(Tau) Flavor Physics at Belle II

Flavor 2019: new Physics in flavor from LHC to Belle II

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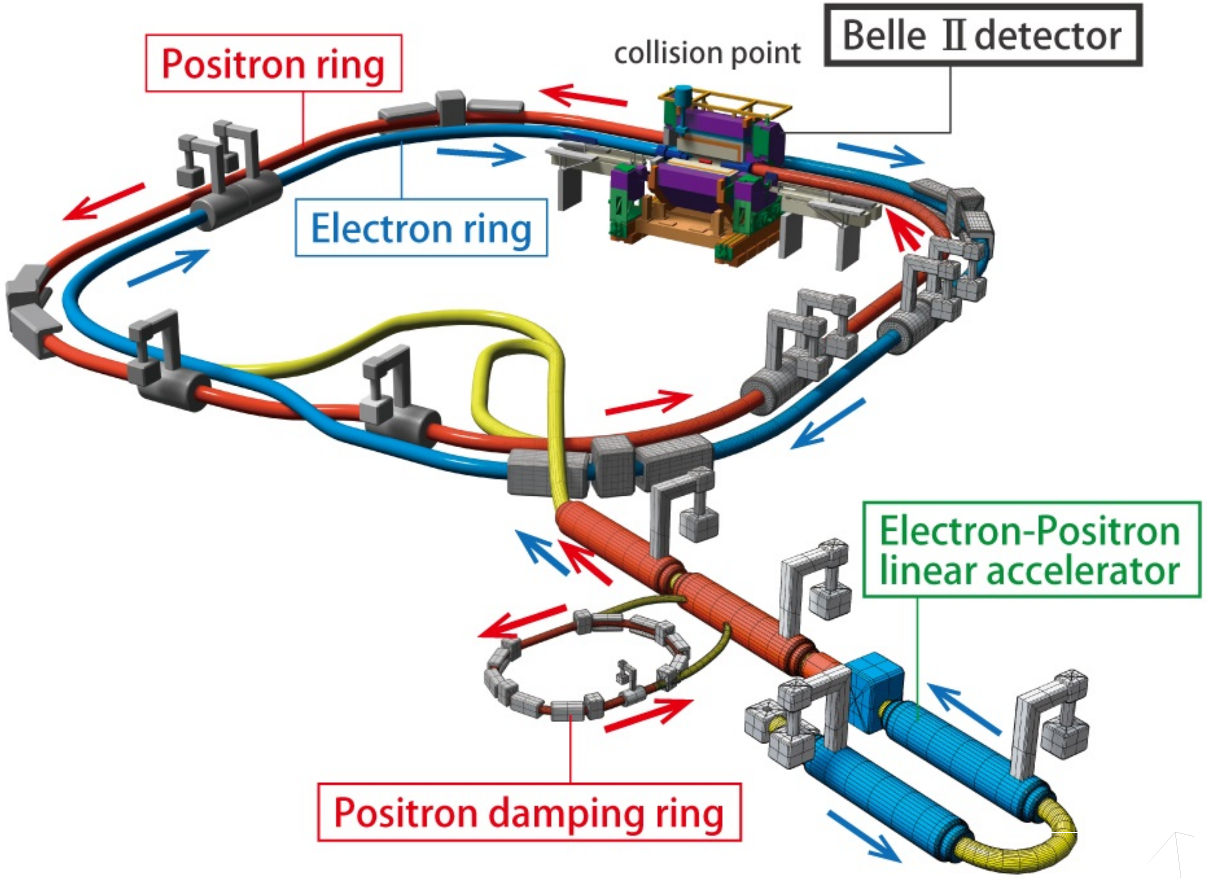
May 20th, 2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

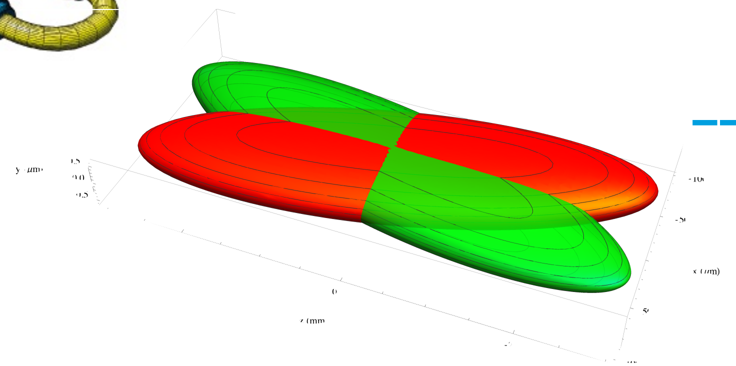
Outline

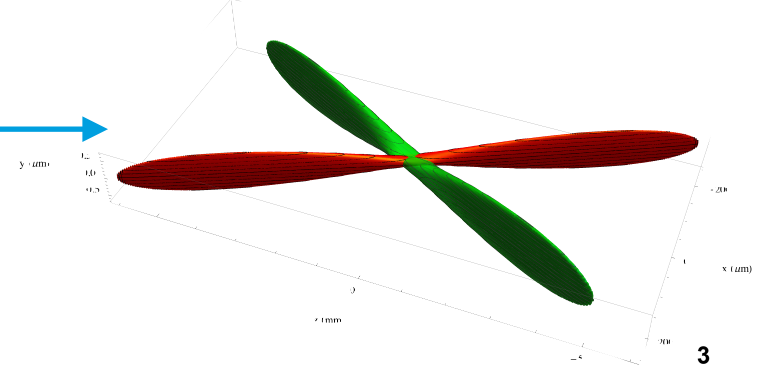
- SuperKEKB and the Belle II experiment
- Commissioning run and results with early data.
- Prospects, focusing on Tau physics.
  - See also:
  - Quarkonium Prospects → Vladimir Savinov
  - (Semi)leptonic results with early data → Lu Cao
- Summary and Outlook

SuperKEKB @KEK, Tsukuba



- **New facility** to search for BSM physics by studying B, D and τ decays.
- Asymmetric electron-positron collider.
- Major upgrade to the KEKB accelerator with **x40 the design luminosity (8×10^{35} cm^{-2}s^{-1})**.
  - **x2** raw beam current.
  - **x20** smaller beam spot (**σ_y^*=50 nm**) with new nano-beam collision scheme
- **First beams and commissioning in 2016**

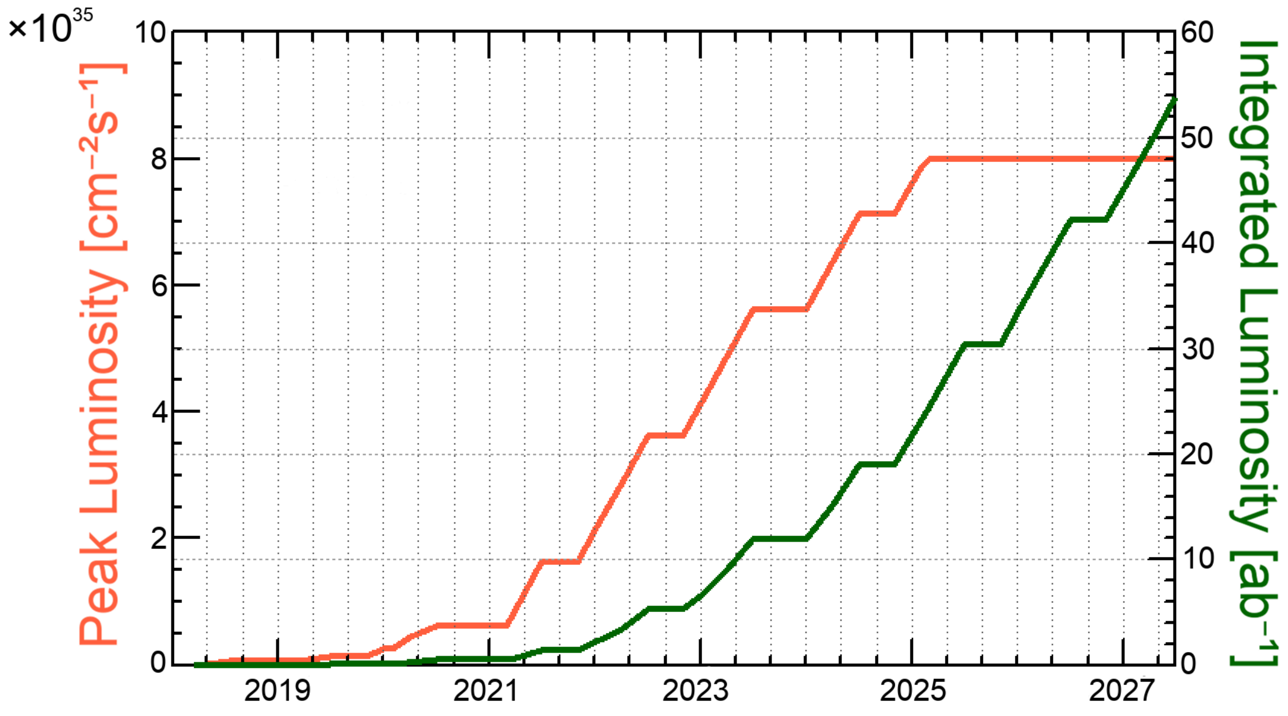




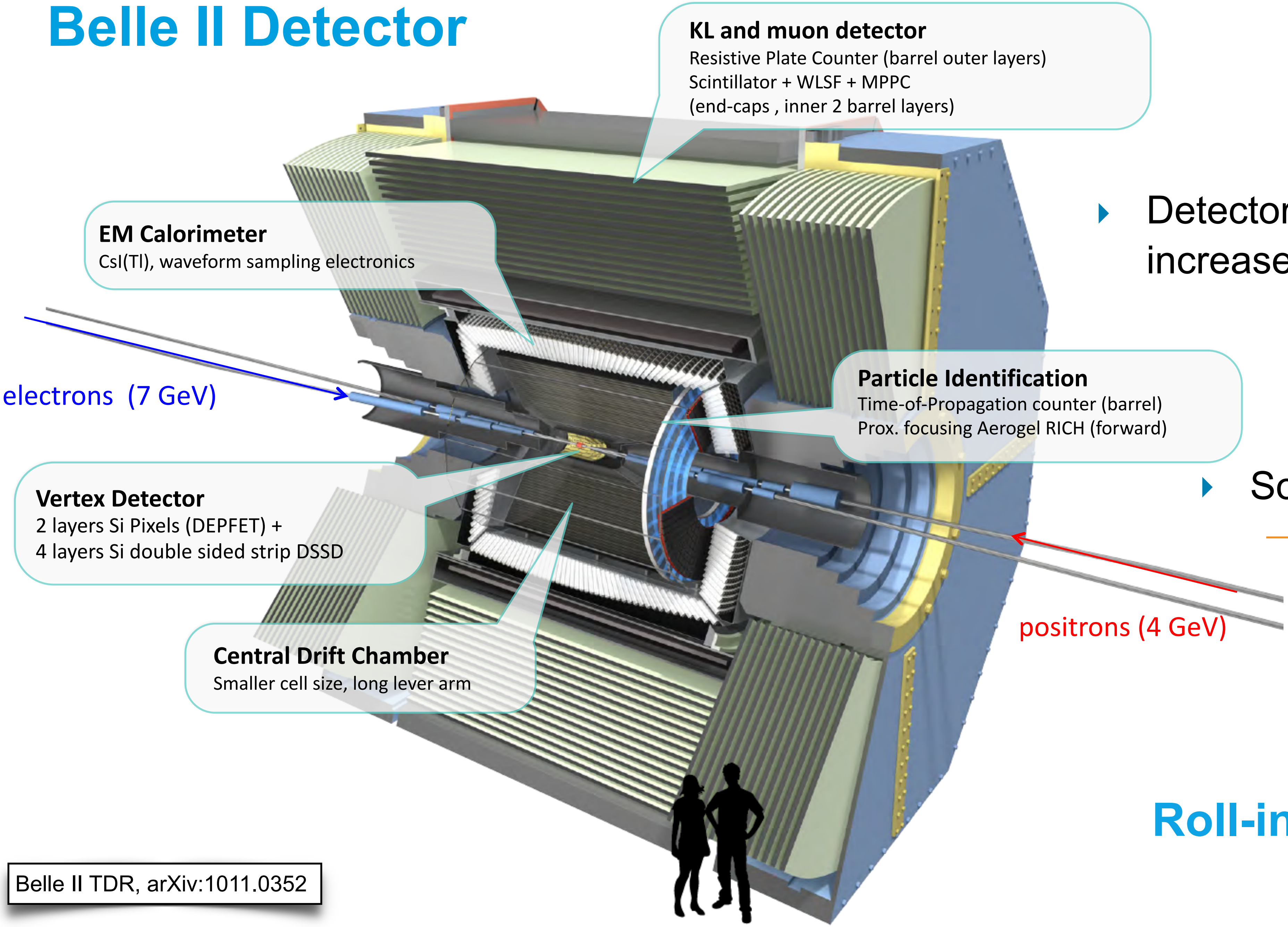
SuperKEKB as a Flavor Factory

- Asymmetric beams colliding at (or near) the Υ(nS) resonances
  - $\sigma(e^+e^-\to\Upsilon(4S)) = 1.05$ nb, $\sigma(e^+e^-\to\tau^+\tau^-) = 0.92$ nb
- Not just a B-factory, but also a charm and **τ factory**

- Over its operation, Belle II plans to collect 50ab^{-1} of collision data (vs ~1ab^{-1} of Belle)
- Unique environment for precision flavor measurements



Belle II Detector



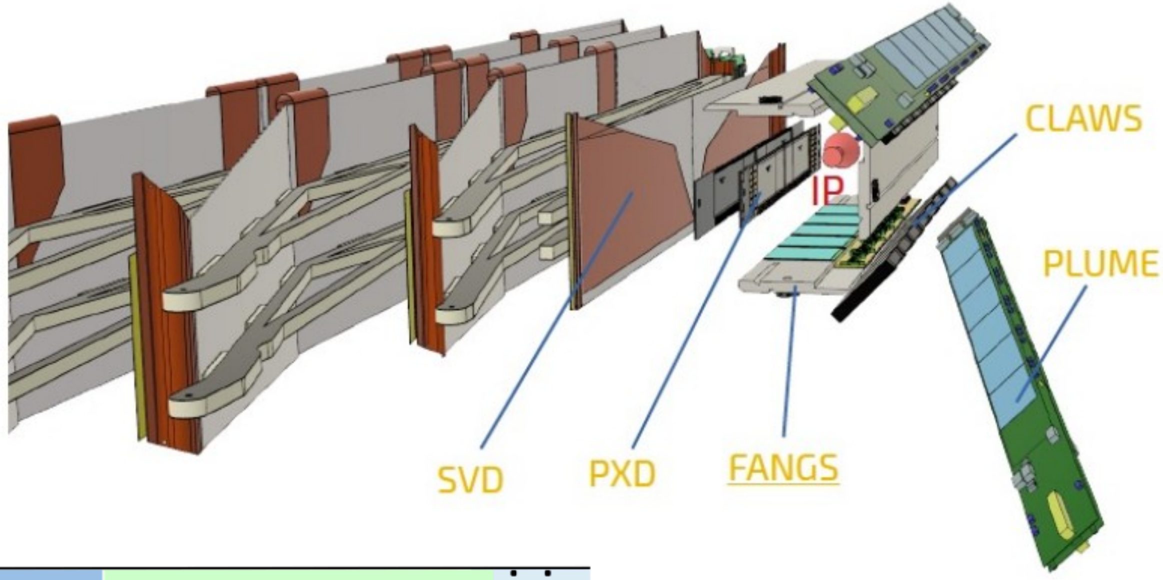
- Detector upgrade to mitigate the increased beam background
- Solid angle coverage >90% → High hermeticity for E_{miss} measurements

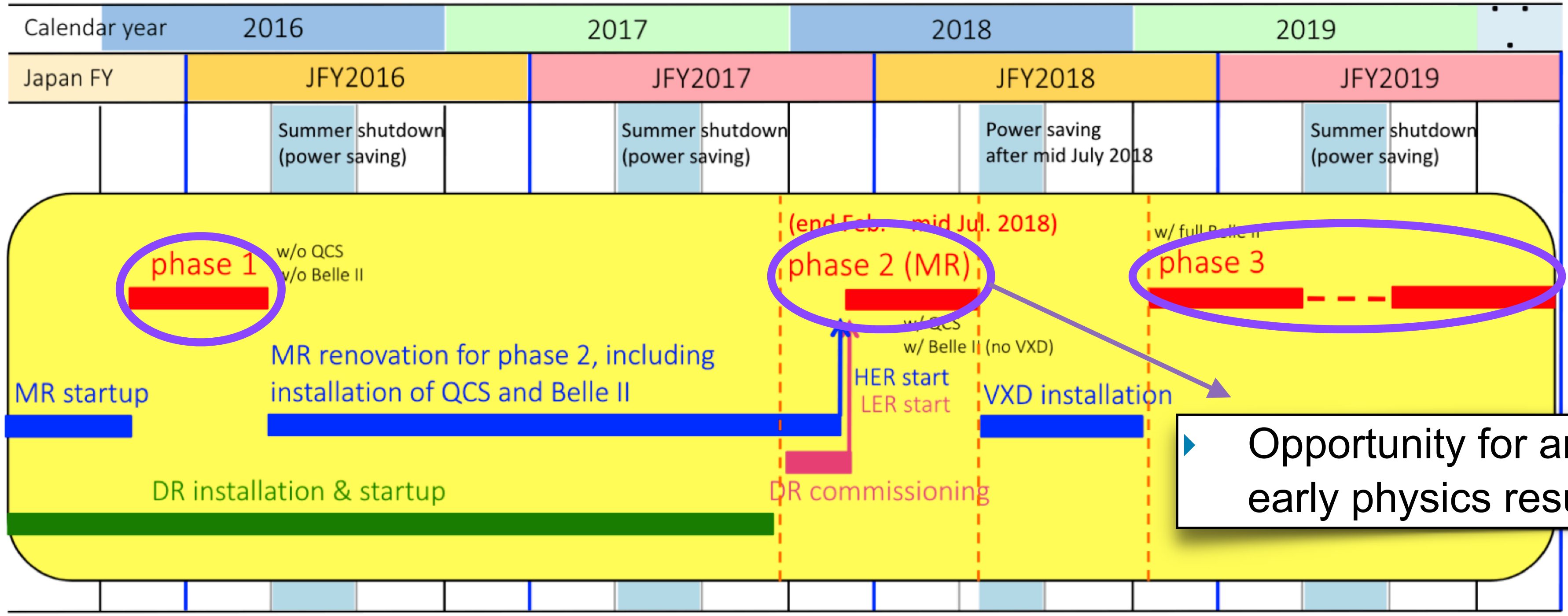
Roll-in: April 2017

Belle II TDR, arXiv:1011.0352

"Phase 2"

- Follows from Phase 1 (accelerator commissioning)
- Pilot run to test nano-beam scheme
  - Partial vertex detector (2 PXD + 4 SVD modules)
  - BEAST II: commissioning detector to study beam and background conditions



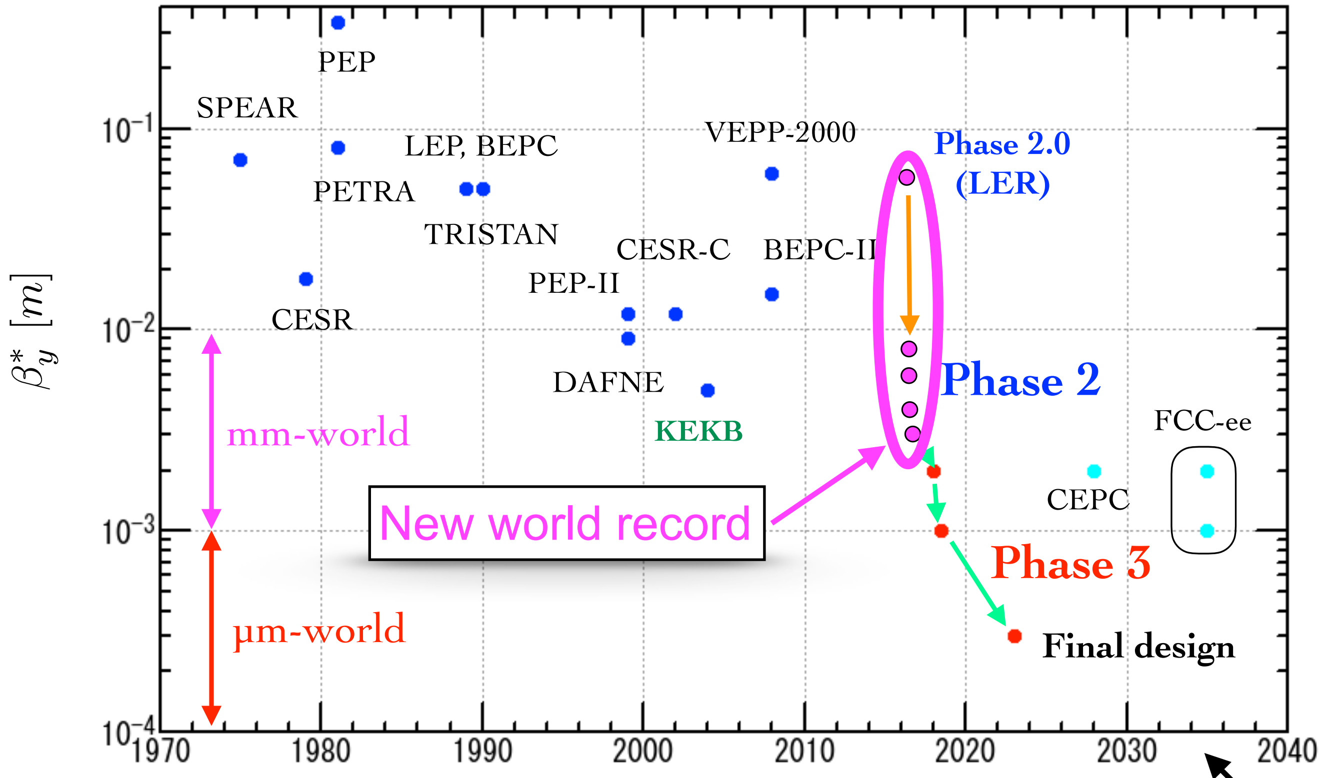


- Opportunity for analysis preparation and early physics results

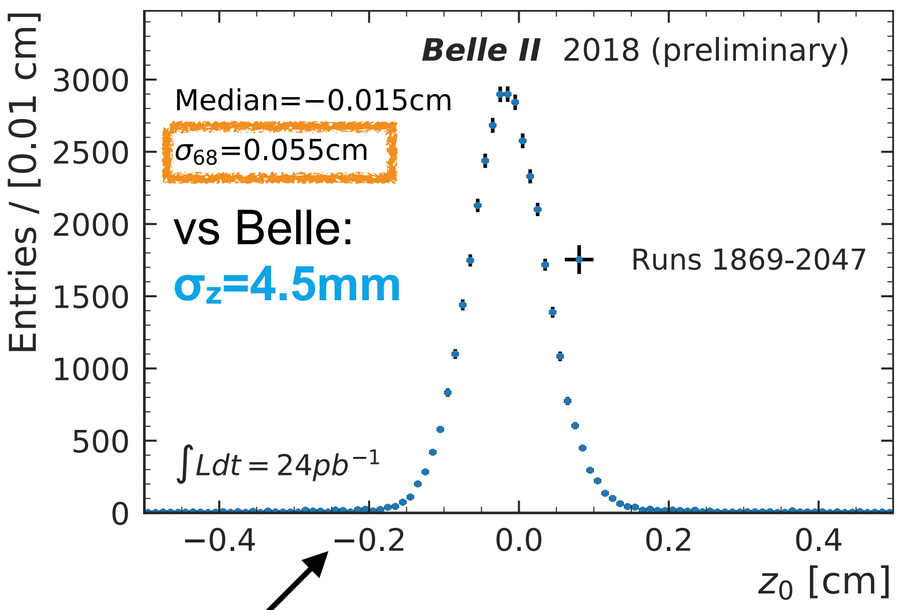
First Collisions - April 2018

Thightening the Luminous Region

- Key to high luminosity is strong vertical focusing of beams to σ_y = 50 nm



- Reached **β^*_y = 3mm** in Phase 2
- Final luminosity will require **β^*_y = 300μm**



- Possible thanks to rapid feedback between accelerator team and tracking group

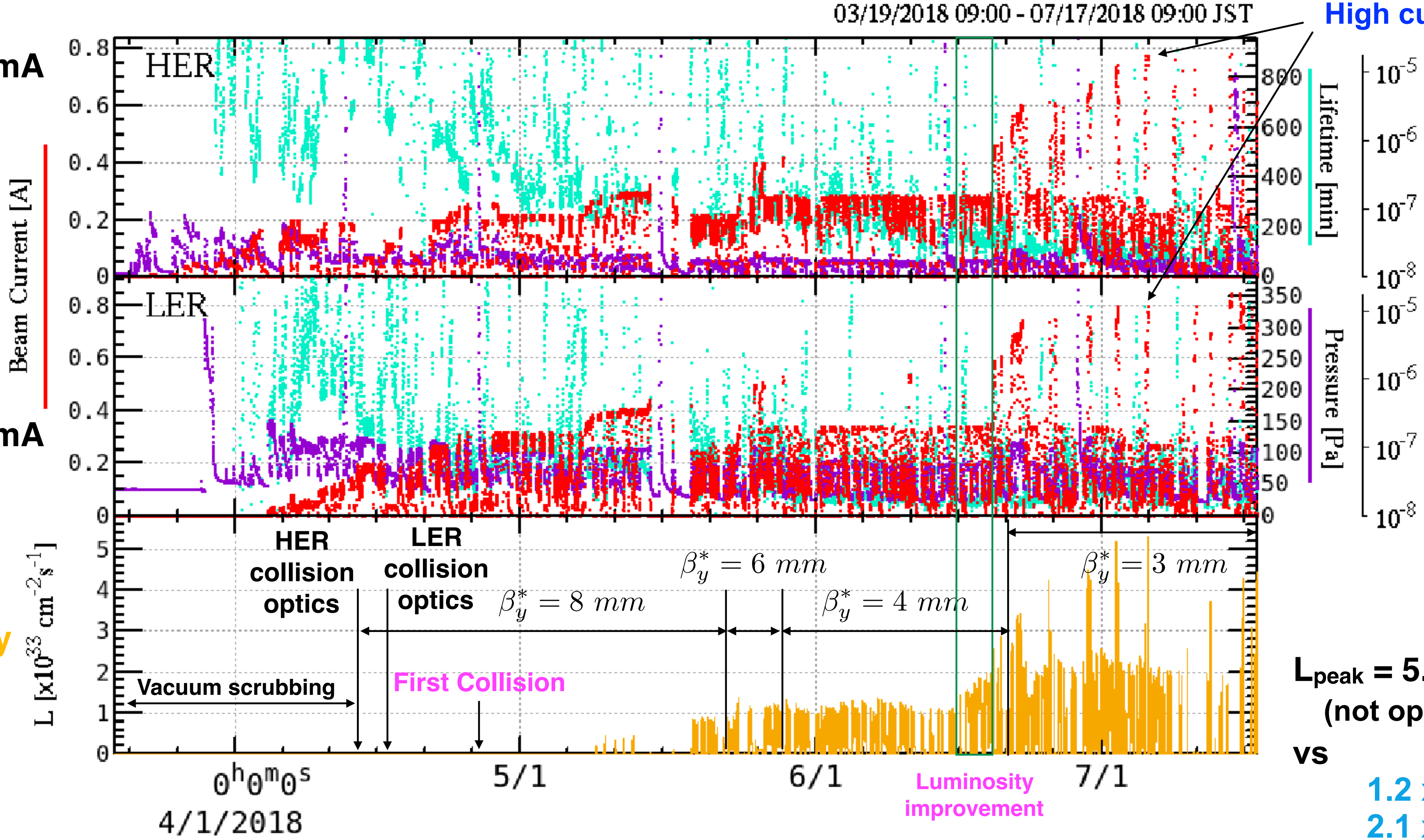
Phase 2 Operation: April-July 2018

Max 800 mA (HER)

Beam Current

Max 860 mA (LER)

Luminosity



High current trial

$L_{peak} = 5.55 \times 10^{33}\ cm^{-2}s^{-1}$
(not optimized)

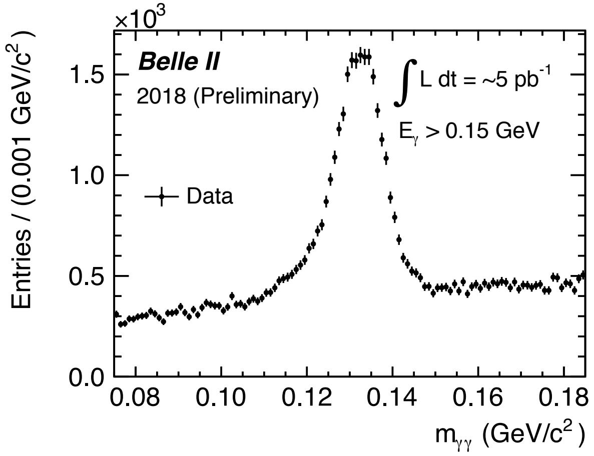
vs

1.2×10^{34} (BaBar)
2.1×10^{34} (Belle)

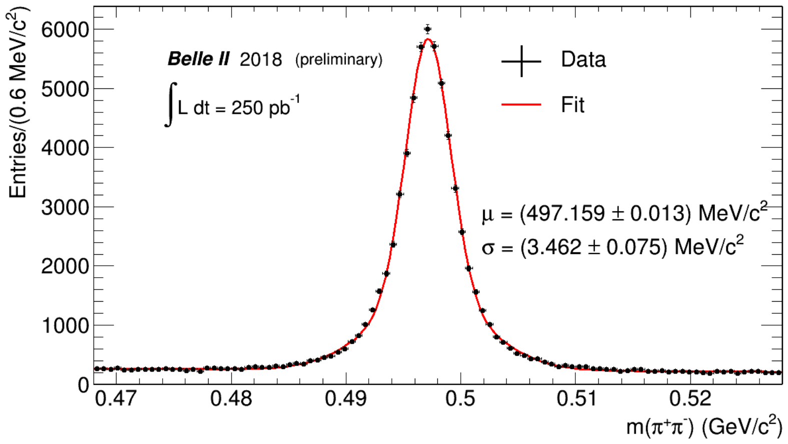
Physics Rediscovery

- **472 pb^{-1}** of physics data → first rediscoveries of known processes

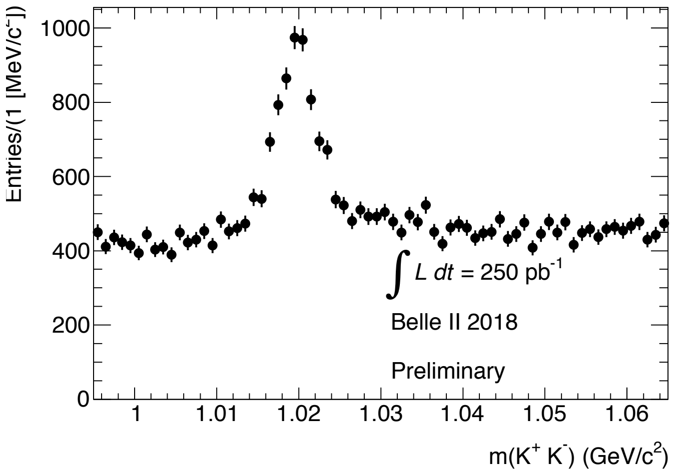
$\pi^0 \rightarrow \gamma\gamma$



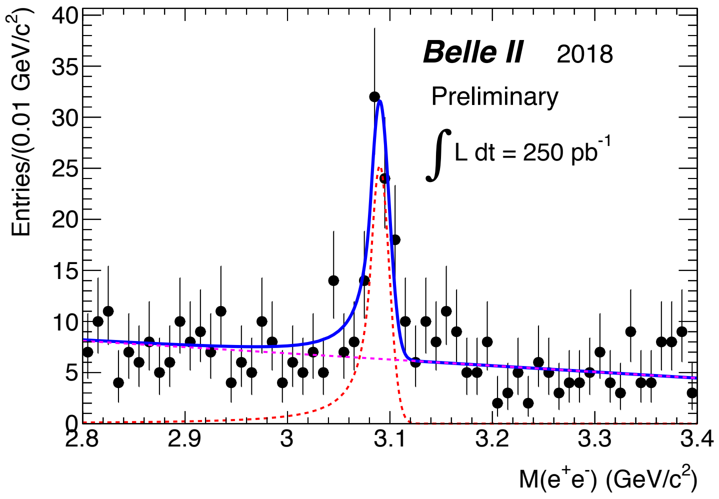
$K_S \rightarrow \pi\pi$



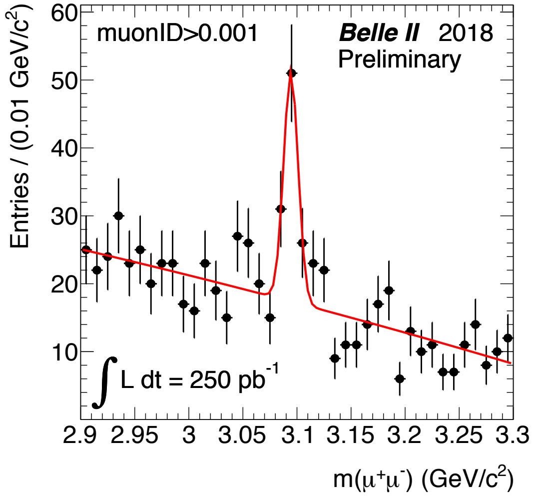
$\phi \rightarrow KK$



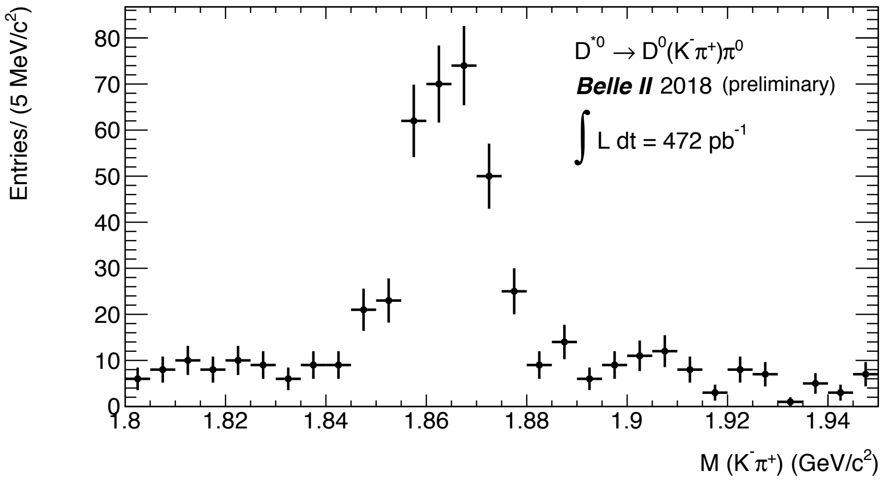
$J/\Psi \rightarrow ee$



$J/\Psi \rightarrow \mu\mu$



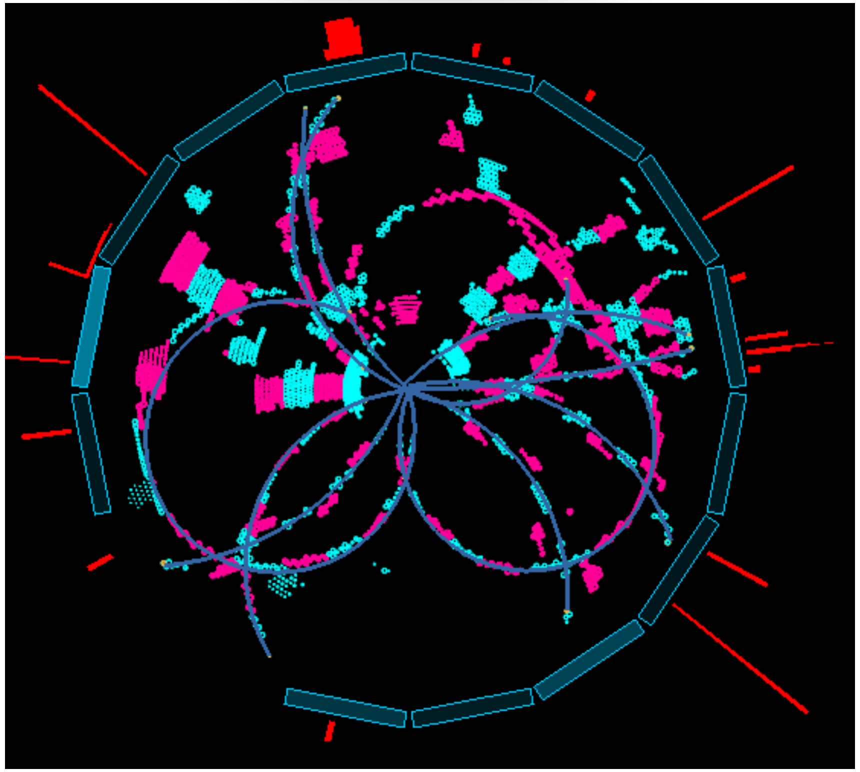
$D \rightarrow K\pi$



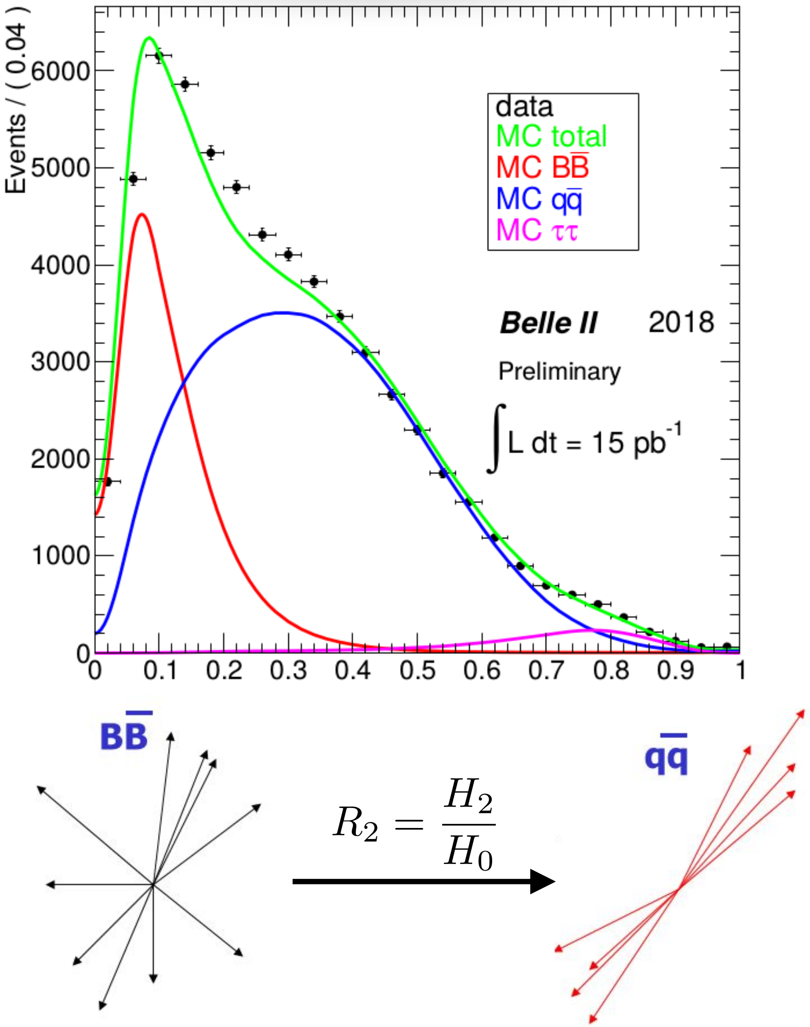
First B Mesons

- **B pairs** produced on Y(4S) threshold (at rest in CMS frame)

BB-like event

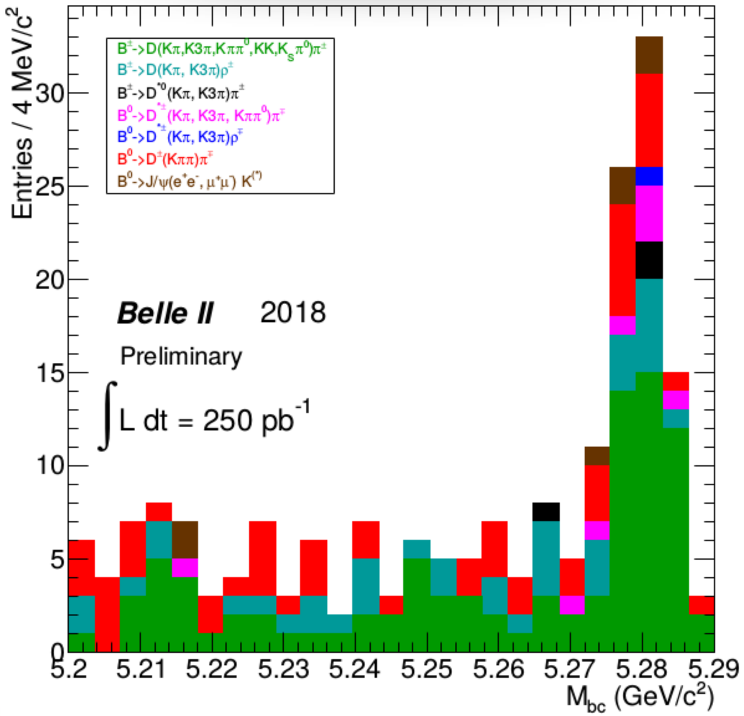


Event shape

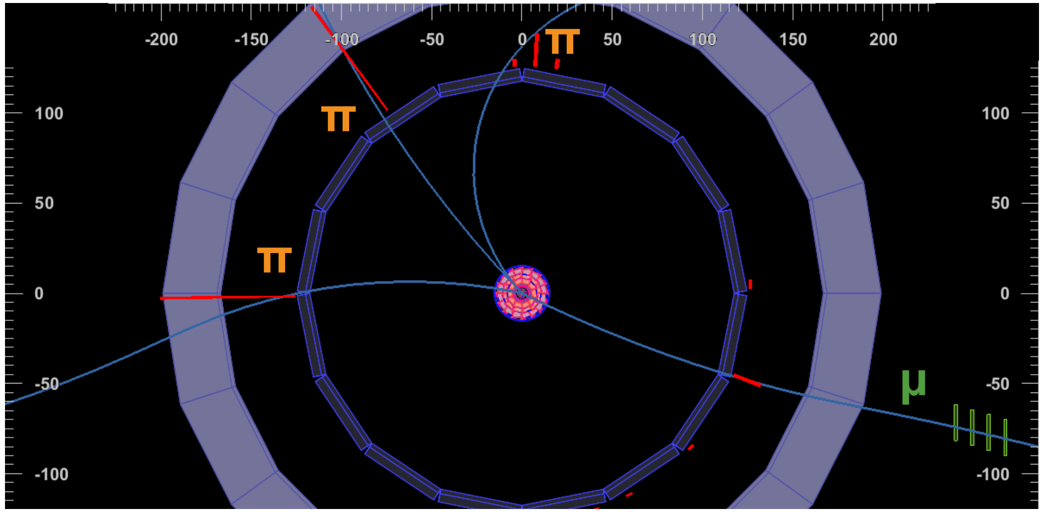


$$R_2 = \frac{H_2}{H_0}$$

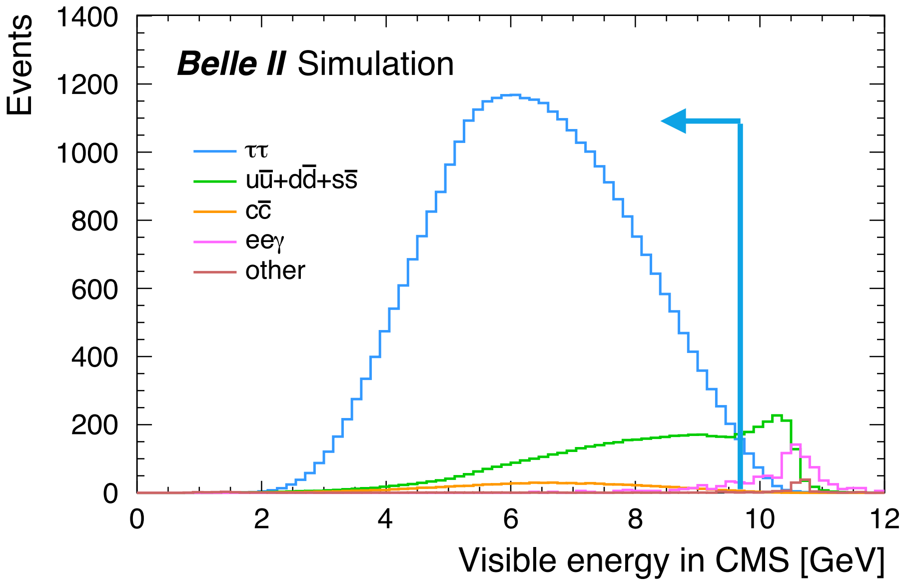
Hadronic modes

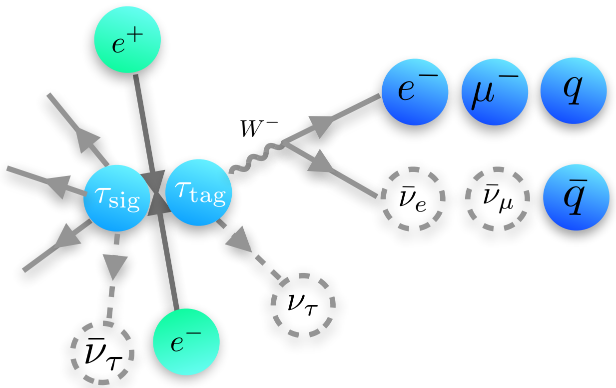


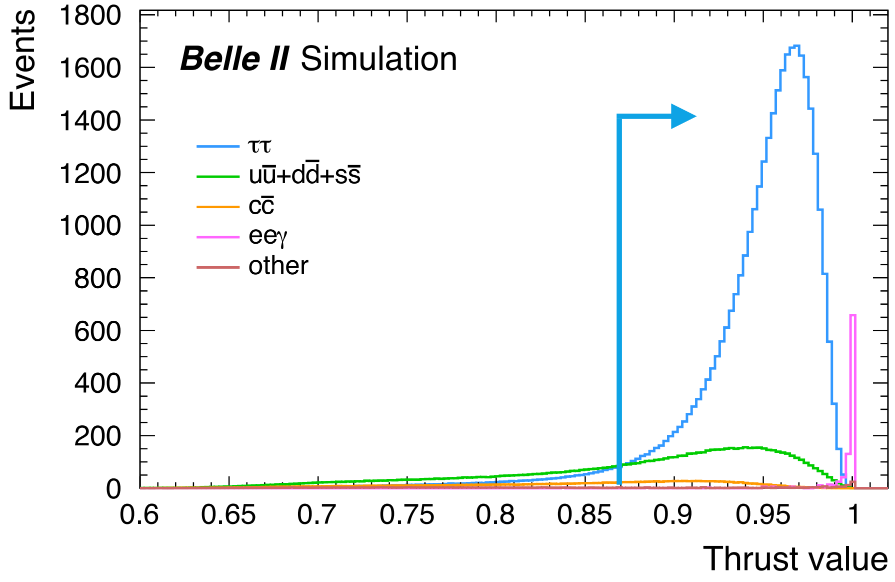
Tau Observation



- Preliminary study and preparation for future analyses
- 3x1-prong topology:
  - $\tau_{\text{signal}} \rightarrow 3\pi\nu$ ($+n\pi^0$), $\tau_{\text{tag}} \rightarrow \ell\nu\bar{\nu}/\pi\nu$
  - Identified through event thrust = $\sum_h \frac{\vec{p} \cdot \hat{T}}{|p_h|}$
- Dominant backgrounds: $q\bar{q}$ and $ee\gamma$ (radiative Bhabha)



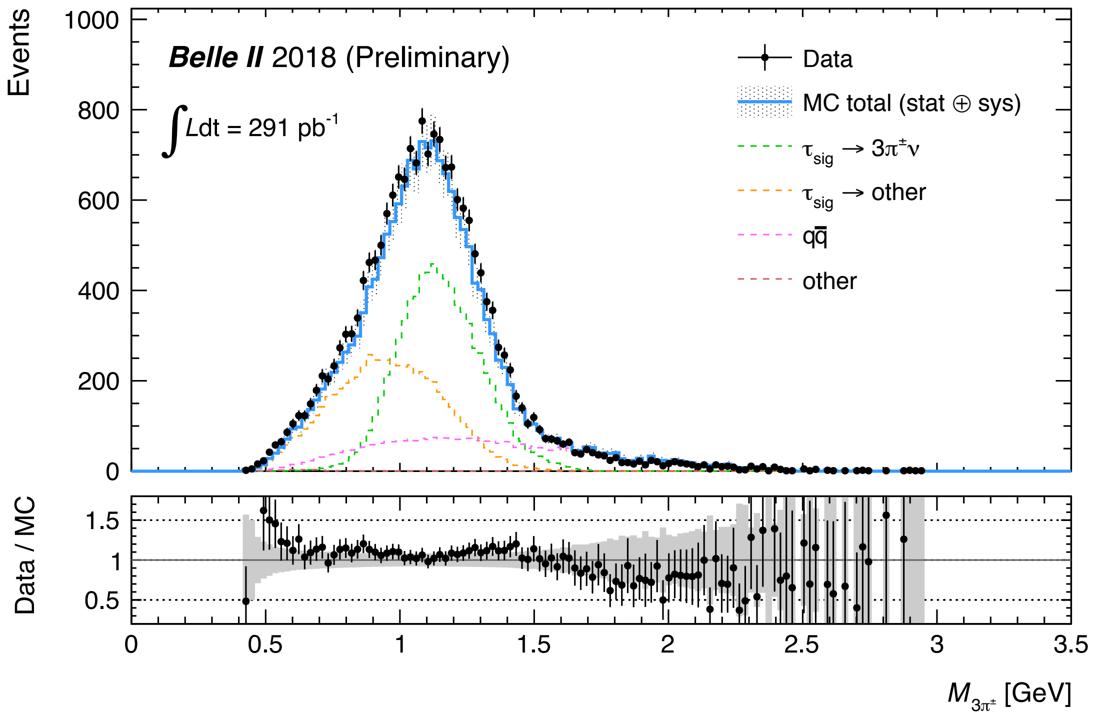




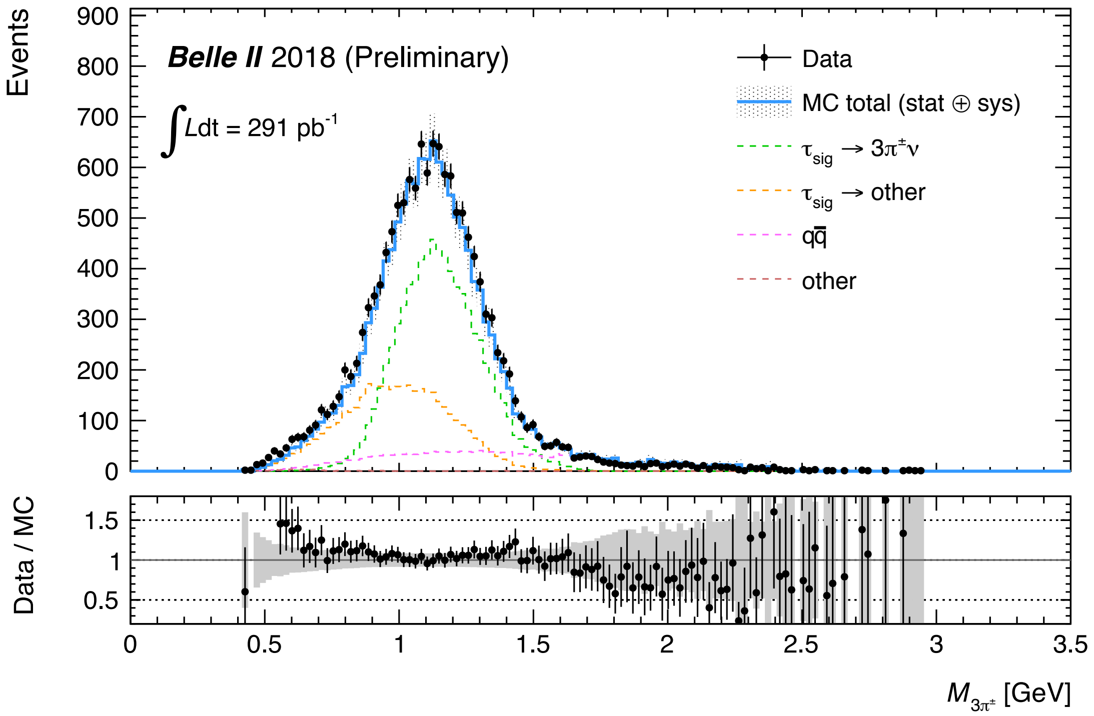
Tau Observation

- Correct for trigger efficiency (3+ tracks in CDC) → 291 fb^{-1} useable data
- After correction, good agreement between data and MC

Inclusive ($\tau_{signal} \to 3\pi\nu + n\pi^0$)



Exclusive ($\tau_{signal} \to 3\pi\nu$)

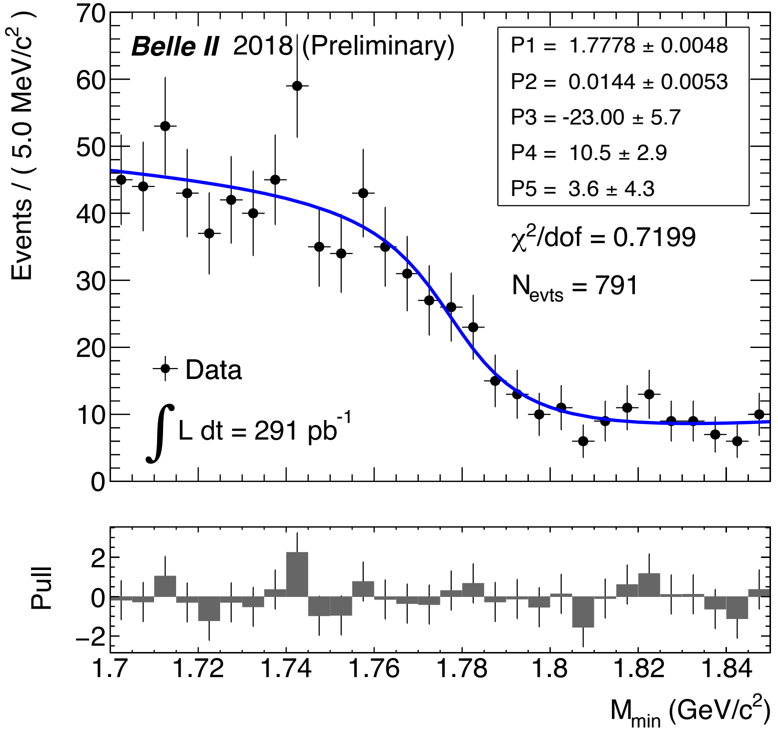


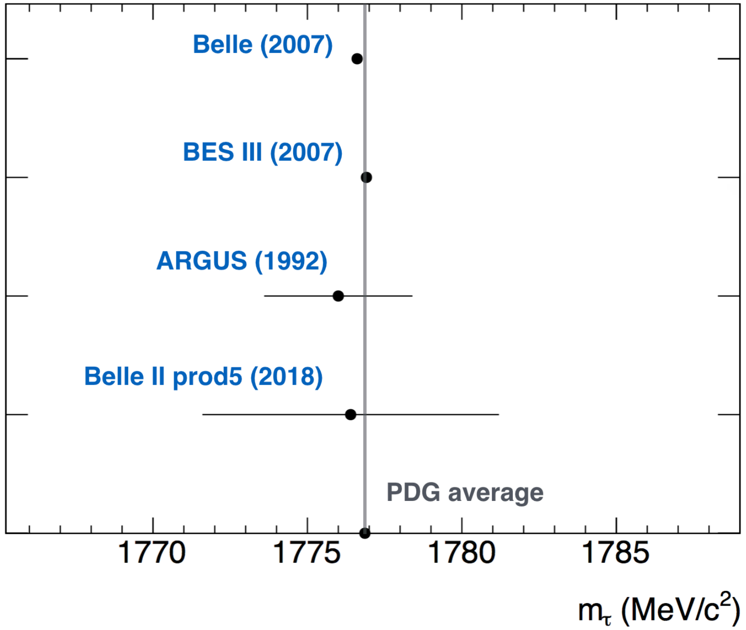
Tau Mass Measurement

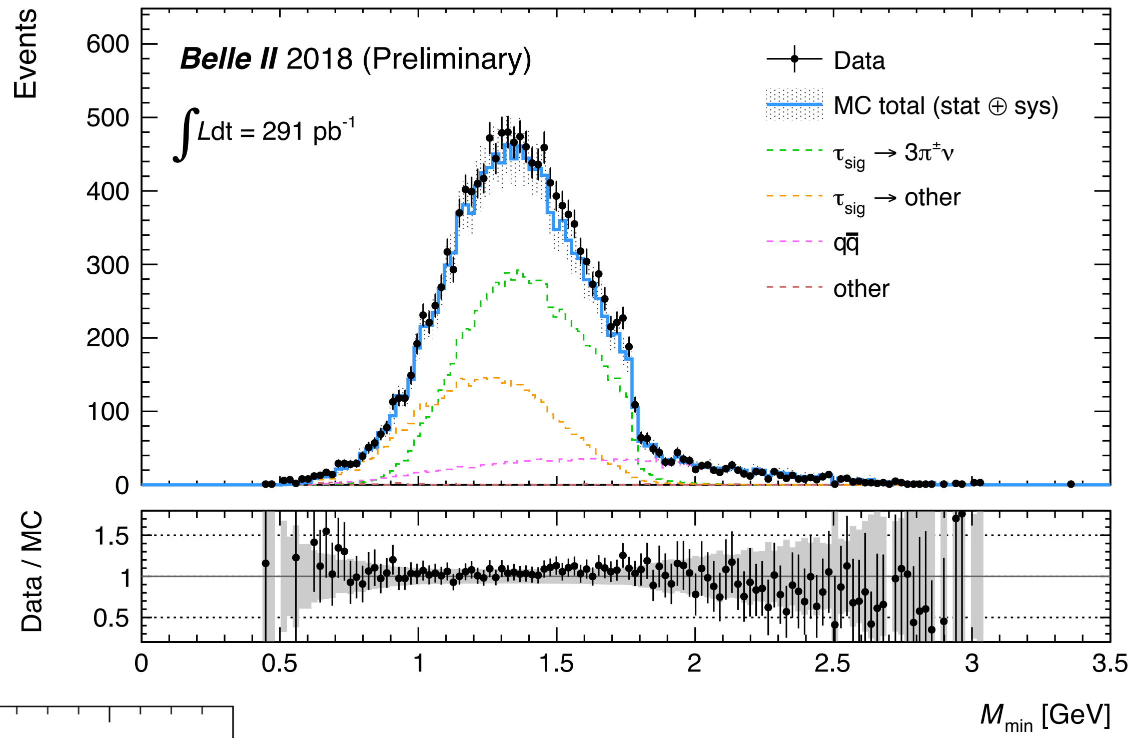
- Measurement in the exclusive $\tau \to 3\pi\nu$ channel using pseudomass technique developed at ARGUS:

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

- Fit with empirical edge function



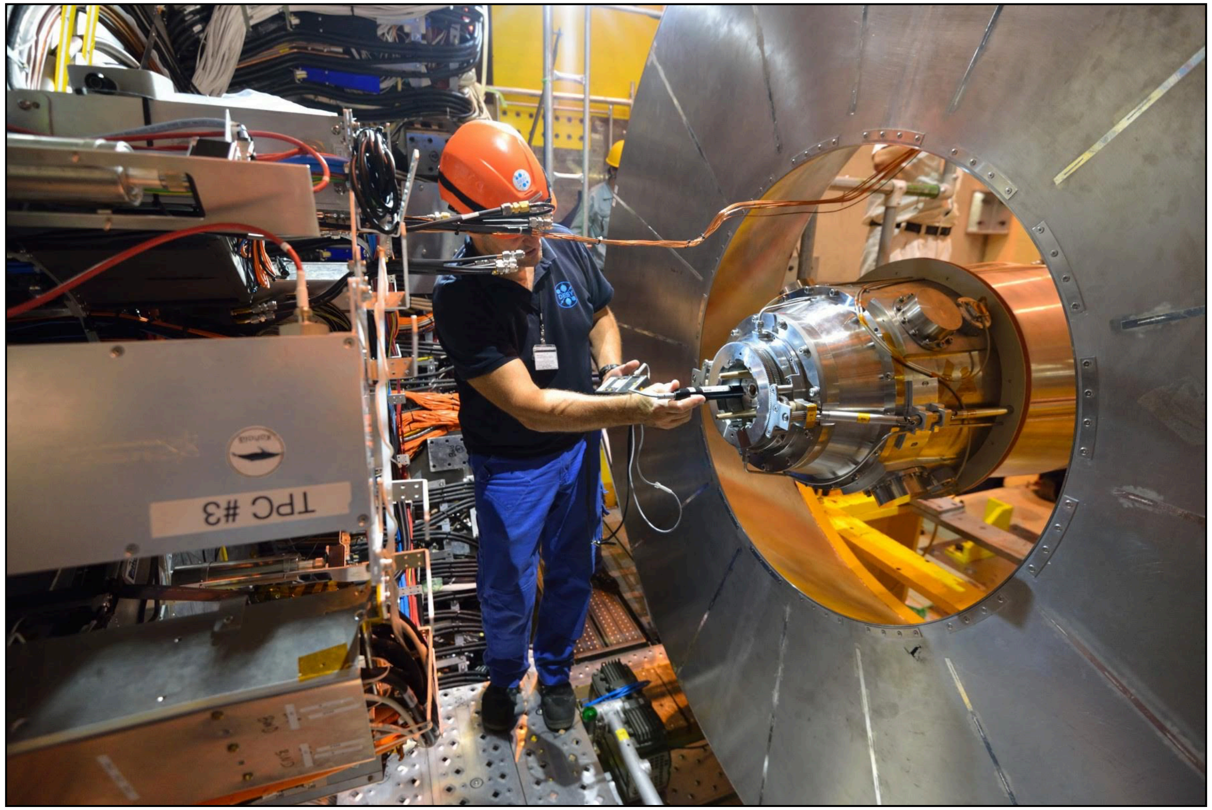




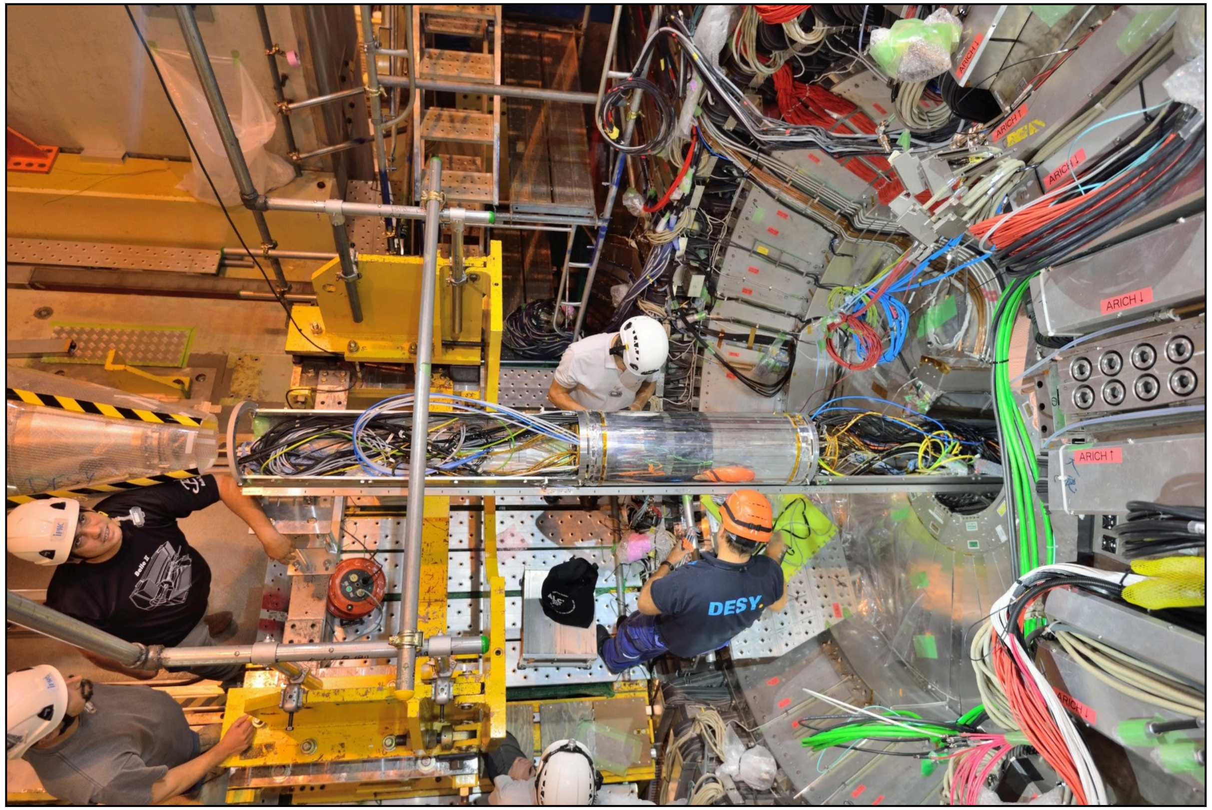
$m_\tau = (1776.4 \pm 4.8(\text{stat}))\ \text{MeV}/c^2$

- First τ physics result from Phase 2
- Good agreement with existing measurements!

Phase 3 Preparations

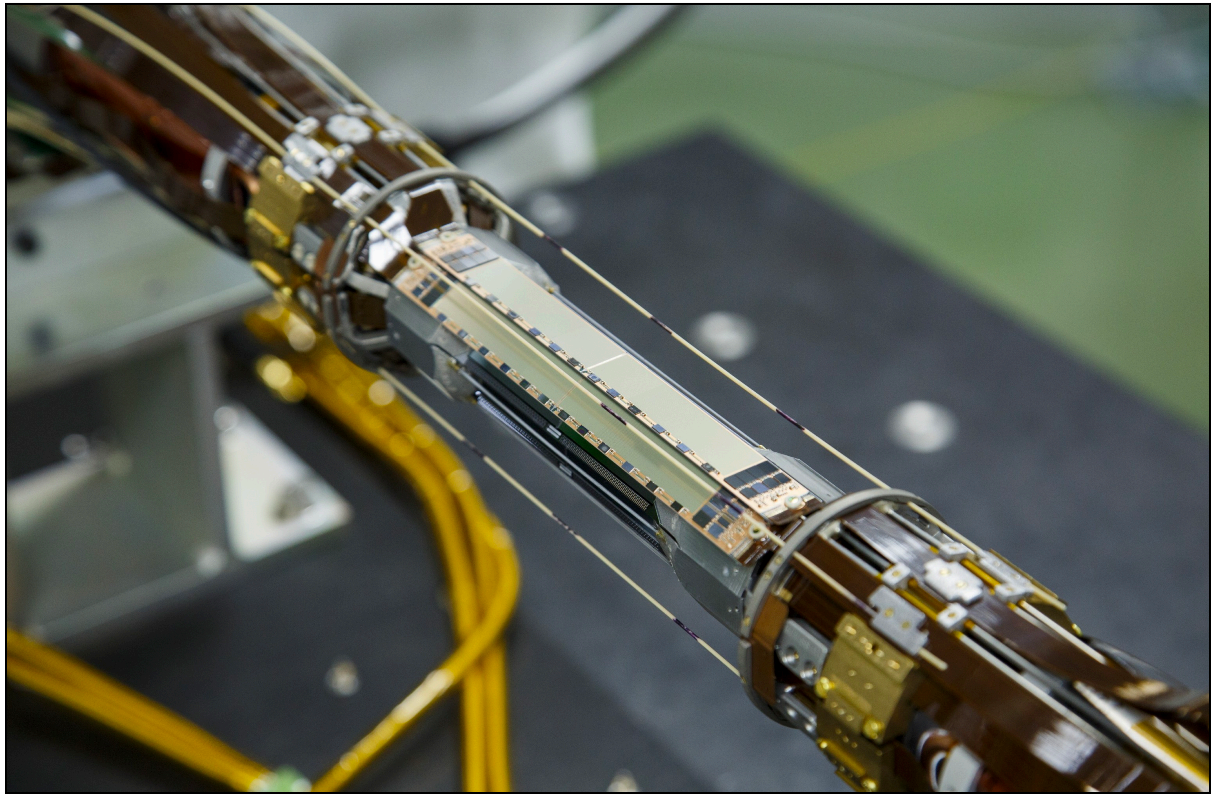


RVC opening and QCS extraction

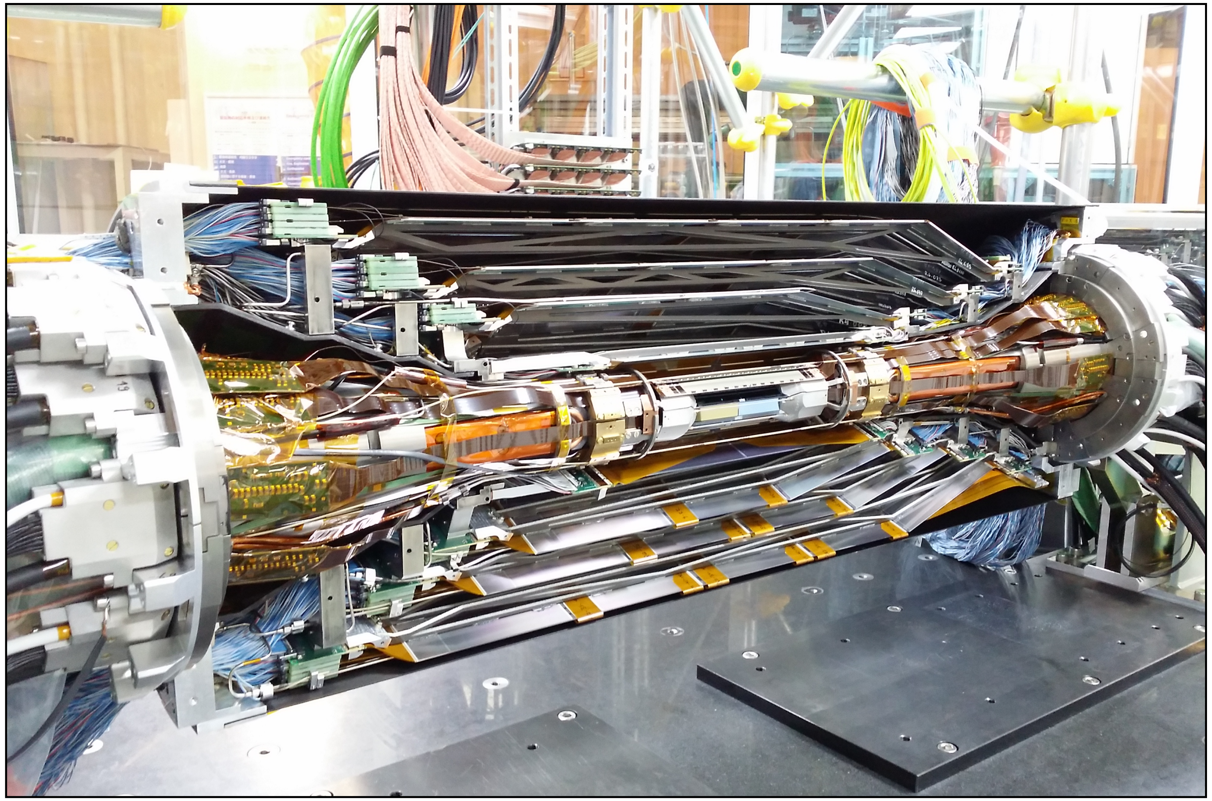


BEAST II extraction

Phase 3 Preparations



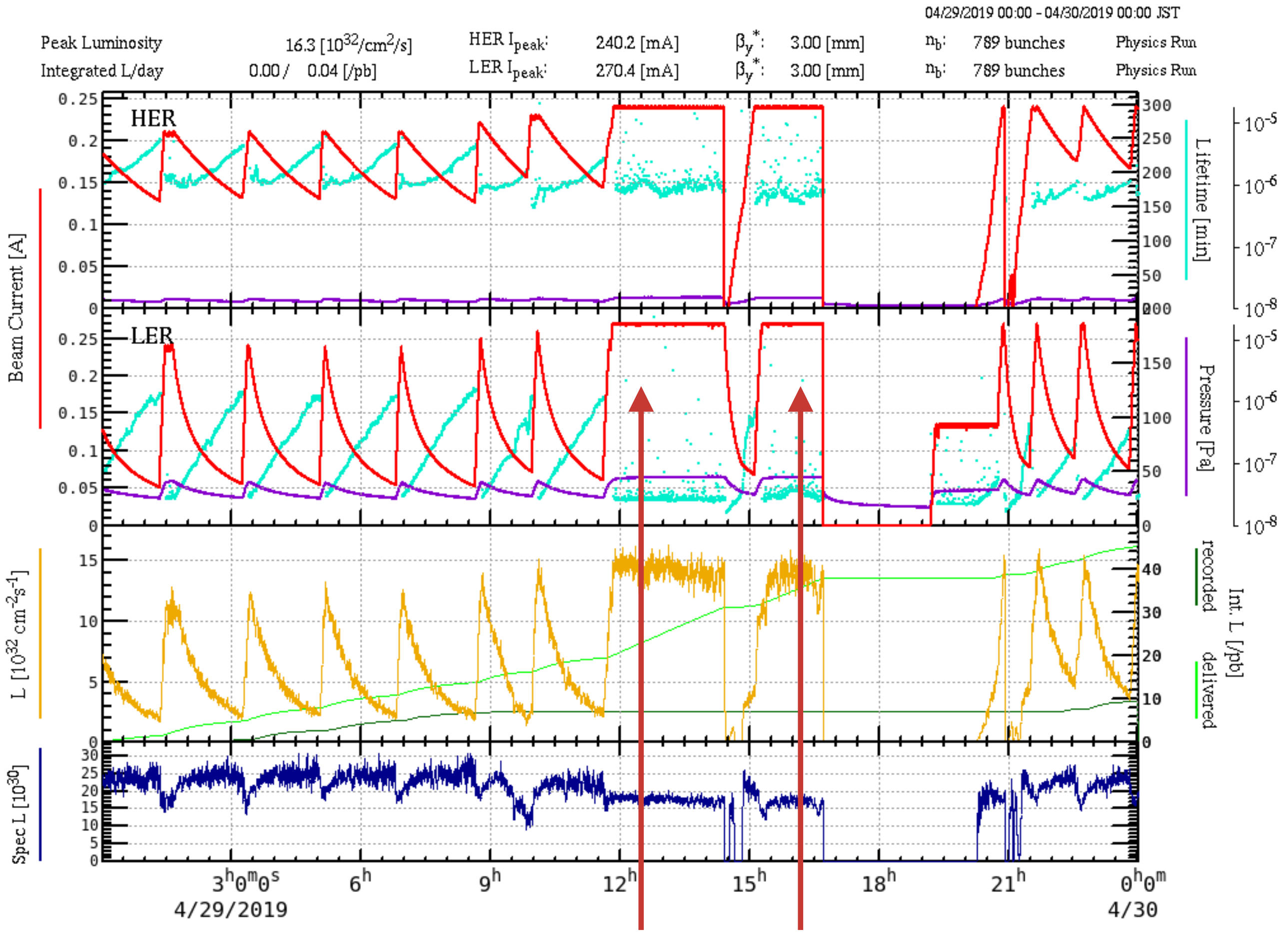
PXD mounted on beam pipe at KEK



PXD combined with one half of SVD

→ Full PXD operation (with 2 layers) scheduled for 2020

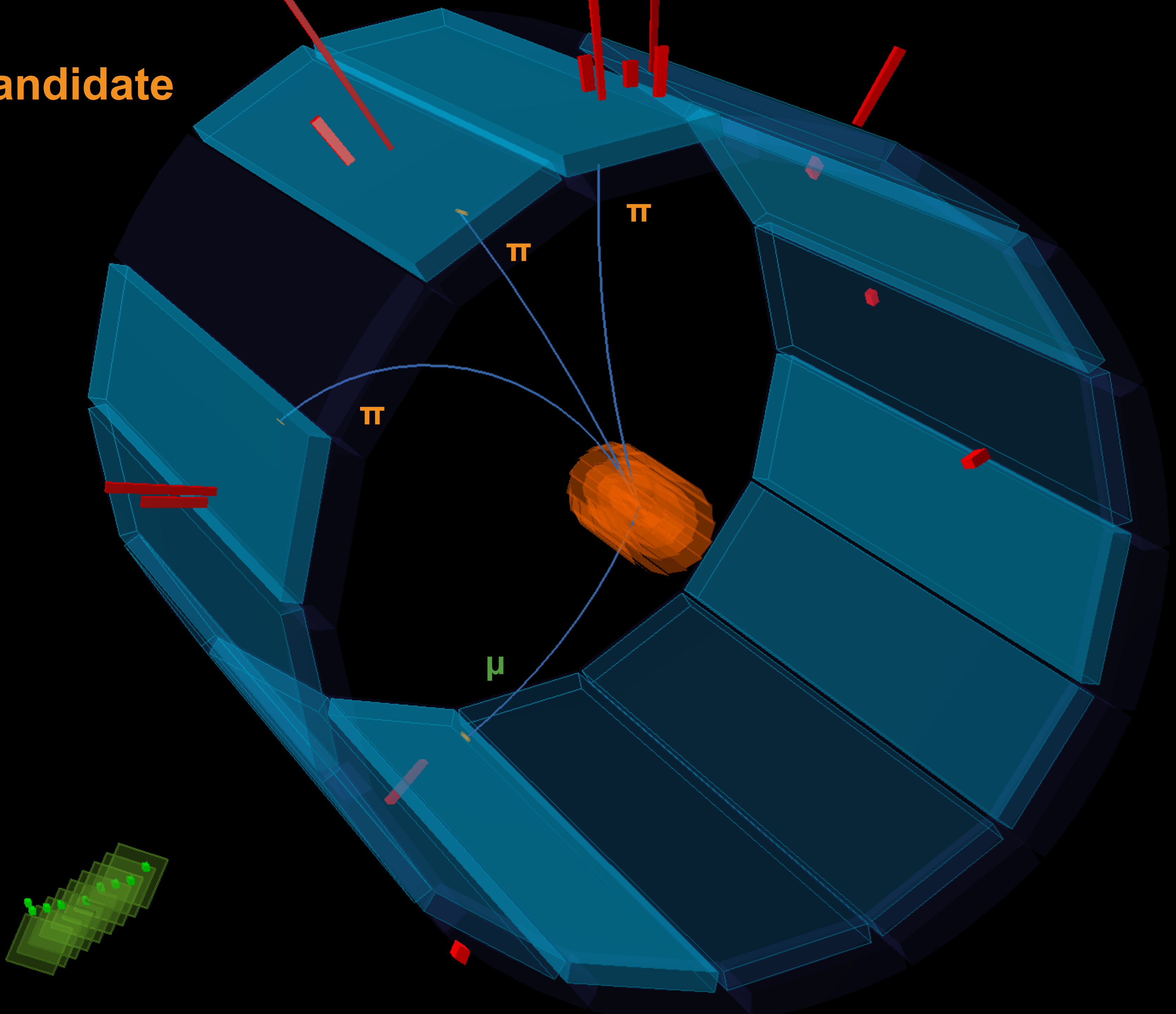
Start of Phase 3



Continuous Injection

- Regular operation started again in March
- Already collected 0.5 fb^{-1}, comparable with Phase 2
- Continuous injection for ~60% luminosity increase
- Current goal is keeping beam background in check

τ event candidate

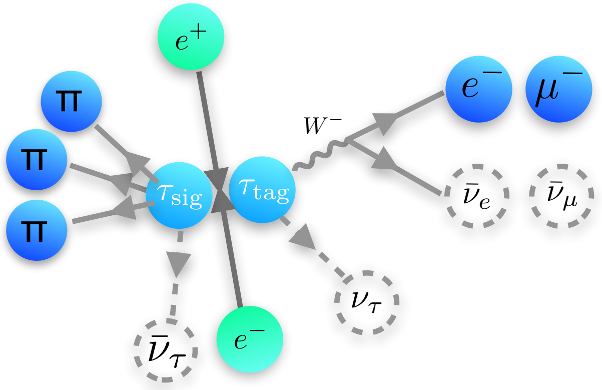


Phase 3 Studies

- Belle II is expected to deliver 50 ab^{-1} between 2019-2027, enabling a rich τ physics program.
- Covered in detail in the **Belle II Physics Book** (arXiv:1808.10567)

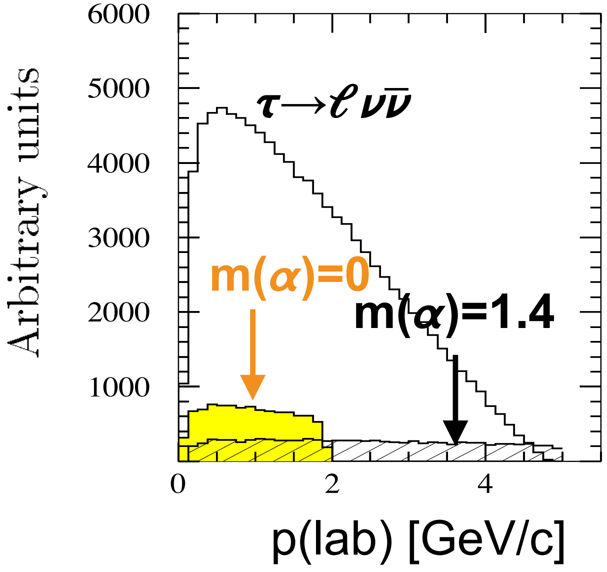
- **Already underway (feasible with ~1fb^{-1}):**
  - Branching ratio of main τ decay modes
  - τ mass measurement
  - $\tau \to \ell \alpha$(invisible)
- **Under preparation:**
  - $\tau \to \eta\pi\nu$ (Second Class Currents)
  - CP Violation in $\tau \to K_S\pi(+n\pi^0)\nu$
  - τ Lepton Flavor Violation

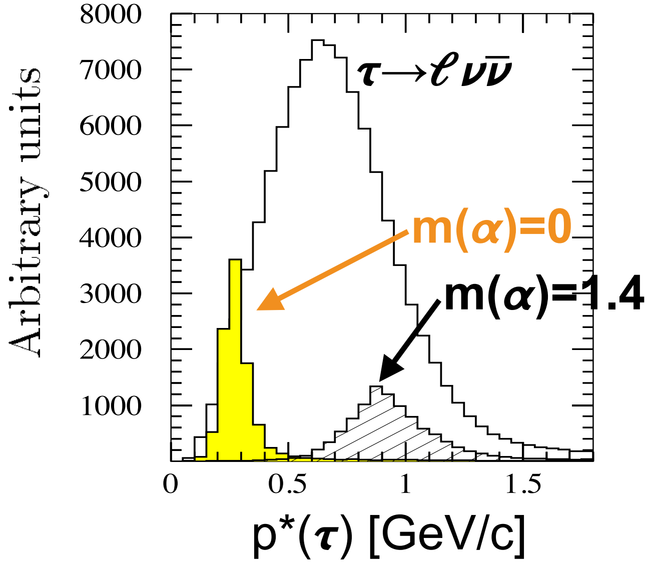
Search for $\tau \to \ell + \alpha$ (invisible)

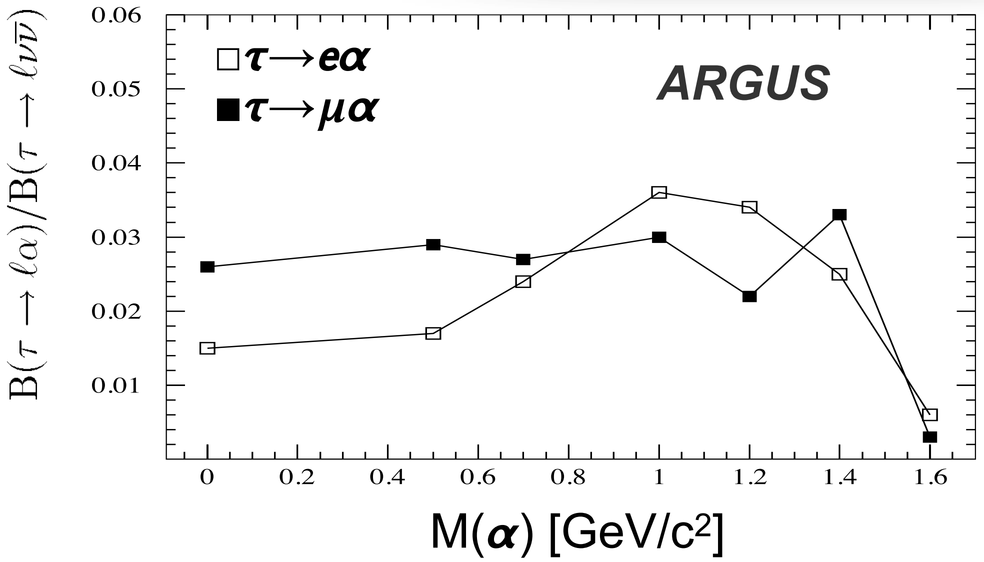


- Last studied at ARGUS using 0.5 fb^{-1} → Belle II is already competitive
- Study the lepton momentum spectrum in the τ frame:
  - Exploit same 3x1 topology as the mass measurement: $\tau_{tag} \to 3\pi\nu$, $\tau_{signal} \to \ell\alpha$
  - $E^*(\tau) = \sqrt{s}/2$ and $\vec{p}(3\pi) \sim \vec{p}(\tau)$ → signal τ frame can be approximated.
- Sensitivity is mostly independent from the α mass:

Z.Phys. C68 (1995) 25-28

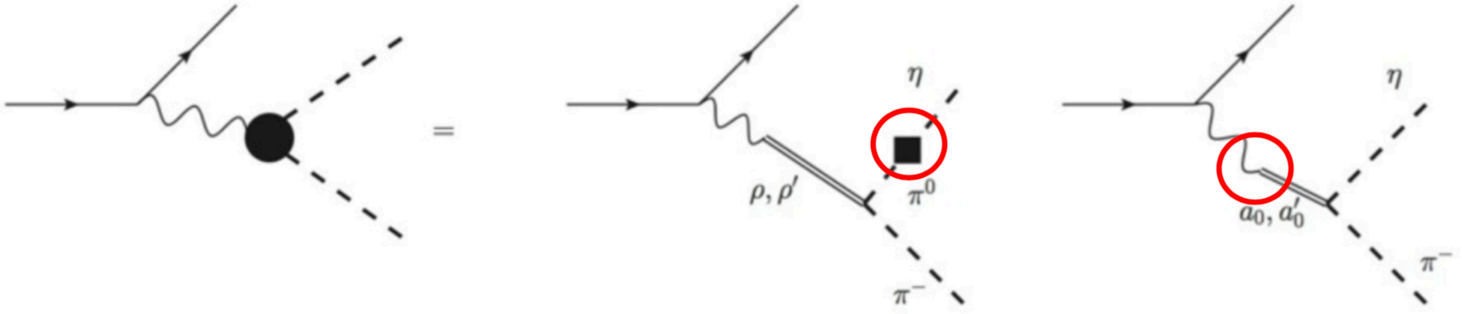


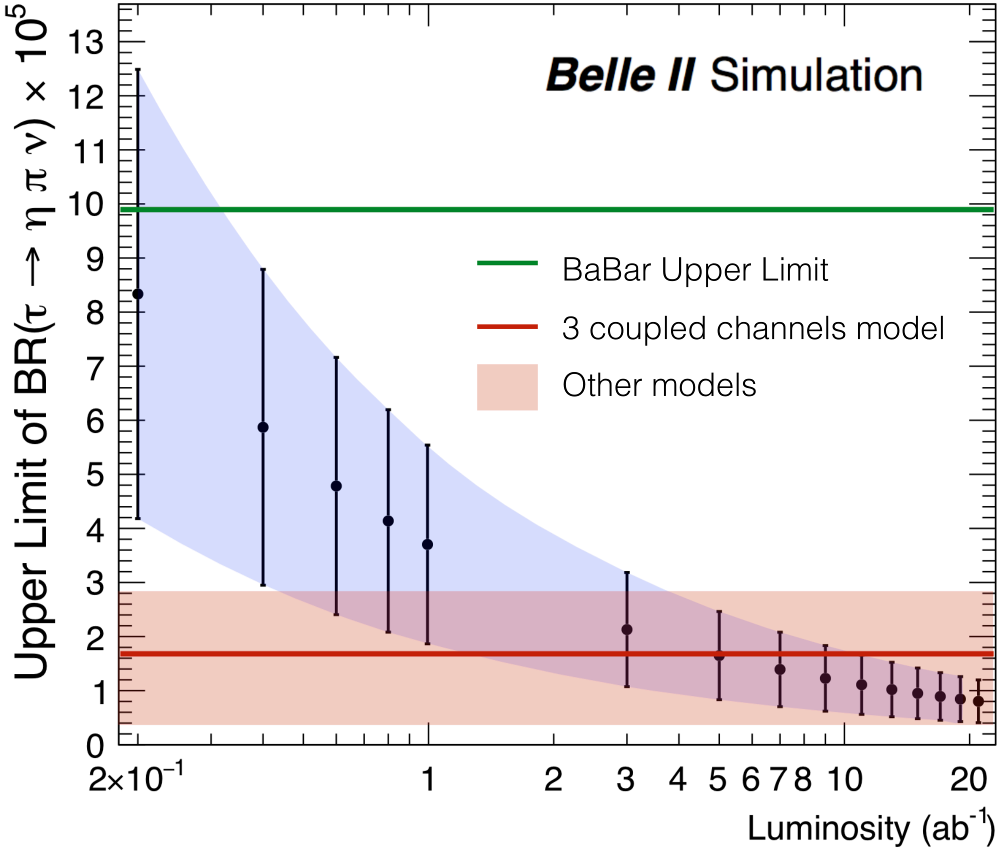




Second class currents in $\tau \to \eta\pi\nu$

- In the SM, the $\tau \to \eta\pi\nu$ decay proceeds through SCCs (isospin-violating, e.g. π-η mixing):
  - **SM prediction:** BR ~ $O(10^{-5})$
- Searched for at last-gen B factories but not observed:
  - Belle: BR < 7.3×10^{-5}
  - BaBar: BR < 9.9×10^{-5}
- Observation becomes possible at Belle II **within the first years** of data taking (1 ab^{-1})
- **Large deviation could indicate New Physics!**
- An accurate measurement could also apply strong bounds to NP models.





CP Violation in the Tau sector

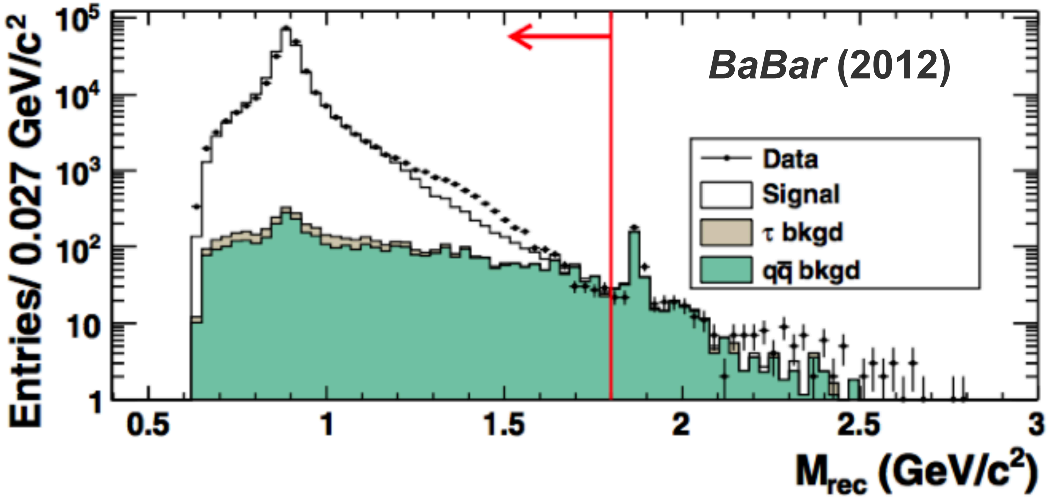
Phys.Rev D85 (2012) 031102

- CP violation in the Kaon sector induces a decay rate asymmetry in the SM:

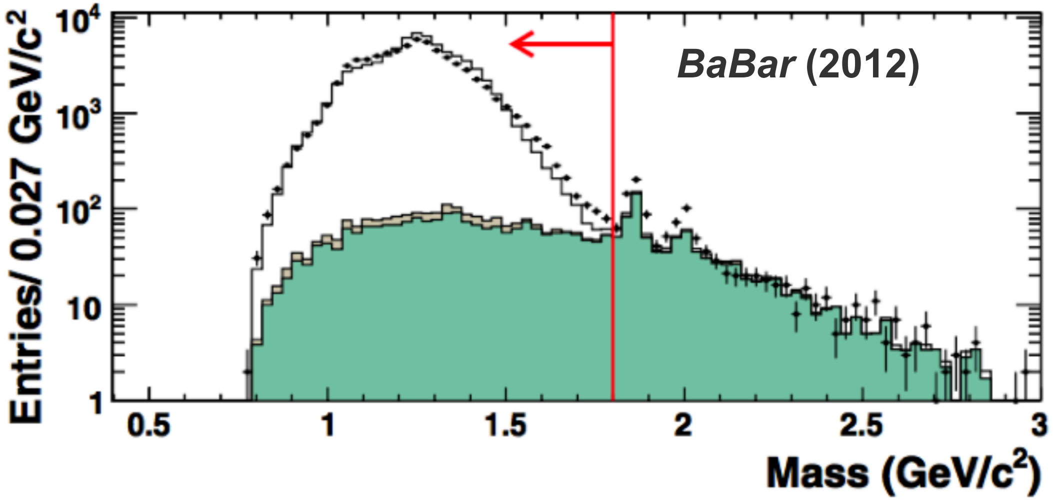
$$A_\tau = \frac{\Gamma(\tau^+ \to \pi^+ K_s^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_s^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_s^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_s^0 \nu_\tau)}$$

- **SM prediction:** $(3.6 \pm 0.1) \times 10^{-3}$
- **BaBar:** $(-3.6 \pm 2.3 \pm 1.1) \times 10^{-3}$ (**2.8σ** deviation)
- High priority improved measurement at Belle II

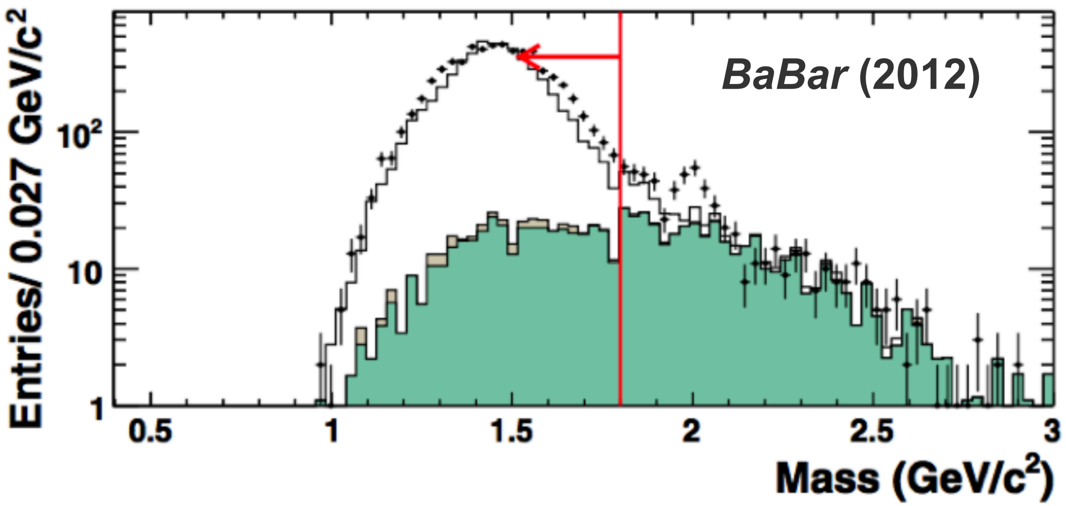
$\tau \to K_s \pi^\pm \nu_\tau$



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



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

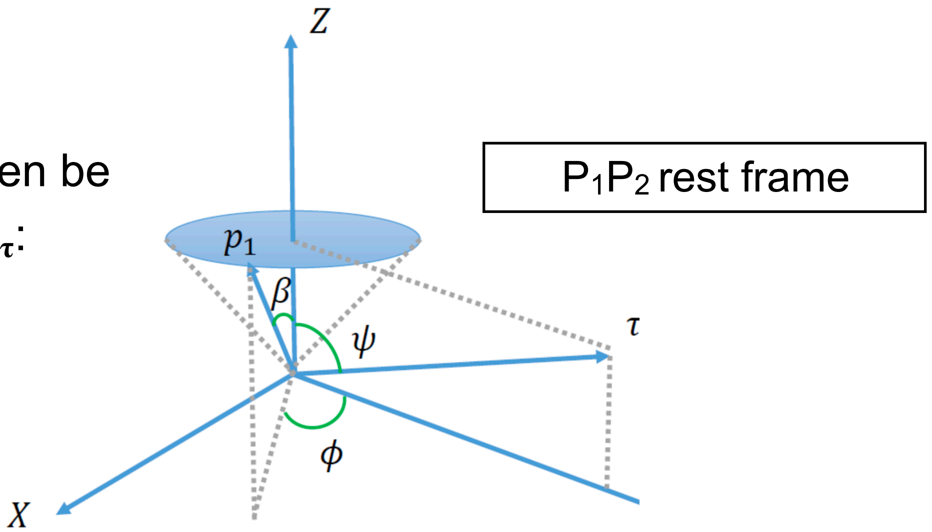


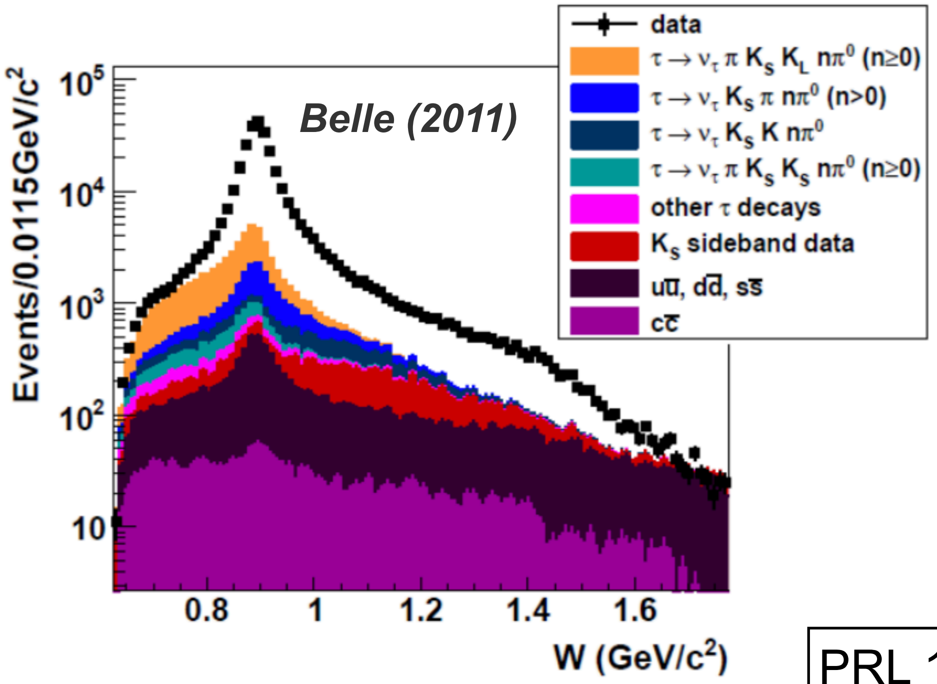
CP Violation in the Tau sector

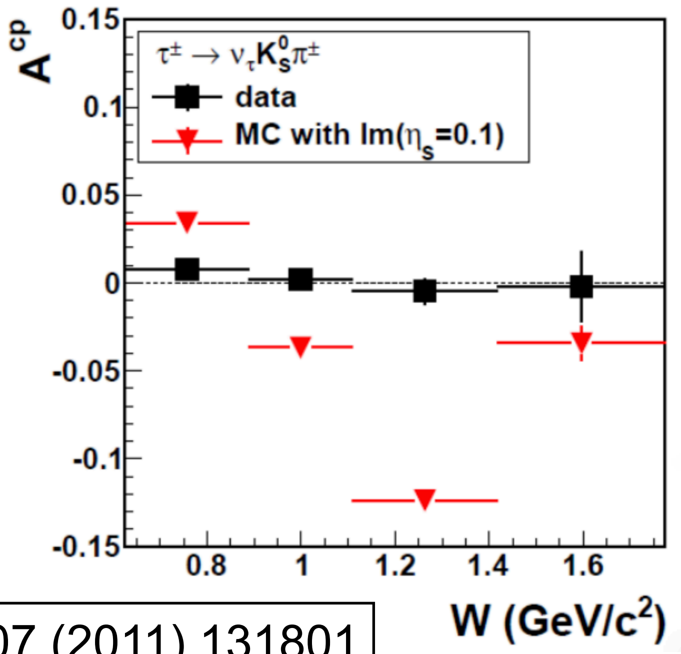
- Charged scalar boson exchange could also induce CPV, which would then be detected as a difference in the decay angular distributions for $\tau \to P_1 P_2 \nu_\tau$:

$$A_i^{CP} \simeq \langle \cos\beta \cos\psi \rangle^i_{\tau^-} - \langle \cos\beta \cos\psi \rangle^i_{\tau^+}$$

$\cos\beta \to$ measured
$\cos\psi \to$ decay kinematics







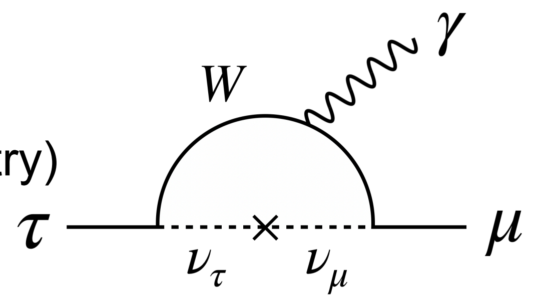
PRL 107 (2011) 131801

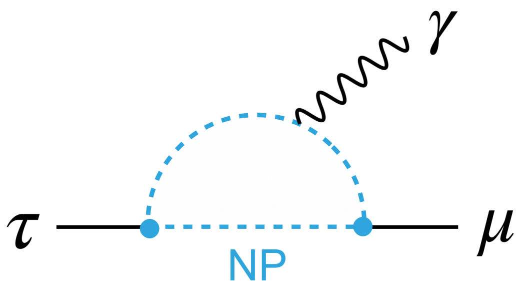
- Studied at Belle
- With 50 ab^{-1} of data, Belle II is expected to provide a $\sqrt{70}$ more precise measurement:

$$\boxed{|A_{CP}| < (0.4\text{-}2.6) \times 10^{-4}}$$

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

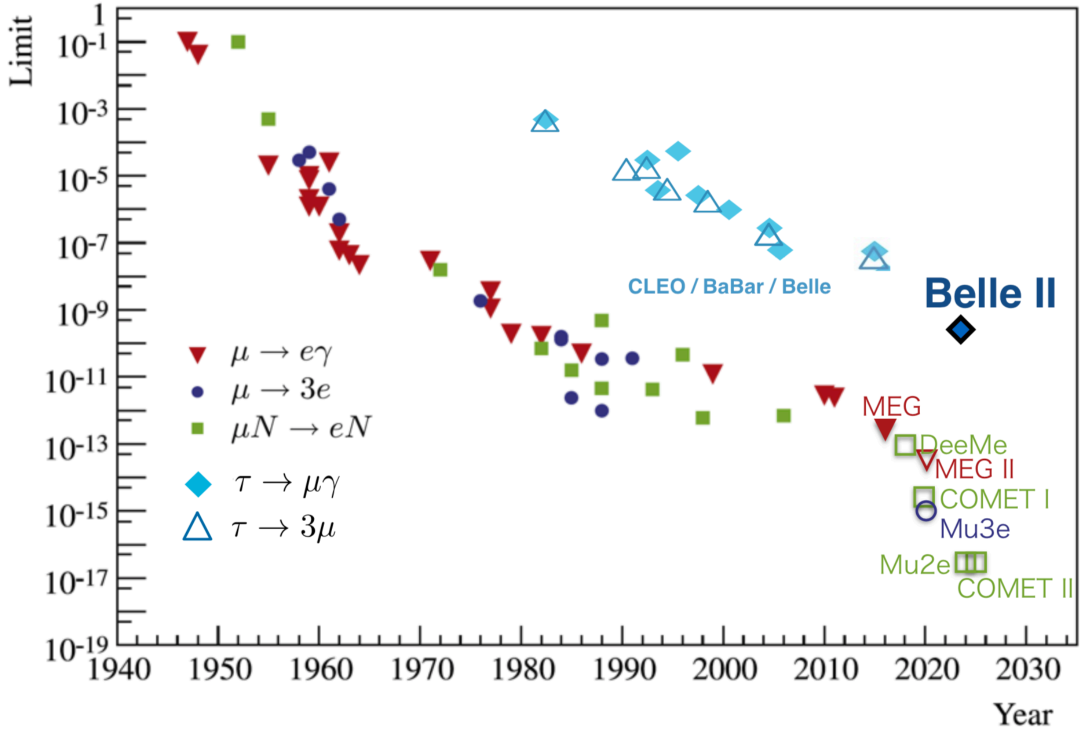
Charged Lepton Flavor Violation





- Lepton flavor is conserved in the SM (accidental symmetry)
- Observed in the neutral sector (**ν** oscillation)
  → first sign of BSM physics!
- Also implies (immeasurably small) cLFV: $\mathcal{B}_{\nu SM}(\tau \to \mu\gamma) = \frac{3\alpha}{32\pi}\left|U^*_{\tau i}U_{\mu i}\frac{\Delta m^2_{3i}}{m^2_W}\right|^2 < 10^{-40}$

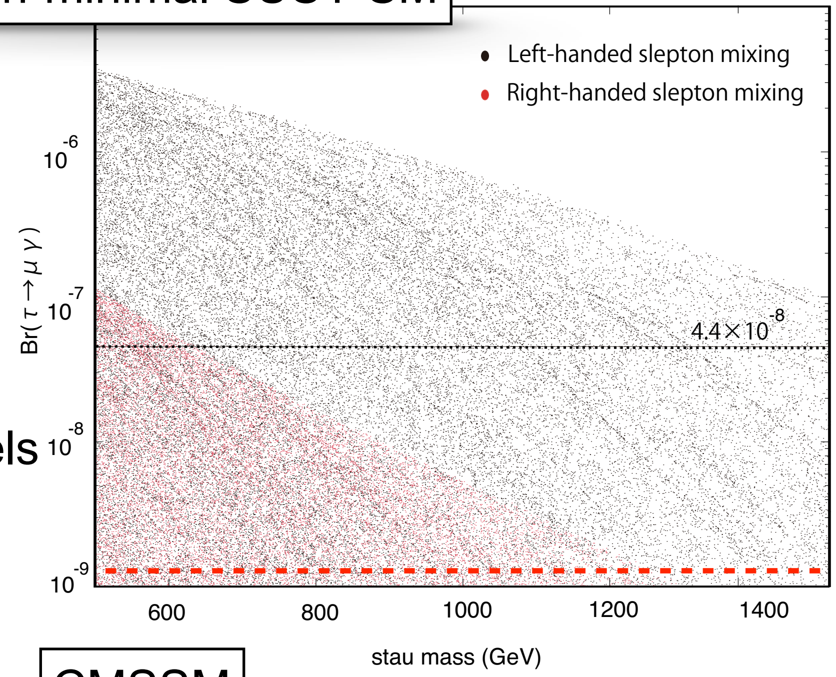
- **Powerful probe for new physics!**
  - Several NP models enhance this process
  - **μ→eγ**: strong bounds from MEG
  - **τ→ℓγ**: weaker constraints from CLEO, BaBar, Belle, CMS...

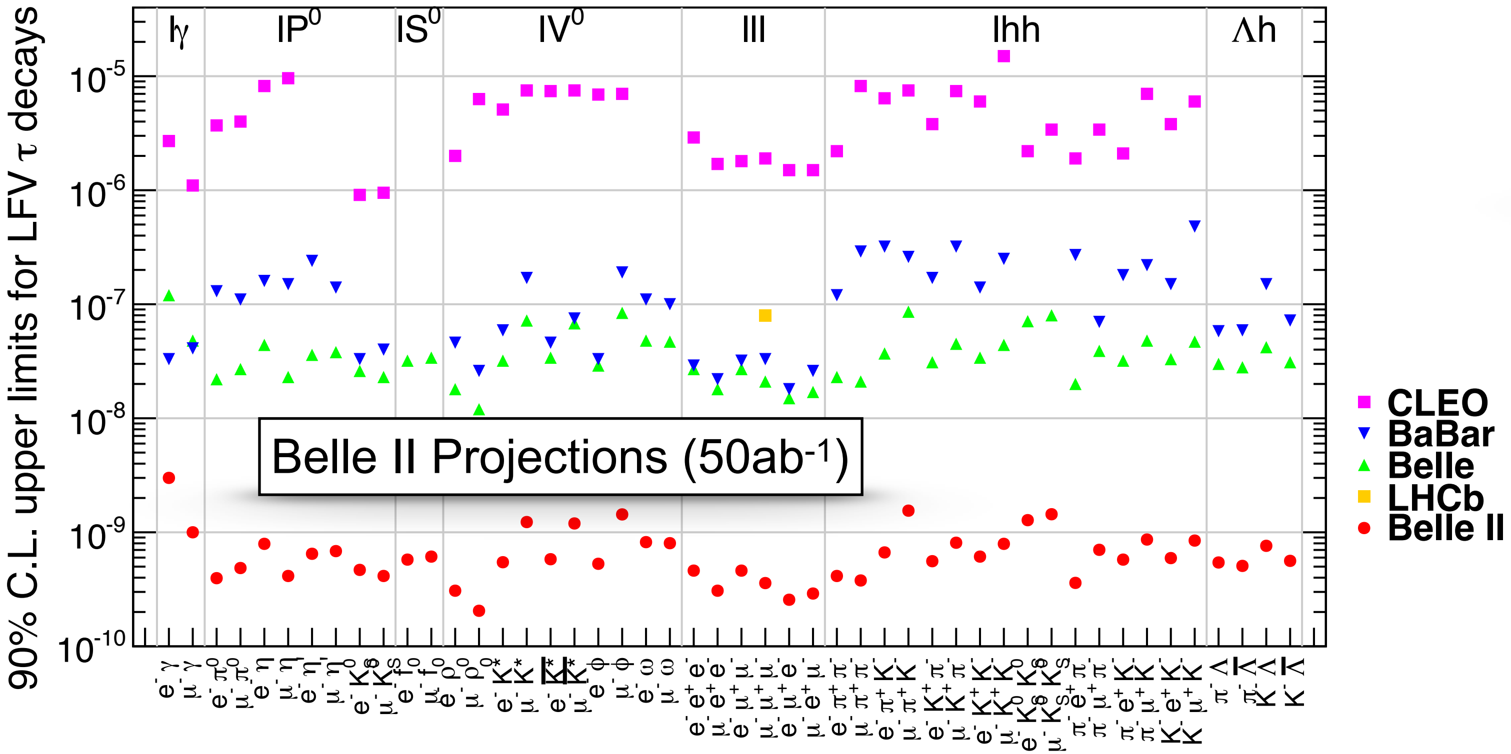


Prospects for cLFV at Belle II

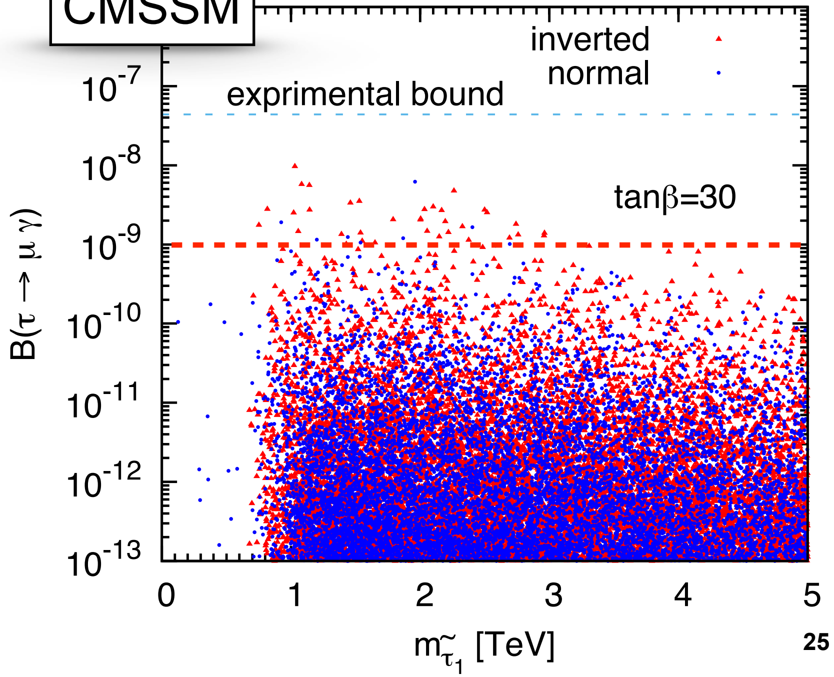
- Due to its mass, τ decays allow to probe for additional LFV/LNV couplings:
  - $\tau \to \ell\gamma$, $\tau \to \ell\ell\ell$ but also $\tau \to \ell h(h)$
- Past experiments approached the regime sensitive to New Physics
- Belle II will push the boundaries by O(10) to rule out or confirm NP models

non-minimal SUSY SM



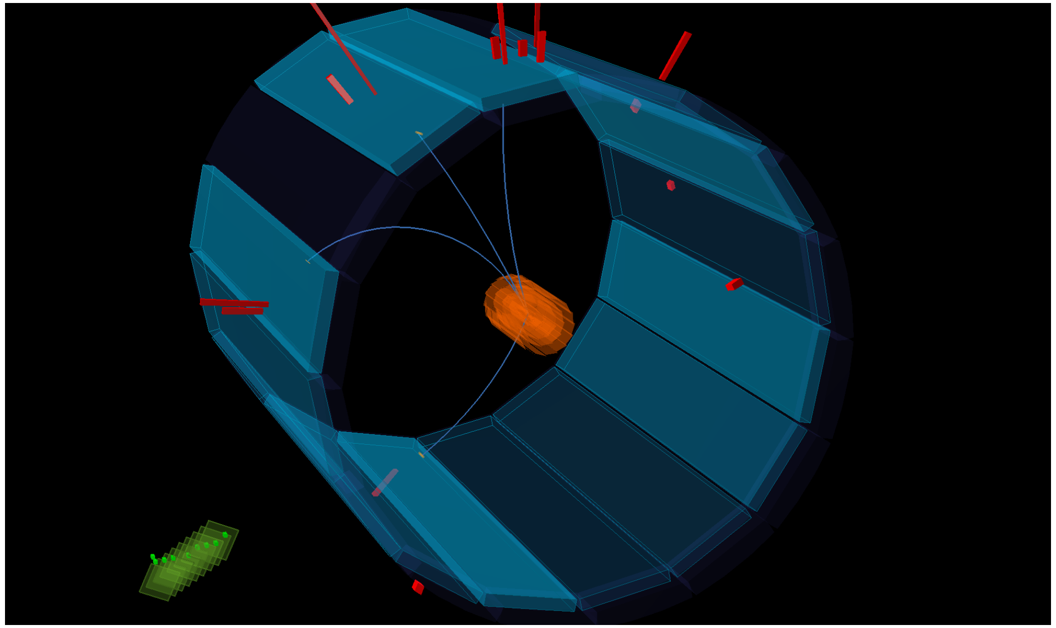


CMSSM



Conclusions and Outlook

- The Belle II commissioning phase has concluded, providing a pilot test of the new collision scheme as well as some preliminary physics measurements.
- Full detector operation has begun earlier this year in March.
- Belle II has a broad physics program to probe the τ sector for New Physics
- Potential already exists for exciting results in the first years of data taking.



Thank you for your attention!