Recent results in Belle and Belle II experiments

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- Introduction of Belle and Belle II experiments
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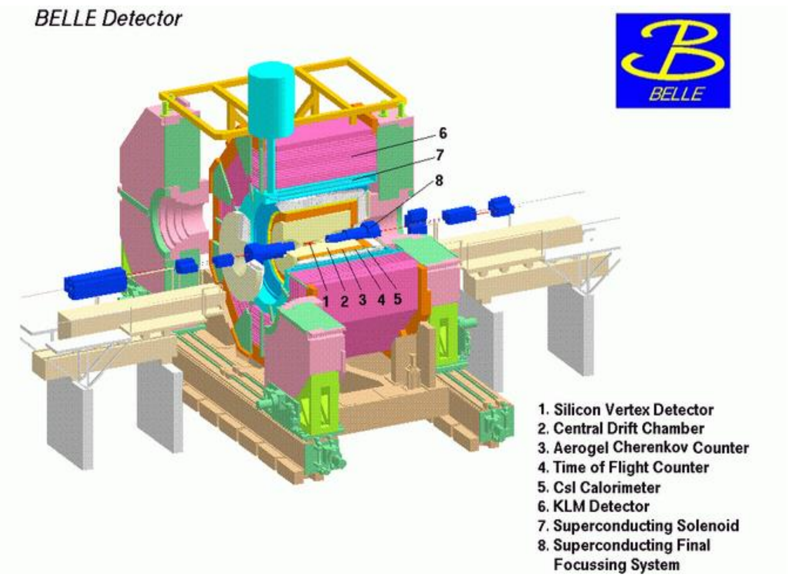
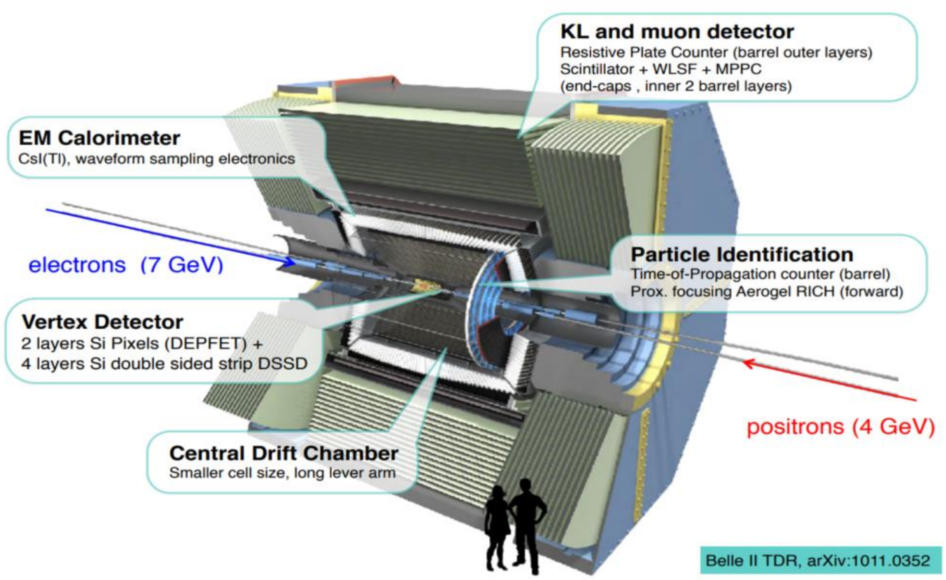
Belle and Belle II Experiments

- Belle (1999-2010) and Belle II (2018-) are *B*-factories
  - Located in Tsukuba (KEK laboratory) - Japan
  - Asymmetric e^+e^- collider
  - Operated around 10.58 GeV (= $m_{\Upsilon(4S)}$)
  - Lower background compared to hadron colliders
  - Closed detectors with almost 4π coverage
    - FEI, m^2_{miss}, p_{miss}, E_{ECL}, etc.

Belle: recorded ～1 ab^{-1}

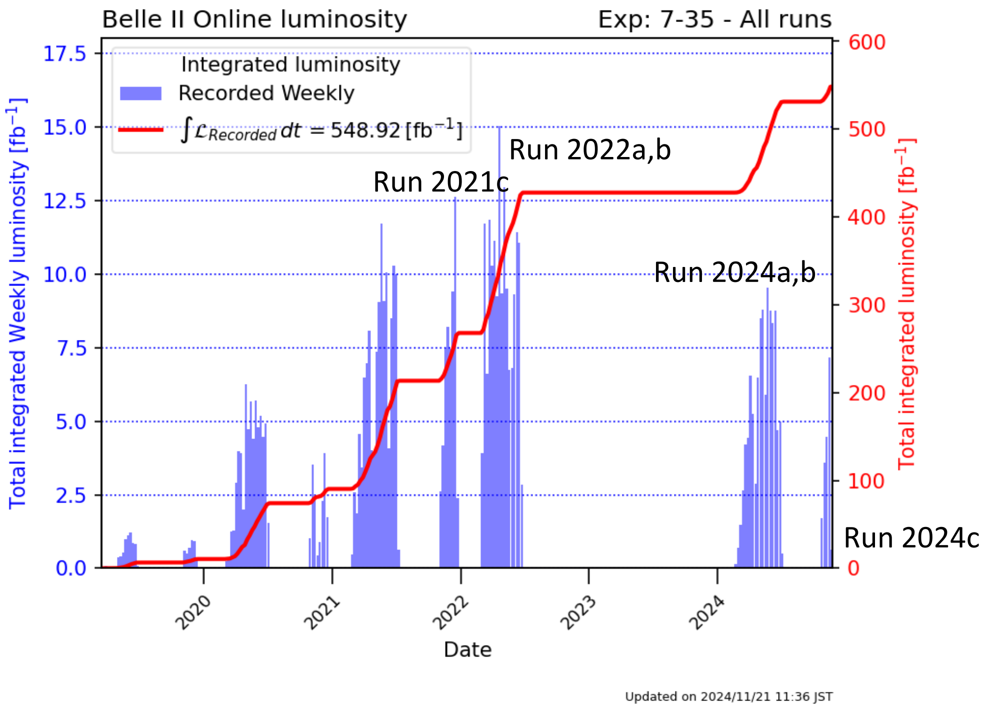


Belle II: recorded 427 fb^{-1} in Run1 (2018-2022) and 120 fb^{-1} in Run2 (2024-)



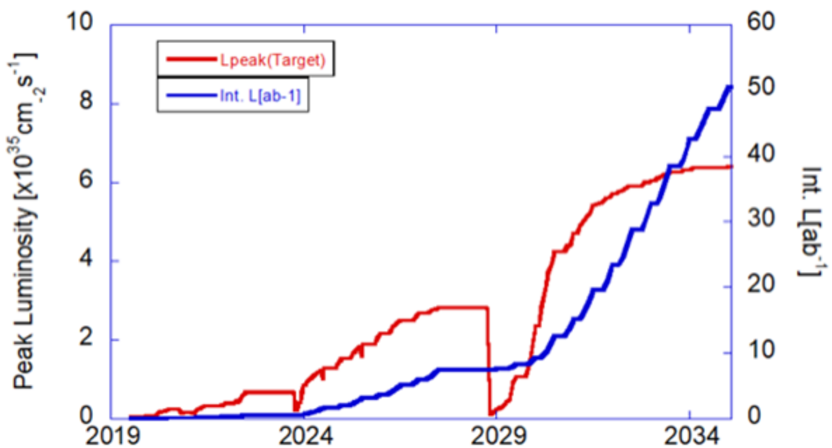
Belle II Luminosity

- Physics runs started spring 2019.
- Run 1 ended June 2022.
  - Peak luminosity at $L_{peak} = 4.7 \times 10^{34} cm^{-2} s^{-1}$, the world record set on June 22th, 2022.
  - Run 1 integrated luminosity at $\int L_{\mathrm{Recorded}} dt = 424\ \mathrm{fb}^{-1}$. (~BaBar, ~1/2 Belle sample size)
- Long shutdown 1 (LS1): 2022-2023
- Run 2 started February 2024.
  - Integrated luminosity at $548.92\ \mathrm{fb}^{-1}$ now.



Belle II Run Plan

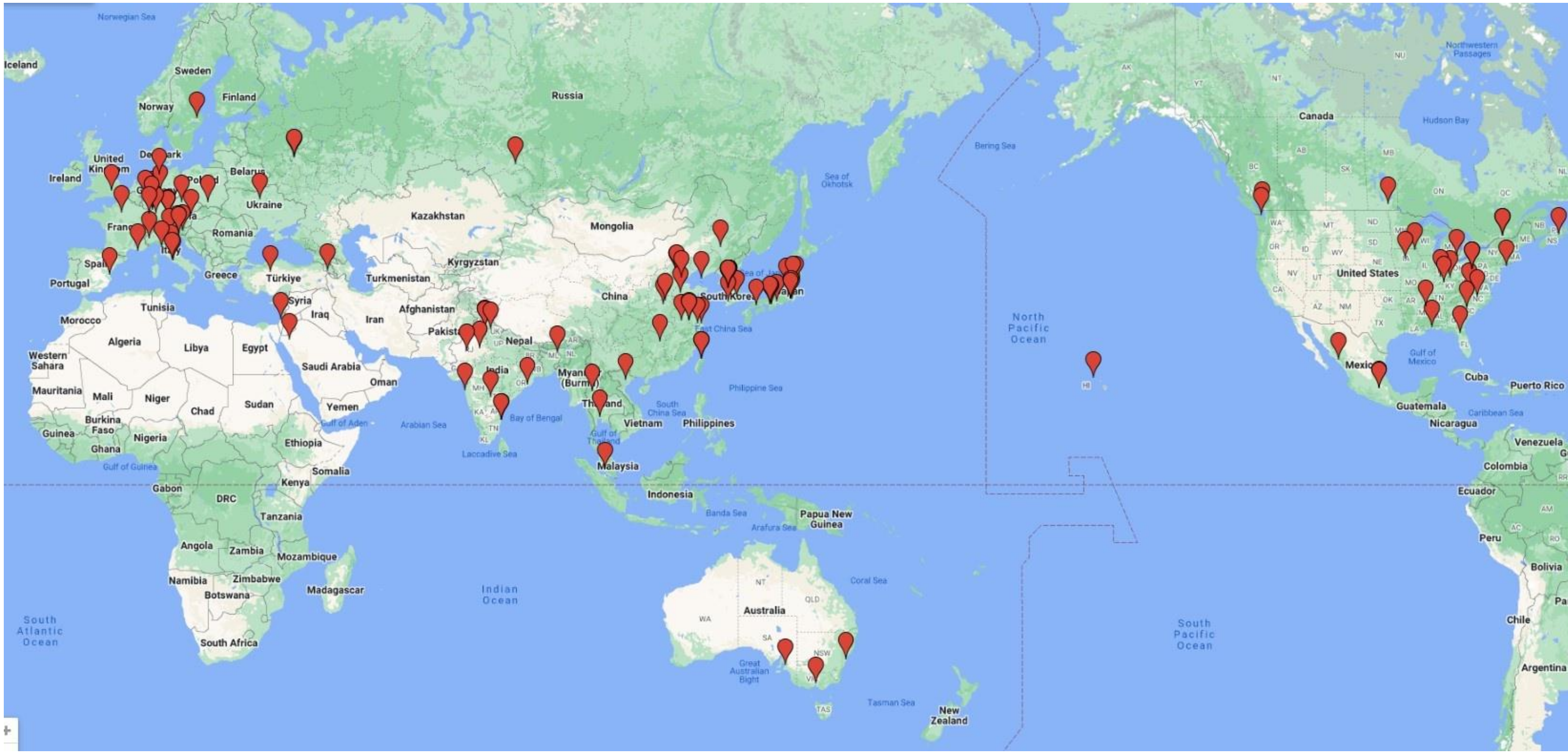
- 2024 current plan: Run 2024c
- 2025 run plan
  - Shutdown at summer (June to October)
- Medium term: another long shutdown (LS2) is planned after 2027-2028.
  - Upgrade of interaction region is being considered.



Fiscal year	4	5	6	7	8	9	10	11	12	1	2	3
2024	2024b						**2024c (current)**					2025a
2025	2025b						2025c			2026a		
2026	2026b						2026c			2027a		

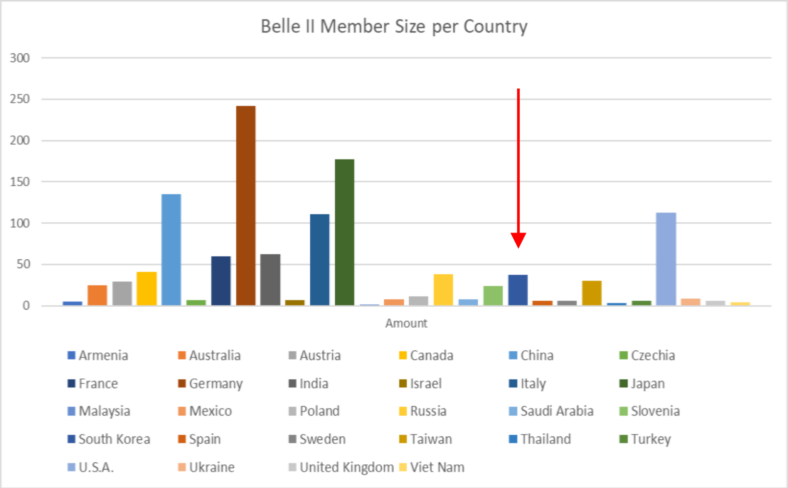
Belle II Collaboration

- 28 countries, 120 institutes, 1,200 researchers

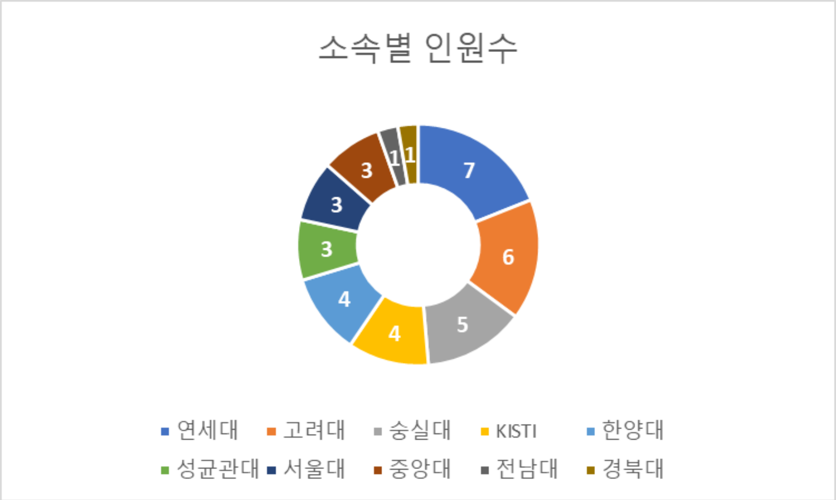


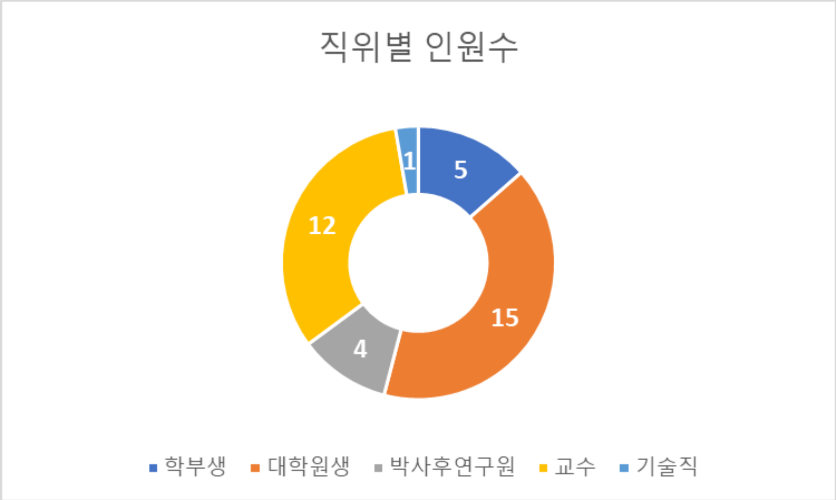
Korean Belle II Group

- 10th largest size per country in Belle II collaboration



- Details
  - 10 institutes (SNU, Yonsei, KU, SKKU, SSU, Hanyang, CAU, KNU, CNU, KISTI)
  - 37 people (12 professors, 4 post-docs, 15 PhD or master course, 5 undergraduate, 1 technician)
  - Working on physics analysis, hardware work and software work
    ⇒Remarkable work though ~4% of collaboration





Recent Results on Belle/Belle II Collaboration

- Lepton Flavor Violation (LFV)

Belle II $\boldsymbol{\tau^+ \to \mu^+\mu^-\mu^+}$ — JHEP 09 (2024) 062

BELLE $\tau^+ \to \ell^+ V^0$ — JHEP 06 (2023) 118

Belle II $\boldsymbol{\Upsilon(2S) \to \ell^\pm \tau^\mp}$ — JHEP 02 (2024) 187

- Dark sector

Belle II **X(Z', S) search in the** $\boldsymbol{e^+e^- \to \mu^+\mu^- X\ (X \to \mu^+\mu^-)}$ — PRD 109 (2024) 112015

Belle II Long-lived scalar(S) in B decays — PRD 108 (2023) L111104

BELLE Leptophilic scalar(ϕ_L) in $e^+e^- \to \tau^+\tau^-\ell^+\ell^-$ — PRD 109 (2024) 112015

BELLE Heavy Neutral Leptons (HNL) in τ decays — PRD 109 (2024) L111102

- Semileptonic (SL) measurements ($B \to D^*\ell\overline{\nu}_\ell$)

BELLE Angular coefficients — PRL 133 (2024) 131801

Belle II **Lepton flavor universality(LFU) with measurement of** $\boldsymbol{R(D^*)}$ — PRD 110 (2024) 072020

Belle II Determination of $|V_{cb}|$ — PRD 108 (2023) 092013

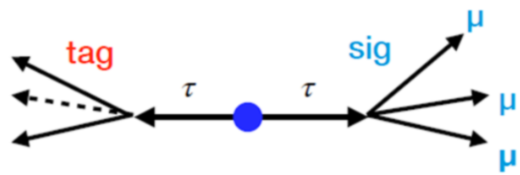
Belle II Light-lepton universality in angular asymmetries — PRL 131 (2023) 181801

JHEP 09 (2024) 062

$\tau^+ \to \mu^+\mu^-\mu^+$ (1/2)

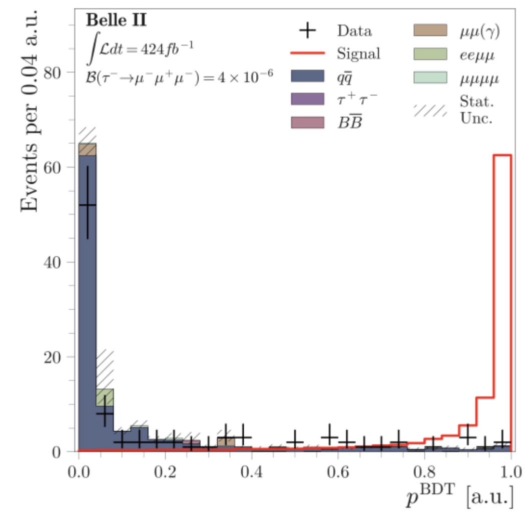
424 fb^{-1} of Belle II $\tau^+\tau^-$ data

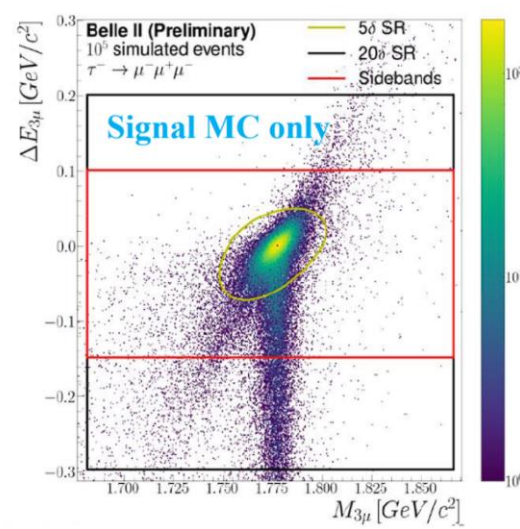
- Two hemispheres
  - For τ_{sig} and τ_{tag}
  - Separated by a plane $\hat{\boldsymbol{n}}_T$ (thrust axis), maximizing T



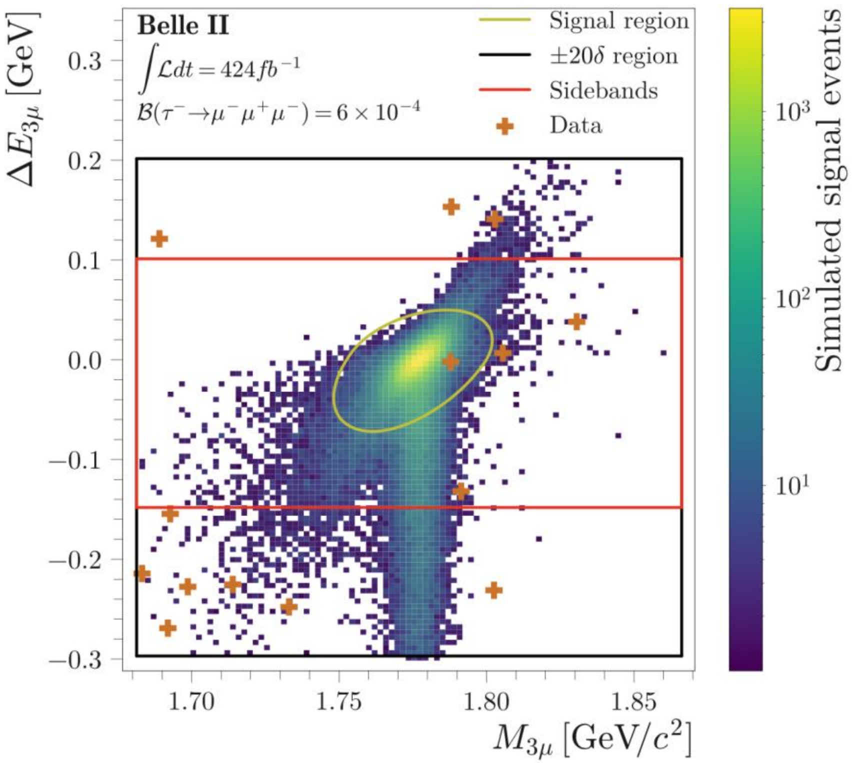
$$T = \max_{\hat{\mathbf{n}}_T} \left(\frac{\sum_i |\mathbf{p}^*{}_i \cdot \hat{\mathbf{n}}_T|}{\sum_i |\mathbf{p}^*{}_i|} \right)$$

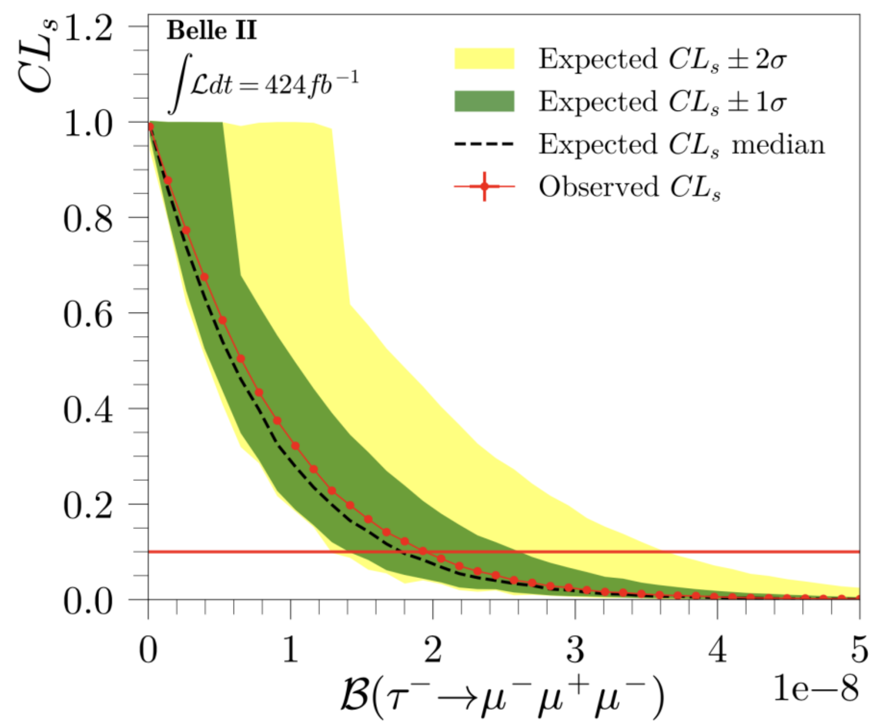
- Inclusive tagging
  - τ_{sig} hemisphere selection: 3 μ included hemisphere
  - Signal optimization and background rejection by BDT
  - 2D analysis of $M_{3\mu} = \sqrt{E_{3\mu}^2 - P_{3\mu}^2}$ and $\Delta E_{3\mu} = E_{3\mu}^{CM} - \sqrt{s}/2$





$\tau^+ \to \mu^+\mu^-\mu^+$ (2/2)





$\mathcal{B}(\tau^+ \to \mu^+\mu^-\mu^+) = \left(2.1^{+5.1}_{-2.4} \pm 0.4\right) \times 10^{-9}$

- Dominant systematic uncertainties from momentum scale (16%), signal region ($^{+2.9}_{-3.9}$%)

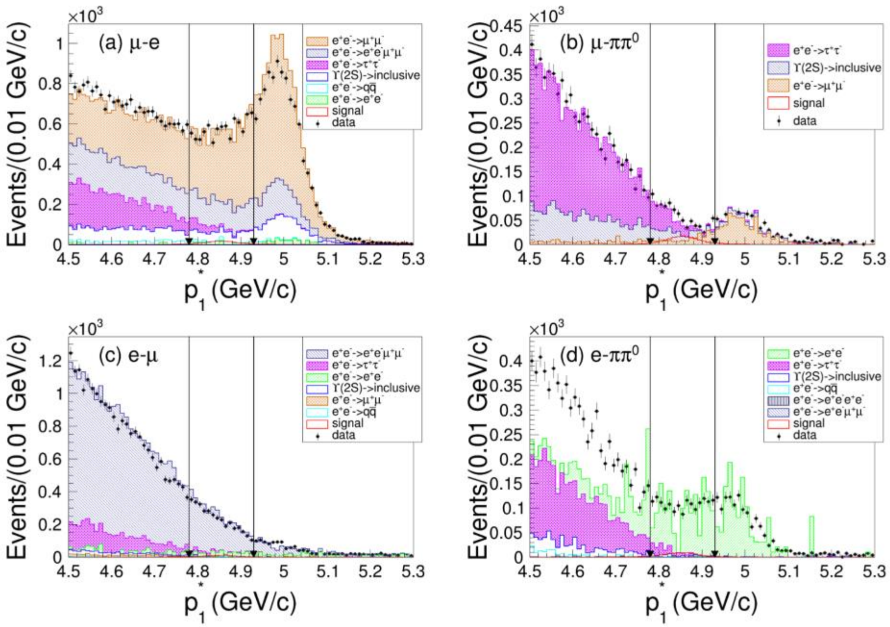
Observed (expected) limit:
$\mathcal{B} < 1.9\ (1.8) \times 10^{-8}$
Most stringent to date

BELLE JHEP 02 (2024) 187

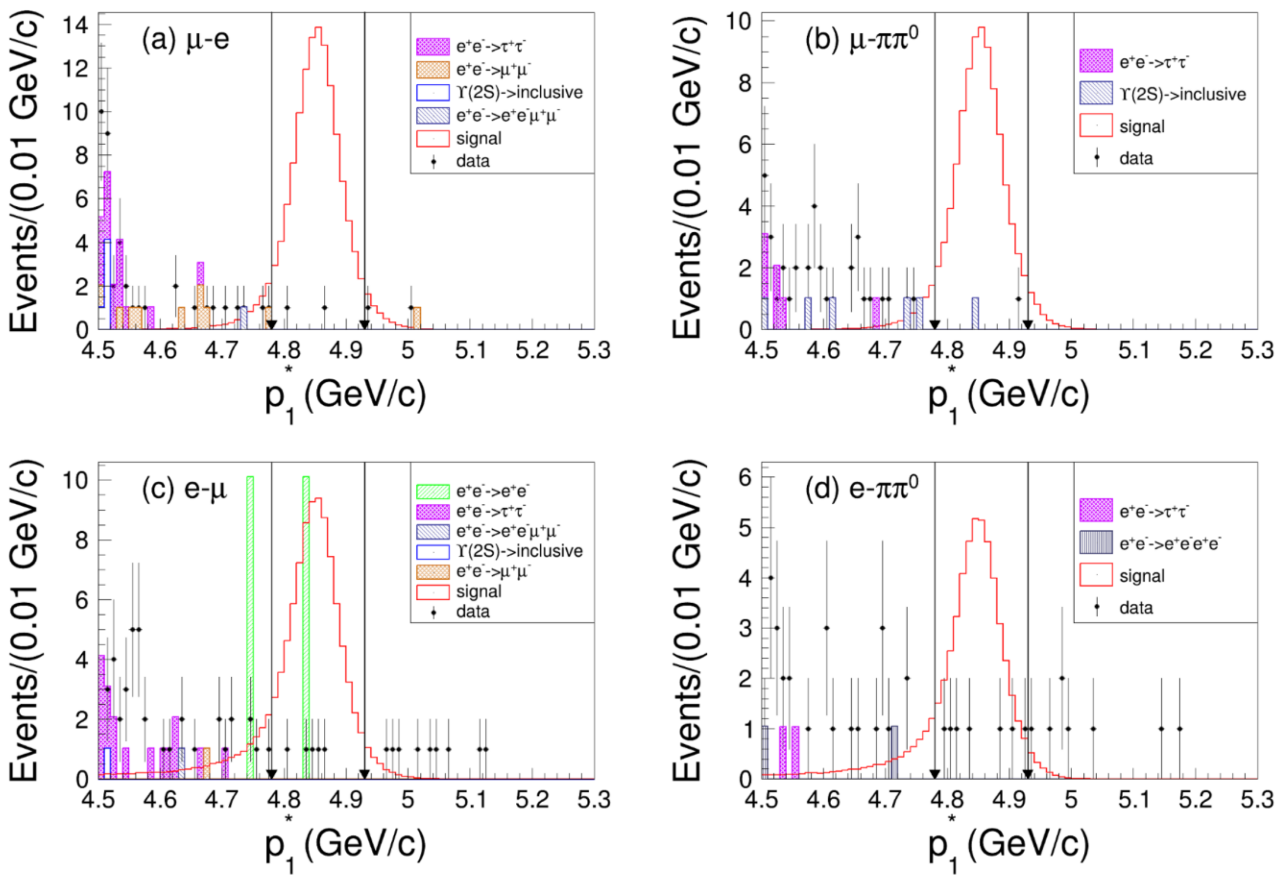
$\Upsilon(2S) \to \ell^{\pm}\tau^{\mp}$ (1/2)

25 fb^{-1} of Belle data @ $\Upsilon(2S)$

- **Motivations**
  - 2-body CLFV decay of a quarkonium
  - Can provide complementary constraints on the Wilson coefficients of the $\mathcal{L}_{\text{eff}}$ of new physics models (D. E. Hazard and A. A. Petrov, PRD 94 (2016) 074023)
- **Analysis features**
  - Belle data analysis in Belle II Analysis Framework (B2BII)
  - High-momentum primary lepton ℓ_1 from $\Upsilon(2S) \to \ell_1^{\pm}\tau^{\mp}$
  - Use τ^+ decays to $\ell_2^+\nu\bar{\nu}$ or $\pi^+\bar{\nu}$
  - ℓ_2 to have different flavor w.r.t. ℓ_1, to suppress copious background from Bhabha processes
  - FastBDT for further background suppression



$\Upsilon(2S) \to \ell^{\pm}\tau^{\mp}$ (2/2)



Modes	$\epsilon_{\rm sig}$ (%)	$N_{\rm exp}^{\rm bkg}$	$N_{\rm obs}$
$\Upsilon(2S) \to \mu^{\mp}\tau^{\pm}$	12.3 ± 0.8	3.9 ± 1.8	3
$\Upsilon(2S) \to e^{\mp}\tau^{\pm}$	8.1 ± 1.1	5.9 ± 2.6	12

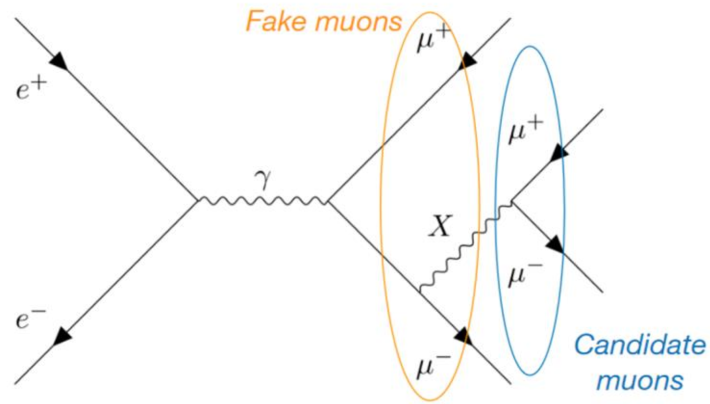
$$\mathcal{B}(\Upsilon(2S) \to \mu\tau) < 0.23 \times 10^{-6}$$
$$\mathcal{B}(\Upsilon(2S) \to e\tau) < 1.12 \times 10^{-6}$$

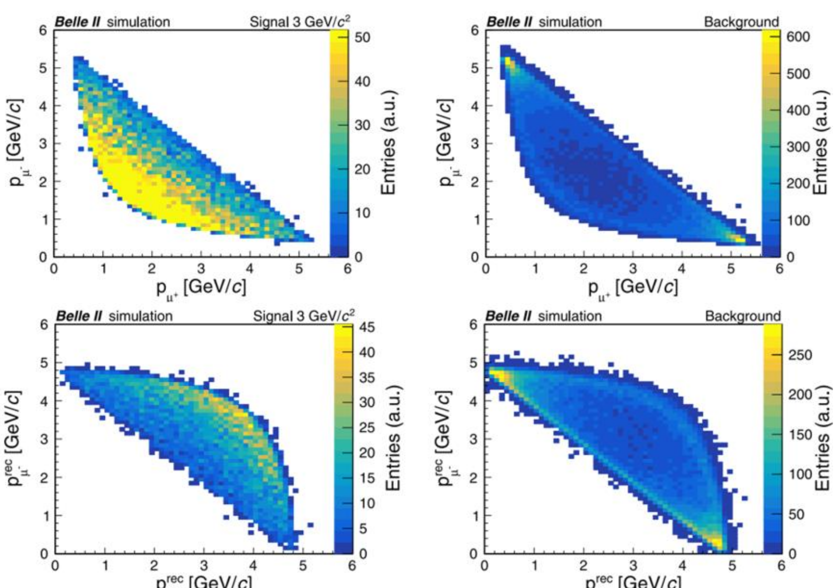
@ 90% CL

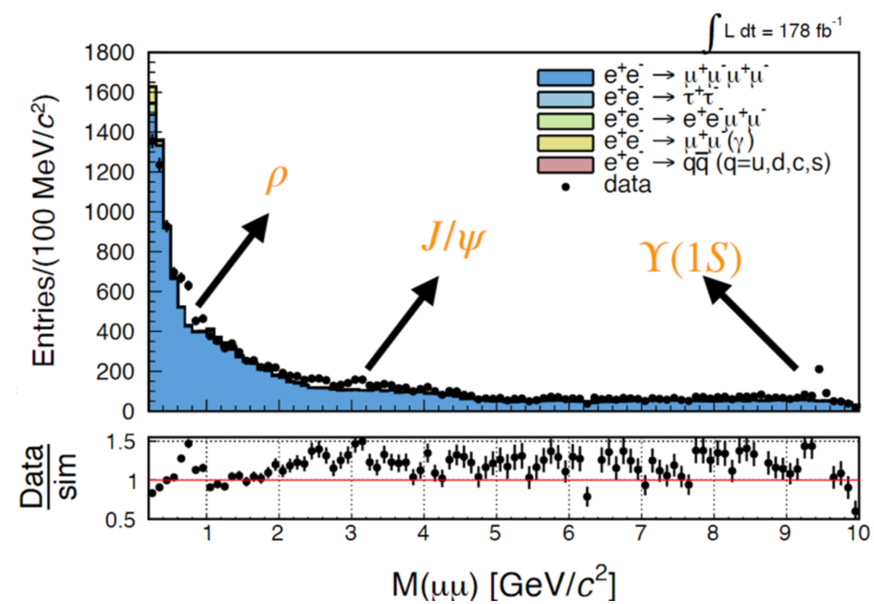
Belle (this) results are 14 (3) times more stringent than BaBar (PRL, 2010)

$e^+e^- \to \mu^+\mu^- \boldsymbol{X}\ (X \to \mu^+\mu^-)$ (1/2) 178 fb^{-1} of Belle II data

- Motivation
  - Probing two different models to find X
    - $L_\mu - L_\tau$ vector mediator (Z'): couple only to $\mu,\ \tau$
    - Muonphillic scalar S : couple only to μ
- Analysis features
  - Mass region: 0.212 – 9 GeV/c^2
  - Background suppression with momentum 2D distribution, helicity angle, muon pair momentum and so on

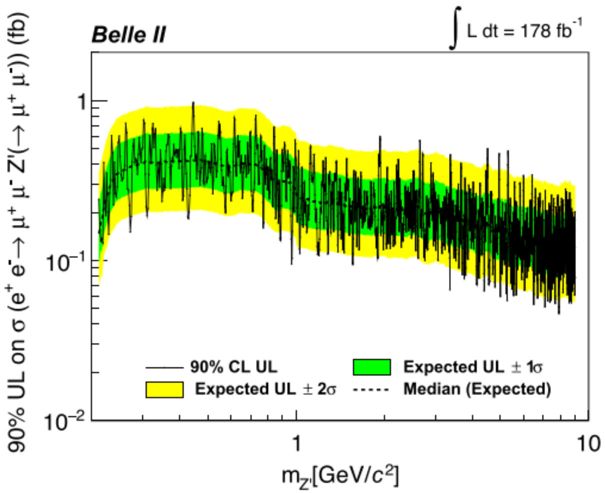


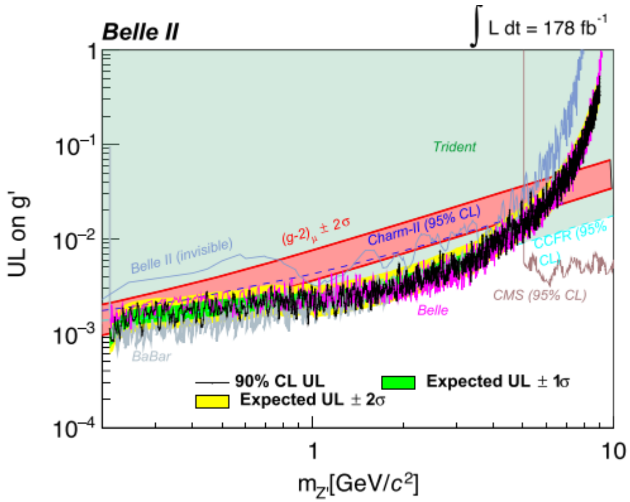


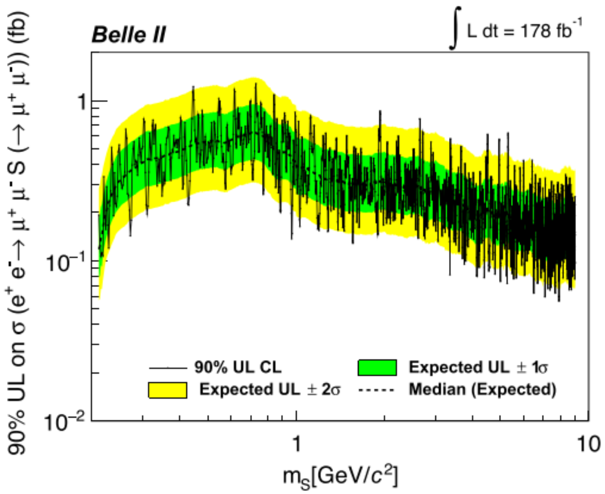


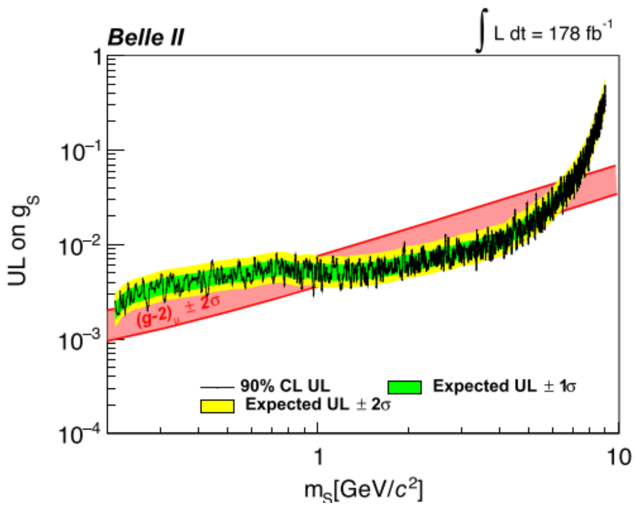
$e^+e^- \to \mu^+\mu^- \boldsymbol{X}\ (X \to \mu^+\mu^-)$ (2/2)

- Result

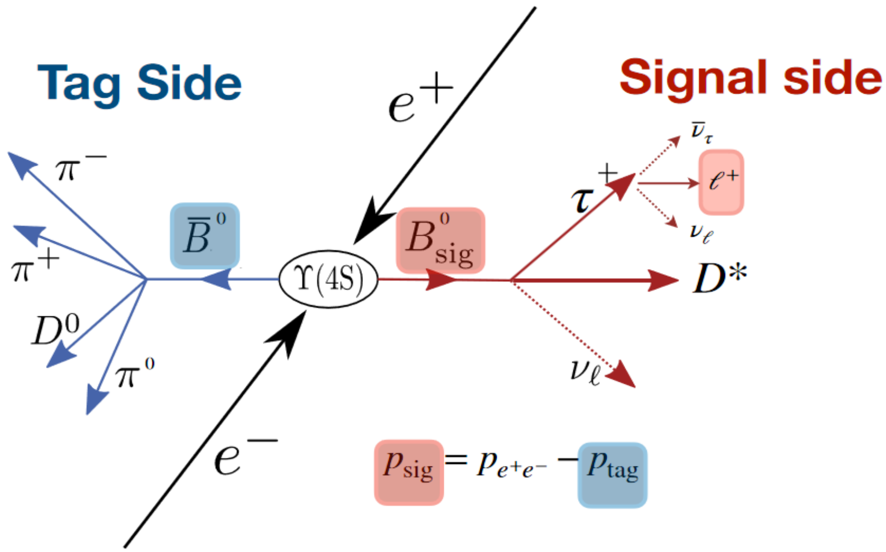


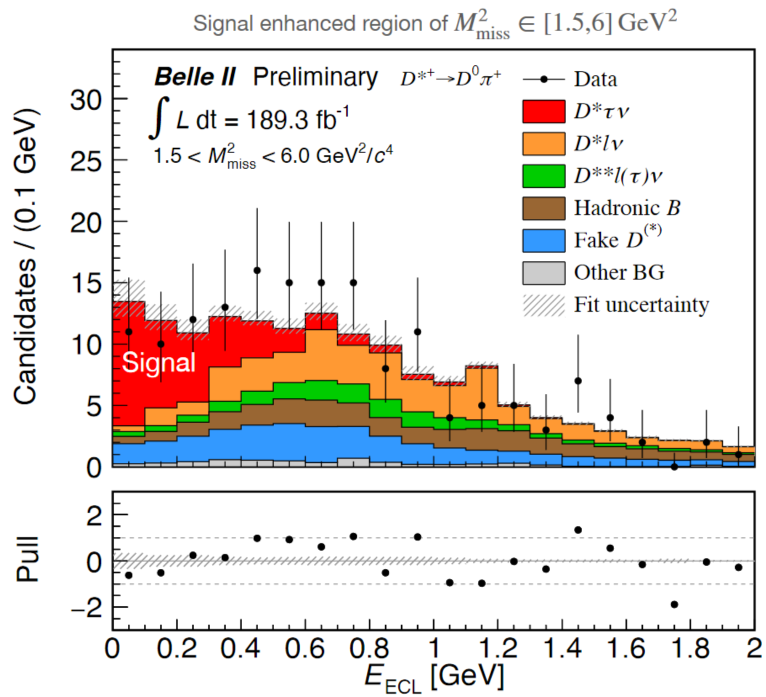


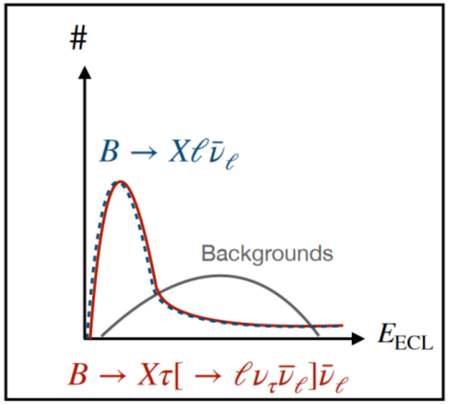


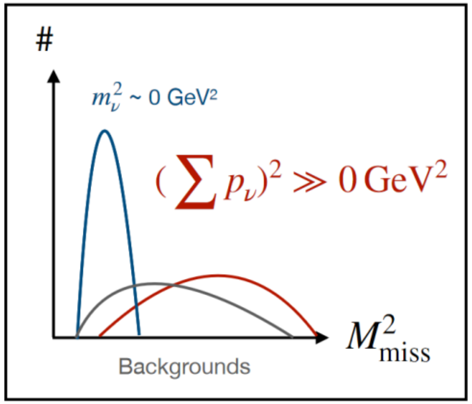


LFU with Measurement of $R(D^*)\left(=\frac{\mathcal{B}(\bar{B}\to D^*\tau\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to D^*\ell\bar{\nu}_\ell)}\right)$









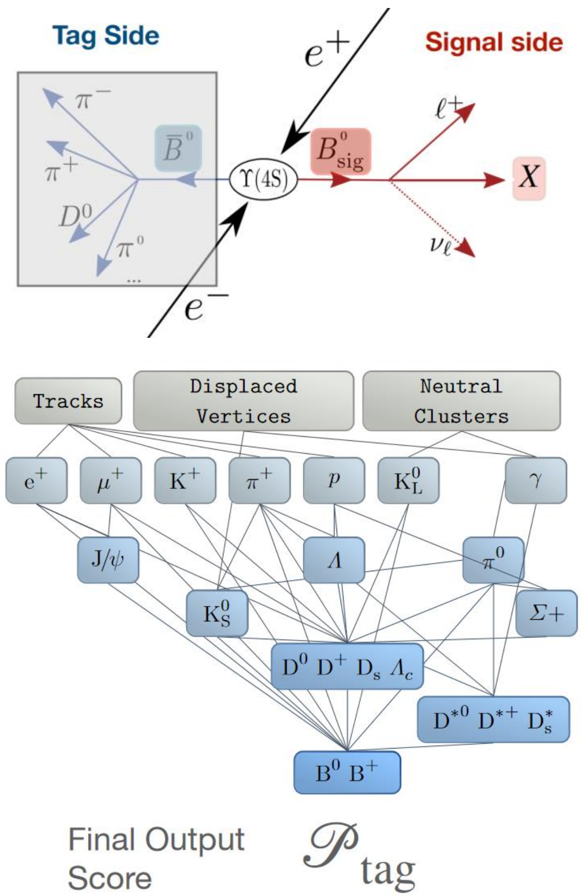
2D likelihood fit:

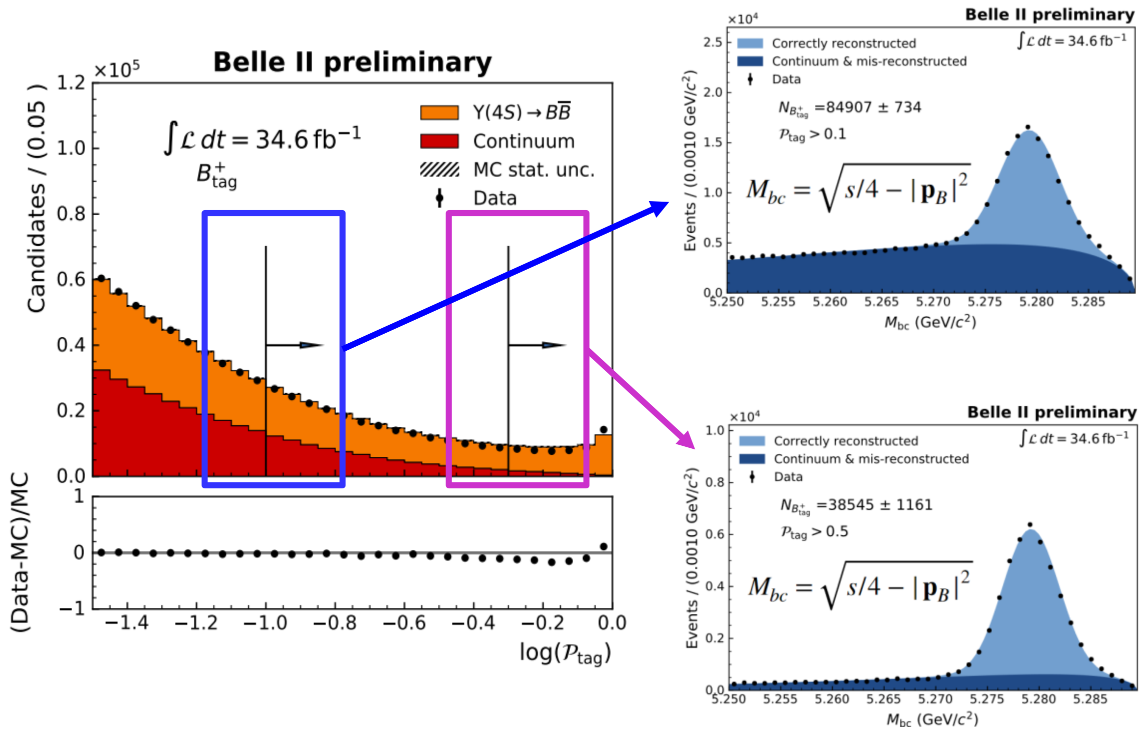
SM expectation: 0.249 +/- 0.002

$$R(D^*) = 0.262\ ^{+0.041}_{-0.039}(\mathrm{stat})\ ^{+0.035}_{-0.032}(\mathrm{syst}),$$

Exclusive Tagging for SL Analysis

- At e^+e^--B-Factories we can use the known initial collision kinematics
  - We can gain more information if we ‘reconstruct second B’ (B tagging).





Recent Progress of Korean Belle II Group

- B meson decay
  - LFV $B^0 \rightarrow \ell^{\pm}\tau^{\mp}$ with B2BII and FEI (김경호, KISTI)
  - DS $B^+ \rightarrow K^{(*)+}A'A'(A' \rightarrow e^+e^-, \mu^+\mu^-)$ (김용규, 연세대학교)
  - ALP $B \rightarrow K^{(*)}a'(a' \rightarrow \gamma\gamma)$ (조성진, 연세대학교)
  - ALP $B^+ \rightarrow K^+a'(a' \rightarrow \gamma\gamma)$ (김현아, 연세대학교)
  - $B^0 \rightarrow \tau^+\tau^-$ (김철훈, 한양대학교)
- τ^+ decay
  - LFV $\tau^+ \rightarrow \ell^+\pi^0$ (조한얼, 한양대학교)
  - LFV $\tau^+ \rightarrow \ell^+\eta$ (이호빈, 서울대학교)
- D meson decay
  - $D \rightarrow$ invisible with Charm tagger (김찬호, 연세대학교)
  - $D^+ \rightarrow \eta\pi^+$ (김재영, 연세대학교)
- Baryon-involved decay
  - $\Lambda_c^+ \rightarrow pK_S^0\pi^0$ (김영준, 고려대학교)
  - $X(3872) \rightarrow \omega J/\psi$, $X(3915) \rightarrow \omega J/\psi$ (안용헌, 고려대학교)
  - $X(3872) \rightarrow J/\psi\,\pi^+\pi^-, J/\psi\,\rho(\rightarrow \pi^+\pi^-)$ (장은지, 중앙대학교)

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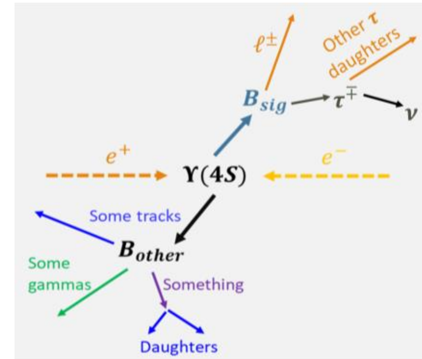
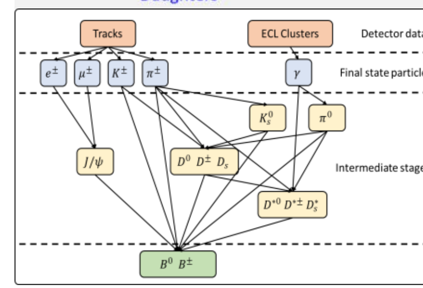
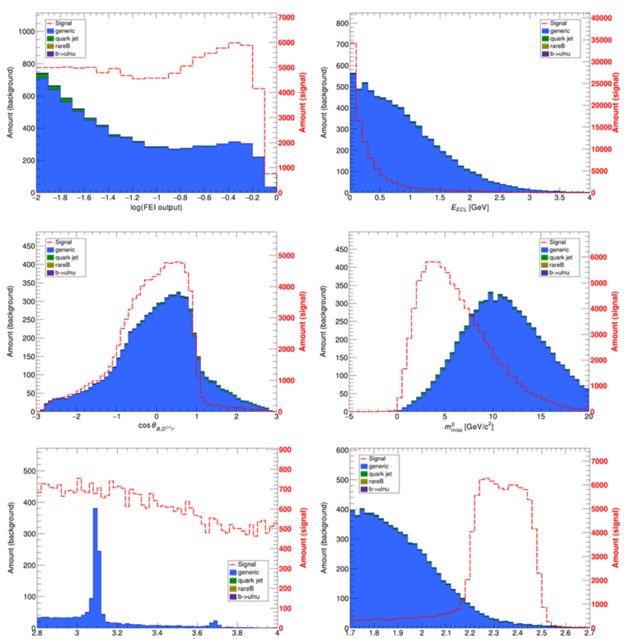
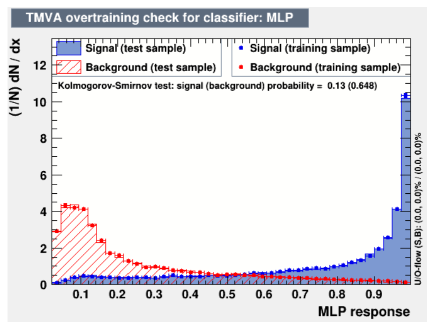
$B^0 \to \ell^\pm \tau^\mp (\ell = e, \mu)$

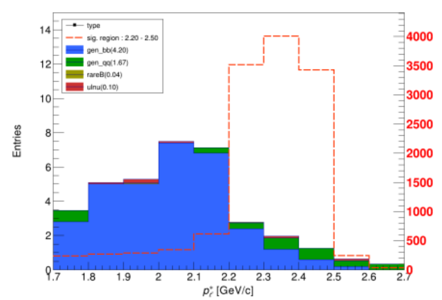
- LFV involved decay mode
  - Recent results
    - $\Gamma(B^0 \to e^\pm \tau^\mp) < 1.6 \times 10^{-5}$ (Belle, PRD 104 (2021) L091105)
    - $\Gamma(B^0 \to \mu^\pm \tau^\mp) < 1.4 \times 10^{-5}$ (LHCb, PRL 123 (2019) 211801)
  - B2BII and Full Event Interpretation (FEI)
    - FEI: non-signal B tagging method with machine learning
  - MC upper limit calculation done









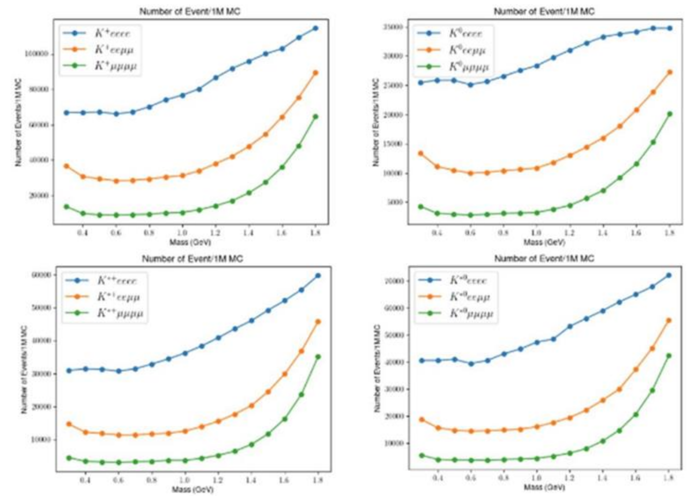


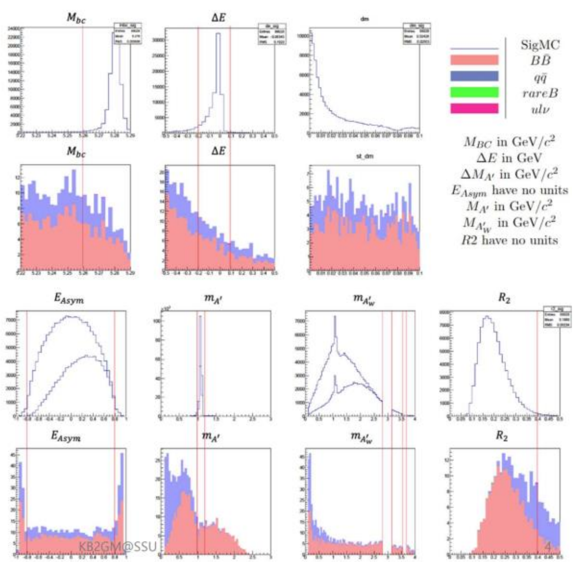
Full decay mode	$B^0 \to e^\pm \tau^\mp$		$B^0 \to \mu^\pm \tau^\mp$	
τ subdecay mode	$\tau \to e\nu\nu$	$\tau \to \mu\nu\nu$	$\tau \to e\nu\nu$	$\tau \to \mu\nu\nu$
Assumed N_{sig}	0	0	0	0
N_{obs}	6	3	5	5
N_{bkg}	6 ± 2.45	3 ± 1.73	5 ± 2.24	5 ± 2.24
Estimated N_{sig}	0 ± 2.45	0 ± 1.73	0 ± 2.24	0 ± 2.24
Branching ratio	$(0\pm2.52)\times10^{-6}$	$(0\pm2.31)\times10^{-6}$	$(0\pm2.39)\times10^{-6}$	$(0\pm3.11)\times10^{-6}$
Combined BR	$(0\pm3.42)\times10^{-6}$		$(0\pm3.92)\times10^{-6}$	
ML upper limit of BF @ 90% CL	$< 5.62\times10^{-6}$		$< 6.45\times10^{-6}$	

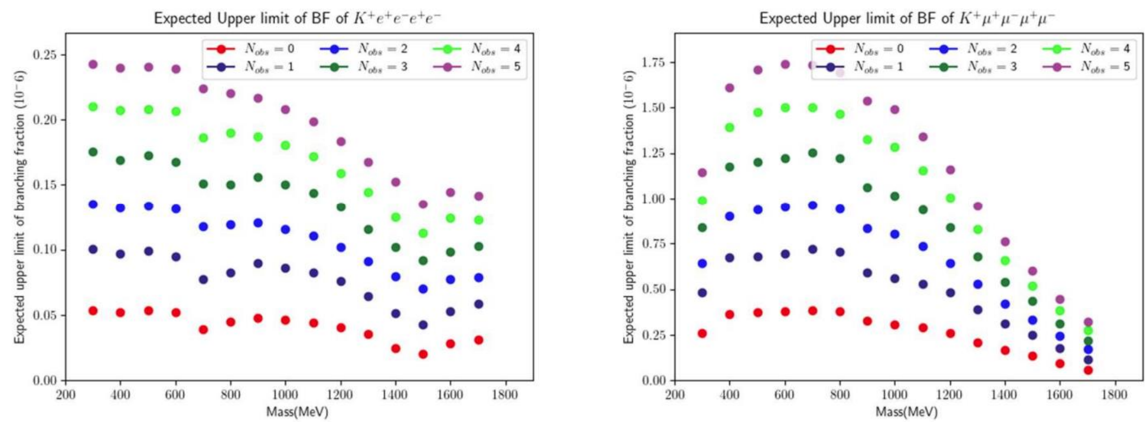
YK Kim, Yonsei

$B \to K^{(*)} A' A' (A' \to e^+ e^-, \mu^+ \mu^-)$

- Motivations
  - $B \to KS(S \to A'A', A' \to \ell^+\ell^-)$
    - Scalar particle S can be dark-Higgs or off-shell Higgs.
    - $B \to K\gamma\gamma$ with $\gamma - A'$ kinetic mixing can be contribute this final state although its branching fraction is expected less than 10^{-9}.
- Analysis features
  - 12 possible modes: 4 type of K, 2 type of A'
  - Various A' mass scan: 0.1 – 1.8 GeV
  - MC upper limit: 10^{-8} – 10^{-6}



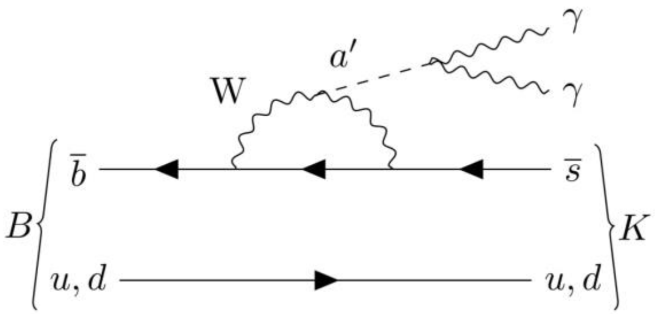


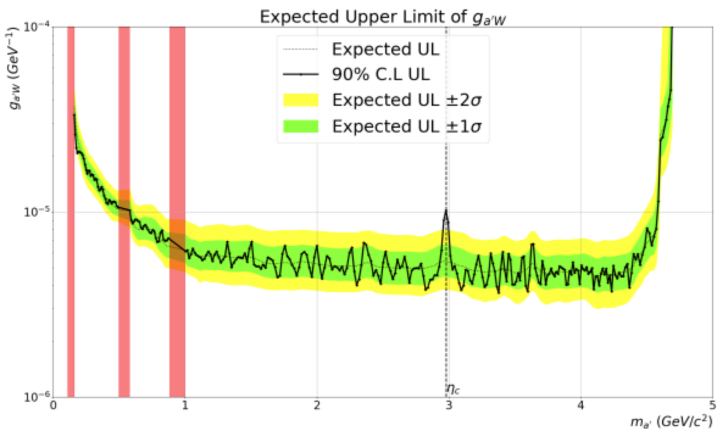


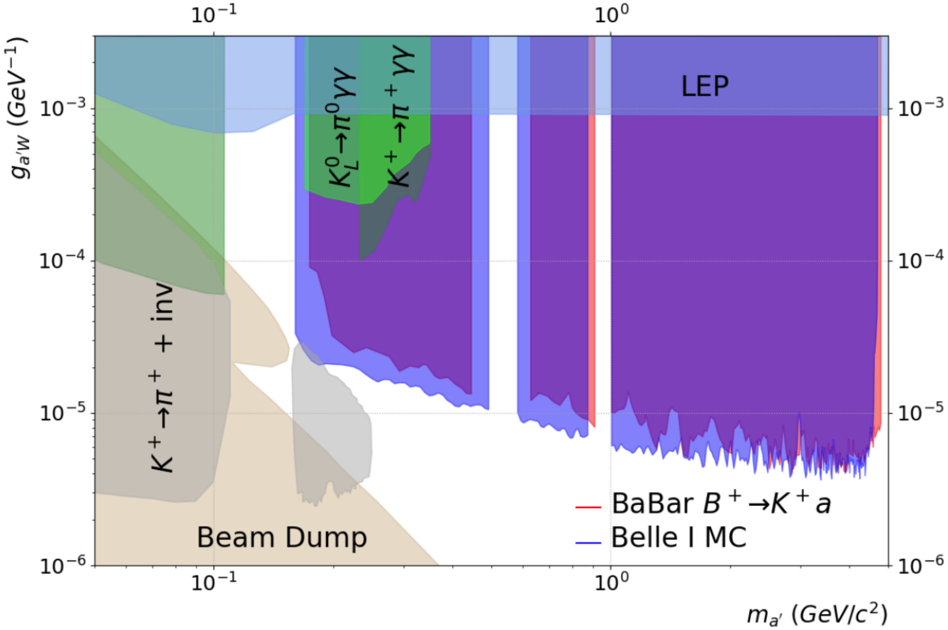
S. Cho, Yonsei

$B \to K^{(*)} a'(a' \to \gamma\gamma)$

- Motivation: Searching for ALPs
  - a': spinless pseudoscalar particle, decays to $\gamma\gamma$ 100%
    - Mass scanning: 0.16 ~ 4.50(4.20) GeV/c^2, 0.1 GeV/c^2 step
    - π^0, η, η' mass region is excluded.
- Analysis features
  - B2BII is applied to adopt BASF2
  - FastBDT for continuum suppression
  - FastBDT for $\pi^0, B \to X_s\gamma$ veto
  - Long-lived ALP is considered



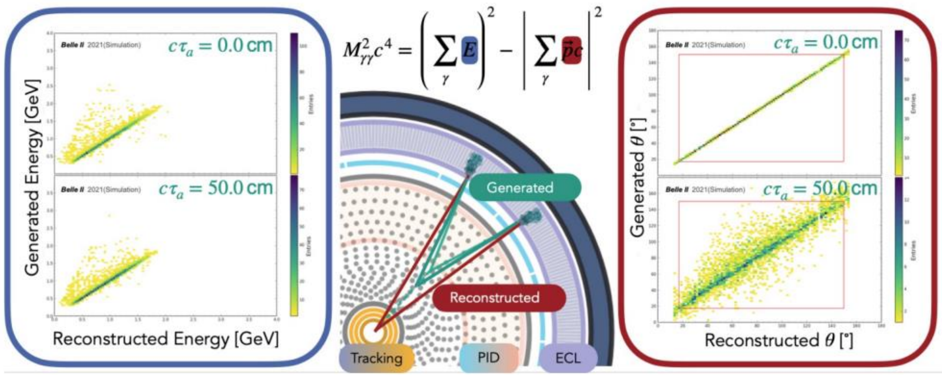


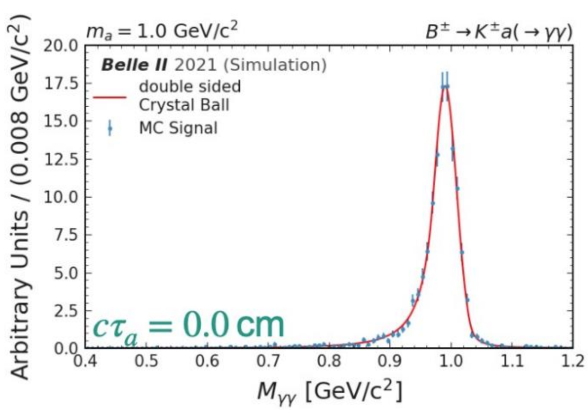


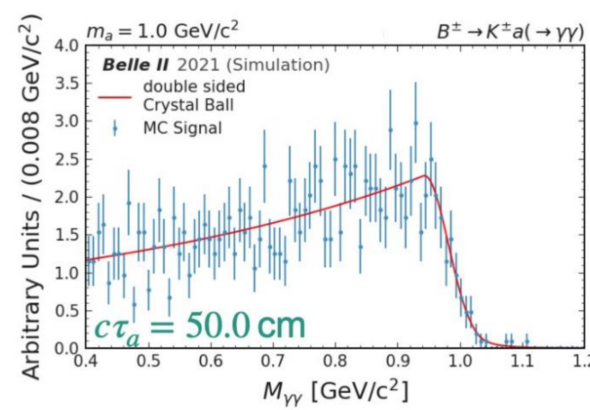
H. Kim, Yonsei

$B^+ \to K^+ a'(a' \to \gamma\gamma)$

- Analysis features
  - Mass scanning: 0.1, 1.0, 2.0, 3.0, 4.0, 4.78 GeV/c^2
  - Long lived ALP flight distance: 0, 1, 10, 20, 30, 40, 50 cm
  - Worse resolution with longer flight distance
    - Perform the analysis for each lifetime independently.
  - Ongoing analysis







C. Kim, Hanyang

$B^0 \to \tau^+\tau^-$

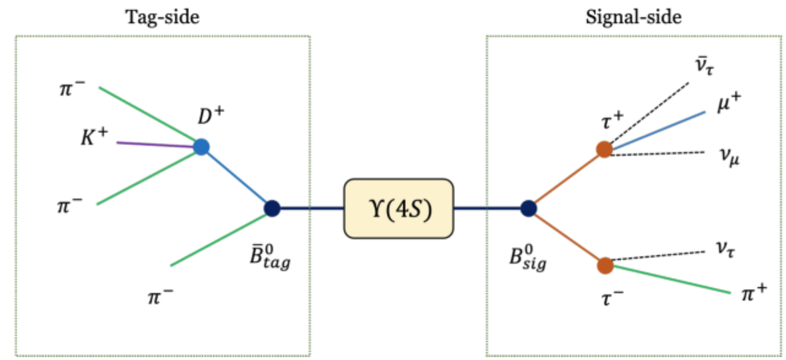
Motivation

- The result of $B^0 \to \tau^+\tau^-$ study constraints the free parameter of the BSM models.
- τ pair decay: high BR, (very) hard to deal with
  - Subdecay modes should have missing particle(s).

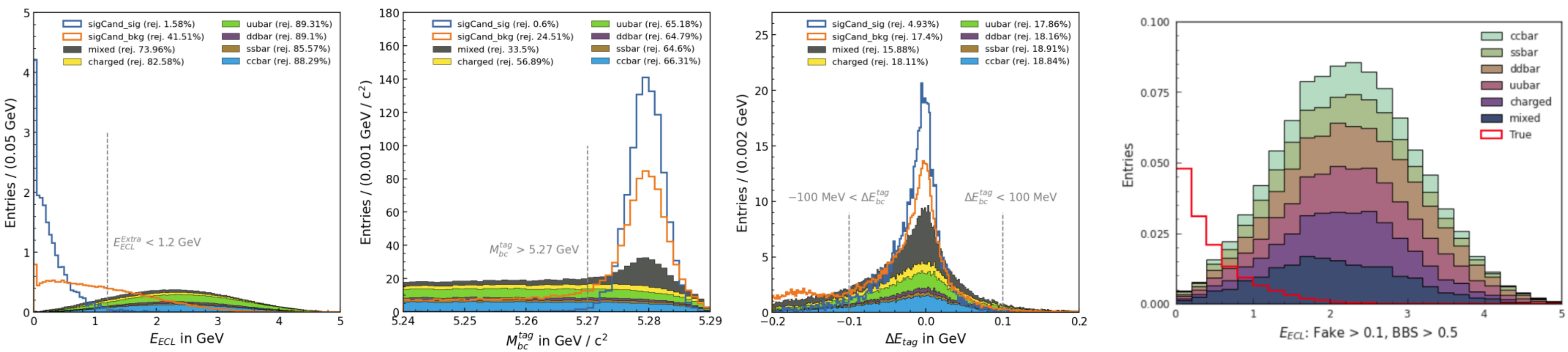
$$\mathcal{B}(B^0 \to \ell^+\ell^-) = \frac{G_F^4 M_W^4 M_B^3}{8\pi^5 \Gamma_B} \cdot \underbrace{f_B^2}_{\text{Decay constant}} \cdot \underbrace{|V_{tb}^* V_{td}|^2}_{\text{CKM elements}} \cdot \underbrace{\frac{4m_\ell^2}{M_B^2}}_{\substack{\text{Helicity suppression} \\ \text{(HS)}}} \cdot \underbrace{\sqrt{1 - \frac{4m_\ell^2}{M_B^2}}}_{\substack{\text{Phase space factor} \\ \text{(PSF)}}} \cdot |C_A(\mu)|^2$$

Analysis features

- Four τ subdecay are considered.
  - $\tau \to e\nu\bar{\nu},\ \mu\nu\bar{\nu},\ \pi\bar{\nu},\ \rho\bar{\nu}$
- Continuum suppression with FastBDT is done.



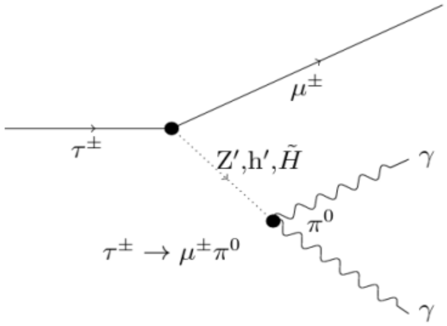
$B^0 \to \tau^+\tau^-$ *decay example graph*



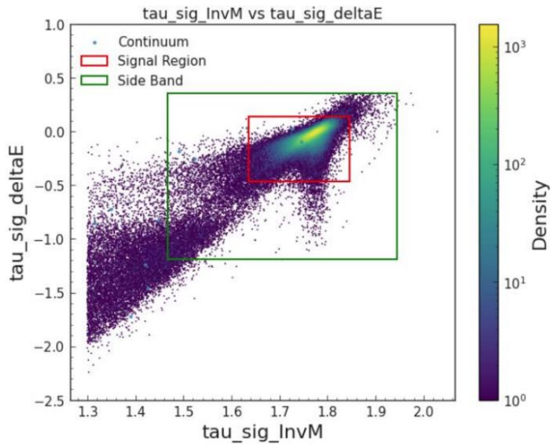
H. Cho, Hanyang

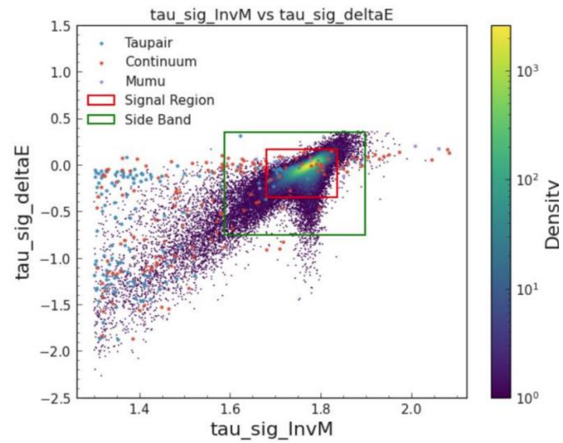
$\tau^+ \to \ell^+ \pi^0$

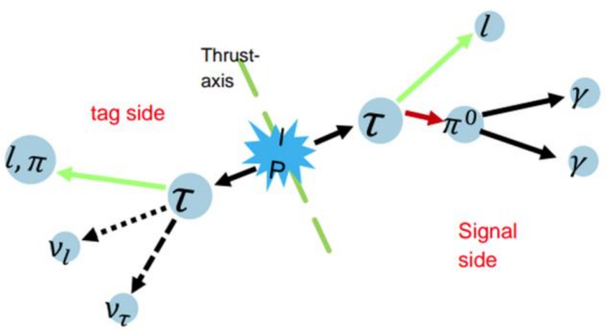
- Motivation: LFV
  - SM prediction $\sim 10^{-55}$ (PLB 852 (2024) 138621)
  - NP prediction $\sim 10^{-14}$ (Eur. Phys. J. C (2020) 80:1167)



- Analysis features
  - 1×1 prong: 1 prong has ~85% branching fraction
  - Two hemisphere
  - MVA to continuum suppression







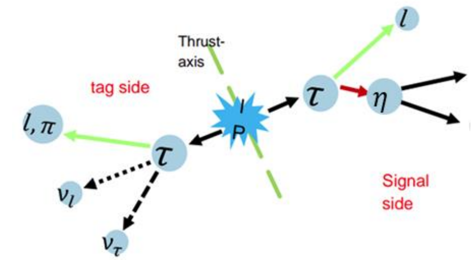
		ε_{sig} (%)	N_{bkg}	$N_{UL}^{90\%}$	$BF_{UL}^{90\%}$
$\tau \to e\pi^0$	Belle II	6.0	$0.18^{+0.42}_{-0.18}$	2.26	5.7E-08
	Belle	3.9	0.20 ± 0.20	2.2	8.0E-08
$\tau \to \mu\pi^0$	Belle II	7.5	3.46 ± 1.86	0.76	1.5E-08
	Belle	4.5	0.58 ± 0.34	2.8	1.2E-07

$\tau^+ \to \ell^+ \eta$

H. Lee, SNU

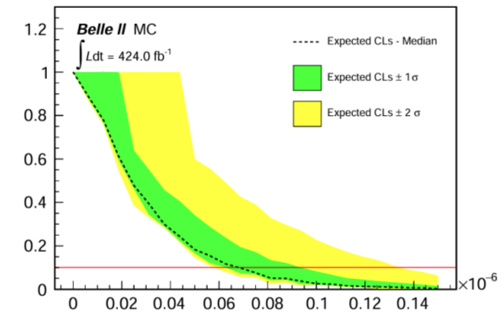
Motivation: LFV

- SM prediction ~ 10^{-55} (PLB 852 (2024) 138621)
- BSM allowing $\tau^+ \to \ell^+ \eta$
  - Supersymmetry(SUSY), leptoquarks, Type III seesaw model, etc.
- Expected UL with Type III seesaw model
  - $UL_{90}^{\text{theory}}(\tau^- \to e^- \eta) < 0.6 \times 10^{-8}$
  - $UL_{90}^{\text{theory}}(\tau^- \to \mu^- \eta) < 1.0 \times 10^{-8}$

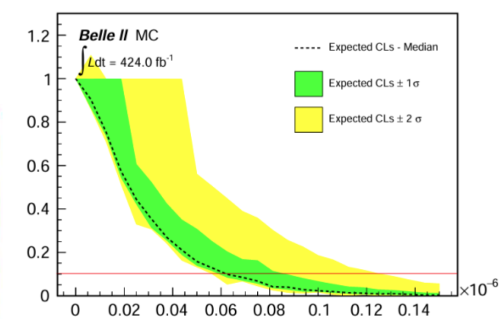


Analysis features

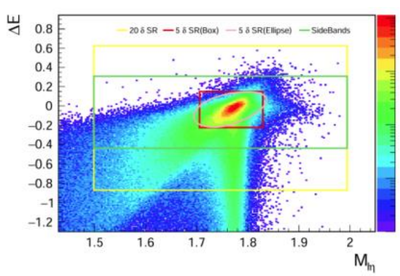
- Generic MC 424 fb^{-1}
- $\eta \to \gamma\gamma$ (~40% BR) and $\eta \to \pi^+\pi^-\pi^0$(~20% BR) are considered.
- Estimated MC upper limit
  - $UL_{90}^{\text{Belle II}}(\tau^- \to e^- \eta) < 9.2 \times 10^{-8}$
  - $UL_{90}^{\text{Belle II}}(\tau^- \to \mu^- \eta) < 6.5 \times 10^{-8}$



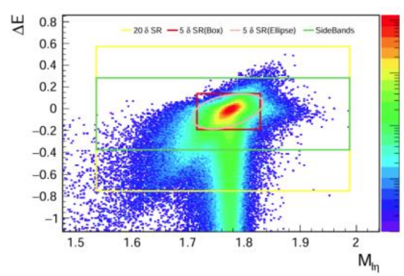
(a) electron channel



(b) muon channel



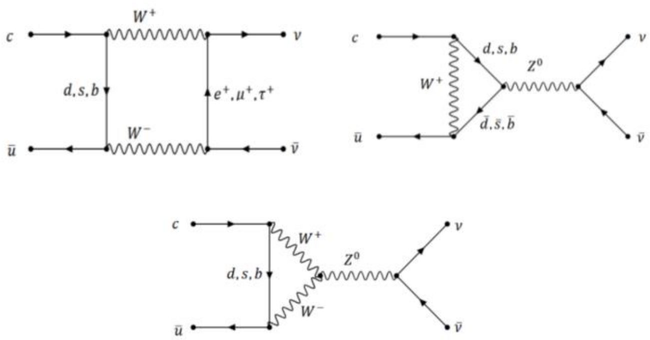
(a) Electron channel

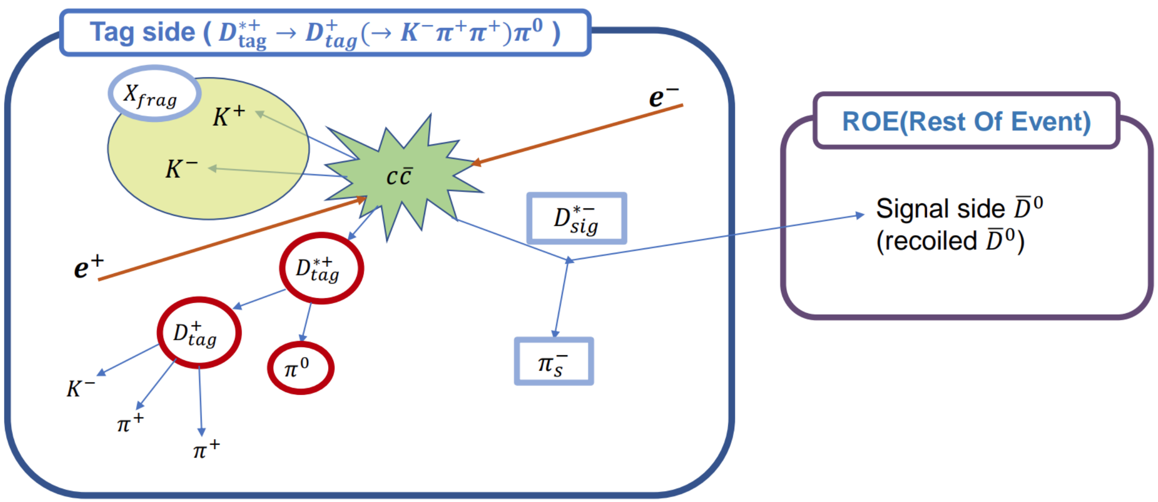


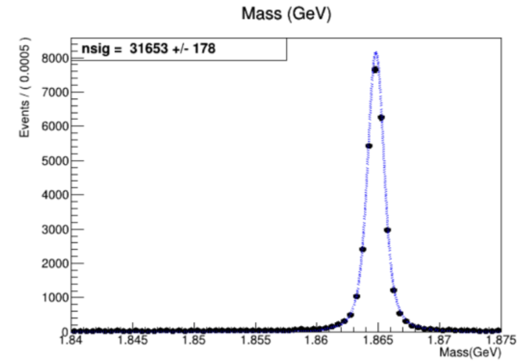
(b) Muon channel

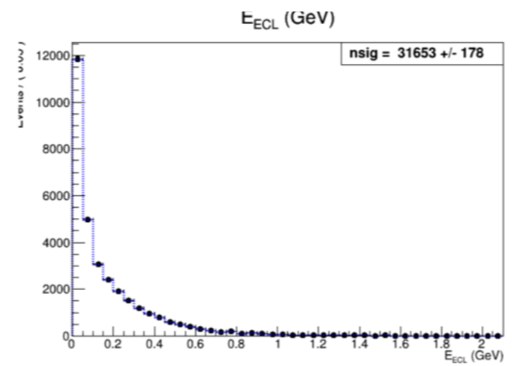
$D \rightarrow$ invisible

- Motivation
  - In the SM, expected $\mathcal{B}(D^0 \rightarrow \nu\bar{\nu}) = 1.1 \times 10^{-30}$
  - So, search for this mode is sensitive to new physics.
  - Previous result: $\mathcal{B}(D^0 \rightarrow \nu\bar{\nu}) < 9.4 \times 10^{-5}$ (924 fb^{-1}, Belle, PRD 95 (2017) 011102)
- Analysis features
  - Charm Tagger to reconstruct full
    - Automatically reconstruct D meson with FastBDT
  - $\mathcal{B}(D^0 \rightarrow \nu\bar{\nu}) < 5.53 \times 10^{-5}$









J. Kim, Hanyang

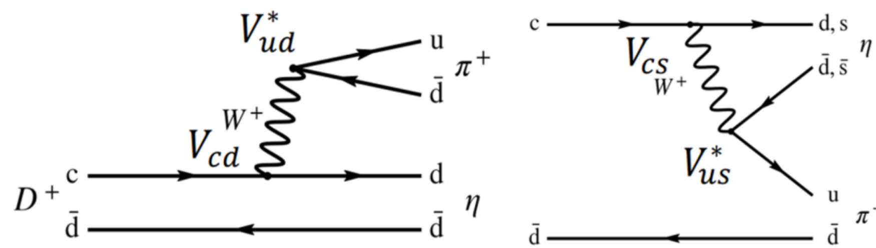
$D^+ \to \eta\pi^+$

Motivation

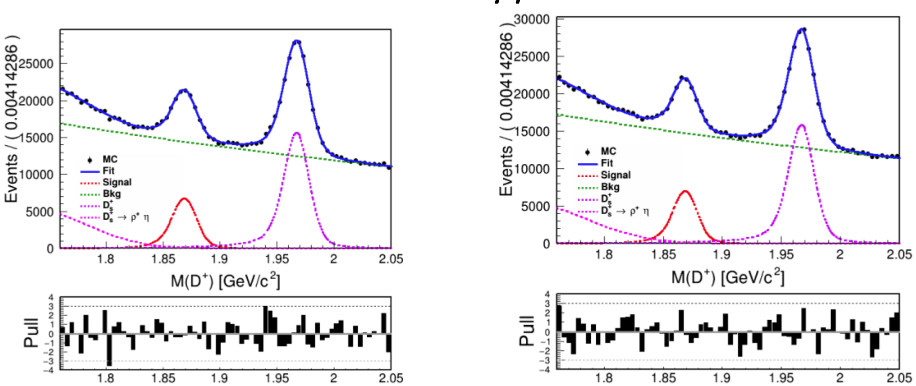
- $D^+ \to \eta\pi^+$ (Singly Cabbibo-Suppressed) decay
  - Where two difference from weak phases from CKM matrix elements: $V_{cd}V^*_{ud}, V_{cs}V^*_{us}$
  - It allows CPV at tree-level

Analysis features

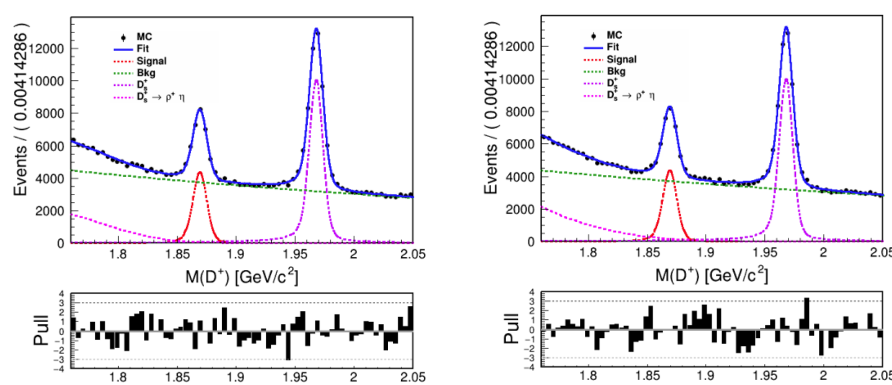
- 1 ab^{-1} MC used
- $\eta \to \gamma\gamma$ (~40% BR) and $\eta \to \pi^+\pi^-\pi^0$(~20% BR) are considered.



$D^+ \to \eta_{\gamma\gamma}\pi^+$



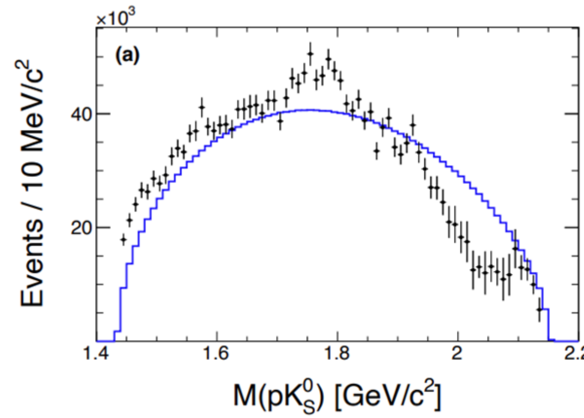
$D^+ \to \eta_{3\pi}\pi^+$



YJ Kim, KU

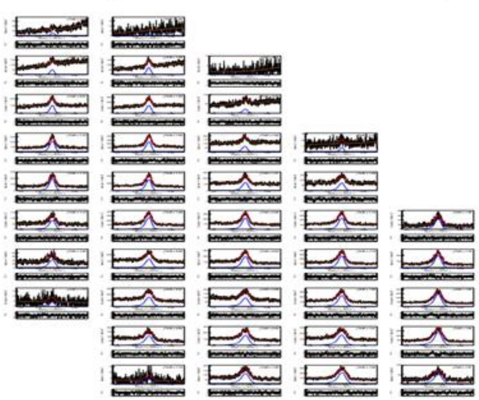
$\Lambda_c^+ \to pK_S^0\pi^0$

- **Motivation**
  - Updates on the relative BR $\mathcal{B}(\Lambda_c^+ \to pK_S^0\pi^0)/\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$: isospin symmetry test in $N\bar{K}\pi$ system
  - Reconfirmation of peak structure in the pK_S^0 system near $1665\ \mathrm{MeV/c^2}$

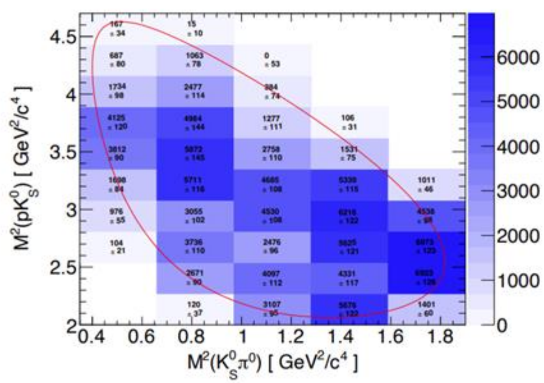


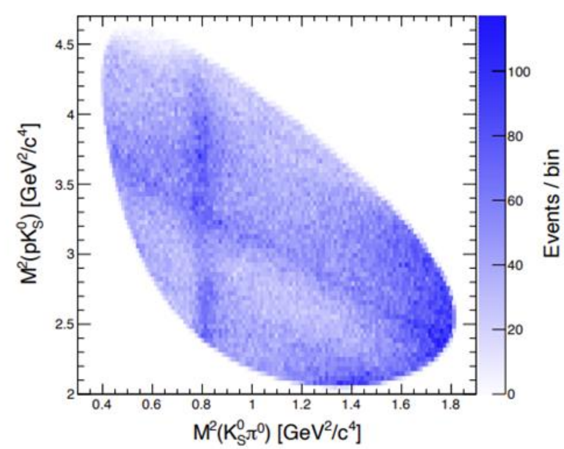
- **Analysis features**
  - Dalitz plot analysis
  - Signal yield extraction from bin by bin efficiency correction
  - $\mathcal{B}(\Lambda_c^+ \to pK_S^0\pi^0)/\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = 0.339 \pm 0.002(\mathrm{stat.}) \pm 0.009(\mathrm{syst.})$
  - No significant peak in the pK_S^0 system near $1665\ \mathrm{MeV/c^2}$

Fit with two asymmetric Gaussians + 3rd polynomial



Yield extraction



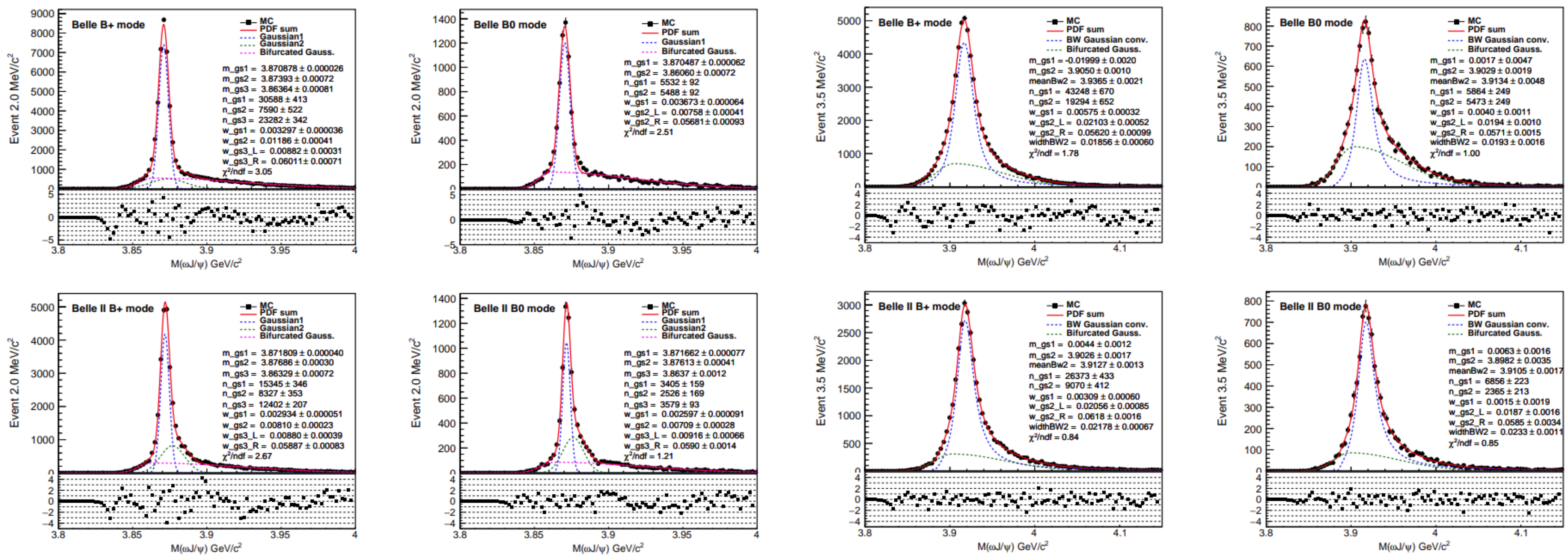


Y. Ahn, KU

$X(3872) \rightarrow \omega\, J/\psi\,,\, X(3915) \rightarrow \omega\, J/\psi$

BELLE Belle II

- Motivation
  - To identify states of X(3872) and X(3915)
- Analysis features
  - $B \rightarrow KX(3872)\ (X(3872) \rightarrow \omega\, J/\psi, \omega \rightarrow \pi^+\pi^-\pi^0, J/\psi \rightarrow \ell^+\ell^-)$
  - $B \rightarrow KX(3915)\ (X(3915) \rightarrow \omega\, J/\psi, \omega \rightarrow \pi^+\pi^-\pi^0, J/\psi \rightarrow \ell^+\ell^-)$
  - Using Belle 711 fb^{-1} and Belle II 1444 fb^{-1}
  - Difference of BR between input and fit result are $\sim 1.5\sigma$



E. Jang, CAU

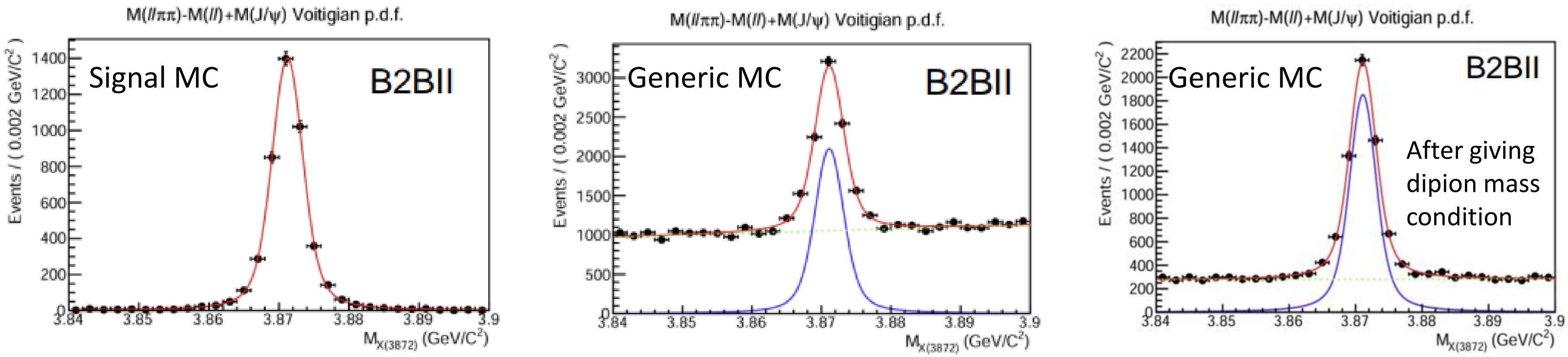
$X(3872) \to J/\psi\,\pi^+\pi^-, J/\psi\,\rho(\to \pi^+\pi^-)$

Motivation

- To identify states of X(3872) by lineshape measurement

Analysis features

- $B \to KX(3872)\ (X(3872) \to\ J/\psi\rho^0,\ \rho^0 \to \pi^+\pi^-,\ J/\psi \to \ell^+\ell^-)$
- $B \to KX(3872)\ (X(3872) \to\ J/\psi\pi^+\pi^-,\ J/\psi \to \ell^+\ell^-)$
- 711 fb^{-1} Belle data analysis with B2BII and BASF2
- Dipion invariant mass condition reduces ~73% of background
- Ongoing



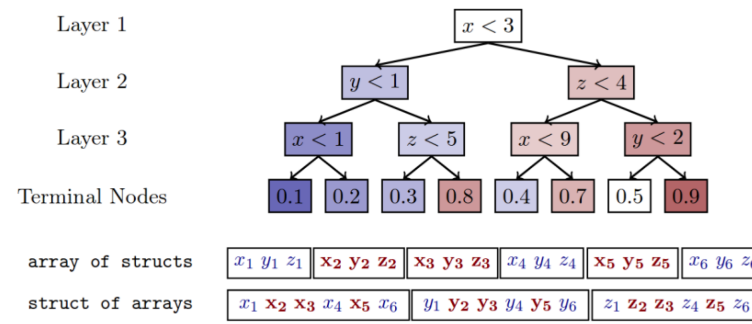
Summary

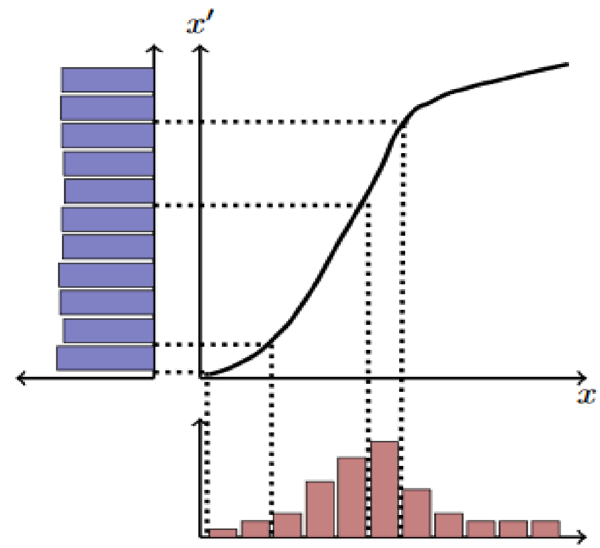
- Belle II has returned from LS1 and started Run 2 data taking in February this year, collecting more 0.5 ab^{-1} data sample in total.
- With an advantage of clean event of e+e- collider, Belle II experiment are ongoing many analyses related to NP including lepton flavor violation, dark sector and so on.
  - We show recent researches for
    - LFV processes, $\tau^+ \to \mu^+\mu^-\mu^+$, $\Upsilon(2S) \to \ell^\pm\tau^\mp$ at Belle II.
    - dark sectors, X(Z', S) search in the $e^+e^- \to \mu^+\mu^- X$ $(X \to \mu^+\mu^-)$ at Belle II.
    - Semileptonic measurements, lepton flavor universality with measurement of $R(D^*)$ at Belle II.
- Korean Belle 2 group are 10^{th} largest size per country in Belle II collaboration and doing many analyses for searching the evidence of new physics, precise measurement and identifying the states.

Backup

FastBDT : Classification Algorithm of FEI

- Requirements for FEI classification algorithm
  - Fast during fitting and application
  - Robust enough to be trained in an automated environment
  - Can be reliably used by non-experts
- FastBDT : BDT with speed-optimized and cache-friendly implementations for multivariate classification
  - Trial to reduce run time
    - Storing data as an array of structs
    - Computing cumulative probability histograms (CPH) of nodes in the same layer of the tree simultaneously
    - BDT cut decisions optimized based on equal frequency bins






```
int a = 0;
int b = 0;
for(int i=0; i<1e9; ++i) {
 if(rand()%2 == 0) a++;
 else              b++;
}
cout<<a<<" "<<b<<endl;
```

(a) Straight-forward implementation – Execution time 10.1 sec

```
int a[] = {0,0};

for(int i=0; i<1e9; ++i) {
  a[rand()%2]++;

}
cout<<a[0]<<" "<<a[1]<<endl;
```

(b) If statement replaced by array lookup – Execution time 6.9 sec

Reference: T. Keck, https://arxiv.org/abs/1609.06119

Benchmark of FastBDT and Others for FEI

- Benchmarks of reconstruction using $D^0 \to K^- \pi^+ \pi^0$
  - Fitting time measured about 28 features and 355,000 events
  - Inference time measured about 28 features and 3,900,000 events

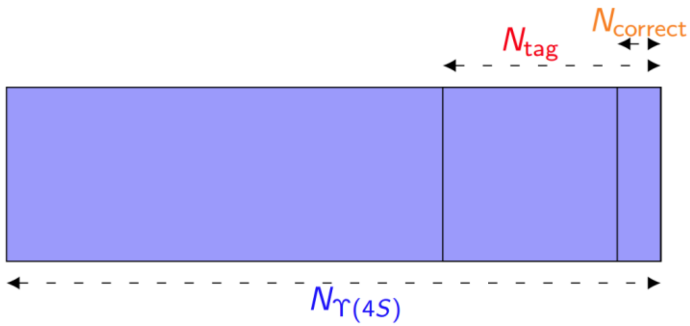
do nothing during the fitting phase → Trivial

Method	Fitting time in s	Inference time in s	AUC ROC	WeightFile size in KB
Trivial	0.2	4.9	0.066	2
Stochastic Gradient Boosted Decision Tree				
FastBDT	3.7	6.9	0.435	58
SKLearn-BDT	32.1	7.8	0.429	69
XGBoost	18.0	11.4	0.415	34
TMVA-BDT	19.8	16.5	0.297	101
Artificial Neural Network				
SKLearn-NN	27.6	7.2	0.401	32
Tensorflow	201.9	9.4	0.399	30
NeuroBayes	112.3	75.4	0.377	182
FANN	50.6	7.1	0.316 ± 0.061	21
TMVA-NN	510.6	16.8	0.156	53

Performances of FEI

- Maximum tag-side efficiency of reconstruction algorithm
  - Comparison to other tag-side reconstruction algorithm of Belle and BaBar

Tag	FR (Belle)	SER (BaBar)	FEI (Belle)	FEI (Belle II)
Methods	Neurobayes	Neural network	FastBDT	
Hadronic B^+	0.28%	0.4%	0.76%	0.66%
SL B^+	0.31%	0.3%	1.80%	1.45%
Hadronic B^0	0.18%	0.2%	0.46%	0.38%
SL B^0	0.34%	0.6%	2.04%	1.94%



Tagging efficiency = $N_{tag}/N_{\Upsilon(4S)}$

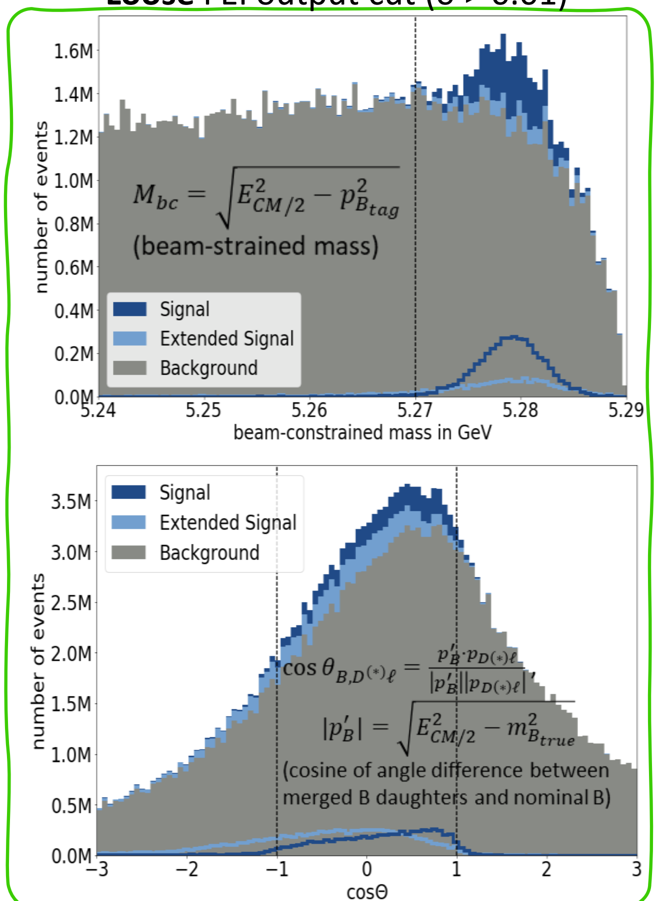
Tag-side efficiency = $N_{correct}/N_{\Upsilon(4S)}$

Purity = $N_{correct}/N_{tag}$

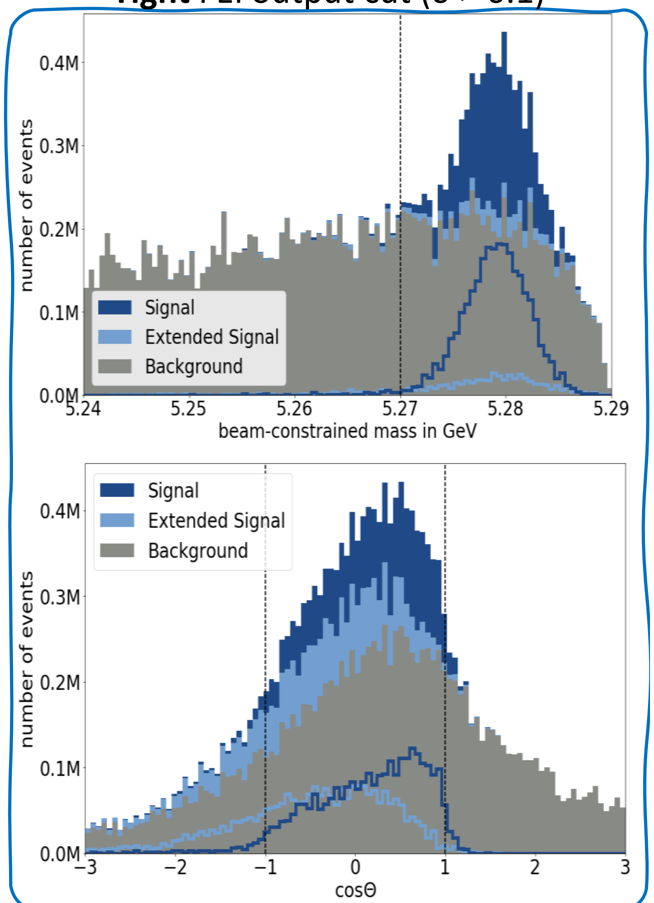
FEI Performance Check

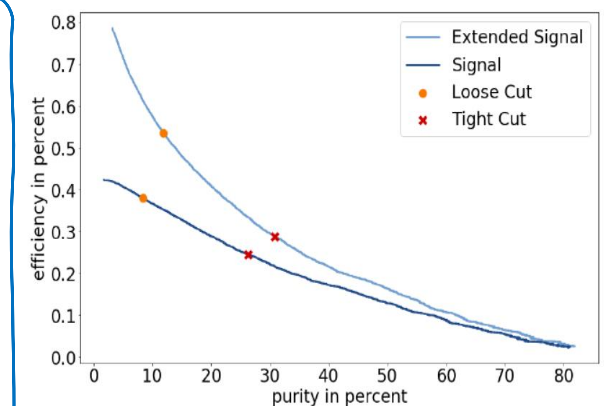
- Distribution of the kinematic variable of B_{tag} at Belle II MC
  - 180M BB pair signal and $1ab^{-1}$ scaled backgrounds from BB, e^+e^- to qq pair and $\tau^+\tau^-$

Loose FEI output cut (σ > 0.01)

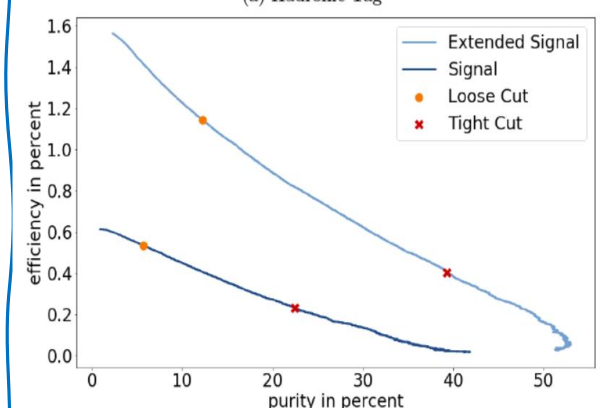


Tight FEI output cut (σ > 0.1)





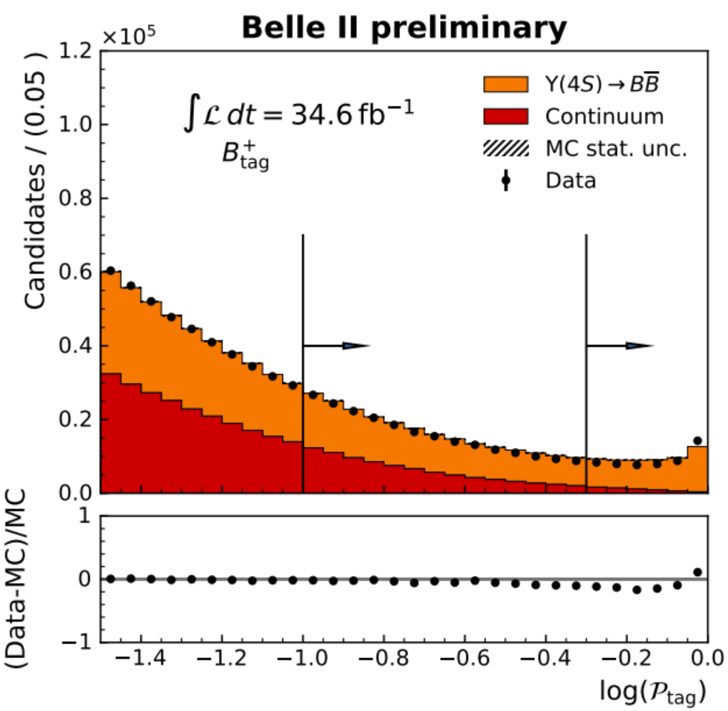
(a) Hadronic Tag



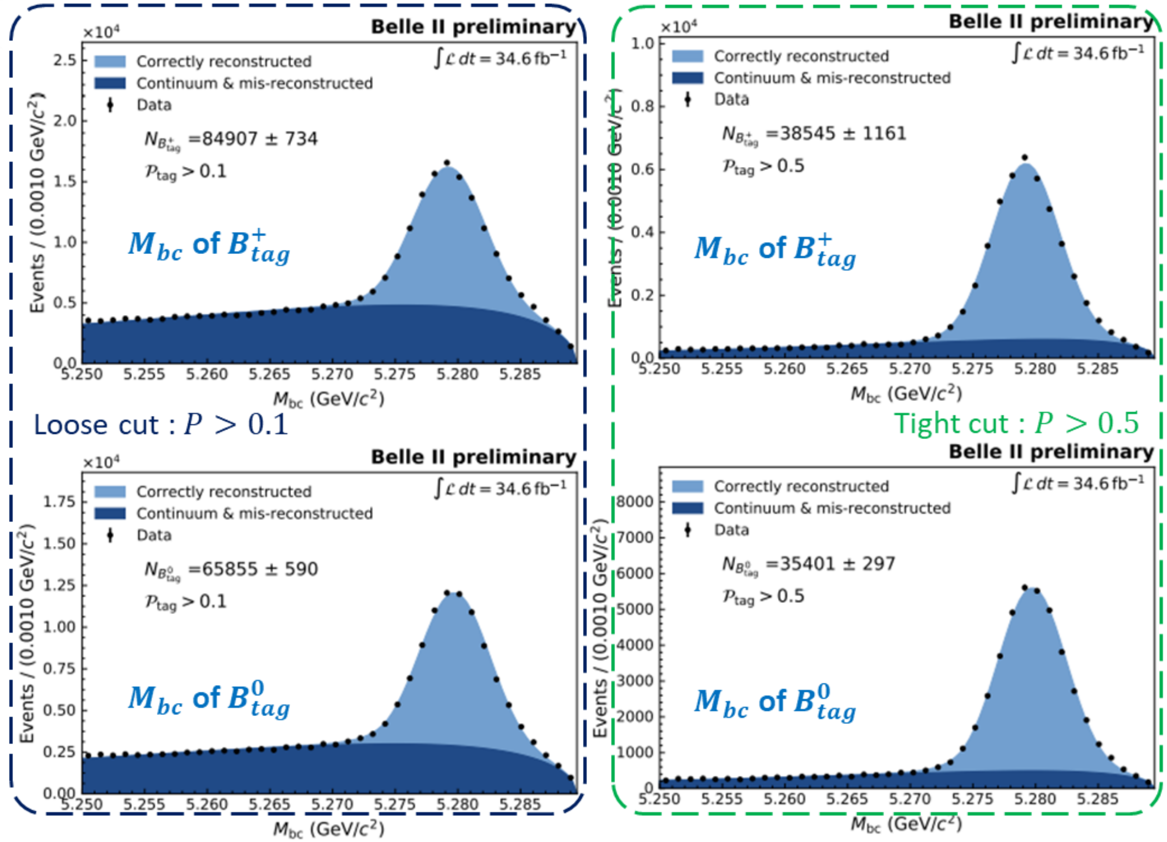
(b) Semileptonic Tag

Application : Hadronic FEI Performance ($B \to X\ell\nu$)

- Used data & MC samples : 34.6 fb^{-1} data, samples of 100 fb^{-1} generic BB decay and 100 fb^{-1} generic qq decay



Probability of FEI with B^+_{tag}

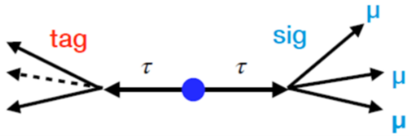


Distribution of M_{bc}

$\tau^+ \to \mu^+\mu^-\mu^+$

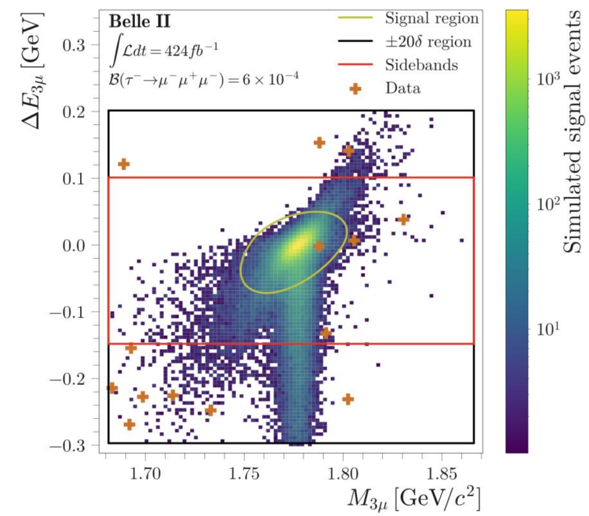
424 fb^{-1} of Belle II $\tau^+\tau^-$ data

- Two hemispheres
  - For τ_{sig} and τ_{tag}
  - Separated by a plane $\hat{\boldsymbol{n}}_T$ (thrust axis), maximizing T

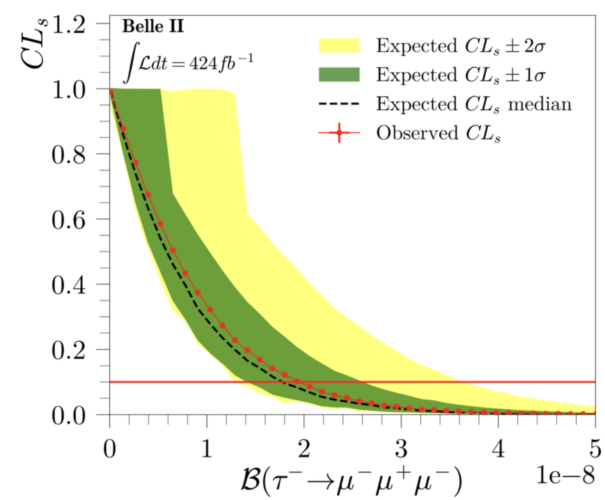


$$T = \max_{\hat{\mathbf{n}}_T} \left(\frac{\sum_i |\mathbf{p}^*{}_i \cdot \hat{\mathbf{n}}_T|}{\sum_i |\mathbf{p}^*{}_i|} \right)$$

- Inclusive tagging
  - Allow 3×1 and 1×1 (measure all the neutrals, too)
  - Signal optimization and background rejection by BDT
  - 2D analysis of $M_{3\mu} = \sqrt{E_{3\mu}^2 - P_{3\mu}^2}$ and $\Delta E_{3\mu} = E_{3\mu}^{CM} - E_{beam}^{CM}$



- Result
  - $\mathcal{B}(\tau^+ \to \mu^+\mu^-\mu^+) = \left(2.1^{+5.1}_{-2.4} \pm 0.4\right) \times 10^{-9}$
    - Dominant systematic uncertainties from momentum scale (16%), signal region ($^{+2.9}_{-3.9}$%)
- UL estimated with CLs method (modified frequentist in RooStat)
  - Observed (expected) limit: $\mathcal{B} < 1.9\ (1.8) \times 10^{-8}$
    - Most stringent to date



BELLE JHEP 02 (2024) 187

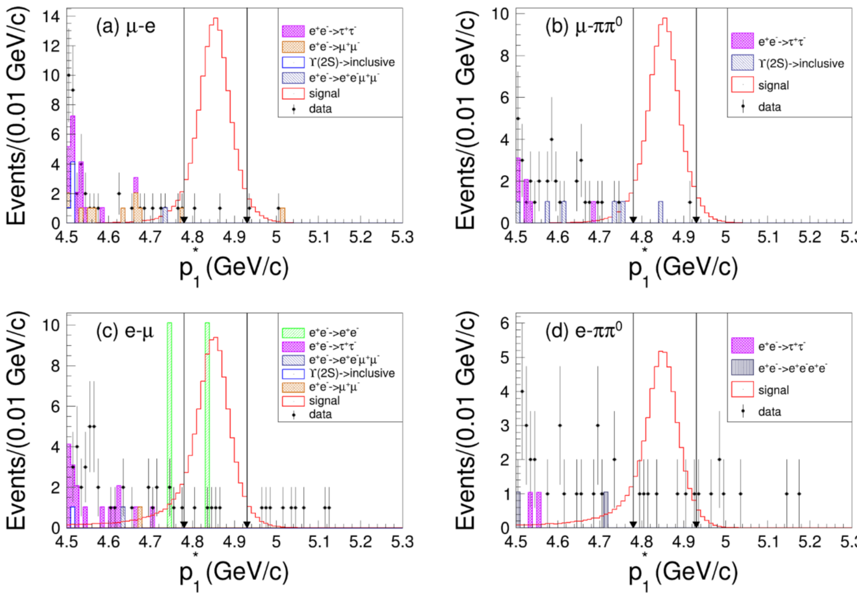
$\Upsilon(2S) \to \ell^{\pm}\tau^{\mp}$ 25 fb^{-1} of Belle data @ $\Upsilon(2S)$

Motivations

- 2-body CLFV decay of a quarkonium
- Can provide complementary constraints on the Wilson coefficients of the $\mathcal{L}_{\text{eff}}$ of new physics models (D. E. Hazard and A. A. Petrov, PRD 94 (2016) 074023)

Analysis features

- Belle data analysis in Belle II analysis framework
- High-momentum primary lepton ℓ_1 from $\Upsilon(2S) \to \ell_1^{\pm}\tau^{\mp}$
- Use τ^+ decays to $\ell_2^+\nu\bar{\nu}$ or $\pi^+\bar{\nu}$
- ℓ_2 to have different flavor w.r.t. ℓ_1, to suppress copious background from Bhabha processes
- FastBDT for further background suppression



$$\mathcal{B}(\Upsilon(2S) \to \mu\tau) < 0.23 \times 10^{-6}$$
$$\mathcal{B}(\Upsilon(2S) \to e\tau) < 1.12 \times 10^{-6}$$

@ 90% CL

Belle (this) results are 14 (3) times more stringent than BaBar (PRL, 2010)