Prospects with taus at LHCb, Belle II and more…

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$b \to s\ell\ell$ 2019
7th Workshop on Rare Semileptonic B Decays

In this talk

- τ LFV decays
- B → τ LFV decays
- b→s$\tau\tau$ decays

Not covered:

- LUV tests in τ decays
- Mass and Michel parameters
- τ g-2, EDM
- …

Material stolen from different presentations (Alberto Luisano, Giampiero Mancinelli, Stéphane Monteil, Mogens Dam,…..)

Why caring about taus ?

1) Anomalies seen in violation of LFU suggests a special role of the third family

- enhancements of $\tau \rightarrow \mu/e$ and $B \rightarrow \tau\, \mu/e$ LFV decays
- enhancements of $b \rightarrow s\tau\tau$ decays

C. Cornella, J. Fuentes-Martin, et G. Isidori, « Revisiting the vector leptoquark explanation of the B-physics anomalies », *arXiv:1903.11517*

L. Calibbi, A. Crivellin, et T. Li, « A model of vector leptoquarks in view of the B-physics anomalies », *arXiv:1709.00692*

B. Bhattacharya, A. Datta, J.-P. Guévin, D. London, et R. Watanabe, « Simultaneous Explanation of the RK and R(D(*)) Puzzles: a Model Analysis », *Journal of High Energy Physics*, vol. 2017, nº 1, janv. 2017

D. Buttazzo, A. Greljo, G. Isidori, et D. Marzocca, « B-physics anomalies: a guide to combined explanations », *Journal of High Energy Physics*, vol. 2017, nº 11, nov. 2017.

D. Bečirević, N. Košnik, O. Sumensari, et R. Z. Funchal, « Palatable Leptoquark Scenarios for Lepton Flavor Violation in Exclusive $b\to s\ell_1\ell_2$ modes », *arXiv:1608.07583*

D. Choudhury, A. Kundu, R. Mandal, et R. Sinha, « R_K(*) and R(D(*)) anomalies resolved with lepton mixing », *arXiv:1712.01593*

A. Crivellin, D. Müller, et T. Ota, « Simultaneous Explanation of R(D(*)) and $b \rightarrow s\mu\mu$: The Last Scalar Leptoquarks Standing », *Journal of High Energy Physics*, vol. 2017, nº 9, sept. 2017

S. L. Glashow, D. Guadagnoli, et K. Lane, « Lepton Flavor Violation in B Decays? », *Physical Review Letters*, vol. 114, nº 9, mars 2015.

D. Guadagnoli et K. Lane, « Charged-Lepton Mixing and Lepton Flavor Violation », *Physics Letters B*, vol. 751, p. 54-58, déc. 2015.

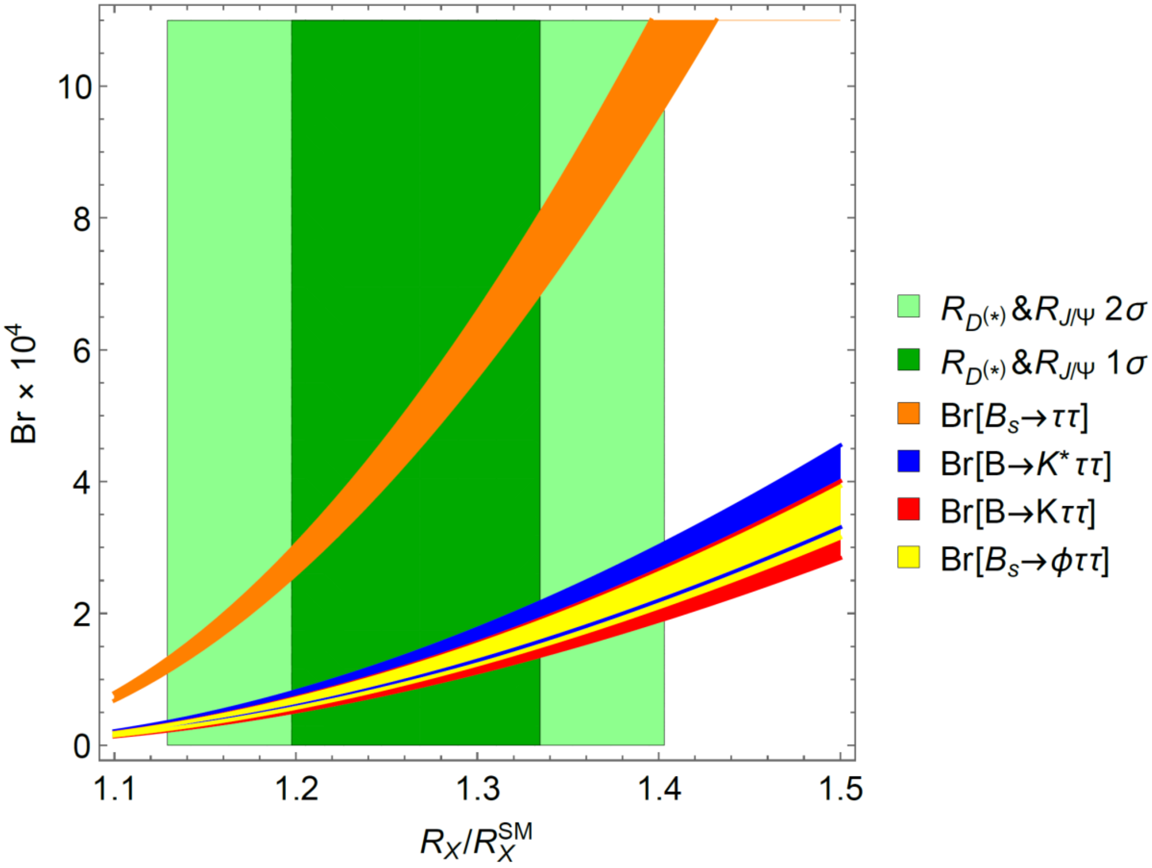
R. Alonso, B. Grinstein, et J. M. Camalich, « Lepton universality violation and lepton flavor conservation in B-meson decays », *arXiv:1505.05164*

B. Capdevila, A. Crivellin, S. Descotes-Genon, L. Hofer, et J. Matias, « Searching for New Physics with $b \rightarrow s\tau^+\tau^-$ processes », *arXiv:1712.01919*

F. Feruglio, P. Paradisi, et A. Pattori, « Revisiting Lepton Flavor Universality in B Decays », *Phys.Rev.Lett.*, vol. 118, p. 011801

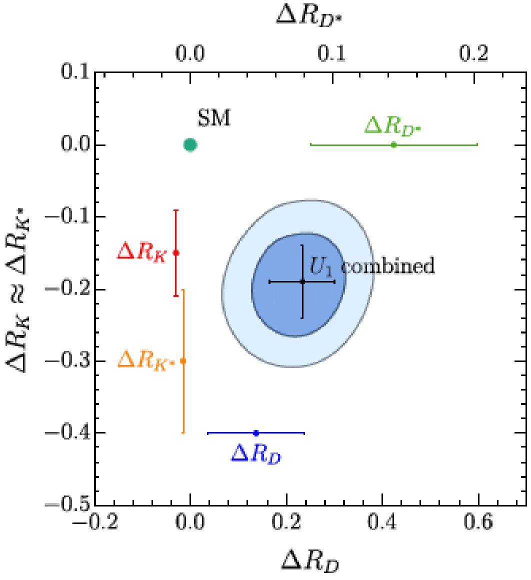
Etc ……..

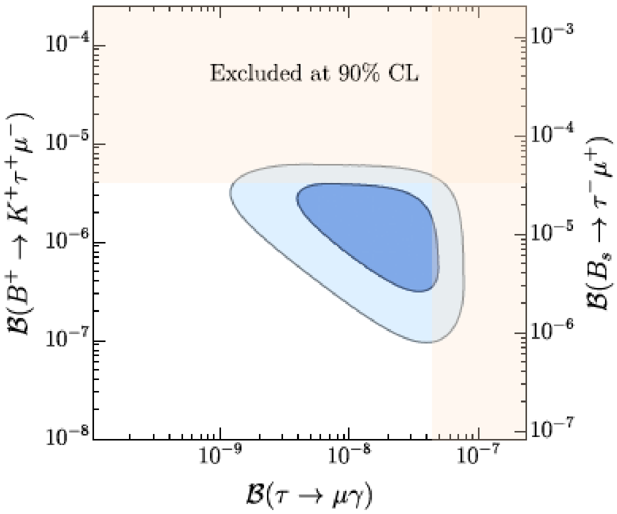
Correlations between charged current anomalies and b→sττ decays, assuming NP contributions in $C^{\tau\tau}_{9(')}$ and $C^{\tau\tau}_{10(')}$



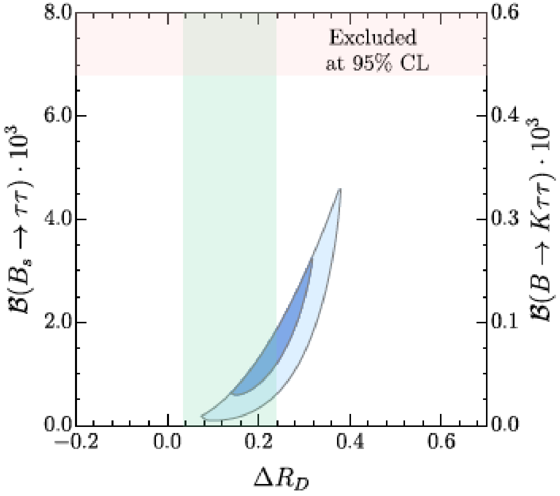
B. Capdevila, A. Crivellin, S. Descotes-Genon, L. Hofer, et J. Matias, *arXiv:1712.01919*, *PRL 120, 181802*

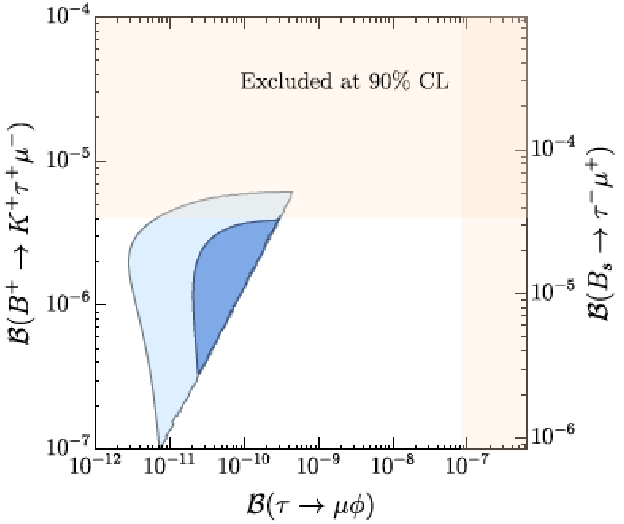
Interpretation of the anomalies in terms of vector leptoquarks





C. Cornella, J. Fuentes-Martin, et G. Isidori, *arXiv:1903.11517* , JHEP 1907 (2019) 168





Why caring about taus ?

2) b→τ decays are much less well known than their e/μ counterparts

Decays	SM prediction	Best 90% CL UL
$B \to \tau\, e/\mu$	-	$2.8/1.2\ 10^{-5}$ [3][4]
$B_s \to \tau\, \mu$	-	$3.4\ 10^{-5}$ [4]
$B \to K \tau\, e/\mu$	-	$3.0/4.8\ 10^{-5}$ [5]
$B \to \pi \tau\, e/\mu$	-	$7.5/7.2\ 10^{-5}$ [5]
$B \to K^* \tau\, e/\mu$	-	-
$B^0 \to \tau\tau$	$(2.22\pm0.19)\ 10^{-8}$ [1]	$1.6\ 10^{-3}$ [6]
$B_s \to \tau\tau$	$(7.73\pm0.49)\ 10^{-7}$ [1]	$5.2\ 10^{-3}$ [6]
$B \to K^*\tau\tau$	$(0.98\pm0.10)\ 10^{-7}$ [2]	-
$B \to K\tau\tau$	$(1.20\pm0.12)\ 10^{-7}$ [2]	$2.25\ 10^{-3}$ [7]

[1] PRL 112(2014)101801
[2] PRL 120(2018)181802
[3] Babar PRD 77(2008)091104
[4] LHCb arXiv:1905.06614
[5] Babar PRD 86(2012)012004
[6] LHCb PRL 118(2017)251802
[7] Babar PRL 118(2017)031802

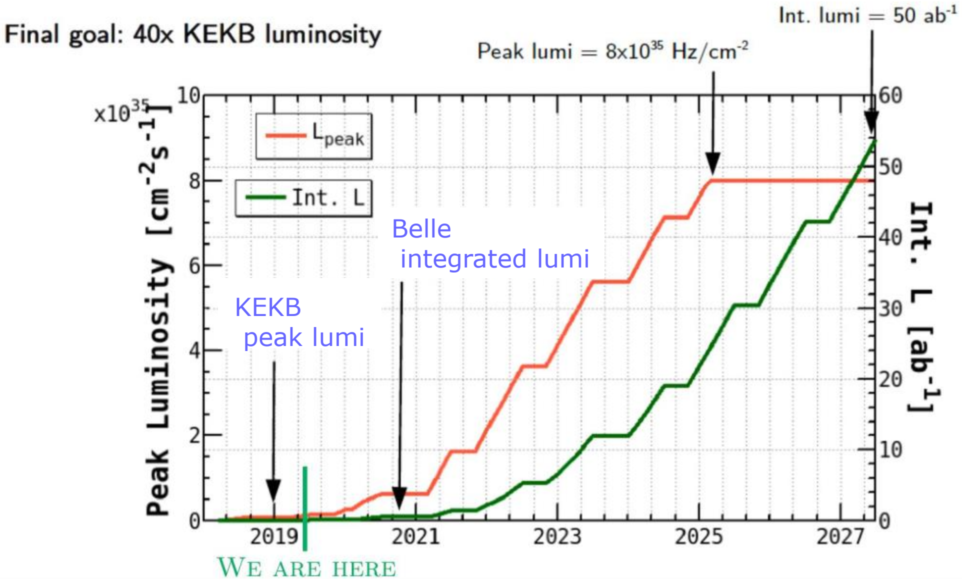
3) Tau is the heaviest lepton, giving access to many LFV decays

→ ideal probe for NP, different types of coupling can be tested

Main players

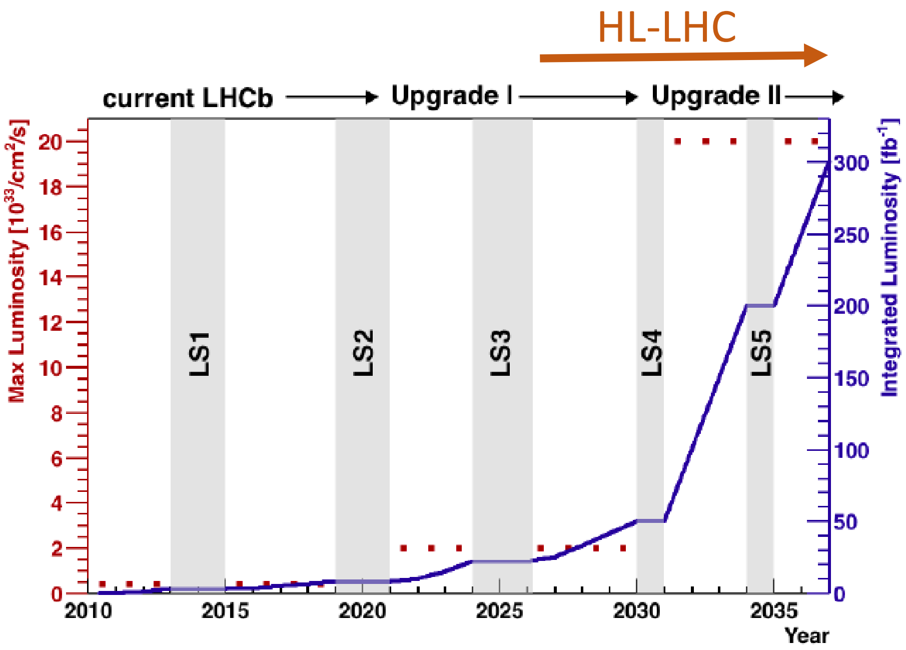
Belle II

Physics data taking started in 2019
Expect 50 x Belle statistics by 2027



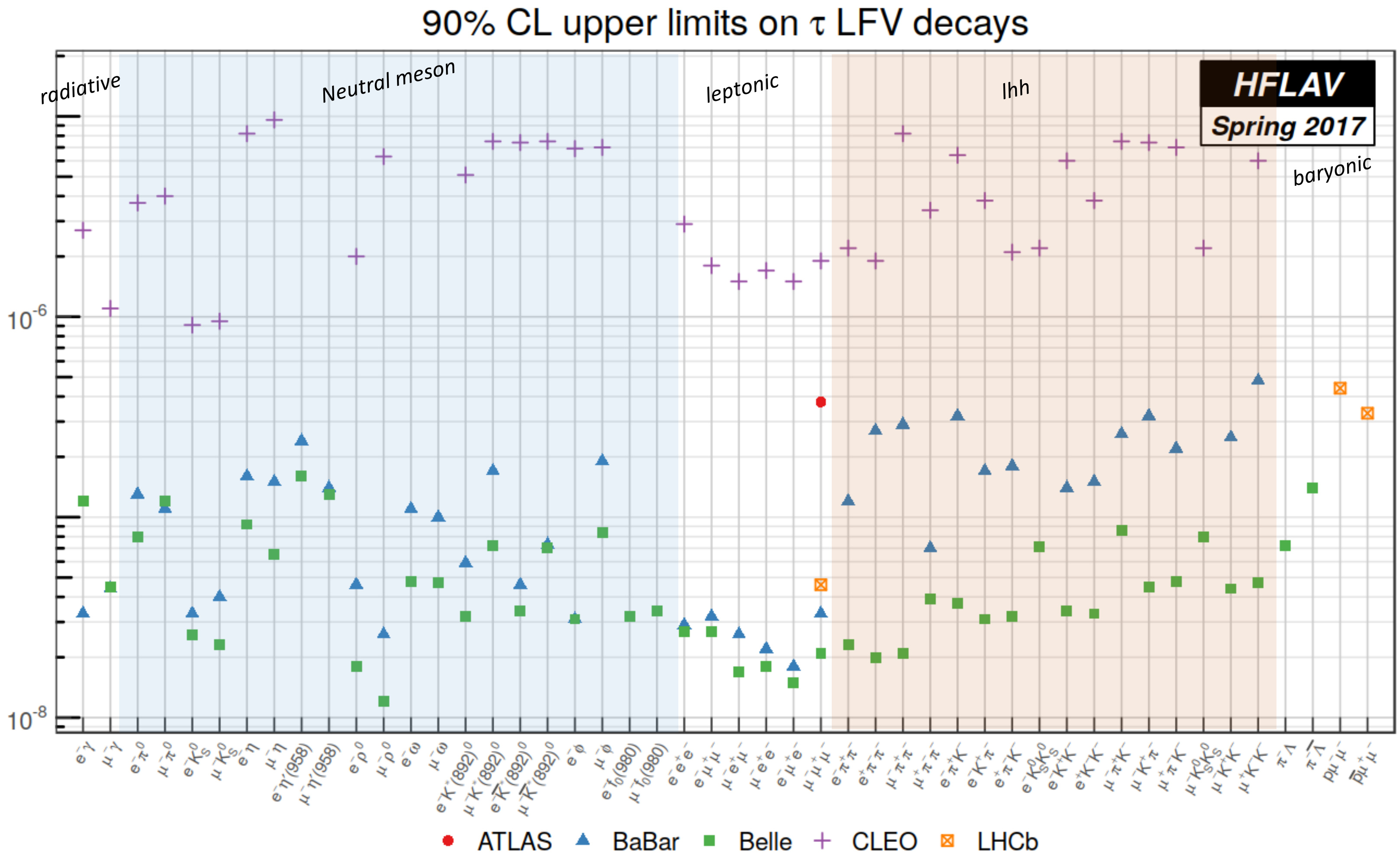
LHCb

Recorded ~9fb-1
Current upgrade I ongoing to increase peak luminosity by factor 5
Upgrade II under discussion



τ LFV decays

Tau LFV : status

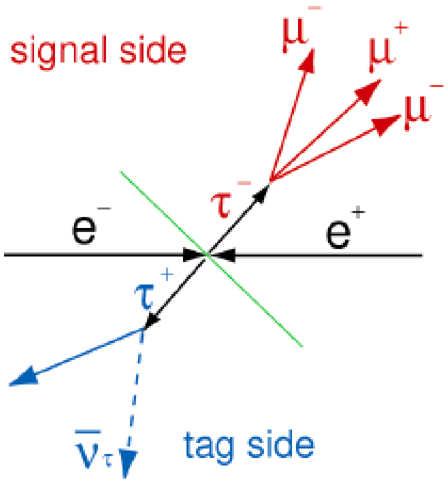


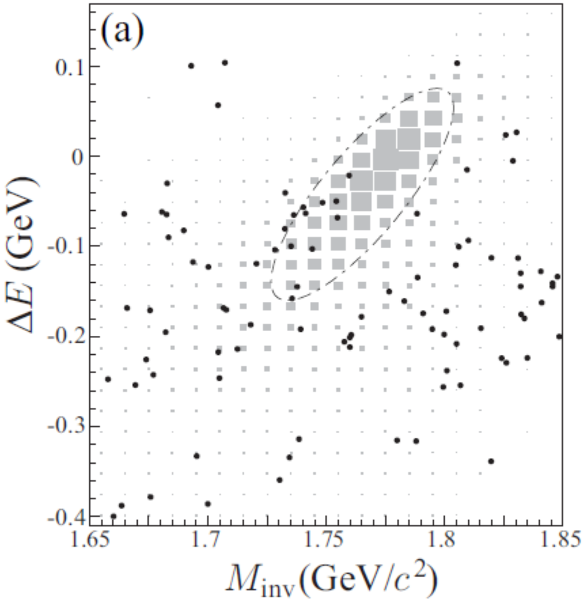
Current limits at few 10^{-8} dominated by Belle

In μ→e transitions, limits are at 10^{-13} level!

Tau LFV at B factories

- $\sigma_{\tau\tau}$=0.9 nb ~ σ_{bb} : B factories are also τ factories
- Reconstruct the entire events (sometimes only leptonic or one prong decays of τ tag are used)
- Use variables related to event topology to suppress B backgrounds
- Background evaluated from sidebands in m_τ and $\Delta E=E^{CM}_{sig}-E^{CM}_{beam}$ variables



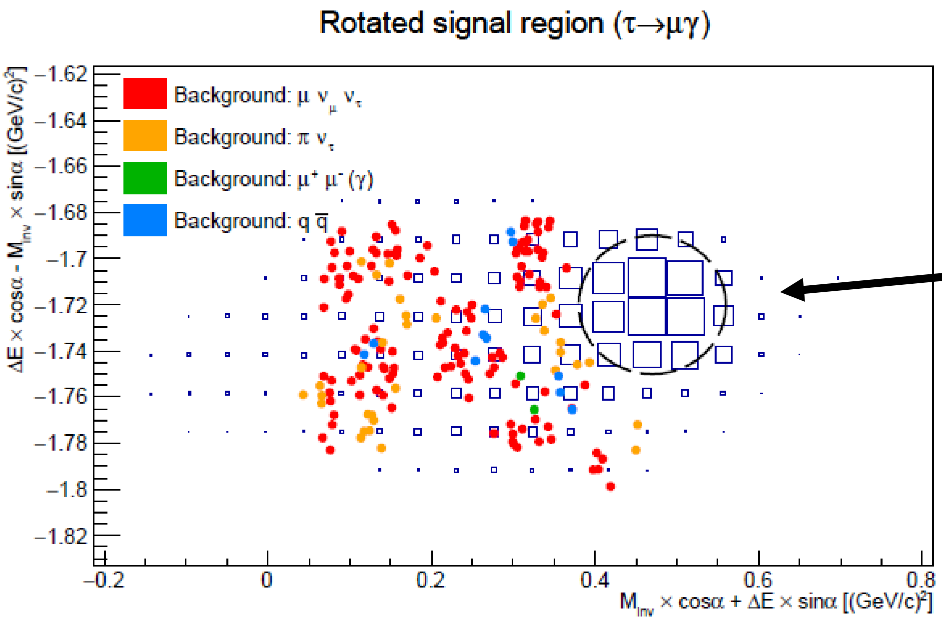


Belle τ → μγ

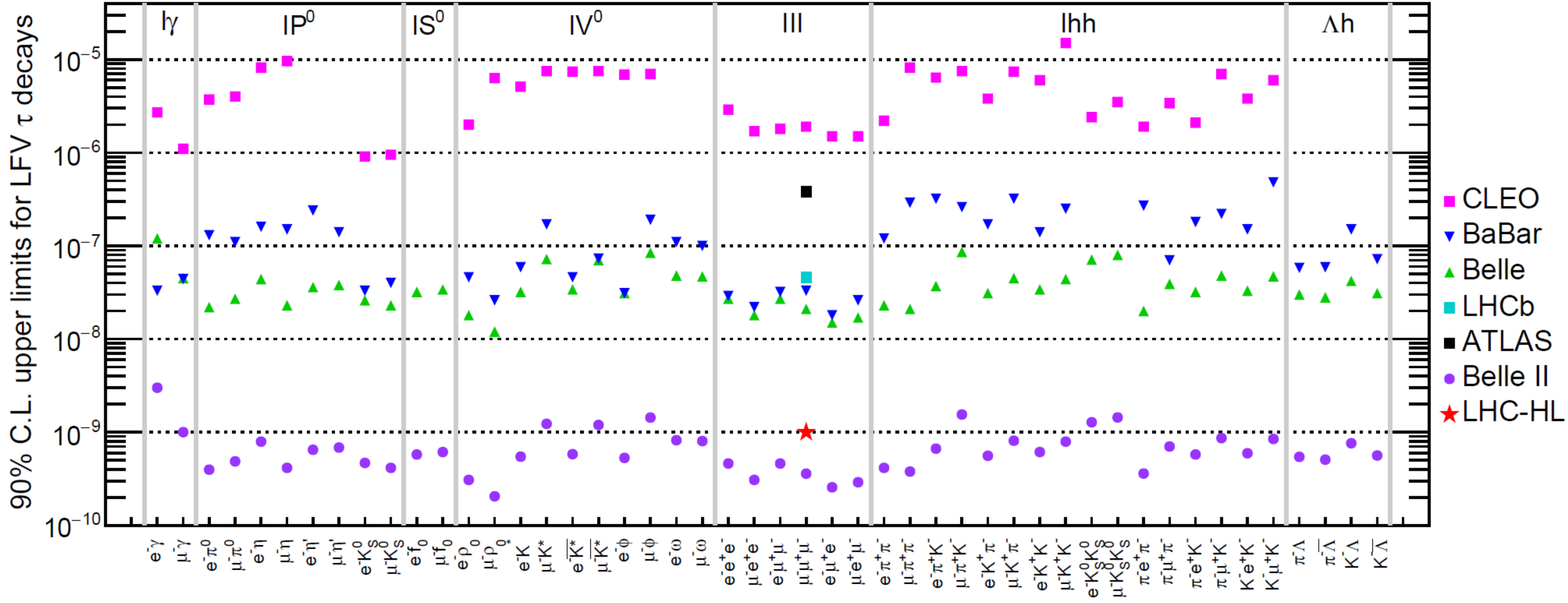
PLB 666 16-22 (2008)

Prospects for Belle II

- Most of LFV analyses are background free, expected limits scale as luminosity
- This may not be the case for $\tau \rightarrow \mu/e\gamma$ due to higher beam induced backgrounds than in Belle
  Dedicated MC analysis showed that this can be mitigate
- Improved photon position reconstruction in ECL also helps



Signal region, background free (Belle II physics book, arXiv:1808.10567)



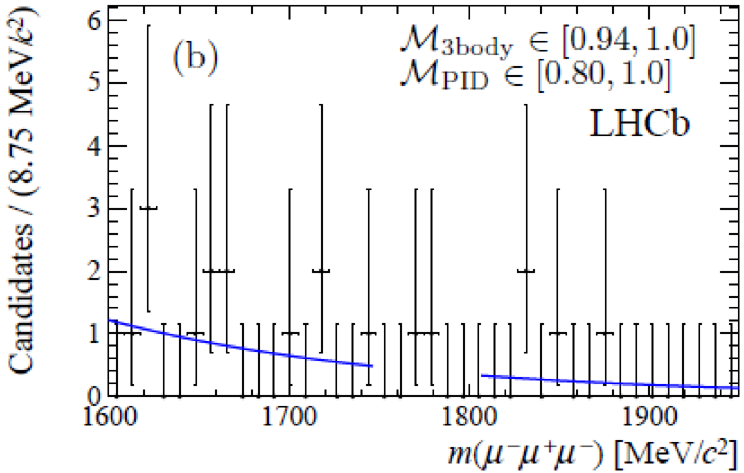
From HL-LHC and HE-LHC opportunities arXiv:1812.07638

Tau LFV at LHC

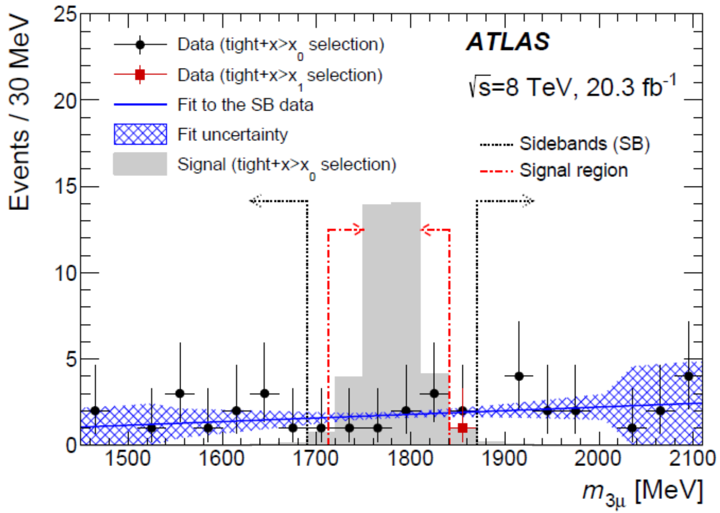
- $\sigma_{\tau\tau}$ at the LHC about 5 orders of magnitude larger than at Belle II
- Reconstruct only τ decay products (no tagging)
- Fit m_τ in bins of a multivariate classifier

- Use τ produced from $D_s \rightarrow \tau\nu$ (LHCb) and/or $W \rightarrow \tau\nu$ (ATLAS)
- LHCb normalises to $D_s \rightarrow \phi(\rightarrow\mu\mu)\,\pi$ channel / ATLAS estimates the number of τ produced from MC
- Only $\tau \rightarrow \mu\mu\mu$ and $\tau \rightarrow \overset{(-)}{p}\mu\mu$ studied so far

JHEP 02(2015)121

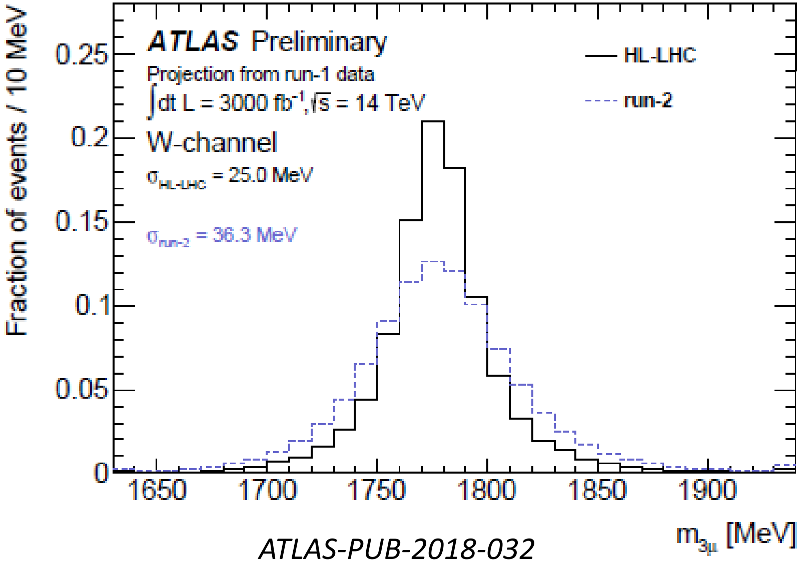


EPJC 76(2016)232



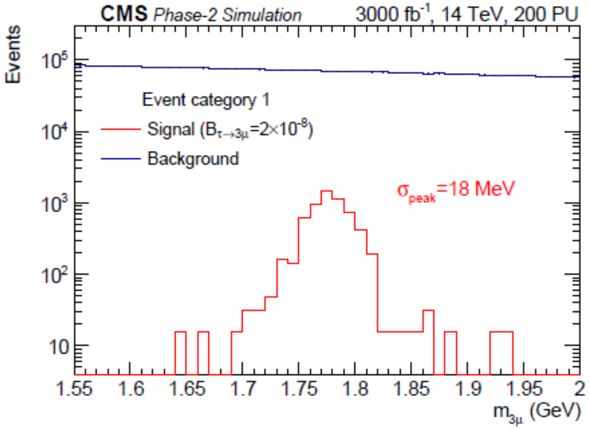
Prospects for HL-LHC

- ATLAS will benefit from improved tracking and trigger system
- CMS will benefit from the upgraded muon system with better coverage $|\eta|=2.4 \rightarrow 2.8$
- LHCb Upgrade 1 will enable a better trigger efficency. Improved calorimeters in Upgrade II will help reducing background from Ds → η(→ μμγ)μν events

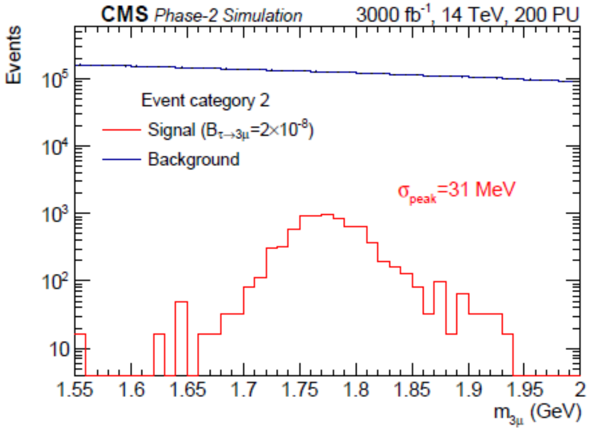


ATLAS-PUB-2018-032

Phase-1 detector only



At least one mu in new detector



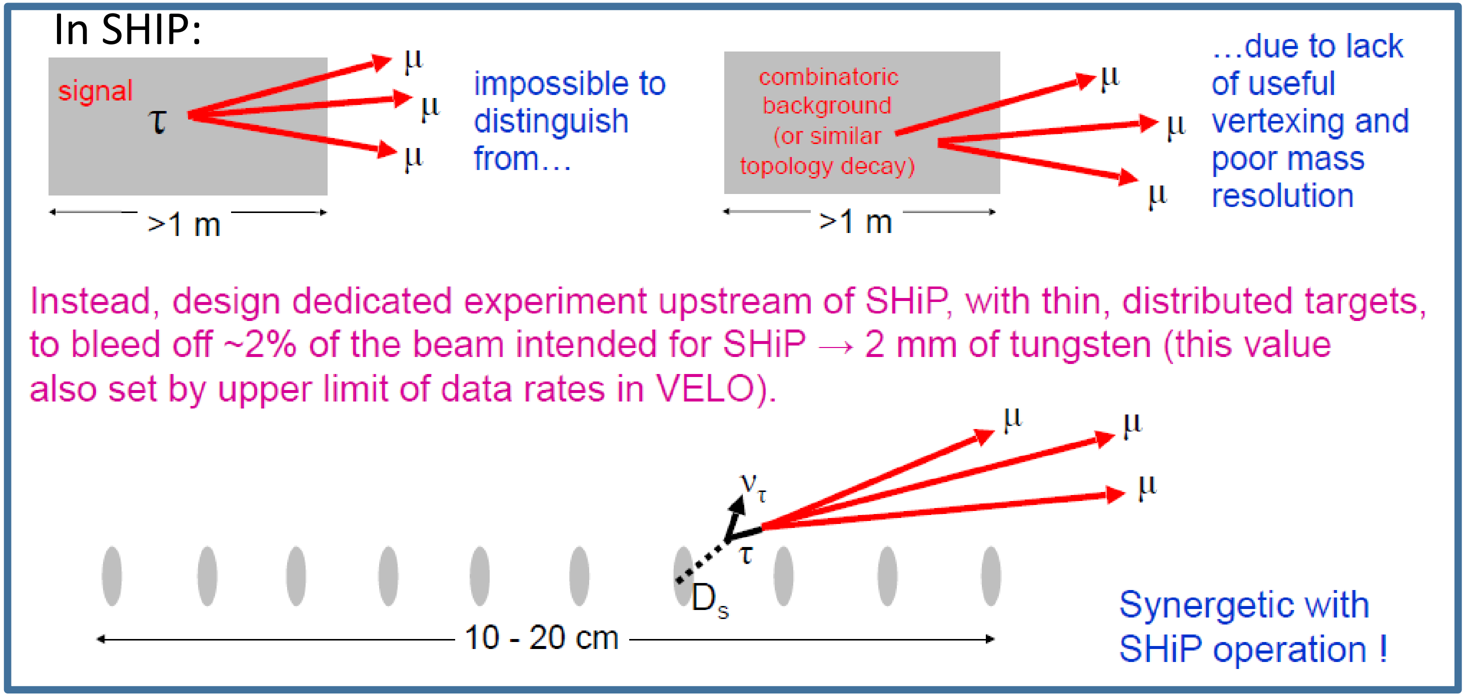
Prospects for HL-LHC

Opportunities in flavour physics at the HL-LHC and HE-LHC, arxiv:1812.07638

$BR(\tau \to 3\mu)$ (90% CL limit)	Ref.	Comments
3.8×10^{-7}	ATLAS [429]	Actual limit (Run 1)
4.6×10^{-8}	LHCb [428]	Actual limit (Run 1)
3.3×10^{-8}	BaBar [417]	Actual limit
2.1×10^{-8}	Belle [423]	Actual limit
3.7×10^{-9}	CMS HF-channel at HL-LHC	Expected limit (3000 fb^{-1})
6×10^{-9}	ATLAS W-channel at HL-LHC	Expected limit (3000 fb^{-1})
2.3×10^{-9}	ATLAS HF-channel at HL-LHC	Expected limit (3000 fb^{-1})
$\mathcal{O}(10^{-9})$	LHCb at HL-LHC	Expected limit (300 fb^{-1})
3.3×10^{-10}	Belle-II [196]	Expected limit (50 ab^{-1})

$\tau \to \mu\mu\mu$ @ tauFV

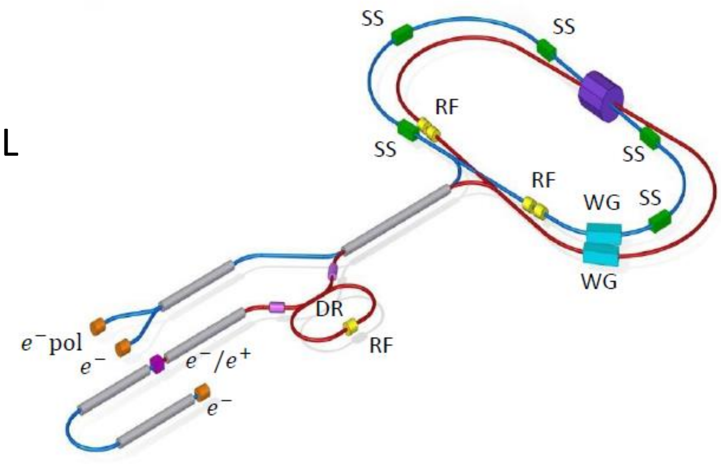
- « A fixed target experiment to search for flavour violation in tau decays »
- Proposal discussed in the 'physics beyond collider' workshops organized at CERN (here) and ESPP
- Beam dump experiment located at the SPS, upstream of SHIP



- Earliest start date : 2026-2027 (2030 more realistic)
- $B(\tau \to \mu\mu\mu)$ UL down to $\sim 10^{-10}$
- Other $\tau \to 3l$, kaon and charm decays can be studied

$\tau \rightarrow \mu\mu\mu$ @ Super Tau/Charm Factory

- SCT factroy project at BINP, Novosibirsk
- Input to the ESPP here, workshop held in december 2018 at LAL
- E from 2 to 6 GeV, L = 10^{35} $cm^{-2}s^{-1}$, polarized e- beam
- Begin data taking in 2029-2030
- 10^{10} taus produced per year at max $\tau\tau$ cross section



- Similar project in China (HIEPA)

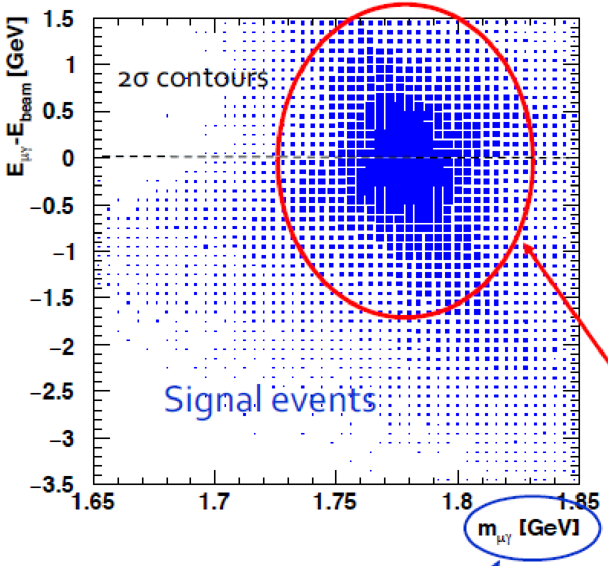
- Many LFV modes and other tau measurements possible

$\tau \rightarrow \mu\mu\mu$ @Z peak

Talk by M. Dam at TAU 2018

- FCC-ee at CERN, running at Z peak: 15×10^{10} tau pairs
- Start date ~2039
- Dedicated study gives a limit at $2\ 10^{-9}$ on $\tau \rightarrow e/\mu\gamma$ and $<10^{-10}$ on $\tau \rightarrow 3\ell$

- CEPC in China, running at Z peak: 3×10^{10} tau pairs
- Could be approved in 2022



In order to de-correlate the E and m variables, this mass, $m_{\gamma\mu}$, is in fact the measured mass scaled by measured energy over beam energy:

$$m_{\gamma\mu} = m_{raw} \times (E_{\gamma\mu}/E_{beam})$$

Smear with assumed FCC-ee detector resolutions:

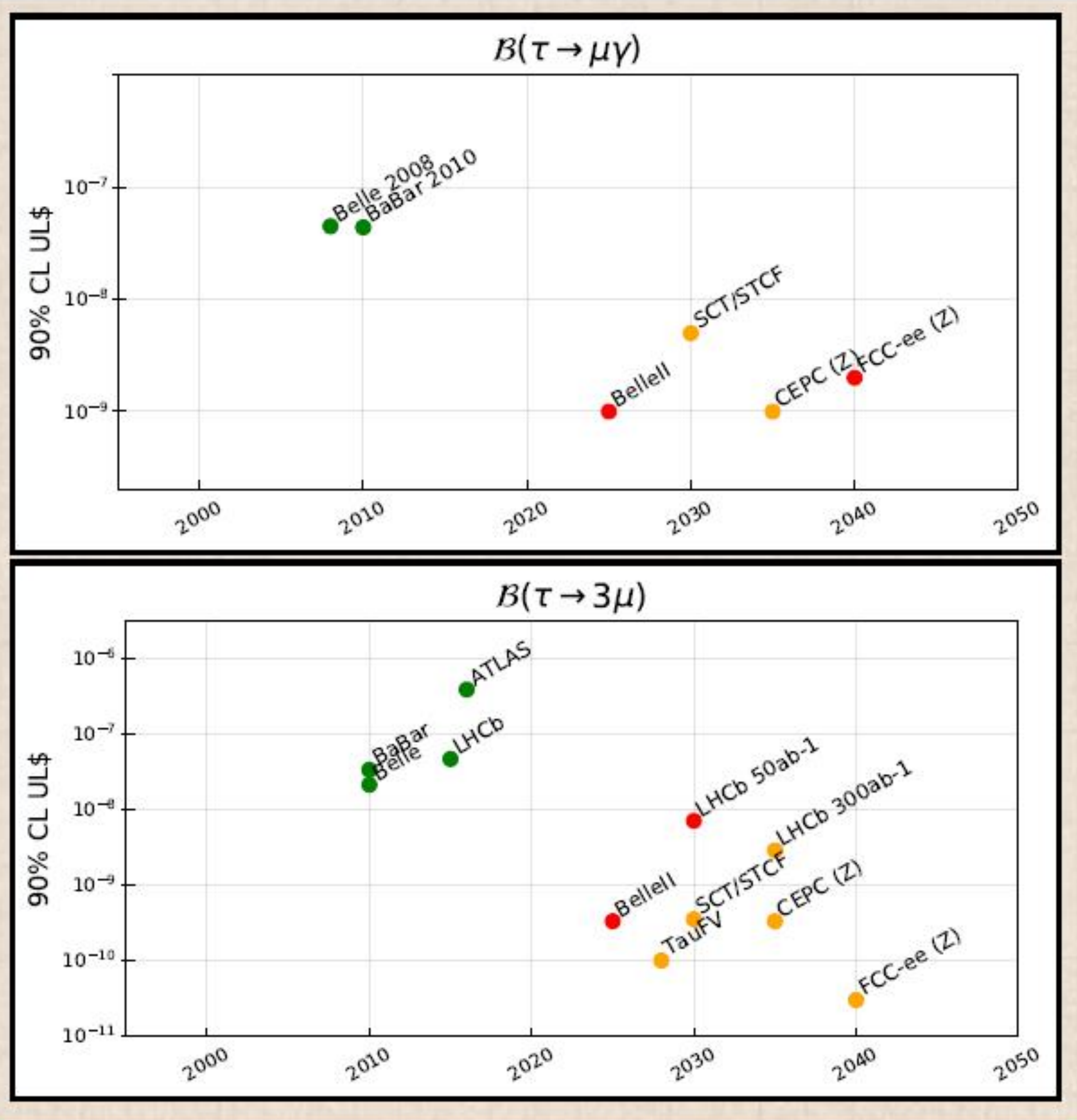
- Muon momentum [GeV]
  $\sigma(p_T)/p_T = 2 \times 10^{-5} \times p_T \oplus 1 \times 10^{-3}$
- Photon ECAL energy [GeV]
  $\sigma(E)/E = 0.165/\sqrt{E} \oplus 0.010/E \oplus 0.011$
- Photon ECAL spatial
  $\sigma(x) = \sigma(y) = (6/E \oplus 2)$ mm

From this, determine **FCC-ee** effective detector resolution for $\tau \rightarrow \mu\gamma$

$\sigma(m_{\gamma\mu}) = 26$ MeV; $\sigma(E_{\gamma\mu}) = 850$ MeV

Indicative benchmarks

Estimates from A. Lusiani shown at the Grenada symposium
Green are published
Red are reliable estimate based on dedicated studies
Orange are estimates with less solid fundations



B→τ decays

B→τ LFV at B factories

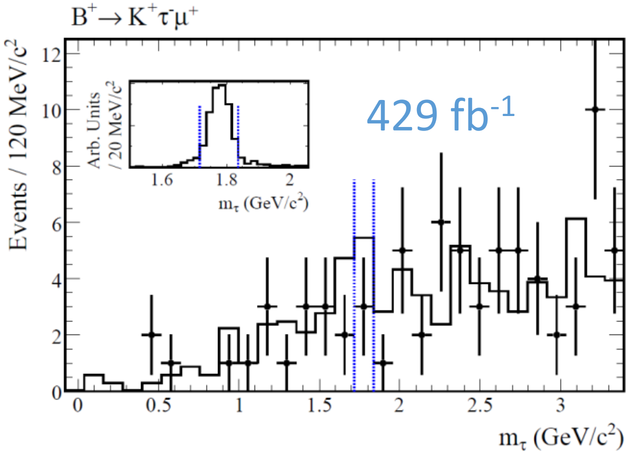
- Dominted by Babar
- Reconstruct the entire event using hadronic tagging → signal B momentum is known, τ mass indirectly reconstructed

$$
\begin{aligned}
\vec{p}_\tau &= -\vec{p}_{\rm tag} - \vec{p}_h - \vec{p}_\ell, \\
E_\tau &= E_{\rm beam} - E_h - E_\ell, \\
m_\tau &= \sqrt{E_\tau^2 - |\vec{p}_\tau|^2},
\end{aligned}
$$

$B^+ \to h^+\tau l$ (h=K,π)

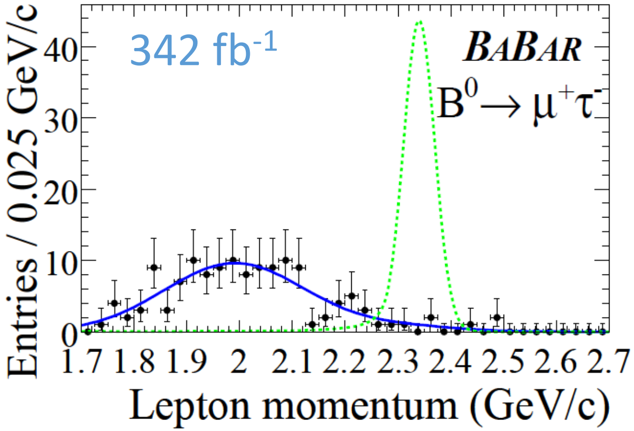
See talk by F. Polci

- Use one prong tau decay
- Normalized to B+ → D(*)l+nu
- Signal yield determined from the reconstructed tau mass distribution (cut and count)



$B^0 \to \tau l$

- Use one and three prong tau decay
- Signal yield determined fitting l momentum in signal frame

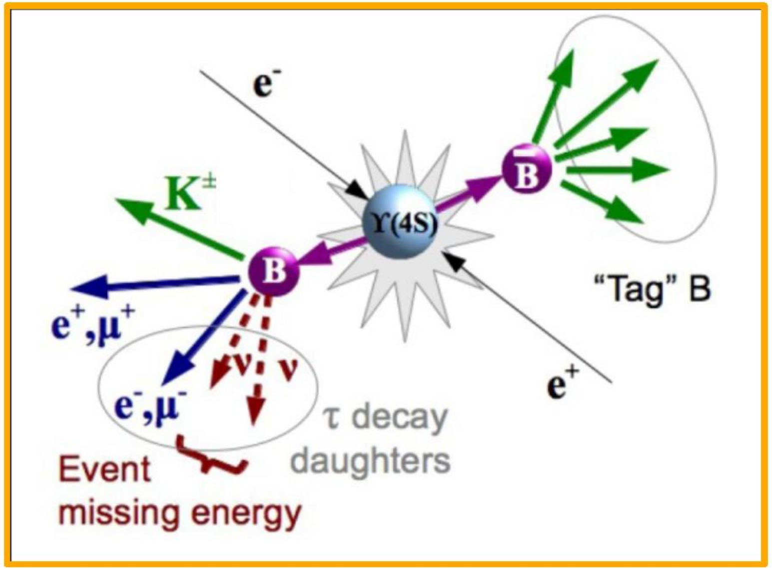


$b \to s\tau\tau$ at B factories

- Only one published analysis by Babar on $B^+ \to K^+\tau\tau$
- Use hadronic tagging and leptonic τ decays only
- Selection based on MLP
- Cut and count analysis, compare observed events with expected background yield:
    - Combinatorial from mES sidebands

$$m_{\mathrm{ES}} = \sqrt{(E^*_{\mathrm{CM}}/2)^2 - \vec{p}^{*2}_{B_{\mathrm{tag}}}}$$

    - Peaking (with correct tag) from MC, crosschecked on $B \to D\,l\nu$ control sample



	e^+e^-	$\mu^+\mu^-$	$e^+\ \mu^-$
N^i_{bkg}	49.4±2.4±2.9	45.8±2.4 ±3.2	59.2±2.8 ±3.5
$\epsilon^i_{\mathrm{sig}}(\times 10^{-5})$	1.1 ±0.2±0.1	1.3±0.2±0.1	2.1±0.2±0.2
N^i_{obs}	45	39	92
Significance (σ)	-0.6	-0.9	3.7

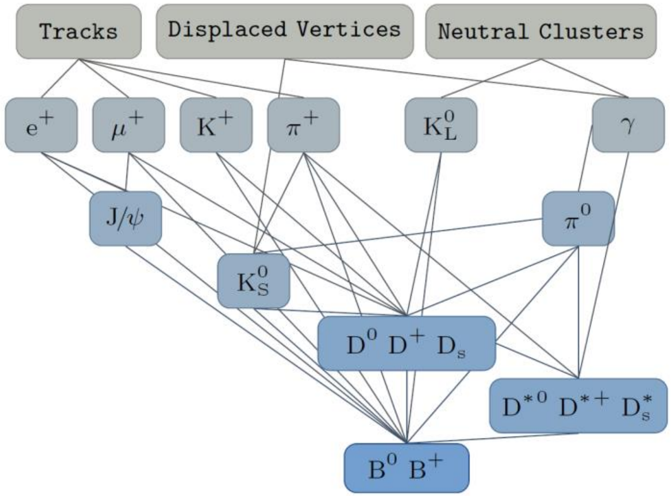
Combined upper limit:
$BR < 2.25\ 10^{-3}$ at 90% CL

- Expected limit from Belle presented by S. Wehle : $3.2\ 10^{-4}$ at 90% CL

Prospects for Belle II

- Improved tagging thanks to Full Event Interpretation tagging algorithm (arXiv:1807.08680)
  - Hierarchical approach
  - MVA-based
  - Highly tunable
  - Already used in Belle analyses

Tag	FR[10] @ Belle	FEI @ Belle MC	FEI @ Belle II MC
Hadronic B^+	0.28 %	0.49 %	0.61 %
Semileptonic B^+	0.67 %	1.42 %	1.45 %
Hadronic B^0	0.18 %	0.33%	0.34 %
Semileptonic B^0	0.63 %	1.33%	1.25 %



Other possible improvements:

- Use of semileptonic tagging, as e.g. in Belle B→ hνν analysis (PRD 96(2017)091101)
- Use inclusive analysis (no tagging): for B→ τμ, CLEO reached limit at 3.8 10^{-5} with $10fb^{-1}$! PRL93(2004)241802 (1.7x Babar)
- Additionnal tau modes

Prospects for Belle II

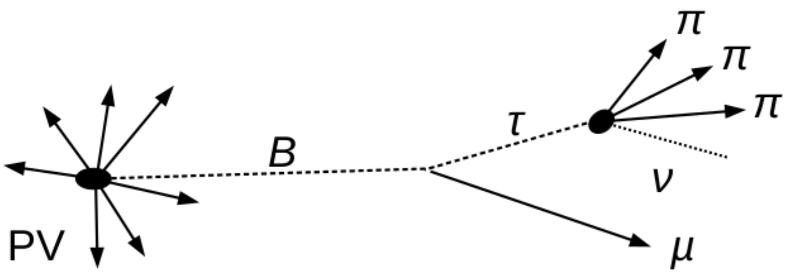
From Belle II physics book, arXiv:1808.10567

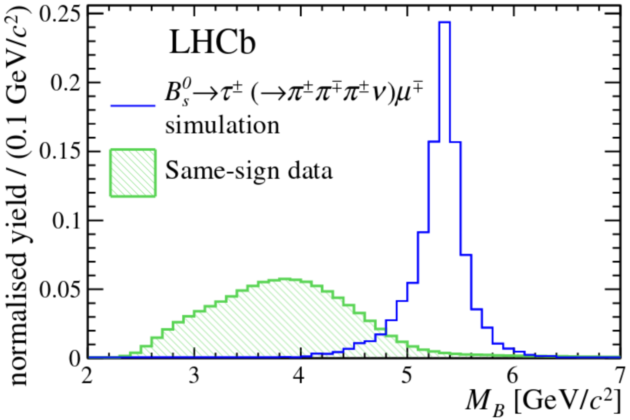
Observables	Belle $0.71\,\mathrm{ab}^{-1}$ $(0.12\,\mathrm{ab}^{-1})$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B^+ \to K^+\tau^+\tau^-)\cdot 10^5$	< 32	< 6.5	< 2.0
$\mathrm{Br}(B^0 \to \tau^+\tau^-)\cdot 10^5$	< 140	< 30	< 9.6
$\mathrm{Br}(B_s^0 \to \tau^+\tau^-)\cdot 10^4$	< 70	< 8.1	–
$\mathrm{Br}(B^+ \to K^+\tau^\pm e^\mp)\cdot 10^6$	–	–	< 2.1
$\mathrm{Br}(B^+ \to K^+\tau^\pm \mu^\mp)\cdot 10^6$	–	–	< 3.3
$\mathrm{Br}(B^0 \to \tau^\pm e^\mp)\cdot 10^5$	–	–	< 1.6
$\mathrm{Br}(B^0 \to \tau^\pm \mu^\mp)\cdot 10^5$	–	–	< 1.3

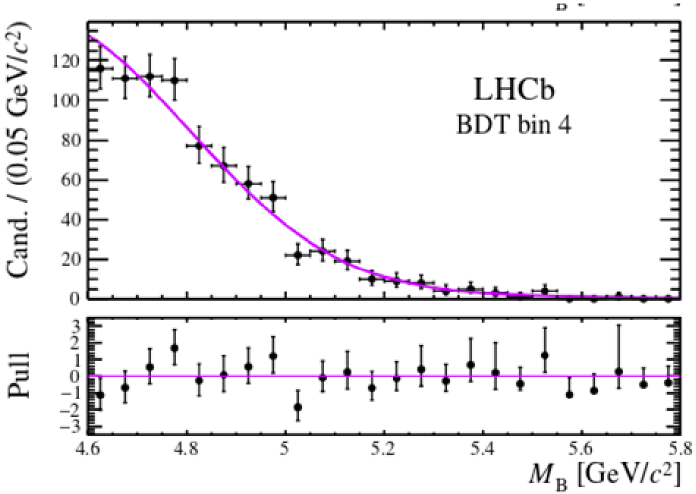
See talk
by F. Polci

$B \to \tau$ LFV at LHCb

- Only one public analysis, based on 3 fb^{-1}: $B_{(s)} \to \tau\mu$
- Use $\tau \to \pi\pi\pi\nu$ decays (τ decay vertex)
- B mass reconstruction possible with a 2-fold ambiguity



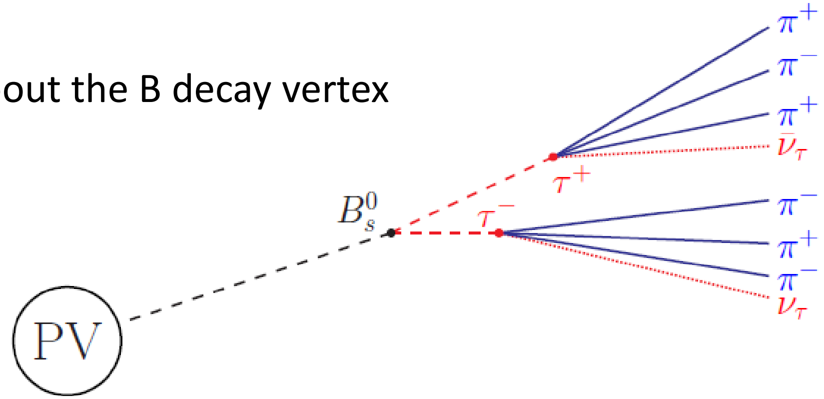


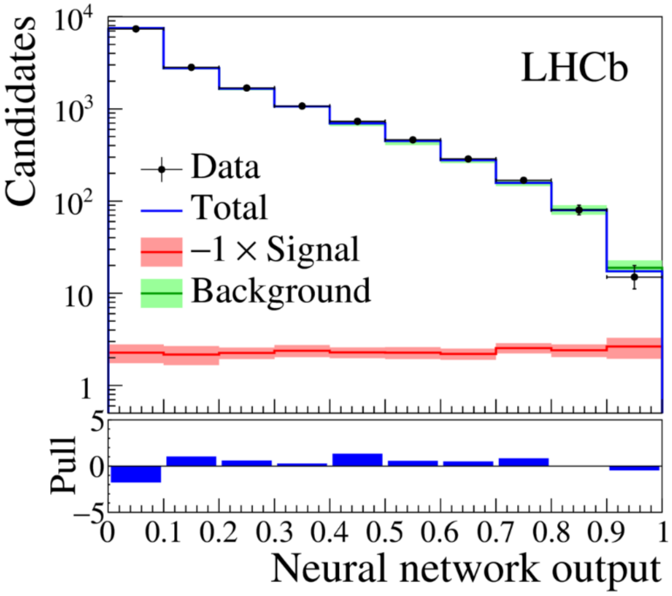


- Signal yield obtained from a fit to the mass in 4 bins of a BDT
- Limited Bs and Bd signal separation
  - $\to$ Bs signal fit, assuming no B0 contribution
- BR normalised to the $B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+$ mode
- First limit on Bs mode, best limit on B^0 mode

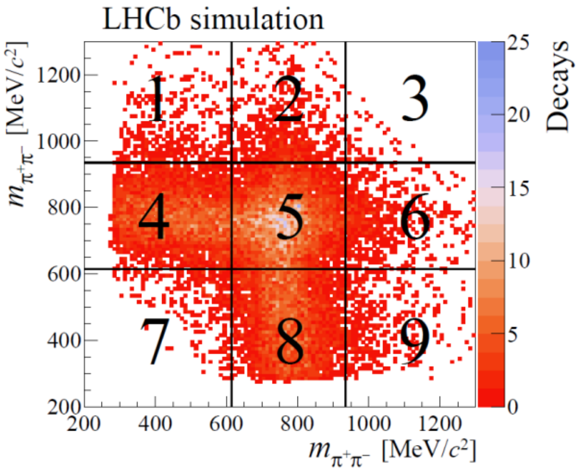
b→sττ at LHCb

- Only one analysis on $B_{(s)} \to \tau\tau$
- Analysis complicated by the fact that we have no indication about the B decay vertex
- But using $\tau \to \pi\pi\pi\nu$ we can access to the 2 τ decay vertex
- Signal yield obtained from a fit to a NN,
- Background taken from CR region based on τ Dalitz plane
- First limit on Bs mode, best limit on B^0 mode



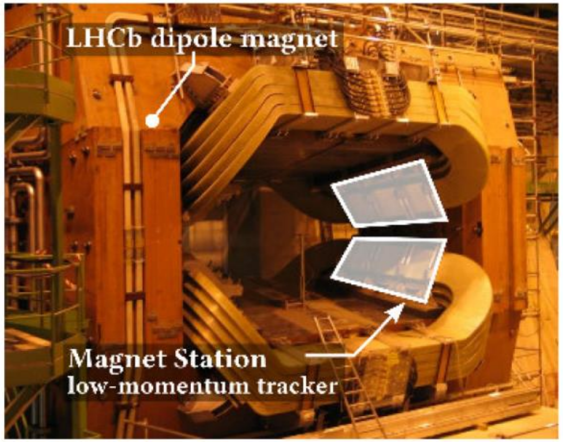


Bs signal fit, assuming no B^0 contribution



Prospects at LHCb

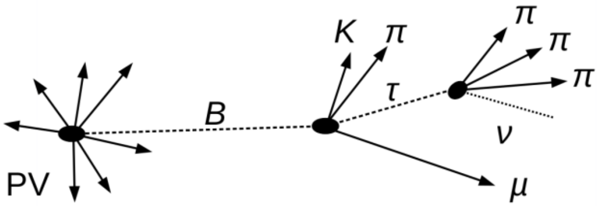
- More data (~6 fb^{-1} for Run2) and modes to analyze!
- Will benefit from higher trigger efficiency from Upgrade I and additional tracking stations from LS3 (+ further possible tracking improvements)
- $B \to \tau\mu$: unofficial estimates from G. Mancinelli (SM@LHC 2019)



Decays	LHCb RUN3 (95% CL)	LHCb RUN5 (95% CL)
$B \to \tau\mu$	1-2 10^{-6}	4-7 10^{-7}
$B_s \to \tau\mu$	5-9 10^{-6}	1-3 10^{-6}

Adding $\pi\pi\pi\pi^0$ mode and improved upgrade trigger and tracking and better analysis

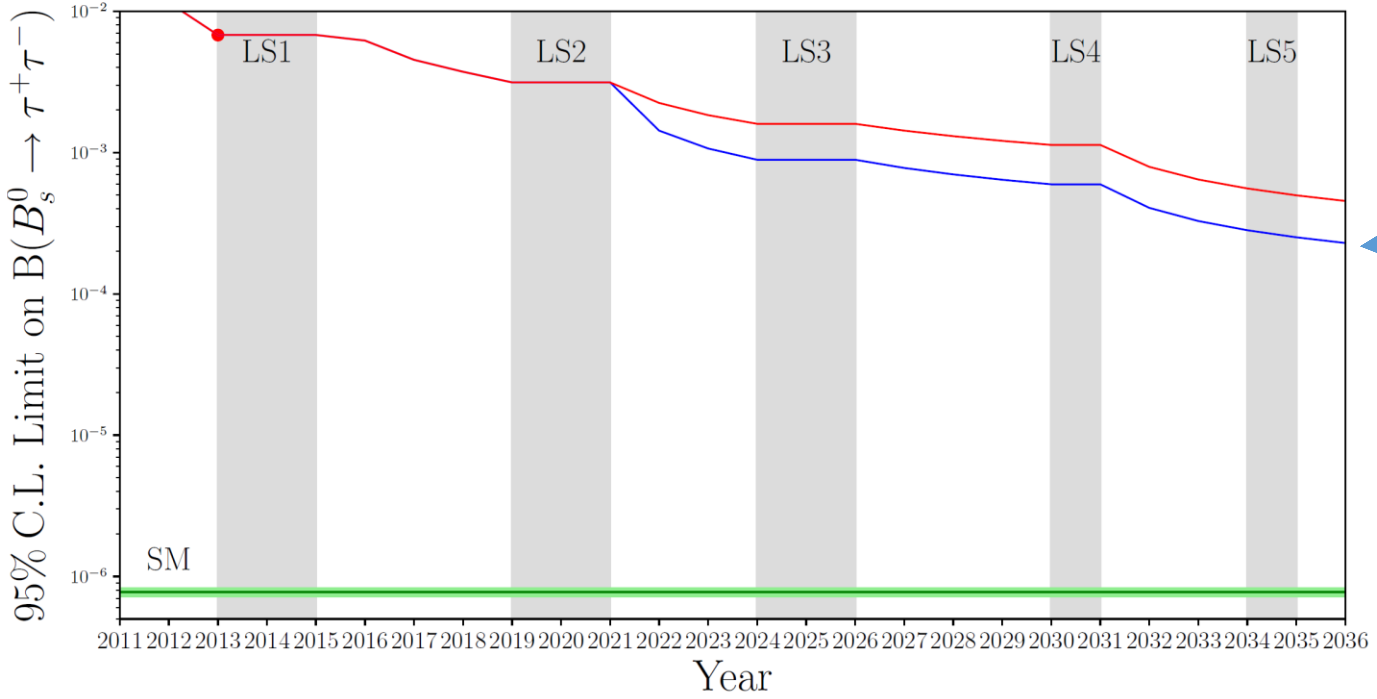
- Ongoing analysis of $B \to K^*\tau\mu$
  - 6 tracks in the final state but B decay vertex known
  - Expect limit at few 10^{-6} for Run1+Run2



- Work in progress on a method using $(B_s^* \to K)B_u \to K\tau\mu$, full mass reconstruction possible

Prospects at LHCb

- $B_{(s)} \rightarrow \tau\tau$:
  - Feasibility study using final state (3π,μ) but unfortunately not competitive with (3π, 3π)
  - Limits at few 10^{-4} reachable with Run4 or Run5



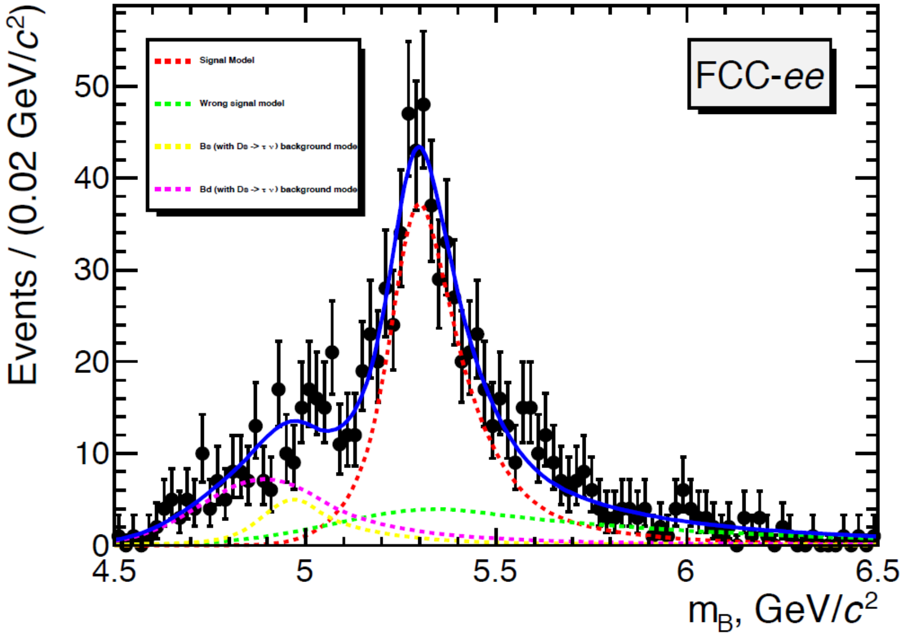
Assuming a factor 4 improvement thanks to trigger, tracking and analysis reoptimization

Prospects at FCC-ee

- Dedicated study for B → K*ττ analysis
- Make use of partial reconstruction technique to solve the kinematic of the decay
- Assume detector performance similar to ILD
- At baseline luminosity, assuming SM BR more than 1000 events observables!

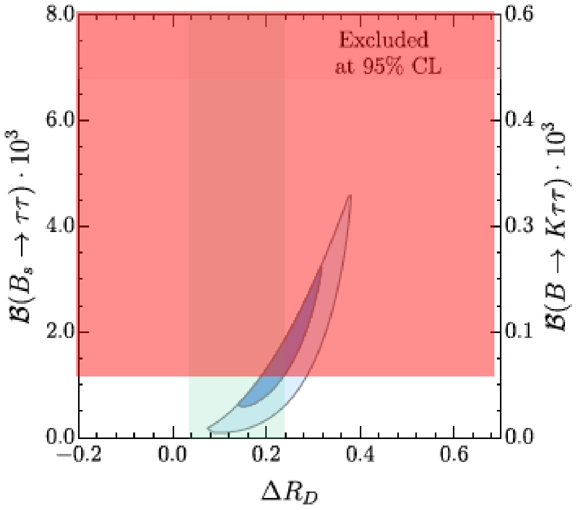
- Other B → τ decays should be feasible

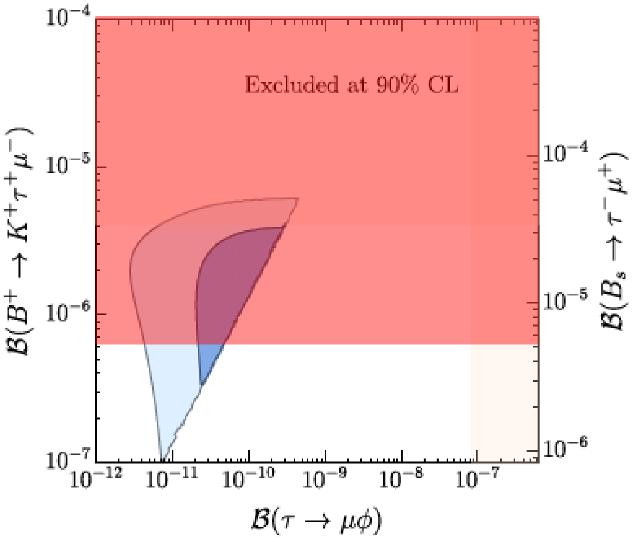
Backgrounds: (pink - DsK*taunu and DsDsK*) [signal in red+green].

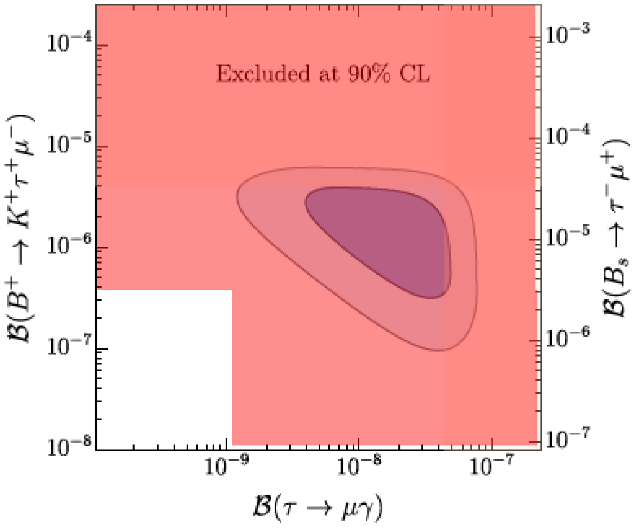


Conclusion

- We start to master taus!
- Many interesting results will come from Belle II and LHCb in the coming years (and possibly others in a longer time scale)
- In 2028, the picture could be:

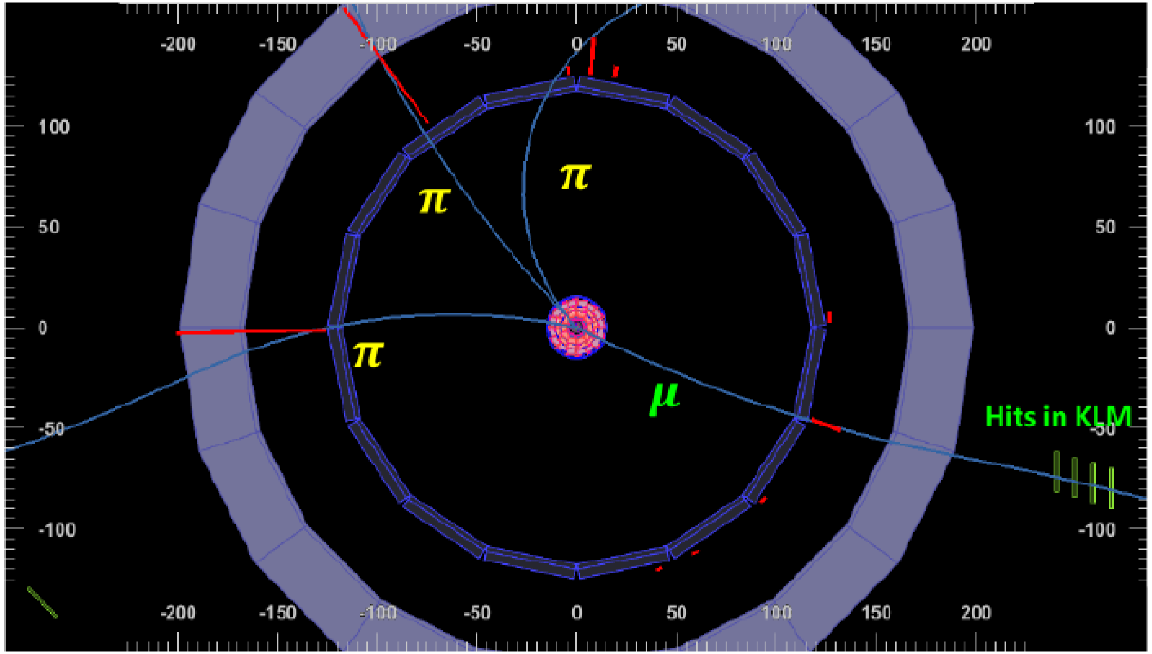






First τ @Belle II

Phase 2 lasted from April 26^{th} to July 17^{th}, 2018



Main τ decays

τ decay	BF (%)
$\tau^+ \rightarrow \mu^+\nu\nu$	17.39±0.04
$\tau^+ \rightarrow e^+\nu\nu$	17.82±0.04
$\tau^+ \rightarrow \pi^+\nu$	10.82±0.05
$\tau^+ \rightarrow \pi^+ \pi^0\nu$	25.49±0.09
$\tau^+ \rightarrow \pi^+ \pi^0 \pi^0\nu$	9.26±0.10
$\tau^+ \rightarrow \pi^+ \pi^+ \pi^-\nu$	9.31±0.05
$\tau^+ \rightarrow \pi^+ \pi^+ \pi^- \pi^0\nu$	4.62±0.05

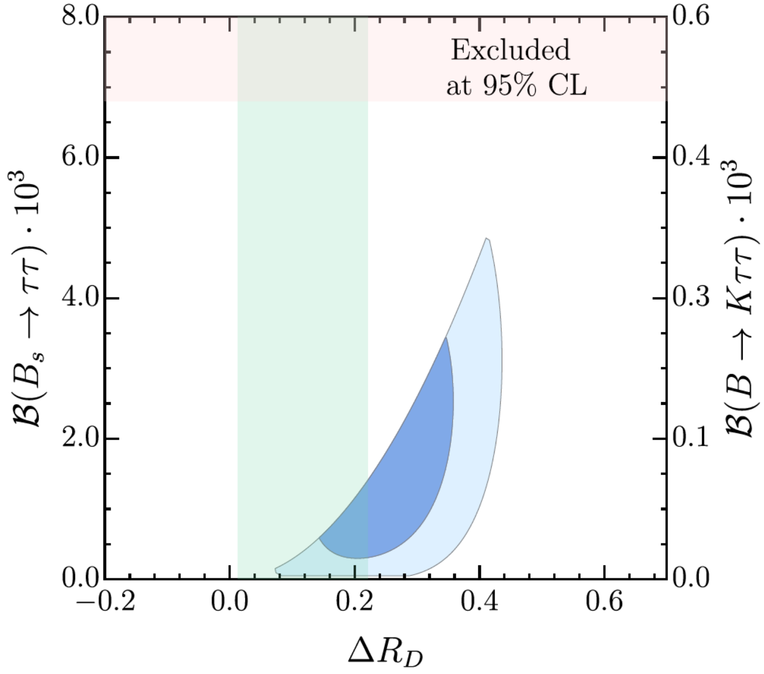
One prong
~81% of decays

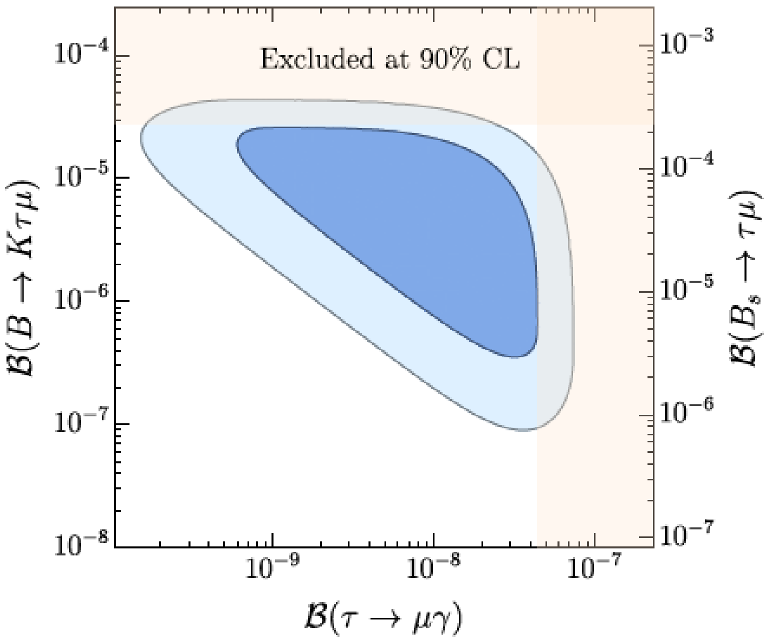
three prong
~14% of decays

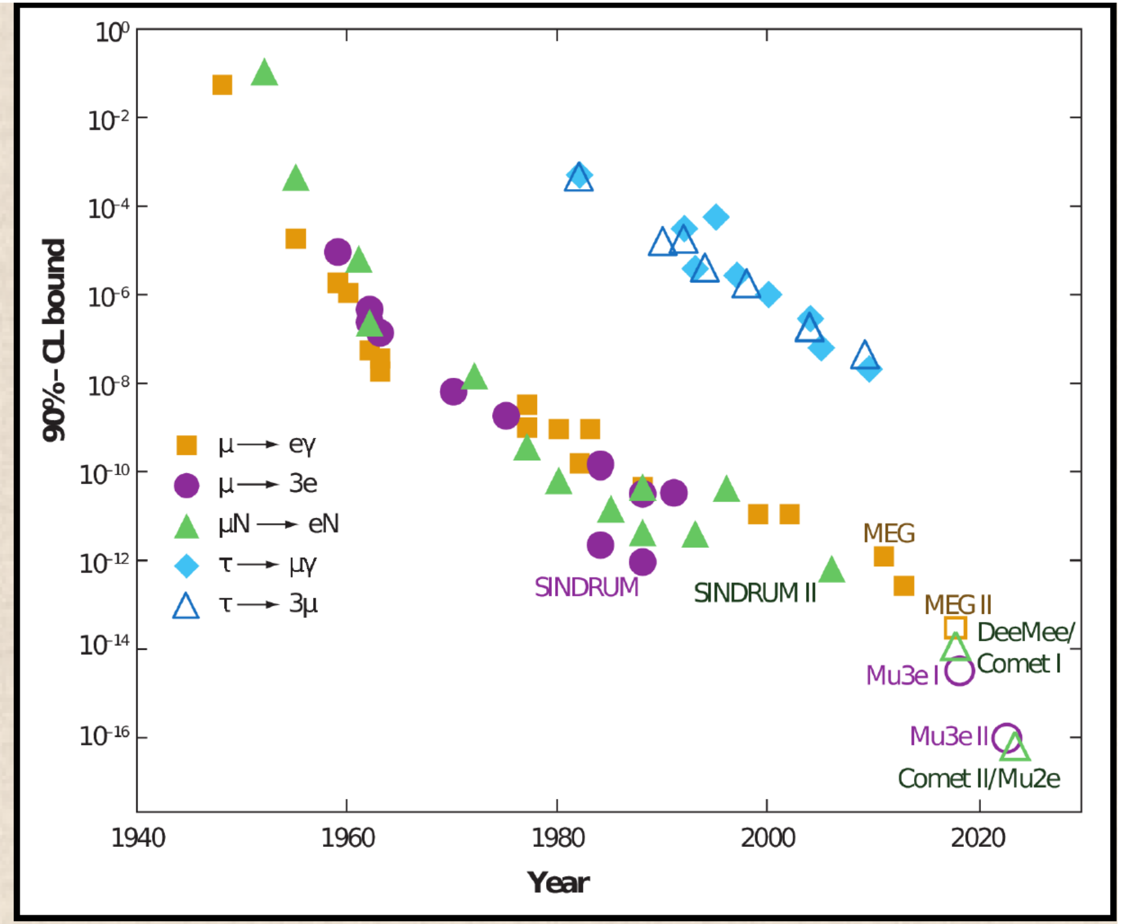
Leptonic
~35% of decays

hadronic

Before LHCb B->taumu:







A. Signer, Tau 2018