LFV τ searches at Belle II: $\tau\to3\mu$ and $\tau\to l\phi$ prospects

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DESY (Deutsches Elektronen-Synchrotron)

On behalf of the Belle II collaboration

Anomalies and Precision Workshop, 6-8 September 2021, Wien

Status of the τ LFV searches at B-factories

Lepton Flavor Violation (LFV) is allowed in various extensions of the Standard Model (SM) but it has never been observed

Advantages of studying τ physics at B-factories:

- τ produced in pairs
- Well defined initial state energy
- Clean environment
- High hermeticity of the detector

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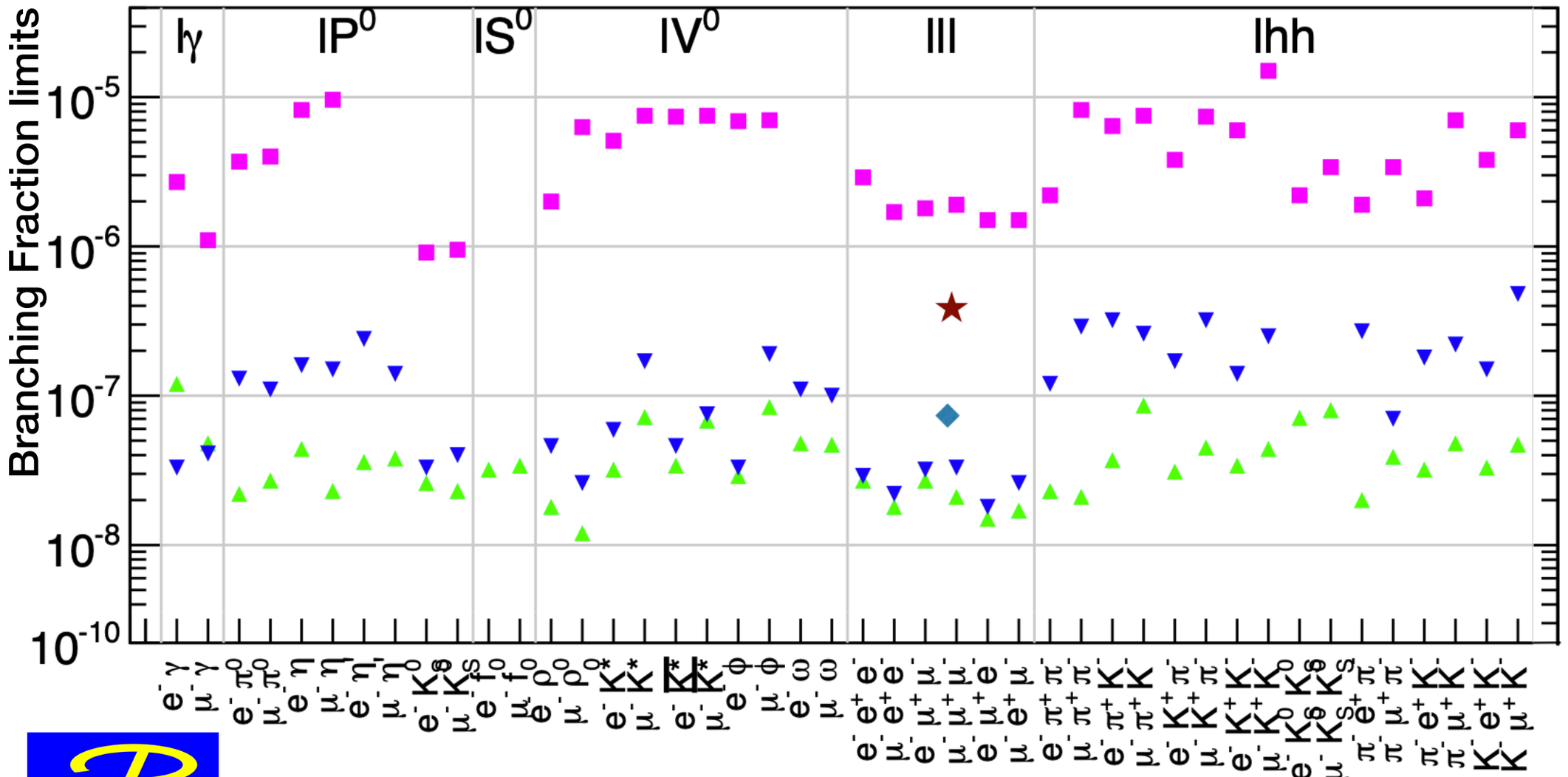


τ LFV channels

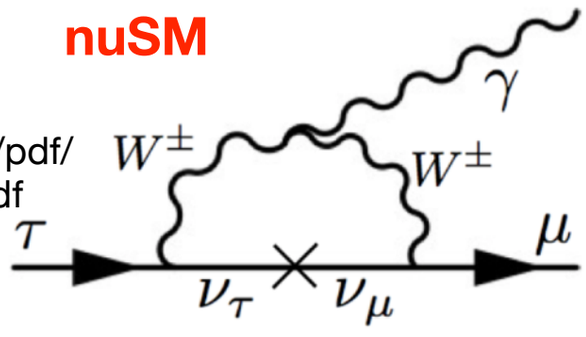
Search various decay modes:

- $\tau \to \ell\ell\ell$
- $\tau \to \ell K_s, \Lambda h$
- $\tau \to \ell V_0 (\to hh')$
- $\tau \to \ell P^0 (\to \gamma\gamma)$
- $\tau \to \ell hh'$
- $\tau \to \ell\gamma$

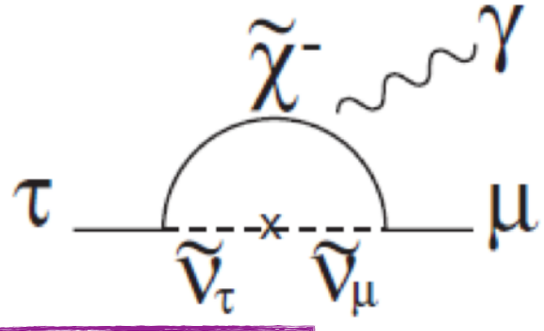
Difficulty of background reduction

Golden channel: $\tau \to \mu\gamma$

nuSM



SUSY



Ref:
https://arxiv.org/pdf/1301.4652.pdf

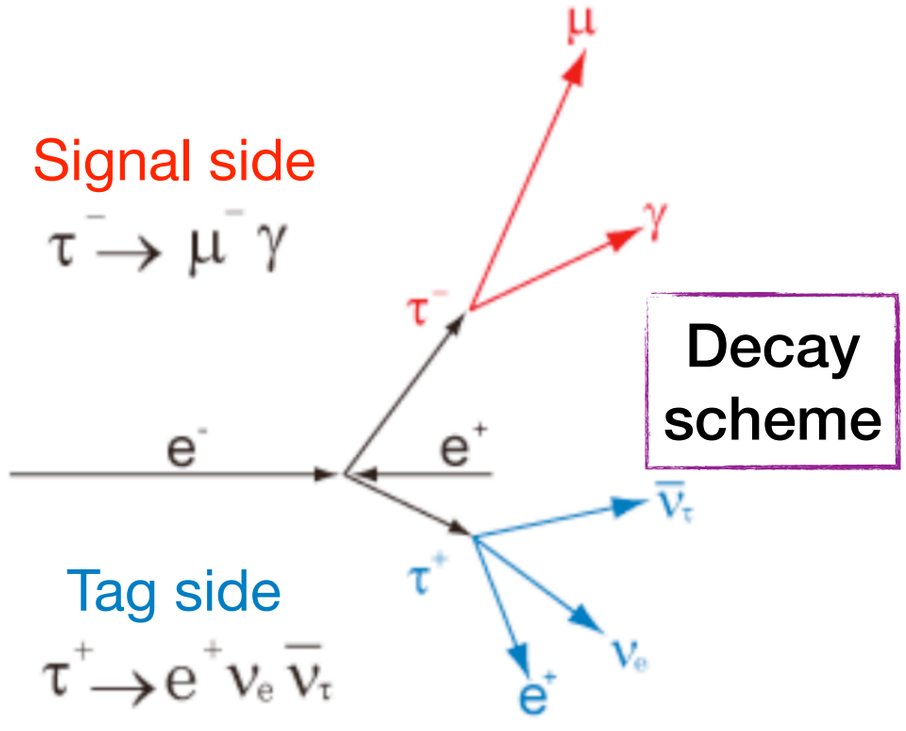
Highest non-SM BF contribution

Signal side

$\tau^- \to \mu^- \gamma$

Tag side

$\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$



Decay scheme

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Simple → Hard

Difficulty of background reduction

$\tau \to \ell\ell\ell$: Very good determination of τ mass and energy + few physical background sources

$\tau \to \ell\gamma$: Irreducible physics backgrounds + large uncertainty in mass and energy determination

Golden channel: $\tau \to \mu\gamma$

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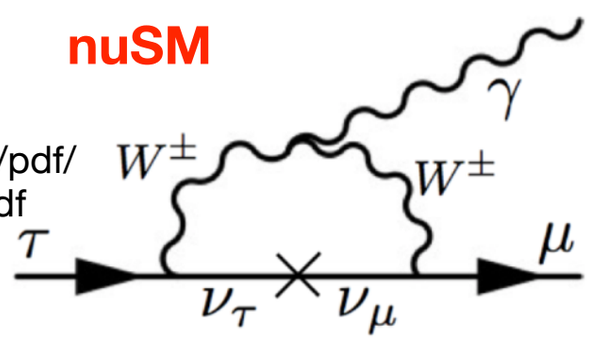

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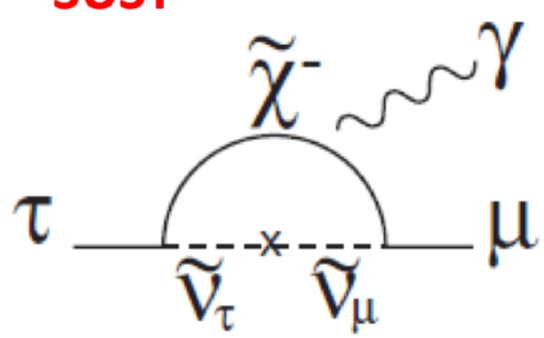

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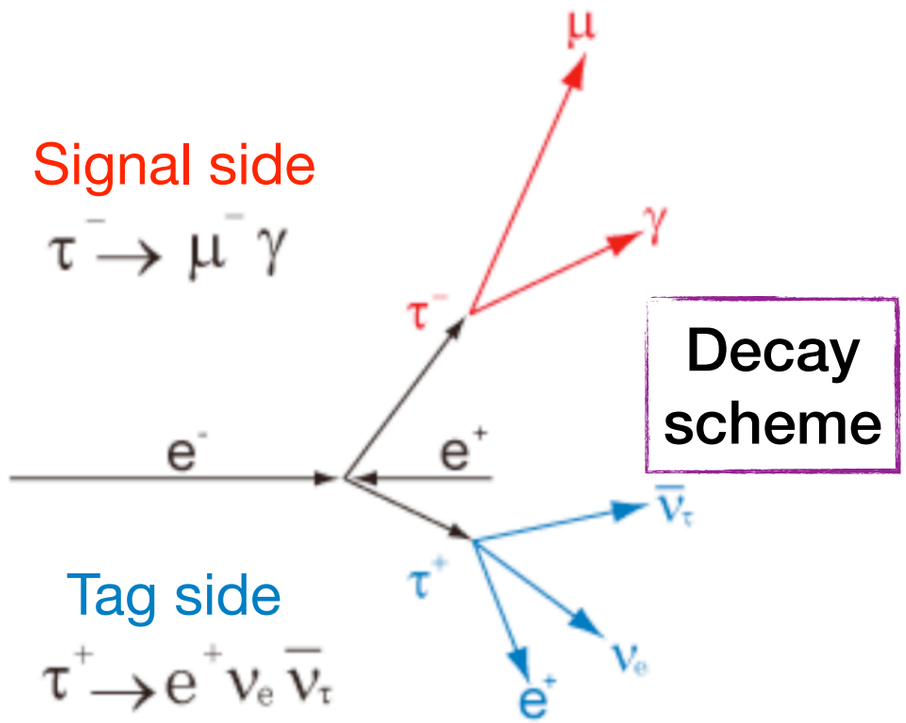

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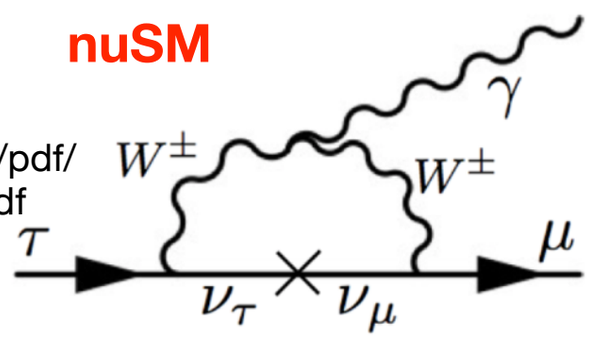

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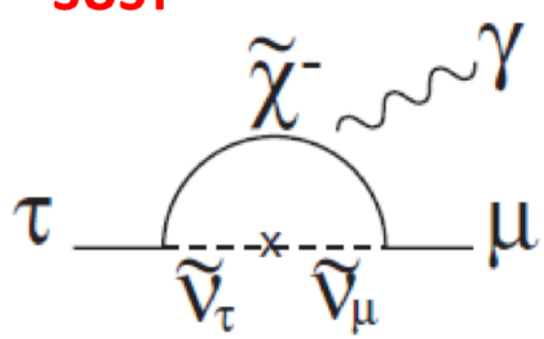

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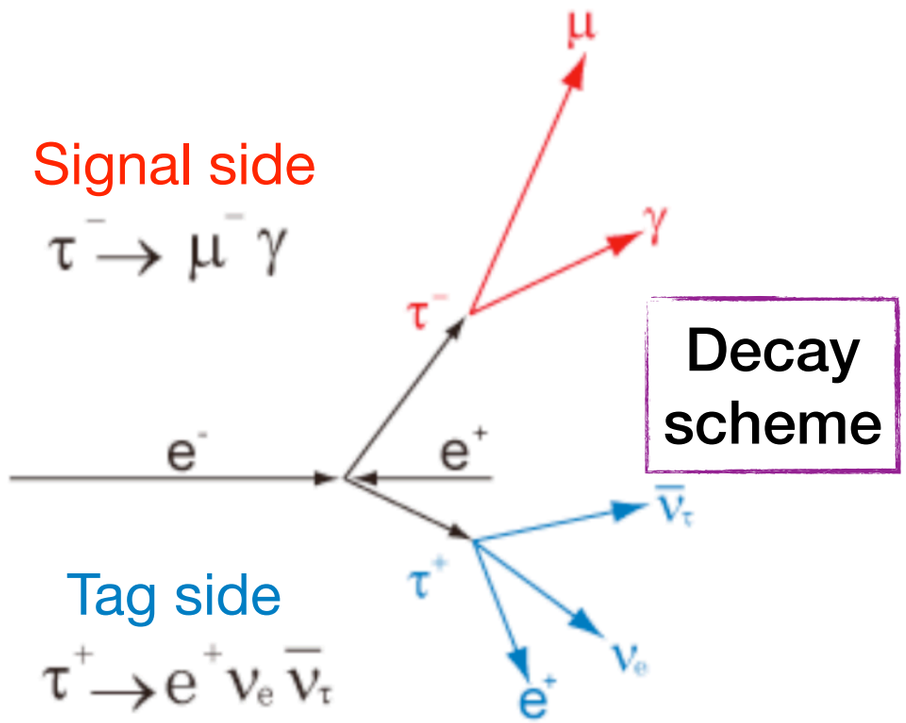

Analysis motivations: $\tau \to 3\mu$

Experimental upper limits from **Belle** and **BaBar** on $\tau \to 3\mu$:

- Belle: **2.1 x 10^{-8}** @90% confidence level using $\int Ldt = 782 fb^{-1}$
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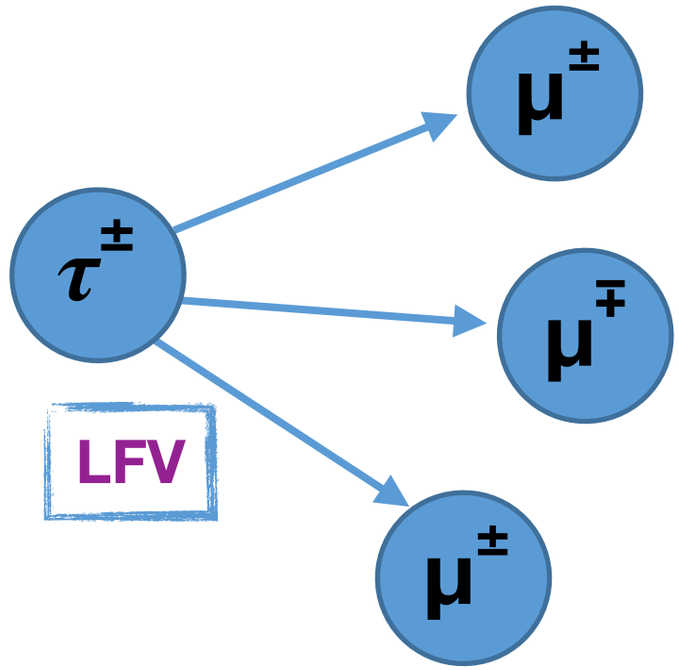

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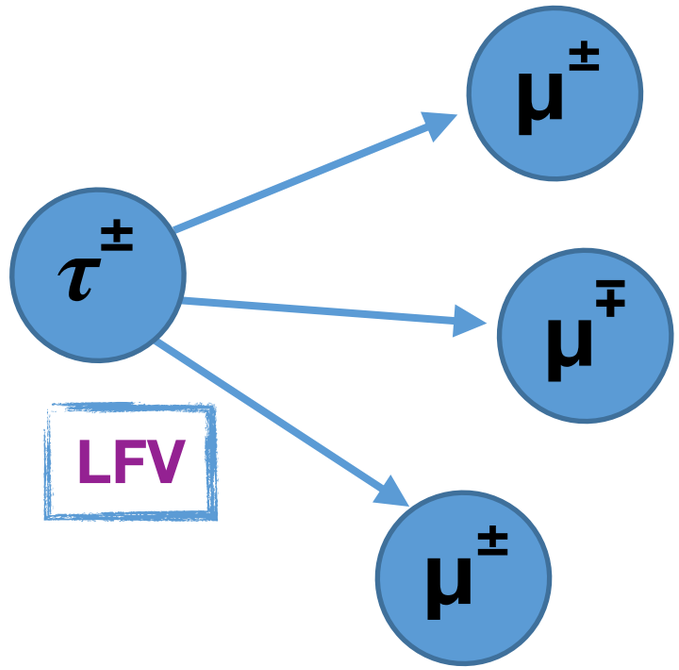


Extrapolating Belle results to full ***BelleII luminosity*** **(see A. Gaz talk on the Belle II experiment) ~10^{-10} range is accessible**

Physics models	$B(\tau \to \mu\gamma)$	$B(\tau \to \mu\mu\mu)$
SM + ν mixing	$10^{-49} \sim 10^{-52}$	$10^{-53} \sim 10^{-56}$ [1]
SM+heavy Majorana ν_R	10^{-9}	10^{-10}
Non-universal Z'	10^{-9}	10^{-8}
SUSY SO(10)	10^{-8}	10^{-10}
mSUGRA + seesaw	10^{-7}	10^{-9}
SUSY Higgs	10^{-10}	10^{-7}

BF limits on τ LFV decays allow to discriminate NP models!

Ref.

[1]: M. Blanke, et al., Charged Lepton Flavour Violation and (g – 2)μ in the Littlest Higgs Model with T-Parity: a clear Distinction from Supersymmetry, JHEP 0705, 013 (2007).

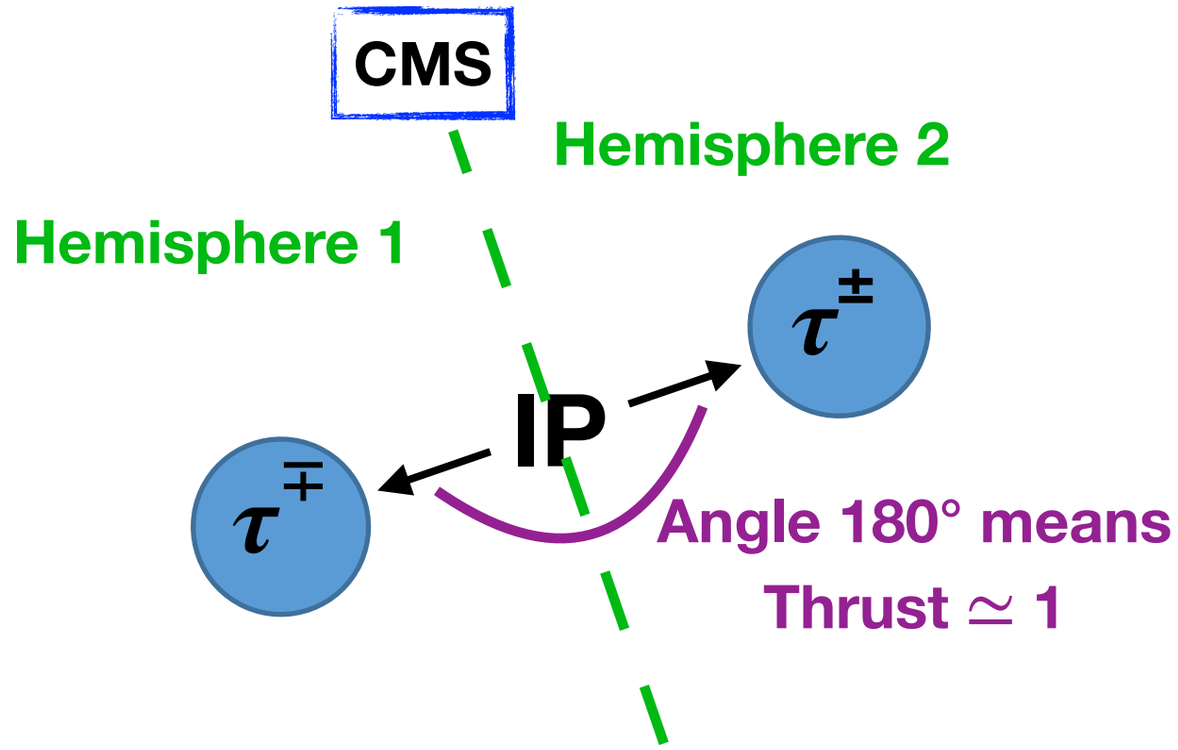
An observation of LFV in τ decays would be a clear signature of NP

Belle II

Signal preselection

Requirement adopted to reconstruct the decay:

- **thrust**: discriminate between spherical and boosted events;
- the two τ point to opposite **hemispheres**;



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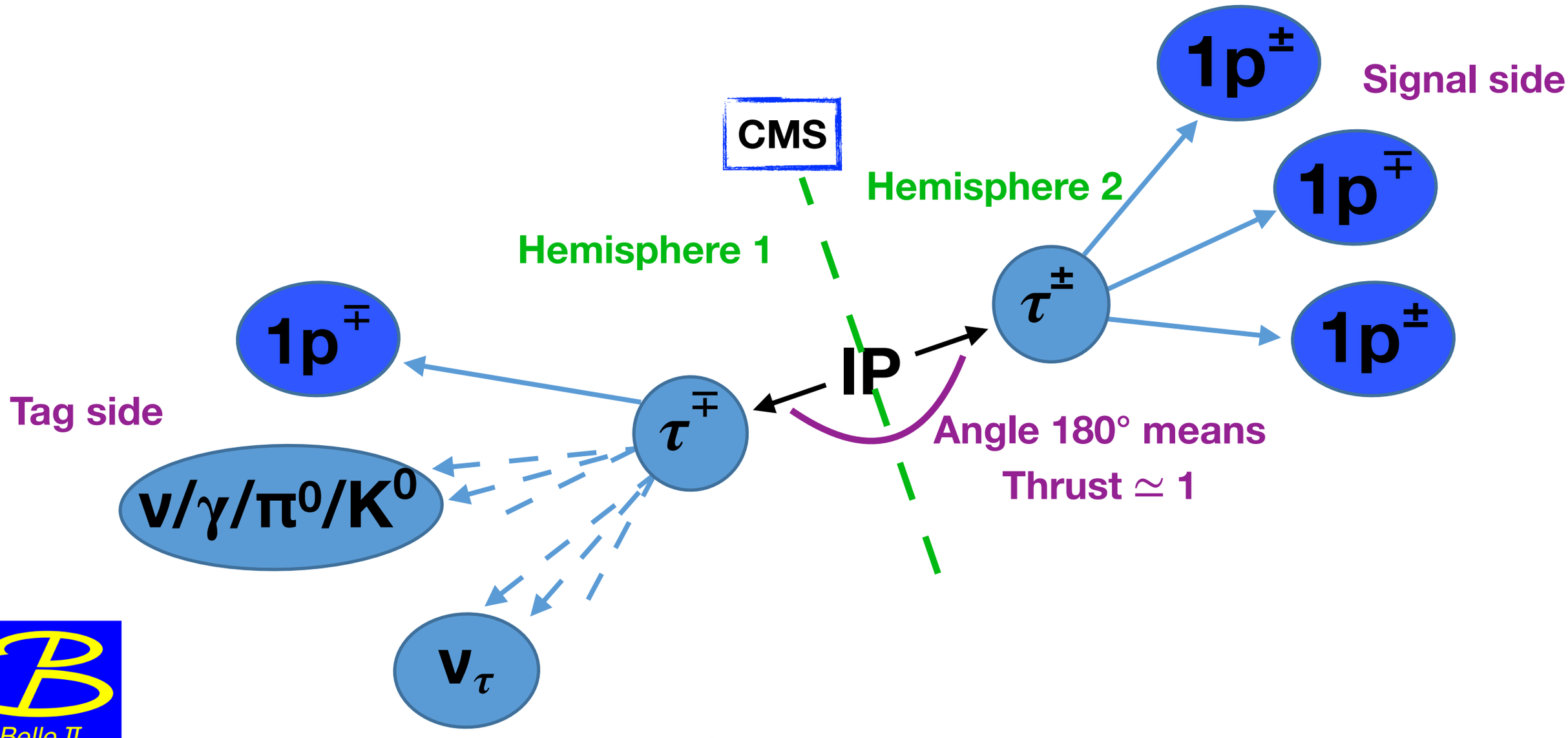
- Exactly **4 tracks** coming nearby the IP;

$1p^{\mp}$ = 1 prong



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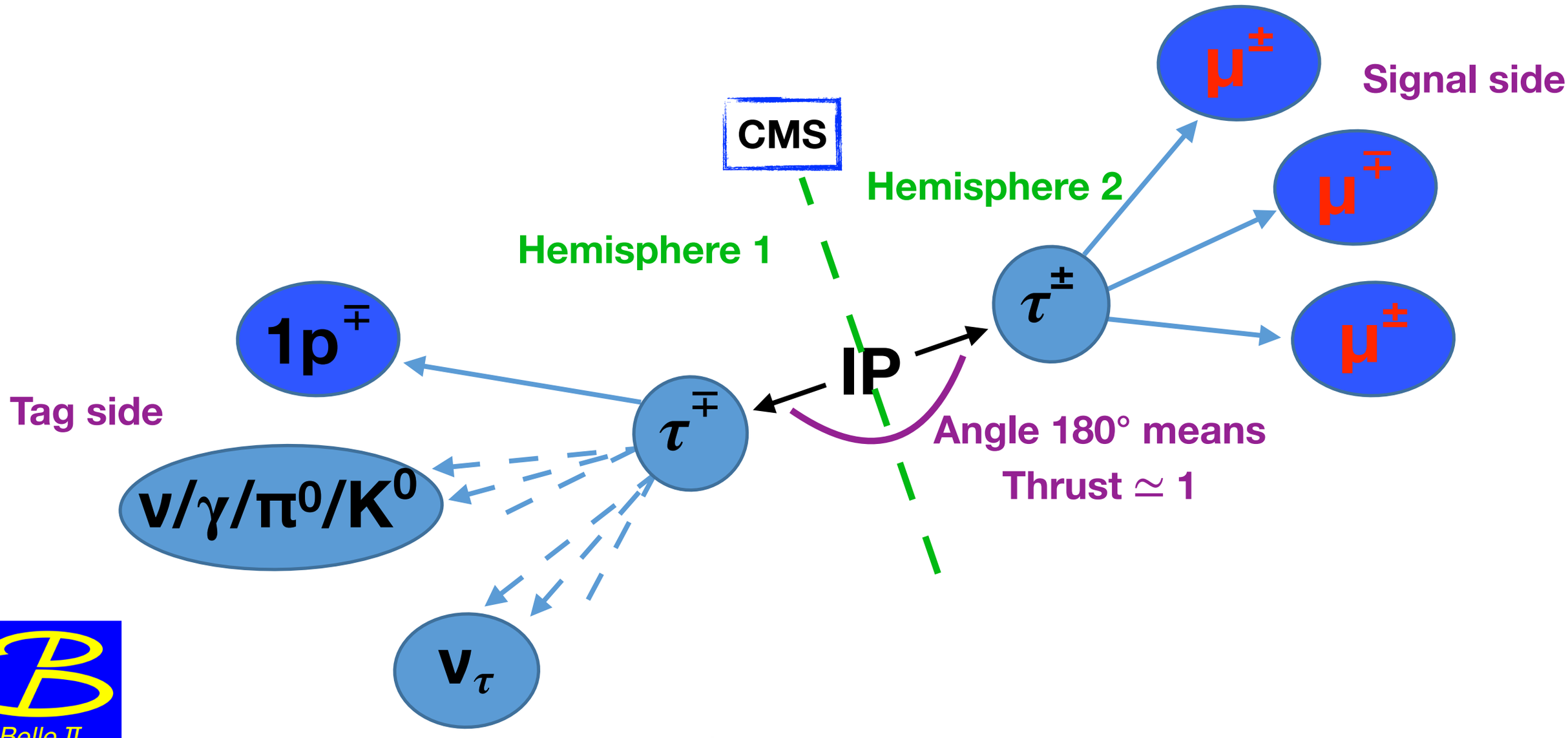

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- **Signal** tracks loosely identified as **muons**
- **1prong track nature divides the study into leptonic and hadronic tag cases**

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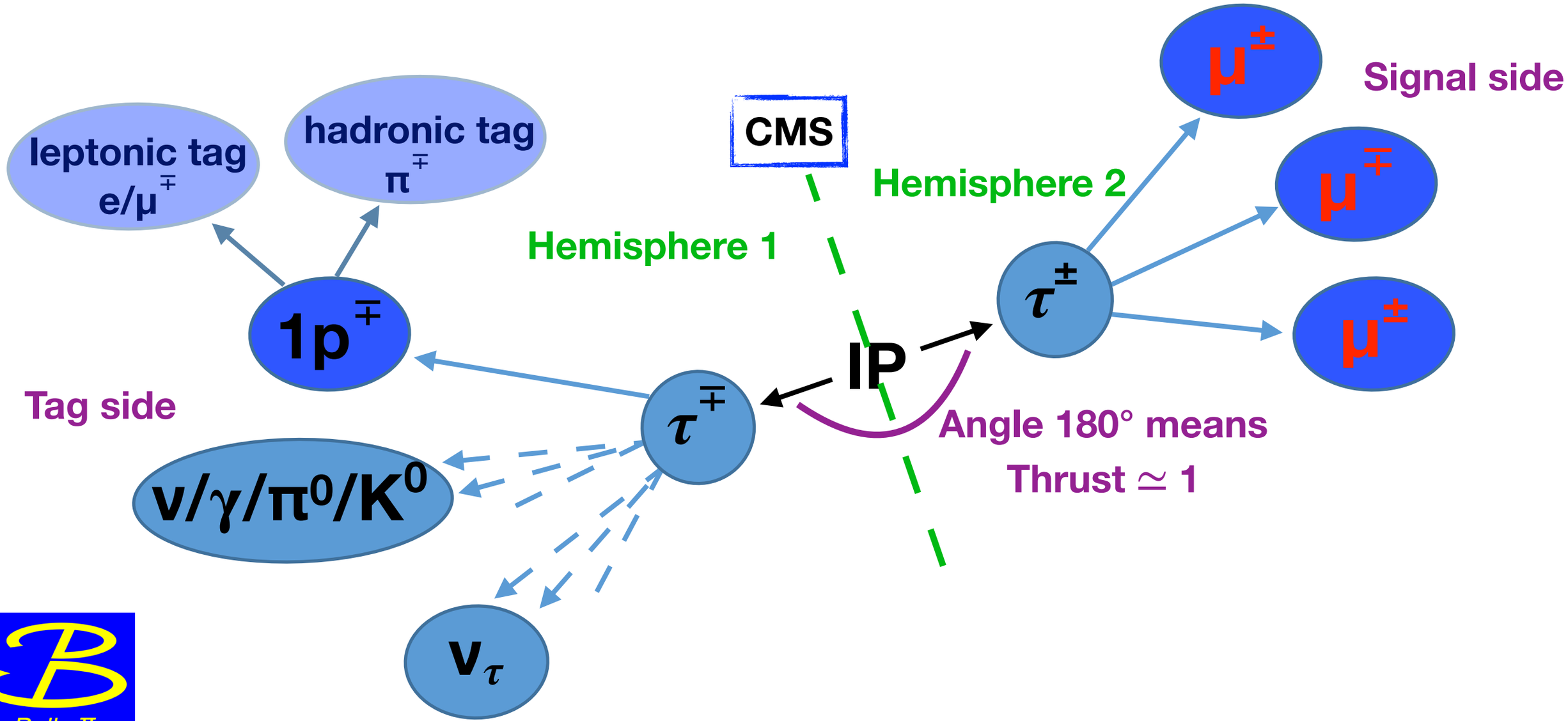


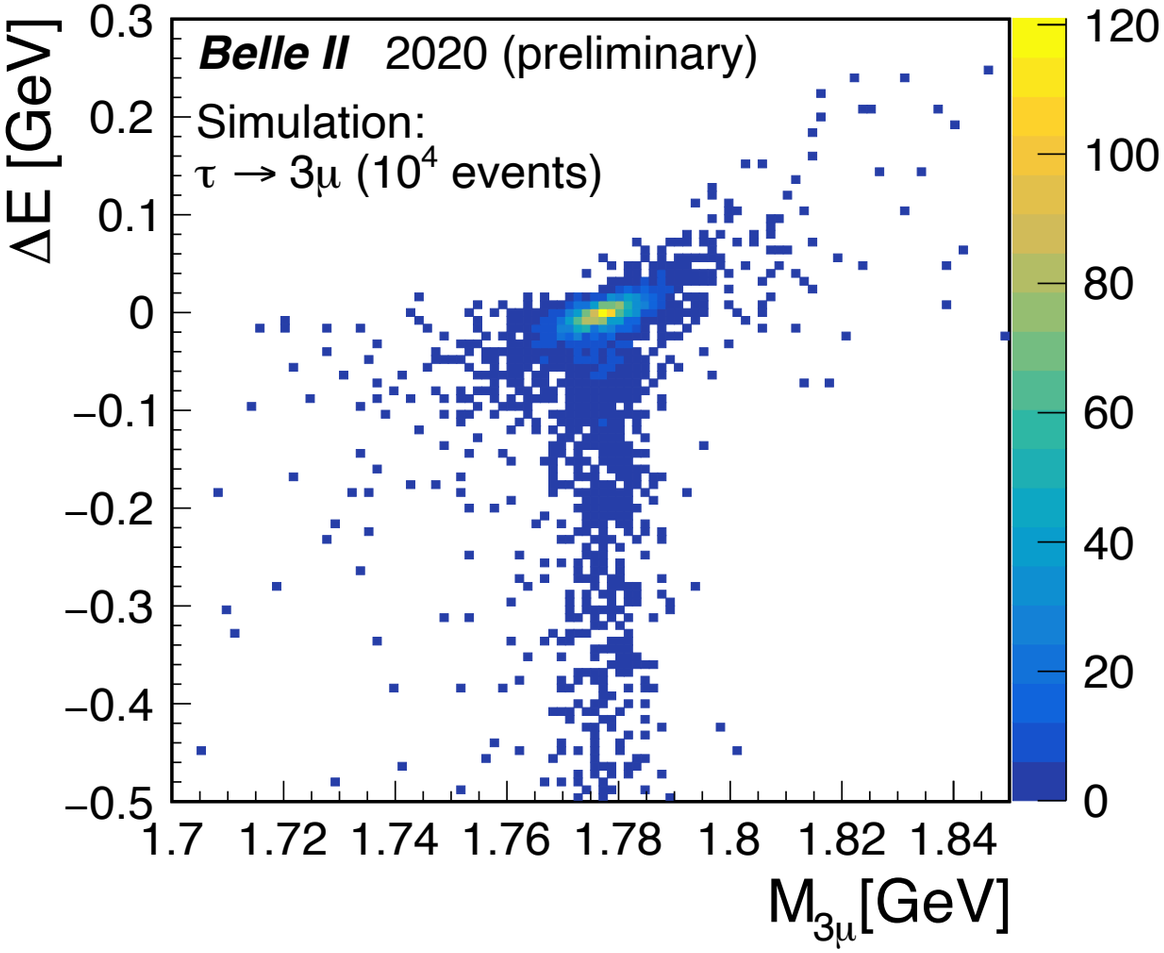
Signal determination: signal region

Signal identification in LFV τ analysis is usually done using a τ mass and ΔE selection

$$\Delta E \equiv E_\tau - E_{beam}$$

$E_\tau \rightarrow E_{3\mu}$, $E_{beam} \rightarrow \sqrt{s}/2$

ΔE VS M of signal τ



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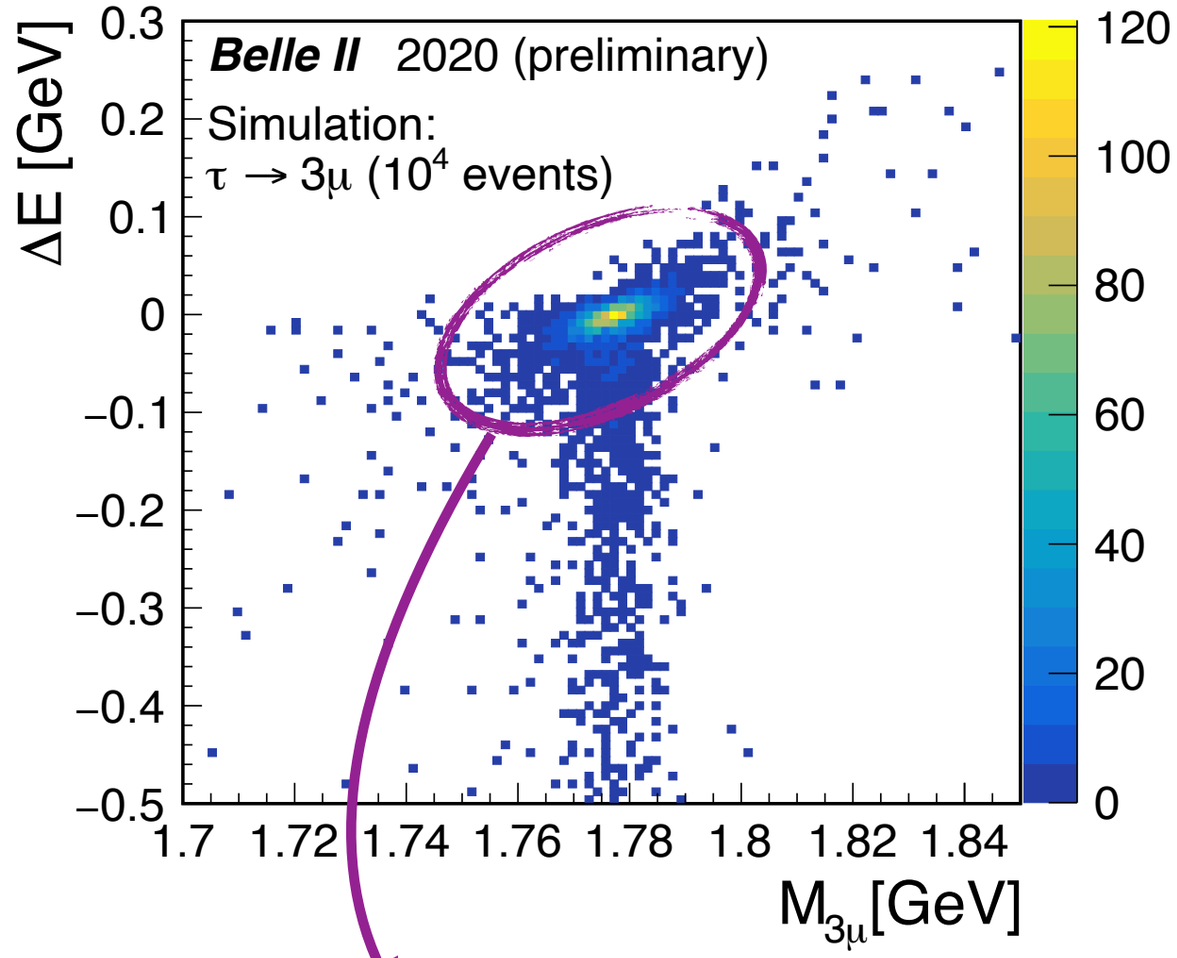
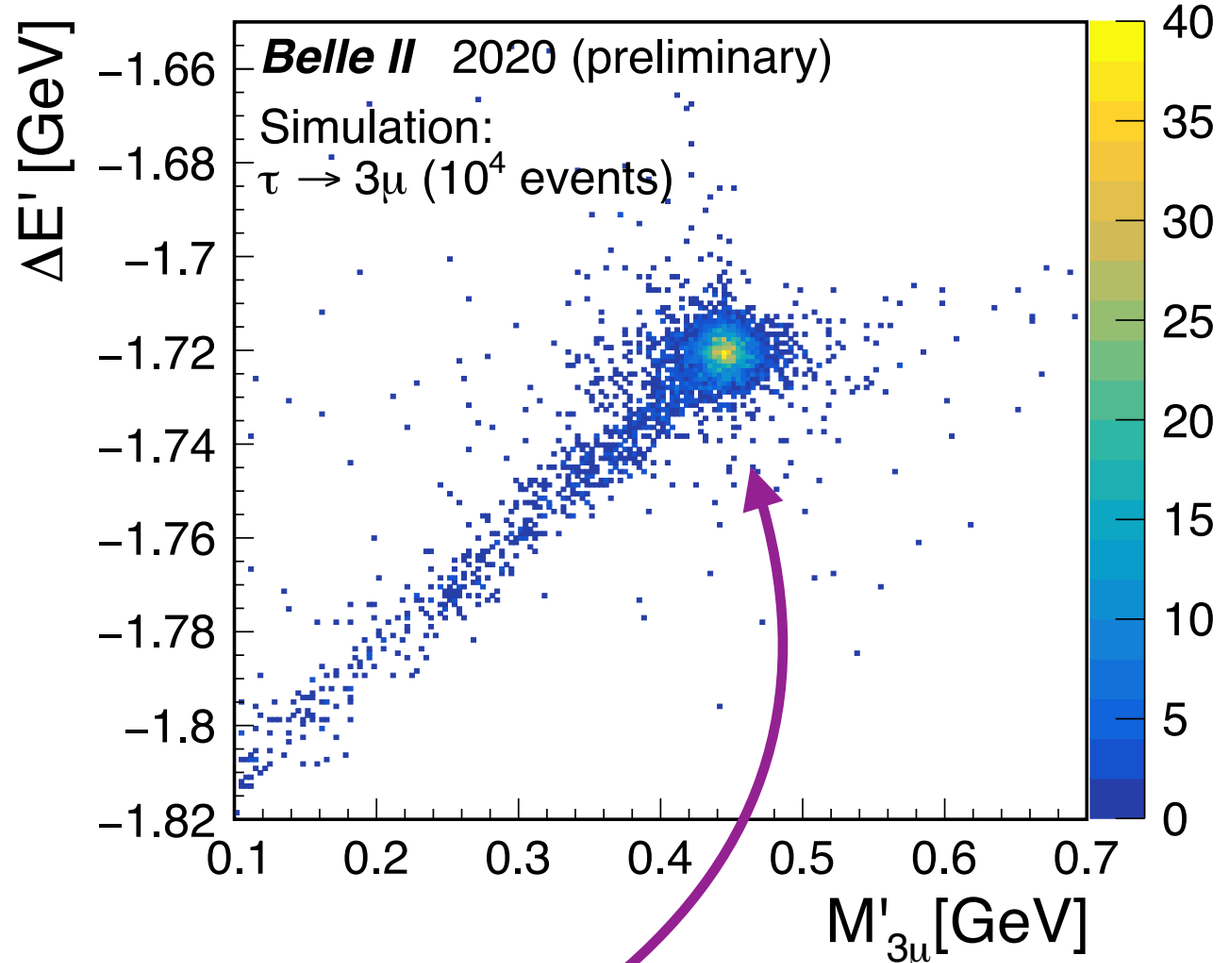


ΔE' VS M' of signal τ

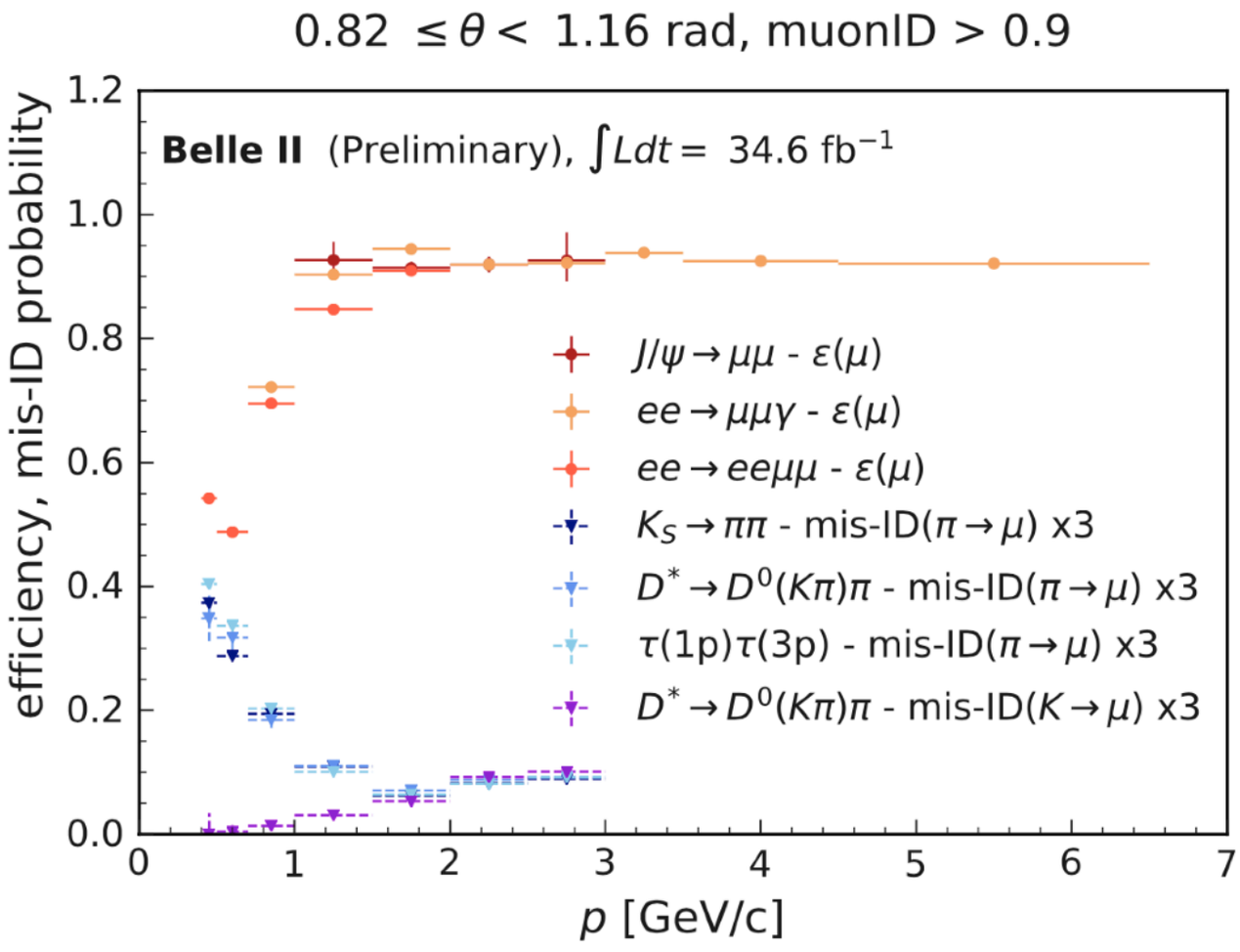


$$\begin{pmatrix} M'_{3\mu} \\ \Delta E' \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} M_{3\mu} \\ \Delta E \end{pmatrix}$$

axis rotation of $\theta \simeq 75°$ to reduce variable correlation→improve selection performances

Background rejection: signal side

The most **powerful discriminating variable** between signal and background is the **muonID**



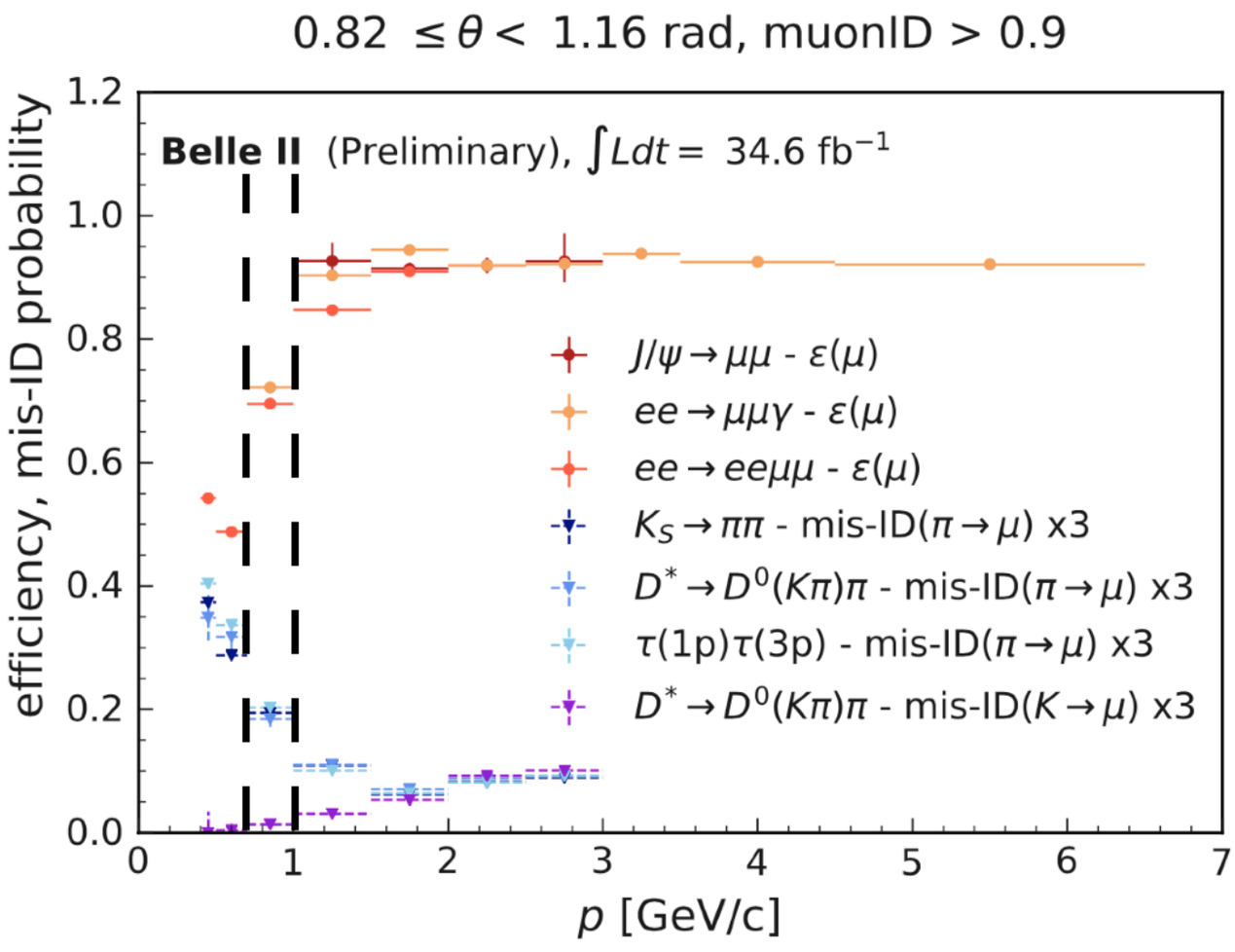
Ref: https://docs.belle2.org/record/2062/files/BELLE2-NOTE-PL-2020-027.pdf

Background rejection: signal side

The most **powerful discriminating variable** between signal and background is the **muonID** →cut-based selection optimised in bins of muon momentum (**new wrt BaBar and Belle**)

Momentum ranges:

- **p_μ<0.7 GeV**: μ do not reach the μ detector (KLM)
- **0.7<p_μ<1 GeV**: μ reach KLM but not many layers are crossed
- **p_μ>1 GeV**: μ reach KLM and many layers are crossed



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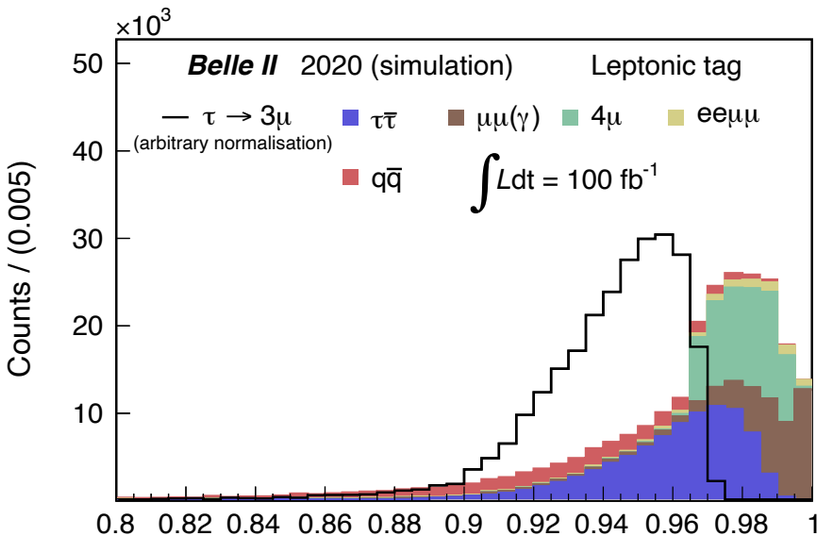
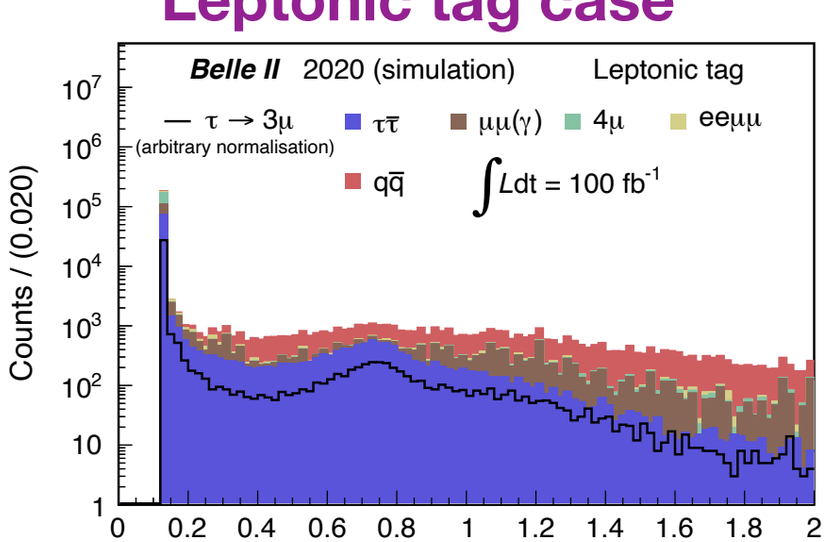
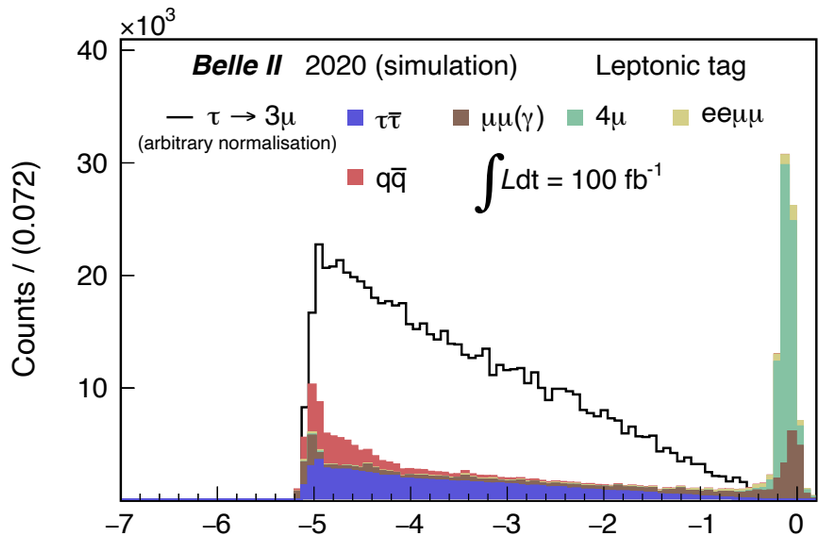
Background rejection: event/tag side

Cuts on event and tag side variables useful to reduce background contributions

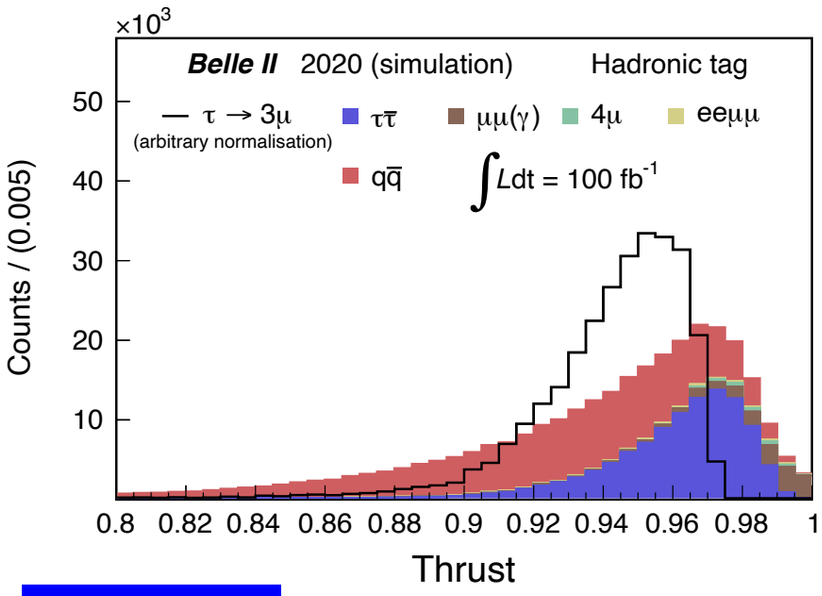
Leptonic tag case

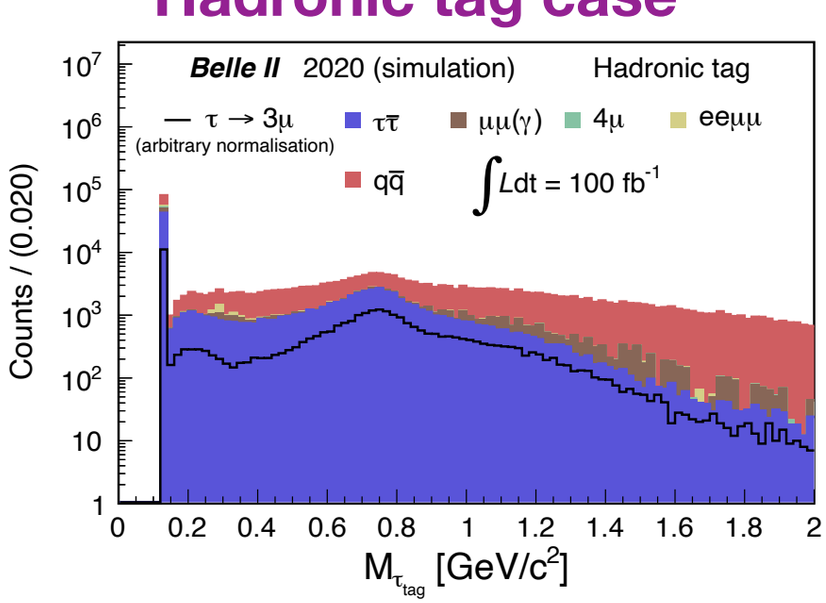


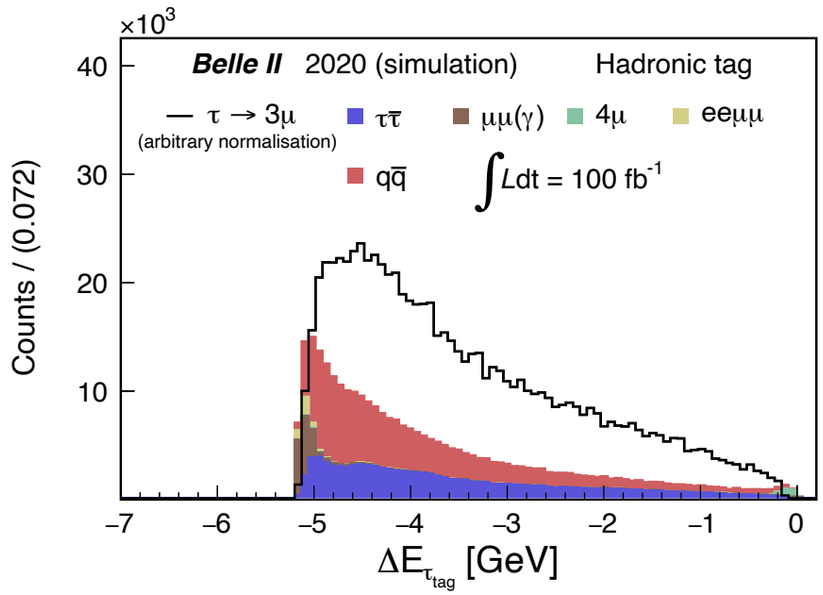




Hadronic tag case





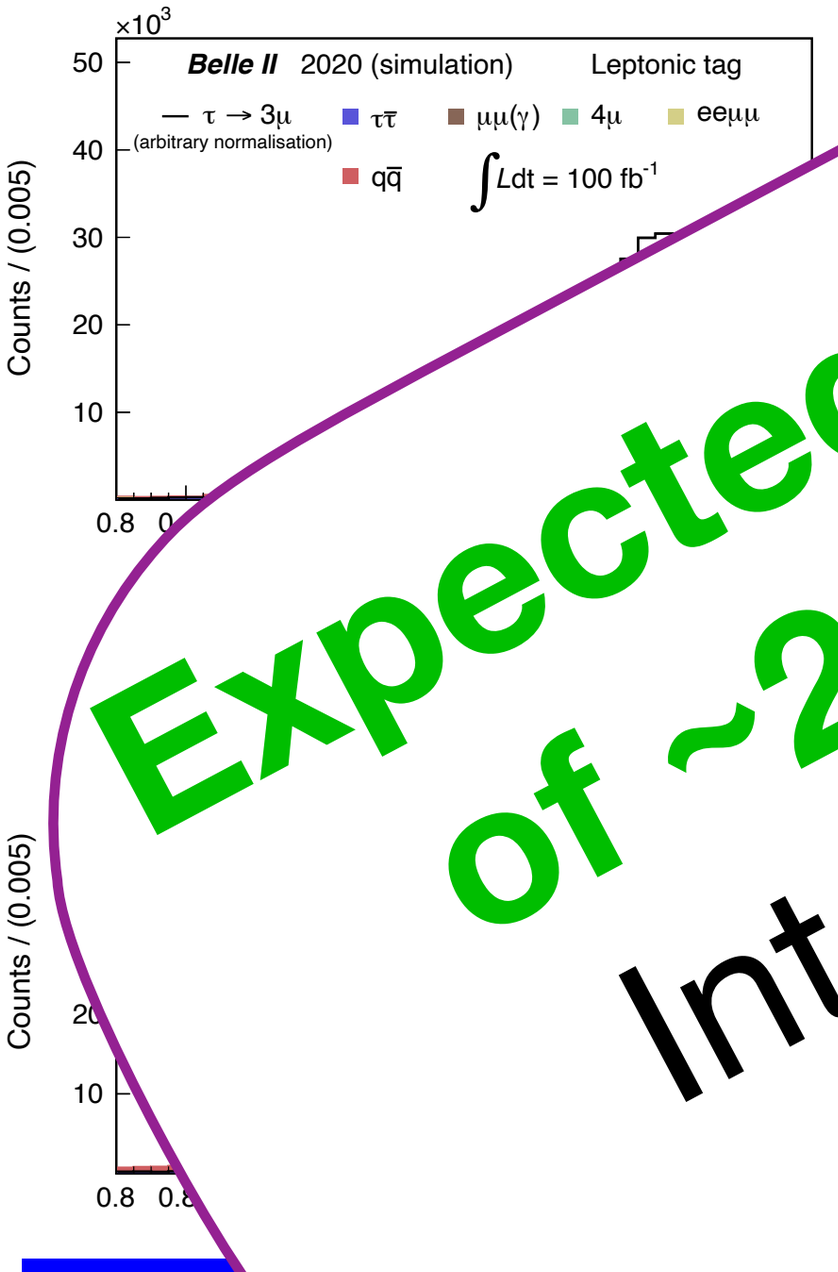


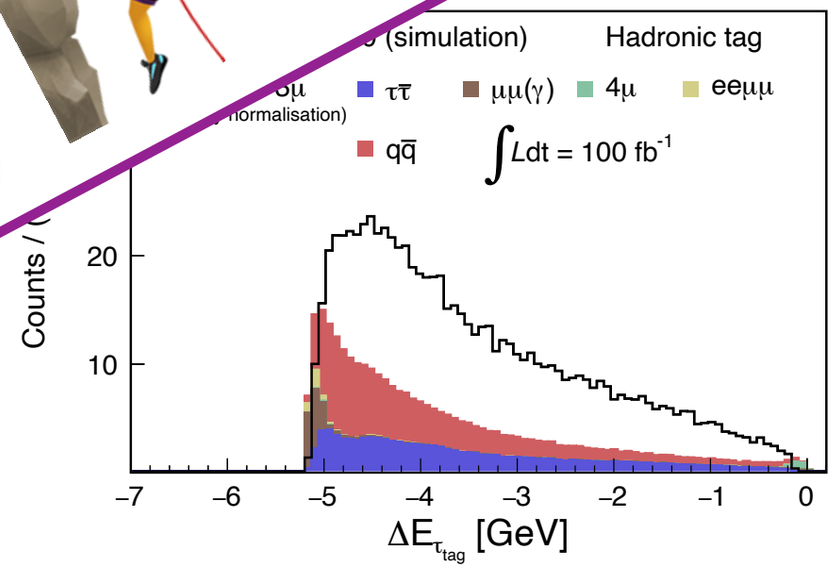
Distribution of variables at an early stage of the selection

Background rejection: eve… side

Cuts on event and tag side variables useful…

Lept…





Expected improvements of ~2x in efficiency!

Internal approval is ongoing

variables at an early stage of the selection

Analysis motivations: $\tau \to l V^0(\phi \to h^+h^-)$

Experimental upper limits from **Belle** and **BaBar** for $\tau \to e/\mu\phi$:

- Belle: **3.1/8.4 x 10^{-8}** @90% confidence level using $\int Ldt = 845 fb^{-1}$
  https://arxiv.org/pdf/1101.0755.pdf
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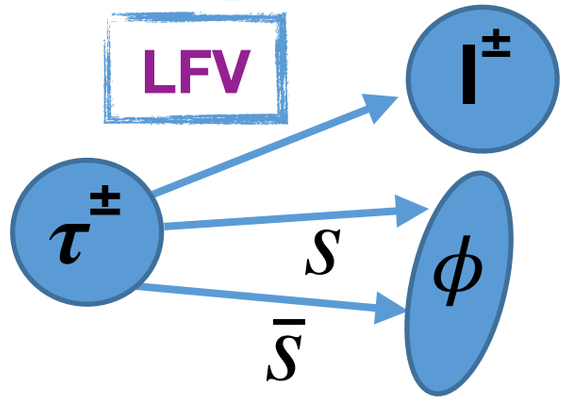

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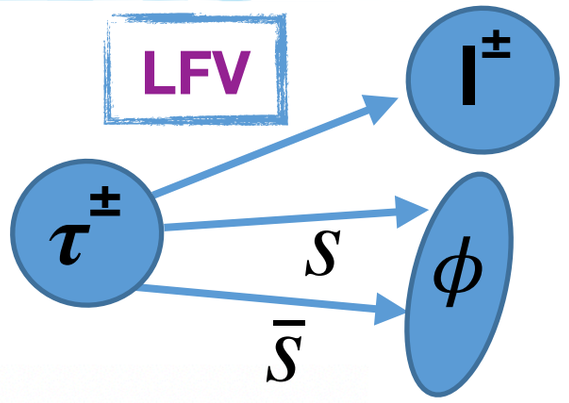

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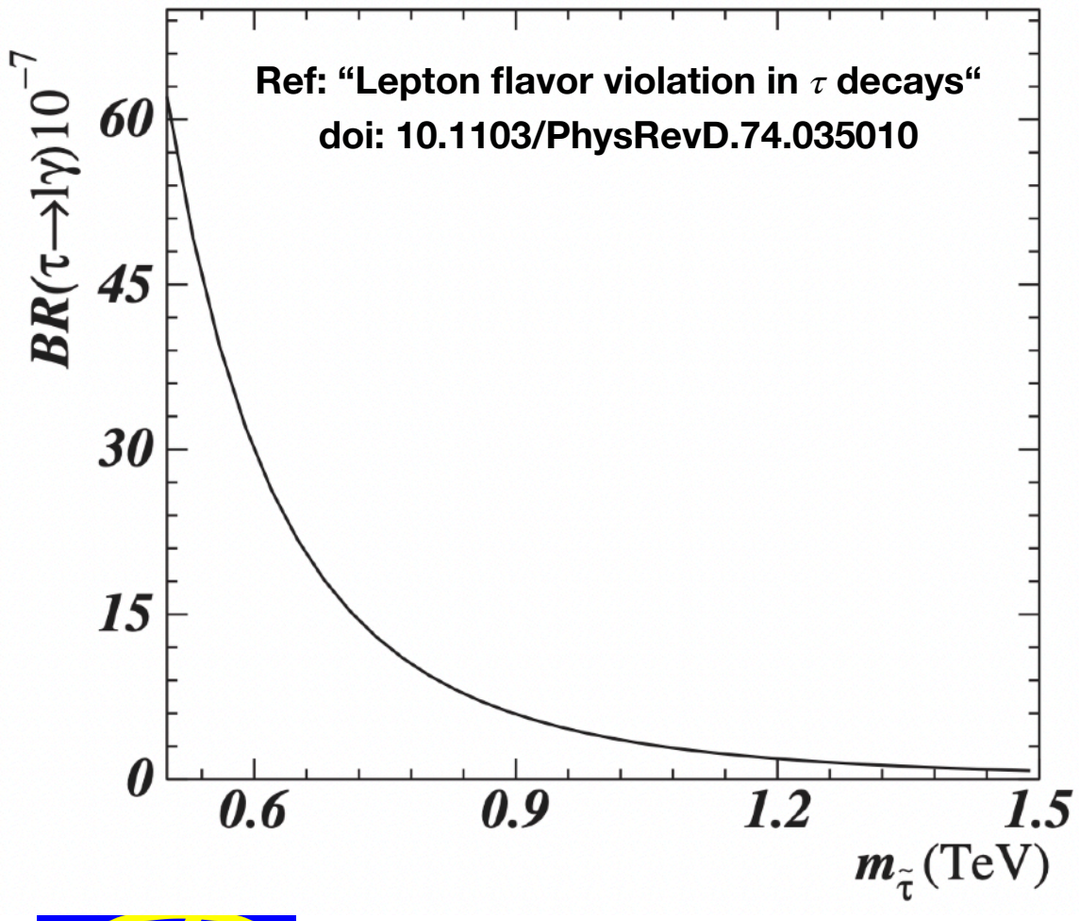
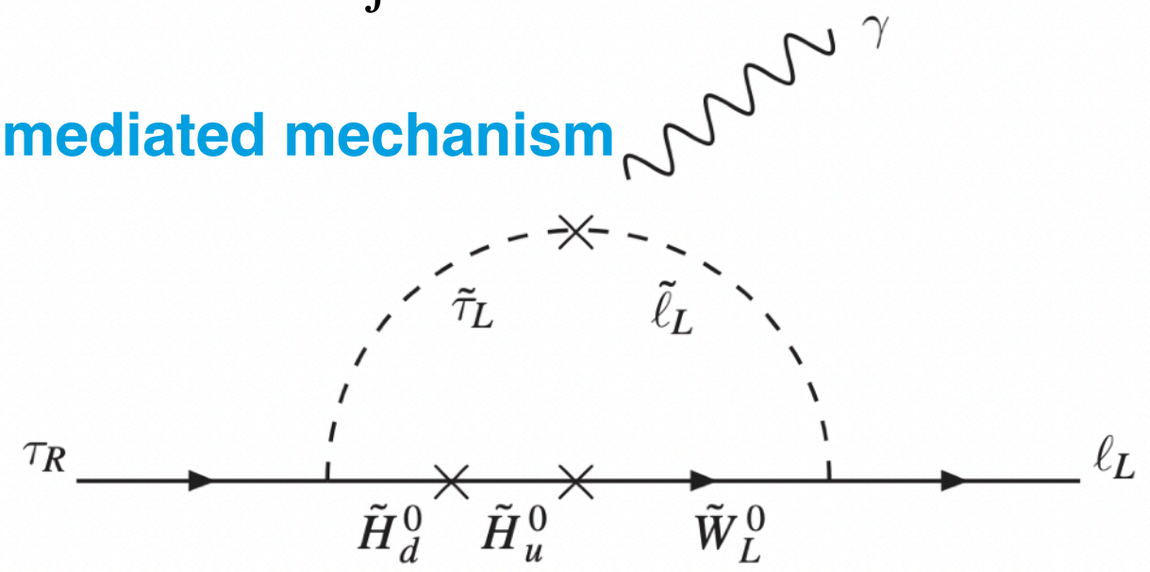
Model: Higgs-mediated mechanism





$$R_\ell^\gamma = \frac{\mathrm{BR}(\tau \to \ell X_\gamma)_\gamma}{\mathrm{BR}(\tau \to \ell\gamma)} = O\left(\frac{\alpha_{em}}{\pi}\right) \sim \mathbf{10^{-3}}$$

$$(X_\gamma = \mu^+\mu^-, \phi, K^+K^-).$$

No possibility to improve current limits on this model

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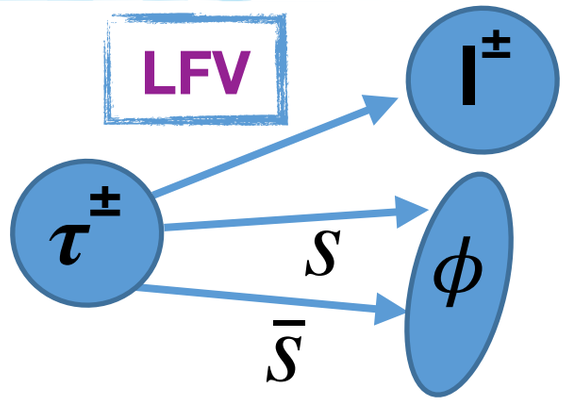
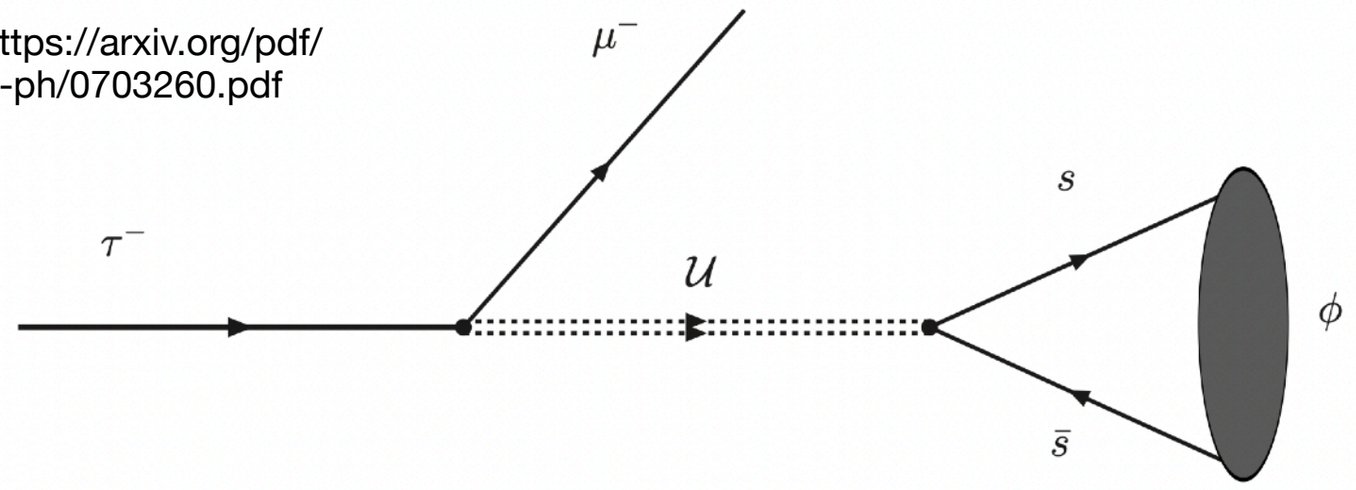


Unparticle model

Ref: https://arxiv.org/pdf/hep-ph/0703260.pdf



$$Br(\tau \to lV^0) \gg Br(\tau \to lP^0) \gg Br(\tau \to l\gamma)$$

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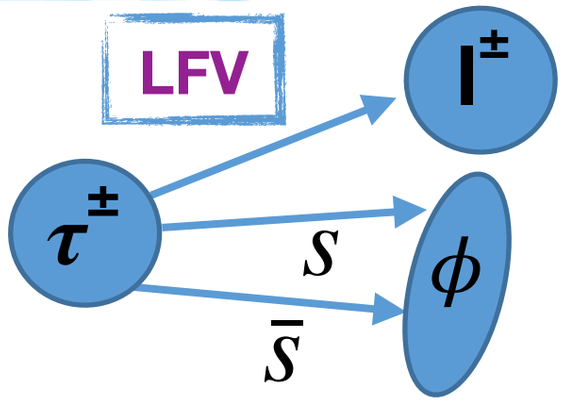
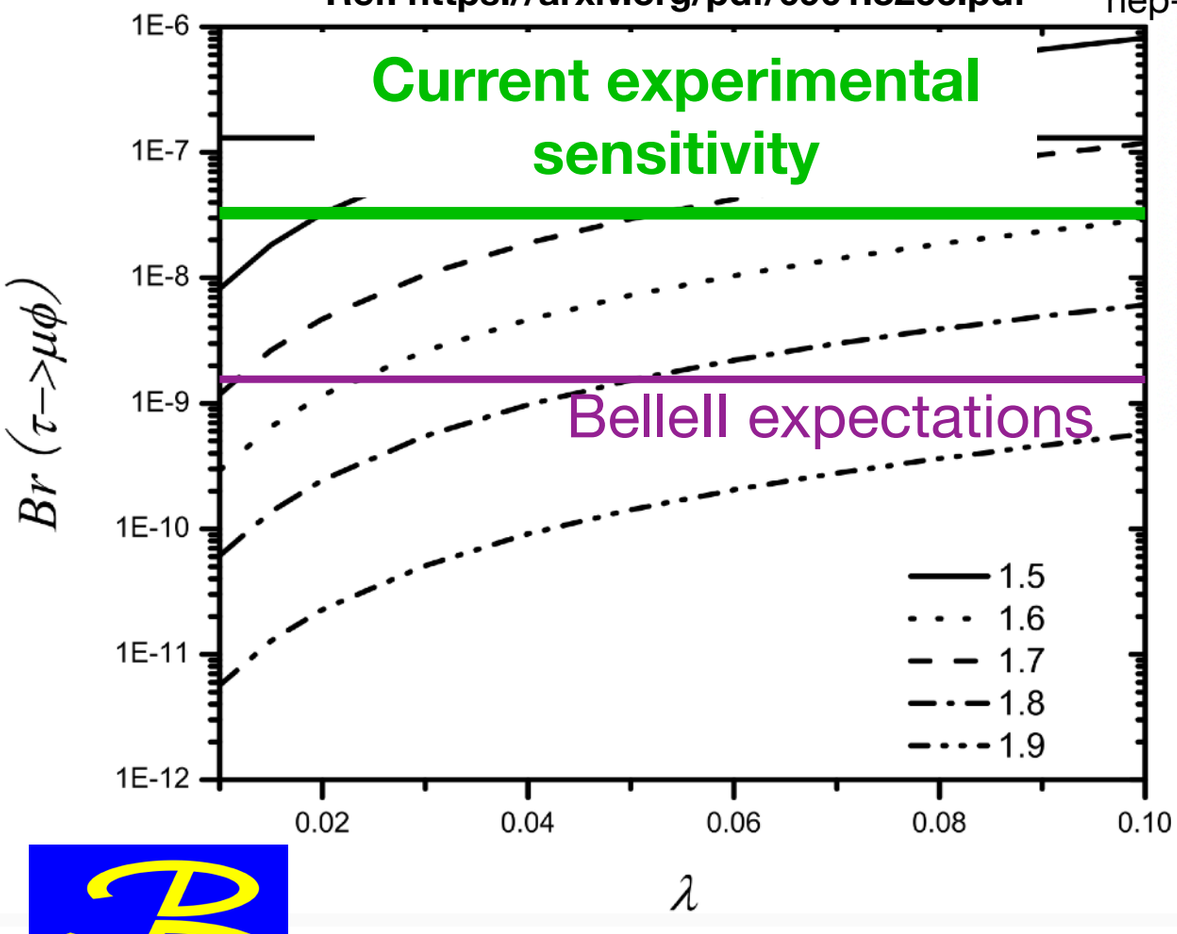


Ref: https://arxiv.org/pdf/0901.3266.pdf



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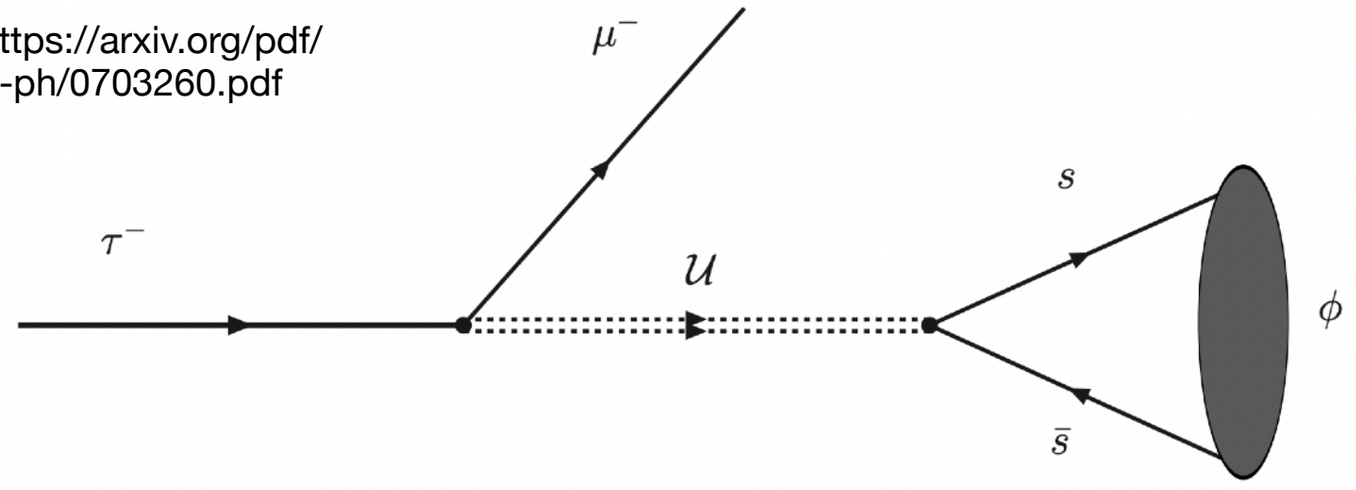


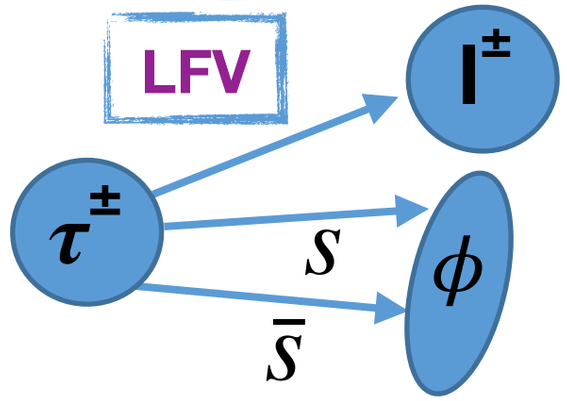
$$Br(\tau \to lV^0) \gg Br(\tau \to lP^0) \gg Br(\tau \to l\gamma)$$

One of the golden channel for this model

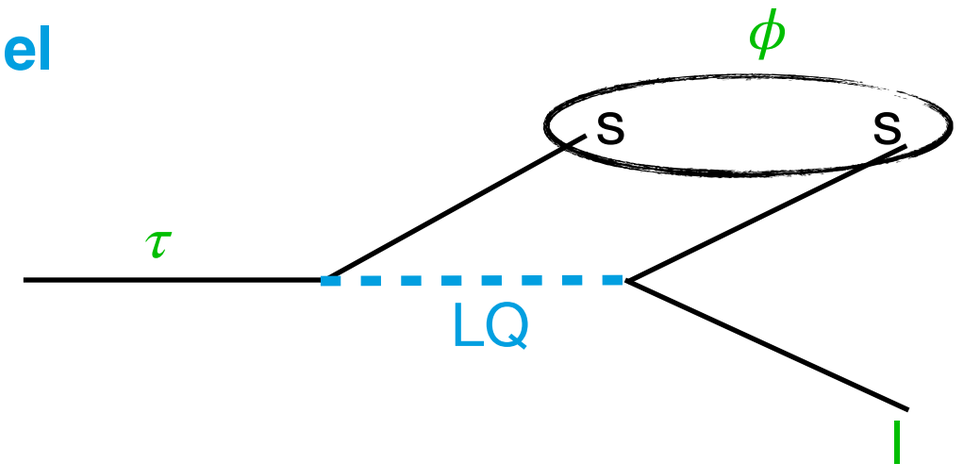
Analysis motivations: $\tau \to l V^0(\phi \to h^+h^-)$

Experimental upper limits from **Belle** and **BaBar** for $\tau \to e/\mu\phi$:

- Belle: **3.1/8.4 x 10^{-8}** @90% confidence level using $\int Ldt = 845 fb^{-1}$
  https://arxiv.org/pdf/1101.0755.pdf
- BaBar: **3.1/19 x 10^{-8}** @90% confidence level using $\int Ldt = 451 fb^{-1}$
  https://arxiv.org/pdf/0904.0339.pdf



Leptoquark model



Expectations: $\tau \to l V^0(\phi \to h^+h^-)$

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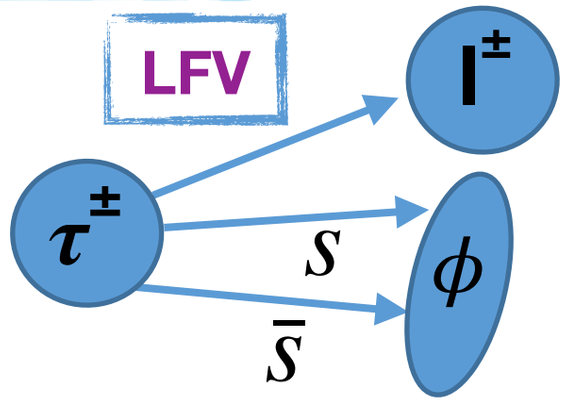
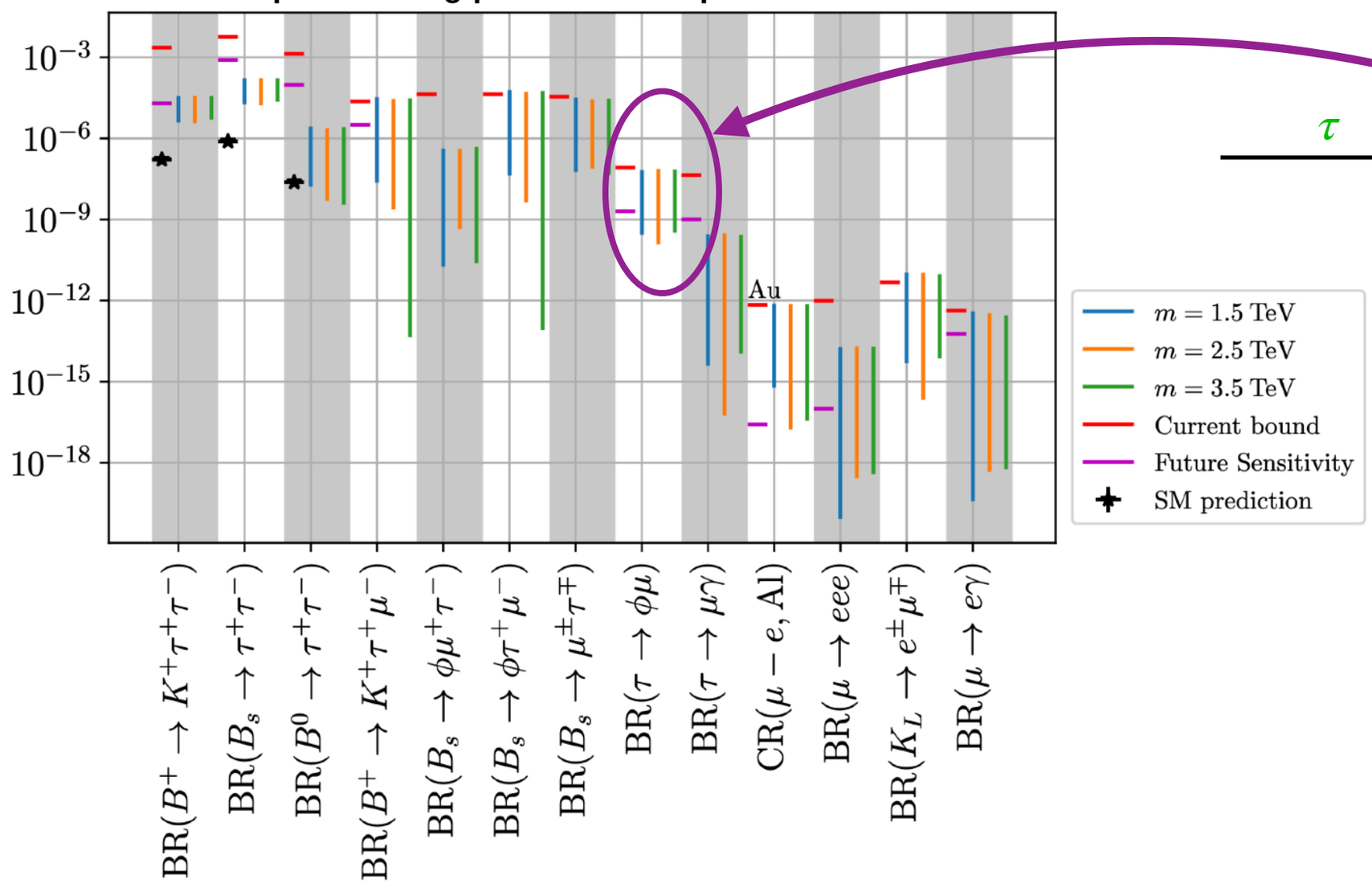
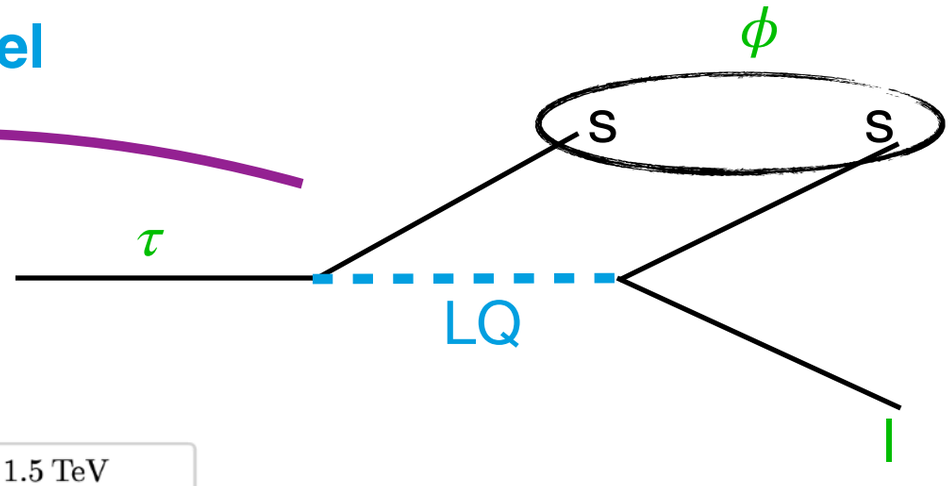
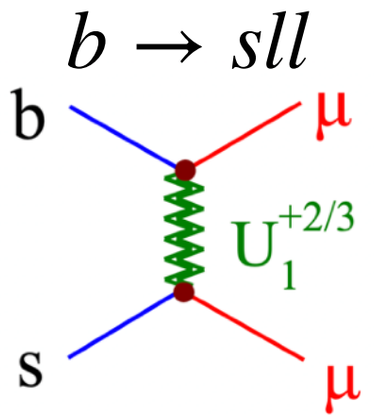


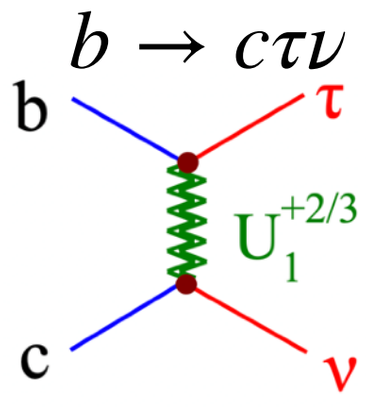
Ref: https://arxiv.org/pdf/2104.00015.pdf



Leptoquark model







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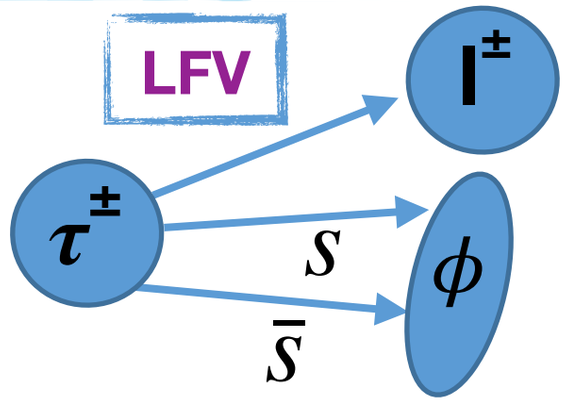
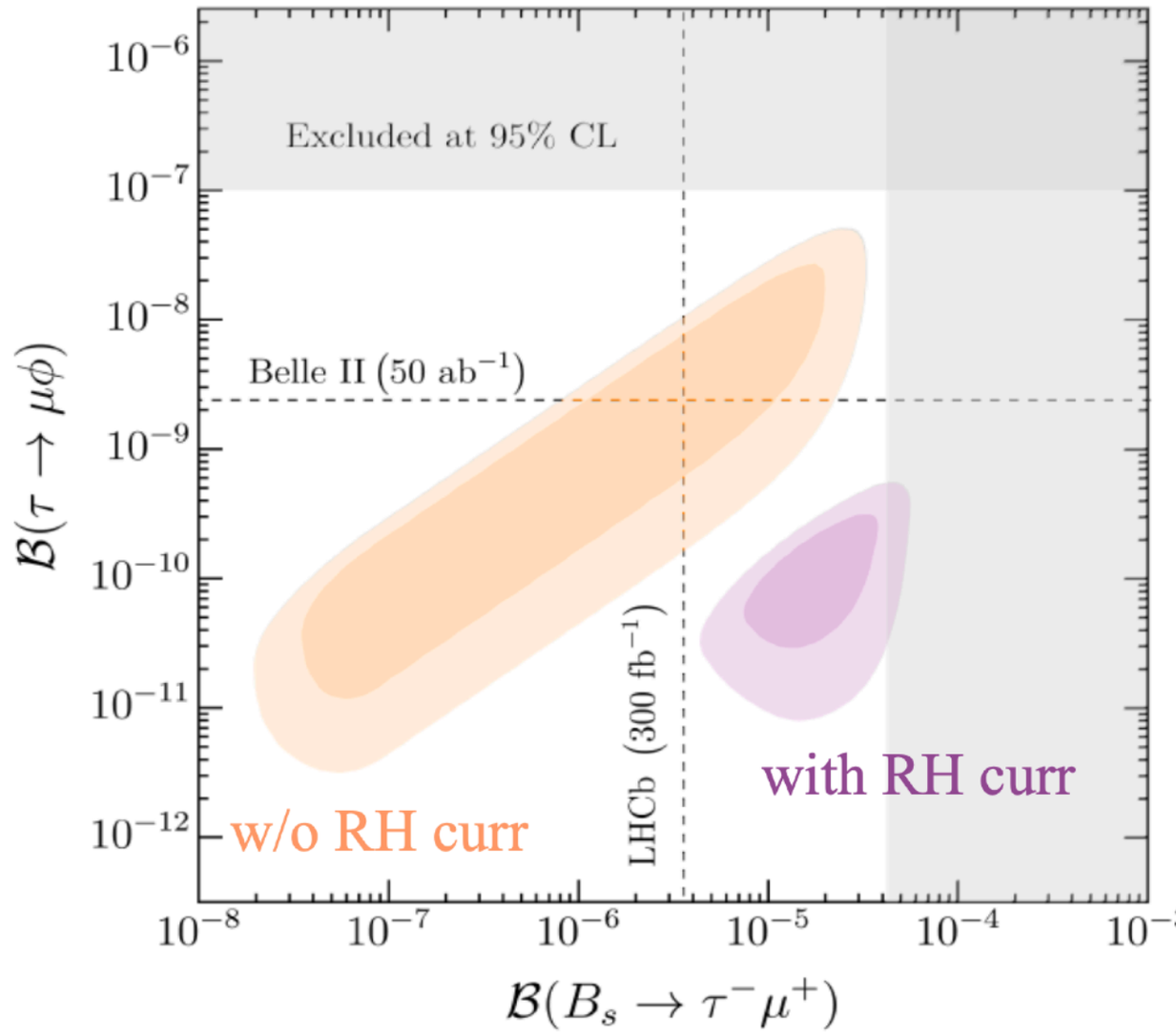


Leptoquark model

Ref: https://arxiv.org/pdf/2103.16558.pdf

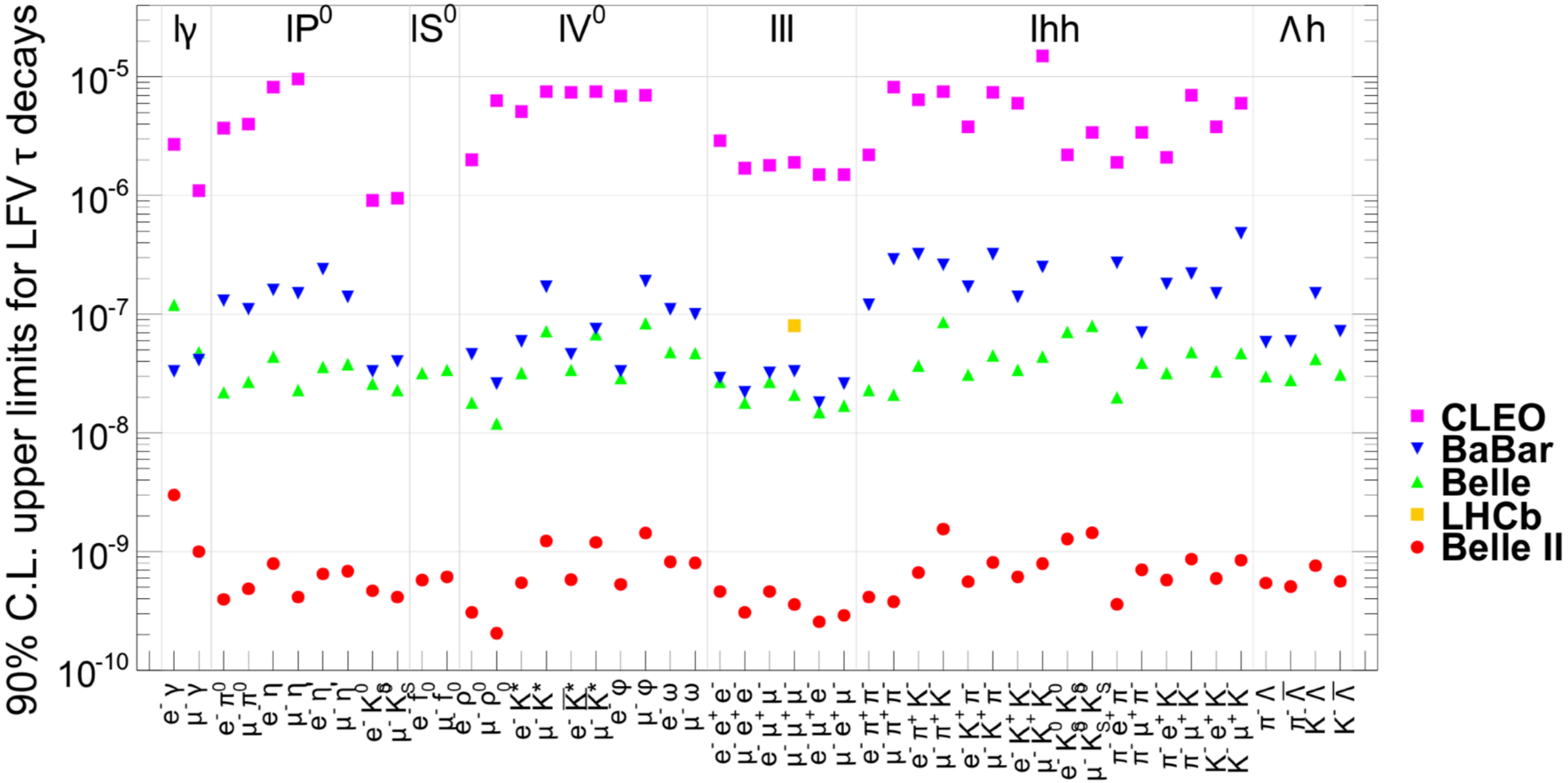
Model	$R_{K(*)}$	$R_{D(*)}$	$R_{K(*)}$ & $R_{D(*)}$
Scalars $S_1 = (3,1)_{-1/3}$	✗	✓	✗
$R_2 = (3,2)_{7/6}$	✗	✓	✗
$\widetilde{R}_2 = (3,2)_{1/6}$	✗	✗	✗
$S_3 = (3,3)_{-1/3}$	✓	✗	✗
Vector $U_1 = (3,1)_{2/3}$	✓	✓	✓
$U_3 = (3,3)_{2/3}$	✓	✗	✗

Angelescu, Becirevic, DAF, Sumensari [1808.08179]



Nice interplay between B and τ physics!

Expected limits results



Belle II is expected to improve the results of previous B-factory by a factor ~100 with statistics only but…

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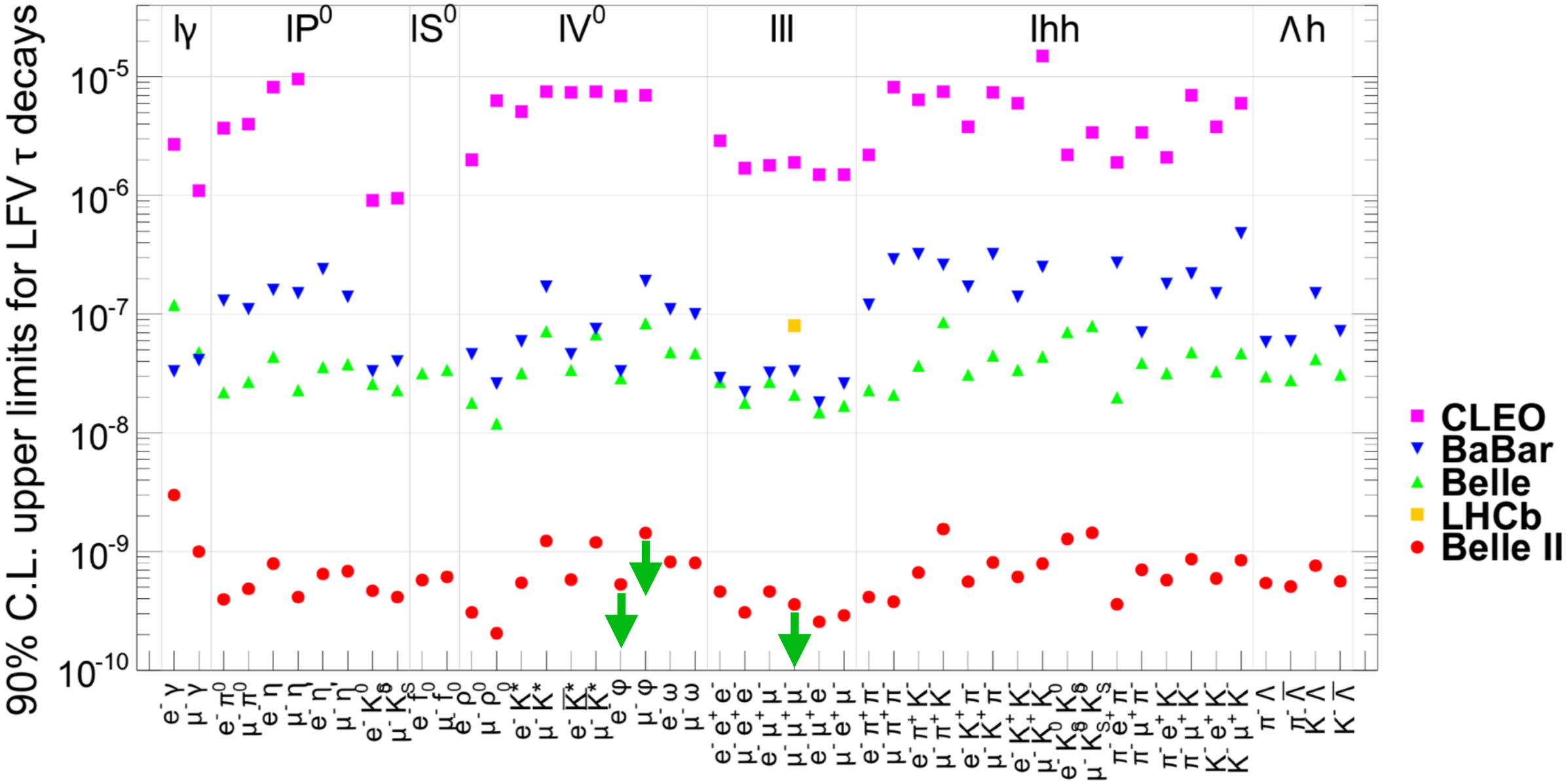

Belle II is expected to improve the results of previous B-factory by a factor ~100 with statistics only but…

With a better analysis strategy the results can be even better… and they are coming soon!

Conclusions

- **The Belle II experiment will be able to search for many LFV τ decays** within the next years thanks to advantages provided by the B-factory

- Several NP contributions are accessible by Belle II → the aim is to further **improve existing limits and search for NP hints**

- **$\tau \to 3\mu$ channel is promising:**
  - New optimised analysis is being performed @ Belle II
  - Improved μID algorithm is expected to improve previous results

- Unique **measurements of $\tau \to l V^0$ → probe different NP scenarios**

- **Results are coming → let's wait for more data to come!**

Emergency slides!!