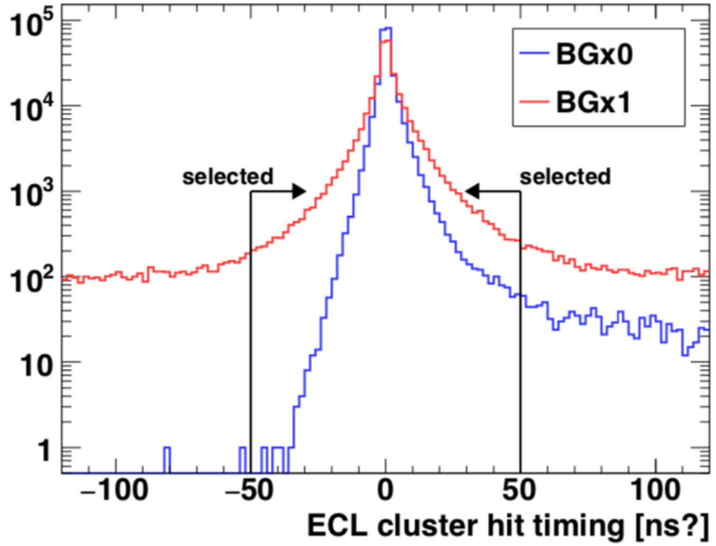
- For photon clusters:
  - $E_\gamma > 0.100(\text{forward endcap}), 0.090(\text{barrel}), 0.160(\text{backwards endcap})$ GeV;
  - $|\Delta t_{cluster}| < 50$ ns.
- For charged particles:
  - Track fit p-value > 0.01;

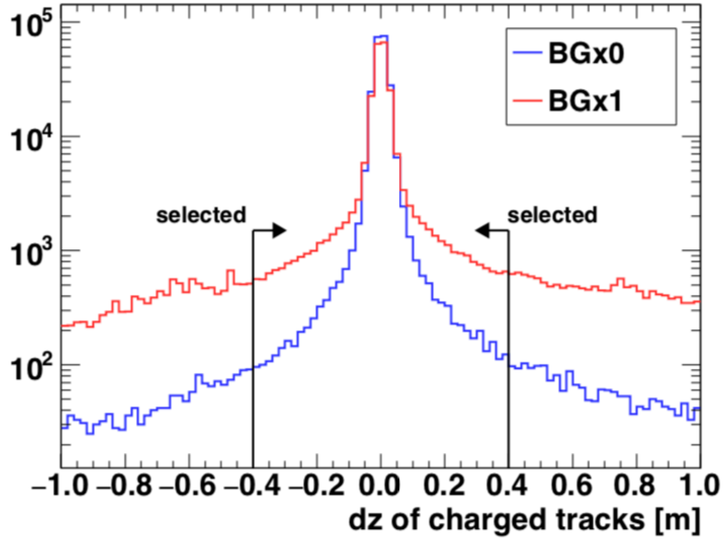
arXiv:1808.10567v2



- Beam background rejection mainly coming from two-energy based selections



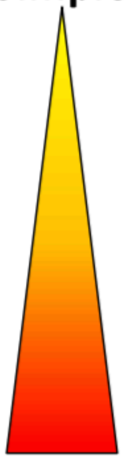




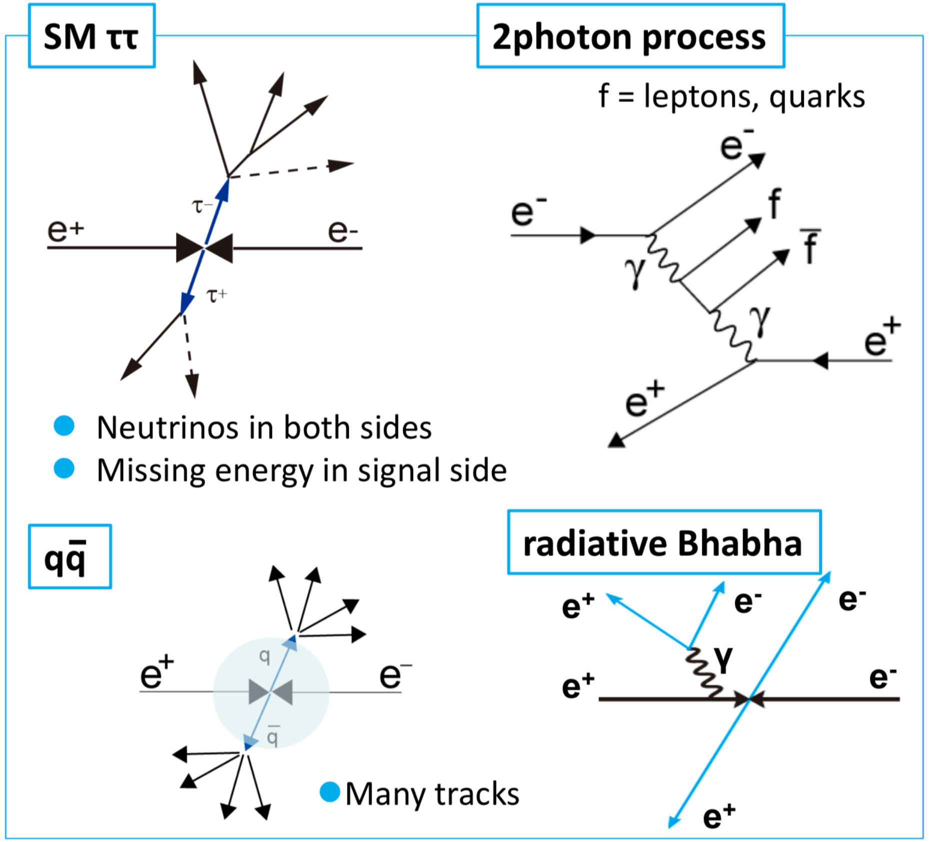
Analysis strategy for LFV τ decays

- Rare decay search:
  ⇒ understand and reduce as much as possible the backgrounds

- Search in various decay modes:
  - $\tau \to \ell\ell\ell$
  - $\tau \to \ell K_s, \Lambda h$
  - $\tau \to \ell V_0(\to hh')$
  - $\tau \to \ell P^0\ (\to \gamma\gamma)$
  - $\tau \to \ell hh'$
  - $\tau \to \ell\gamma$

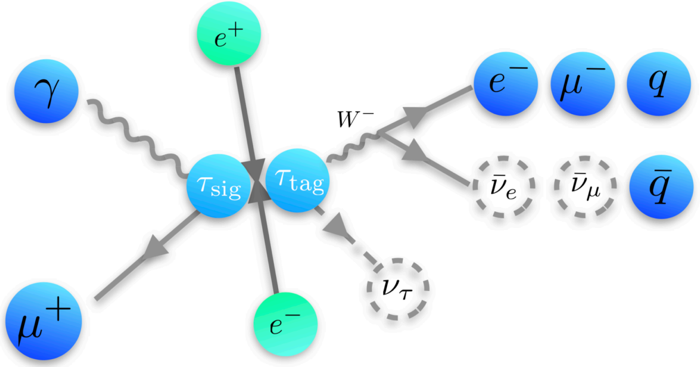


Difficulty of background reduction

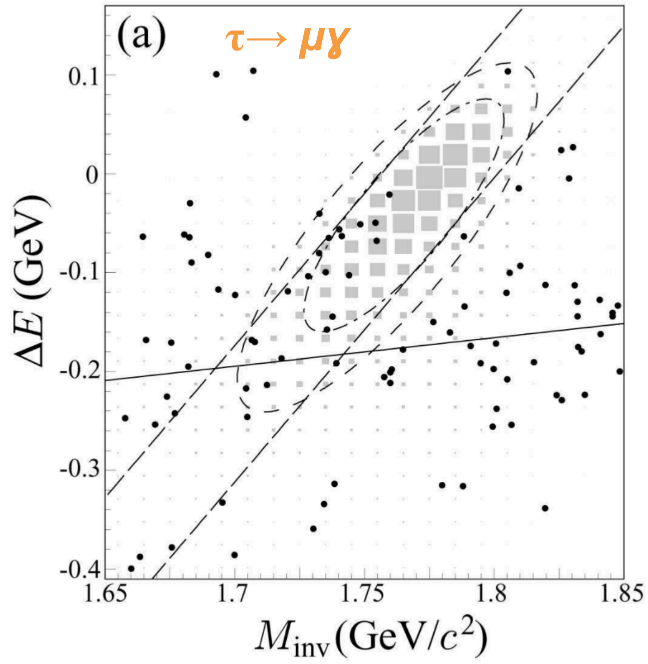


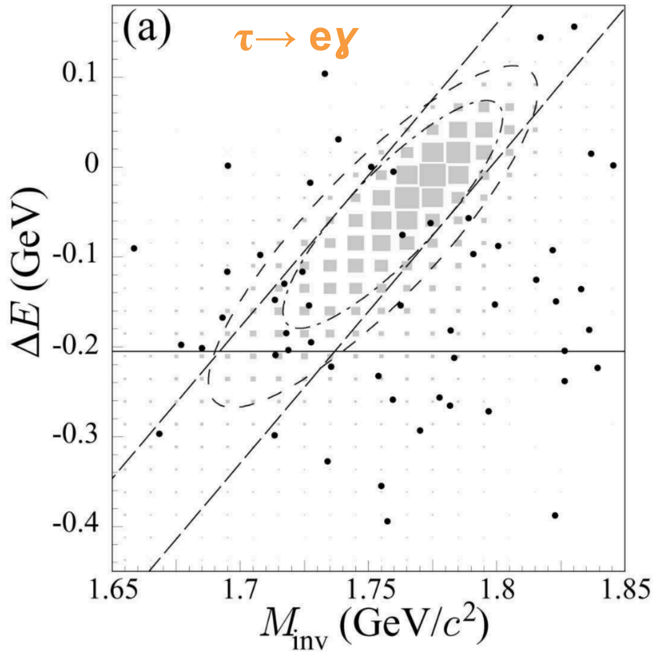
Search for LFV $\tau \to l\gamma$

- Two independent variables are used to evaluate signal yield: $$M_{\mu\gamma} = \sqrt{E_{\mu\gamma}^2 - P_{\mu\gamma}^2}$$
- For signal: ΔE close to 0 and $M_{\mu\gamma}$ close to τ-mass $$\Delta E = E_{\mu\gamma}^{\mathrm{CM}} - E_{\mathrm{beam}}^{\mathrm{CM}}$$
- Feasibility studies were performed, using MC that included the larger beam bkg. They show that the larger bkg should have minimal impact on sensitivity @ Belle II.

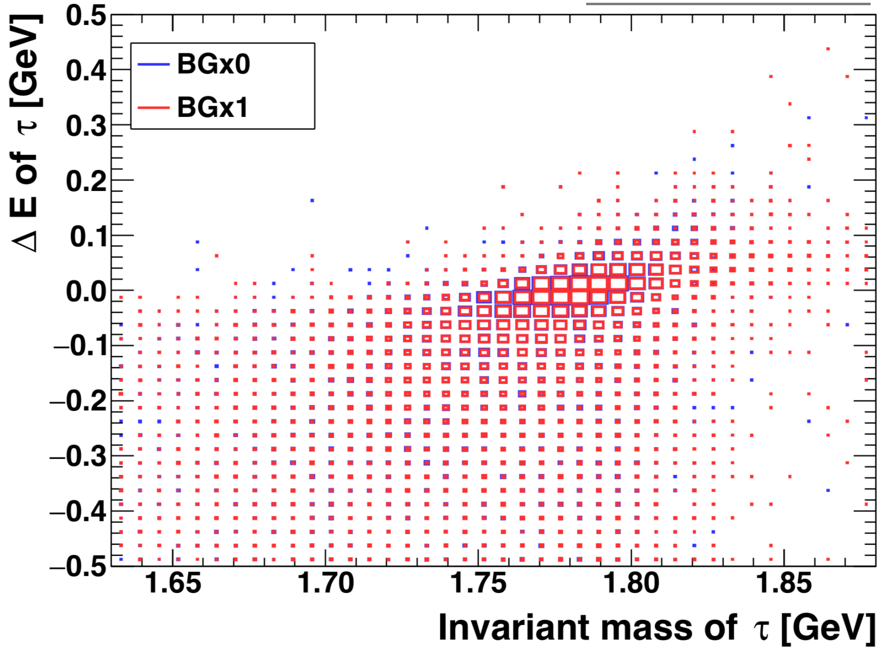


Phys. Lett., B666, 16-22 (2008)





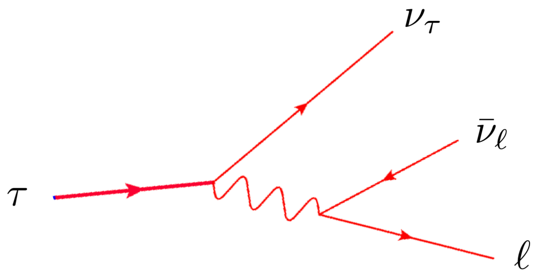
arXiv:1808.10567v2



Michel Parameters

- In SM, τ lepton decay is due to the interaction with a charged weak current

- Leptonic decays are of particular interest since absence of strong interaction allows precise study of EW Lorentz structure



- When spin of τ lepton is not determined, only four bilinear combinations of the coupling constants are experimentally accessible:
  - ρ, η, ξ and δ
  - in SM: 3/4, 0, 1 and 3/4

- With full dataset (50 ab^{-1}), the stat uncertainty is expected to be $\sim 10^{-4}$

- Systematic uncertainties will be challenging at Belle II ($\sim 10^{-3}$)