



Belle II

Pedro Luis Manuel Podesta Lerma
Universidad Autonoma de Sinaloa

Outline

- *SuperKEK and Belle II*
- *Luminosity*
- *Motivation for Tau studies*
- *Physics studies*
 - $\tau \rightarrow \mu K \gamma$
 - $\tau \rightarrow lll$
 - $\tau \rightarrow K_s(\pi^+\pi^-) l(e^\pm\mu^\pm)$
 - $\tau^- \rightarrow \pi^- K_s \nu_\tau$
- *The LABM*

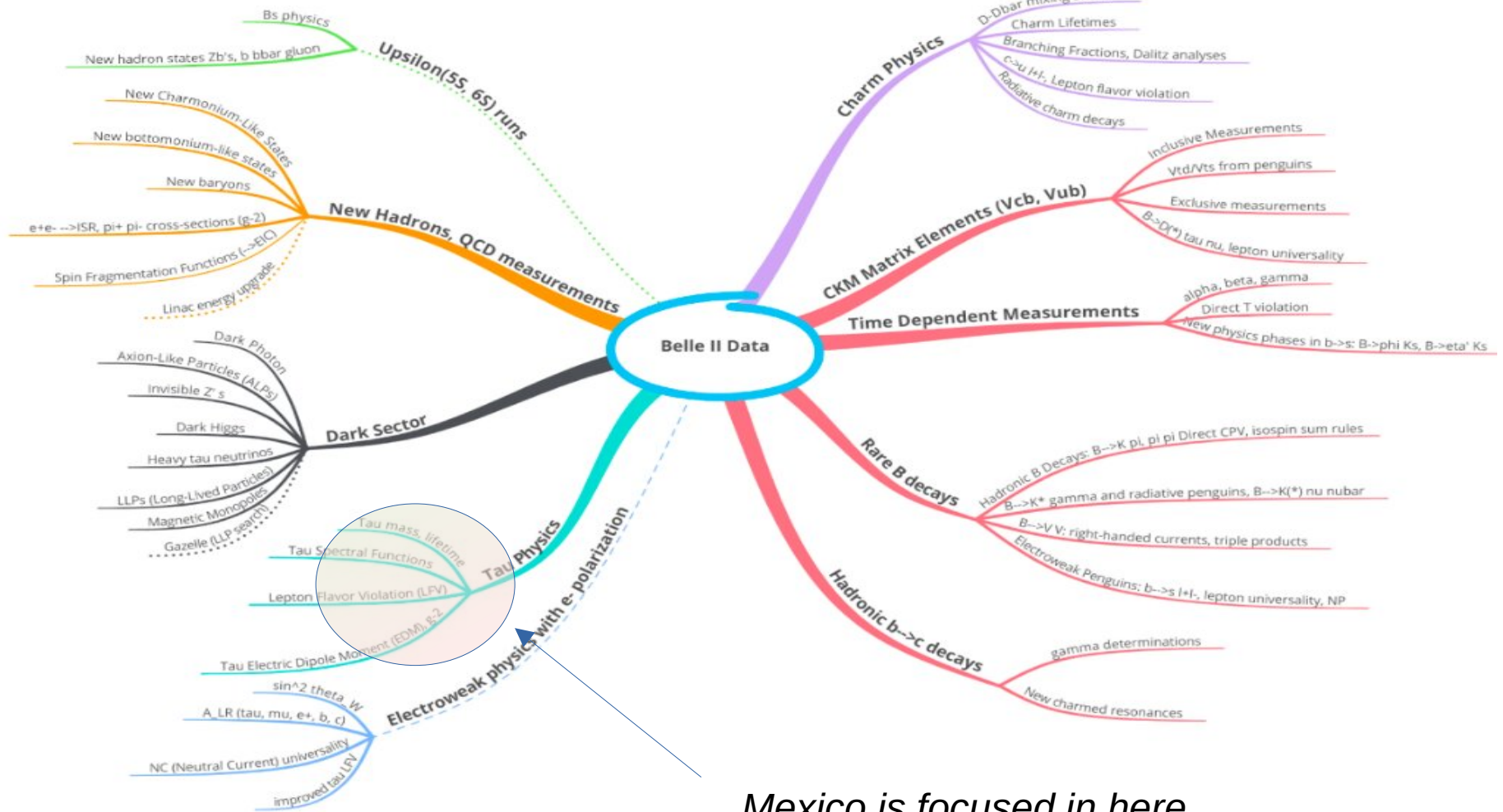
Belle II Collaboration



26 countries , 123 institutions, ~1100 collaborators

Armenia (1), Australia (3), Austria (1), Canada (5), China (12), Czechia (1), France (3), Germany (12), India (9), Israel (1), Italy (9), Japan (16), Malaysia (1), **Mexico (3)(UAS-UNAM-CINVESTAV)**, Poland (1), Russia(6), Saudi Arabia(1), Slovenia(2), South Korea(9), Spain(1), Taiwan(3), Thailand(2), Turkey(1), USA (18), Ukraine (1), Viet Nam(1).

Physics from Belle II



Mexico is focused in here.

Plenty of New and Old Physics

From KEKB to SuperKEKB

Instantaneous Target Luminosity: $L = 6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$

Achieved Luminosity (world record): $L = 4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Target (Achieved)

e^+ 4GeV 3.6 A (~2.0 A)

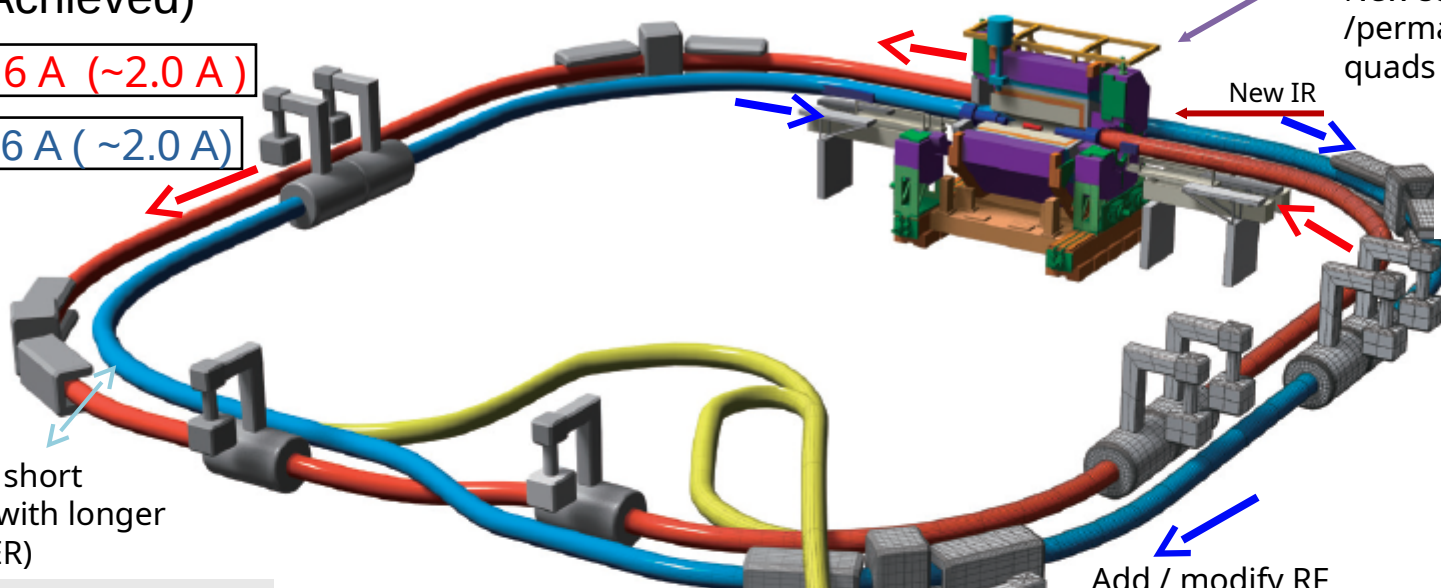
e^- 7GeV 2.6 A (~2.0 A)

Belle II

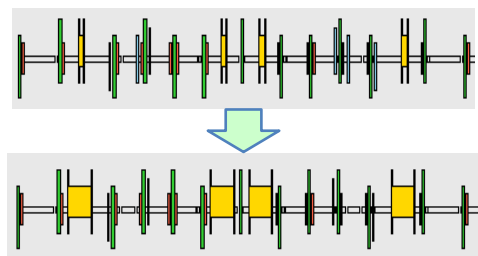
New superconducting / permanent final focusing quads near the IP

New IR

Colliding bunches



Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance



TiN-coated beam pipe with antechambers

Damping ring

Low emittance positrons to inject

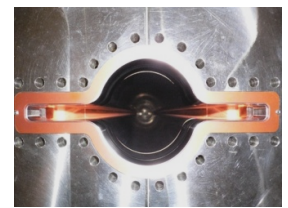
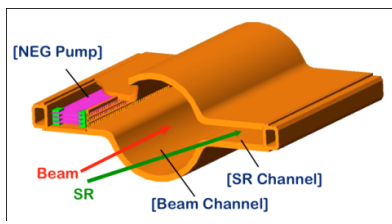
Add / modify RF systems for higher beam current

Positron source
New positron target / capture section

Low emittance gun

Low emittance electrons to inject

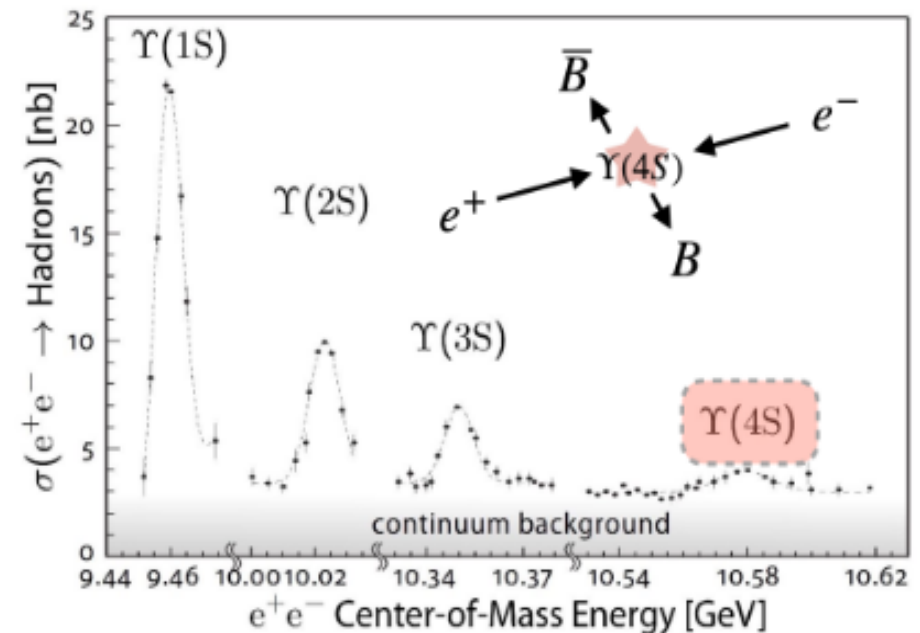
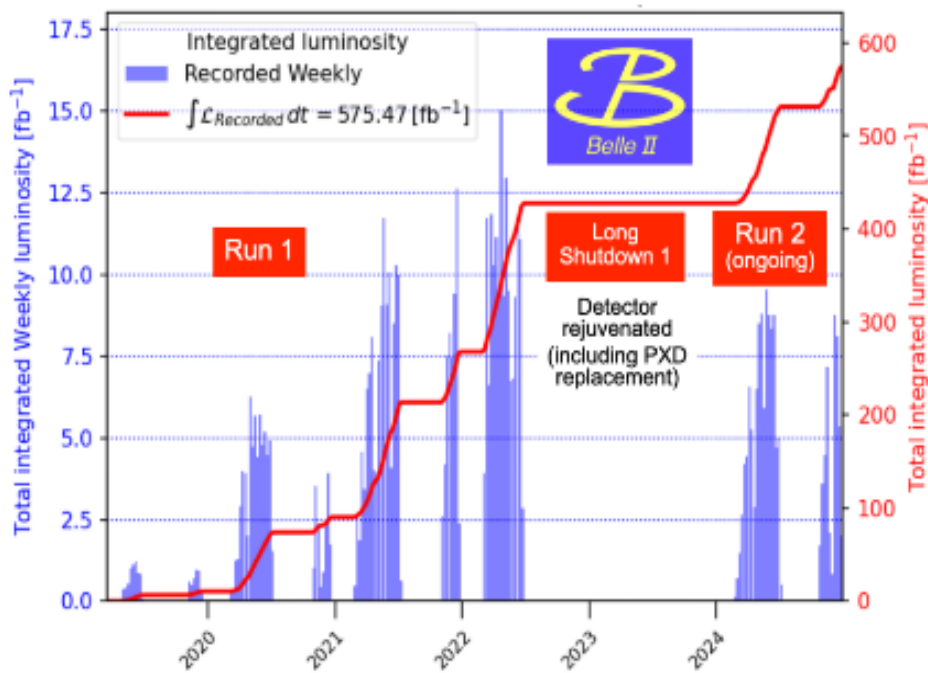
$$L = \frac{\gamma_{\pm}}{2e r_e} \left(1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \frac{I_{\pm} \xi_{\pm y}}{\beta_y^*} \left(\frac{R_L}{R_y} \right)$$



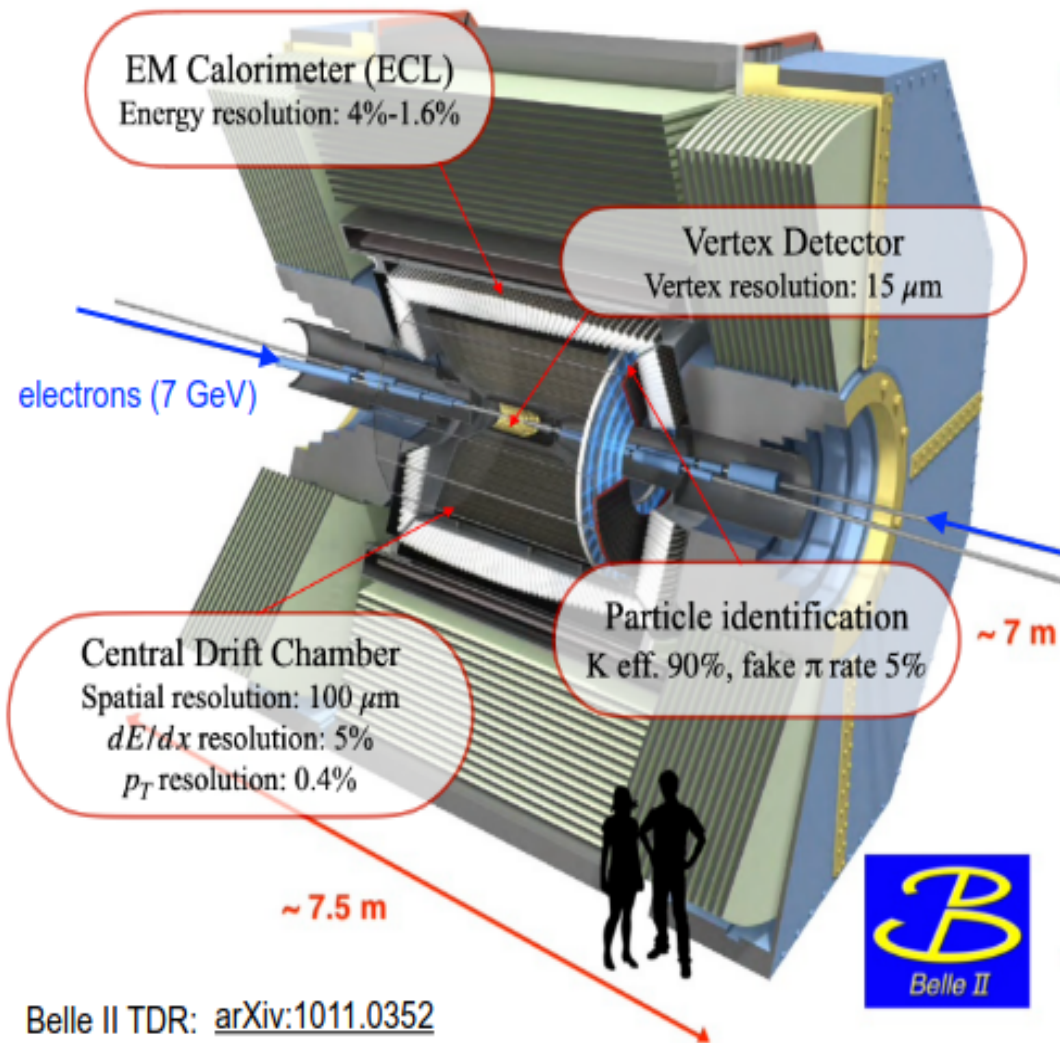
Luminosity from Belle II

- Belle from 1999 - 2010: 1 ab^{-1}
- Belle II from 2019 - now: 862 fb^{-1}
 - ▶ Peak instantaneous luminosity world record ($5.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)
 - ▶ Run 2 is ongoing. Resuming data-taking in November.
 - ▶ Aiming to collect 50 ab^{-1} over next ~ 10 years.

	Integrated luminosity	
	Belle	Belle II
Y(4S)	711 fb^{-1}	757 fb^{-1}
Y(nS)	155 fb^{-1}	19 fb^{-1}
Off resonance	90 fb^{-1}	59 fb^{-1}



Belle II Detector



Belle II TDR: [arXiv:1011.0352](https://arxiv.org/abs/1011.0352)

- High resolution (momentum, vertex) hermetic detectors.
- Efficient reconstruction of neutrals (γ , π^0 , η) and excellent PID capabilities.
- Well-known initial state condition.
Clean environment & low backgrounds.

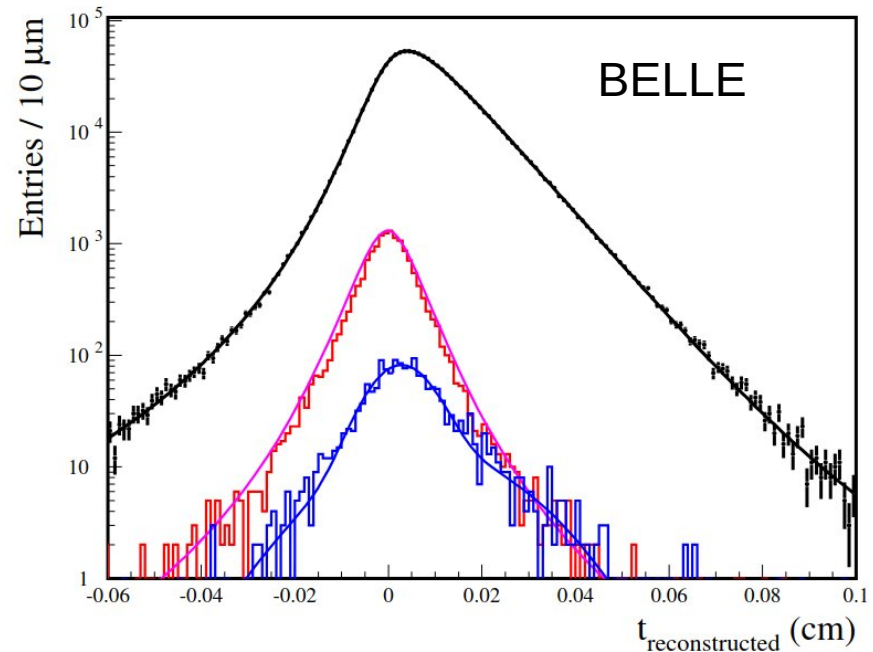
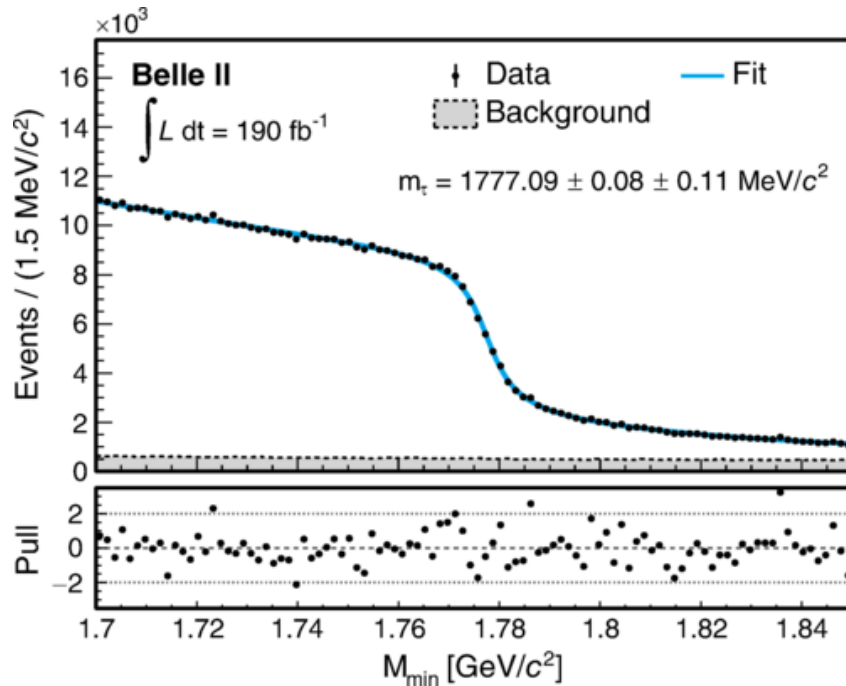
• Belle \rightarrow Belle II detector

- ▶ 2-layer Pixel Detector (PXD) with first layer at 1.4cm, significantly improves vertexing.
- ▶ 4-layer Silicon Vertex Detector (SVD) with larger acceptance.
- ▶ Central Drift Chamber (CDC) with larger outer radius.
- ▶ Improved particle ID: TOP + new ARICH (K/ π separation).
- ▶ Improved trigger, and faster electronics in general.

Why Taus ?

The heaviest lepton in the standard model
The only one who can hadronize.

The most precise measurement is from Belle II



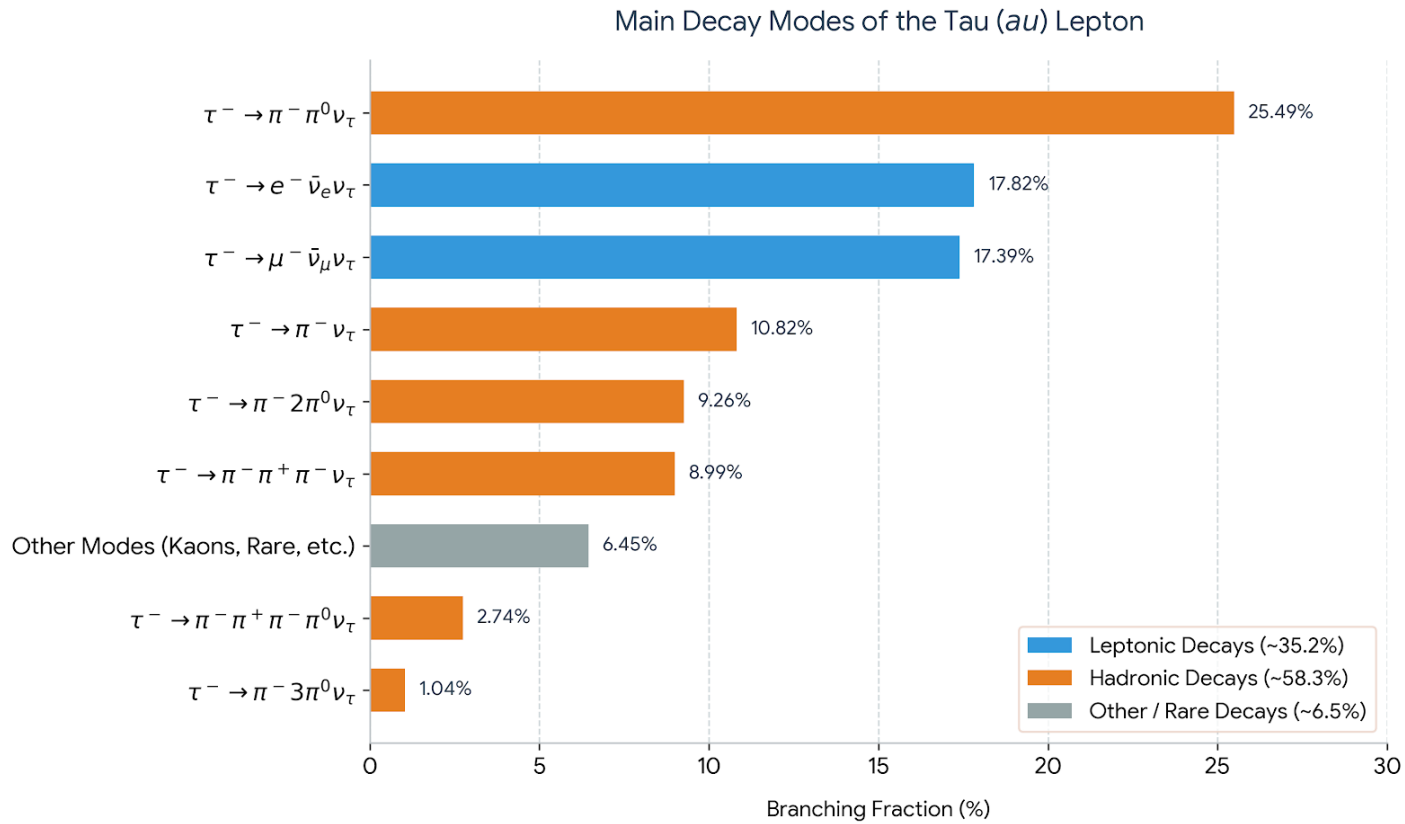
$$\tau = (290.17 \pm 0.53(\text{stat.}) \pm 0.33(\text{syst.})) \cdot 10^{-15} \text{ s.}$$

Belle II, PRD 108, 032006 (2023)] (Analysis Leader Michelle Villanueva Convestav)

Tau lifetime: [Belle, PRL 112, 031801 (2014)]

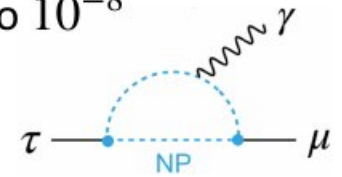
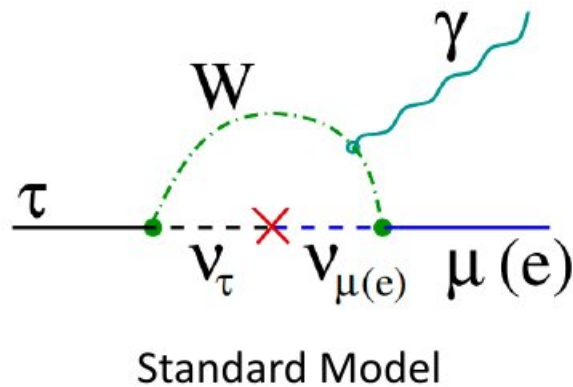
In what do Taus decay

252 Modes up to now



Some BSM predict LFV in Taus

- The lepton-flavor-violating (LFV) τ decays are extremely small in SM, $\mathcal{B}(\tau \rightarrow \ell \nu) \sim \left(\frac{\Delta m_\nu^2}{m_W^2}\right) < 10^{-54}$
- Many models beyond the SM predict LFV decays with branching fractions up to 10^{-8}



Channel	$\mathcal{O}(\mathcal{B}_{\text{pred}})$	Model
$\tau^- \rightarrow \mu^- \gamma$	10^{-10}	SUSY Higgs [1]
	10^{-10}	Littlest Higgs [2]
	10^{-9}	SM + seesaw [3]
	10^{-9}	Non-universal Z' [4]
	10^{-8}	SUSY SO(10) [5]
$\tau^- \rightarrow \ell \eta$	10^{-8}	Littlest Higgs [6]
	10^{-8}	Leptoquark [7]
	10^{-8}	type-III seesaw [8]

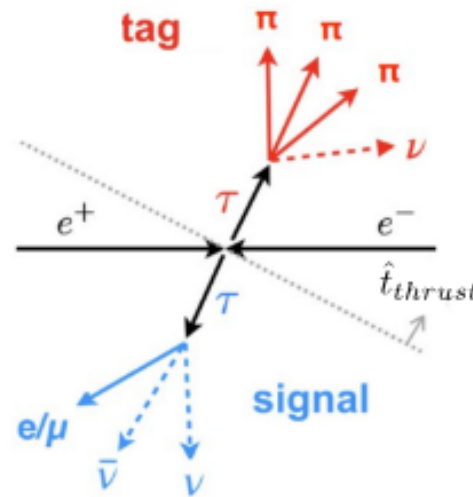
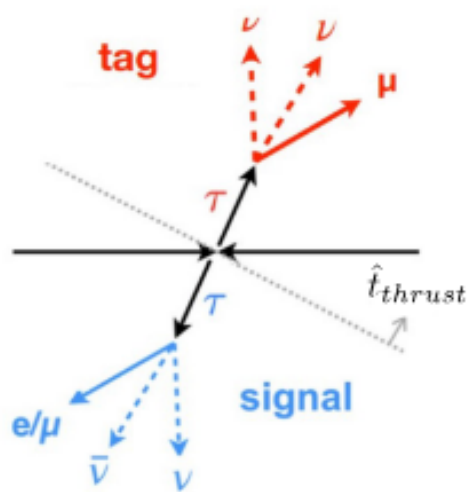
Taked From Yipu Lao PsiPhi2026

Taus in Belle II

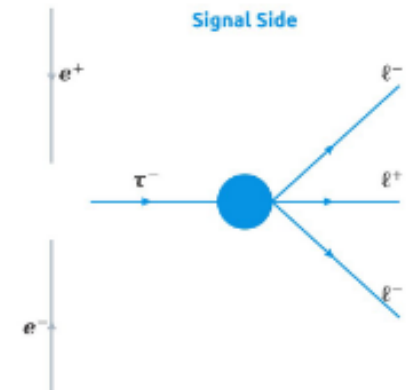
τ are produced in pairs in the $e^+e^- \rightarrow \tau^+\tau^-$ collisions, back-to-back and boosted in the c.m. !
 → We exploit this geometrical separation : define two hemispheres separated by a plane perpendicular to the thrust axis

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

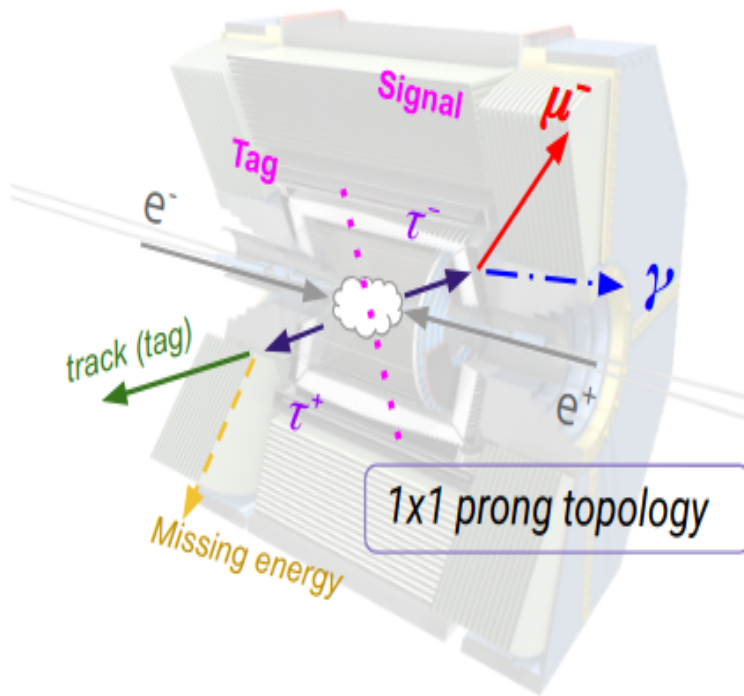
Reconstruct different topologies : 1x1, 3x1,
 and even **untagged!**



Rest Of Event



LFV: $\tau \rightarrow \mu\gamma$



Signal μ^-

Muon candidate

$$P_\mu = \frac{L_\mu}{L_e + L_\mu + L_\pi + L_K + L_p + L_d} > 0.95$$

High momentum magnitude $p_\mu > 1.0 \text{ GeV}/c$

Signal γ

Single photon candidate with
 $E_\gamma > 1.0 \text{ GeV}$

Tag

Single charged track.

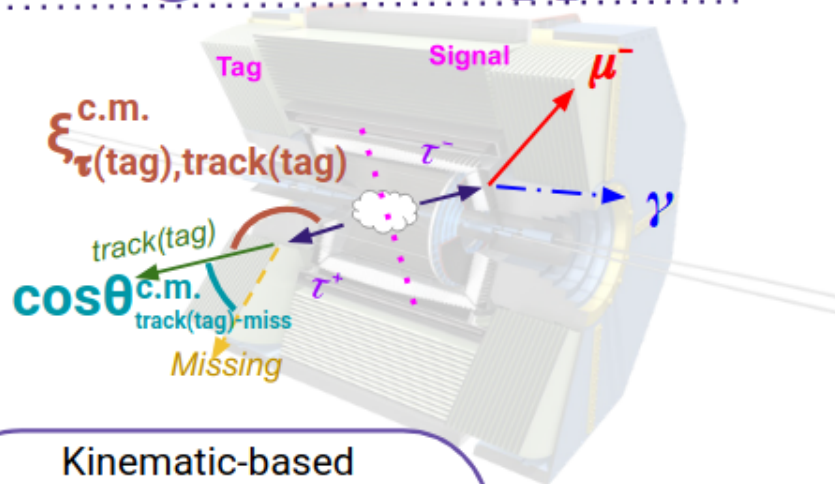
Muon veto $P_\mu < 0.1$

1 prong decays as:

$$\tau^+ \rightarrow \mu^+ \nu \nu, e^+ \nu \nu, \pi^+ \nu, \rho^+ \nu.$$

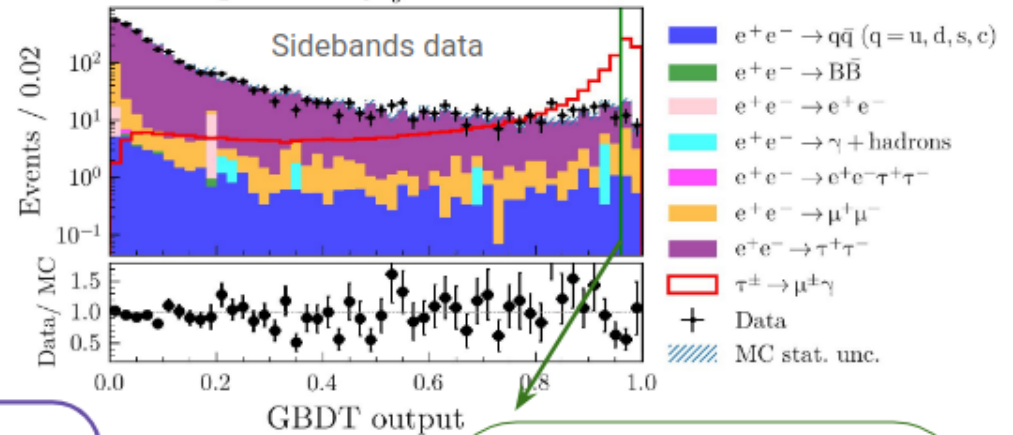
The background

Background Suppression



We train the GBDT(xGBoost) with main backgrounds $\tau\tau^+$ and $\mu\mu^+$.

Belle II preliminary $\int \mathcal{L} dt = 427.9 \text{ fb}^{-1}$



Kinematic-based

- $\xi_{\tau(\text{tag}), \text{track}(\text{tag})}^{\text{c.m.}}$ $\star \frac{\vec{p}_{\tau(\text{tag})} \cdot \vec{p}_{\text{track}(\text{tag})}}{|\vec{p}_{\tau(\text{tag})}| |\vec{p}_{\text{track}(\text{tag})}|}$
- $E_{\text{total}}^{\text{c.m.}} = E_{\mu}^{\text{c.m.}} + E_{\gamma}^{\text{c.m.}} + E_{\text{tag}}^{\text{c.m.}}$
- $|E_{\mu}^{\text{c.m.}} - E_{\gamma}^{\text{c.m.}}| / (E_{\mu}^{\text{c.m.}} + E_{\gamma}^{\text{c.m.}})$
 - $\cos \theta_{\text{track}(\text{tag})\text{-miss}}^{\text{c.m.}}$
 - E_{γ}
 - $\vec{p}_{\text{track}(\text{tag})}$

Event-based

- $M_{\nu}^2 = (E_{\mu\gamma}^{\text{c.m.}} - E_{\text{tag}}^{\text{c.m.}})^2 - (P_{\text{miss}}^{\text{c.m.}})^2$
- N_{γ}^{tag}
- $N_{\pi^0}^{\text{tag}}$
- V_{thrust}
- $|\vec{p}_{\text{miss}}|$

Cut-based

Multivariate classifier



The selection is optimized by maximizing:

$$FOM = \frac{\epsilon_{\text{sig}}}{\frac{1}{2}\epsilon + \sqrt{N_B}}$$

After the GBDT selection:
Signal reduction **50 %**.
Background suppression:

- \triangleright **99.8 % of $\tau\tau^+$**
- \triangleright **97.9 % of $\mu\mu^+(\gamma)$**
- \triangleright **98.7% of qq**
- \triangleright **$\sim 100\%$ others**

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Results

Events in Fit region

Expected events from sidebands data
 15.7 ± 3.4 , compared to 18 observed events.

Fit Result

Consistent with zero.

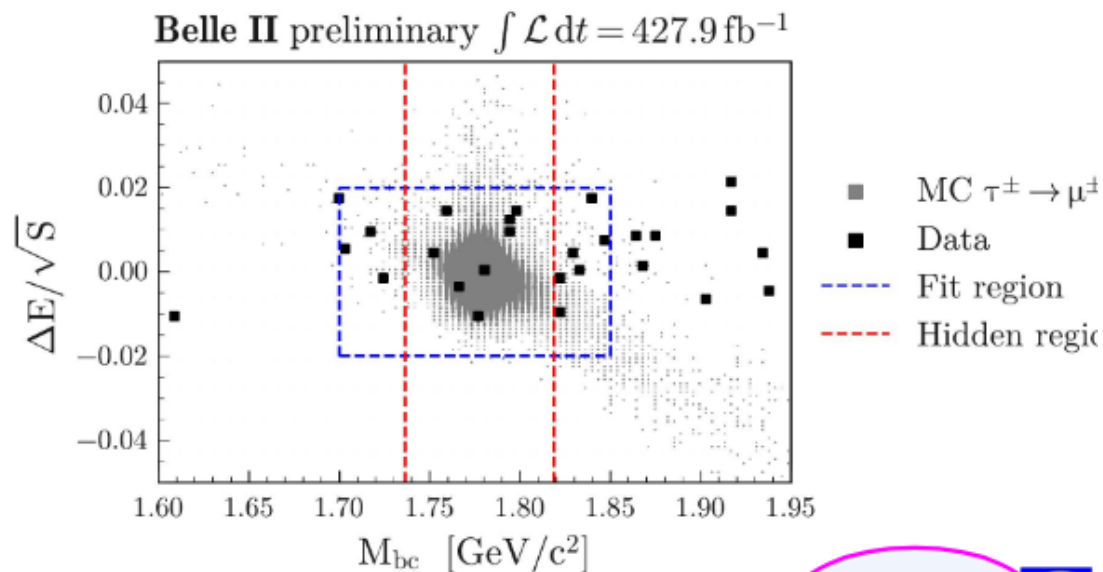
$$\mathcal{B}(\tau^- \rightarrow \mu^- \gamma) = (2.8^{+4.4}_{-2.6}) \times 10^{-8}$$

Equivalent to $\left\{ \begin{array}{l} \tilde{s} = 1.3^{+2.0}_{-1.2} \\ \tilde{b} = 16.7^{+4.6}_{-3.9} \end{array} \right.$

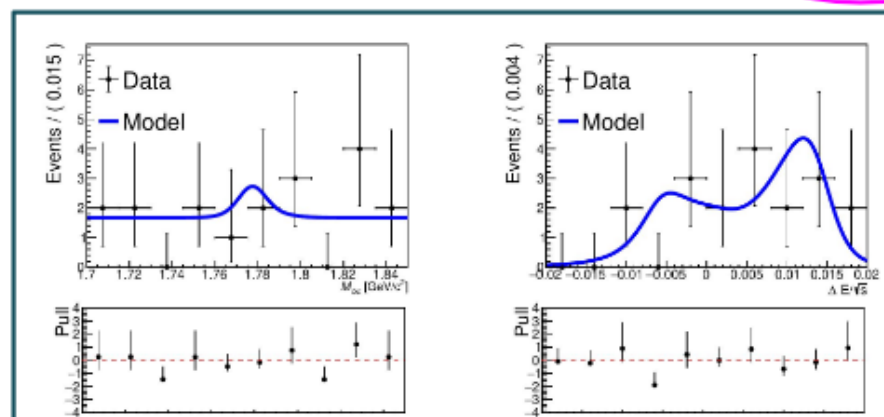
UL calculation

Using the CLs technique

$$\left. \begin{array}{l} \mathcal{B}(\tau^- \rightarrow \mu^- \gamma)^{\text{exp}} < 5.8 \times 10^{-8} \\ \mathcal{B}(\tau^- \rightarrow \mu^- \gamma)^{\text{obs}} < 9.5 \times 10^{-8} \end{array} \right\} \begin{array}{l} 427.9 \text{ fb}^{-1} \\ @ 90 \text{ C.L.} \end{array}$$



Large fit region



LFV: $\tau \rightarrow lll$

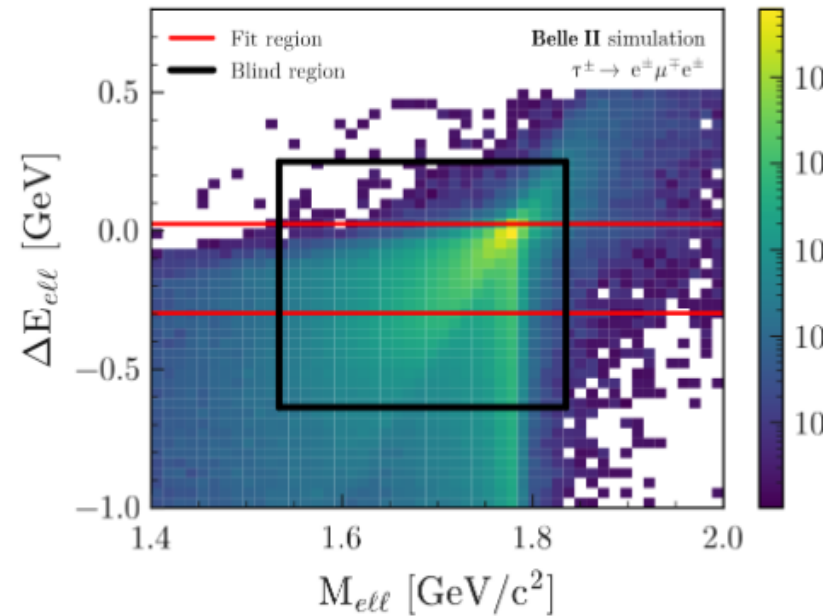
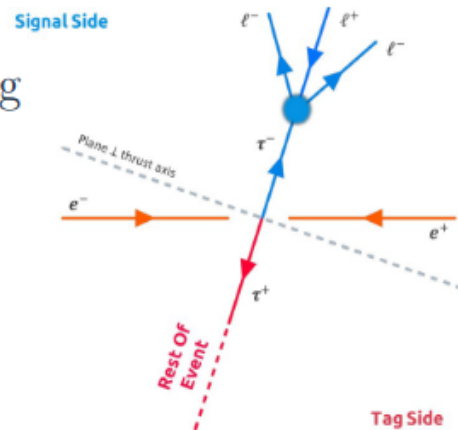
- Discovery potential not as high as $\mu \rightarrow e$ transition
- But can help to **differentiate** between the different models & the LFV operators
- Previous limit on the branching fractions $\mathcal{B}(\tau \rightarrow 3l)$ by Belle

using 782 fb^{-1}

Mode	Belle	Belle II	
$e^-e^+e^-$	2.7	-	$\times 10^{-8}$
$e^- \mu^+ \mu^-$	2.7	-	
$e^-e^+\mu^-$	1.8	-	
$e^+ \mu^- \mu^-$	1.7	-	
$\mu^+e^-e^-$	1.5	-	
$\mu^- \mu^+ \mu^-$	2.1	1.9	

Signal reconstructed from any combination of 3 leptons (e & μ)

Inclusive tagging: the other τ is not reconstructed & not limiting efficiency

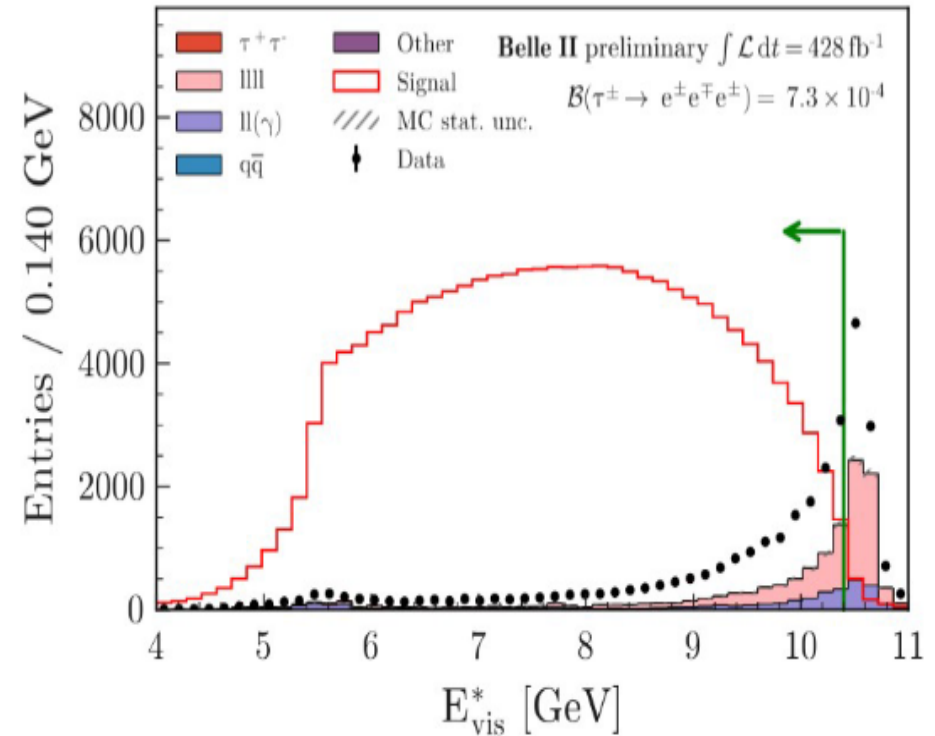
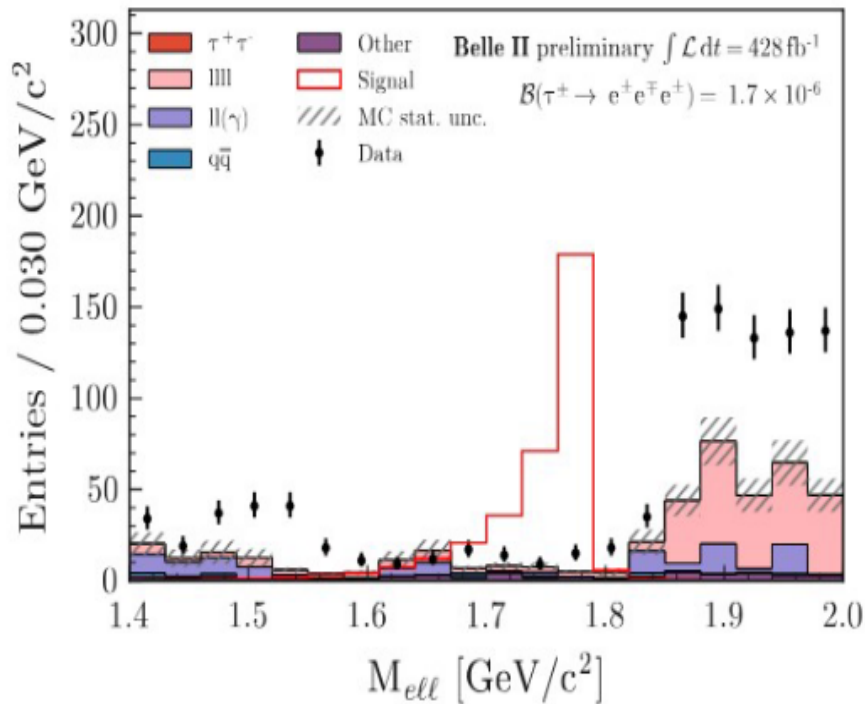


The background

Challenge: main background contribution from radiative low multiplicity processes
 $e^+e^- \rightarrow 2\ell(\gamma)$ & $e^+e^- \rightarrow 4\ell(\gamma)$

- Missing from the simulation and not far from the signal

- Veto on e^+e^- pairs from photon conversion and reject events with no missing energy



Results

- No excess observed across the 5 modes \rightarrow compute upper limits
- World's **leading upper limits** at 90% CL for 4 modes

	$\mathcal{B}_{obs}^{UL} \times 10^{-8}$	$\mathcal{B}_{Belle}^{UL} \times 10^{-8}$	ϵ_{sig}	ϵ_{Belle}
$e^-e^+e^-$	★ 2.5	2.7	15.0%	6.0%
$e^-e^+\mu^-$	★ 1.6	1.8	20.4%	9.3%
$e^-\mu^+e^-$	1.6	1.5	23.5%	11.5 %
$\mu^-\mu^+e^-$	★ 2.4	2.7	20.1%	6.1%
$\mu^-e^+\mu^-$	★ 1.3	1.5	24.1%	10.1%

@ 428 fb⁻¹
@ 782 fb⁻¹

- Improvement in signal efficiency thank to inclusive tagging

J. High Energ. Phys. 2025, 169 (2025)

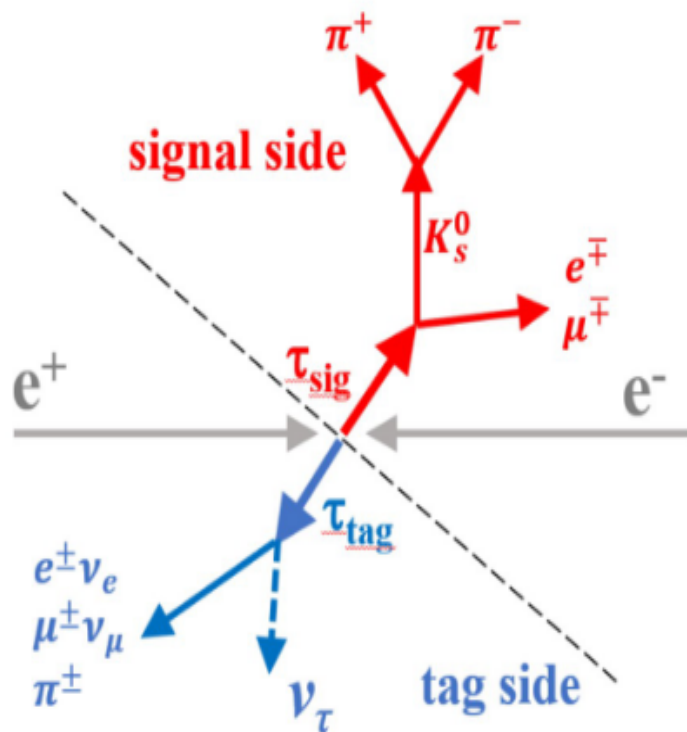
$$\tau \rightarrow K_s(\pi^+\pi^-) l(e^\pm\mu^\pm)$$

Reconstruct events with exactly 4 tracks
and 0 net charge

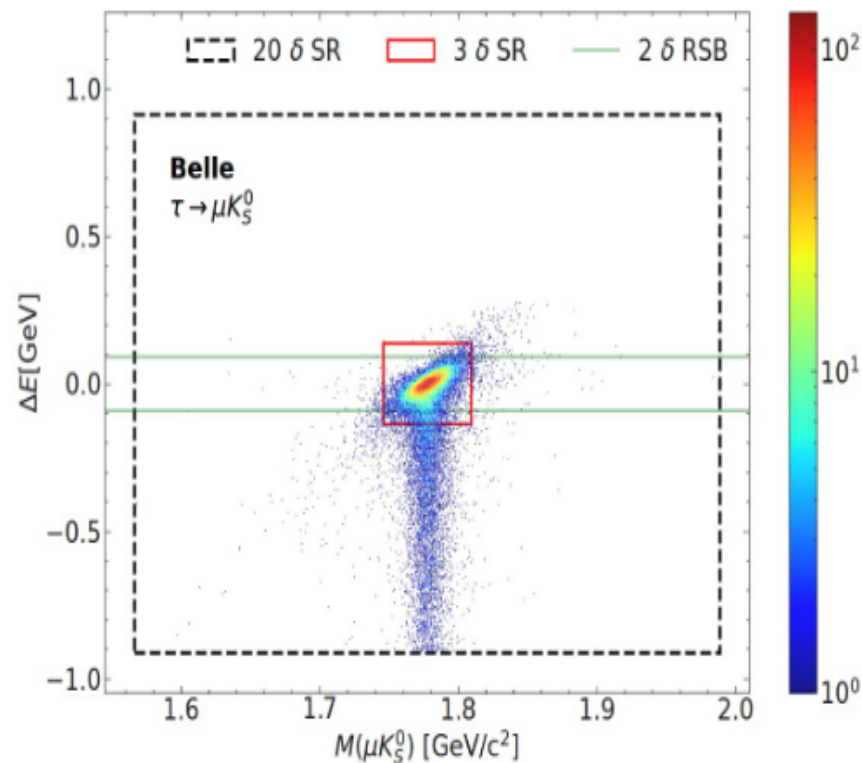
3x1 topology :

Signal side: 2 pions that form a K_s^0
and one lepton (e/μ)

Tag side : one charged particle $\rightarrow e, \pi$ or μ



- Use the $(M, \Delta E = E - E_{beam}/2)$ plane to define the search region
 \rightarrow signal peaks sharply in $(m_\tau, 0)$
- 1 workflow per mode & experiment



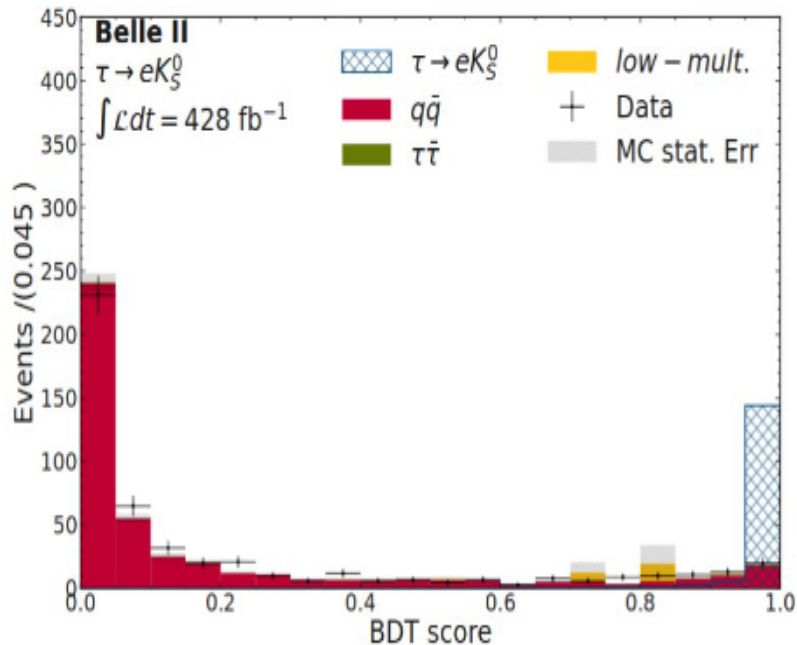
The background

Background suppression :

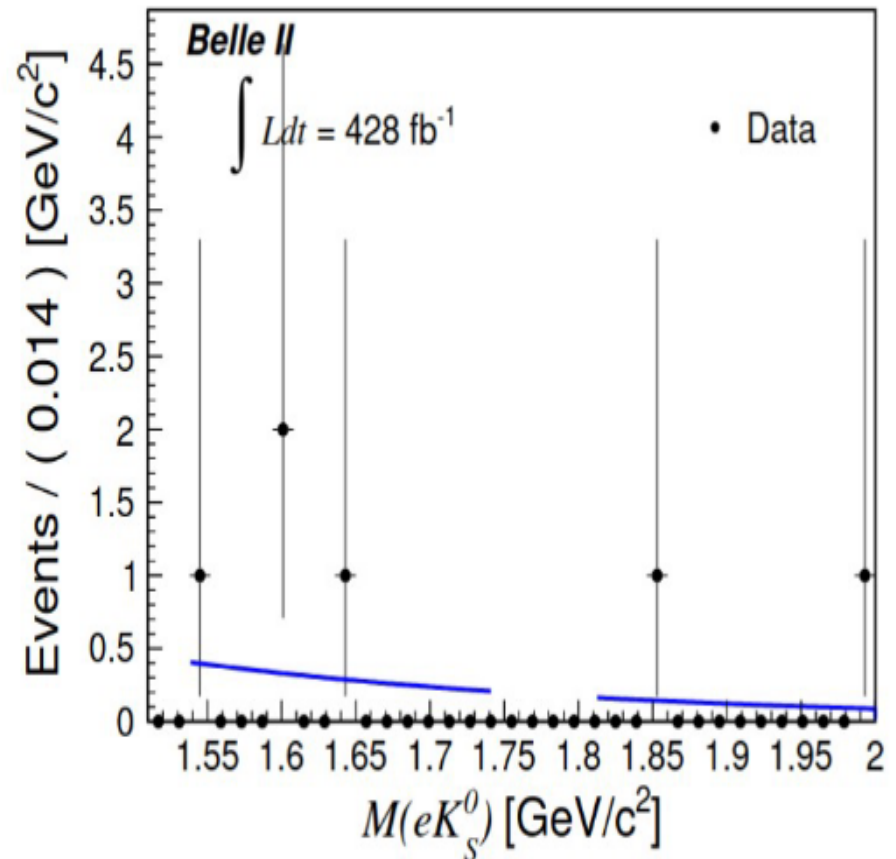
- Light quark pairs (udsc) continuum
- Low multiplicity $2\ell(\gamma), 4\ell(\gamma)$ ($\ell = e, \mu$)

Preselection + BDT (1 per mode/experiment) to suppress background

- Optimisation of the BDT cut depends on the tag



Remaining background is estimated from a fit in sidebands in $M_{\ell K_S}$ and integrated in the signal region



Results

10% signal selection **efficiency** &
~ 0.5 **background** events **expected**

- Cut and count method
- **No excess** observed in **elliptical** signal regions

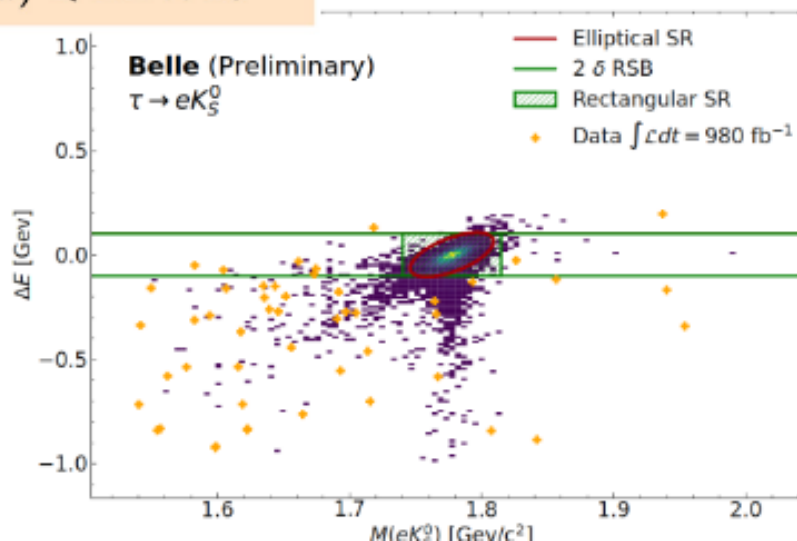
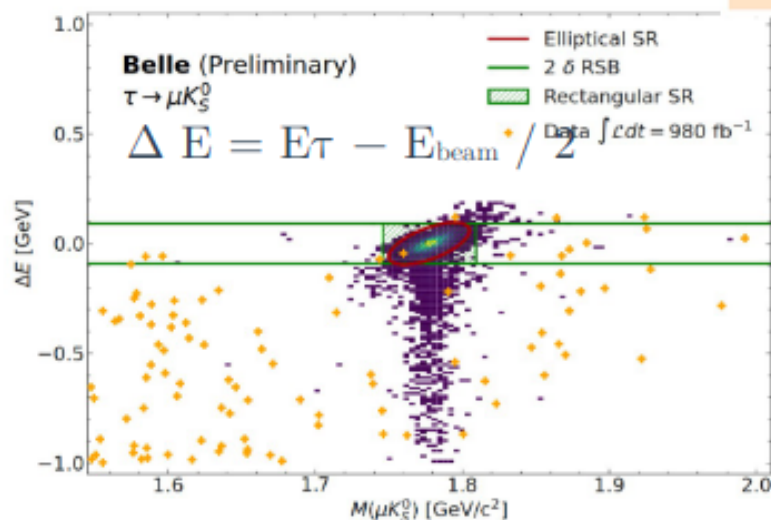
First τ LFV search with **combined** Belle & Belle II datasets (980 + 424 fb^{-1})

World most stringent limits at **90% CL**:

$$\mathcal{BR}(\tau \rightarrow K_S^0 e) < 0.8 \times 10^{-8}$$

[JHEP 08, 092 (2025)]

$$\mathcal{BR}(\tau \rightarrow K_S^0 \mu) < 1.2 \times 10^{-8}$$

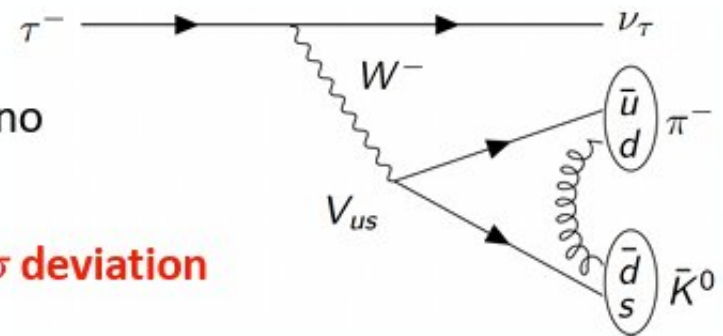


Search for CPV in $\tau^- \rightarrow \pi^- K_S^0 \nu_\tau$ decays at Belle II

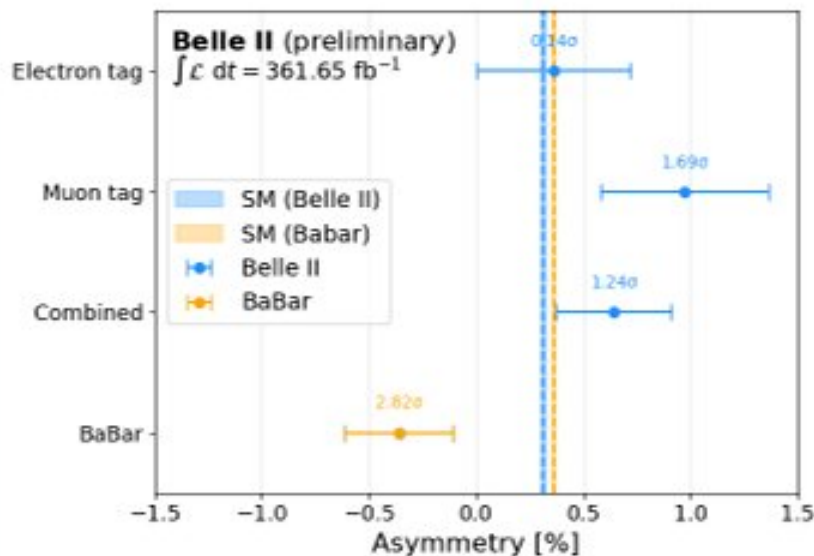
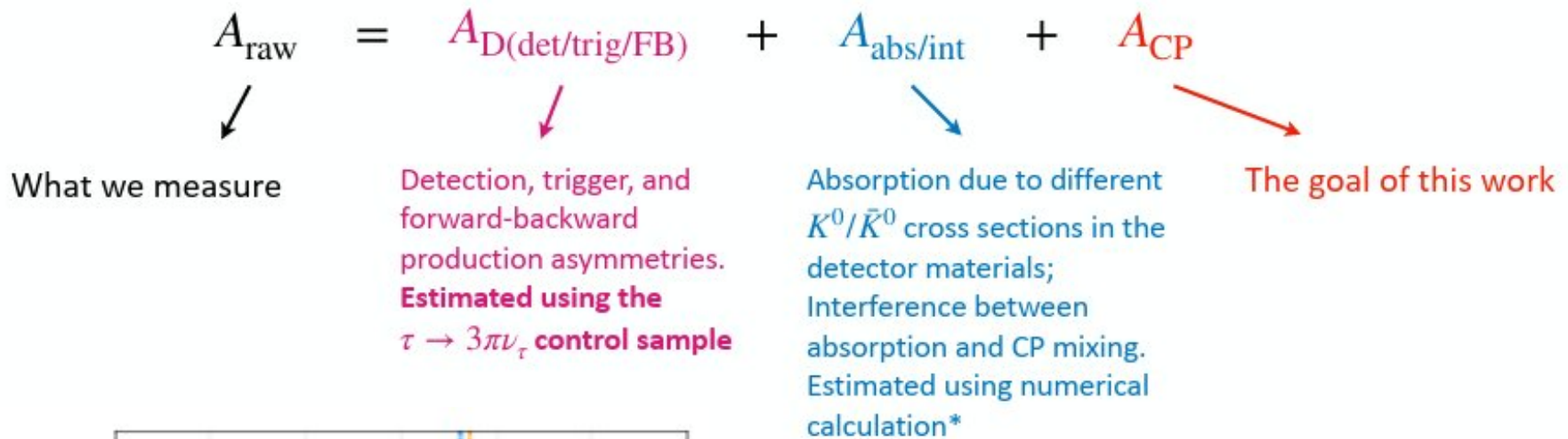
- Charge-Parity Violation (CPV) in τ decays **remains far less unexplored** compared to the K^0 , B , D , and baryon sectors
 - Sensitive probe for new CP-Violating phases
- Search for the direct CPV in the $\tau^- \rightarrow \pi^- K_S^0 \nu_\tau$ decays with known $K^0 - \bar{K}^0$ mixing

$$A_{CP} = \frac{\Gamma(\tau^+ \rightarrow \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \rightarrow \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \rightarrow \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \rightarrow \pi^- K_S^0 \nu_\tau)}$$

- The SM predicts $A_{CP}^{SM} \sim (0.33 \pm 0.01) \%$
- The Belle measured the A_{CP} using angular analysis, but no significant A_{CP}^{Belle} were reported: $|\text{Im}(\eta_s)| < 0.026$
- The BaBar result: $A_{CP}^{BaBar} = (-0.36 \pm 0.23 \pm 0.11) \%$, **2.8 σ deviation from SM expectation**



- (1x3)-prong topology: $\tau_{\text{sig}}^- \rightarrow \pi^- [K_S^0 \rightarrow \pi^+ \pi^-] \nu_\tau (\geq 0\pi^0)$ with $\tau_{\text{tag}}^+ \rightarrow \ell^+ \nu_\ell \bar{\nu}_\tau$
- Obtain >98% of signal purity using a two-step Boosted Decision Tree (BDT) method to suppress background (continuum and $\tau\tau$ events)
- Raw asymmetry in data (A_{raw}) corrected with different factors to get true A_{CP}

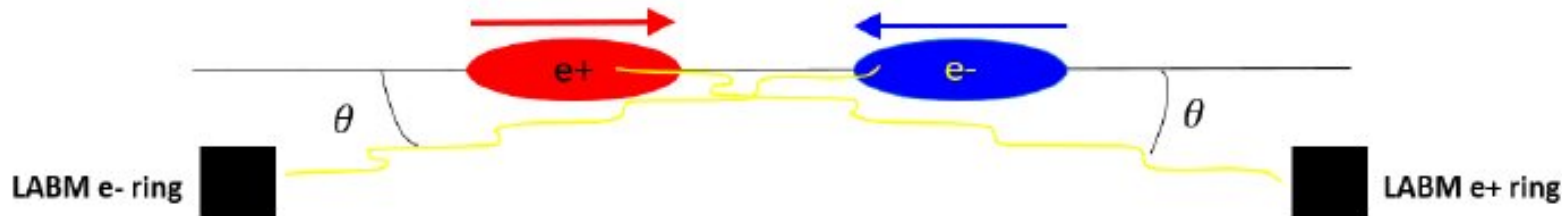


México participation

- We joined the LABM group
- Small group interested in an experimental beam monitor
- Good opportunity to do R&D

Collaboration between USA, JAPAN, Saudi Arabia and Mexico.

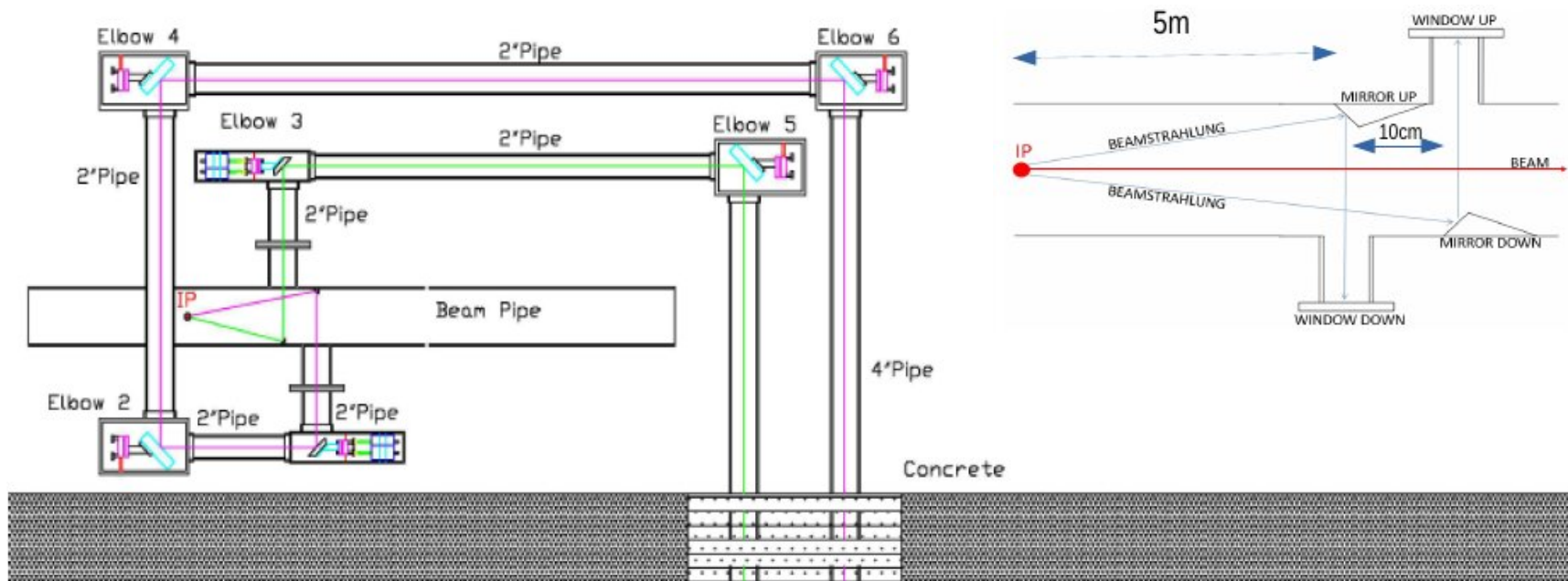
$$L = \frac{\gamma_{\pm}}{2er_e} \left(1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \frac{I_{\pm} \xi_{\pm y}}{\beta_y^*} \left(\frac{R_L}{R_y} \right)$$



Large Angle Beamstrahlung Monitor (LABM)

- Beamstrahlung light produced by the interaction of one beam and the electromagnetic field of the other.
- At large angle, Beamstrahlung is strongly polarized and contamination from synchrotron radiation is small
- Visible light (350-650 nm)
 - Easy to work
 - Fraction 10^{-11} (e-) to 10^{-12} (e+) of total Beamstrahlung energy emitted but enough for LABM

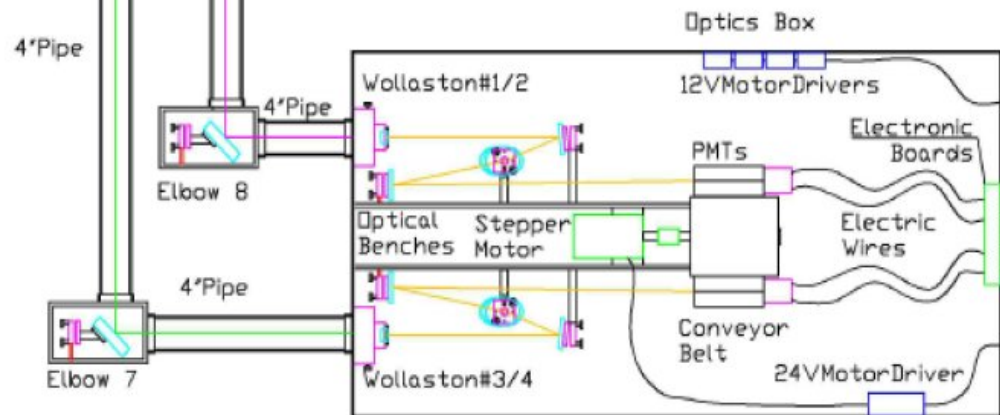
LABM diagram (2015)

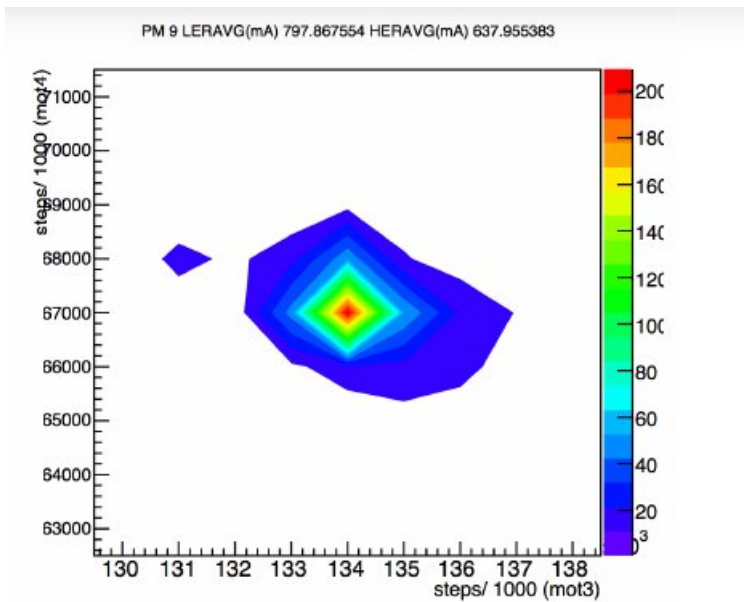


Four telescopes

Two for High Energy Ring e-
Two for Low Energy Ring e+

32 PMT





The good

- BEAMSL can be measured in superKEK

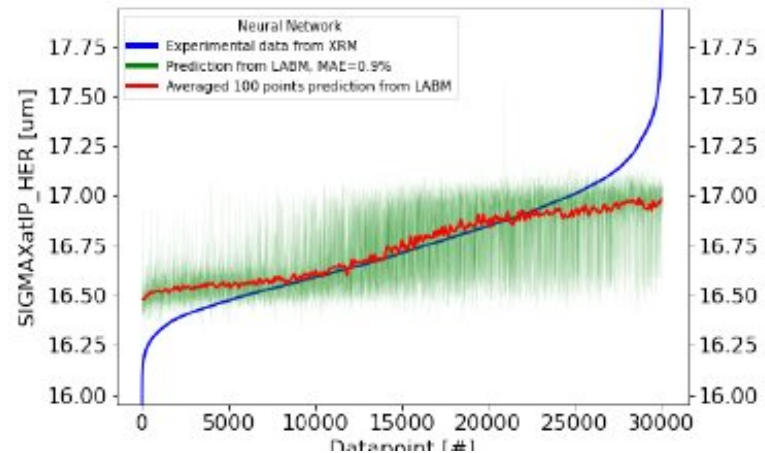
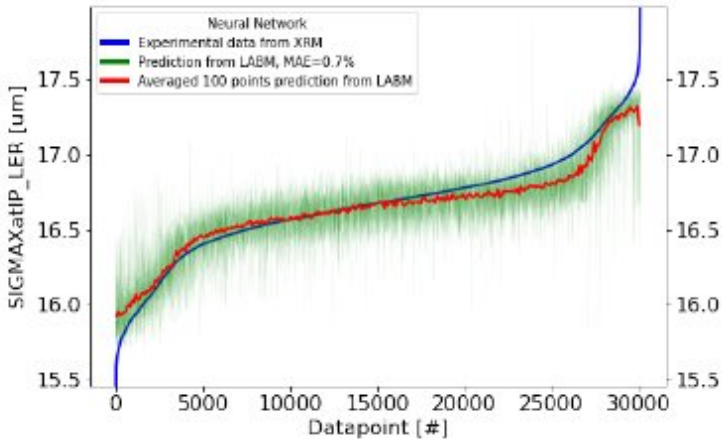
The Bad

- Took long time to do one plot

The ugly

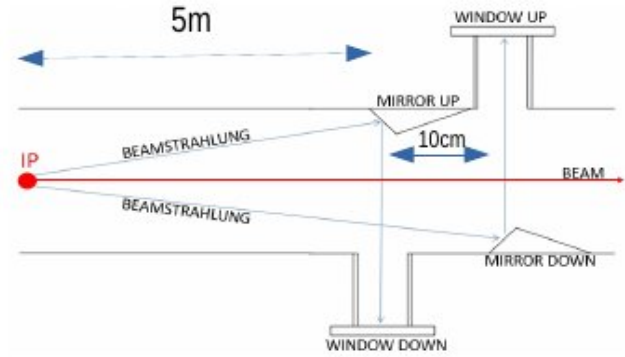
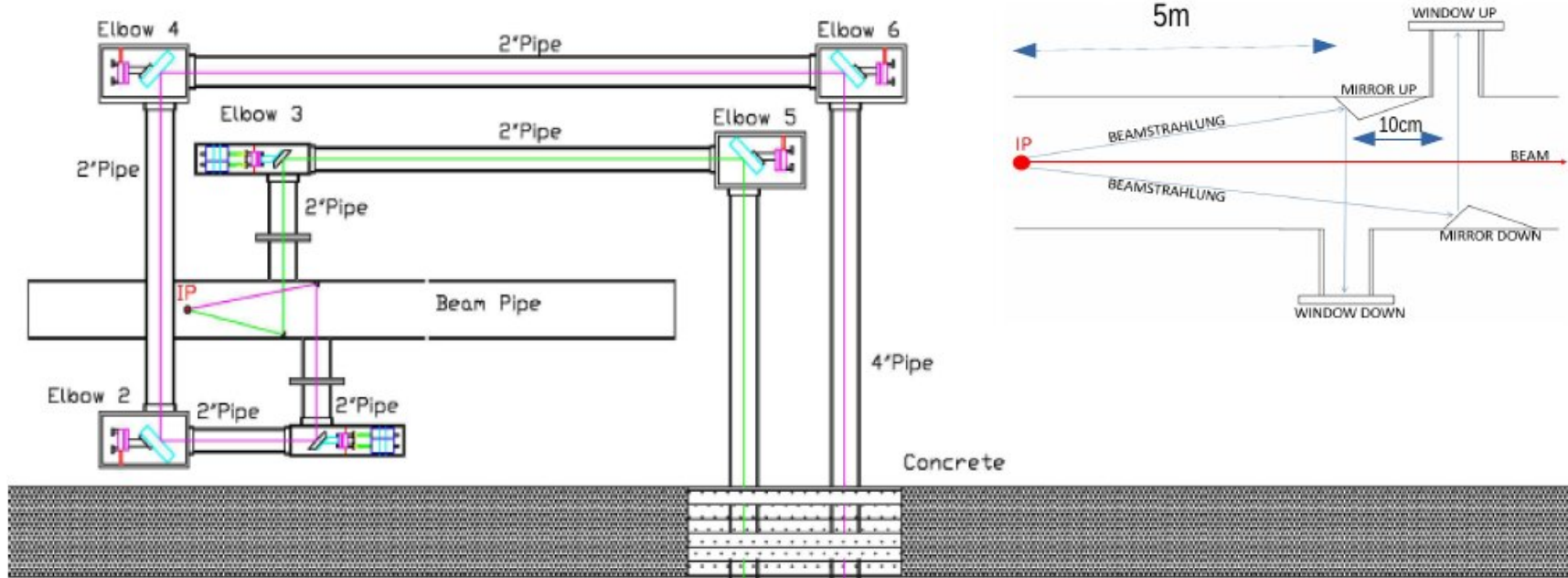
- The Beam dynamics and motor movement demands constant calibration

Several measurement around brightest area ,



Predicted values : Right LER (e+) , Left HER (e-)

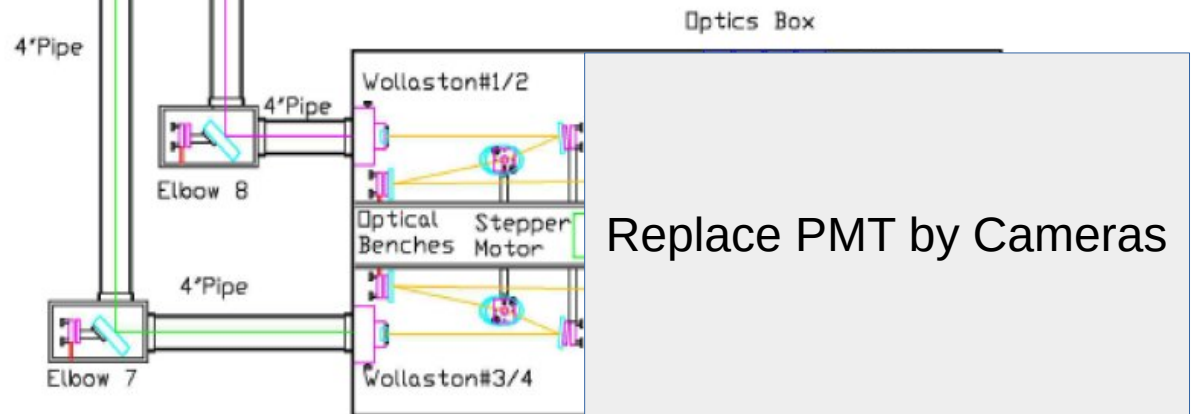
LABM diagram (2023)



Four telescopes

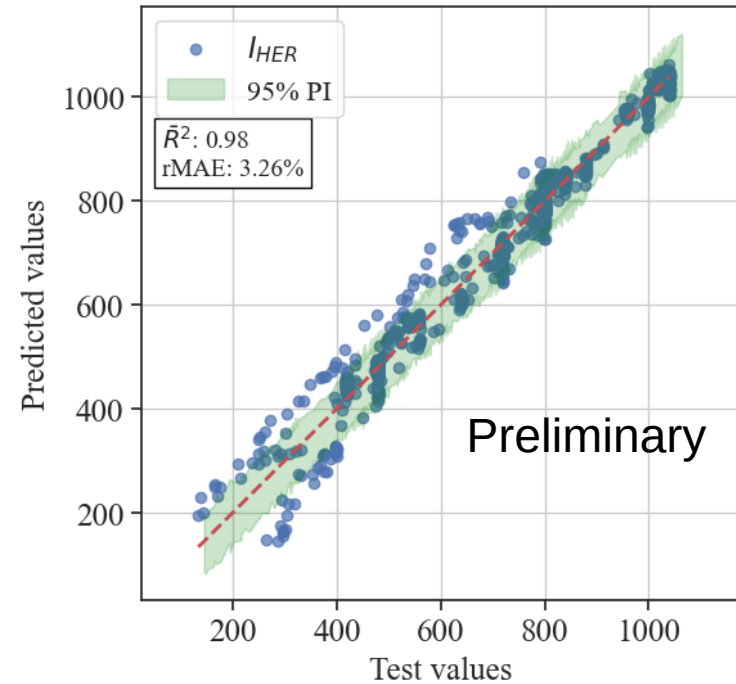
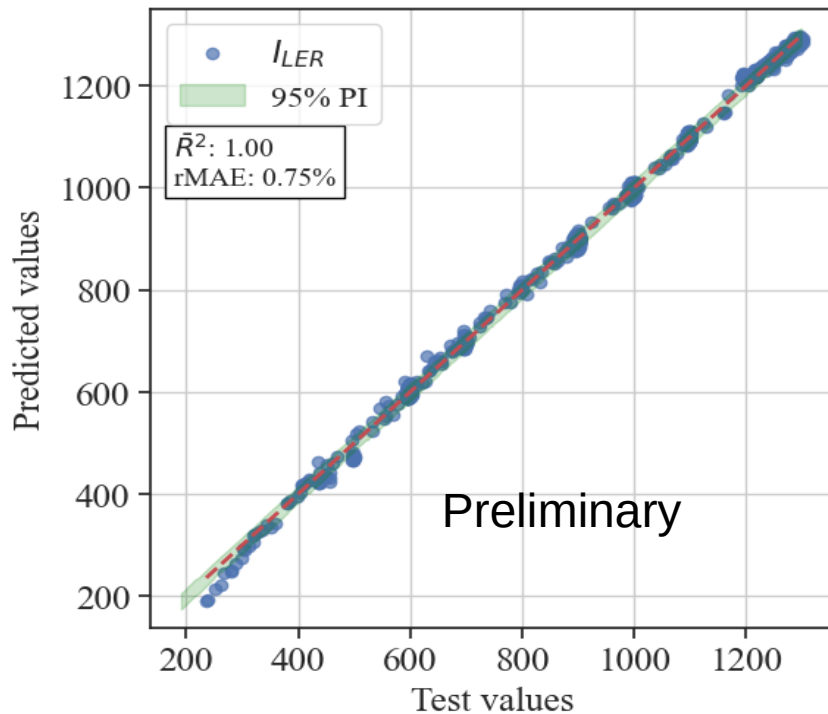
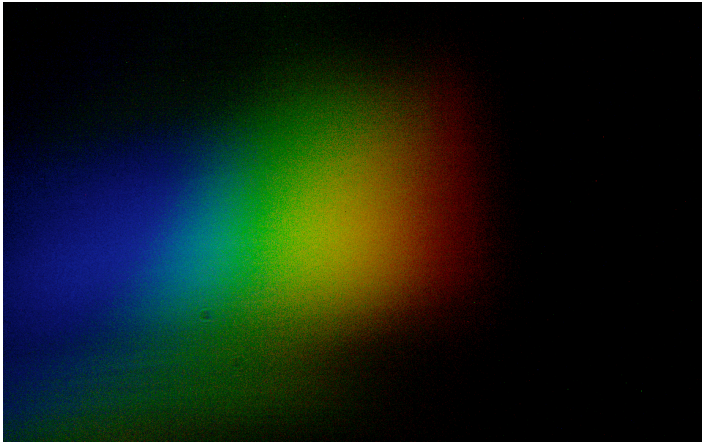
Two for High Energy Ring e-
Two for Low Energy Ring e+

32 PMT



Replace PMT by Cameras

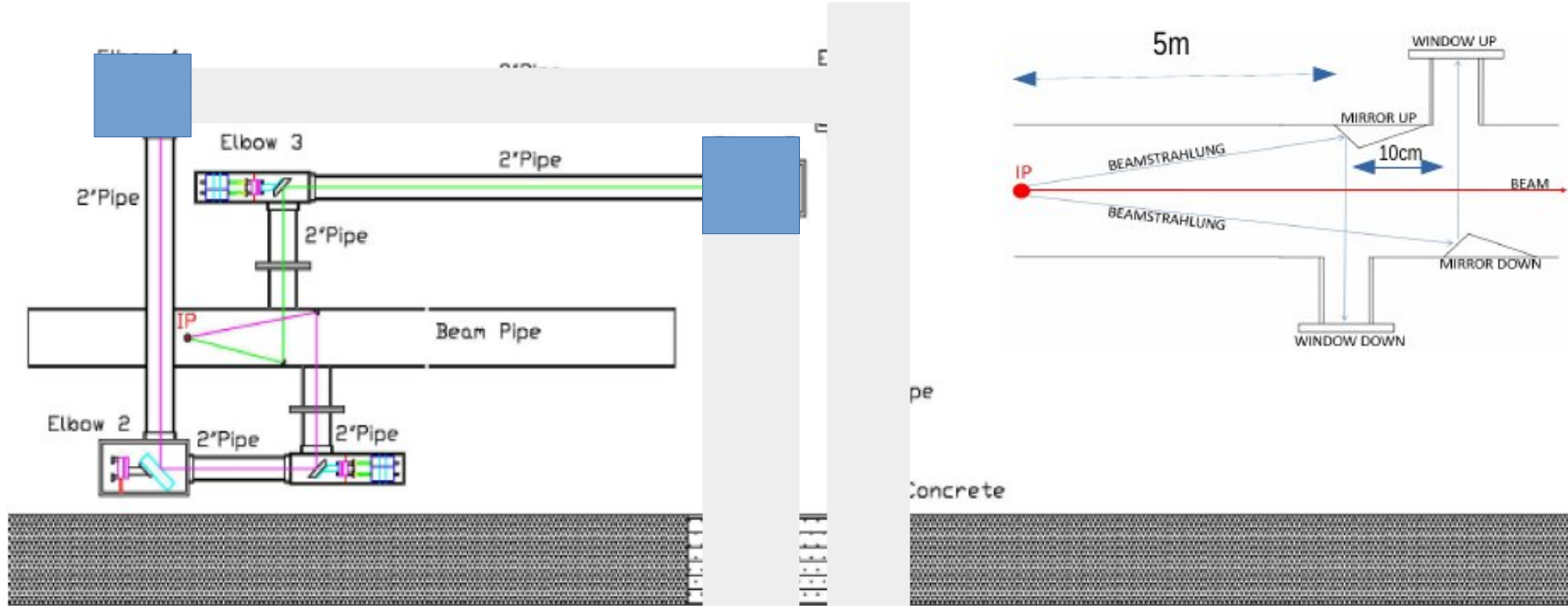
LABM Results (2024)



Top left : Real Image (7x brighter)
Top right: Predicted HER current
Bottom Left : Predicted LER current

Paper under LABM group Revision
Raymundo Bueno (UAS) Thesis

LABM diagram (2025)

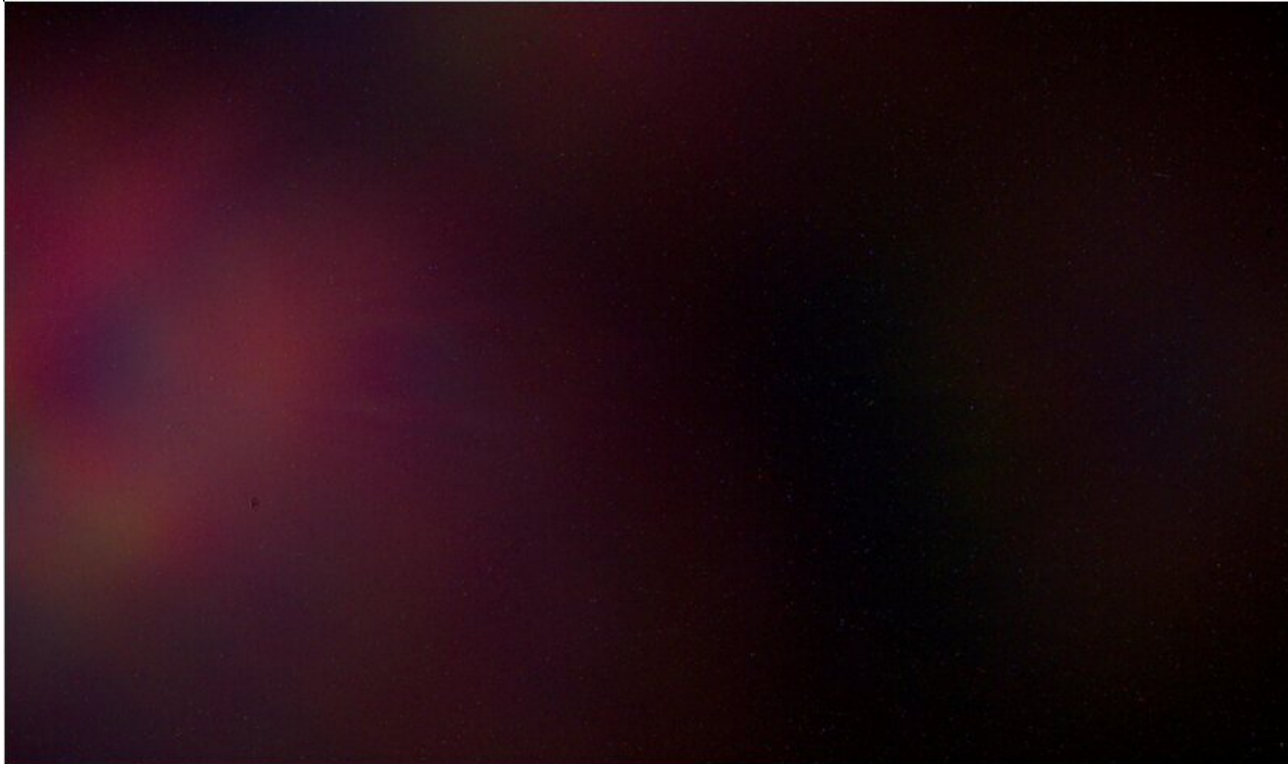


Four telescopes

Eight Cameras

Eight Motors

What about 2025 and 20026 images



- They are closer so optics is quite important
- Quite a lot of hot cells , they are in a High radiation area
- Analysis an upgrade is ongoing

Summary

- Belle II is advancing toward the designed goals the data collected is now more than Belle
- Combining Belle and Belle II da
- No signal of LFV violation in the Tau sector
- The D/D^* anomaly is still present
- We expect to collect more data over the next years.
- Mexico participation in Belle II is strong.



Belle II Mexico

UAS

- Dra Isabel Dominguez
- Dr Pedro Podesta

CINVESTAV

- Dr Eduard de la Cruz Burelo
- Dr Gabriel Lopez Castro
- * DR Pablo Roig

UNAM

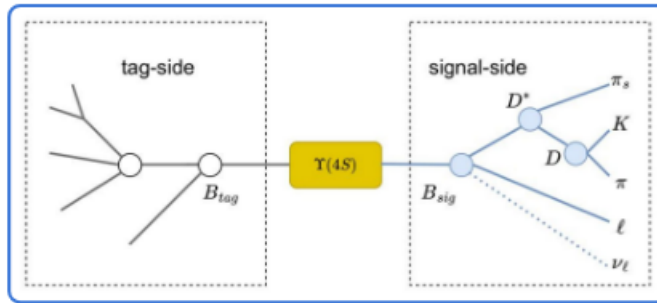
- Dr. Genaro Toledo

*Not oficial but great colaborator.

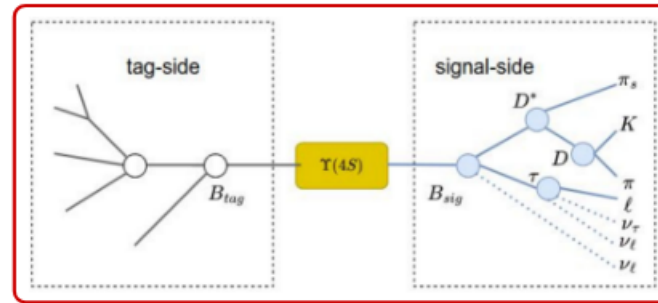
Backup

The signal

$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu_\tau)}{\mathcal{B}(B \rightarrow D^{(*)} \ell \nu_\ell)}$$

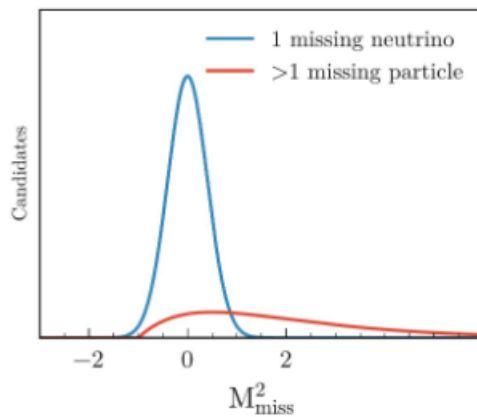


1 neutrino



3 neutrinos

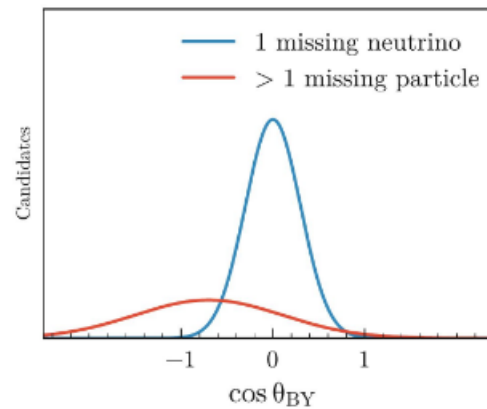
Hadronic tagging



$$M_{\text{miss}}^2 = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^{(*)}\ell})^2$$

squared missing mass

Semileptonic decays



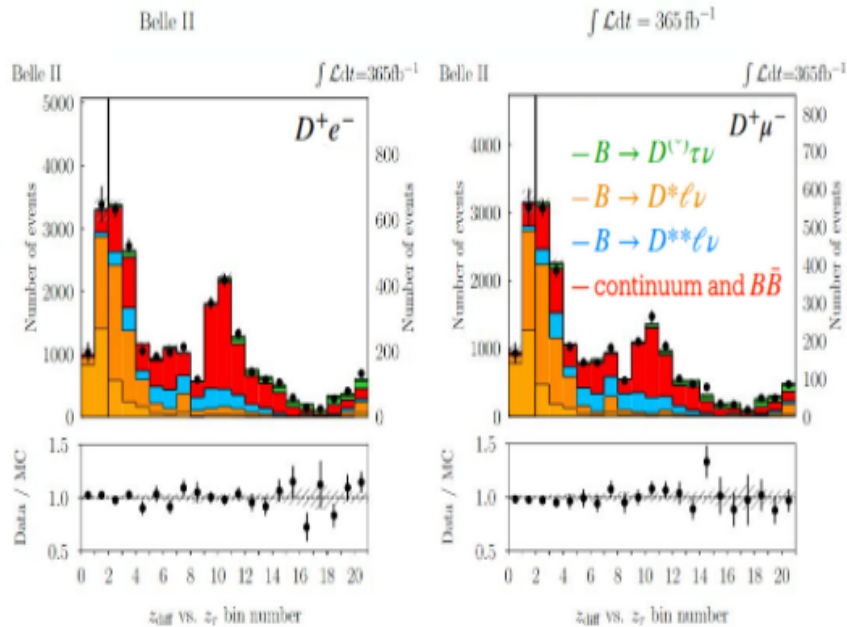
$$\cos \theta_{BY} = \frac{2E_B^* E_Y^* - m_B^2 - m_Y^2}{2|\vec{p}_B^*||\vec{p}_Y^*|}$$

angle between B and Y = D^{(*)}\ell

Semileptonic Tag

Belle II 365 fb⁻¹

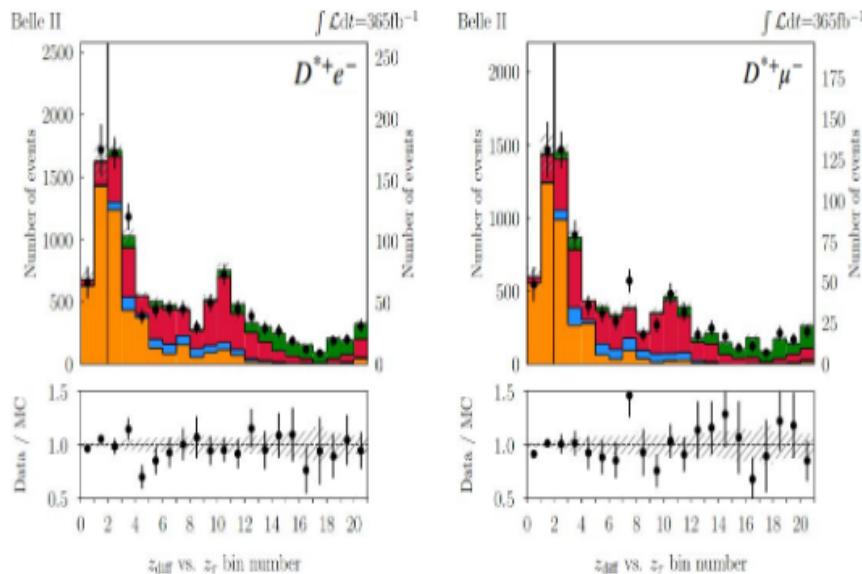
[PRD 112, 032010 \(2025\)](#)



- simultaneous template fit in four final states
 - $D^+ e^-$, $D^+ \mu^-$, $D^{*+} e^-$, $D^{*+} \mu^-$
- result compatible with world average + SM (1.7σ)

$$\mathcal{R}(D^+) = 0.418_{-0.073}^{+0.075} \text{ (stat)}_{-0.056}^{+0.049} \text{ (syst)}$$

$$\mathcal{R}(D^{*+}) = 0.306_{-0.033}^{+0.035} \text{ (stat)}_{-0.018}^{+0.016} \text{ (syst)}$$

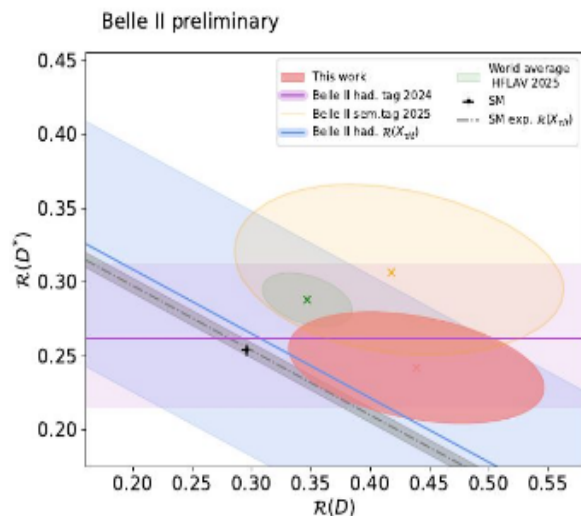


- leading systematic uncertainties on $\mathcal{R}(D)$ ($\mathcal{R}(D^*)$)

	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$
MC Statistics:	8%	4%
Lepton identification:	9%	1%
SL Gap:	6%	0.1%

Hadronic Tag result

Belle II 365 fb⁻¹



$$R(D^*) = 0.242 \pm 0.019(\text{stat}) \pm 0.016(\text{syst})$$

$$R(D) = 0.439 \pm 0.055(\text{stat}) \pm 0.045(\text{syst})$$

- in agreement with SM within 1.5 σ
- in agreement with the world average within 1.3 σ

Source	$R(D^*)$	$R(D)$	ρ
Simulation sample size	4.8%	8.4%	-0.44
gap-mode branching fraction	2.6%	2.6%	0.00
$B \rightarrow D^{*+} \tau^- / (\ell^-) \bar{\nu}_\ell$ branching fractions	0.3%	1.3%	0.25
Hadronic B decay branching fractions	1.6%	1.5%	-0.26
Form factors	0.5%	0.9%	-0.70
Fraction of misreconstructed $D^{(*)}$	0.5%	1.2%	0.00
Continuum background	2.4%	2.1%	0.93
Fit biases	0.3%	1.2%	0.00
Low-momentum π^0, γ efficiency	2.2%	2.4%	0.99
Other efficiency corrections	0.7%	1.4%	0.92
B -tagging efficiency of data	0.9%	1.8%	-1.00
B -tagging efficiency of $B \rightarrow D\tau\nu$	0.1%	1.8%	1.00
M_{miss}^2 resolution	0.5%	0.8%	0.48
Total systematic uncertainty	6.7%	10.2%	-0.20
Statistical uncertainty	8.3%	16.3%	-0.40