10/01/2021

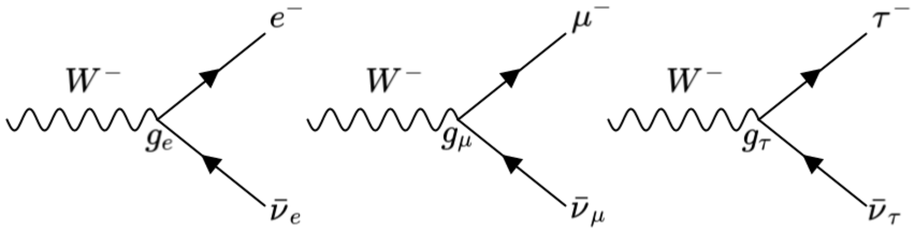
XXVII Cracow EPIPHANY Conference

τ lifetime measurement method at Belle II

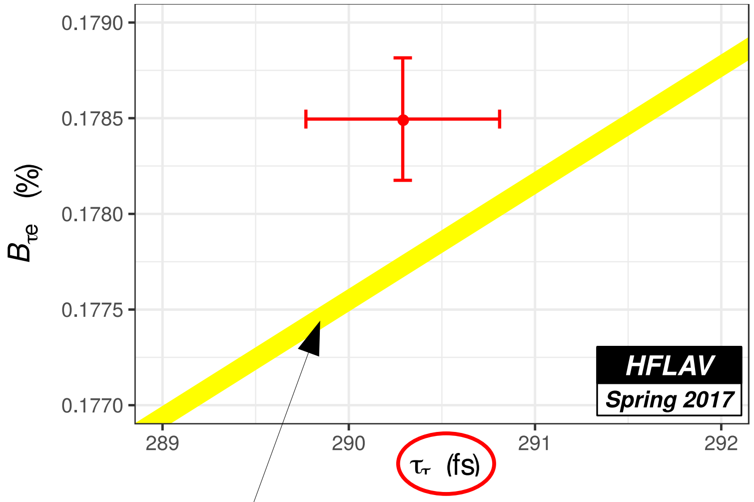
Stefano Moneta
on behalf of the Belle II Collaboration

τ lifetime: physics motivation

- important parameter in SM (e.g. measure α_S QCD at m_τ)
- test **lepton flavor universality** (LFU)



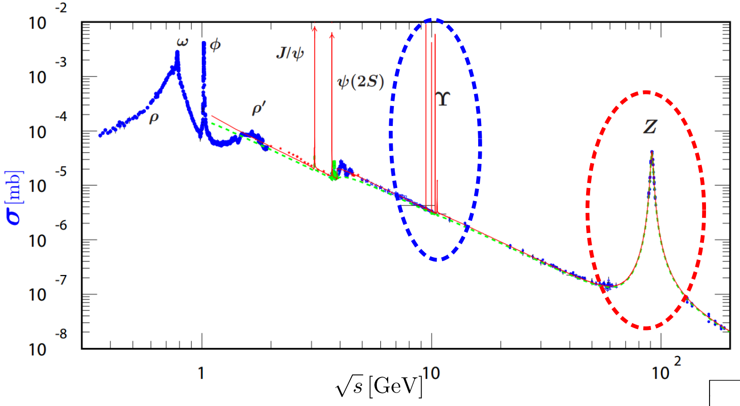
$$g_e \stackrel{?}{=} g_\mu \stackrel{?}{=} g_\tau$$



SM assuming LFU (/$_\ell$)=1
Uncertainty dominated by **mass**

Another **Belle II** measurement
arXiv:2008.04665

Previous measurements

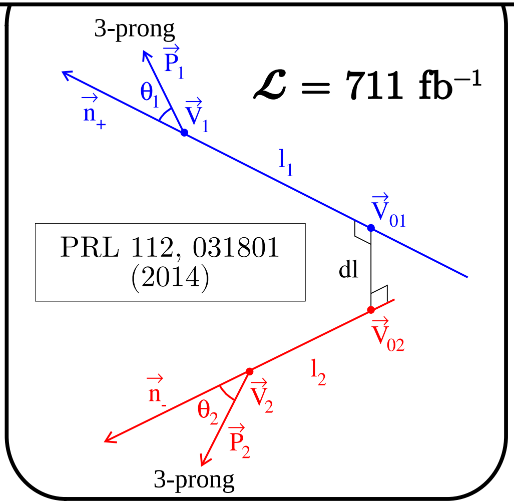


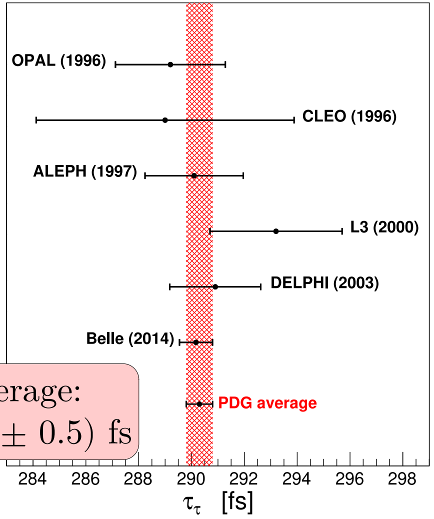
Previous measurements of τ lifetime in $e^+e^- \to \tau^+\tau^-$

- **Z-peak** $\to$ LEP (DELPHI, L3, ALEPH, OPAL)
- **ϒ-peak** $\to$ CLEO, Babar, <u>Belle</u>

<u>World-best measurement</u>

$\tau_\tau = (290.17 \pm 0.53_{stat} \pm 0.33_{syst})$ fs

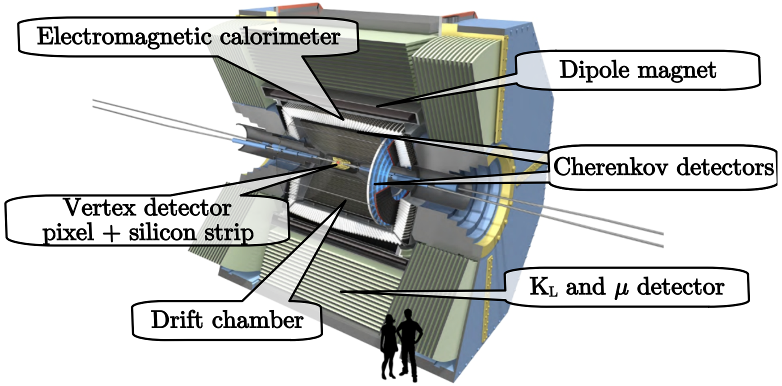


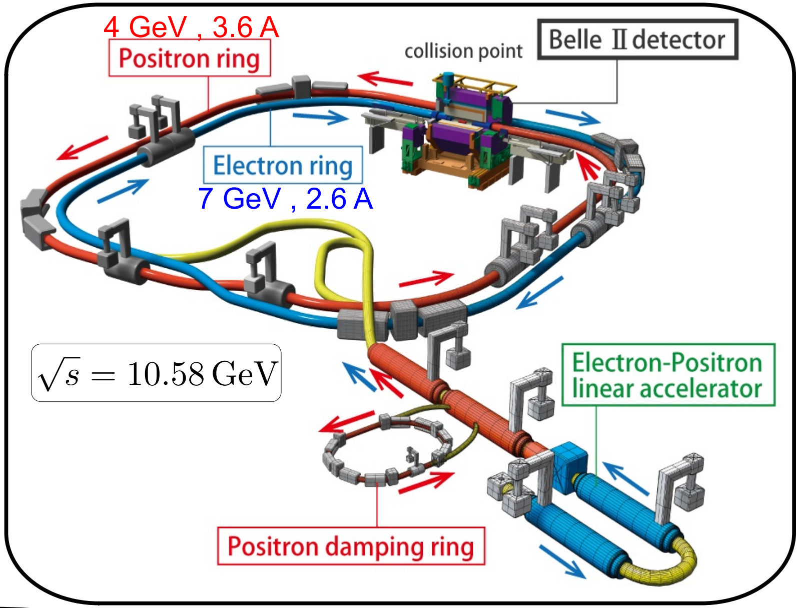


PDG average:
$\tau_\tau = (290.3 \pm 0.5)$ fs

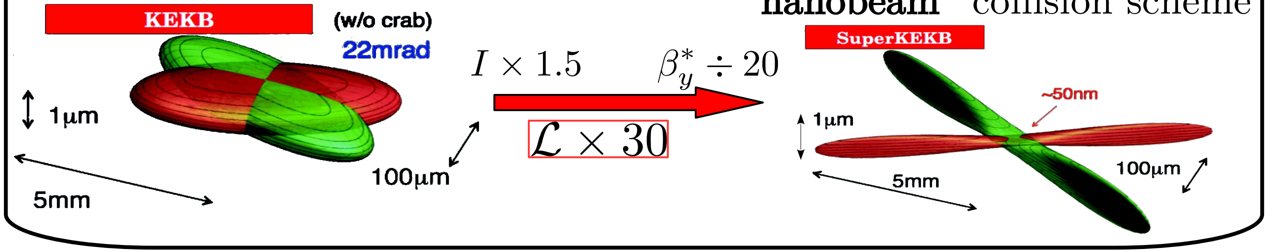
Belle II and SuperKEKB

Belle II $\rightarrow$ 2nd generation B factory





"nanobeam" collision scheme



***τ* factory**:

- 50 $\mathrm{ab}^{-1} \rightarrow \sim 46\times10^9$ produced tau pairs
- Clean environment

Measurement strategy

Proper decay time distribution:

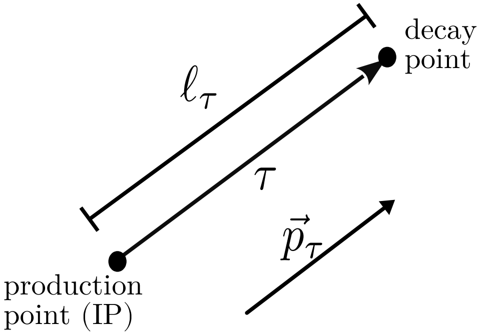
$$p(t;\,\tau_\tau) = \frac{1}{\tau_\tau} e^{-\frac{t}{\tau_\tau}} * \mathcal{R}(t)$$

Proper time resolution

Need to reconstruct $t = \frac{\ell_\tau}{\beta\gamma c} = \ell_\tau \frac{m_\tau}{p_\tau c}$

- **decay length** $\ell_\tau \rightarrow$ **production vertex** + **decay vertex**
- **momentum** $p_\tau \rightarrow$ neutrinos in final state

$\langle \ell_\tau \rangle \approx 250\ \mu\text{m}$



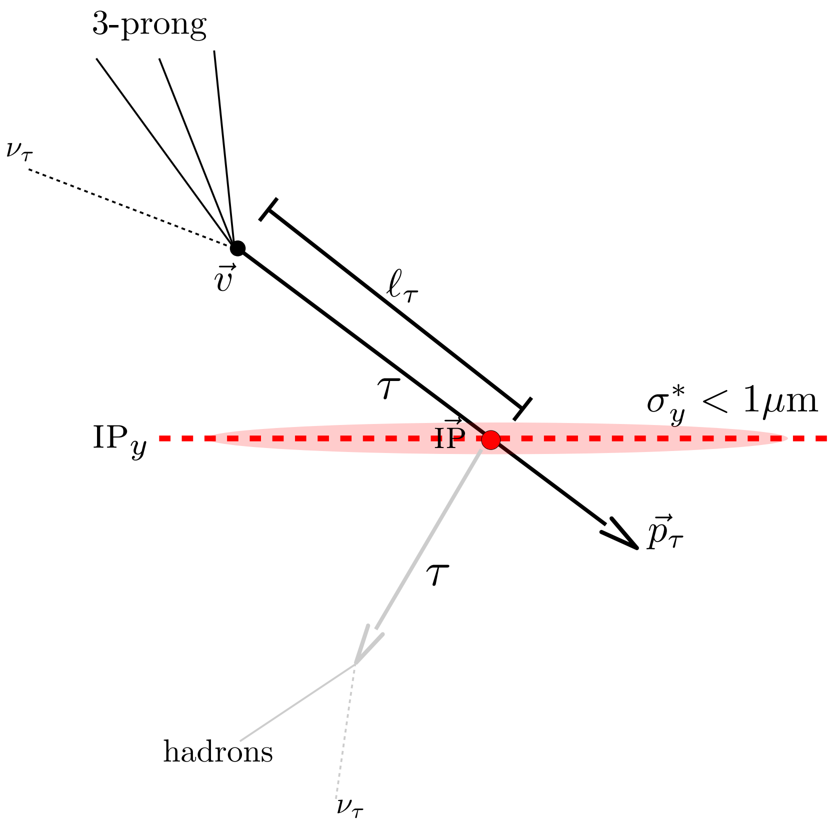
Measurement strategy

Strategy at Belle II

(1) **decay vertex** $\rightarrow$ reconstruct vertex for 3-prong τ

(2) estimate **tau momentum** $\vec{p}_\tau \rightarrow$ use events where both τ decay with 1 neutrino

(3) **production vertex** $\rightarrow$ intersection of $\vec{p}_\tau$ direction with plane $y = \mathrm{IP_y}$



With respect to Belle:

- exploit **nanobeam scheme** $\rightarrow$ use beam-spot constraint
- need **just one 3-prong τ** $\rightarrow$ higher statistics

p_τ reconstruction

When both τ decay to hadrons $h^\pm$

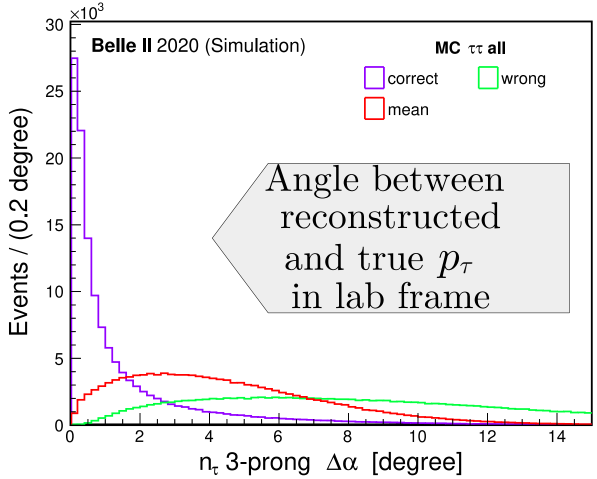
$\Longrightarrow$ tau momentum can be found explicitly

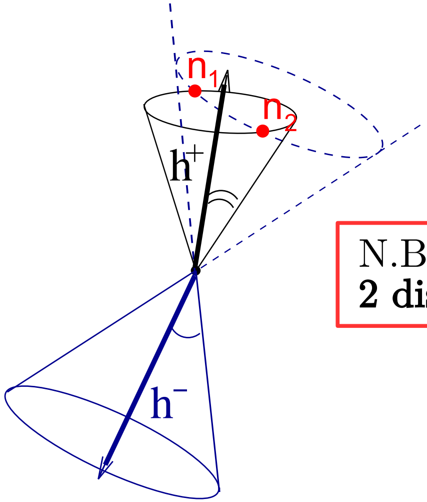
General solution in **CM frame**:

$\vec{m}$=mean vector

Δ=discriminant

$$\vec{p}_\tau^{\,\mathrm{CM}} = \vec{m} \pm \sqrt{\Delta}\,\vec{n}$$





N.B.: in general there are **2 distinct solutions**!

Strategy

1) select events with discriminant $\Delta \geq 0$
2) estimate $\vec{p}_\tau$ in CM as **mean** vector $\vec{m}$
3) **boost** $\vec{p}_\tau$ to the laboratory frame

ℓ_τ reconstruction and IP constraint

χ^2-like minimization of a function $F(\ell_\tau, \mathrm{IP_x}, \mathrm{IP_z})$ using:

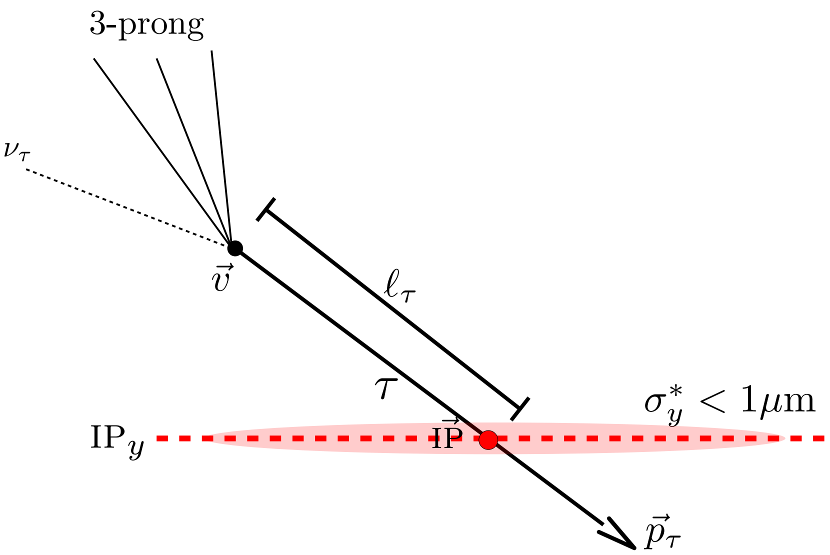
- Beam-spot constraints
- Relation between tau candidate displacement and production/decay vertexes:

$$\overrightarrow{\mathrm{IP}} + \ell_\tau \hat{n}_\tau = \vec{v}_{3\pi}$$

constraint on $\mathrm{IP_y}$

$\hat{n}_\tau = \vec{p}_\tau / |\vec{p}_\tau|$

3-prong vertex



Event topology

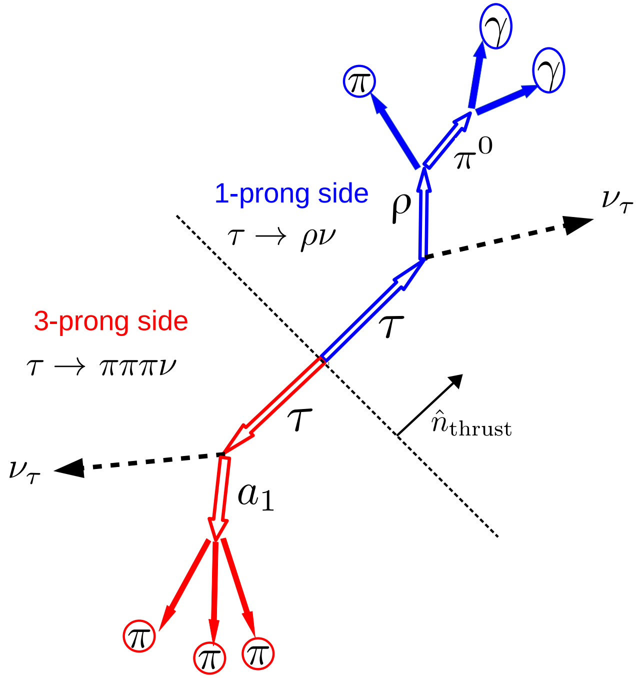
Study **1-prong×3-prong** topology:

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

$$\boldsymbol{\tau \to \rho\nu} \quad \times \quad \boldsymbol{\tau \to \pi\pi\pi\nu}$$

- BR($\tau \to \rho\nu$)≃25%
- Good signature (ρ-peak)
- Need π^0 reconstruction

Roughly **×5** more events than in the channel analyzed by Belle ($\tau \to \pi\pi\pi\nu \times \tau \to \pi\pi\pi\nu$)
→ already competitive at ~150 fb^{-1}!

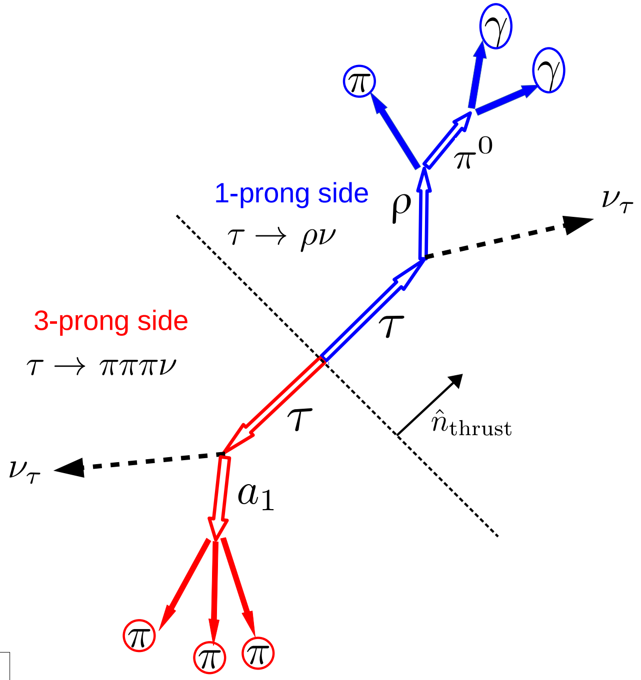


Simulation study on 200 fb^{-1} of MC

Event selection

Use 200 fb^{-1} of MC

- Divide event into **two hemispheres**:
  - 3-prong side $\rightarrow$ 3 charged π
  - 1-prong side $\rightarrow$ 1 charged π + 1 π^0
- Total energy of additional photons: $\sum E_\gamma < 600$ MeV
- **ρ-peak**: 0.5 GeV $< M_\rho < 1.3$ GeV
- Reject possible kaons
- At least 1 **hit** in **pixel detector** for each π on 3-prong side



$N_{\text{events}} \simeq 456$ k

τ pair events		
86.3%	yellow	$\tau(\rightarrow \rho\nu)\tau(\rightarrow \pi\pi\pi\nu)$
11.7%	green	$\tau\tau$ others

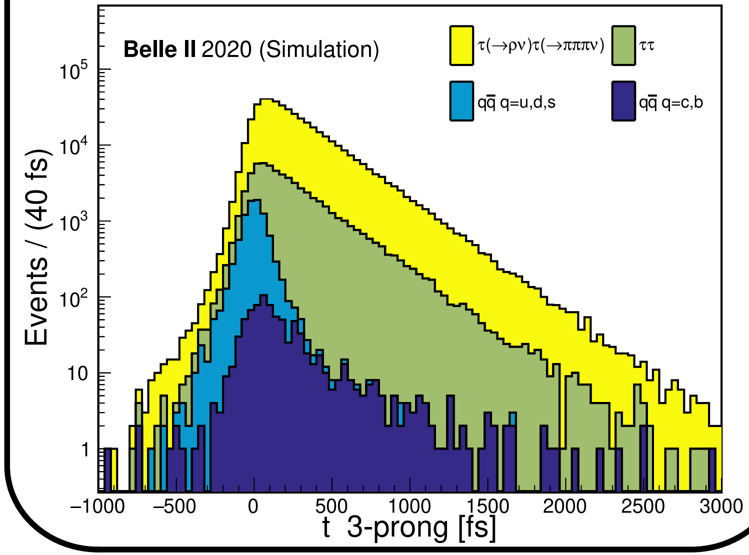
$q\bar{q}$ background events		
1.8%	light blue	$q\bar{q}$ q=u,d,s
0.2%	dark blue	$q\bar{q}$ q=c,b

Proper decay time reconstruction

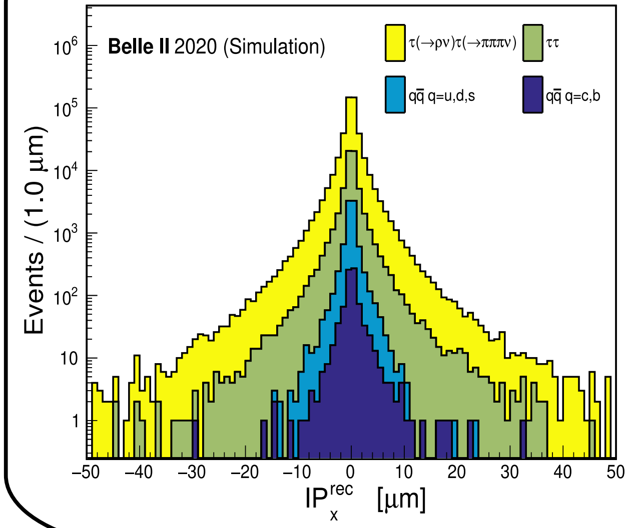
Find the minimum event per event → optimized value of ℓ_τ, IP_x and IP_z

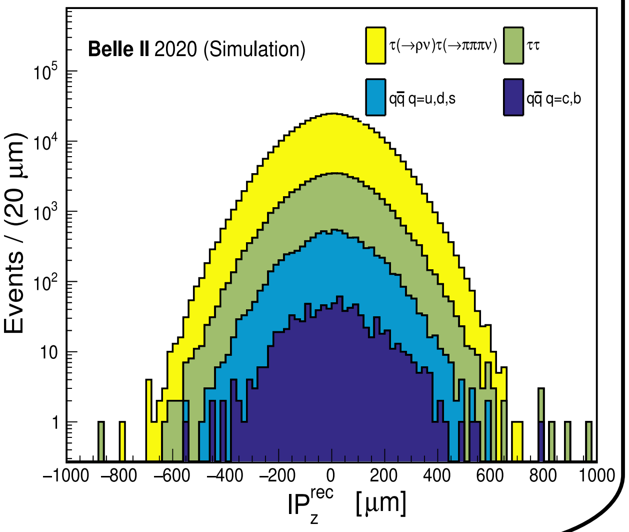
Proper decay time distribution

$$t = \ell_{\text{3-prong}} \frac{m_\tau}{|\vec{p}_{\text{3-prong}}|c}$$



Reconstructed x and z **IP coordinates**





Proper time resolution

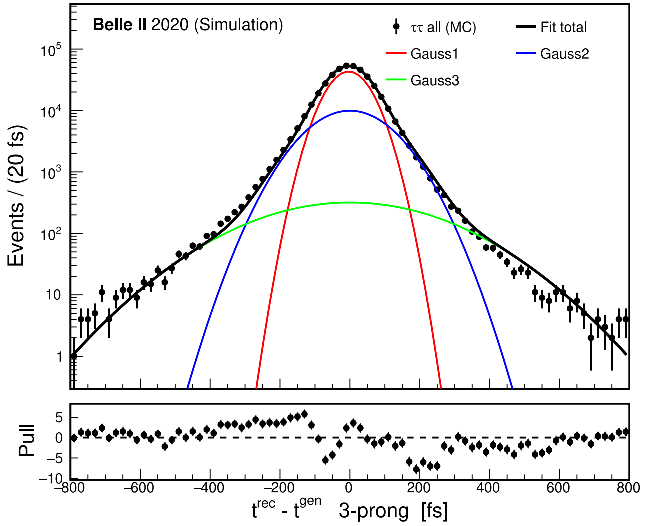
For all tau pair events with MC-truth:

$\rightarrow$ compute residual proper time on 3-prong side

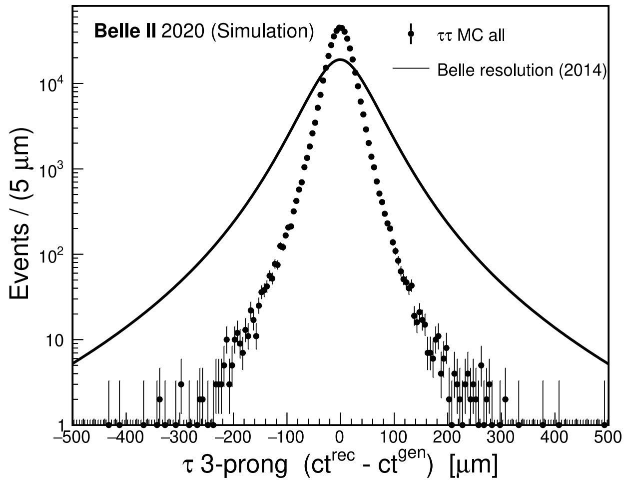
$$\Delta t = t^{rec} - t^{gen}$$

Binned ML fit with 3 Gaussians:

μ_1 [fs]	-3.43 ± 0.13
σ [fs]	79.3 ± 0.7



Compare to Belle resolution



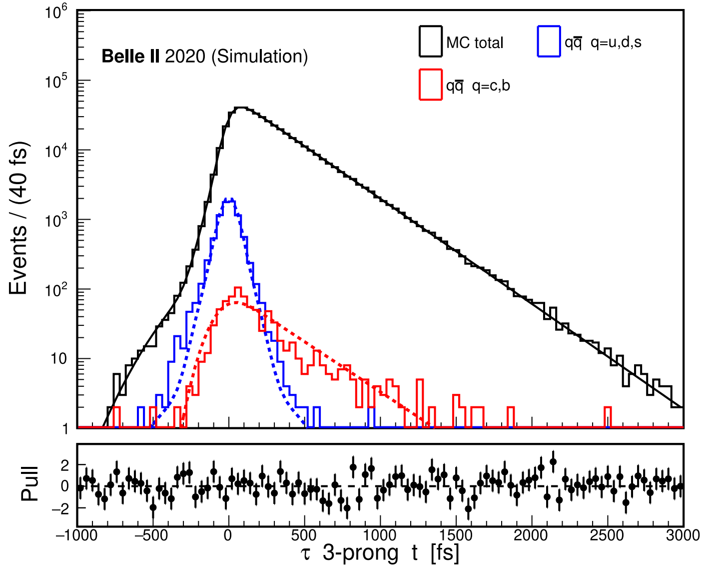
Belle II $\rightarrow$ Factor $\simeq$2 narrower

Lifetime extraction

- Subtract u,d,s and c,b backgrounds
- Fit proper time distribution with **convolution** of resolution function and exponential distribution:

$$p(t;\,\tau_\tau) = \frac{1}{\tau_\tau} e^{-\frac{t}{\tau_\tau}} * \mathcal{R}(t) \rightarrow \tau[\text{fs}] \quad 287.2 \pm 0.5$$

Generated lifetime $\tau_\tau = 290.57$ fs



1) Same **statistical uncertainty** of **Belle** (200 fb^{-1} vs 711 fb^{-1})

2) τ_τ presents $\simeq$**3 fs bias**:

- ISR/FSR losses $\rightarrow p_\tau$ overestimation $\rightarrow$ **underestimate proper time**

$$t = \ell_\tau \frac{m_\tau}{p_\tau c}$$

Remove ISR/FSR losses

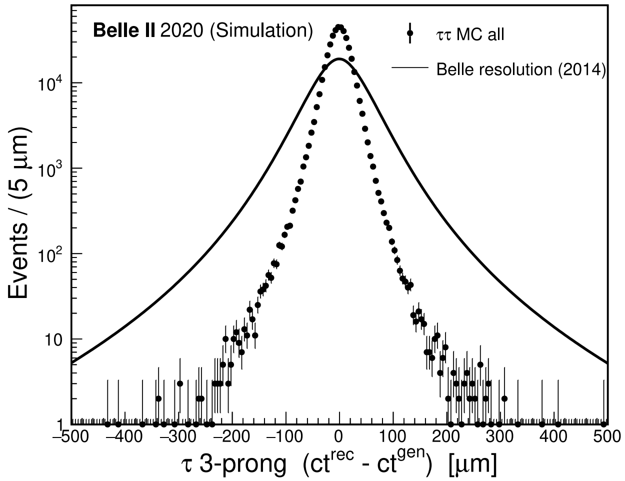
Resolution:		Convolution:	
μ_1[fs]	-0.80 ± 0.20	τ[fs]	290.6 ± 0.7

- intrinsic in the measurement $\rightarrow$ rescale final result from MC

Conclusions and outlook

With respect to Belle:

- Use information on beam-spot region (**nanobeam scheme**)
- $\times$**3.6** effective **luminosity** (711 $fb^{-1} \rightarrow$ 200 fb^{-1})
  - Tight selection $\rightarrow$ gain "only" a factor $\times$**1.4** in **event yield** (1615 events/$fb^{-1} \rightarrow$ 2280 events/fb^{-1})
  - **Proper time resolution** $\rightarrow$ $\times$**2** narrower



Collected $\simeq$80 fb^{-1} during 2020 $\Longrightarrow$ already competitive by end 2021

Further studies to estimate **systematics** (not exhaustive):

1. Test dependence from resolution function in the fit
2. Background parameterization
3. Beam-spot position, ISR/FSR simulation
4. Vertex detector alignment (dominant at Belle and Babar)

Thanks for your attention!

Backup slides

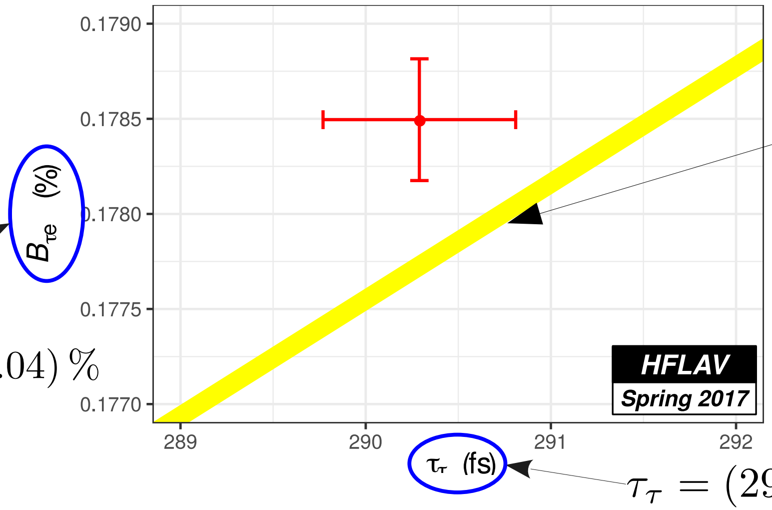
LFU test with precise τ-decay measurements

From the ratios between partial decay widths of leptons:

$$\left(\frac{g_\tau}{g_e}\right)^2 = \frac{\mathcal{B}_{\tau\mu}}{\mathcal{B}_{\mu e}}\frac{\tau_\mu}{\tau_\tau}\left(\frac{m_\mu}{m_\tau}\right)^5 R_{\tau e} \qquad \left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\mathcal{B}_{\tau e}}{\mathcal{B}_{\mu e}}\frac{\tau_\mu}{\tau_\tau}\left(\frac{m_\mu}{m_\tau}\right)^5 R_{\tau\mu}$$

R = phase-space and radiative corrections

Present values are: $\frac{g_\tau}{g_e} = 1.0029 \pm 0.0014$ $\quad \frac{g_\tau}{g_\mu} = 1.0010 \pm 0.0014$



Assuming LFU $(g_\tau/g_\ell)=1$

$$\mathcal{B}_{\tau e}^{\rm SM} = \left[\frac{\mathcal{B}_{\mu e}}{\tau_\mu}\left(\frac{m_\tau}{m_\mu}\right)^5 R'_{\tau e}\right]\tau_\tau$$

$m_\tau = (1776.86 \pm 0.12)$ MeV

$\mathcal{B}(\tau \to e\overline{\nu}_e\nu_\tau) = (17.85 \pm 0.04)$ %

$\tau_\tau = (290.3 \pm 0.5)$ fs

Others τ LFU tests

τ LFU in W decay

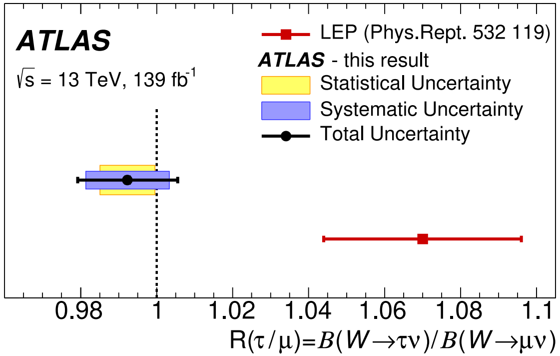
$W \to \ell\,\nu$ produced at W-resonance (**LEP**):

$$\frac{2\,\mathcal{B}(W \to \tau\bar{\nu}_\tau)}{\mathcal{B}(W \to e\bar{\nu}_e) + \mathcal{B}(W \to \mu\bar{\nu}_\mu)} = 1.066 \pm 0.025$$

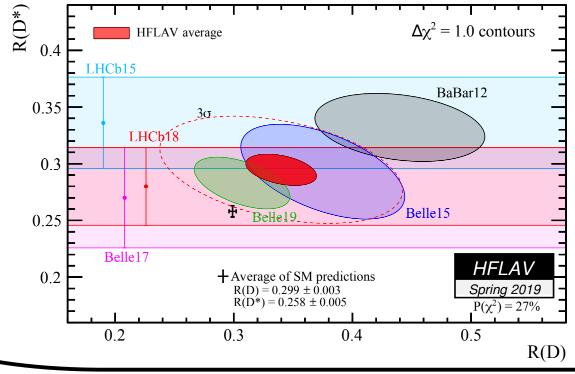
2.6 σ

$W \to \ell\,\nu$ from top-pair events (**LHC**):

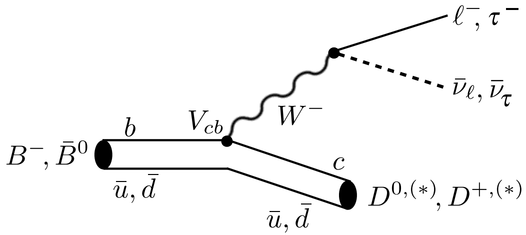
$$\frac{\mathcal{B}(W \to \tau\bar{\nu}_\tau)}{\mathcal{B}(W \to \mu\bar{\nu}_\mu)} = 0.992 \pm 0.013$$



τ LFU in $b \to c$ transitions

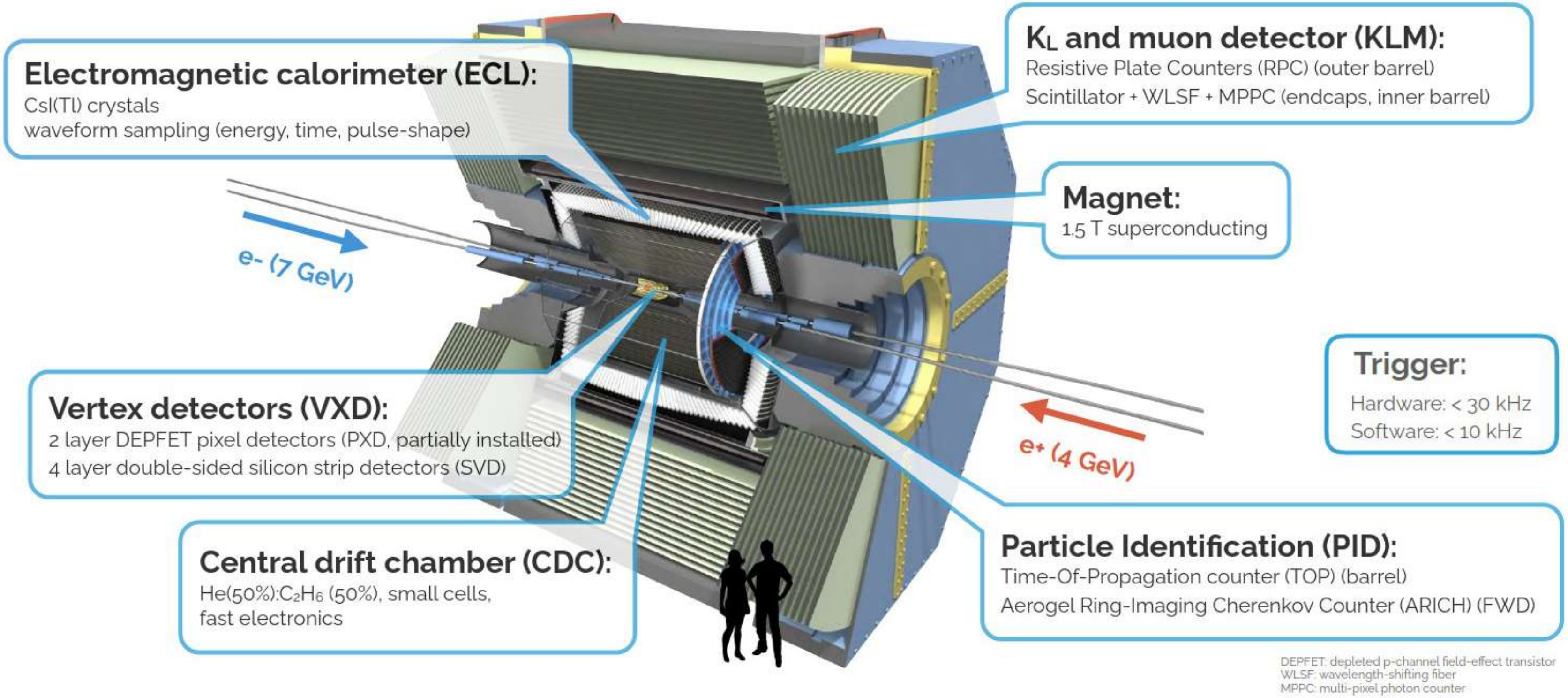


$$R(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell)}$$



Belle II detector

- general purpose spectrometer
- high hermeticity
- designed to deal with high background rate

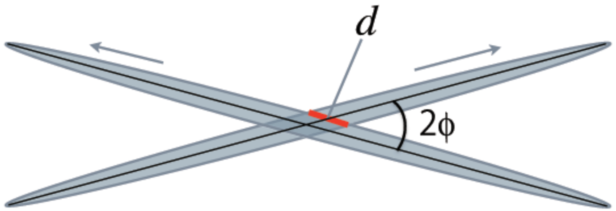


SuperKEKB luminosity

$$\mathcal{L} = \frac{\gamma_{e^\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e^\pm}\cdot\xi_{y,e^\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

- Lorentz factor: $\gamma_{e^\pm}$
- Beam currents ↑: $I_{e^\pm}$
- Vertical beam-beam tune shift: $\xi_{y,e^\pm}$
- Geometrical reduction factor: R_L/R_{ξ_y}
- Beam aspect-ratio at the IP: σ_y^*/σ_x^*
- Vertical beta-fuction at IP ↓: β_y^*

Nanobeam scheme → reduce "hourglass" effect



$$d = \frac{2\,\sigma_x^*}{\sin 2\phi} \simeq \frac{\sigma_x^*}{\phi} \qquad 2\phi = 83\text{mrad}$$

ℓ_τ reconstruction and IP constraint

Use constraint on IP_y

$\hat{n}_\tau = \vec{p}_\tau / |\vec{p}_\tau|$

3-prong vertex

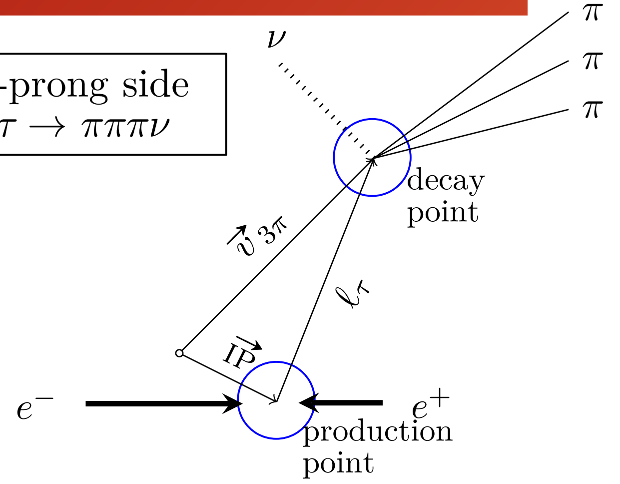
$$\vec{IP} + \ell_\tau \hat{n}_\tau = \vec{v}_{3\pi}$$

$$F = \frac{(IP_x + \ell_\tau n_x - v_x)^2}{\sigma^2_{v_x}} + \frac{(IP_y^{nom} + \ell_\tau n_y - v_y)^2}{\sigma^2_{v_y}} + \frac{(IP_z + \ell_\tau n_z - v_z)^2}{\sigma^2_{v_z}} +$$

$$+ \frac{(IP_x - IP_x^{nom})^2}{\sigma^2_x} + \frac{(IP_z - IP_z^{nom})^2}{\sigma^2_z}$$

← beam-spot constraints

3-prong side
$\tau \to \pi\pi\pi\nu$



Minimize $F(\ell_\tau, IP_x, IP_z) \to \sim\chi^2$ with 2 d.o.f.

Dataset

MC samples:

MC run-indepedent, $\Upsilon(4S)$ energy

- **200 fb^{-1}** "generic":

$e^+e^- \rightarrow \tau^+\tau^- \implies \tau_\tau = 87.11\ \mu\text{m} = 290.57\ \text{fs}$

$e^+e^- \rightarrow q\bar{q} \quad q = u, d, s, c, b$

Particles:

Tracks:

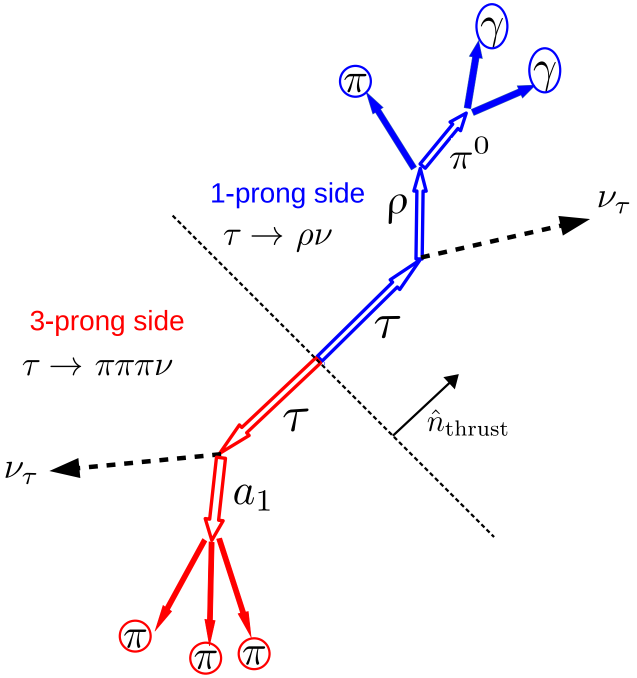
- $|dz| < 3$ cm $\quad dr < 1$ cm
- $E_{\mathrm{ECL}}/p < 0.8$

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

- 105 MeV $< M_{\gamma\gamma} <$ 150 MeV

"Good γ" :

- $E_{\mathrm{ECL}} >$ 200 MeV
- Not from a π^0



Event requirements

- **4** charged tracks (zero total charge)
- **1** reconstructed $\pi^0 \to \gamma\gamma$

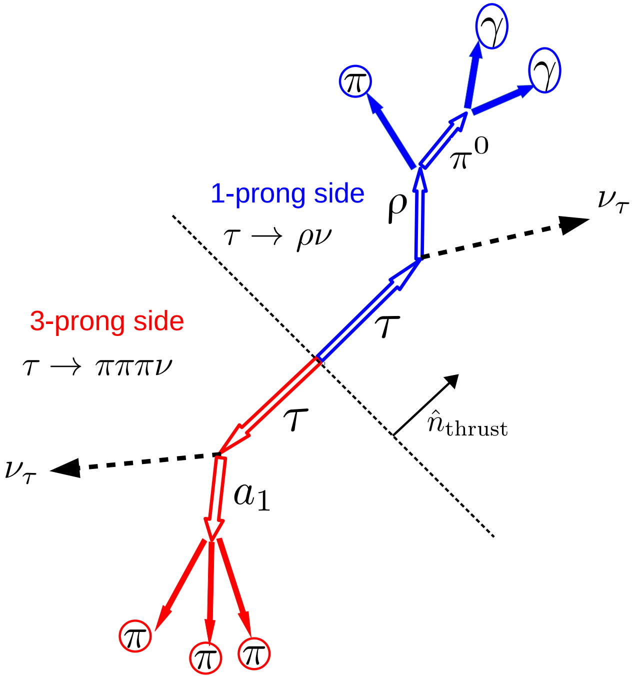
$$T = \max_{\hat{n}} \frac{\sum_i |\vec{p}_i^{\,\mathrm{CMS}} \cdot \hat{n}|}{\sum_i |\vec{p}_i^{\,\mathrm{CMS}}|}$$

Divide in 2 hemispheres

3-prong side: 3 charged tracks

3-prong vertex: $P(\chi^2) > 0.001$

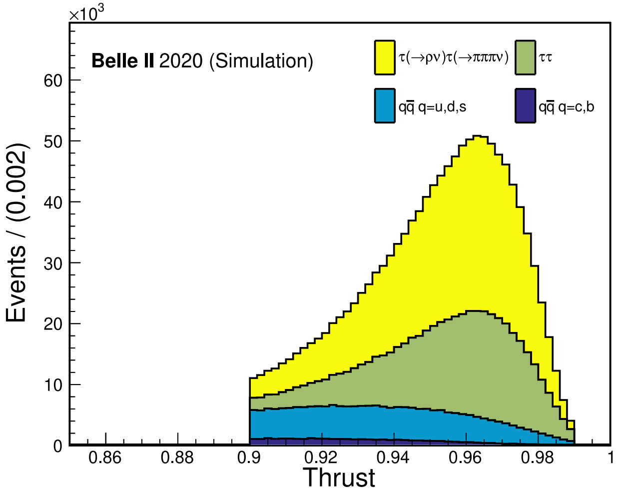
1-prong side: 1 charged track, 1 reconstructed π^0

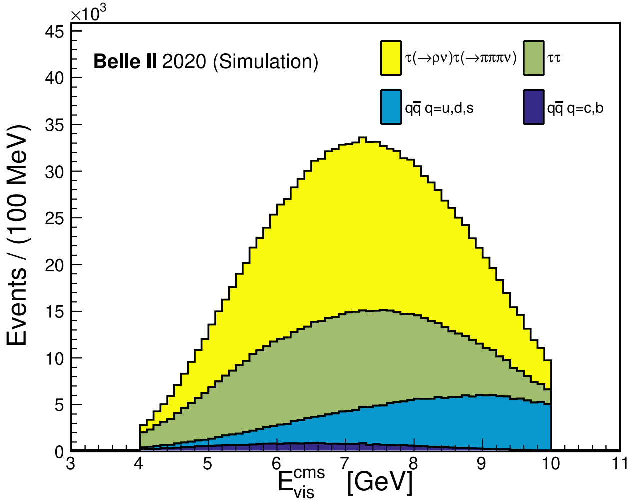


Event preselection

- $0.90 < \text{Thrust} < 0.99$
- $4\text{ GeV} < E_{\text{vis, cms}} < 10\text{ GeV}$

} Reduce qq and beam backgrounds





Optimized selection

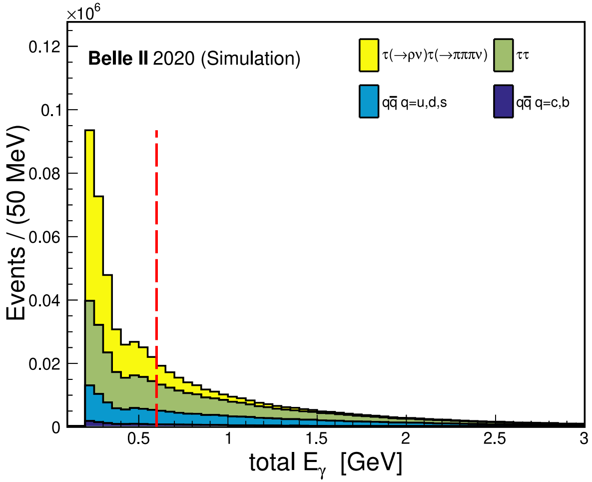
Maximize $\mathcal{E} \cdot \mathcal{P}$ — Equivalent to $\frac{N_{sgn}}{\sqrt{N_{sgn} + N_{bkg}}}$

$$\mathcal{E} = \frac{N_{sgn}}{N_0} \qquad \mathcal{P} = \frac{N_{sgn}}{N_{sgn} + N_{bkg}}$$

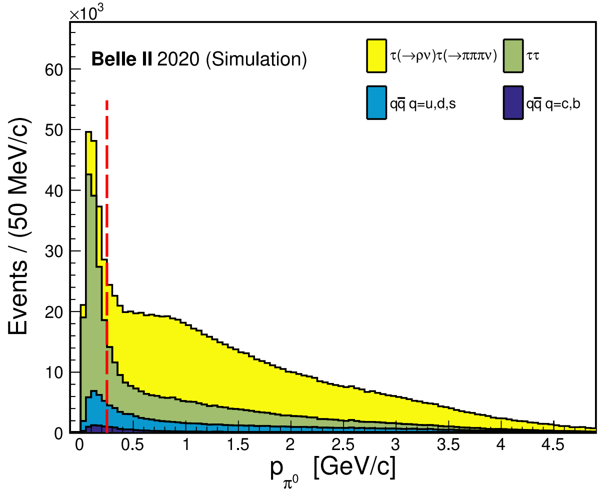
N_{sgn}: $\tau(\to \rho\nu)\tau(\to \pi\pi\pi\nu)$

N_{bkg}:
- $\tau\tau$
- $q\bar{q}$ q=u,d,s
- $q\bar{q}$ q=c,b

1) $\sum E_\gamma < 600$ MeV



2) $p_{\pi 0} > 250$ MeV



Optimized selection

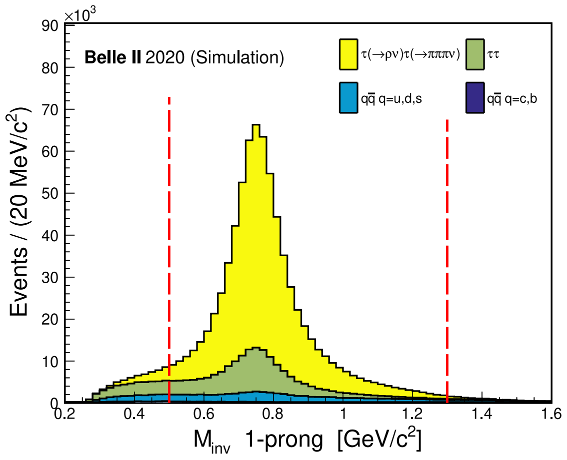
Maximize $\mathcal{E} \cdot \mathcal{P}$ — Equivalent to $\frac{N_{sgn}}{\sqrt{N_{sgn} + N_{bkg}}}$

$$\mathcal{E} = \frac{N_{sgn}}{N_0} \qquad \mathcal{P} = \frac{N_{sgn}}{N_{sgn} + N_{bkg}}$$

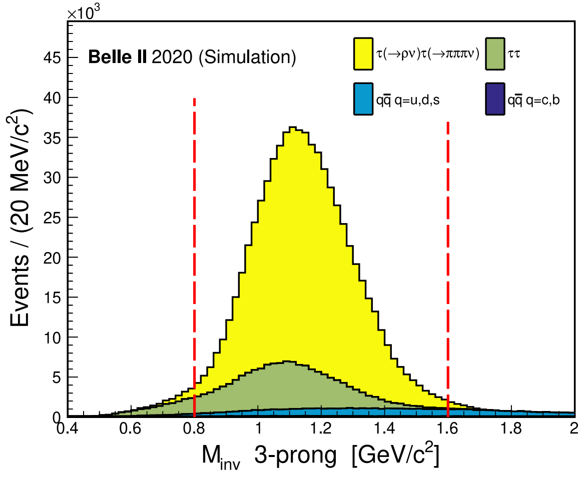
N_{sgn}: $\tau(\to \rho\nu)\tau(\to \pi\pi\pi\nu)$

N_{bkg}: $\tau\tau$; $q\bar{q}$ q=u,d,s; $q\bar{q}$ q=c,b

3) $0.5\ \text{GeV} < M_{inv}(\text{1-prong}) < 1.3\ \text{GeV}$



4) $0.8\ \text{GeV} < M_{inv}(\text{3-prong}) < 1.6\ \text{GeV}$



Optimized selection

Maximize $\mathcal{E} \cdot \mathcal{P}$

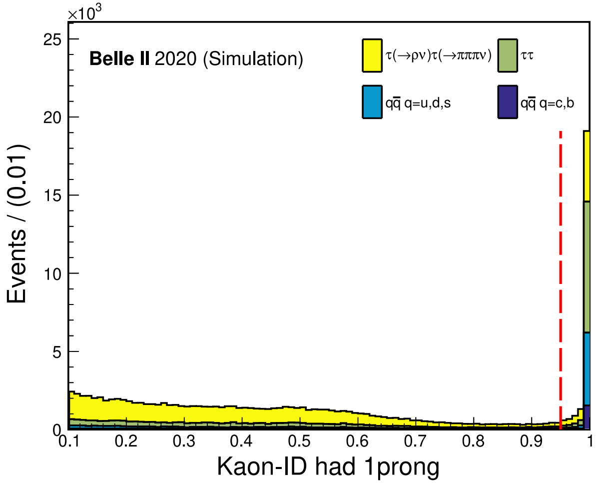
Equivalent to $\frac{N_{\text{sgn}}}{\sqrt{N_{\text{sgn}} + N_{\text{bkg}}}}$

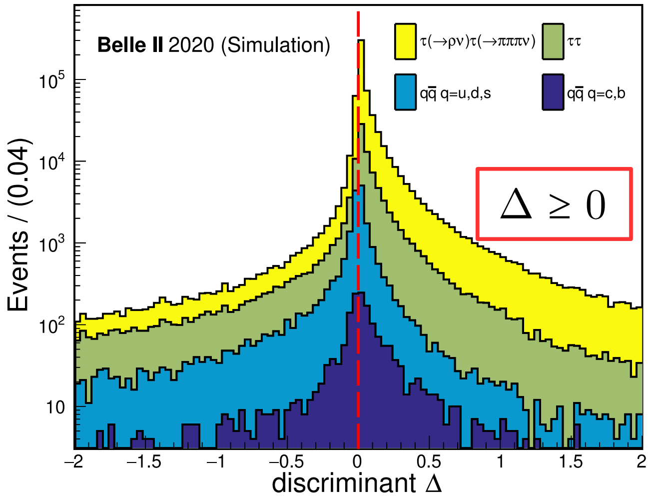
$$\mathcal{E} = \frac{N_{\text{sgn}}}{N_0} \qquad \mathcal{P} = \frac{N_{\text{sgn}}}{N_{\text{sgn}} + N_{\text{bkg}}}$$

N_{sgn}: $\tau(\to \rho\nu)\tau(\to \pi\pi\pi\nu)$

N_{bkg}: $\tau\tau$, $q\bar{q}$ q=u,d,s, $q\bar{q}$ q=c,b

5) kaon-ID < 0.95 for all tracks

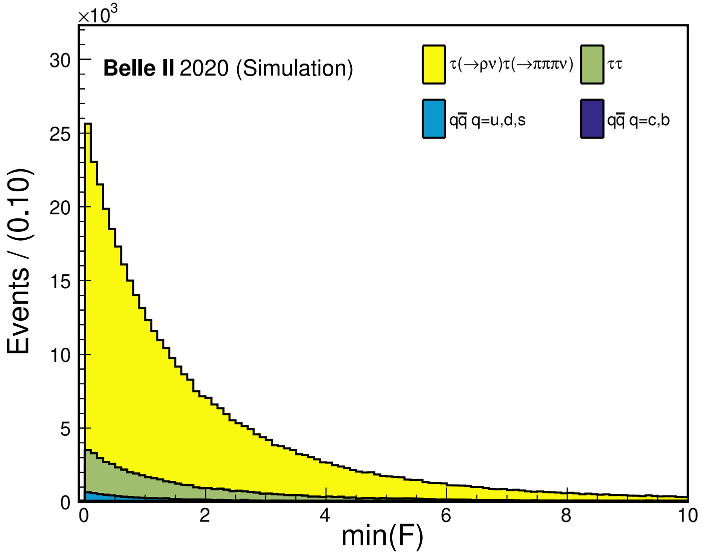




Proper decay time and IP reconstruction

Find the minimum of event per event → optimized value of ℓ_τ, IP_x and IP_z

Minimum of $F(\ell_\tau, IP_x, IP_z)$



Lifetime extraction (correct p_τ)

Look at the proper time reconstructed from the **correct** solution of tau momentum:

Resolution:

N	$(4.297 \pm 0.006)\,10^5$
μ_1[fs]	-3.80 ± 0.12
σ_1[fs]	52.7 ± 0.3
ε[%]	26.4 ± 0.8
σ_2[fs]	101 ± 1
δ[%]	1.8 ± 0.2
σ_3[fs]	243 ± 5

Convolution:

N	$(4.317 \pm 0.007)\,10^5$
τ[fs]	286.6 ± 0.5
μ_1[fs]	-1.0 ± 0.4
σ_1[fs]	54 ± 1
ε[%]	23 ± 3
σ_2[fs]	105 ± 4
δ[%]	0.88 ± 0.15
σ_3[fs]	305 ± 16

Remove ISR/FSR losses

Resolution:

μ_1[fs]	-0.98 ± 0.17

Convolution:

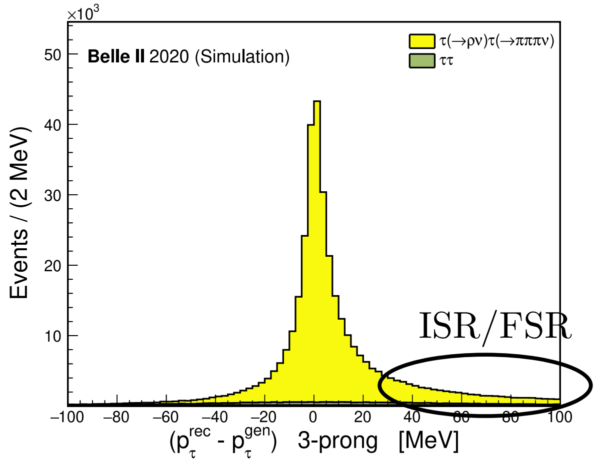
τ[fs]	290.2 ± 0.7
μ_1[fs]	-1.2 ± 0.5

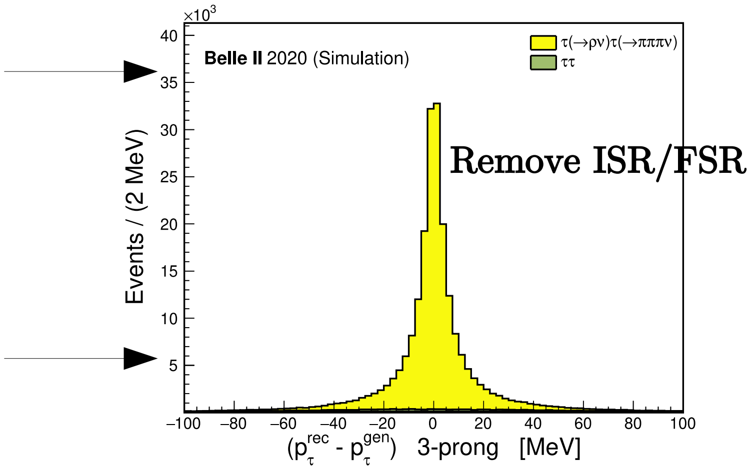
Lifetime extraction (correct p_τ)

The offset μ_1 in the resolution **depends** on **generated proper time** → scale factor

t^{gen}[fs]	(0, 80)	(80, 200)	(200, 400)	> 400
μ_1[fs]	-1.21 ± 0.23	-2.55 ± 0.24	-4.58 ± 0.26	-7.01 ± 0.24

ISR/FSR → overestimate momentum $p_\tau \implies t = \ell_\tau \frac{m_\tau}{p_\tau c}$





Lifetime extraction (wrong p_τ)

Look at the proper time reconstructed from the **wrong** solution of tau momentum:

Resolution:

N	$(4.297 \pm 0.007)\,10^5$
μ_1[fs]	-9.75 ± 0.13
σ_1[fs]	60.0 ± 0.2
ε[%]	23.0 ± 0.5
σ_2[fs]	127 ± 1
δ[%]	2.7 ± 0.2
σ_3[fs]	278 ± 6

Convolution:

N	$(4.317 \pm 0.007)\,10^5$
τ[fs]	279.7 ± 0.5
μ_1[fs]	-3.1 ± 0.4
σ_1[fs]	53 ± 1
ε[%]	24 ± 3
σ_2[fs]	104 ± 4
δ[%]	0.92 ± 0.16
σ_3[fs]	292 ± 15

Remove ISR/FSR losses

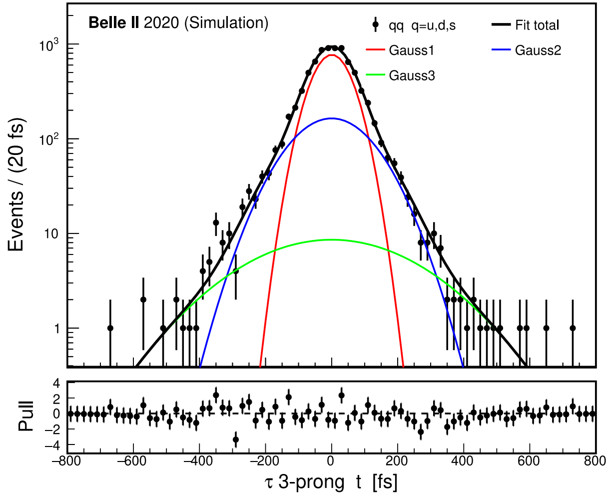
Resolution:

μ_1[fs]	-7.3 ± 0.2

Convolution:

τ[fs]	283.1 ± 0.7
μ_1[fs]	-3.1 ± 0.5

Background subtraction



All the non $\tau\tau$ events (1.9%) are **qq** bkg:

- **q=u,d,s** quarks (1.7%)
  - no lifetime component
  - fit proper time with resolution function
  - find bias μ_1^{uds}=(0.3±1.0) fs

- **q=c,b** quarks (0.2%)
  - possible long-lived particles (e.g. D_0, $D^{\pm}$, $B^{\pm}$)
  - include a decay time component (convolution of Gaussian and exponential)
  - find τ^{cb} = (300±10) fs