The tau lepton mass measured at Belle II

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(on behalf of the Belle II Collaboration)

Dec 4, 2023
Louisville

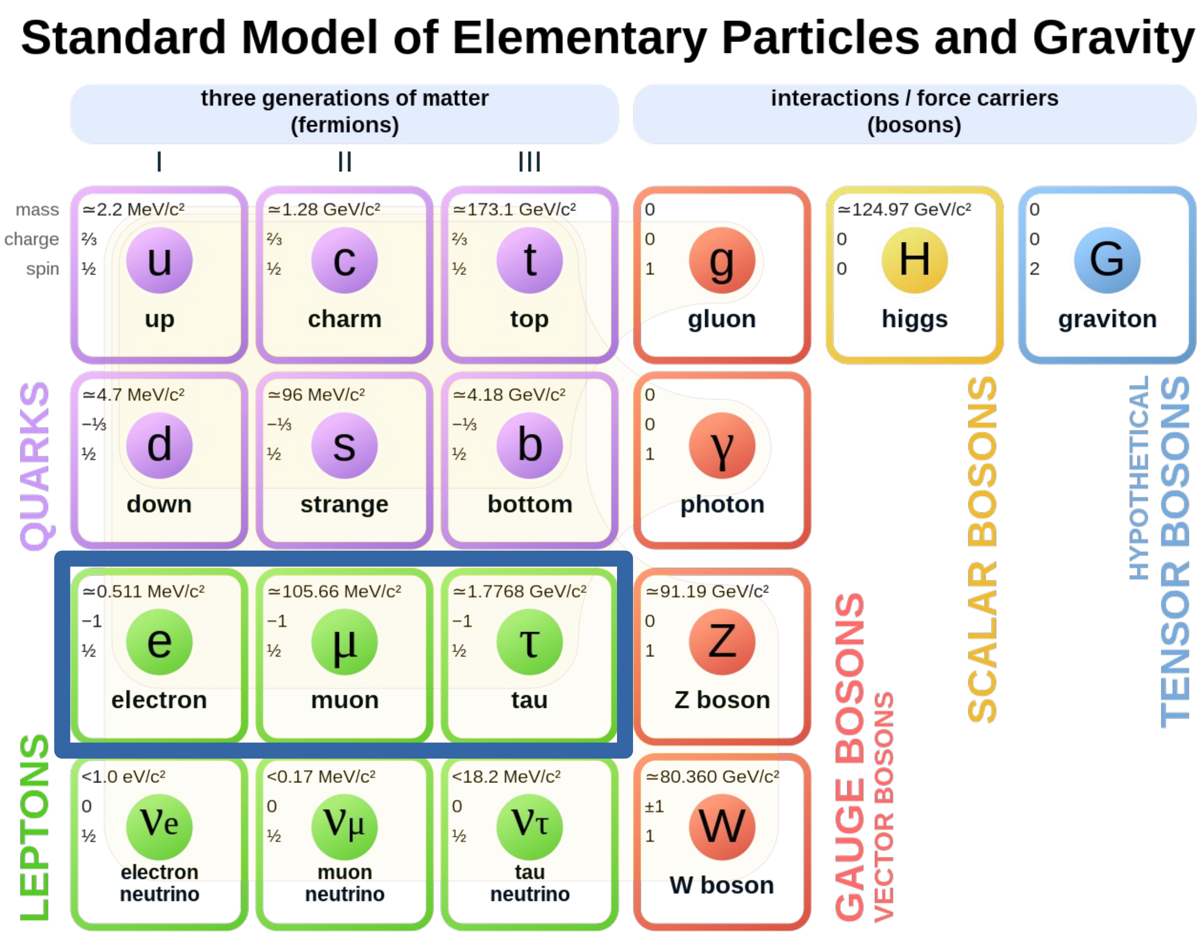
Belle II, Phys.Rev.D 108 (2023) 3

Particle Zoo

Masses of leptons

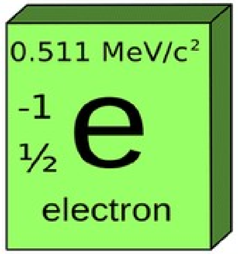
$$
\begin{aligned}
m_e &= (0.51099895000 \pm 0.00000000015)\ \mathrm{MeV} \\
m_\mu &= (105.6583755 \pm 0.0000023)\ \mathrm{MeV} \\
m_\tau &= (1776.86 \pm 0.12)\ \mathrm{MeV}
\end{aligned}
$$

PDG 2022

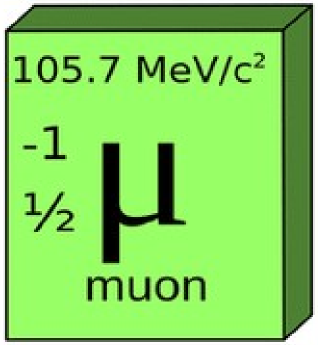


Relative precision of masses

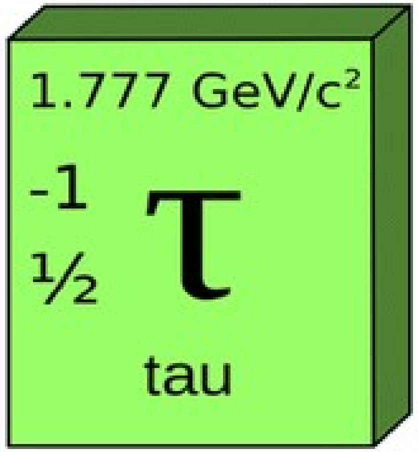
$$m_e = \frac{2R_\infty h}{c\alpha^2}$$



0.3 x 10^{-9}



22 x 10^{-9}



68000 x 10^{-9}

$$\frac{\Delta m_\tau}{m_\tau} = 6.8 \times 10^{-5}$$

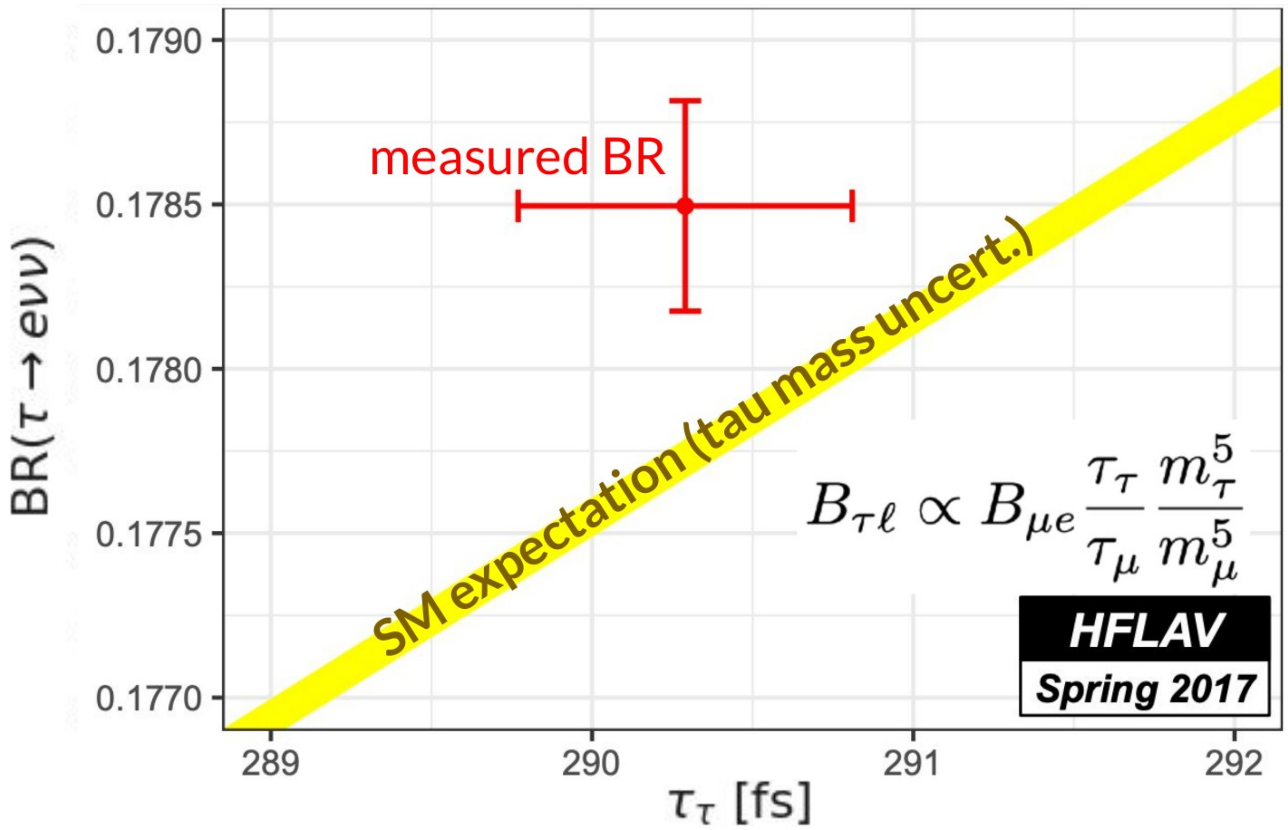
36 x 10^{-9}

Needed precision

300 USD

Lepton flavor universality & tau lepton mass

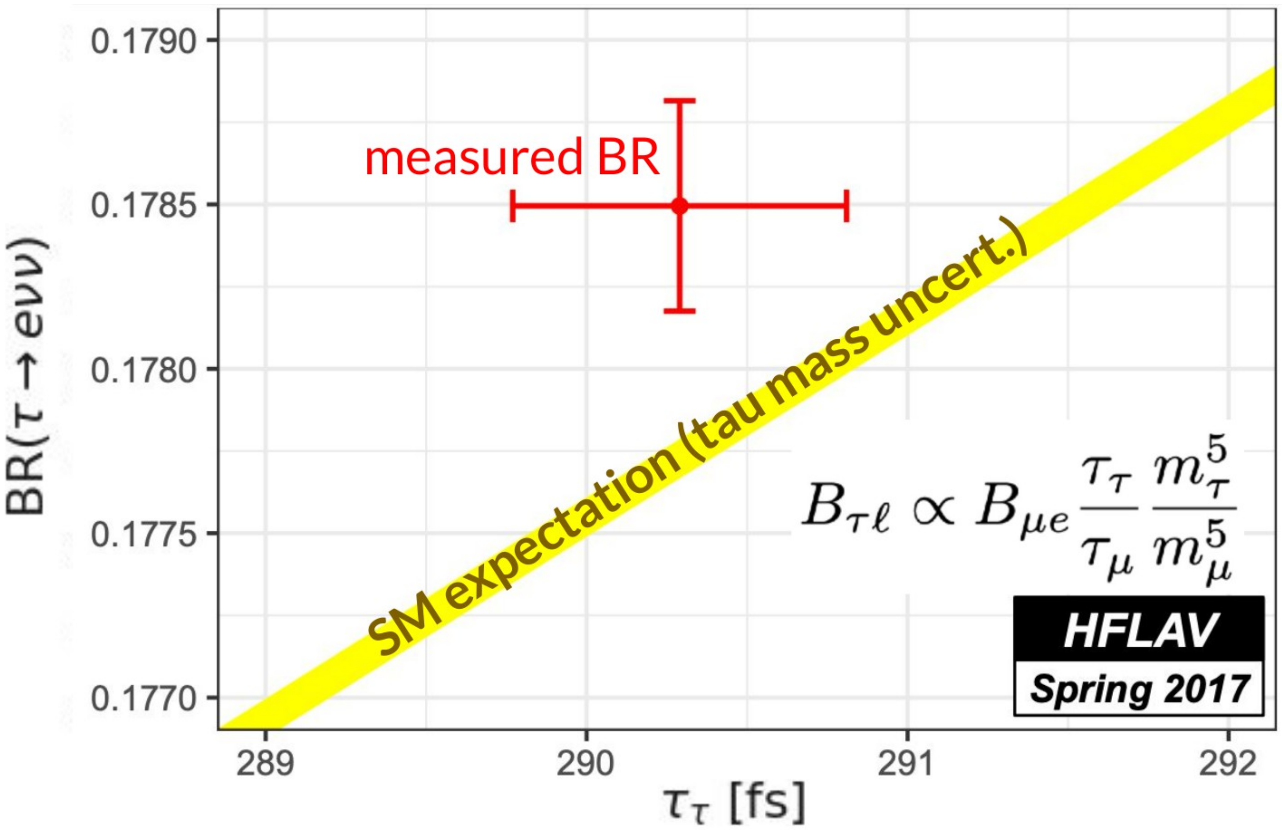
$$BR = \frac{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e) = \frac{G_F^2 m_\tau^5}{192\pi^3}}{(\tau\ \text{lifetime})^{-1}}$$



Is the fraction of tau decays to electron consistent with SM?

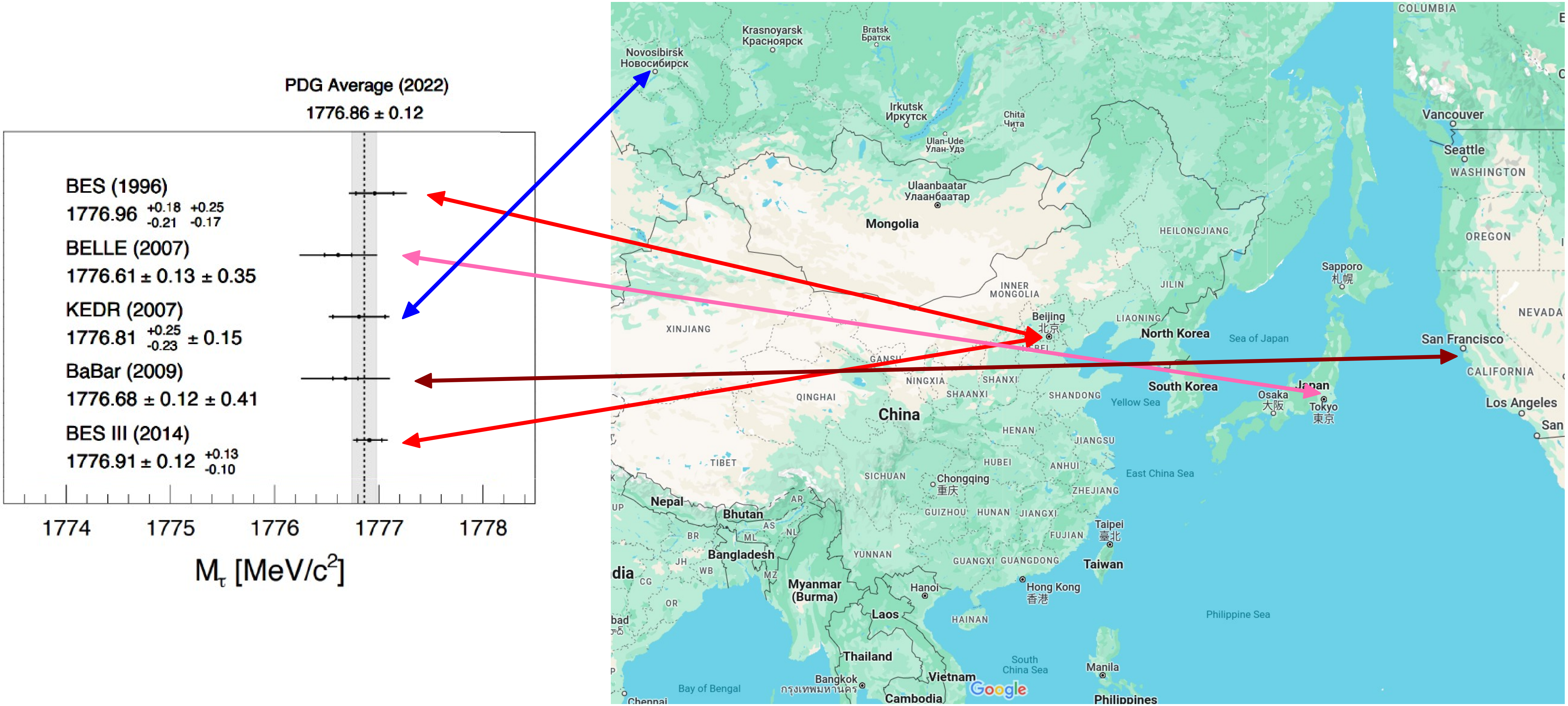
Lepton flavor universality & tau lepton mass

$$BR = \frac{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e) = \frac{G_F^2 m_\tau^5}{192\pi^3}}{(\tau \text{ lifetime})^{-1}}$$

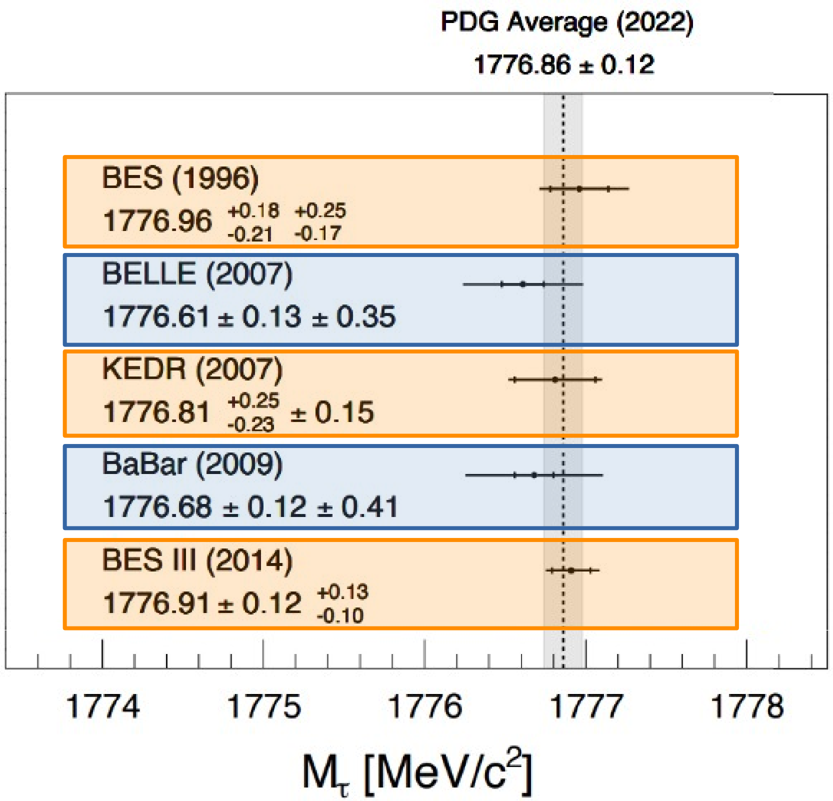


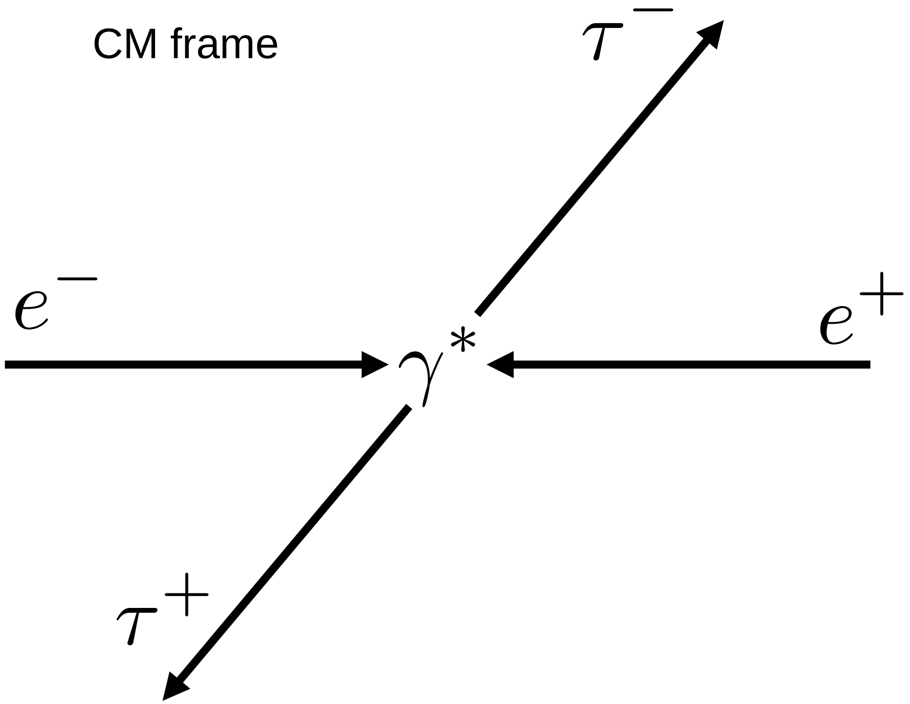
Tau lepton mass is exciting on its own!

Previous measurements



Methods





B factories : E_{cms} = 10.58 GeV — ***Pseudo-mass***

τ factories : E_{cms} = 3.56 GeV — ***Pair-production cross section***

Give me a scale!

τ factories

Source	Δm_τ (MeV/c^2)
Theoretical accuracy	0.010
Energy scale	$^{+0.022}_{-0.086}$
Energy spread	0.016
Luminosity	0.006
Cut on number of good photons	0.002
Cuts on PTEM and acoplanarity angle	0.05
mis-ID efficiency	0.048
Background shape	0.04
Fitted efficiency parameter	$^{+0.038}_{-0.034}$
Total	$^{+0.094}_{-0.124}$

BES III Phys.Rev.D 90 (2014)

Systematic uncertainties of the tau mass

B factories

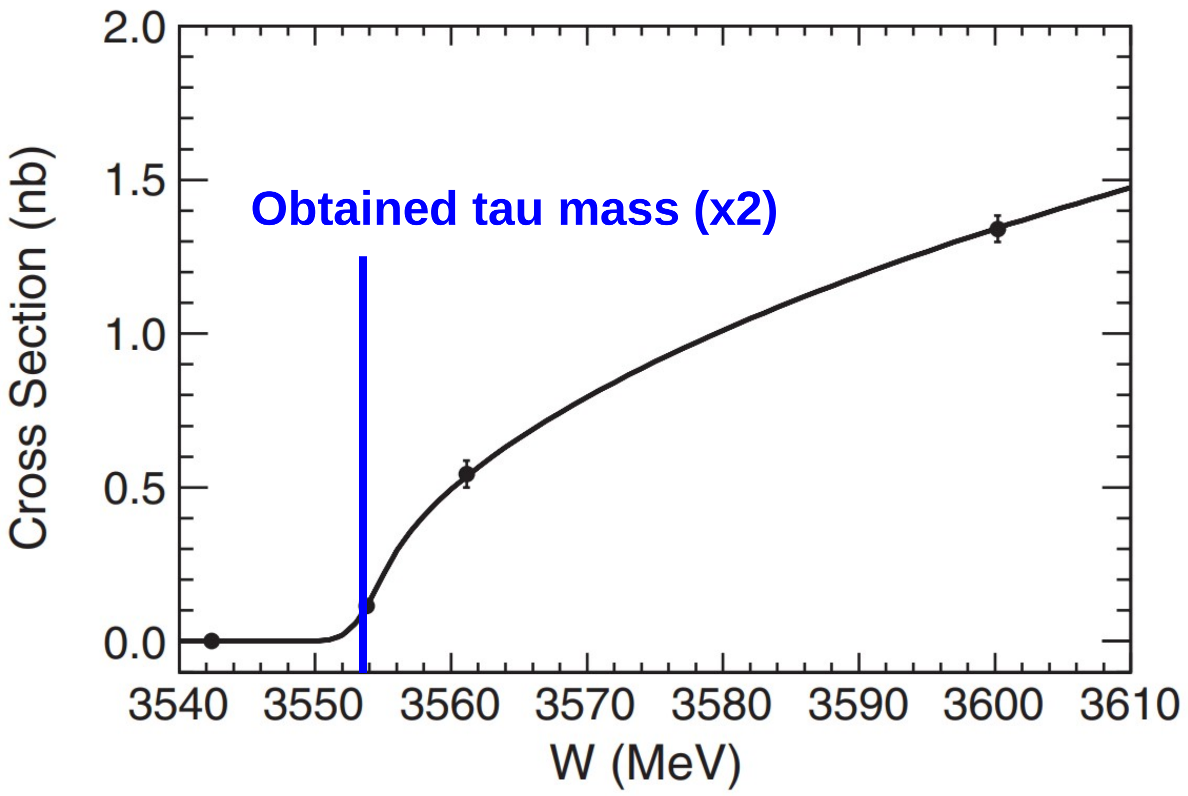
Source	Uncertainty (MeV)
Momentum Reconstruction	0.39
CM Energy	0.09
MC Modeling	0.05
MC Statistics	0.05
Fit Range	0.05
Parameterization	0.03
Total	**0.41**

BaBar Phys.Rev.D 80 (2009)

Source of systematics	σ, MeV/c^2
Beam energy and tracking system	0.26
Edge parameterization	0.18
Limited MC statistics	0.14
Fit range	0.04
Momentum resolution	0.02
Model of $\tau \to 3\pi\nu_\tau$	0.02
Background	0.01
Total	0.35

Belle Phys.Rev.Lett. 99 (2007)

BES III method



BESIII (τ factory)

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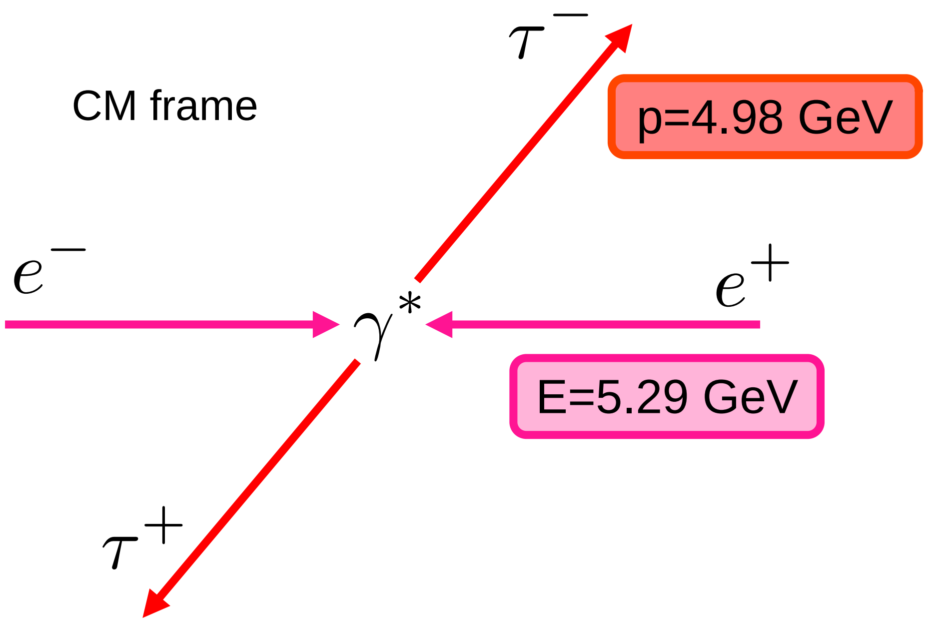
BES III *Phys.Rev.D 90 (2014)*

Compton-scattering of laser light used to measure beam energies.

Challenges for B factories



B factories : E_{cms} = 10.58 GeV

BaBar (B factory)

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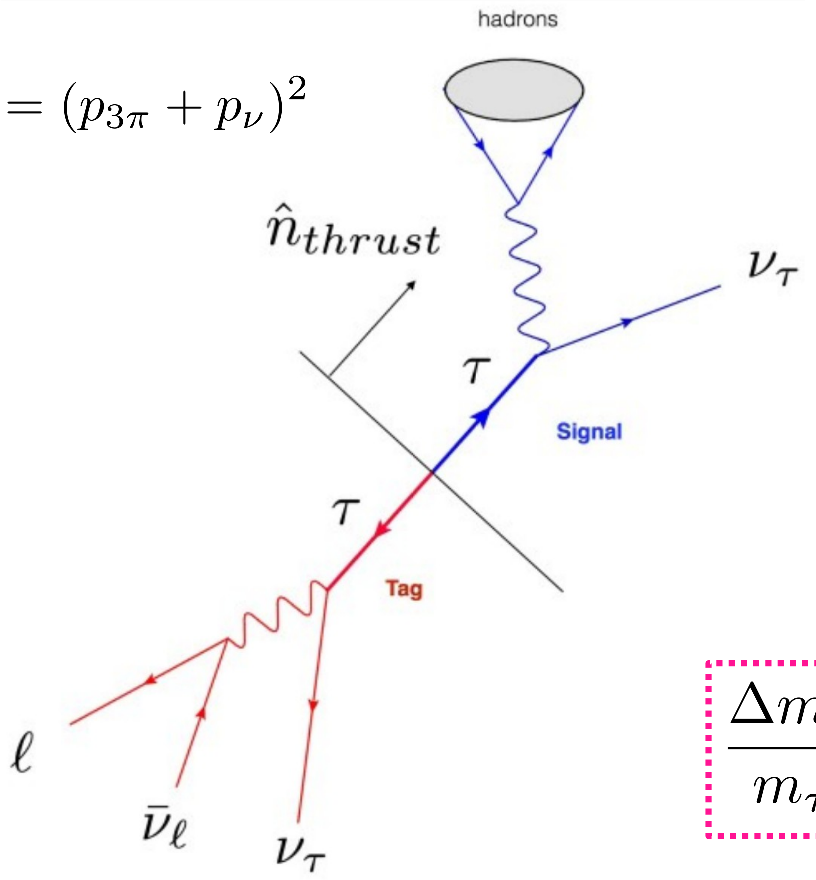
BaBar *Phys.Rev.D 80 (2009)*

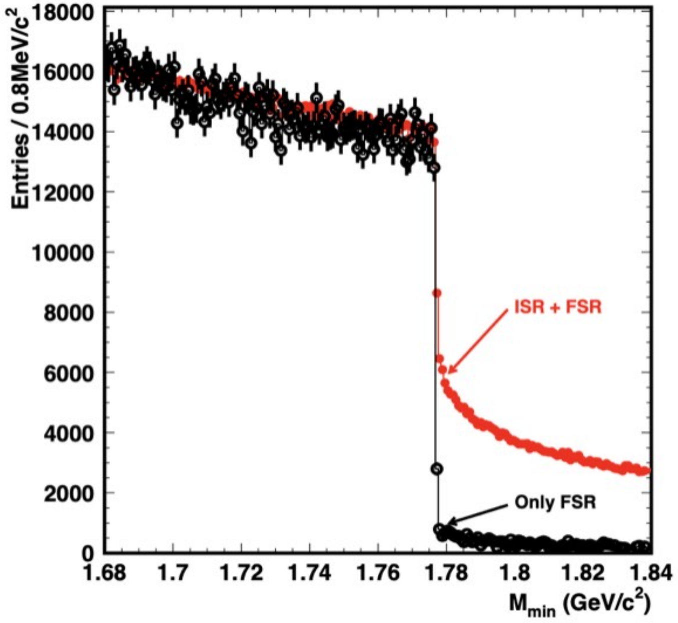
The pseudomass method

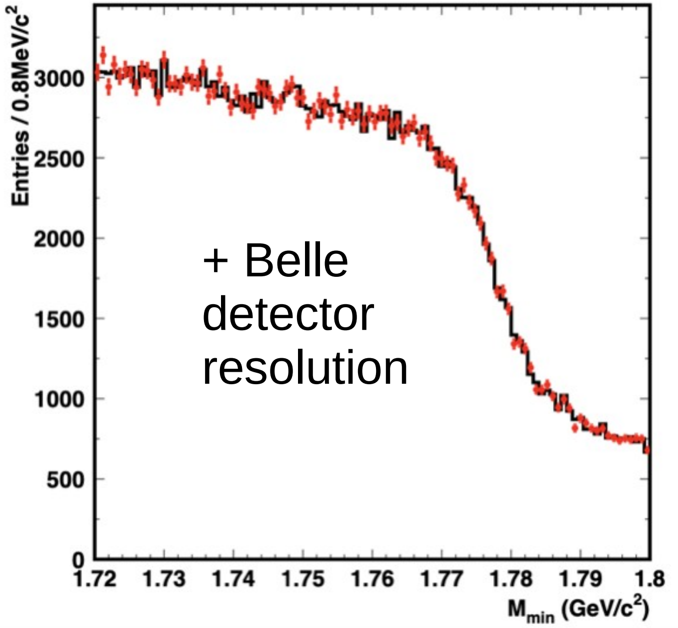
$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)} \leq m_\tau$$

$$m_\tau^2 = (p_{3\pi} + p_\nu)^2$$



$$\frac{\Delta m_\tau}{m_\tau} \approx \frac{1}{2} \frac{\Delta\sqrt{s}}{\sqrt{s}}$$

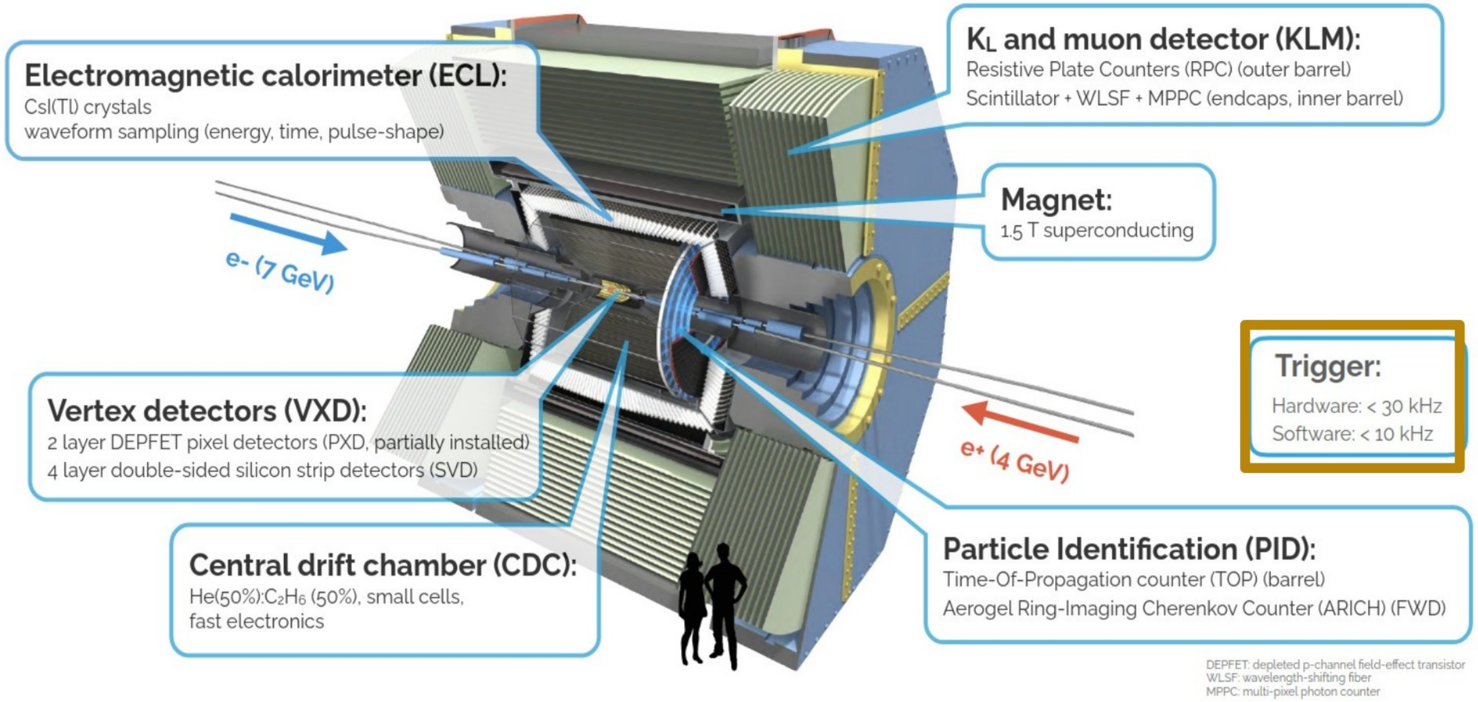




Belle II

Unprecedented luminosity,
4.7x10^{34} cm^{-2}s^{-1} world record

- Belle II at asymmetric-energy SuperKEKB e+e- collider
- B & charm & tau factory
  $\sigma_{bb} \sim \sigma_{cc} \sim \sigma_{\tau\tau} \sim 1\ \mathrm{nb}$
- Clean environment of ee collisions:
  → Efficient reconstruction neutrals
  → Missing energy
  → Interaction vertex
- Belle II tracking resolution superior to its predecessor
  → Sharper step in M_{min}
- Data taking is getting restarted (LS1 July 2022 - January 2024)
- Accumulated 424 fb^{-1}
  (190 fb^{-1} used in the tau-mass analysis)



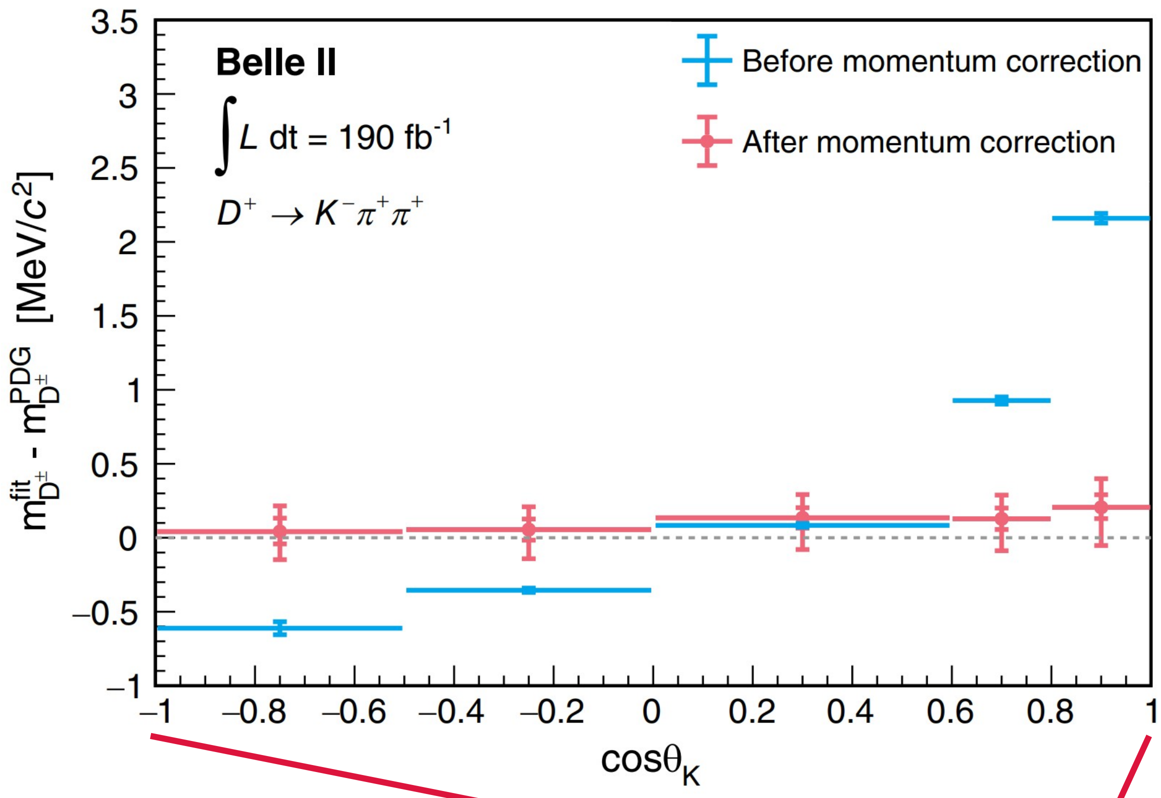
The z-axis of the coordinate system points towards electron momentum

Final-state momentum scale

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

$$m_\tau^2 = (p_{3\pi} + p_\nu)^2$$

- Calibration of track momenta using $D^0 \to K\pi$ as standard candle
- Momentum SFs are derived by comparing D^0 peak position with PDG value
  → SFs function of charge & cos θ
- Benefiting from better tracking performance compared to Belle/BaBar
- Systematic uncertainties:
  → m(D^0) PDG uncertainties
  → peak position modeling
  → detector misalignment



Validation channels:

$$D^0 \to K\pi\pi\pi, J/\psi \to \mu\mu, K_S^0 \to \pi\pi, D^\pm \to K\pi\pi$$

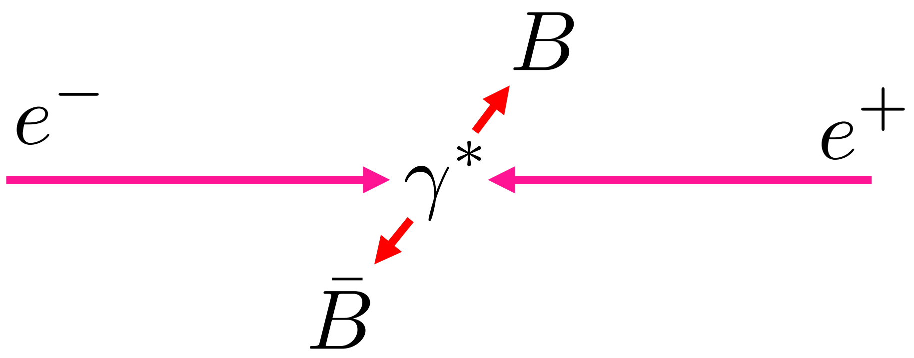
Tau mass unc. from momentum-scale

0.39 MeV (BaBar) → 0.06 MeV (Belle II)

Calibration of the collision energy

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

Exploiting proximity to the B$\overline{\text{B}}$ production threshold



$$E_B^* = m_B + \frac{1}{2m_B}(p_B^*)^2$$

From LHCb
Precision: 4×10^{-5}

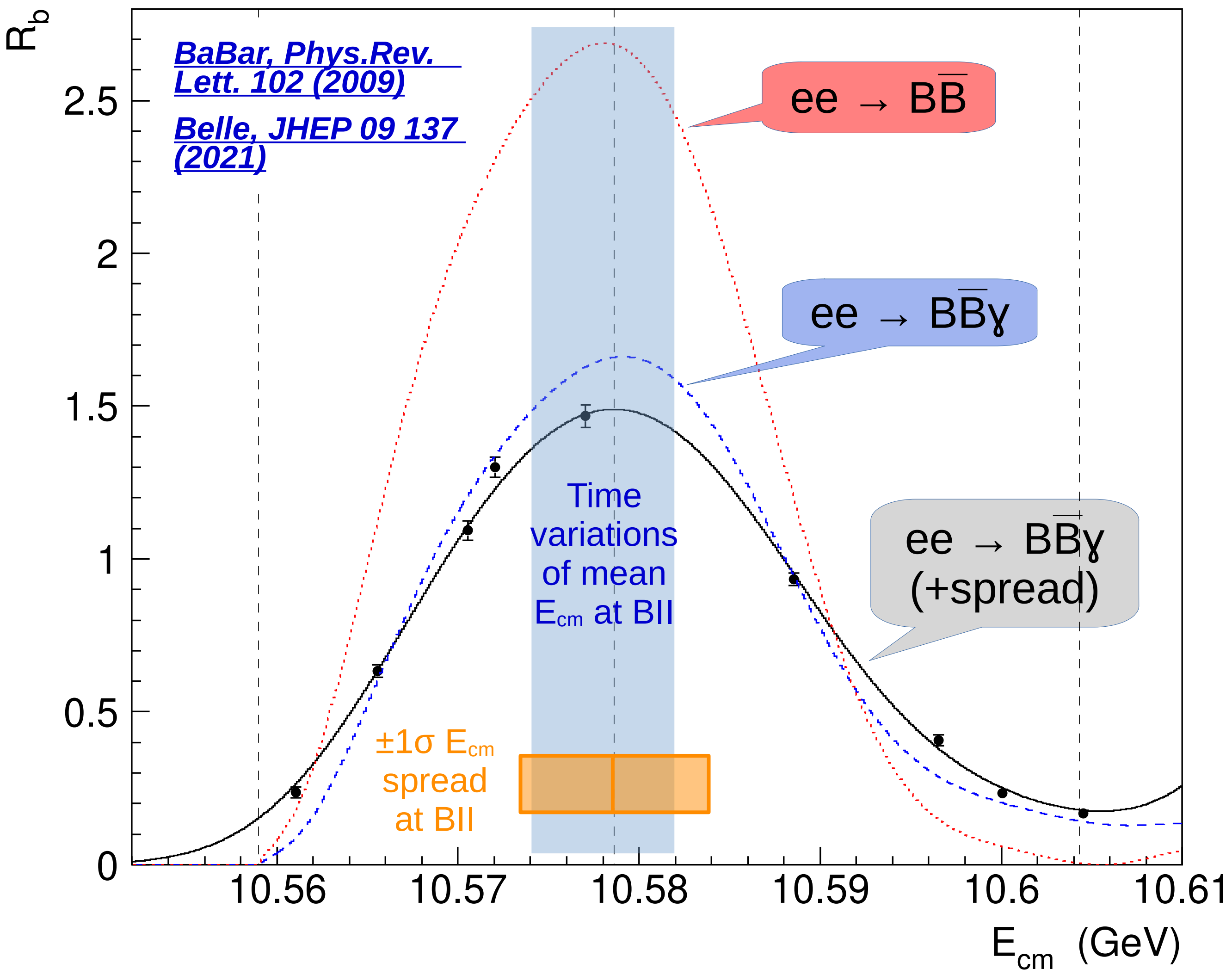
Our business

Phys.Rev.Lett. 122 (2019)
Phys.Lett.B 708 (2012)

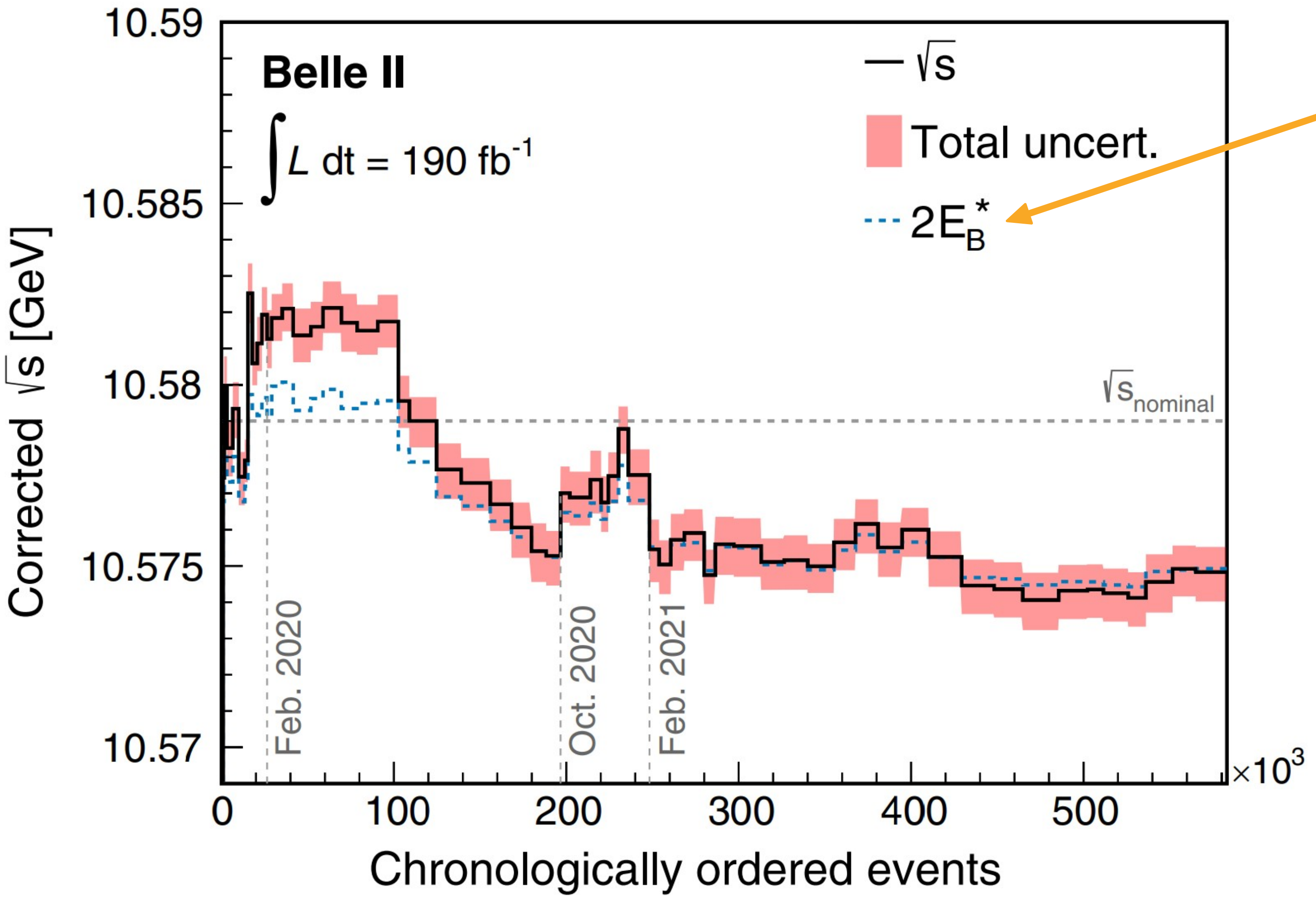
Y4S resonance

- The energy of the colliding particles has not a "sharp" value but varies from collision to collision
  → There is a spread of CMS energy
- The ee → $B\bar{B}$ cross section is not flat in energy but we run at Y4S resonance
  → B mesons have tendency to have energy closer to the Y4S mass, i.e. $\langle E_B^* \rangle \neq \langle E_{\mathrm{cm}} \rangle / 2$
- To correct for this effect, the Y4S resonance shape has to be known
  → Using data from BaBar 2009 Y4S resonance scan

$$R_b = N(B\bar{B})/N(\mu^+\mu^-)$$

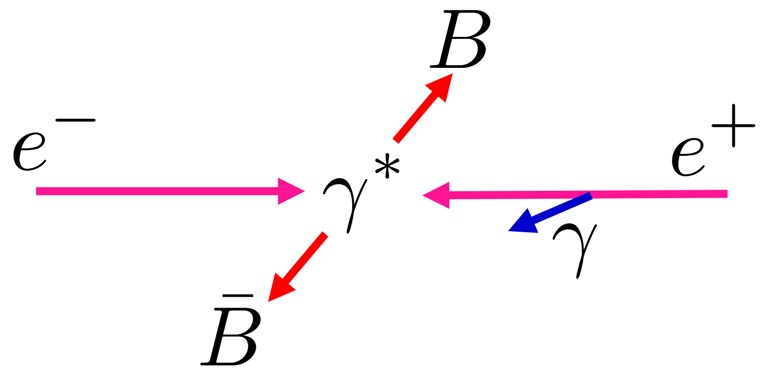


Time dependence of collision energy



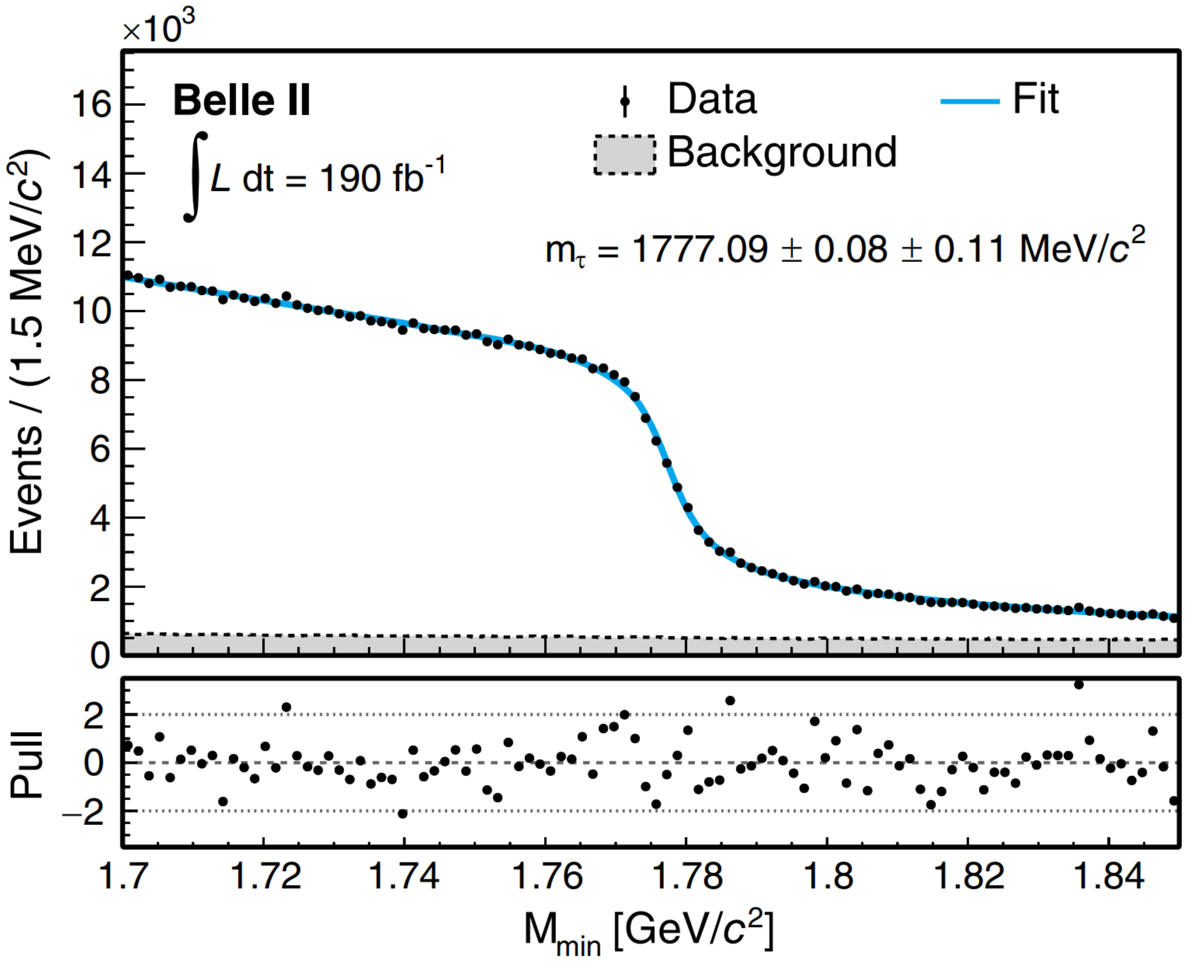
Uncorrected energy from

$$E_B^* = m_B + \frac{1}{2m_B}(p_B^*)^2$$



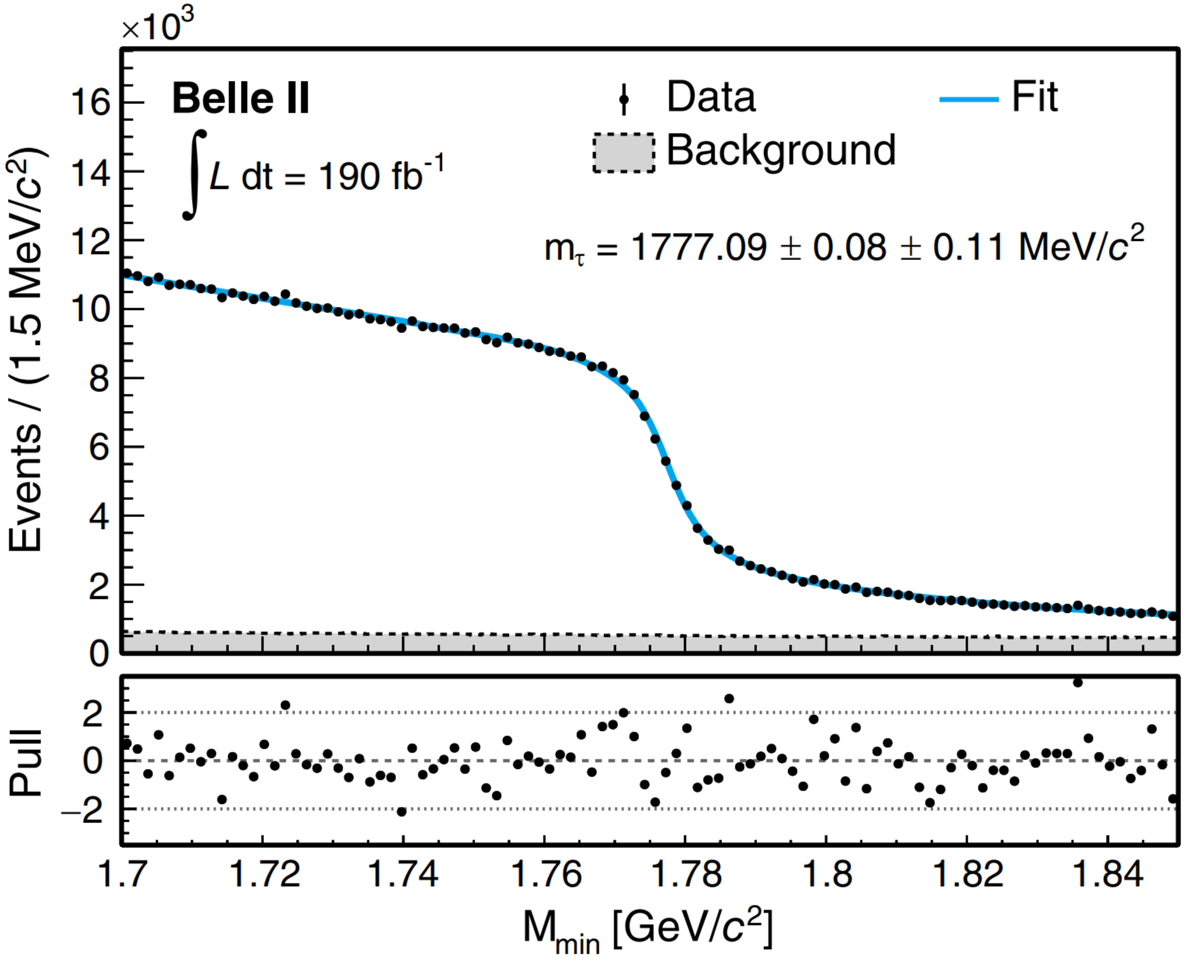
- + γ radiation correction
- ± Y4S shape correction

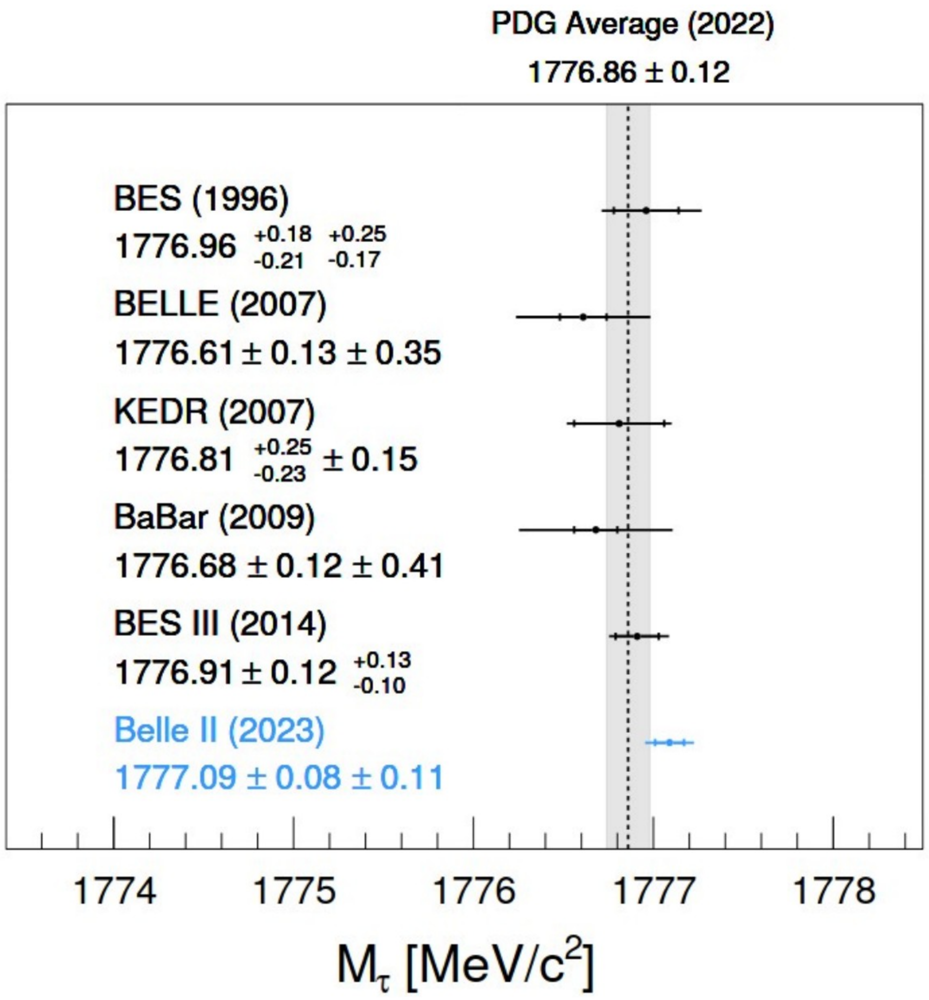
Belle II results



Source	Uncertainty [MeV/c^2]
Knowledge of the colliding beams:	
Beam energy correction	0.07
Boost vector	≤ 0.01
Reconstruction of charged particles:	
Charged particle momentum correction	0.06
Detector misalignment	0.03
Fitting procedure:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	≤ 0.01
Imperfections of the simulation:	
Detector material budget	0.03
Modeling of ISR and FSR	0.02
Momentum resolution	≤ 0.01
Neutral particle reconstruction efficiency	≤ 0.01
Tracking efficiency correction	≤ 0.01
Trigger efficiency	≤ 0.01
Background processes	≤ 0.01
Total	0.11

Belle II results





Conclusions

$$m_\tau = 1777.09 \pm 0.08 \pm 0.11\,\mathrm{MeV}/c^2$$

- Belle II m_τ determination has much higher accuracy than Belle / BaBar due to:
  → Better detector resolution
  → More advanced calibration procedures

- Belle II achieved even slightly better precision than BESIII (tau-factory)

- Substantial part of the m_τ uncertainty comes from external inputs, e.g. Y4S resonance shape & B mass