Future directions on τ physics with Belle II

The 16th International Workshop on Tau Lepton Physics
Bloomington, Indiana University
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Belle II

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(on behalf of the Belle II collaboration)

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

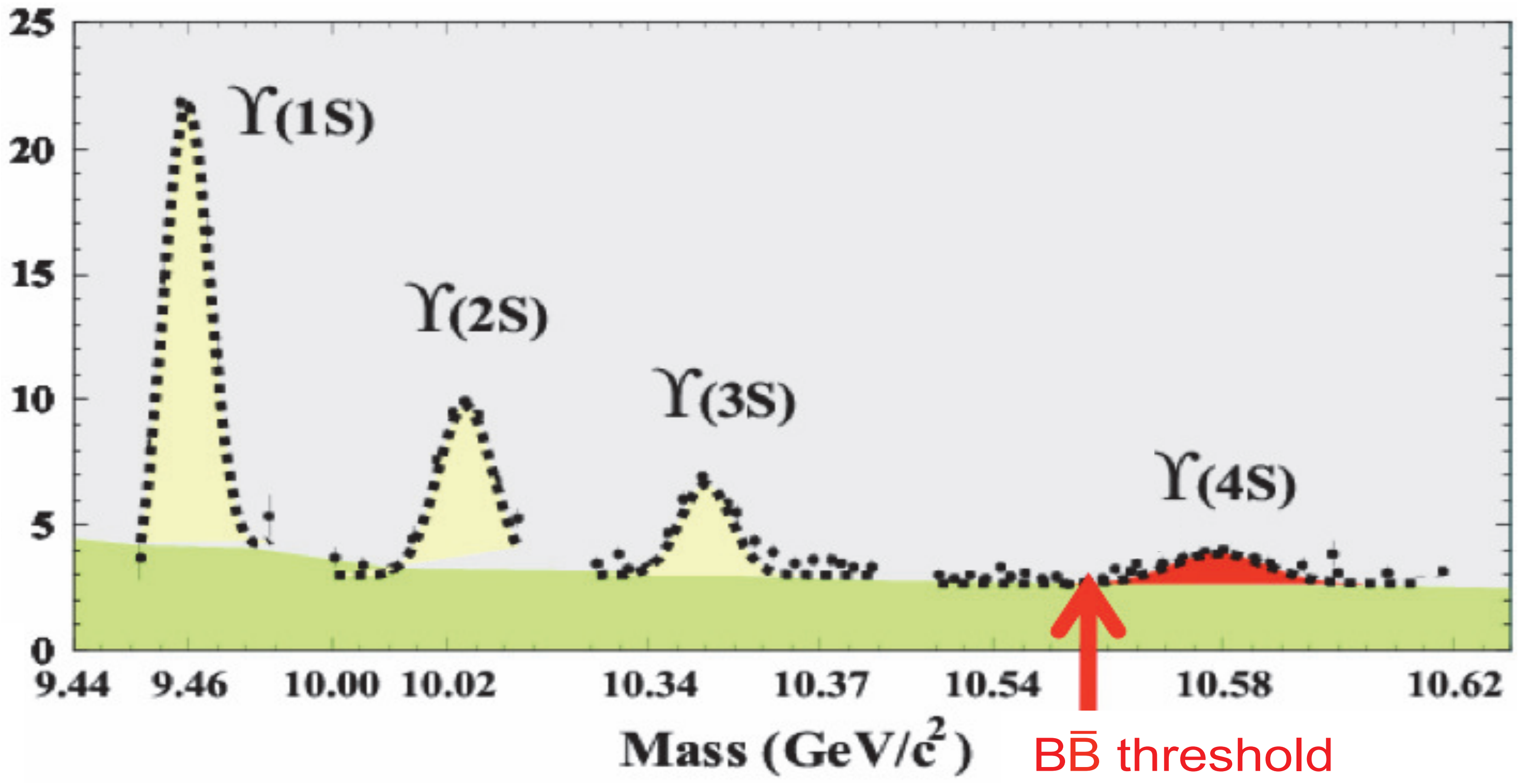
DESY.

τ physics program @ B factories

Historically B-factories provided a variety of very interesting results in the last two decades.

B-factories: Belle@KEKB and BaBar@PEP-II

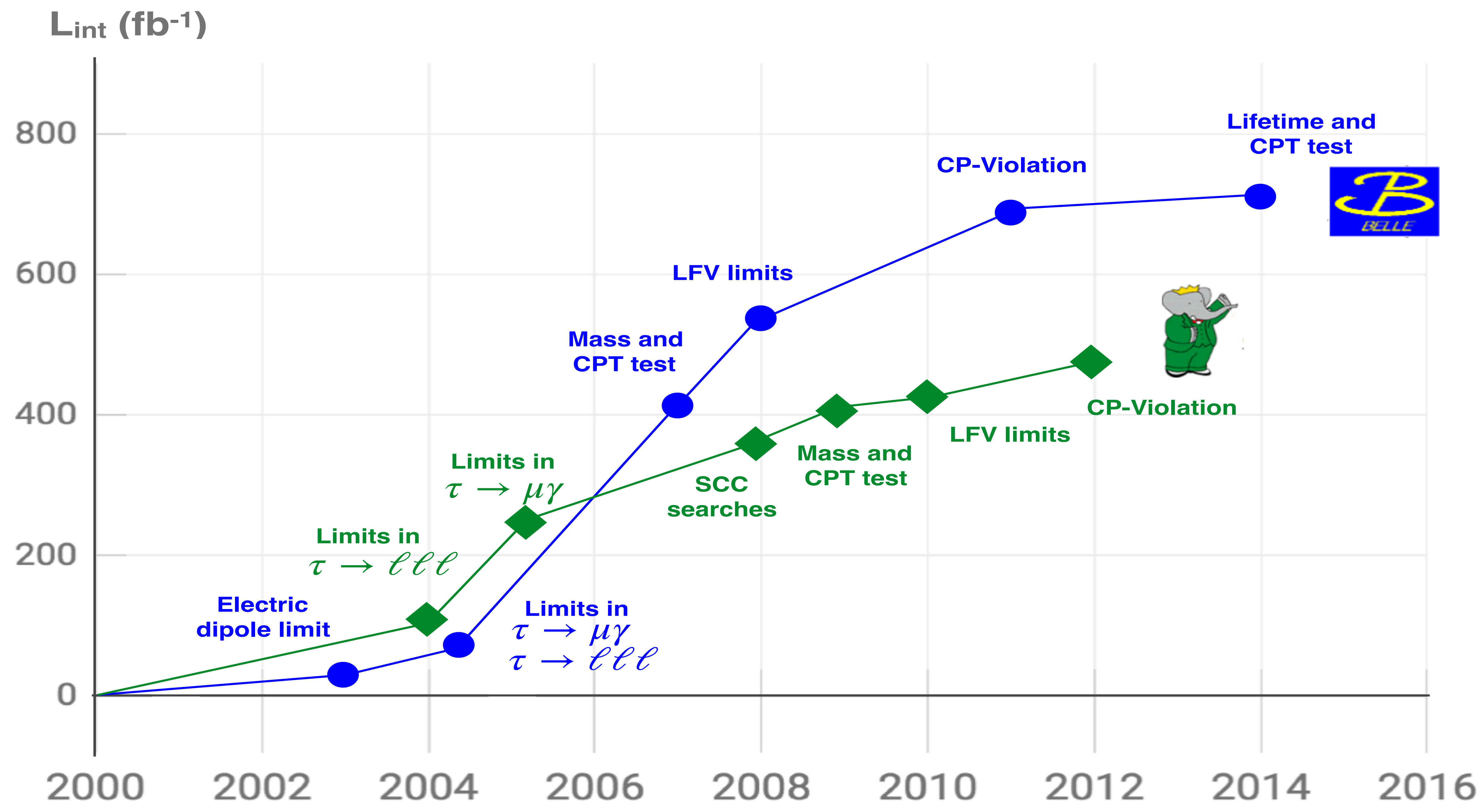
- Collision energy at Υ(nS)
  - BR(Υ(4S)→ $B\bar{B}$) > 96%



- Asymmetric beam energies
  - Boosted $B\bar{B}$ pairs
- High luminosities

~Belle: 711 fb^{-1} @ Υ(4S)

~ BaBar: 424 fb^{-1} @ Υ(4S)

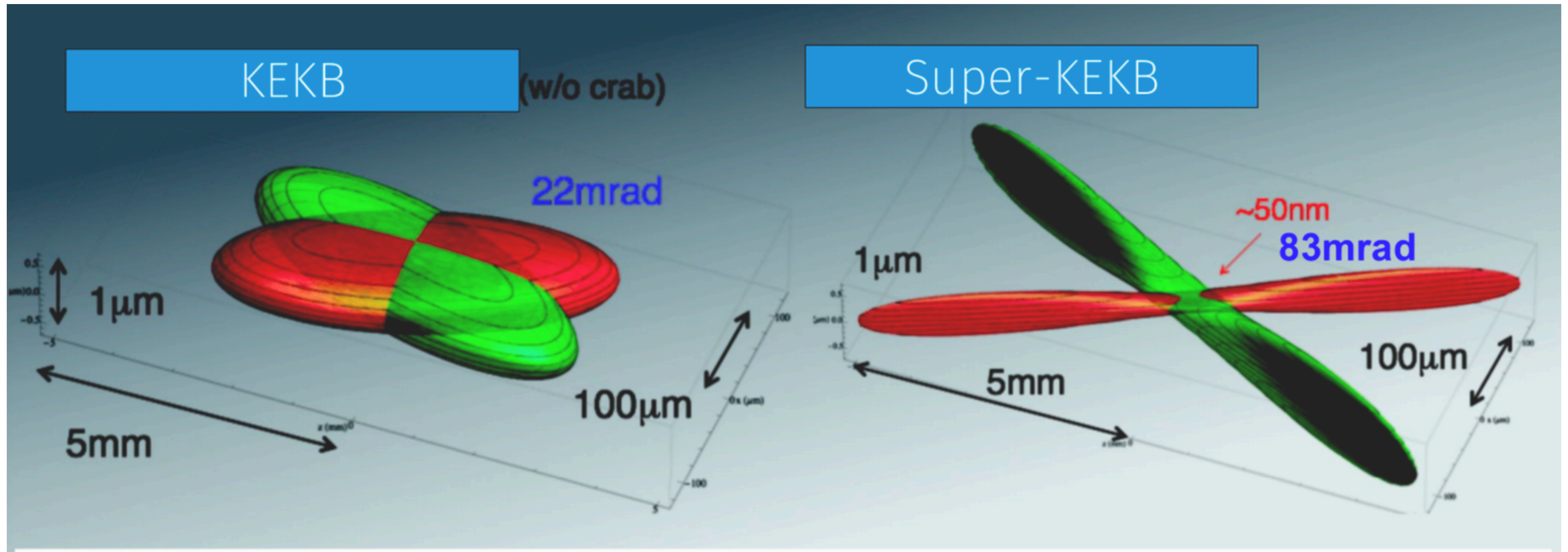


Wide physics program

- Precision SM measurement
- CP asymmetries
- Angular distributions
- Searches for lepton flavor/universality/number violations
- …

Belle II @ SuperKEKB

Unprecedented design luminosity of ~ 6×10^{35} $cm^{-2}s^{-1}$



	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

factor 20 factor 2-3

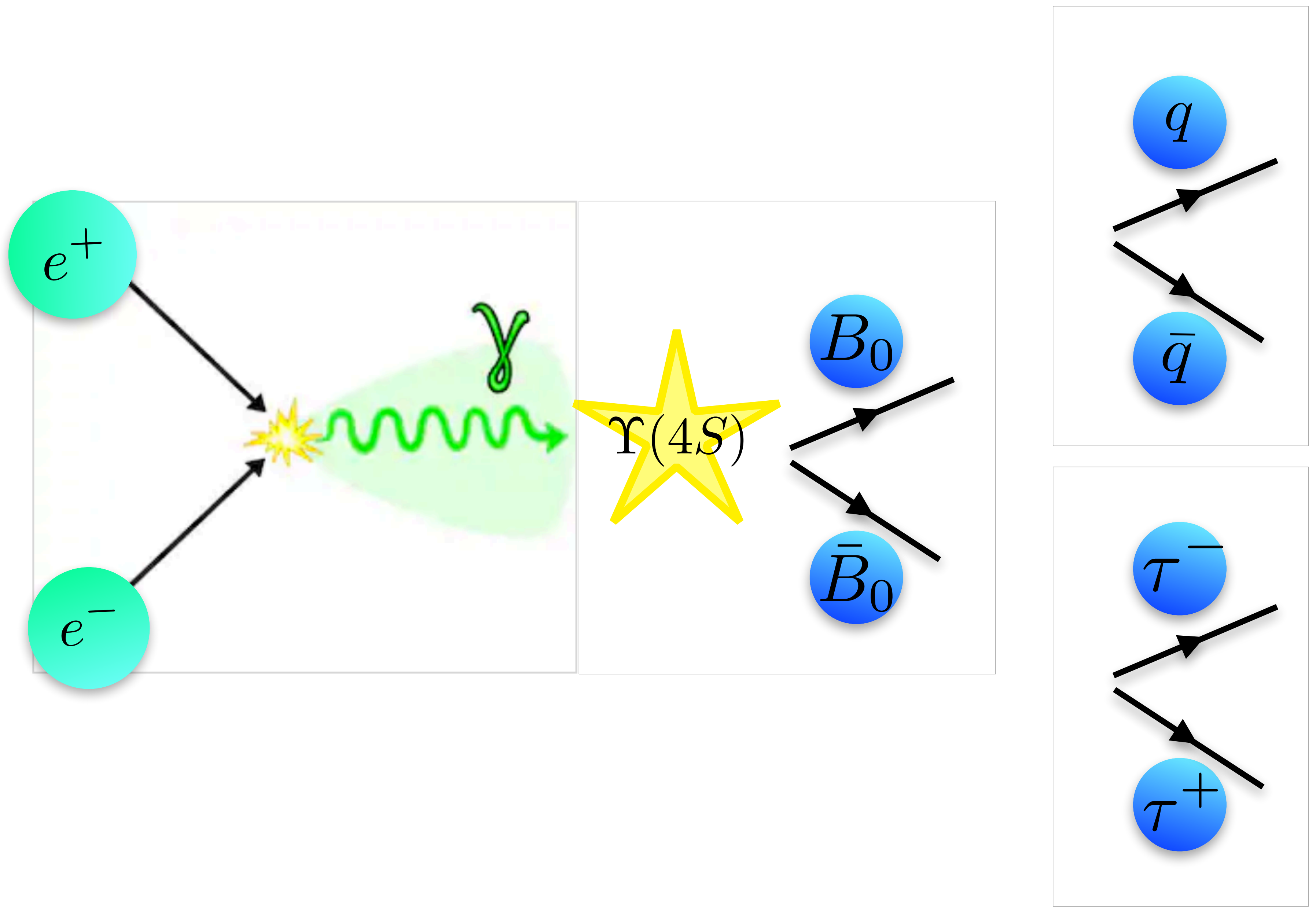
SuperKEKB – major upgrade of the KEKB

- an asymmetric electron-positron collider
  7.0 GeV (e^-) / 4.0 GeV (e^+)
- smaller interaction point
- increased currents

First collisions in 2018

Belle II - next generation B-factory

Not just B-factory but also τ factory!



Wide range of observables in τ sector to confront theory!

Does NP couple to 3rd generation strongly?

Precision measurements or indirect search of BSM

➡ ***significant deviations from SM*** are unambiguous signatures of NP

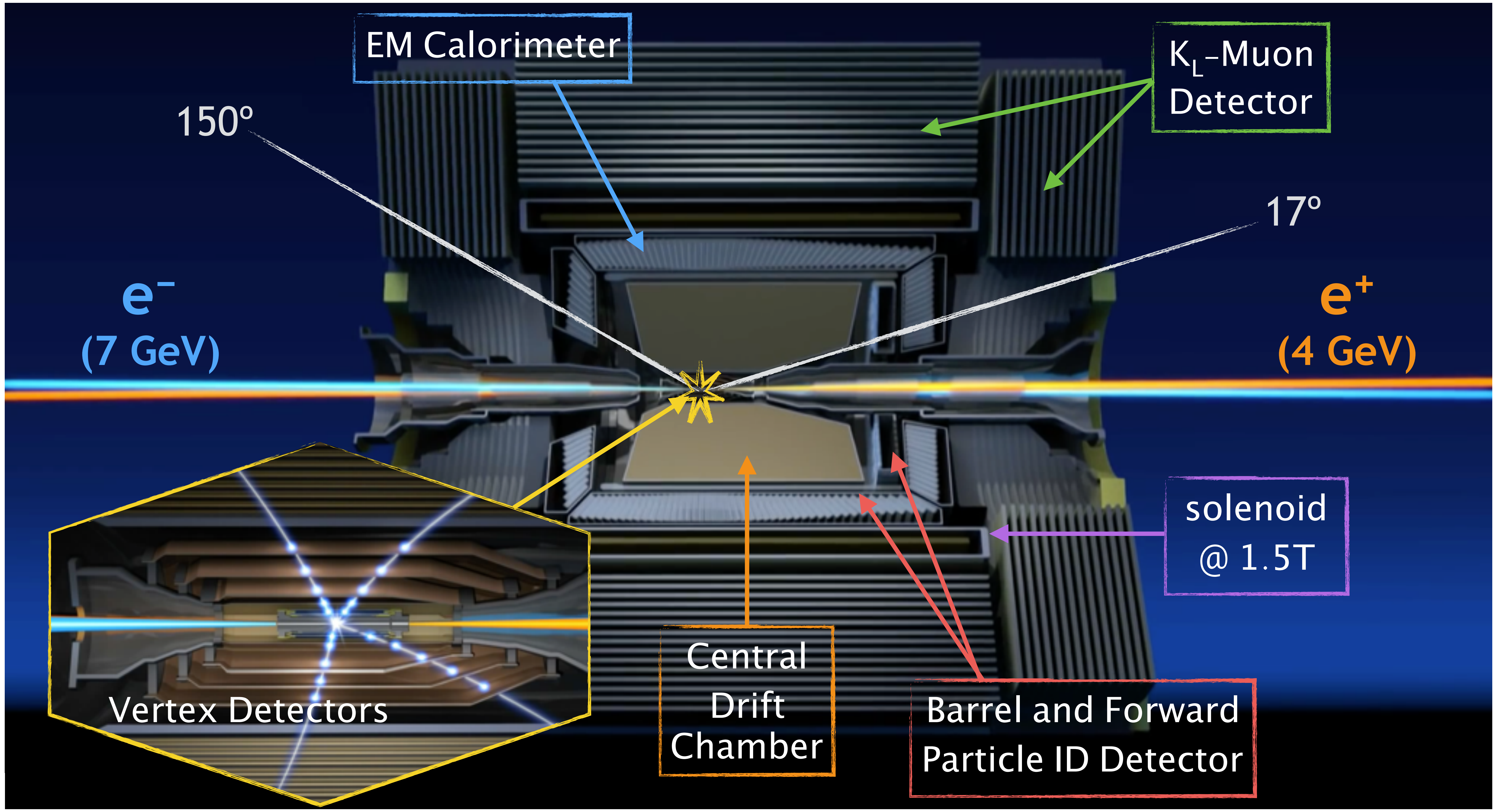
$$\sigma\left(e^+e^- \to \Upsilon(4S)\right) = 1.05\ [\text{nb}]$$
$$\sigma\left(e^+e^- \to q\bar{q}\right) = 3.69\ [\text{nb}]$$
$$\sigma\left(e^+e^- \to \tau^+\tau^-\right) = 0.919\ [\text{nb}]$$

Direct search of forbidden decays

➡ ***any signal*** is unambiguous signature of NP

Belle II @ SuperKEKB

Belle II detector – upgraded Belle detector



Performance

- ➡ upgraded trigger system
- ➡ improved impact-parameter resolution
- ➡ excellent tracking efficiency
- ➡ smarter software
- ➡ more precise algorithms

Luminosity records

- ➡ June 2020: $L = 2.4 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- ➡ June 2021: $L = 3.1 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Collected ~ 200 fb^{-1} of data

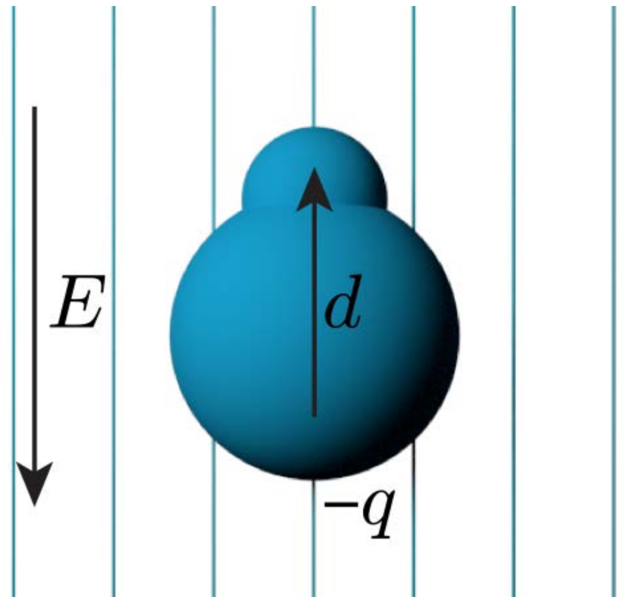
Important for τ analysis: discriminate between e, μ, π, K; reconstruct neutrals!

The τ lepton

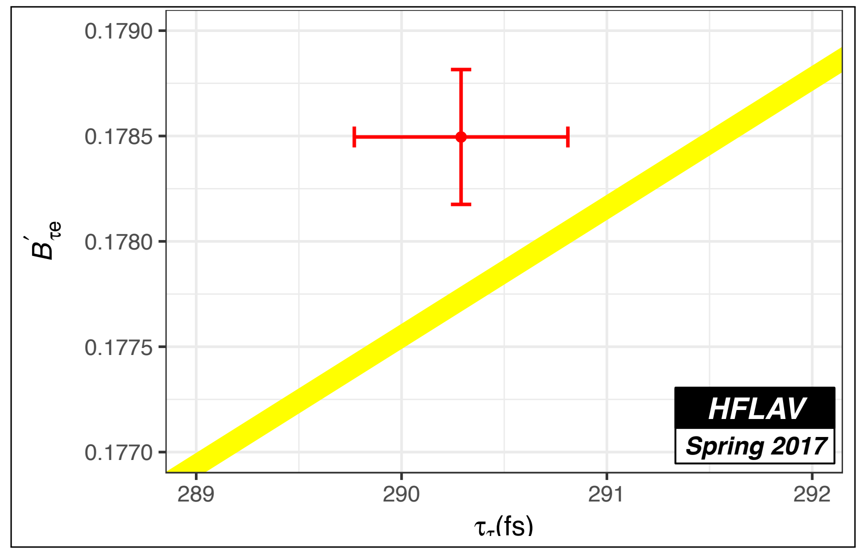
light → heavy

stable → unstable

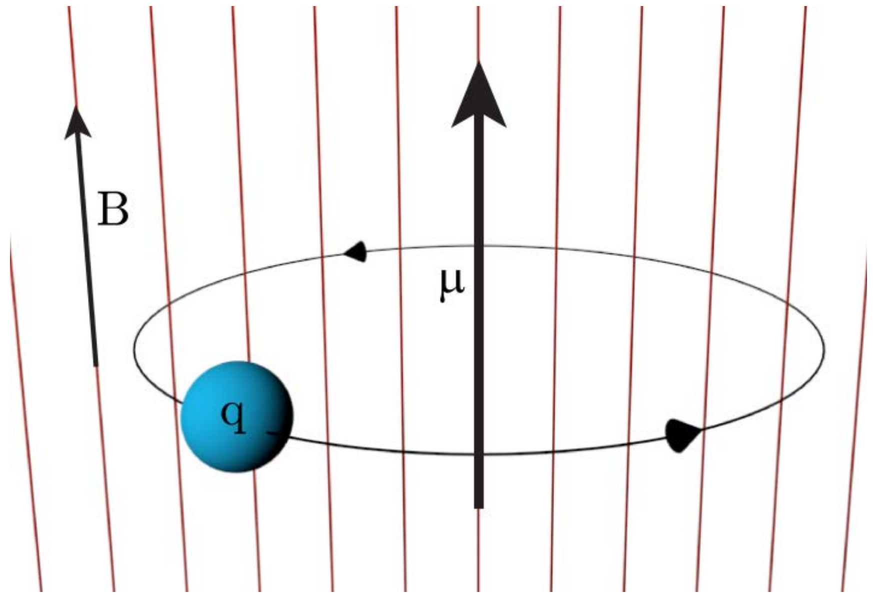
A. Lusiani et al: arXiv:1804.08436

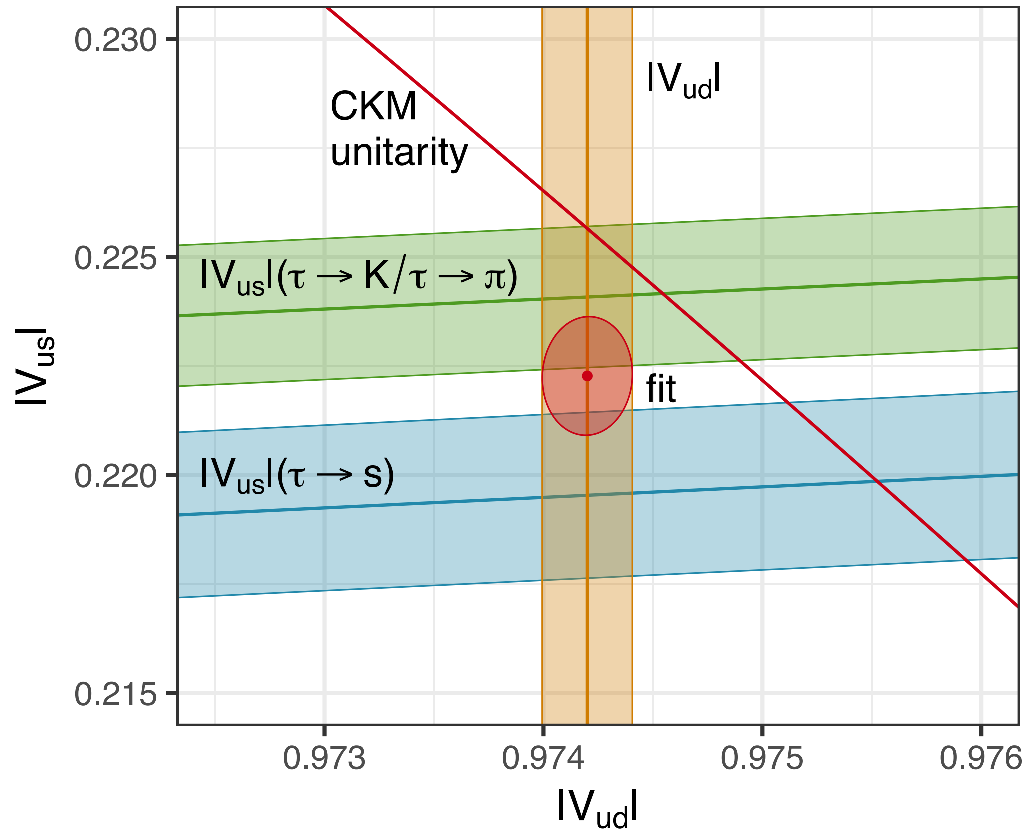


sourse



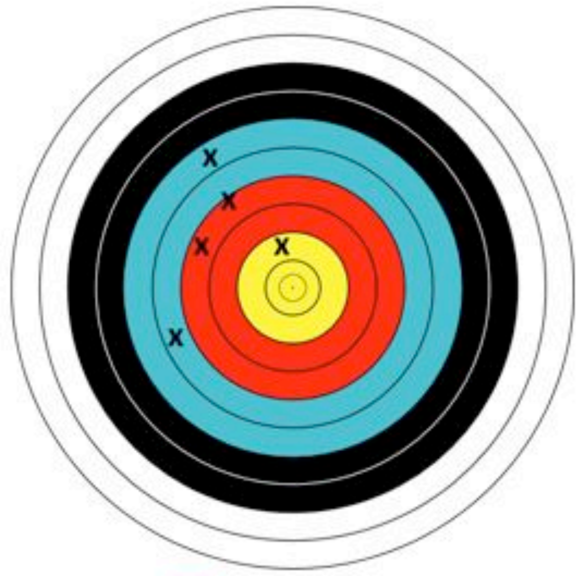
well known → not that much





In principle one could address

- CPT conservation
- lepton universality
- CKM unitarity
- new sources of CP violation
- lepton flavour and number violation
- …



The problem is the precision!

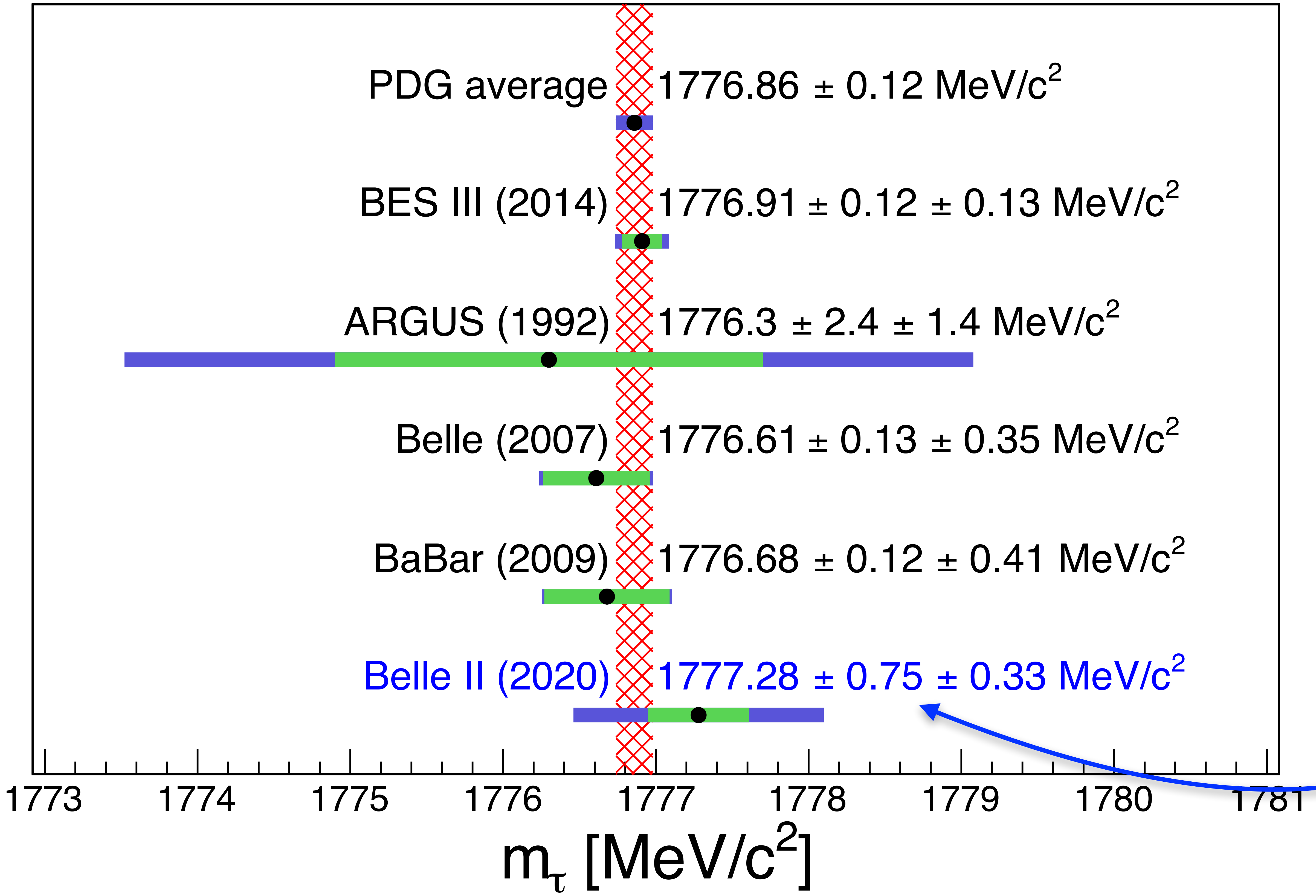
The mass

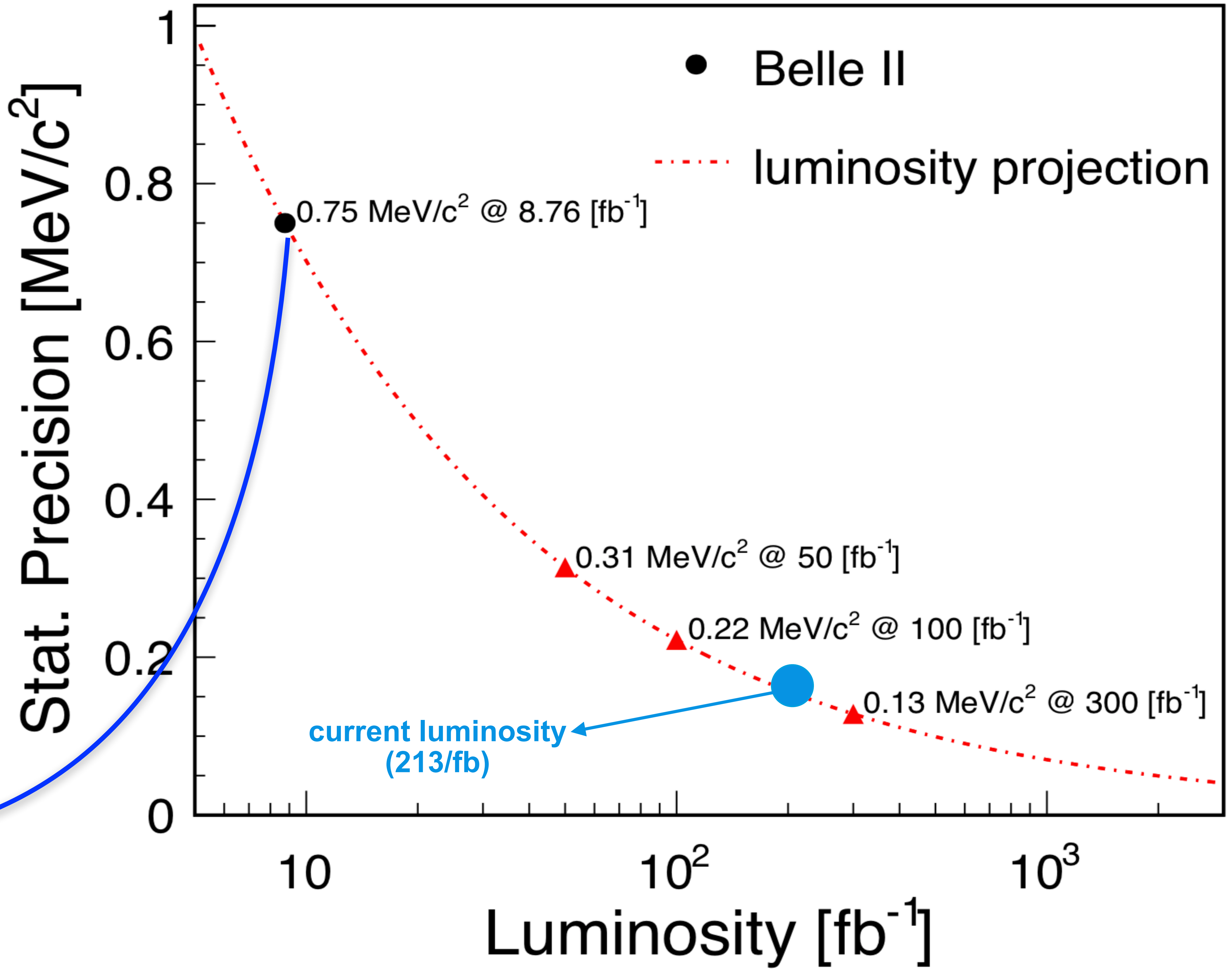
See poster of N. Rad
slides of M. Villanueva

Goal: achieve best precision among pseudomass measurements

arXiv:2008.04665

- best result from BES III from pair production at threshold energy
- best measurement from pseudomass technique by Belle
- match statistical precision of Belle/BaBaR with ~300 fb^{-1}
- future improvements of **reconstruction efficiency** and **systematic uncertainty**





The lifetime

See poster of S. Moneta
slides of M. Villanueva

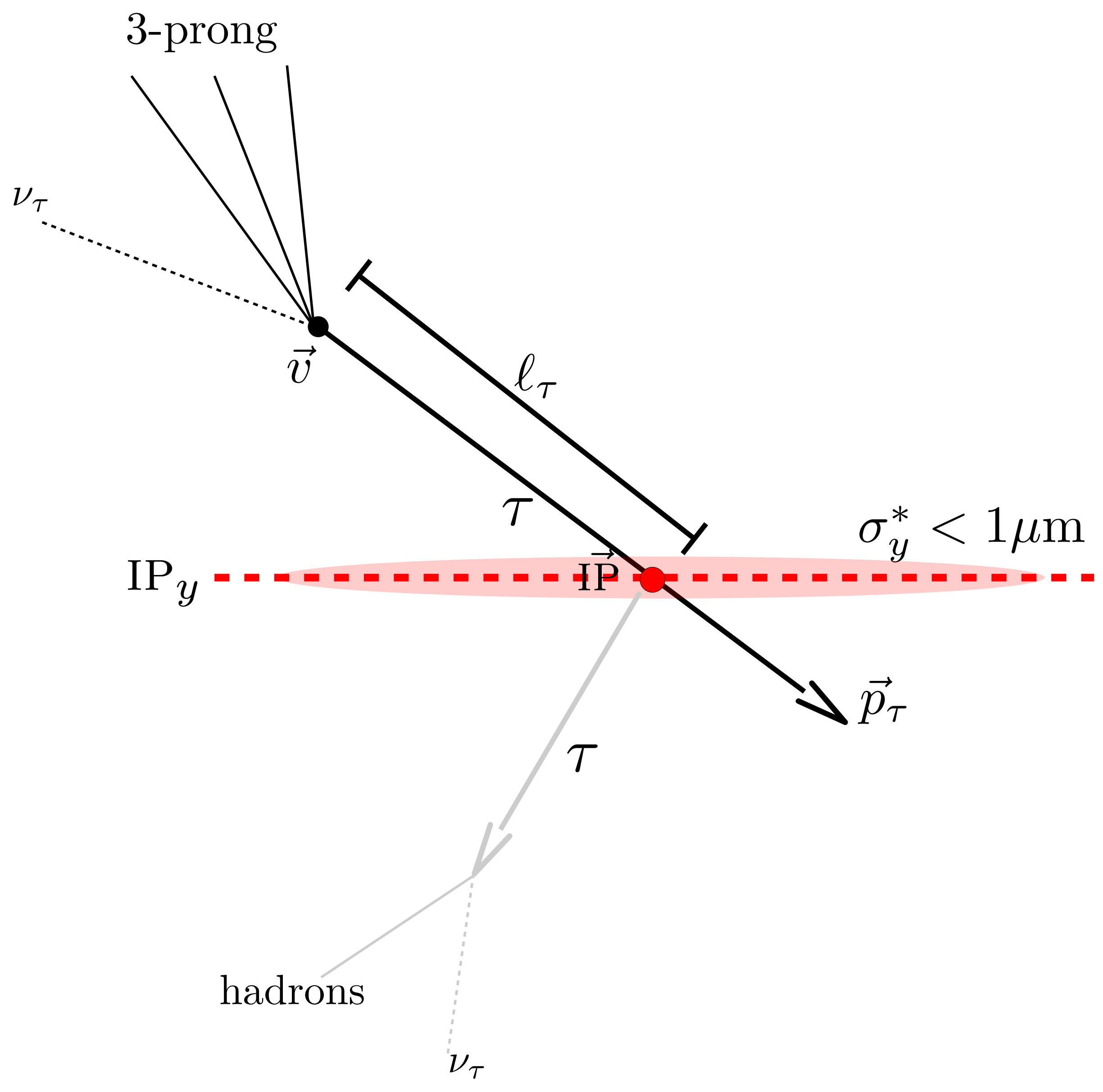
World best measurement from Belle using 711 fb-1 of data and 3x3 topology

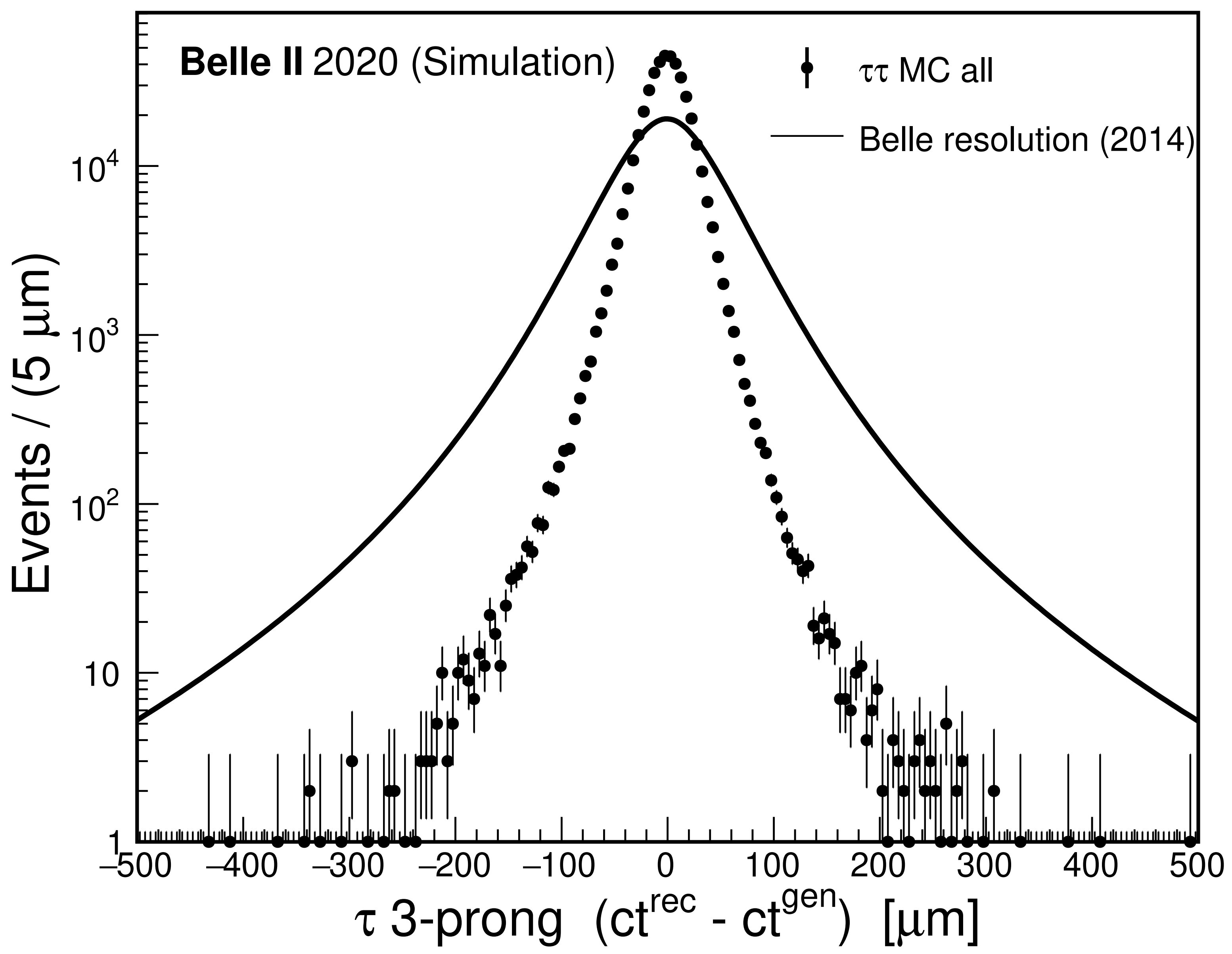
$$\tau_\tau = (290.17 \pm 0.53_{stat} \pm 0.33_{sys})\text{fs}$$

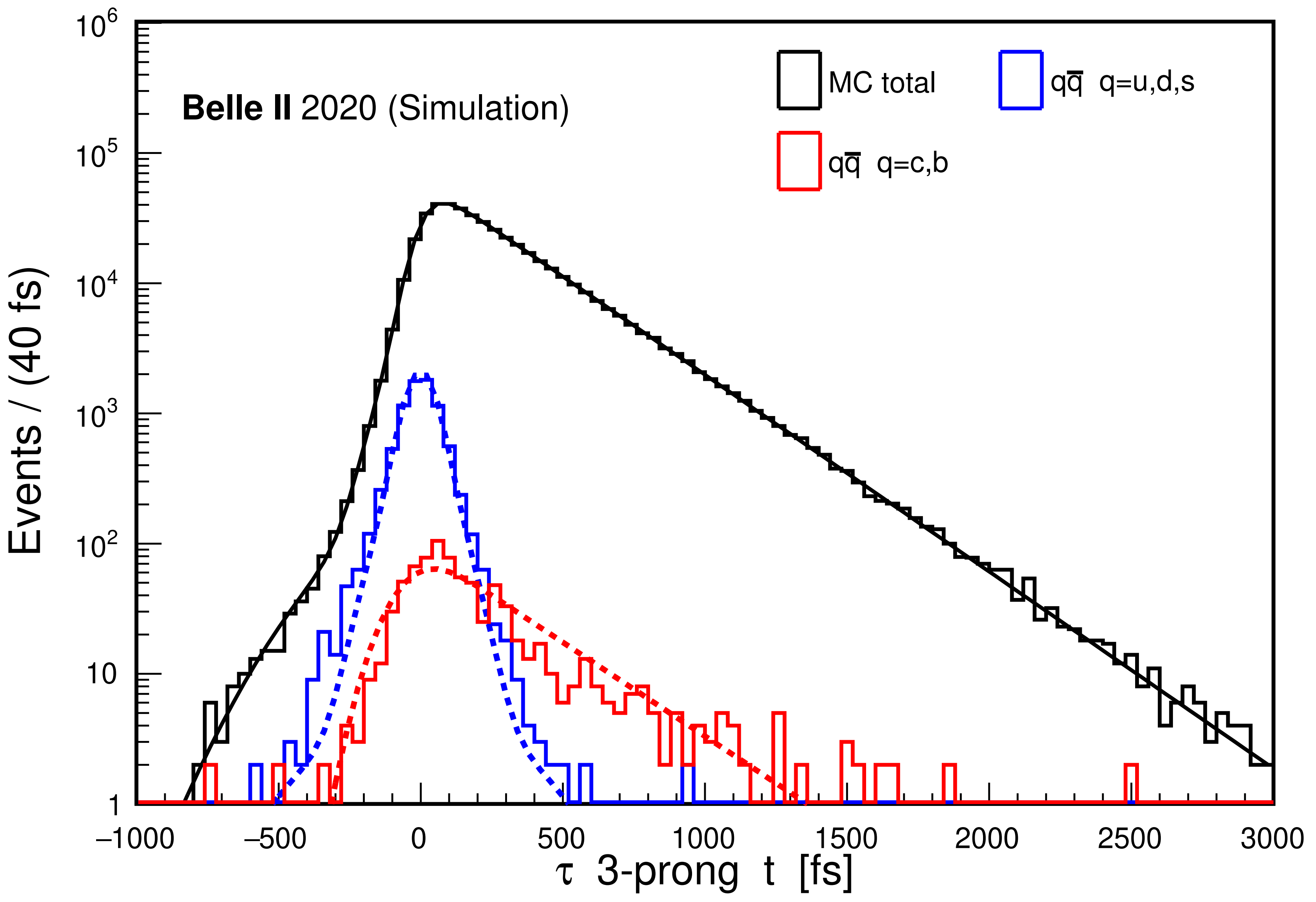
$$p(t;\tau) = \frac{1}{\tau} e^{-t/\tau} \times \mathscr{R}(t)$$

Belle II w.r.t. Belle: exploit

- the tiny beam spot size at the IP
- the 3x1 event topology to increase the statistical precision of the measurement







- the resolution @Belle II is nearly x2 narrower than @Belle

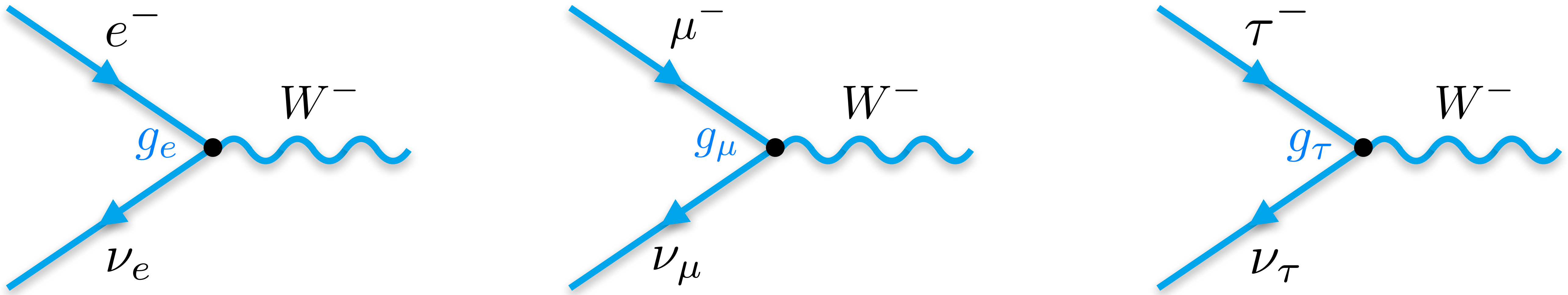
Competitive statistical precision can already be reached with 200 fb^{-1}

e-μ-τ universality

e, μ and τ differ only by

- the mass
- different and separately conserved lepton numbers

The coupling of leptons to W bosons is flavour-independent: $g_e = g_\mu = g_\tau$

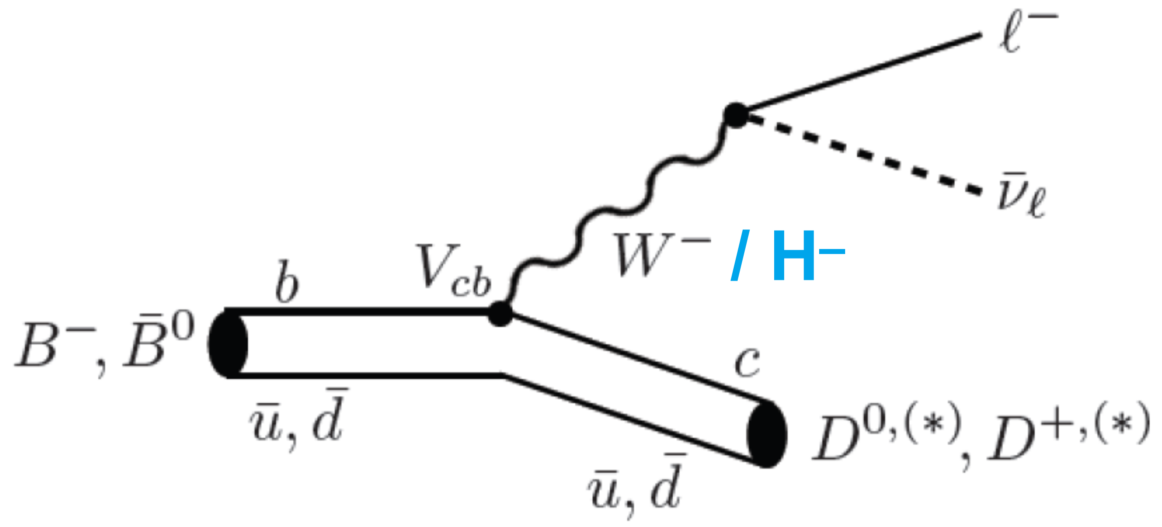


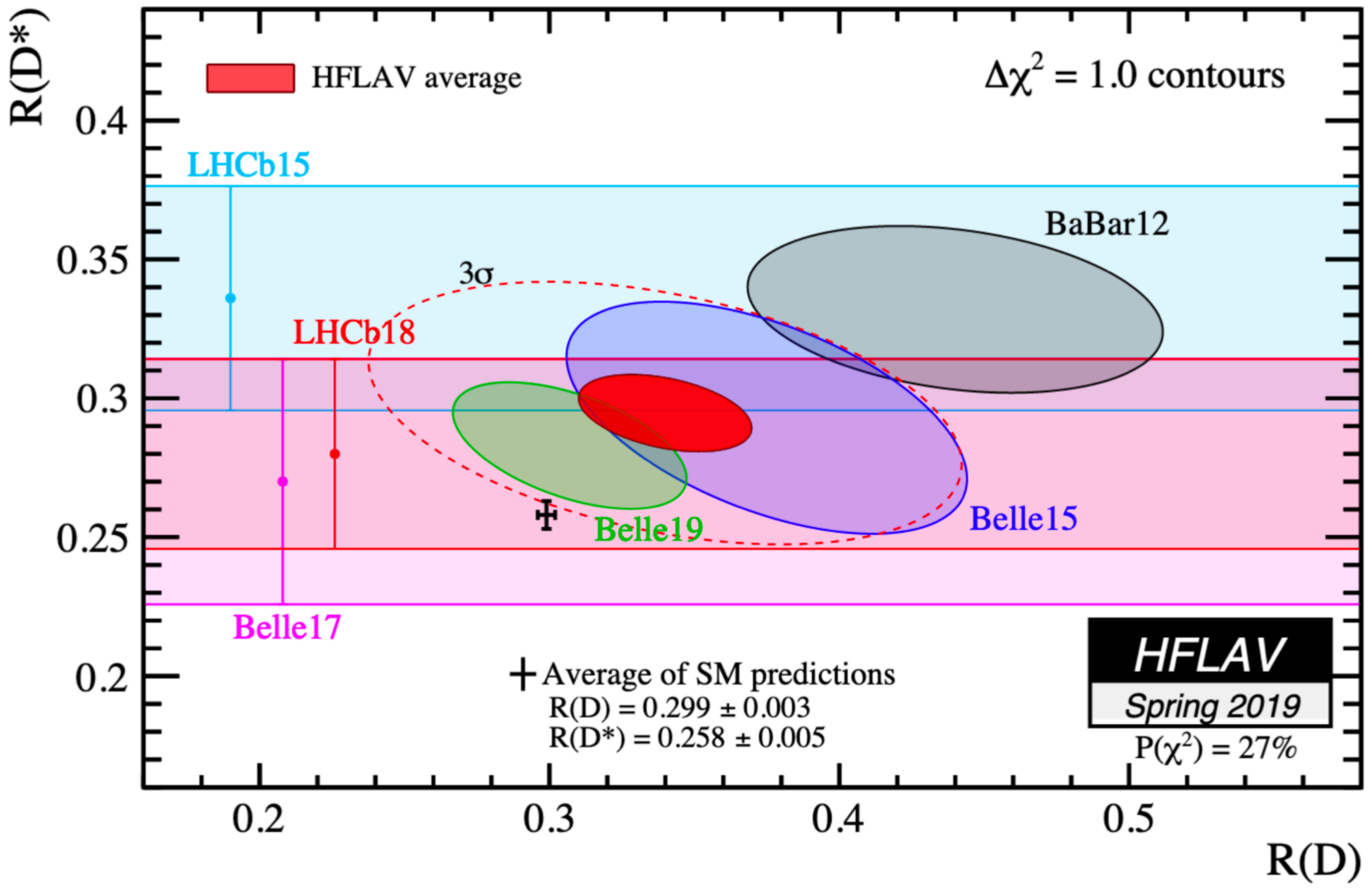
Identical lepton interaction rates involving e, μ or τ

Anomalies in quark sector

- R(D)-R(D*) plane (~3.1σ)
- R(K) (3.1σ), also P_5' in B→$K^*\mu\mu$ (~3.4σ)
- and more…

$$R(D^*) = \frac{\mathcal{BR}(B \to D^*\tau\nu)}{\mathcal{BR}(B \to D^*\ell\nu)} \quad \text{with } \ell = e, \mu$$





Significant tensions in lepton sector

- anomalous magnetic moment of μ (4.2σ) and e (~2.5σ)

Are these hints of a new fundamental interaction that violates LFU?

Any hint in the tau sector?

Test of e–μ universality

$$\left(\frac{g_\mu}{g_e}\right)^2_\tau \propto \frac{B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$$

Test of τ–μ universality

$$\left(\frac{g_\tau}{g_\mu}\right)^2_h \propto \frac{B(\tau \to h\nu_\tau)}{B(h \to \mu\nu_\mu)}$$

Most precise measurement from BaBar *Phys.Rev.Lett.105:051602 (2010)*

$$\left(\frac{g_\mu}{g_e}\right)_\tau = 1.0036 \pm 0.0020$$

➡ in agreement with SM

$$\left(\frac{g_\tau}{g_\mu}\right)_h = 0.9850 \pm 0.0054$$

➡ 2.8 σ below the SM expectation

➡ The BR measurements dominated by systematic uncertainty

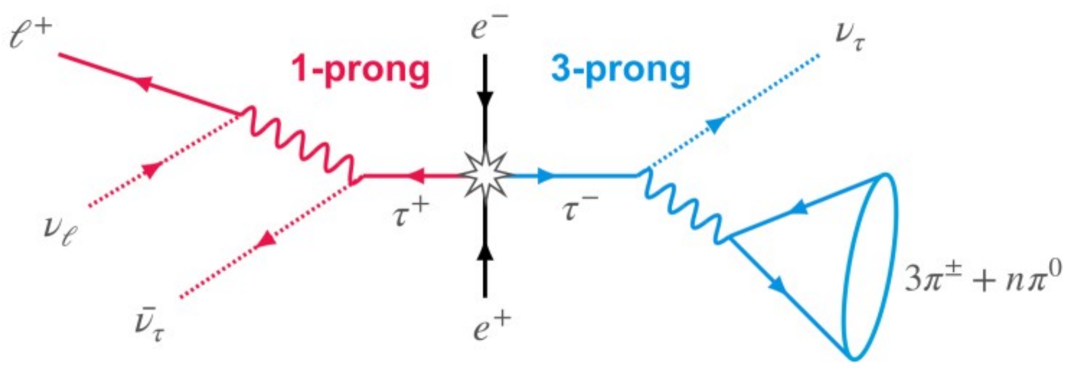
- ➡ μ: PID due limited size of data and MC samples
- ➡ h: additional contribution to systematics detector modelling and associated BGs

	μ	π	K
$\mathbf{N}^{\mathrm{D}}$	731102	369091	25123
Purity	97.3%	78.7%	76.6%
Total Efficiency	0.485%	0.324%	0.330%
Particle ID Efficiency	74.5%	74.6%	84.6%
Systematic uncertainties:			
Particle ID	0.32	0.51	0.94
Detector response	0.08	0.64	0.54
Backgrounds	0.08	0.44	0.85
Trigger	0.10	0.10	0.10
$\pi^-\pi^-\pi^+$ modelling	0.01	0.07	0.27
Radiation	0.04	0.10	0.04
$\mathcal{B}(\tau^- \to \pi^-\pi^-\pi^+\nu_\tau)$	0.05	0.15	0.40
$\mathcal{L}\sigma_{e^+e^-\to\tau^+\tau^-}$	0.02	0.39	0.20
Total [%]	0.36	1.0	1.5

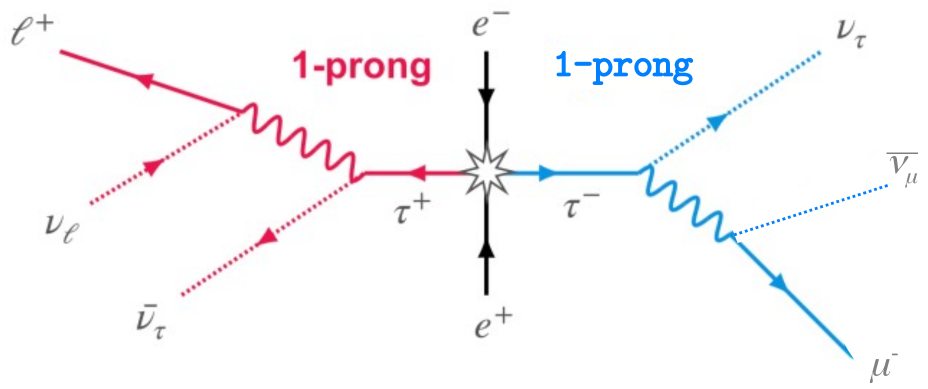
Prospects @ Belle II

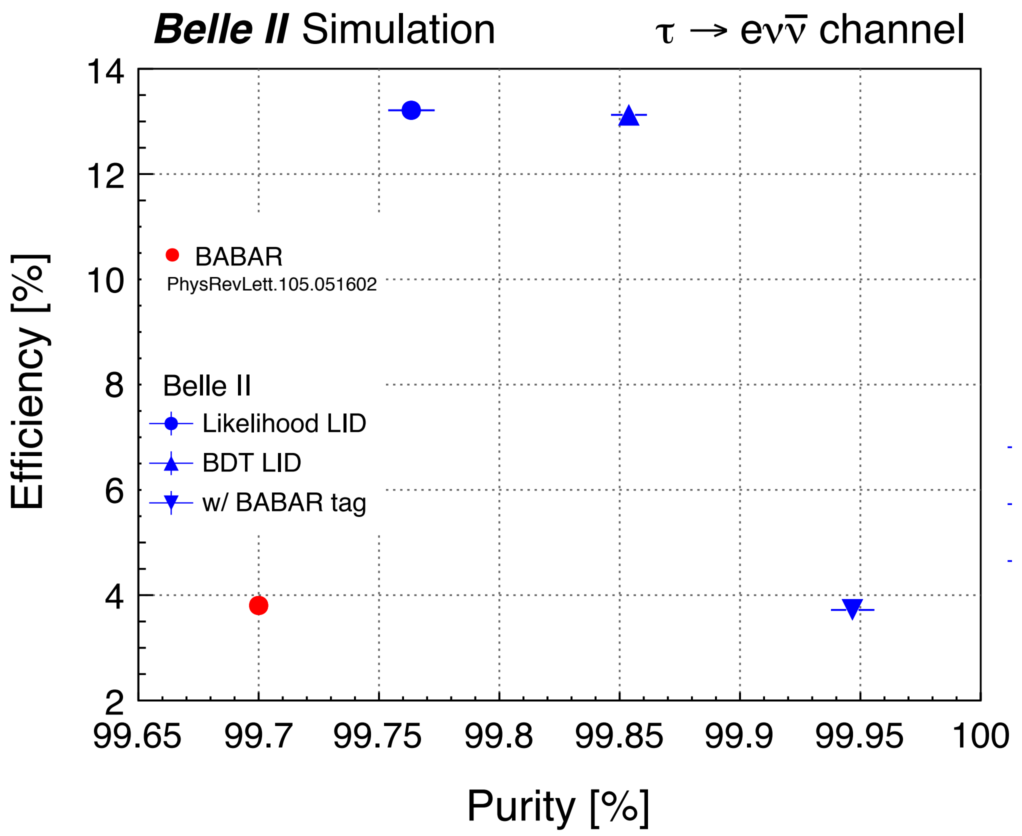
See slides of A. Martini

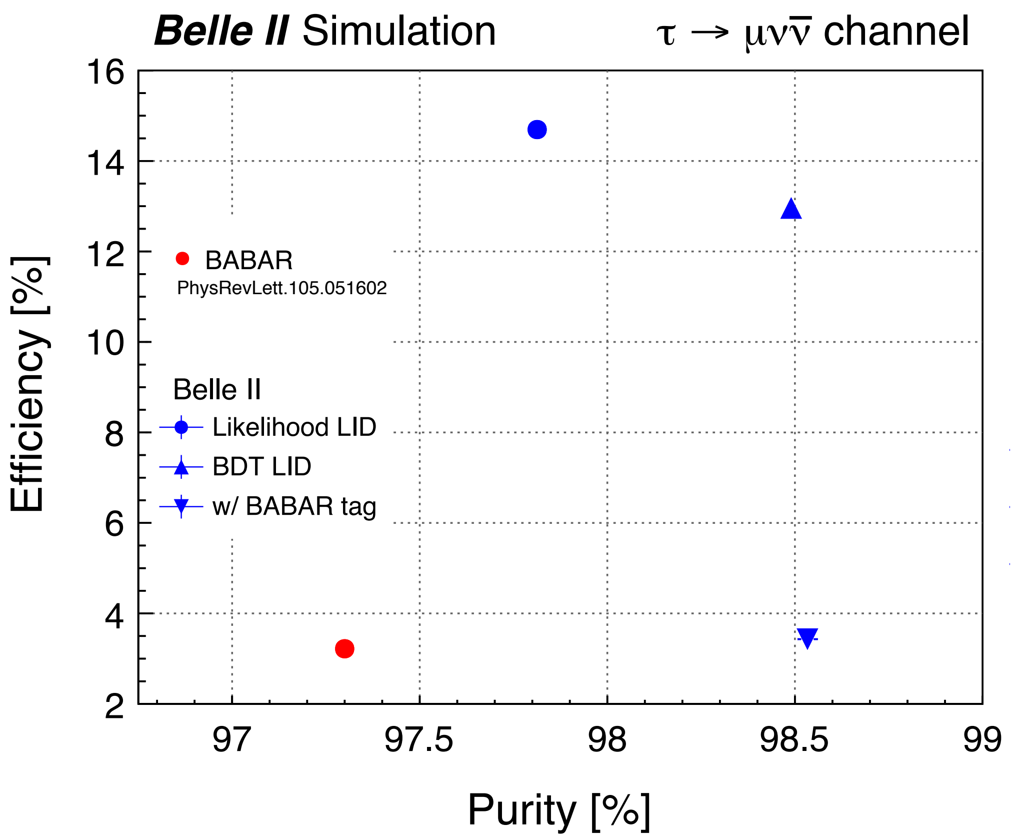
Use 3x1 and 1x1 (not used @BaBar)

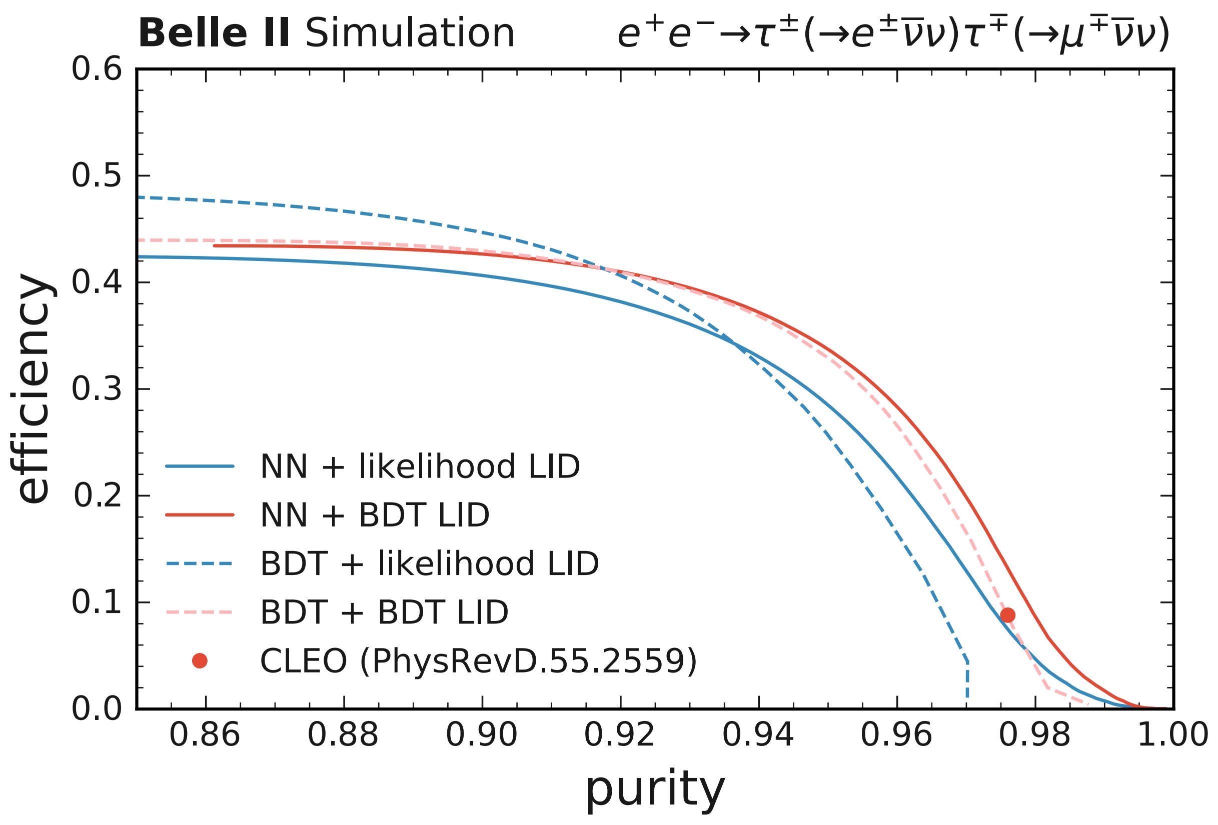


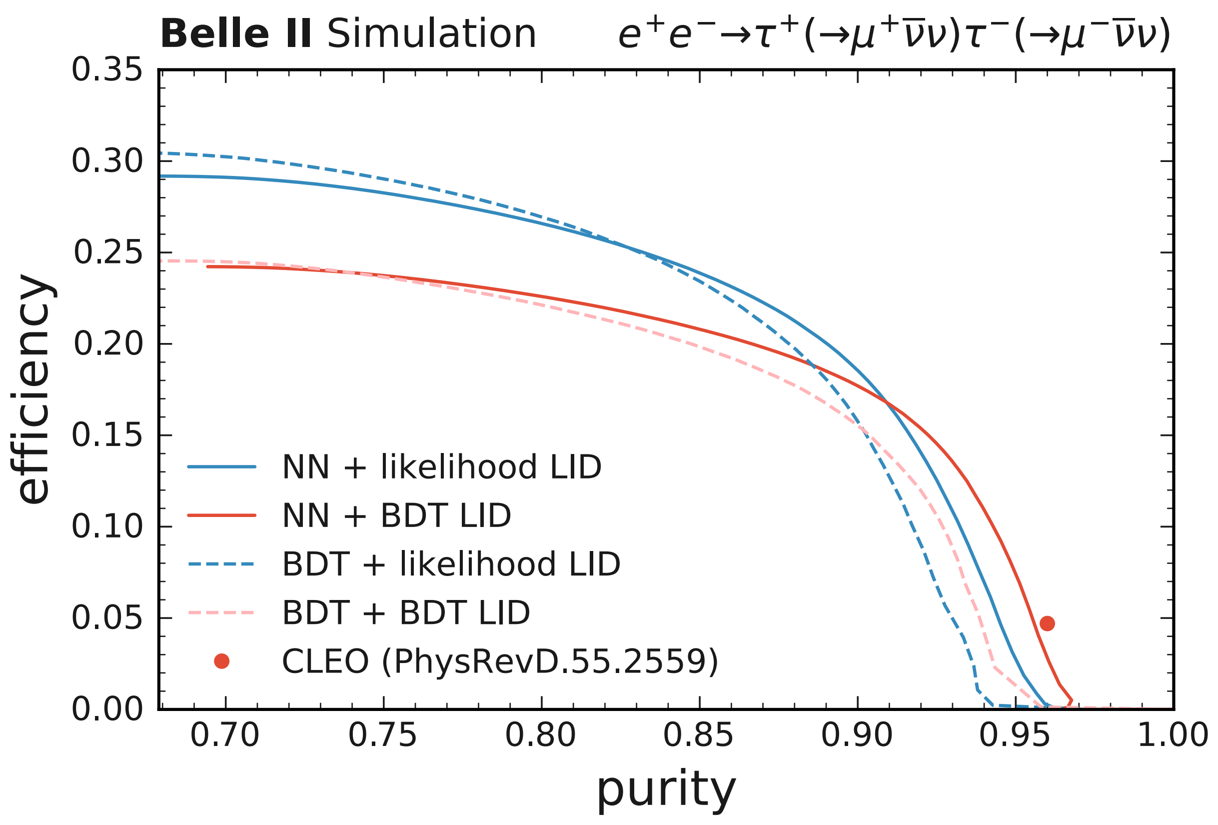
BELLE2-NOTE-PL-2021-009











➡ ~4x higher efficiency with better purity compared to BaBar

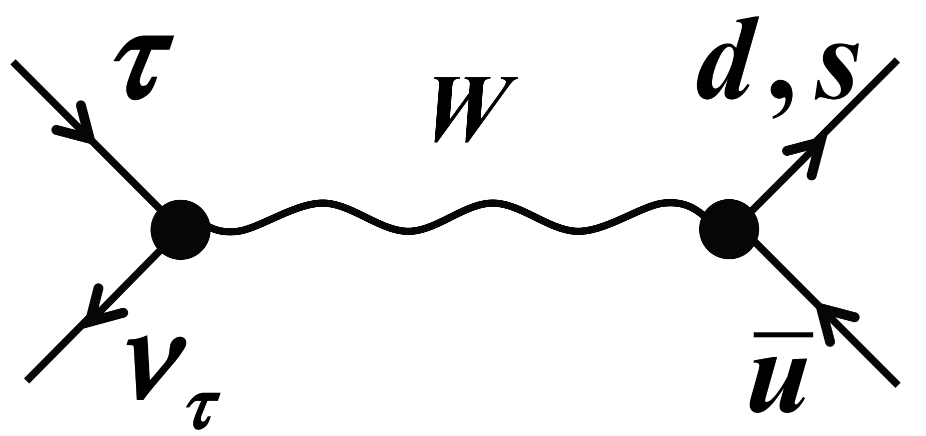
➡ better (very close) performance for eμ (μμ) compared to CLEO

➡ **Belle II can already exceed BaBar and CLEO on statistical precision for BR ratio.**

➡ The goal: achieve better **systematic precision**

- ➡ **lepton ID uncertainties** should scale well with luminosity & higher MC statistics
- ➡ **trigger uncertainty** already at few % level

Test of unitarity



Unique opportunity for probing the coupling strength of the weak current to the first and second generation of quarks to a very high precision

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Weak Eigenstates **CKM Matrix** **Flavour Eigenstates**

Test of unitarity

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 \stackrel{?}{=} 1$$

V_{ud}: $0^+ \to 0^+$, $K \to \mu\nu_\mu / \pi \to \mu\nu_\mu$

V_{us}: $K \to \pi\ell\nu$, $K \to \mu\nu_\mu / \pi \to \mu\nu_\mu$

V_{ub}: $\sim 1.6 \cdot 10^{-5}$

B decays

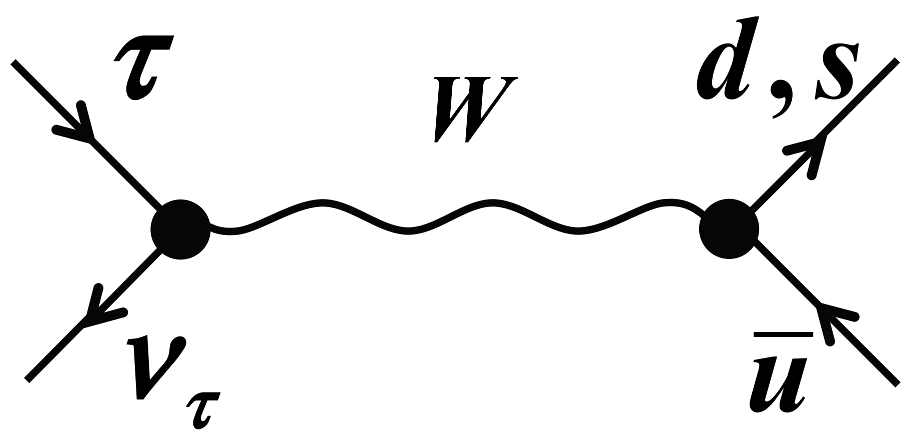
➡ From kaon, pion, baryon and nuclear decays

V_{ud}	$0^+ \to 0^+$ $\pi \to \pi e \nu_e$	$n \to p e \nu_e$	$\pi \to \ell \nu_\ell$
V_{us}	$K \to \pi \ell \nu$	$\Lambda \to p e \nu_e$	$K \to \ell \nu_\ell$

➡ From τ decays

V_{ud}	$\tau \to \pi\pi^0\nu_\tau$	$\tau \to \pi\nu_\tau$	$\tau \to h_{NS}\nu_\tau$
V_{us}	$\tau \to K\pi\nu_\tau$	$\tau \to K\nu_\tau$	$\tau \to h_S\nu_\tau$

Two methods of V_{us} from τ decays



Exclusive: compare the BR of $\tau \to \pi\nu$ and $\tau \to K\nu$

- BaBar, Phys. Rev. Lett. 105 051602 -

Fermi constant *electroweak corrections*

$$B(\tau^- \to K^-\nu_\tau) = \frac{G_F^2 f_K^2 |V_{us}|^2 m_\tau^3 \tau_\tau}{16\pi}\left(1 - \frac{m_K^2}{m_\tau^2}\right)^2 S_{\text{EW}}$$

$V_{us} = 0.2193 \pm 0.0032$

➡ within 2σ of the value predicted by the CKM unitarity

$$\frac{B(\tau^- \to K^-\nu_\tau)}{B(\tau^- \to \pi^-\nu_\tau)} = \frac{f_K^2 |V_{us}|^2}{f_\pi^2 |V_{ud}|^2} \frac{(m_\tau^2 - m_K^2)^2}{(m_\tau^2 - m_\pi^2)^2}(1 + \delta_{LD})$$

decay constant *electroweak corrections*

$V_{us} = 0.2255 \pm 0.0024$

➡ consistent with CKM unitarity

Inclusive: compare the BR of $\tau \to (\bar{u}d)\,\nu$ and $\tau \to (\bar{u}s)\,\nu$

fundamental parameters of SM

$(\alpha_s\,,\,|V_{us}|\,,\,m_s\,)$

BR w.r.t. BR($\tau \to e\nu\nu$)

hadrons with S=0 *hadrons with S=1*

$$\Delta R_{\text{SU(3) breaking}} = \frac{R_{\text{NS}}}{|V_{ud}|^2} - \frac{R_{\text{S}}}{|V_{us}|^2}$$

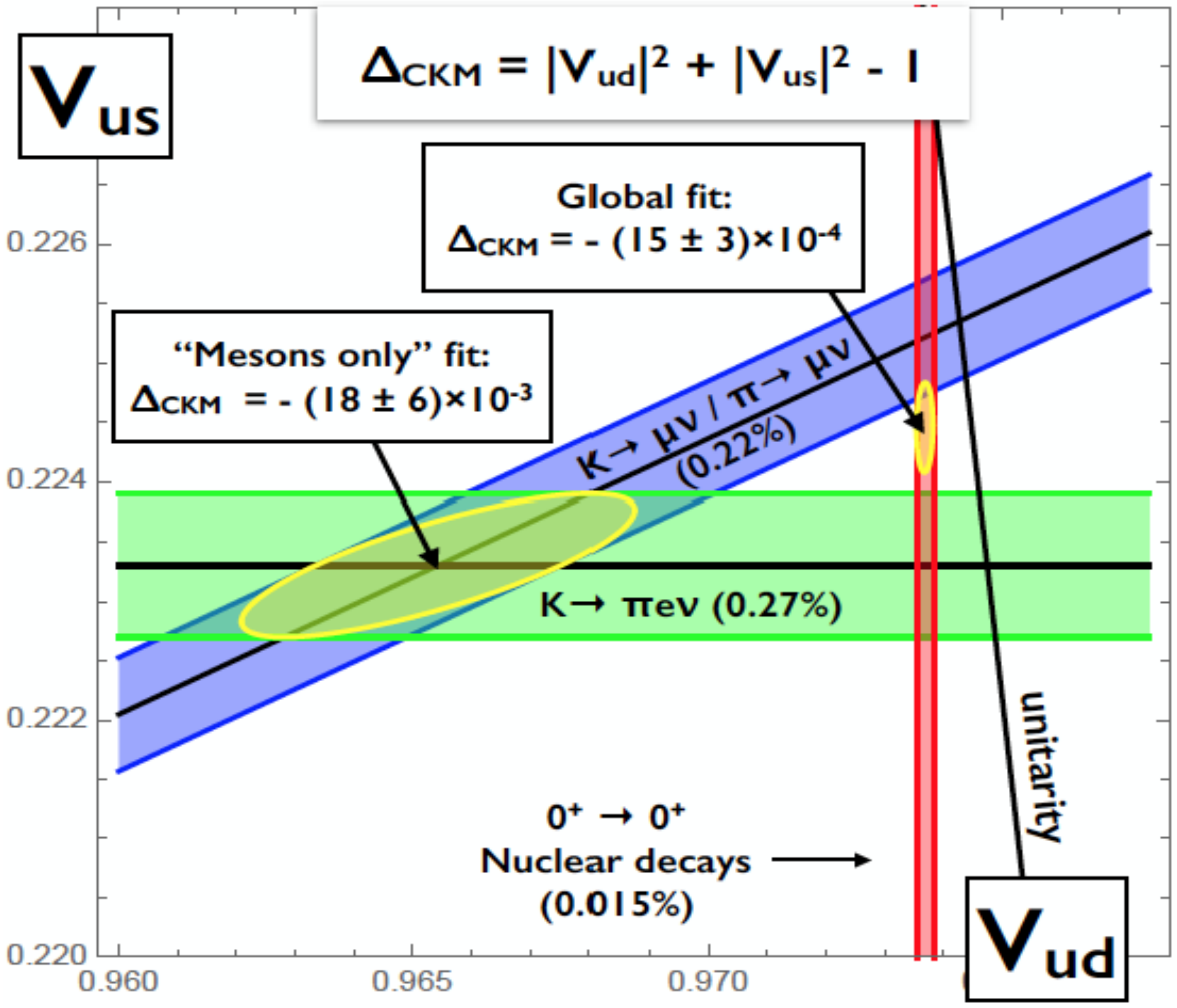
$V_{\text{us}} = 0.2186 \pm 0.0021$

➡ within 3.1σ of the value predicted by the CKM unitarity

V_{us} from τ decays @Belle II

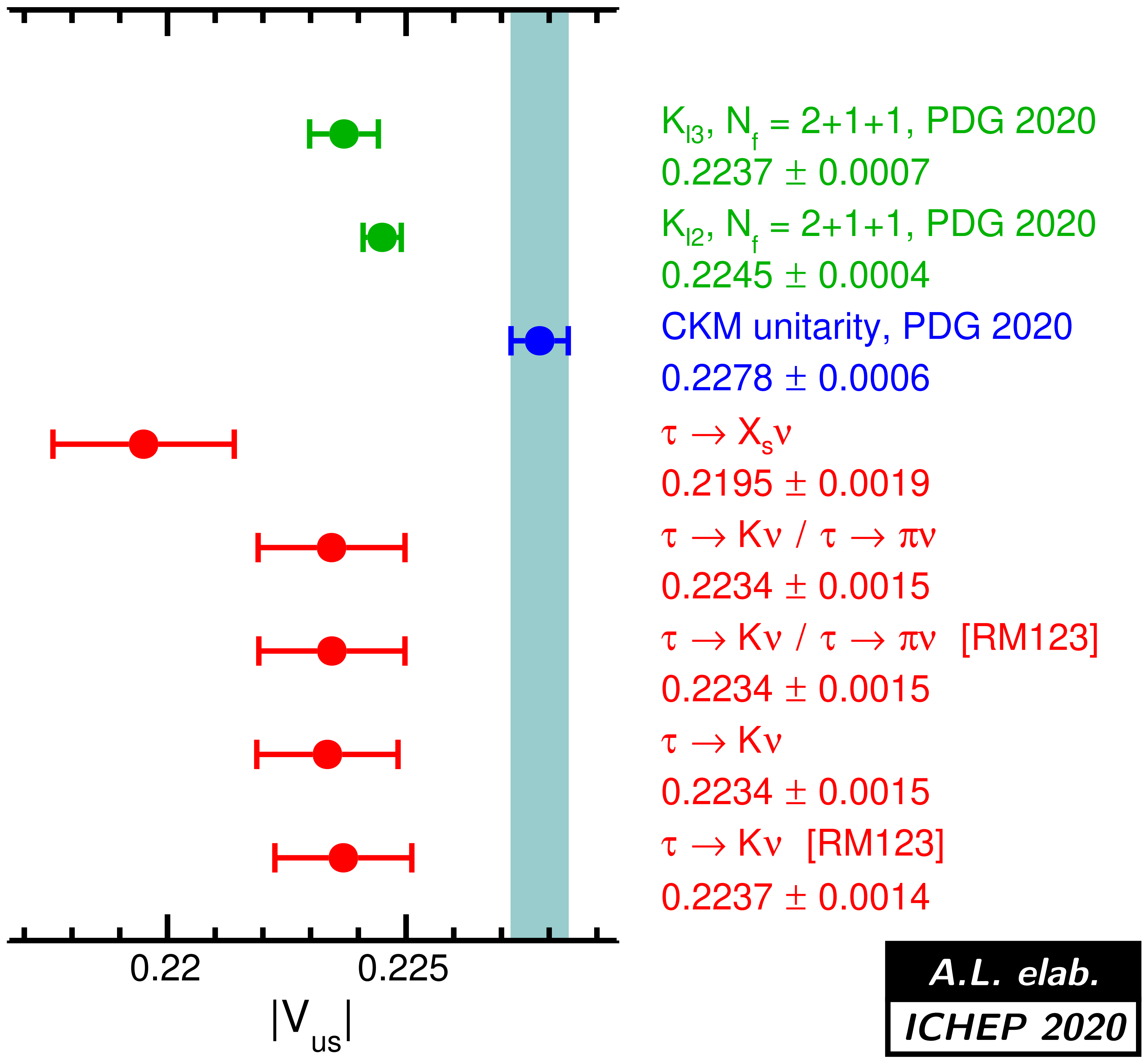
New results with improved theoretical input

- precise determination of V_{us} from kaon and nuclear decays
- discrepancy with CKM unitarity at 4.8 σ



Can τ physics help?

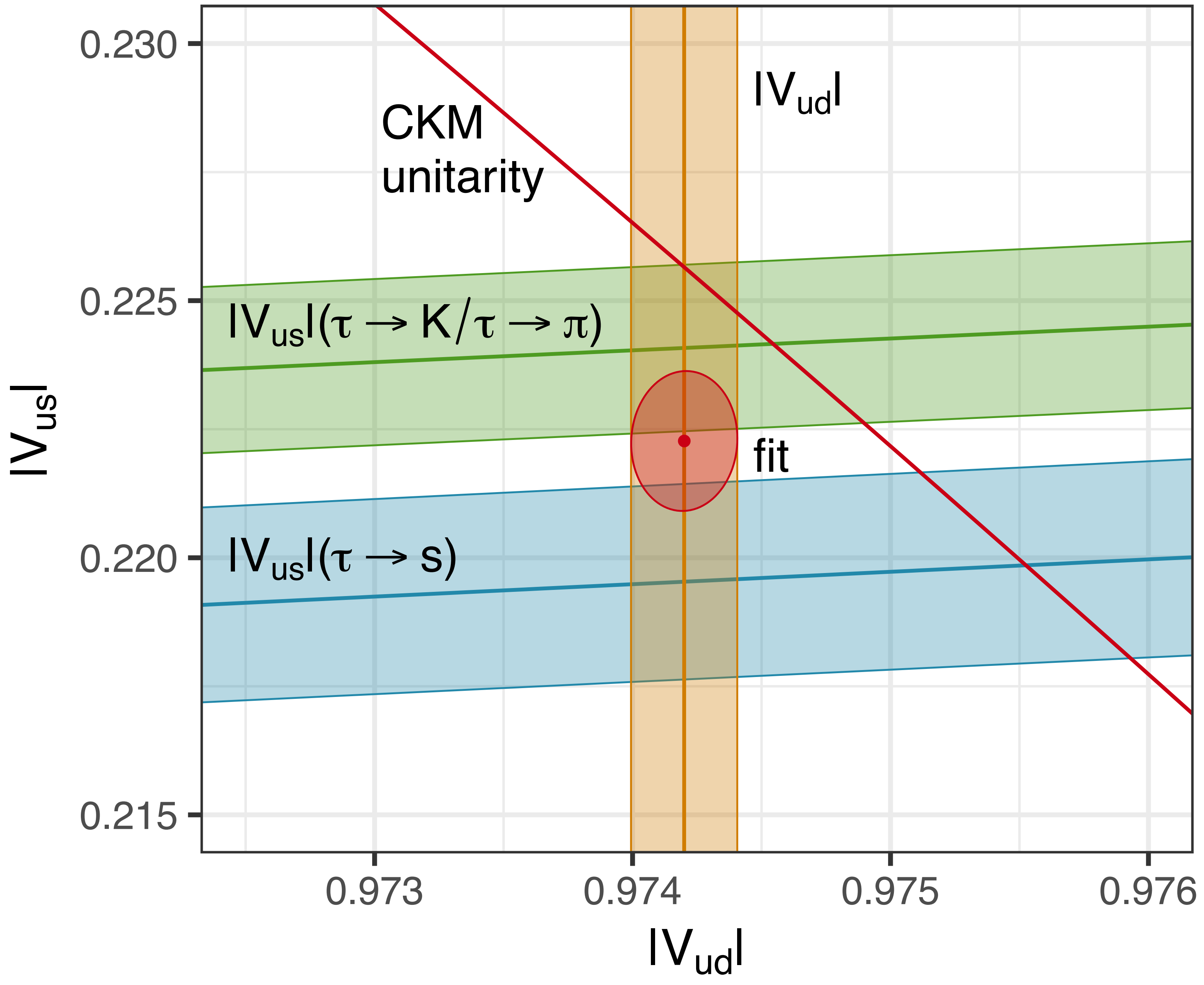
- currently less precise determination of V_{us}
- large PID systematic uncertainties @BaBar
- inclusive measurement not truly inclusive

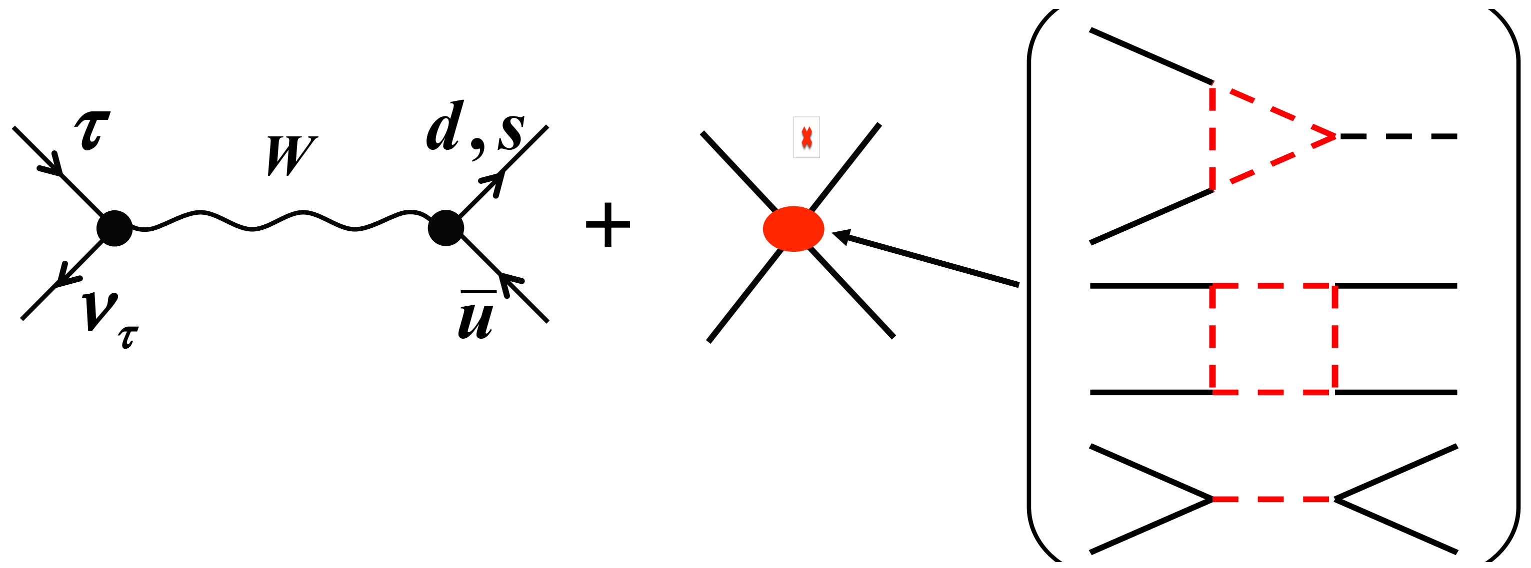


V_{us} from τ decays @Belle II

3σ tension between $|V_{us}|$ from the CKM matrix unitarity and $\tau \to s$.

SciPost Phys. Proc. 1, 001 (2019)



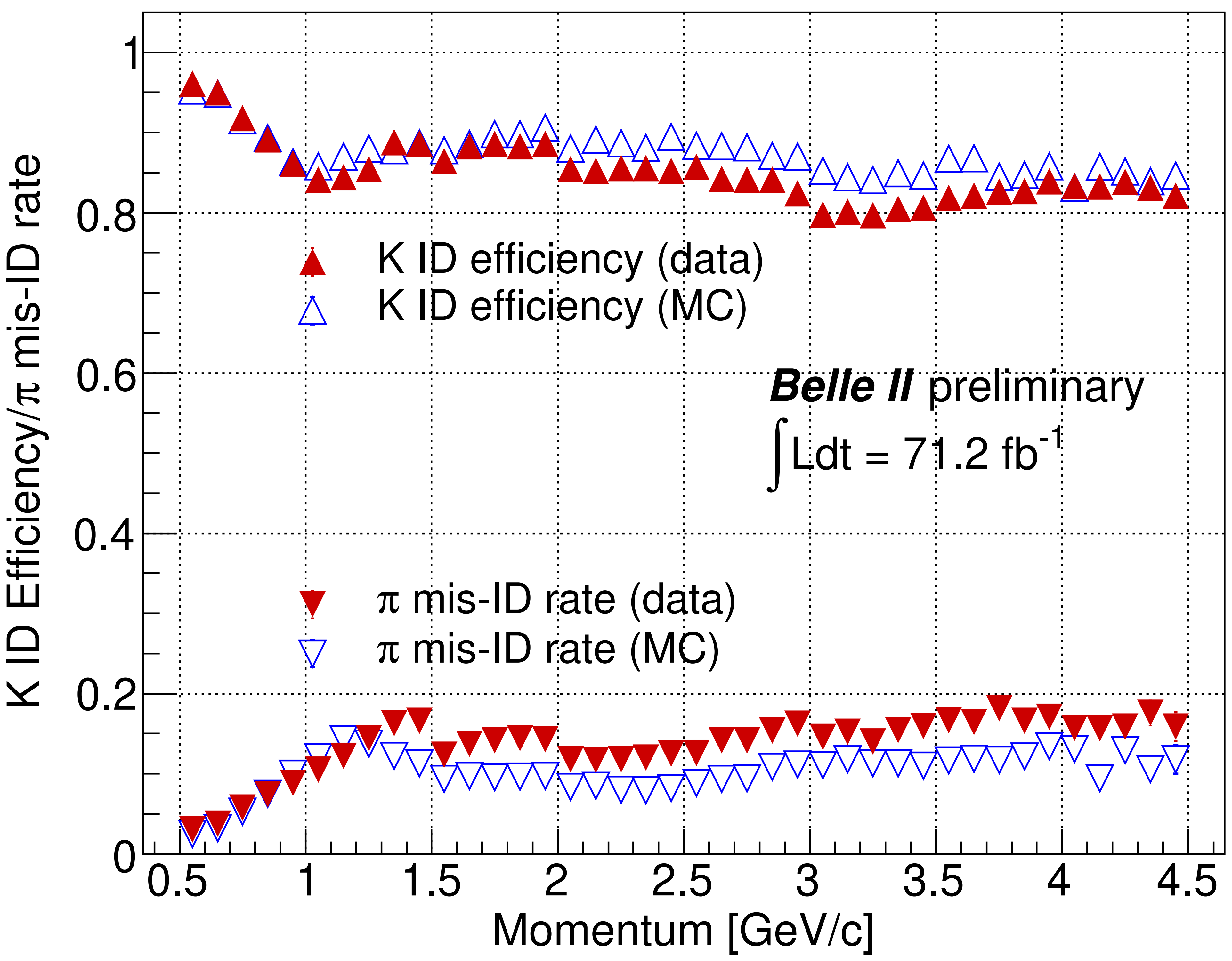


SUSY loops,
Leptoquarks,
Z', Charged Higgs
Right-Handed
Currents,….

What can we do @BelleII?

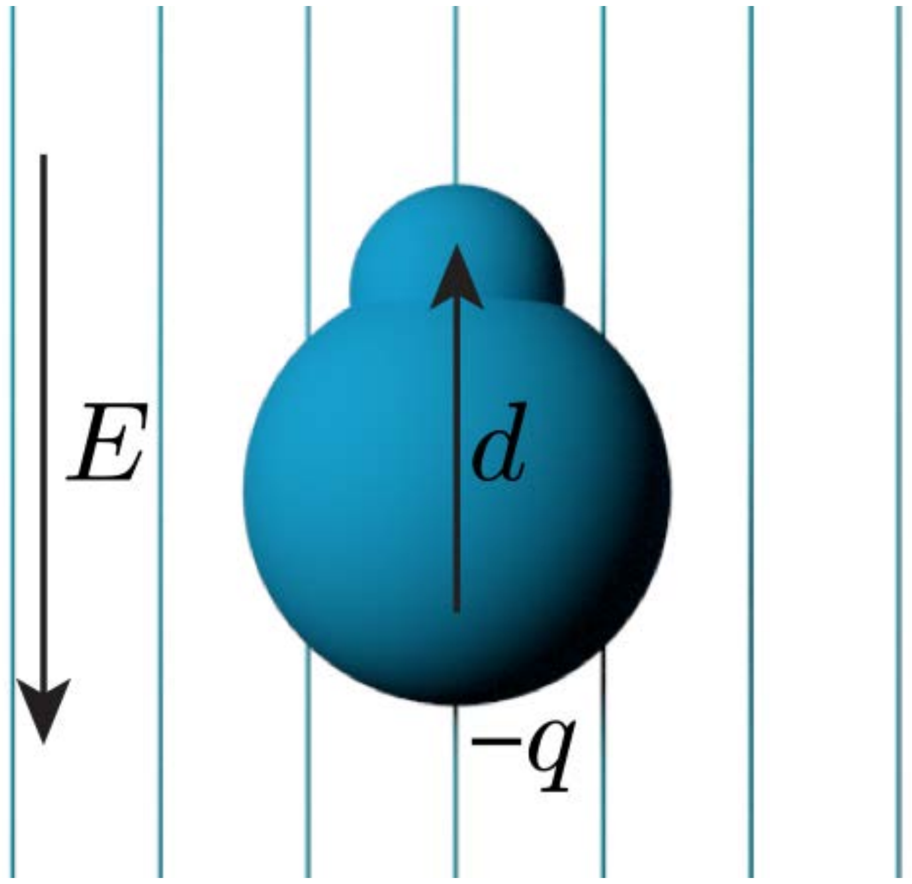
- larger data sample will be available
- similar to LFU analysis use 3x1 and 1x1 topologies
- improve the understanding of the detector (PID, trigger, …)

$D^{*+} \to D^0[K^-\pi^+]\pi^+$

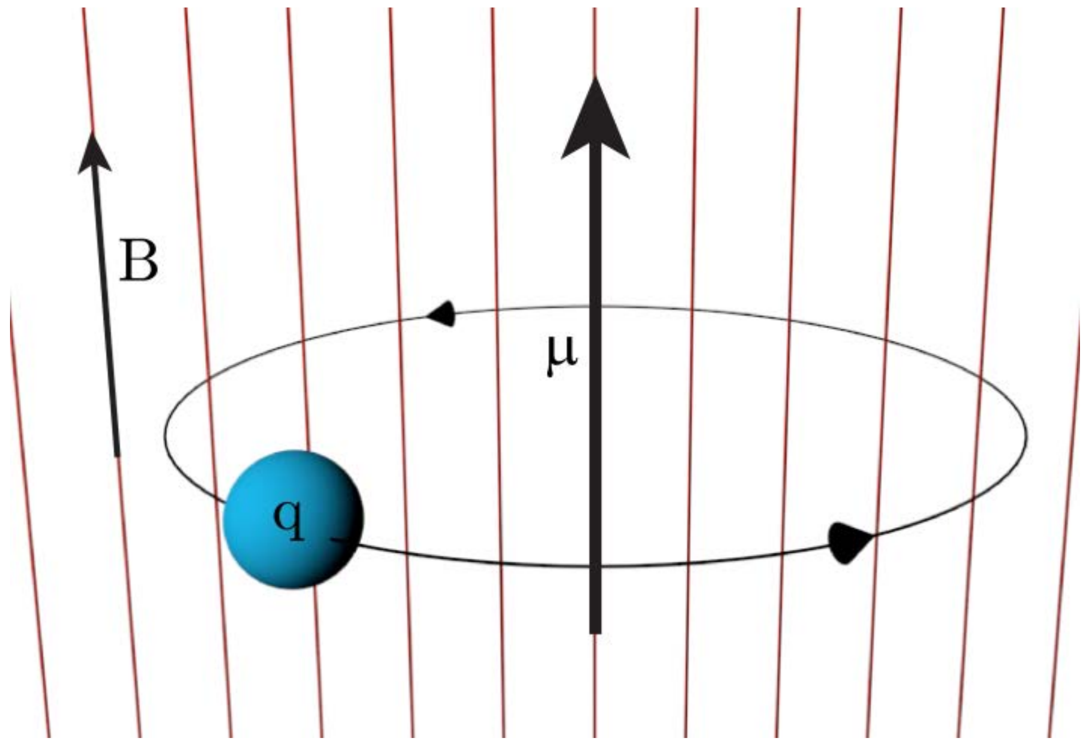


τ electric and magnetic dipole moments

EDM



MDM



Unveil or constrain NP effects

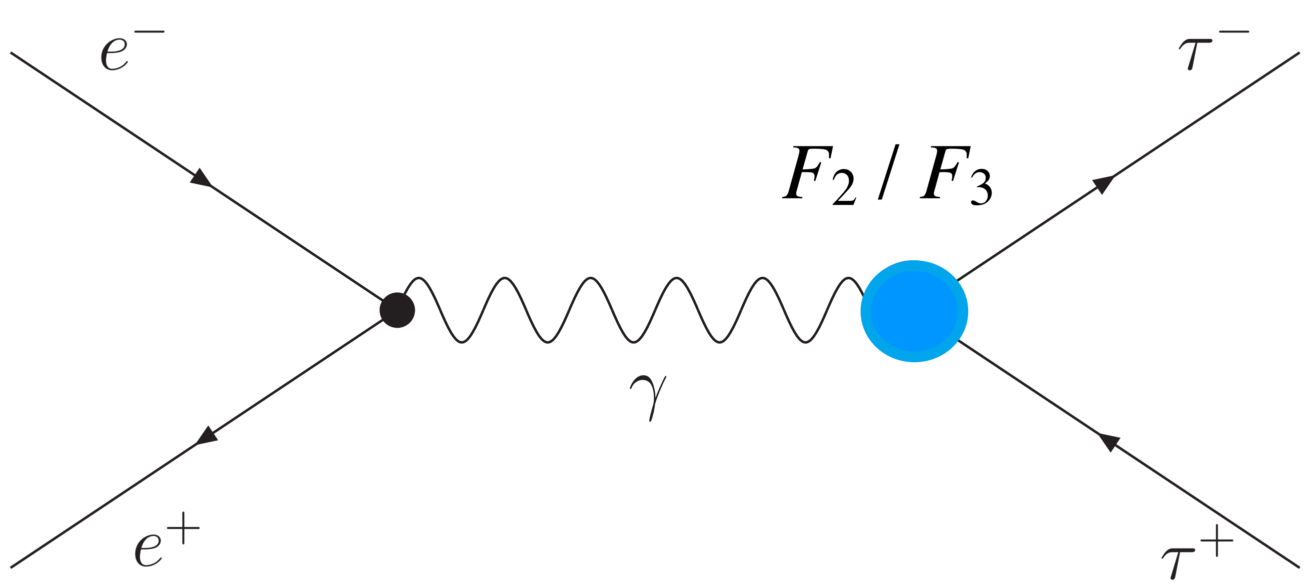
- induced at multi-loop level and therefore highly suppressed in SM
- NP contribution expected $\propto \frac{m_\ell}{\Lambda^2}$

- induced at one-loop level in SM
- NP contribution expected $\propto \frac{m_\ell^2}{\Lambda^2}$

The lifetime is very short to measure its interaction with an electromagnetic field

EDM & MDM

When NP exists in the loop diagrams of the γ-τ interaction vertex, τ can possess extra EDM and/or MDM.



In EFT interactions between τ and photon

$$\Gamma^\mu(q^2) = F_1(q^2)\gamma^\mu + F_2(q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2m_\tau} + F_3(q^2)\frac{\sigma^{\mu\nu}q_\nu\gamma_5}{2m_\tau}$$

- ➡ $F_1(q^2)$: Dirac form factor $F_1(0) = 1$
- ➡ $F_2(q^2)$: Pauli form factor $F_2(0) = a_\tau$
- ➡ $F_3(q^2)$: $F_3(0) = d_\tau \cdot 2m_\tau \ / \ eQ_\tau$

$$f_g := F_2(s)$$
$$f_d := F_3(s)$$
$$\sqrt{s} = \Upsilon(4S) = 10.58 \text{ GeV}$$

EDM probes CP-violating new physics

- ➡ SM prediction for EDM: $d_\tau = 10^{-37} e\text{cm}$
- ➡ NP models predict $d_\tau = 10^{-19} e\text{cm}$
- ➡ World best measurement from Belle *- arXiv:2108.11543 -*

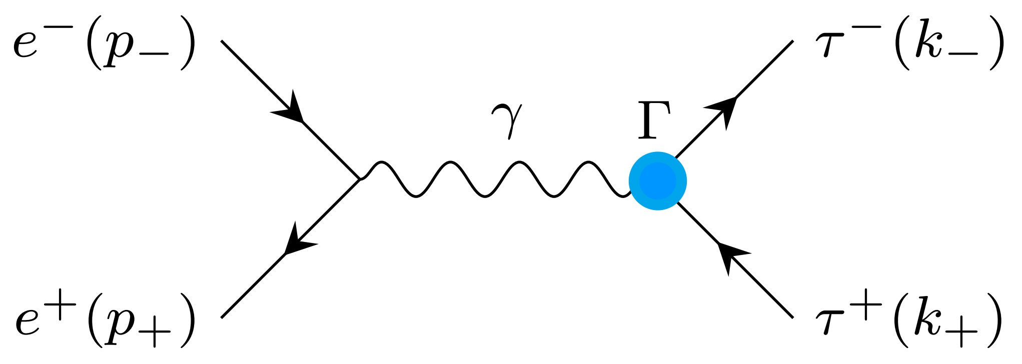
$$-1.85 \times 10^{-17} < \mathcal{R}(\tilde{d}_\tau) < 0.61 \times 10^{-17} e\text{cm (95 \% CL)}$$
$$-1.03 \times 10^{-17} < \mathfrak{I}(\tilde{d}_\tau) < 0.23 \times 10^{-17} e\text{cm (95 \% CL)}$$

MDM of the fast-decaying τ

- ➡ SM prediction:
$a_\tau^{\text{SM}} = a_\tau^{\text{QED}} + a_\tau^{\text{EW}} + a_\tau^{\text{HLO}} + a_\tau^{\text{HHO}} = 117\,721(5) \times 10^{-8}$
- ➡ World best measurement from DELPHI *- EPJ.C 35:159, 2004 -*
$-0.0052 < \tilde{a}_\tau < 0.013 (95\,\%\ \text{CL})$
- ➡ Every deviation assumed to stem from a_τ

EDM & MDM from τ-pair production

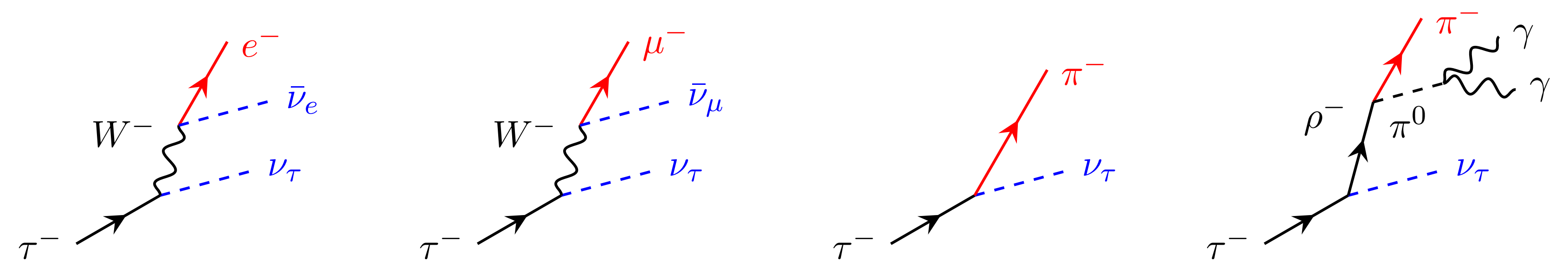
τ pair production



Matrix element

$$-i\, M^{\gamma}_{\alpha\beta,\rho\sigma} = \left[\bar{v}^{\rho}_{e}(p_+) ie\gamma^{\mu} u^{\sigma}_{e}(p_-)\right] \times \frac{-ig_{\mu\nu}}{q^2} \times \left[\bar{u}^{\beta}_{\tau}(k_-) ie\Gamma^{\nu} v^{\alpha}_{\tau}(k_+)\right]$$

Decay modes



$$\frac{d\sigma}{d\Omega} \propto \sum_{\alpha\alpha'\beta\beta' = \pm 1/2} \underbrace{\chi_{\alpha\alpha'\beta\beta'}\left[e^-e^+ \to \tau^-\tau^+\right]}_{\text{SDM}} \times \underbrace{D_{\beta\beta'}\left[\tau^- \to a + X\right]}_{\tau^-\ \text{decay}} \times \underbrace{D_{\alpha\alpha'}\left[\tau^+ \to b + Y\right]}_{\tau^+\ \text{decay}}$$

$$\chi_{\alpha\alpha'\beta\beta'} = \chi^{\text{SM}}_{\alpha\alpha'\beta\beta'} + \chi^{\text{EDM}}_{\alpha\alpha'\beta\beta'} f_d + \chi^{\text{MDM}}_{\alpha\alpha'\beta\beta'} f_g$$

no NP contribution

Extraction of anomalous EDM and MDM

- ➡ using the optimal observables

$$\mathcal{O}(f_k^{\text{SM}}) = \left(\frac{\partial \sigma_{\text{SM}}}{\partial \Omega}\right)^{-1} \cdot \left.\frac{\partial \frac{\partial \sigma}{\partial \Omega}}{\partial f_k}\right|_{f_k = f_k^{\text{SM}}} \qquad f_k \in \{\Re(f_g), \Im(f_g), \Re(f_d), \Im(f_d)\}$$

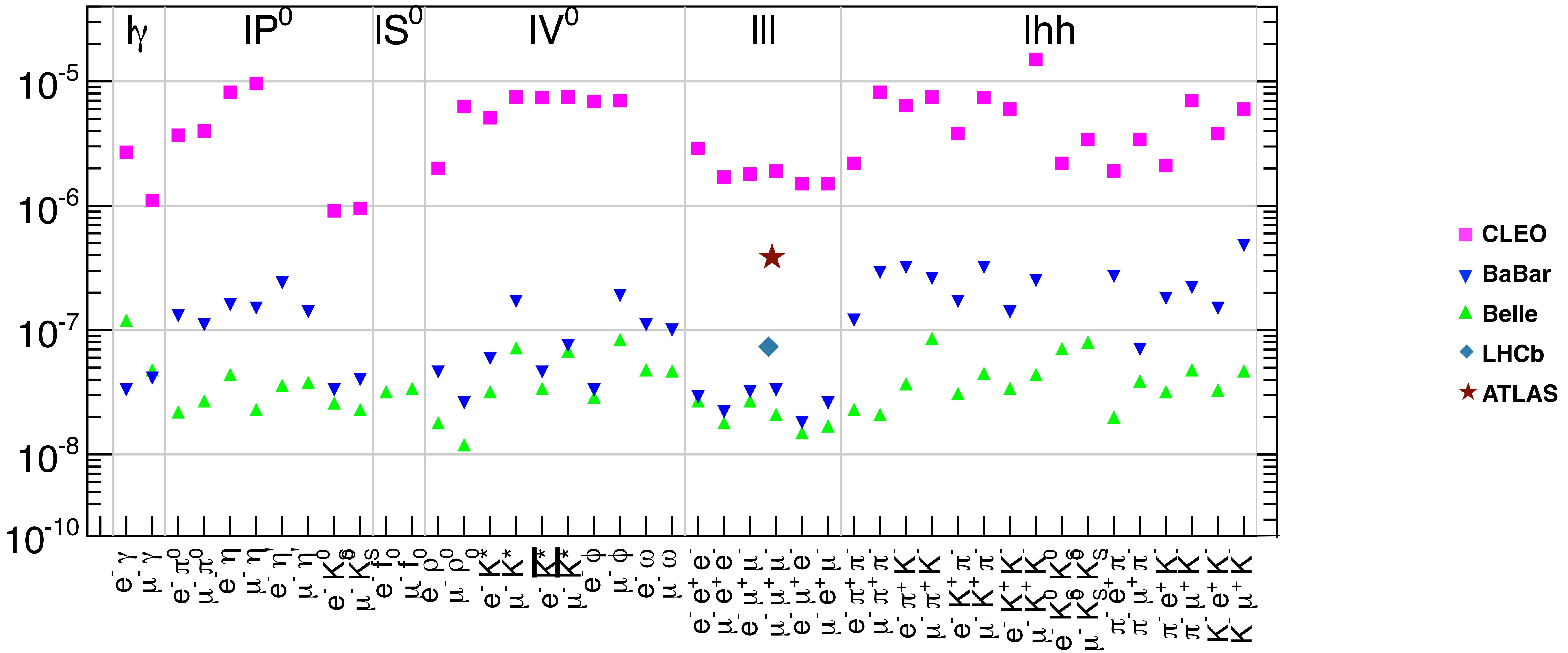
- ➡ provide the best statistical precision

Prospects @Belle II

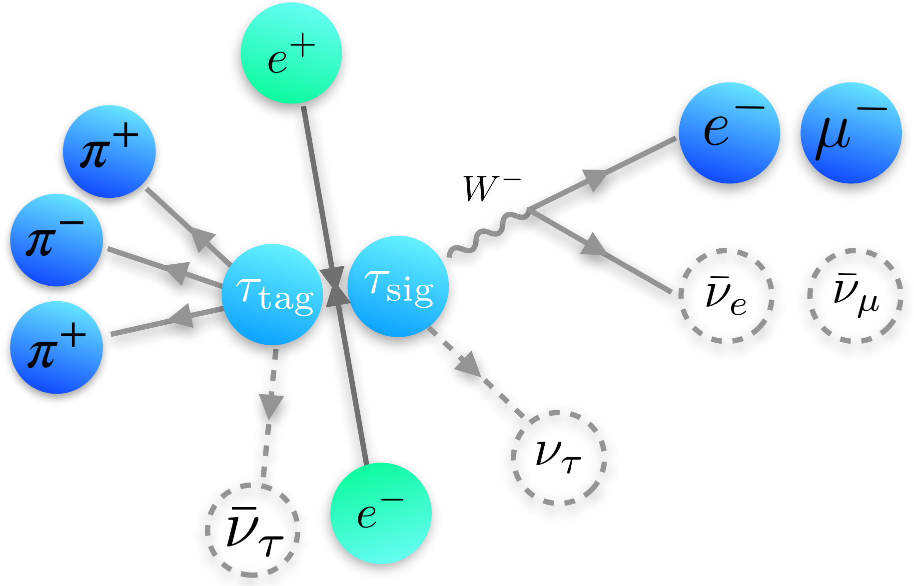
(with better tracking, PID, trigger simulation, etc…)

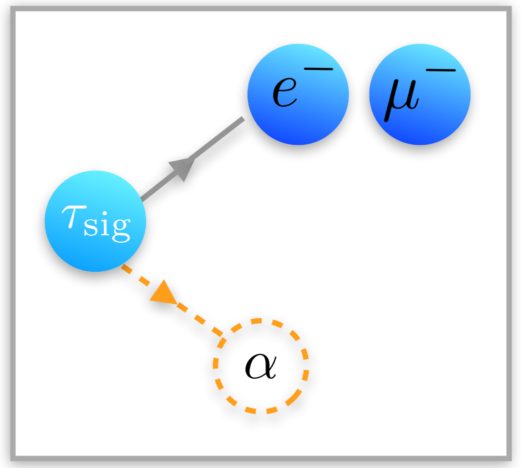
- ➡ EDM: significant improvements expected
- ➡ MDM: similar sensitivity as for EDM expected
  - ➡ attention of the theorists is need for interpretation

LVF & LNV



Probe the existence of a new boson α in $\tau \to \ell\ \alpha$



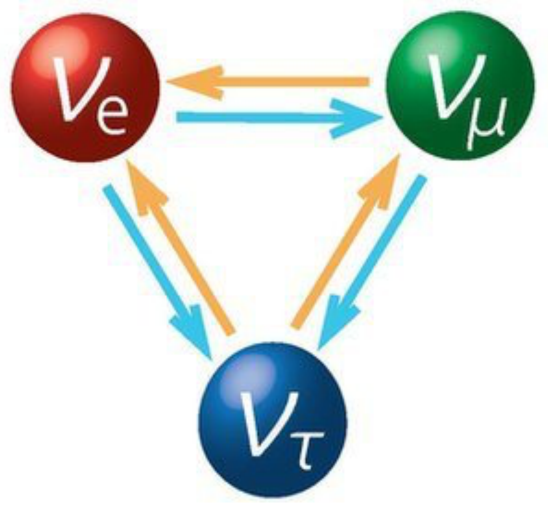


See slides of A. De Yta Hernandez

Lepton flavour and number conservation

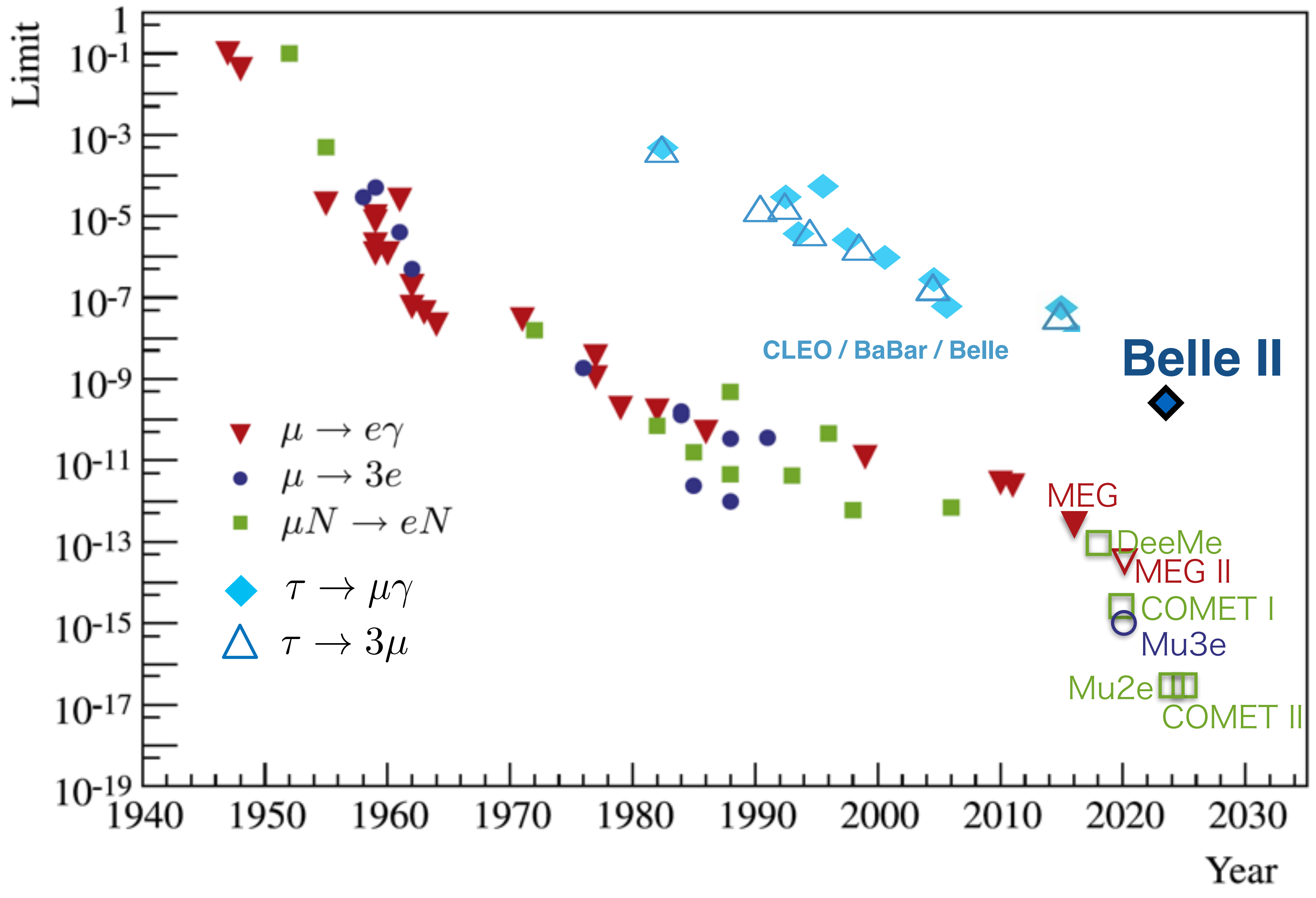
Conservation of the individual lepton-flavour and the total lepton numbers within the SM ($m_\nu = 0$)

$$G_{SM}^{global} = U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$

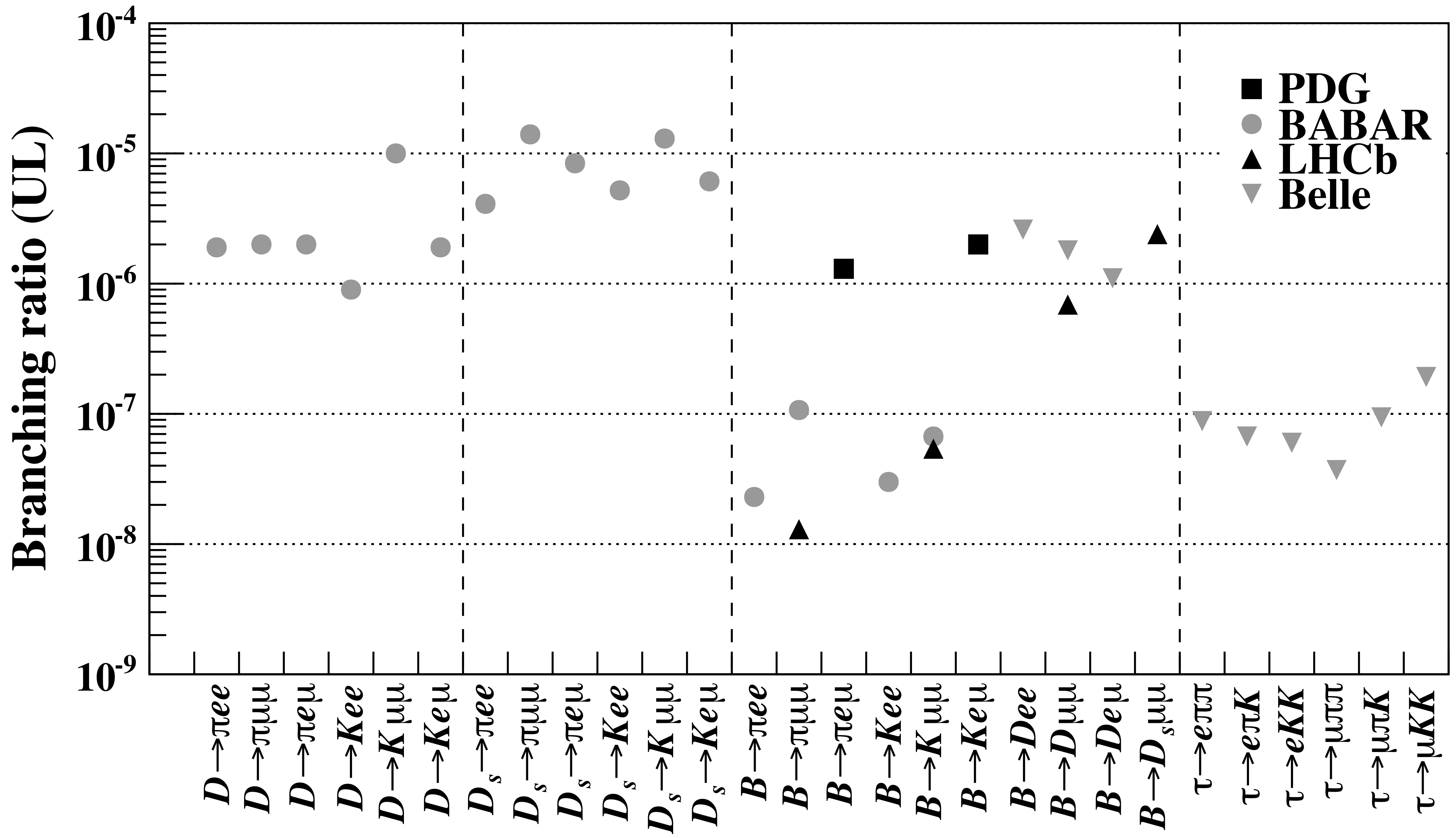


➡ The observation of neutrino oscillations as a first sign of LFV beyond the SM!

What about charged leptons?



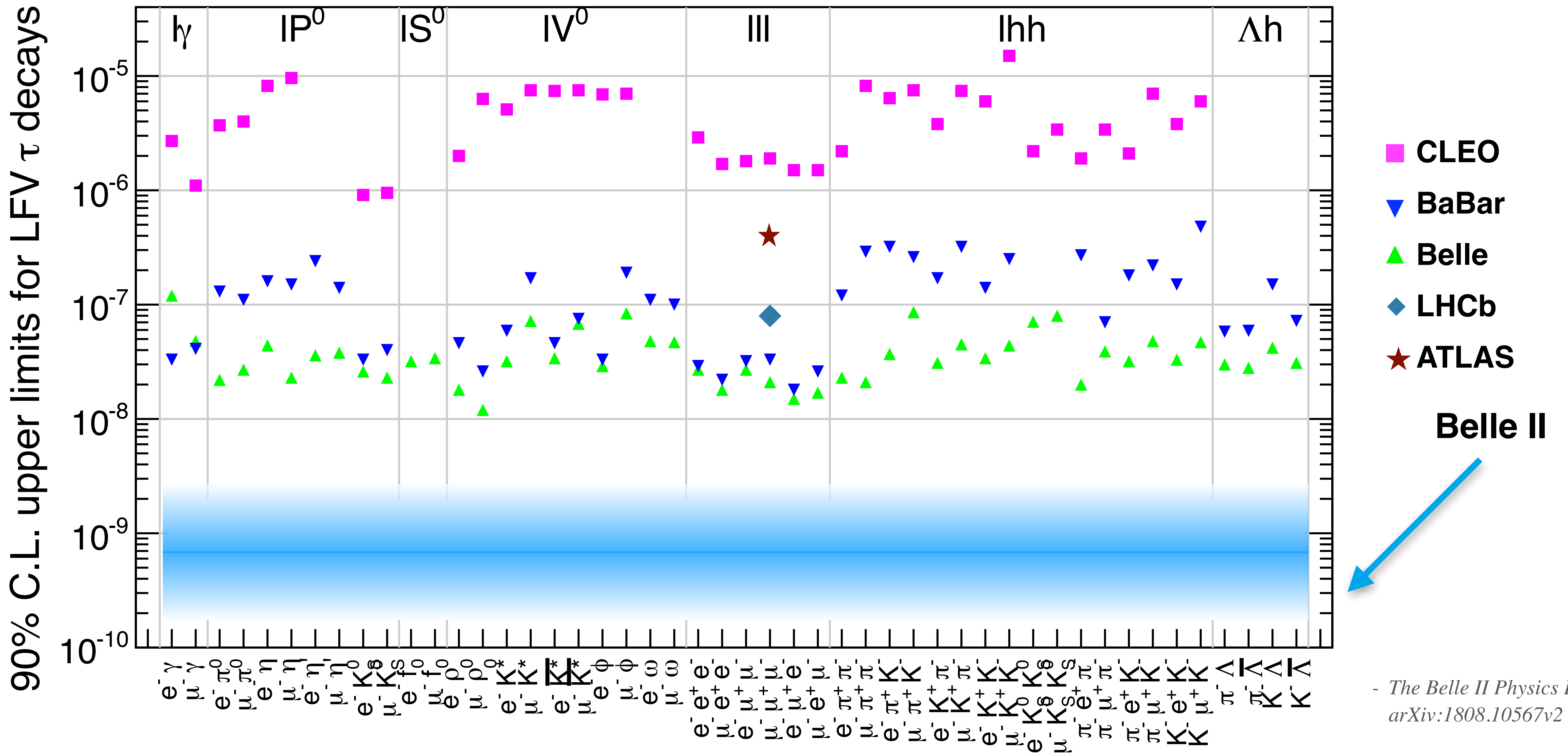
Are neutrinos Dirac (|ΔL| = 0) or Majorana (|ΔL| = 2) particles?



Observation of LFV or LNV will be a clear signature of NP!

Perspectives at Belle II

… mostly occurred at the B-factories



- The Belle II Physics Book - arXiv:1808.10567v2

Test the SM in a variety of ways

- radiative ($\tau \to \ell\gamma$)
- leptonic decays ($\tau \to \ell\ell\ell$)
- a large variety of LFV and LNV semi-leptonic decays
- τ → μ and τ → e: test of the lepton flavour structure

- One of the factors pushing up the sensitivity of probes is the increase of the luminosity
- Equally important is the increase of the signal detection efficiency
  - high trigger efficiencies; improvements in the vertex reconstruction, charged track and neutral-meson reconstructions, particle identification, refinements in the analysis techniques…

The searches at Belle II will push the current bounds further by more than one order of magnitude

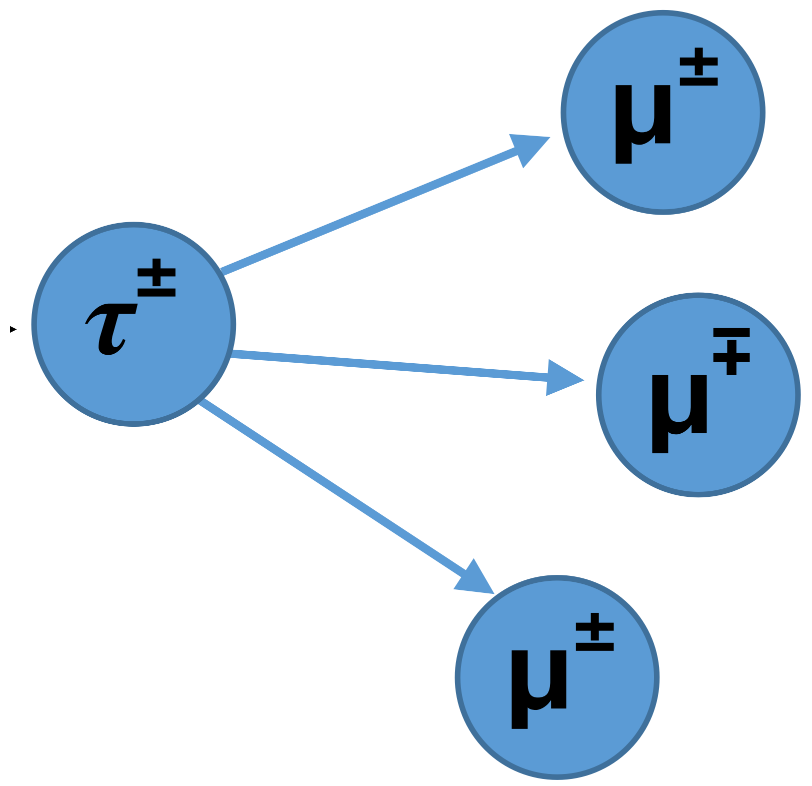
$\tau \to \mu\mu\mu$

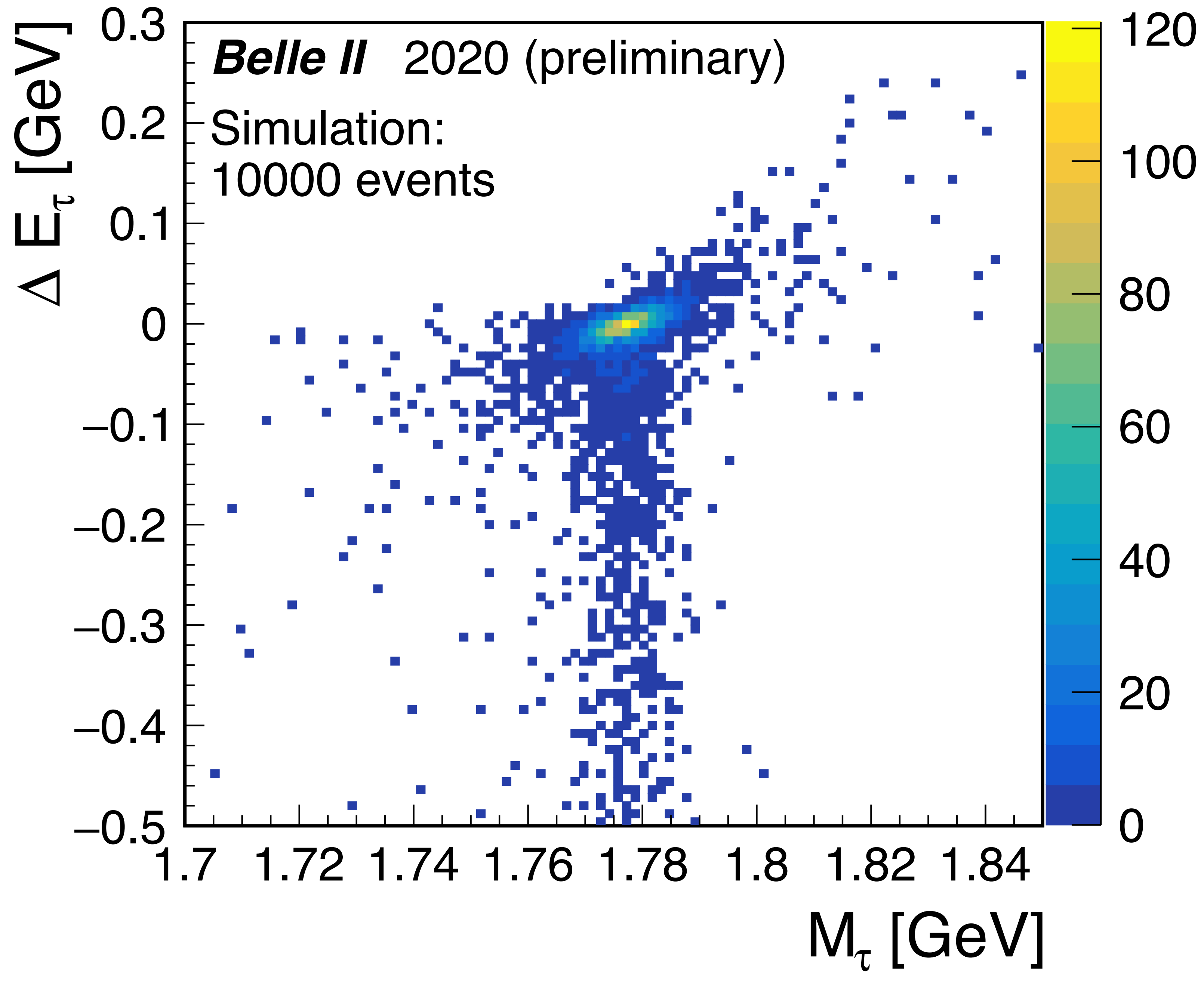
Signal-background discrimination using kinematics of the event

μID - the most powerful discriminating variable

Momentum dependent optimisation of the muID requirement

- $P_\mu < 0.7$ GeV
  - μ do not reach the μ detector (KLM)
- $0.7 < P_\mu < 1$ GeV
  - μ reach KLM but not many layers are crossed
- $P_\mu > 1$ GeV
  - μ reach KLM and many layers are crossed





Other requirement used @Belle but not @Belle II:

- μ veto on tag track
- $P_\mu > 0.6$ GeV

Two independent variables:

$$M_\tau = \sqrt{E^2_{\mu\mu\mu} - P^2_{\mu\mu\mu}}$$

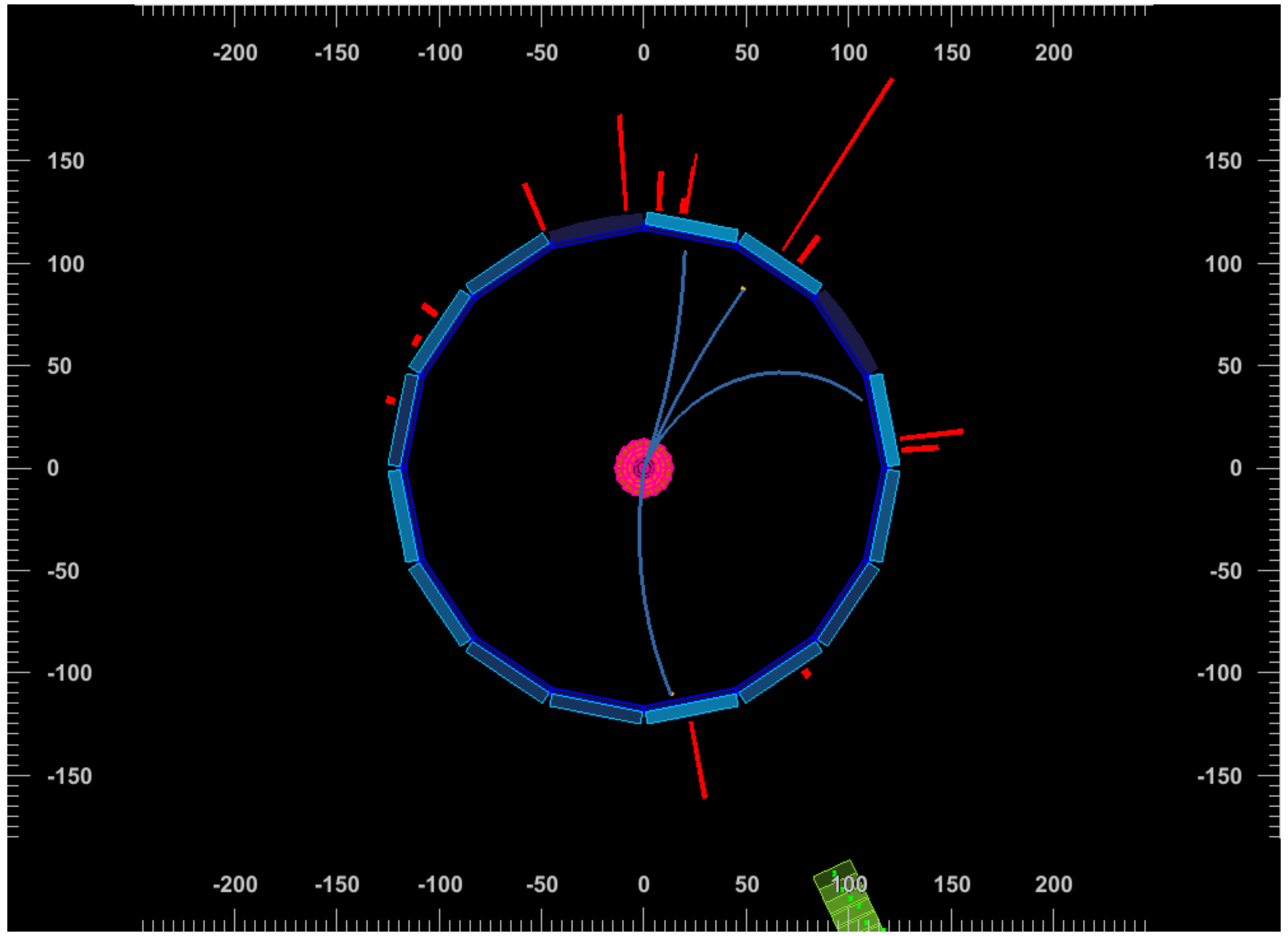
$$\Delta E = E^{CMS}_{\mu\mu\mu} - E^{CMS}_{\text{beam}}$$

- For signal → ΔE close to 0 and $M_{\mu\mu\mu}$ close to τ mass

Higher efficiency is foreseen @Belle II than @Belle or @BaBar

Summary

e^+e^- annihilation data is ideal for precision measurements and NP searches in τ physics!



Belle II experiment started

- Achieved world record luminosity $L = 3.1 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Will provide the world largest number ($5\mathrm{x}10^{10}$) of $e^+e^- \to \tau^+\tau^-$events
- **Precision measurements**
  - promising results on **τ mass, lifetime and LFU** with the early data
- **NP searches**
  - **τ → μμμ** shows the potential of LFV searches @ Belle II
- Many more analysis in progress

Belle II will be the major player in τ physics in the near future!