Tau Physics at Belle II

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HEPHY Seminar

13th October 2020

HELMHOLTZ

RESEARCH FOR GRAND CHALLENGES

Outline

(1) Overview of SuperKEKB accelerator and Belle II detector

(2) How we reconstruct τ-pair events

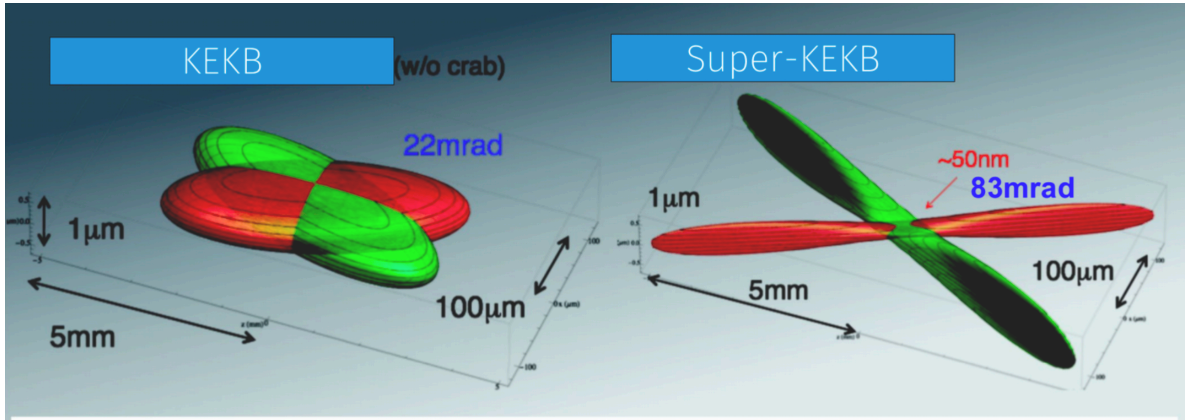
(3) Performance studies with taus

(4) First results and prospects for Tau Physics at Belle II

(5) Summary and outlook

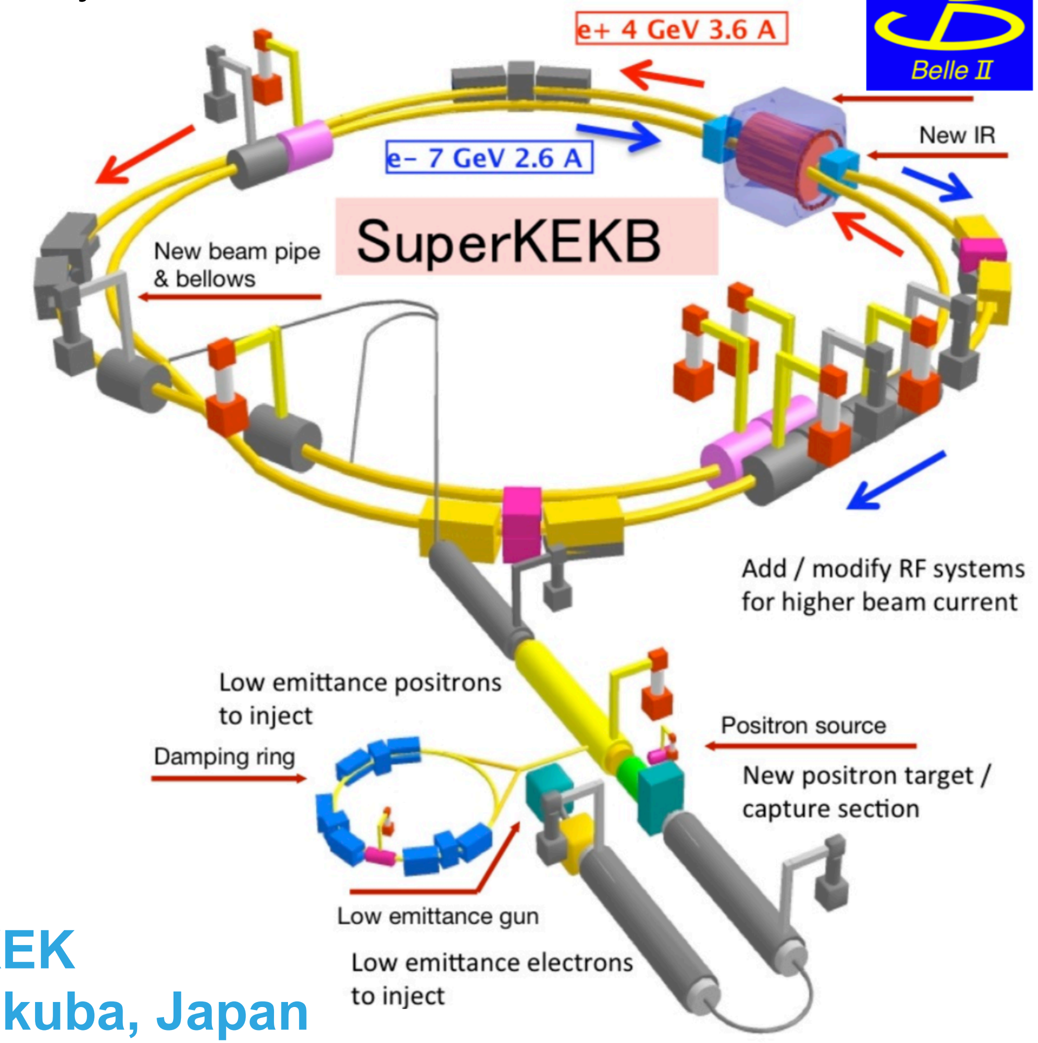
SuperKEKB Accelerator

- New facility to search for new physics by studying *B*, *D* and τ decays
- Electron-positron collisions at $\sqrt{s} \approx 10.6$ GeV



	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

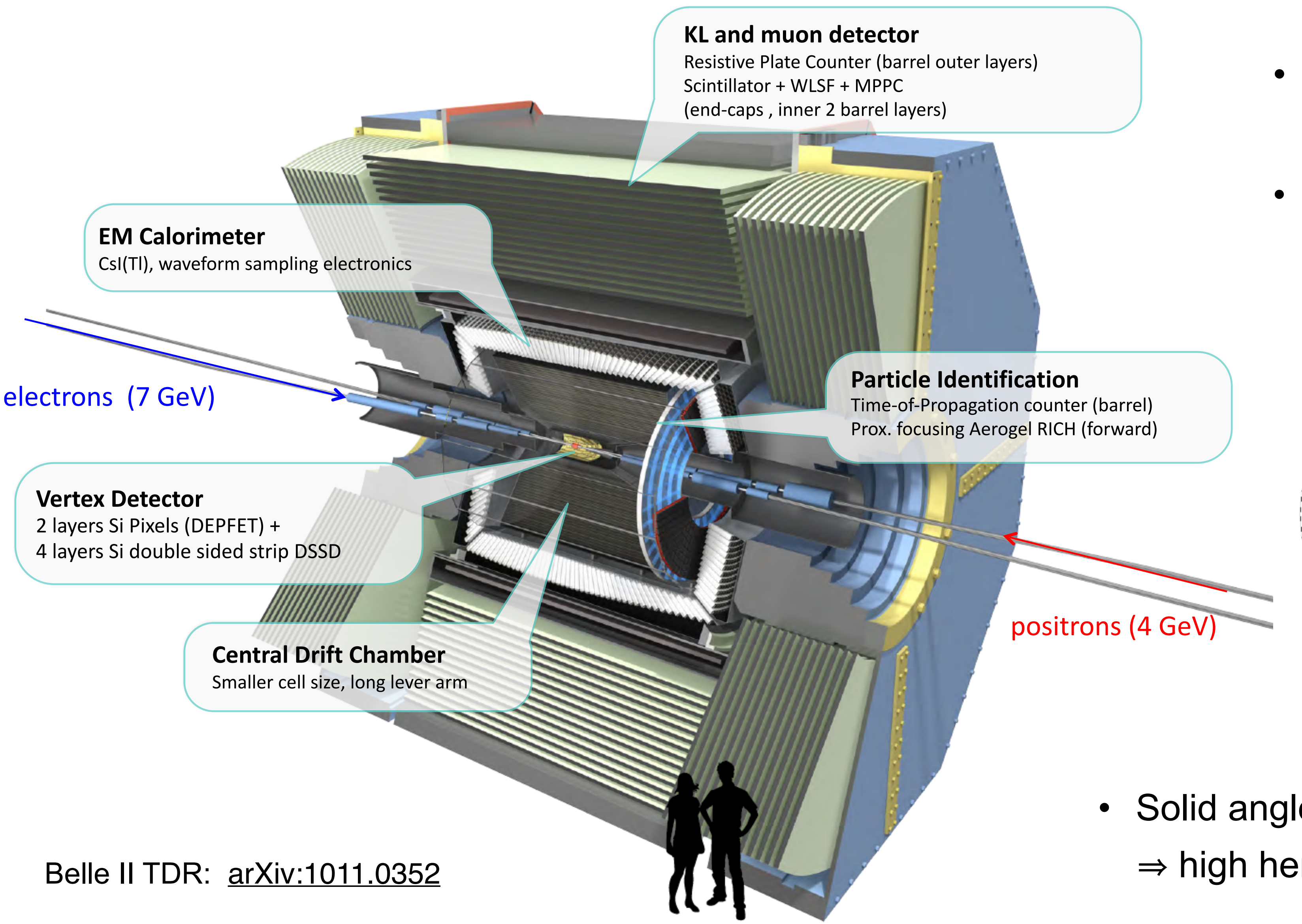
factor 20 factor 2-3



- Unprecedented design luminosity of ~6×10^{35} $cm^{-2}s^{-1}$
- First beams/commissioning in 2016. Broke the world lumi record in June 2020! (2.4×10^{34} $cm^{-2}s^{-1}$)

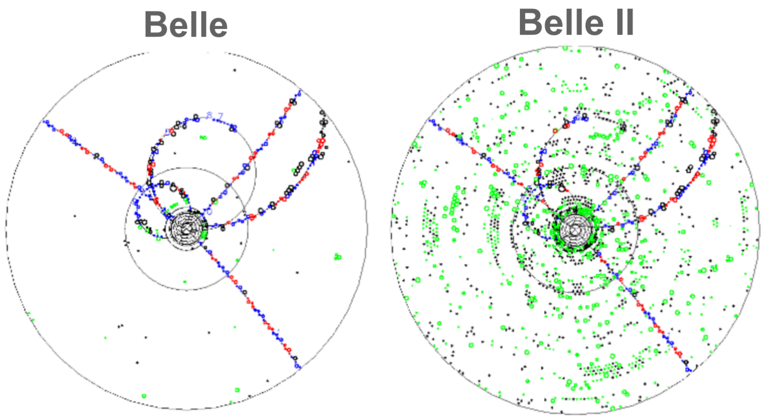
@KEK
Tsukuba, Japan

Belle II Detector



Belle II TDR: arXiv:1011.0352

- Rolled in: April 2017
- Detector upgrade to mitigate increased beam background

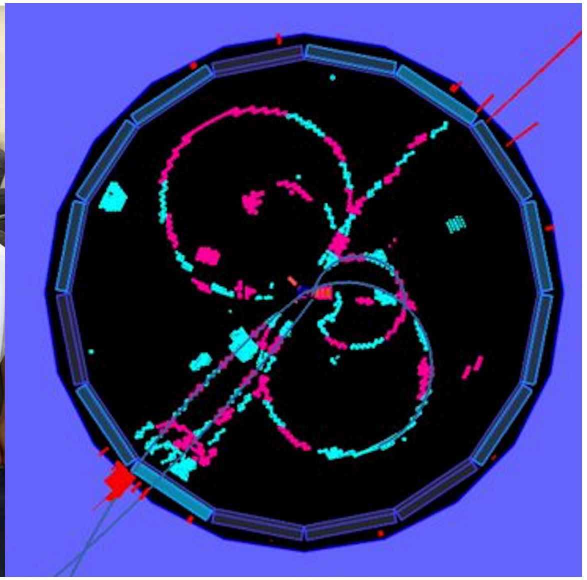


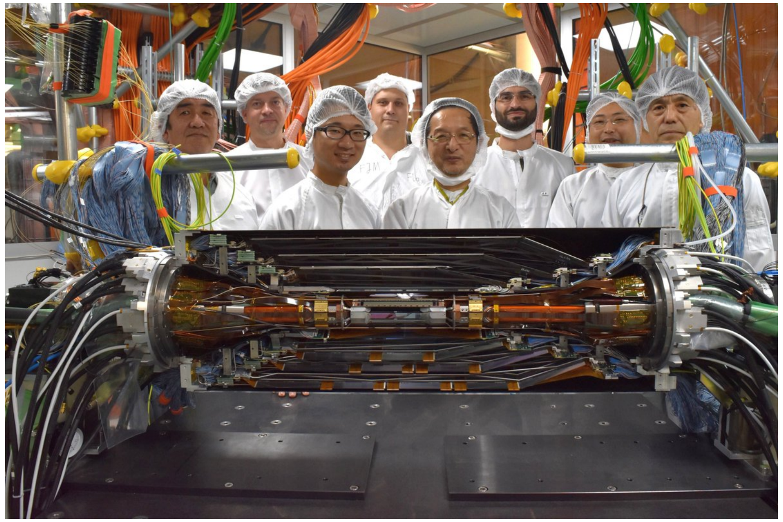
- Solid angle coverage > 90%

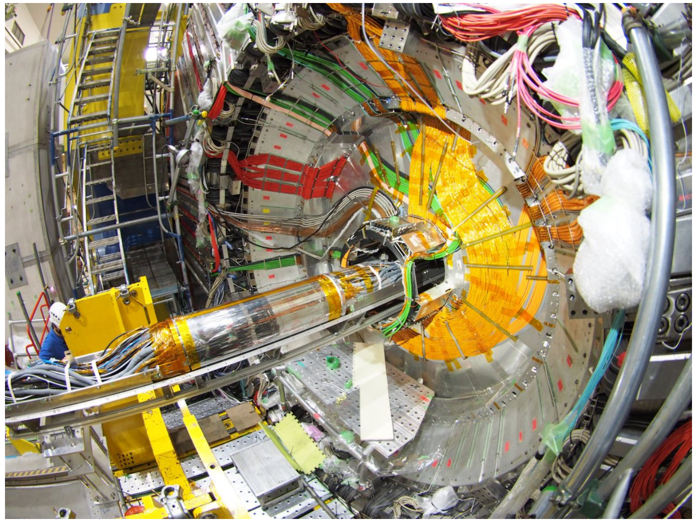
  ⇒ high hermeticity for E_{miss} measurements

First collisions @ Belle II

- First collisions recorded by Belle II on 26th April 2018
- During **Phase 2** (April-July 2018) recorded ~0.5 fb^{-1} of data
- Data taking was performed with all subsystems, excluding the full vertex detector



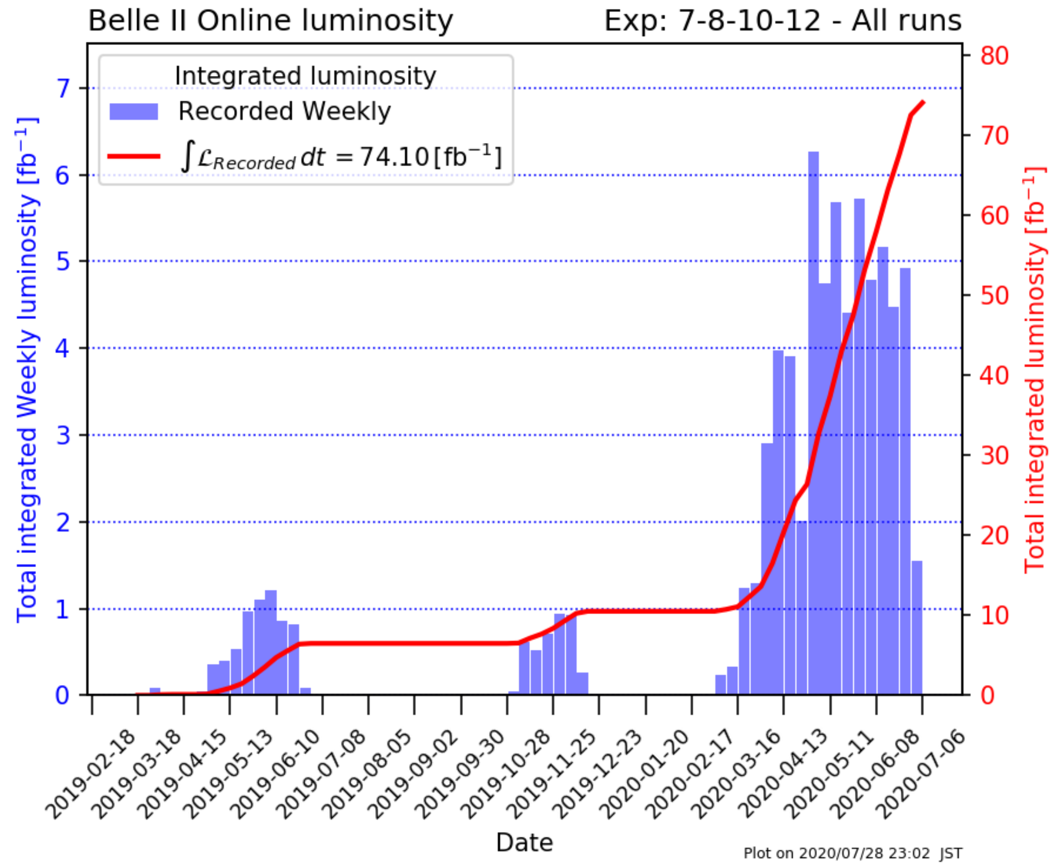


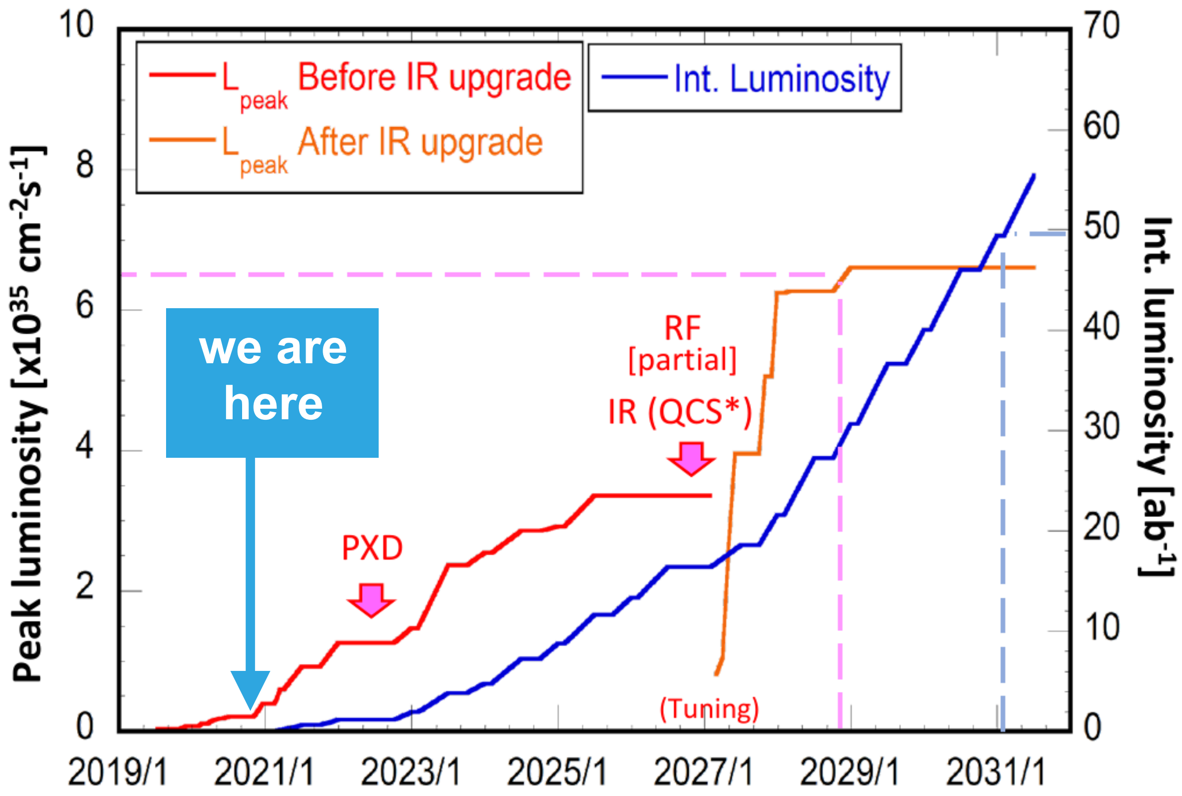


- Since then, the vertex detector including one pixel layer has been installed
- **Phase 3** ongoing since March 2019
- Overall good performance of the detector subsystems

Luminosity status and goals

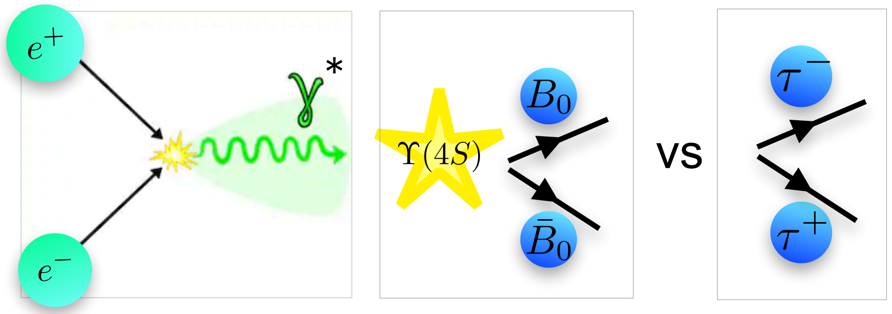
- So far we have collected **~74 fb^{-1}** during Phase 3, with the 2020c data taking period starting this month.
- Aiming for **50 ab^{-1}** over the next ~10 years (50 x Belle dataset)

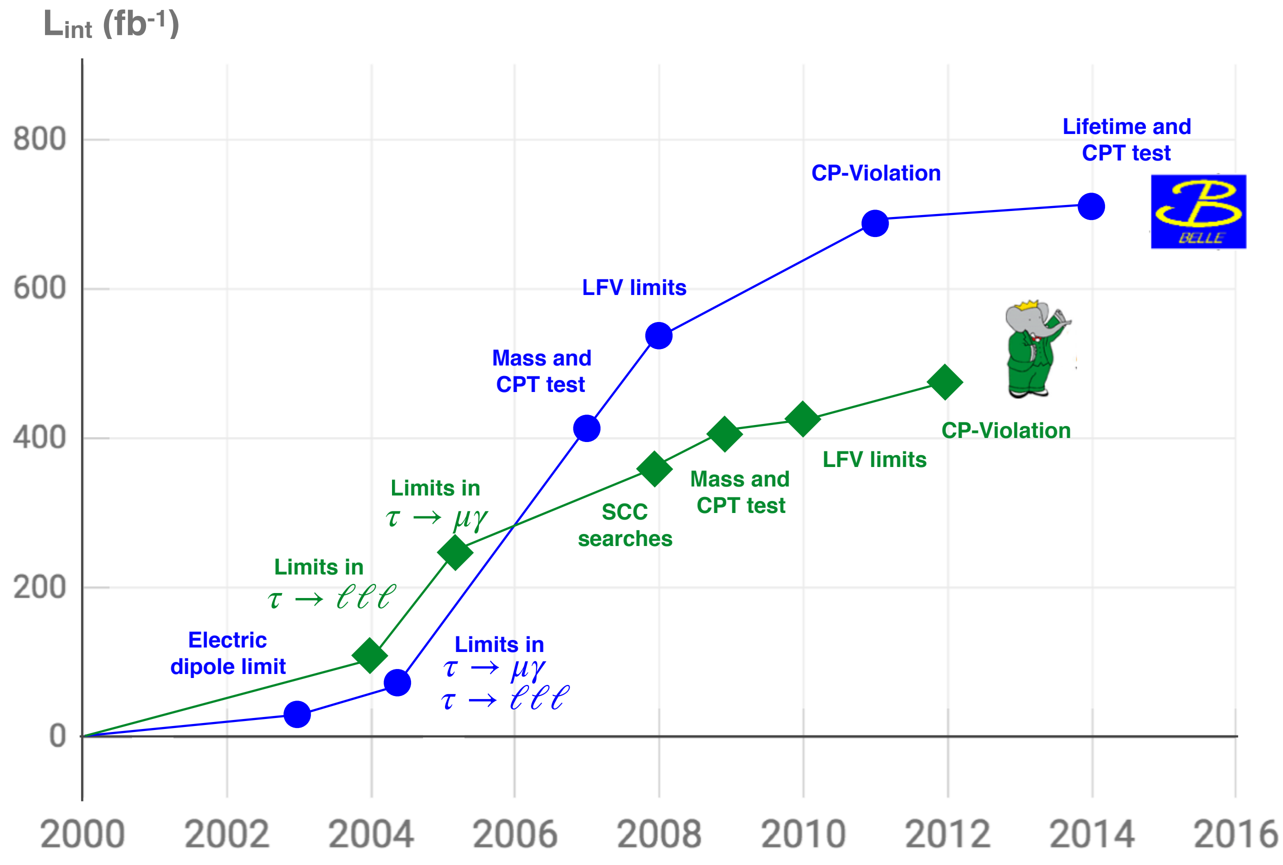




Belle II as a τ-factory

- **B-factories are also τ-factories!**
  - $\sigma(e^+e^- \to \Upsilon(4s)) = 1.05$ nb
  - $\sigma(e^+e^- \to \tau^+\tau^-) = 0.92$ nb





- Last generation B-factories provided a variety of very interesting τ physics results in the last two decades

- Over its lifetime Belle II will collect by far the worlds largest sample of τ-pair events (~4.6×10^{10})

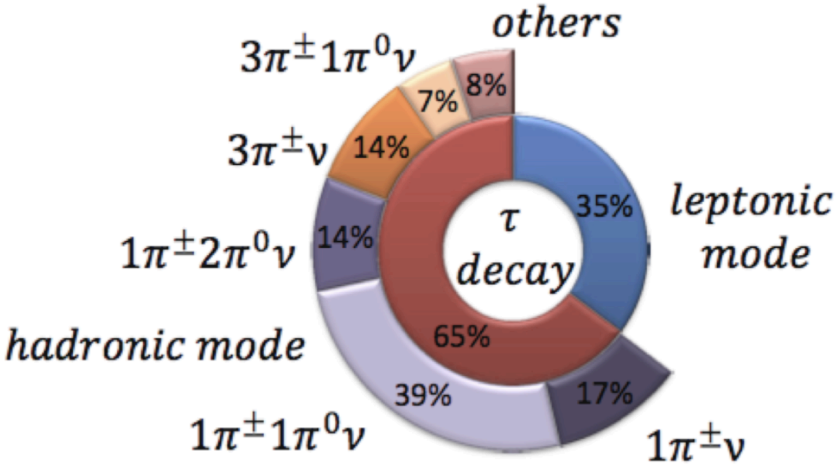
⇒ a unique environment to study τ physics with high precision!

τ-pair reconstruction

- Tau leptons will decay before reaching the active regions of the Belle II detector

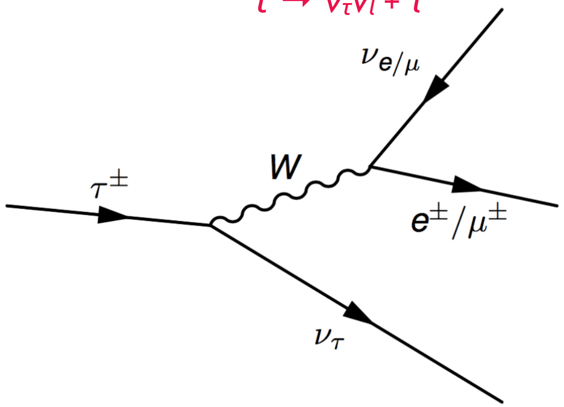
- Identified via decay products:
  - 1-prong: 35.2% leptonic, 49.5% hadronic
  - 3-prong: 15.2% hadronic

- Wide variety of low multiplicity signatures involving $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, π^{0} and neutrinos (missing energy)



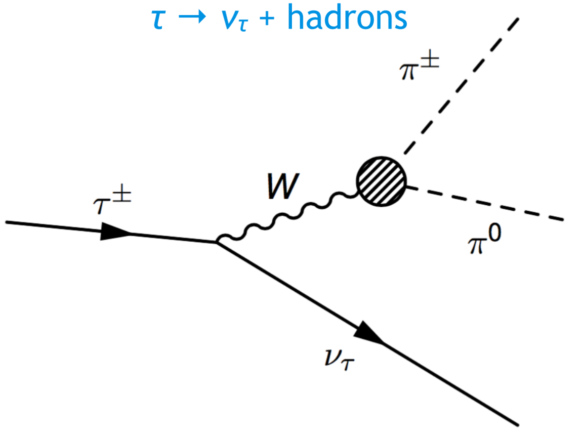
leptonic decay

$\tau \rightarrow \nu_\tau \nu_l + l$

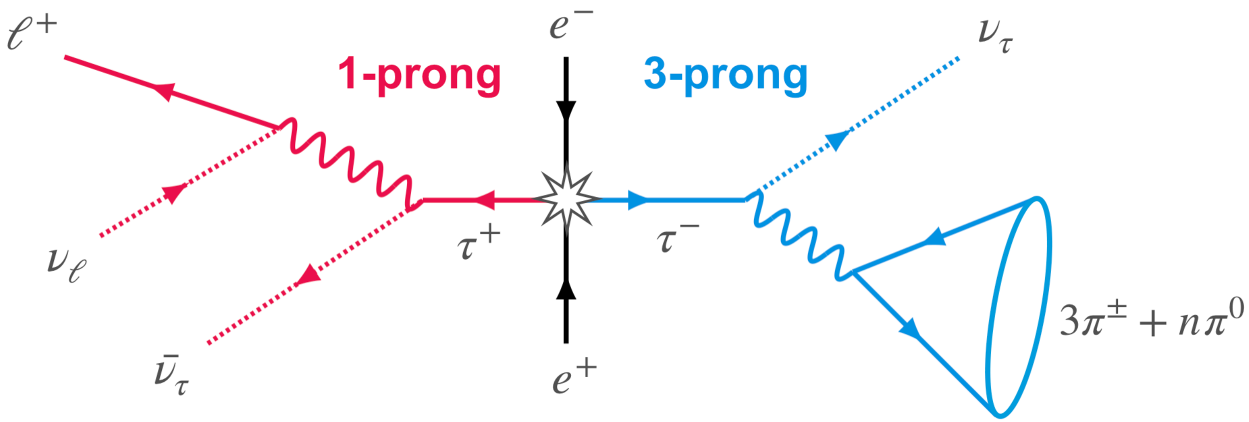


hadronic decay

$\tau \rightarrow \nu_\tau$ + hadrons

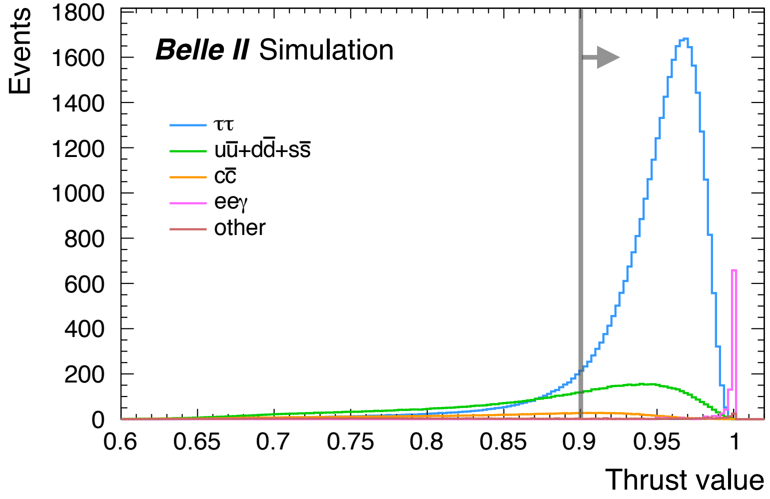


- τ-pairs reconstructed as 1x3 (4 track) or 1x1 (2 track) events



τ-pair reconstruction

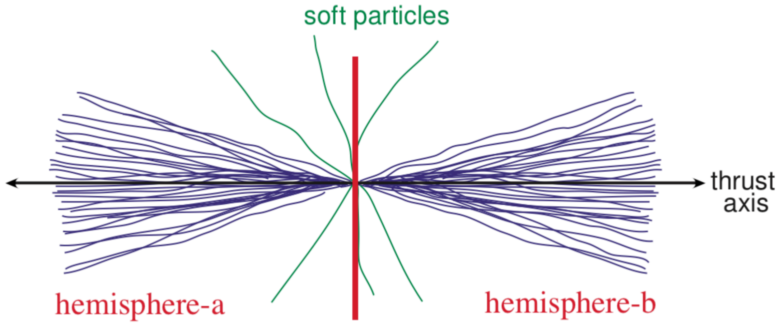
- We exploit the unique topology and kinematic of τ-pair events to suppress the main $q\bar{q}$ and eeγ backgrounds

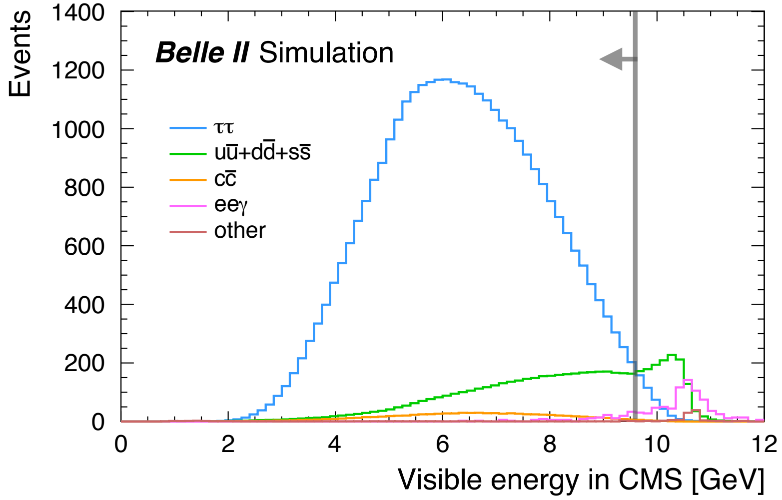


⇒ **Relatively mild deviation of τ decay particles from the primary trajectory**

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

thrust axis ($\check{T}$) is maximising the event shape variable

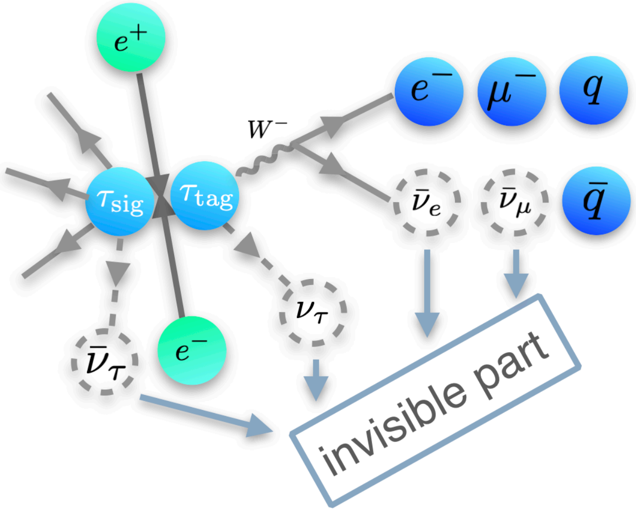




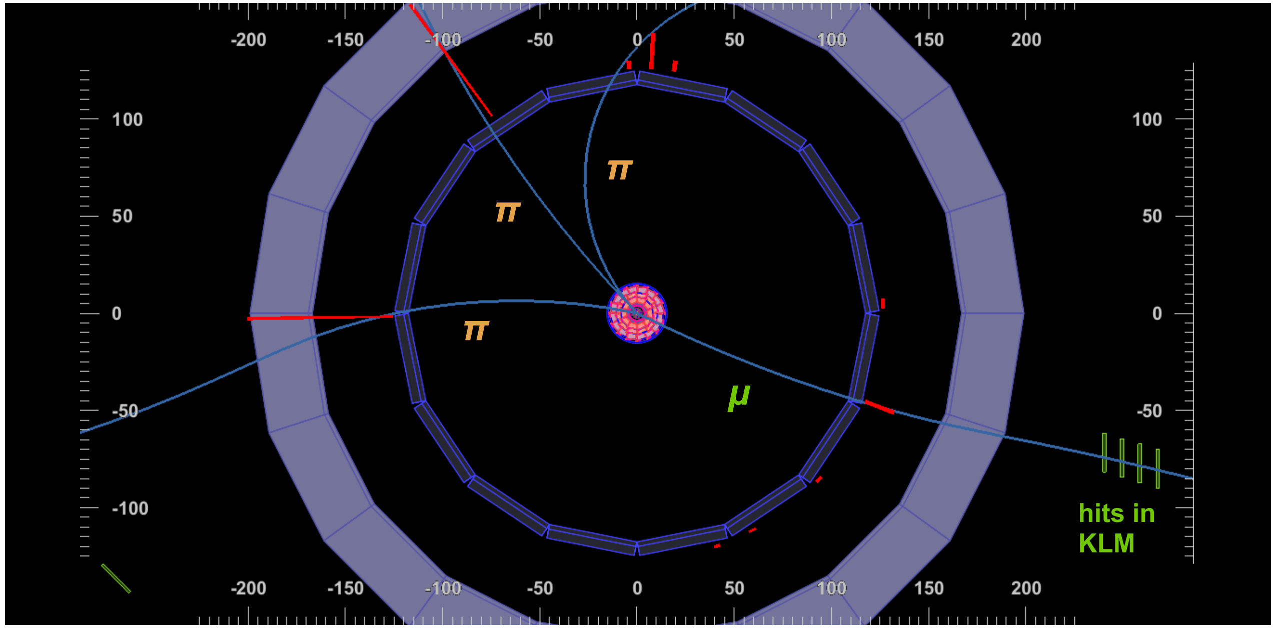
⇒ **Undetected neutrinos in τ events**

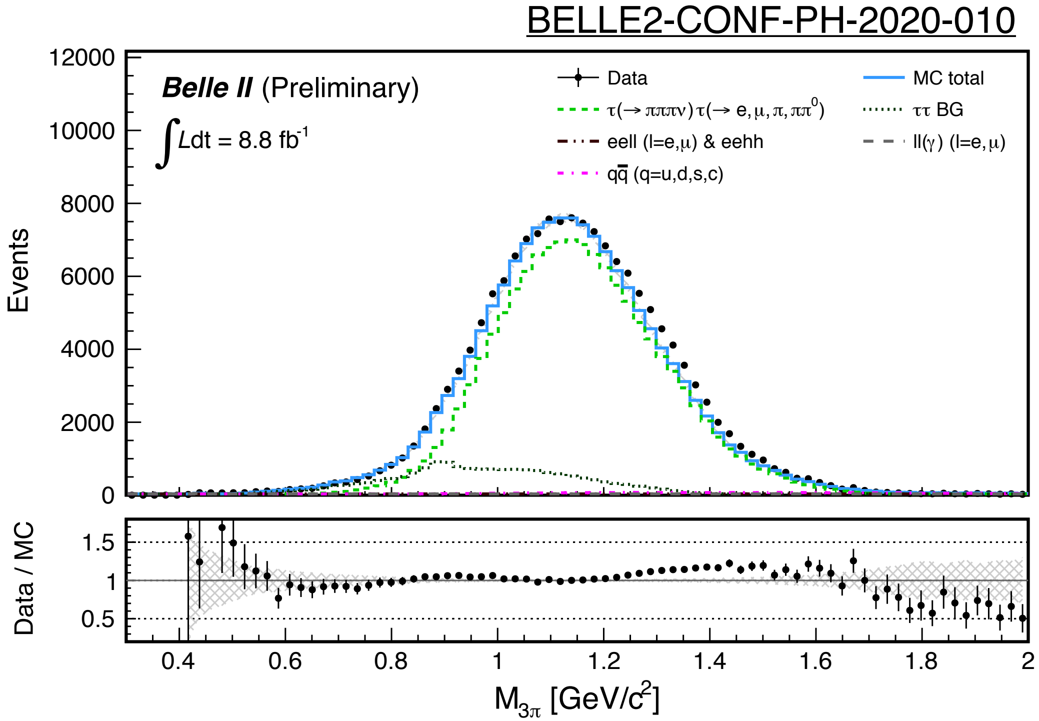
$$\text{visible energy} = \sum_h E_h$$

e^+e^- data allows for precise determination of the missing energy



τ-pair reconstruction in early data





- Clear evidence of τ-pair production in the early Belle II data
- Clean sample with high statistics
- **τ-pair events provide an ideal testbed of the Belle II performance!**
  - **trigger efficiency**
  - **tracking efficiency**
  - **particle identification**
  - **π^0 reconstruction**

L1 Trigger System

- **Good L1+HLT performance is critical to achieving tau physics goals!**

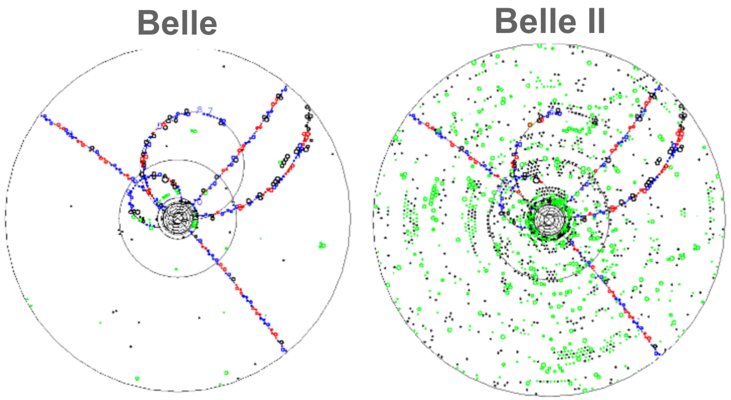
- Total physics rate at SuperKEKB design luminosity is ~**20 kHz**

- Beam background increases this rate significantly!

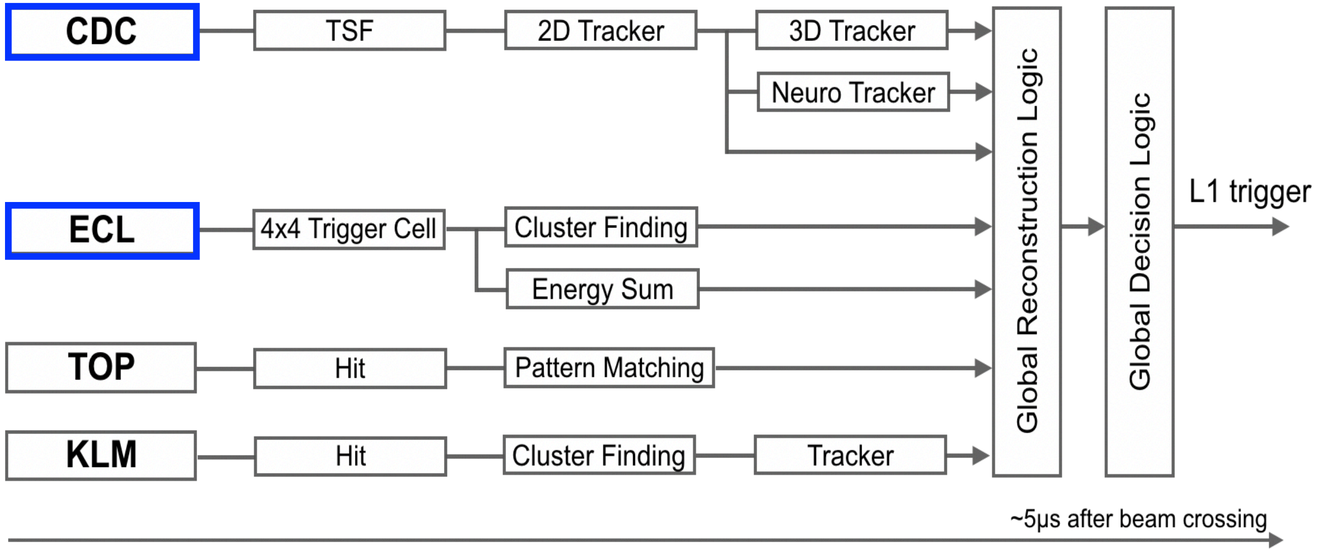
- L1 trigger must reduce physics + bkg rate to a maximum of **30 kHz**

- Requirements
  - high efficiency for high <u>and</u> low multiplicity physics
  - trigger latency ~5μs, timing precision $\leq$ 10 ns
  - two event separation $\geq$ 200 ns

- Two primary components: **CDC** and **ECL** triggers
  - CDC 2D (r-ϕ space) track finding
  - ECL total energy and cluster finding, Bhabha veto



Physics process	Cross section (nb)	Rate (Hz)
$\Upsilon(4S) \rightarrow B\bar{B}$	1.2	960
$e^+e^- \rightarrow$ continuum	2.8	2200
$\mu^+\mu^-$	0.8	640
$\tau^+\tau^-$	0.8	640
Bhabha ($\theta_{\rm lab} \geq 17°$)	44	350 [a]
$\gamma\gamma$ ($\theta_{\rm lab} \geq 17°$)	2.4	19 [a]
2γ processes [b]	~ 80	~ 15000
Total	~ 130	~ 20000



Trigger efficiency for 1x3 prong

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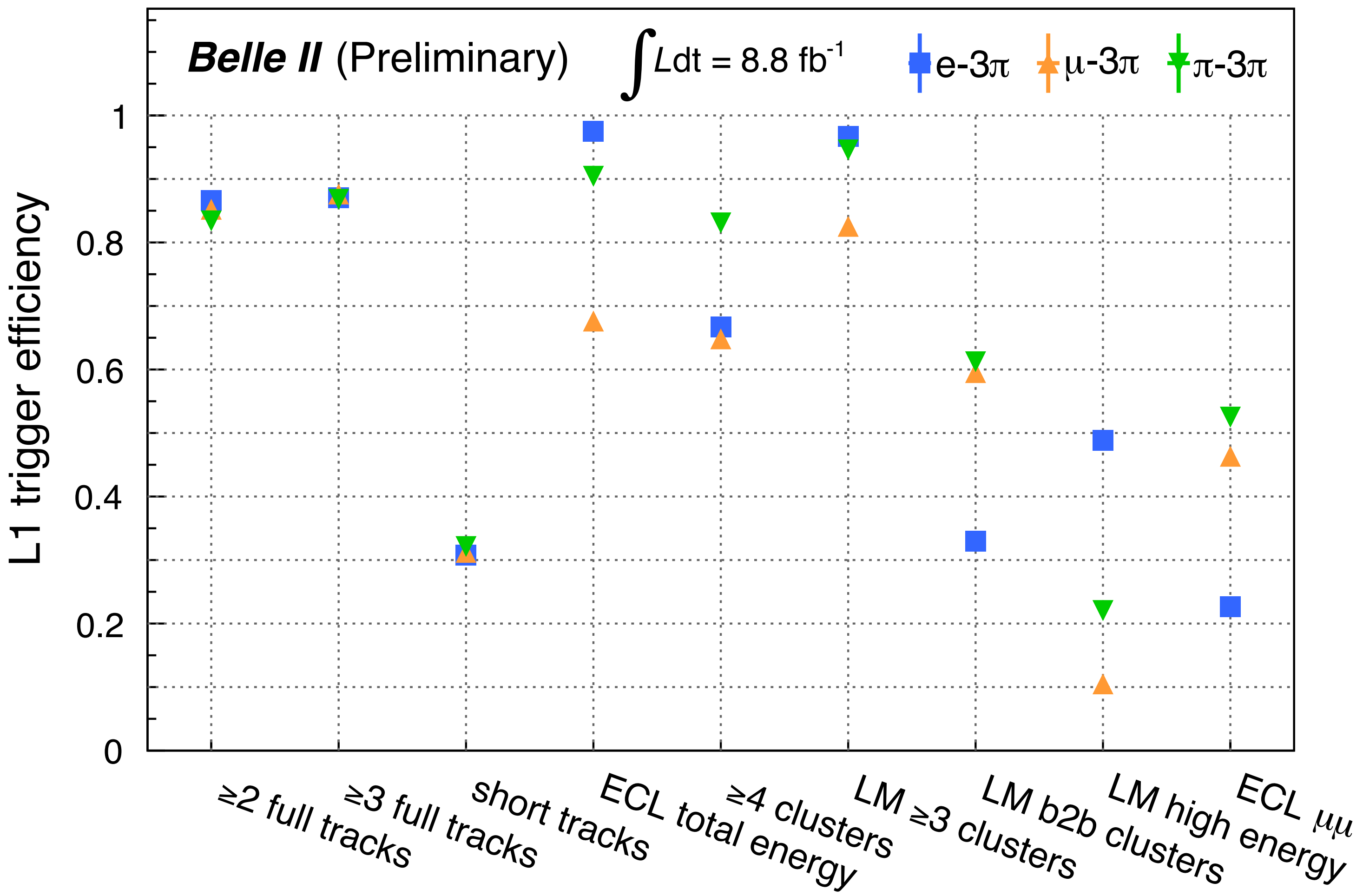

- Main trigger types for tau and other low-multiplicity physics
  - CDC number of 2D full tracks
  - CDC number of 2D short tracks
  - ECL total energy threshold
  - ECL number of isolated clusters
  - ECL low multiplicity
  - ECL di-muon

- Trigger decision is made independently using only CDC or ECL information. Allows measurement of L1 efficiency in data.

- Efficiency of a CDC/ECL trigger:

$$\frac{(\text{OR of } \textbf{ECL}/\textbf{CDC} \text{ bits}) \text{ AND } \textbf{CDC}/\textbf{ECL} \text{ bit}}{(\text{OR of } \textbf{ECL}/\textbf{CDC} \text{ bits})}$$

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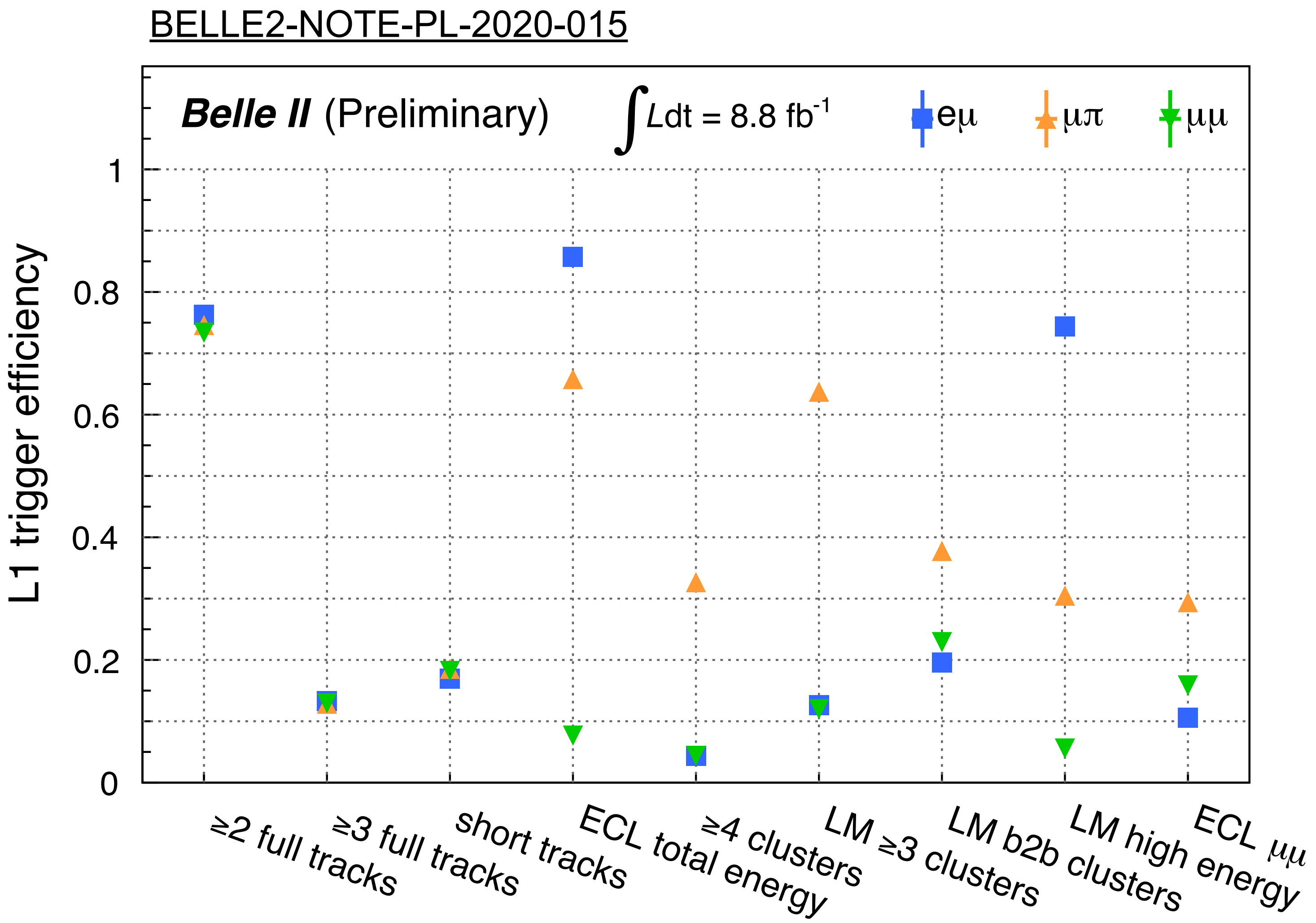

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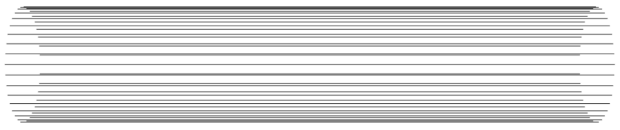
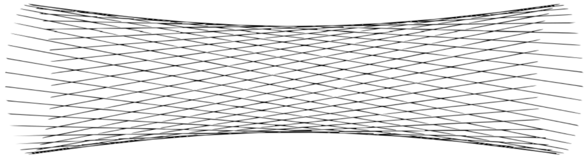
Full and short track triggers

- "**full tracks**" pass through all axial CDC superlayers and reach the barrel

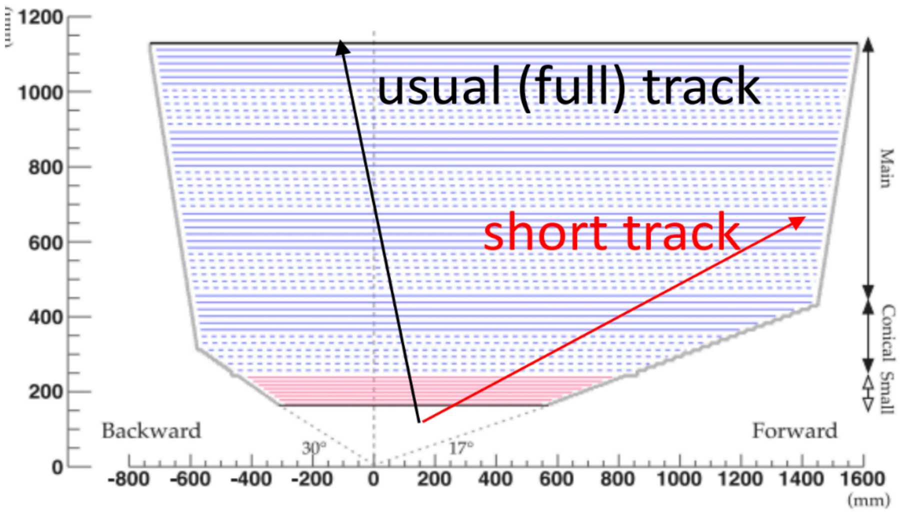
axial wires



stereo wires

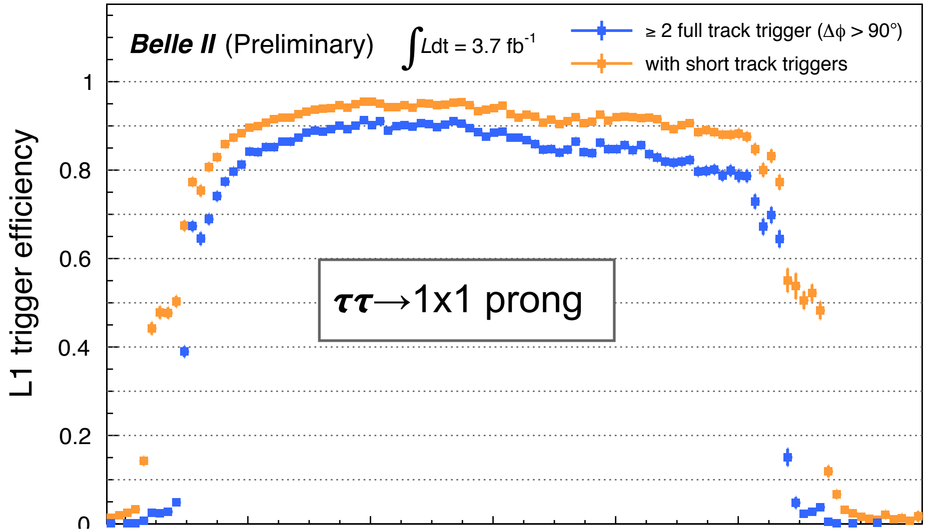


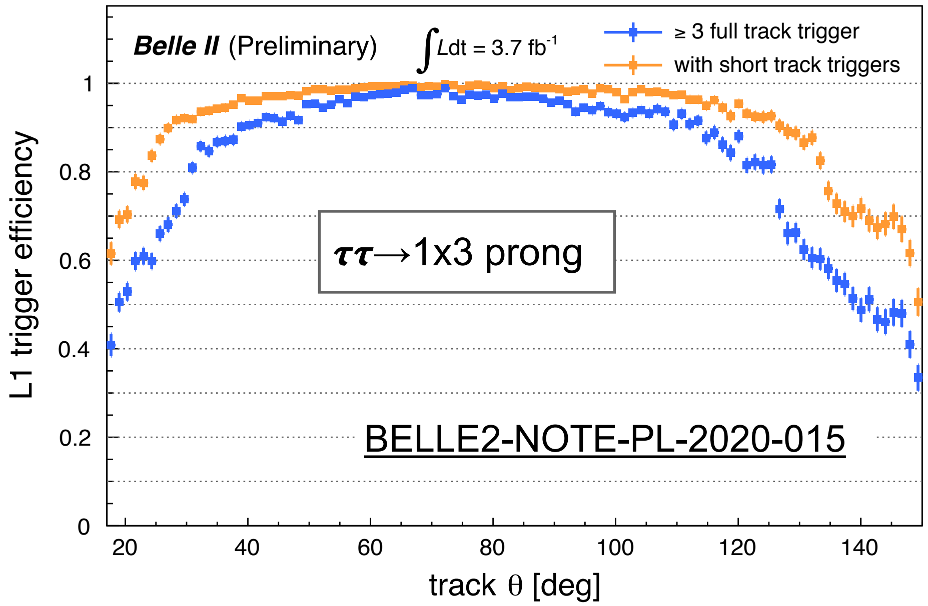
- **Full track triggers** have low efficiency in endcaps, putting limitations on tau and other low multi physics
- To help compensate, the CDC trigger also searches for "**short tracks**" that pass through inner most 5 axial + stereo SLs. Operational since Oct 2019.



- **Short track triggers** provide a significant gain in efficiency for endcaps / low p_T!
- **neural-z triggers** might become active in 2020c

⇒ we keep a close eye!





ECL triggers

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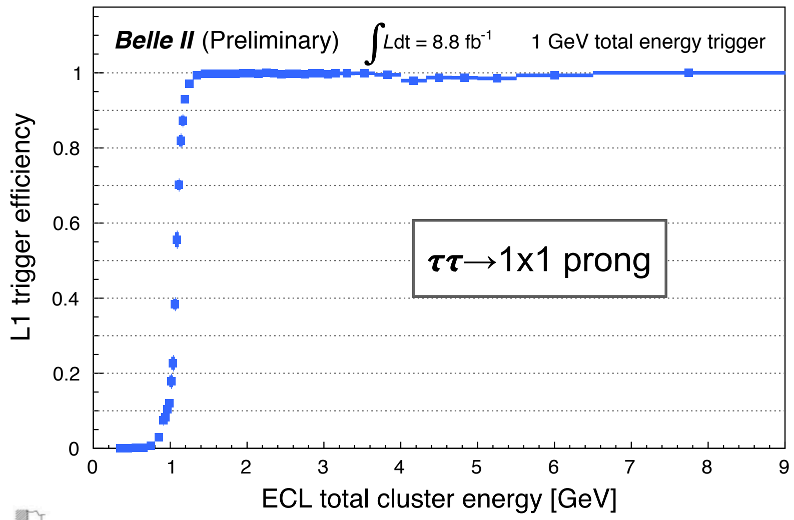
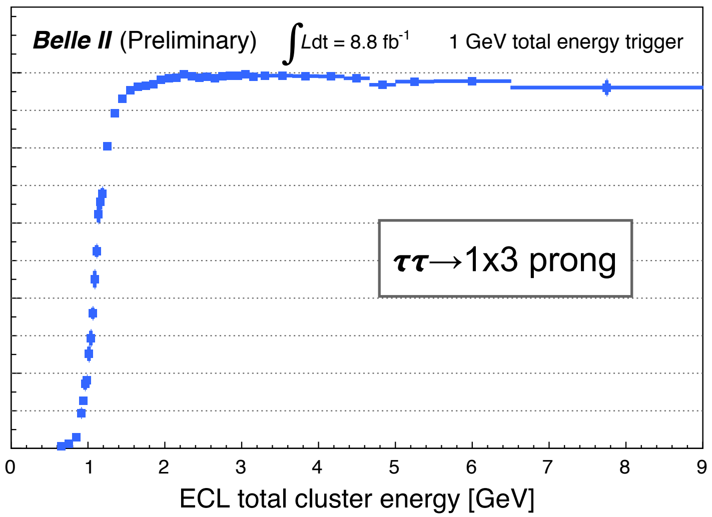
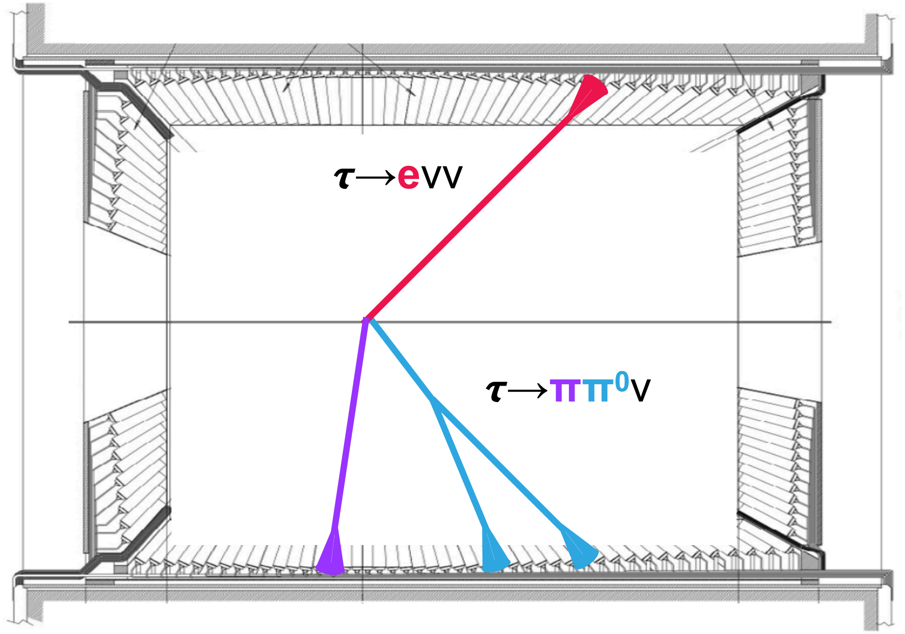
- Unprescaled <u>total energy trigger</u> has a 1 GeV threshold. Sum over L1 Cells. ⇒ 4x4 tower of CsI(Tl) crystals.
- Performs well for ee→ττ events that have high EM energy deposition (e.g. τ → eνν, 3ππ^{0}ν, ππ^{0}ν)

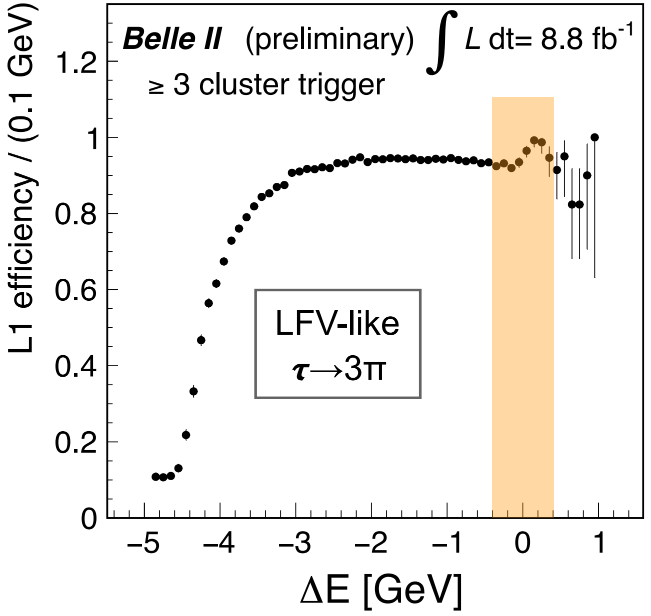






- τ→3μ is one of the most difficult LFV signatures to trigger on @ L1.
- ECL low multiplicity triggers are new at Belle II.

  Most performant for LFV-like events is the ≥3 ECL isolated cluster trigger



Tracking efficiency with taus

- Track-finding efficiency is another key performance driver for tau physics @Belle II

- Real detector != simulated detector.

  Goal: asses systematic uncertainty, based on the measured discrepancy in the tracking efficiency between simulation and data

- Tag-and-probe method on ee→ττ→1x3 prong
  - large τ-pair cross section
  - low multiplicity but high track density (boosted $\tau \to 3\pi\nu$)
  - wide momentum range: $0.2 < p_T < 4$ GeV

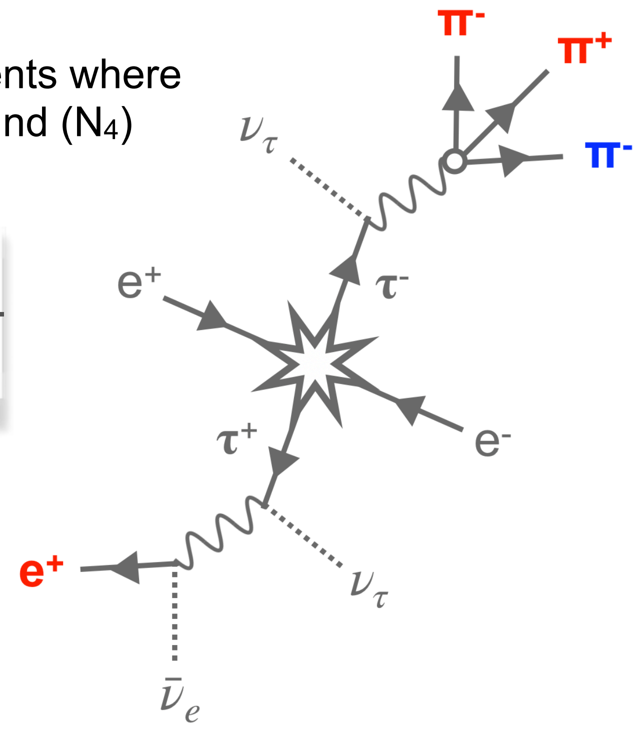
Method

- **tag** = 3 good quality tracks with $\sum q = \pm 1$
- **probe** = look for 4th track that passes loose selections, and conserves charge ($\sum q = 0$)
- Count number of events where the probe track is found (N_4) and not found (N_3):

$$\epsilon \cdot A = \frac{N_4}{N_3 + N_4}$$

where:

- ∊ is tracking efficiency
- A is geometric acceptance



Tracking efficiency with taus

- **Tag tracks**: |dz| < 3cm, dr < 1cm, p_T > 200 MeV, e/μ/π PID
- **Probe track**: p_T and PID dropped
- **Trigger**: hie (e-3π), lml0 (μ-3π)

background suppresion

- Angular isolation b/w 1-prong track and each π (cos(θ) < -0.5)
- vertex fit (Rave) to tag π (χ^2 > 0.01)
- 1-prong $p_{cms}/E_{beam} \in [0.2, 0.8]$
- tag π, $\Delta\theta_{\pi\pi}$ > 0.2 (0.05) for e (μ)
- mass cuts: m_{tag} < 8.5 GeV, $m_{\pi\pi} < m_{a1}$
- eeγ* veto for electron-OS channel
  - p_{miss} $\theta_{cms} \in$ [40°, 135°]
  - missing M^2 > 20 GeV^2

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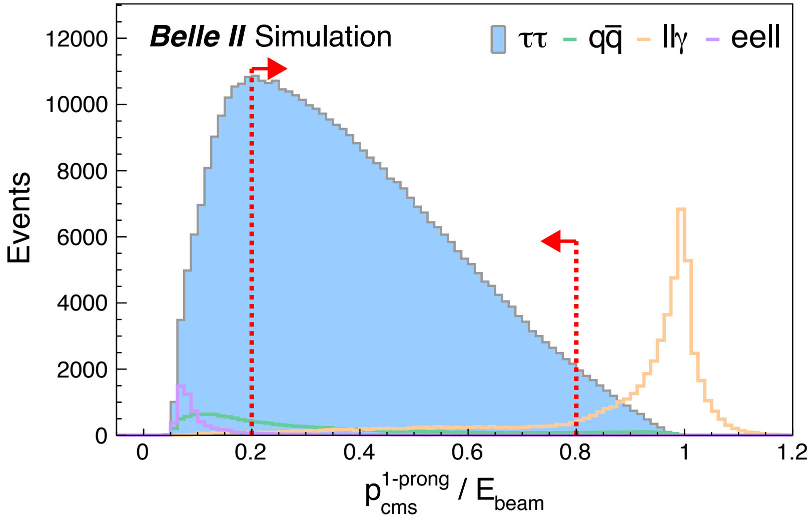

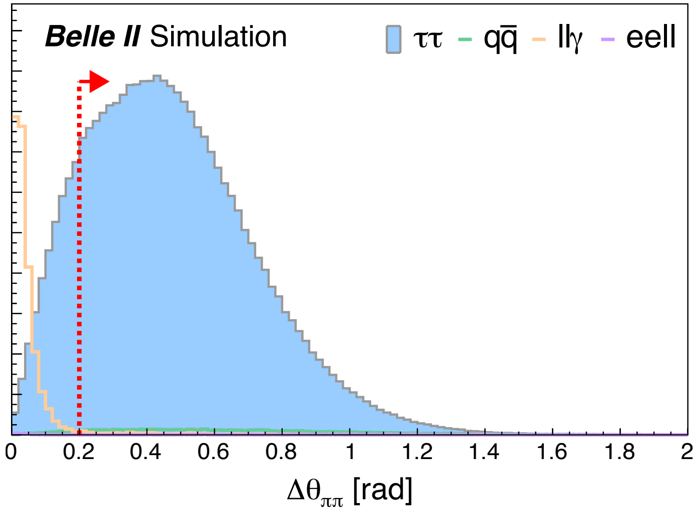

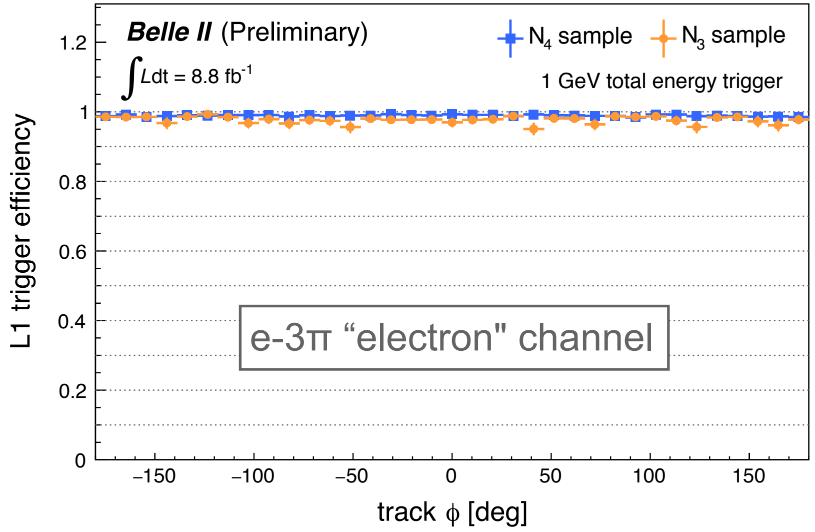

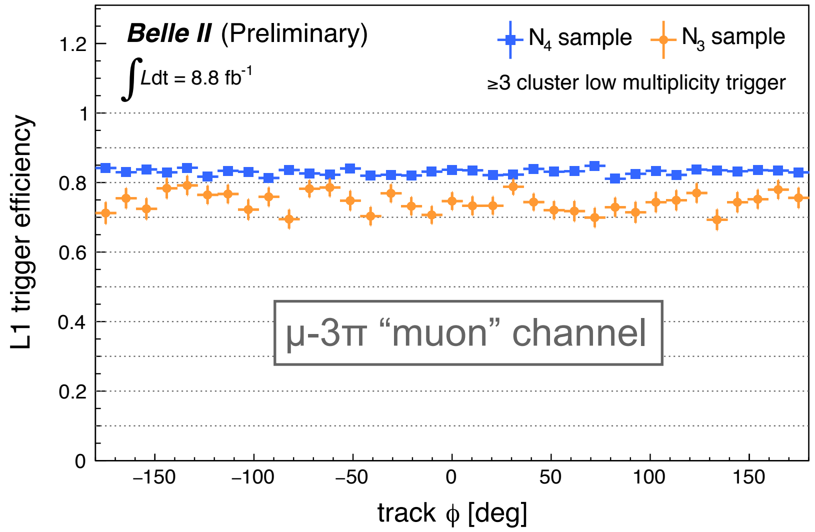

Tracking efficiency with taus

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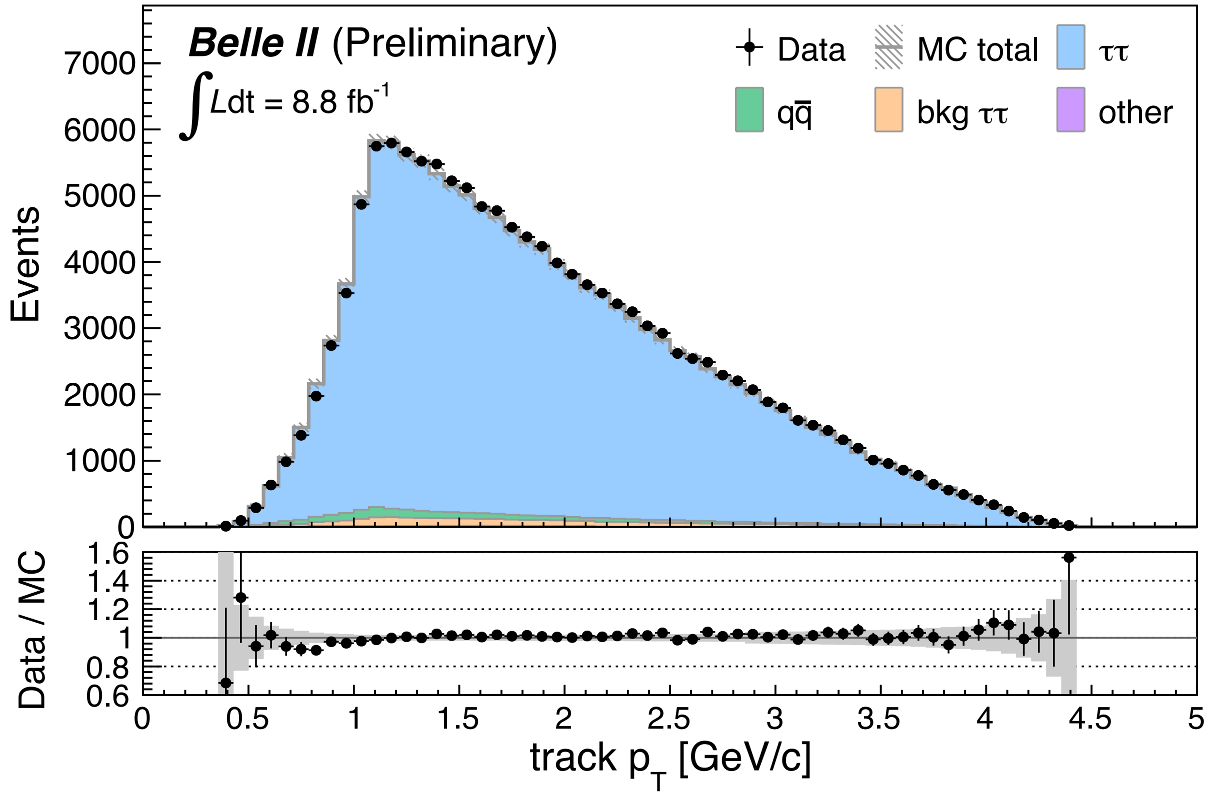
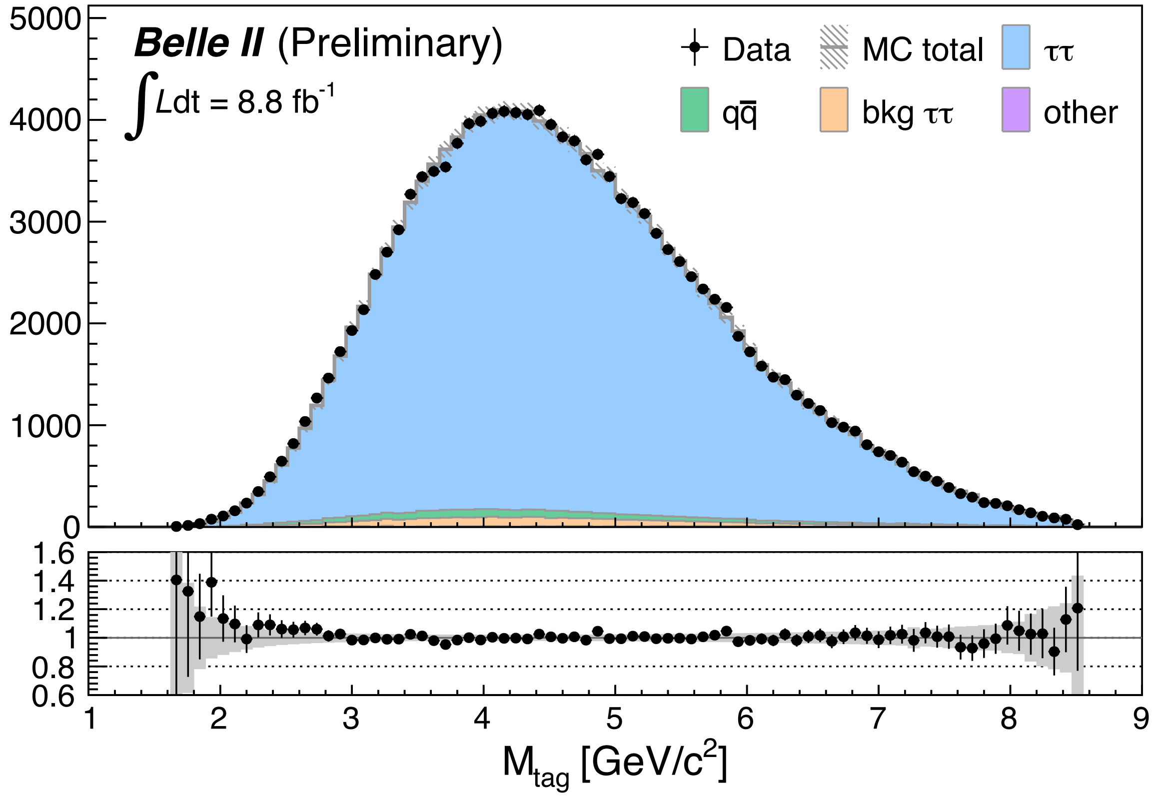




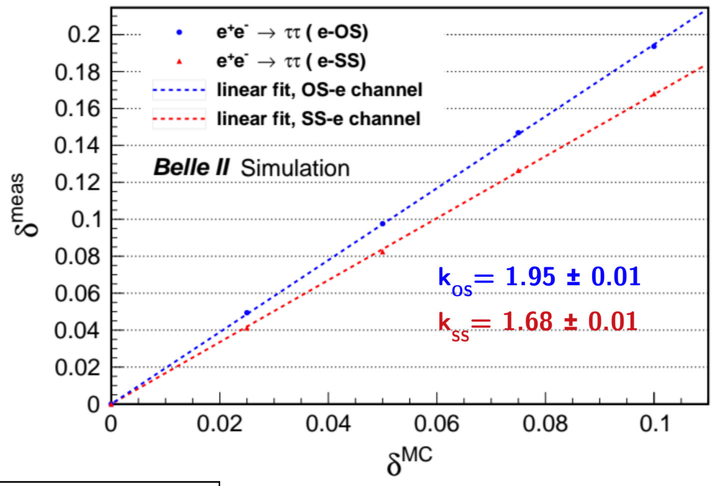
- After trigger and all offline selections, good agreement between data and MC
- Clean sample with high statistics

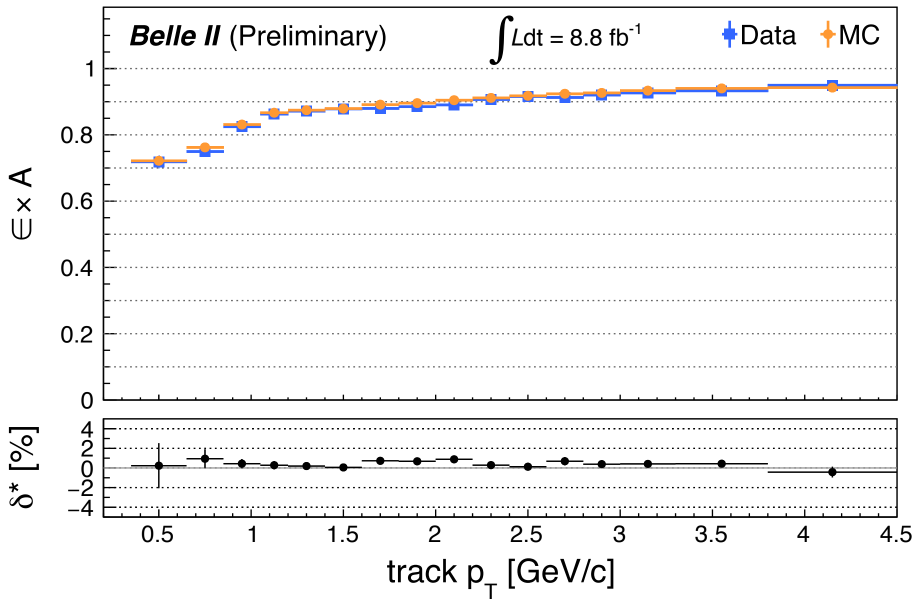
Tracking efficiency with taus

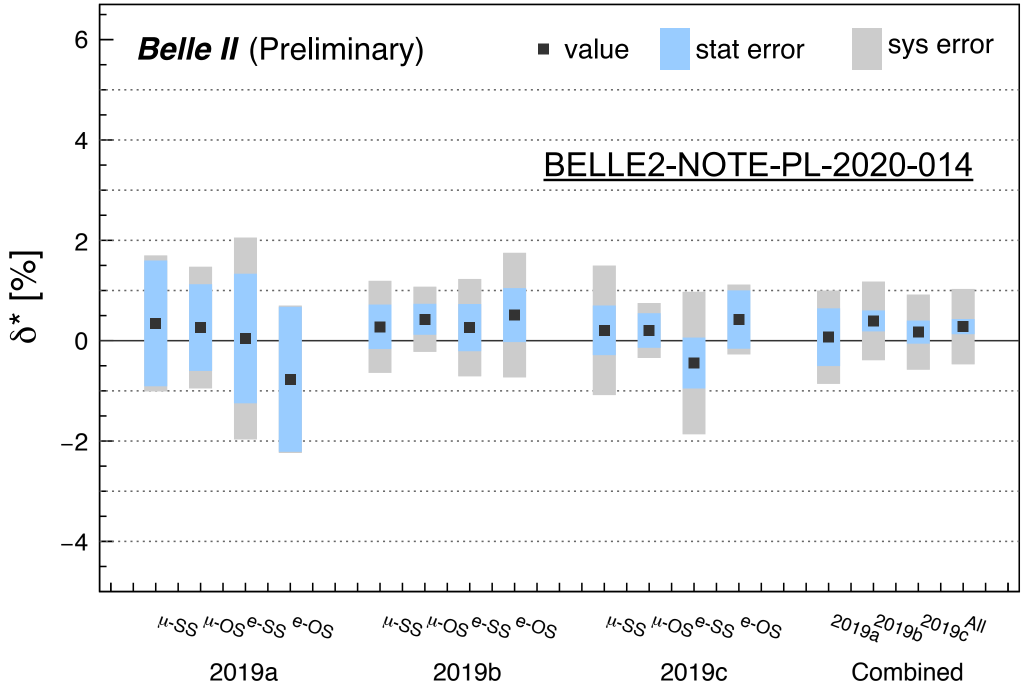
- Data-MC discrepancy:

$$\delta^* = 1 - \epsilon^*_{Data}/\epsilon^*_{MC} = \frac{1}{k}(1 - \epsilon^{meas}_{Data}/\epsilon^{meas}_{MC})$$

- k-factors from calibration procedure
  - combinatorial effects
  - impact of bkg suppression cuts







$$\delta^*_{overall} = 0.13 \pm 0.16\,(\text{stat}) \pm 0.89\,(\text{sys})\,\%$$

- Includes systematics related to:
  - trigger efficiency
  - charge dependence (dominant)
  - calibration procedure
  - background subtraction
  - luminosity

- Aiming for tracking performance paper in early/mid 2021

Particle ID with taus

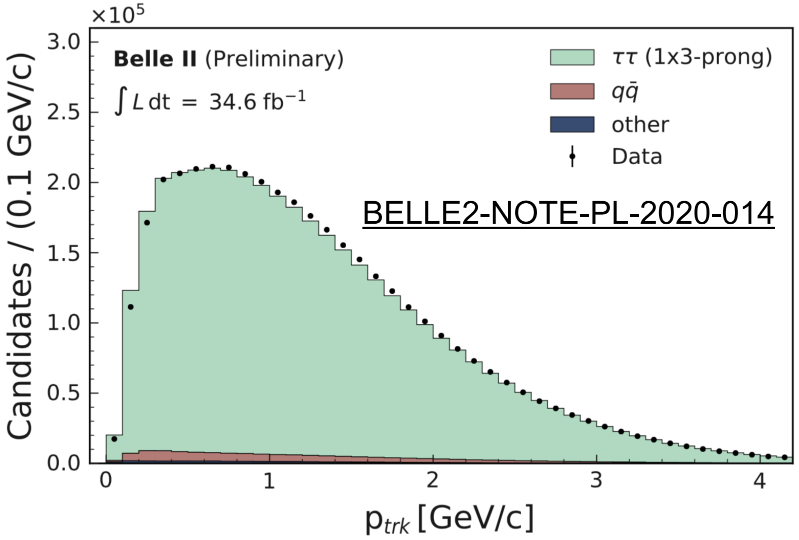
- ~95% of $\tau \to$3-prong decays contain 3π ⇒ powerful handle on **πID efficiency** and **π→e/μ misID rates**

$$\epsilon_{\text{data}} = \frac{N_{\text{pid}} - \sum_i N_{\text{pid}}^{\text{bkg},i} \cdot r^i_{\text{mis-id}}}{N_{\text{total}} - \sum_i N^{\text{bkg},i}} \qquad i \in \{\mu, e, K, p, d\}$$

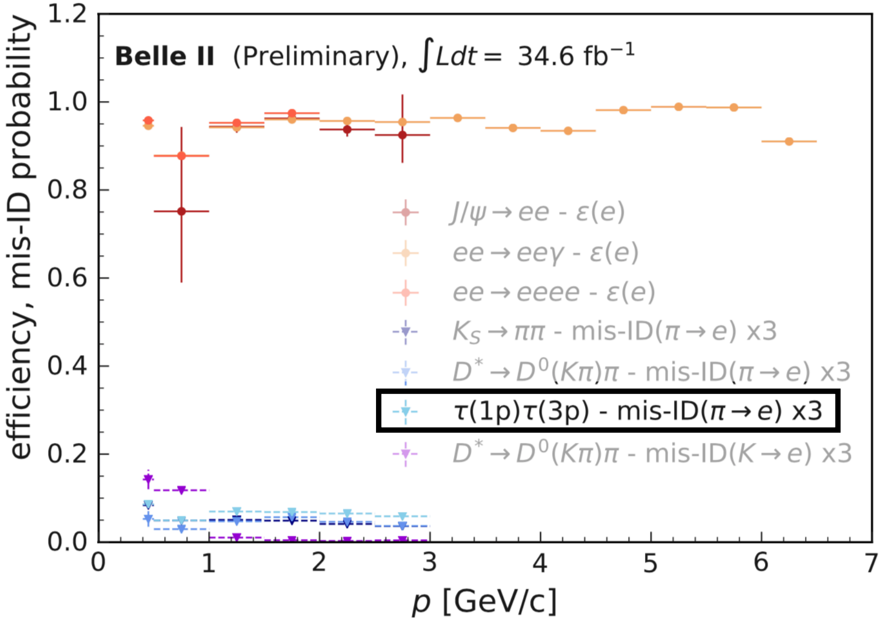
- N_{pid}: probe selection
  - π efficiency ⇒ pionID > x
  - π→μ misID ⇒ muonID > x
  - π→e misID ⇒ electronID > x

$$\epsilon_{\text{MC}} = \frac{N_{\text{pid}}}{N_{\text{total}}}.$$

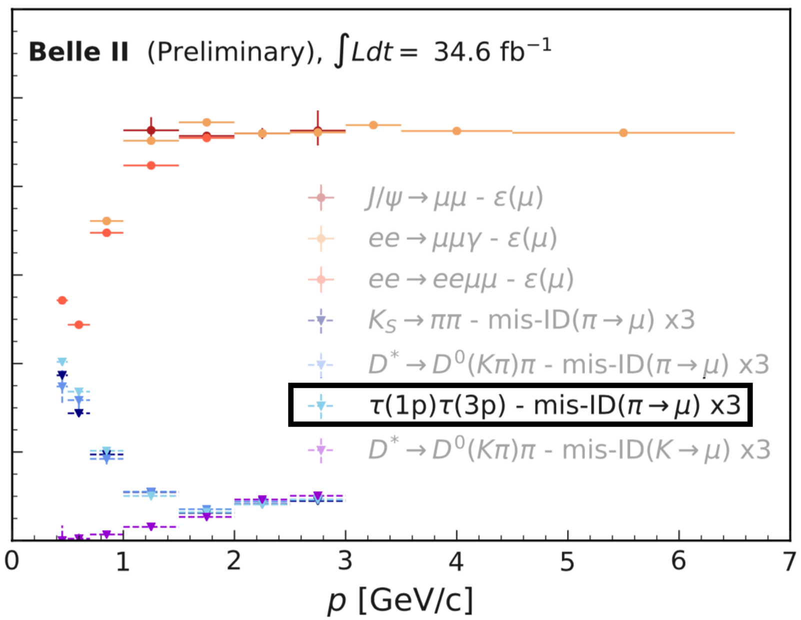
- calculated using truth-matched MC



$1.13 \le \theta < 1.57$ rad, electronID > 0.9



$0.82 \le \theta < 1.16$ rad, muonID > 0.9



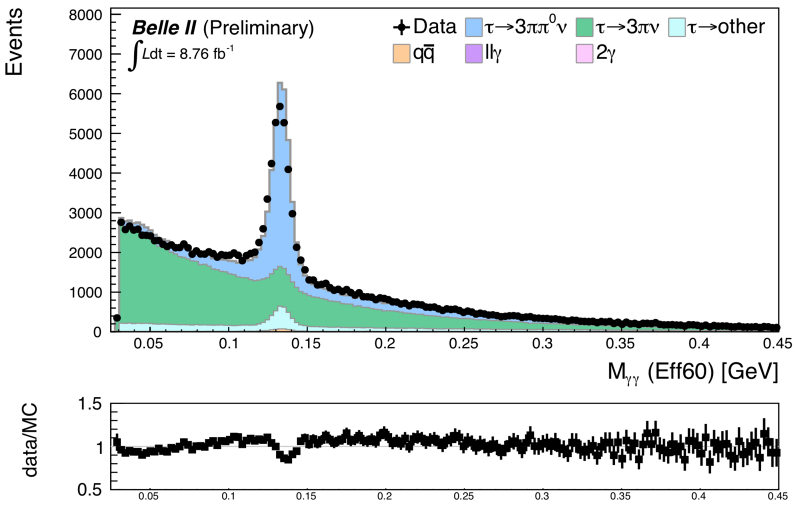
- Ongoing work (from **Paul** 🙂)
  - studying the dependency on track isolation
  - improve systematics
  - studies of sub-detector performance
- Aiming for PID performance paper in early/mid 2021

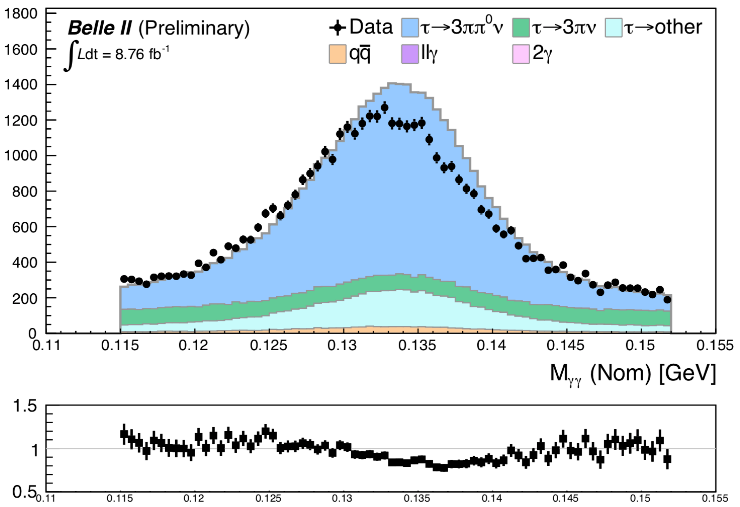
π^0 reconstruction with taus

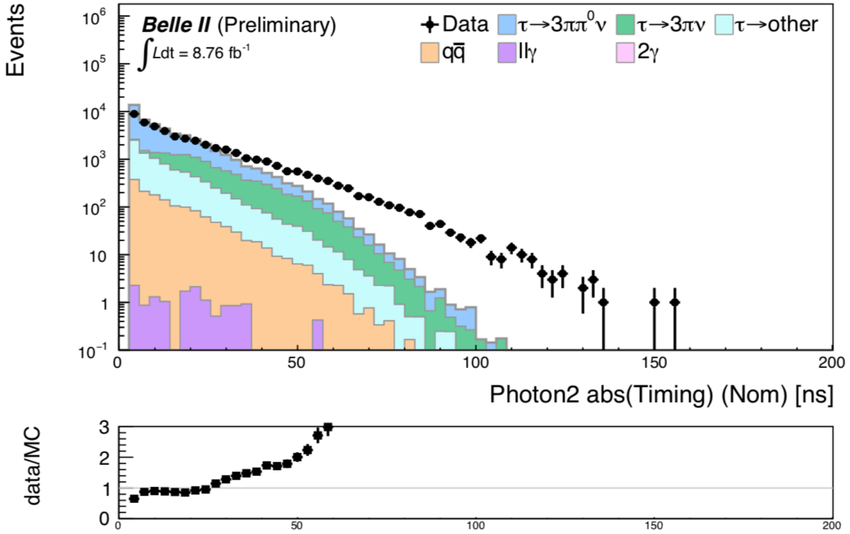
- π^0 efficiency corrections can be measured by taking the double ratio:

$$\eta_{\pi^0} = \frac{N^{data}(\tau \to 3\pi\pi^0\nu_\tau)}{N^{MC}(\tau \to 3\pi\pi^0\nu_\tau)} \div \frac{N^{data}(\tau \to 3\pi\nu_\tau)}{N^{MC}(\tau \to 3\pi\nu_\tau)}$$

⇒ covers π^0 momentum from 0.2 - 4.5 GeV, and is complimentary to the studies of π^0 from B decays







Current nominal π^0 reco in Tau Group:

- E_γ > 100 MeV
- -0.8660 < cosθ < 0.9563
- clusterNHits > 1.5
- 115 < $M_{\gamma\gamma}$ < 152 MeV

- ~2 MeV shift observed in data, also seen in B decay modes

⇒ will by mitigated by improved γ energy calibration

- Studies in early stages.
  Ongoing work to reduce fakes in data using γ timing cuts, and development of BDT based π^0 ID.

- Aiming for Neutrals performance paper in early/mid 2021

Tau Physics Program

- Belle II will provide the world's largest sample of τ-pair events, enabling a rich program of new physics searches and precision tests of the Standard Model

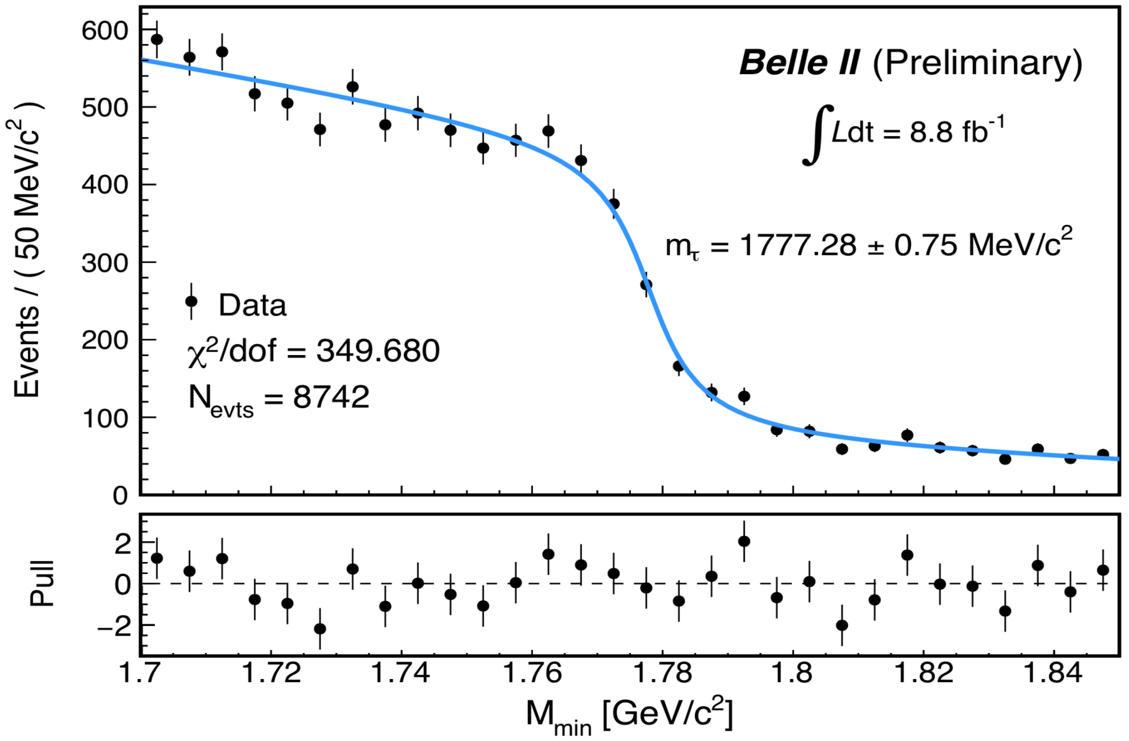
  - **tau mass measurement**
  - **search for lepton flavour violating decays: $\tau \rightarrow l\gamma$, lll, $lh(h)$, $l\alpha$, …**
  - **lepton universality tests**
  - **search for heavy neutral leptons**
  - **CP violation in $\tau \rightarrow K_s \pi \nu$**
  - and much more!
    - electric dipole moment (CP/T violation)
    - Dalitz analysis
    - τ lifetime (3x3 prong)
    - ν_τ mass
    - $|V_{us}|$ and g_τ/g_l from $\tau \rightarrow K\nu$, $\pi\nu$
    - $Y(nS) \rightarrow \tau\mu$ decays
    - search for second class currents in $\tau \rightarrow \pi\eta\nu$
    - …

Tau Mass Measurement

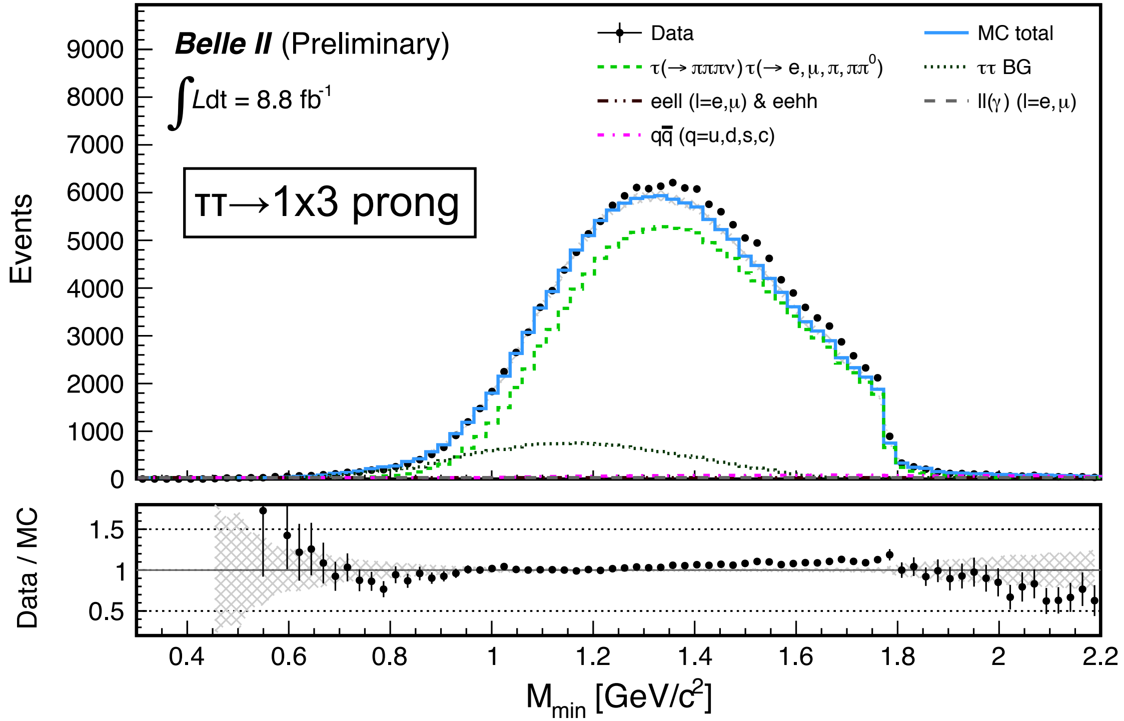
- Tau mass measurement in early Belle II data (8.8 fb^{-1})
- Using a pseudomass technique on $\tau \rightarrow 3\pi\nu$ decays

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

- sharp threshold behaviour in region close to m_τ



arXiv:2008.04665



- M_{min} is fitted to an empirical mass function ($P_1 \Rightarrow m_\tau$) within a 1.7-1.85 GeV window:

$$F(M, \overrightarrow{P}) = (P_3 + P_4 M) \cdot \tan^{-1}[(M - P_1/P_2)] + P_5 M + 1$$

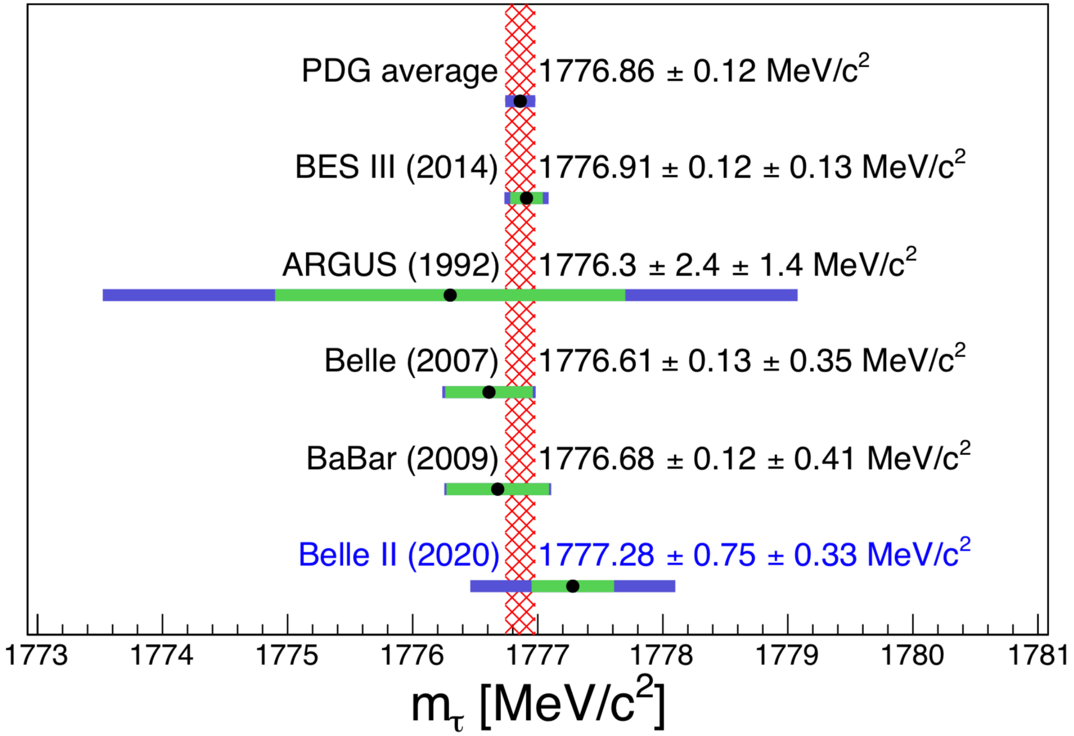
$$m_\tau = 1777.28 \pm 0.75\ (\text{stat}) \pm 0.33\ (\text{sys})\ \text{MeV}$$

Tau Mass Measurement

- **Belle II** in good agreement with previous measurements
- Current best result comes from **BES III** from pair production at threshold energy
- Best measurement from psuedomass technique comes from **Belle**

Systematic uncertainty	MeV/c^2
Momentum shift due to the B-field map	0.29
Estimator bias	0.12
Choice of p.d.f.	0.08
Fit window	0.04
Beam energy shifts	0.03
Mass dependence of bias	0.02
Trigger efficiency	≤ 0.01
Initial parameters	≤ 0.01
Background processes	≤ 0.01
Tracking efficiency	≤ 0.01

arXiv:2008.04665

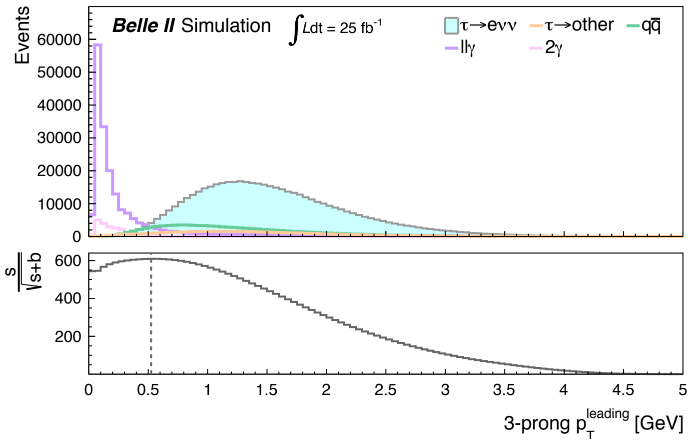


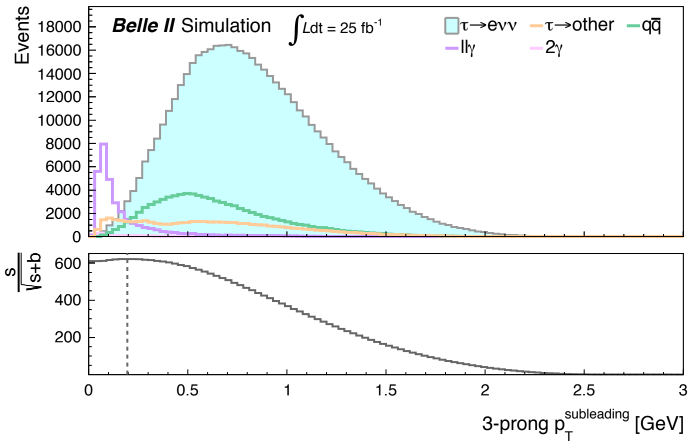
- **Belle II** currently has similar systematic error as last generation B-factory results
- **B-field maps** will be updated soon, significantly reducing the dominant uncertainty

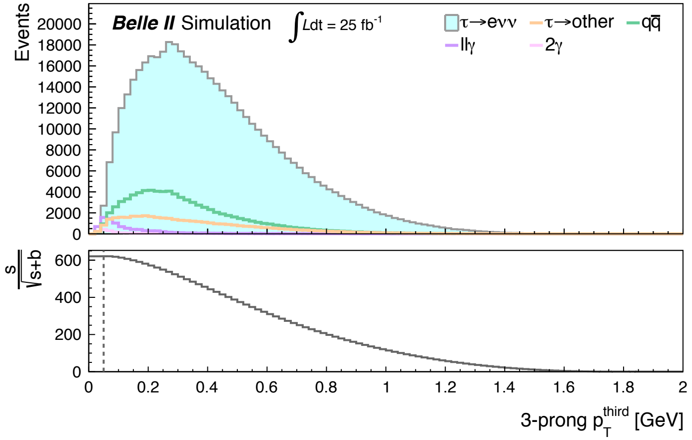
Tau Mass Prospects

- **Goal**: achieve at Belle II the best tau mass precision amongst the pseudomass techniques

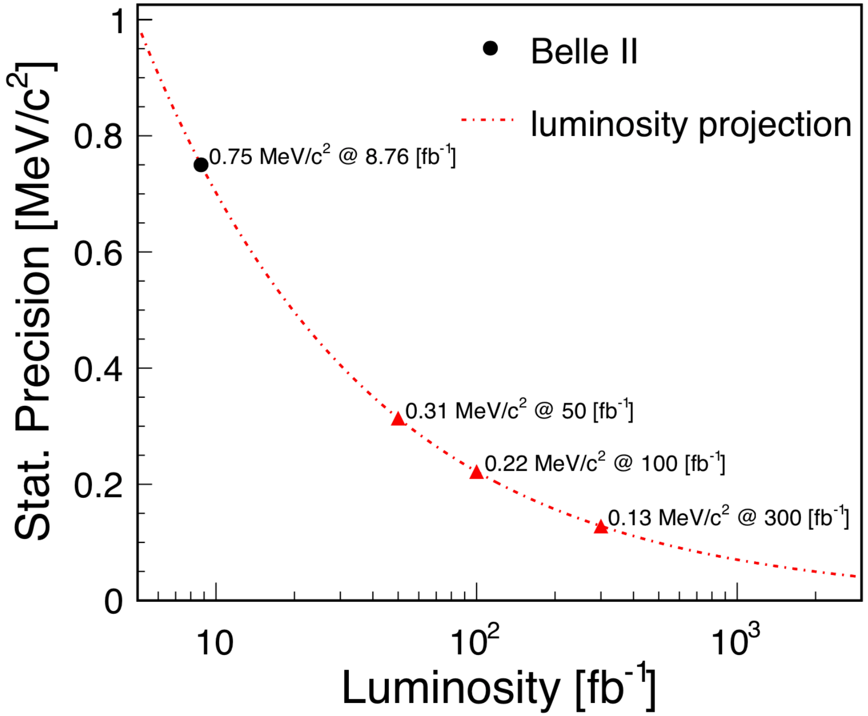
- Current analysis will reach Belle precision with ~300 fb^{-1}







arXiv:2008.04665



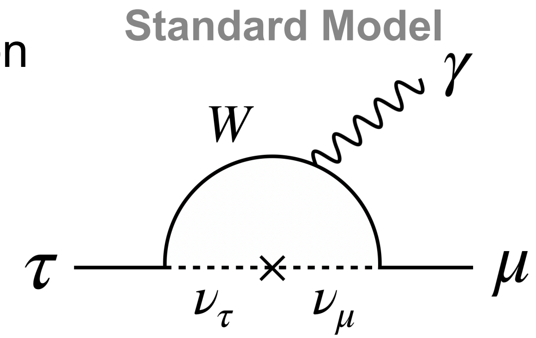
- Recent studies indicate that with a more optimal 3-prong selection (E/p cuts → asymmetric p_T cuts) we can get a **2-3x higher efficiency** at ~same purity

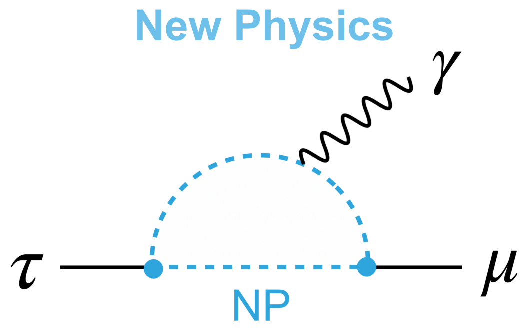
⇒ **Belle II could become competitive with Belle in the near future!**

Searches for charged LFV

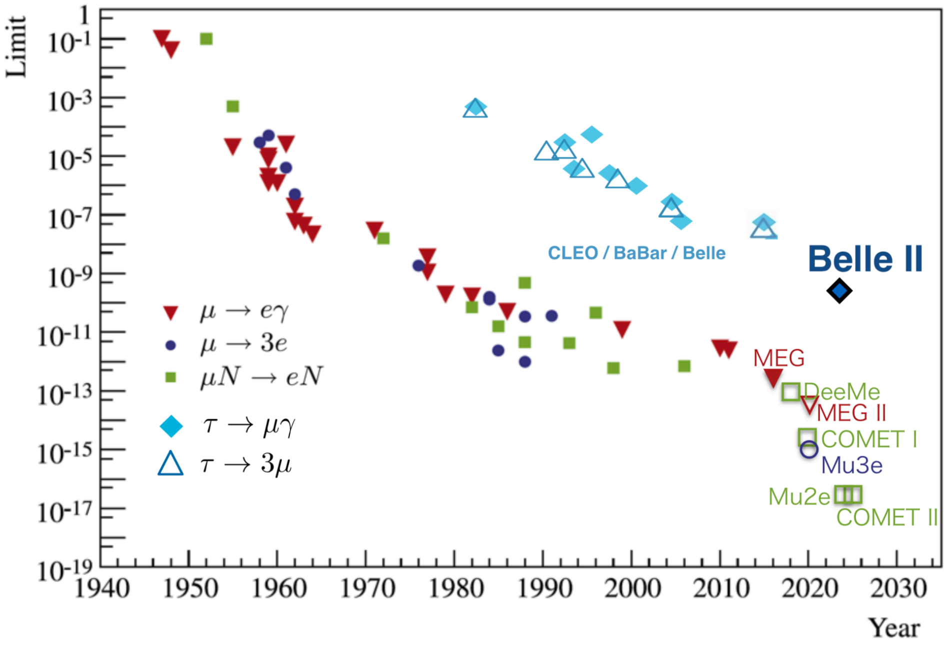
- LFV has been established for the neutrinos, but what about their charged partners (e, μ and τ)?
- In the SM, charged LFV decays via neutrino oscillation are highly suppressed and immeasurably small:

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





- **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)



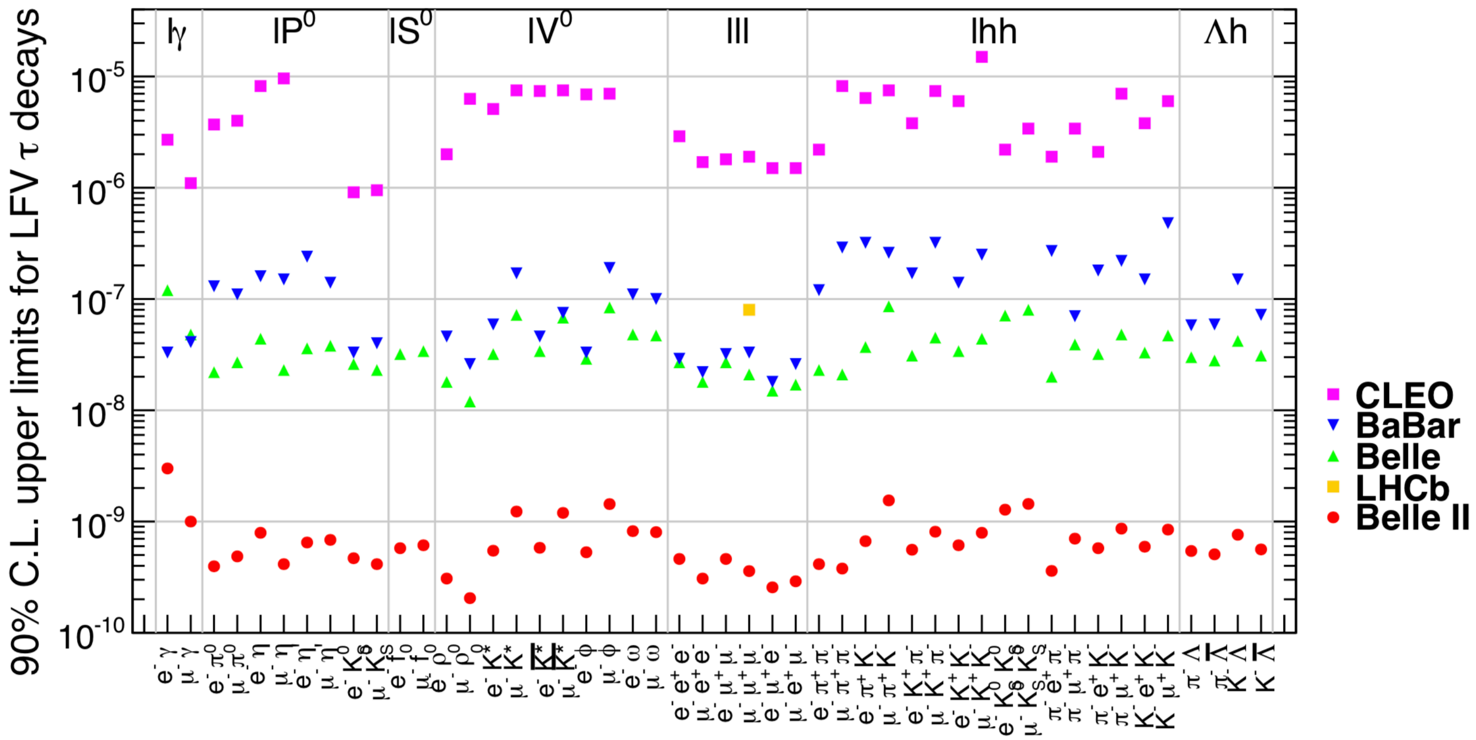
- As heaviest lepton, NP can have preferential τ LFV couplings

Prospects for τ LFV

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

  - "golden channels" for discovery: τ→μμμ, τ→μγ
  - complementary: semileptonic modes allow us to test LFV couplings b/w quarks and leptons, and better discriminate b/w NP models

arXiv:1808.10567



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

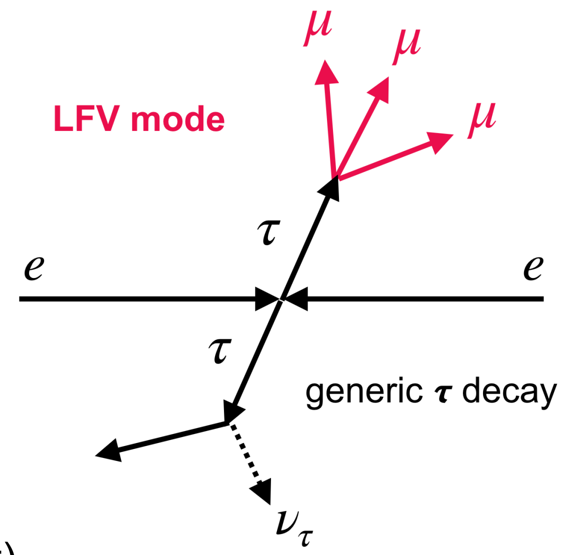
Belle II will push the current bounds forward by at least one order of magnitude!

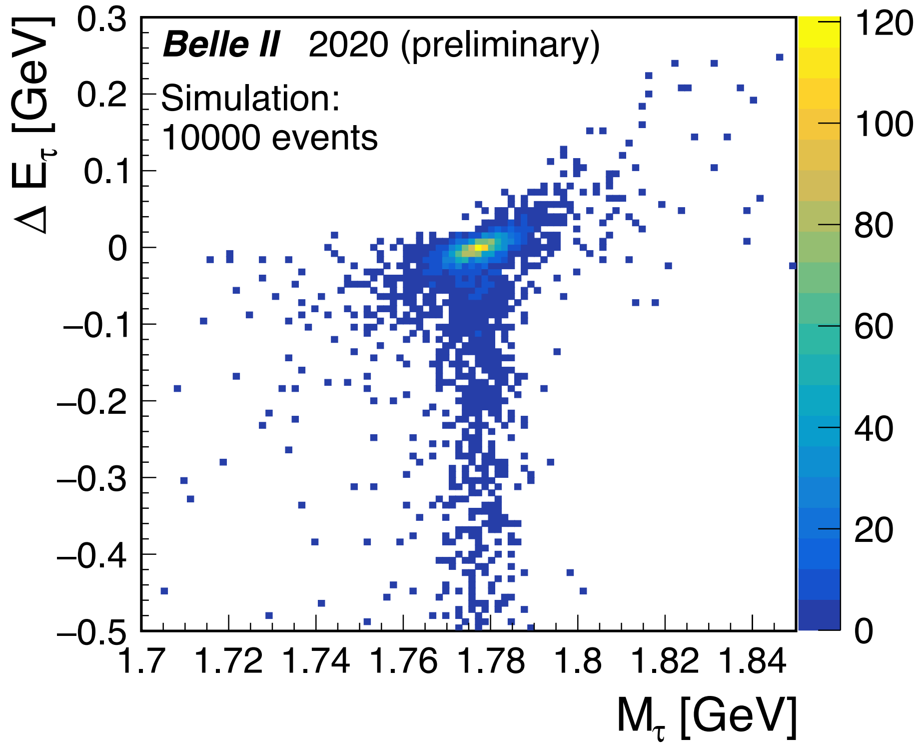
- This only accounts for ↑ luminosity
- Equally important will be improvements in signal detection efficiency

  better trigger, tracking, vertexing, PID, π^0 reconstruction, more refined analysis techniques, …

Search for LFV $\tau \to \mu\mu\mu$

- tag side: generic 1-prong decay, signal side: fully reconstructed $\tau \to 3\mu$
- Consider two independent variables: $M_\tau = \sqrt{E^2_{\mu\mu\mu} - P^2_{\mu\mu\mu}}$ $\Delta E = E^{CMS}_{\mu\mu\mu} - E^{CMS}_{beam}$
- Signal extraction in $M_{3\mu}$-ΔE plane (or rotated plane to reduce correlation)
- Side-bands to study / evaluate background contributions



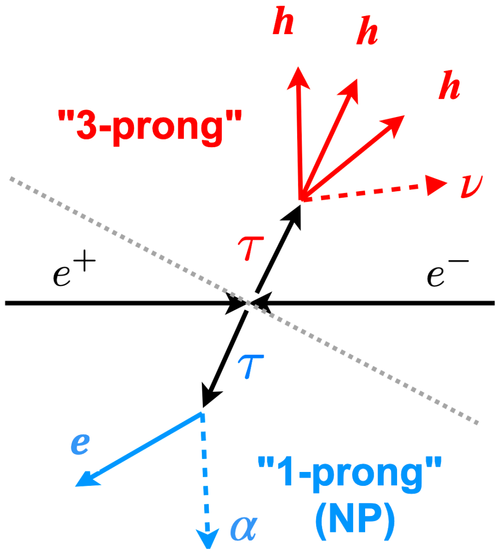


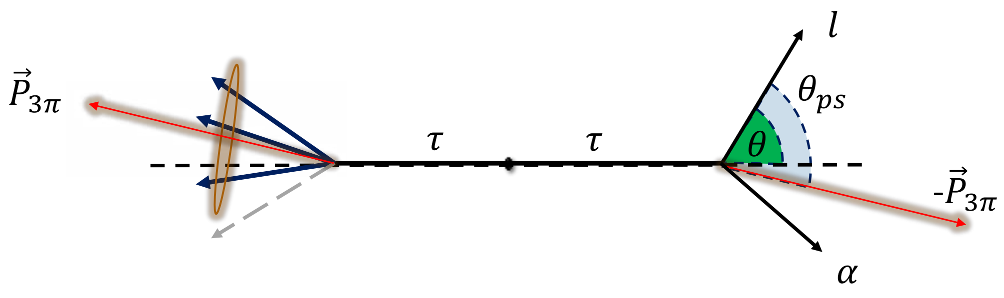
- Good μID performance is critical to achieving the necessary level of background suppression (mainly SM ττ)
- Momentum dependent μID optimisation
  - $p_\mu < 0.7$ GeV ⇒ μ does not reach the KLM
  - $0.7 < p_\mu < 1$ GeV ⇒ reaches KLM but not many layers crossed
  - $p_\mu > 1$ GeV ⇒ reaches KLM with many layers
- Can avoid tag μ-veto and $p_\mu > 0.6$ GeV requirements used @Belle. New low-multi 3-cluster triggers (>95% efficiency for ΔE~0).

  ⇒ higher efficiency foreseen @Belle II compared to Belle/BaBar!

Search for LFV τ→lα

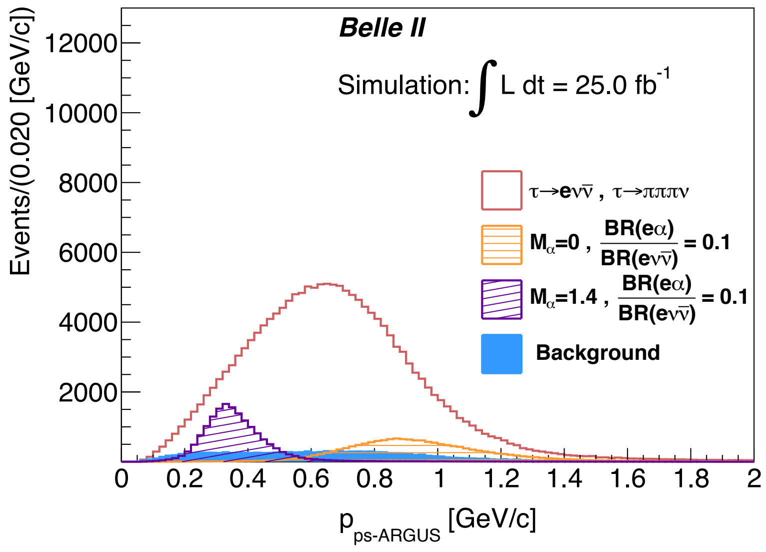
- Search for two body decay **τ→ e/μ + α**, where α is unobserved (missing energy)
- LFV process that appears in several NP models (Goldstone boson, LFV Z', light ALP, …)
- Previously studied at MARK III (9.5 pb^{-1}) and ARGUS (476 pb^{-1})

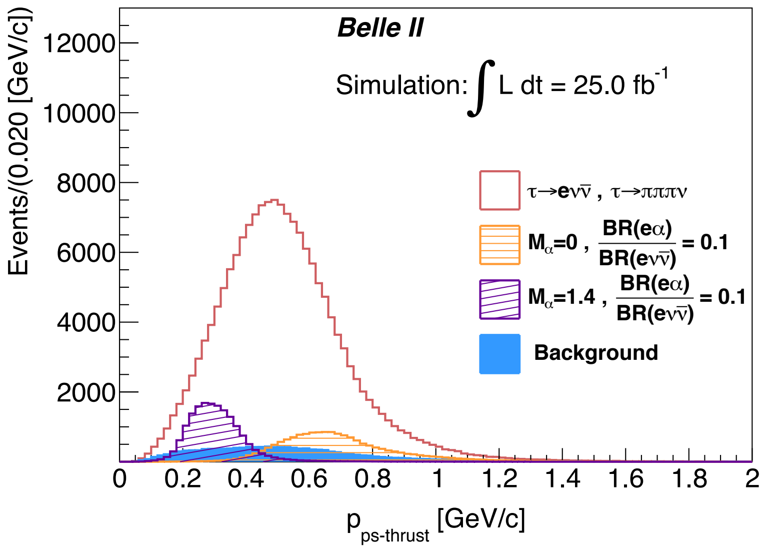




- Signal will manifest as a peak in the τ rest frame, against the SM τ→lνν background

BELLE2-NOTE-PL-2020-018

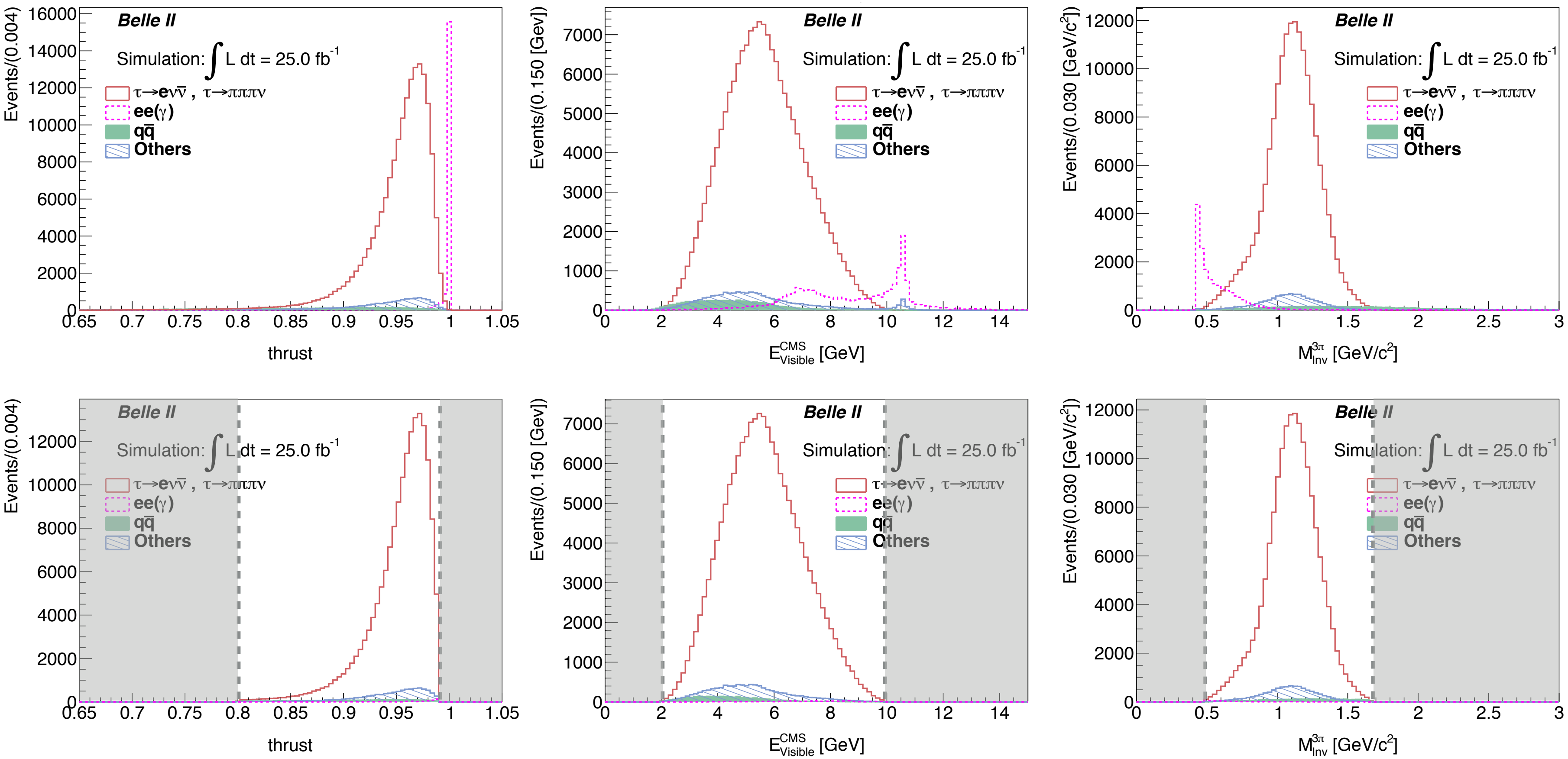




- cannot access τ rest frame directly due to neutrino
- approximate with the following assumptions:
  - $E_\tau = \sqrt{s}/2$
  - ARGUS method: $\overrightarrow{p_\tau} \approx -\overrightarrow{p_{3\pi}}$
  - Thrust method: $\overrightarrow{p_\tau} \approx \overrightarrow{T}$

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

- Follows τ-pair 1x3 prong reconstruction criteria described earlier (4 good tracks, thrust-based hemisphere separation)
- Dominant background is **SM $\tau \to l\nu\nu$ (irreducible)**. Since we don't know M_α, we optimise for the SM.



- Cut-based selection

$$\text{FOM} = \frac{S_{SM}}{\sqrt{S_{SM} + B}}$$

- $0.8 < \text{thrust} < 0.99$
- $2.0 < E_{vis}^{CMS} < 9.9$ GeV
- $0.48 < M_{3\pi} < 1.66$ GeV

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

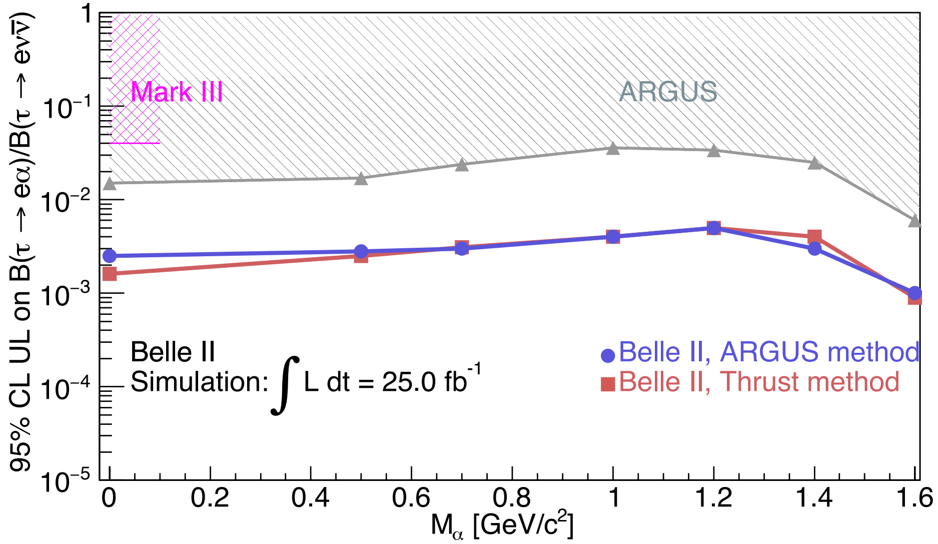
- UL estimation for the ratio **Br(τ→eα) / Br(τ→evv)** was shown at ICHEP (no systematics) BELLE2-NOTE-PL-2020-018

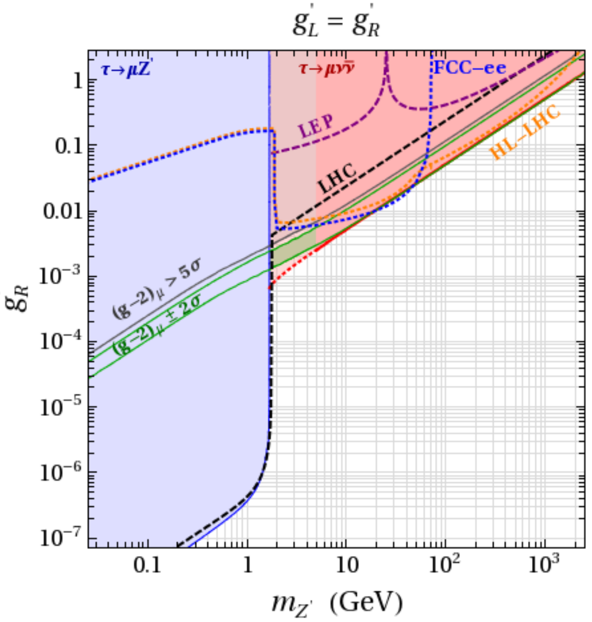
- **With only 25 fb^{-1} we can push forward current bounds by an order of magnitude!** Aiming for a paper in early-mid 2021.

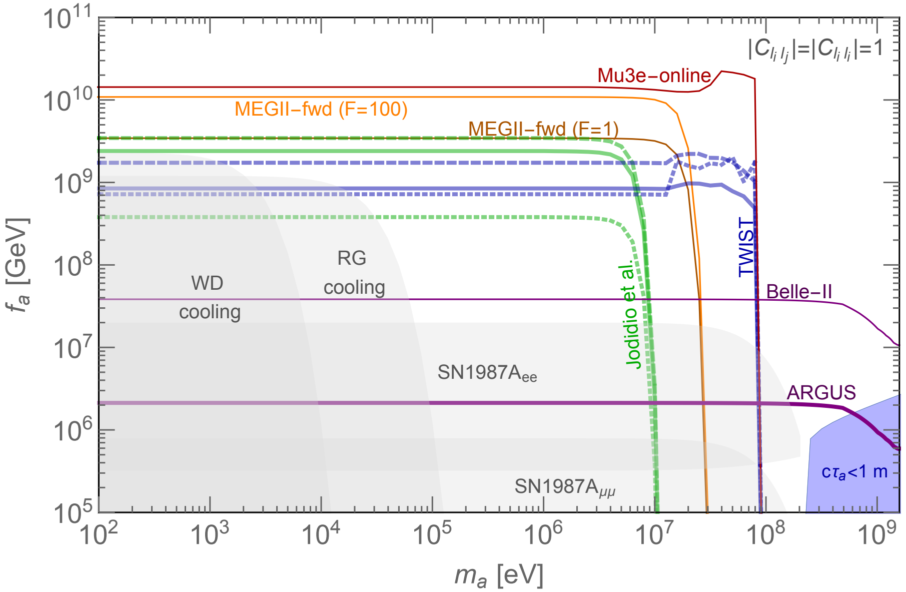
- Current status of the analysis:
  - including systematics uncertainties
  - include τ→μα channel
  - development of BDT, and better 3-prong selection (see earlier)
  - UL cross-check using Bayesian approach

Can set strong constraints on NP models, e.g:

- LFV Z' ⇒ strong bound already set from ARGUS for $m_{Z'} \lesssim m_\tau - m_\mu$
- light ALP ⇒ exploring regions of parameter space not reachable by other experiments

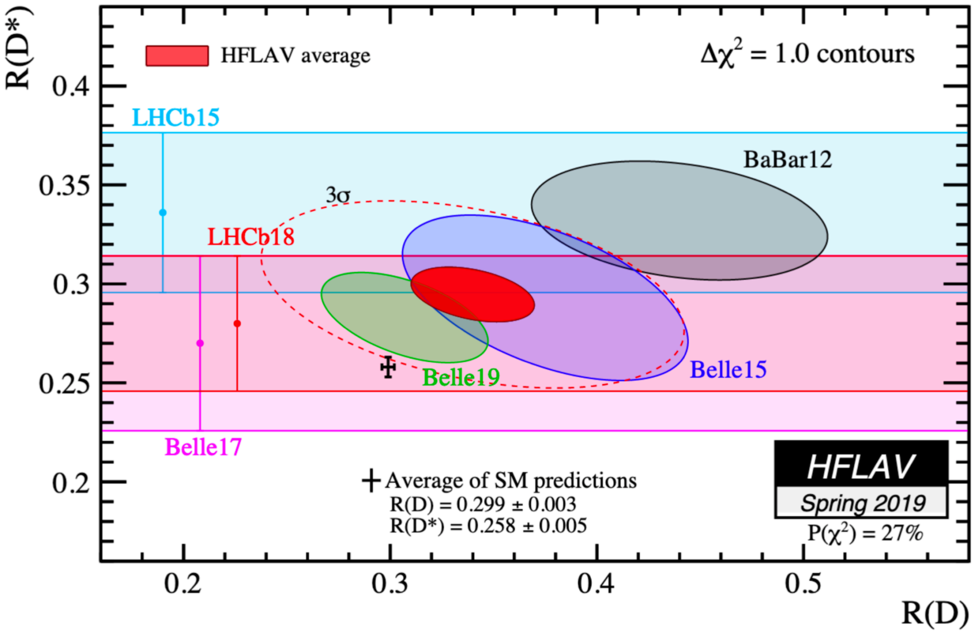






Tests of Lepton Flavour Universality

- LFU refers to the SM property that the electroweak (gauge) bosons have the same coupling to all lepton generations



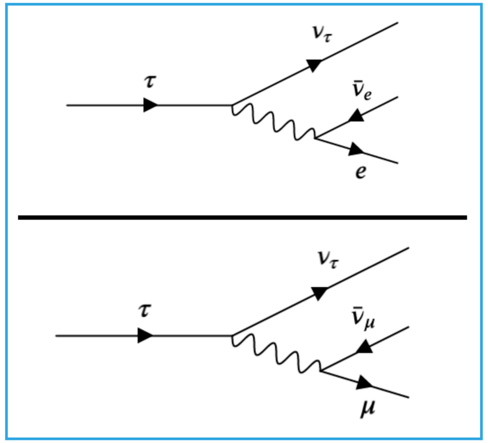
- Anomalies in **quark sector**
  - R(D)-R(D*) plane (~3.9σ)
  - R(K) and R(K^{*0}) (~2.2-2.5σ), also P_5' in $B \to K^* \mu\mu$ (~3.4σ)
  - and more…

- Tensions also in **lepton sector**
  - anomalous magnetic moment of μ (~3.8σ) and e (~2.5σ)

- **Are these hints of a new fundamental interaction that violates LFU?**

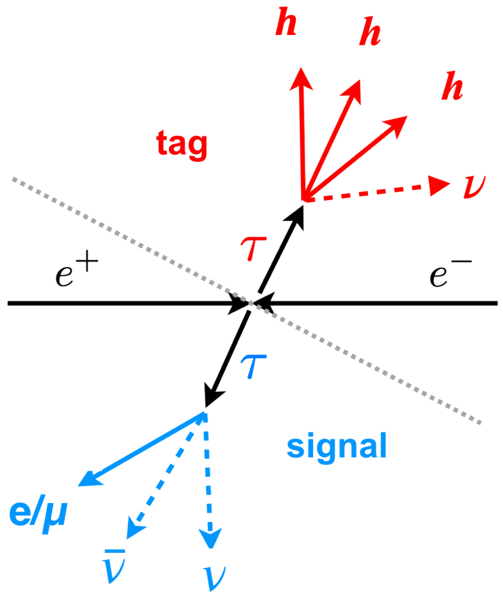
- If so, then we should also see hints in the **tau sector**, where the most stringent test of μ-e universality comes from the ratio:

$$\frac{\mathcal{B}(\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \overline{\nu}_e \nu_\tau)}$$



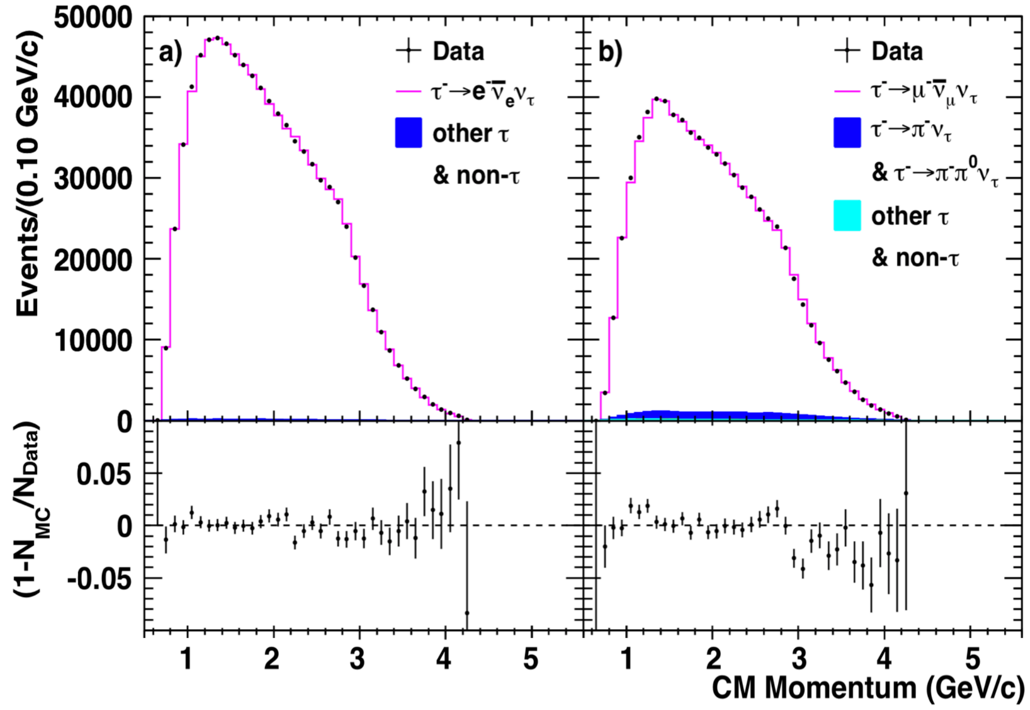
Tests of LFU in τ decays

$$\left(\frac{g_\mu}{g_e}\right)^2_\tau = \frac{\mathcal{B}(\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \overline{\nu}_e \nu_\tau)} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}, \quad \text{where } f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x$$



- Most precise measurement from **BaBar** (467 fb^{-1}): Phys.Rev.Lett.105:051602 (2010)

$$R_\mu \equiv \frac{\mathcal{B}(\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \overline{\nu}_e \nu_\tau)} = 0.9796 \pm 0.0016\,(\text{stat}) \pm 0.0036\,(\text{sys})$$



	μ
N^D	731102
Purity	97.3%
Total Efficiency	0.485%
Particle ID Efficiency	74.5%
Systematic uncertainties:	
Particle ID	0.32
Detector response	0.08
Backgrounds	0.08
Trigger	0.10
$\pi^-\pi^-\pi^+$ modelling	0.01
Radiation	0.04
$\mathcal{B}(\tau^- \to \pi^-\pi^-\pi^+\nu_\tau)$	0.05
$\mathcal{L}\sigma_{e^+e^-\to\tau^+\tau^-}$	0.02
Total [%]	0.36

Can we do better at Belle II?

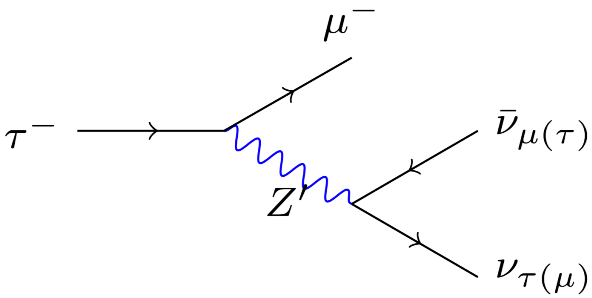
⇒ **Yes!**

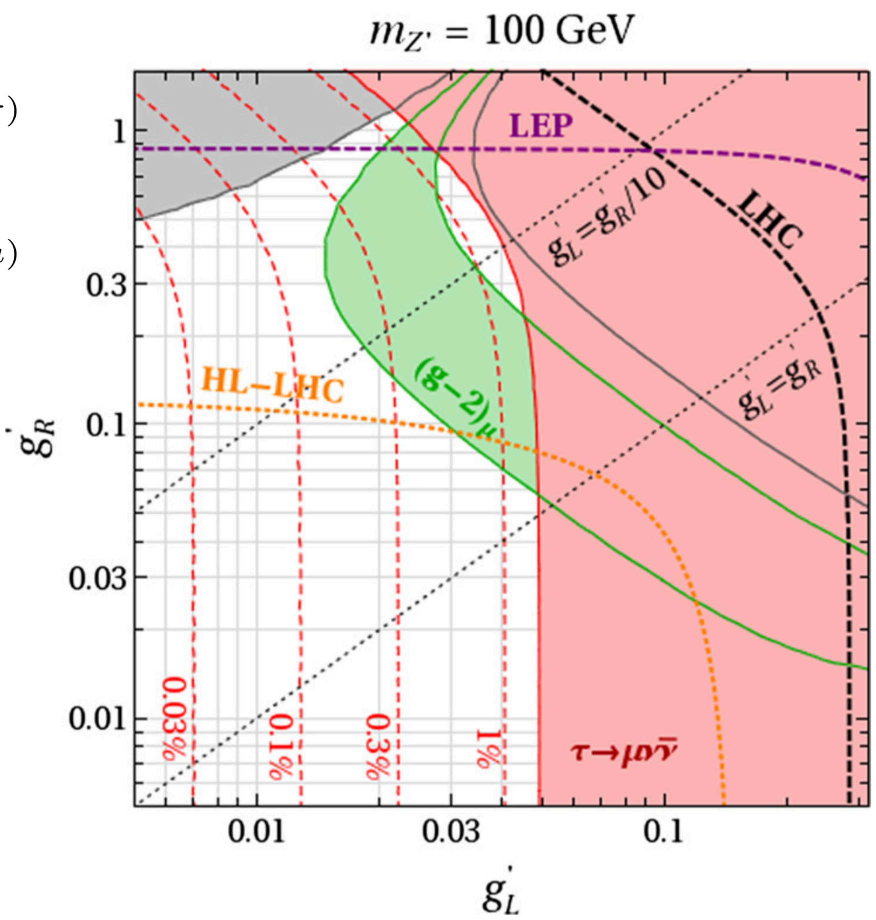
More data and higher signal reconstruction efficiency.

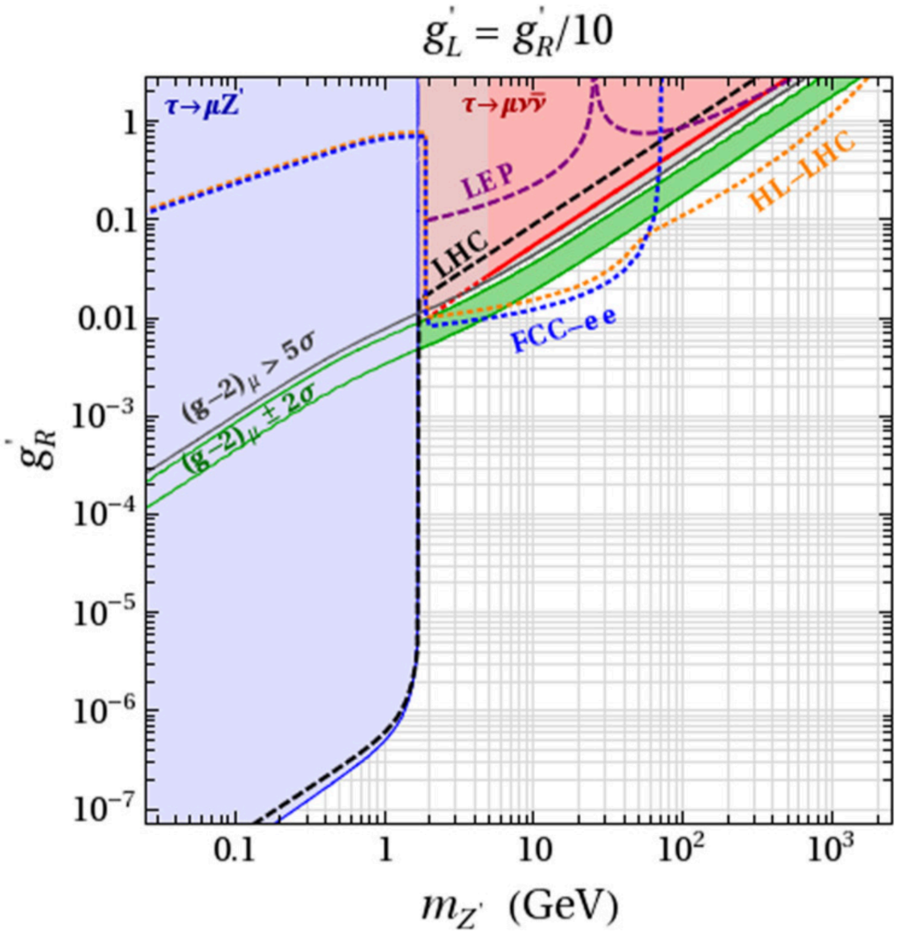
PID uncertainties should scale well with luminosity and higher stat MC samples.

- R_μ can put strong constraints on lepton flavour violating Z' models

Physics Letters B 762 (2016) 389–398







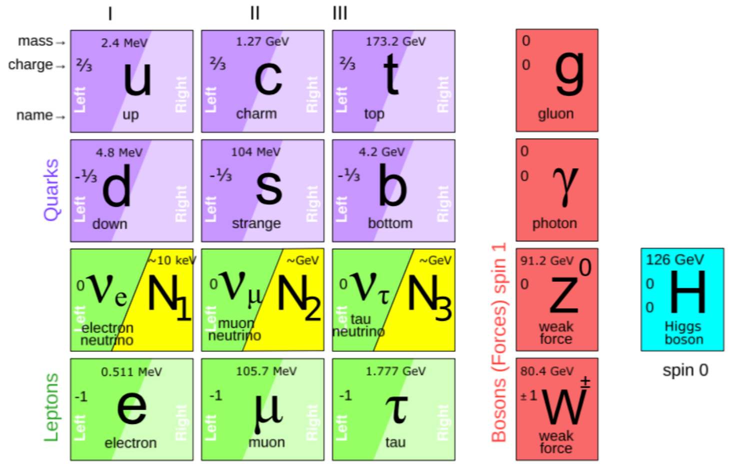
- BaBar has already excluded a significant region of parameter space

- Sensitivity @**Belle II** will depend on how well we can control the systematics

Search for Heavy Neutral Leptons

- Neutrino masses can be incorporated into the SM by introducing sterile RH (Majorana) neutrino(s)

- For example, the ***ν*MSM** model introduces three RH singlet HNLs. Can solve:
  - origin and smallness of ν_{SM} mass (with GeV scale $N_{1,2}$ and see-saw mechanism)
  - dark matter (N_1 with mass ~keV)
  - BAU: leptogenesis due to Majorana mass term

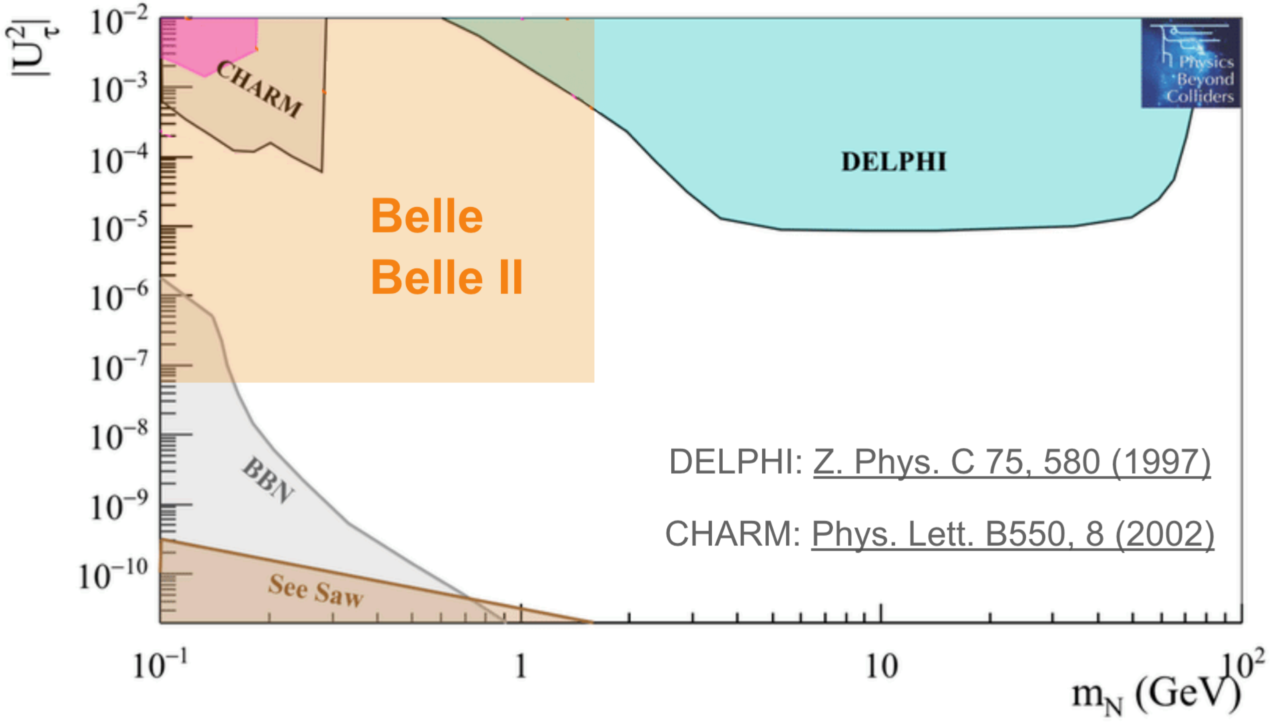


- HNL interacts with ν_{SM} via $N \leftrightarrow \nu_{SM}$ mixing.
  Long lifetime due to small M_N and small mixing.

- Tight limits already exist on HNL mixing with ν_e and ν_μ.
  Weaker limits on $|U_{\tau N}|^2$, motivating $|U_{\tau N}|^2 \gg |U_{eN}|^2, |U_{\mu N}|^2$

- By studying τ decays at **Belle II**, we can significantly improve existing limits for **$M_N < M_\tau$**

⇒ **No measurement was done at Belle/BaBar!**



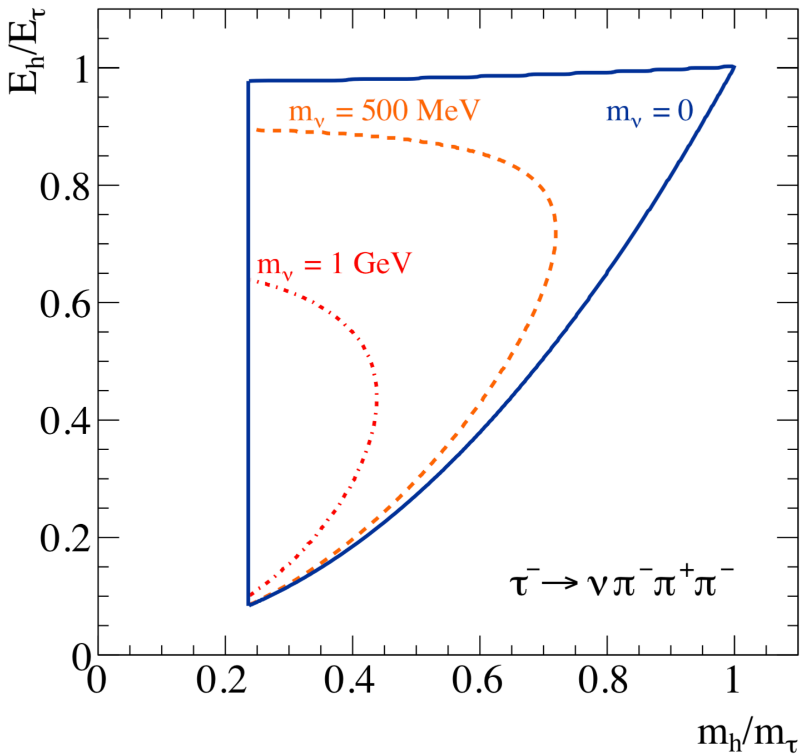
DELPHI: Z. Phys. C 75, 580 (1997)

CHARM: Phys. Lett. B550, 8 (2002)

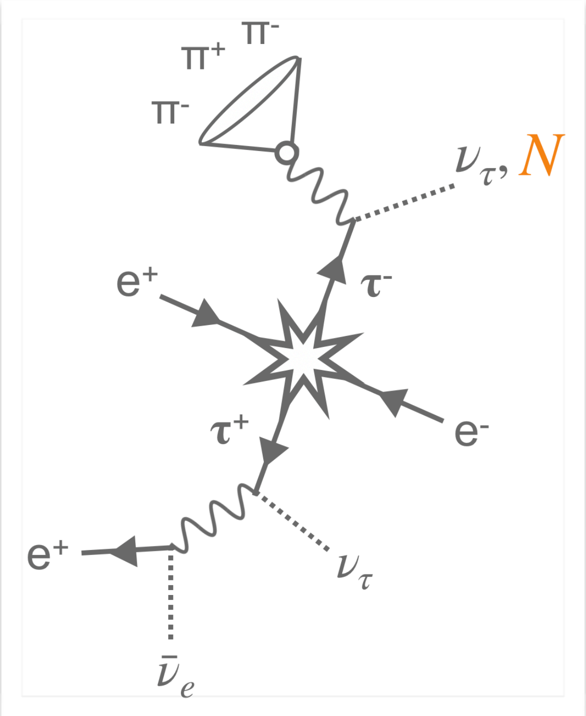
HNL in τ decay kinematics

- Proposed search for HNL in **$\tau \to 3\pi\nu$** decays   arXiv:1412.4785v2
- Phase space of 3π-system could be superposition of massless neutrinos and HNL

$$\frac{d\Gamma_{tot}(\tau^- \to \nu h^-)}{dm_h dE_h} = (1-|U_{\tau 4}|^2)\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\Big|_{m_\nu=0} + |U_{\tau 4}|^2 \frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\Big|_{m_\nu=m_4}$$



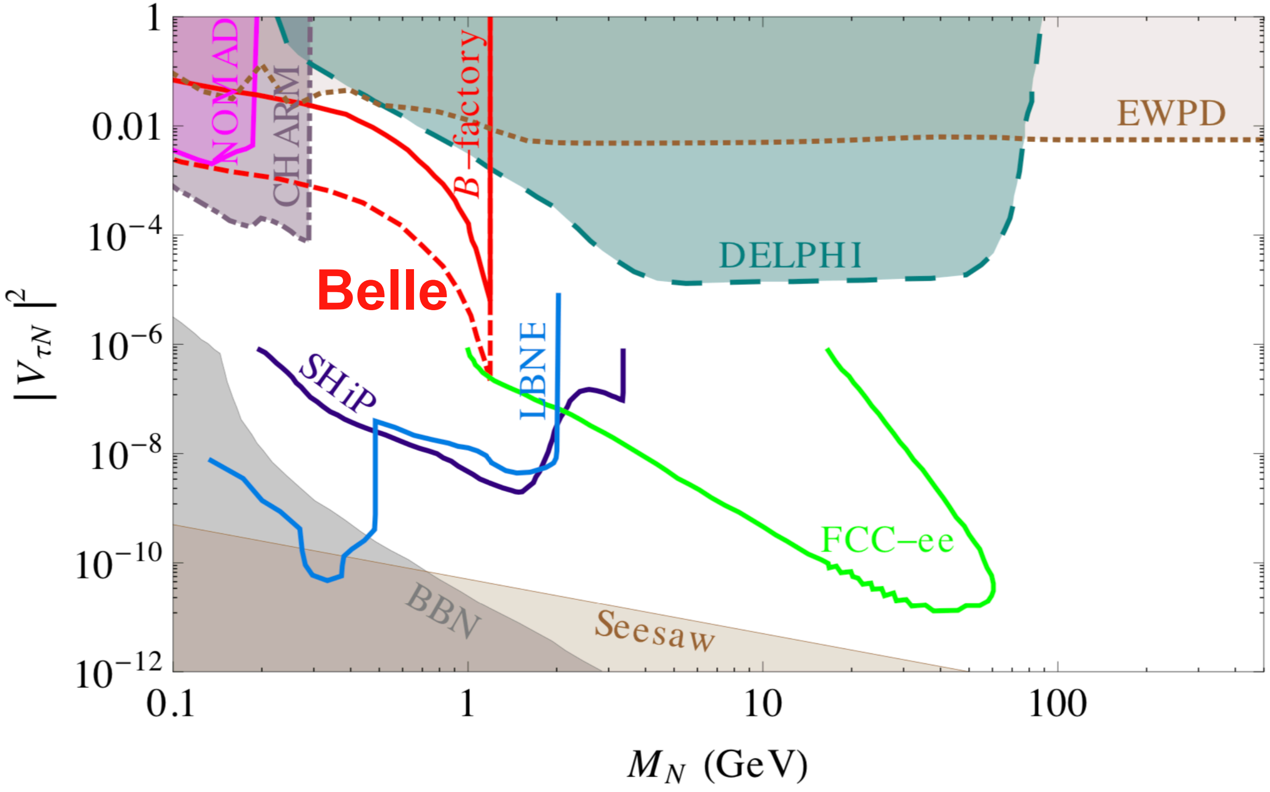
- Kinematics of **τ** decay will contain info on whether 3π recoiled against HNL
- **General idea**:
  Measure a crescent-shaped endpoint in the $E_{3\pi}$-$M_{3\pi}$ plane



- Method is insensitive to details of HNL decay, lifetime or whether it is Majorana/Dirac
- Would require large data statistics and excellent E/M resolution
  ⇒ Possible at Belle and definitely at Belle II!

HNL in τ decay kinematics

aXiv:1502.06541v3



- Sensitivity estimate based on pseudo-data study
- MC sample of ee→ττ with τ→3πν decay(s)
  - assuming Belle lumi
  - smearing to mimic typical Belle resolution
  - both optimistic and conservative scenarios wrt systematics
- **Belle** may be able to place stringent limits on $|U_{\tau N}|^2$ as low as $\mathcal{O}$(**10^{-7} - 10^{-3}**) for **100 MeV ≲ M_N ≲ 1.2 GeV**

⇒ In the coming years **Belle II** will be able to push these limits even further!

Other players in the game will be **SHiP**, **LBNE** and **FCC-ee**

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

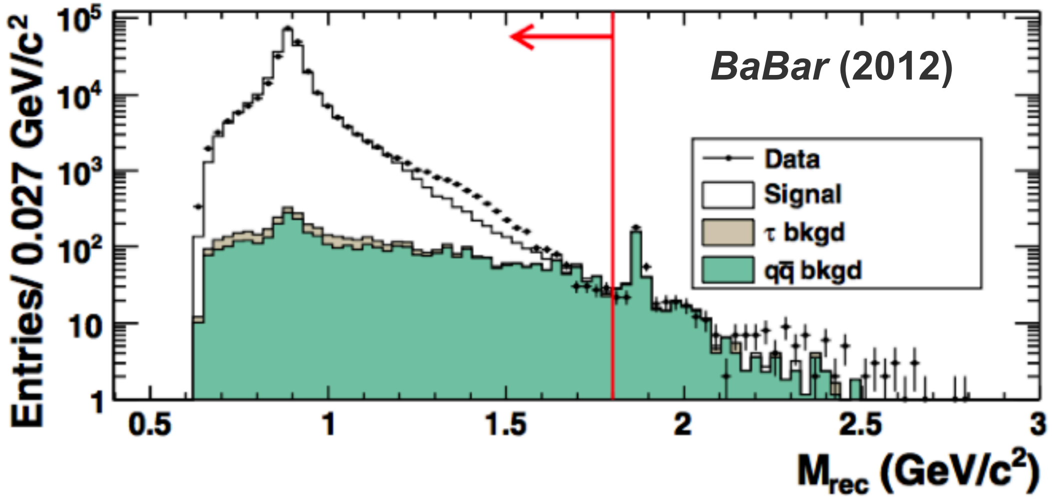
- Due to CP violation in the kaon sector, $\tau \to K_S \pi^\pm \nu_\tau$ decays in the SM have a nonzero decay-rate asymmetry:

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

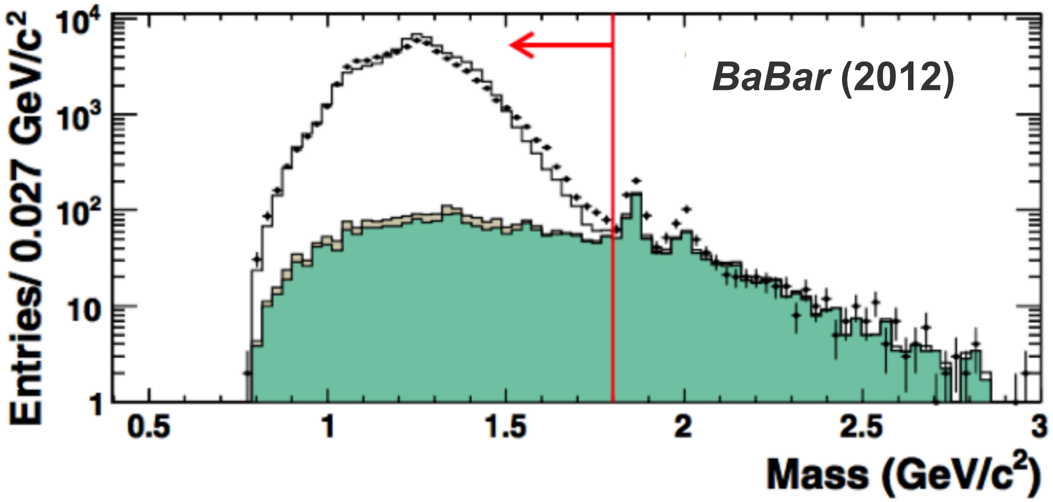
  - SM prediction: $(3.6 \pm 0.1) \times 10^{-3}$
  - BaBar measurement: **$(-3.6 \pm 2.3 \pm 1.1) \times 10^{-3}$ (2.8σ)**

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

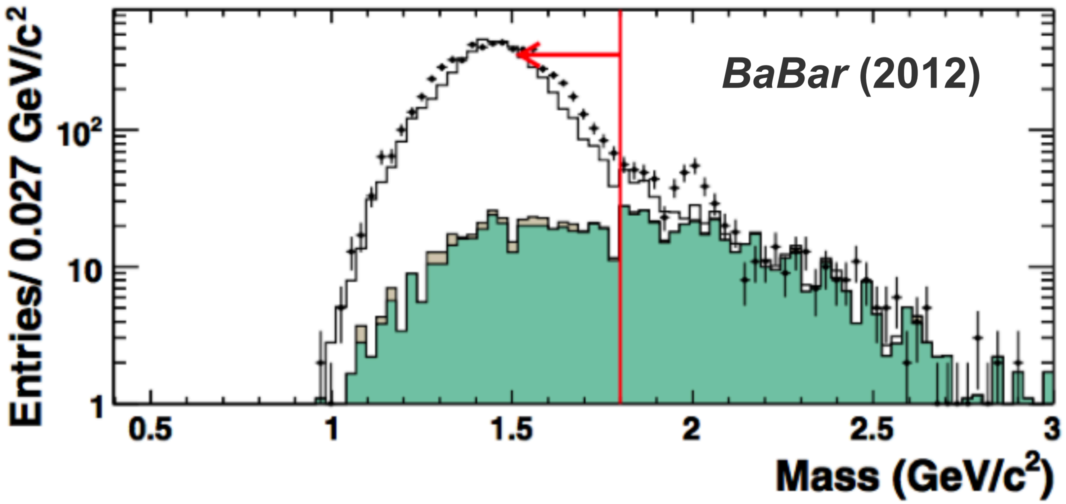
$\tau \to K_S \pi^\pm \nu_\tau$ Phys.Rev D85 (2012) 031102



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

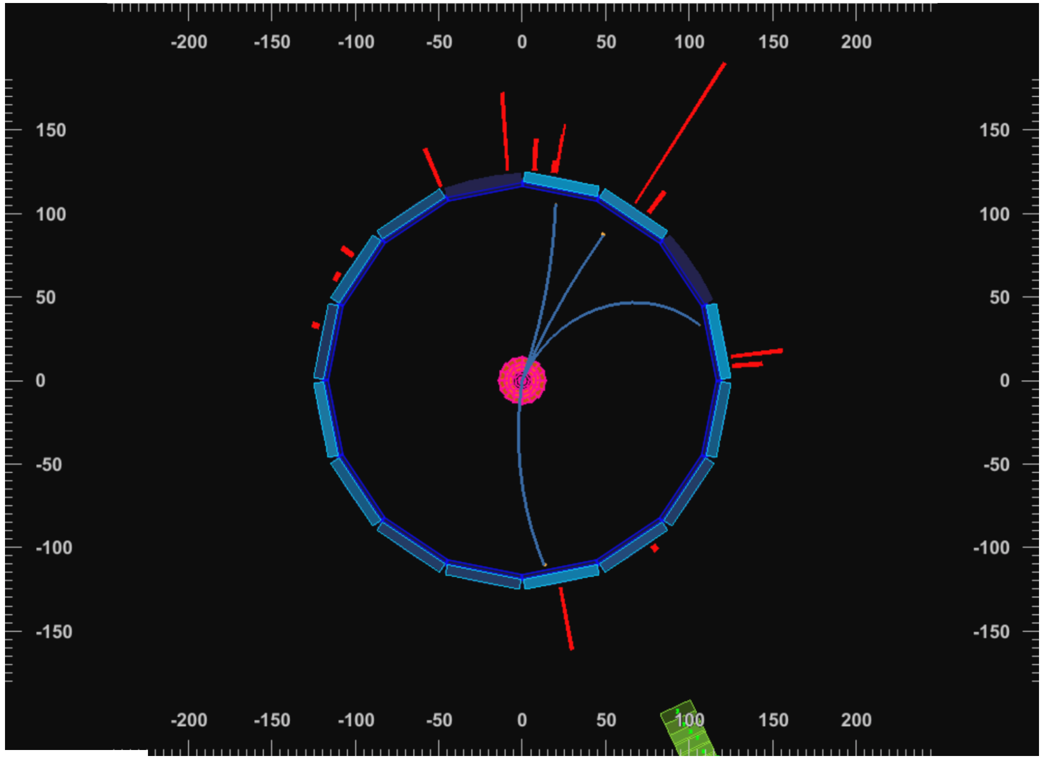


$\tau \to K_S \pi^\pm \nu_\tau + 2\pi^0$



Summary and Outlook

- Belle II is now well into the Phase 3 data taking period, breaking the peak luminosity world record in June and collecting ~74 fb^{-1} of data so far.
- On target to deliver the world's largest sample of τ-pair events in the coming years, enabling a rich program of both **performance** and **physics results**.



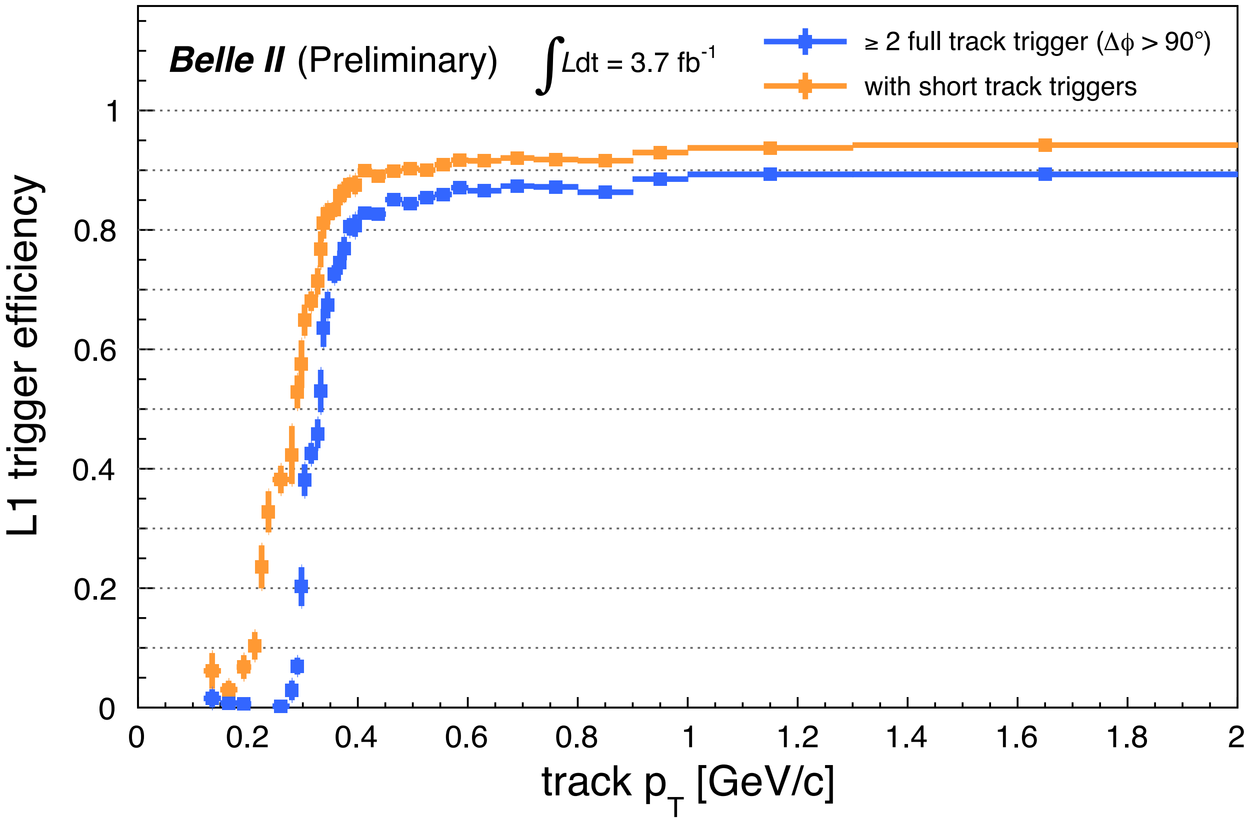
- Tau physics goals/highlights:
  - Most precise τ mass measurement amongst the pseudomass techniques.
  - Searches for LFV τ decays, with a potential first paper on τ→lα coming early/mid 2021.
  - Pushing the limits of LFU with the world's leading measurement of R_μ.
  - Search for HNLs through a novel probe of $N \leftrightarrow \nu_\tau$ mixing
  - and <u>much</u> more!

⇒ **Exciting times ahead!**

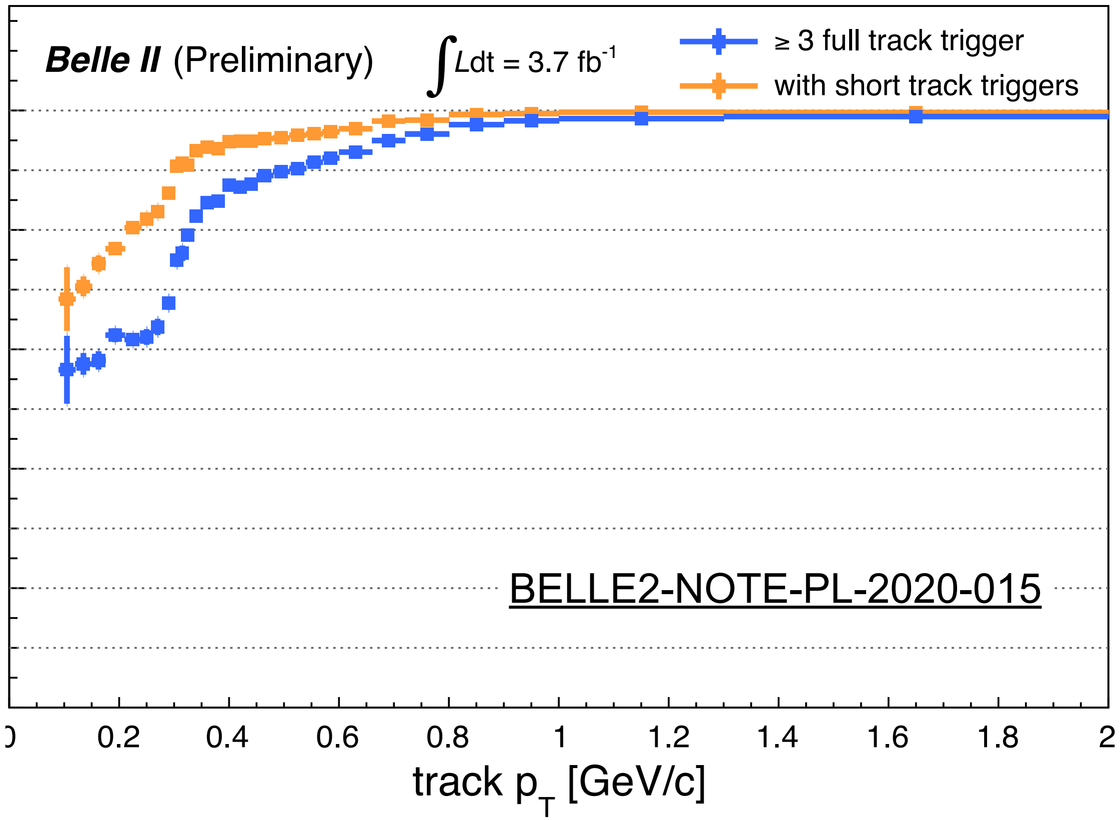
BACKUP

Full and short track triggers

ee→ττ→1x1 prong

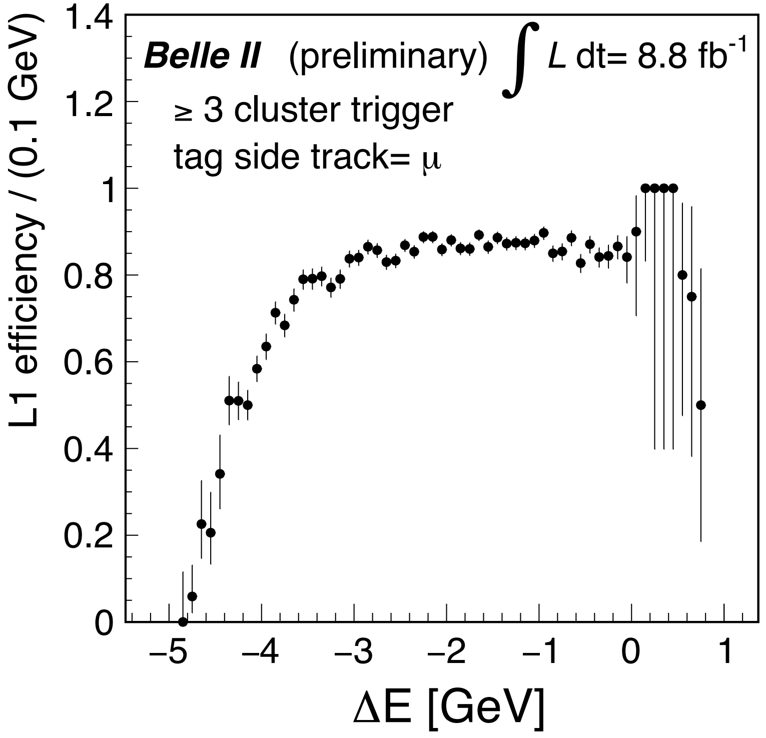


ee→ττ→1x3 prong

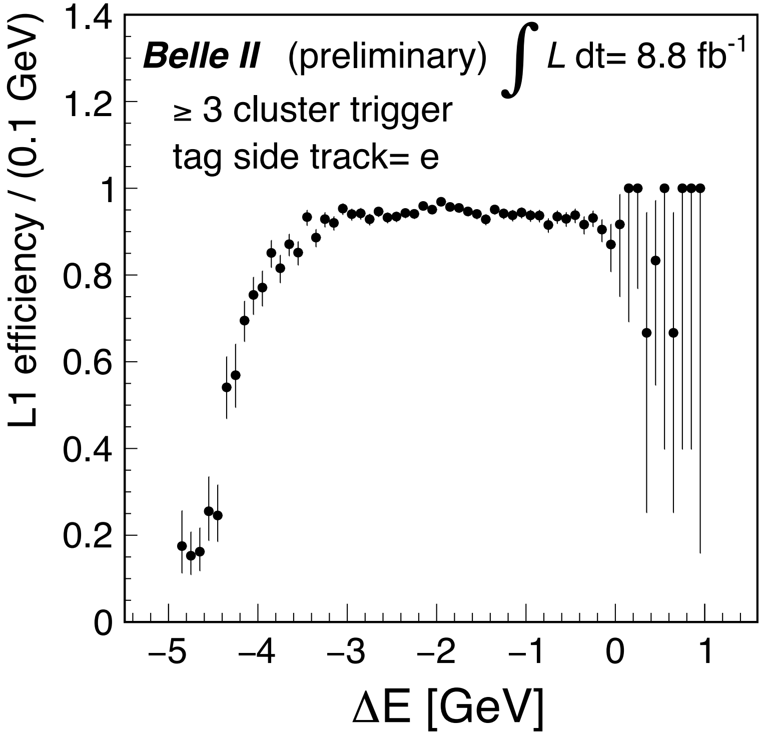


Trigger efficiency for τ LFV

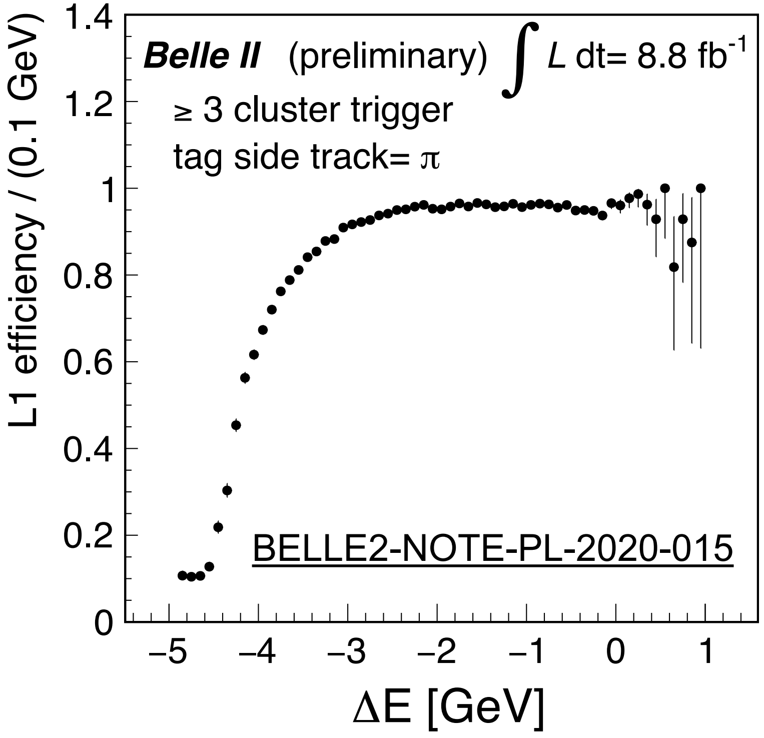
μ-3π, LFV-like event



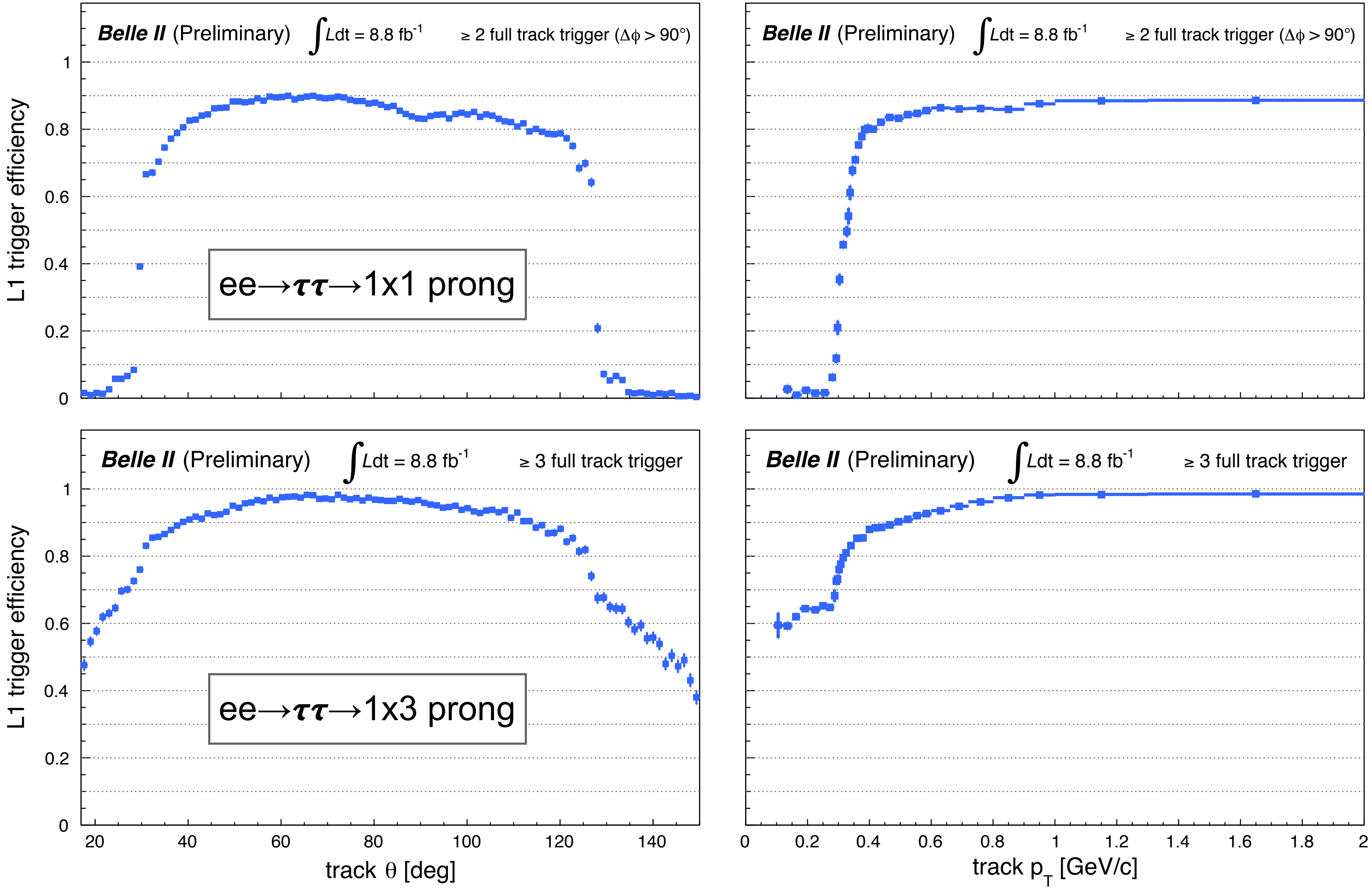
e-3π, LFV-like event



π-3π, LFV-like event



Full track triggers



- L1 requirement
  - ≥2 full tracks
  - track pair with $\Delta\phi > 90°$
  - ECL Bhabha veto

⇒ low efficiency in endcaps, puts limitations on tau + other low multi physics

- L1 requirement
  - ≥3 full tracks

⇒ less sever drop in endcaps and at low p_T

(due to one track redundancy)

Trigger definitions

- **ffo** : ≥ 2 full tracks, track pair with $\Delta\phi > 90^\circ$ and not an ECL Bhabha.
- **fff** : ≥ 3 full tracks.
- **fso** : ≥ 1 full tracks, ≥ 1 short tracks, track pair with $\Delta\phi > 90^\circ$ and not an ECL Bhabha.
- **sso** : ≥ 2 short tracks, track pair with $\Delta\phi > 90^\circ$ and not an ECL Bhabha.
- **ffs** : ≥ 2 full tracks and ≥ 1 short tracks.
- **fss** : ≥ 1 full tracks and ≥ 2 short tracks.
- **sss** : ≥ 3 short tracks.
- **hie** : total energy above 1 GeV and not an ECL Bhabha.
- **c4** : ≥ 4 isolated clusters with energy above 100 MeV and not an ECL Bhabha.
- **eclmumu** : cluster pair each with $E^* < 2$ GeV, $165^\circ < \sum\theta < 190^\circ$ and $160^\circ < \Delta\phi < 200^\circ$.

Trigger definitions

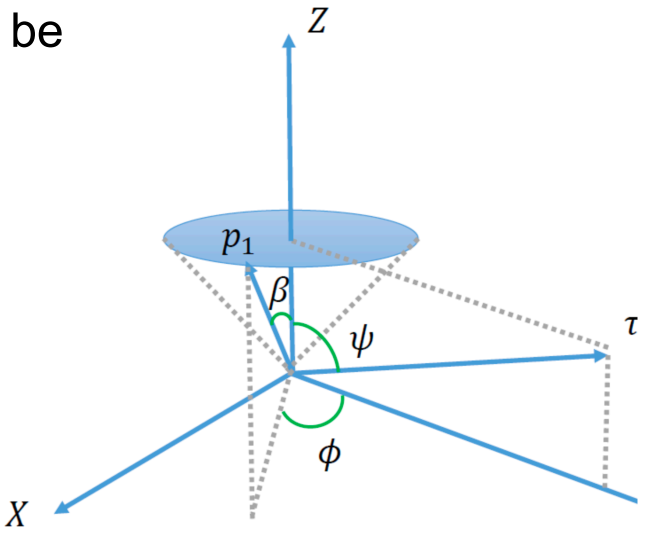
- **lml0** : ≥ 3 clusters with at least one having $E^* > 300$ MeV, $1 < \theta_{ID} < 17$ (corresponding to $18.5° < \theta < 139.3°$, full ECL) and not an ECL Bhabha.
- **lml1** : exactly 1 cluster with $E^* > 2$ GeV and $4 < \theta_{ID} < 14$ ($32.2° < \theta < 124.6°$)
- **lml2** : ≥ 1 cluster with $E^* > 2$ GeV, $\theta_{ID} = 2$, 3, 15, or 16 ($18.5° < \theta < 32.2°$ or $124.6° < \theta < 139.3°$) and not an ECL Bhabha.
- **lml4** : ≥ 1 cluster with $E^* > 2$ GeV, $\theta_{ID} = 1$ or 17 ($\theta < 18.5°$ or $\theta > 139.3°$) and not an ECL Bhabha.
- **lml6** : exactly 1 cluster with $E^* > 1$ GeV, $4 < \theta_{ID} < 15$ ($32.2° < \theta < 128.7°$, full ECL barrel) and no other cluster with $E >$ 300 MeV anywhere.
- **lml7** : exactly 1 cluster with $E^* > 1$ GeV, $\theta_{ID} = 2$, 3 or 16 ($18.5° < \theta < 31.9°$ or $128.7° < \theta > 139.3°$) and no other cluster with $E >$ 300 MeV anywhere.
- **lml8** : cluster pair with $170° < \Delta\phi < 190°$, both clusters with $E^* > 250$ MeV and no 2 GeV cluster in the event.
- **lml9** : cluster pair with $170° < \Delta\phi < 190°$, one cluster with $E^* < 250$ MeV with the other having $E^* > 250$ MeV, and no 2 GeV cluster in the event.
- **lml10** : cluster pair with $160° < \Delta\phi < 200°$, $160° < \sum\theta < 200°$ and no 2 GeV cluster in the event.
- **lml12** : ≥ 3 clusters with at least one having $E^* > 500$ MeV, $2 < \theta_{ID} < 16$ (corresponding to $18.5° < \theta < 139.3°$, full ECL) and not an ECL Bhabha.

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

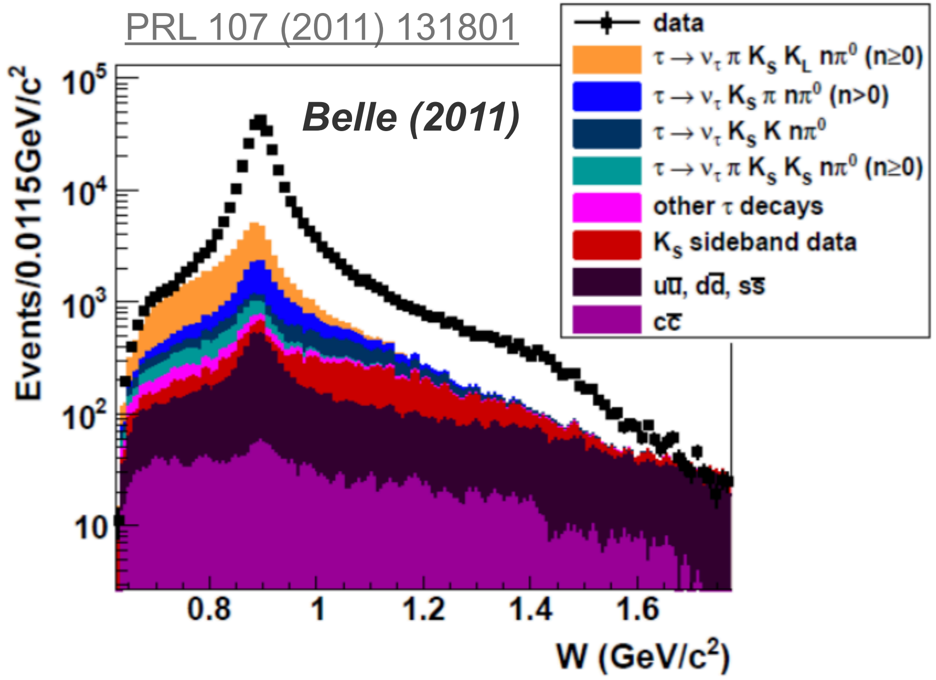
- CP violation could also arise from a charged scalar boson exchange. It would be detected as a difference in the decay angular distributions:

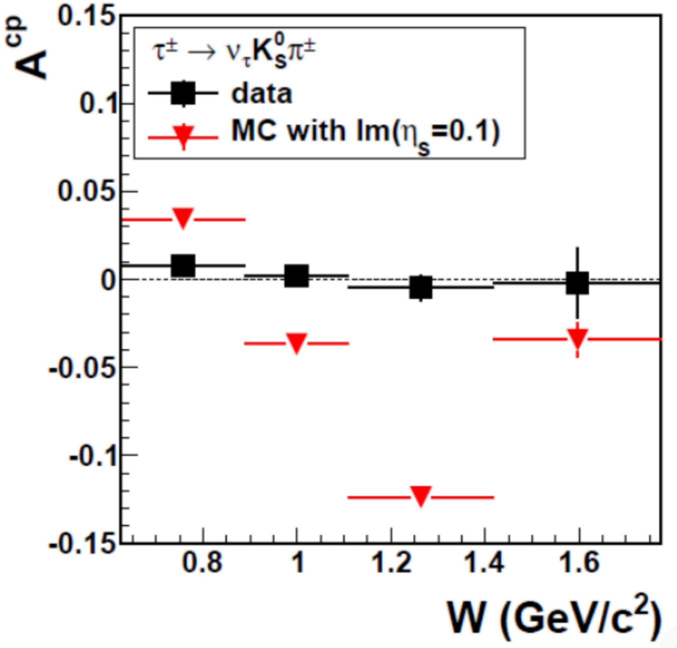
$$A_i^{CP} = \frac{\iint_{Q^2_{1,i}}^{Q^2_{2,i}} \cos\beta \cos\psi \left(\frac{d\Gamma_{\tau^-}}{d\omega} - \frac{d\Gamma_{\tau^+}}{d\omega}\right) d\omega}{\frac{1}{2}\iint_{Q^2_{1,i}}^{Q^2_{2,i}} \left(\frac{d\Gamma_{\tau^-}}{d\omega} + \frac{d\Gamma_{\tau^+}}{d\omega}\right) d\omega} \simeq \langle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

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



PRL 107 (2011) 131801





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

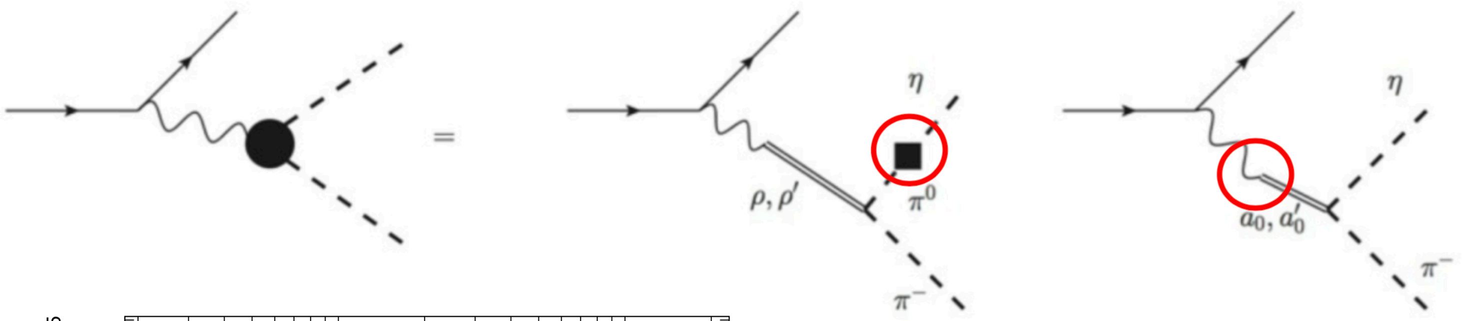
$|A_{CP}| < (0.5\text{-}3.8) \times 10^{-4}$

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

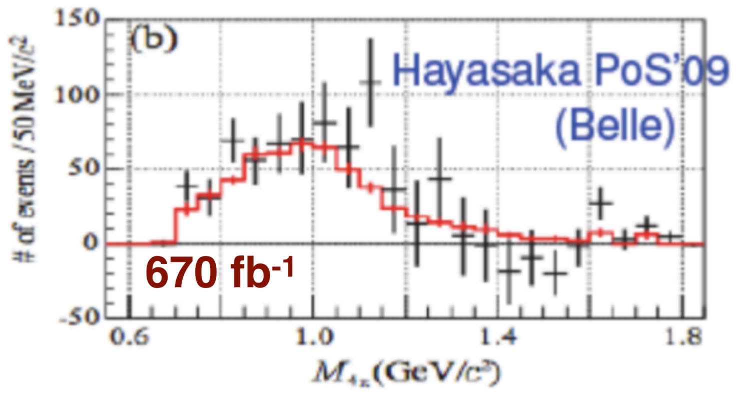
Second class currents in $\tau \to \eta\pi\nu$

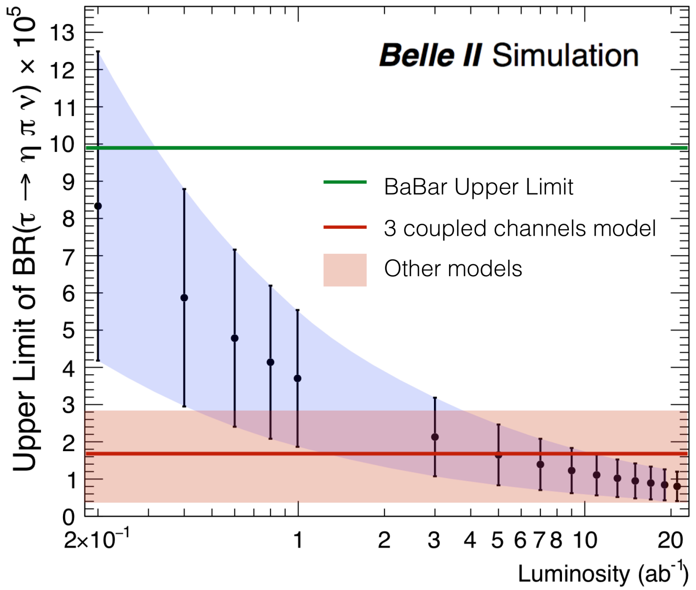
- Hadronic currents classified as first or second class according to their spin, parity and G-parity quantum numbers
  - Second Class Current (SCC): J^{PG} = 0^{+-} (a_0), 0^{-+} (η), 1^{++} (b_1), 1^{--} (ω) **⇒ yet to be observed!**

- 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!**

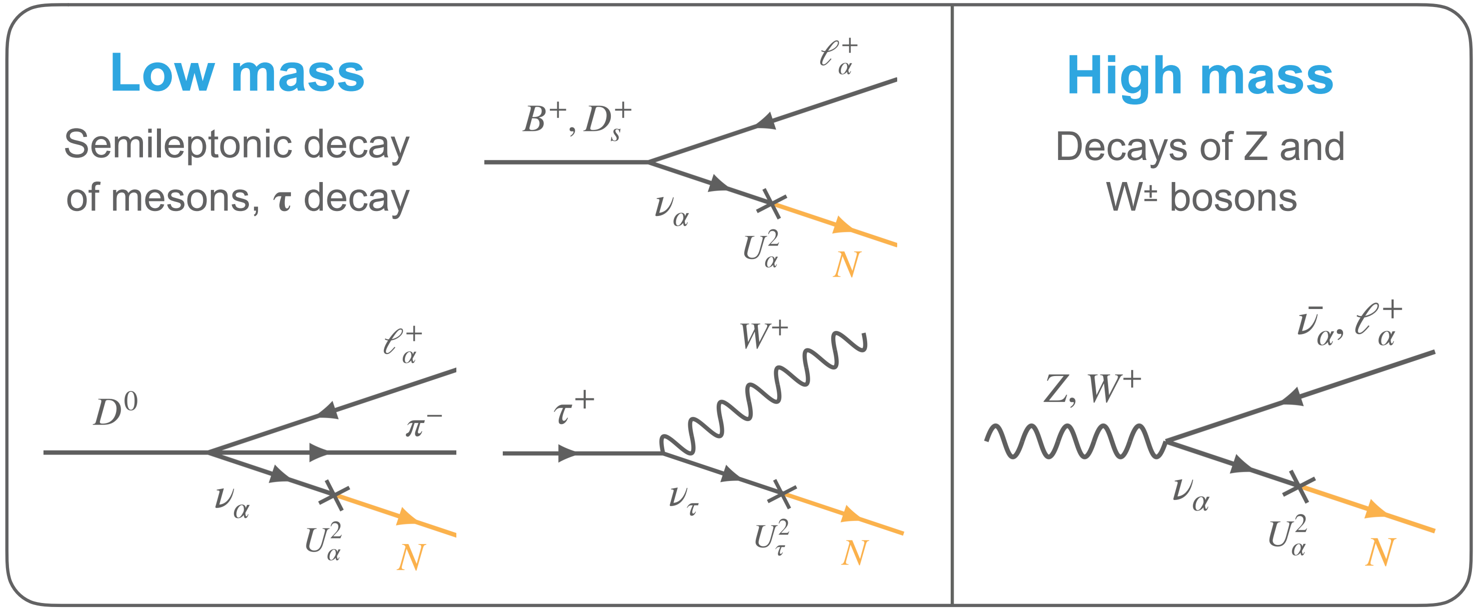
HNL Production and Decay

- Neutrino flavour and mass eigenstates need not coincide, but may be related through a unitary transformation

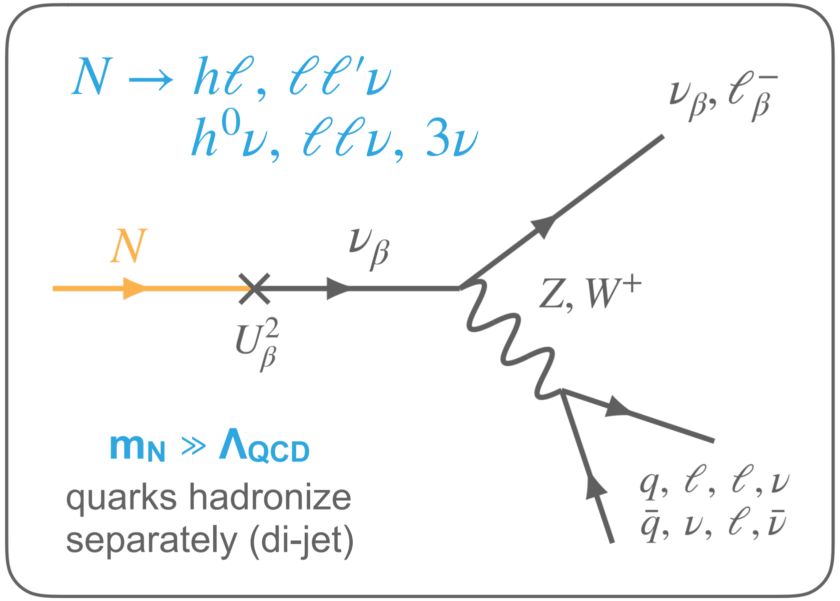
$$\nu_\alpha = \sum_i U_{\alpha,i}\nu_i, \quad \alpha = e,\mu,\tau,\ldots, \quad i = 1,2,3,4,\ \ldots$$

- HNL production can occur through mixing with the SM neutrinos ⇒ suppressed by factor of $\mathbf{U_\alpha^2}$
- They can then decay (after long flight length) by mixing again with SM neutrinos ⇒ additional $\mathbf{U_\alpha^2}$

Production



Decay



Status of Direct Searches for HNL

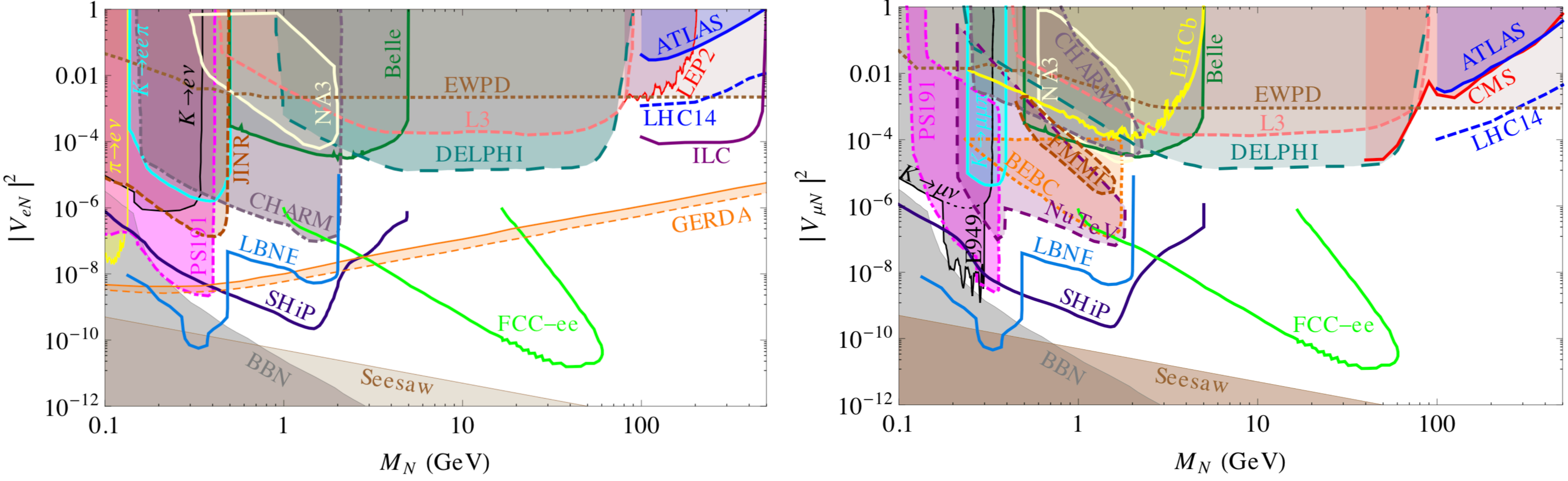
- Existing experiments have explored M_N from 100 MeV up to almost 1 TeV

- ***$M_N > M_Z$***
  direct search @LHC ($pp \rightarrow Nl^{\pm}$)

- ***$M_N < M_{Z,W}$***
  DELPHI ($Z^0 \rightarrow \nu N$)
  ATLAS/CMS ($W^{\pm} \rightarrow Nl^{\pm}$)

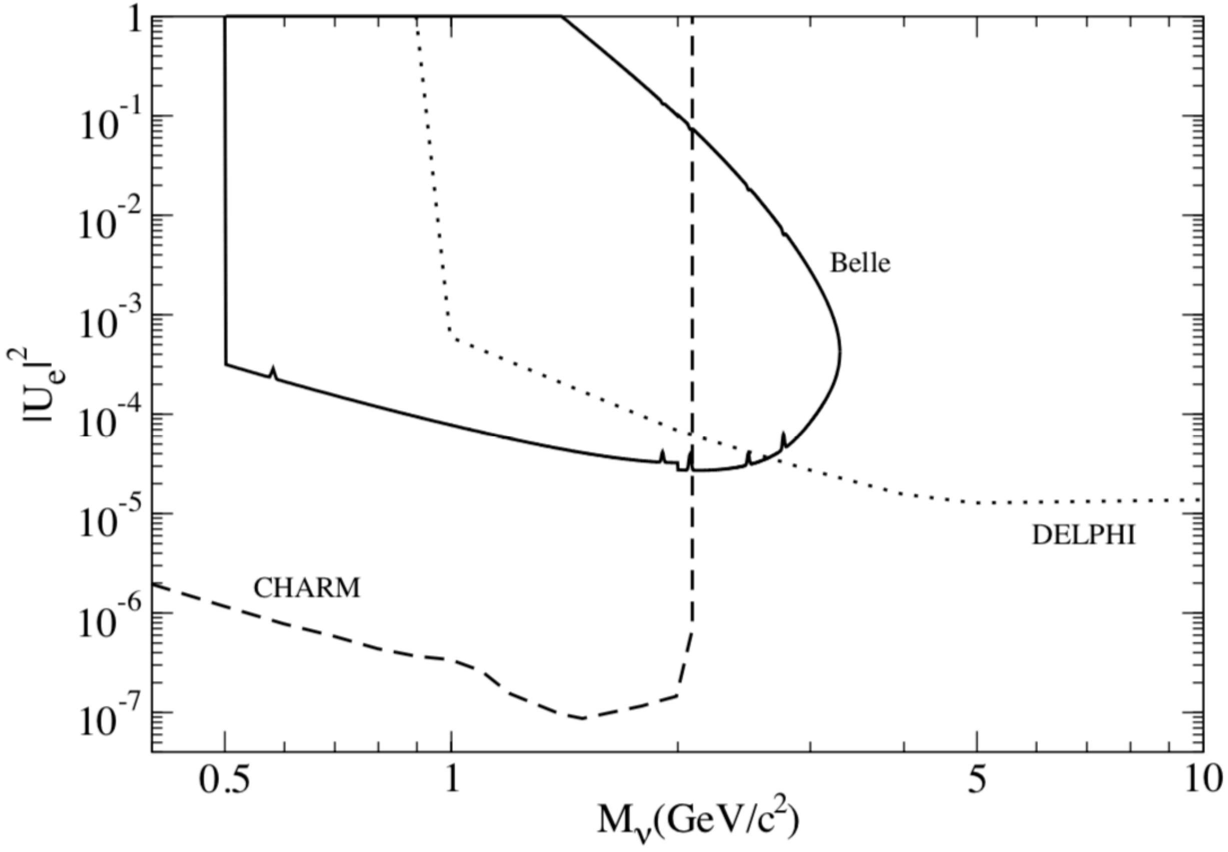
- ***$M_N < M_{B,D,K}$***
  beam-dump, NA62, etc.
  LHCb, **Belle**, soon also **Belle II**

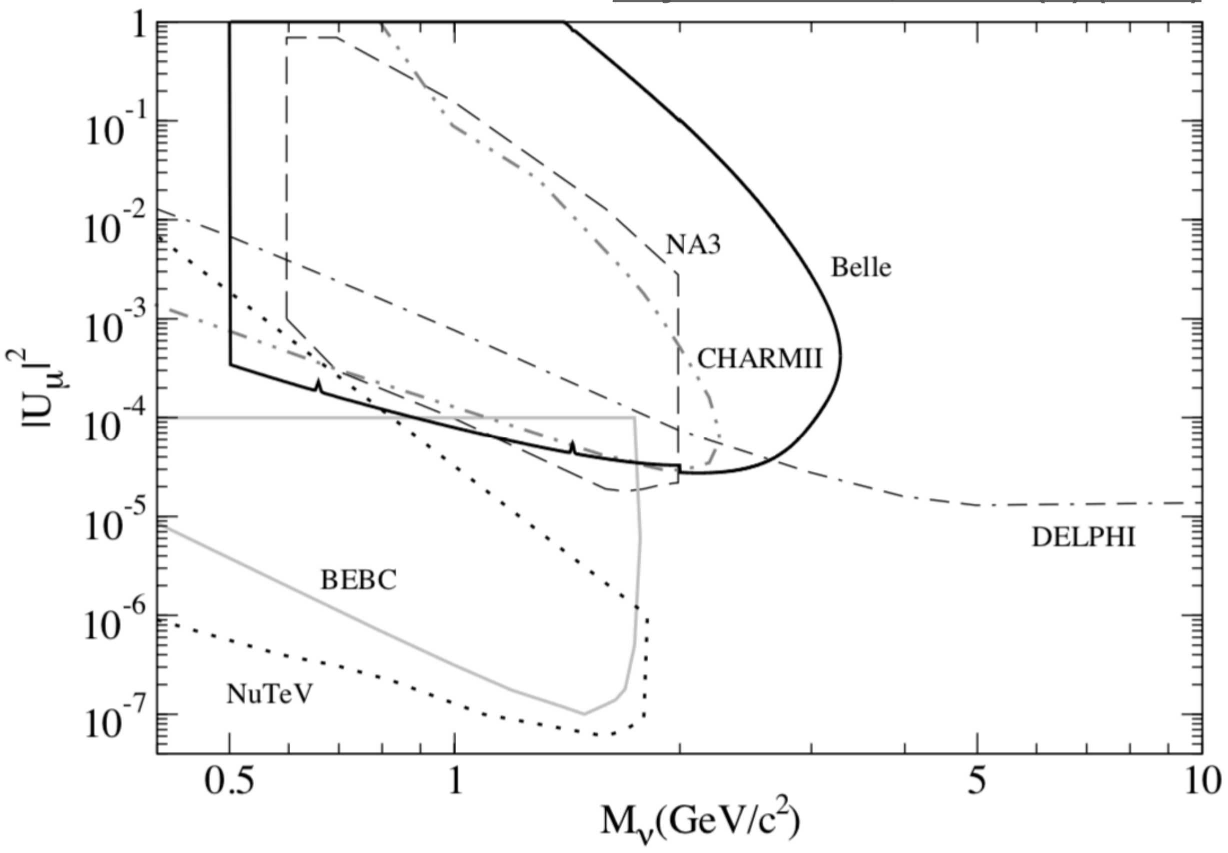
F. Deppisch et al: **aXiv:1502.06541v3**



Comparison with other experiments

Phys. Rev. D 95, 099903(E) (2017)

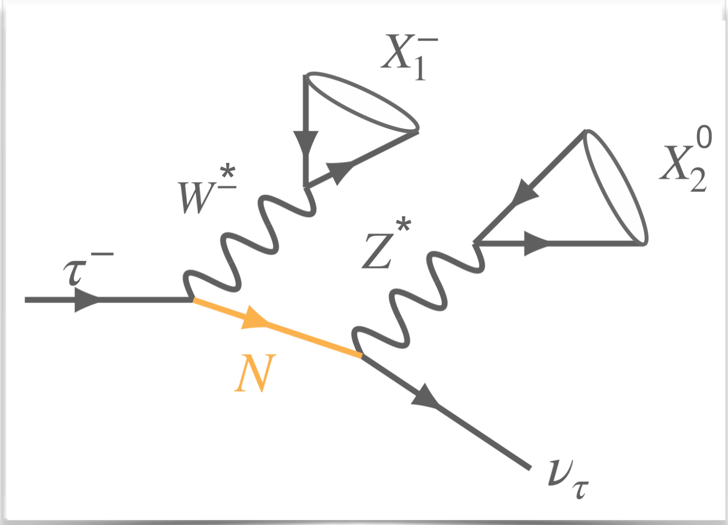


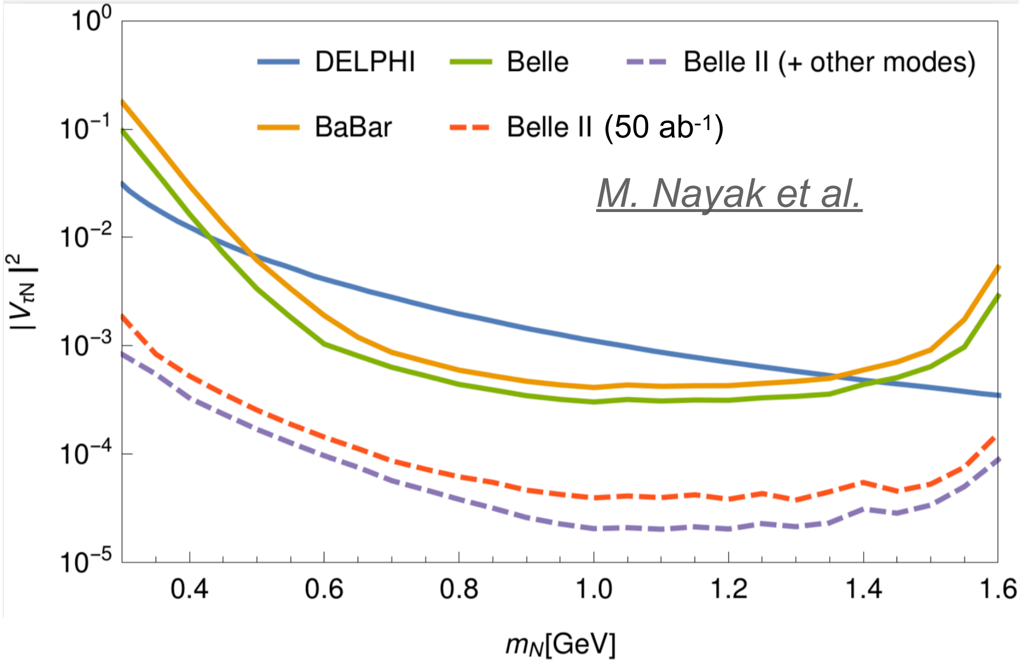


- Results are shown from Belle, CHARM, CHARMII, DELPHI, NuTeV, BEBC and NA3

Search for HNL vertex with taus

- Proposed search for displaced HNL vertex in $ee \to \tau\tau \to 1\text{x}3$ prong
- For $|U_{\tau N}|^2 \gg |U_{eN}|^2, |U_{\mu N}|^2$ and $m_N < m_\tau$, decay occurs via $N \to \nu_\tau (Z^* \to X^0)$
- For this preliminary sensitivity study:
  - **X_1** restricted to π or $\pi\pi^0$
  - **X_2** restricted to $\mu\mu$ or ee (hadronic X_2 could enter final analysis)
- Long lifetime ($c\tau \propto |U_{\tau N}|^{-2} m_N^{-5}$) ⇒ tiny background but low signal efficiency





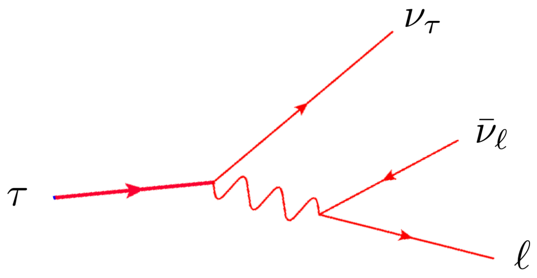
- Bkg suppression driven by $N \to ee/\mu\mu$ vertex-based constraints and flight length > 10 cm
- Signal yields extracted from fit to reconstructed M_N distribution
- Assumption of zero background search
  - achievable based on studies with official Belle II MC
  - more comprehensive bkg studies are ongoing

In this channel alone, Belle or Belle II could exceed DELPHI limits!

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 **~10^{-4}**

- Systematic uncertainties will be challenging at Belle II (**~10^{-3}**)