Tau and Low Multiplicity at Belle and Belle II

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on behalf of the Belle II collaboration

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58th Rencontres de Moriond
QCD & High Energy Interactions

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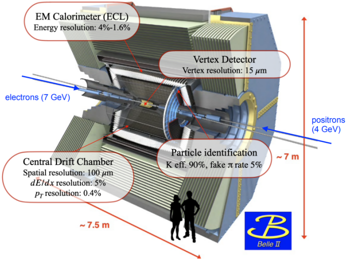
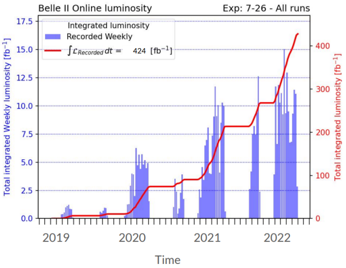
- B factories offer clean environment to study τ and low-multiplicity physics
  - Well defined initial state conditions
  - Hermetic detectors allow determination of missing energy $\&$ momentum
- Belle II operates since 2018:
  - Excellent particle identification
  - High efficiency neutral reconstruction
  - Inclusive trigger scheme with dedicated low multiplicity triggers
- Finished run1 data-taking in 2023:
  - 424 fb^{-1} on tape
  - **362 fb**$^{-1}$ @ $\Upsilon(4S)$
  - ↪ Comparable to size of full BABAR data sample



[Belle II TDR: arXiv:1011.0352]

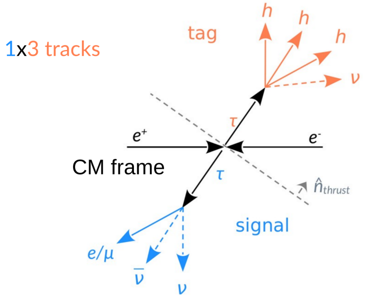


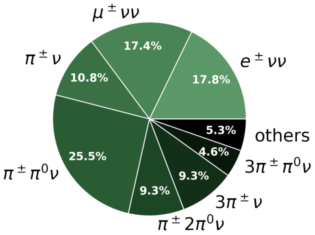
τ physics at Belle II

- $\sigma(ee \to bb) \simeq 1.1$ nb
- $\sigma(ee \to \tau\tau) \simeq 0.9$ nb
  - $\hookrightarrow$ Belle II is not just B factory, but also τ factory!
    - $\sim 4 \cdot 10^8$ τ pairs recorded in run1 data
- $\tau\tau$ events are characterized by low track multiplicities and large missing energies
- Identify τ events by reconstructing thrust axis
  - Separate into hemispheres

$$V_{\text{thrust}} \overset{\max}{=} \frac{\sum_i |\vec{p}_i^{\,\text{CM}} \cdot \hat{n}_{\text{thrust}}|}{\sum_i |\vec{p}_i^{\,\text{CM}}|}$$

  - Use one side to tag by reconstructing decays with 1 or 3 charged tracks (1-prong and 3-prong)
  - Reconstruct signal on other hemisphere



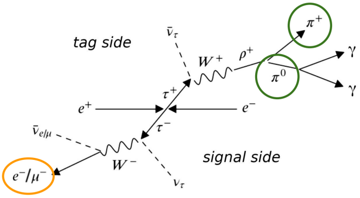


Lepton flavor universality in τ decays

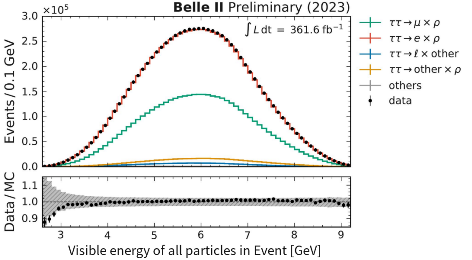
- Measurement of coupling of light leptons to EW gauge bosons:

$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{\frac{\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)}{\mathcal{B}(\tau^- \to e^-\overline{\nu}_e\nu_\tau)} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}} \stackrel{SM}{=} 1$$

$$R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)}{\mathcal{B}(\tau^- \to e^-\overline{\nu}_e\nu_\tau)} \stackrel{SM}{=} 0.9726$$



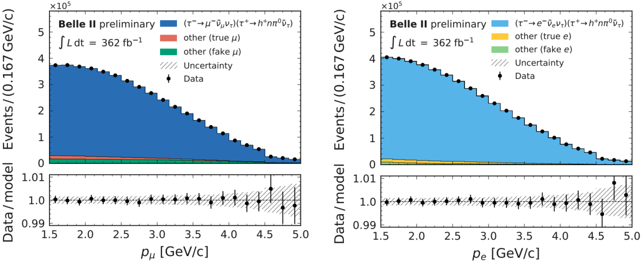
- 1-prong decays on tag side:
  - Require one charged hadron and at least one π^0
  - Large branching ratio, low backgrounds, high trigger efficiency



- Suppress backgrounds using NN
- Combined $e-\mu$ sample: 94% purity at 9.6% signal efficiency
- Main backgrounds:
  - $\sim 3.3\%$ $e^+e^- \to \tau^+\tau^-$ with $\pi^\pm$ faking lepton
  - $\sim 2.3\%$ $e^+e^- \to \tau^+\tau^-$ with wrongly reconstructed tagside

Lepton flavor universality in τ decays

- Extract signal yields with binned maximum likelihood fit in p_ℓ using `pyhf`[1]



- Most systematic uncertainties cancel in ratio
- Challenge: careful treatment of leading particle identification (PID) systematic
  - Restrict to region least impacted by PID uncertainties:
    - $0.82 < \theta_\ell < 2.13$
    - $1.5 < p_\ell < 5.0$ GeV
  - Obtain correction factors and uncertainties from calibration samples
    - e efficiency 99.7 %, μ efficiency 93.9%
    - π faking e: 0.9 %, π faking μ 3.1%

	Leading systematics
Charged lepton identification	0.32%
Trigger efficiency	0.10%

↪ Implement systematic uncertainties as nuisance parameter on fit templates

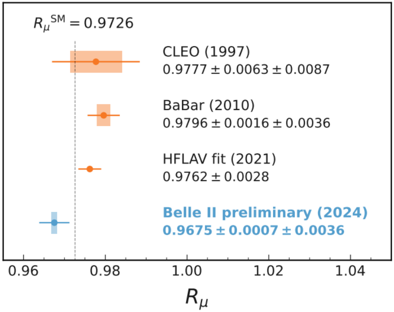
- 0.37 % total relative systematic uncertainty

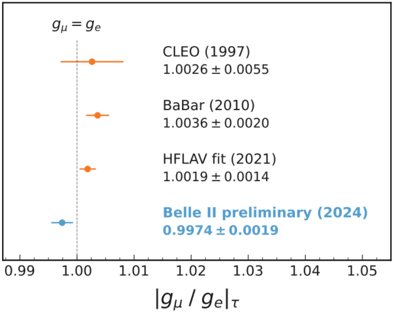
[1] Documentation

$$R_\mu = 0.9675 \pm 0.0007_{\text{stat.}} \pm 0.0036_{\text{syst.}}$$

(Preliminary)

- Converted to couplings $\left(\frac{g_\mu}{g_e}\right)_\tau = 0.9974 \pm 0.0019$
- World's most precise measurement of $\mu - e$ universality in τ
- Consistent with SM expectation within 1.4σ





- τ lepton flavour violation decay modes:

$\tau \to \ell\ell\ell$

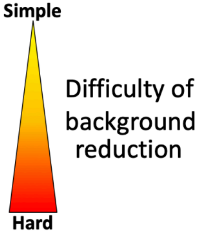
$\tau \to \ell K_s, \Lambda h$

$\tau \to \ell V^0(\to hh')$

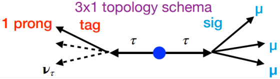
$\tau \to \ell P^0 \ (\to \gamma\gamma)$

$\tau \to \ell hh'$

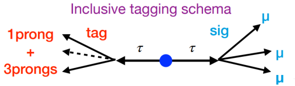
$\tau \to \ell\gamma$



Belle:



Belle II:

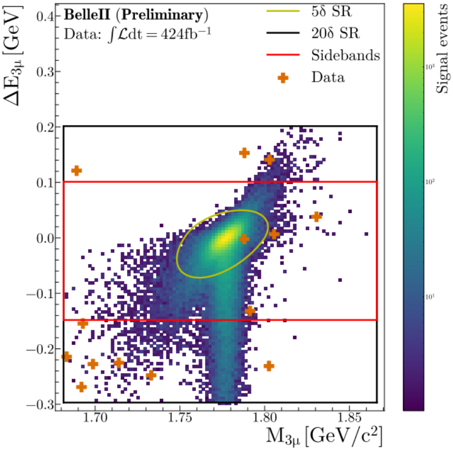


Experimentally most accessible: $\tau \to \mu\mu\mu$

- No expected SM backgrounds
- Branching ratio in ν mixing SM: $10^{-53} \sim 10^{-56}$
- Enhanced in new physics models:

	$\mathcal{B}(\tau^- \to \ell^-\ell^+\ell^-)$
SM + seesaw	10^{-10}
SUSY + Higgs	10^{-8}
SUSY + SO(10)	10^{-10}
Non-universal Z'	10^{-8}

- Inclusive 1prong + 3prong tag at Belle II
- Train BDT to suppress residual backgrounds
- Signal efficiency $\varepsilon_{sig} = 20.42 \pm 0.06\%$
  - $\sim 3\times$ higher than Belle at $0.5^{+1.4}_{-0.5}$ expected background events
  - More strigent expected limit with $\sim 50\%$ data sample



- Large background subtraction using $\Delta E_{3\mu} = E_{\tau,sig} - E_{beam}$ and $M_{3\mu}$
- Observed 1 event in the signal region
  - Expected $0.5^{+1.4}_{-0.5}$ background events

$$\mathrm{UL@90\%CL} : \mathcal{B}(\tau \to \mu\mu\mu) < 1.9 \times 10^{-8}$$

(Preliminary)

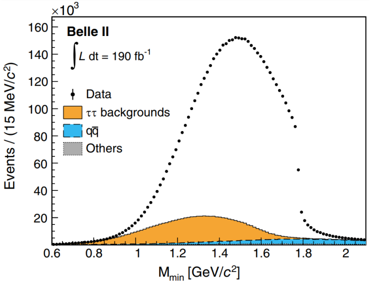
- Most stringent limit up to date:

	UL@90% CL on $\mathcal{B}(\tau \to 3\mu)$
Belle	$2.1 \times 10^{-8}(\mathcal{L}_{int} = 782\mathrm{fb}^{-1})$[a]
BaBar	$3.3 \times 10^{-8}(\mathcal{L}_{int} = 468\mathrm{fb}^{-1})$[b]
CMS	$2.9 \times 10^{-8}(\mathcal{L}_{int} = 131\mathrm{fb}^{-1})$[c]
LHCb	$4.6 \times 10^{-8}(\mathcal{L}_{int} = 2.0\mathrm{fb}^{-1})$[d]
Belle II	$1.9 \times 10^{-8}(\mathcal{L}_{int} = 424\mathrm{fb}^{-1})$

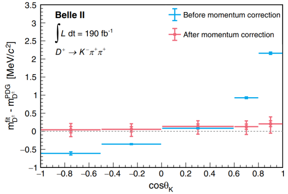
[a] Phys. Lett. B 687 (2010) 139
[b] Phys. Rev. D 81 (2010) 111101
[c] JHEP 01 (2021) 163
[d] JHEP 02 (2015) 121

- Precise determination of m_τ with $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ in $\mathcal{L} = 190\ \mathrm{fb}^{-1}$
  - Fundamental parameter, important input e.g. for LFU tests
- Pseudomass method:

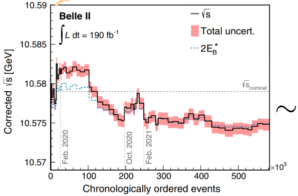
$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} < m_\tau$$



- Challenge:
  - High accuracy in p and $\sqrt{s}$
  - p : calibrate track momentum correction with $D^0 \to K^-\pi^+$
  - $\sqrt{s}$: calibrate using B decays



$\sim 70\mathrm{keV}$

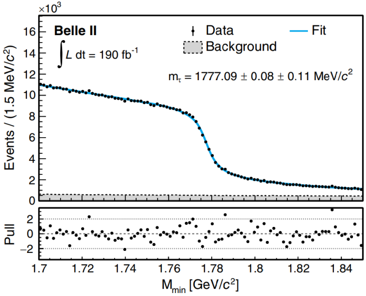


$\sim 60\mathrm{keV}$

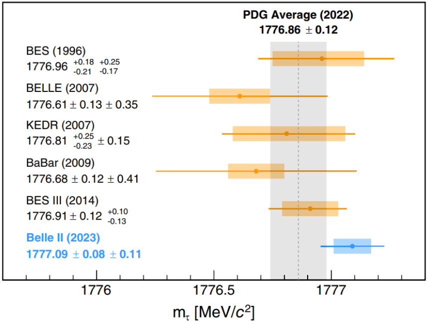
$D^0 \to K^-\pi^+\pi^+$ validation

τ mass measurement

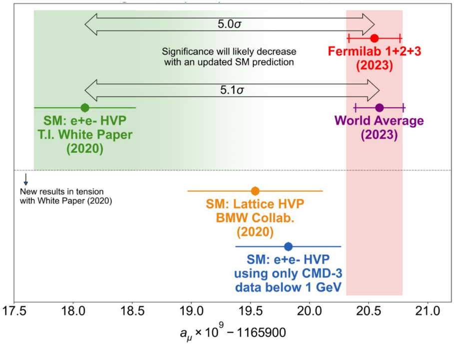
[Phys. Rev. D 108, 032006]



- Measure $m_\tau = 1777.09 \pm 0.08 \pm 0.11 \mathrm{MeV/c^2}$
- World's most precise measurement of tau mass
- Leading systematics: track momentum scaling and beam-energy calibration



$(g-2)$ of the muon



- Tension between theory and experiment in the muon magnetic anomaly

$$a_\mu = \frac{(g-2)_\mu}{2} = a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{QCD}}$$

- Tension reduces to $\sim 1\sigma$ with newly included calculations and data:
  - $a_\mu^{\mathrm{HVP,LO}}$ from BMW Lattice QCD group [1]
  - π form-factor from CMD-3 in $a_\mu^{\mathrm{HVP,LO}}$[2]

[1]Nature 593, (51–55) (2021)
[2]arXiv:2302.08834

$$a_\mu = \frac{g-2}{2} = a_\mu^{EW} + a_\mu^{QED} + a_\mu^{QCD}$$

Hadron-contribution

$$a_\mu^{QCD} = a_\mu^{HVP} + a_\mu^{HLbL}$$

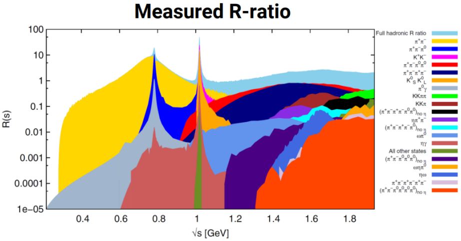
Leading order HVP-term

$$a_\mu^{HVP,LO} = \frac{\alpha^2}{3\pi^2}\int_{m_\pi^2}^{\infty}\frac{ds}{s}R(s)K(s)$$

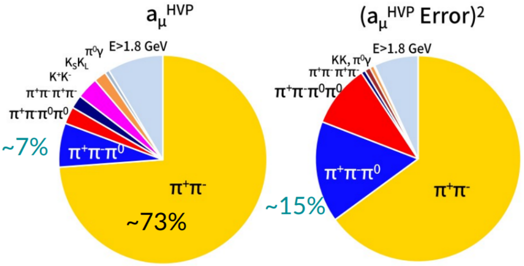
HVP = hadron vacuum polarization; 82% of a_μ^{QCD}

HLBL = light-by-light; 18%

$$R(s) = \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



(a) The hadronic R-ratio.

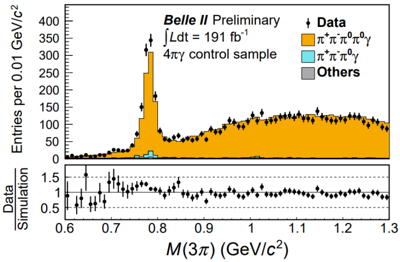


- Belle II can provide $e^+e^- \to \mathrm{hadrons}$ cross sections to improve predictions
- Second largest contribution $e^+e^- \to \pi^+\pi^-\pi^0$ presented today

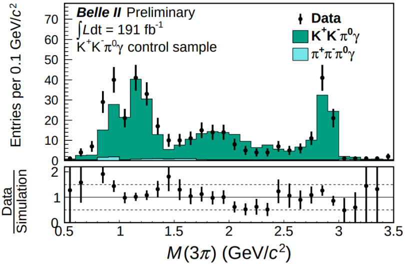
New for Moriond 2024!

- Reconstruct $e^+e^- \to \pi^+\pi^-\pi^0$ decays in $\mathcal{L} = 190\ \text{fb}^{-1}$
- Measure at different $\sqrt{s}$ by using initial state radiation technique
  - Reconstruct ISR photon $e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR}$
  - Pion invariant mass range from 0.62 to 3.5 GeV
- Effectively suppress background by using kinematic fit:
  - Constrain sum of $\pi^+\pi^-\pi^0\gamma_{ISR}$ momenta to e^+e^- beam momentum
- Validate main backgrounds in control samples:

$e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma$



$e^+e^- \to K^+K^-\pi^0\gamma$



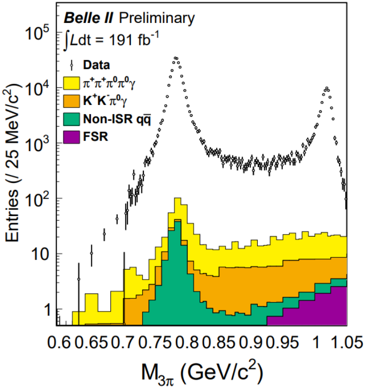
$\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$

New for Moriond 2024!

- Major analysis challenge is handling π^0 efficiency
  - Evaluate efficiency using partial reconstruction of ω resonance decays:

$$\varepsilon_{\pi^0} = \frac{N(\text{Full reconstruction of } \gamma_{ISR}\,\pi^+\pi^-\pi^0)}{N(\text{Partial reconstruction of } \gamma_{ISR}\,\pi^+\pi^-)}$$

  - Determines π^0 efficiency up to 1% $\to$ systematic uncertainty
- Fit $M_{\gamma\gamma}$ in each bin of $M_{3\pi}$:



- Integrate over 3π cross section from $0.62 - 1.8$ GeV (Preliminary):

$$a^{3\pi}_{\mu,0.62\text{-}1.8} \times 10^{10} = 48.91 \pm 0.23_{\text{stat.}} \pm 1.07_{\text{syst.}}$$

- 6.7% or 2.5σ higher than current global average, obtained from BABAR, CMD-2 and SND

↪ Slightly smaller anomaly

- Leading systematics are π^0 efficiency and missing NNLO in generator

Summary

Results
$\left(\frac{g_\mu}{g_e}\right)_\tau = 0.9974 \pm 0.0019$
$\mathcal{B}(\tau \to \mu\mu\mu) < 1.9 \times 10^{-8}(90\%\mathrm{CL})$
$m_\tau = 1777.09 \pm 0.08_{\mathrm{stat.}} \pm 0.11_{\mathrm{syst.}} \mathrm{MeV/c^2}$
$a^{3\pi}_{\mu,0.62\text{-}1.8} \times 10^{10} = 48.91 \pm 0.23_{\mathrm{stat.}} \pm 1.07_{\mathrm{syst.}}$

- Belle II is providing leading precision in τ and low multiplicity measurements
  - Precision measurements of τ properties
  - Studies of standard model parameters
  - Searches for beyond SM physics
- Improvements on multiple frontiers
  - Results with $362\mathrm{fb}^{-1}$ of run1 data
  - Improved analysis techniques and reduced systematics

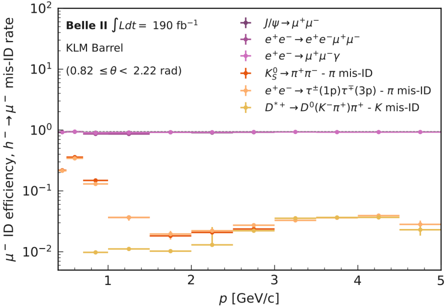
Run 2 started on February 20, 2024!

Backup

Tau LFU

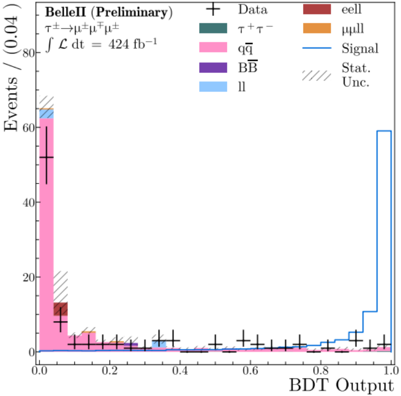
- Challenge in this analysis: careful treatment of leading particle identification (PID) systematic
  - Restrict to region least impacted by PID unceratinties:
    - $0.82 < \theta_\ell < 2.13$
    - $1.5 < p_\ell < 5.0$ GeV
  - Obtain correction factors and uncertainties from correlation factors
  - PID Efficiency:
    - $J/\psi \to \ell^+\ell^-$, $e^+e^- \to e^+e^-\ell^+\ell^-$, and $e^+e^- \to \ell^+\ell^-(\gamma)$
    - e efficiency 99.7 %, μ efficiency 93.9%
  - PID fake rates:
    - $K_S^0 \to \pi^+\pi^-$ and $\tau \to \pi\pi\pi\nu$
    - π faking e: 0.9 %, π faking μ 3.1%

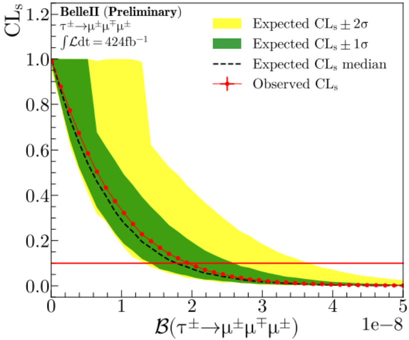
↪ Implement PID uncertainty as nuisance parameter on fit templates



Tau LFU

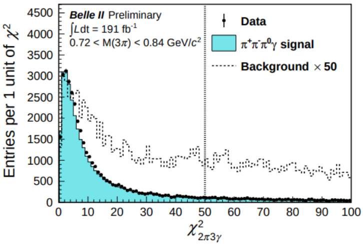
Source	Uncertainty [%]
Charged-particle identification:	
Electron identification	0.22
Muon misidentification	0.19
Electron misidentification	0.12
Muon identification	0.05
Trigger	0.10
Imperfections of the simulation:	
Modelling of FSR	0.08
Normalisation of individual processes	0.07
Modelling of the momentum distribution	0.06
Tag side modelling	0.05
π^0 efficiency	0.02
Modelling of ISR	0.01
Photon efficiency	< 0.01
Photon energy	< 0.01
Size of the samples	
Simulated samples	0.06
Luminosity	0.01
Charged-particle reconstruction:	
Particle decay-in-flight	0.02
Tracking efficiency	0.01
Detector misalignment	< 0.01
Momentum correction	< 0.01
Total	0.37

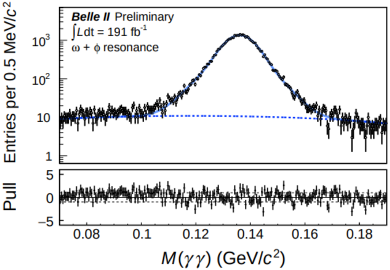


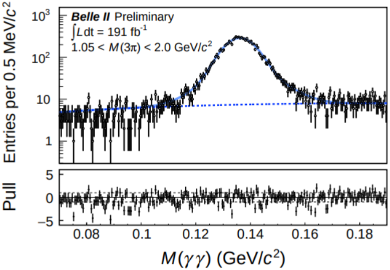


Quantity	Source	Systematics uncertainty (%) Low	High
ε_{sig}	PID	2.1	2.4
	Tracking	1.0	1.0
	Trigger	0.9	0.9
	BDT	1.5	1.5
	SR	2.9	3.9
$\mathcal{L}$		0.6	0.6
$\sigma_{\tau\tau}$		0.3	0.3
N^{SB}_{data}	Momentum Scale	16	16

$\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$







$\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$