First Results and Prospects for τ Lepton Physics at Belle II

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on behalf of the Belle II collaboration

04.06.2021
CHARM 2020/21

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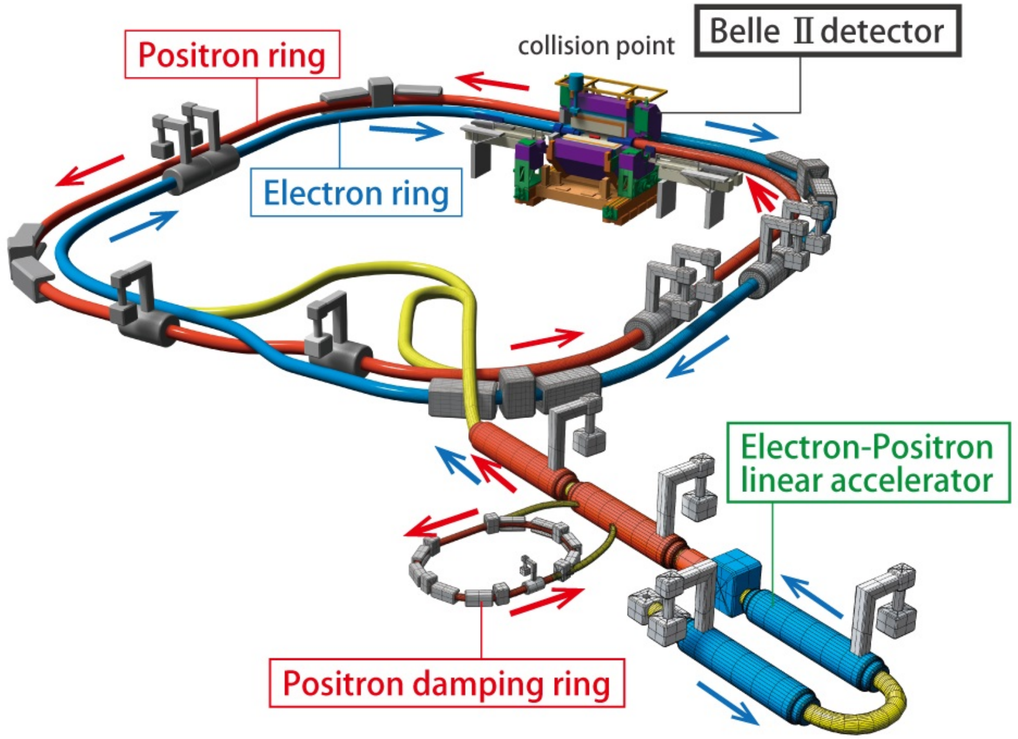
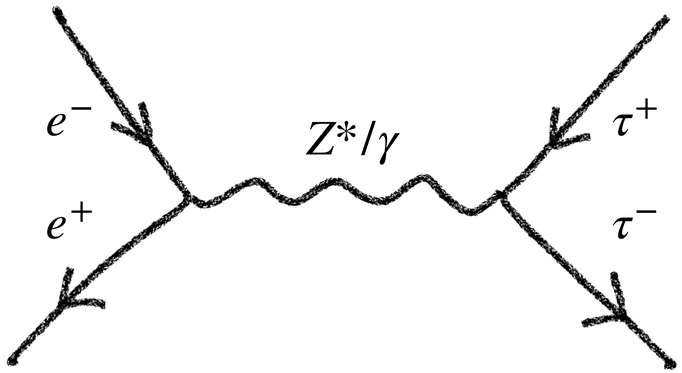
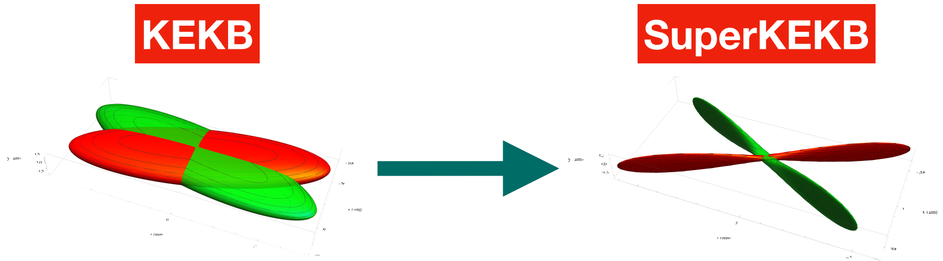
τ-Pair Production at Belle II

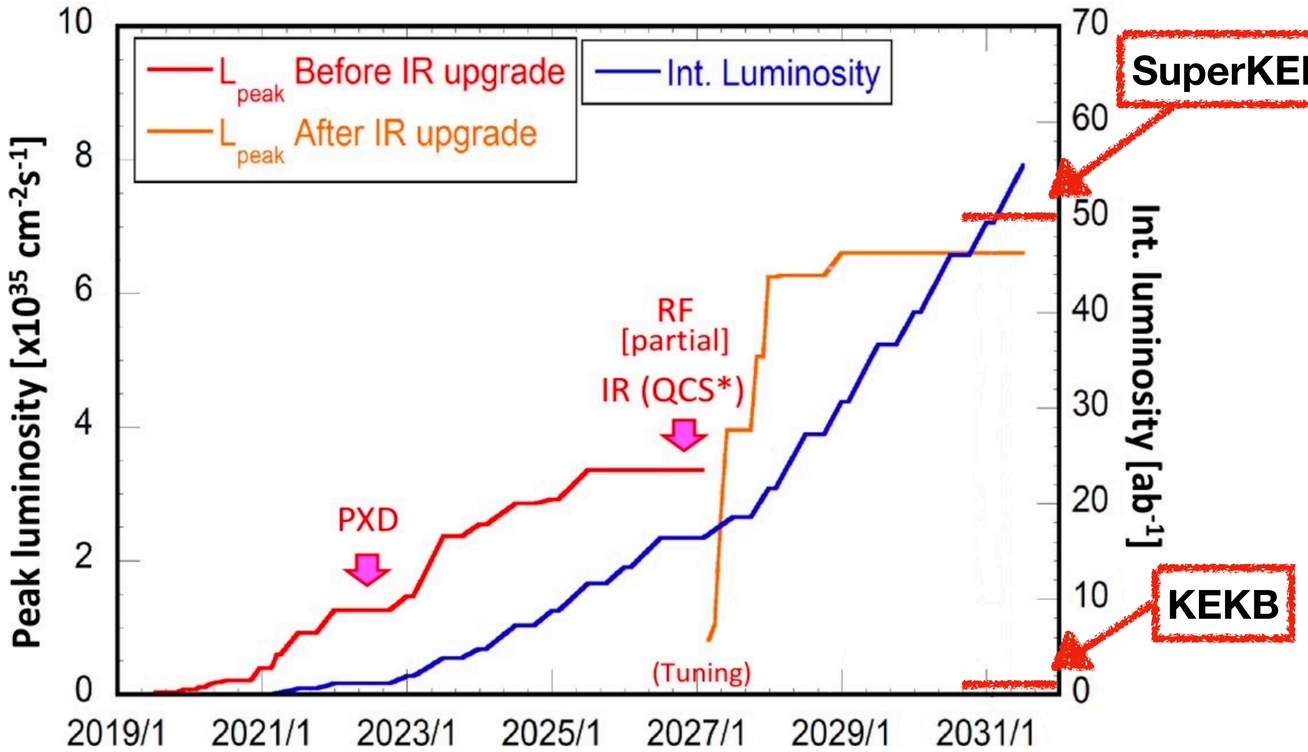


- At e^+e^- machines there is a low background and a well understood production mechanism for τ
- SuperKEKB is a τ-factory!
  - $\sigma(e^+e^- \to \tau^+\tau^-) \approx \sigma(e^+e^- \to \Upsilon(4S)) \approx 1$ [nb]



SuperKEKB a (Super-)τ-Factory





- At e^+e^- machines there is a low background and well understood production mechanism for τ
- Exploit τ-tag method
- SuperKEKB collider
  - Increased Integrated Luminosity:
    1 ab^{-1}(KEKB) → 50 ab^{-1}(SuperKEKB)
  - ~ 45 billion tau pairs
    for full Belle II program
  - World Record Peak Luminosity
    so far: 2.9×10^{34} [cm^{-2}s^{-1}]

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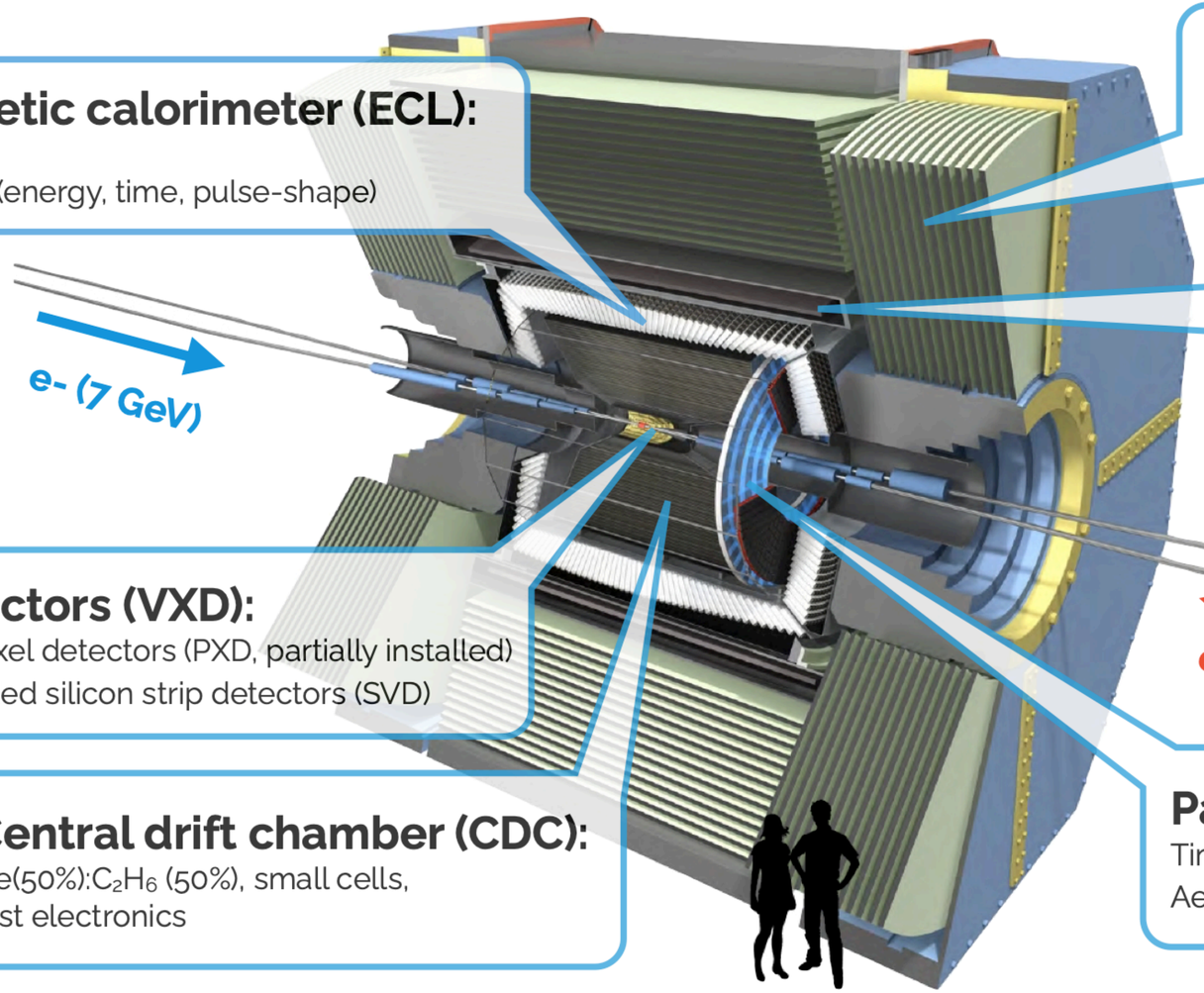
The Belle II Detector



Electromagnetic calorimeter (ECL):
CsI(Tl) crystals
waveform sampling (energy, time, pulse-shape)

K_L and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

Magnet:
1.5 T superconducting

Trigger:
Hardware: < 30 kHz
Software: < 10 kHz

Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD, partially installed)
4 layer double-sided silicon strip detectors (SVD)

Central drift chamber (CDC):
He(50%):C_2H_6 (50%), small cells,
fast electronics

Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

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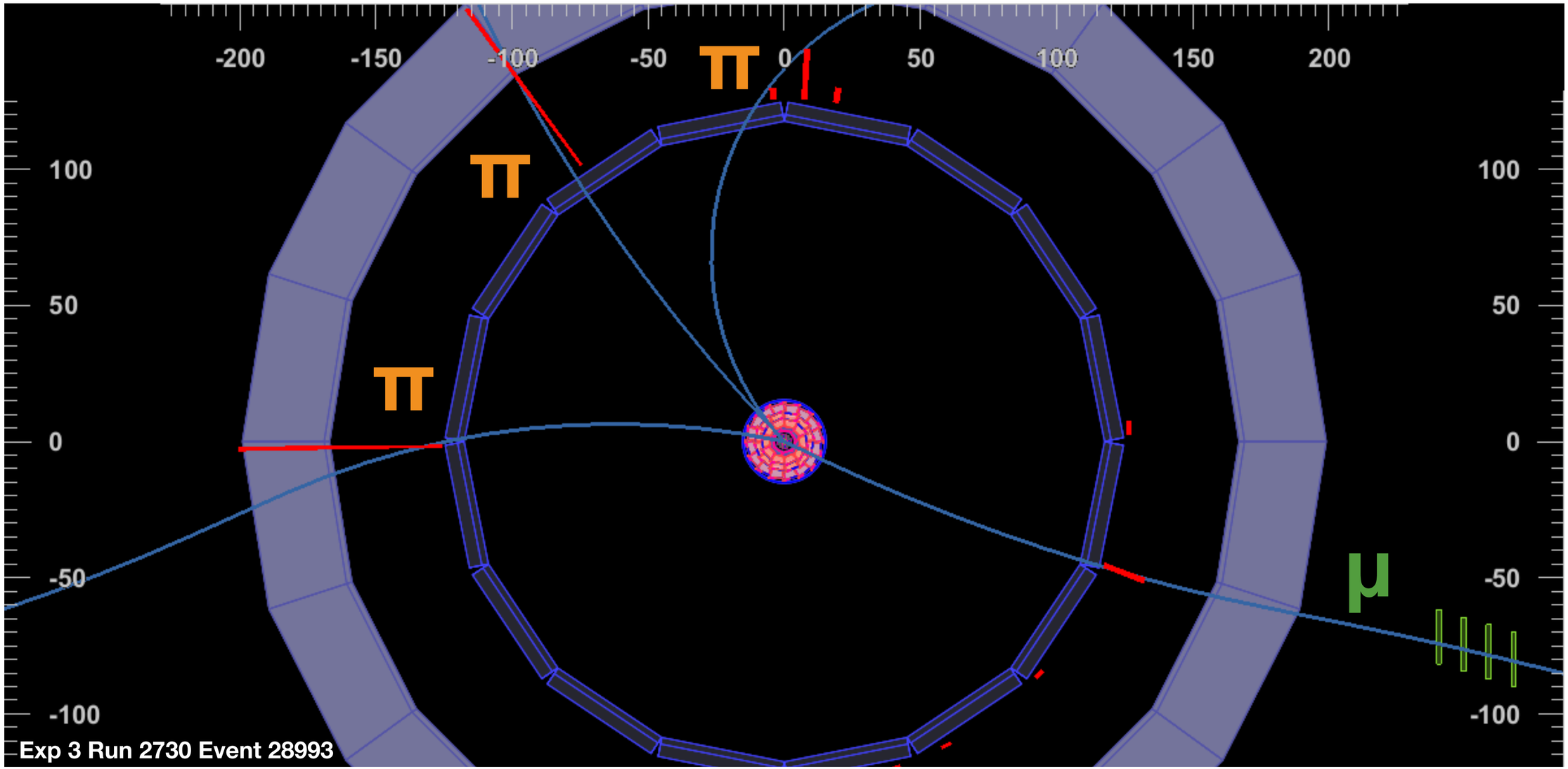
One of The First $\tau^+\tau^-$ Events



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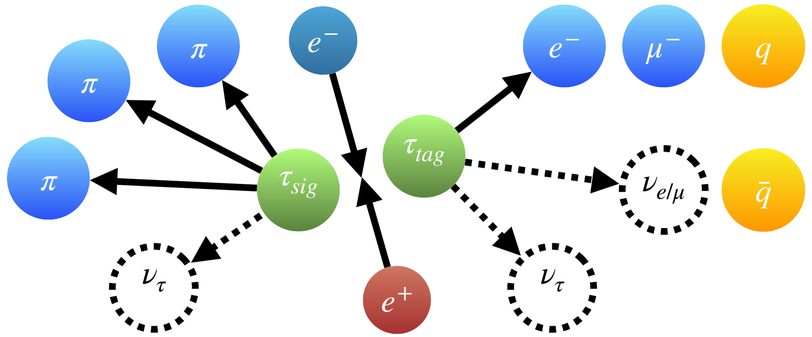
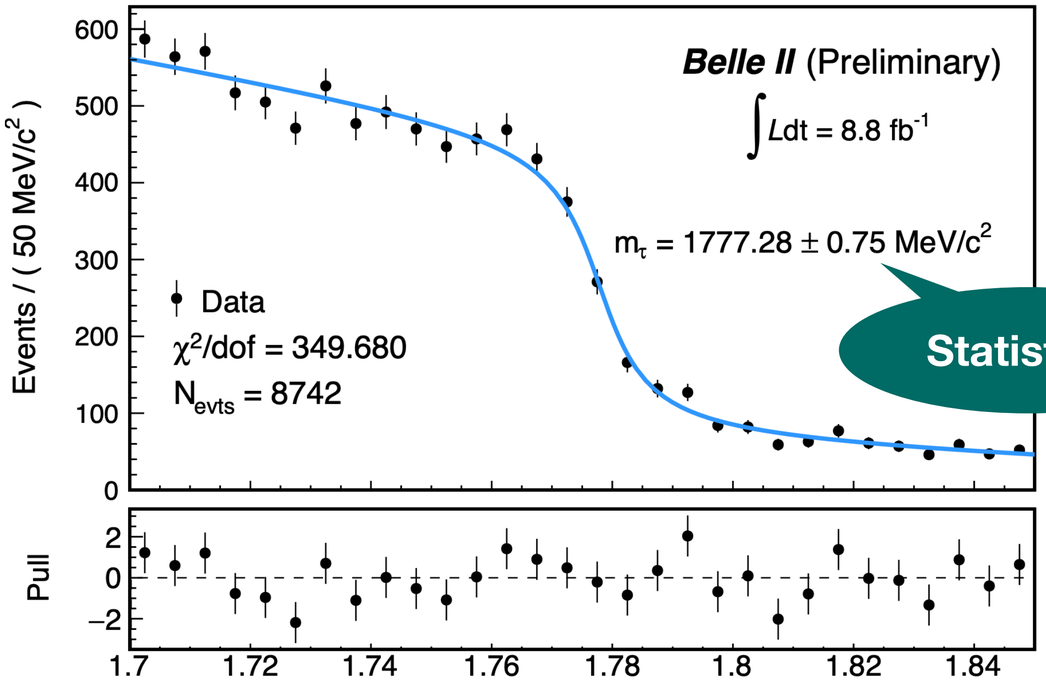
τ Mass Measurement (Preliminary)





BELLE2-CONF-PH-2020-010

$$M_{min} \propto \sqrt{M_{3\pi}^2 + \textbf{Corrections}}$$

- τ mass measured using an analysis of 3x1 prong decays.
  - Mass extraction from 3-pion decay channel
- Using a dataset of approximately 8.8 fb^{-1} of data.
- Systematic uncertainty dominated by track momentum scale
  → Already improve!

Statistical

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	$\leq$ 0.01
Initial parameters	$\leq$ 0.01
Background processes	$\leq$ 0.01
Tracking efficiency	$\leq$ 0.01

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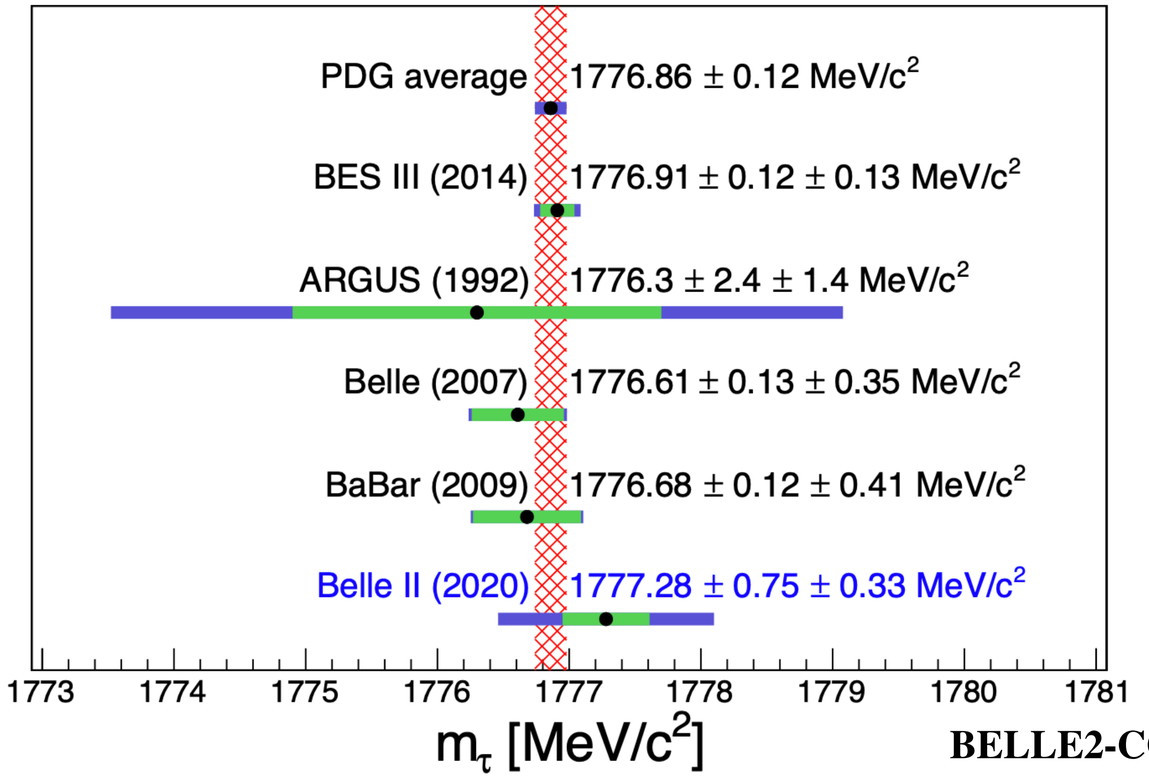
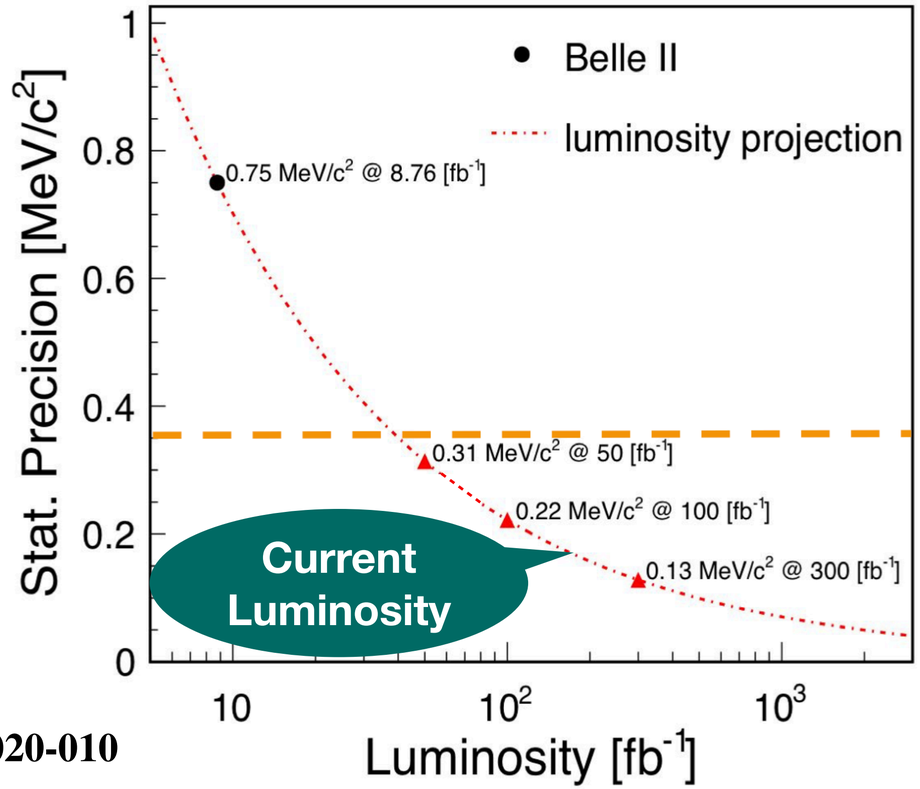
τ Mass Measurement (Preliminary)

- $m_\tau = (1777.28 \pm 0.75 \pm 0.33)\,\mathrm{MeV}/c^2$
- First τ physics results with early data: consistent with previous measurements!
- Future improvements of statistical precision and systematic uncertainties





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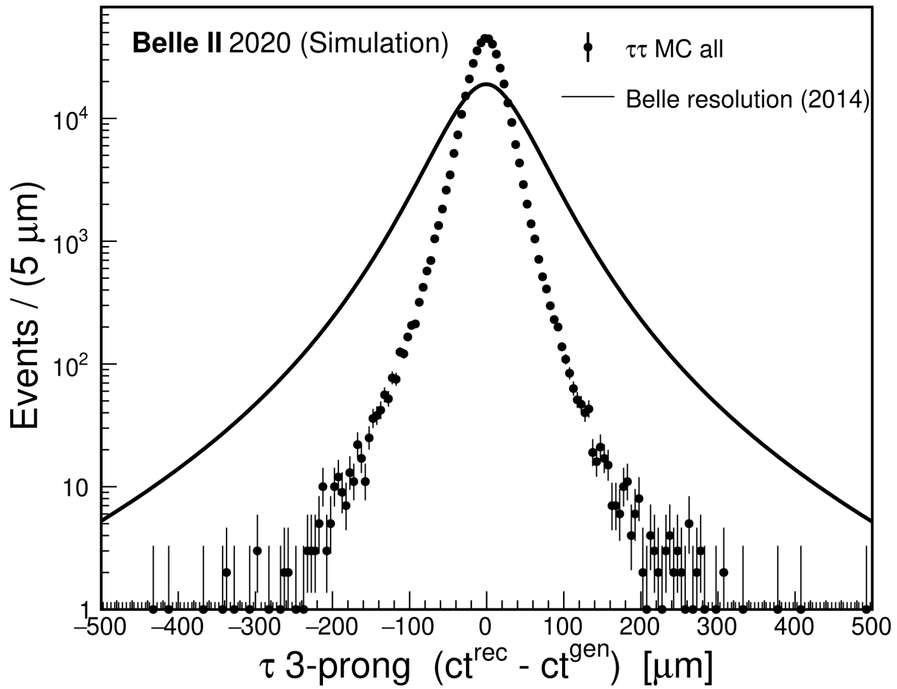
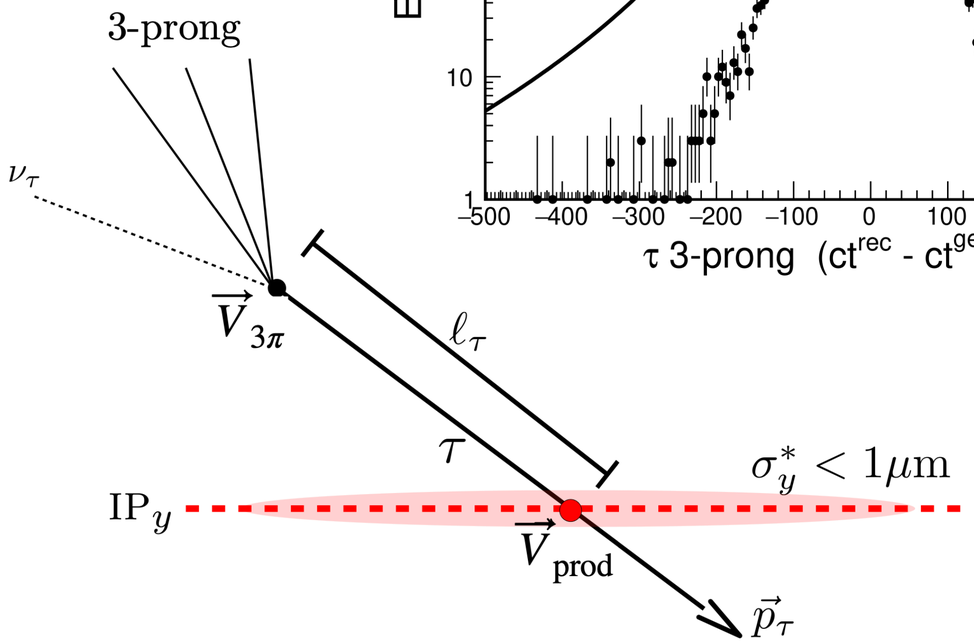
τ lifetime measurement





- Decay time given by $t_\tau = m_\tau \frac{l_\tau}{p_\tau}$
- Belle: $\tau_\tau = 290.17 \pm 0.53 \pm 0.33$ [fs]
- Exploits Belle II unique
  - Small beam spot size
  - High resolution of the vertex detector
    → Almost twice as good resolution as Belle demonstrated already.
- Competitive results may be feasible with a dataset of 200 fb^{-1}
  (collected up to now > 150 fb^{-1})

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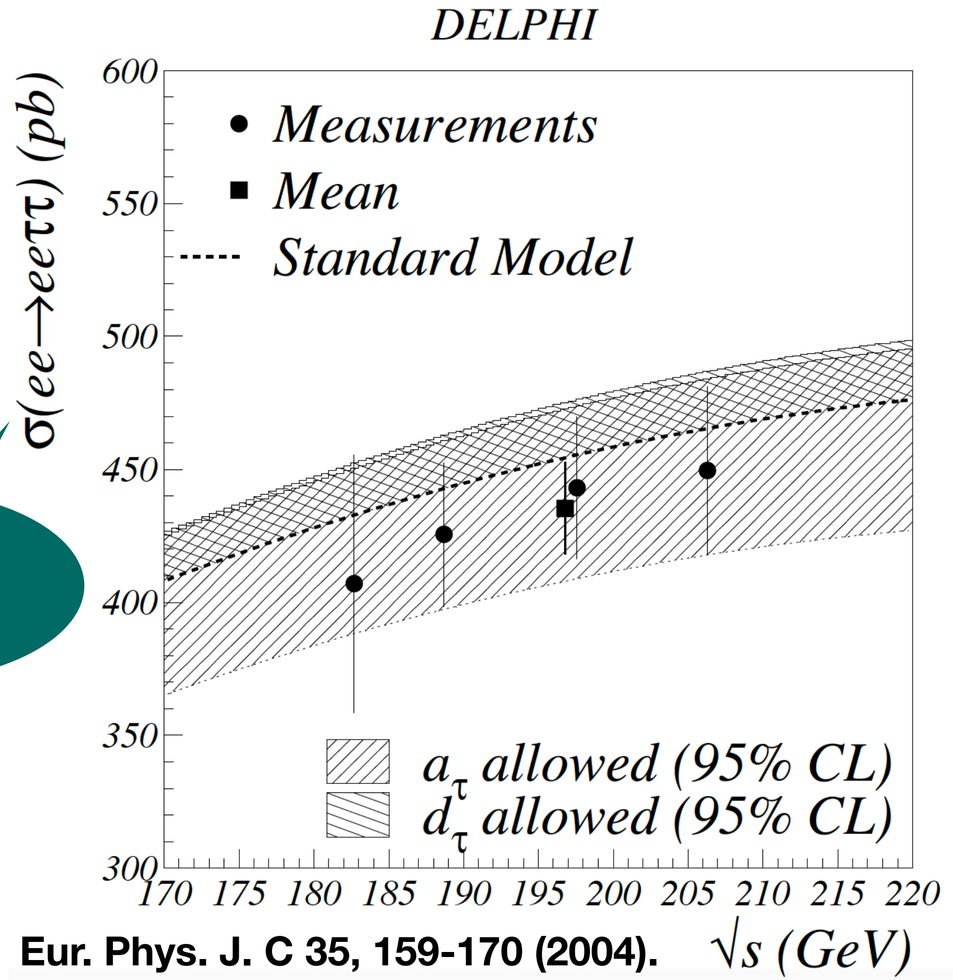
Further Standard Model Measurements



g-2 influences correction

Eur. Phys. J. C 35, 159-170 (2004).
https://doi.org/10.1140/epjc/s2004-01852-y

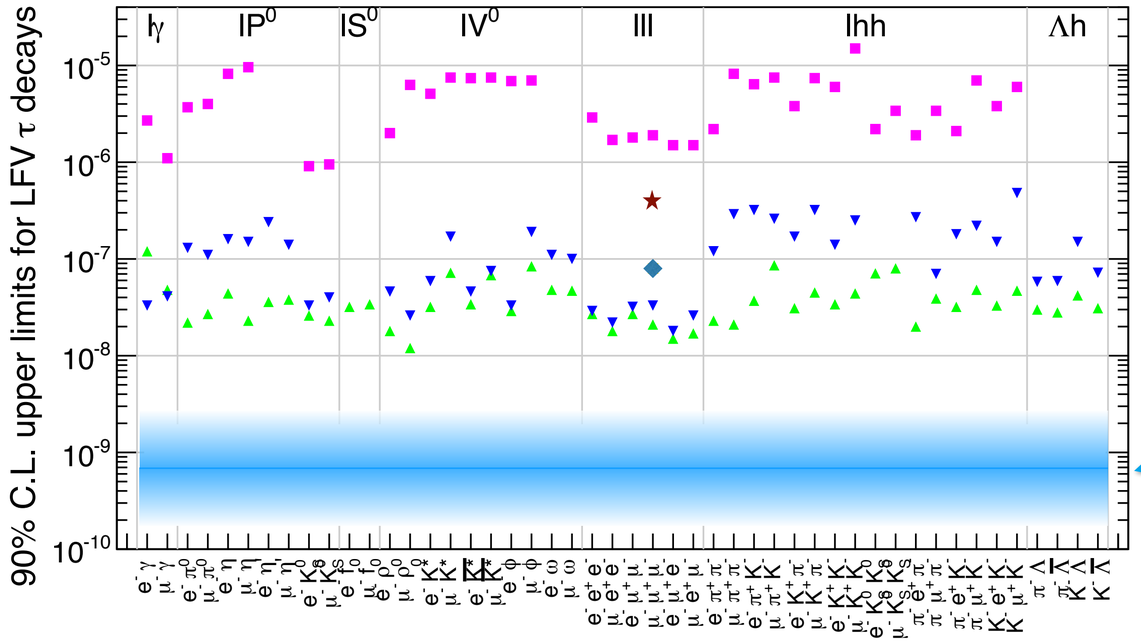
- Michel Parameters
- τ $g-2$ and EDM
  - Belle (30 fb^{-1}): EDM < $\mathcal{O}(10^{-17})$
  - Prospect for first significant measurement of non-zero SM $g-2$, with full Belle II luminosity!

$$\frac{g-2}{2} \equiv a_\tau^{SM} = (1{,}17721 \pm 0.00005) \cdot 10^{-3}$$

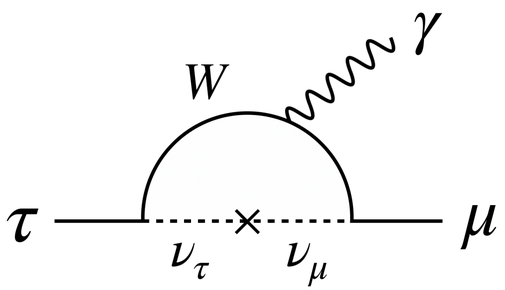
$$a_\tau^{Exp} = 0.018 \pm 0.017$$

Lepton Flavour Violation Motivation

The Belle II Physics Book, E. Kou et al., PTEP Vol. 2019 Issue 12
https://doi.org/10.1093/ptep/ptz106

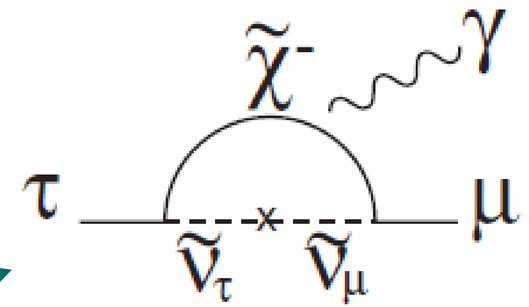


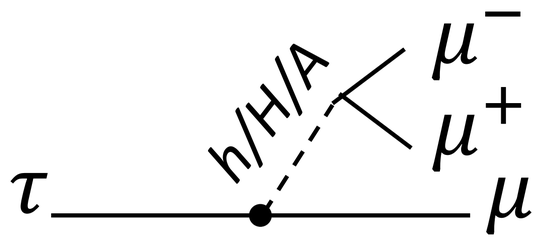
- We expect LFV in many Beyond the Standard Models (BSM)
- For τ at Belle II the "golden modes" are:
  $\tau \to \mu\gamma$
  $\tau \to lll$
- $\tau \to 3\mu$ one of the priorities



SM: $\mathcal{O}(10^{-54})$-$\mathcal{O}(10^{-49})$

NP: $\mathcal{O}(10^{-10})$-$\mathcal{O}(10^{-7})$





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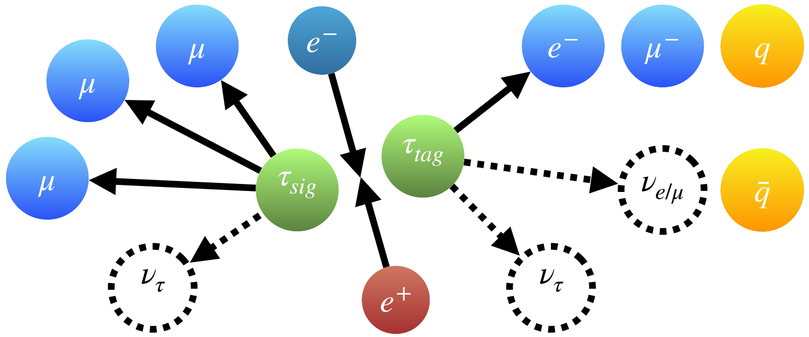
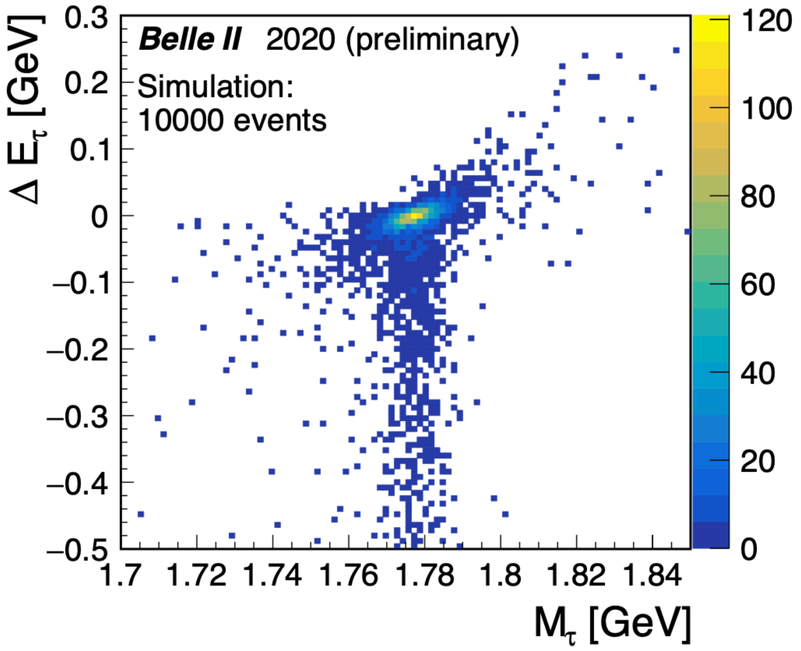
Looking Forward To $\tau \to \mu\mu\mu$

- Highly suppressed backgrounds.
- Current limits are $B(\tau \to \mu\mu\mu) = 2.1 \times 10^{-8}$.
- Prospects for 50 ab^{-1}: $\mathcal{O}(10^{-10})$
- Uncertainties scale with sample size!
  - Improvements through:
    - increase in luminosity
    - increase in signal detection efficiency
      → Motivation to improve efficiency





- Belle II could improve the efficiency by
  - Introducing momentum dependent muID optimisation
  - Increasing muon momentum range
  - Allowing a muon tag

Two Independent Variables

1. $M_\tau = \sqrt{E^2_{\mu\mu\mu} - P^2_{\mu\mu\mu}}$
2. $\Delta E_\tau = E^{CMS}_{\mu\mu\mu} - E^{CMS}_{beam}$

⇒ For Signal:
→ ΔE_τ close to 0
→ M_τ close to m_τ

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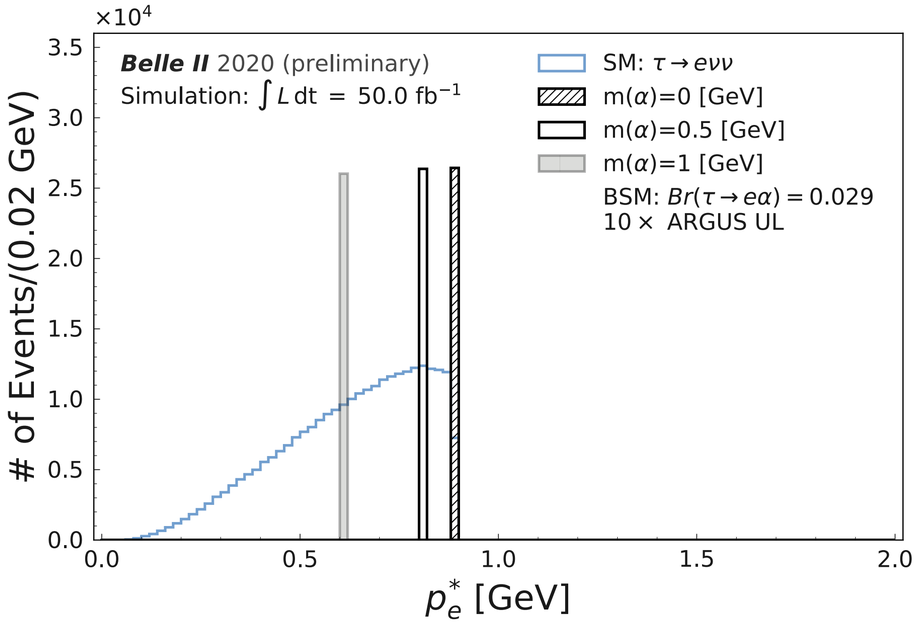
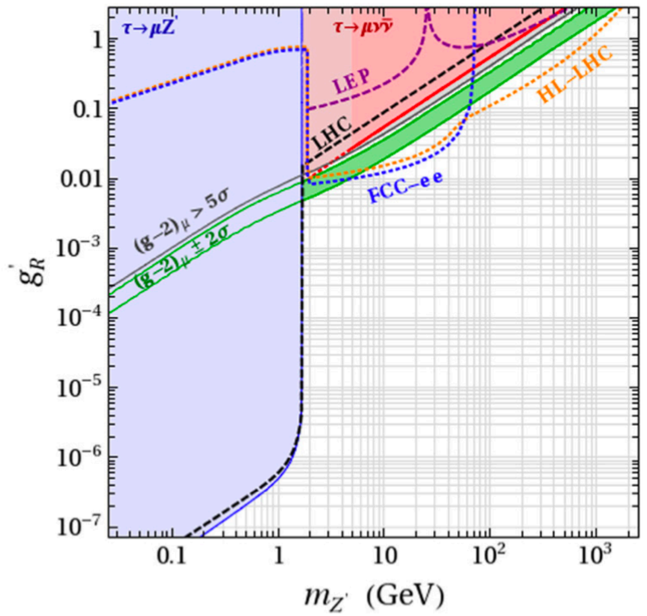
Looking Forward To $\tau \to l + \alpha$ (invisible)

- Search for a two body decay spectrum
- Signal will manifest as a peak in the τ-rest-frame (TRF)

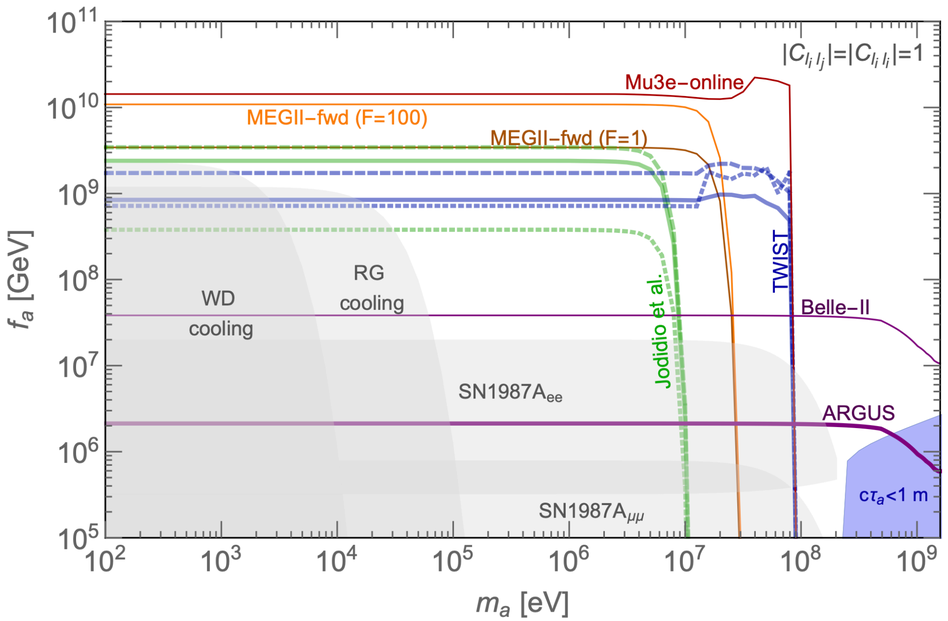


Various NP Scenarios:

- **LFV Z':** strong bound from ARGUS
- **Light ALP a:**
  unique parameter space accessible



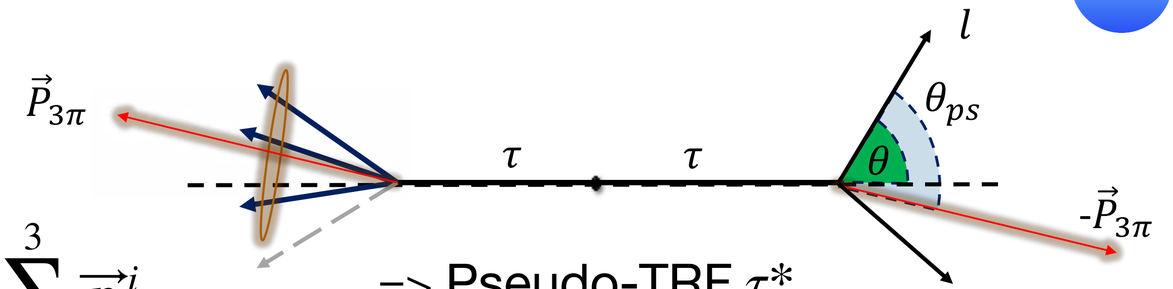
Wolfgang Altmannshofer, Chien-Yi Chen, P.S. Bhupal Dev, Amarjit Soni



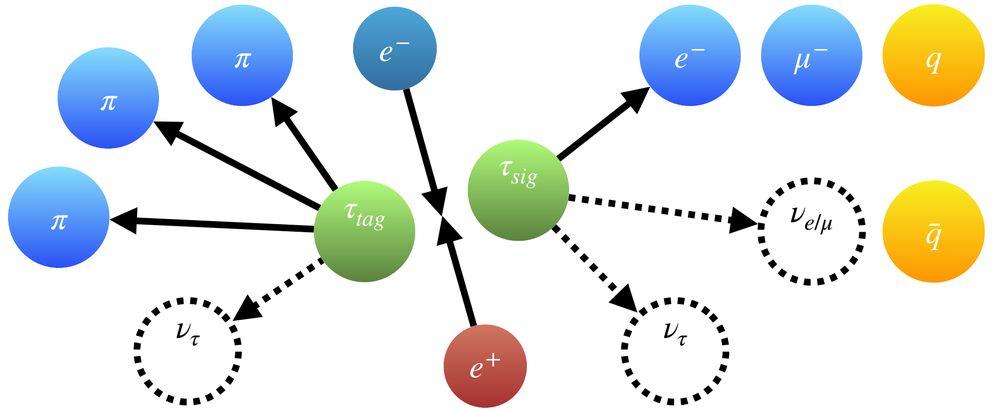
Lorenzo Calibbi, Diego Redigolo, Robert Ziegler, Jure Zupan,

Current status: $\tau \to l + \alpha$ (invisible)

- Idea: search for a two body decay spectrum
  - Challenge: Estimate TRF with missing ν_τ momentum
  - Using
    $E_\tau \approx E_{CMS}/2$
    $\vec{p}_\tau \approx \vec{p}_{3\pi} = \sum_{i=1}^{3} \vec{p}^{\,i}_{\pi}$

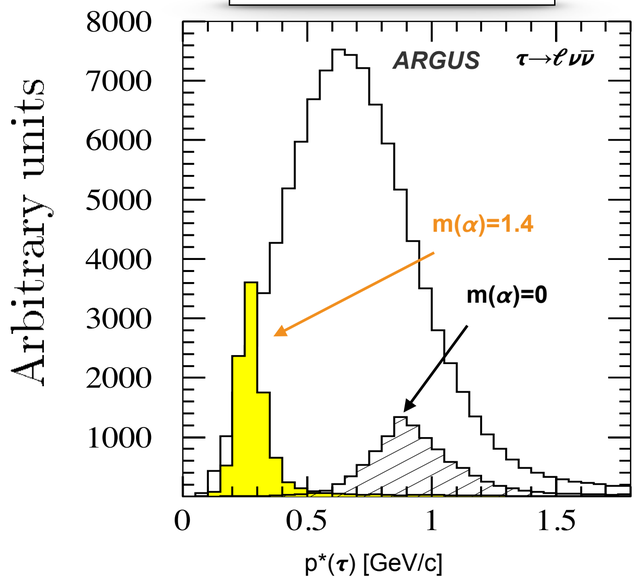


=> Pseudo-TRF τ^*



- No signal region → fit full spectrum with
  - SM expectation
  - SM + BSM expectation
  - → compare likelihood of the two models

Z.Phys. C68 (1995) 25-28



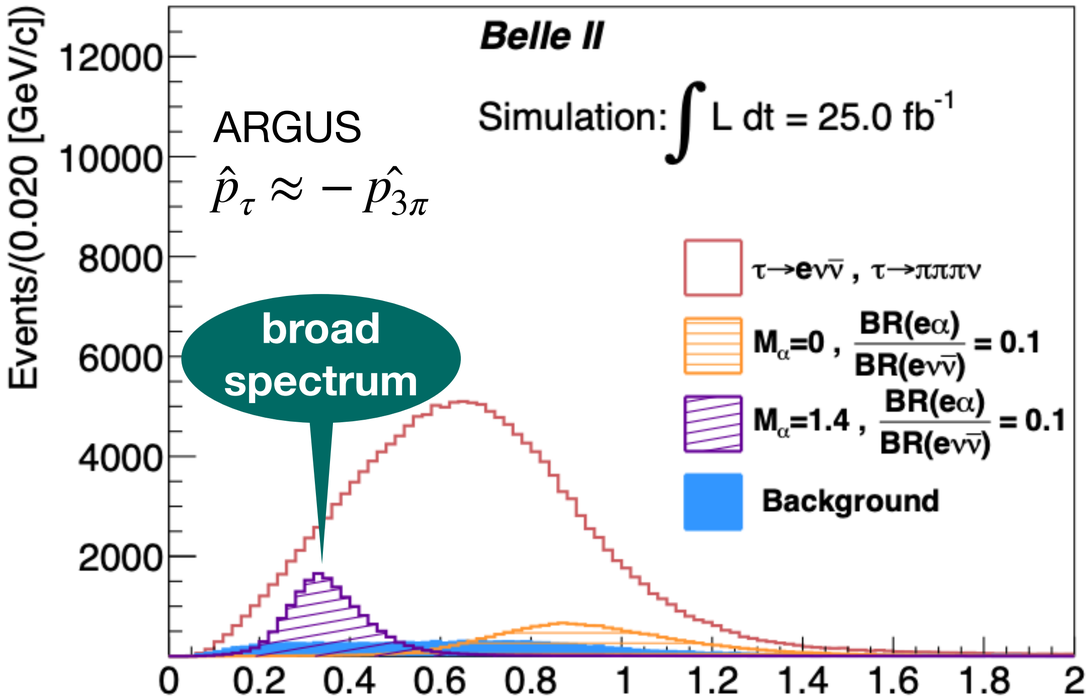
- Sensitivity depends on m_α
  - Last results from
    - ARGUS (472 pb^{-1})
    - MARK III (9.4 pb^{-1})

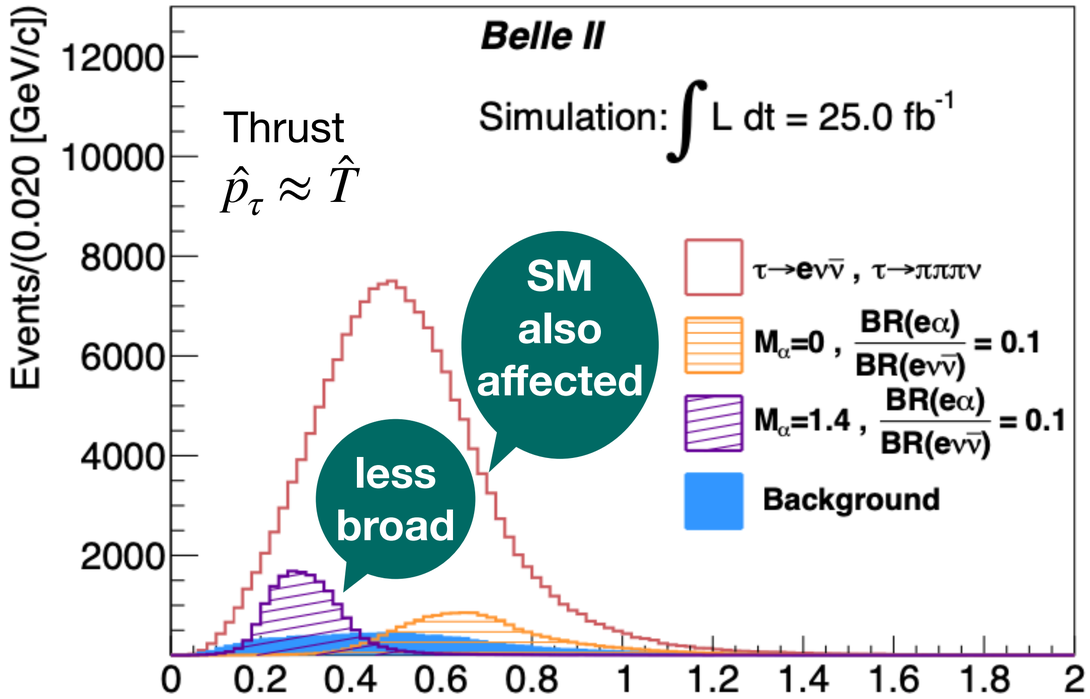
→ **Belle II is competitive with early data ~60 fb^{-1}**

Analysis Strategy

- Using a cut-based Selection
- Statistical treatment with a template Fit
- The data can be modelled as: $f(x) = N_{sig} \cdot f_{e\alpha}(x) + N_{e\nu\ nu} \cdot f_{e\nu\nu}(x) + N_{BG} \cdot f_{BG}(x)$
  - With x being the momentum in the tau rest-frame
- Upper Limit estimated with a Frequentist profile-like-hood method:

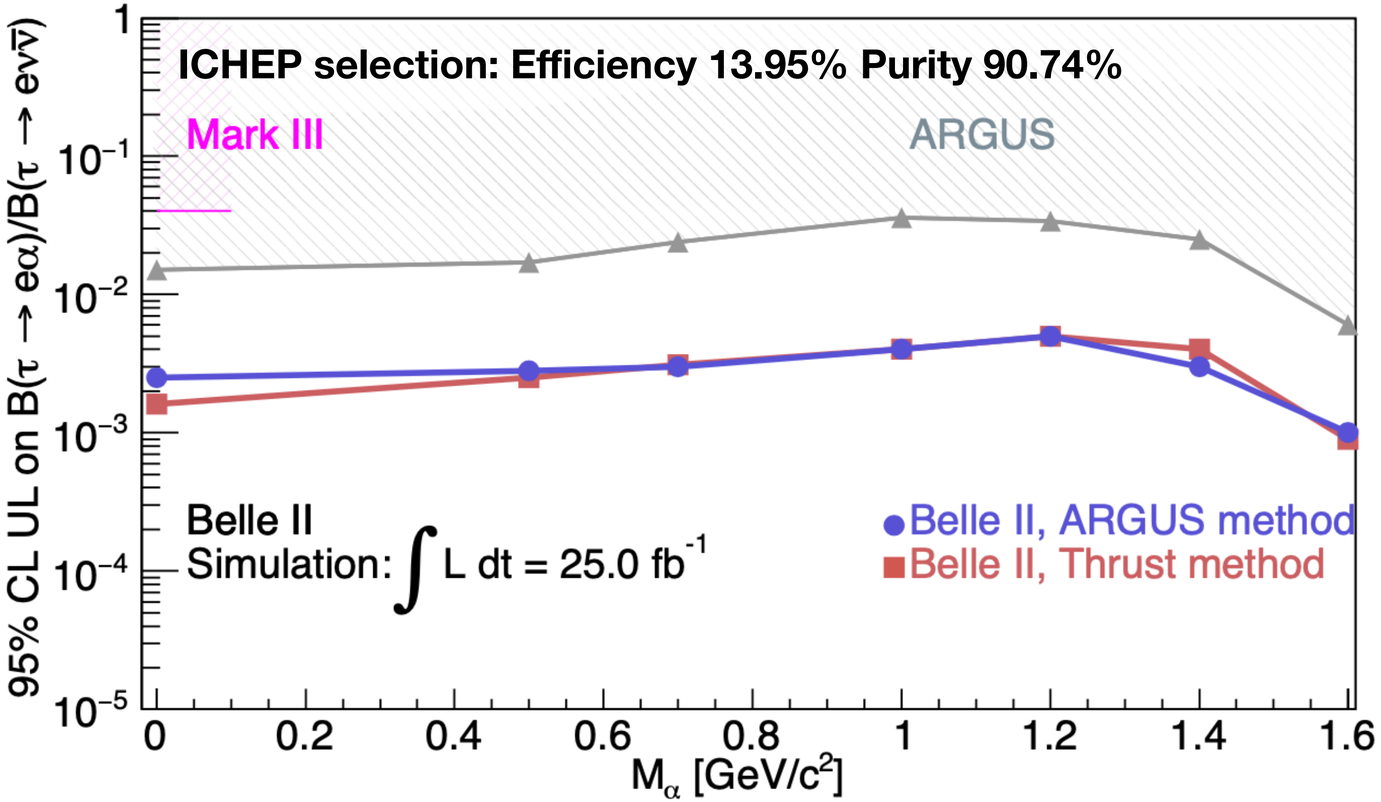
$$CL_{sig} = \frac{CL_{sig+bg}}{CL_{bg}}$$





ICHEP MC-study: Upper Limit Estimate

- UL estimate for ratio $Br(\tau \to e\alpha)/Br(\tau \to e\nu\nu)$
- No systematics were taken into account
  → work in progress



	UL(95% c.l.)		
$M(\alpha)$ $[\mathrm{GeV/c^2}]$	ARGUS (1995)	Argus method	Thrust method
0	0.015	0.0025	0.0016
0.5	0.017	0.0028	0.0025
0.7	0.024	0.003	0.0031
1.0	0.036	0.004	0.004
1.2	0.034	0.005	0.005
1.4	0.025	0.003	0.004
1.6	0.006	0.001	0.0009

Performance of ARGUS and Thrust method is similar

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Conclusion And Outlook

- The τ has various interesting physics prospects at Belle II:
  - Potential observation of LFV
    - $\tau \rightarrow l + \alpha$
    - $\tau \rightarrow \mu\mu\mu$
    - $\tau \rightarrow l\gamma, \ldots$
  - Improvements of SM Parameters
    - τ-mass
    - τ-lifetime
  - Potential measurements/verifications of SM parameters: $g - 2$ or EDM
  - Potential verification of non SM CP violation

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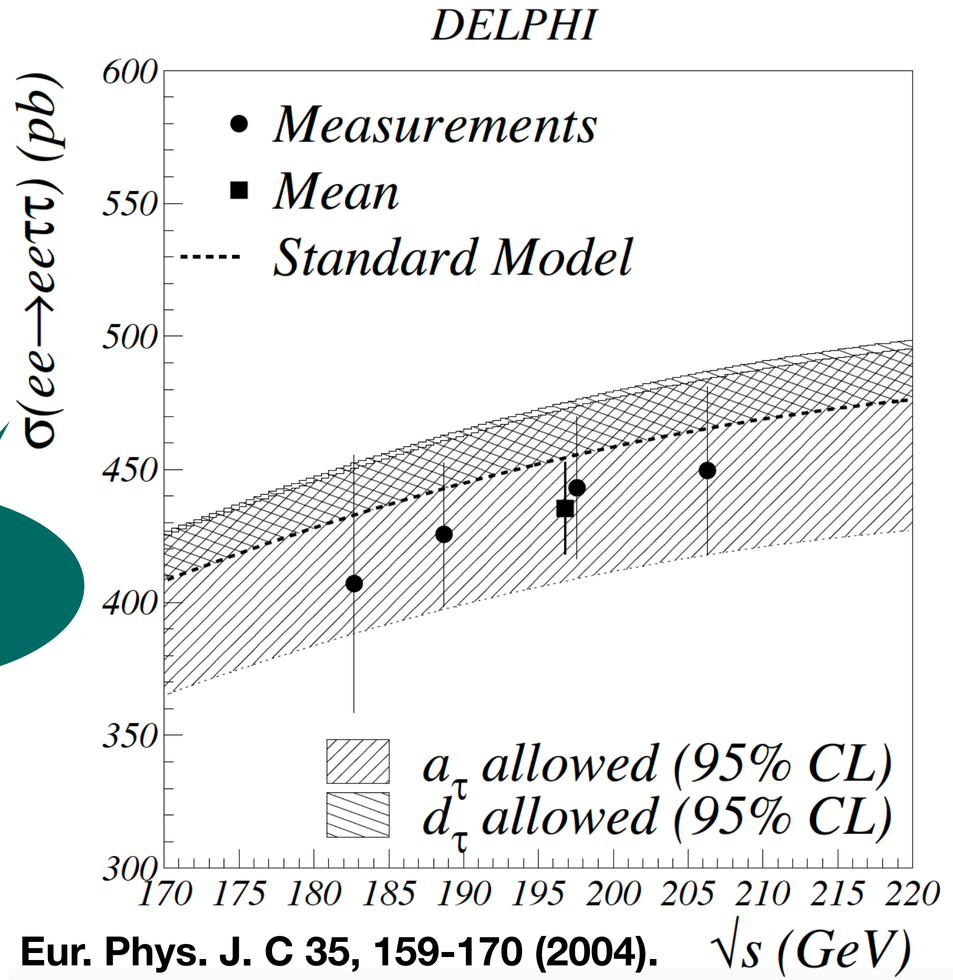
Motivation

- The Standard Model (SM) is in trouble, as it can not answer questions to:
  - Dark Matter, CP problem, …
- Precision measurements of Leptons to test the SM and new physics models
  - Well understood QED
  - Parameters measured are
    - Free parameters: mass, lifetime,…
    - Predicted observable: g-2, EDM,…

τ

- **3rd Generation Lepton**
  - **Mass:** $1776 \pm 0.12\,\mathrm{MeV}$
  - **Lifetime:** $290.3 \pm 0.5\,\mathrm{fs}$
- **Properties**
  - **Hadronic Decays**
    - **Probe QCD**
    - **CP violation**
  - **Bigger coupling to New Physics?**
    - **Lepton Flavour Violation**
    - **4th Generation Neutrino**
    - **…**

g-2 and EDM Measurements



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  - Belle (30 fb^{-1}): EDM < $\mathcal{O}(10^{-17})$
  - Prospect for first significant measurement of non-zero SM $g-2$, with full Belle II luminosity!

$$\frac{g-2}{2} \equiv a_\tau^{SM} = (1{,}17721 \pm 0.00005) \cdot 10^{-3}$$

$$a_\tau^{Exp} = 0.018 \pm 0.017$$

- Interaction vertex for off-shell γ and on-shell $\tau\tau$:

$$\Gamma^\mu(q^2 \to 0) \propto i a_\tau - \frac{2 m_\tau d_\tau}{e}$$

  - e: positron charge
  - m_τ: τ-mass
  - d_τ : electric dipole moment

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