Search for $\tau \to 3\mu$ at Belle II

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On behalf of the Belle II Collaboration

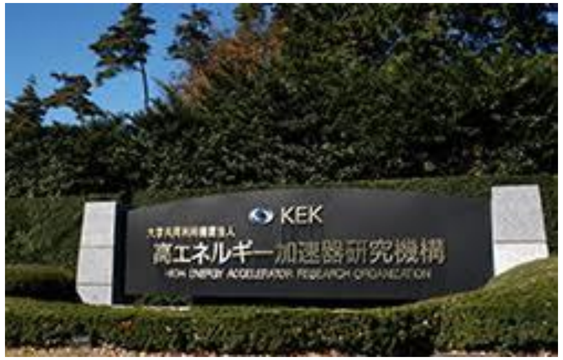
Topical workshop on LFV decays of the tau

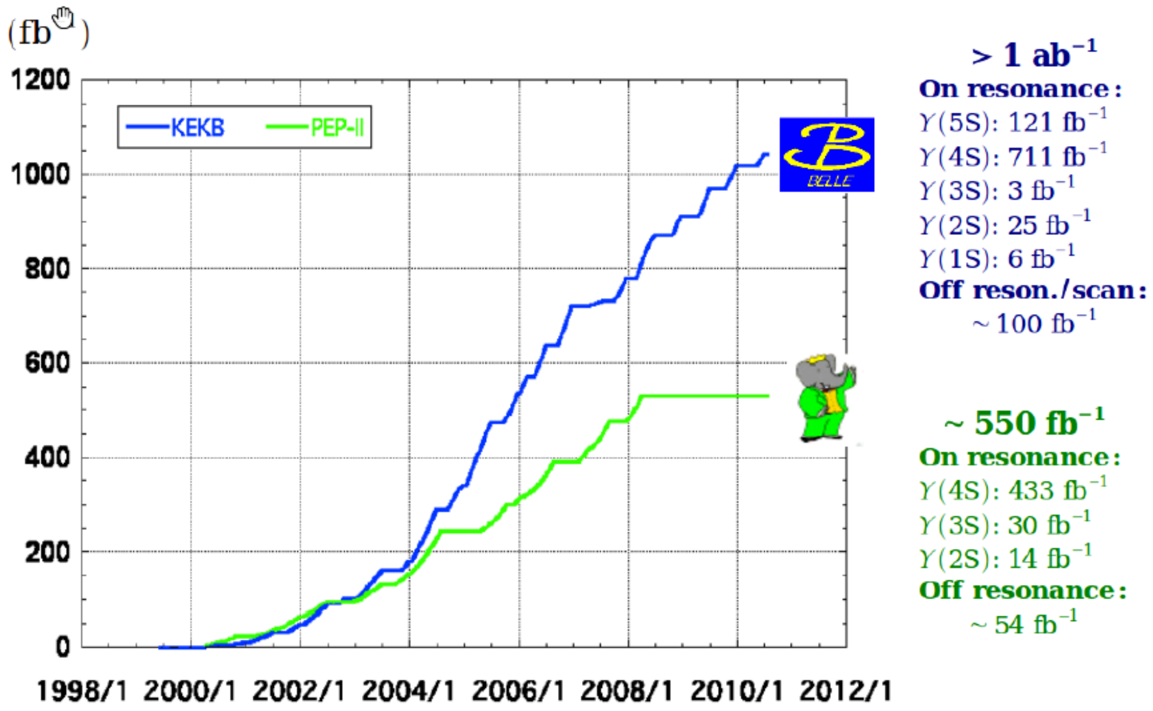
Orsay, April 11th 2024

European Research Council
Established by the European Commission

Back in the 2000s : Belle and Babar era

Belle at KEKB
Japan

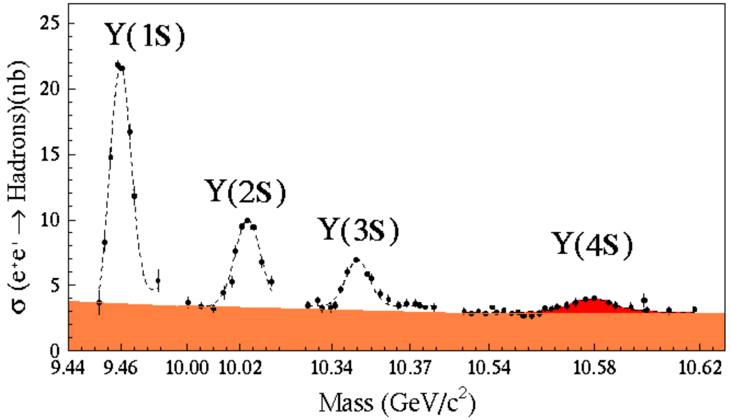


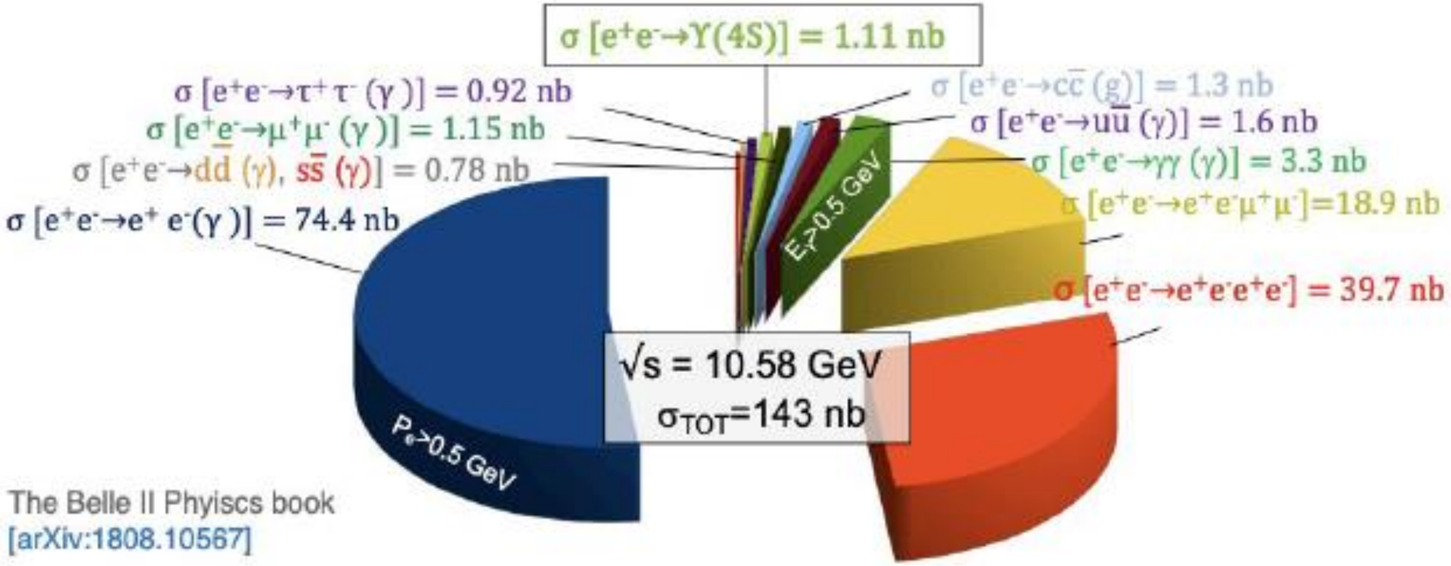


Babar at PEP-II
California

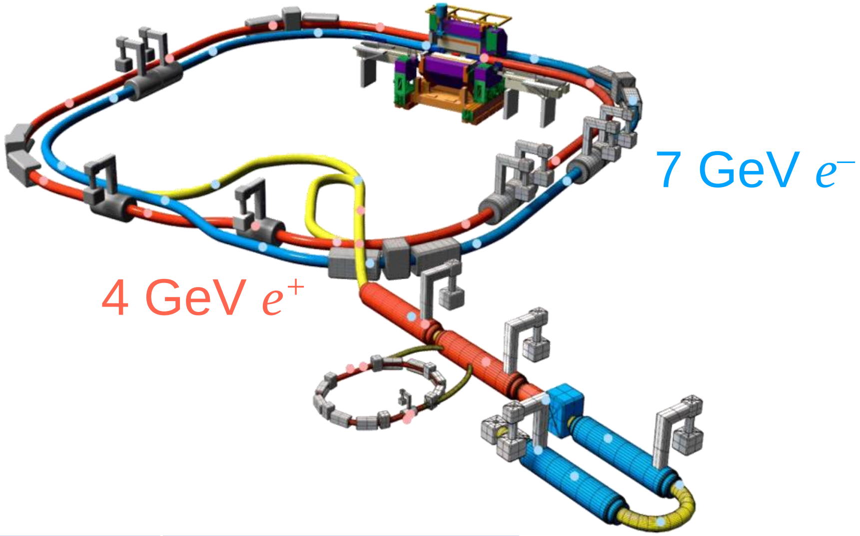
Physics processes at B-factories

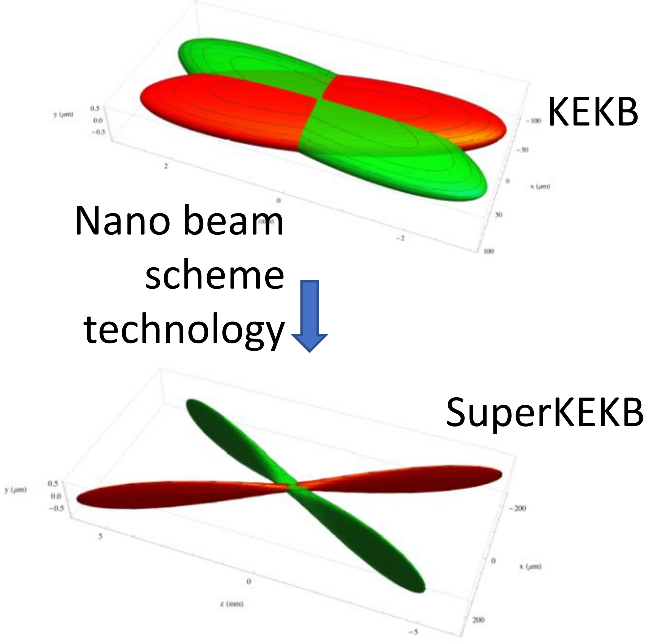
- e^+e^- collider, mainly working at the Υ(4S) energy which produce pairs of B^+B^- and (quantum correlated) $B^0\bar{B}^0$
- Asymmetric beams → study time dependent effects in B hadron decays
- Also τ /charm factory (similar cross section as B)!





Back to the future: SuperKEKB and Belle II



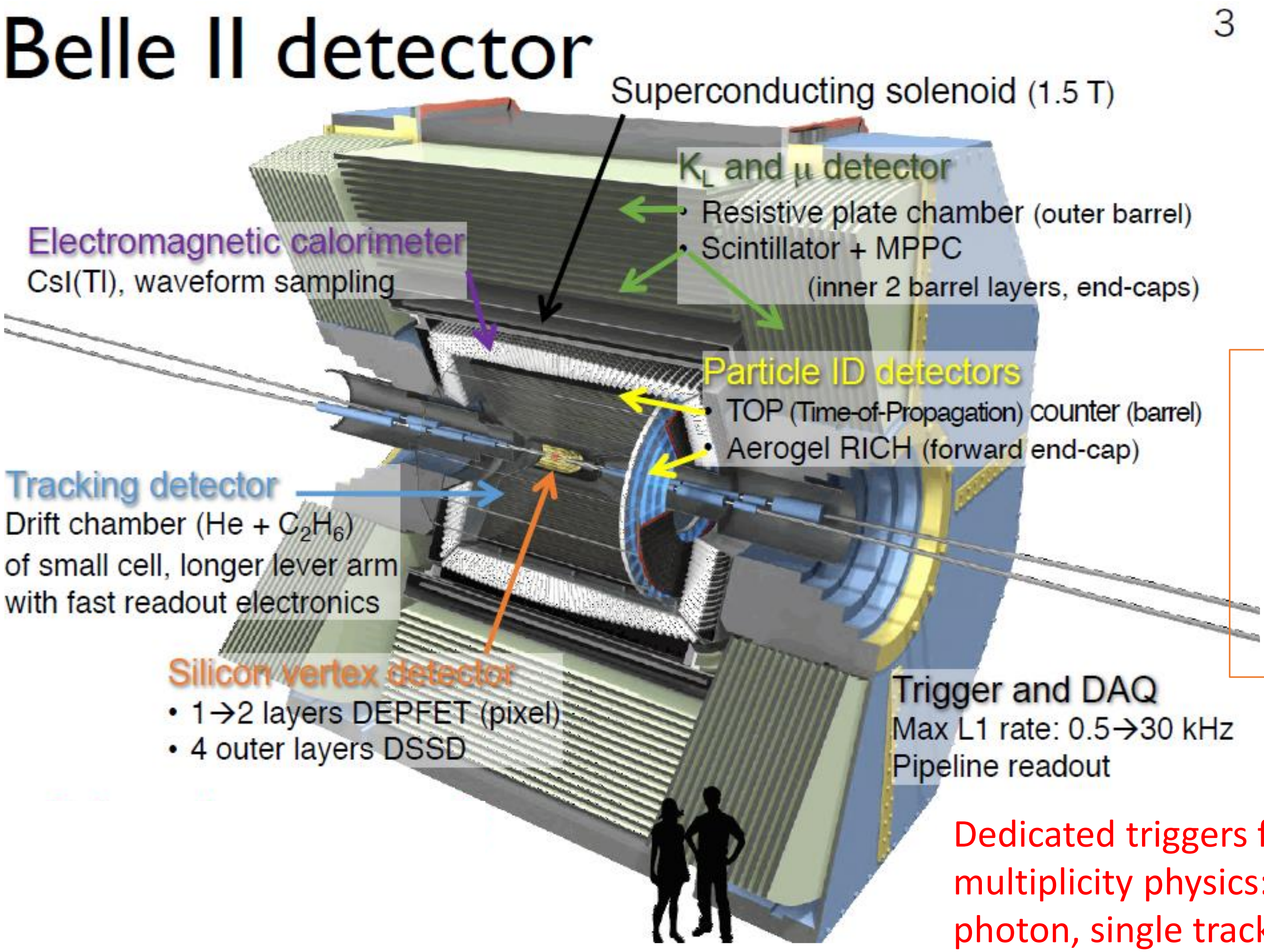


	KEKB	SuperKEKB
Energy (GeV) LER/HER	3.5/8	4/7
Current (A) LER/HER	1.6/1.2	2.8/2.0
β^*_y (mm)	5.9	0.3
Inst. Lumi (cm^{-2}/s^{-1})	2.1 x10^{34}	6 x10^{35}

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

Lorentz factor; beam current; beam-beam parameter; geometrical reduction factors; beam aspect ratio at the IP; vertical beta-function at the IP

Belle II detector



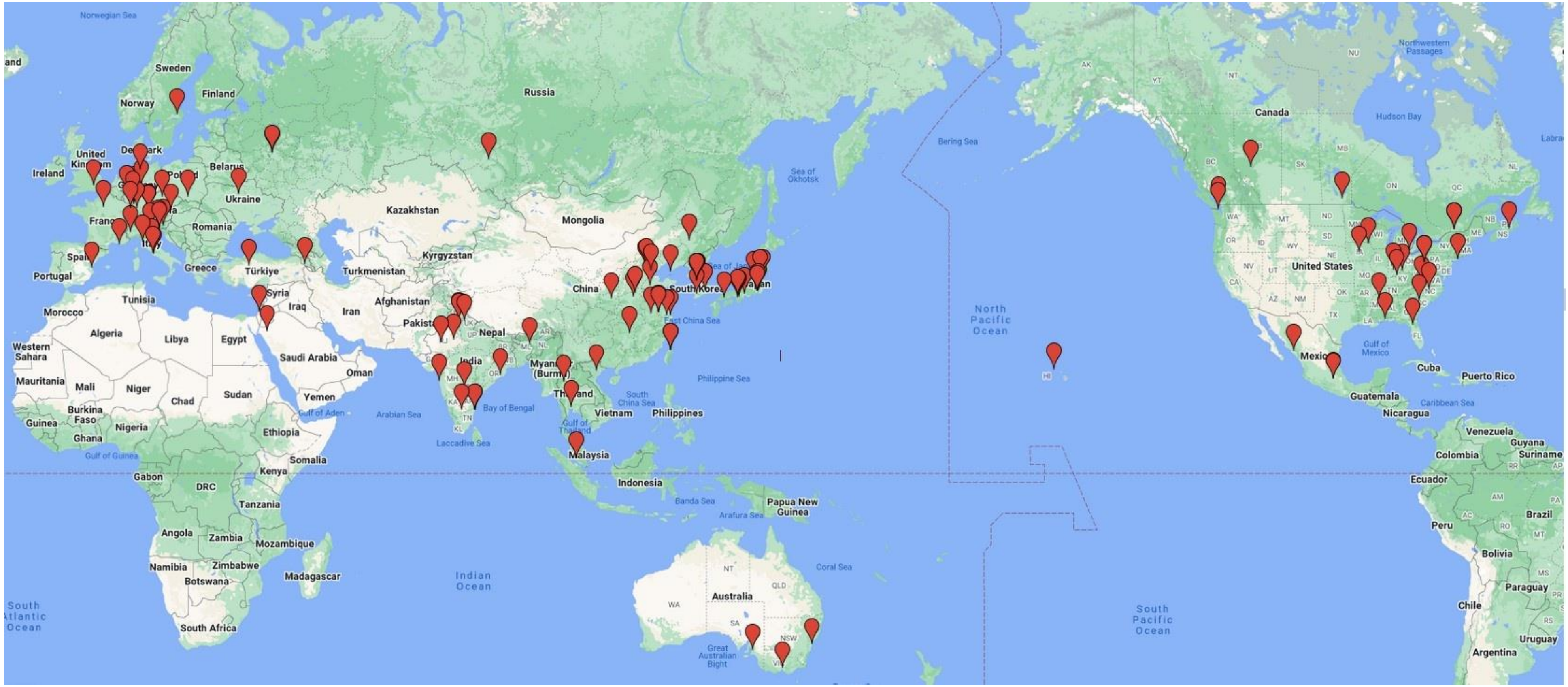
Advantage for τ studies:

- almost hermetic detector + well defined initial state energy= measurement of missing energy
- Clean environment
- excellent PID for e and μ

Dedicated triggers for low multiplicity physics: single-photon, single track, two-track,..

Belle II collaboration

- About 1100 physicists from 120 countries

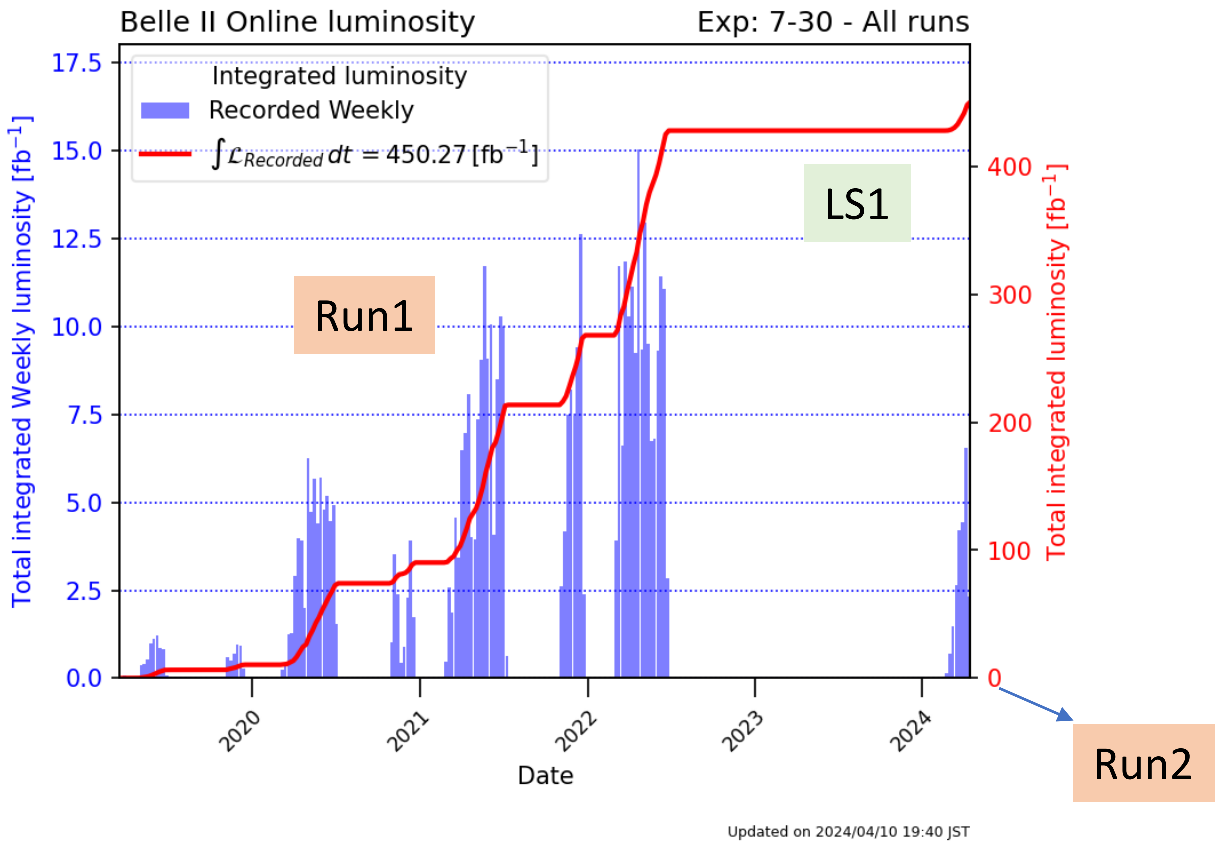


Experiment status

Run1 end 2019-mid 2022 with complete detector (except for PXD layer 2)
Long shutdown 1 mid 2022 – beginning 2024 : improvements on accelerator and installation of complete pixel detector
Run2 started February 2024

Achieved so far:

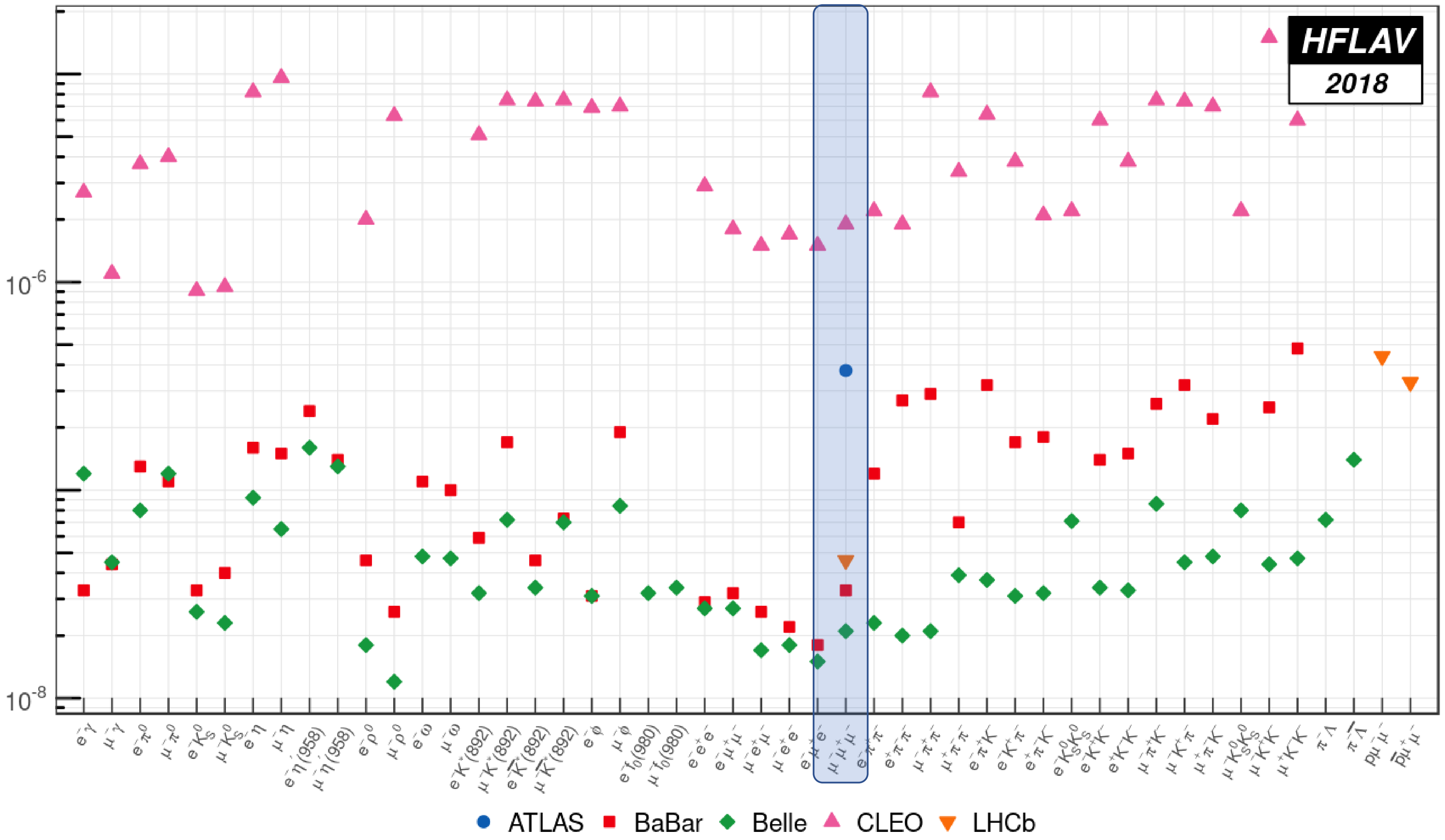
- World record of instantaneous lumi at 4.7×10^{34} $cm^{-2}s^{-1}$
- Recorded 450 fb^{-1} since 2019
- The analysis presented here is based on Run1 data (424 fb^{-1} among which 362fb^{-1} at Υ(4S))

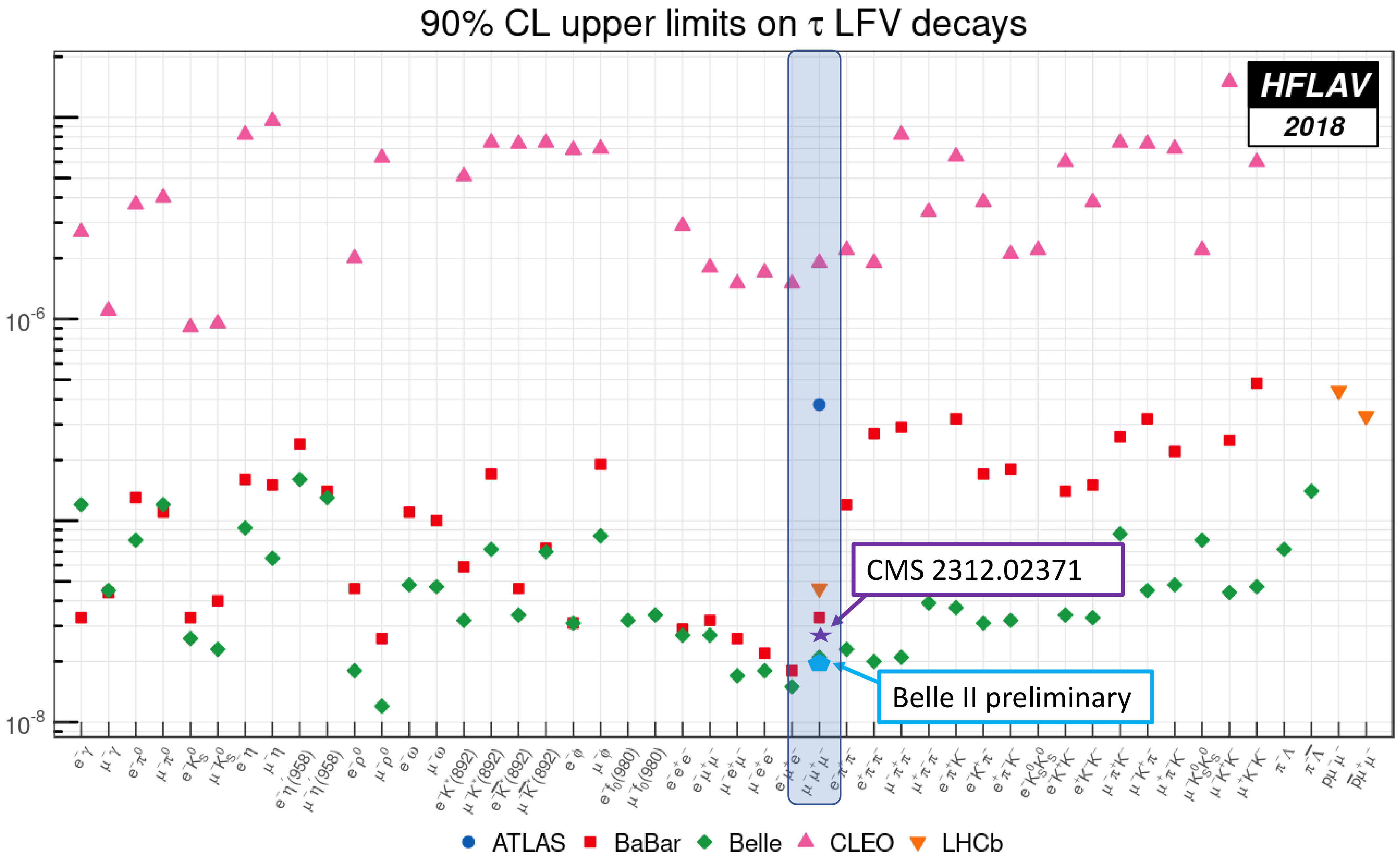


Main limitations to the luminosity during Run1:

- Shorter beam lifetime (sudden beam losses) and lower bunch-current limit than expected
- Beam beam effects
- Low machine operation efficiency

90% CL upper limits on τ LFV decays





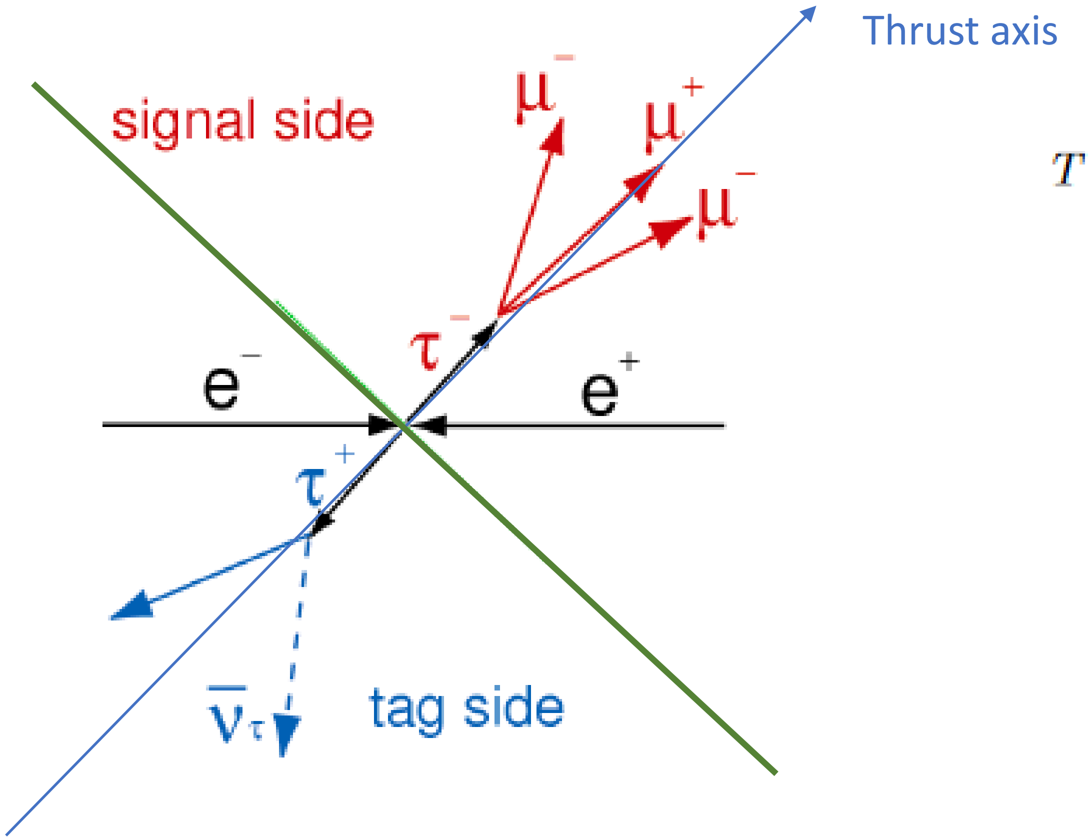
90% CL upper limits on τ LFV decays
HFLAV
2018
CMS 2312.02371
Belle II preliminary
10^-6
10^-8
ATLAS
BaBar
Belle
CLEO
LHCb

τ LFV searches at B factories

Historical approach uses a **full reconstruction** of the event:

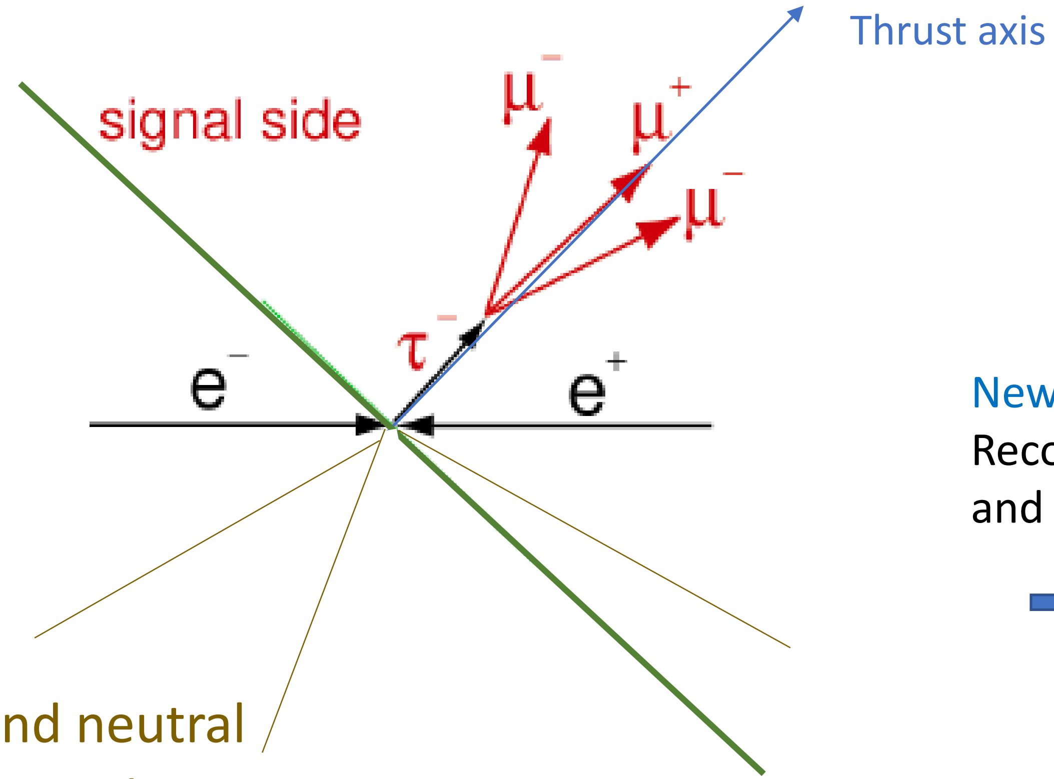
- Signal side $\tau \to 3l$
- Tag side: $\tau \to e/\mu/\pi/\rho$ (+ν's)

⇨ Require exactly 4 tracks in the event following the '3x1 topology'



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

τ LFV searches at B factories



Rest-of-event
= all charged and neutral particles that are not coming from the signal tau

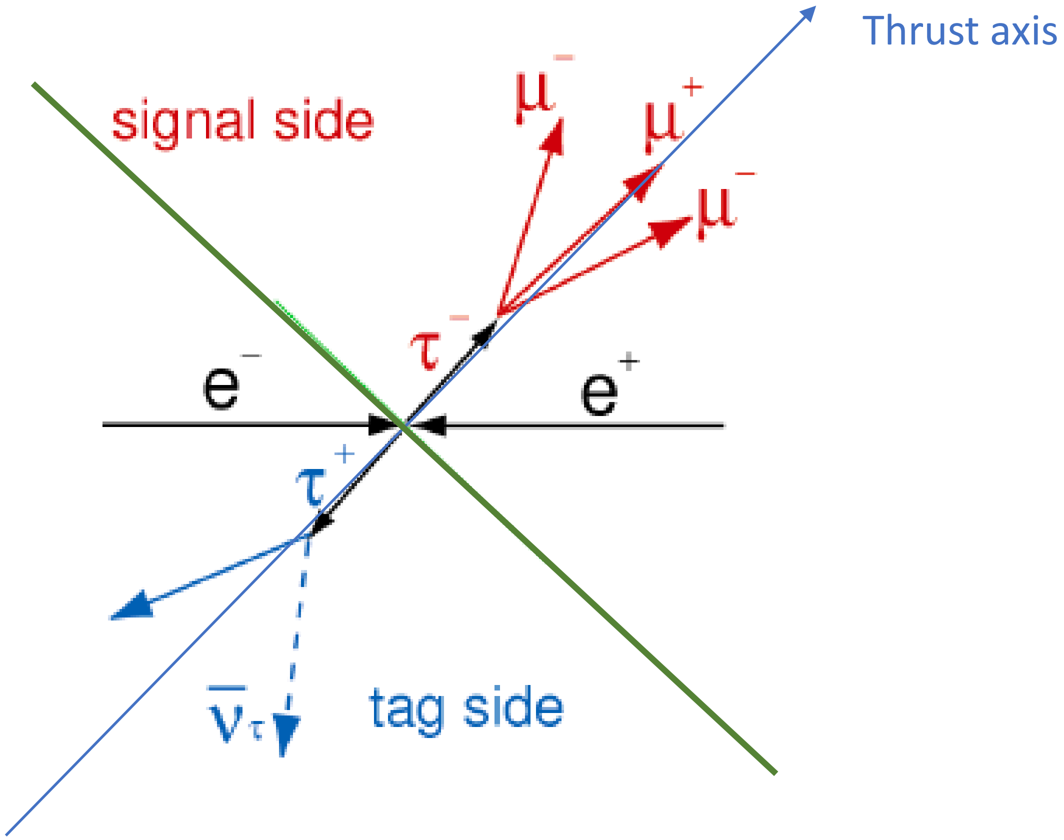
New inclusive approach:
Reconstruct only the signal tau and the ‘rest-of-event’

→ Higher signal efficiency (inclusion of 3-prong decays, …) and ‘higher background’ contamination

$\tau \to 3\mu$ selection

Signal selection:

- Require 3 muons well identified in the same hemisphere
- They should come from the interaction point |dz|<3cm, |dr|<1 cm
- Events should pass the L1 triggers based on ECL or CDC (~95% efficiency)



τ→3μ selection

Signal selection:

- Require 3 muons well identified in the same hemisphere
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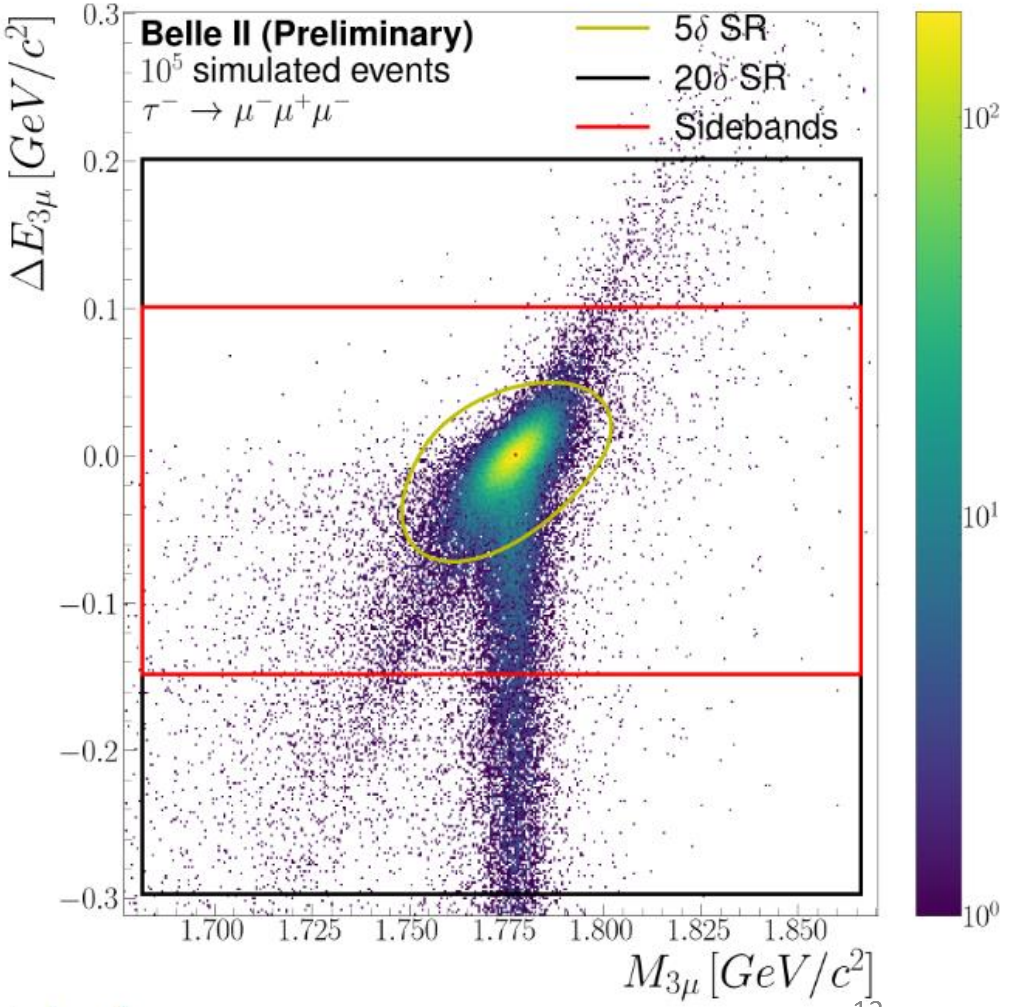
Define **2D plane** made of $M_{3\mu}$ and $\Delta E_{3\mu} = E^*_\tau - \sqrt{s}/2$

- Signal peaks in $M_{3\mu}$ =1.777 GeV/c^2 and $\Delta E_{3\mu}$= 0, with tails due to ISR and FSR
- Obtain resolutions δ fitting the signal simulation
- Define the signal region as ellipse of ±5δ, **blinded**
- Define the sideband region as box of ±10δ in $\Delta E_{3\mu}$ and ± 20δ in $M_{3\mu}$, used to check data/MC agreement



Backgrounds

Main background contributions :

- $e^+e^- \to q\bar{q}$ (q=u,d,c,s)
- $e^+e^- \to e^+e^-$, $\mu^+\mu^-$, $e^+e^-\mu^+\mu^-$, $\mu^+\mu^-\mu^+\mu^-$
- $e^+e^- \to \tau^+\tau^-$
- Other (non simulated) low multiplicity events

Backgrounds

Main background contributions :

- e+e- → qq (q=u,d,c,s)
- e+e- → e+e-, μ+μ-, e+e-μ+μ-, μ+μ-μ+μ-
- e+e- → τ+τ-
- Other (non simulated) low multiplicity events

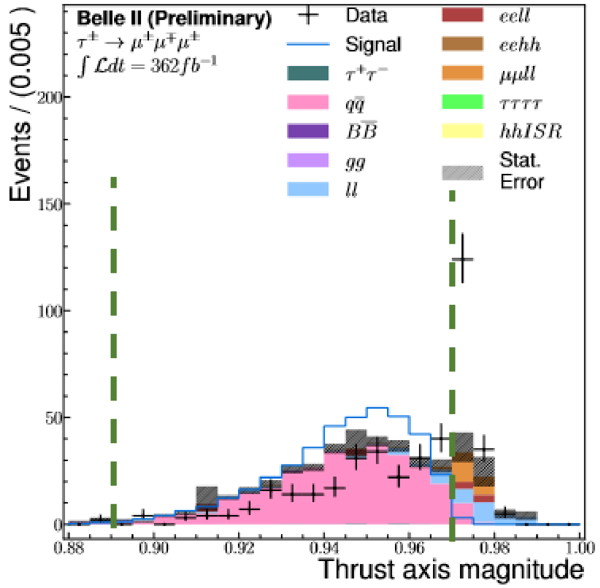
Most of backgrounds corresponds to pions/kaons/electrons misidentified as muons

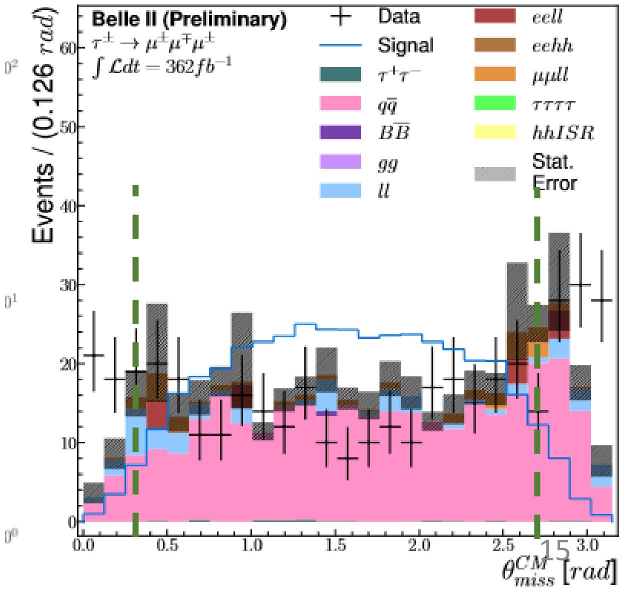
→ Tighten muon identification criteria for 2 muons out of the 3

Low multiplicity backgrounds have high thrust values and missing momentum pointing towards the beam axis:
$0.89<T<0.97$ and $0.3< \theta^*_{miss}< 2.7$

Main remaining background events after selection are e+e- → qq

Data in SB region





BDT selection

Train a BDT against qq and ττ events using simulation equivalent to 4 ab-1 for the background (3400 events), and 176k signal events:

- Use **32 input variables** based on
  - Signal τ properties : muon p_T, flight time, isolation,…
  - ROE properties : mass, ΔE, thrust axis,…
  - Event properties: tracks and photons multiplicities, thrust, missing momentum related variables,…
- BDT based on XGBoost library, hyperparameters optimized with Optuna
- Use k-folding to reduce sensitivity to fluctuations

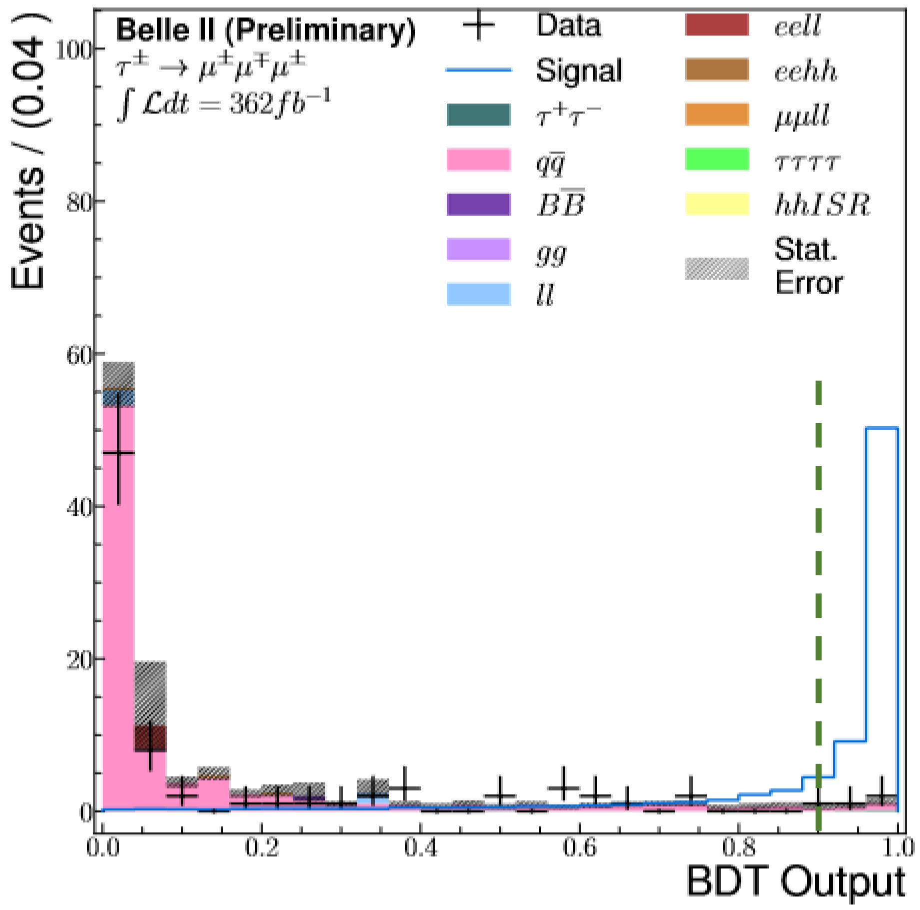
Final selection on BDT output optimize according to Punzi FOM : BDT>0.9

$$\frac{\varepsilon_{3\mu}}{\alpha/2+\sqrt{B}}$$

3σ significance α=3

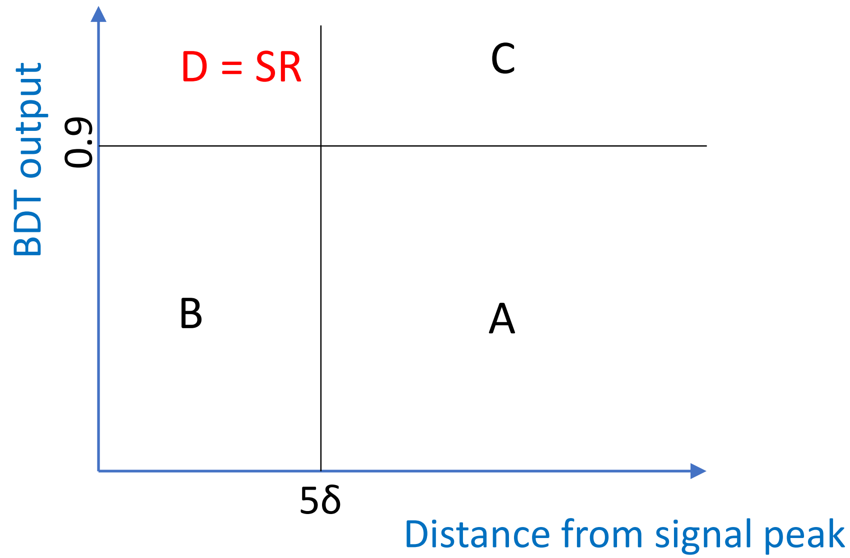
Number of expected background

Data in SB region



+ Final cut to require total charge=0

Expected background in SR and BR measurement

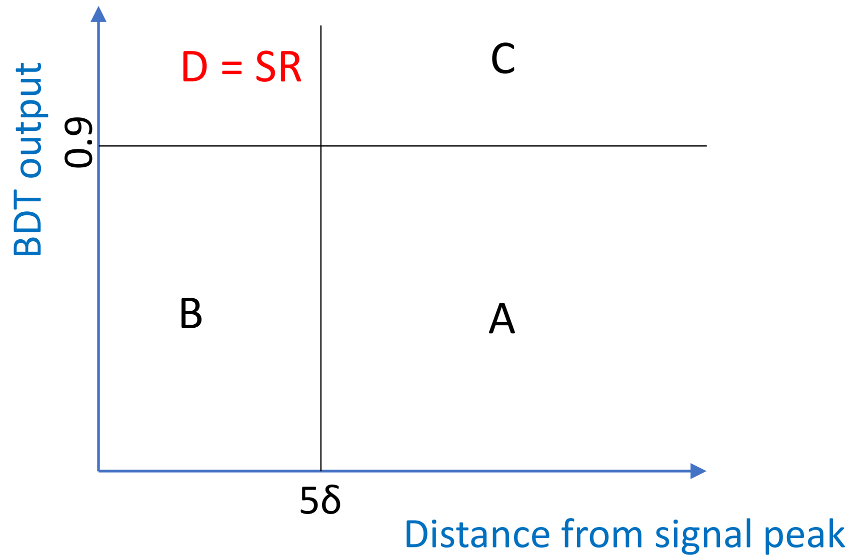


Use a data-driven method 'ABCD' based on 2 uncorrelated variables : BDT output and distance to the signal peak

$ND = NB \times NC / NA = 0.5^{+1.4}_{-0.5}$

Method validated with simulation

Expected background in SR and BR measurement



Use a data-driven method 'ABCD' based on 2 uncorrelated variables : BDT output and distance to the signal peak

$ND = NB \times NC / NA = 0.5^{+1.4}_{-0.5}$

Method validated with simulation

Systematic uncertainties:

Quantity	Source	Uncertainty (%) Low	High
$\varepsilon_{3\mu}$	PID	2.1	2.4
	Tracking	1.0	1.0
	Trigger	0.9	0.9
	BDT	1.5	1.5
	Signal region	3.9	2.9
N_{exp}	Momentum Scale	16	16
$\mathcal{L}$		0.6	0.6
$\sigma_{\tau\tau}$		0.3	0.3

Branching fraction is then measured as

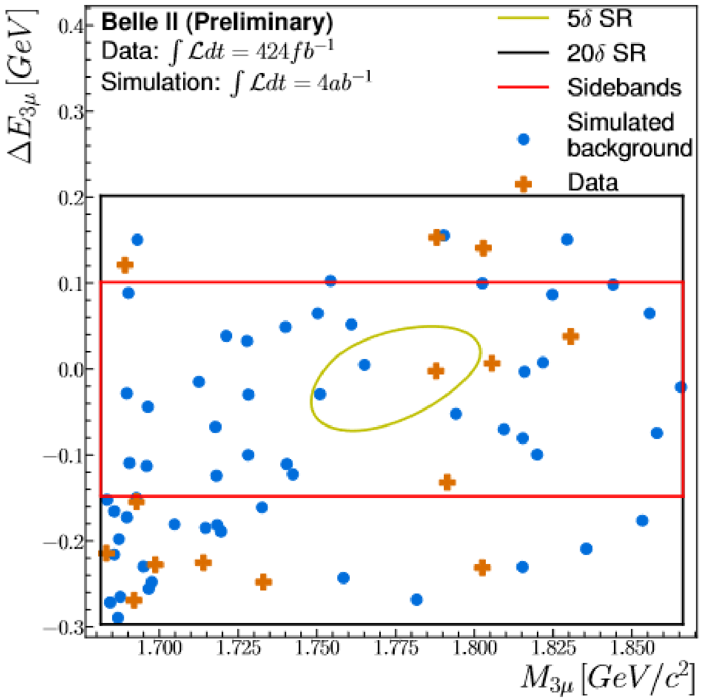
$$\mathcal{B}(\tau^- \to \mu^- \mu^+ \mu^-) = \frac{N_{obs} - N_{exp}}{\mathcal{L} \times 2\sigma_{\tau\tau} \times \varepsilon_{3\mu}}$$

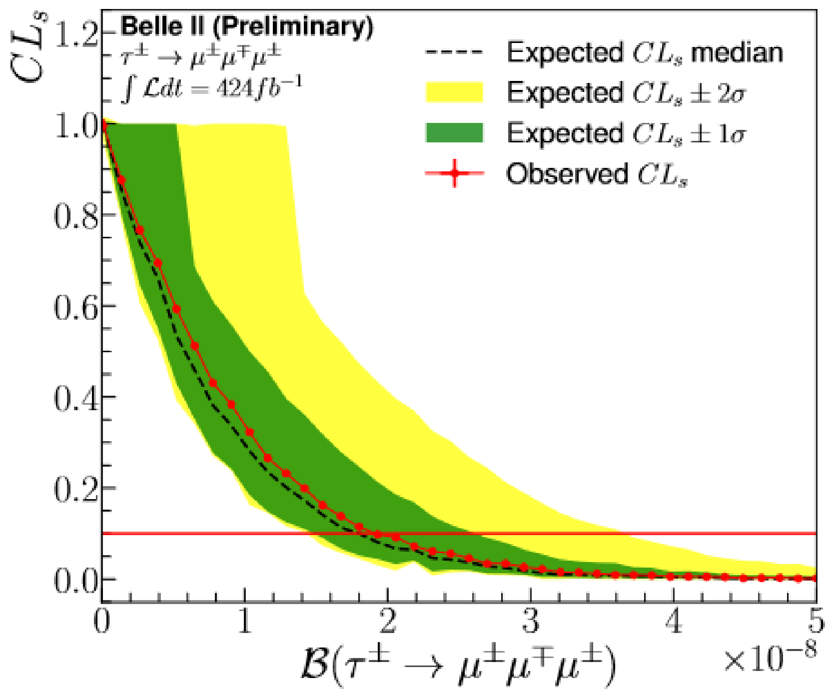
$N_{exp} = 0.5^{+1.4}_{-0.5}$

$L = 424$ fb-1, $\sigma_{\tau\tau} = 0.919$ nb

$\varepsilon_{3\mu} = 20.4\%$ *2.7x Belle efficiency*

Box opening and limit





We observe one event, compatible with bkg expectation

Limit at 90%CL:

Expected B(τ→3μ)< 1.8 x 10^{-8}

Observed B(τ→3μ)< 1.9 x 10^{-8} *Most stringent limit!*

Belle with 782 fb^{-1}

$\mathcal{B}_{UL}$	ε_{sig} (%)	N_{bkg}	N_{obs}
2.1×10^{-8}	7.6	0.13	0

Independent measurement with classical 3x1 selection

Signal selection:

- Require 3 muons well identified in the same hemisphere and 1 prong in the other hemisphere
- Cut-based selection optimized using the Punzi FOM

Signal efficiency: 14.9% (*2 x Belle efficiency*)

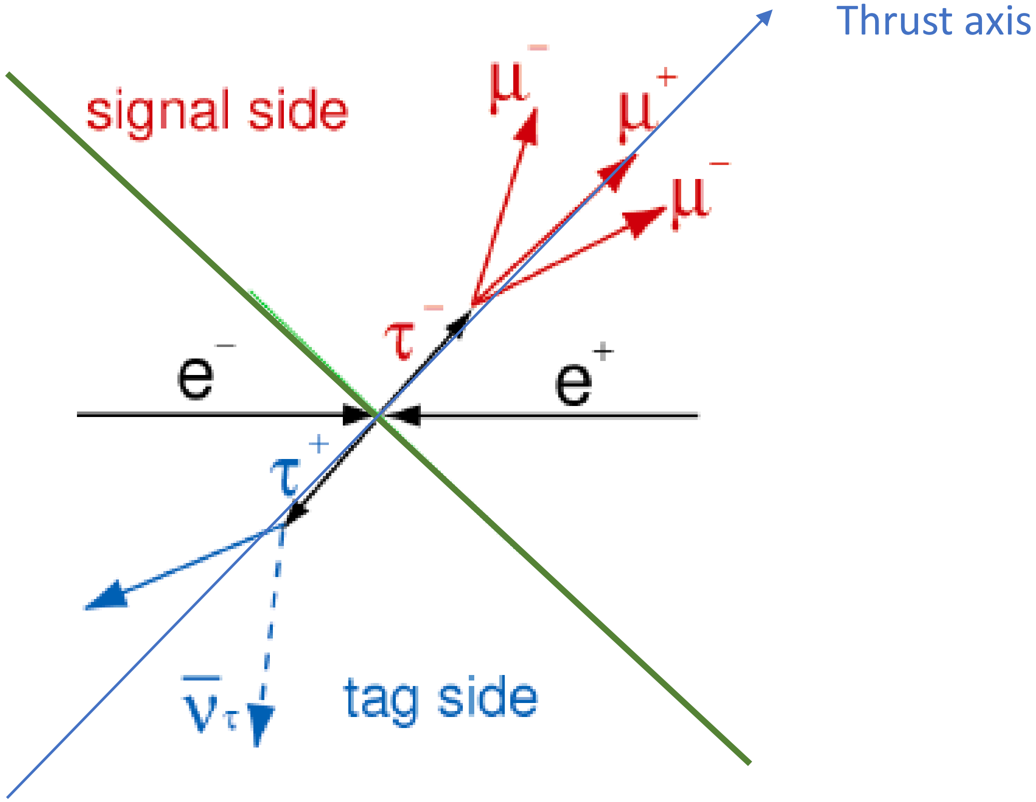
Number of expected background from simulation : 0.43

We observe 0 event, compatible with bkg expectation

Limit at 90%CL:

Expected $B(\tau \to 3\mu) < 2.0 \times 10^{-8}$

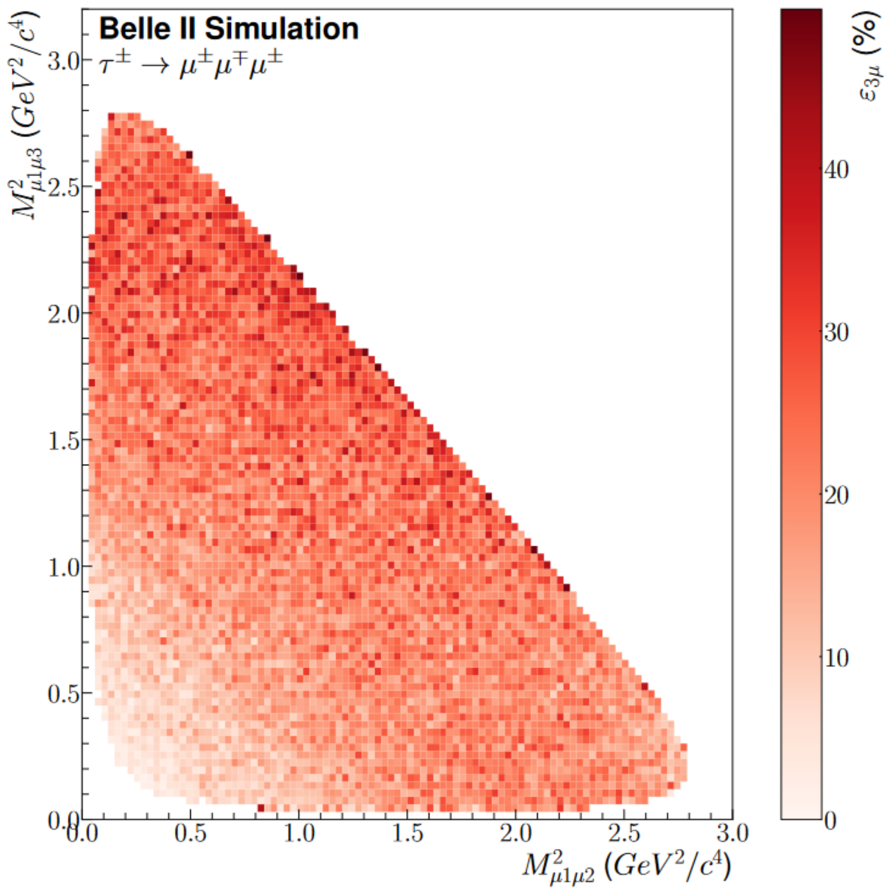
Observed $B(\tau \to 3\mu) < 2.0 \times 10^{-8}$



Additional information

We provide the efficiency as function of the Dalitz plane.

Is there anything else that can be useful to interpret the result ?



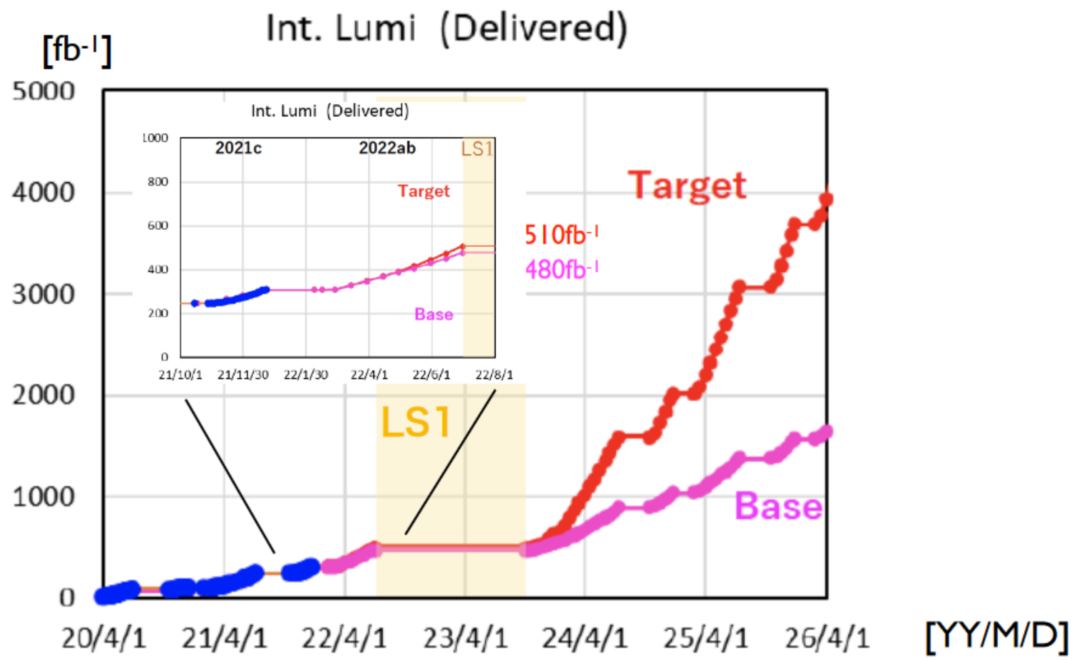
Summary and outlook

Belle II provided the most stringent limit on $B(\tau \to 3\mu)$ at 1.9×10^{-8} @90% CL
Improved performances wrt to Belle thanks to more optimal selection and use of inclusive tagging reconstruction
More results are coming based on Run1 data for the modes with electrons, stay tuned!

Belle II has recently resumed data taking, the goal is to reach an instantaneous luminosity of $10^{35}/cm^2/s$
Belle II dataset will increase up to few ab^{-1} in coming years

Target scenario: extrapolation from 2021 run including expected improvements.

Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run



Wide τ program at Belle II in the coming years

Precision test of SM

- Test of LFU: first result of B(τ→μνν)/B(τ→eνν) shown at TAU2023 using 1x1 topology, 3x1 on track
- CPV in hadronic τ decays
- V_{us} measurement
- τ lifetime measurement (τ mass already published)
- Partial wave analysis of 3-prong decays

Search for non-SM processes

- Search for LFV and BNV decays

Any other idea ?

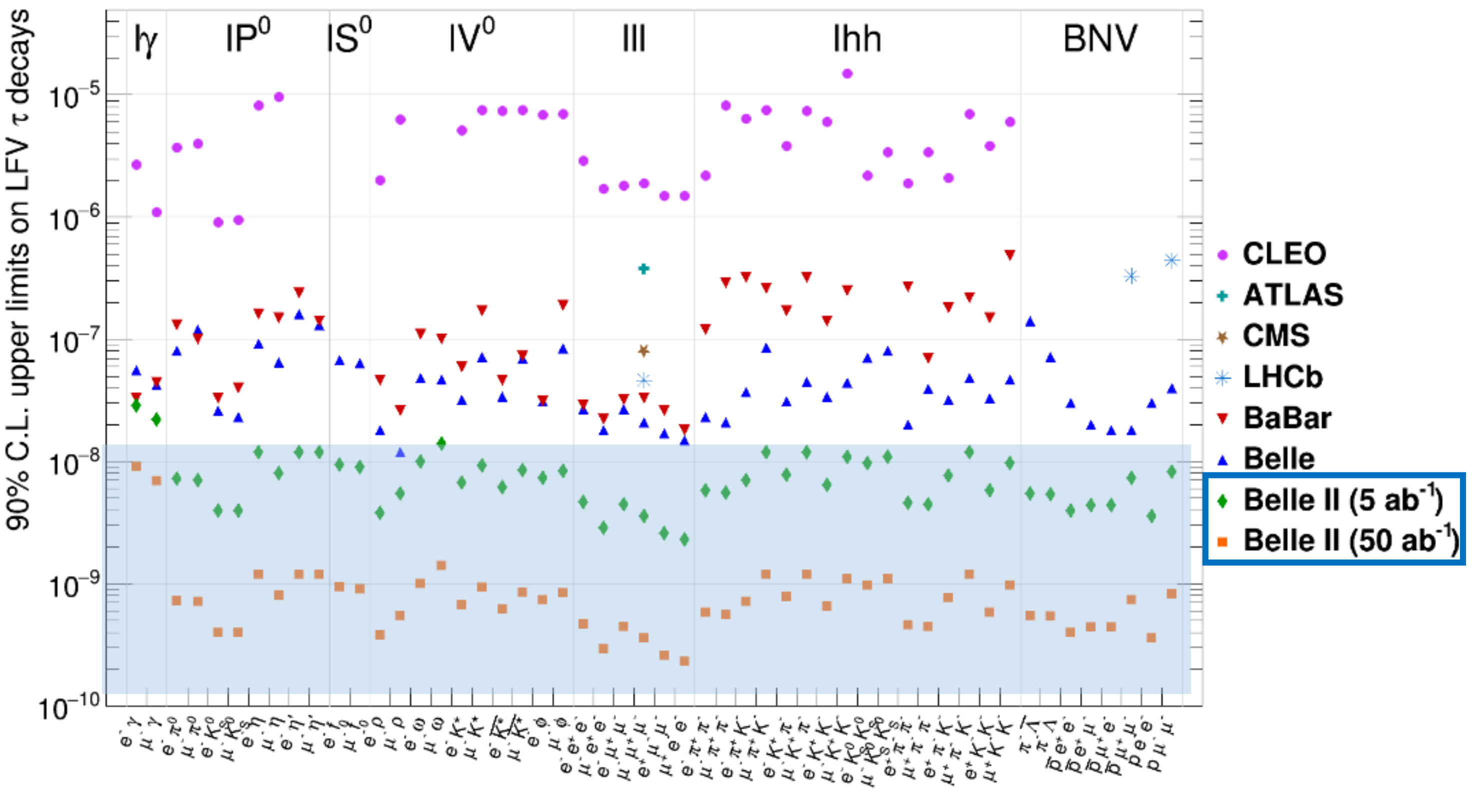
Beyond Run2

Discussions ongoing on a upgrade of the Belle II detector

- Improved robustness against backgrounds and performances
- CDR to be released soon

Studies ongoing to introduce polarization of the e- beam arXiv:2205.12847

Snowmass 2021, arXiv: 2203.14919



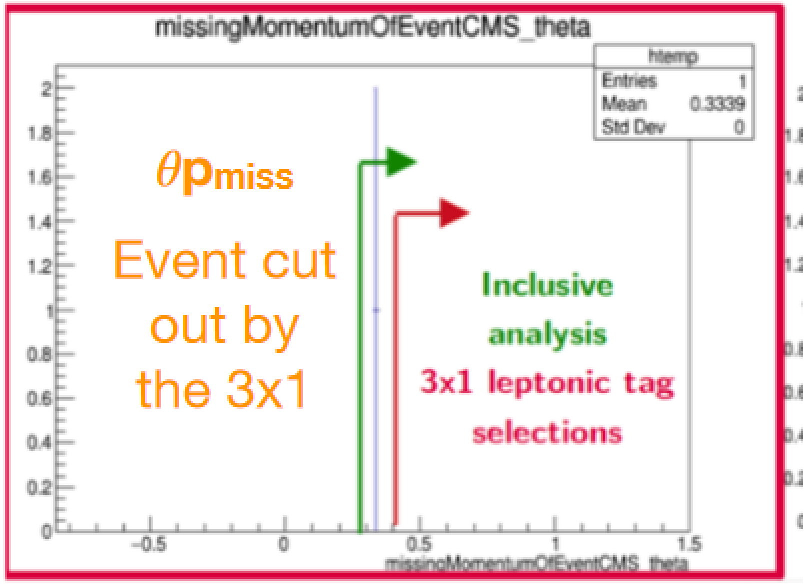
projections

Thanks for you attention!

Inclusive vs tagged

- Surviving event in SR does not pass the tagged requirement on missing momentum θ

- It looks compatible with
  - 4muons events with missed soft photon
  - τ+τ-
  - continuum processes

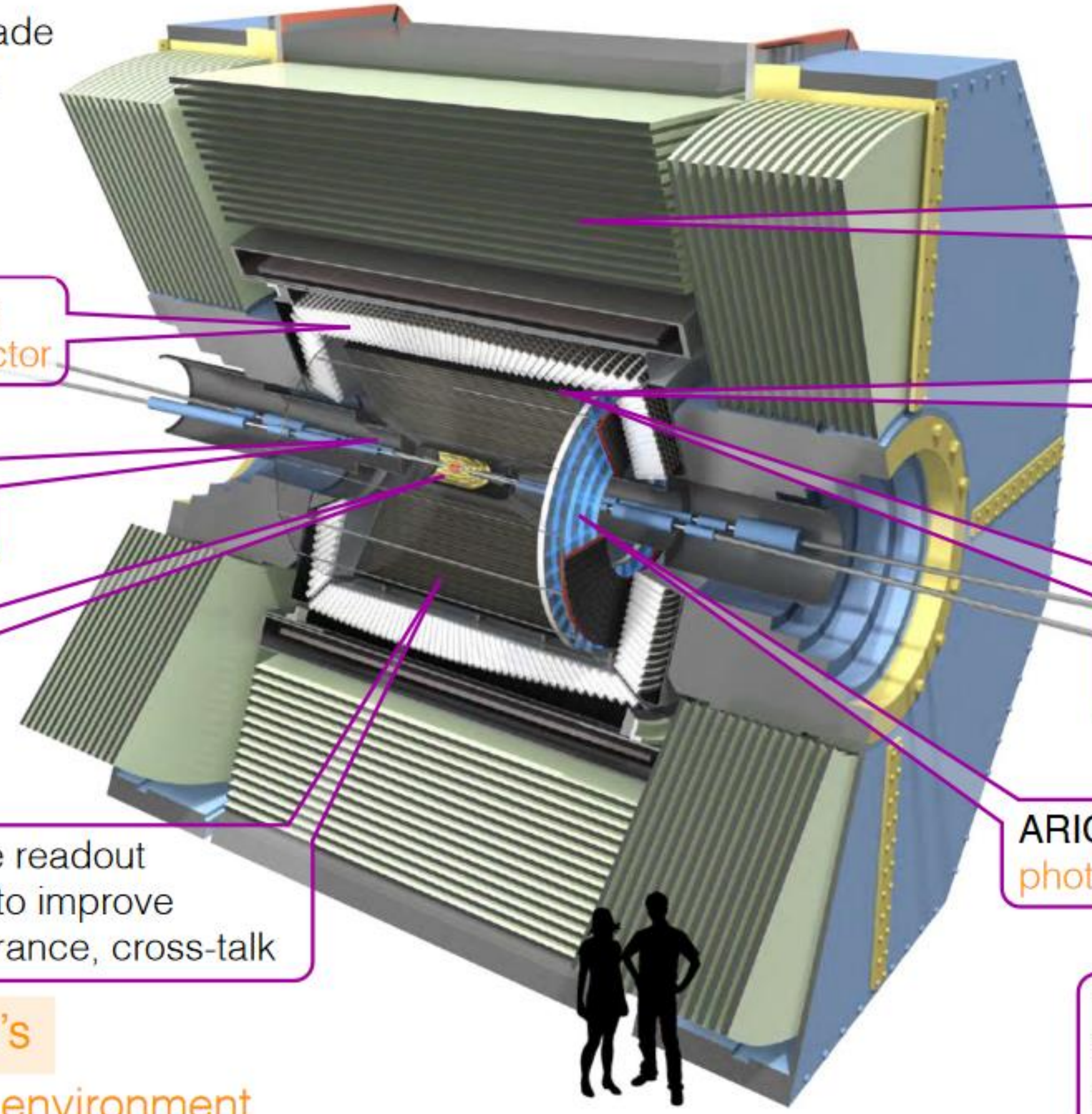


$\tau \rightarrow 3l$ experimental limits

Mode	Belle	Babar	LHCb	ATLAS	CMS
$\mu^-\mu^+\mu^-$	2.1	3.3	4.6	3.8	2.9
$e^-e^+e^-$	2.7	2.9	-	-	-
$e^-\mu^+\mu^-$	2.7	3.2	-	-	-
$e^-e^+\mu^-$	1.8	2.2	-	-	-
$e^+\mu^-\mu^-$	1.7	2.6	-	-	-
$\mu^+e^-e^-$	1.5	1.8	-	-	-

Detector upgrades during LS2 or beyond

See Snowmass white papers:
arXiv:2203.11349 for detector upgrade
arXiv:2207.06307 for physics reach
arXiv:2203.05731 for backgrounds



KLM: replace RPCs with scintillators in barrel (some with fast timing for K_L time-of-flight); replace readout

ECL: replace crystals with pure CsI; APD readout; add pre-shower detector

TOP: replace readout to reduce size & power; replace all PMTs with extended-lifetime ALDs (or SiPMs?)

IR: accommodate QCS replacement and repositioning

STOPGAP: close gaps between TOP quartz bars, provide timing layers for track trigger

VXD: all pixels
- DMAPS
- SOI-DUTIP

ARICH: possible photosensor upgrade

CDC: replace readout ASIC+FPGA to improve radiation tolerance, cross-talk

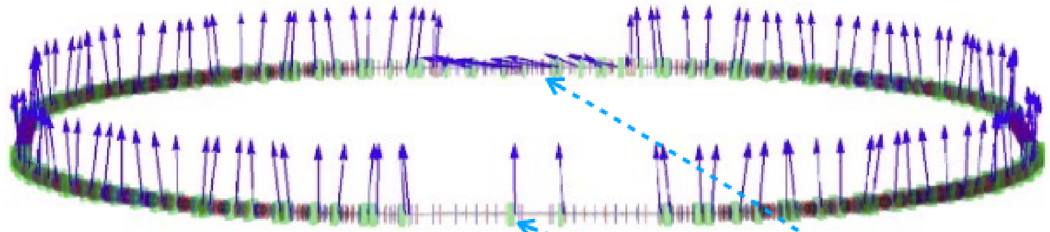
TRIGGER: replace with latest tech to increase bandwidth, allow for new trigger primitives

More distant future: ~mid-2030's

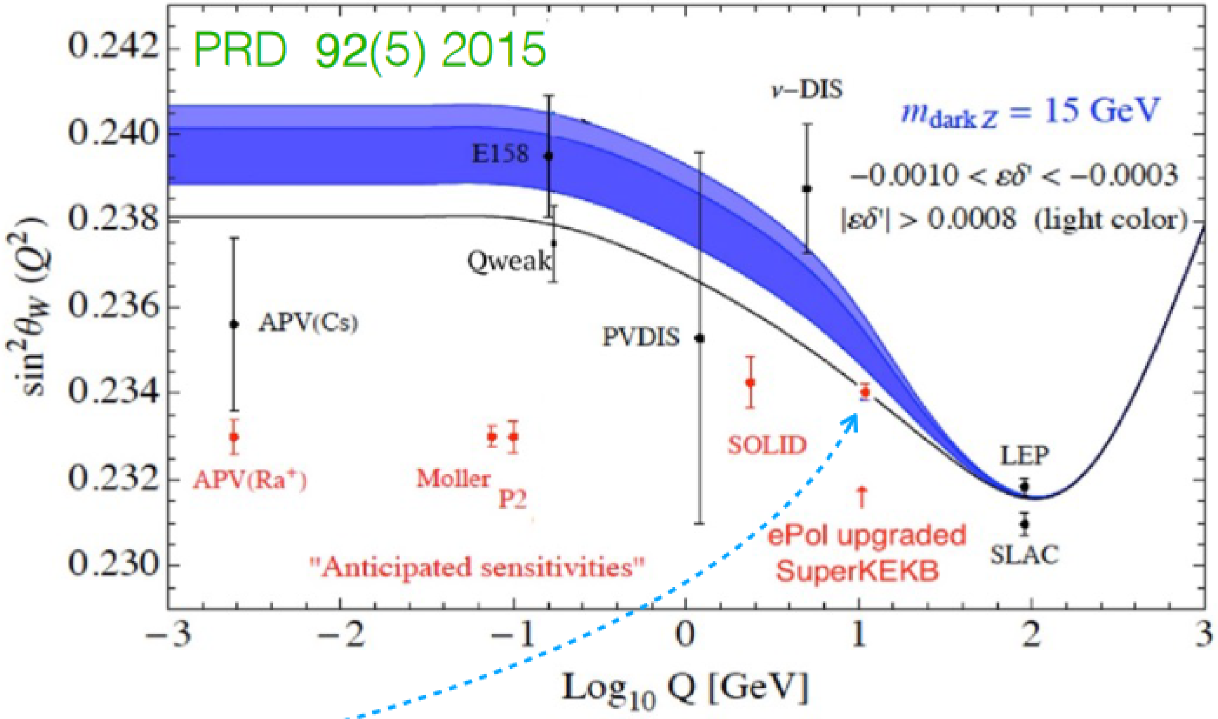
✓ Detector R&D for extreme-$\mathcal{L}$ environment

Beam polarization & "Chiral Belle" beyond LS2 [or sooner?]

See Snowmass white paper arXiv:2205.12847



e− spin vector in SuperKEKB



✓ **Polarized electrons (70%)**

- Transverse polarization at injection
- Rotate to longitudinal at interaction point
- Compton polarimeter for 0.5% precision

✓ **with polarized electrons …**

- sensitivity to EW neutral vector current
- sensitivity to light Z_{dark} via $\sin^2\theta_W$
- left-right asymmetries with 5 fermions
- tau g–2: sensitivity of $\mathcal{O}(10^{-5})$ w/50 ab^{-1}
- background suppression in $\tau \to \ell\,\gamma$ using helicity distributions