The tau lepton mass measured at Belle II

Radek Žlebčík
(on behalf of the Belle II Collaboration)

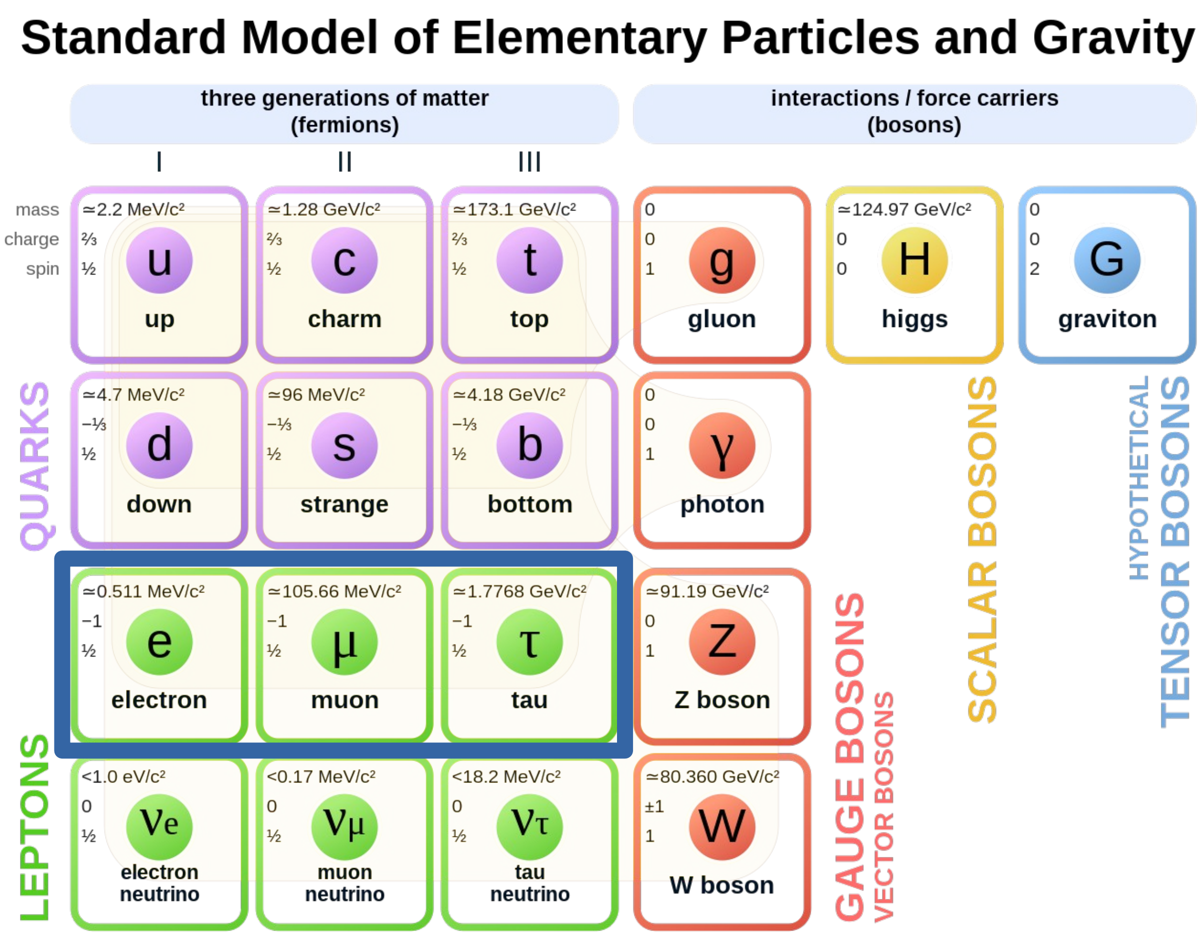
Dec 4, 2023
Louisville

Particle Zoo

Masses of leptons

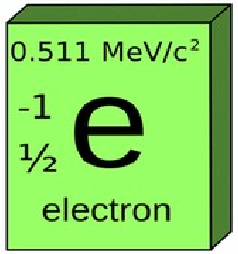
$$m_e = (0.51099895000 \pm 0.00000000015)\ \mathrm{MeV}$$
$$m_\mu = (105.6583755 \pm 0.0000023)\ \mathrm{MeV}$$
$$m_\tau = (1776.86 \pm 0.12)\ \mathrm{MeV}$$

PDG 2022

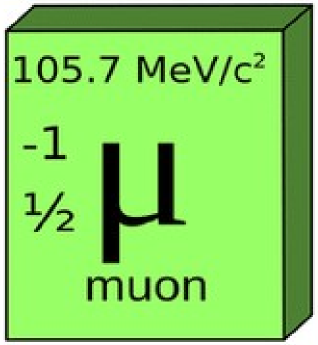


Relative precisions of masses

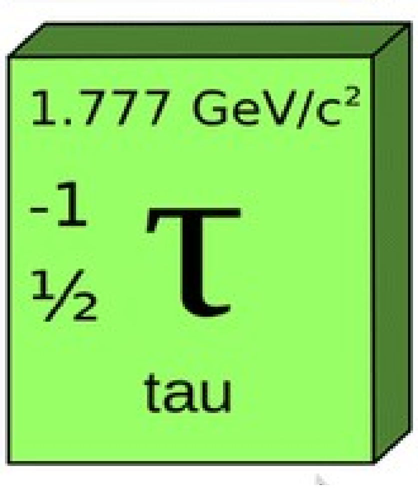
$$m_e = \frac{2R_\infty h}{c\alpha^2}$$



0.3 x 10^{-9}



22 x 10^{-9}



68000 x 10^{-9}

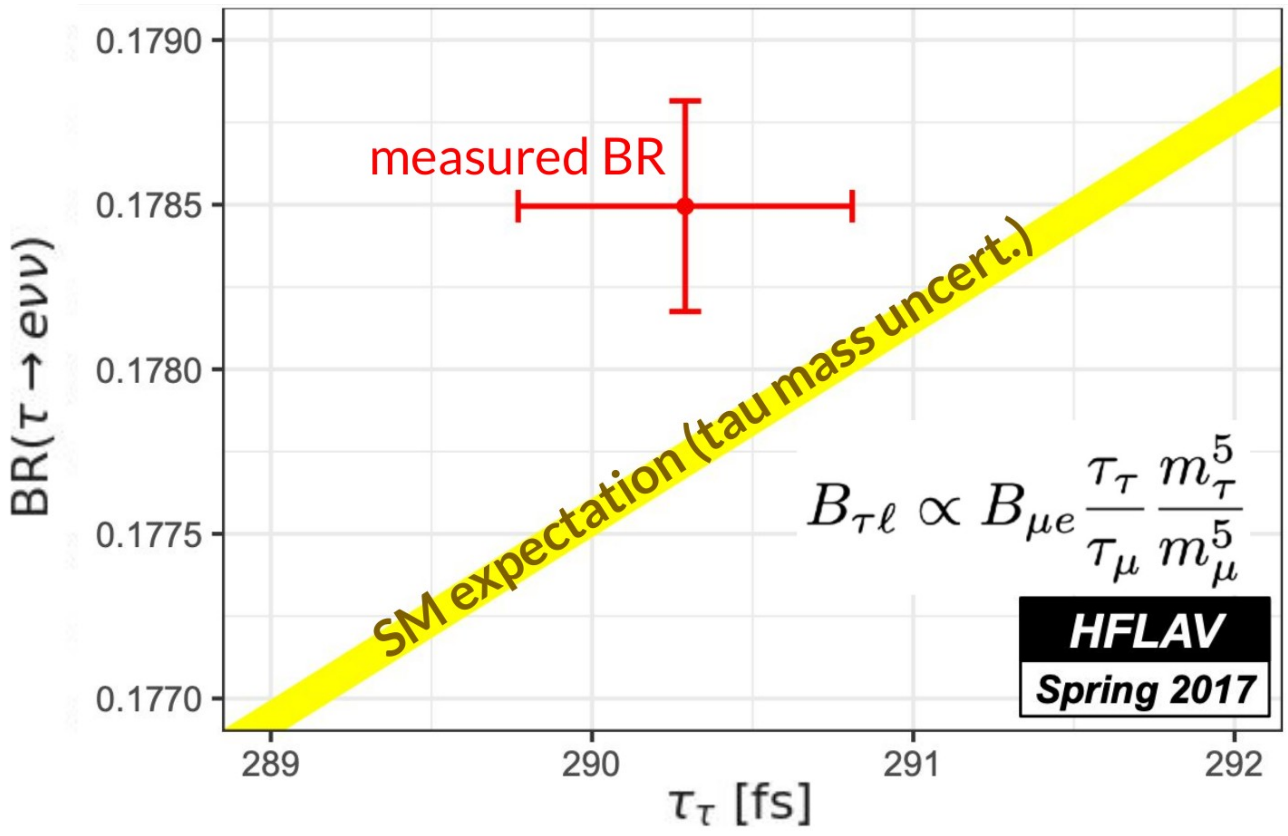
36 x 10^{-9}

Needed precision

300 USD

Lepton flavor universality & tau lepton mass

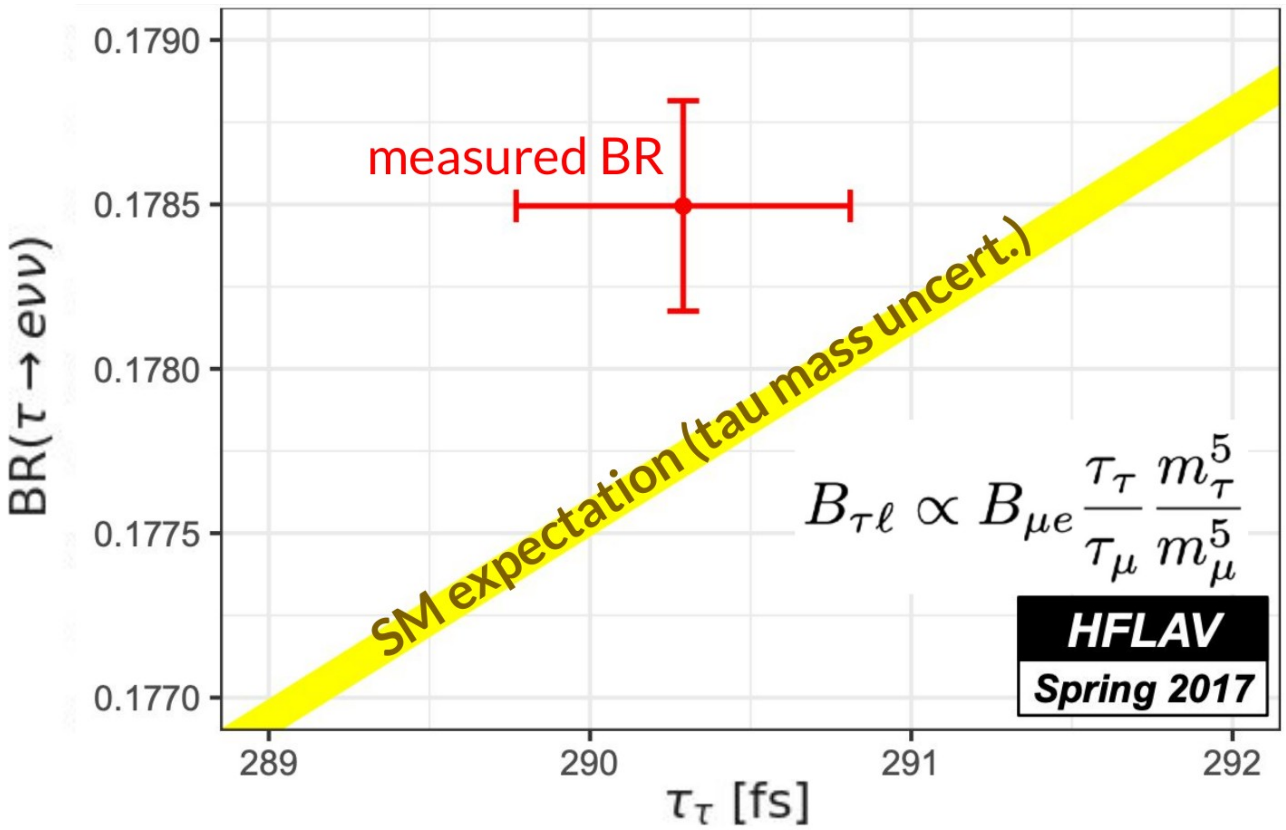
$$BR = \frac{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e) = \dfrac{G_F^2 m_\tau^5}{192\pi^3}}{(\tau \text{ lifetime})^{-1}}$$



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

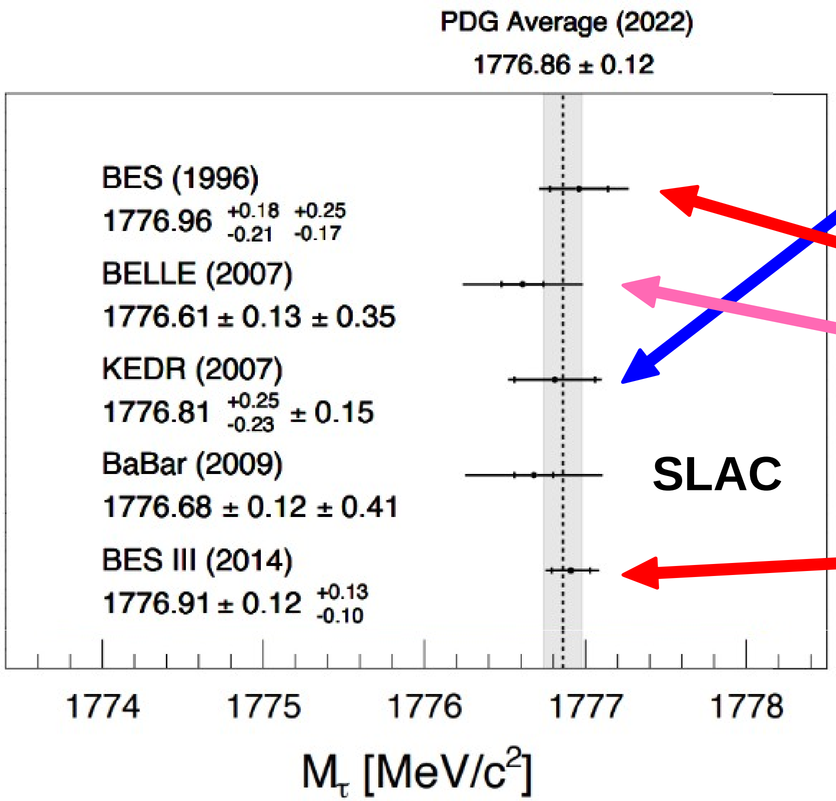
Lepton flavor universality & tau lepton mass

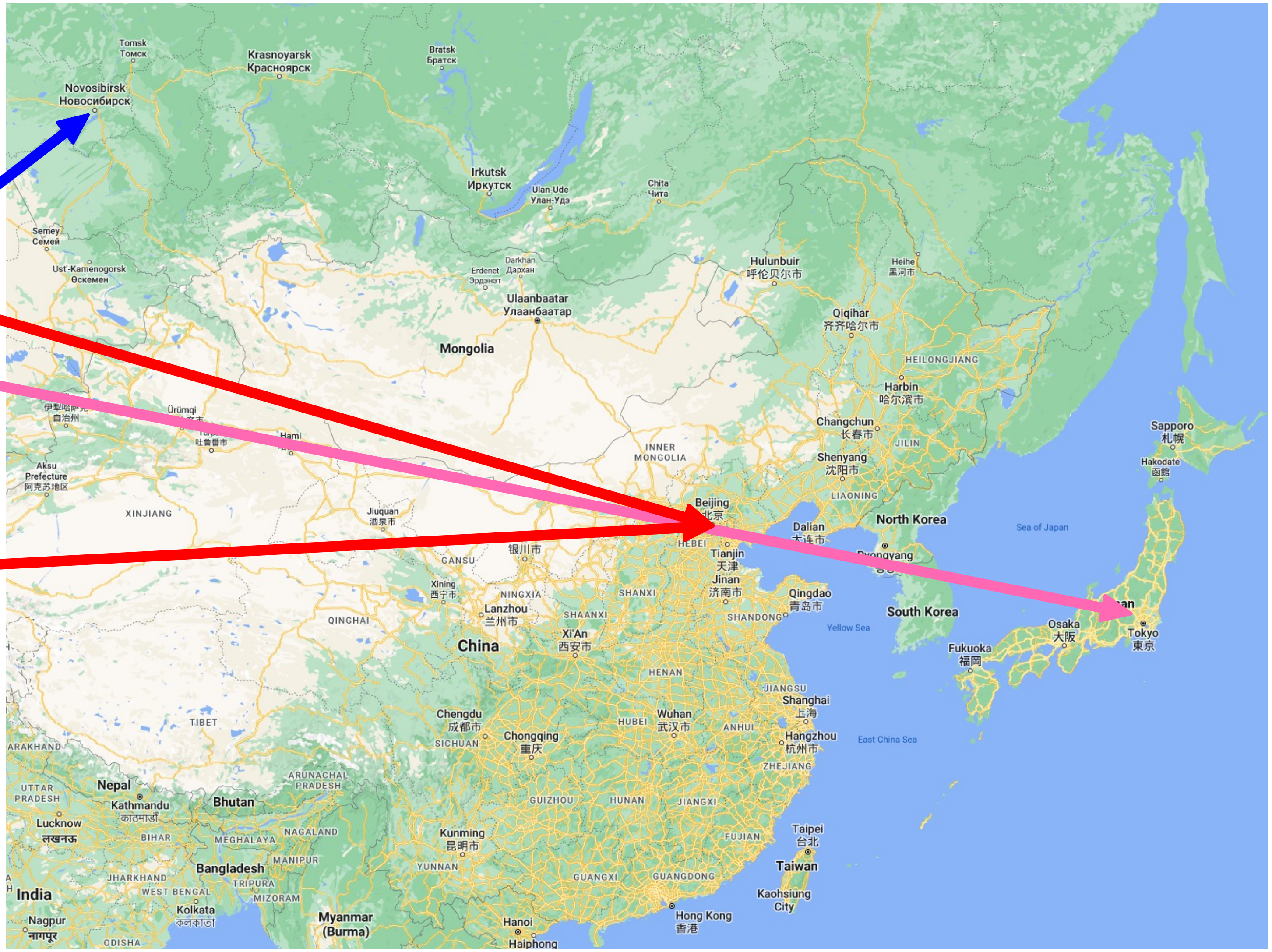
$$\mathrm{BR} = \frac{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e) = \dfrac{G_F^2 m_\tau^5}{192\pi^3}}{(\tau\ \text{lifetime})^{-1}}$$



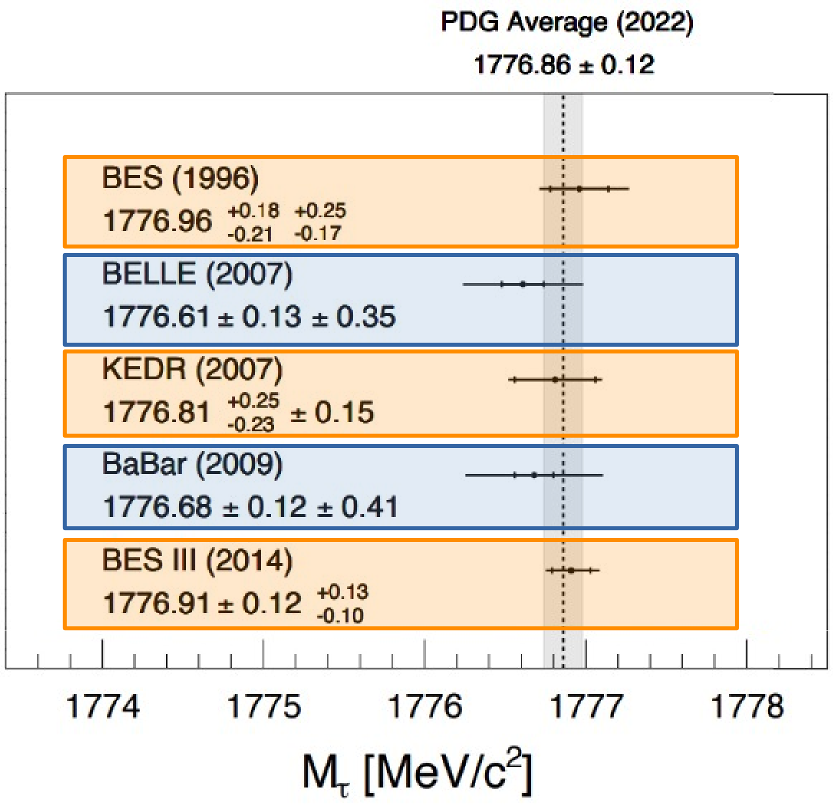
Tau lepton mass is exciting on its own!

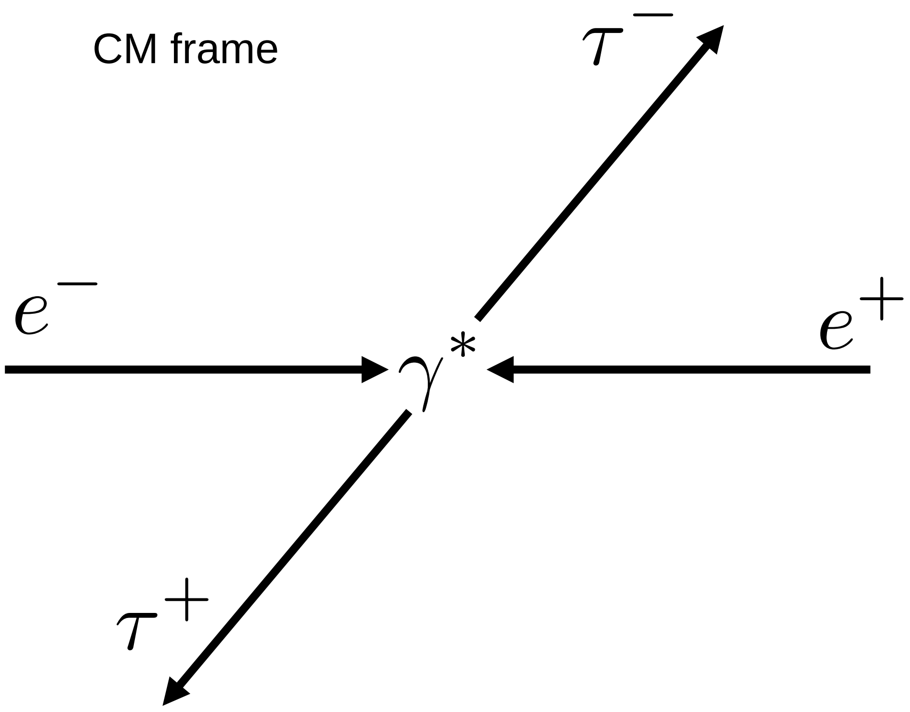
Previous measurements





Methods





B factories : E_{cms} = 10.58 GeV

τ factories : E_{cms} = 3.56 GeV

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 70% *Phys.Rev.D 90 (2014)*

Systematic uncertainties of the tau mass

B factories

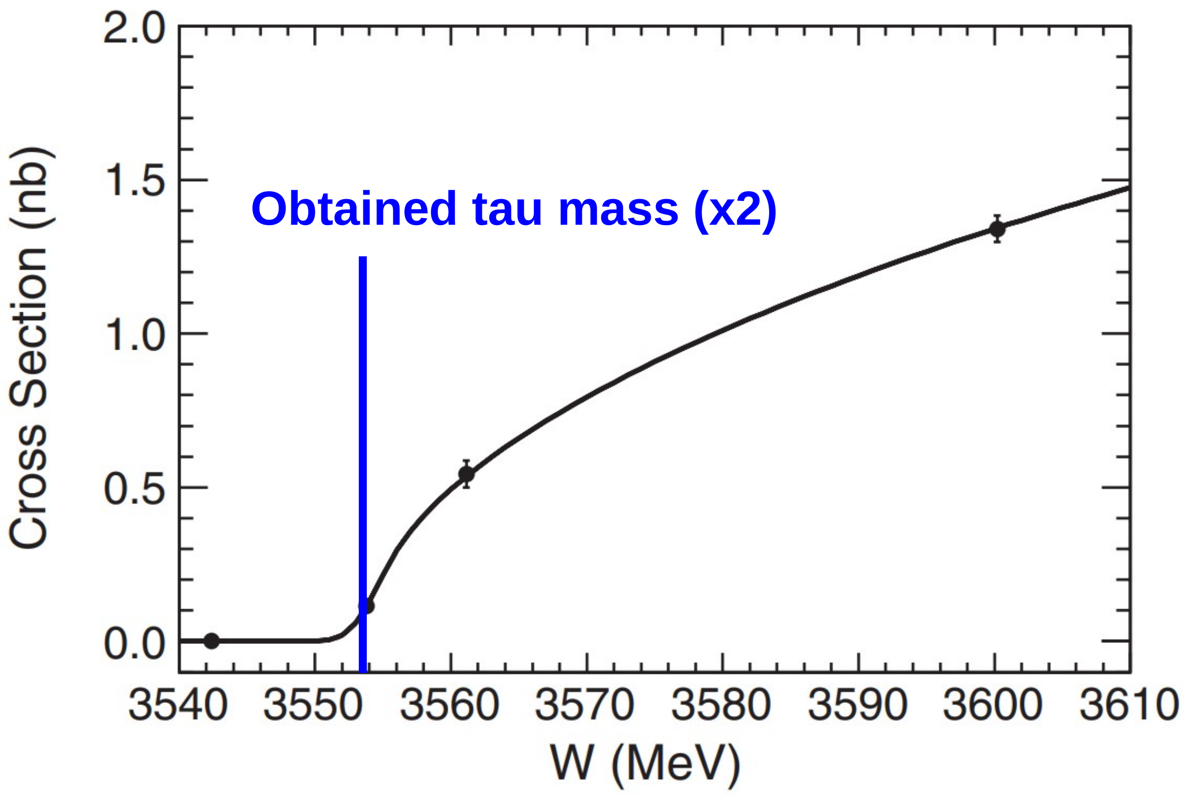
Source	Uncertainty (MeV)
Momentum Reconstruction	0.39
CM Energy	0.09
MC Modeling	0.05
MC Statistics	0.05
Fit Range	0.05
Parameterization	0.03
Total	**0.41**

BaBar 98% *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 74% *Phys.Rev.Lett. 99 (2007)*

BES III method



BESIII (τ factory)

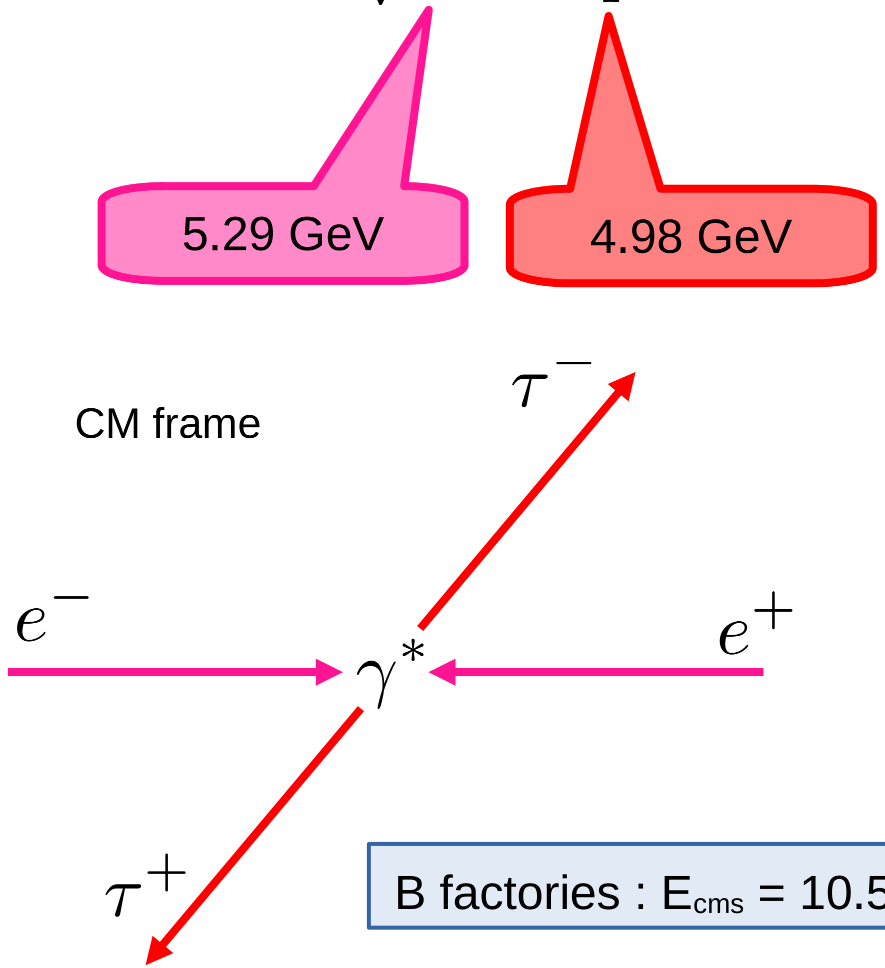
Source	Δm_τ (MeV/c^2)
Theoretical accuracy	0.010
Energy scale	$^{+0.022}_{-0.086}$
Energy spread	0.016
Luminosity	0.006
Cut on number of good photons	0.002
Cuts on PTEM and acoplanarity angle	0.05
mis-ID efficiency	0.048
Background shape	0.04
Fitted efficiency parameter	$^{+0.038}_{-0.034}$
Total	$^{+0.094}_{-0.124}$

BES III 70% *Phys.Rev.D 90 (2014)*

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

Challenges for B factories

$$m_\tau = \sqrt{E^2 - p^2}$$



B factories : E_{cms} = 10.58 GeV

BaBar (B factory)

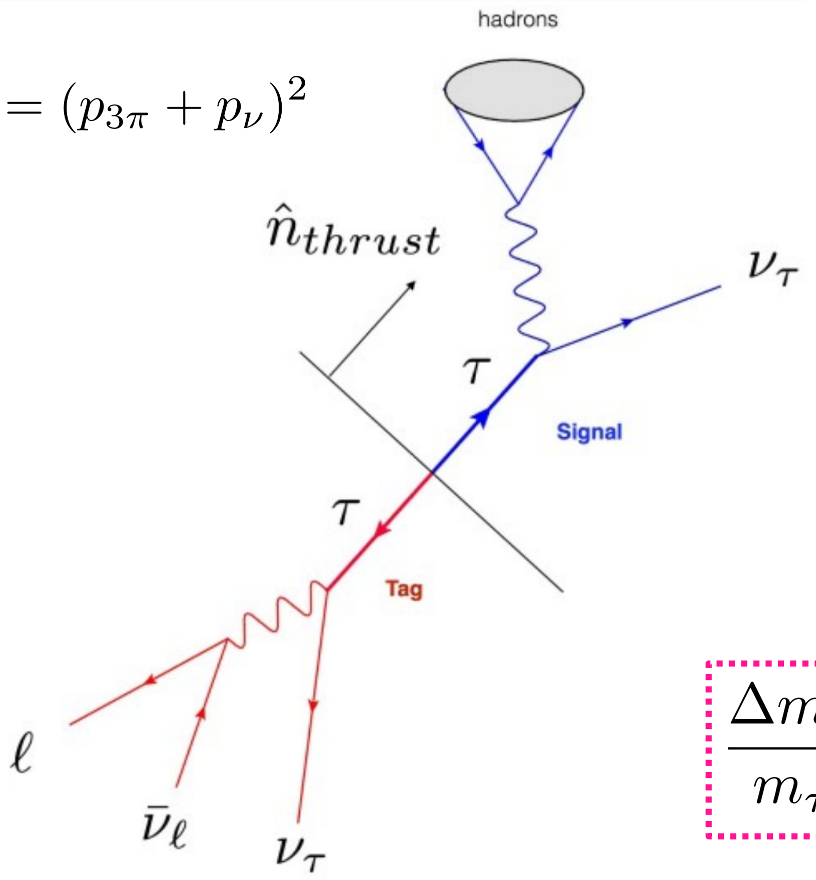
Source	Uncertainty (MeV)
Momentum Reconstruction	0.39
CM Energy	0.09
MC Modeling	0.05
MC Statistics	0.05
Fit Range	0.05
Parameterization	0.03
Total	**0.41**

BaBar 98% *Phys.Rev.D 80 (2009)*

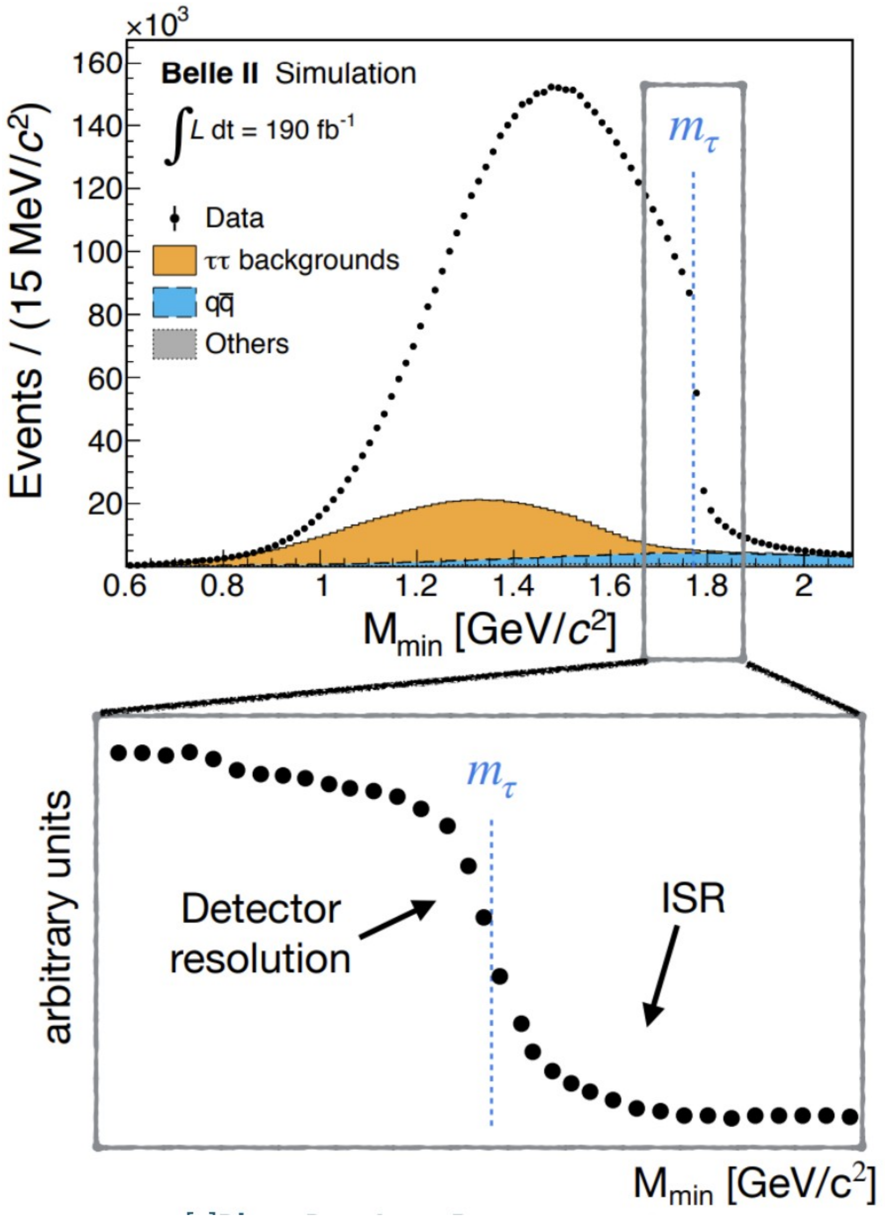
Pseudo-mass

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

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



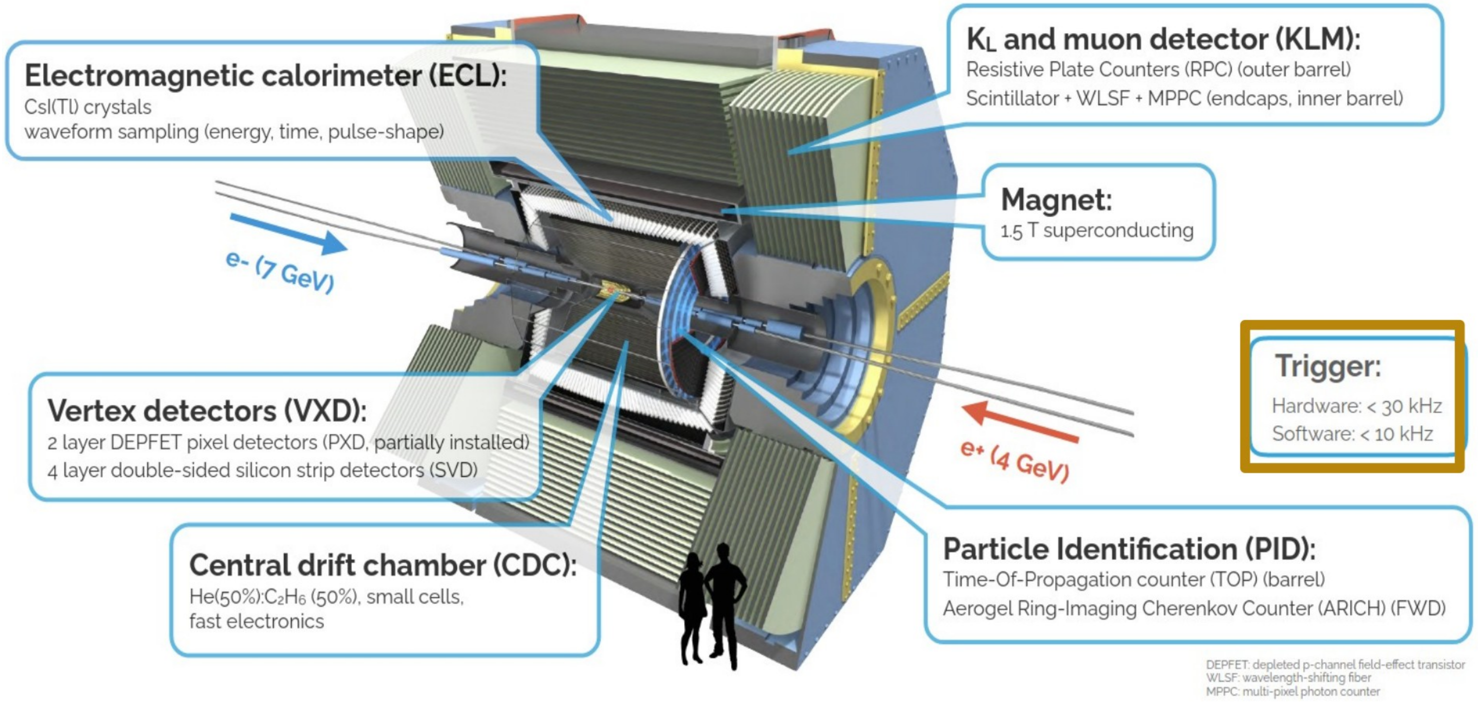
$$\frac{\Delta m_\tau}{m_\tau} \approx \frac{1}{2}\frac{\Delta\sqrt{s}}{\sqrt{s}}$$



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
- Data taking is getting restarted
  (LS1 July 2022 - November 2023)
- Accumulated 424 fb^{-1}
  (190 fb^{-1} used in the tau-mass analysis)



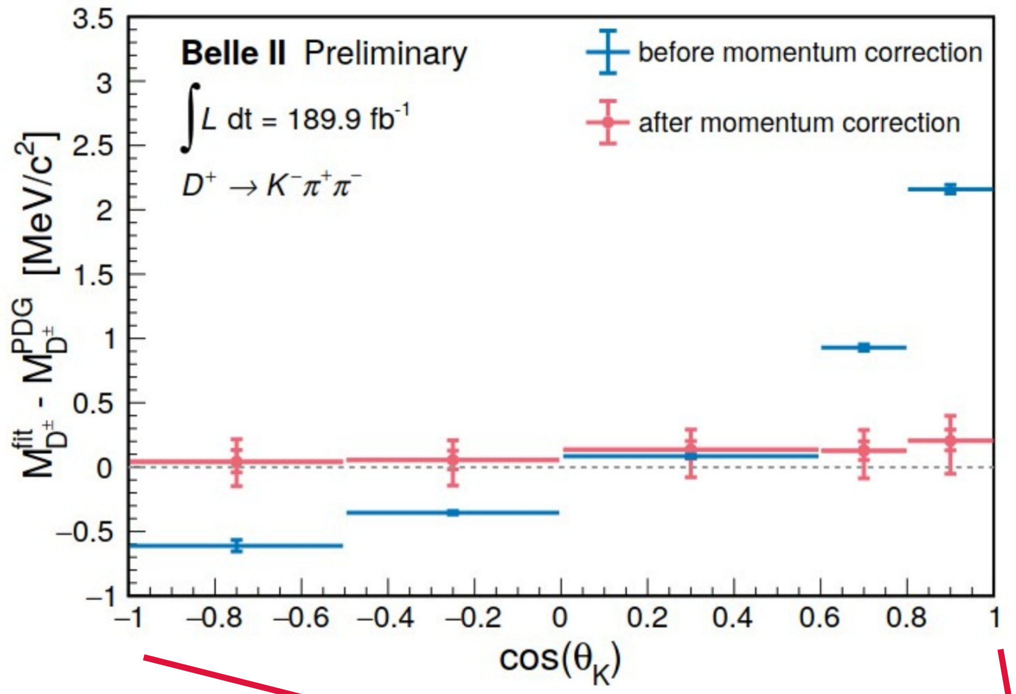
The z-axis of the coordinate system points towards electron momentum

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
- Systematic uncertainties:
  → $m(D^0)$ PDG uncertainties
  → peak position modeling
  → detector misalignment



Tau mass unc. from momentum-scale
0.39 MeV (BaBar) → 0.07 MeV (Belle II)

Validation channels:

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

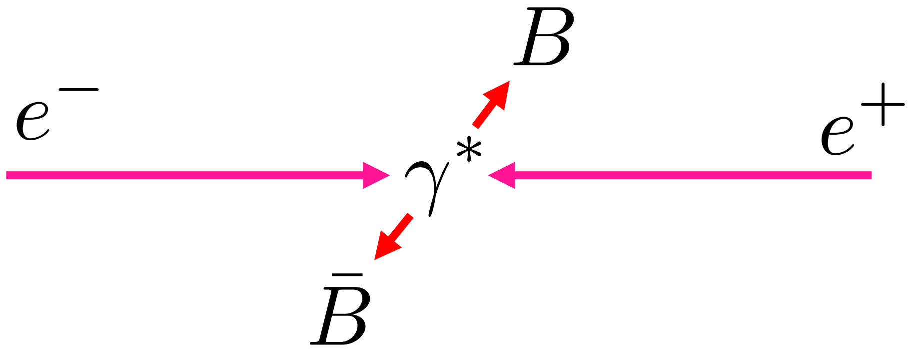
Calibration of the collision energy

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

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

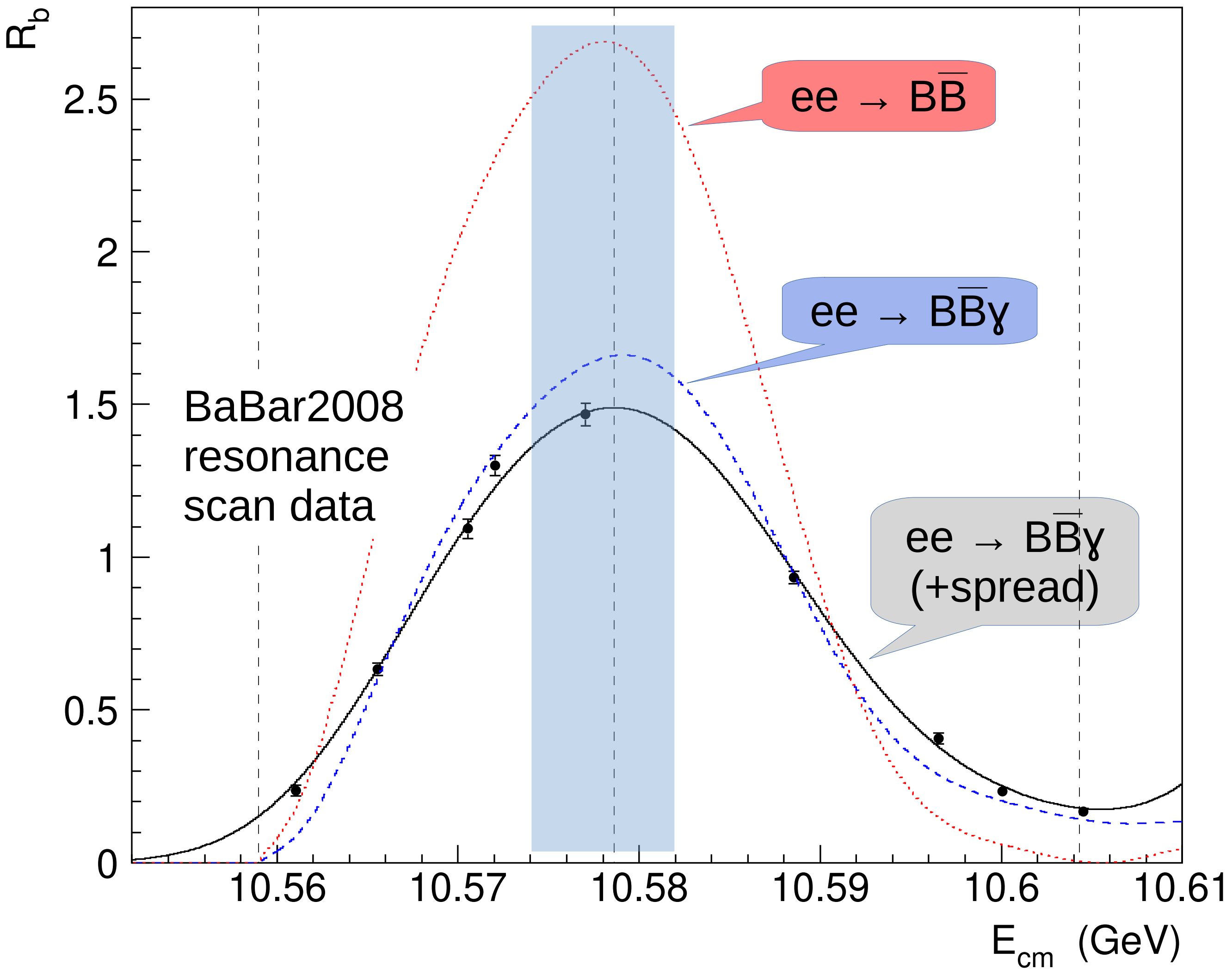
From LHCb
Precision: 4 x 10^{-5}

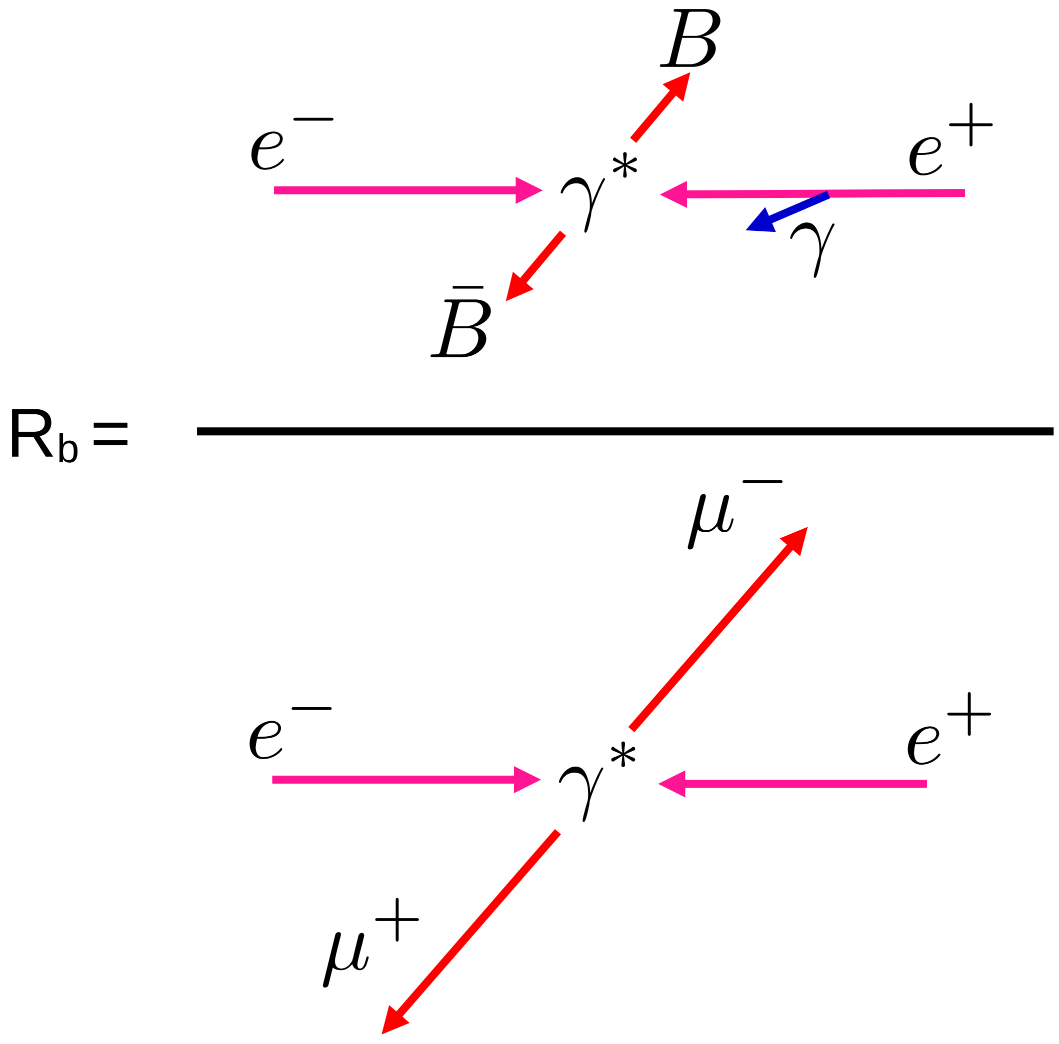
Our business



Y4S resonance

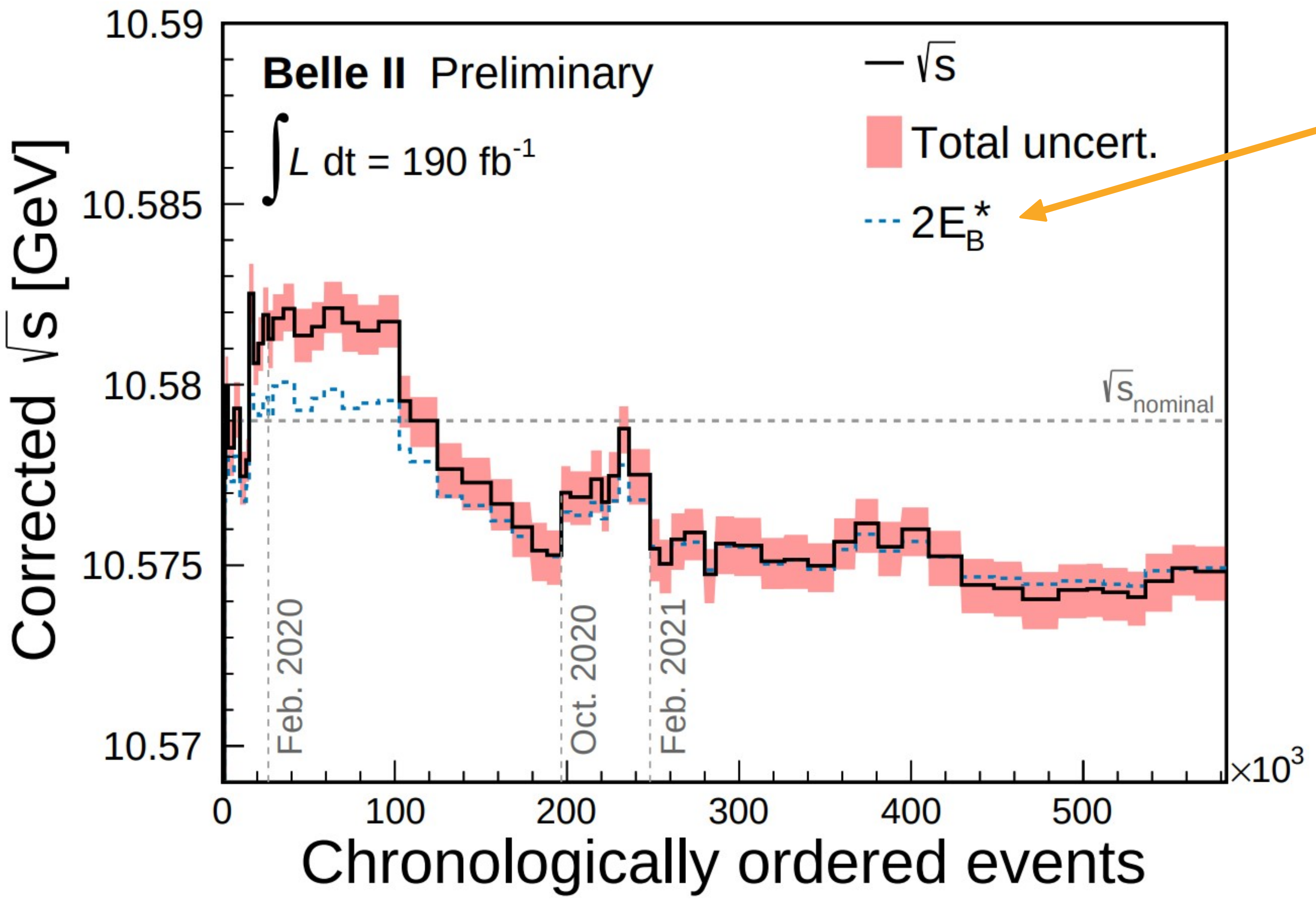
$$R_b = N(B\bar{B})/N(\mu^+\mu^-)$$





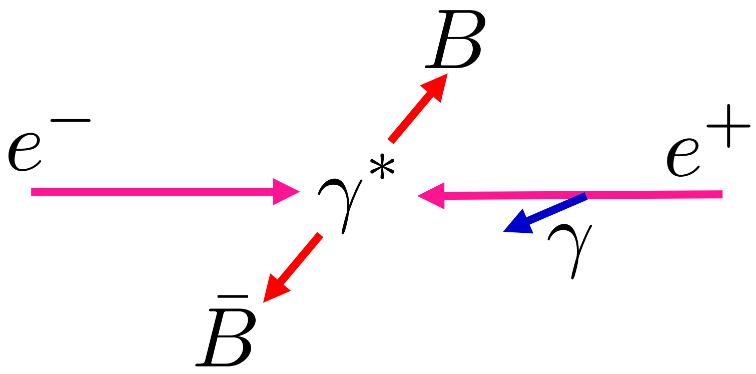
Mean B meson energy biased towards $M(Y_{4S})$ due to beam energy smearing

Time dependence of collision energy



Uncorrected energy from

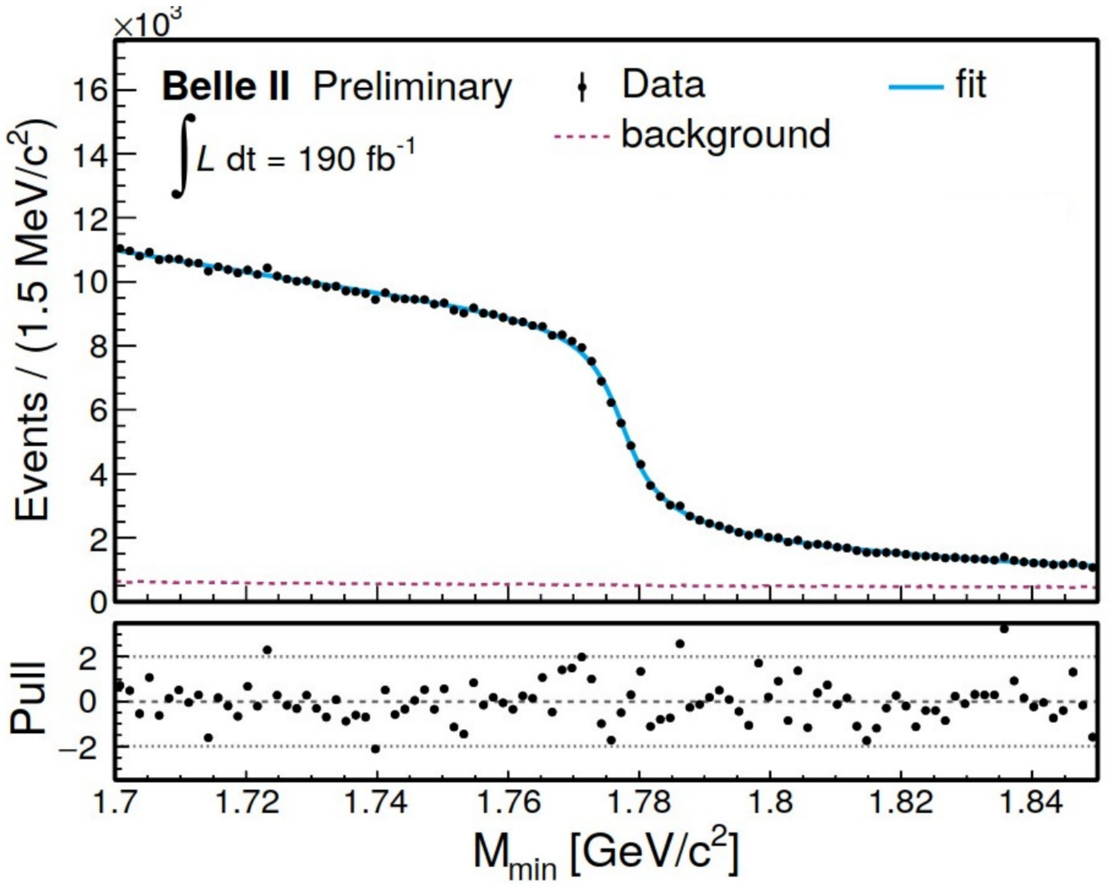
$$E_B^* = m_B + \frac{1}{2m_B}(p_B^*)^2$$



+ γ radiation correction

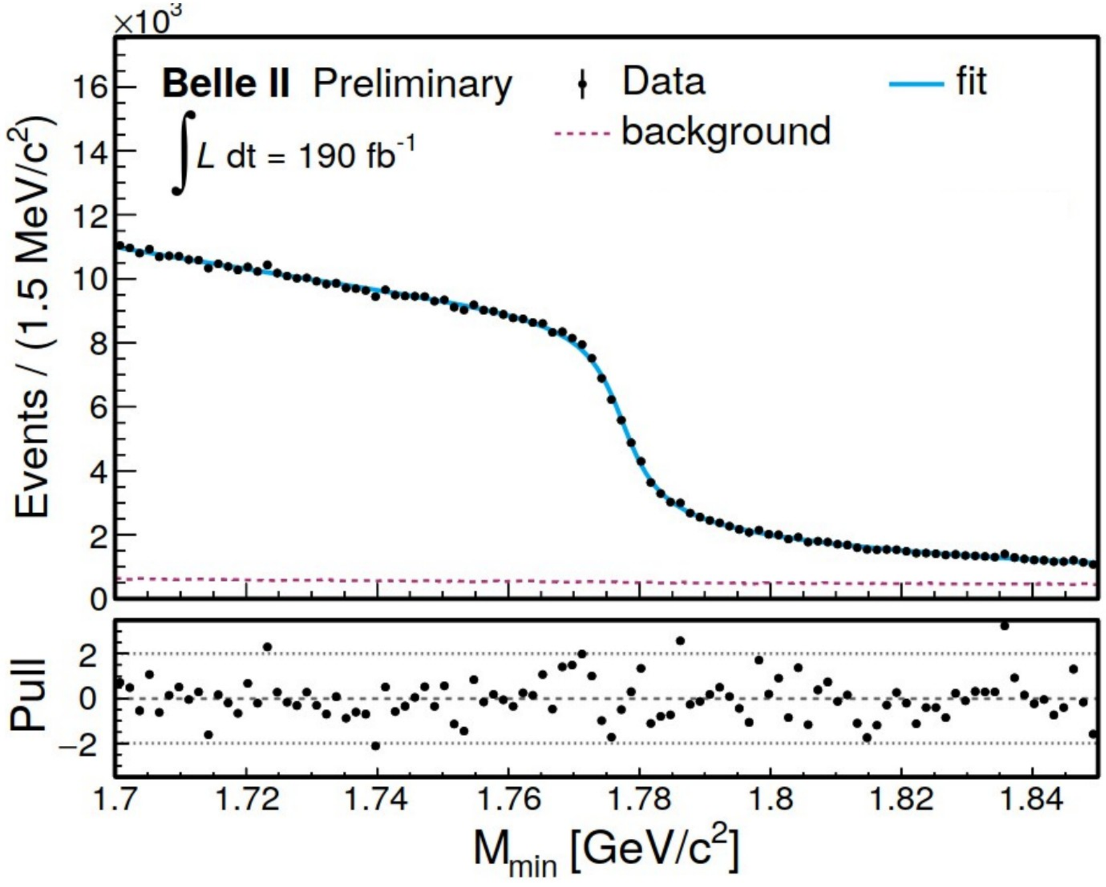
± Y4S shape correction

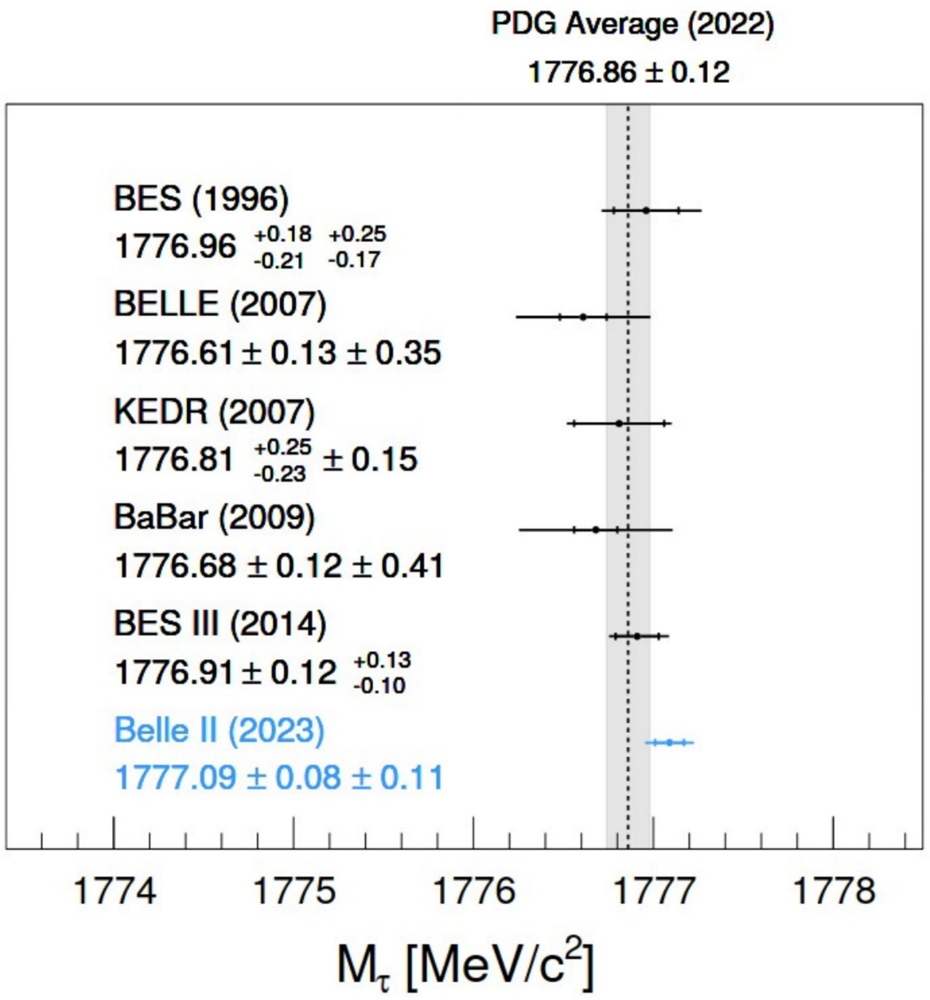
Belle II results



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
- 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
  $\rightarrow$ plan to reduce external-input dependence