Tau Physics at Belle II

Current Status and Prospects

CEPC味物理-新物理和相关探测技术研讨会

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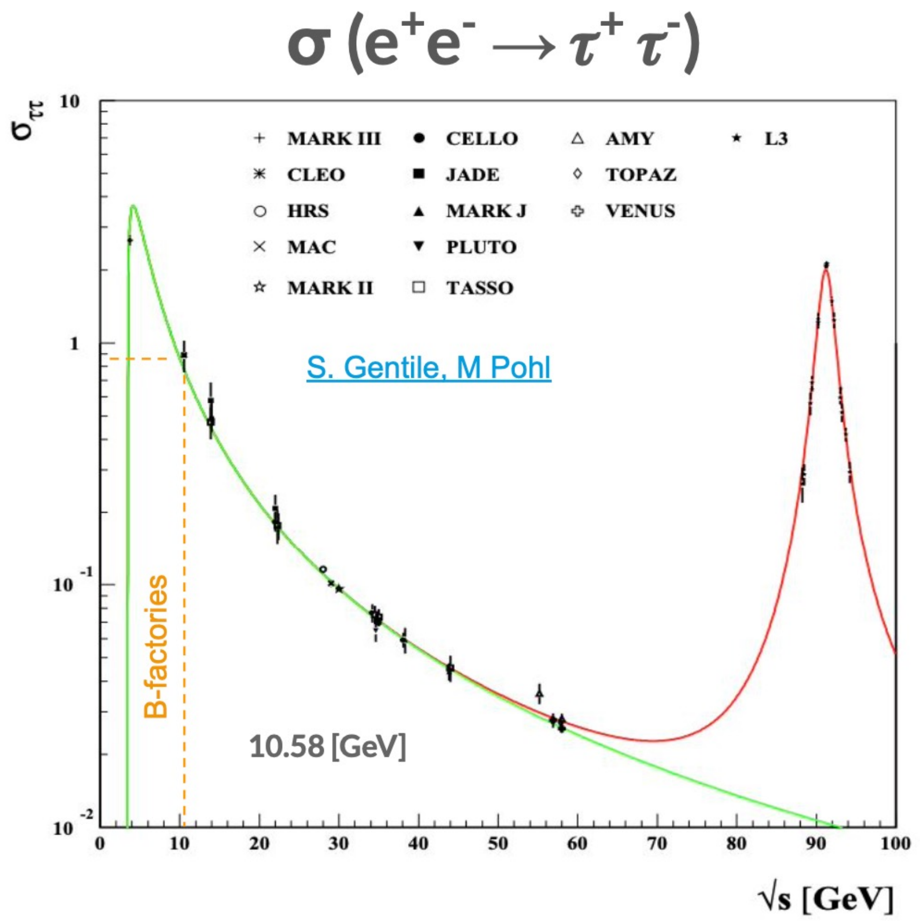
2023/06/18

B factory is also τ factory



@10.58 GeV:

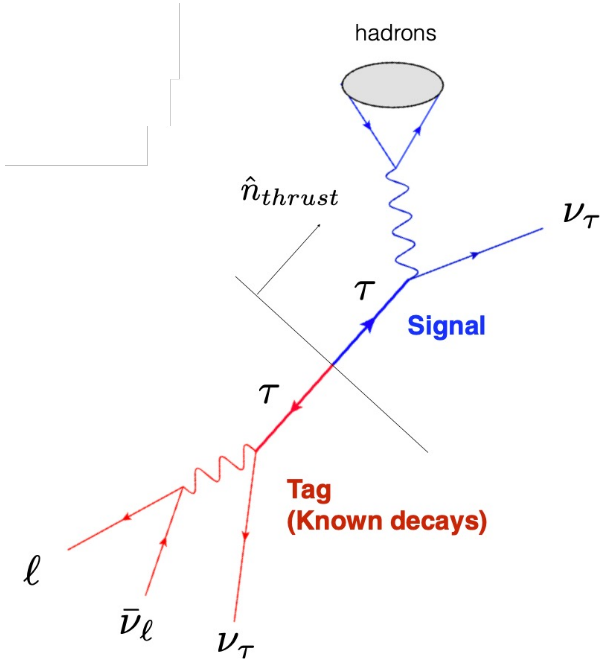
$$\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.92\, nb$$
$$\sigma(e^+e^- \rightarrow \Upsilon(4S)) = 1.11\, nb$$

Features of a B-Factory (super τ-charm Factory):

- High luminosity.
- Well-defined initial state.
- High vertex resolution.
- Excellent calorimetry.
- Sophisticated particle ID.
- Ability to trigger low-multiplicity event

Also see Nishida-san's talk

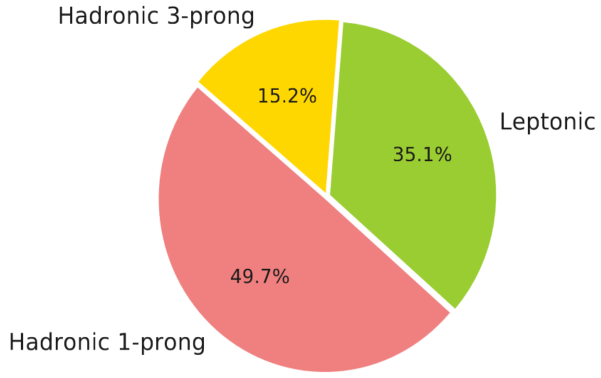
How we reconstruct τ at Belle II (in general cases)

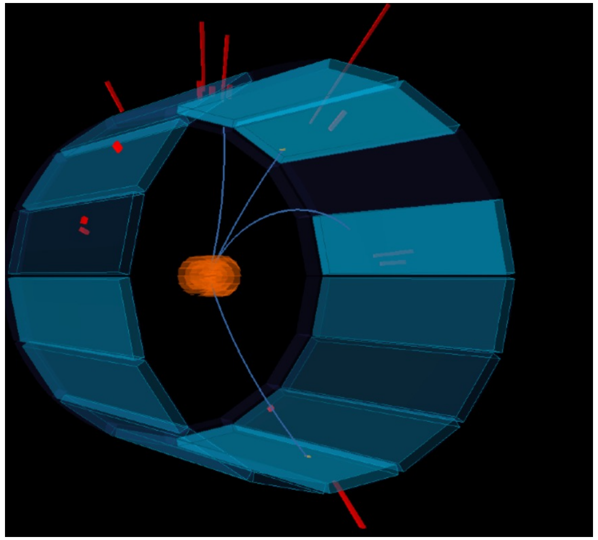


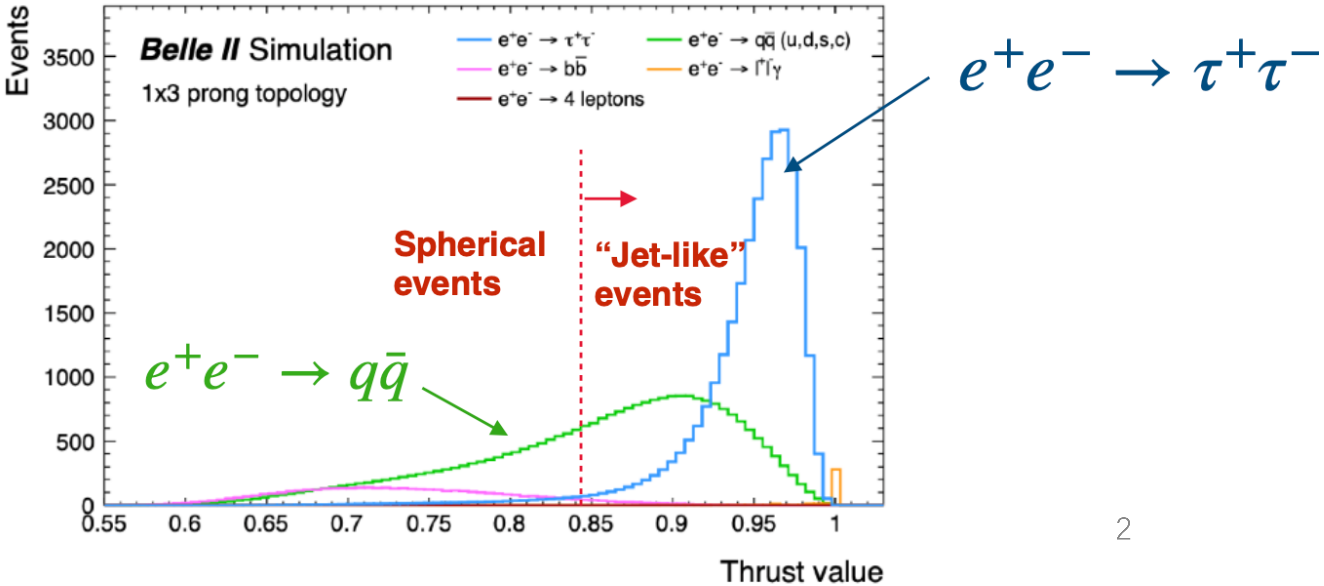
- $e^+e^- \rightarrow \tau^+\tau^-$ decays are reconstructed
- Event separated based on ***thrust*** axis ($\hat{n}_{thrust}$)

$$V_{thrust} = \frac{\Sigma_i |\vec{p}_i^{cm} \cdot \hat{n}_{thrust}|}{\Sigma_i |\vec{p}_i^{cm}|}$$

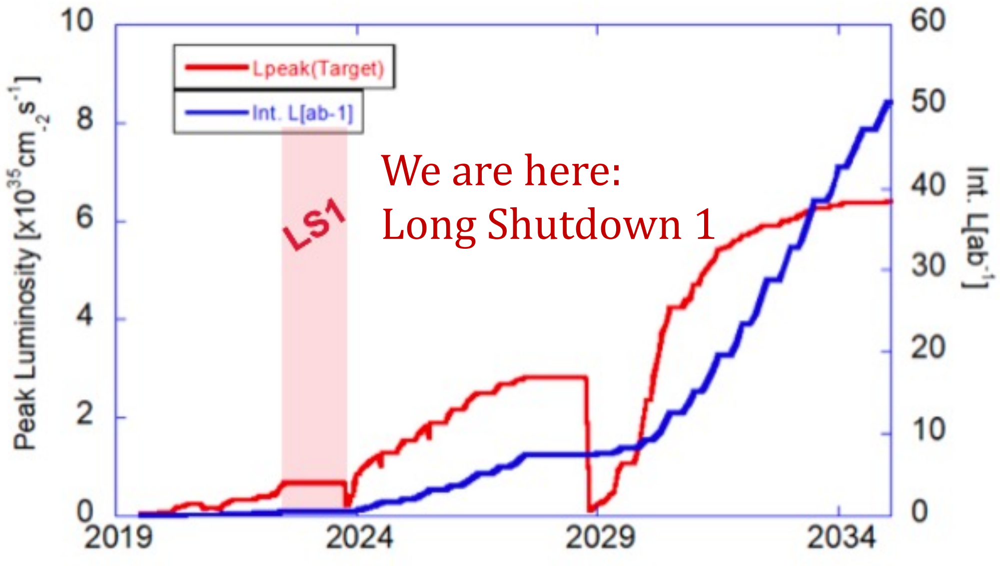
- $\vec{p}_i^{cm}$: momenta of detectable tracks
- $\hat{n}_{thrust}$: values maximize V_{thrust}

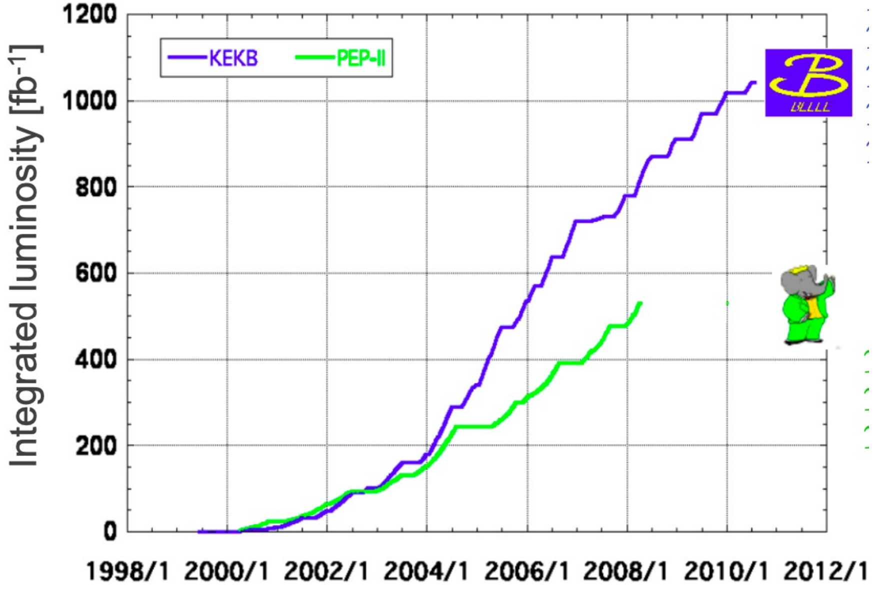






Current status of Belle II





Current:

peak $\mathcal{L}$: 4.7×10^{34} cm^{-2} s^{-1} (world-record)

integral $\mathcal{L}$: 428 fb^{-1}

Goal:

peak $\mathcal{L}$: 6×10^{35} cm^{-2} s^{-1}

integral $\mathcal{L}$: 50 ab^{-1}

The Belle II's integral luminosity is only half those of Belle/Babar. **But** some results are better!

- Better vertex resolution
- Better trigger efficiency
- ……

What Belle II has done:

τ properties:

-- mass: arXiv:2305.19116

-- lifetime (Sensitivity study)

Beyond Standard Model

--LFV

- $\tau^- \to \ell^- \phi$ arXiv:2305.04759
- $\tau^- \to \ell^- \alpha$ PRL 130, 181803

Electroweak sector

--Lepton Universality

$$R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$$ (Sensitivity study)

PS: Works on Trigger logical, Particle Identification, Photon calibration … are still ongoing for better performance.

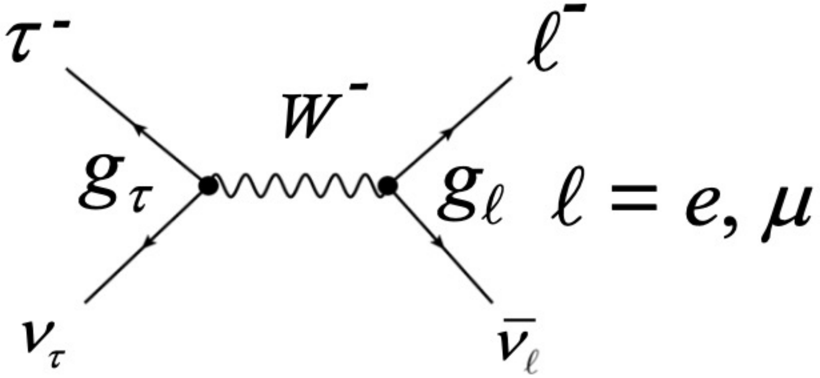
a little background:

$$\Gamma(L^- \to \ell^- \bar{\nu}_\ell \nu_L(\gamma)) = \frac{\mathcal{B}(L^- \to \ell^- \bar{\nu}_\ell \nu_L(\gamma))}{\tau_L} = \frac{g_L^2 g_\ell^2}{32 M_W^4} \frac{m_L^5}{192\pi^3} f\left(\frac{m_\ell^2}{m_L^2}\right) F_{corr}(m_L, M_\ell)$$

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln(x)$$

$$F_{corr}(m_L, M_\ell) = f\left(\frac{m_\ell}{m_L}\right)\left(1 + \frac{3m_\ell^2}{5M_W^2}\right)\left(1 + \frac{\alpha(m_L)}{2\pi}\left(\frac{25}{4} - \pi^2\right)\right)$$

W. Marciano and A. Sirlin PRL. **61, 1815 (1988)**



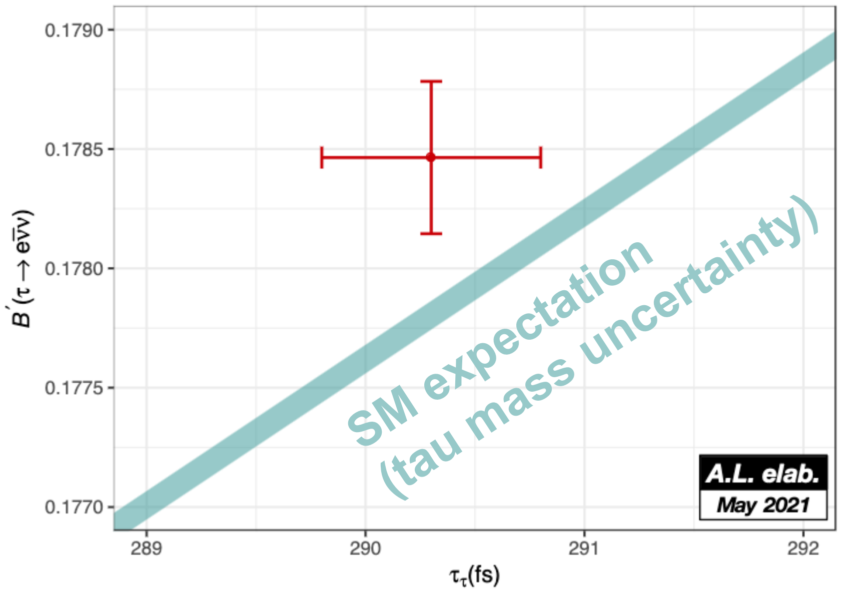
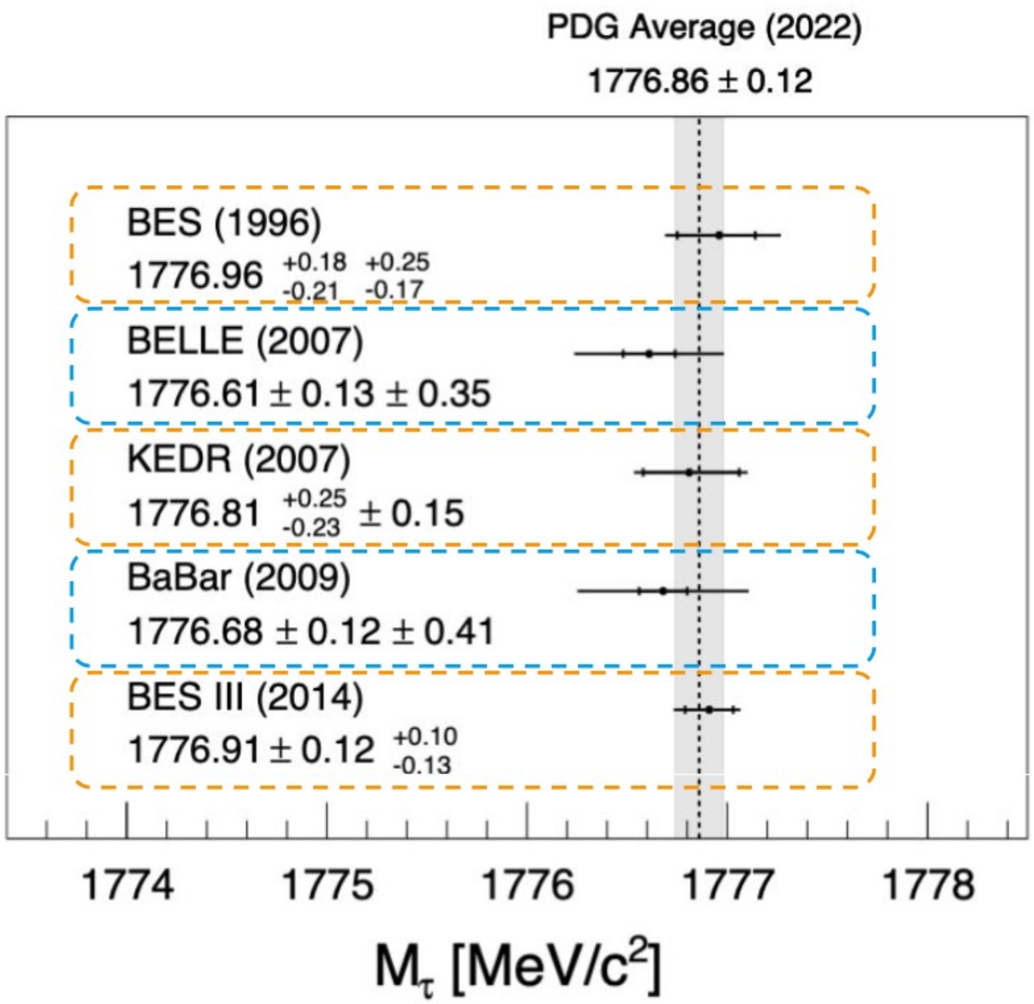


Fig from Alberto Lusiani

input	Uncertainty (%)	Best Measurement
$\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau(\gamma))$	0.180	ALEPH
τ_L	0.172	Belle
m_L^5	0.007	BES III

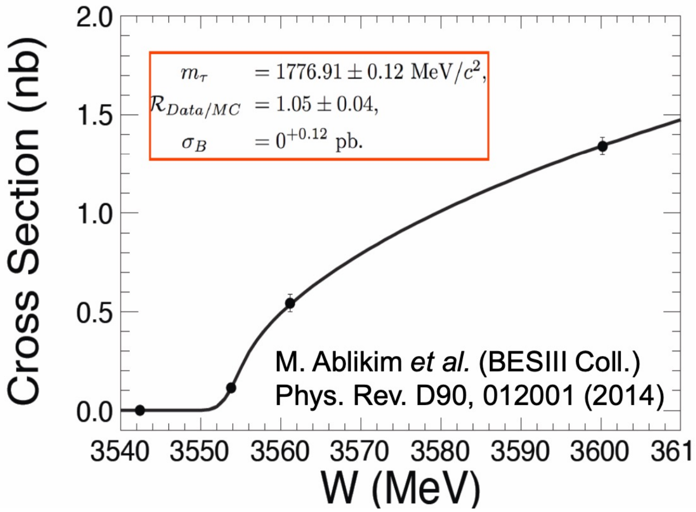
Measurement of τ mass

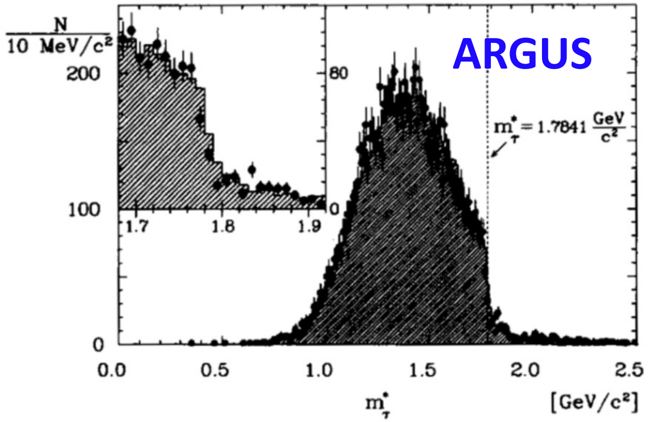


Two main methods for measuring the mass:

1: pair production cross section:

- energy scan around the tau pair production threshold
- extract the mass from the dependence of cross section on collision energy



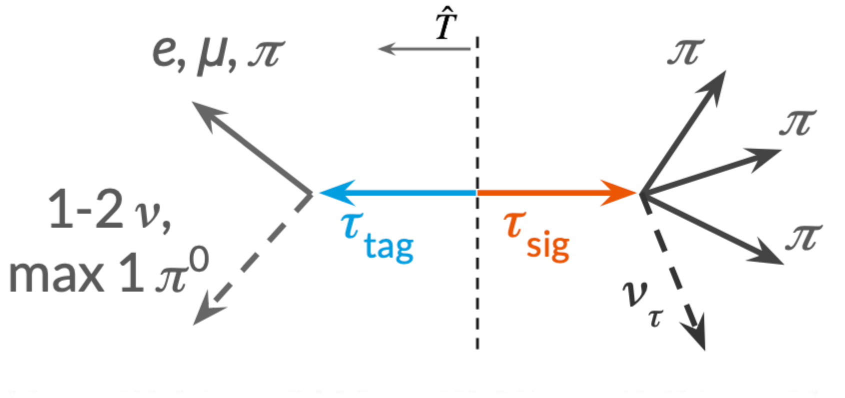


Phys. Lett. B 292 (1992) 221-228

2: Pseudomass method:

developed by ARGUS, and used at BaBar, Belle and Belle II

Measurement of τ mass



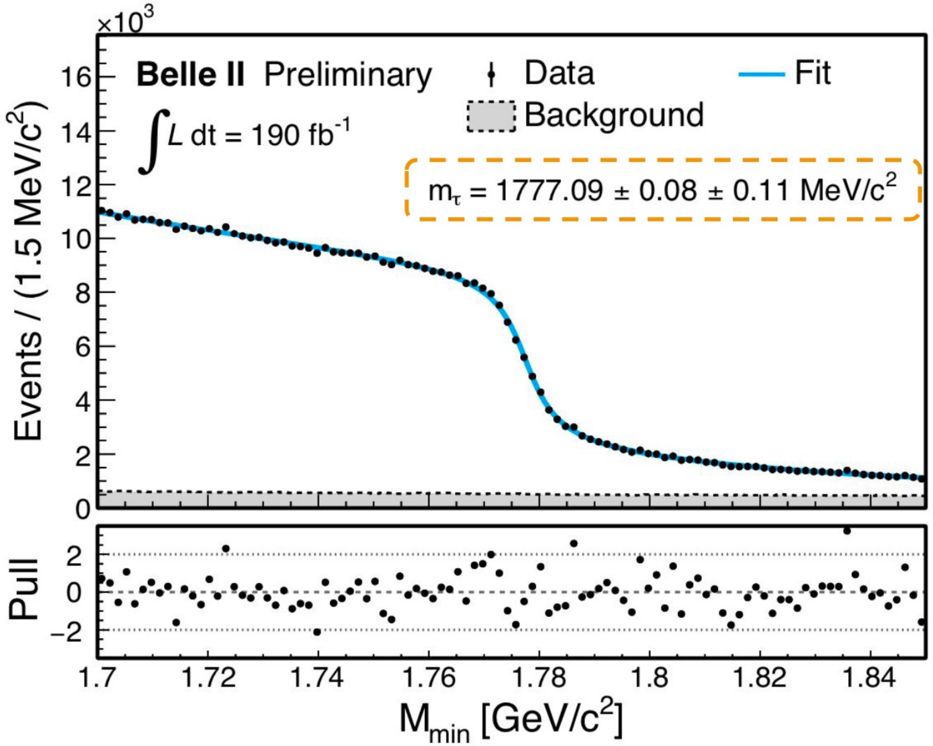
Pseudomass method:

$$m_\tau^2 = (p_h + p_\nu)^2$$
$$= 2\,E_h\,(E_\tau - E_h) + m_h^2 - 2|\vec{p}_h|(E_\tau - E_h)\cos(\vec{p}_h, \vec{p}_\nu)$$

The direction of the neutrino is not known, since $\cos(\vec{p}_h, \vec{p}_\nu) \leq 1$

arXiv:2305.19116

Pseudomass: $\sqrt{2\,E_h\,(E_\tau - E_h) + m_h^2 - 2|\vec{p}_h|(E_\tau - E_h)} \leq m_\tau$



Belle (414 fb^{-1}) arXiv:hep-ex/0608046

TABLE I: Summary of systematic uncertainties

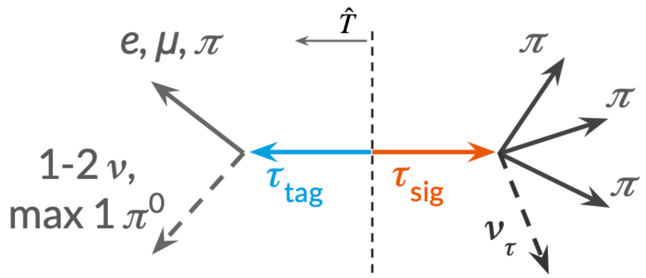
Source of systematics	σ, MeV/c^2
Beam energy and tracking system	0.26
Edge parameterization	0.18
Limited MC statistics	0.14
Fit range	0.04
Momentum resolution	0.02
Model of $\tau \to 3\pi\nu_\tau$	0.02
Background	0.01
Total	0.35

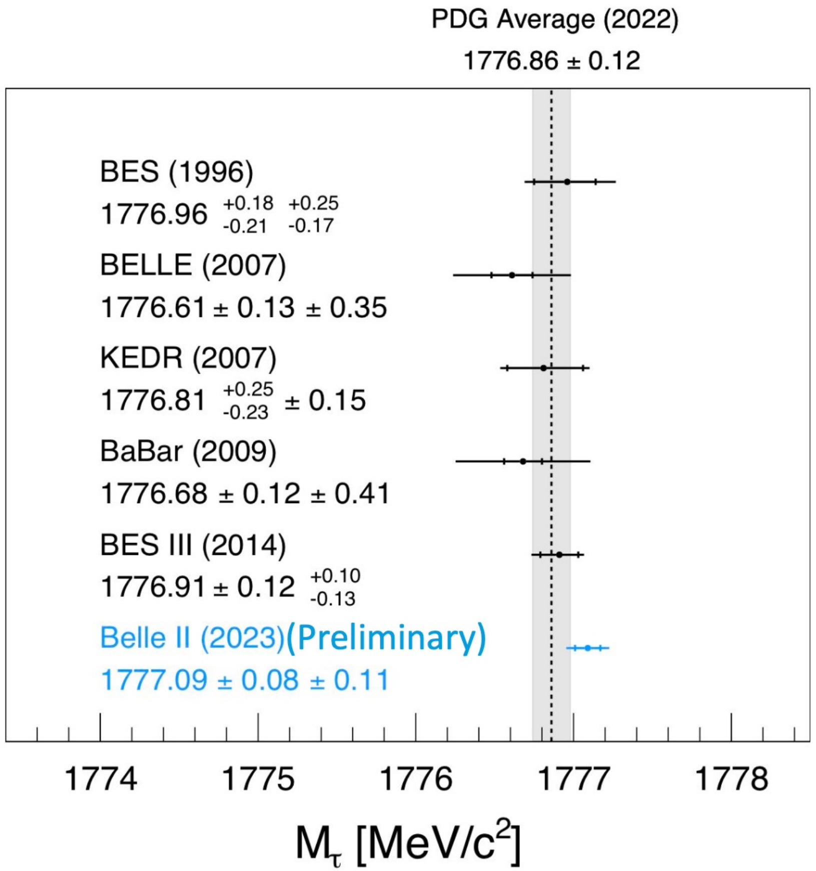
stat: 0.13 MeV

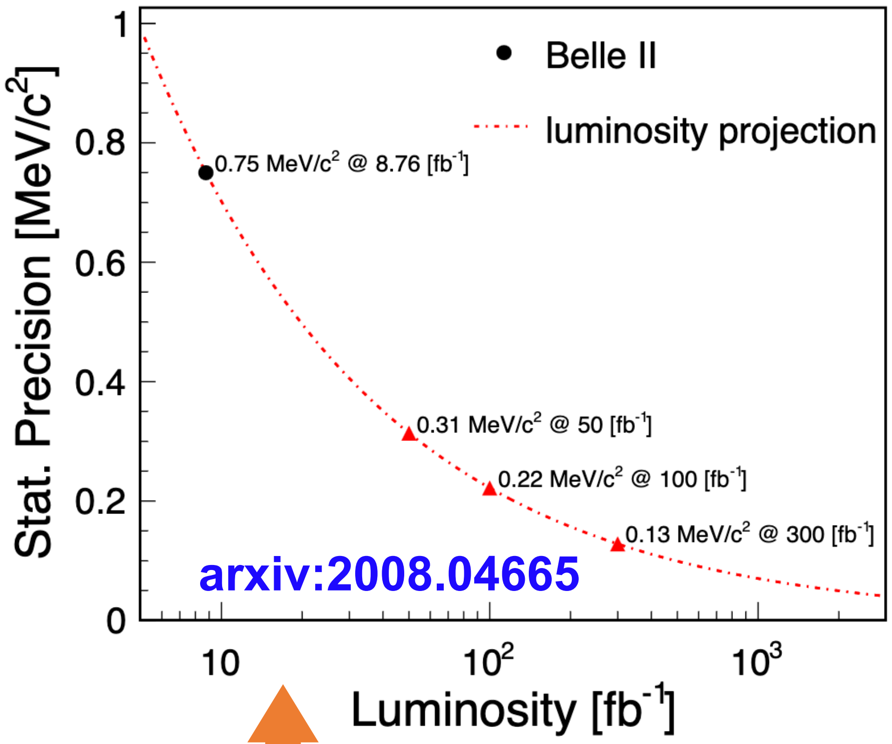
Belle II (190 fb^{-1})

Source	Uncertainty [MeV/c^2]
Knowledge of the colliding beams:	
Beam energy correction	0.07
Boost vector	$\leq$ 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	$\leq$ 0.01
Imperfections of the simulation:	
Detector material budget	0.03
Modeling of ISR and FSR	0.02
Total	0.11

Measurement of τ mass





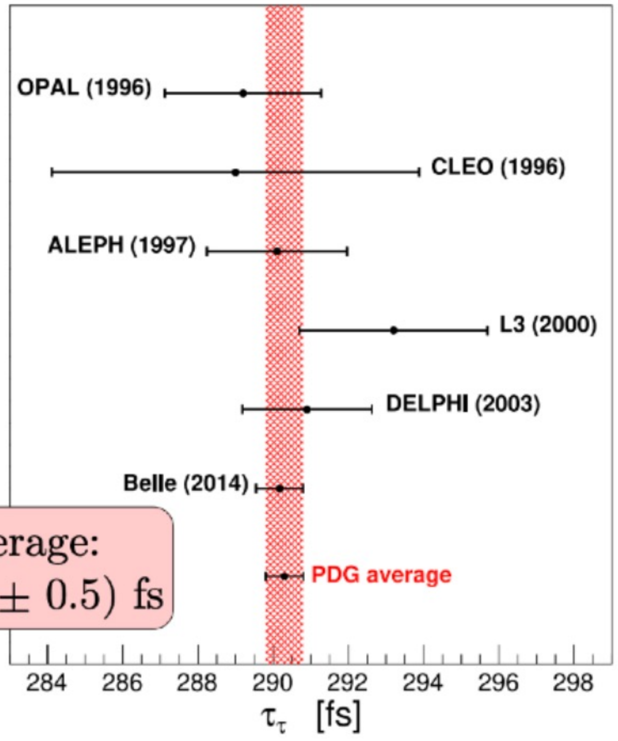


World's best measurement of the τ mass!

half data size as Belle and BaBar, BUT better statistical precision!

Even better than our estimation when using 8.75 fb¹ data!

Sensitivity study of τ lifetime



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

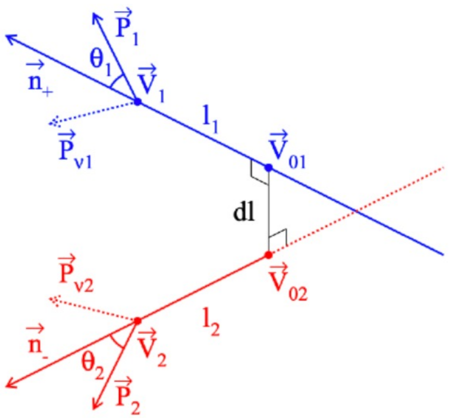
[1] PRL 112, 031801 (2014), arXiv:1310.8503 [hep-ex]

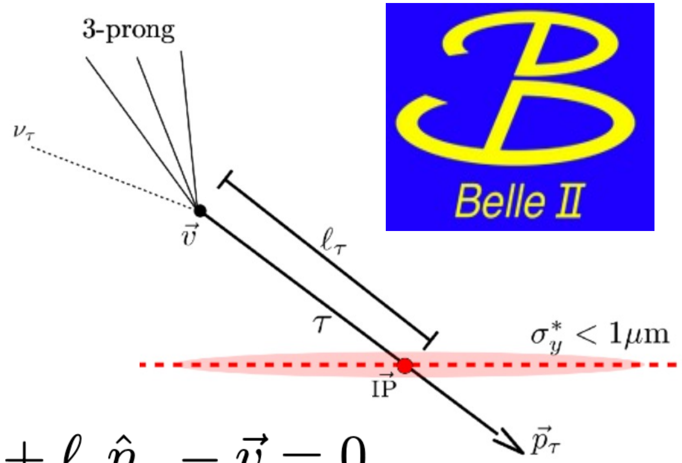
Belle's result:

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

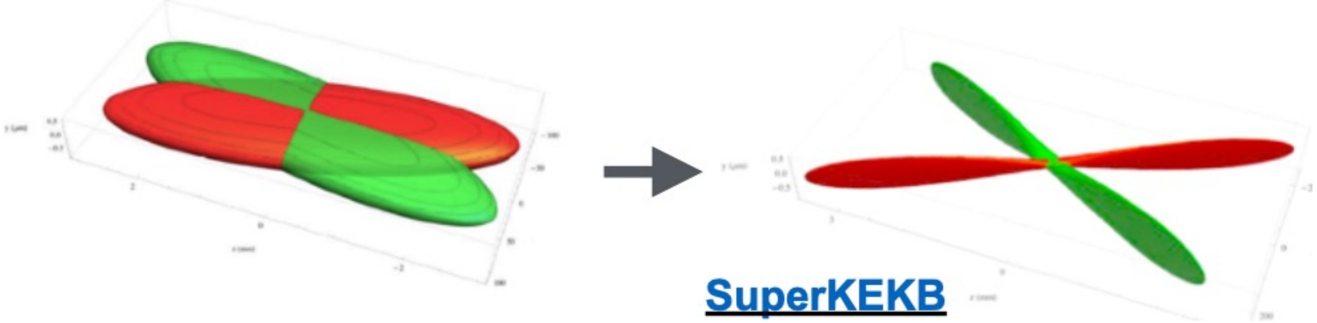
Based on 711 fb^{-1} data, using 3x3 topology

Belle, PRL 112, 031801





$$\vec{\text{IP}} + \ell_\tau \hat{n}_\tau - \vec{v} = 0$$

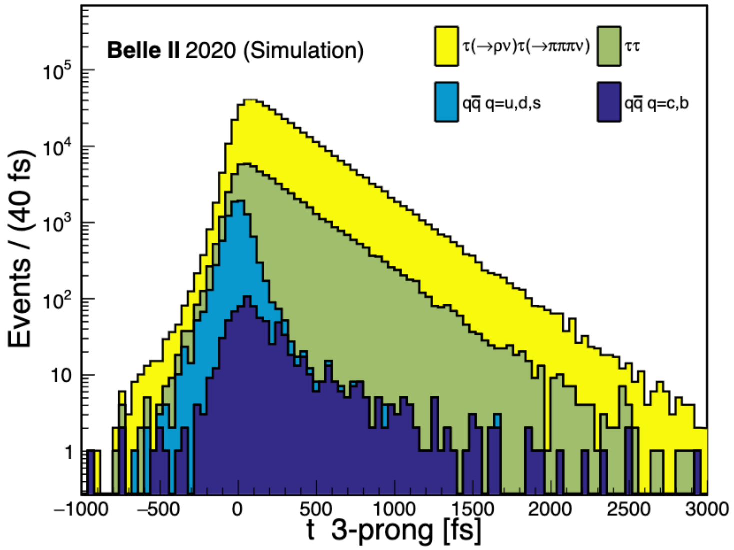


New method at Belle II:

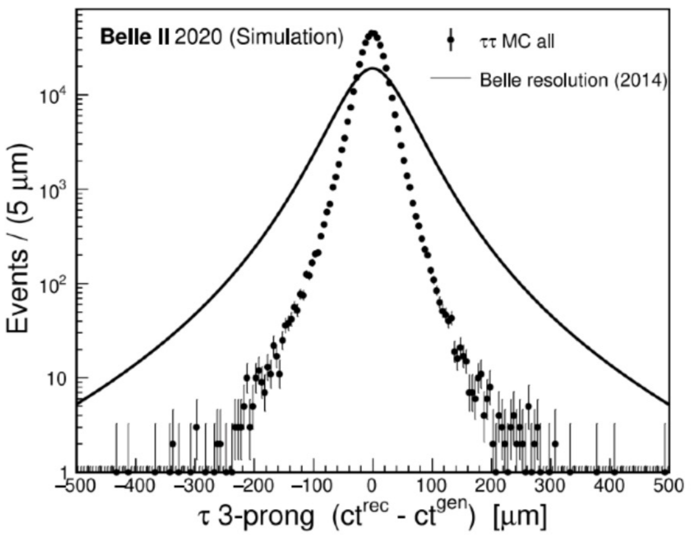
1. **One $\tau \to 3\pi\nu$, another $\tau \to \rho\nu$.**
2. **Estimate the τ momentum $\vec{p}_\tau$**
3. **Find the production vertex.**
   Intersection of $\vec{p}_\tau$ with the plane IPy.

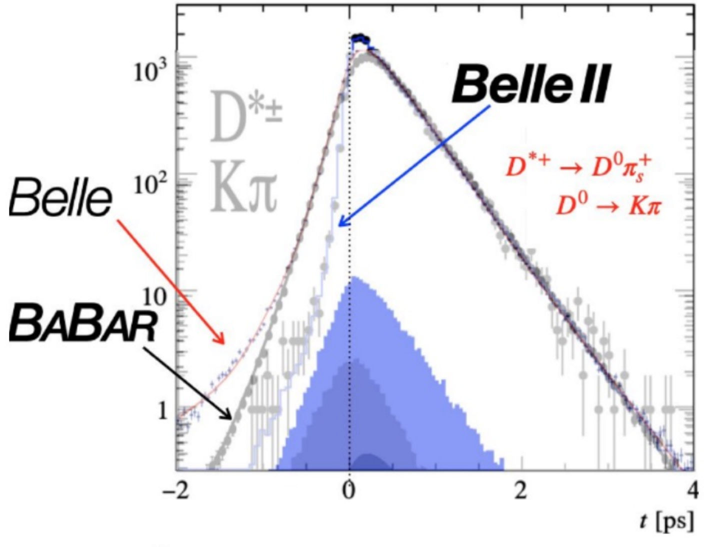
Sensitivity study of τ lifetime

proper decay time: $t = \ell_\tau \frac{m_\tau}{|\vec{p}_\tau| c}$



Proper decay time resolution:





In MC simulations, the Belle II proper time resolution is **~2x better than Belle.**

-- Due to PXD and smaller beam pipe diameter.

Input $\tau_\tau = 290.57$ fs

Output $\tau_\tau = 287.2 \pm 0.5$ (stat) fs

} **3 fs bias**

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

Next step:

- **Revisiting the 3x3 topology**
- **Consider the ISR/FSR effect**
- **……**

Lepton Flavor Universality Violation

$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{\frac{BF\left[\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau\right]}{BF\left[\tau^- \to e^- \bar{\nu}_e \nu_\tau\right]} \frac{f\left(m_e^2/m_\tau^2\right)}{f\left(m_\mu^2/m_\tau^2\right)}}$$

In the SM: $\left(\frac{g_\mu}{g_e}\right)_\tau = 1$

	μ
$\mathbf{N}^D$	731102
Purity	97.3%
Total Efficiency	0.485%
Particle ID Efficiency	74.5%
Systematic uncertainties:	
Particle ID	0.32
Detector response	0.08
Backgrounds	0.08
Trigger	0.10
$\pi^-\pi^-\pi^+$ modelling	0.01
Radiation	0.04
$\mathcal{B}(\tau^- \to \pi^-\pi^-\pi^+\nu_\tau)$	0.05
$\mathcal{L}\sigma_{e^+e^-\to\tau^+\tau^-}$	0.02
Total [%]	0.36

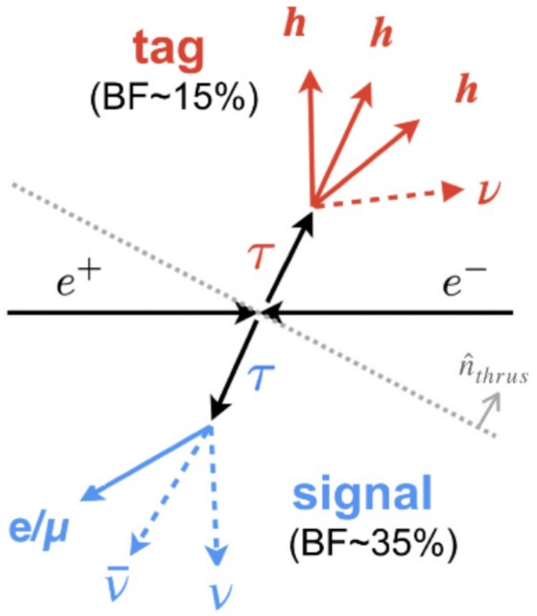
Base measurement form Babar: 467 fb^{-1} ,
PRL.105.051602

Need to improve systematic uncertainty uncertainties due to PID and trigger

- **Belle II can do it!**

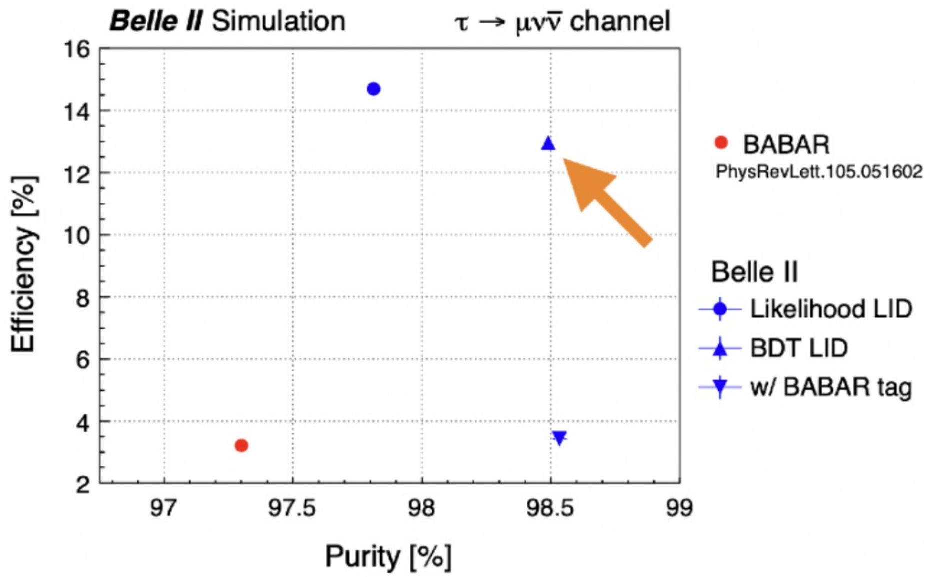
Lepton Flavor Universality Violation

tests with 3x1 topology: same method as Babar



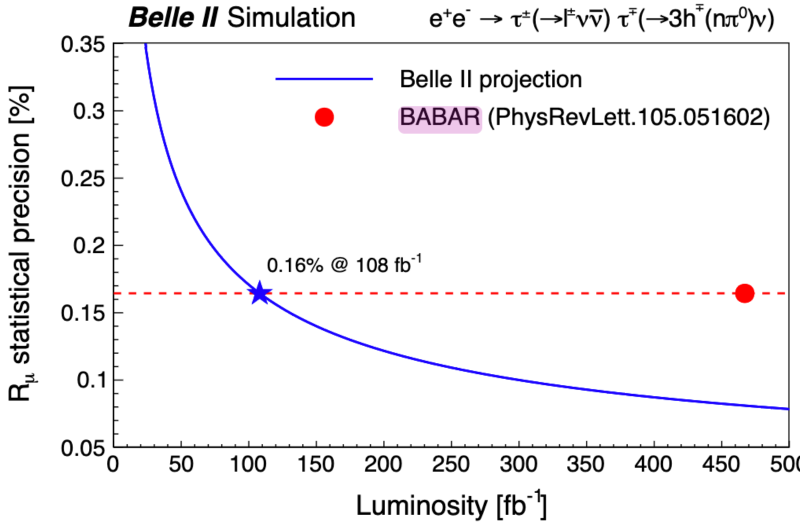
Cut-based performance

- Matches BaBar stat. uncertainty with 100 fb^{-1} of data.
  - Achieved with asymmetric p_t thresholds on lead, sublead and third track on tag side.
  - **x4 higher efficiency** with better purity:

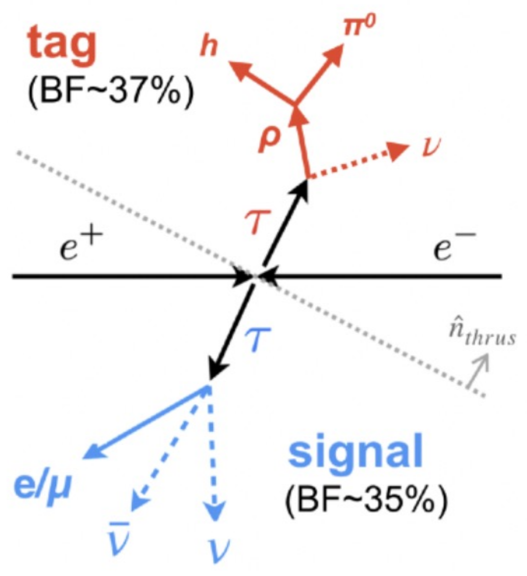


BDT performance

- Training of a XGBoost classifier for combined signal (e or μ in final state).
- 1.7x improvement in efficiency w.r.t. cut-based selection **(x7 than BaBar)**, with a purity of 98%.



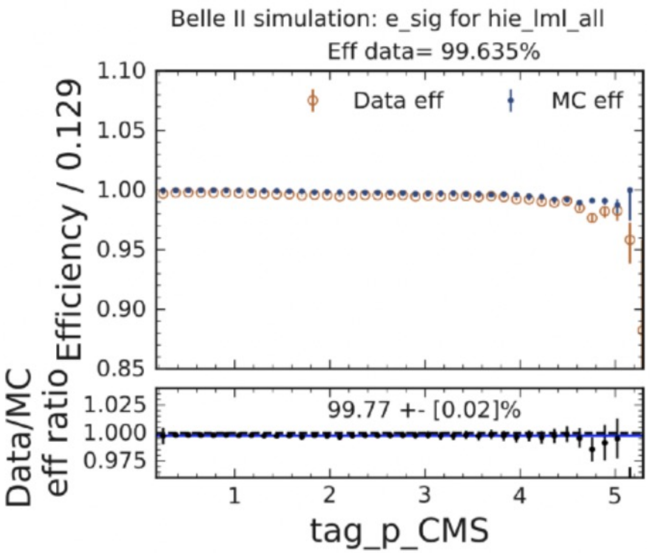
Lepton Flavor Universality Violation

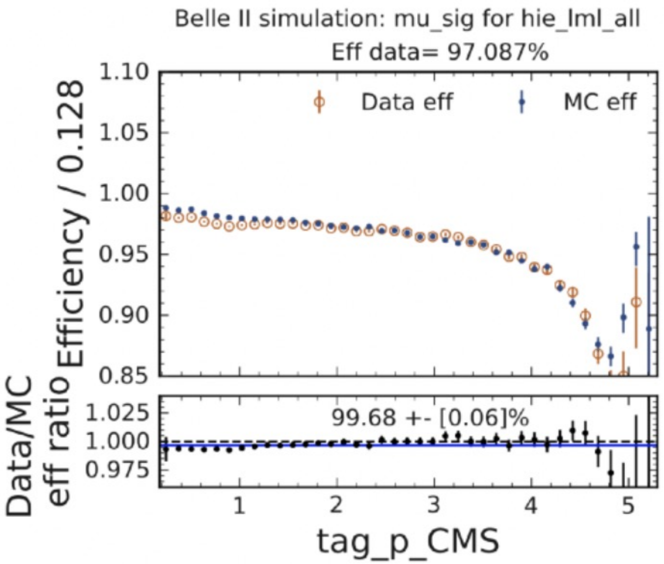


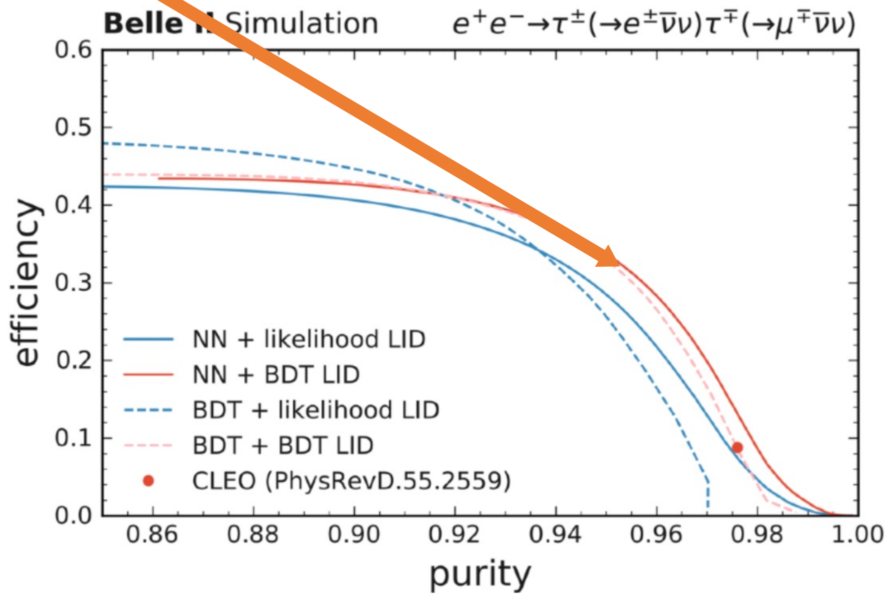
tests with 1x1 topology: same method as CLEO (only 3.56 fb^{-1})

- **Trigger**:
  - ϵ_{trg} = **96 - 100%** for e-channel.
  - ϵ_{trg} = **85 - 99%** for μ-channel.

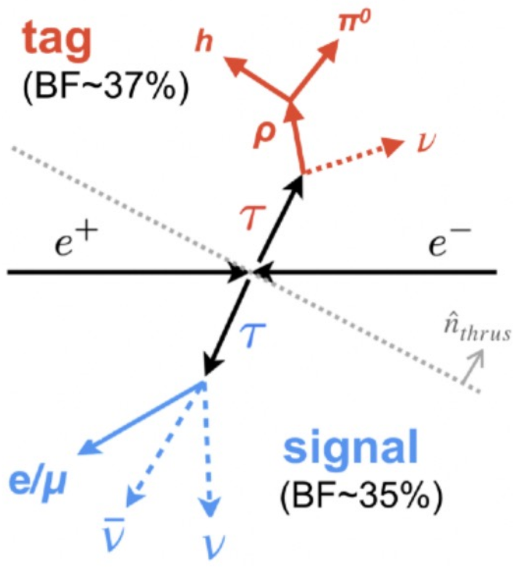
By using the neural network, Belle II achieve better perfermence for elelctron channel







Lepton Flavor Universality Violation



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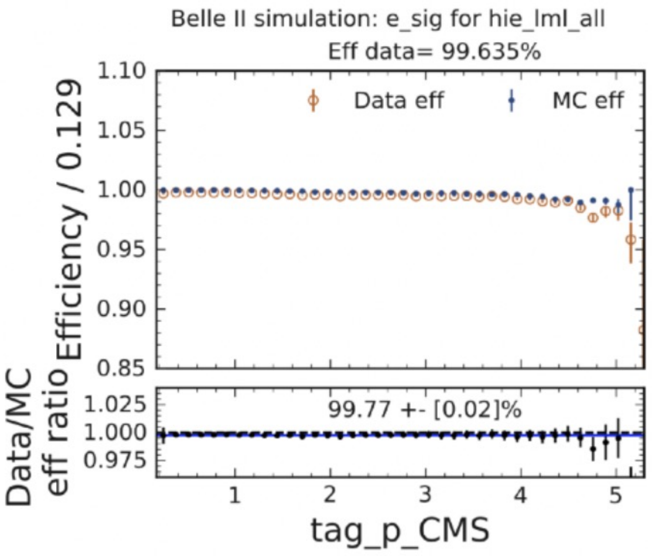
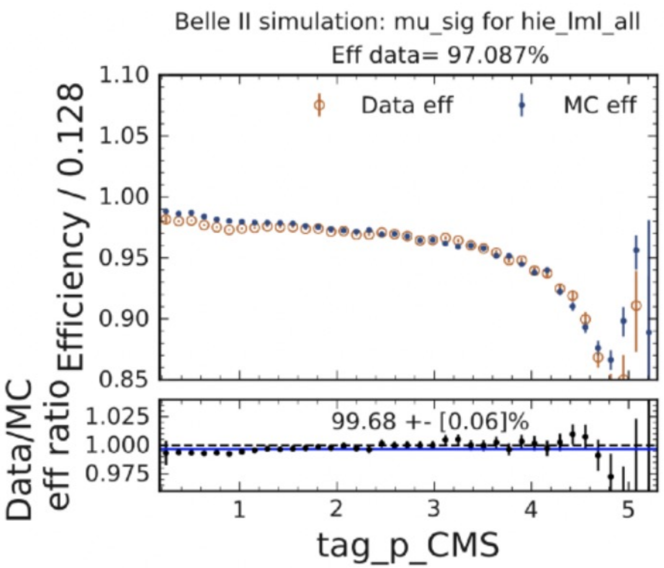
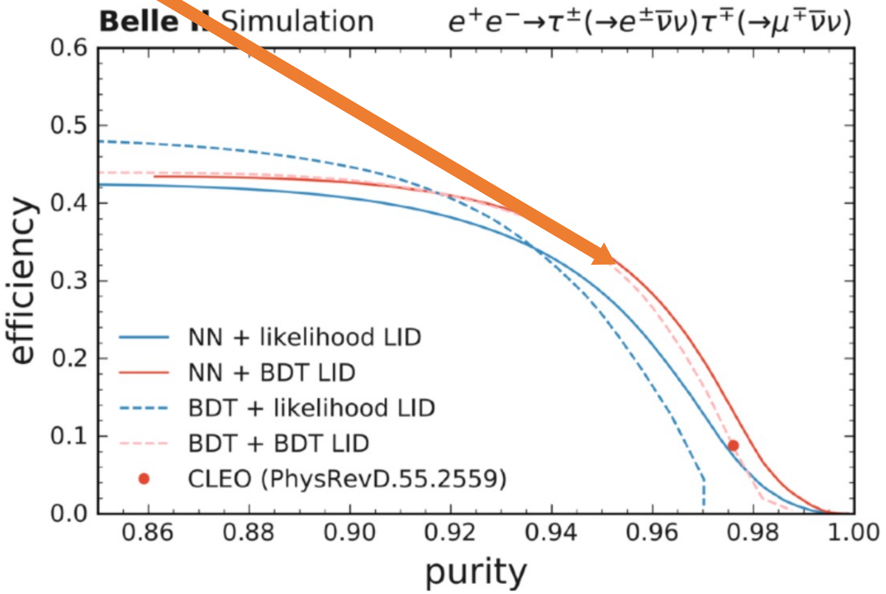


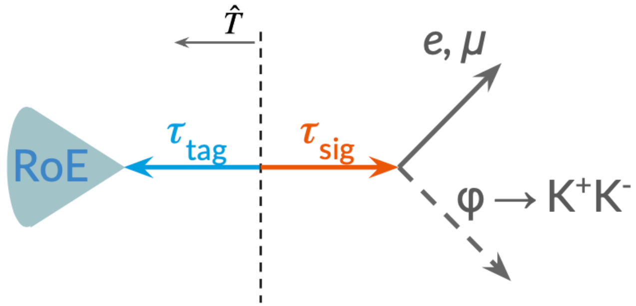




New results coming soon! (Maybe in ESP2023 meeting)

Charged Lepton Flavor Violation

$\tau^- \rightarrow \ell^- \phi$



arXiv:2305.04759

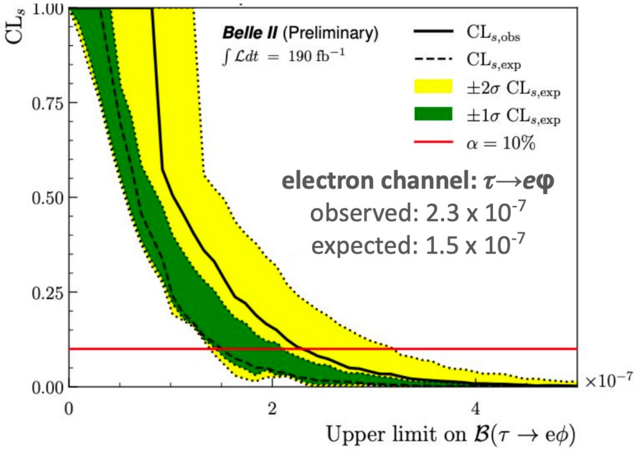
- highly suppressed in SM ($\sim 10^{-50}$)
- leptoquark models predict BF of up to $10^{-8} \sim 10^{-10}$

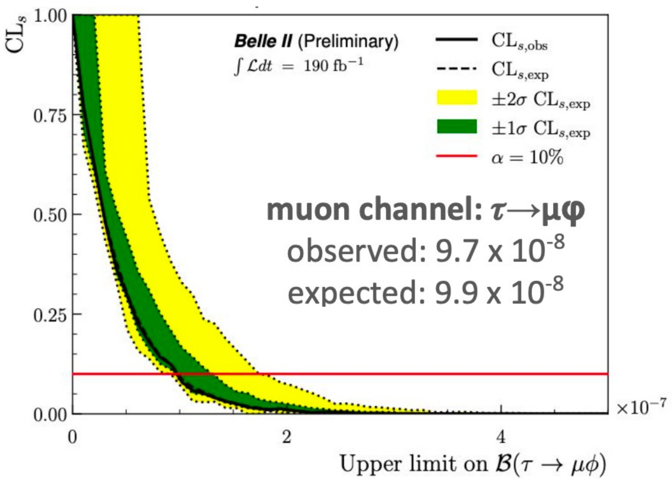
Poisson counting experiment approach in **signal regions** in M_τ and $\Delta E_\tau = E^*_{sig} - \sqrt{s}/2$ plane

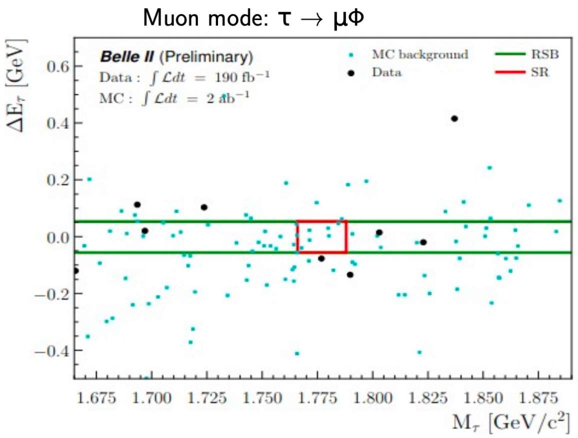
→ expected background evaluated from data **reduced sidebands** with scaling from simulation

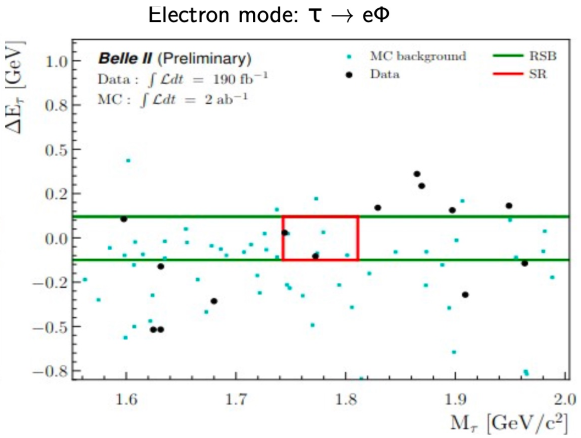
not yet competitive with Belle/BaBar... (only 190 fb-1 data samples are used)

But a successful first application of inclusive tagging at Belle II







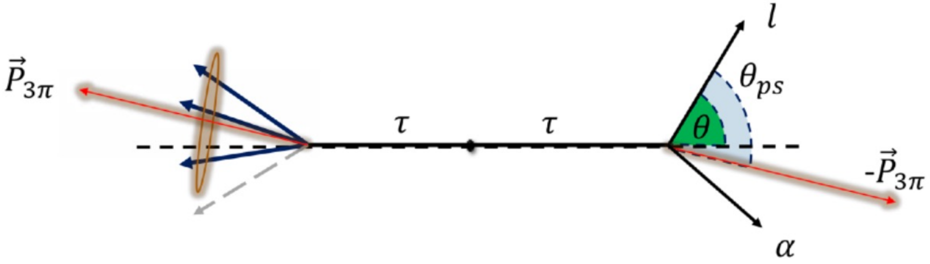


Charged Lepton Flavor Violation

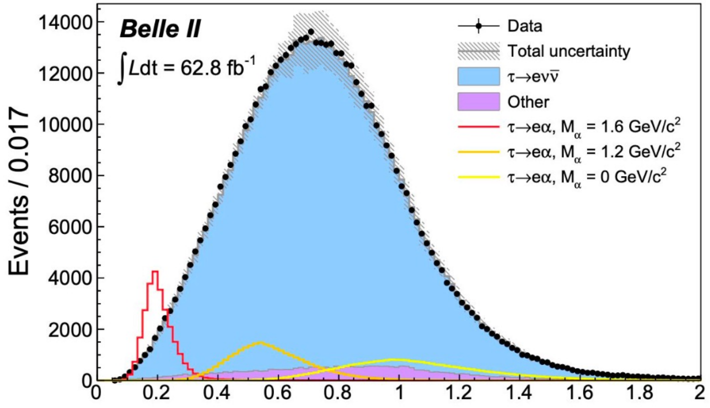
$\tau^- \to \ell^- \alpha$

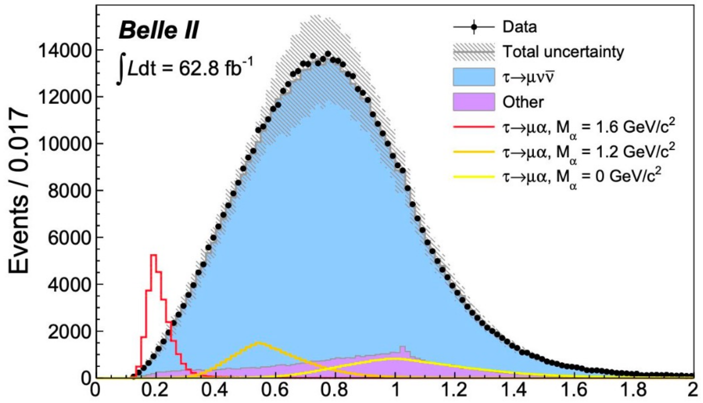
It probes the existence of a **long-lived invisible gauge boson boson** α.

- Possible DM candidate. [PRL 130, 181803]



$$E_\tau = E_{\text{cms}}/2, \quad \hat{p}_\tau \approx \vec{p}_{\text{tag}}/|\vec{p}_{\text{tag}}|$$





x : normalized E pseudo-rest-frame

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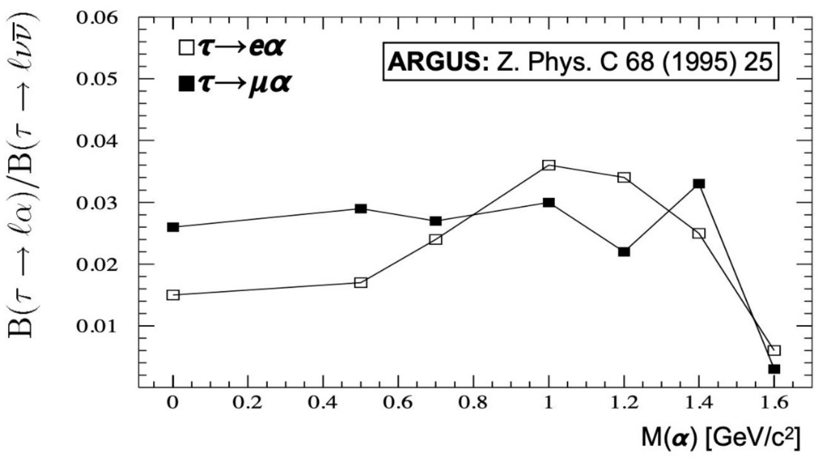
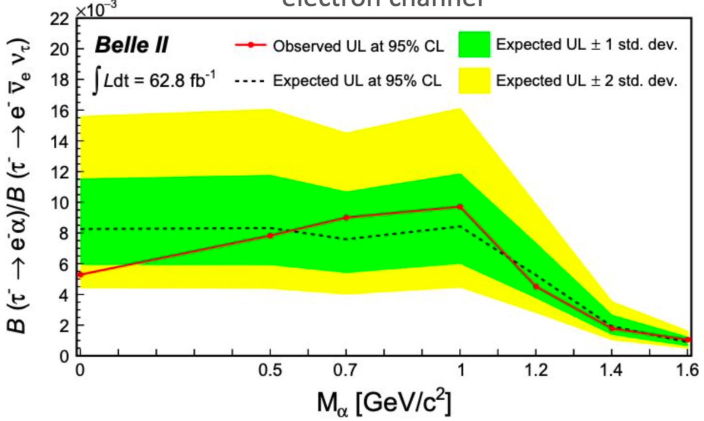
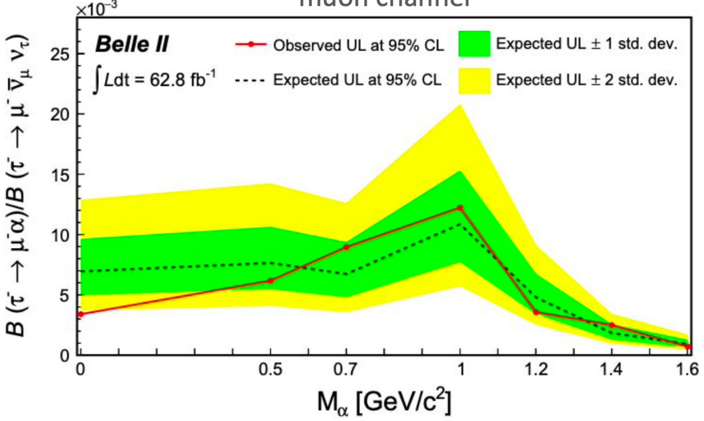


electron channel



muon channel



Most stringent limits in these channels to date! (2-14 times more constraining than Argus)

Summary

Belle II has **advantages in τ** decays studies

- ❖ Has collected 424 fb-1 data samples
- ❖ Lots of works on the way!

τ properties:

-- mass: arXiv:2305.19116

-- lifetime

-- CKM (V_{us}): $\tau^- \to K^-(\ldots)\nu$

Electroweak sector

--Lepton Universality

Beyond Standard Model

--LFV

- $\tau^- \to \ell^-\phi$ arXiv:2305.04759
- $\tau^- \to \ell^-\alpha$ PRL 130, 181803
- $\tau \to 3\ell, \ell\,\gamma, \ell\,\rho, \ell^- K_S^0, \Lambda\pi$

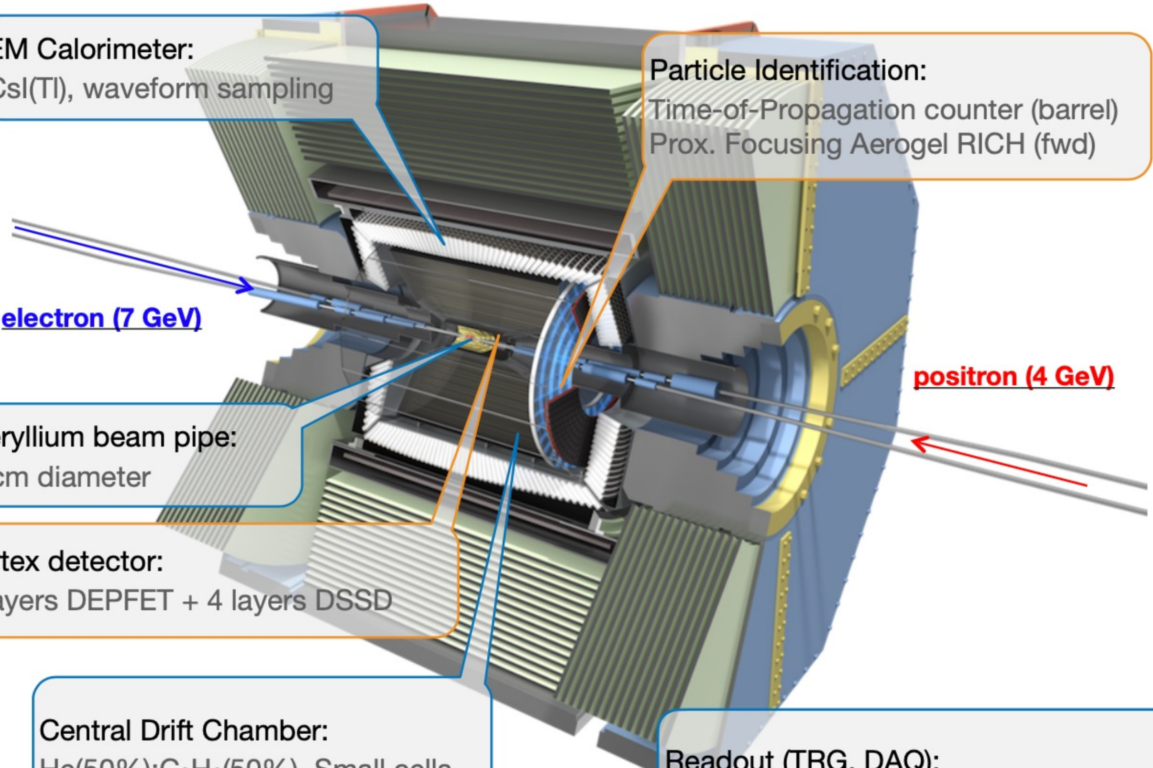
-- CP Violation

$\tau \to K_S^0\pi\nu, 3h\nu$

-- CP/T: EDM and MDM

Backup:

In a nutshell



EM Calorimeter:
CsI(Tl), waveform sampling

Particle Identification:
Time-of-Propagation counter (barrel)
Prox. Focusing Aerogel RICH (fwd)

Beryllium beam pipe:
2 cm diameter

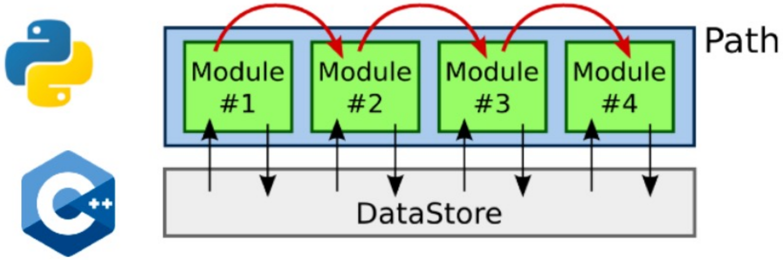
Vertex detector:
2 layers DEPFET + 4 layers DSSD

Central Drift Chamber:
He(50%):C_2H_6(50%), Small cells,
long lever arm, fast electronics

Readout (TRG, DAQ):
Max. 30kHz L1 trigger
~100% efficient for hadronic events.
1MB (PXD) + 100kB (others) per event
- over 30GB/sec to record

arXiv:1011.0352 [physics.ins-det]

Software:
Open-source sophisticated algorithms for simulation, reconstruction, visualization, and analysis.



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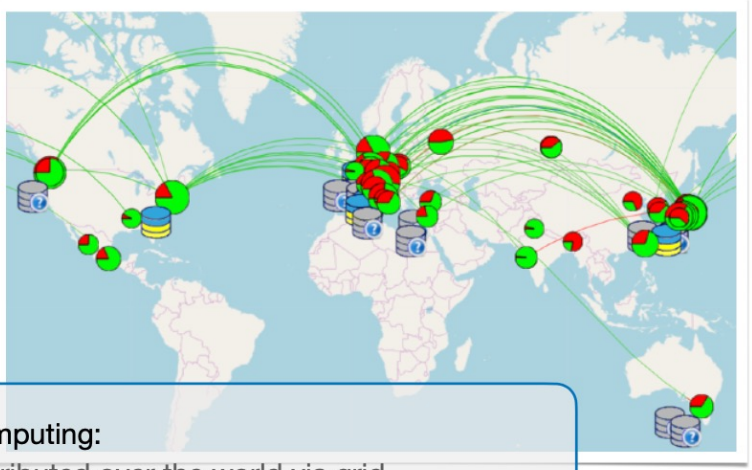


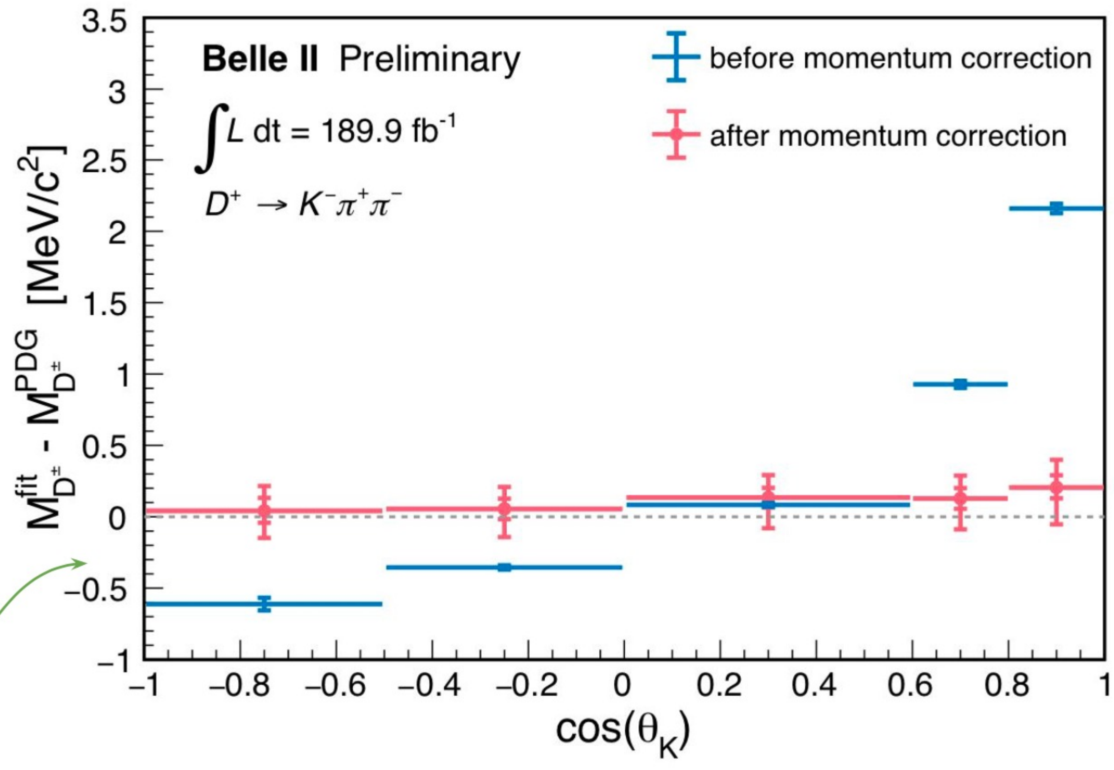
Computing:
Distributed over the world via grid.

Backup:

Tau mass systematics: momentum scale

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

- Momentum of the 3π's is an important ingredient in the M_{min}!
- We use $D^0 \to K\pi$ as a standard candle!
  - get scale factors (SF) for K and π based on difference in peak position and PDG value of D^0
    - phase-space dependent SFs: as a function of charge and cos(θ) of the tracks
  - various systematic effects included for the SF's:
    - $m(D^0)$ PDG uncertainty
    - peak position modelling
    - additional kinematical dependence
    - detector misalignment
- Use other mass peaks as cross check: $D^0 \to K\pi\pi\pi$, $J/\psi \to \mu\mu$, $K_S^0 \to \pi\pi$, $D^\pm \to K\pi\pi$

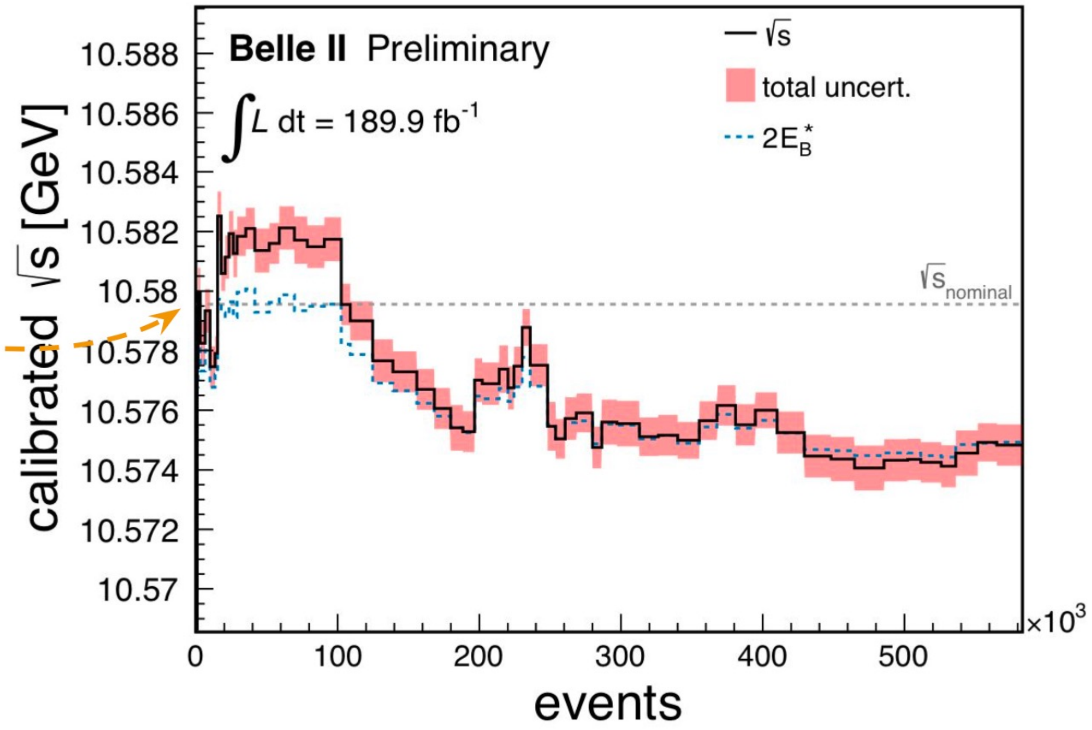


⇒ impact on tau mass: **0.06 MeV**

Backup:
Tau mass systematics: energy scale

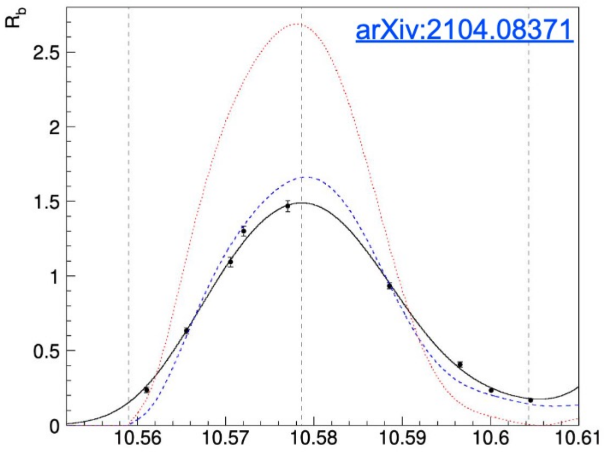
$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)}$$

- Center-of-mass collision energy (√s):
  - used to approximate the energy of the tau
- Use energy of fully reconstructed B mesons (E^*_B) to calibrate √s
  - E^*_B only approximately equals √s, need extra corrections due to subtle effects from:
  - ISR photons
  - spread of the beam energy
  - dependence of ϒ(4S) cross section on the beam energy:



e.g when √s is below the ϒ(4S) peak, due to the beam-energy spread, we produce:
- less low energy B mesons
- more high energy B's

⇒ resulting in a bias in E^*_B values towards the ϒ(4S) peak



⇒ impact on tau mass: **0.07 MeV**

Backup:

- The method:
  - Use an empirical fit function to extract the mass:

$$F(M_{\text{min}}) = 1 - P_3 \cdot \arctan\left(\frac{M_{\text{min}} - P_1}{P_2}\right) + P_4(M_{\text{min}} - P_1) + P_5(M_{\text{min}} - P_1)^2$$

  - P_1: depends on the position of threshold
  - P_2: the slope of the threshold
  - P_3-P_5: the shape away the threshold
- P_1 is an estimator of tau mass!
  - This is a biased estimator of 0.40 MeV, determined from simulation samples, with various generated tau masses
  - **~3x smaller bias** compare to Belle and BaBar (they had slightly different parameterizations)
  - The bias can also depend on the overall shape of the distribution as well