The Tau

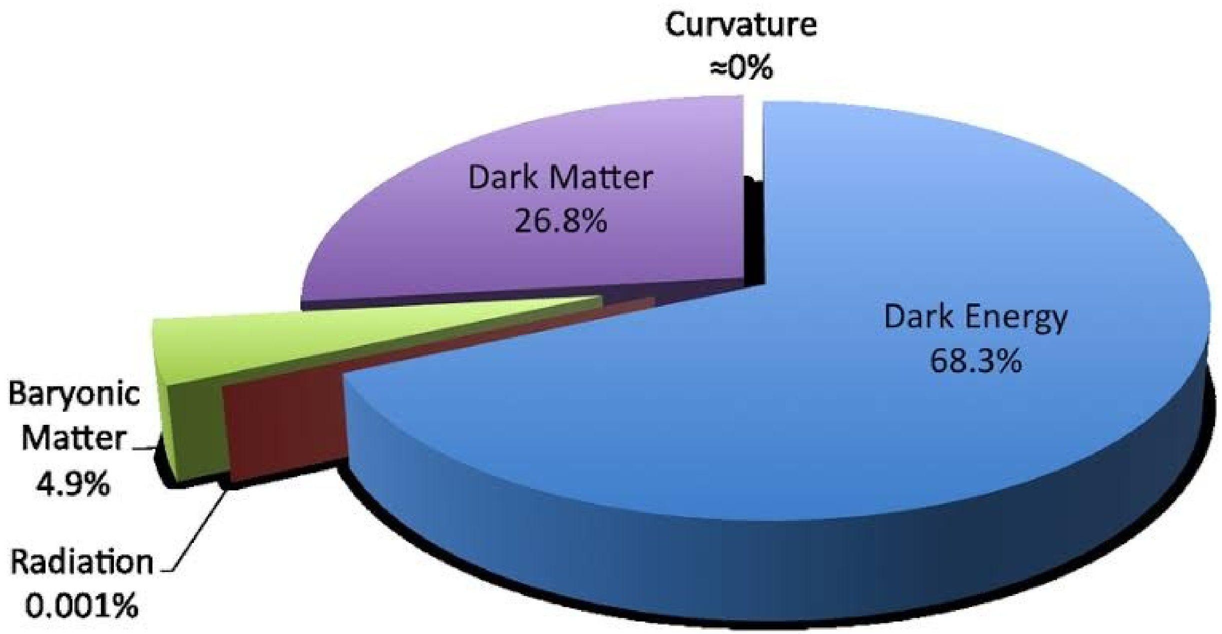
Radek Žlebčík

22.6.2023

FZU Division seminar

Particle Zoo

Mysteries of the Universe

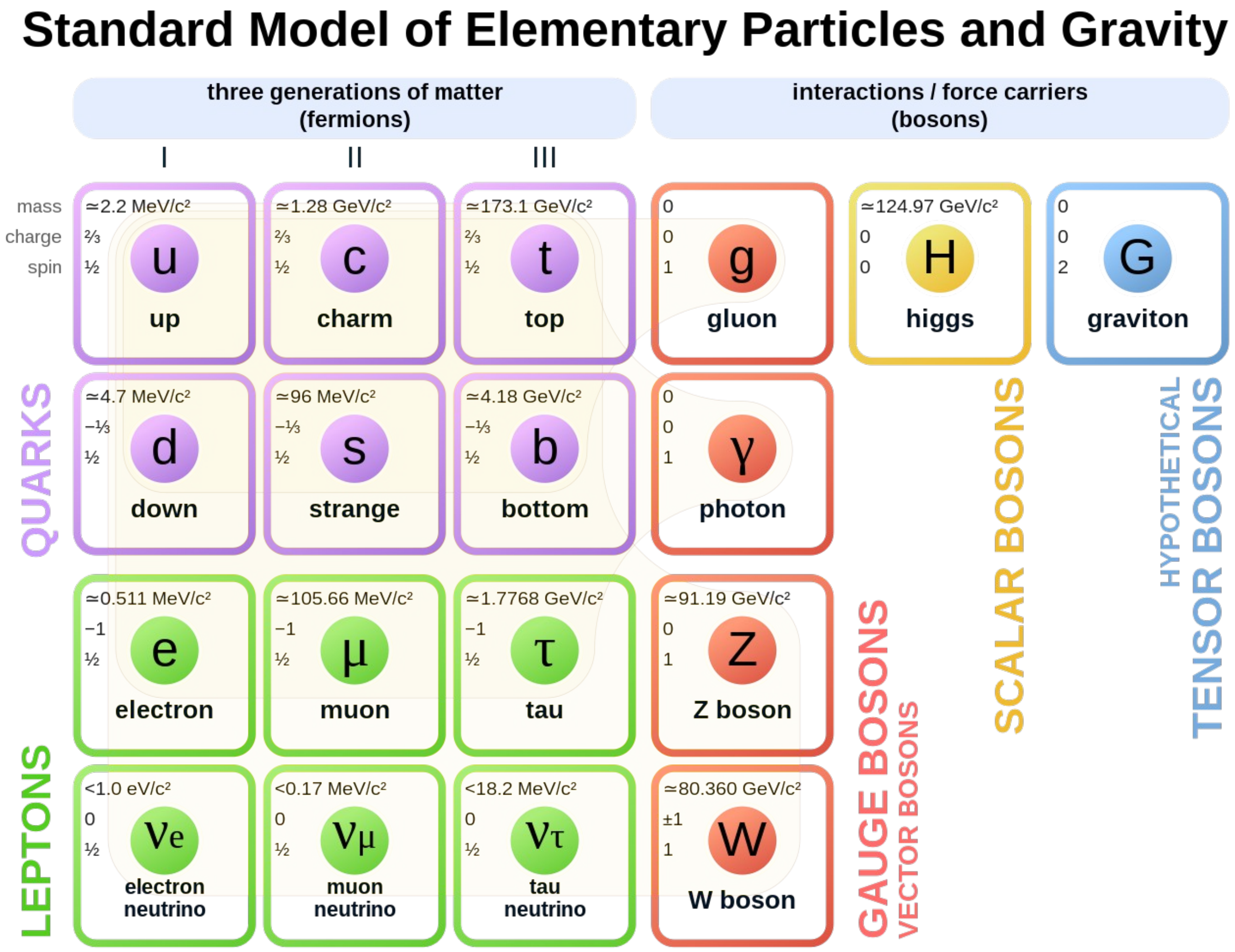


Dark Matter

- At large scale within Λ-CDM universe
- At smaller scale – galaxy rotation curves

Phenomena out of the Standard Model

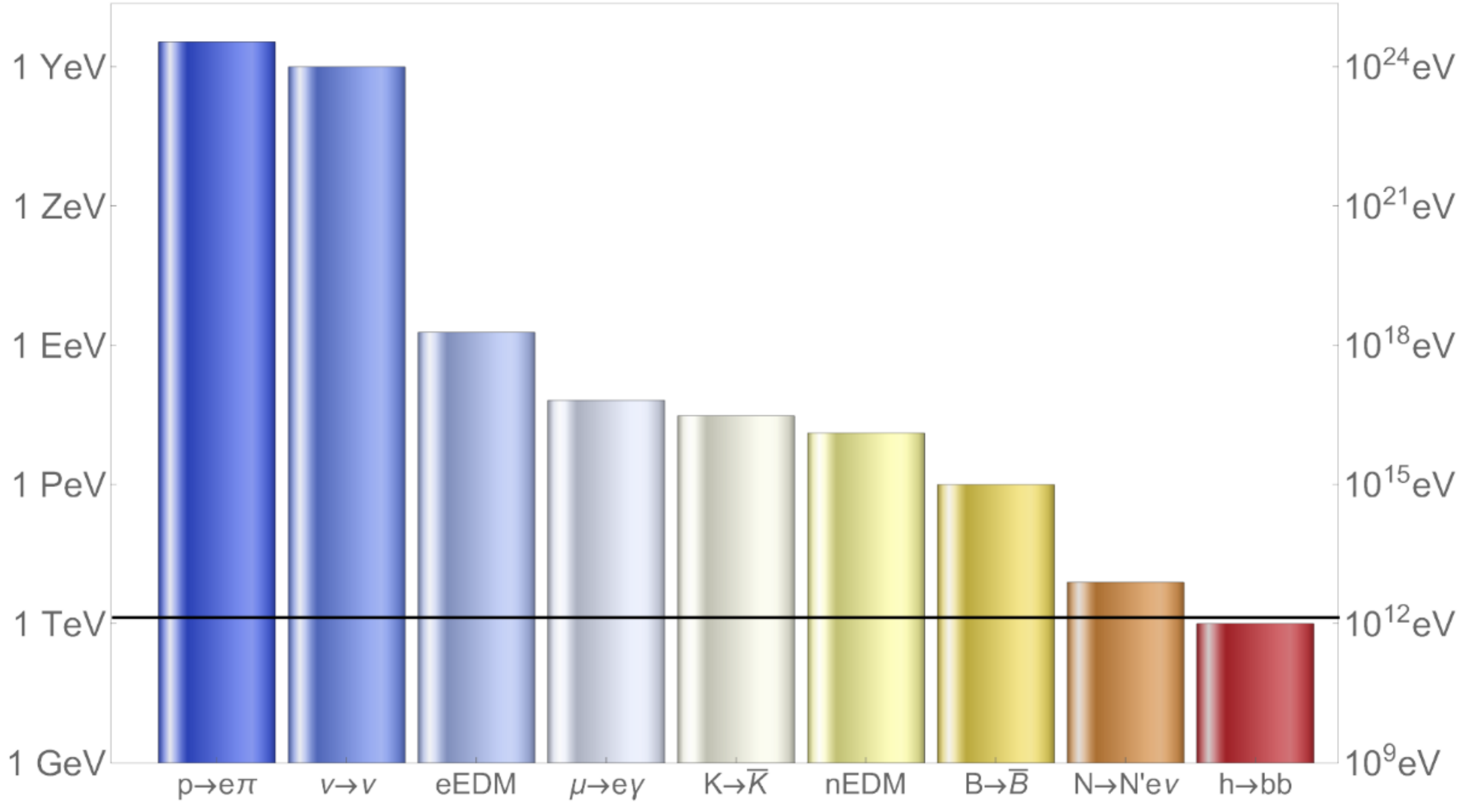
- **Gravity**
- **Dark matter**
- **Dark Energy**
- **Neutrino masses**
- **Matter-antimatter asymmetry**



Searching for Beyond Standard Model phenomena

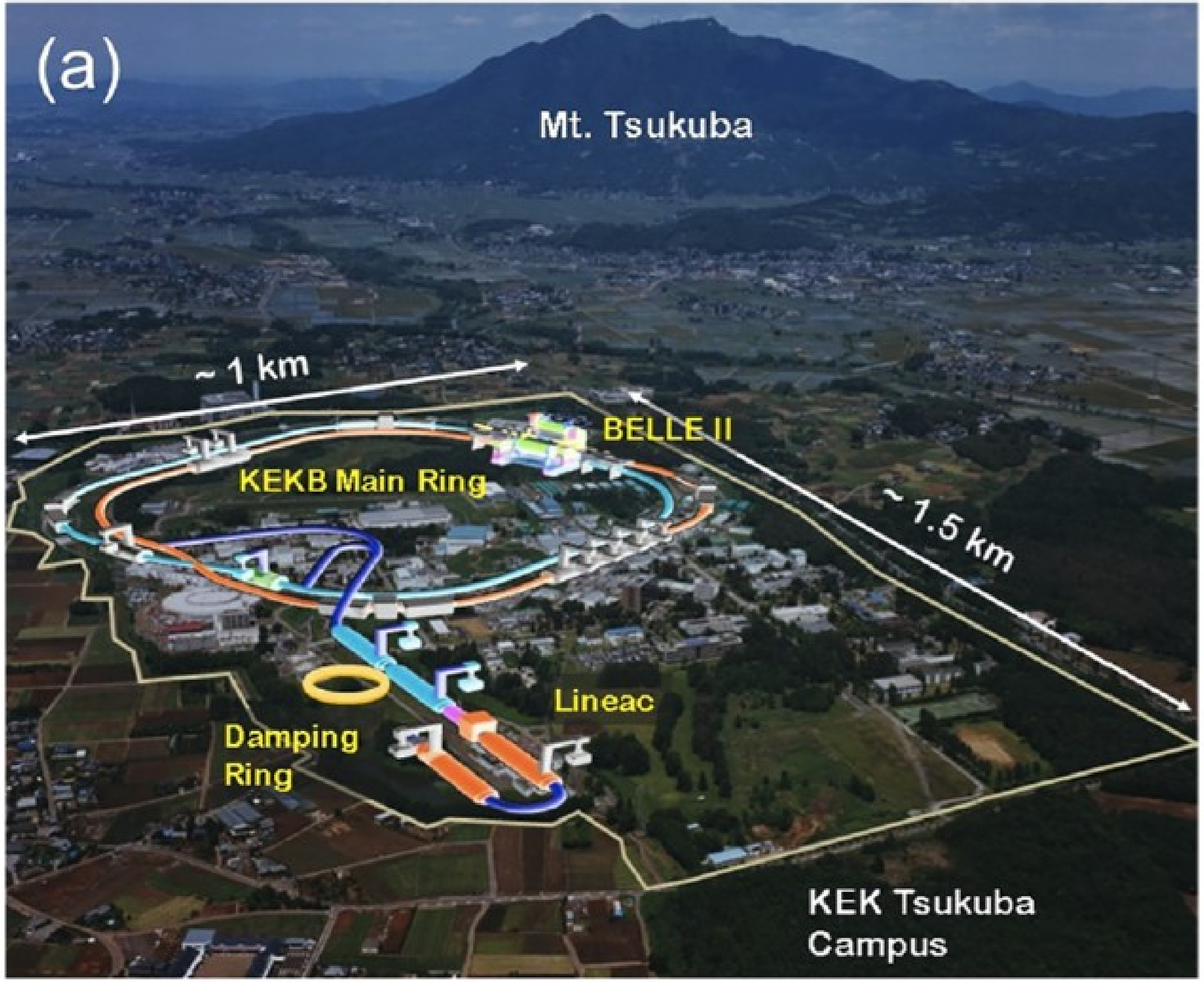
Direct approach
(producing BSM particle)

Indirect approach
(spotting traces of BSM)

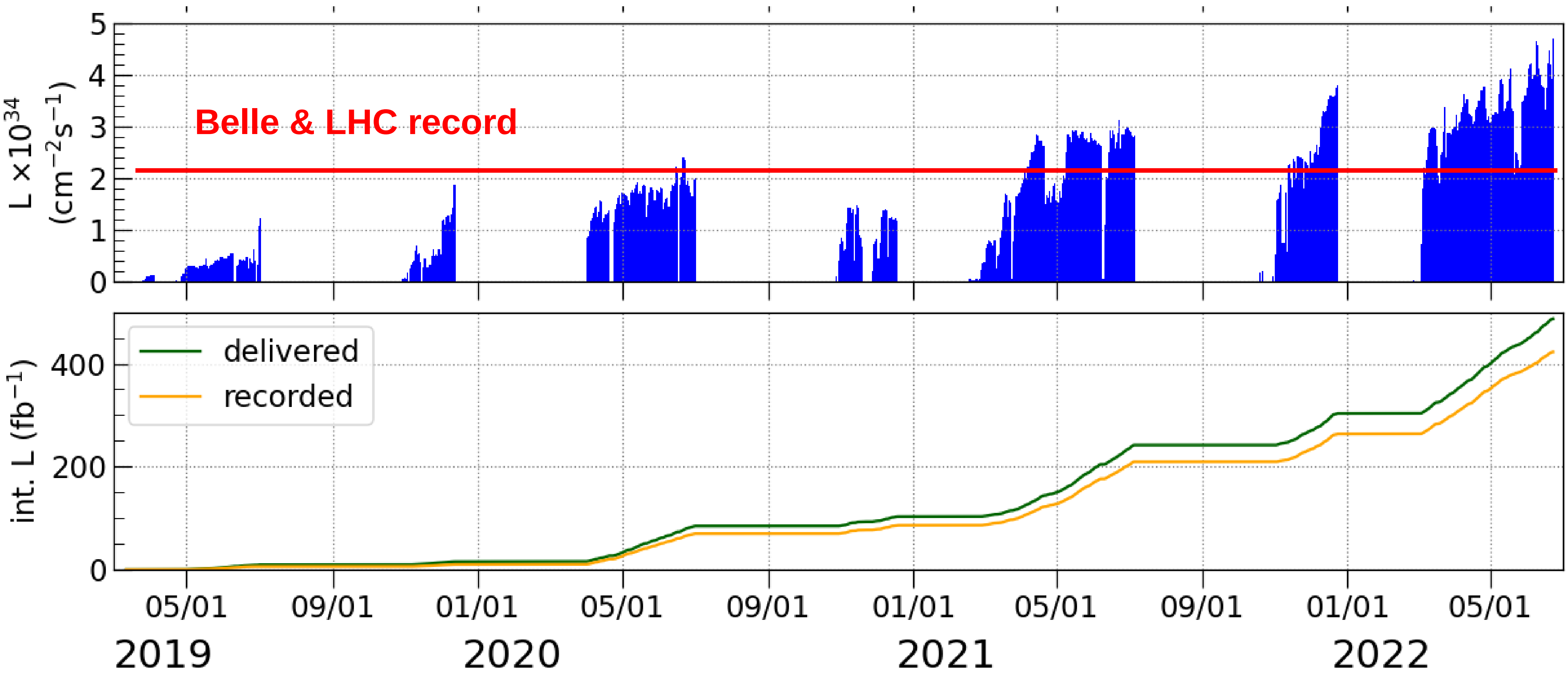


Direct searches at LHC

Belle II – Indirect way

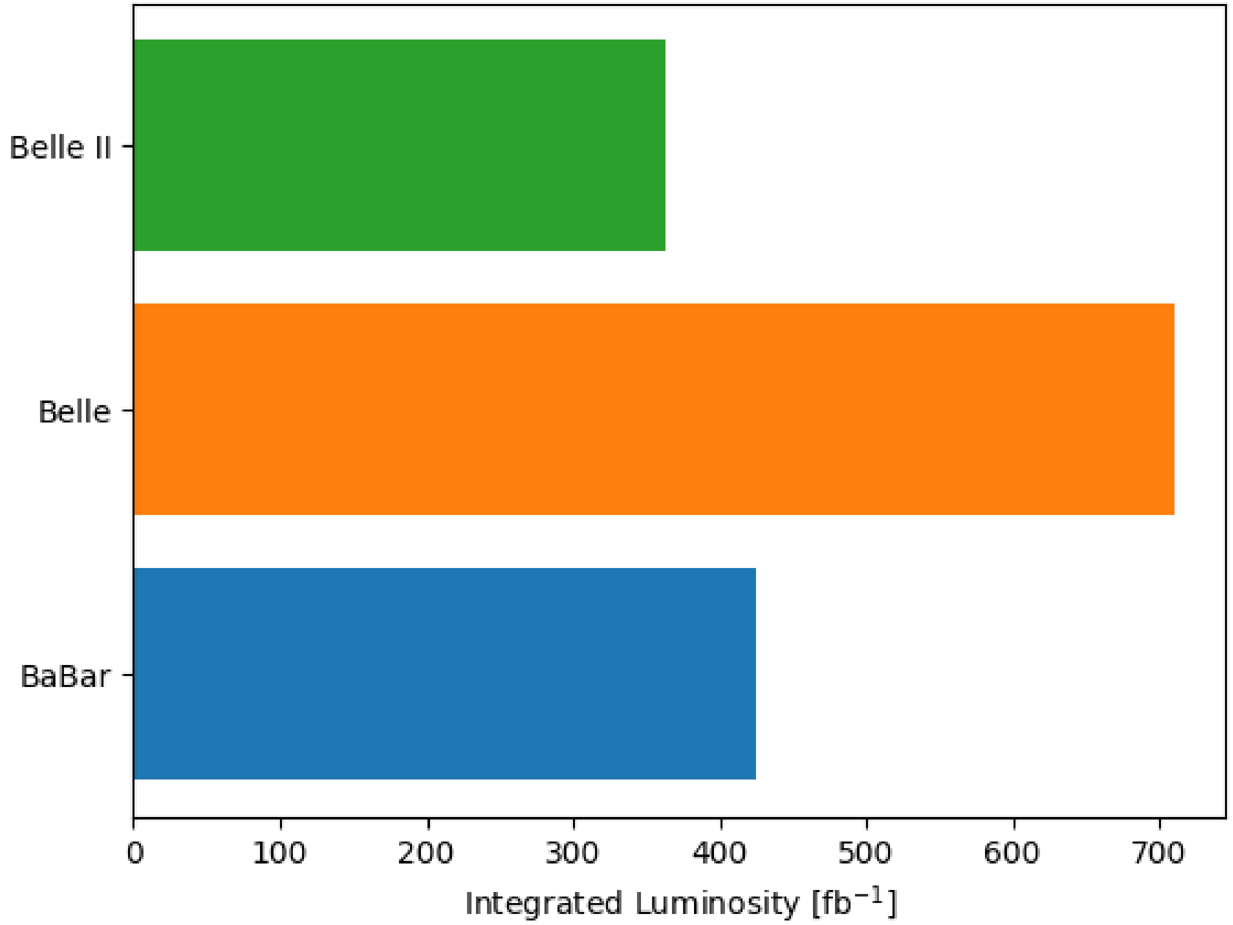


Belle II – Intensity frontier



Belle II – Intensity frontier

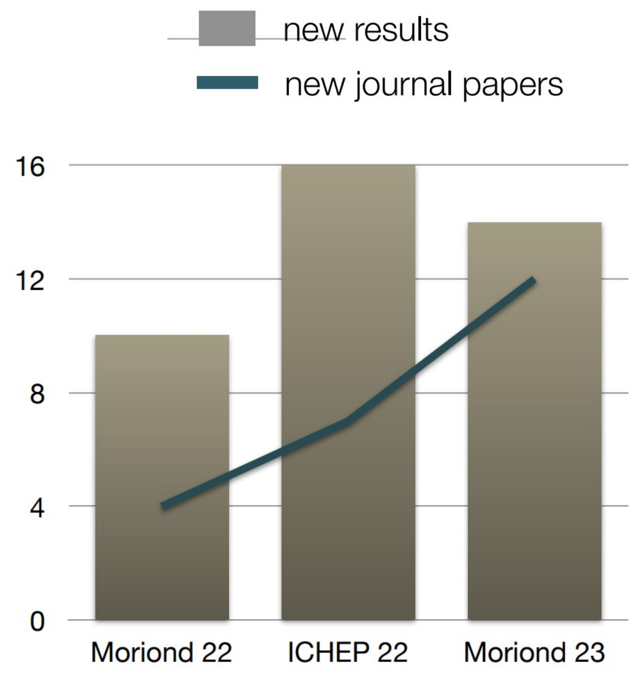
LHCb
9 fb^{-1}



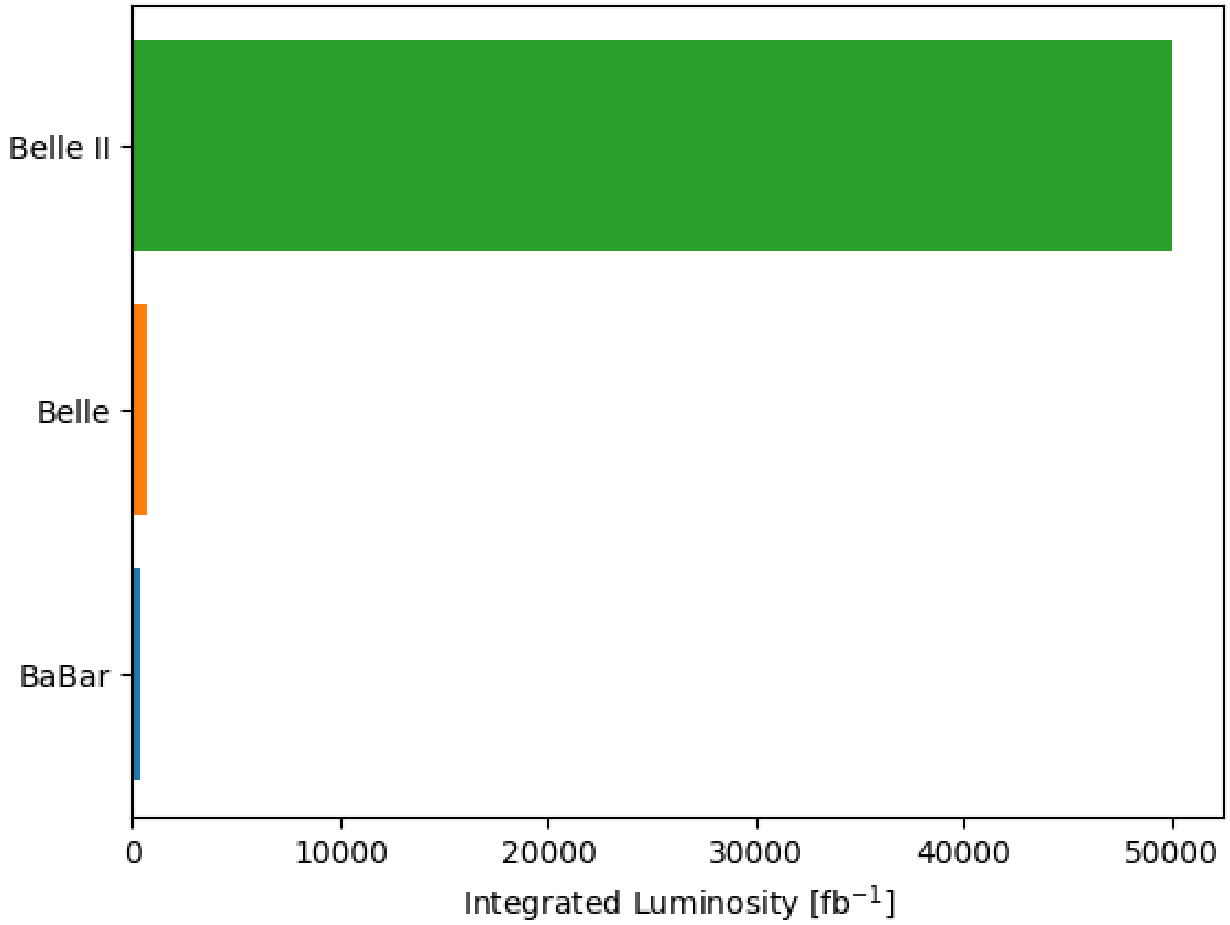
First generation
of B factories

Belle II results in last 16 months

Measurement of the Ds mass — world leading, arXiv: 2306.00365
Energy-dependence of *B(*)B(*)*bar cross section — unique
Observation of *ee* → $\omega\chi b$ at 10.75 GeV — unique, PRL. **130**, 091902 (2023)
Test of light-lepton universality in $B \to D^{*}\ell\nu$ decays — unique
Test of light lepton universality in inclusive $B \to [Xc]\ell\nu$ decays — unique, arXiv: 2301.08266. Accepted
Measurement of CKM angle γ using GLW — Belle + Belle II sample
Measurement of CKM angle γ using GLS — Belle + Belle II sample, arXiv: 2306.02940
Search for long-lived spin-0 mediator in b → s transitions— world leading, arXiv: 2306.02830
Measurement of of the τ mass — world leading, arXiv: 2305.19116
BF and ACP in $B^0 \to h^+h^{0-}$ decays and isospin sum rule — world leading
BF and ACP of $B^0 \to \pi^0\pi^0$ decays — competitive, arXiv: 2303.08354. Accepted
ACP in $B^0 \to K^0_S K^0_S K^0_S$
|Vcb| using untagged $B \to D^{*}\ell\nu$ decays — competitive
CPV in $B^0 \to K^0\pi^0$ decays — competitive, arXiv: 2305.07555
CPV in $B^0 \to \phi K^0_S$
Novel method for charm flavor tagging — unique, arXiv: 2304.02042. Accepted
B^0 lifetime and oscillations in $B^0 \to D^{(*)}h$ decays PRD **107**, L091102 (2023)
Search for a dark-sector ττ resonance in ee → mumu ττ decays — world leading
Search for a dark-sector Z' to invisible — world leading, PRL **130**, 231801 (2023)
Search for $\tau \to \ell\alpha$ — world leading PRL **130**, 181803 (2023)
Search for a dark γ and invisible darkHiggs in μμ+MET— world leading, PRL **130**, 071804 (2023)
Measurement of the Ω^0_c lifetime — PRD **107**, L031103 (2023)



Belle II – Future?



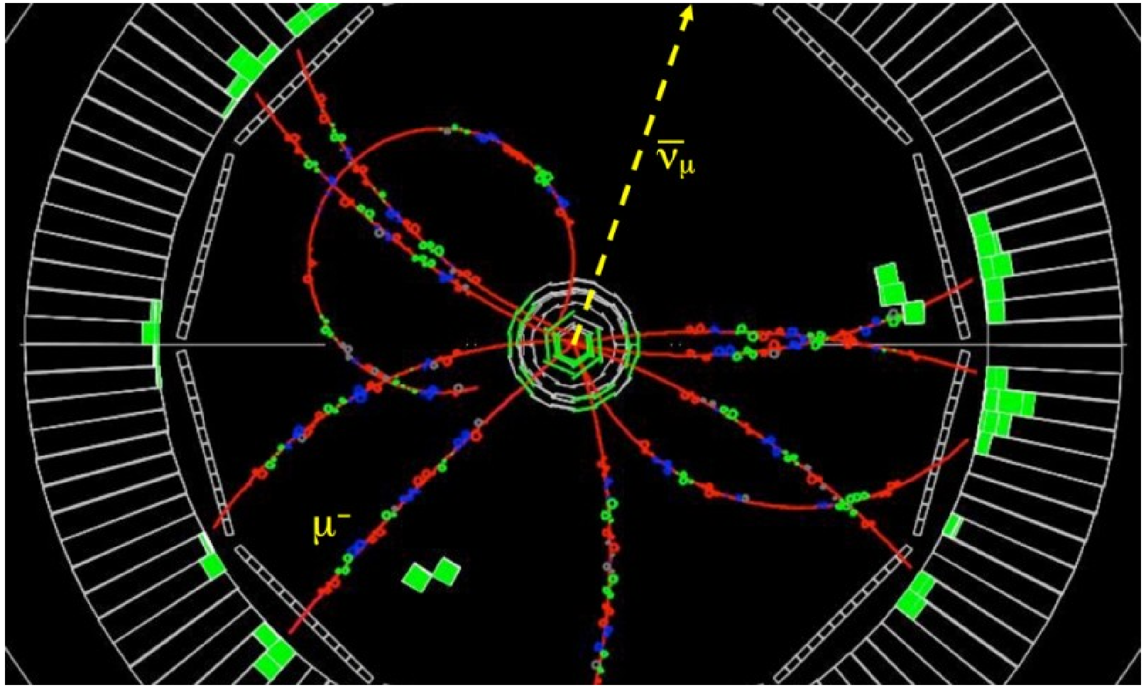
First generation of B factories

pp and ee collisions

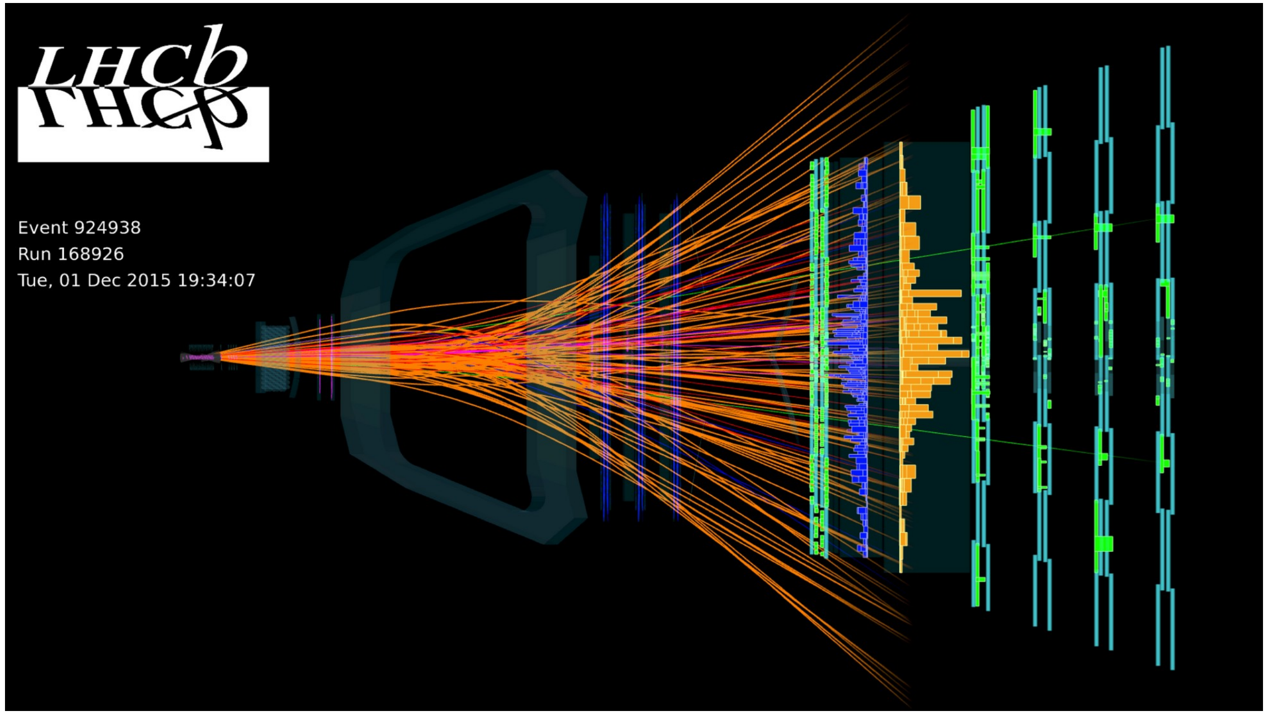
- The ee collisions are cleaner than pp, but less B mesons are produced (1 ab^{-1} in e^+e^- ~ 1 fb^{-1} in pp)

LHCb
9 fb^{-1}

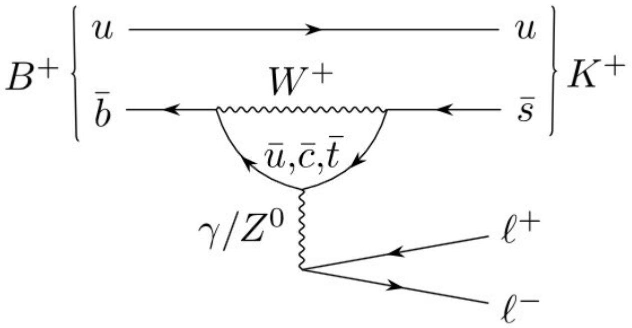
Belle II

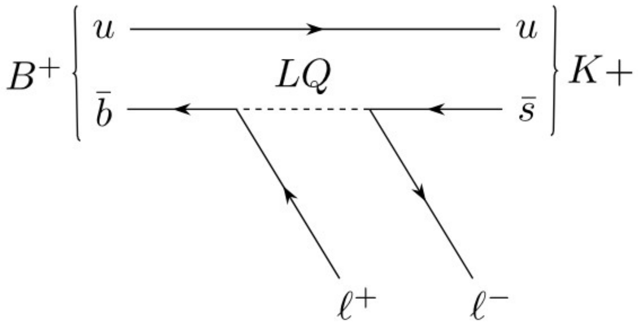


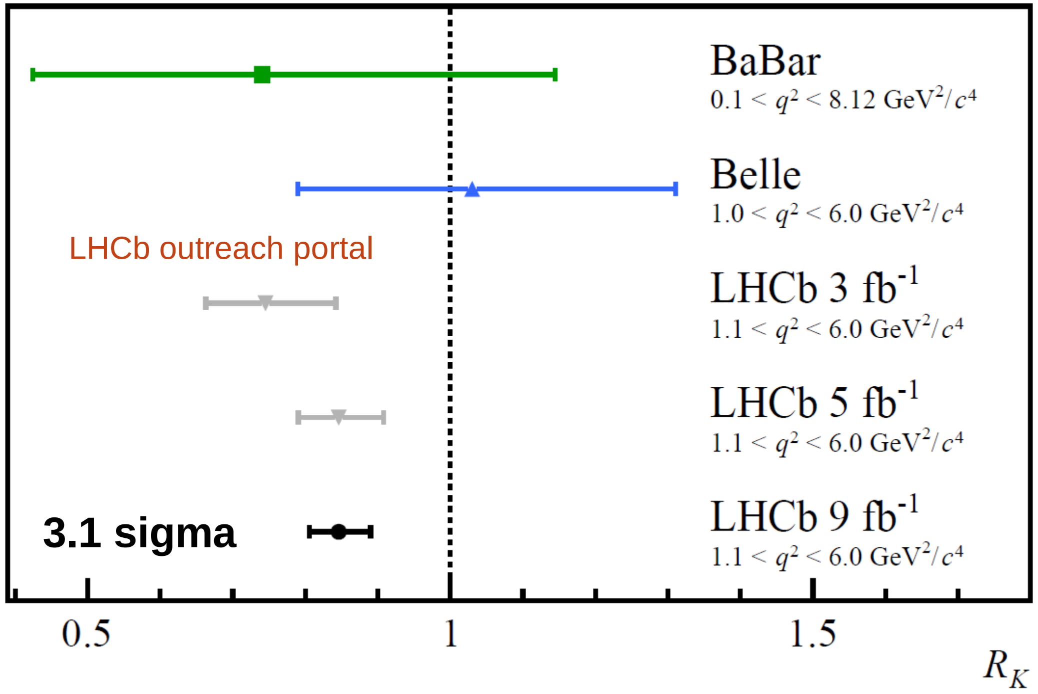
LHCb



Lepton flavor univ. & precision measurements







Cern experiment hints at new force of nature

The Guardian, March 2021

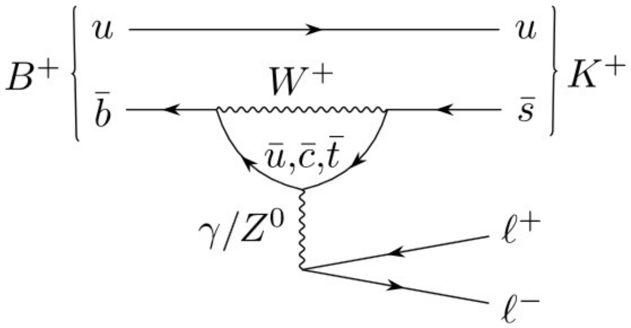
Experts reveal 'cautious excitement' over unstable particles that fail to decay as standard model suggests

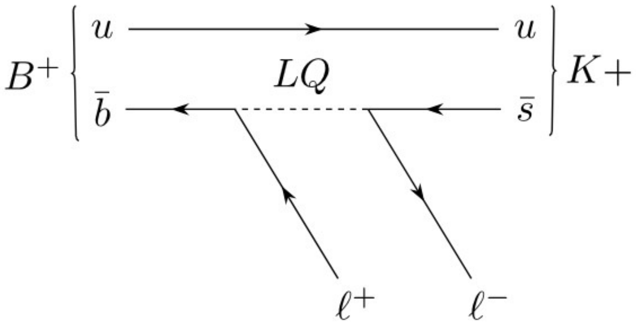
A man rides his bicycle along the beam line of the Large Hadron Collider. Photograph: Valentin Flauraud/AFP via Getty Images

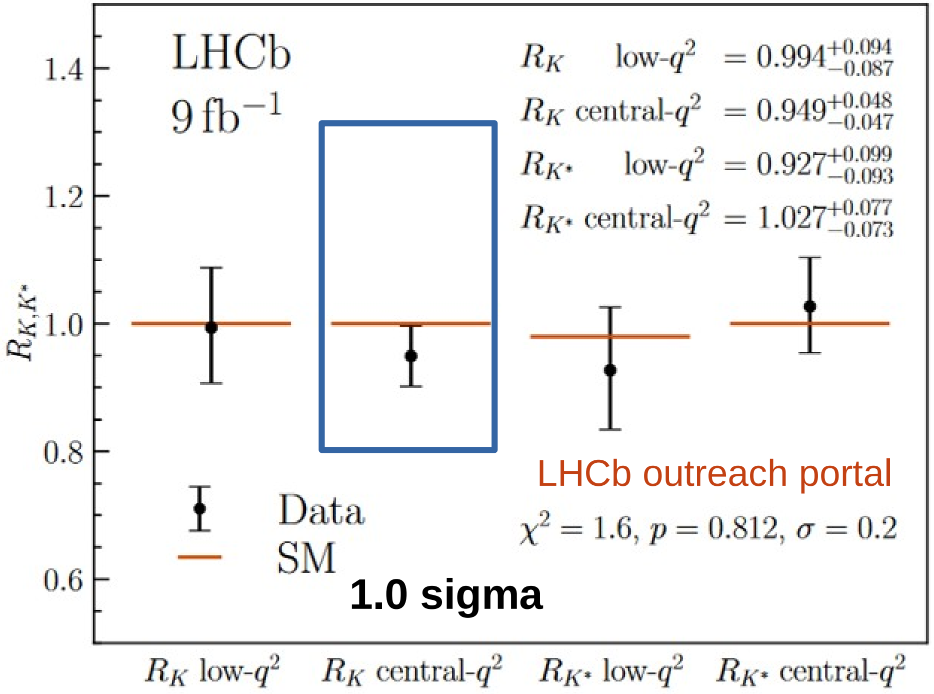
Scientists at the Large Hadron Collider near Geneva have spotted an unusual signal in their data that may be the first hint of a new kind of physics.

The LHCb collaboration, one of four main teams at the LHC, analysed 10 years of data on how unstable particles called B mesons, created momentarily in the vast machine, decayed into more familiar matter such as electrons.

Lepton flavor univ. & precision measurements







LHCb outreach portal

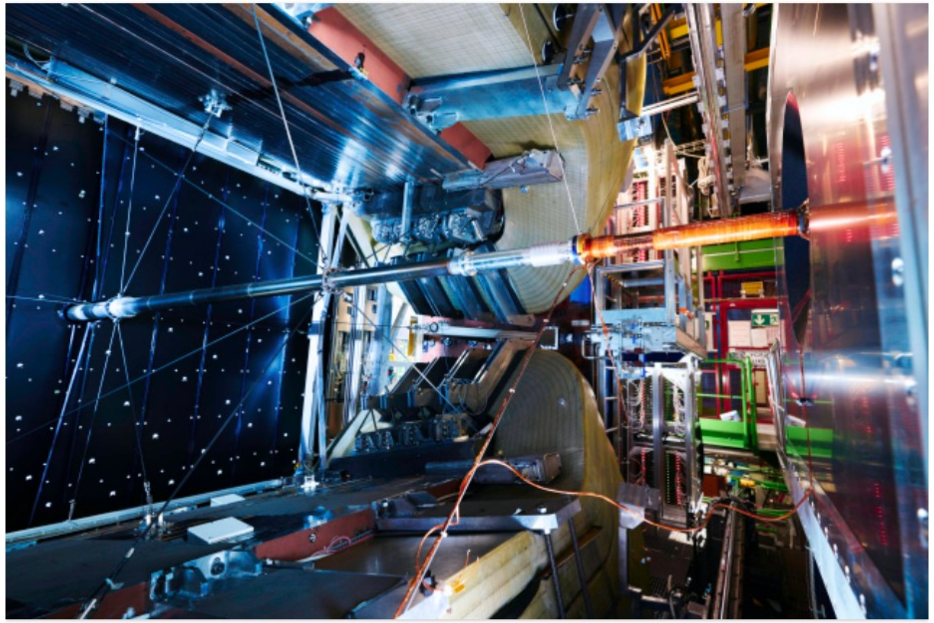
1.0 sigma

LHCb brings leptons into line

Simultaneous measurements of rare B-meson decays using the full LHC Run 1 and 2 data samples agree with the predictions of the Standard Model, superseding previous results that had indicated intriguing departures from the 50-year old theory

20 DECEMBER, 2022

CERN courier, December 2022

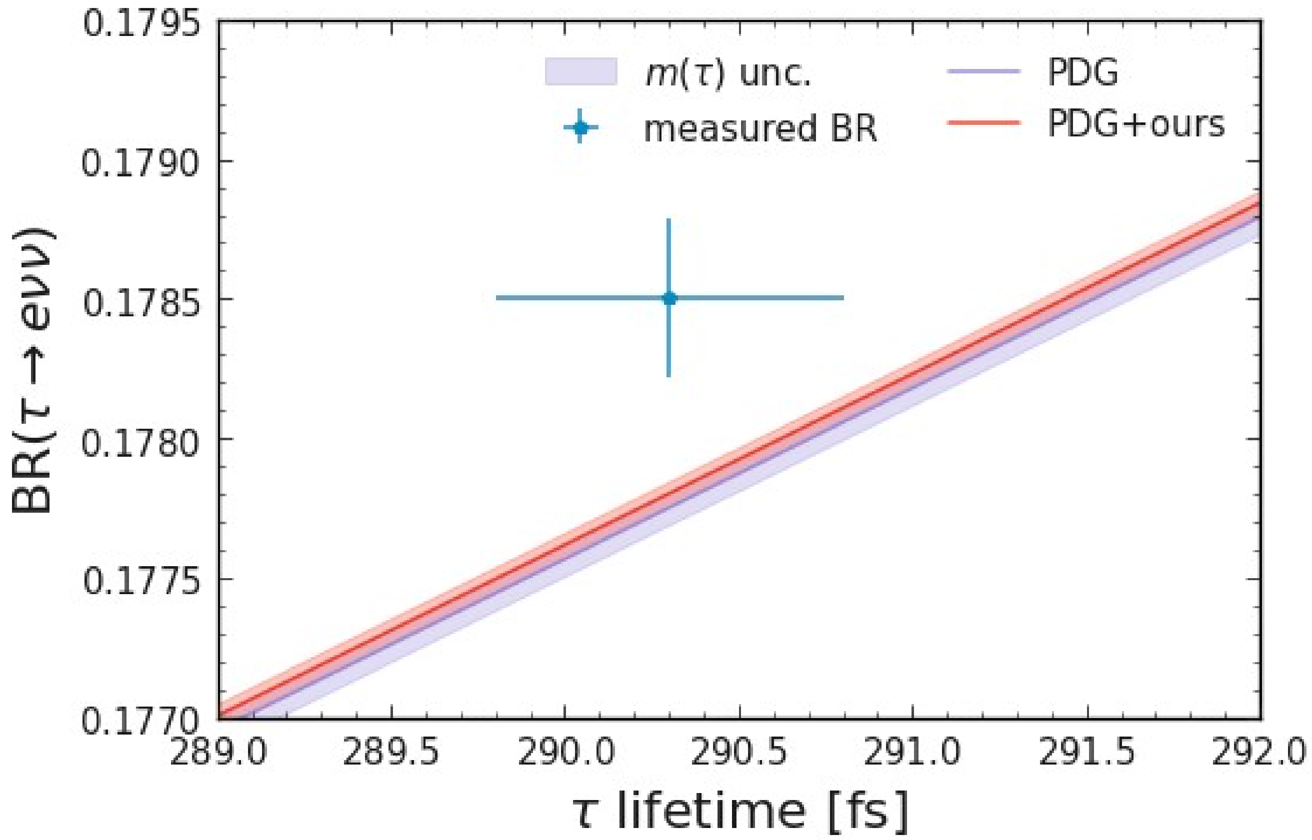


The LHCb experiment (Image: CERN)

Today the international LHCb collaboration at the Large Hadron Collider (LHC) presented new measurements of rare particle transformations, or decays, that provide one of the highest-precision tests yet of a key property of the Standard Model of particle physics, known as lepton flavour universality. Previous studies of these decays had hinted at intriguing tensions with the theoretical predictions, potentially due to the effects of new particles or forces. The results of the improved and wider-reaching analysis based on the full LHC dataset collected by the experiment during Run 1 and Run 2, which were presented at a seminar at CERN held this morning, are in line with the Standard Model expectation.

Lepton flavor universality & tau lepton mass

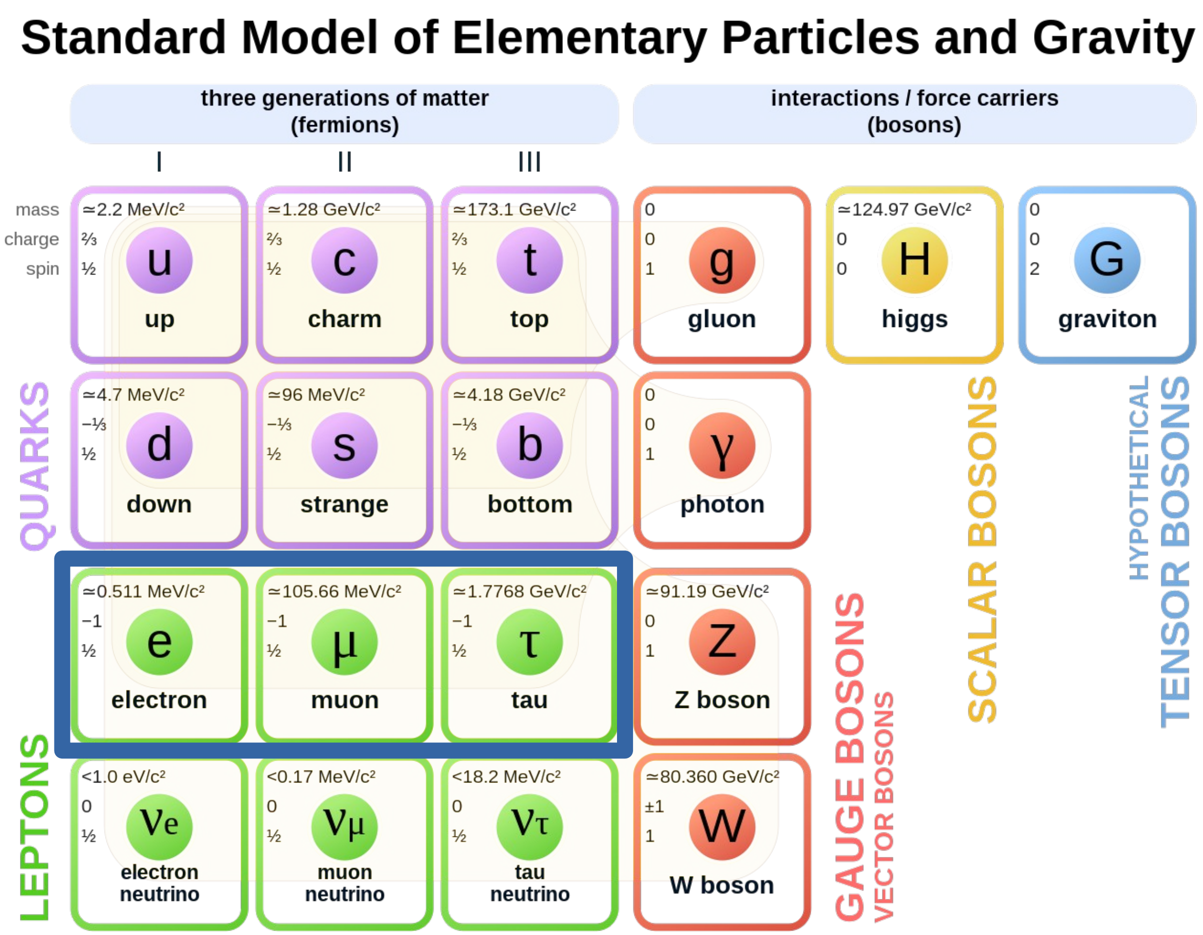
$$BR = \frac{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e) = \dfrac{G_F^2 m_\tau^5}{192\pi^3}}{(\tau\ \text{lifetime})^{-1}}$$



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

Masses of leptons

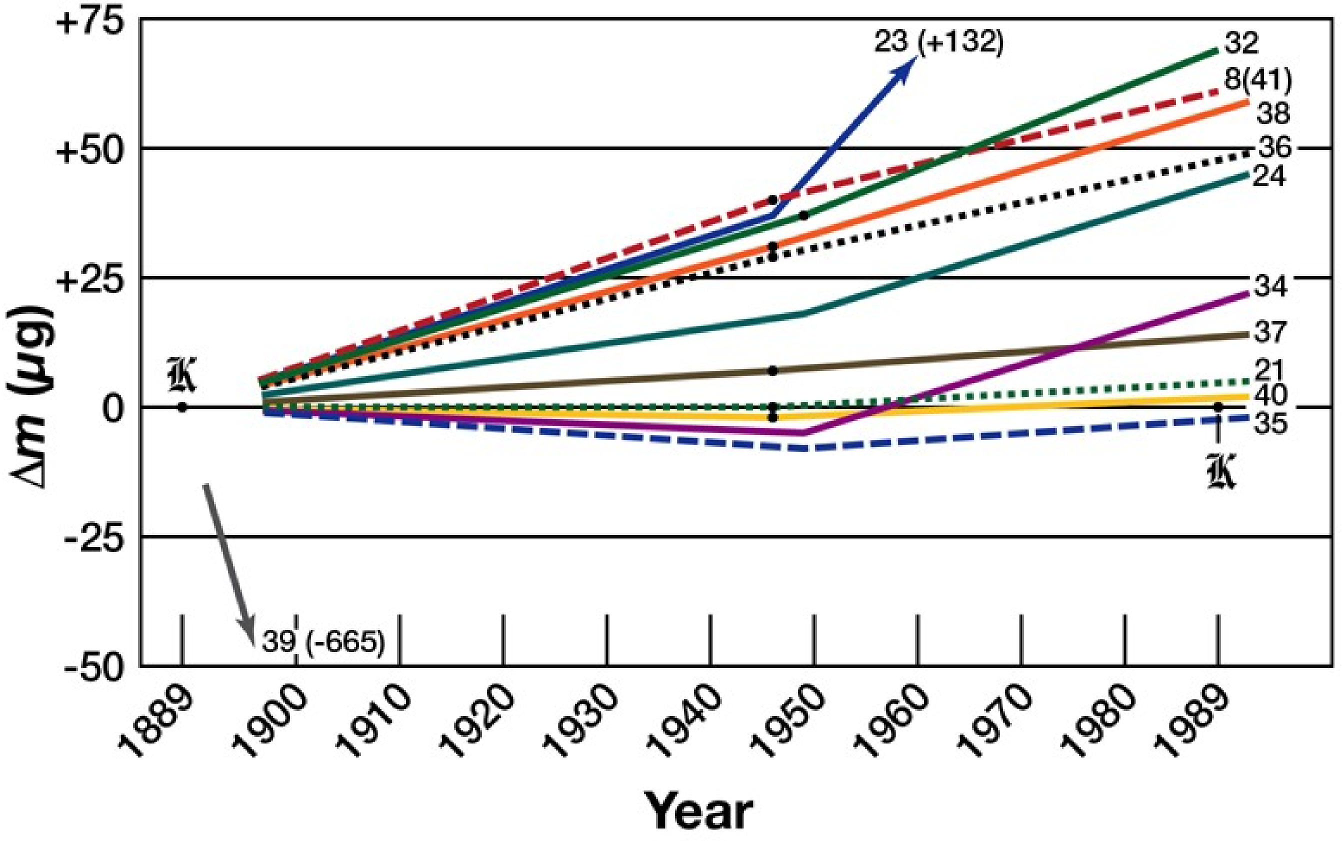
$$m_e = (0.51099895000 \pm 0.00000000015)\ \mathrm{MeV}$$
$$m_\mu = (105.6583755 \pm 0.0000023)\ \mathrm{MeV}$$
$$m_\tau = (1776.86 \pm 0.12)\ \mathrm{MeV}$$

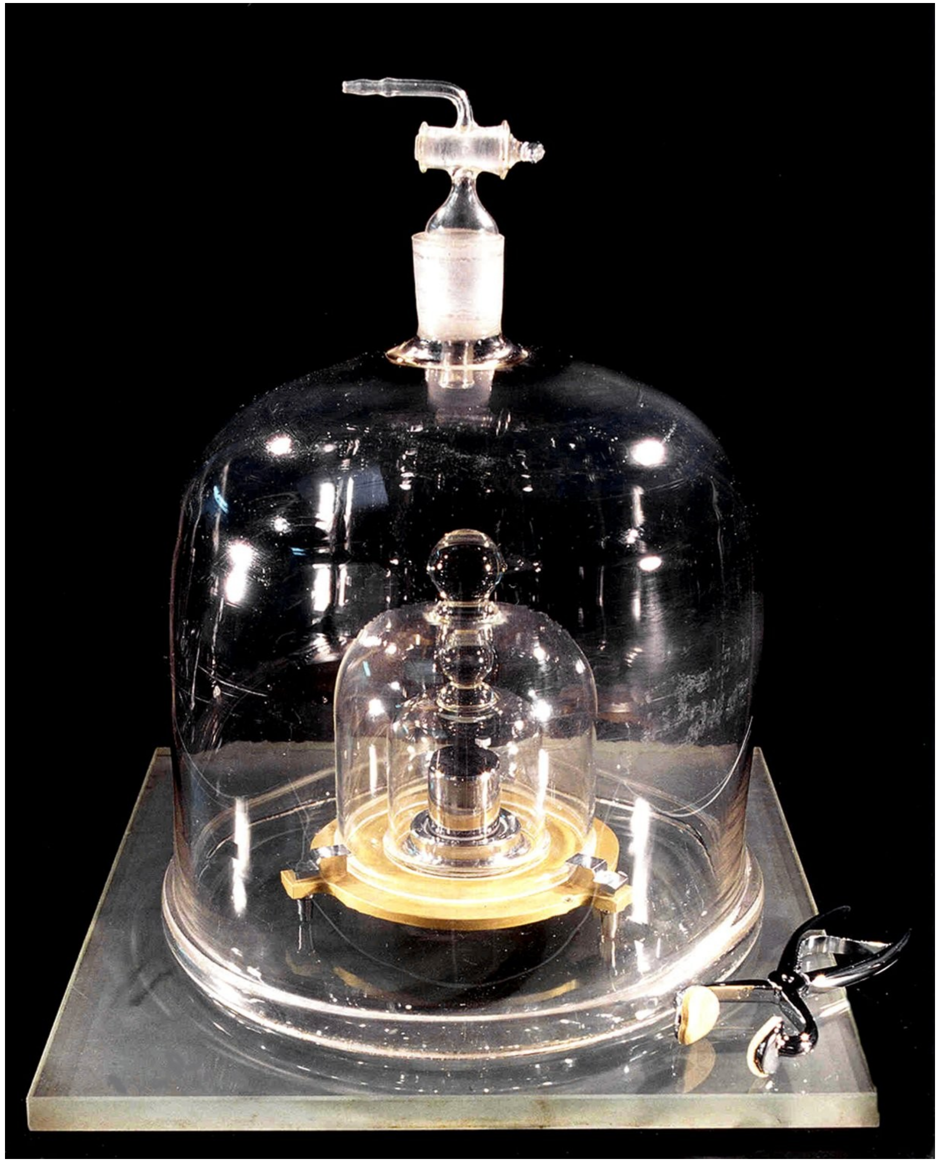


Tau lepton mass is exciting on its own!

(Old) Definition of kilogram

Precision drift up to 70 x 10^{-9} in 100 years





90% platinum and 10% iridium

(New) Definition of kilogram since 2019

Speed of light

$$\text{kg} = \frac{(299\,792\,458)^2}{(6.626\,070\,15 \times 10^{-34})(9\,192\,631\,770)} \frac{h\,\Delta\nu_{\text{Cs}}}{c^2}$$

Planck constant

1 second (Ceasium 133)

Electric force

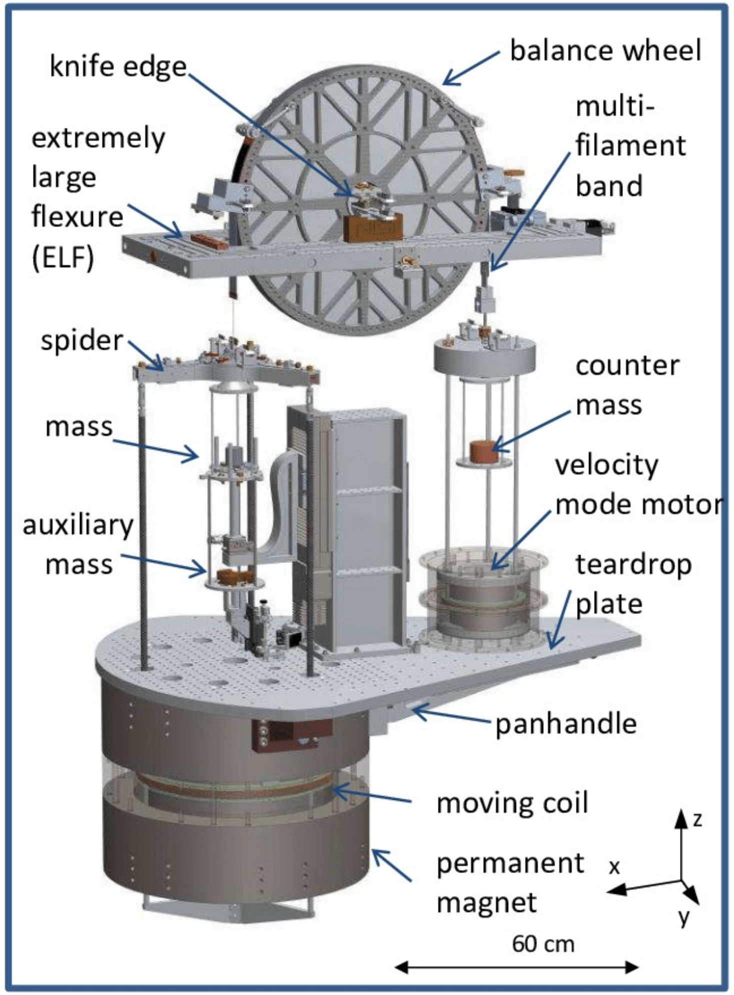
$$I\color{red}{BL}\color{black}{} = mg$$

Electric Induction

$$U = \color{red}{BL}\color{black}{v}$$

$$IU/v = mg$$

From quantum effects

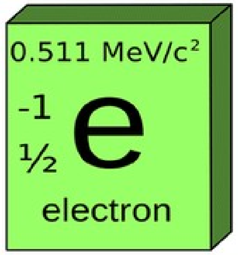


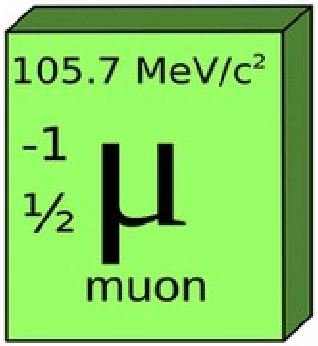
Kibble balance precision: 36 x 10^{-9}

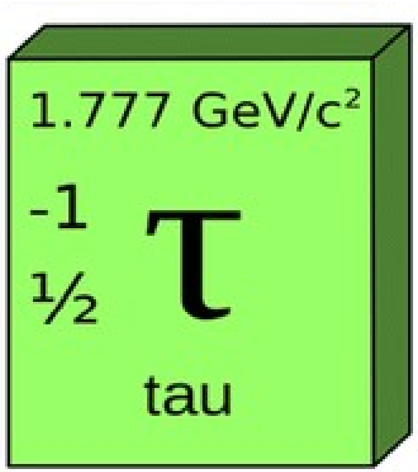
Veritasium: Redefination of kg

Masses of leptons

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







0.3×10^{-9} 22×10^{-9} 68000×10^{-9} 36×10^{-9}

Common precision

3 eur

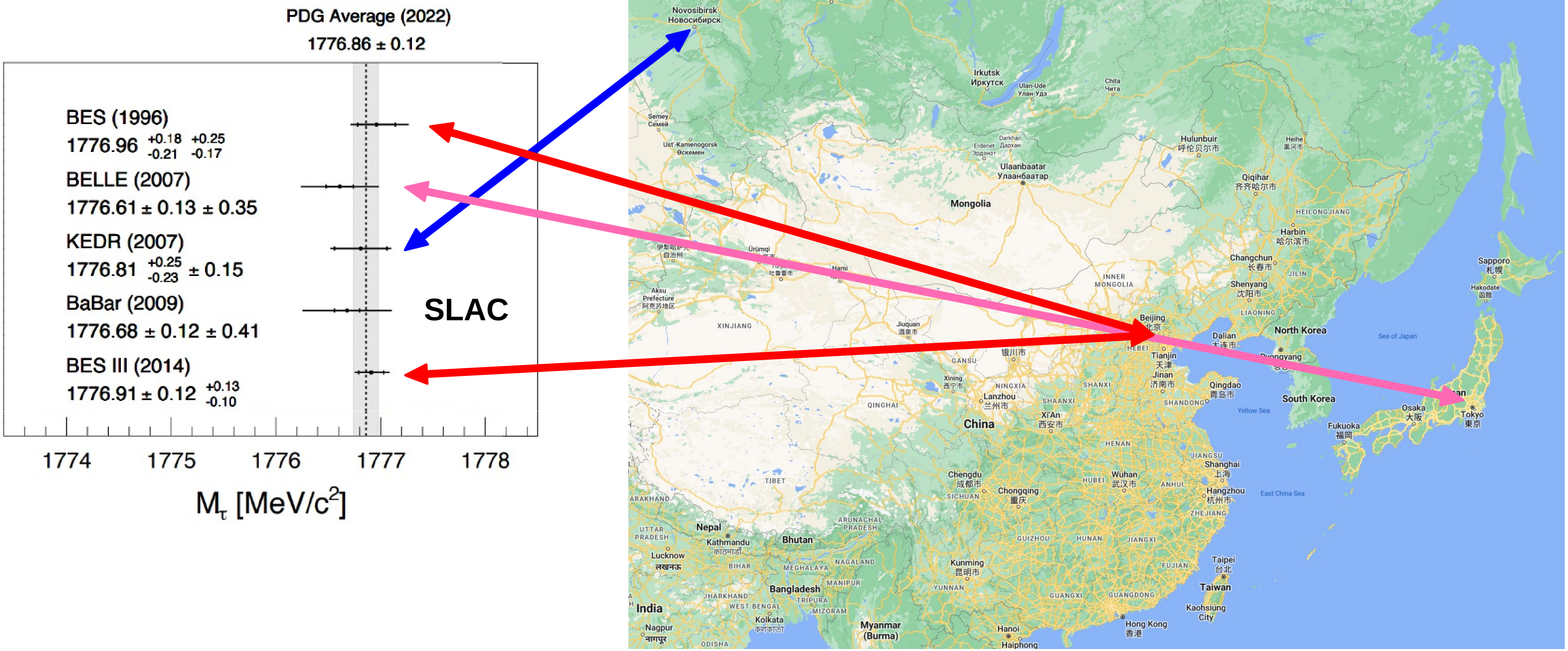
mks1101s

What we need

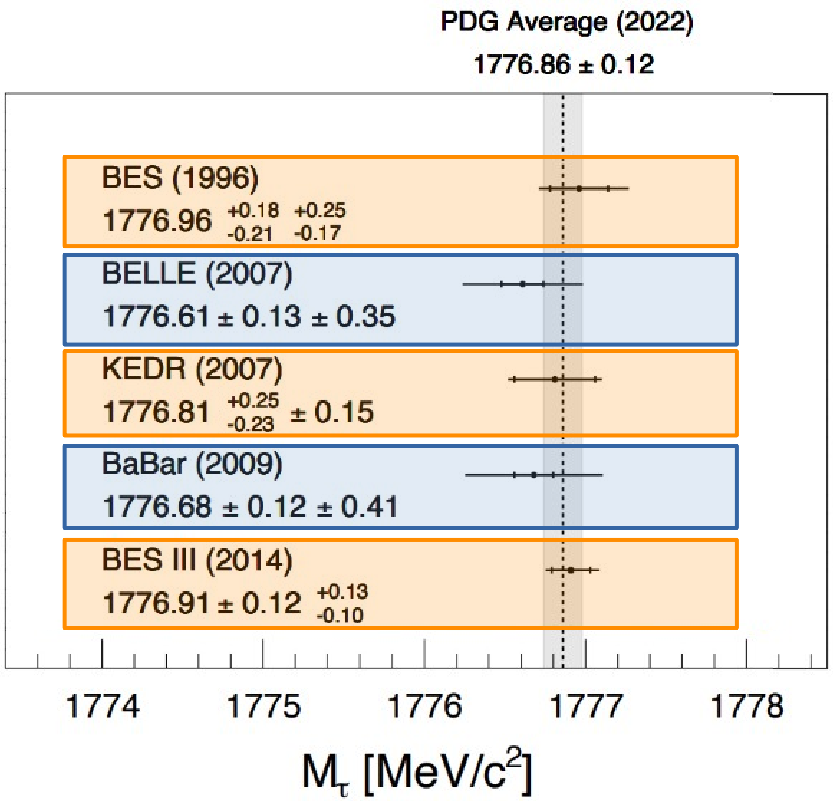
300 eur

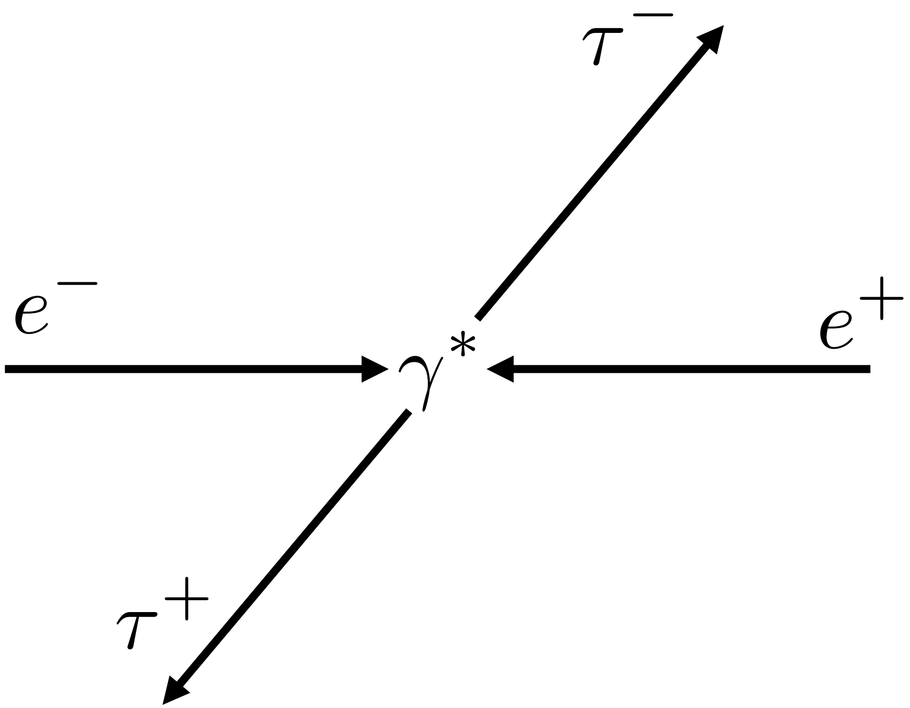
tronix-tx4202b-4200g

Asian business



Methods





B factories : E_{cms} = 10.58 GeV

τ factories : E_{cms} = 3.56 GeV

Give me a scale!

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	$^{+0.094}_{-0.124}$

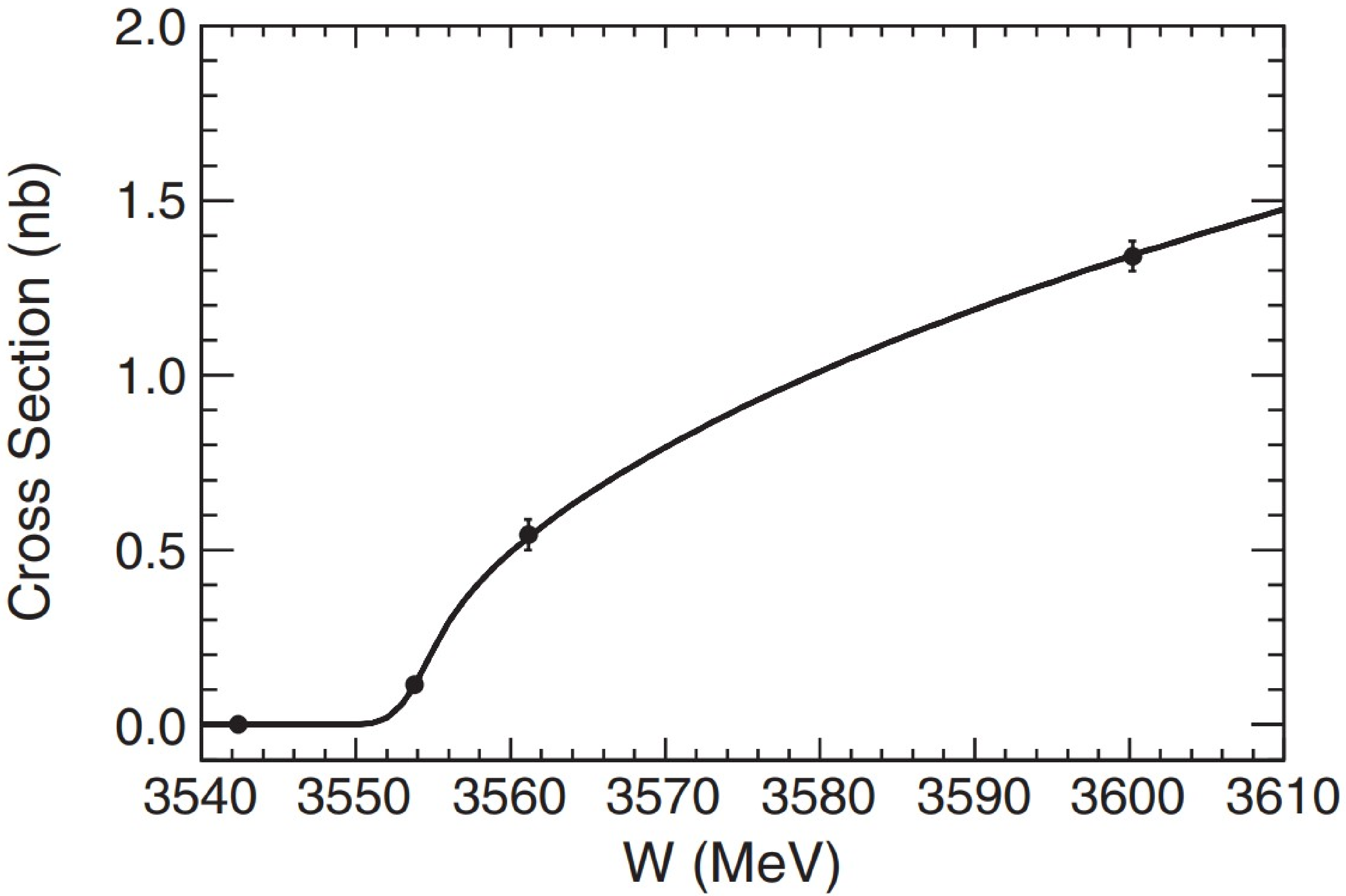
70%

BaBar (B factory)

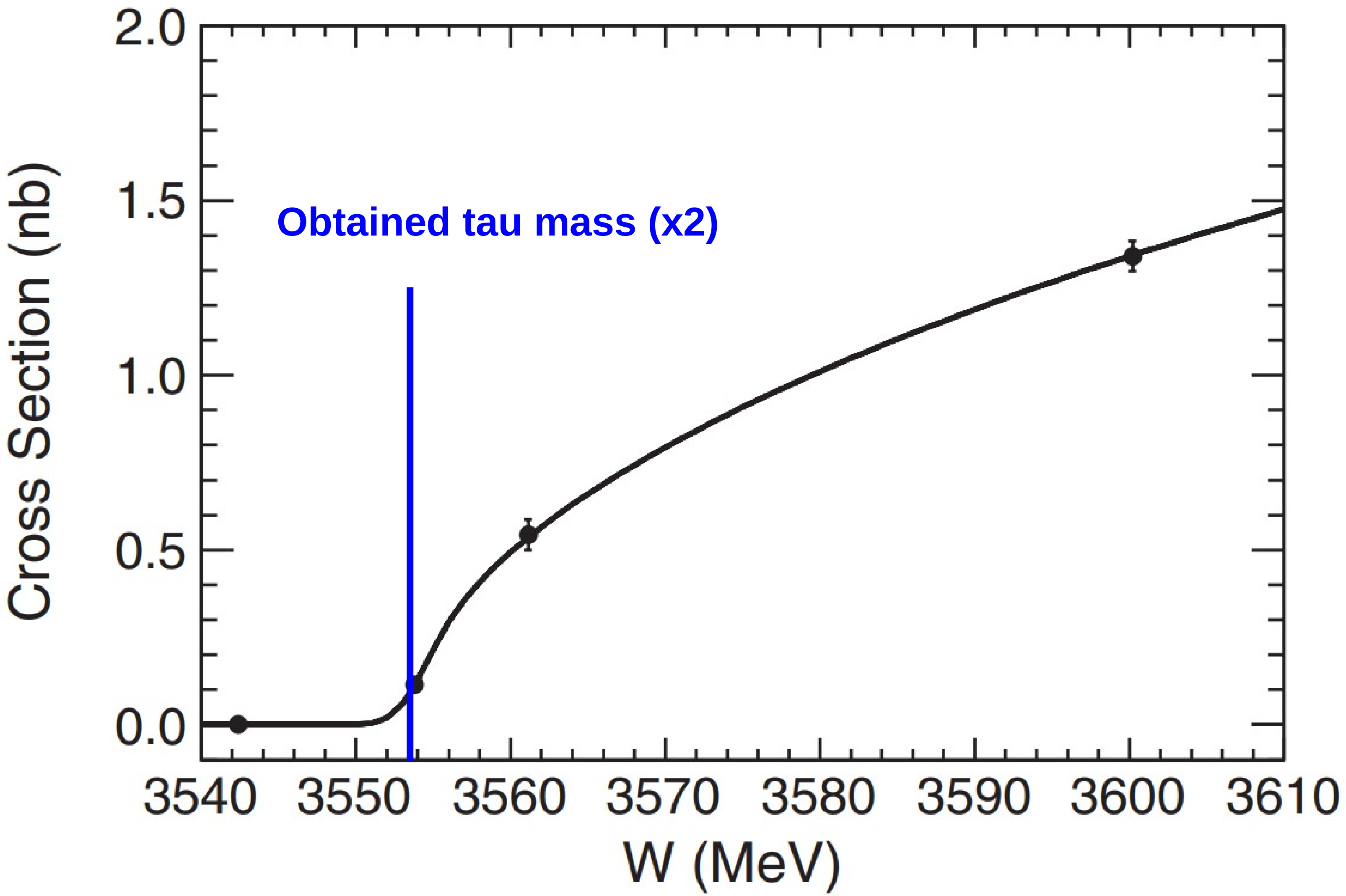
Source	Uncertainty (MeV)
Momentum Reconstruction	0.39
CM Energy	0.09
MC Modeling	0.05
MC Statistics	0.05
Fit Range	0.05
Parameterization	0.03
Total	**0.41**

98%

BES III method

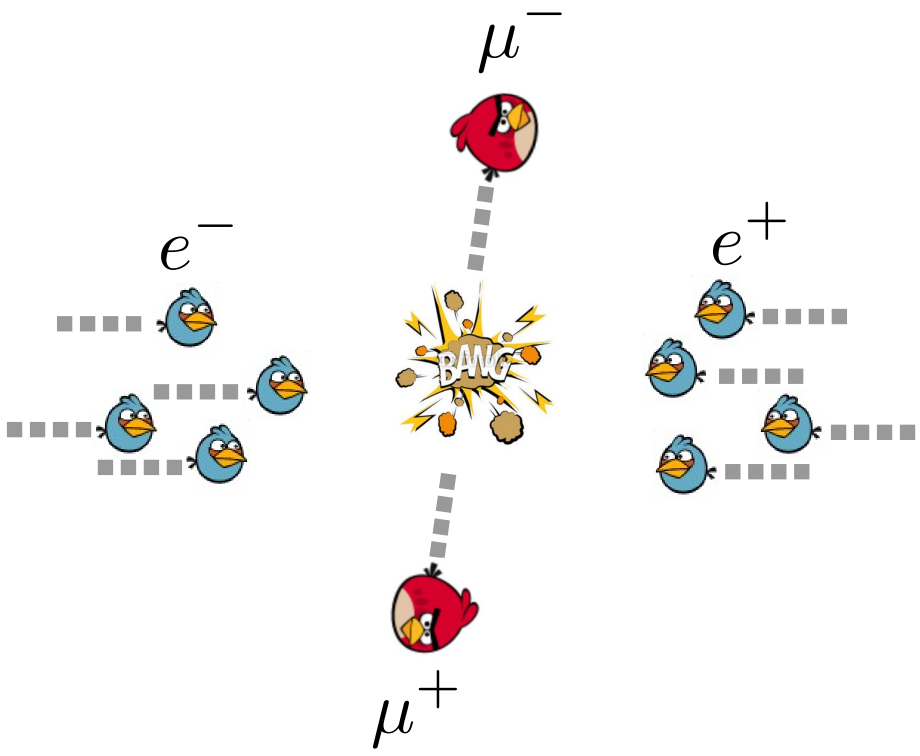


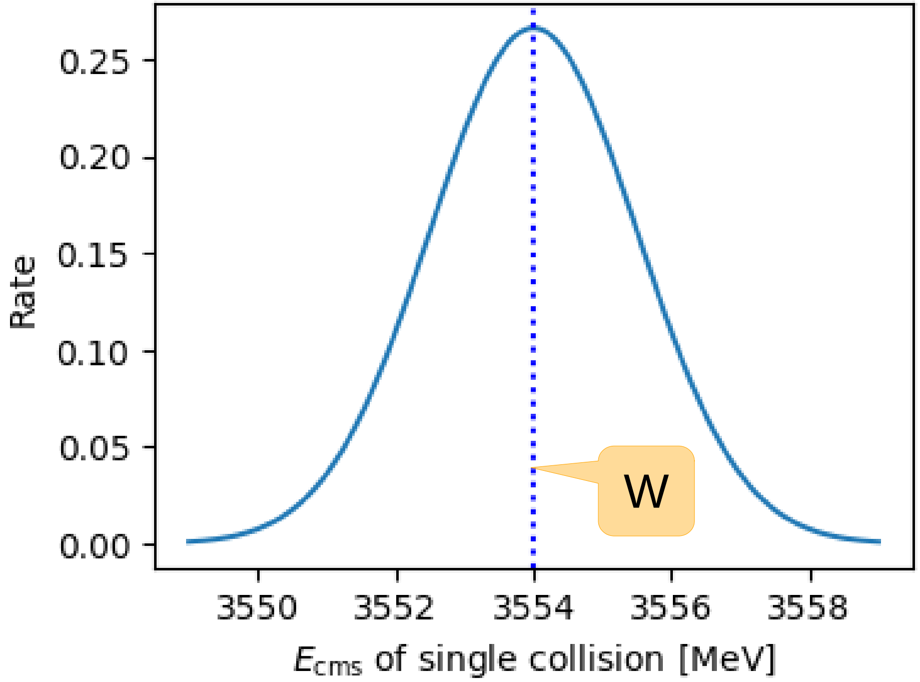
BES III method



BES III method

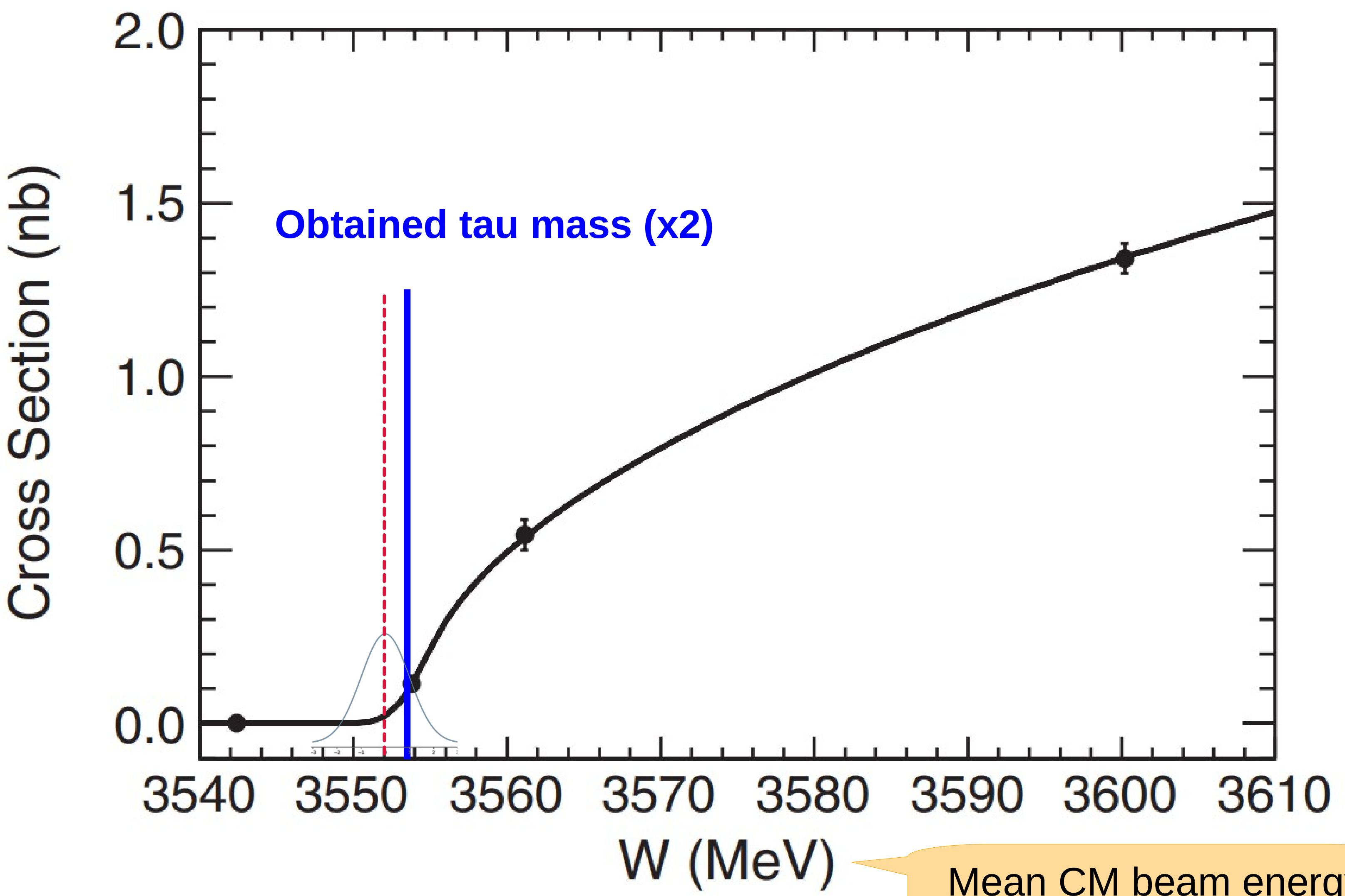
Particles in the accelerator don’t have single “sharp” energy





BES III method

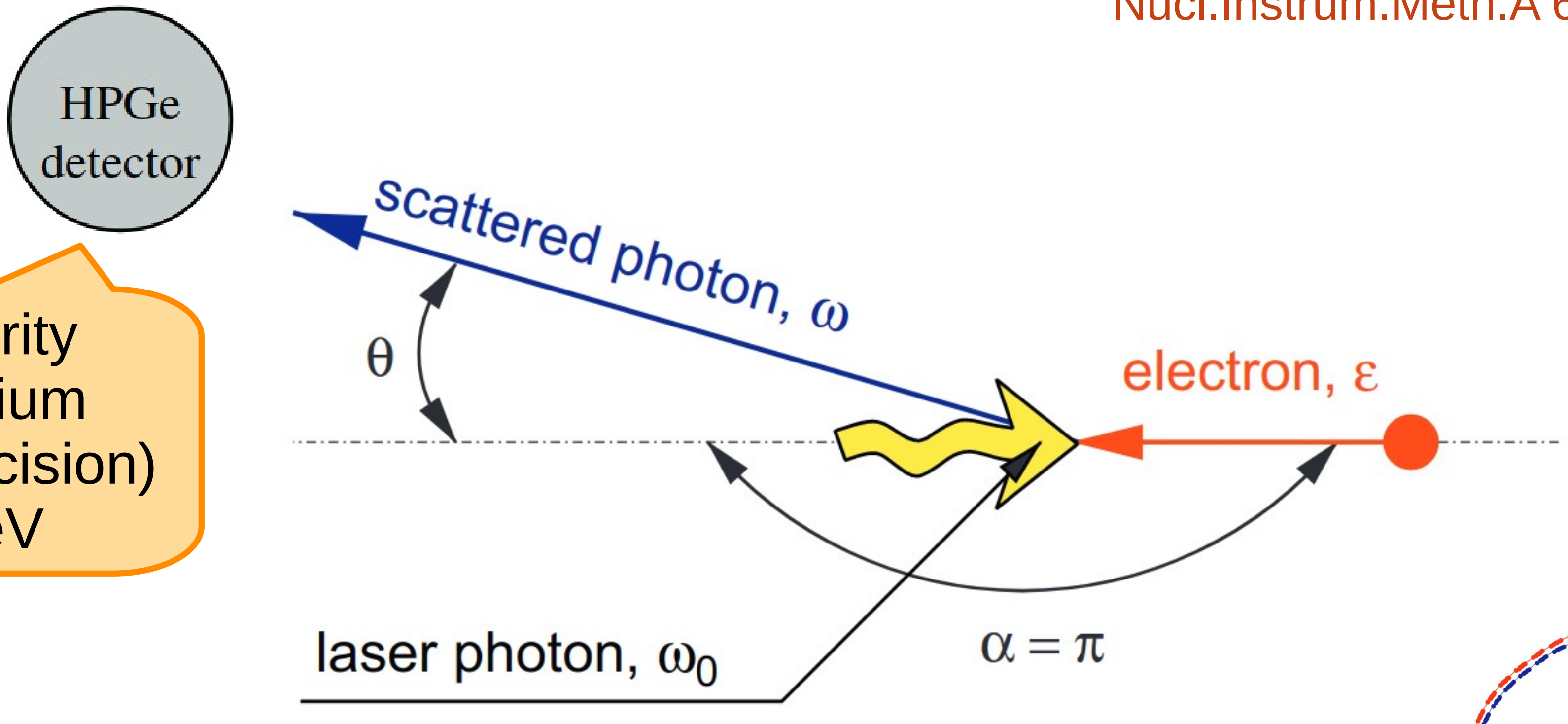
Beam energy spread : 1.5 MeV



Mean CM beam energy

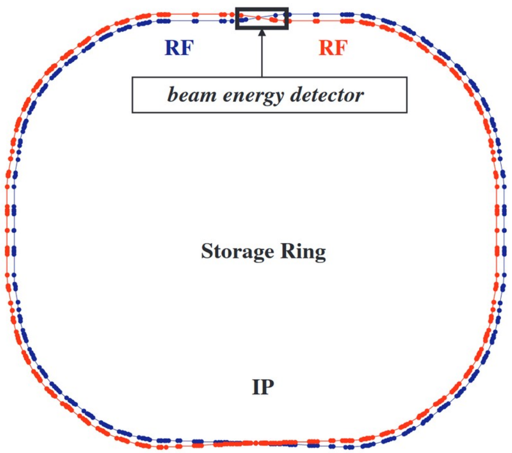
BES III energy measurement : Compton scattering

Nucl.Instrum.Meth.A 659 (2011) 21-29



High **P**urity **G**ermanium
($2x10^{-5}$ precision)
5.5 MeV

Initial laser beam energy
(10^{-8} precision)
0.12 eV (11 μm)

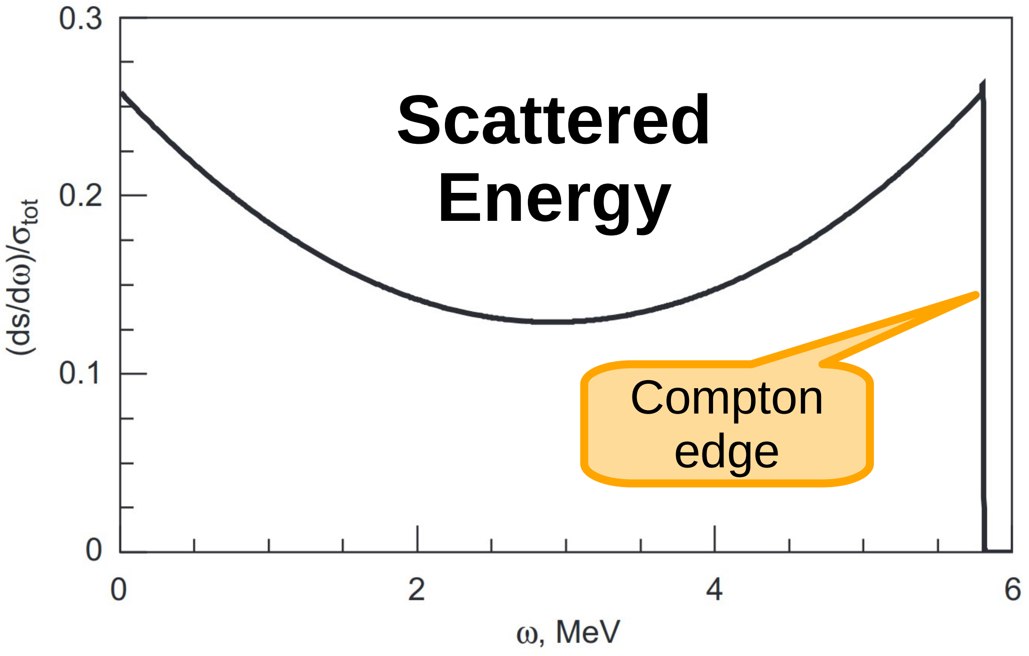


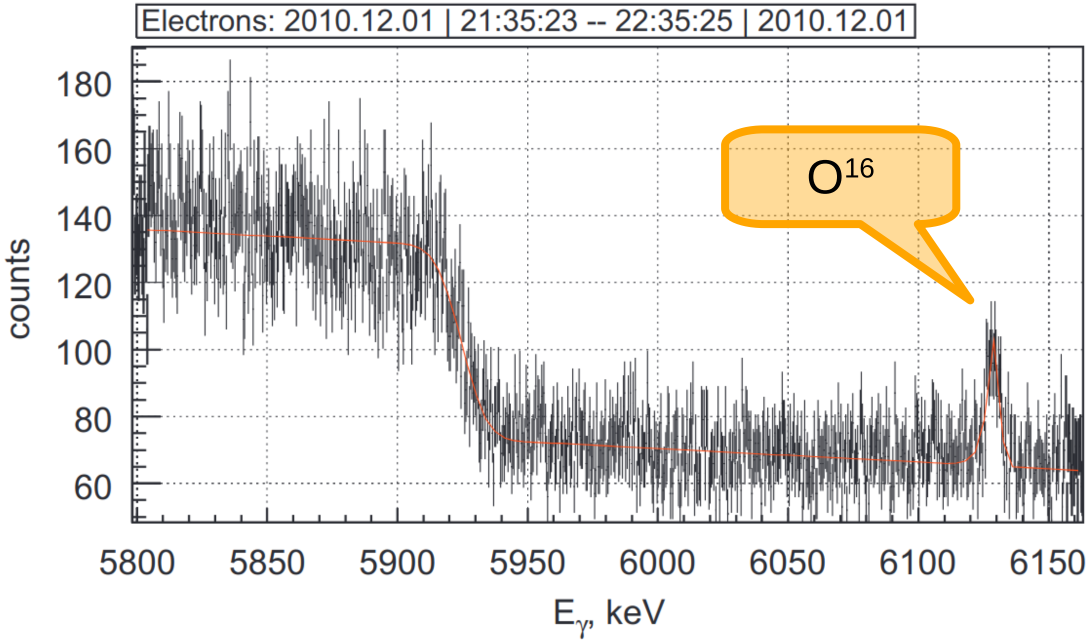
BES III energy measurement : Back to the Labs

$$E_e \approx \frac{m_e}{2\sqrt{E_{\text{in}}}}\sqrt{E_\gamma}$$

740 MeV$^{1/2}$

Nucl.Instrum.Meth.A 659 (2011) 21-29





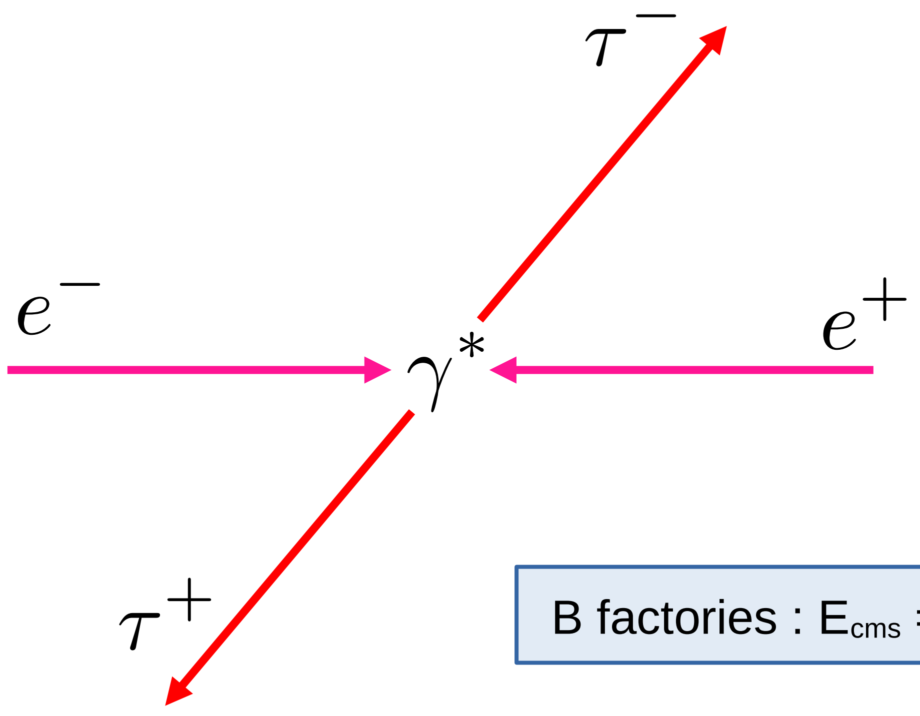
Challenges for B factories

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

5.29 GeV

4.98 GeV

Source	Uncertainty (MeV)
Momentum Reconstruction	0.39
CM Energy	0.09



B factories : E_{cms} = 10.58 GeV

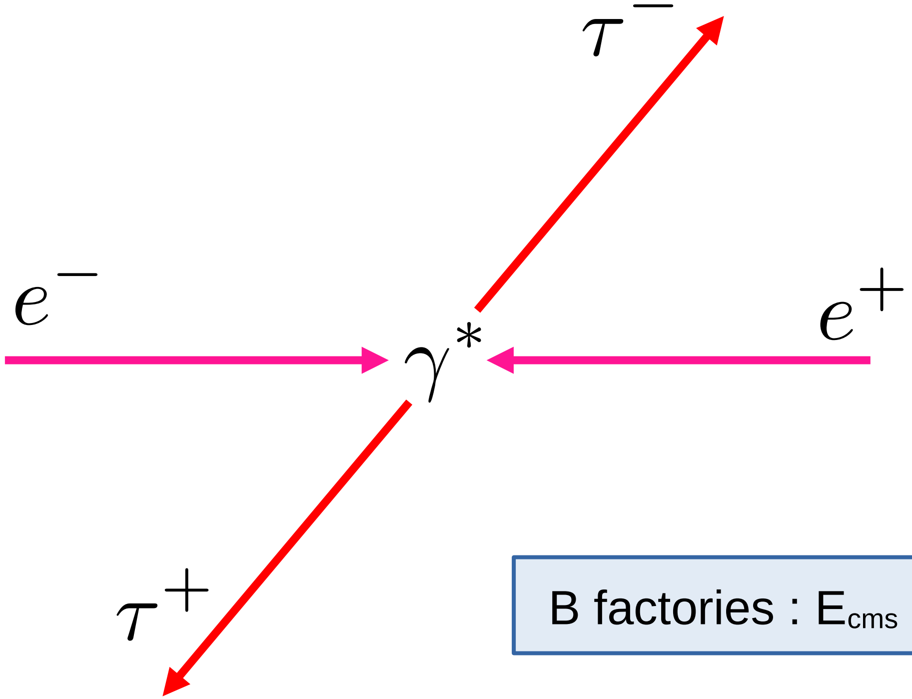
Problems for B factories

Source	Uncertainty (MeV)
Momentum Reconstruction	0.39
CM Energy	0.09

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

5.29 GeV

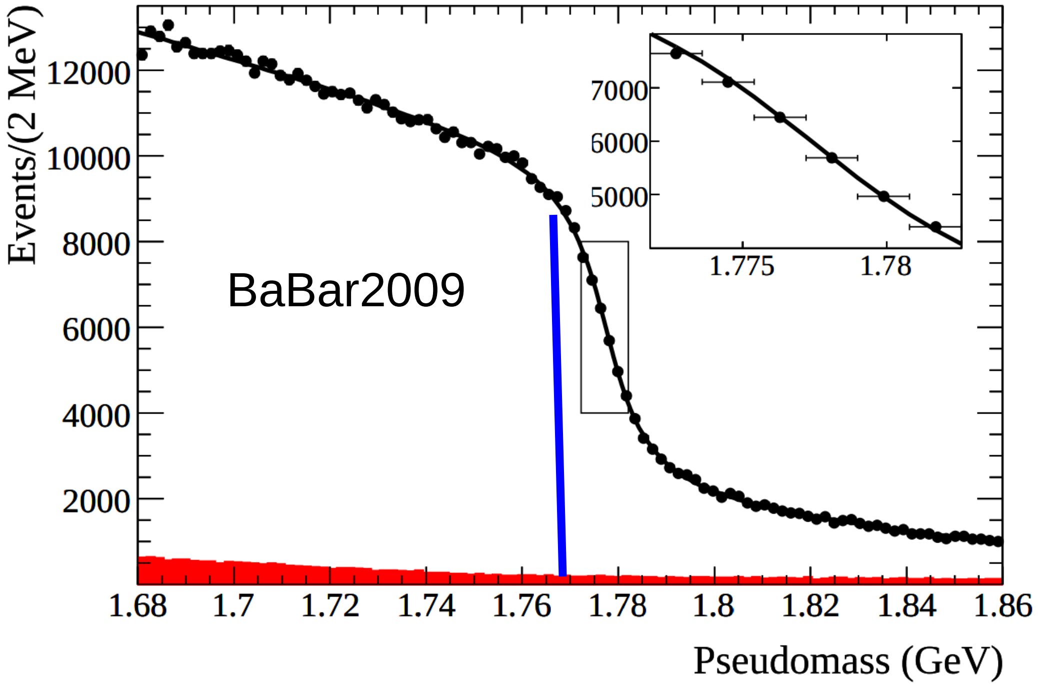
4.98 GeV

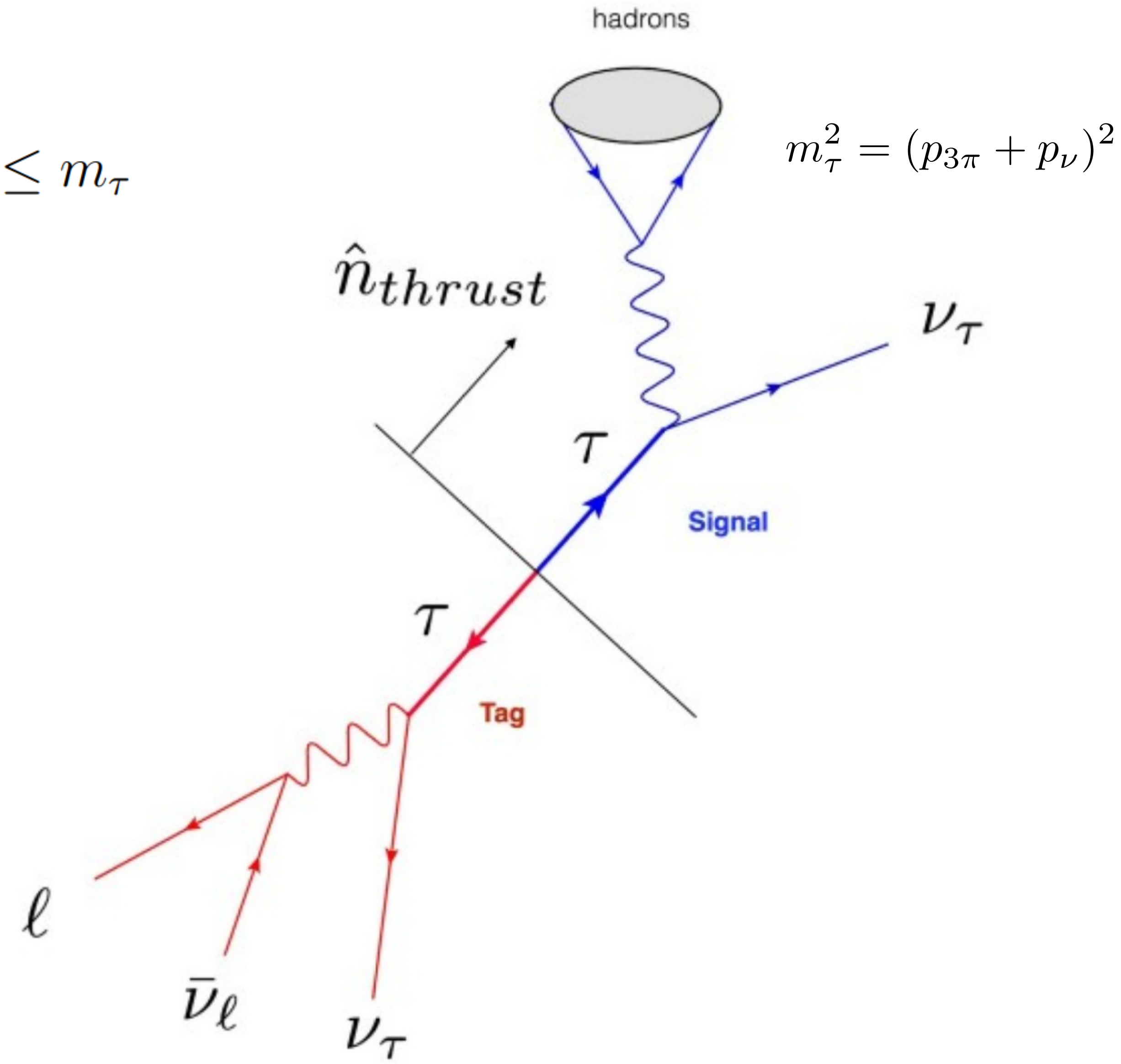


B factories : E_{cms} = 10.58 GeV

Pseudo-mass

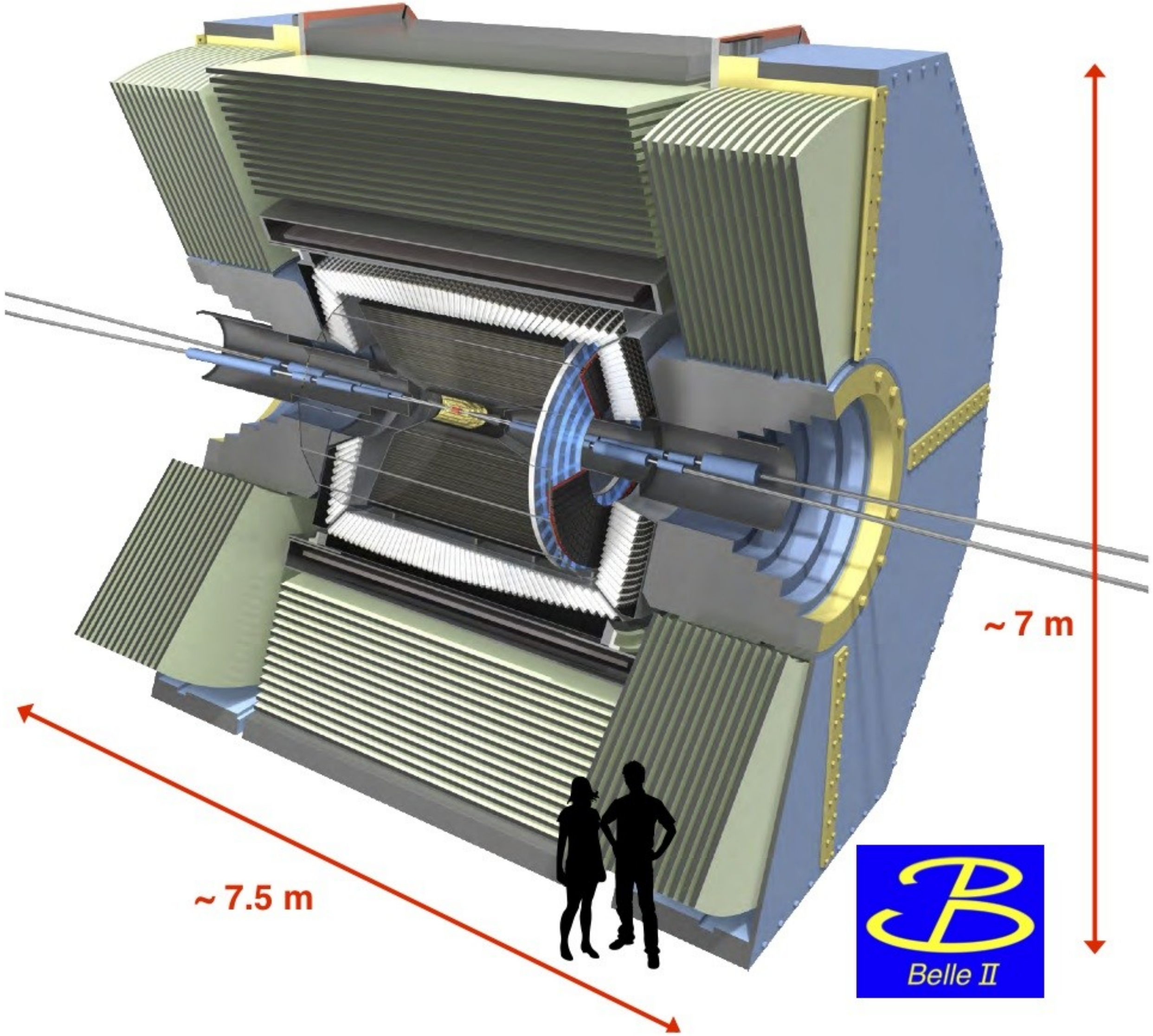
$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)} \le m_\tau$$





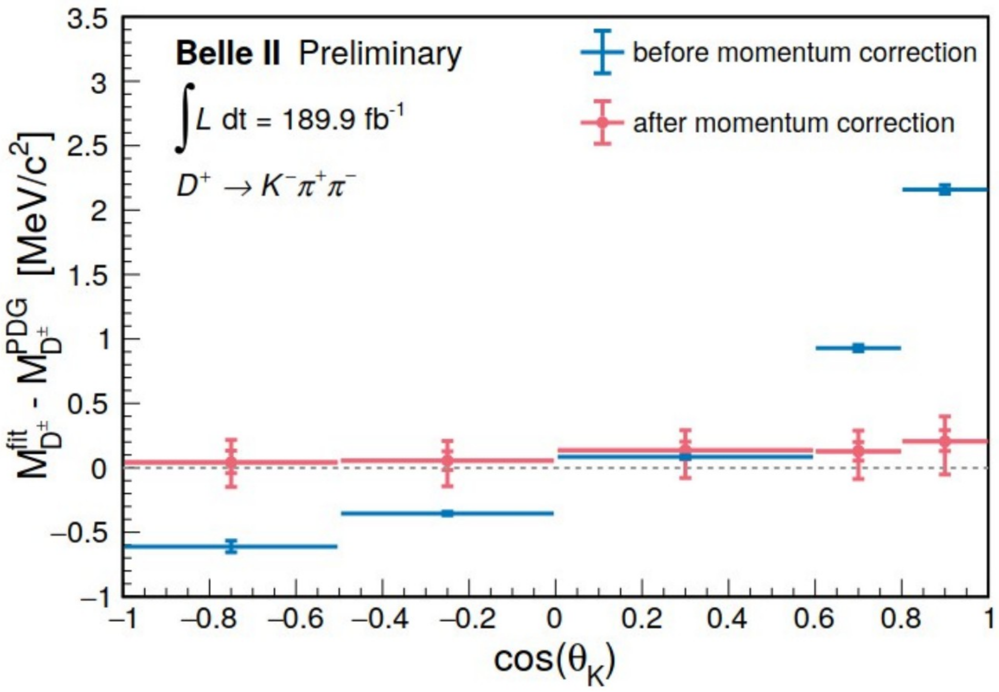
1 MeV in E_{cms} ~ 0.09 MeV in m_τ

Belle II

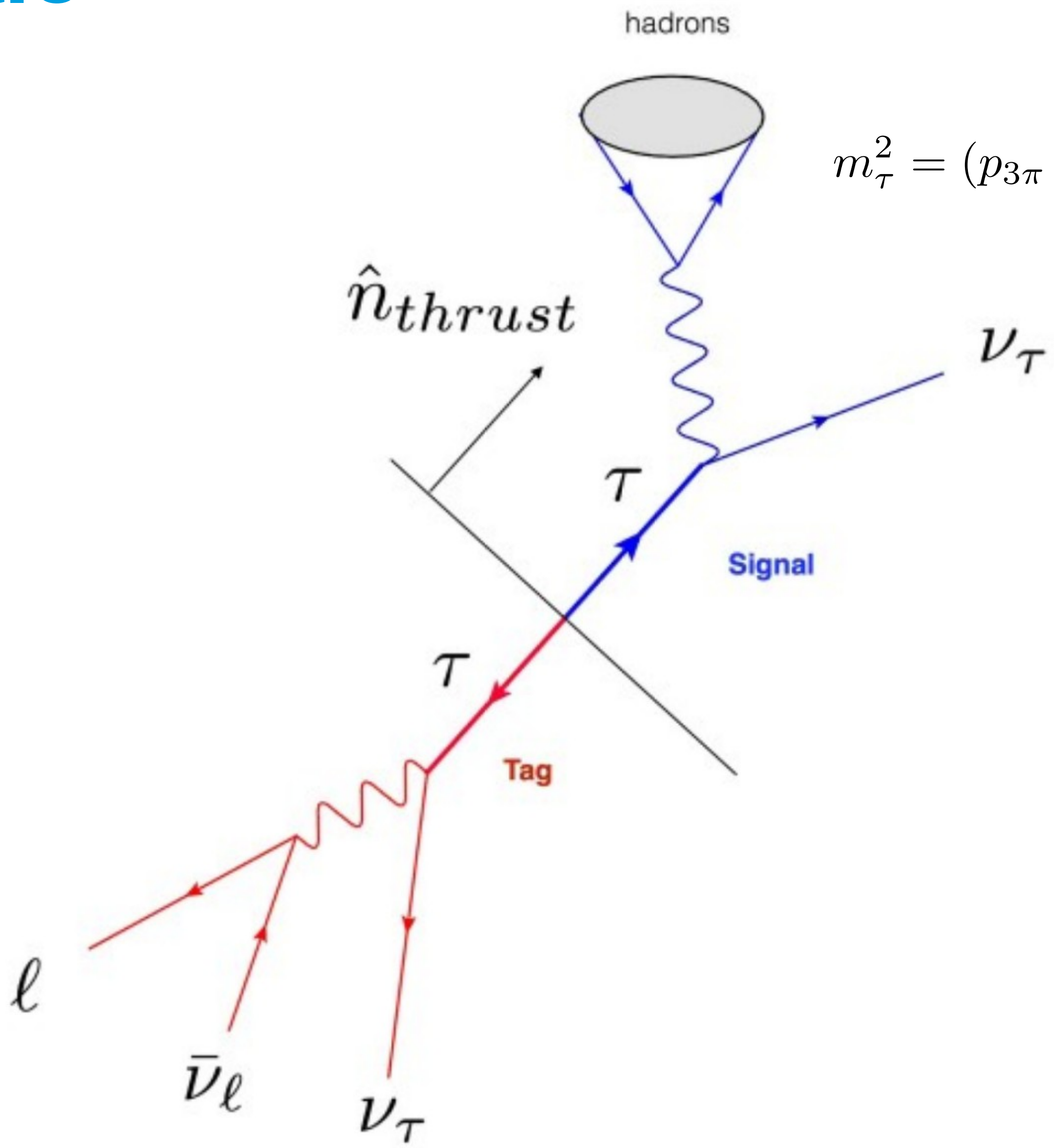


Final-state momentum scale

Fixing via known masses of the D mesons



0.39 MeV → 0.07 MeV



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

Incoming energy scale

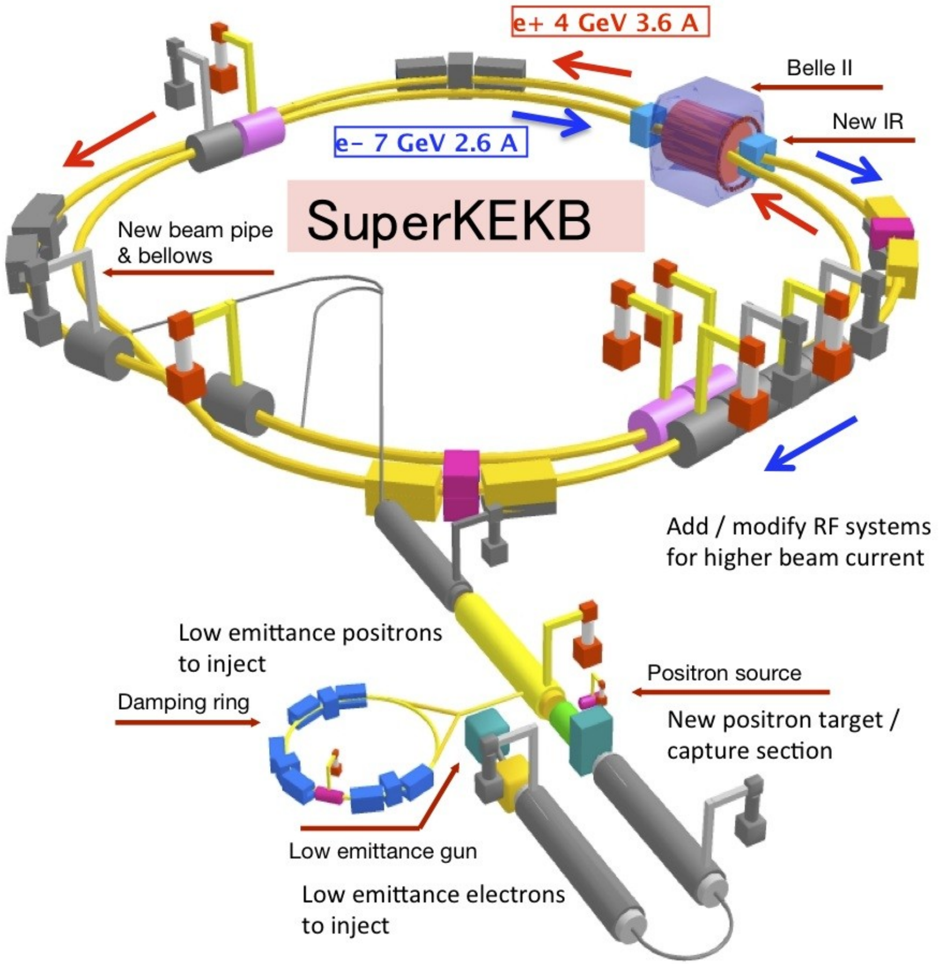
Accelerator instruments don't provide precise absolute energy!

Monitoring energy variations

$$p = eBR$$

$$\Delta E_{\mathrm{beam}} = eB\Delta x$$

From BPMs



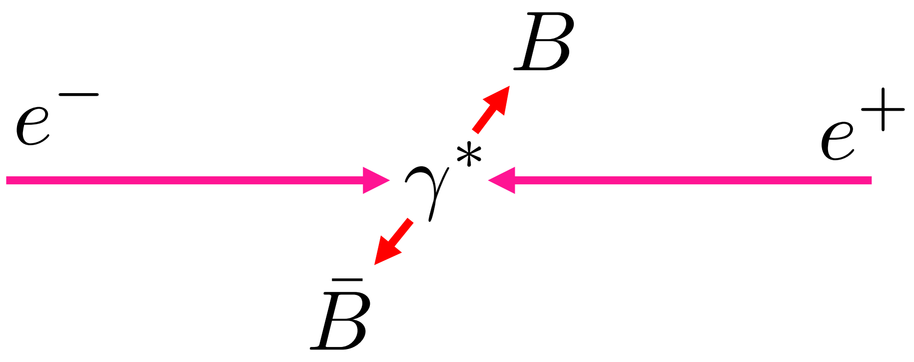
Exploiting the B mesons

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

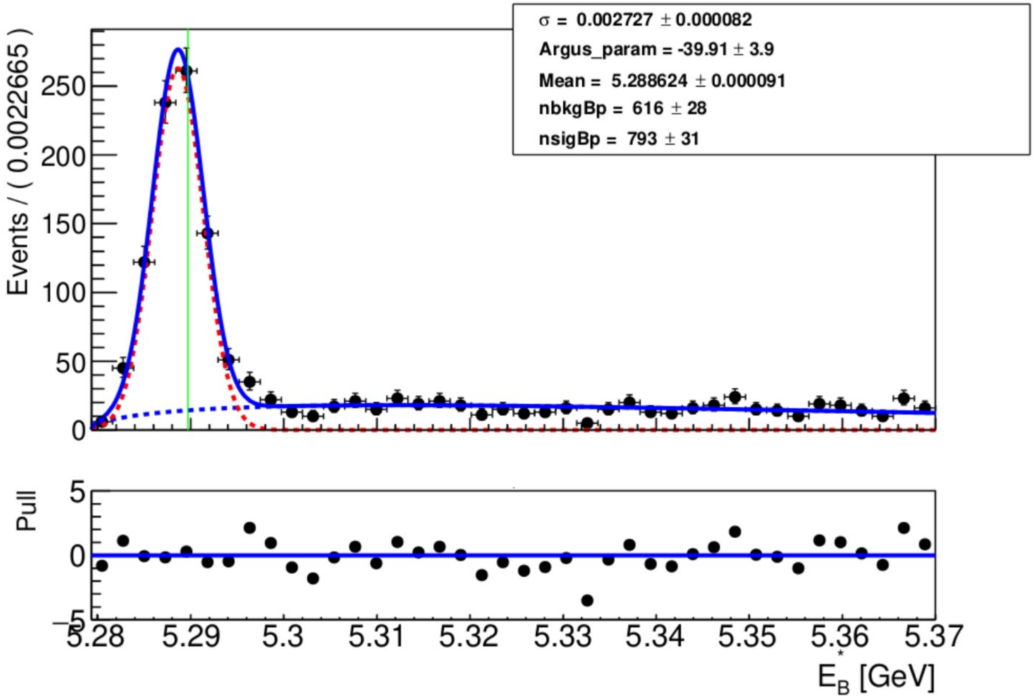
$$E_B^* = m_B + \frac{1}{2m_B}(p_B^*)^2$$

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

Our business



Determination of the B energy



$$E^*_B = m_B + \frac{1}{2m_B}(p^*_B)^2$$

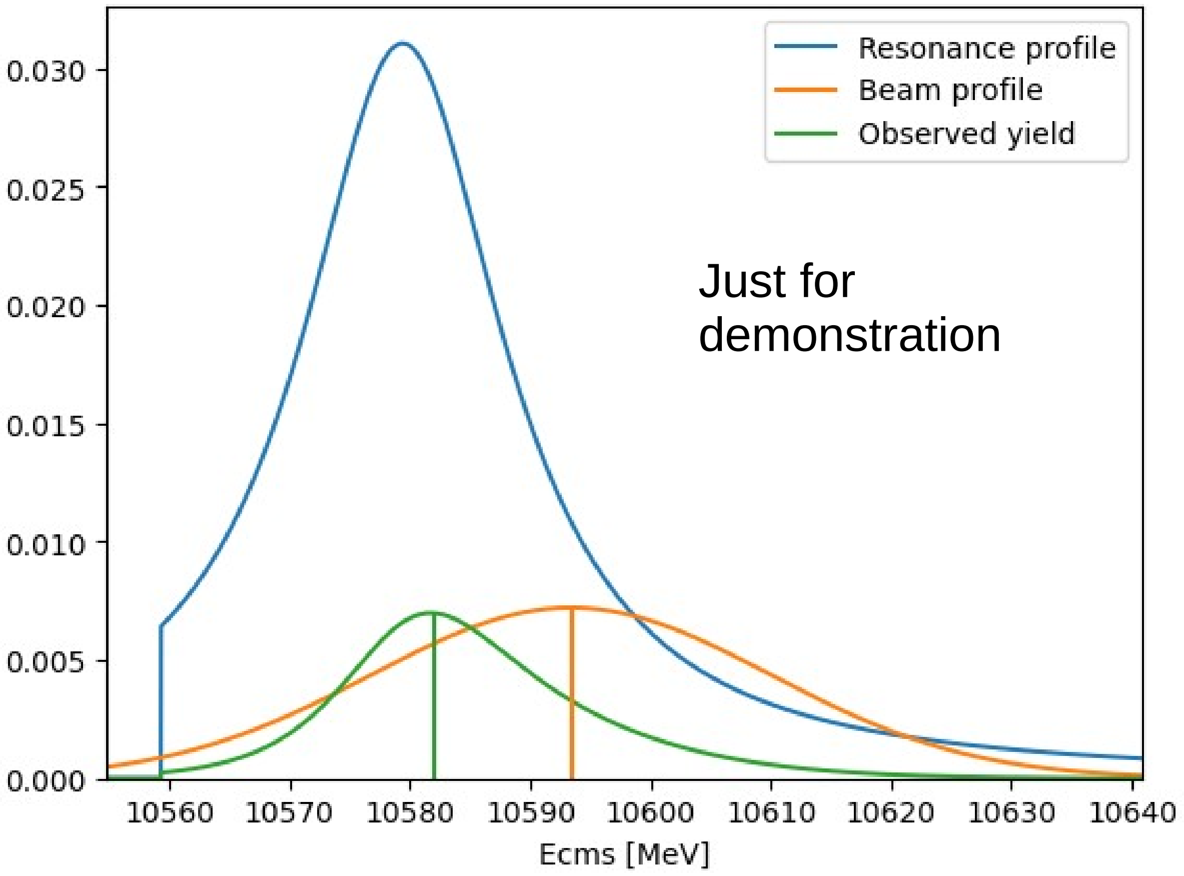
From LHCb
Precision: 4 x 10^{-5}

Our business

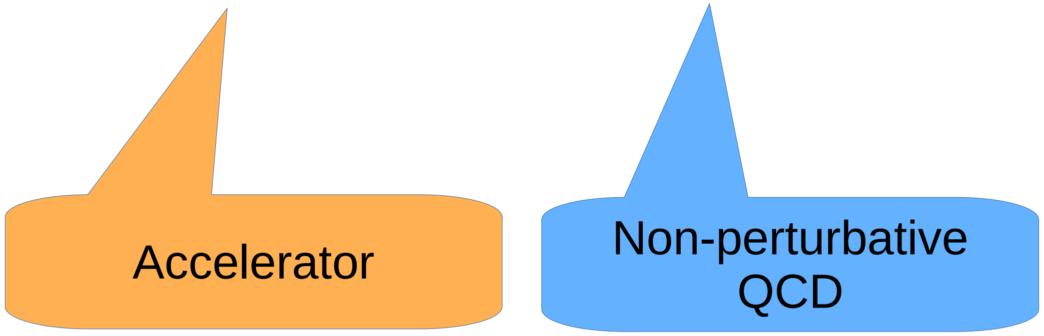
Resonance bias

The B-factories (like Belle II) run at Y4S resonance

$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

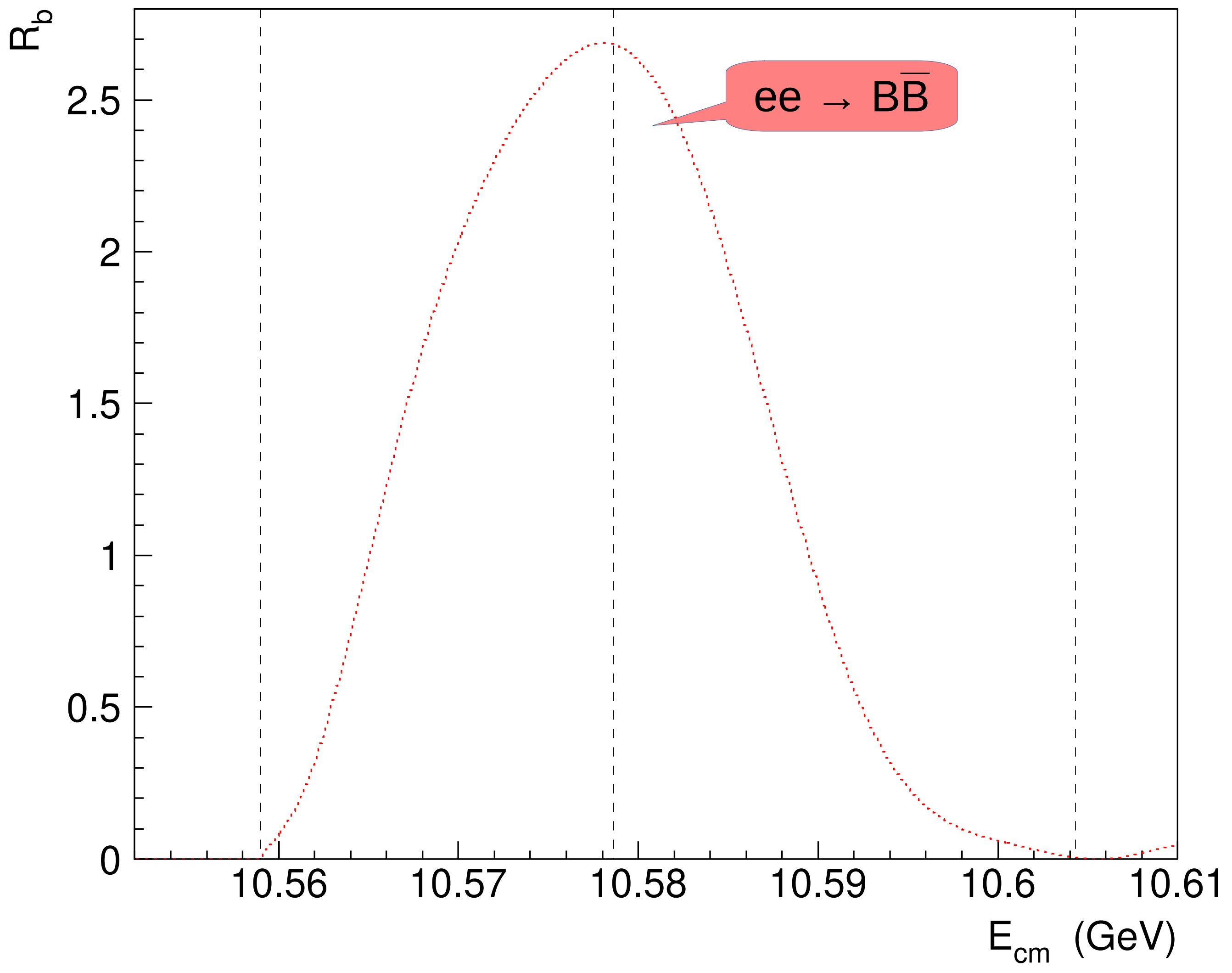


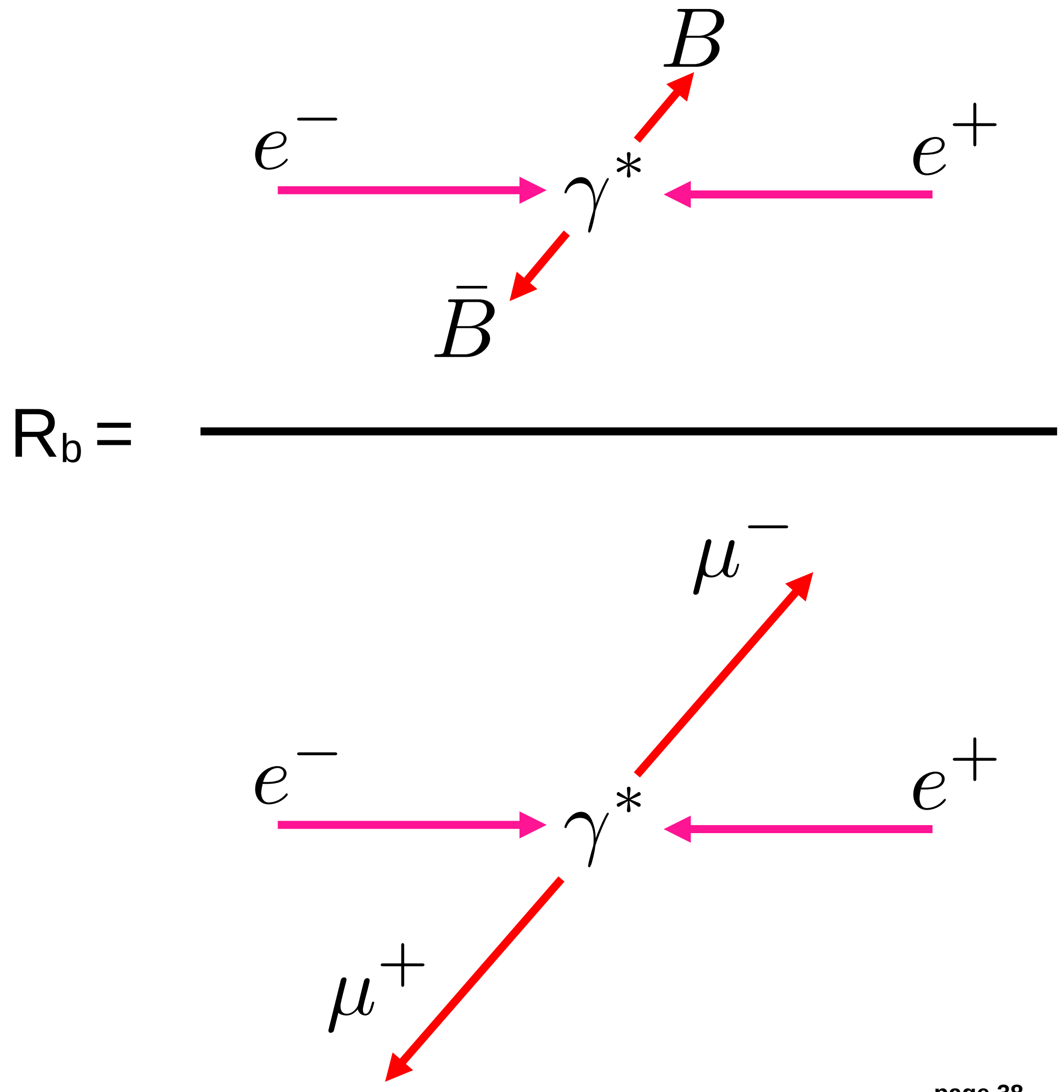
$$\sigma(E_{\text{cms}}) = \text{Gaus}(E_{\text{cms}}) \times \sigma_{\Upsilon(4S)}(E_{\text{cms}})$$



Y4S resonance

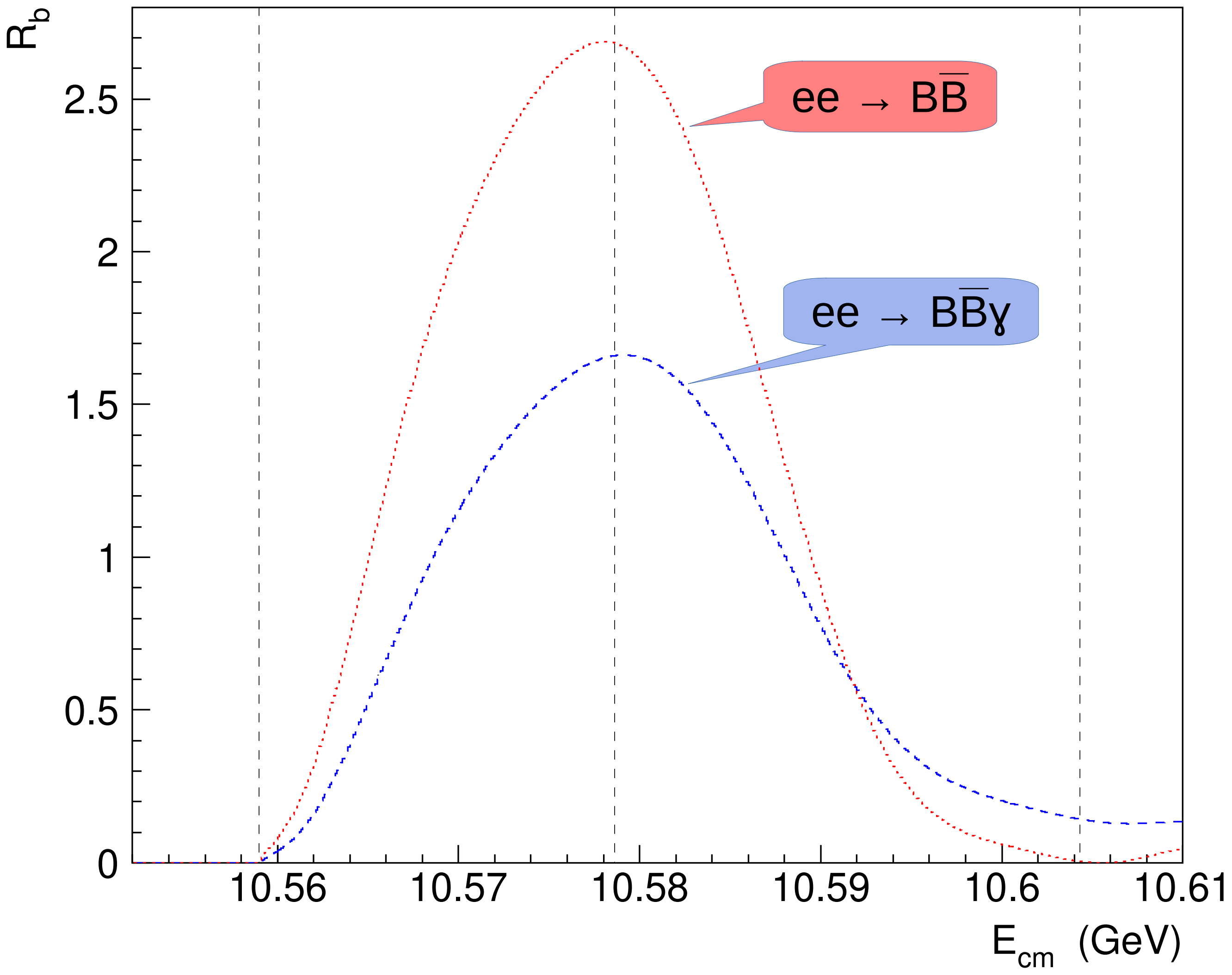
$$R_b = N(B\bar{B})/N(\mu^+\mu^-)$$

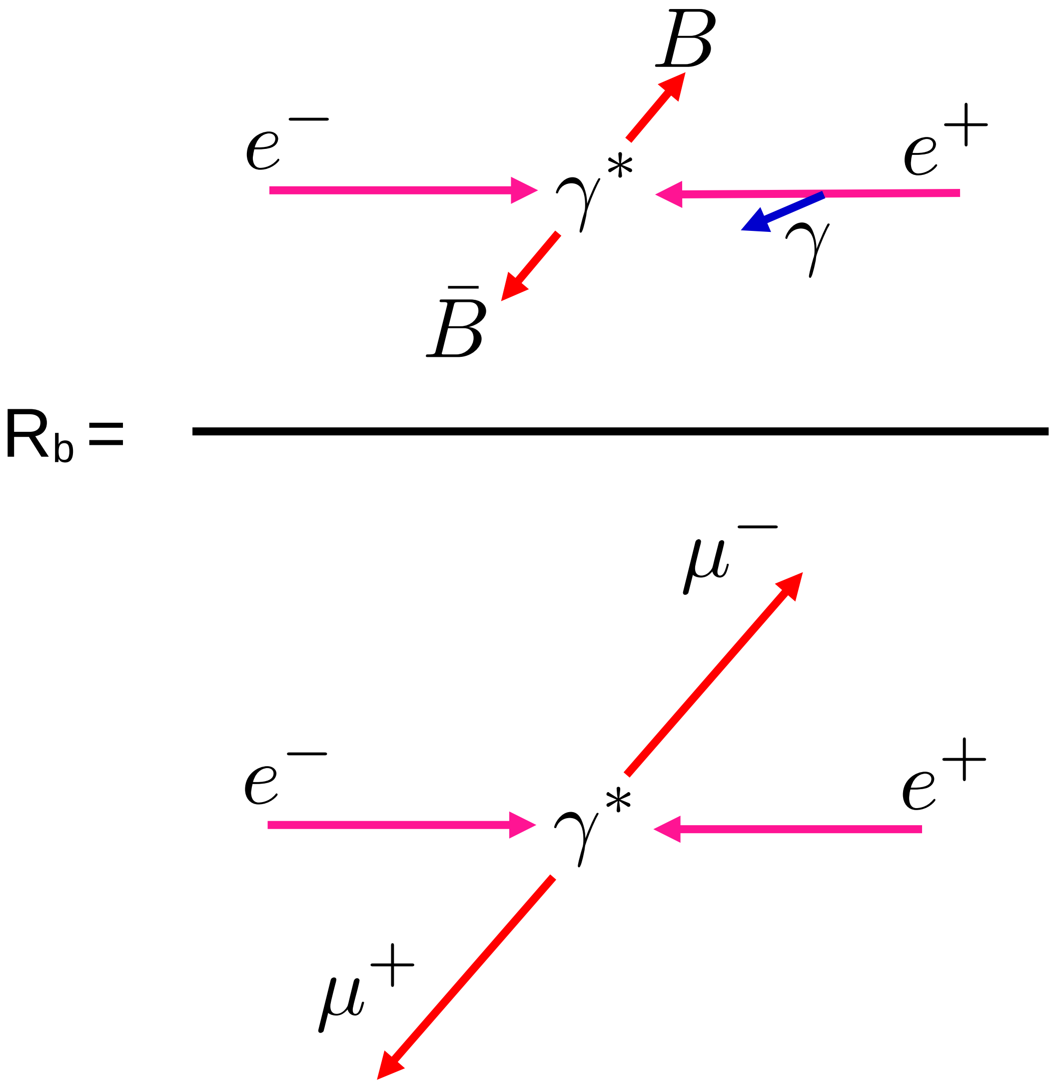




Y4S resonance

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





Y4S resonance

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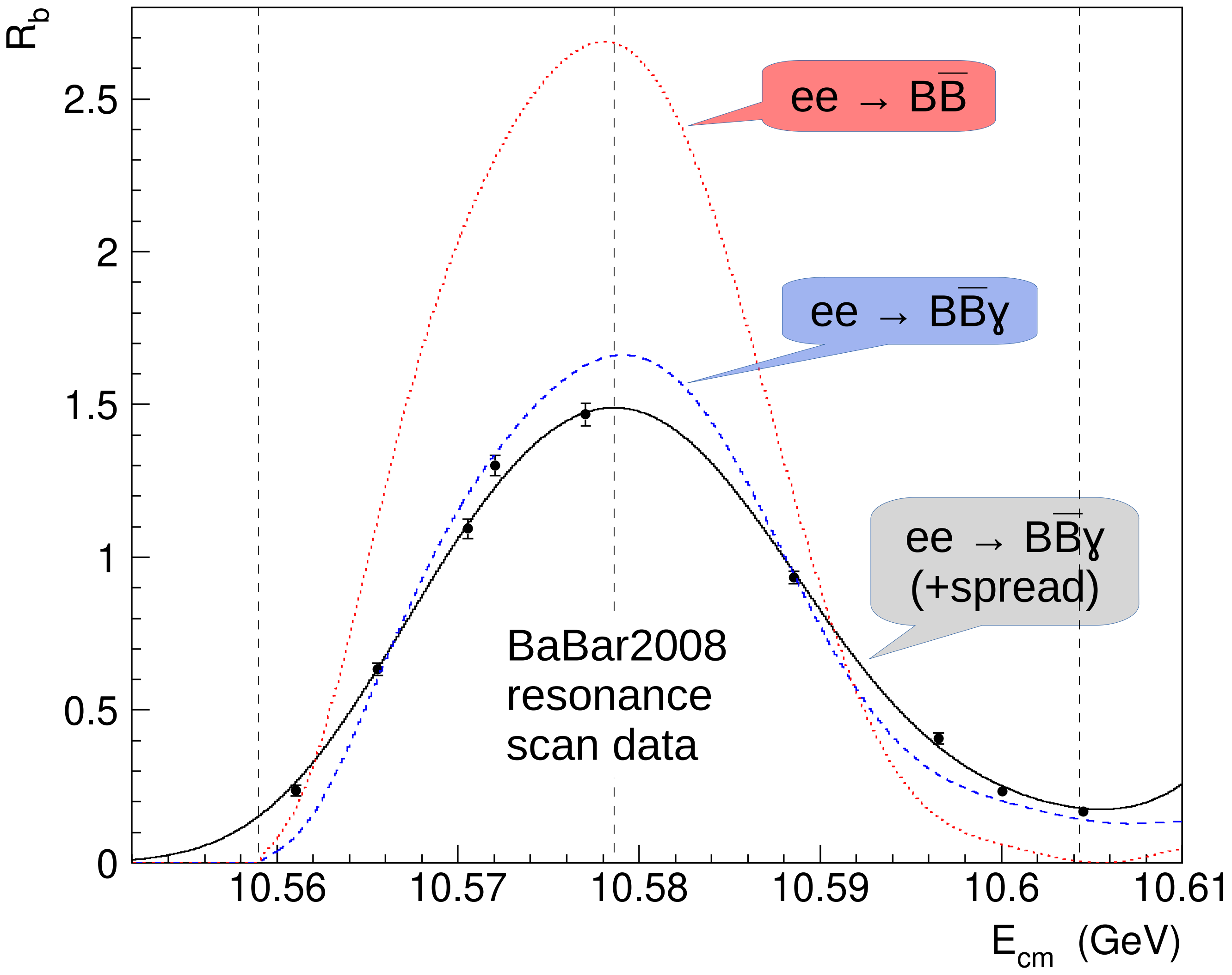
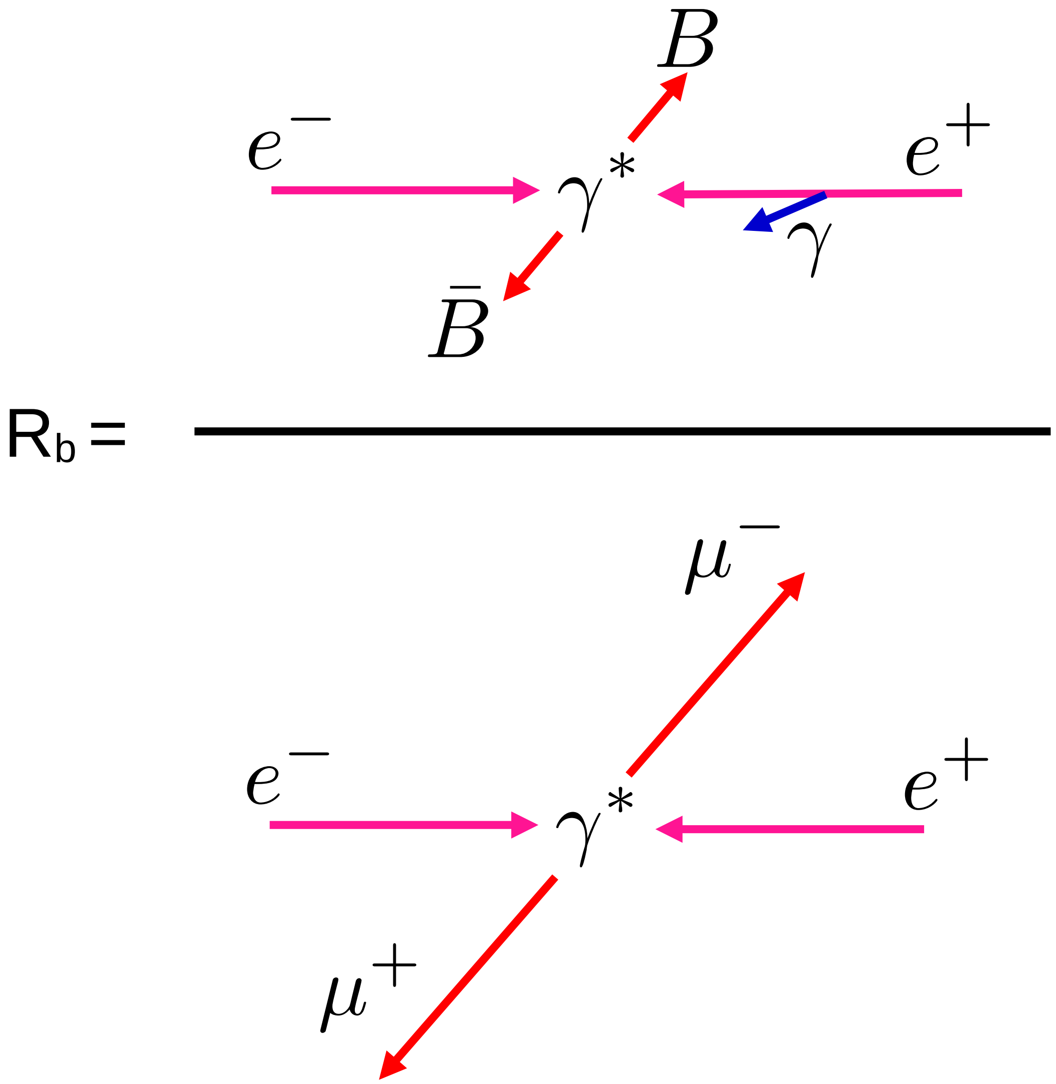
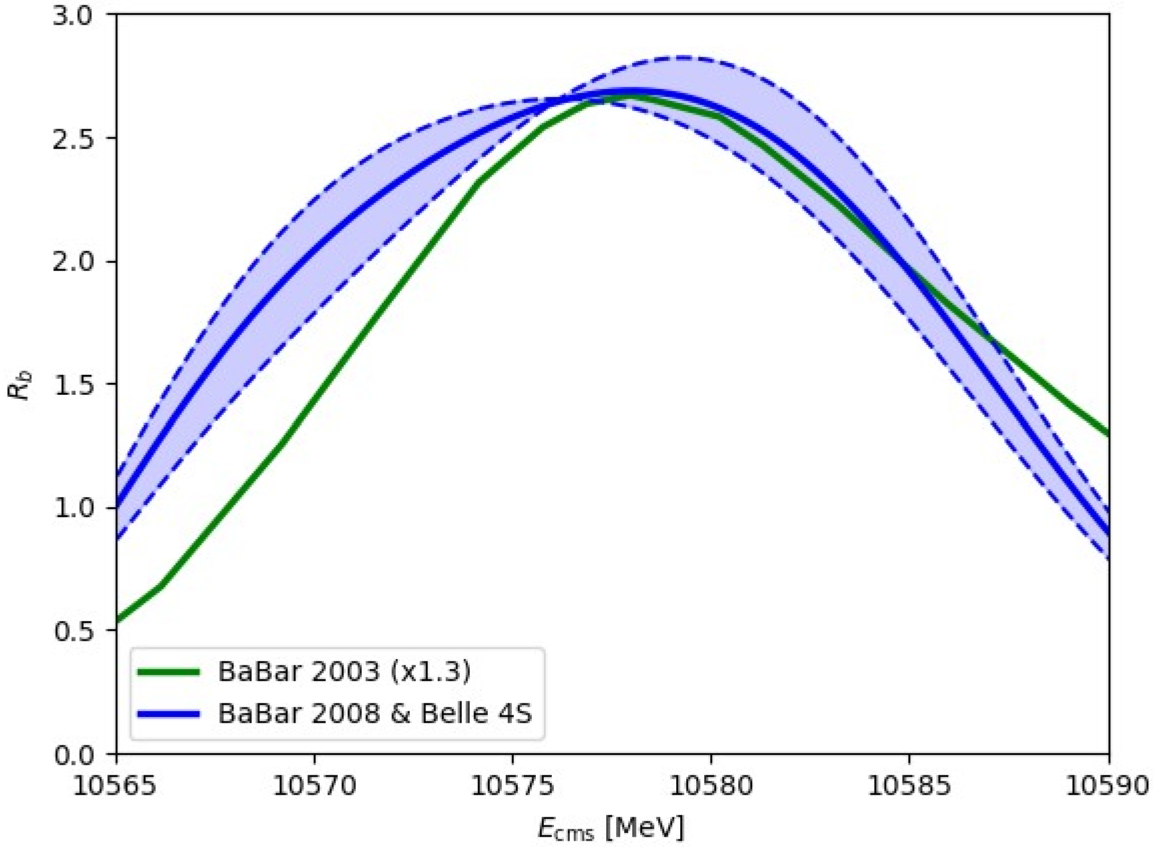
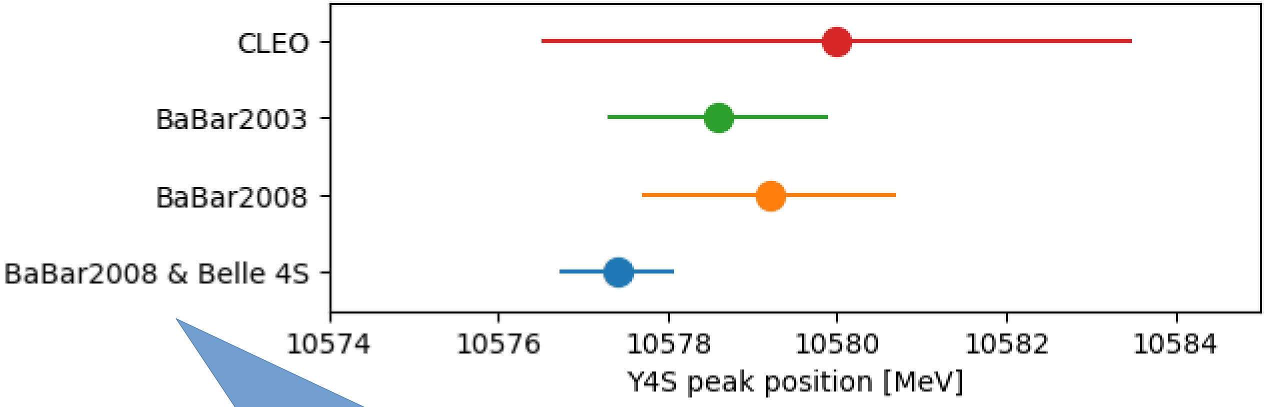




Available Y4S resonance shapes

0.09 MeV → 0.07 MeV

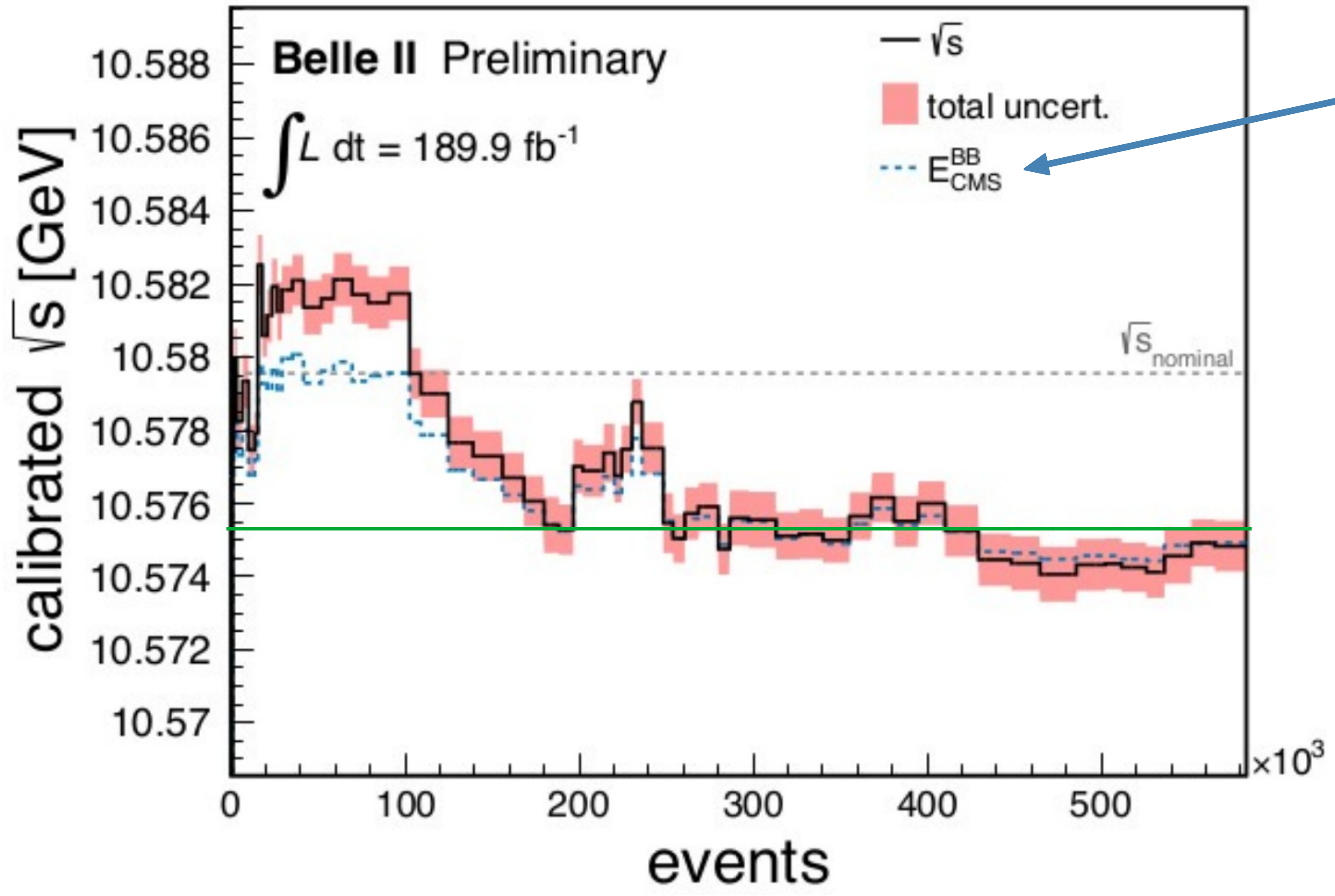




Combined fit of BaBar resonance scan
& Belle 4S data
from Belle colab.

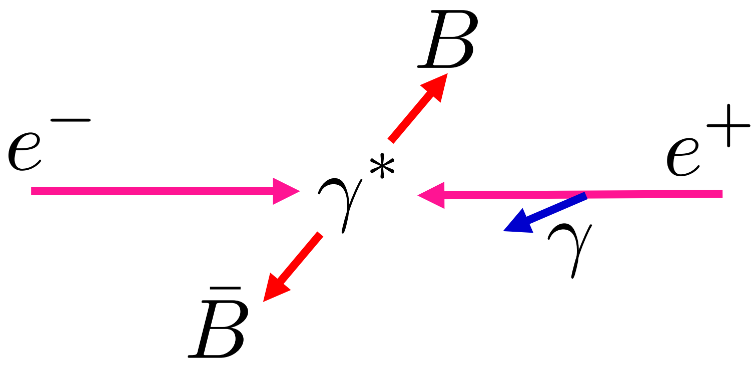
$$0.08(\text{stat}) \pm 0.05(\text{Belle's } \Upsilon_{4S}) \pm 0.05(\text{B mass}) \pm 0.09(\text{rest of sys})$$

Time dependence of collision energy



Uncorrected energy from

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

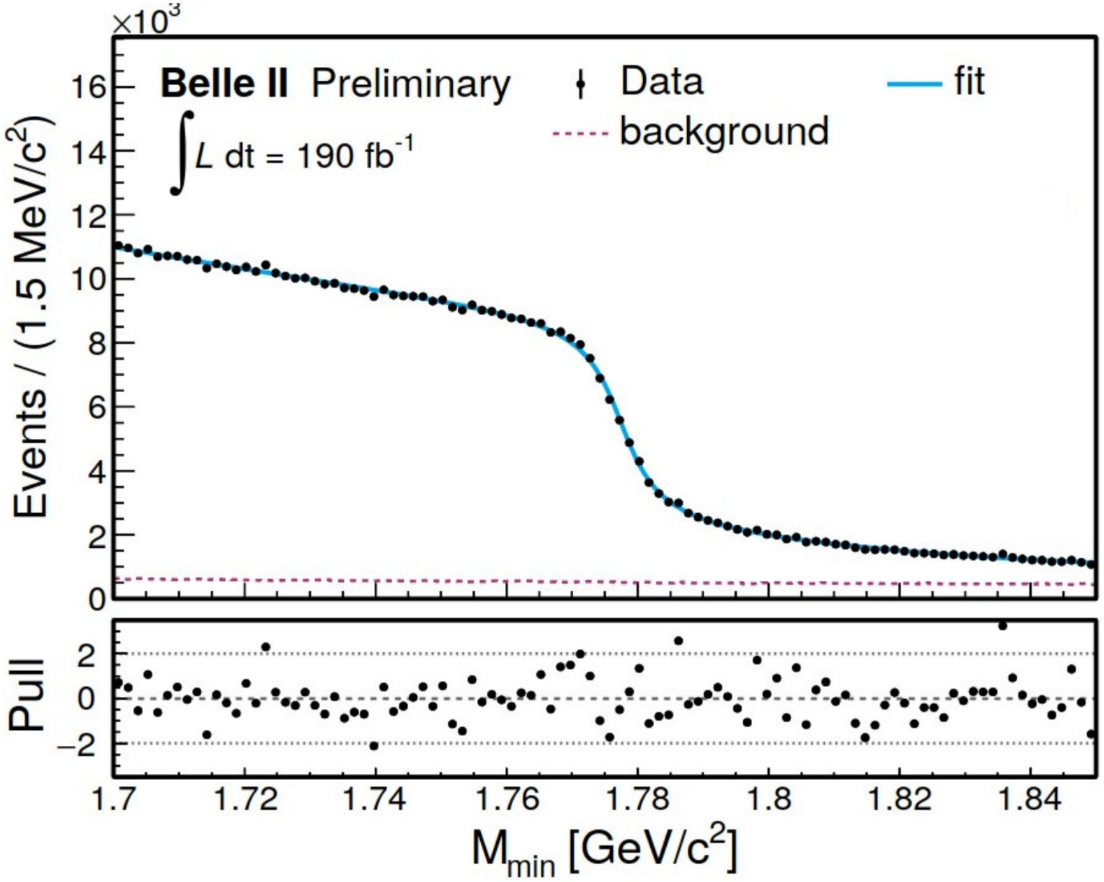


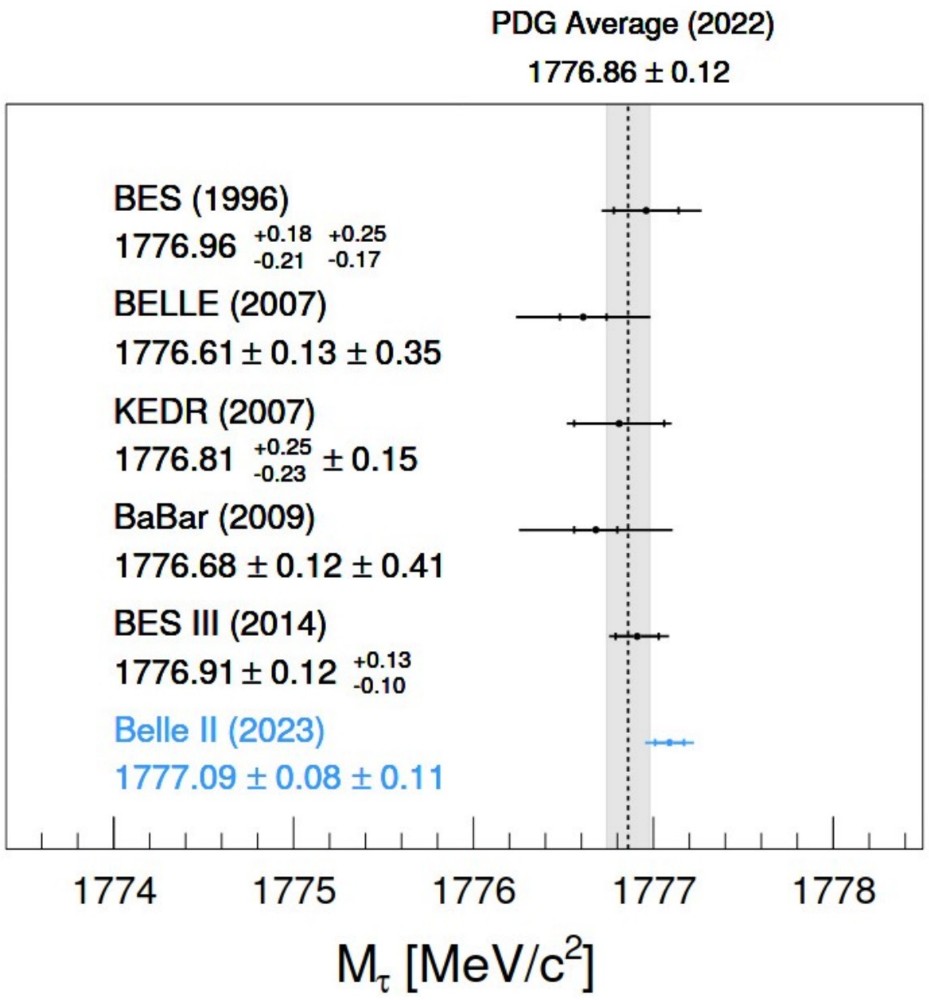
\+ γ radiation correction

± Y4S shape correction

Unblinding

Belle II results





Conclusions

- B factories allows for precise tau mass measurement
- Obtained result from blinded analysis compatible within 1.3σ with world average
- Substantial part of the tau mass uncertainty comes from external inputs