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

Justine Serrano

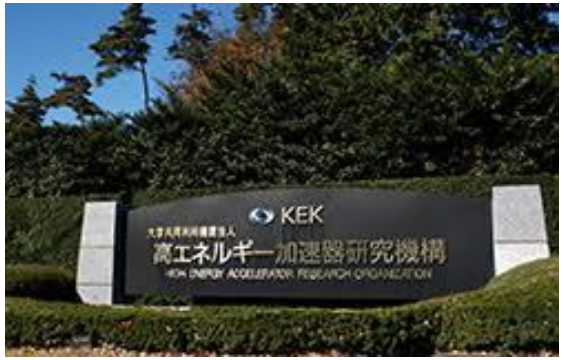
On behalf of the Belle II Collaboration

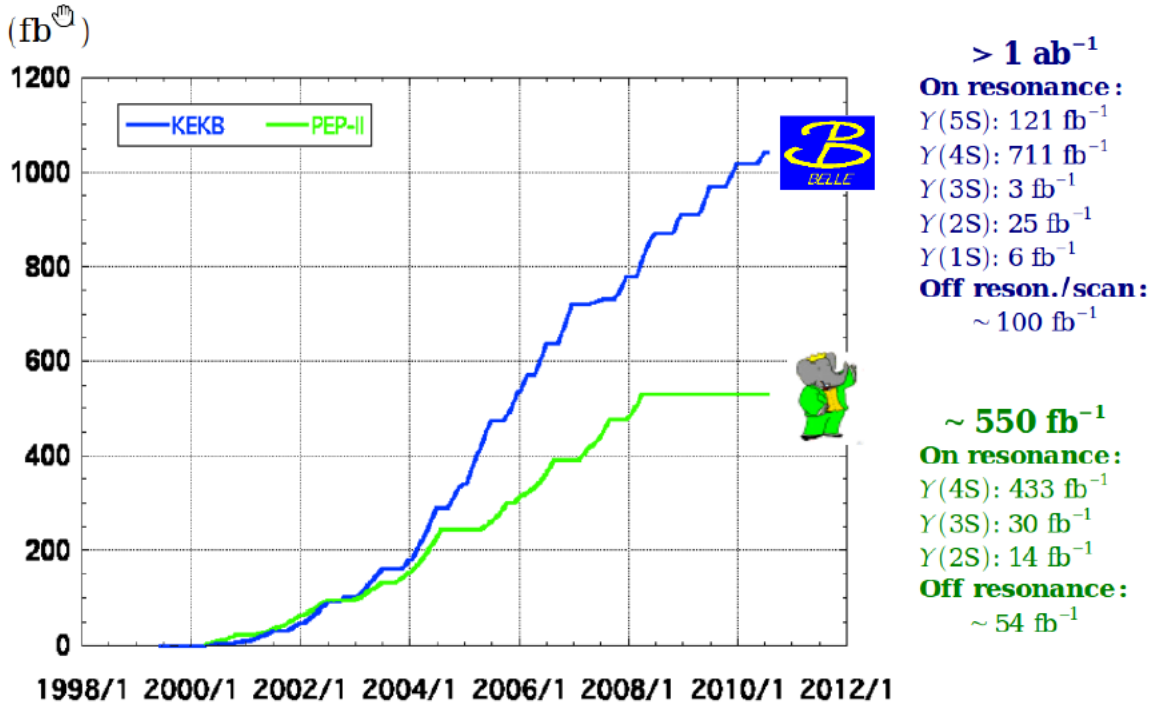
Topical workshop on LFV decays of the tau

Orsay, April 11th 2024

Back in the 2000s : Belle and Babar era

Belle at KEKB
Japan





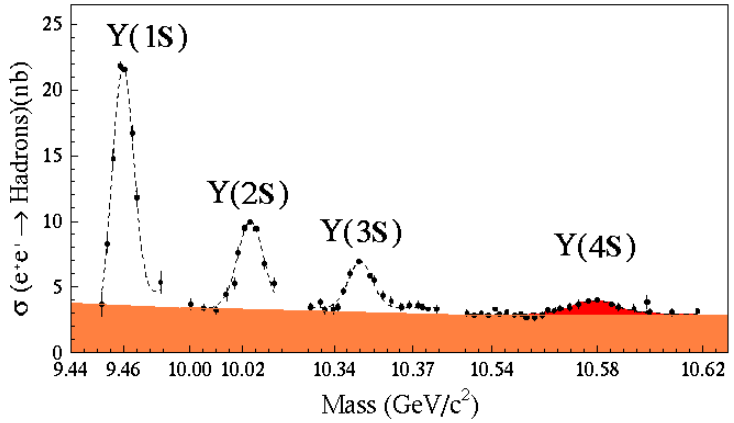
> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

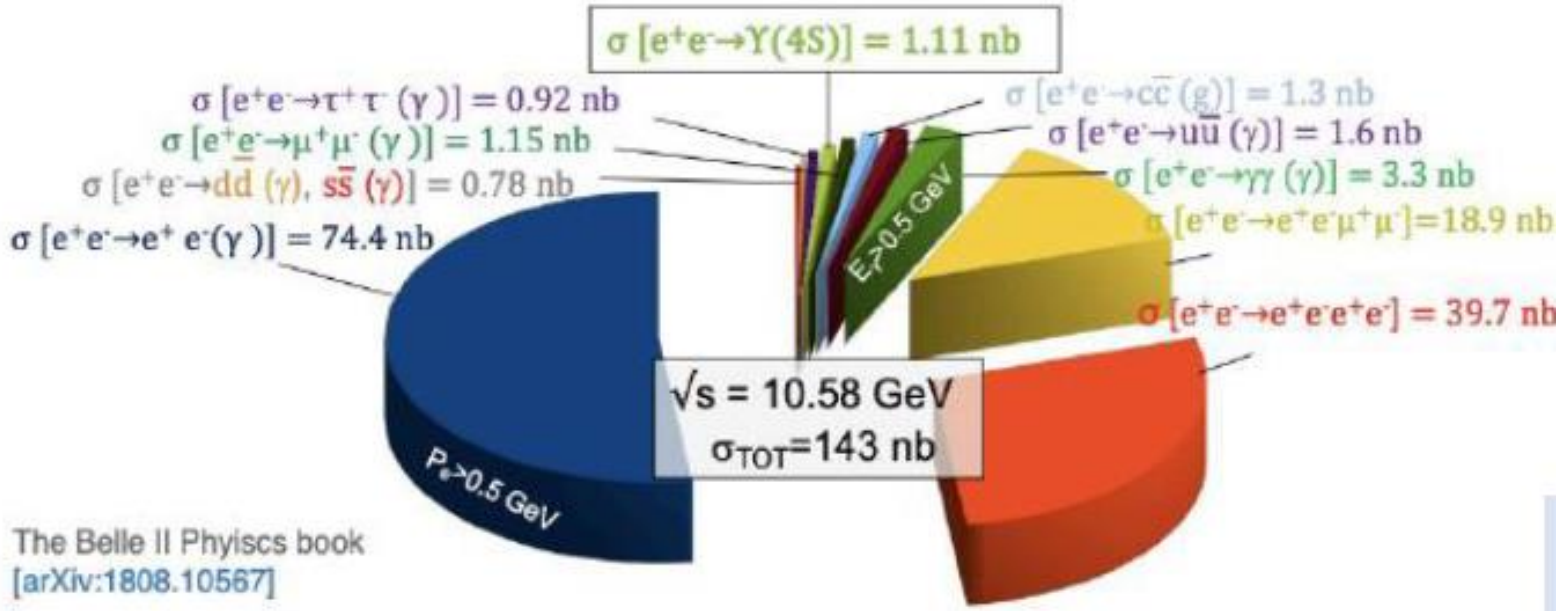
~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

Babar at PEP-II
California

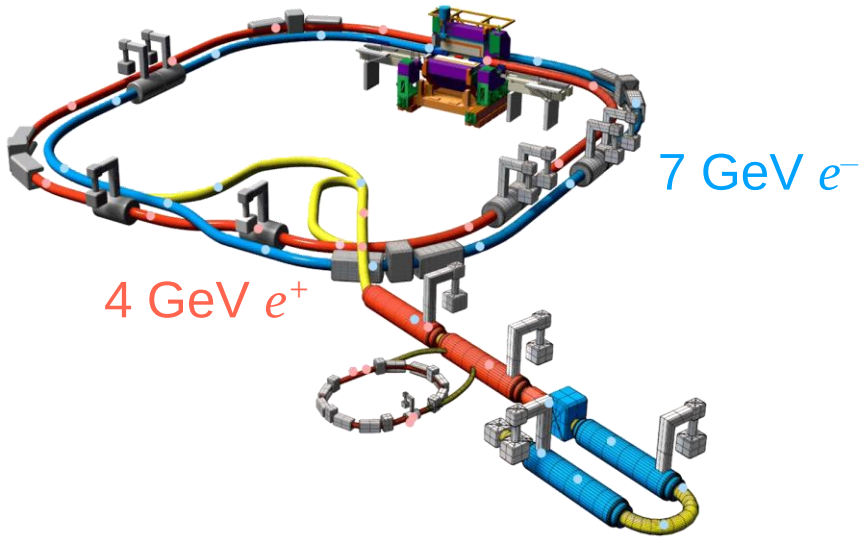
Physics processes at B-factories

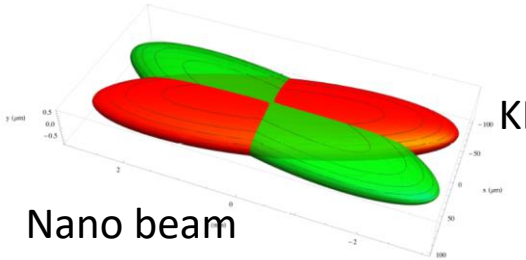
- e^+e^- collider, mainly working at the Y(4s) energy which produce pairs of B^+B^- and (quantum correlated) $B^0\bar{B}^0$
- Asymmetric beams → study time dependent effects in B hadron decays
- Also τ /charm factory (similar cross section as B)!



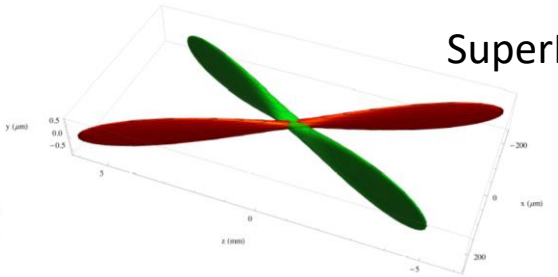


Back to the future: SuperKEKB and Belle II



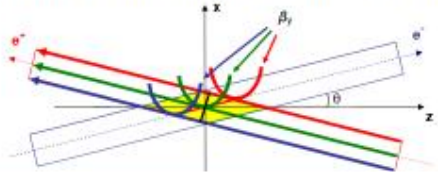


Nano beam scheme technology ⬇



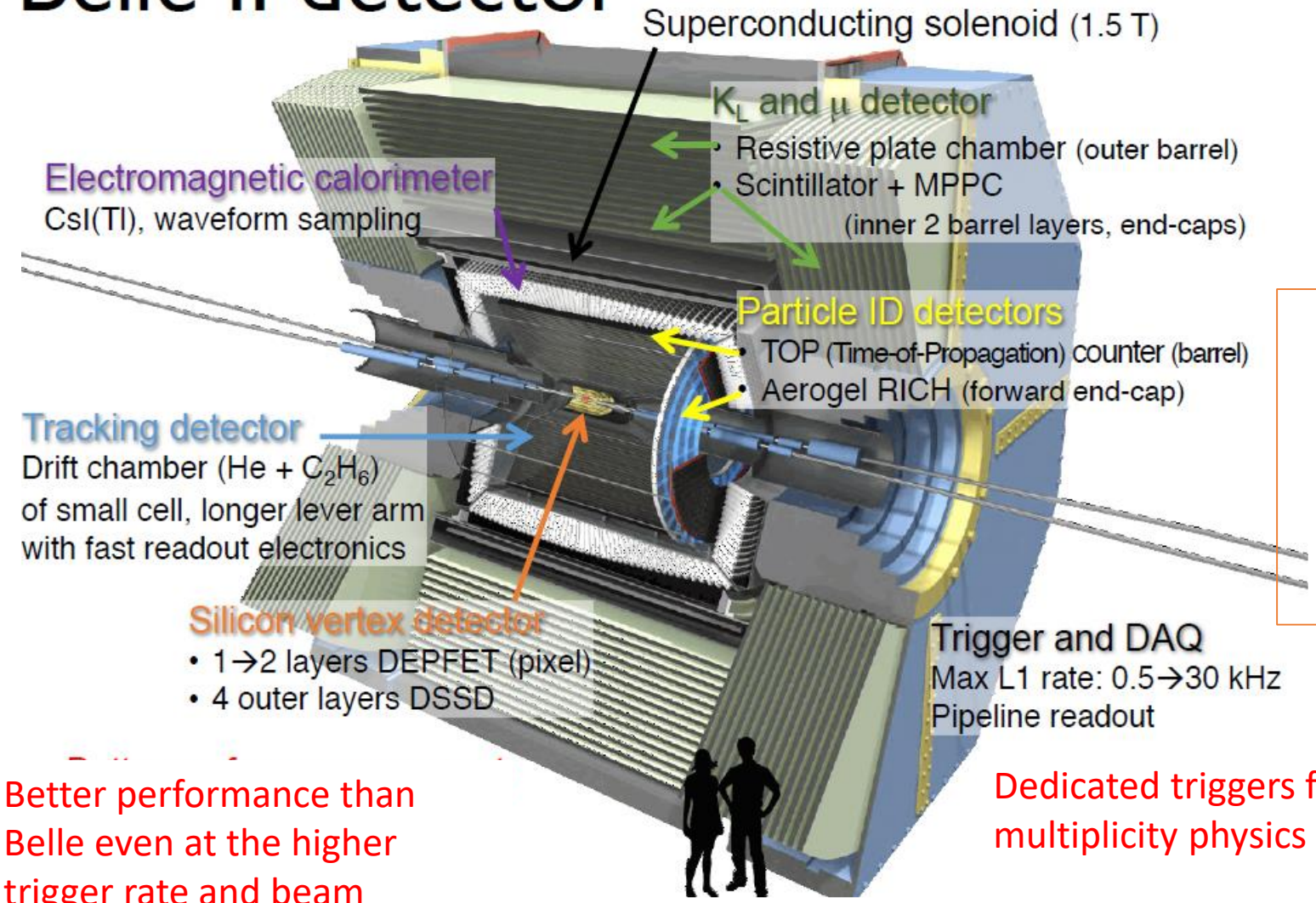
	KEKB	SuperKEKB	
		2020	Nominal
Energy (GeV) LER/HER	3.5 / 8	4 / 7	
Current (A) LER/HER	1.6/1.2	0.7/0.6	2.8 / 2.0
β_y^* (mm)	5.9	0.8	0.3
Instant. Lumi. ($cm^{-2}.s^{-1}$)	2.1×10^{34}	**2.4×10^{34}**	$\sim 6 \times 10^{35}$

Crossing angle (83 mrad) + crab waist (80%)



Belle II detector

3



Advantage for τ studies:

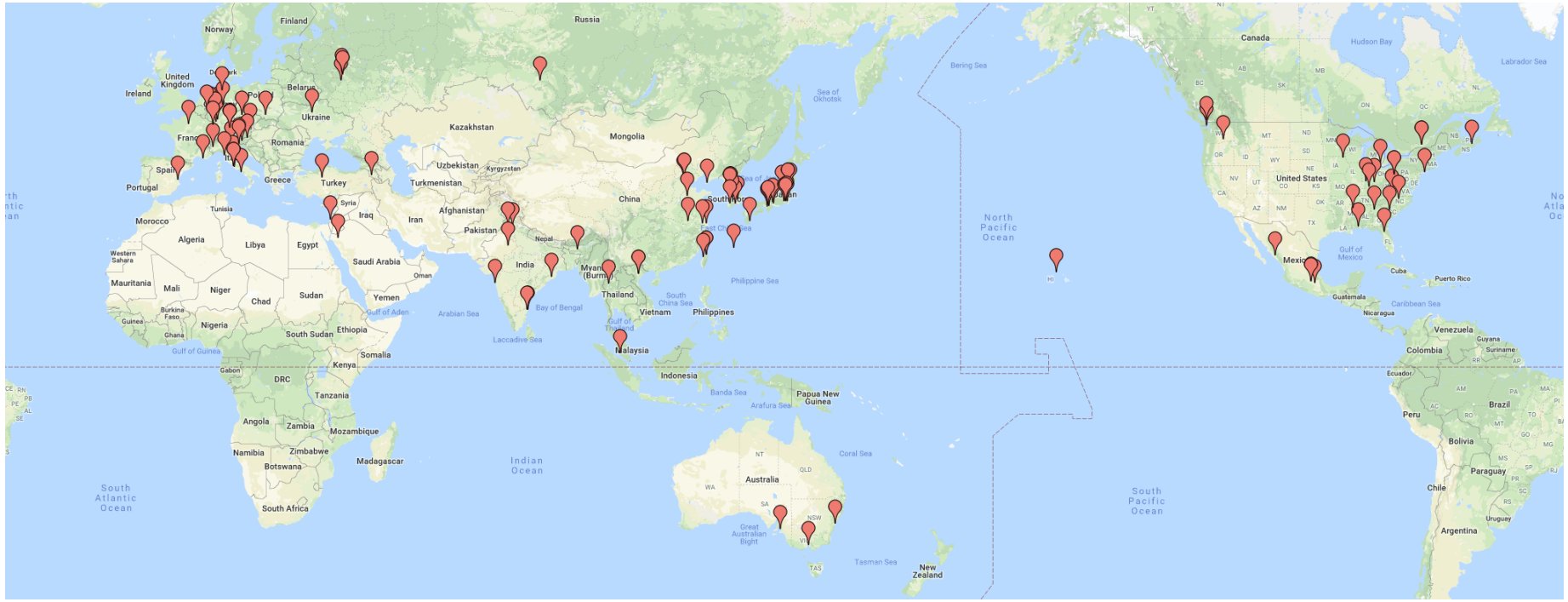
- almost hermetic detector + well defined initial state energy= measurement of missing energy
- Clean environment
- excellent PID for e and μ

Better performance than Belle even at the higher trigger rate and beam background

Dedicated triggers for low multiplicity physics

Belle II collaboration

- About 1100 physicists from 120 countries



Experiment status

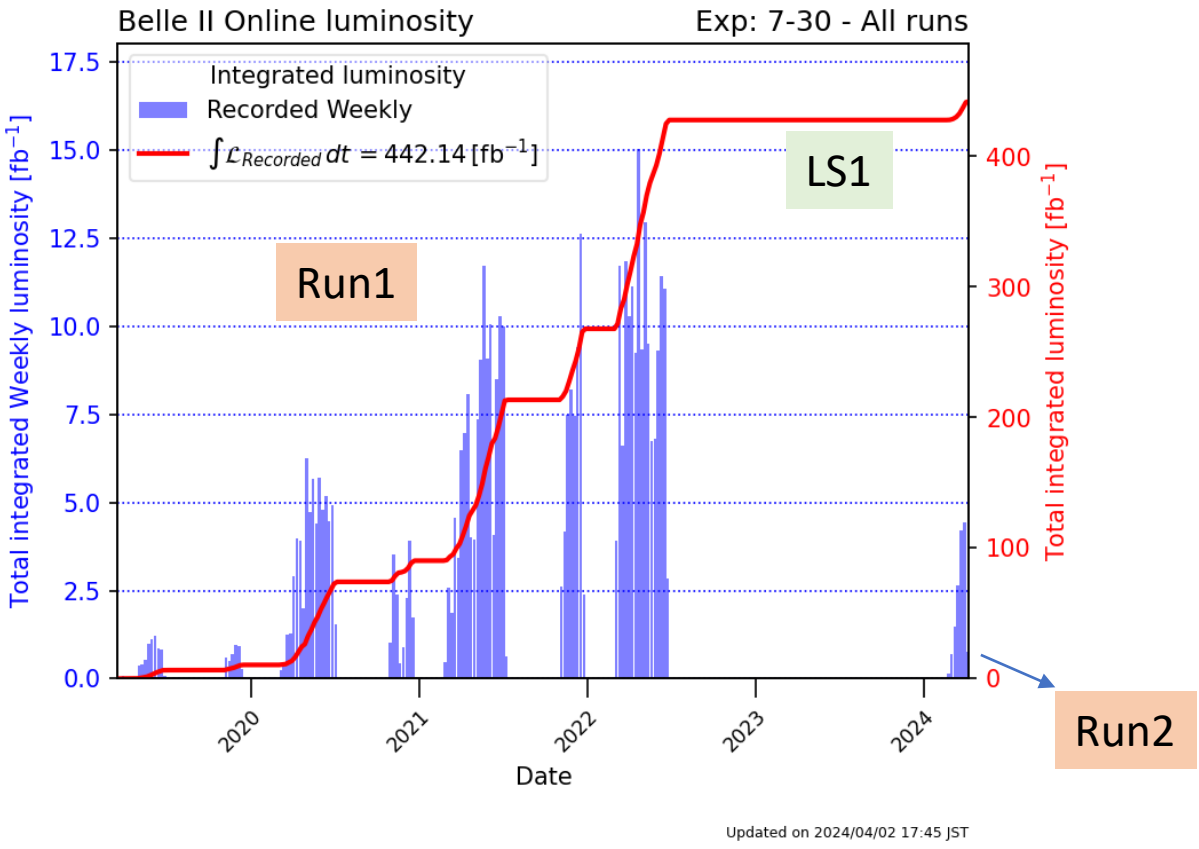
Run1 end 2019-mid 2022 with complete detector (except for PXD layer 2)
Long shutdown 1 mid 2022 – beginning 2024 : improvements on accelerator and installation of complete pixel detector
Run2 started february 2024

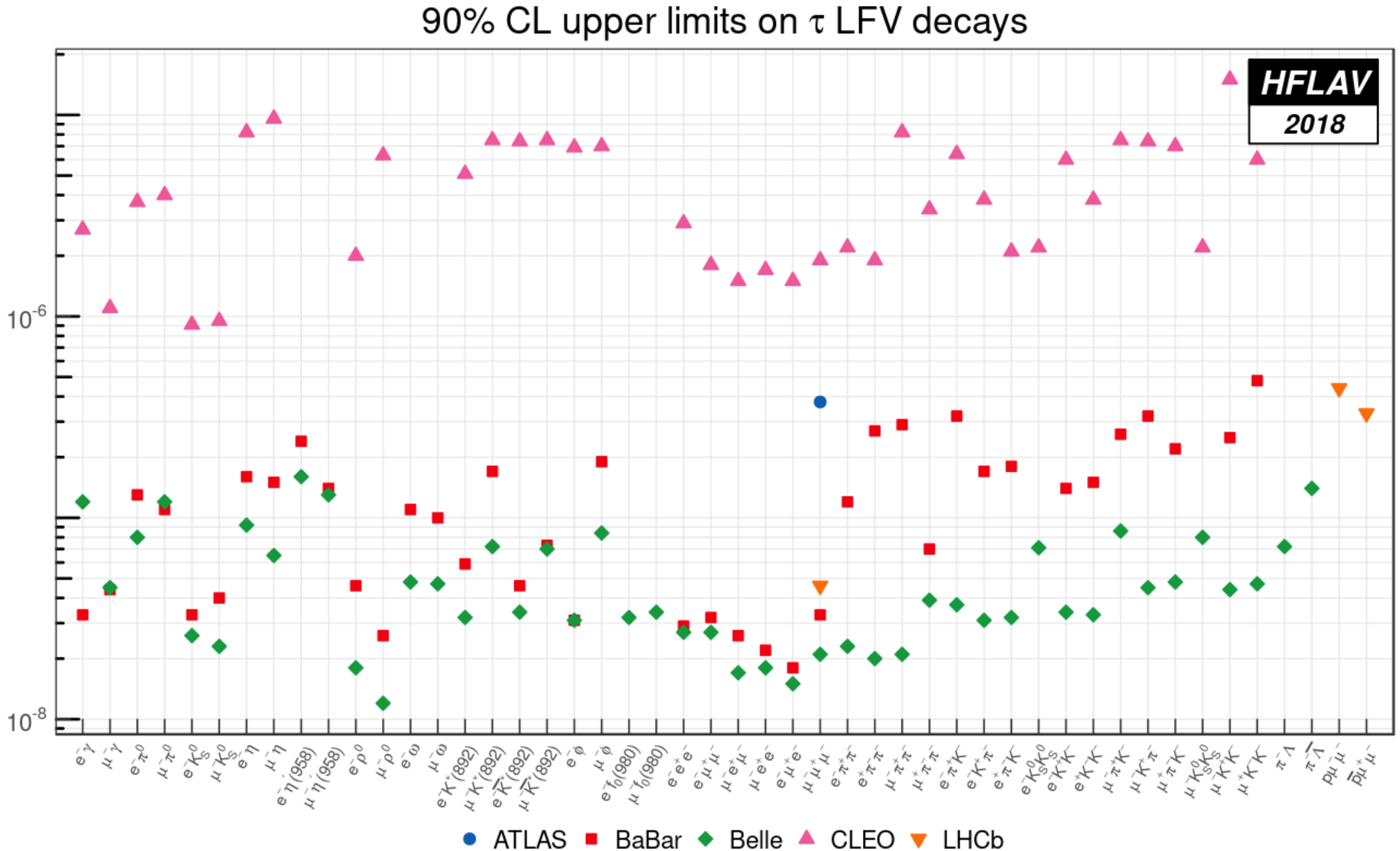
Achieved so far:

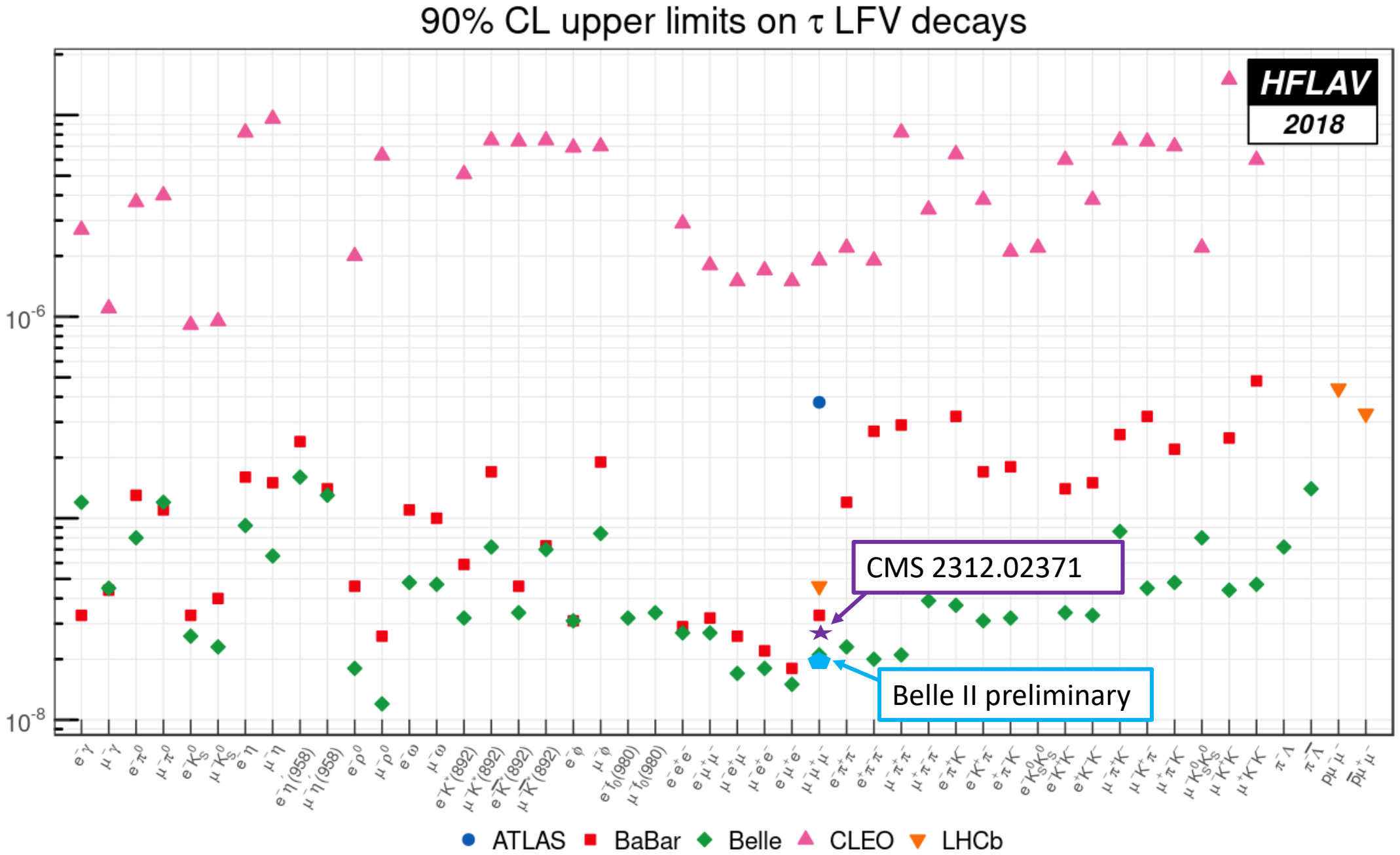
- World record of instantaneous lumi at 4.7×10^{34} $cm^{-2}s^{-1}$
- Recorded 442 fb^{-1} since 2019
- The analysis presented here is based on Run1 data (424 fb-1 among which 362fb-1 at Y(4S))

Main limitations to the luminosity during Run1:

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




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


90% CL upper limits on τ LFV decays
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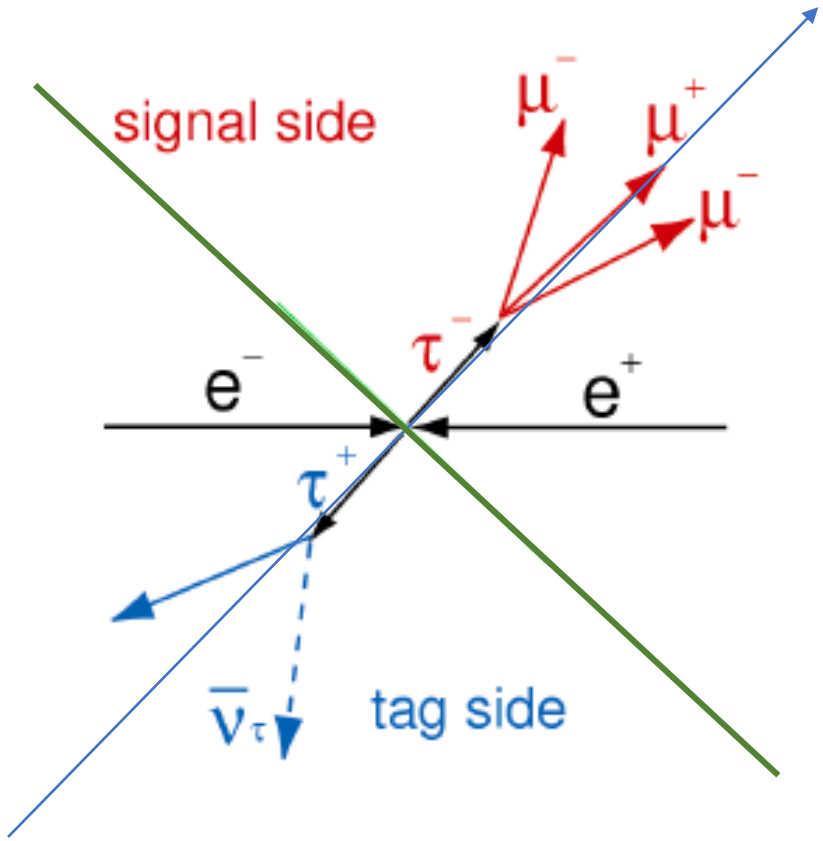
CMS 2312.02371
Belle II preliminary
ATLAS
BaBar
Belle
CLEO
LHCb

τ LFV searches at B factories

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

- Signal side τ→3l
- Tag side: τ→e/μ/π/ρ (+ν)

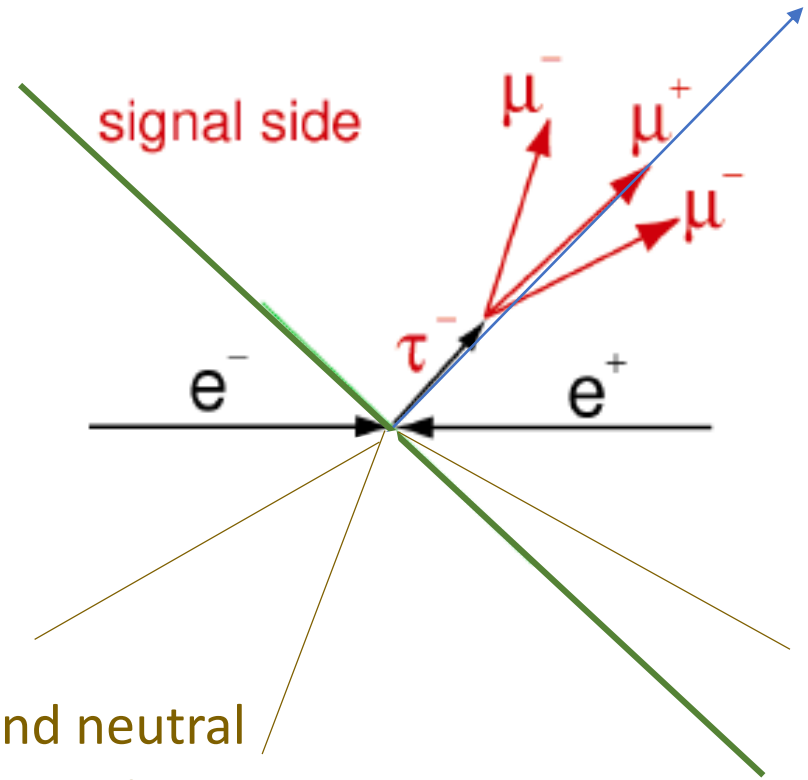
→ Require exactly 4 tracks in the event following the '3x1 topology'



Thrust axis

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

τ LFV searches at B factories



Thrust axis

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

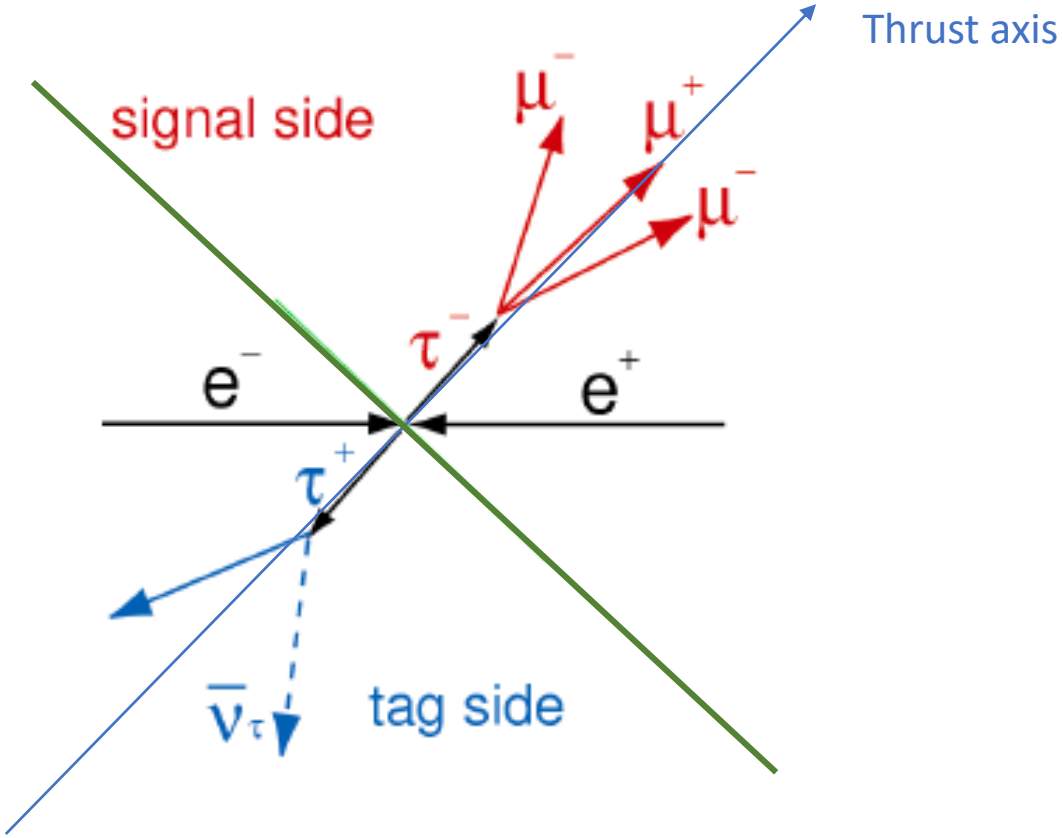
New inclusive approach:
Reconstruct only the signal tau and the 'rest-of-event'

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

τ→3μ selection

Signal selection:

- Require 3 muons well identified (muonID>0.5) 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)



$\tau \to 3\mu$ selection

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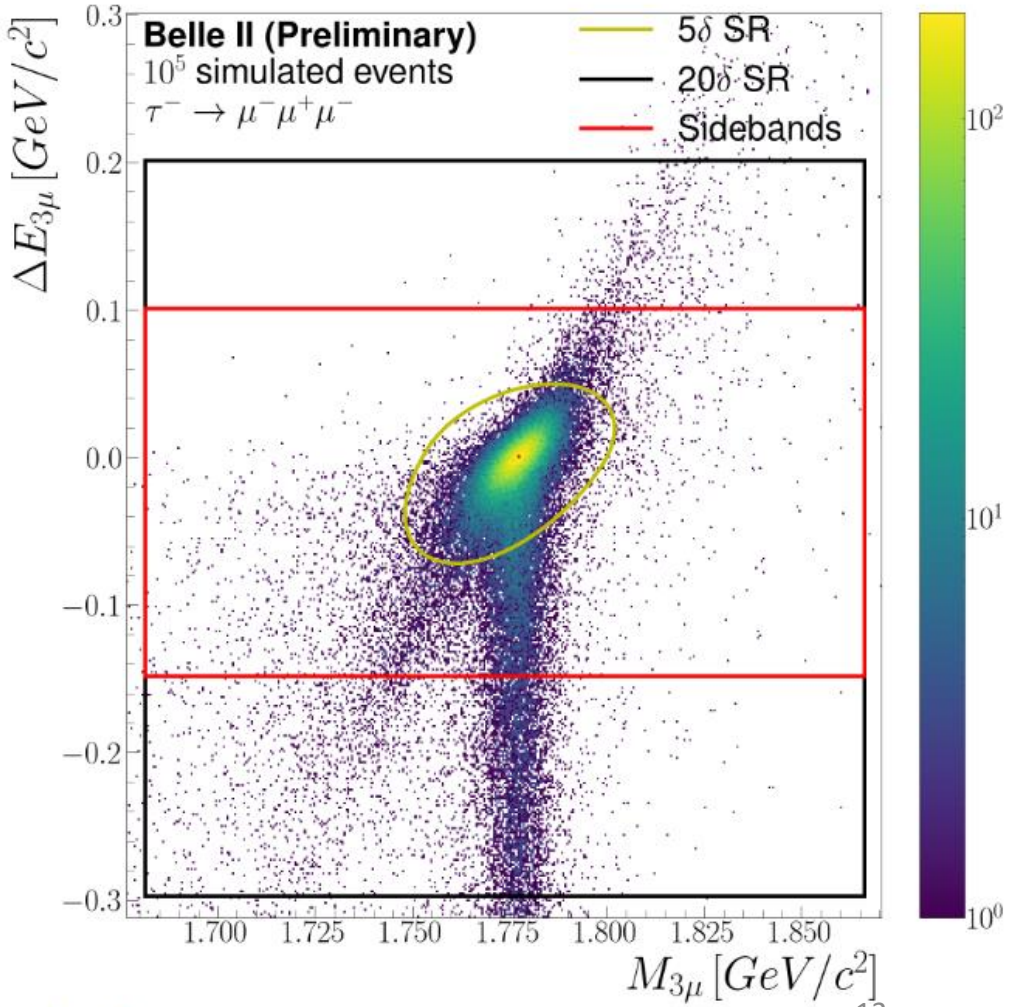
Define **2D plane** made of $M_{3\mu}$ and $\Delta E_{3\mu} = E^*_\tau - \sqrt{s}/2$

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

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- e+e- → τ+τ-
- Other (non simulated) low multiplicity events

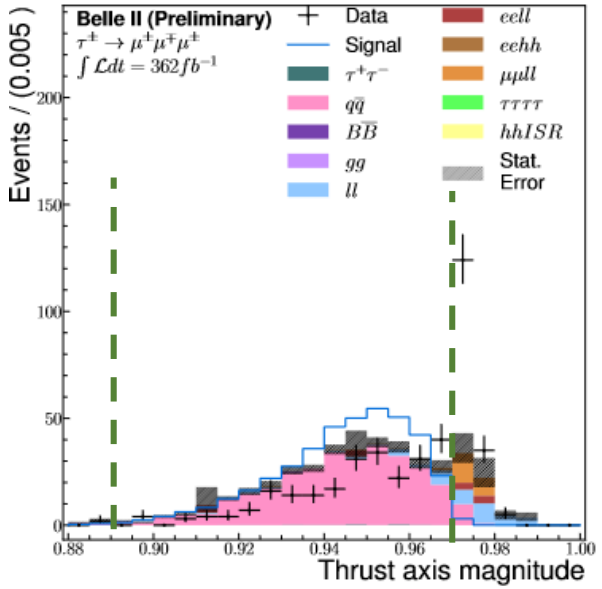
Most of backgrounds corresponds to pions/kaons/electrons misidentified as muons

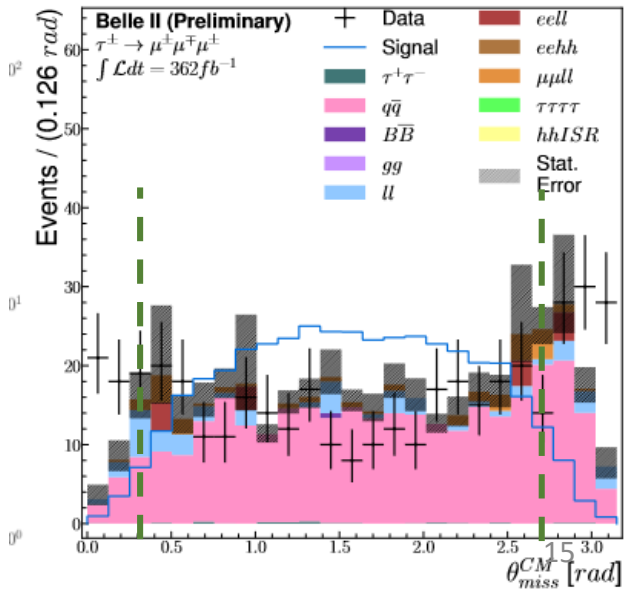
→ Tighten muonID : at least two muons with muonID>0.95

Low multiplicity backgrounds have high thrust values and missing E 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 pT, 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

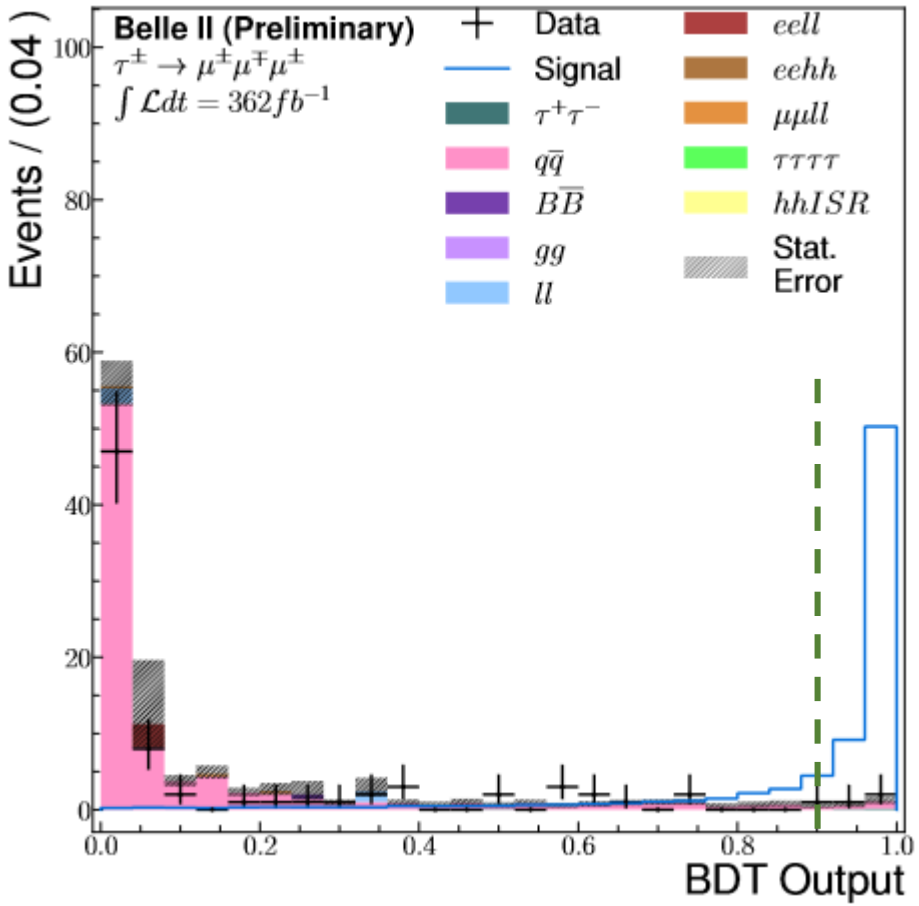
Final selection on BDT output optimize according to Punzi FOM : BDT>0.9

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

3σ significance α=3

Number of expected background

Data in SB region



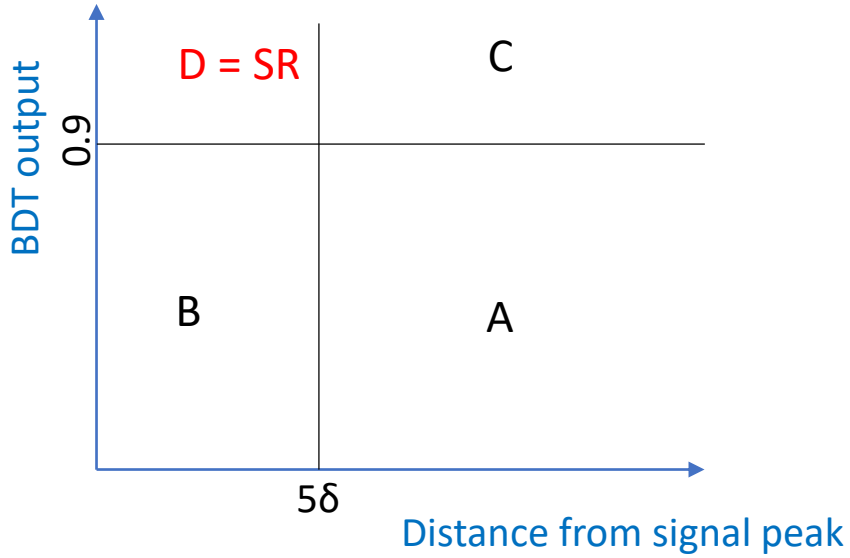
+ Final cut to require total charge=0

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



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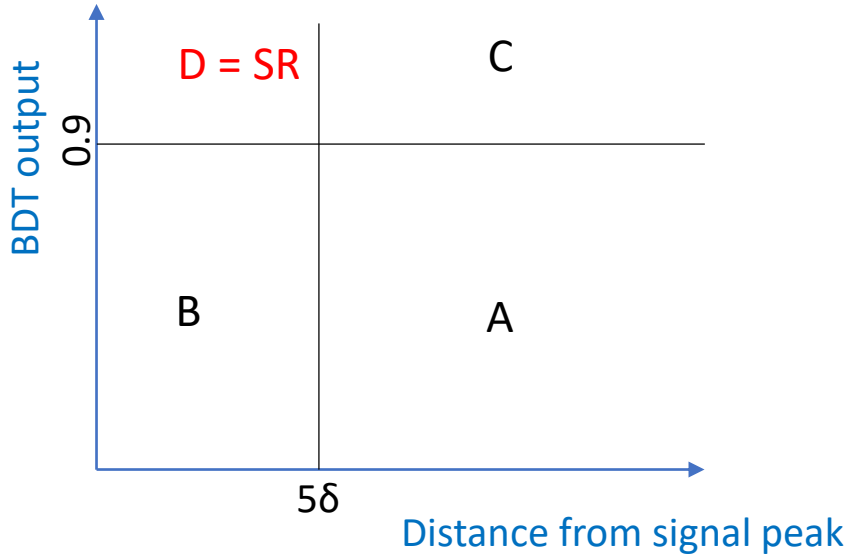


Systematic uncertainties:

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

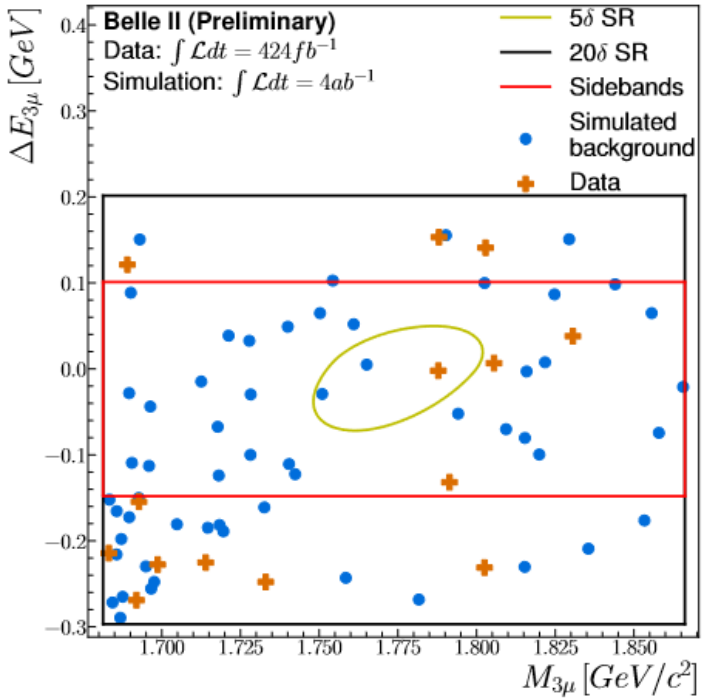
$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) = \frac{N_{obs} - N_{exp}}{\mathcal{L} \times 2\sigma_{\tau\tau} \times \varepsilon_{3\mu}}$$

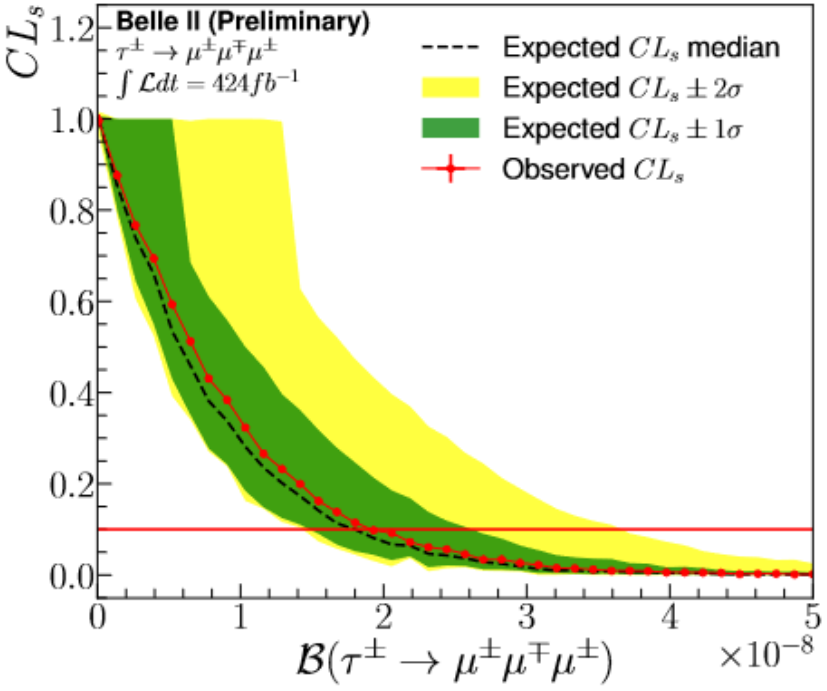
$N_{exp} = 0.5^{+1.4}_{-0.5}$

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

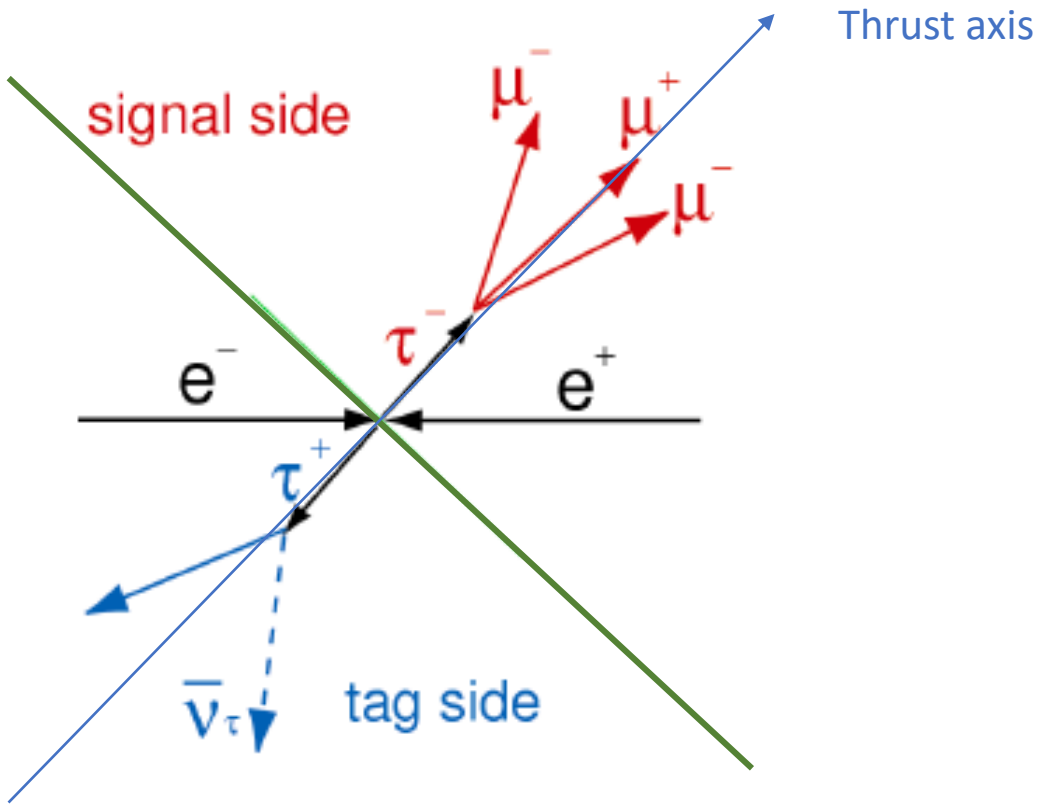
Independent measurement with classical 3x1 selection

Signal selection:

- Require 3 muons well identified (muonID>0.5) 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

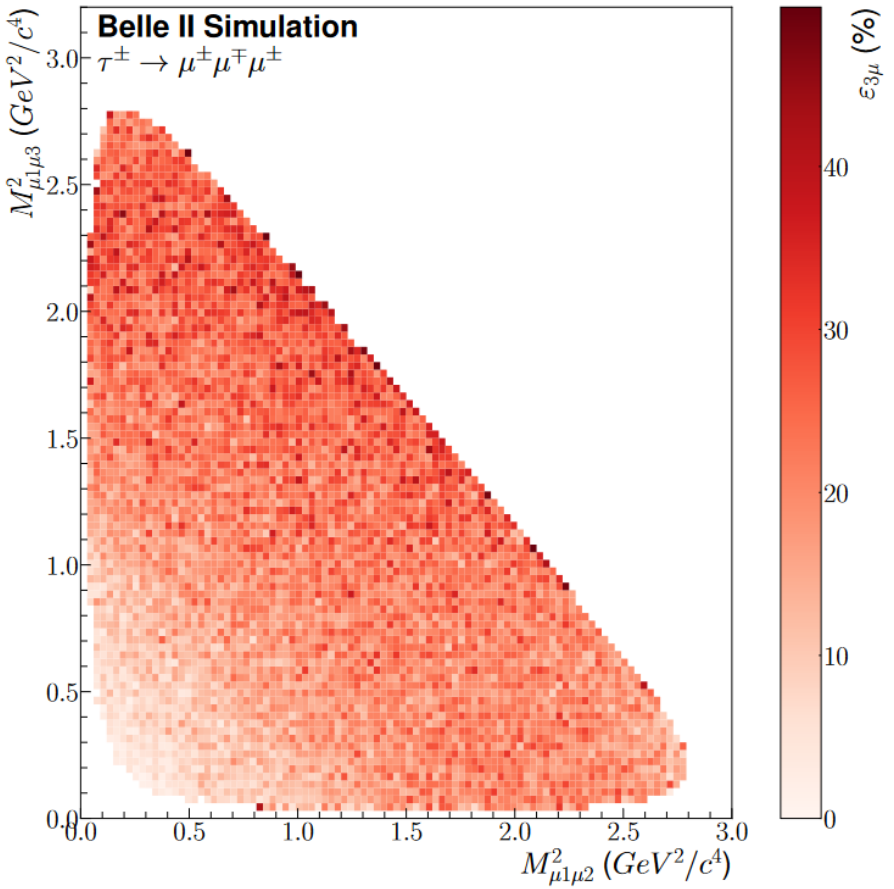
We observe 0 event, compatible with bkg expectation
Limit at 90%CL:
Expected $B(\tau \to 3\mu) < 2.0 \times 10^{-8}$
Observed $B(\tau \to 3\mu) < 2.0 \times 10^{-8}$



Additional information

We provide the efficiency as function of the Dalitz plane.

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



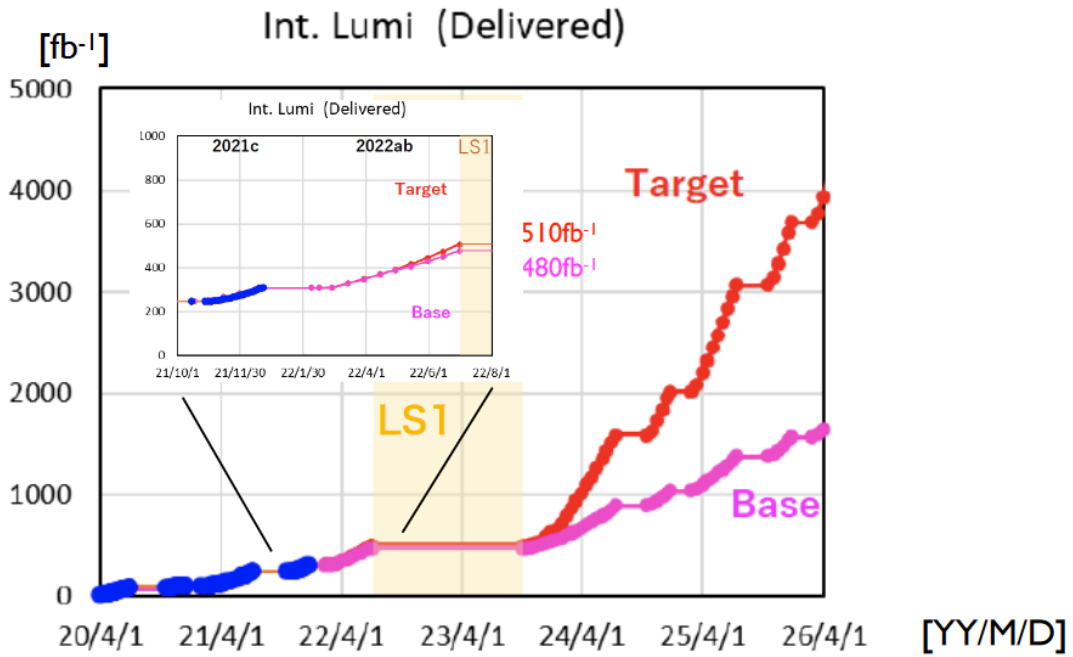
Summary and outlook

Belle II provided the most stringent limit on B(τ→3μ) at 1.9 x 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, he goal is to reach an instantaneous luminosity of $10^{35}/cm^2/s$
Belle II dataset will indrease 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



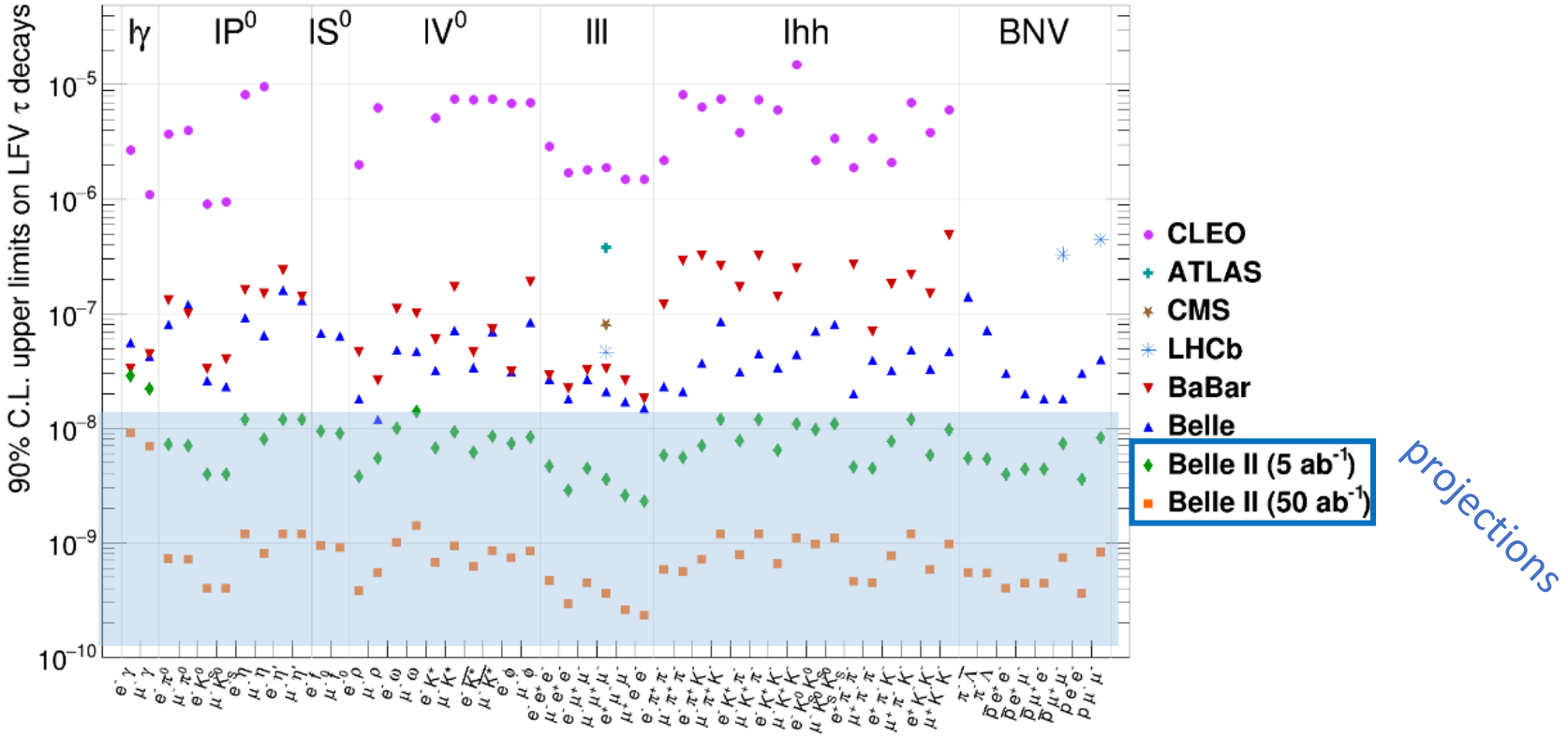
Beyond Run2

Discussions ongoing on a upgrade of the Belle II detector:

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

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

Snowmass 2021, arXiv: 2203.14919



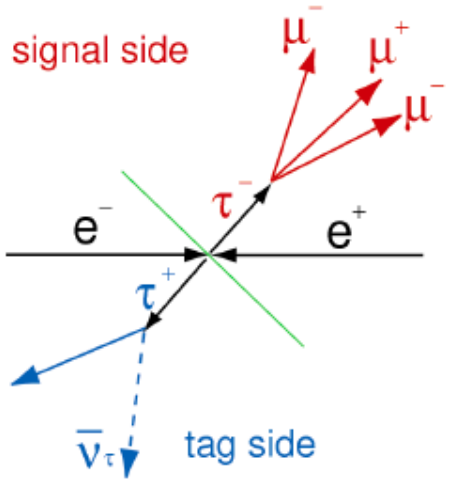
projections

Thanks!

τ LFV searches : analysis strategy

- Signal selection based on topology of the events:
  - τ leptons are produced in pairs and back-to-back in the center of mass frame. Can separate the τ events into 2 ‘hemispheres’ using the thrust axis.
  - τ leptons mainly decay into 1-prong or 3-prong final states
- Depending on the signal searched for, select 1x1, 3x1 or 3x3 topology
- Selection is then refined using simulated signal and background
- Signal region defined in a 2D plane : signal τ mass and $\Delta E = E_{sig} - E_{beam}$
- Expected background evaluated from sidebands (blind analysis)
- Limit obtained with CLs method

τ SM decays	BR (%)
$\tau^+ \to \mu^+ \nu\nu$	17.39±0.04
$\tau^+ \to e^+ \nu\nu$	17.82±0.04
$\tau^+ \to \pi^+ \nu$	10.82±0.05
$\tau^+ \to \pi^+ \pi^0 \nu$	25.49±0.09
$\tau^+ \to \pi^+ \pi^0 \pi^0 \nu$	9.26±0.10
$\tau^+ \to \pi^+ \pi^+ \pi^- \nu$	9.31±0.05
$\tau^+ \to \pi^+ \pi^+ \pi^- \pi^0 \nu$	4.62±0.05



Example of 3x1 topology

τ →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	-	-	-

Add ref and lumi