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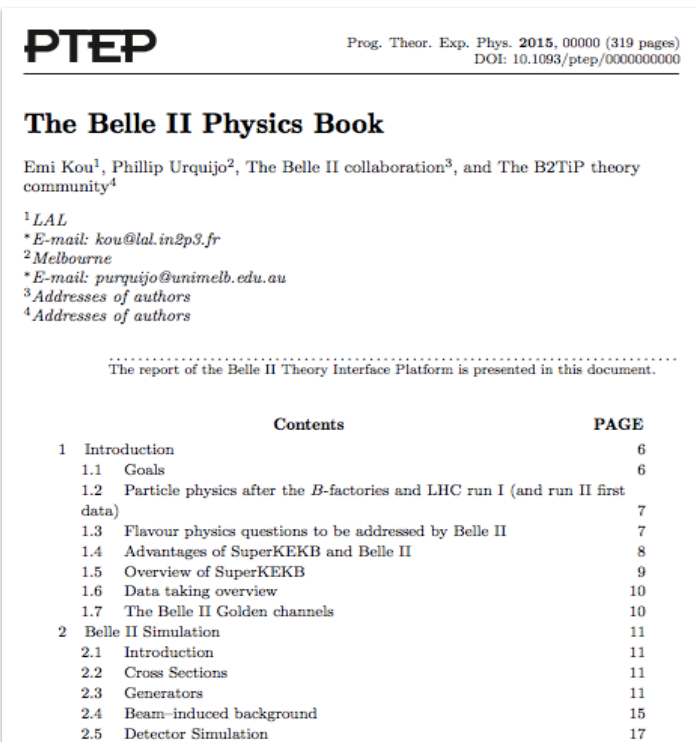
B2TIP view on Belle II



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The Belle II Physics Book

Emi Kou[1], Phillip Urquijo[2], The Belle II collaboration[3], and The B2TiP theory community[4]

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The report of the Belle II Theory Interface Platform is presented in this document.

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RADPyC'17, CINVESTAV

Mexico, May 23, 2017

https://confluence.desy.de/display/BI/B2TiP+ReportStatus

Outline :

1. Introduction and Motivation:
   Why studying flavour physics?

2. Belle II Theory Interface Initiative and Golden Channels for Belle II

3. Examples

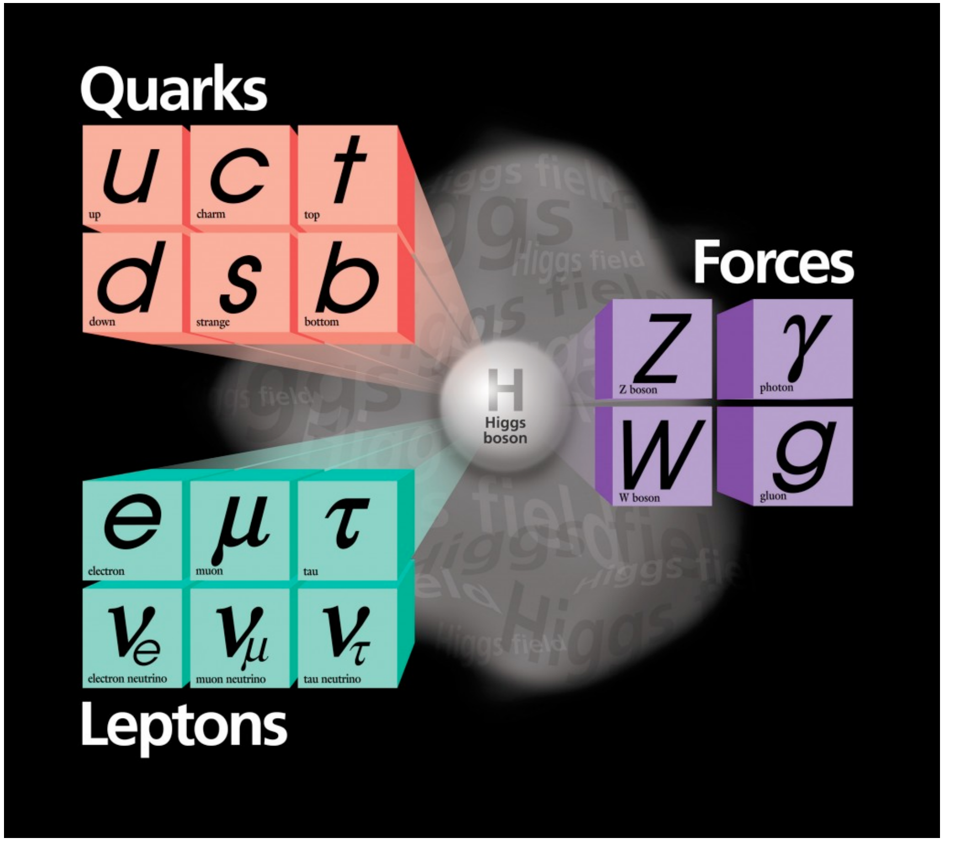
4. Conclusion and outlook

1. Introduction and Motivation: Why studying flavour physics?

1.1 The triumph of the Standard Model

- New era in particle physics :
  ⇨ (unexpected) *success of the Standard Model*: a successful theory of microscopic phenomena with *no intrinsic energy limitation*

- Several decades of experimental successes
  - Gauge sector (*LEP*, *SLC*)
  - Prediction of the quark top before its discovery
  - CP violation measured in Kaons decays (*NA48*, *KLOE*, *KTeV*), and B decays (*BaBar*, *Belle*)
  - Higgs boson



1.2 Quest for New Physics

- *Was this unexpected*?
  Not really! ⇨ *Consistent* with (pre-LHC) indications coming from indirect NP searches (*EWPO* + *flavour physcs*)

- *Shall we continue to test the Standard Model and search for New Physics?*

  Yes! ⇨ Despite its phenomenological successes, the SM has some *deep unsolved* problems:
  - hierarchy problem
  - flavour pattern
  - dark-matter, etc….

- Strong interaction not so well understood:
  confinement, etc

1.2 Quest for New Physics

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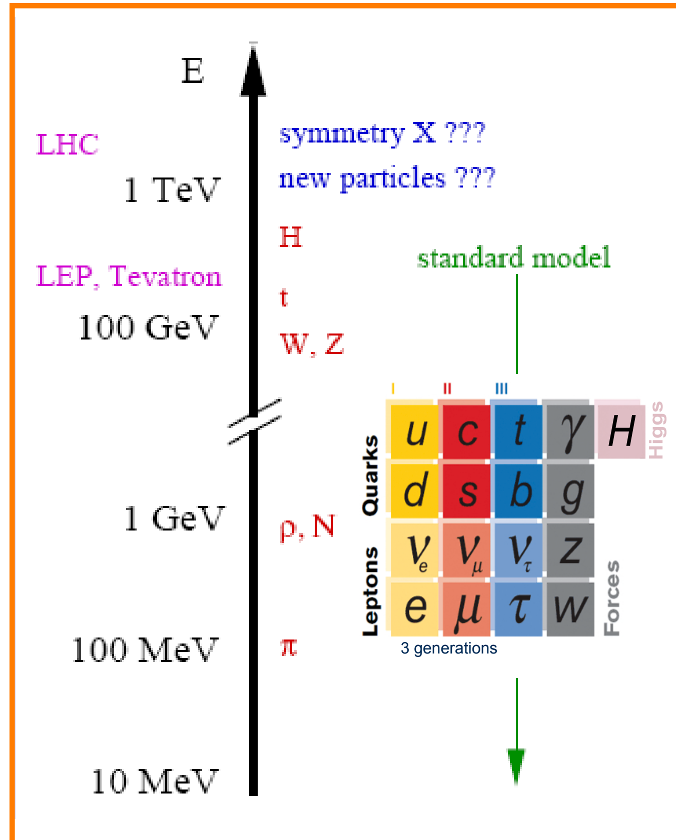


- Consider the SM as as an *effective theory*, i.e. the limit *–in the accessible range of energies and effective couplings–* of a more fundamental theory, with
  - new degrees of freedom
  - new symmetries

1.2 Quest for New Physics

- *Where do we look?* Everywhere!

  ⇨ search for New Physics with a *broad search strategy* given the lack of clear indications on the SM-EFT boundaries (*both in terms of energies and effective couplings*)

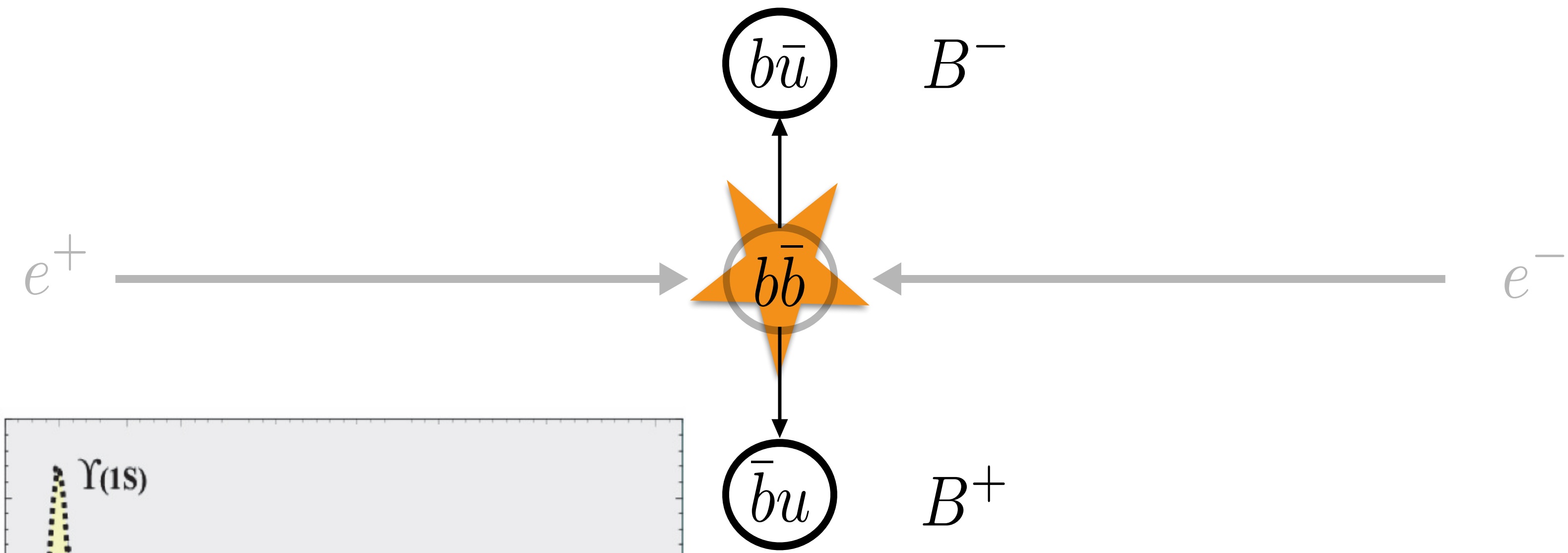
Where is the tail?

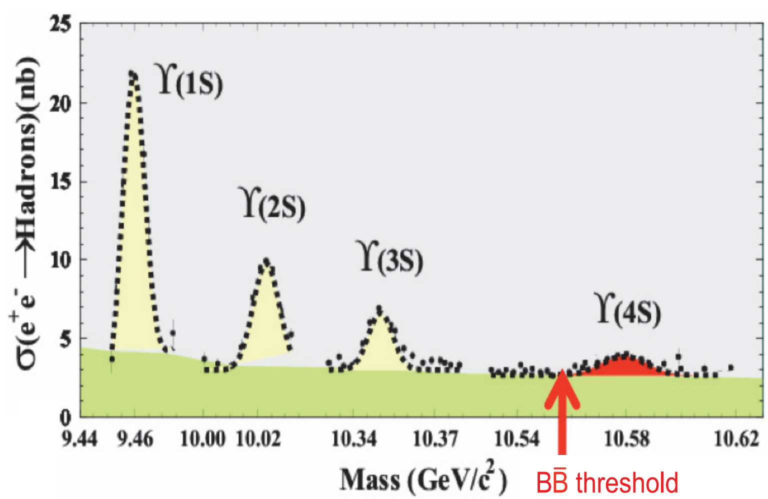
Y. Grossman@KEKFF'14

⇨ Key unique role of *Flavour Physics*

$e^+ e^-$ machines such as Belle II offer a very clean environment

1.3 Belle II environment

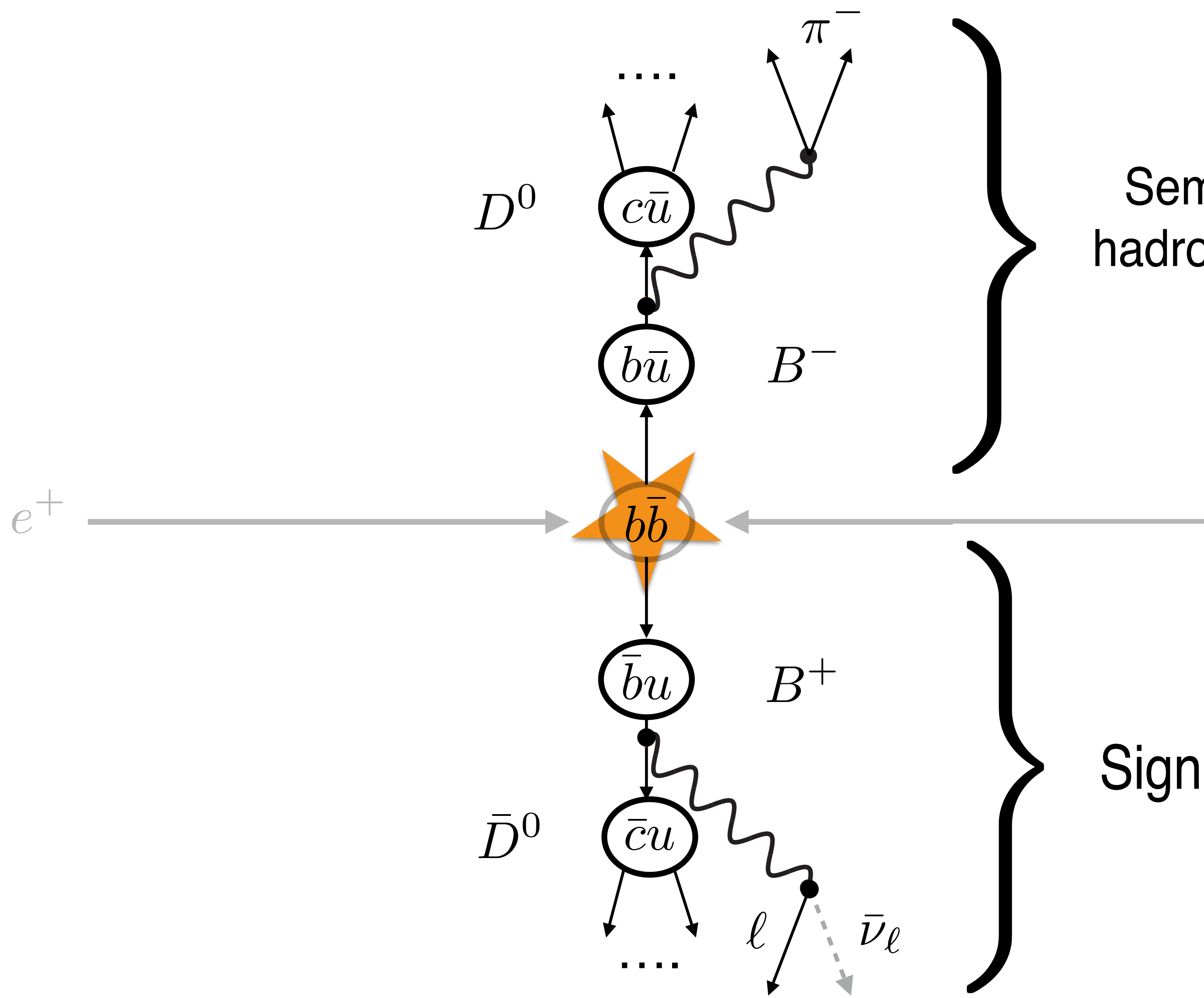




$$\Upsilon(1S) = \langle b\bar{b} \rangle$$

$$\Upsilon(4S) = \langle b\bar{b} \rangle$$

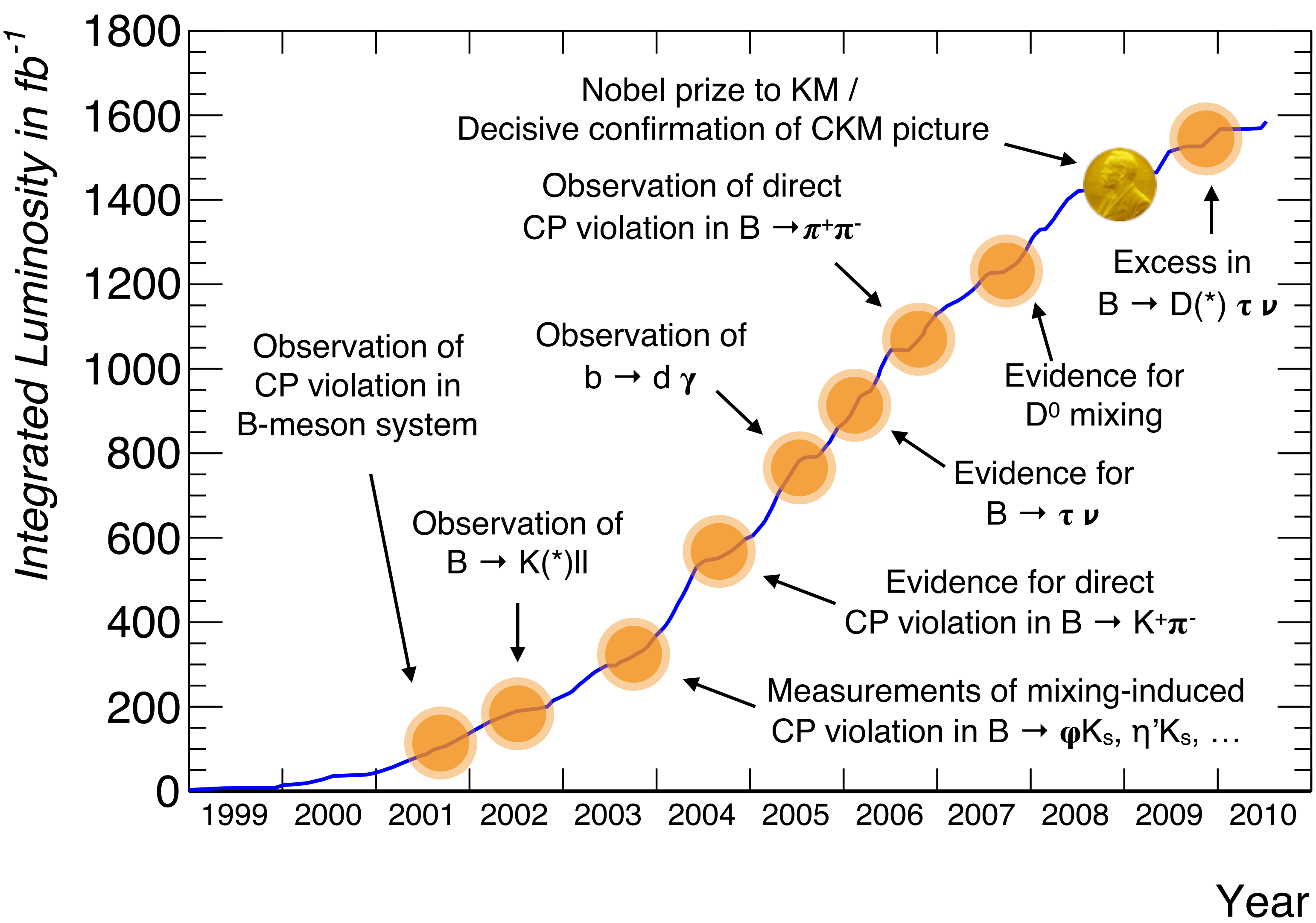
1.3 Belle II environment



Semi-*Inclusive* hadronic 'tagging' side

Signal side

1.4 Recap of the last decade of BaBar & Belle:
a rich harvest



1.5 The case for new physics manifesting in Belle II

- Baryon asymmetry in cosmology
  → New sources of *CPV* in quarks and charged leptons

- Quark and Lepton flavour & mass hierarchy
  → L-R symmetry, extended gauge sector, charged Higgs

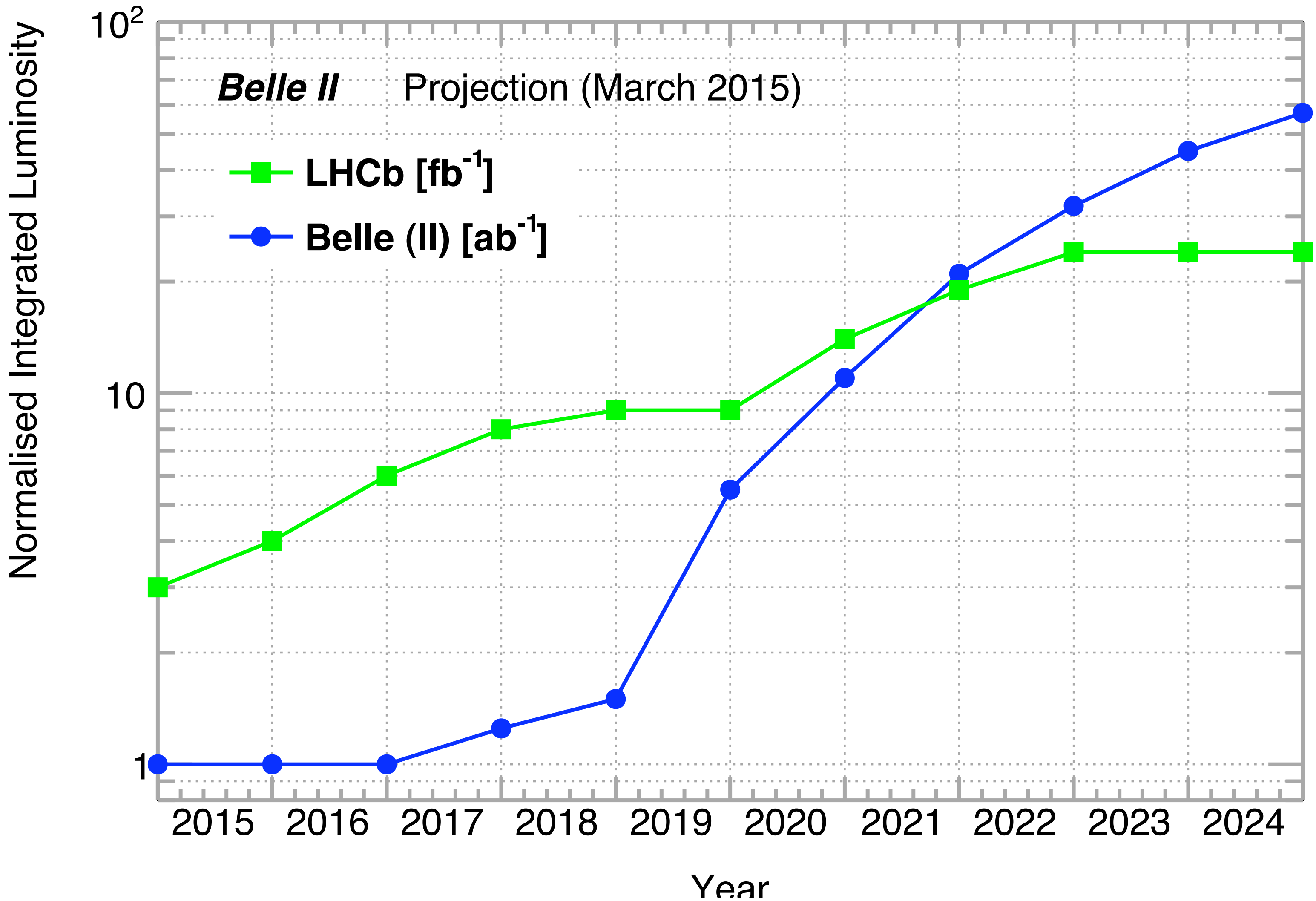
- Finite neutrino masses
  → *Tau LFV*

- 19 free parameters
  → Extensions of SM relate some GUTs

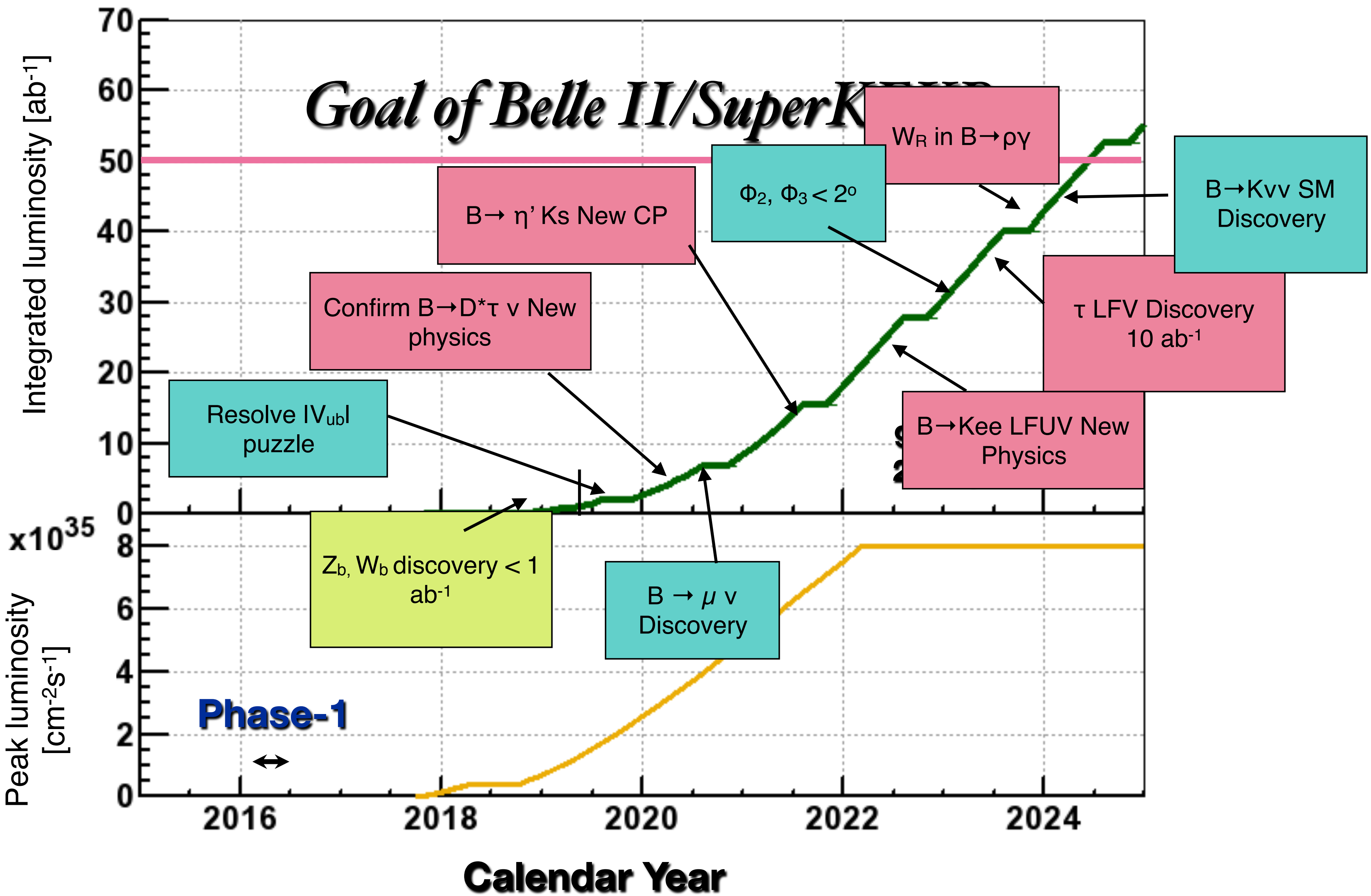
- Puzzling nature of *exotic "new" QCD* states.

- The *hidden* universe (dark matter)

1.6 Belle II expectations



1.6 Belle II expectations



2. Belle II Theory Interface Initiative and Golden Channels for Belle II

2.1 Why B2TIP?

See details on the slide at the kickoff meeting:

http://kds.kek.jp/getFile.py/access?contribId=14&sessionId=0&resId=0&materialId=slides&confId=15226

KEK where Belle II is hosted is the natural gathering point where flavour physics experts meet to discuss and develop topics of flavour physics for Belle II.

What's new in Belle II compared to Babar/Belle?

- ➡ Efficiencies and precision of the new hardware
- ➡ New analysis softwares and methods

What's new in theory after Babar/Belle & LHCb result?

- ➡ Progresses in QCD
- ➡ New physics models and their constraints
- ➡ New observables

NEW IDEAS

Deliverable: "KEK green report" by the early 2017

2.2 9 working groups

See details on the B2TiP website

https://belle2.cc.kek.jp/~twiki/bin/view/Public/B2TIP

WG1	G. De Nardo, A. Zupanic, M. Tanaka, F. Tackmann, A. Kronfeld
WG2	A. Ishikawa, J. Yamaoka, U. Haisch, T. Feldmann
WG3	T. Higuchi, L. Li Gioi, J. Zupan, S. Mishima
WG4	J. Libby, Y. Grossman, M. Blanke
WG5	P. Goldenzweig, M. Beneke, C.-W. Chiang, S. Sharpe
WG6	G. Casarosa, A. Schwartz, A. Kagan, A. Petrov
WG7	Ch.Hanhart, R.Mizuk, R.Mussa, C.Shen, Y.Kiyo, A.Polosa, S.Prelovsek
WG8	K. Hayasaka, T. Feber, E. Passemar, J. Hisano
WGNP	R.Itoh, F.Bernlochner, Y.Sato, U.Nierste, L.Silvestrini, J.Kamenik, V.Lubicz

I: Leptonic/Semi-leptonic II: Radiative/Electroweak III: phi1(beta)/phi2(alpha) IV: phi3 (gamma)
V: Charmless/hadronic B decays VI: Charm VII: Quarkonium(like) VIII: Tau & low multiplicity NP: New Physics

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Crucial contribution from Mexican groups
[Experiment and Theory]

I: Leptonic/Semi-leptonic II: Radiative/Electroweak III: phi1(beta)/phi2(alpha) IV: phi3 (gamma)
V: Charmless/hadronic B decays VI: Charm VII: Quarkonium(like) VIII: Tau & low multiplicity NP: New Physics

2.3 Table of Golden modes for B physics

Observables	Expected th. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	Belle II/LHCb
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CPV			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K^0_S\pi^0\gamma)$	***	0.03	Belle II
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\overline{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\overline{\nu})$ $[10^{-6}]$	***	20%	Belle II
$R(B \to K^*\ell\ell)$	**	0.03	Belle II/LHCb

2.3 Golden modes for Tau, Low Multiplicity and EW

- B factories are also Tau factories!

  ➡ 45 billion $\tau^+\tau^-$ pairs in full dataset

  from $\sigma(\tau^+\tau^-)_{E=\Upsilon(4S)}$ = 0.9 nb

Experiment	Number of τ pairs
LEP	~3x10^5
CLEO	~1x10^7
BaBar	~5x10^8
Belle	~9x10^8
Belle II	~10^{12}

- *Golden modes:*
  - Tau LFV : $\tau \to 3\mu/\mu\gamma/\mu h/\mu hh$
  - CP violation in $\tau \to K\pi\nu_\tau$ and/or $\tau \to K\pi\pi\nu_\tau$
  - Precision two track final state: $e^+e^- \to \pi^+\pi^-$
  - Dark photon → invisible

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- *Golden/Silver modes:*

Process	Observable	Theory	Sys. limit (Discovery) [ab^{-1}]	vs LHCb/BESIII	vs Belle	Anomaly	NP
$\tau \to \mu\gamma$	$Br.$	$\star\star\star$	-	$\star\star\star$	$\star\star\star$	$\star$	$\star\star\star$
$\tau \to lll$	$Br.$	$\star\star\star$	-	$\star\star\star$	$\star\star\star$	$\star$	$\star\star\star$
$\tau \to K\pi\nu$	A_{CP}	$\star\star\star$	-	$\star\star\star$	$\star\star\star$	$\star\star$	$\star\star$
$e^+e^- \to \gamma A'(\to \text{invisible})$	σ	$\star\star\star$	-	$\star\star\star$	$\star\star\star$	$\star$	$\star\star\star$
$e^+e^- \to \gamma A'(\to \ell^+\ell^-)$	σ	$\star\star\star$	-	$\star\star\star$	$\star\star\star$	$\star$	$\star\star\star$
π form factor	$g-2$	$\star\star$	-	$\star\star\star$	$\star\star$	$\star\star$	$\star\star\star$
ISR $e^+e^- \to \pi\pi$ g-2	$g-2$	$\star\star$	-	$\star\star\star$	$\star\star\star$	$\star\star$	$\star\star\star$

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G. Lopez-Castro'17

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Estimated sensititivities

Belle II Report 2017

"Tau and low multiplicity Physics"

	Current sensitivity/	Belle II sensitivity/
$Br(\tau\to\mu\gamma)$	Br <10^{-8}	Br~10^{-9}~10^{-10}
$A_{CP}(\tau\to K_S\pi\nu_\tau)$	(-0.36±0.23±0.11)%	×70 more sensitive
$\lvert Re, Im(d_\tau)\rvert$	≲10^{-17}	≲10^{-18}~10^{-19}
$Br(\tau\to\pi\eta\nu)$	≲10^{-4}	under study
$\rho, \eta, \xi_\rho\xi, \xi_\rho\xi\delta$	Stat Uncert~10^{-3}	Stat Uncert ~10^{-4}
$Br(\tau\to\mu\pi^0,\mu\eta)$	Br<(2.7, 2.3)×10^{-8}	Br<10^{-10}
$Br(\tau\to\mu\mu\mu)$	Br<2.1×10^{-8}	Br<10^{-9}
R(D), R(D*)	±0.047, ±0.017	±0.010, ±0.005

2.3 Golden modes for Tau, Low Multiplicity and EW

- B factories are also Tau factories!

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- *Golden modes:*
  - Tau LFV : $\tau \to 3\mu/\mu\gamma/\mu h/\mu hh$
    Interest of Mexican Group in study of $\tau^- \to l^-(\pi^0\pi^0, \pi^0\eta, \eta\eta)$ channels
  - *CP violation* in $\tau \to K\pi\nu_\tau$ and/or $\tau \to K\pi\pi\nu_\tau$
    $\tau^- \to K_S\,\pi^0\pi^-\nu_\tau$: BR and spectrum measurements interesting for CP violation studies and isospin breaking in K*(892)
  - Precision two track final state: $e^+e^- \to \pi^+\pi^-$
  - Dark photon $\to$ invisible

G. Lopez-Castro'17

Mexican involvment

3. Examples

3.1 Probing the CKM mechanism

- The CKM Mechanism source of *Charge Parity Violation* in SM
- Unitary 3x3 Matrix, parametrizes rotation between mass and weak interaction eigenstates in Standard Model

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

Weak Eigenstates CKM Matrix Mass Eigenstates

$$\sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

3.1 Probing the CKM mechanism

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Weak Eigenstates CKM Matrix Mass Eigenstates

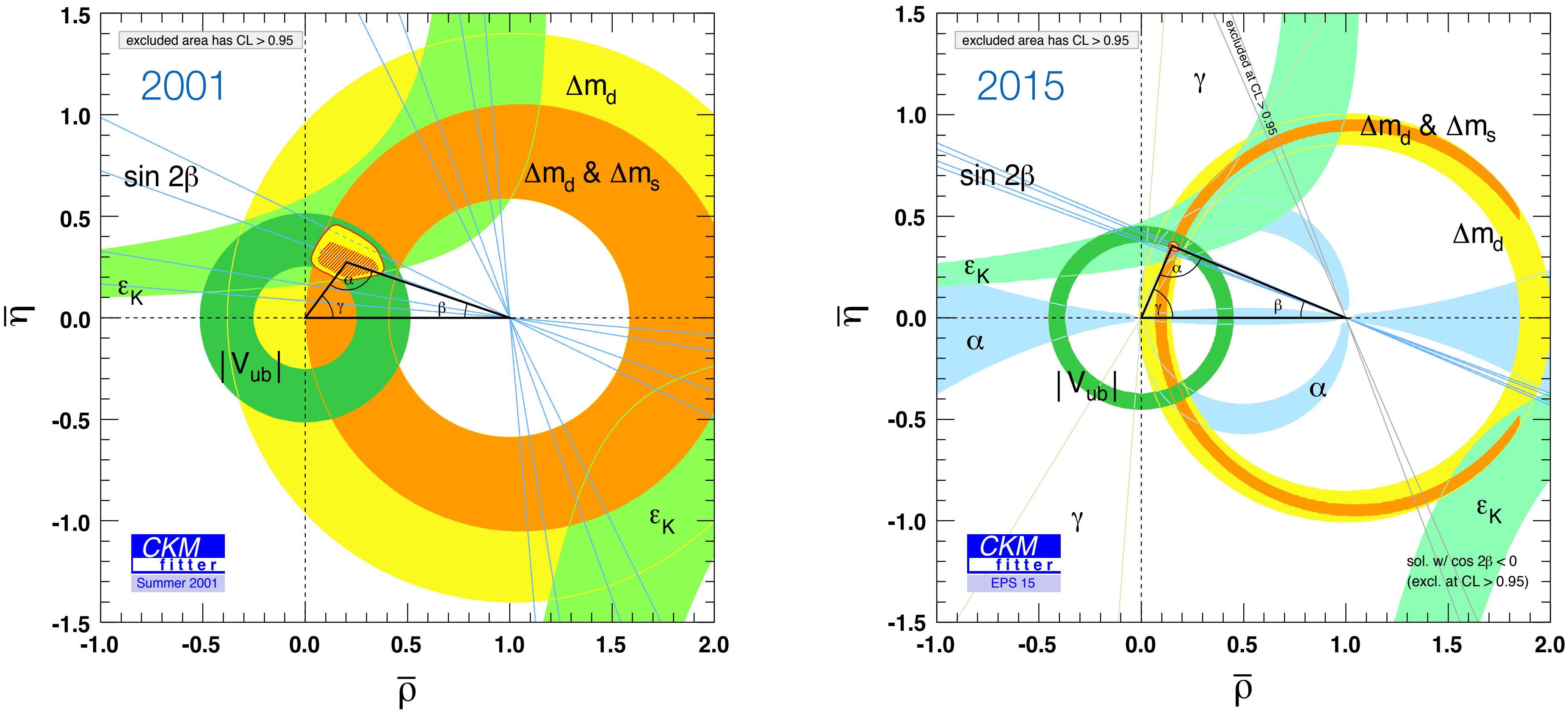
- Fully parametrized by **four** parameters if unitarity holds: three real parameters and *one complex phase* that if non-zero results in *CPV*
- Unitarity can be visualized using triangle equations, e.g.

$$V_{CKM} V_{CKM}^{\dagger} = \mathbf{1} \quad \rightarrow \quad \boxed{V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0}$$

CKM picture over the years: from **discovery** to **precision**

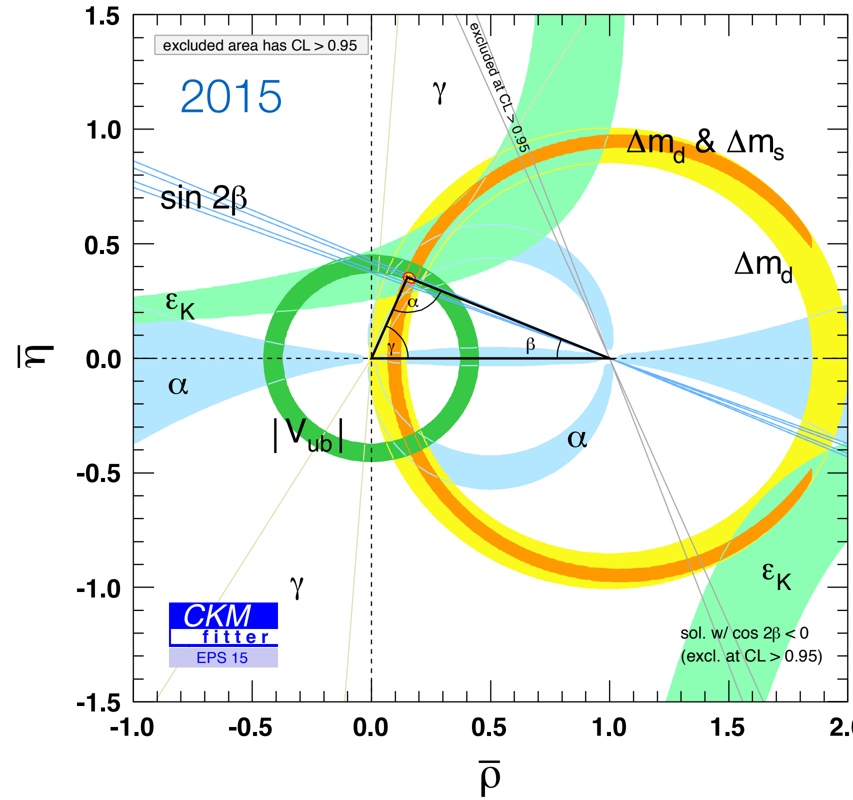
Existence of *CPV* phase established in 2001 by BaBar & Belle

- Picture still holds 15 years later, constrained with remarkable precision
- But: still leaves room for new physics contributions



3.1 Probing the CKM mechanism

Input	World average 2016	Belle II (+LHCb) 2025
$\lvert V_{ub}\rvert(\text{semileptonic})[10^{-3}]$	$4.01 \pm 0.08 \pm 0.22$	± 0.10
$\lvert V_{cb}\rvert(\text{semileptonic})[10^{-3}]$	$41.00 \pm 0.33 \pm 0.74$	± 0.57
$\mathcal{B}(B \to \tau\nu)$	1.08 ± 0.21	± 0.04
$\sin 2\beta$	0.691 ± 0.017	± 0.008
$\gamma[^\circ]$	$73.2^{+6.3}_{-7.0}$	± 1.5 (± 1.0)
$\alpha[^\circ]$	$87.6^{+3.5}_{-3.3}$	± 1.0
Δm_d	0.510 ± 0.003	-
Δm_s	17.757 ± 0.021	-
$\mathcal{B}(B_s \to \mu\mu)$	$2.8^{+0.7}_{-0.6}$	(± 0.5)
f_{B_s}	$0.224 \pm 0.001 \pm 0.002$	0.001
B_{B_s}	$1.320 \pm 0.016 \pm 0.030$	0.010
f_{B_s}/f_{B_d}	$1.205 \pm 0.003 \pm 0.006$	0.005
B_{B_s}/B_{B_d}	$1.023 \pm 0.013 \pm 0.014$	0.005

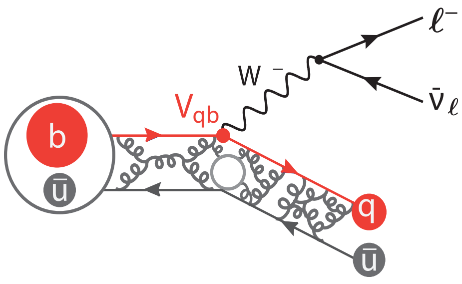


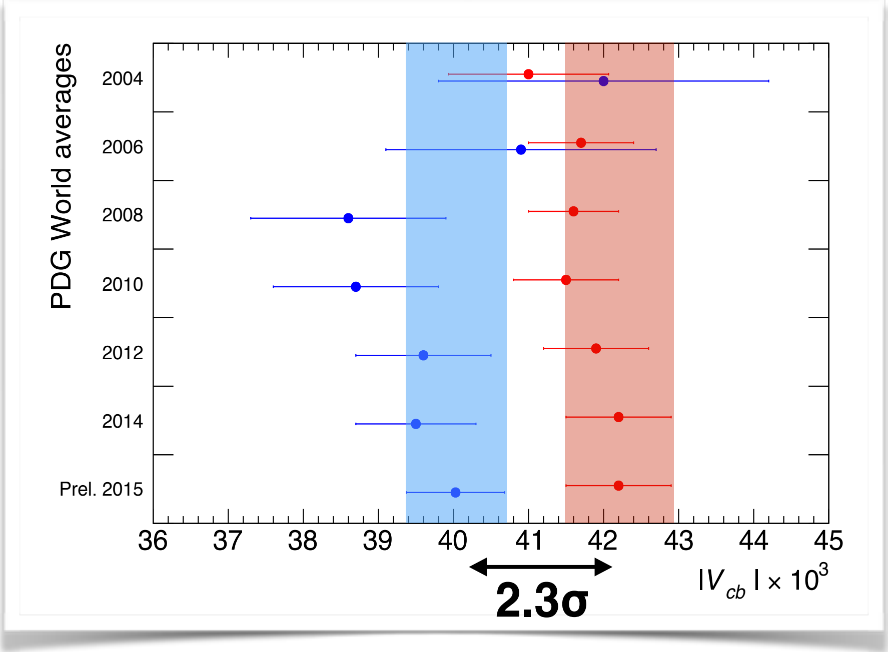
Expect substantial improvements to tree constraints!

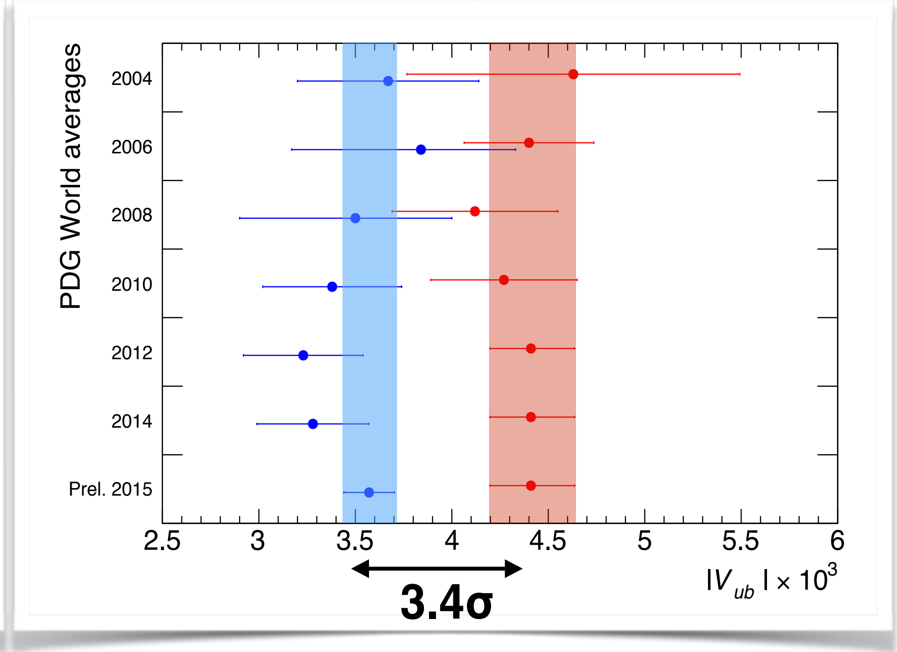
E.g: Solving the discrepancy Vub/Vcb

Sizeable tension in *exclusive* and *inclusive* $|V_{ub}|$ & $|V_{cb}|$

- Both methods considered theoretical and experimental mature
- Individual determinations leave a consistent picture





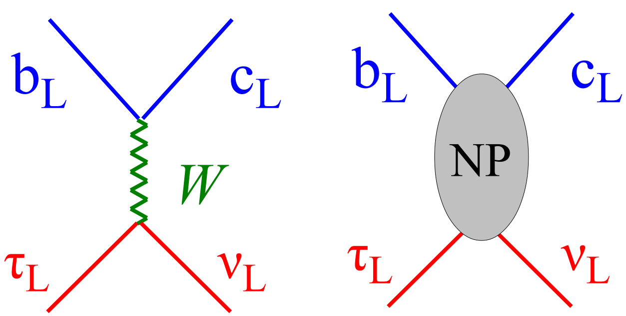


- About **2.3σ** and **3.4σ** disagreement between incl. and excl. for $|V_{cb}|$ & $|V_{ub}|$, respectively

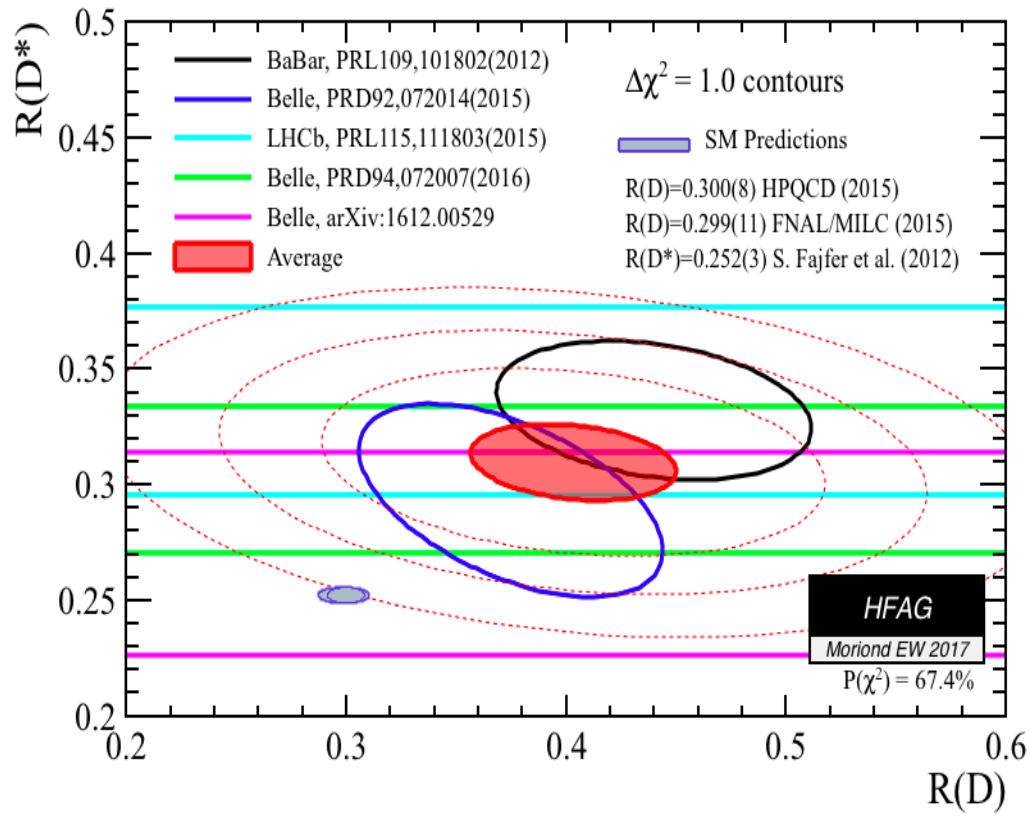
3.2 Lepton universality & NP

- A renewed interest in possible violations of LFU has been triggered by two very different sets of observations in B physics:
  1. LFU test in b → c charged currents: τ vs. light leptons (μ, e) :

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}$$



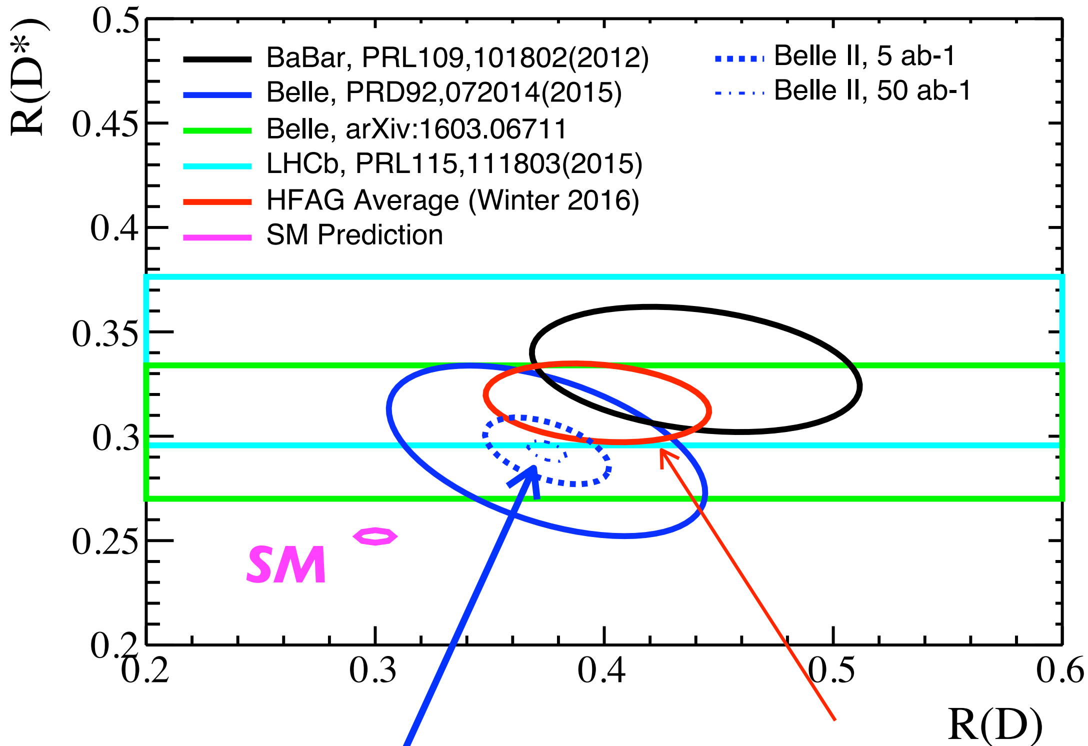
SM prediction solid: f.f. uncertainty cancels (to a good extent...) in the ratio



Consistent results by 3 different exps ⇨ 3.9σ excess over SM (combining D and D*)

3.2 Lepton universality & NP

K. Hara for B2TiP LAL NP-workshop



~ currently 3σ deviation?

Belle II prospect

(with the current Belle central value)

14(6)σ deviation with 50(5)ab^{-1} of data!

3.2 Lepton universality & NP

- A renewed interest in possible violations of LFU has been triggered by two very different sets of observations in B physics:

  2. LFU test in b → s neutral currents: μ vs. e :

$$R_K = \frac{\mathrm{Br}[B^+ \to K^+ \mu^+ \mu^-]_{[1,6]}}{\mathrm{Br}[B^+ \to K^+ e^+ e^-]_{[1,6]}} = 0.745 \cdot (1 \pm 13\%)$$

vs $R_K^{\mathrm{SM}} = 1.003 \pm 0.0001$

LHCb'14

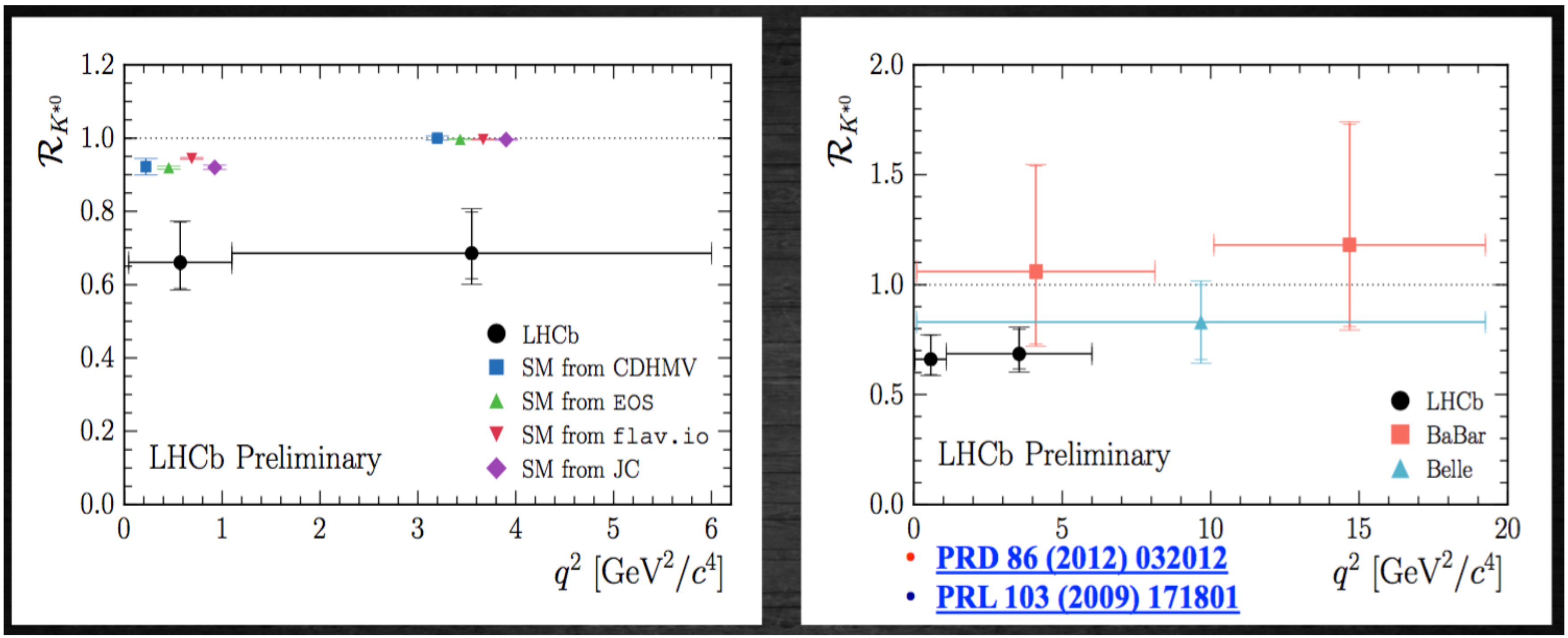
2.6σ deviation from the SM

3.2 Lepton universality & NP

2. LFU test in b → s neutral currents: μ vs. e :

$R_{K^*} = \mathbf{Br}(B \to K^* \mu\mu)/\mathbf{Br}(B \to K^* ee)$ **anomaly'**

S. Bifani, LHCb@CERN'17



Compatibility with SM *2.2-2.4σ* (low-q^2) *2.4-2.5σ* (central-q^2)

3.2 Lepton universality & NP

- A renewed interest in possible violations of LFU has been triggered by two very different sets of observations in B physics

- This has triggered intense theoretical activities:
  D & D* channels are well consistent with a universal enhancement (~15%) of the SM $b_L \to c_L\ \tau_L\ \nu_L$ amplitude (*RH or scalar amplitudes disfavored*)

- Natural to conceive NP models where LFU is violated more in processes involving *3rd gen. quarks & leptons* (↔ *hierarchy in Yukawa coupl.*)

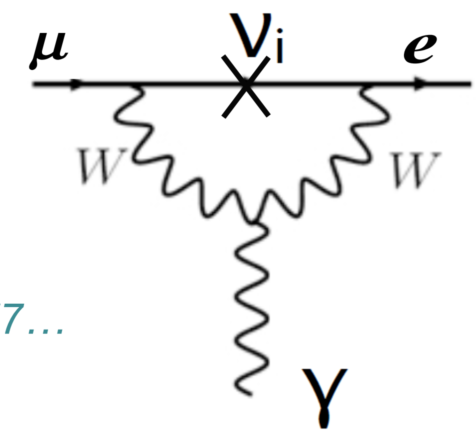
- *Belle II* contribution very important:
  - Cleanest environment: Belle covers ~70% of all tau Inclusive Br decays!
  - Perform *angular distribution* analyses

3.3 Tau LFV

- Lepton Flavour Number is an « accidental » symmetry of the SM (m_ν=0)

- In the *SM* with massive neutrinos effective CLFV vertices are tiny due to GIM suppression ⇨ *unobservably small rates!*

  E.g.: $\mu \to e\gamma$



$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2}\right|^2 < 10^{-54}$$

Petcov'77, Marciano & Sanda'77, Lee & Shrock'77…

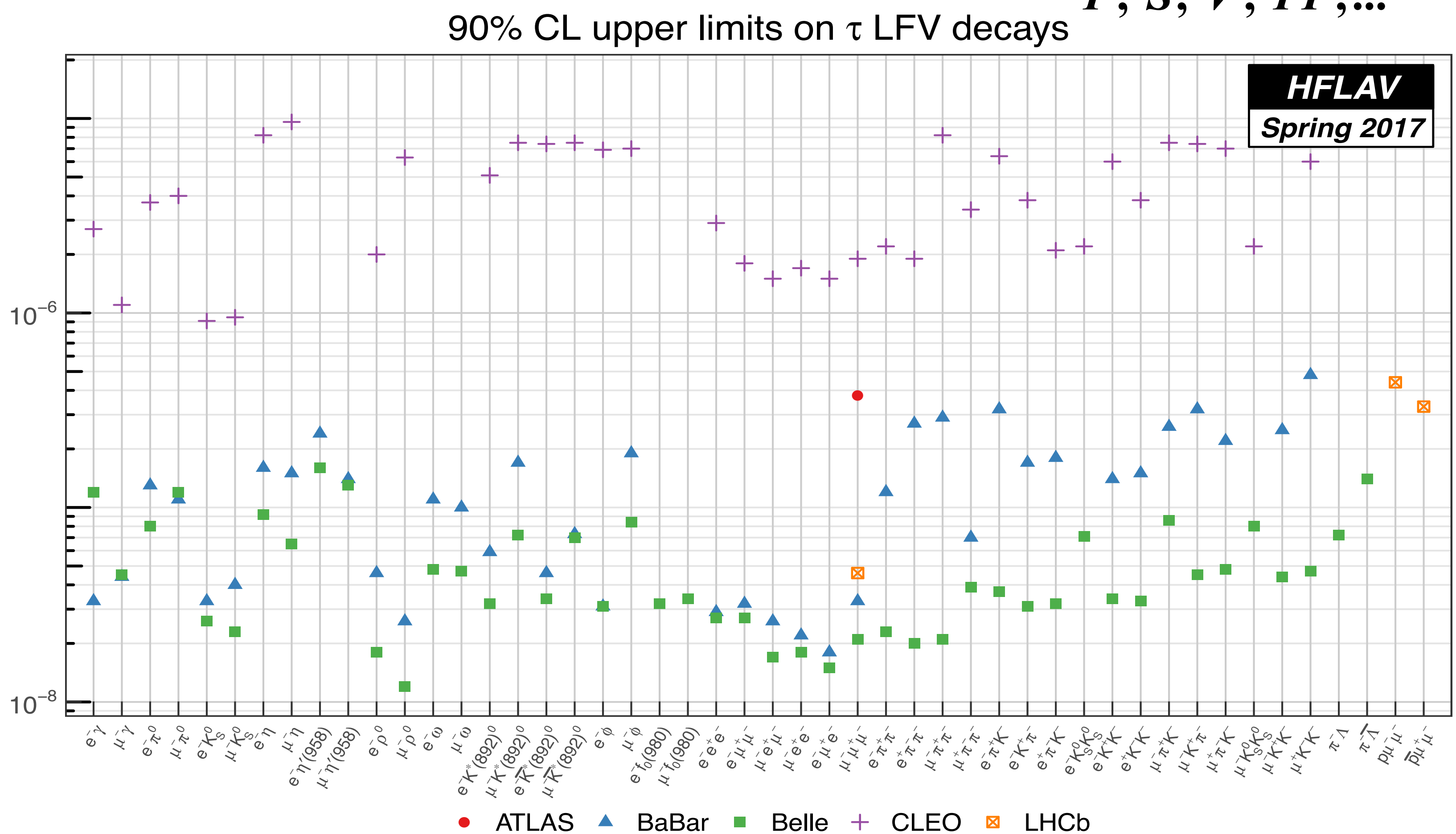
$$\left[Br(\tau \to \mu\gamma) < 10^{-40}\right]$$

- Extremely *clean probe of beyond SM physics*

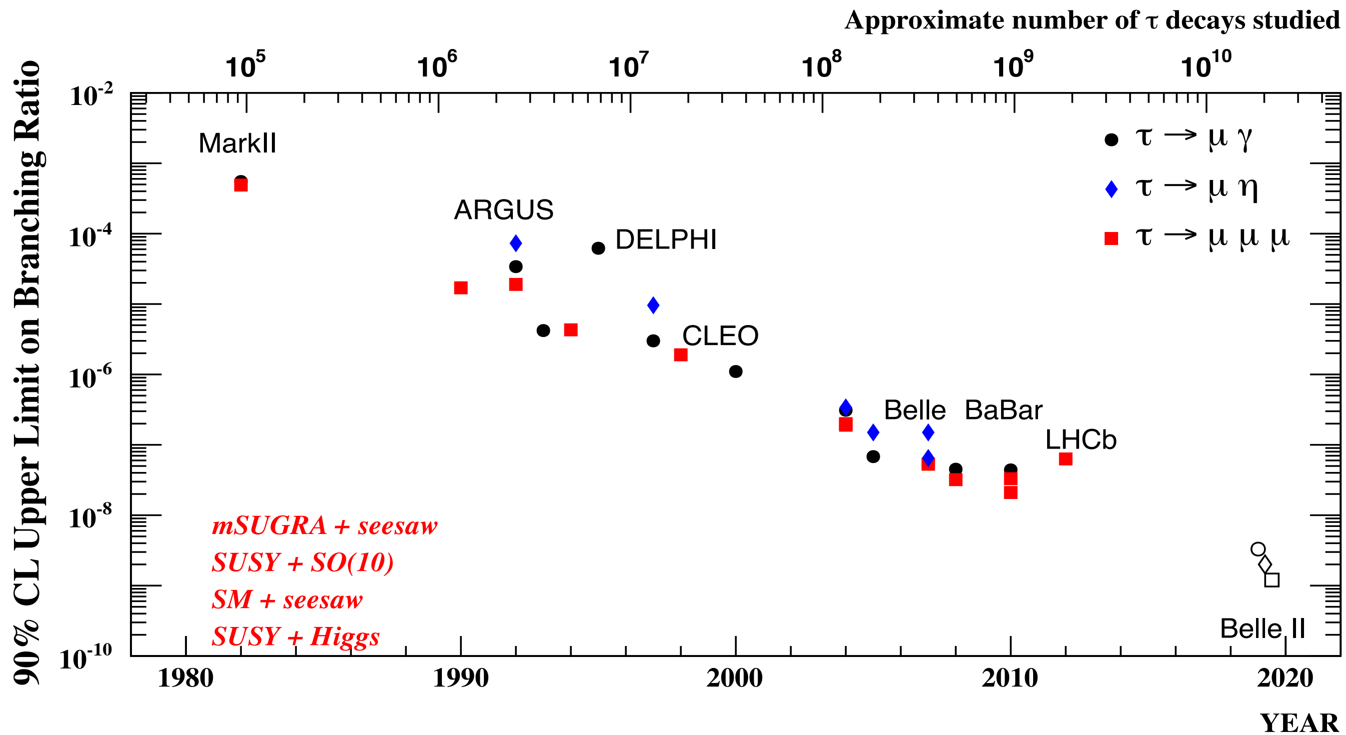
- In New Physics models: seazible effects
  Comparison in muonic and tauonic channels of branching ratios, conversion rates and spectra is model-diagnostic

3.3 Tau LFV

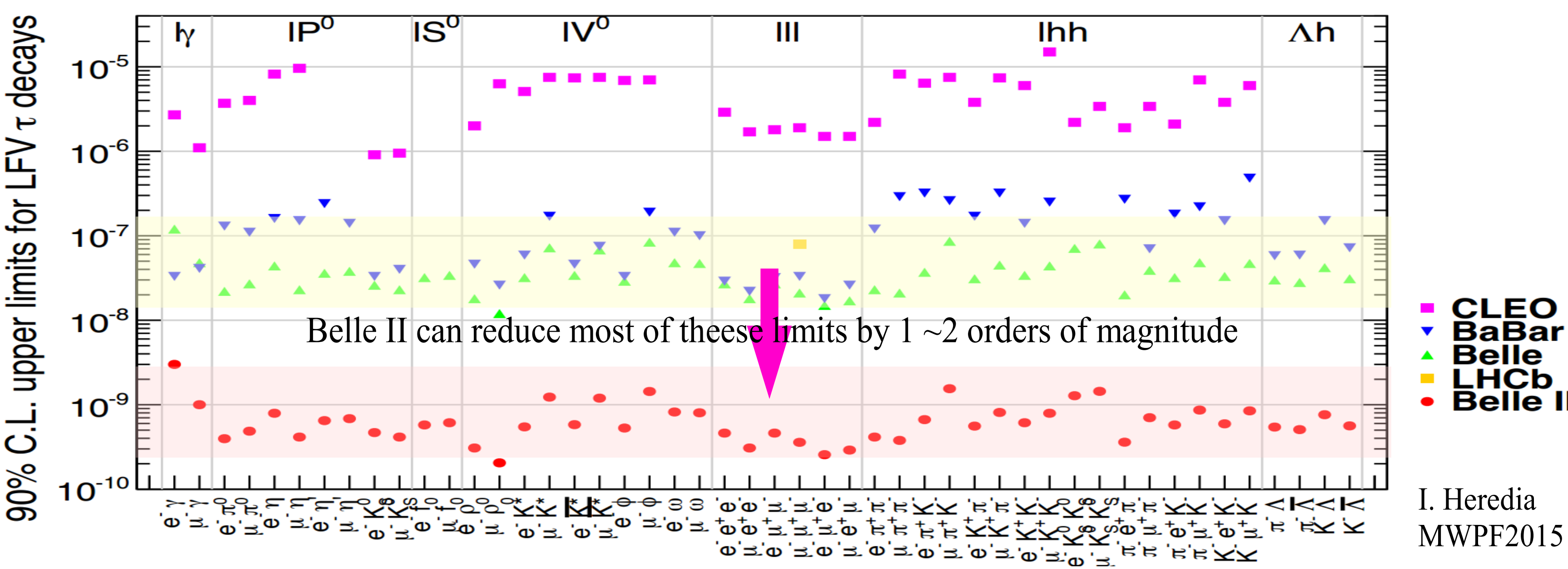
- Several processes: $\tau \to \ell\gamma,\ \tau \to \ell_\alpha \bar{\ell}_\beta \ell_\beta,\ \tau \to \ell Y$ ↖ $P,\ S,\ V,\ P\bar{P}, \ldots$



- 48 LFV modes studied at Belle and BaBar



S. Banerjee'17



I. Heredia
MWPF2015

4. Conclusion and outlook

Conclusion and outlook

- The SM has been very successful so far to describe phenomenology
  But this is not the end of the story

- *Belle II* gives us a unique opportunity to explore the SM very precisely in the sector of *flavour physics*

- Important *B2TIP initiative* to assess the discovery opportunities

- Examples where Belle II can make a difference:
  - CKM determination and Unitary triangles
  - LFU tests in B physics
  - Tau LFVs

- But many others, e.g.: Quarkoniums, exotics, D physics, CP asymmetries, weak mixing angle, second class currents, Di-photon physics, Dark sector, etc.

- Important *Mexican contributions* to Belle II in many sectors

  ⇨ We will hear more during the conference

- Stay tuned! Exciting times are ahead of us

7. Back-up

Conclusion and outlook

- Leptonic Universality hints

- Hadronic τ-decays very interesting to study
  - Very precise determination of α_s
  - Extraction of V_{us}

- Charged LFV are a very important probe of new physics

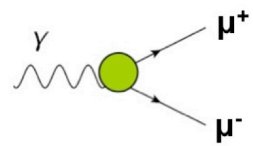
- Several topics extremely interesting to study that I did not address:
  - Michel parameters
  - CPV asymmetry in $\tau \to K\pi\nu_\tau$
  - EDM and g-2 of the tau
  - Neutrino physics

- A lot of *very interesting physics* remains to be done in the tau sector!

5. LFC processes: anomalous magnetic moment of the muon

5.1 Introduction

$$a_\mu = \frac{(g-2)_\mu}{2}$$ **Anomalous magnetic moment**

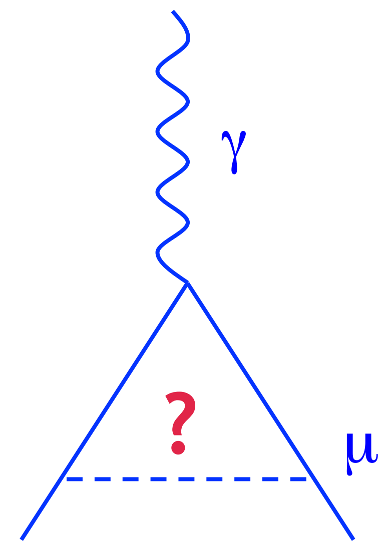


- The gyromagnetic factor of the muon is modified by loop contribution

- We can also study a_e with better experimental precision but if new physics heavy then more sensitivity in a_μ

$$a_\ell^{NP}(\Lambda_{NP}) \propto \mathcal{O}\left(\frac{m_\ell^2}{\Lambda_{NP}^2}\right) \Rightarrow \frac{a_\mu^{NP}}{a_e^{NP}} \propto \mathcal{O}\left(\frac{m_\mu^2}{m_e^2}\right) \approx 43{,}000$$

a_τ even more sensitive but insufficient experimental accuracy *Eidelman, Giacomini, Ignatov, Passera'07*

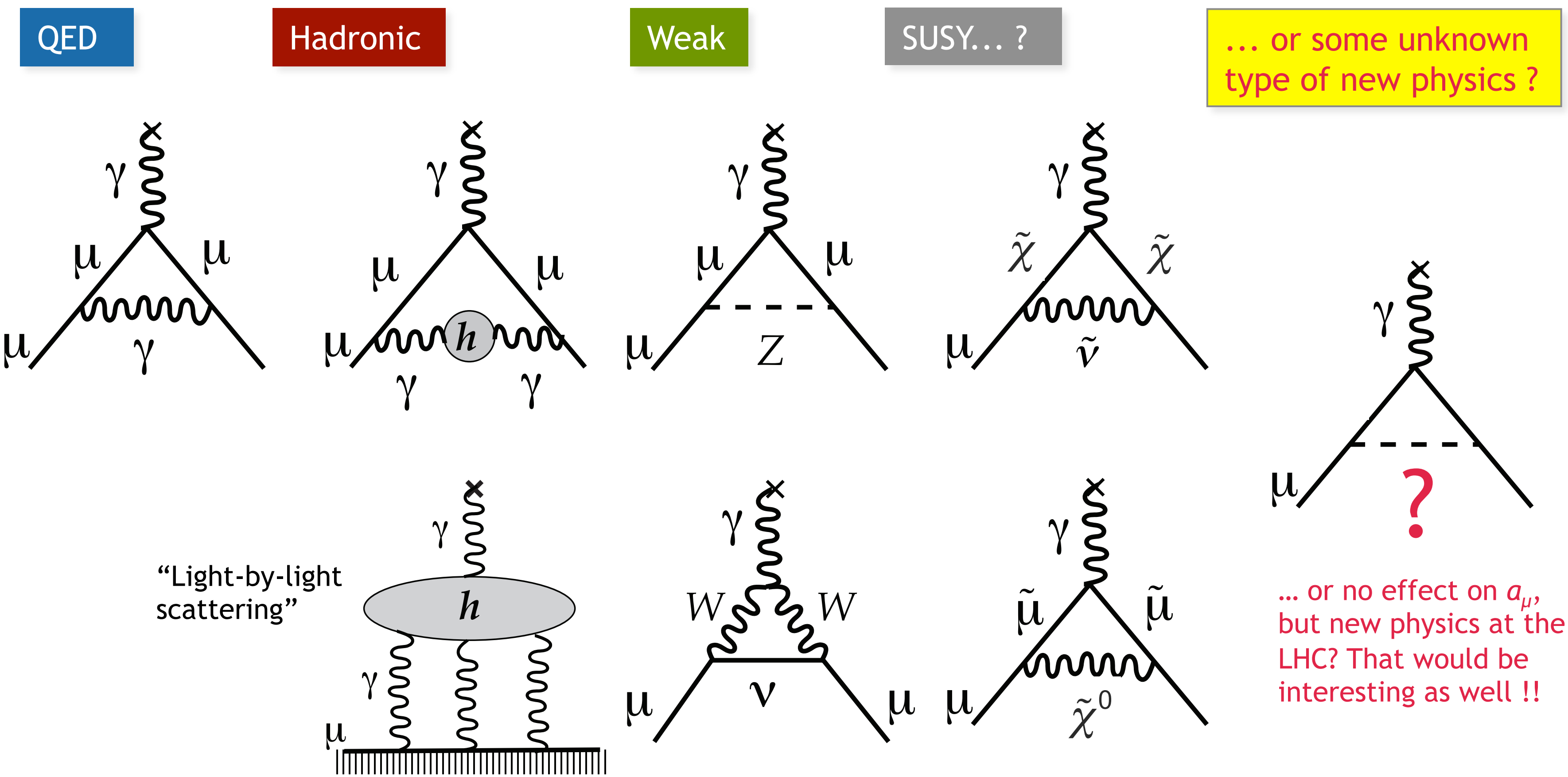


- But a_e important if NP is light
  ⇨ Important constraints on NP scenarios

Giudice, Paradisi, Passera'12

5.2 Contribution to $(g\text{-}2)_\mu$

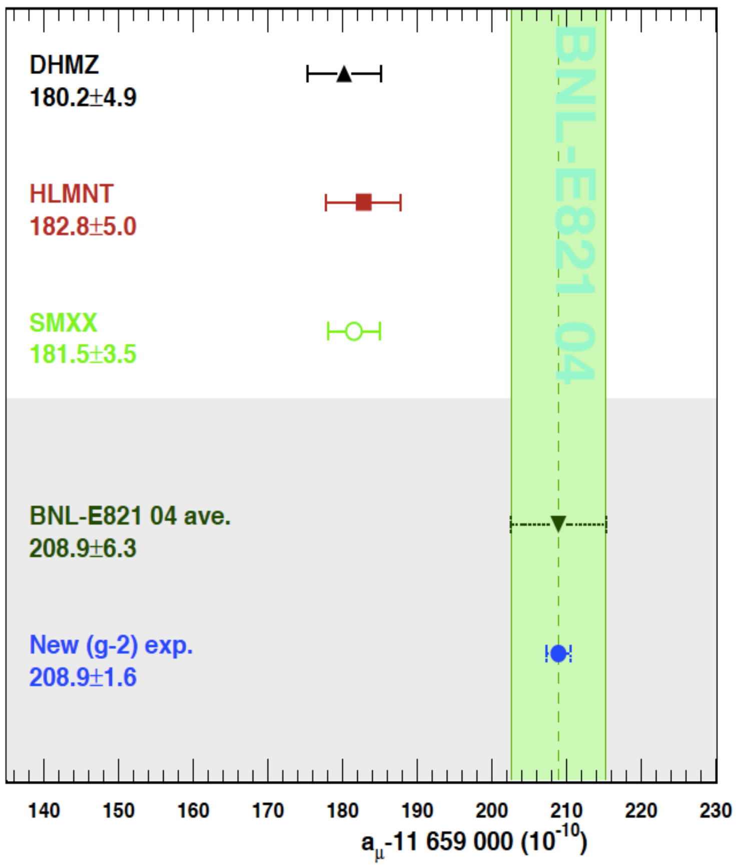
Hoecker'11



Need to compute the SM prediction with high precision! → *Not so easy!*

5.3 Confronting measurement and prediction

Blum et al.'13

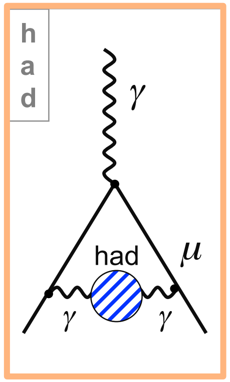


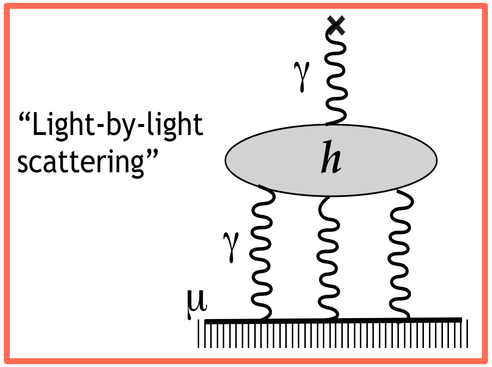
$$a_\mu|_{\rm exp} = 0.001\ 165\ 920\ 80(54)(33)[63]$$
$$a_\mu|_{\rm theo} = 0.001\ 165\ 918\ 40(59)$$
$$a_\mu|_{\rm exp} - a_\mu|_{\rm theo} = 240 \times 10^{-11} \quad 2.9\sigma \text{ diff.}$$

Theoretical Prediction: *Lafferty, summary talk@Tau2014*

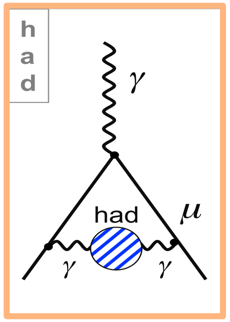
Contribution	Result in 10^{-10} units
QED(leptons)	11658471.885 ± 0.004
HVP(leading order)	690.8 ± 4.7
HVP(higher order) (*)	-10.0 ± 0.02
HLBL	11.6 ± 4.0
EW	15.4 ± 0.1
Total	11659179.7 ± 6.2

Jegerlehner and Nyffeler '09



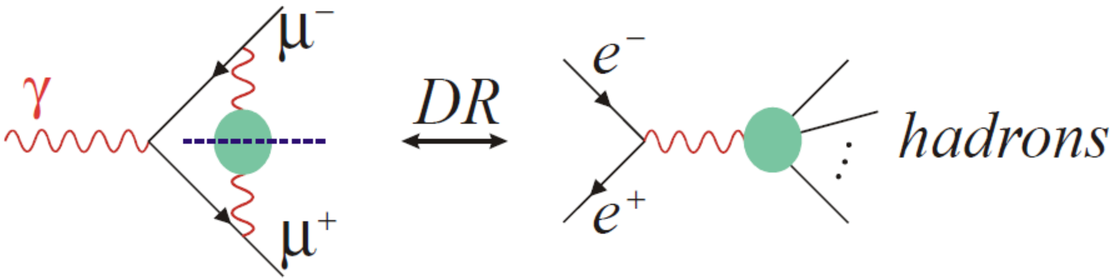


5.4 Towards a model independent determination of HVP and LBL



- Hadronic contribution cannot be computed from first principles due to low-energy hadronic effects

- Use analyticity + unitarity ⇒ real part of photon polarisation function from *dispersion relation* over *total hadronic cross section data*



$$R_V(s) = \frac{\sigma\left(e^+e^- \to hadrons\right)}{\sigma\left(e^+e^- \to \mu^+\mu^-\right)}$$

- Leading order hadronic vacuum polarization :

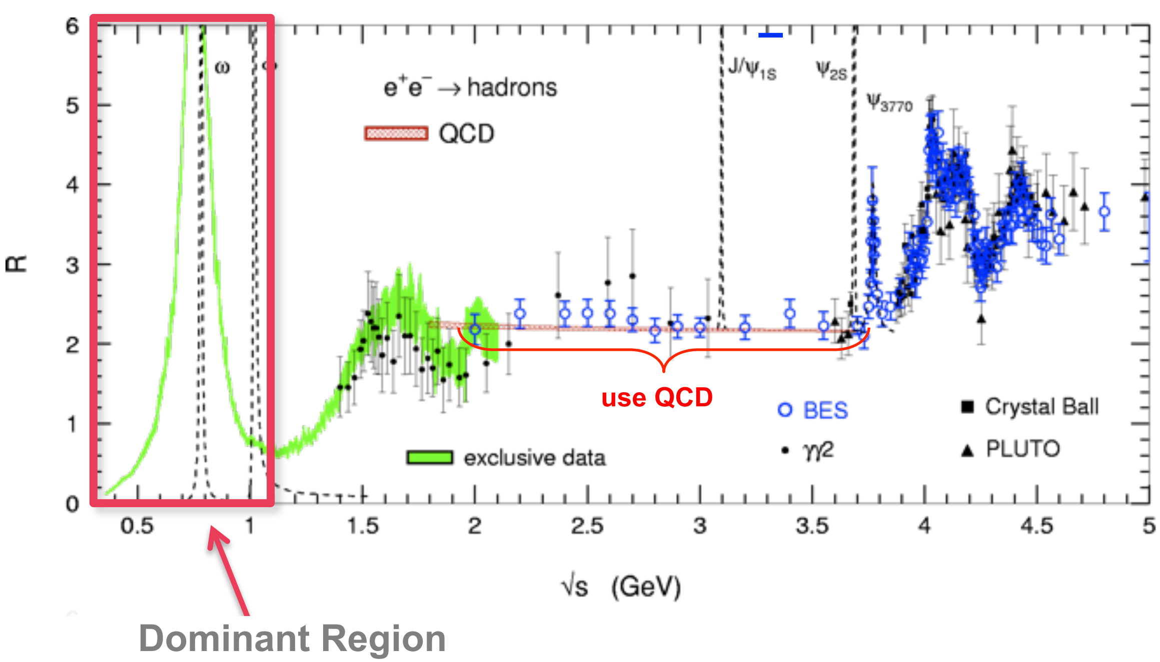
$$a_\mu^{had,LO} = \frac{\alpha^2 m_\mu^2}{(3\pi)^2}\int_{4m_\pi^2}^{\infty} ds\, \frac{K(s)}{s^2} R_V(s)$$

- Low energy contribution dominates : ~75% comes from s < (1 GeV)^2

  ⇒ ππ contribution extracted from data

5.4 Towards a model independent determination of HVP and LBL

- Huge 20-years effort by experimentalists and theorists to reduce error on lowest-order hadronic part
  - ➢ Improved e^+e^- cross section data from Novisibirsk (Russia)
  - ➢ More use of perturbative QCD
  - ➢ Technique of "*radiative return*" allows to use data from Φ and *B* factories
  - ➢ Isospin symmetry allows us to also use τ hadronic spectral functions

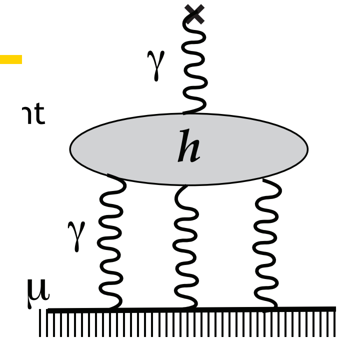


But still some progress need to be done

- ➢ Inconsistencies τ vs. e+e-: *Isospin corrections?*
- ➢ Inconsistencies between ISR and direct data: *Radiative corrections?*
- ➢ Lattice Calculation?

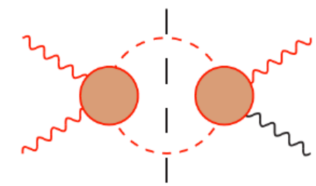
New data expected from VEPP, KLOE2, BES-III?
➡ Belle II

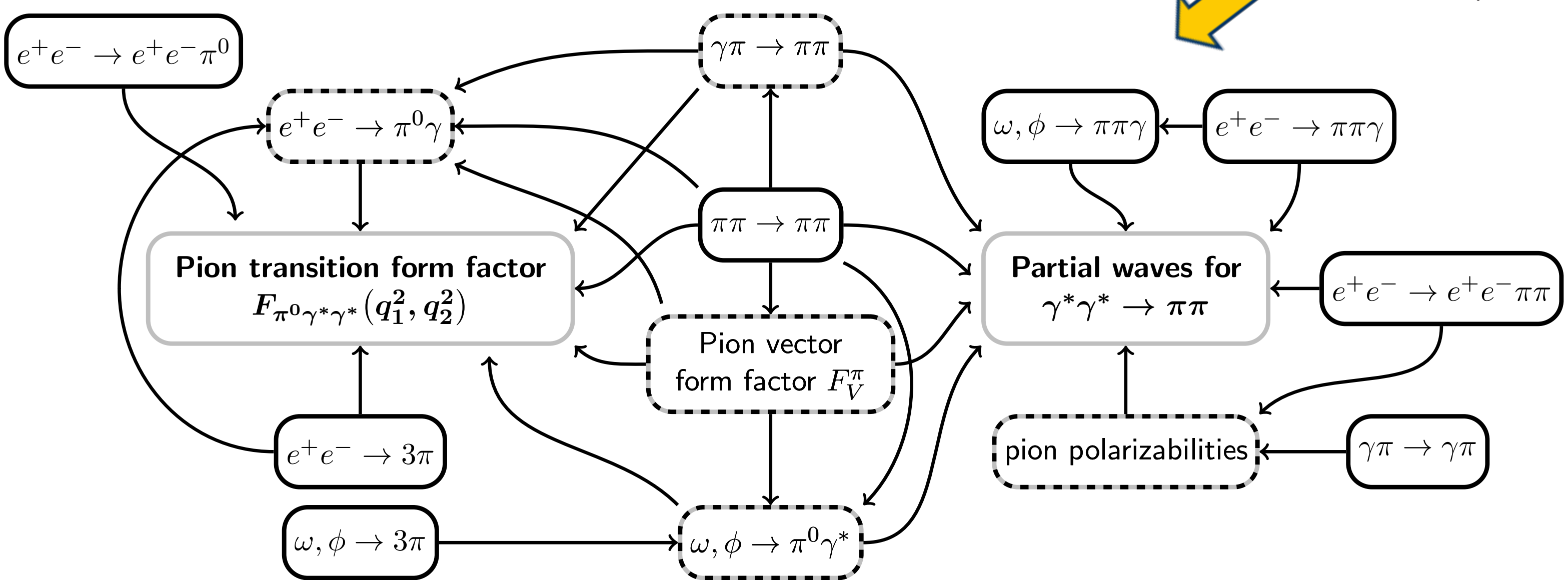
5.4 Towards a model independent determination of HVP and LBL



- For light-by-light scattering: until recently it was believed that dispersion relation approach not possible (4-point function)
  ⇨ only model dependent estimates

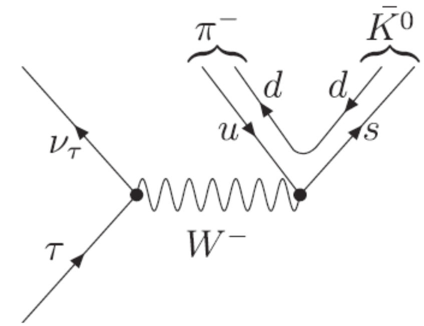
- But recent progress from Bern group: *Colangelo, Hoferichter, Procura, Stoffer'14*
  ⇨ *Data driven* estimate possible using *dispersion relations!*





5. CPV in tau decays

5.1 $\tau \to K\pi\nu_\tau$ CP violating asymmetry



- $$A_Q = \frac{\Gamma\left(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau\right) - \Gamma\left(\tau^- \to \pi^- K_S^0 \nu_\tau\right)}{\Gamma\left(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau\right) + \Gamma\left(\tau^- \to \pi^- K_S^0 \nu_\tau\right)}$$

$$= |p|^2 - |q|^2 \approx (0.36 \pm 0.01)\%$$ in the SM

Bigi & Sanda'05

Grossman & Nir'11

$$|K_S^0\rangle = p|K^0\rangle + q|\overline{K}^0\rangle$$

$$|K_L^0\rangle = p|K^0\rangle - q|\overline{K}^0\rangle$$

$$\langle K_L | K_S \rangle = |p|^2 - |q|^2 \simeq 2\,\mathrm{Re}(\varepsilon_K)$$

- Experimental measurement : *BaBar'11*

$$A_{Q\,\mathrm{exp}} = \left(-0.36 \pm 0.23_{\mathrm{stat}} \pm 0.11_{\mathrm{syst}}\right)\%$$ ⇒ 2.8σ from the SM!

- CP violation in the tau decays should be of opposite sign compared to the one in D decays in the SM

Grossman & Nir'11

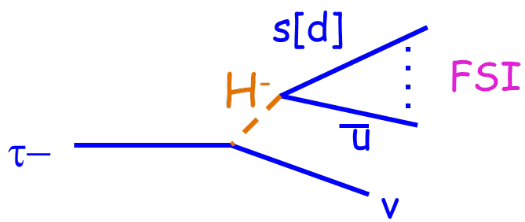
$$A_D = \frac{\Gamma\left(D^+ \to \pi^+ K_S^0\right) - \Gamma\left(D^- \to \pi^- K_S^0\right)}{\Gamma\left(D^+ \to \pi^+ K_S^0\right) + \Gamma\left(D^- \to \pi^- K_S^0\right)} = (-0.54 \pm 0.14)\%$$

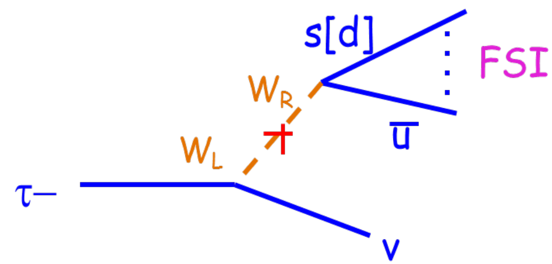
Belle, Babar, CLOE, FOCUS

5.1 $\tau \rightarrow K\pi\nu_\tau$ CP violating asymmetry

- New physics? Charged Higgs, W_L-W_R mixings, leptoquarks, tensor interactions (*Devi, Dhargyal, Sinha'14*)?

Bigi'Tau12





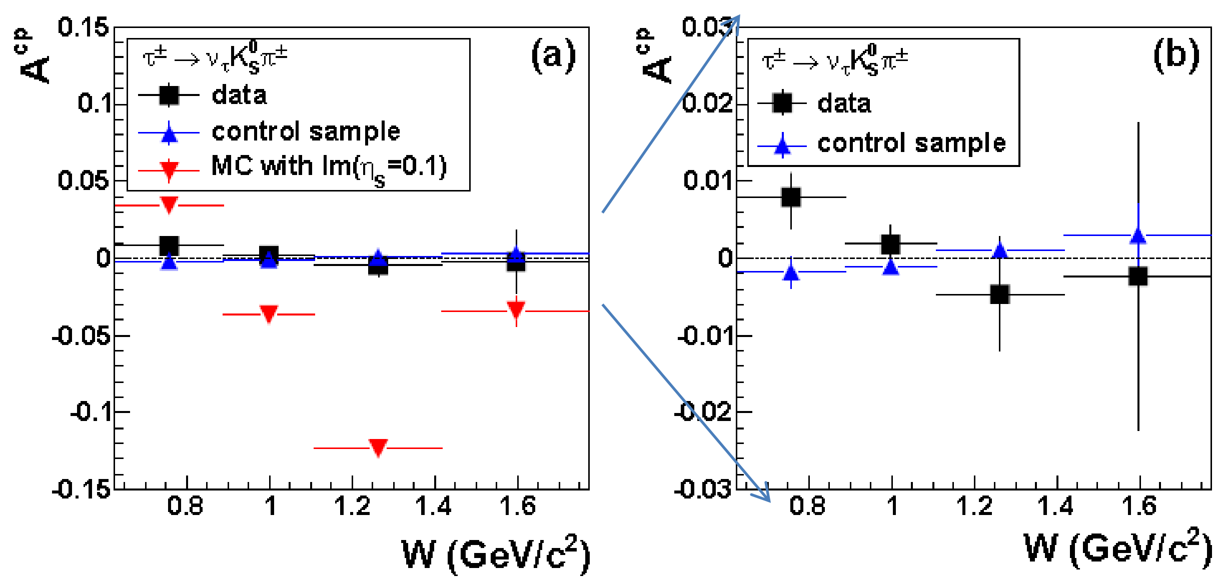
Very difficult to explain!

- Problem with this measurement? ⇨ It would be great to have other experimental measurements from *Belle, BES III or Tau-Charm factory*

Belle'11

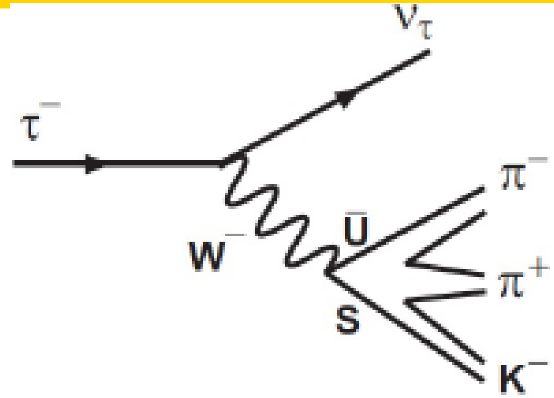
- Measurement of the direct contribution of NP in the angular CP violating asymmetry done by *CLEO* and *Belle*

  ⇨ Belle does not see any asymmetry at the *0.2 - 0.3% level*



5.2 Three body CP asymmetries

- Ex: $\tau \to K\pi\pi\nu_\tau$



- A variety of CPV observables can be studied :
  $\tau \to K\pi\pi\nu_\tau, \tau \to \pi\pi\pi\nu_\tau$ rate, angular asymmetries, triple products,….

  Same principle as in charm, *see Bevan'15*

  Difficulty : Treatement of the hadronic part
  Hadronic final state interactions have to be taken into account!
  ⇒ Disentangle weak and strong phases

e.g., Choi, Hagiwara and Tanabashi'98
Kiers, Little, Datta, London et al.,'08
Mileo, Kiers and, Szynkman'14

- More form factors, more asymmetries to build but same principles as for 2 bodies

Lepton universality - HFAG 2016 prelim.

Standard Model for leptons λ, $\rho = e, \mu, \tau$ (Marciano 1988)

$$\Gamma[\lambda \to \nu_\lambda \rho \overline{\nu}_\rho(\gamma)] = \Gamma_{\lambda\rho} = \Gamma_\lambda B_{\lambda\rho} = \frac{B_{\lambda\rho}}{\tau_\lambda} = \frac{G_\lambda G_\rho m_\lambda^5}{192\pi^3} f\left(\frac{m_\rho^2}{m_\lambda^2}\right) r_W^\lambda r_\gamma^\lambda ,$$

where

$$G_\lambda = \frac{g_\lambda^2}{4\sqrt{2}M_W^2} \qquad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x \qquad f_{\lambda\rho} = f\left(\frac{m_\rho^2}{m_\lambda^2}\right)$$

$$r_W^\lambda = 1 + \frac{3}{5}\frac{m_\lambda^2}{M_W^2} \qquad r_\gamma^\lambda = 1 + \frac{\alpha(m_\lambda)}{2\pi}\left(\frac{25}{4} - \pi^2\right)$$

Tests of lepton universality from ratios of above partial widths:

$$\left(\frac{g_\tau}{g_\mu}\right) = \sqrt{\frac{B_{\tau e}}{B_{\mu e}} \frac{\tau_\mu m_\mu^5 f_{\mu e} r_W^\mu r_\gamma^\mu}{\tau_\tau m_\tau^5 f_{\tau e} r_W^\tau r_\gamma^\tau}} = 1.0012 \pm 0.0015 = \sqrt{\frac{B_{\tau e}}{B_{\tau e}^{SM}}}$$

$$\left(\frac{g_\tau}{g_e}\right) = \sqrt{\frac{B_{\tau \mu}}{B_{\mu e}} \frac{\tau_\mu m_\mu^5 f_{\mu e} r_W^\mu r_\gamma^\mu}{\tau_\tau m_\tau^5 f_{\tau \mu} r_W^\tau r_\gamma^\tau}} = 1.0030 \pm 0.0014 = \sqrt{\frac{B_{\tau \mu}}{B_{\tau \mu}^{SM}}}$$

$$\left(\frac{g_\mu}{g_e}\right) = \sqrt{\frac{B_{\tau \mu}}{B_{\tau e}} \frac{f_{\tau e}}{f_{\tau \mu}}} = 1.0019 \pm 0.0014$$

- precision: **0.20—0.23%** pre-B-Factories $\Rightarrow$ **0.14—0.15%** today
  thanks essentially to the Belle tau lifetime measurement, PRL 112 (2014) 031801
- $r_\gamma^\tau = 1 - 43.2 \cdot 10^{-4}$ and $r_\gamma^\mu = 1 - 42.4 \cdot 10^{-4}$ (Marciano 1988), M_W from PDG 2013

Universality improved $B(\tau \to e\nu\bar{\nu})$ and R_{had} - HFAG 2016 prelim.

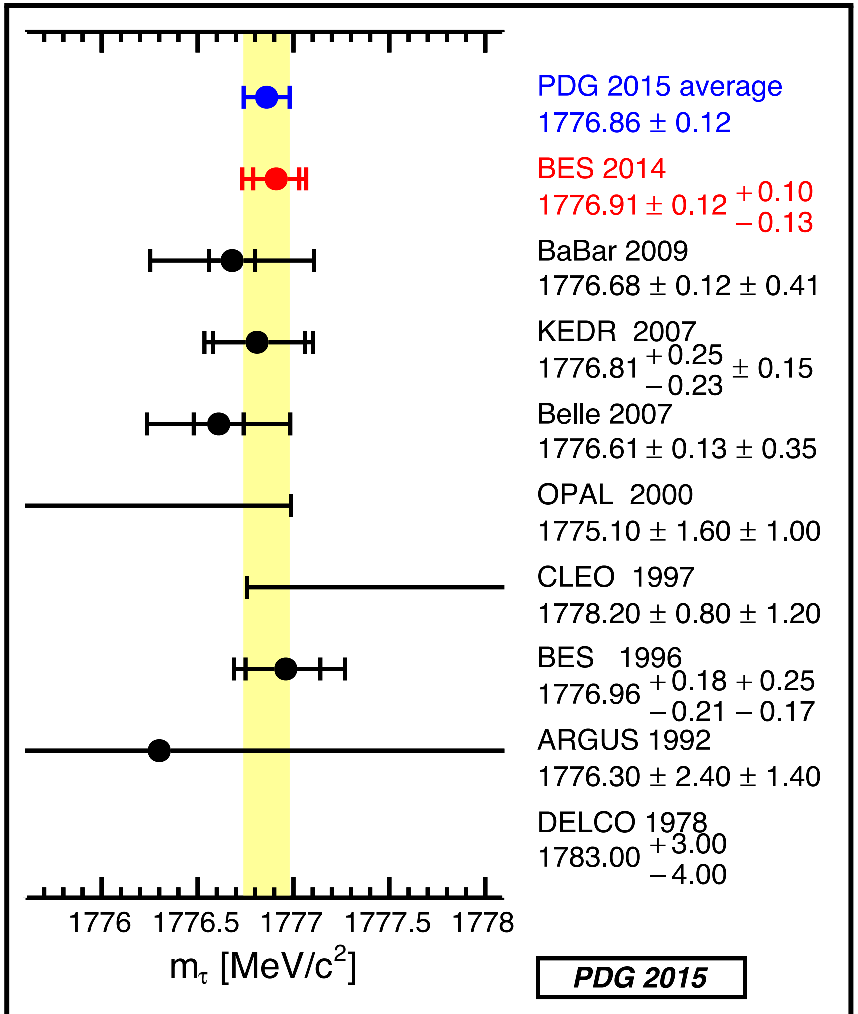
Universality improved $B(\tau \to e\nu\bar{\nu})$

- (M. Davier, 2005): assume SM lepton universality to improve $B_e = B(\tau \to e\bar{\nu}_e\nu_\tau)$ fit B_e using three determinations:
  - $B_e = B_e$
  - $B_e = B_\mu \cdot f(m_e^2/m_\tau^2)/f(m_\mu^2/m_\tau^2)$
  - $B_e = B(\mu \to e\bar{\nu}_e\nu_\mu) \cdot (\tau_\tau/\tau_\mu) \cdot (m_\tau/m_\mu)^5 \cdot f(m_e^2/m_\tau^2)/f(m_e^2/m_\mu^2) \cdot (\delta_\gamma^\tau \delta_W^\tau)/(\delta_\gamma^\mu \delta_W^\mu)$ [above we have: $B(\mu \to e\bar{\nu}_e\nu_\mu) = 1$]
- $\boldsymbol{B_e^{\text{univ}} = (17.818 \pm 0.022)\%}$ HFAG-PDG 2016 prelim. fit

$R_{\text{had}} = \Gamma(\tau \to \text{hadrons})/\Gamma_{\text{univ}}(\tau \to e\nu\bar{\nu})$

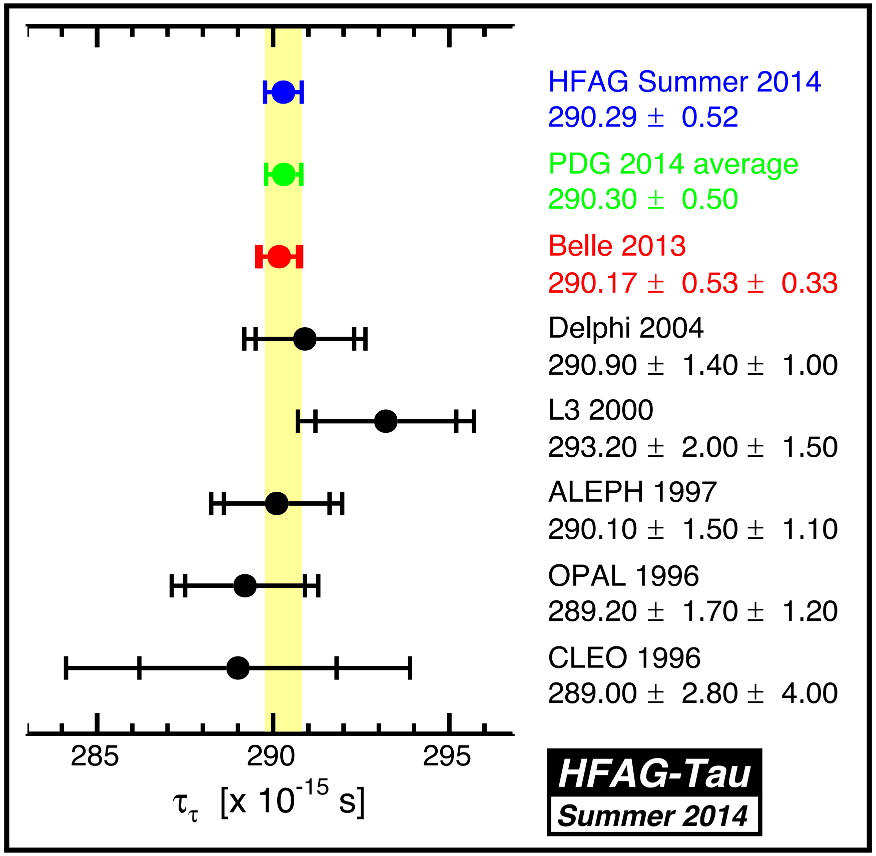
- $$R_{\text{had}} = \frac{\Gamma(\tau \to \text{hadrons})}{\Gamma_{\text{univ}}(\tau \to e\nu\bar{\nu})} = \frac{B_{\text{hadrons}}}{B_e^{\text{univ}}} = \frac{1 - B_e^{\text{univ}} - f(m_\mu^2/m_\tau^2)/f(m_e^2/m_\tau^2) \cdot B_e^{\text{univ}}}{B_e^{\text{univ}}}$$
  - two different determinations, second one not “contaminated” by hadronic BFs
- $\boldsymbol{R_{\text{had}} = 3.6359 \pm 0.0074}$ HFAG-PDG 2016 prelim. fit
- $\boldsymbol{R_{\text{had}}\text{(leptonic BFs only)} = 3.6397 \pm 0.0070}$ HFAG-PDG 2016 prelim. fit

Tau mass



- most precise measurements by **e^+e^- colliders at $\tau^+\tau^-$ threshold**
  - few events but very significant

Tau lifetime

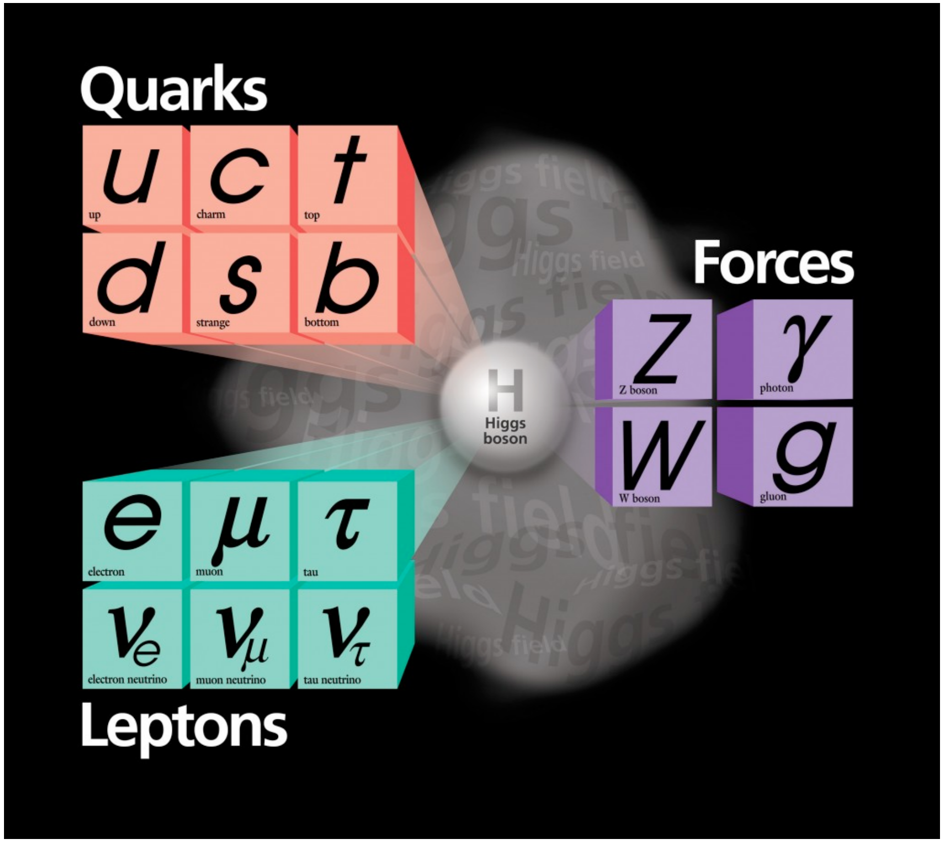


- LEP experiments, many methods
  - impact parameter sum (IPS)
  - momentum dependent impact parameter sum (MIPS
  - 3D impact parameter sum (3DIP)
  - impact parameter difference (IPD)
  - decay length (DL)
- Belle
  - 3-prong vs. 3-prong decay length
  - largest syst. error: alignment

1.1 The triumph of the Standard Model

- New era in particle physics :
  ➡ (unexpected) *success of the Standard Model*: a successful theory of microscopic phenomena with *no intrinsic energy limitation*

- Relies on

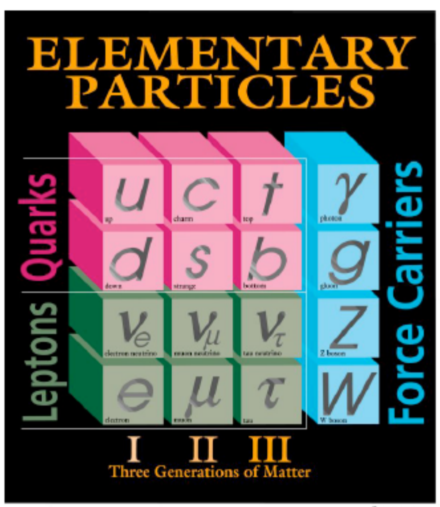


1.2 Quest for New Physics

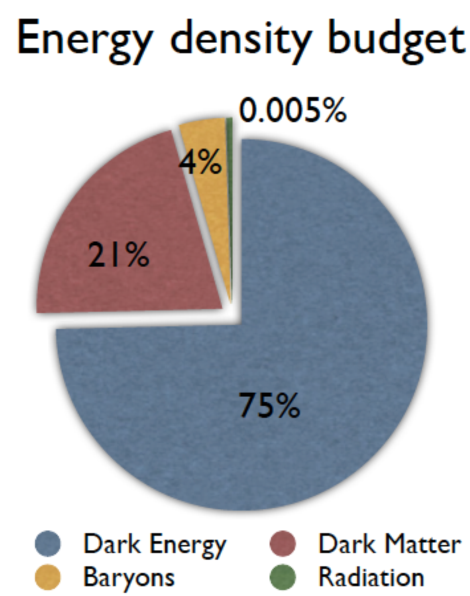
- *Shall we continue to test the Standard Model and search for New Physics?*

  Yes! ⇨ Despite its phenomenological successes, the SM has some *deep unsolved* problems:
  - hierarchy problem
  - flavour pattern
  - dark-matter, etc.…

Strong interaction not so well understood: confinement, etc



+ Higgs boson



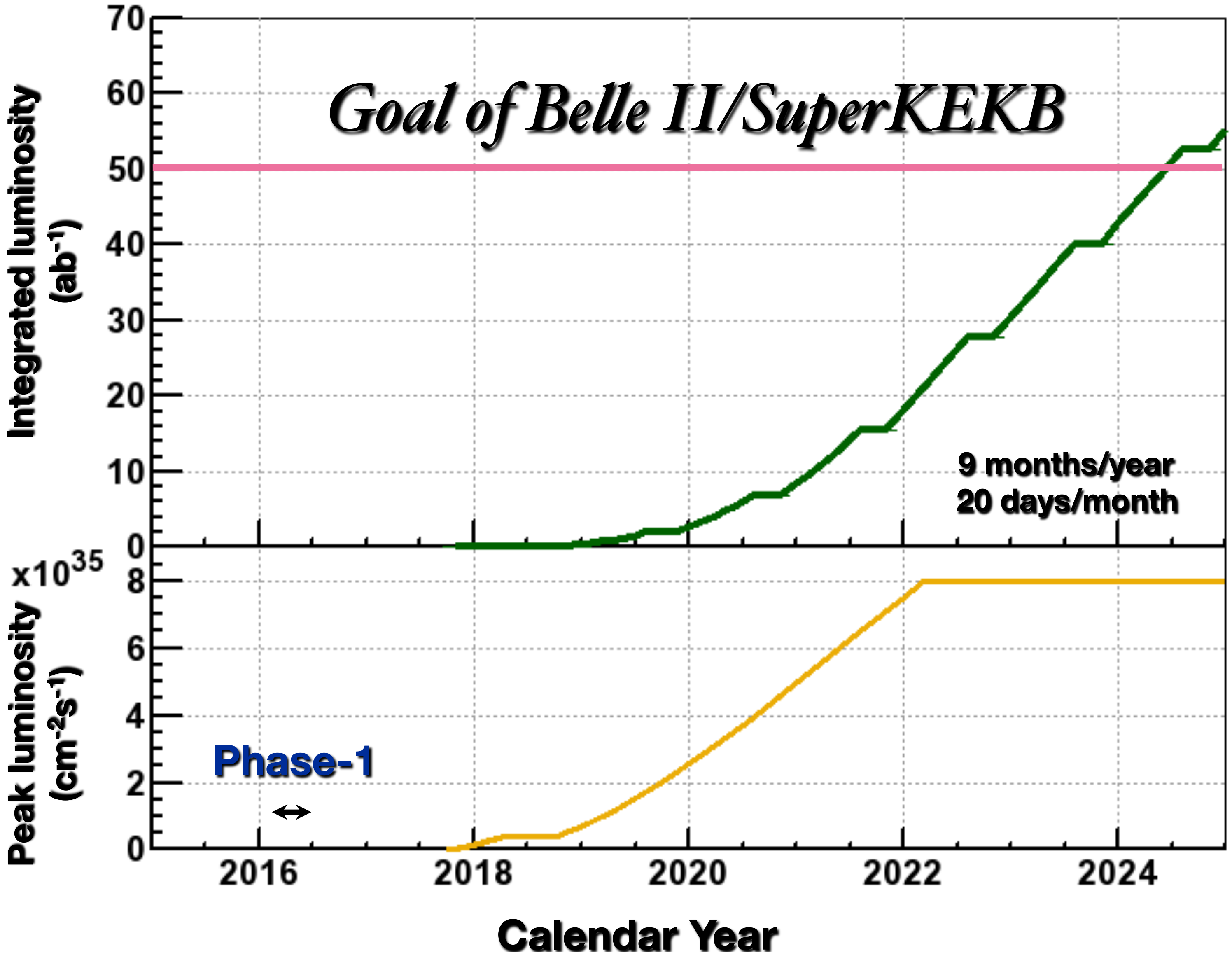
1.1 The triumph of the Standard Model

- New era in particle physics :
  ⇨ (unexpected) *success of the Standard Model*: a successful theory of microscopic phenomena with *no intrinsic energy limitation*

- Key results at LHC after run I + beginning of run II
  - *The Higgs boson* (last missing piece of the SM) has been found:
    ⇨ it looks very standard
  - The Higgs boson is "*light*" (m_h ~ 125 GeV → not the heaviest SM particle)
  - *No* "*mass-gap*" above the SM spectrum (i.e. no unambiguous sign of NP up to ~ 1 TeV)

- *Was this unexpected*?
  Not really! ⇨ *Consistent* with (pre-LHC) indications coming from indirect NP searches (*EWPO* + *flavour physcs*)

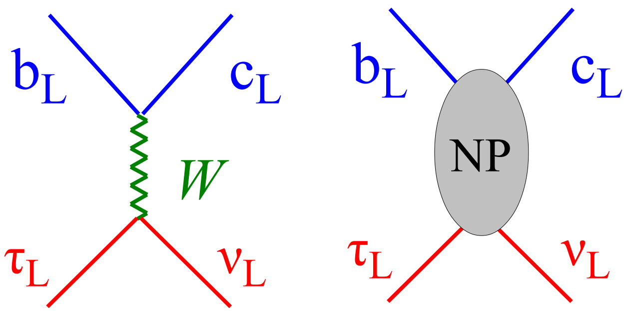
1.4 Belle II expectations

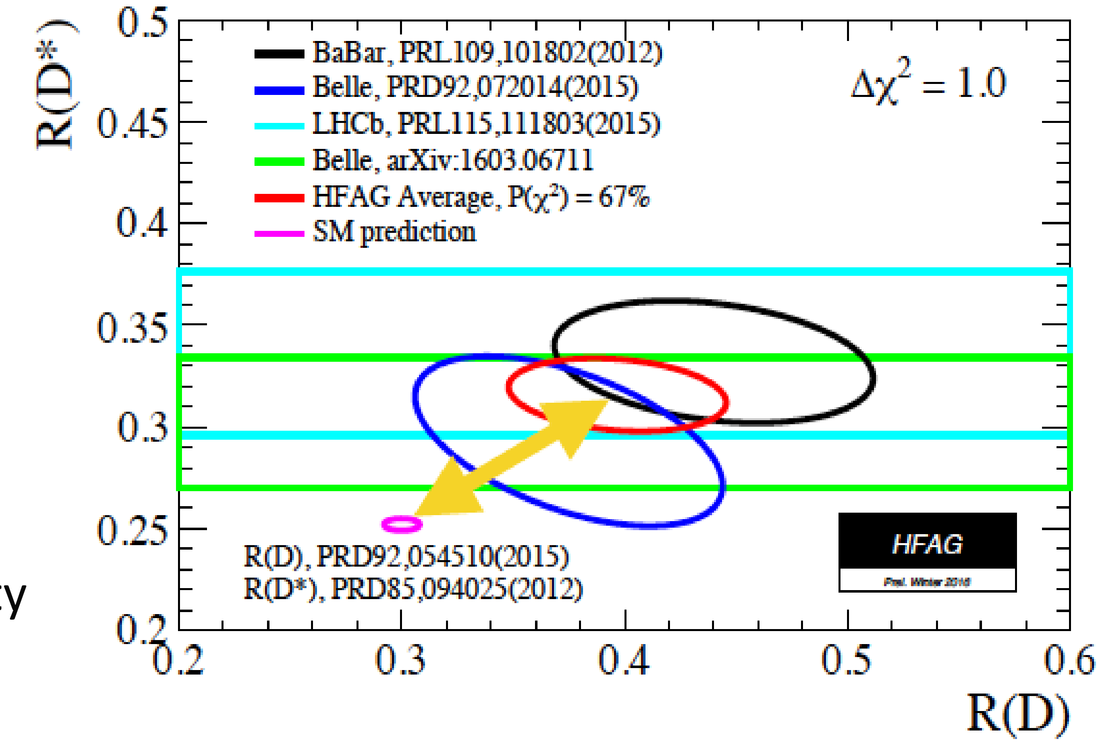


3.2 Lepton universality & NP

- A renewed interest in possible violations of LFU has been triggered by two very different sets of observations in B physics:
  1. LFU test in b → c charged currents: τ vs. light leptons (μ, e) :

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}$$





SM prediction solid: f.f. uncertainty cancels (to a good extent...) in the ratio

Consistent results by 3 different exps ⇒ 4σ excess over SM (combining D and D*)

3.2 Lepton universality & NP

- A renewed interest in possible violations of LFU has been triggered by two very different sets of observations in B physics:

  2. LFU test in b → s neutral currents: μ vs. e :

$$R_K = \frac{\mathrm{Br}[B^+ \to K^+ \mu^+ \mu^-]_{[1,6]}}{\mathrm{Br}[B^+ \to K^+ e^+ e^-]_{[1,6]}} = 0.745 \cdot (1 \pm 13\%)$$

vs $R_K^{\mathrm{SM}} = 1.003 \pm 0.0001$

LHCb'14

2.6σ deviation from the SM

$$R_H = \frac{\int \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B \to He^+e^-)}{dq^2}\, dq^2}$$

2. LFU test in b → s neutral currents: μ vs. e :

$R_{K*} = \mathbf{Br}(B \to K^* \mu\mu)/\mathbf{Br}(B \to K^* ee)$ **anomaly'**

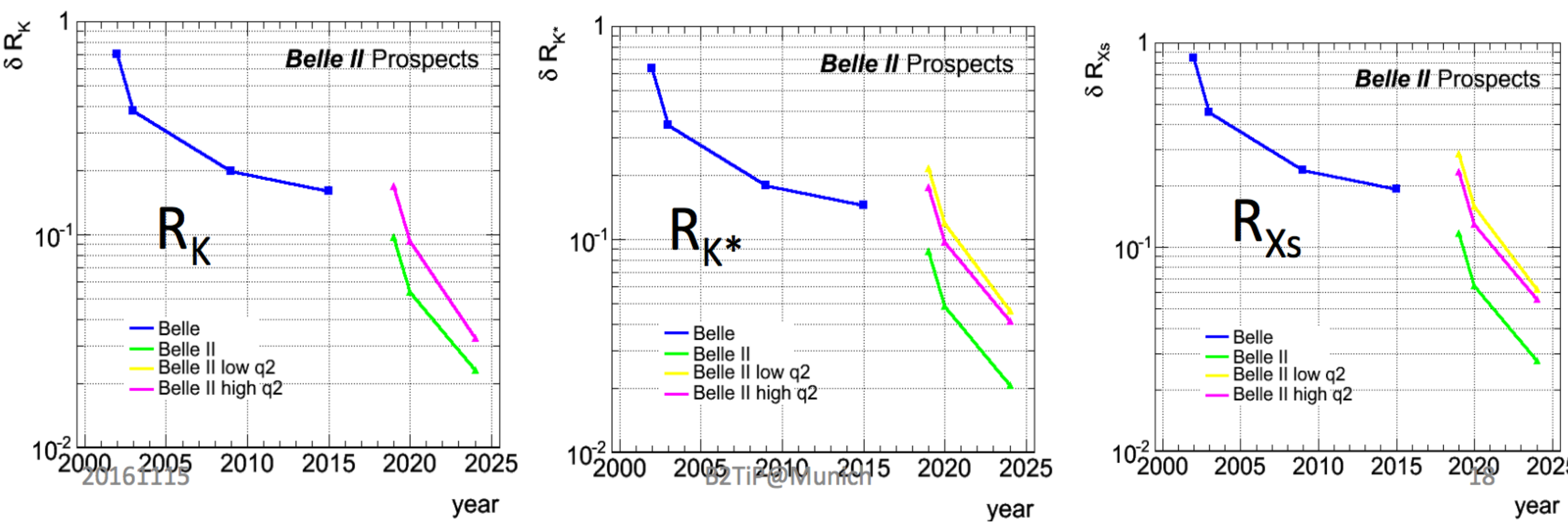
S. Bifani, LHCb@CERN'17

LHCb Preliminary	low-q^2	central-q^2
$\mathcal{R}_{K^{*0}}$	$0.660\ ^{+\ 0.110}_{-\ 0.070} \pm 0.024$	$0.685\ ^{+\ 0.113}_{-\ 0.069} \pm 0.047$
95% CL	[0.517–0.891]	[0.530–0.935]
99.7% CL	[0.454–1.042]	[0.462–1.100]

- Compatibility with SM 2.2-2.4σ (low-q^2) 2.4-2.5σ (central-q^2)

3.2 Lepton universality & NP

Observables	Belle 0.7 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_{X_s} $(1 < q^2 < 6\ \text{GeV}^2)$	32%	12%	4.0%
R_{X_s} $(q^2 > 14.4\ \text{GeV}^2)$	28%	11%	3.4%
R_K $(1 < q^2 < 6\ \text{GeV}^2)$	28%	11%	3.6%
R_K $(q^2 > 14.4\ \text{GeV}^2)$	30%	12%	3.6%
R_{K^*} $(1 < q^2 < 6\ \text{GeV}^2)$	38%	15%	4.6%
R_{K^*} $(q^2 > 14.4\ \text{GeV}^2)$	24%	9.2%	3.4%



3.3 Tau LFV

- In New Physics scenarios CLFV can reach observable levels in several channels

Talk by D. Hitlin @ CLFV2013

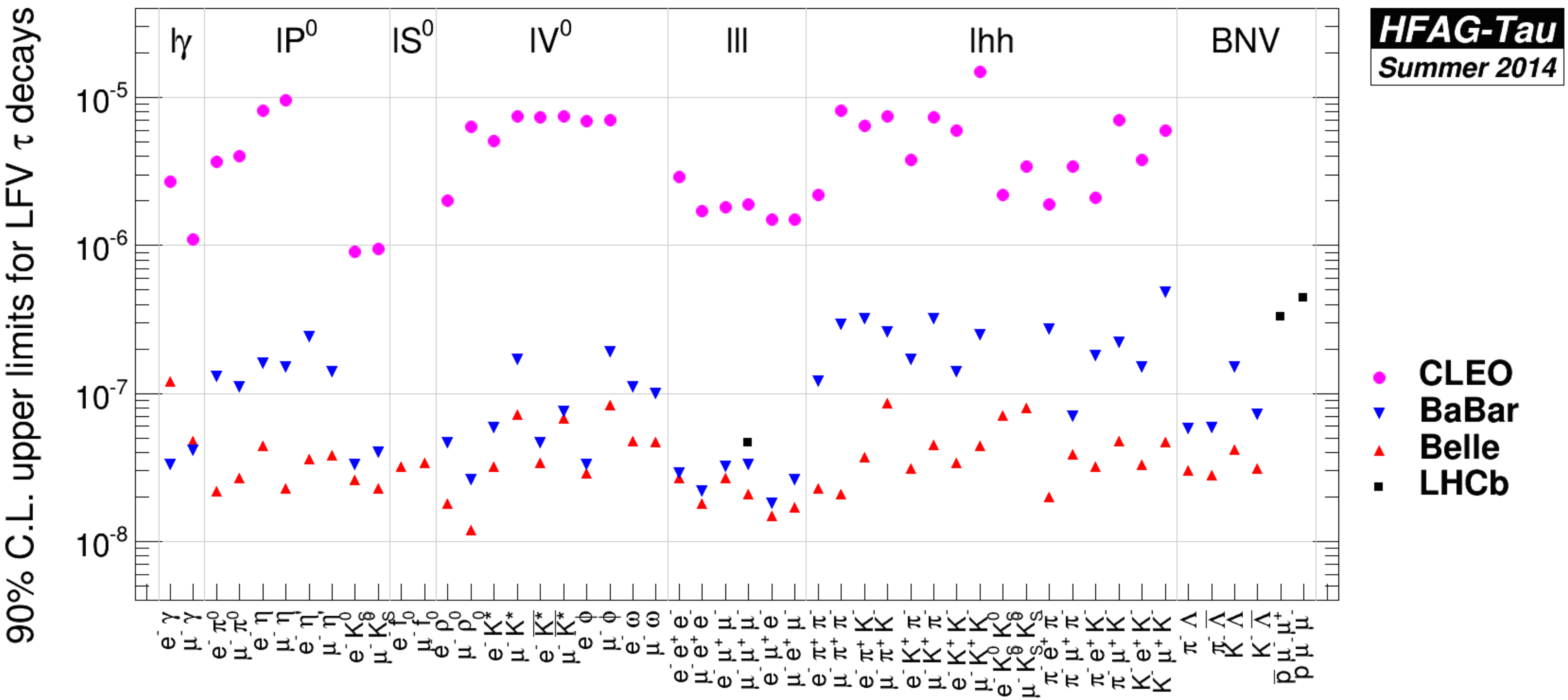
		$\tau \to \mu\gamma$	$\tau \to \ell\ell\ell$
SM + ν mixing	Lee, Shrock, PRD 16 (1977) 1444 Cheng, Li, PRD 45 (1980) 1908	Undetectable	
SUSY Higgs	Dedes, Ellis, Raidal, PLB 549 (2002) 159 Brignole, Rossi, PLB 566 (2003) 517	10^{-10}	10^{-7}
SM + heavy Maj ν_R	Cvetic, Dib, Kim, Kim , PRD66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z'	Yue, Zhang, Liu, PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	Masiero, Vempati, Vives, NPB 649 (2003) 189 Fukuyama, Kikuchi, Okada, PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA + Seesaw	Ellis, Gomez, Leontaris, Lola, Nanopoulos, EPJ C14 (2002) 319 Ellis, Hisano, Raidal, Shimizu, PRD 66 (2002) 115013	10^{-7}	10^{-9}

- But the sensitivity of particular modes to CLFV couplings is model dependent

- Comparison in muonic and tauonic channels of branching ratios, conversion rates and spectra is model-diagnostic

2.2 CLFV processes: tau decays

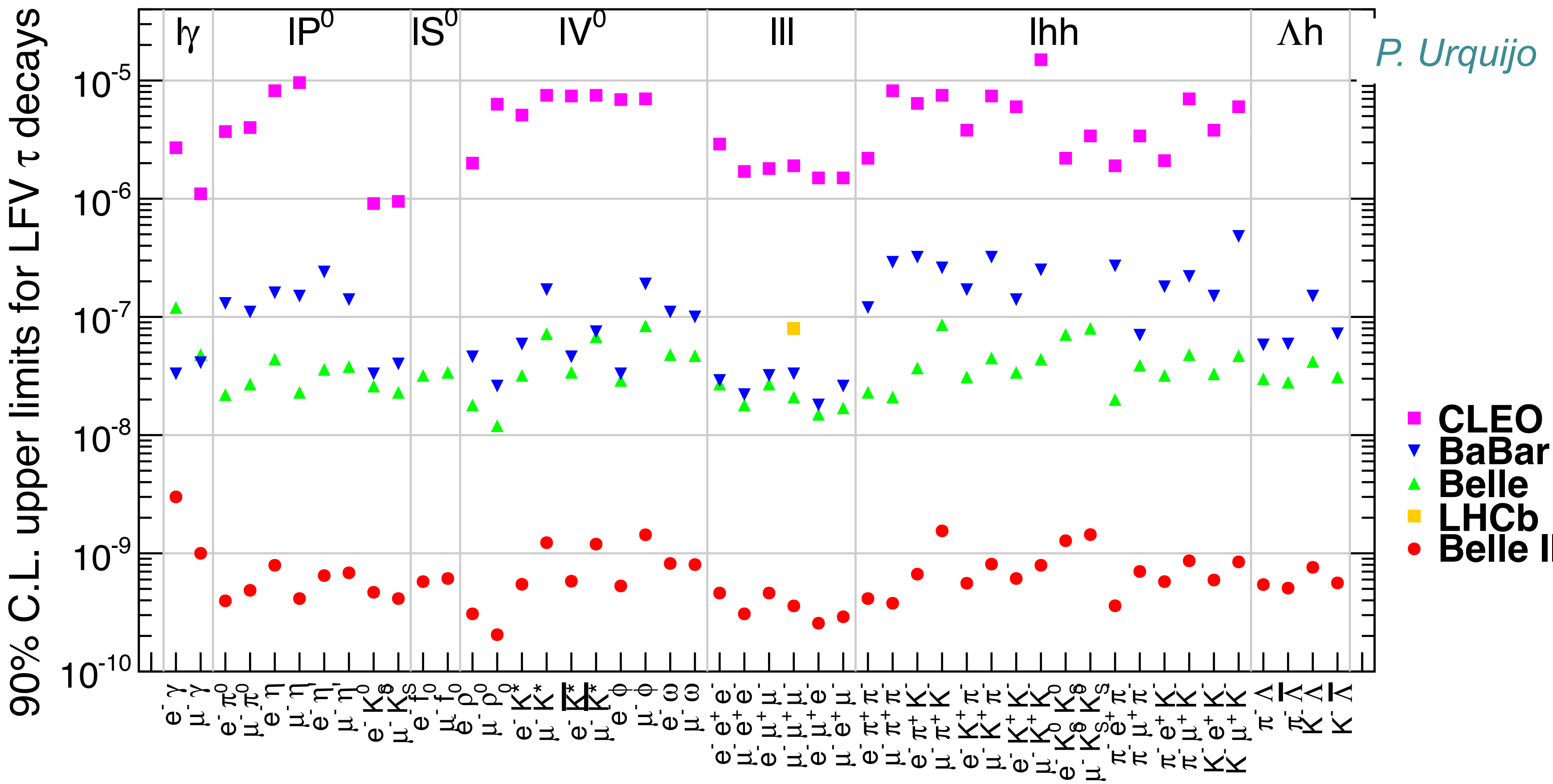
- Several processes: $\tau \to \ell\gamma,\ \tau \to \ell_\alpha \bar{\ell}_\beta \ell_\beta,\ \tau \to \ell Y$ ↖ $P,\ S,\ V,\ P\bar{P}, \ldots$



- 48 LFV modes studied at Belle and BaBar

2.2 CLFV processes: tau decays

- Several processes: $\tau \to \ell\gamma,\ \tau \to \ell_\alpha \bar{\ell}_\beta \ell_\beta,\ \tau \to \ell Y$ $\nwarrow P,\ S,\ V,\ P\bar{P}, \ldots$



P. Urquijo

- Promising prospects at Belle II!

2.3 Effective Field Theory approach

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

See e.g.
Black, Han, He, Sher'02
Brignole & Rossi'04
Dassinger et al.'07
Matsuzaki & Sanda'08
Giffels et al.'08
Crivellin, Najjari, Rosiek'13
Petrov & Zhuridov'14
Cirigliano, Celis, E.P.'14

- Build all D>5 LFV operators:
  - Dipole: $\mathcal{L}_{eff}^{D} \supset -\frac{C_D}{\Lambda^2} m_\tau \bar{\mu}\sigma^{\mu\nu} P_{L,R}\tau F_{\mu\nu}$
  - Lepton-quark (Scalar, Pseudo-scalar, Vector, Axial-vector): $\mathcal{L}_{eff}^{S} \supset -\frac{C_{S,V}}{\Lambda^2} m_\tau m_q G_F \bar{\mu}\,\Gamma P_{L,R}\tau\; \bar{q}\Gamma q$
  - Lepton-gluon (Scalar, Pseudo-scalar): $\mathcal{L}_{eff}^{G} \supset -\frac{C_G}{\Lambda^2} m_\tau G_F \bar{\mu} P_{L,R}\tau\; G_{\mu\nu}^a G_a^{\mu\nu}$
  - 4 leptons (Scalar, Pseudo-scalar, Vector, Axial-vector): $\mathcal{L}_{eff}^{4\ell} \supset -\frac{C_{S,V}^{4\ell}}{\Lambda^2} \bar{\mu}\,\Gamma P_{L,R}\tau\; \bar{\mu}\,\Gamma P_{L,R}\mu$

$\Gamma \equiv 1, \gamma^\mu$

- Each UV model generates a *specific pattern* of them

2.4 Model discriminating power of Tau processes

Celis, Cirigliano, E.P.'14

- Summary table:

	$\tau \to 3\mu$	$\tau \to \mu\gamma$	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K\bar{K}$	$\tau \to \mu\pi$	$\tau \to \mu\eta^{(\prime)}$
$O_{S,V}^{4\ell}$	✓	–	–	–	–	–
O_D	✓	✓	✓	✓	–	–
O_V^q	–	–	✓ (I=1)	✓(I=0,1)	–	–
O_S^q	–	–	✓ (I=0)	✓(I=0,1)	–	–
O_{GG}	–	–	✓	✓	–	–
O_A^q	–	–	–	–	✓ (I=1)	✓ (I=0)
O_P^q	–	–	–	–	✓ (I=1)	✓ (I=0)
$O_{G\tilde{G}}$	–	–	–	–	–	✓

- The notion of "*best probe*" (process with largest decay rate) is *model dependent*

- If observed, compare rate of processes ⇨ key handle on *relative strength* between operators and hence on the *underlying mechanism*

2.6 Model discriminating of BRs

- Studies in specific models *Buras et al.'10*

ratio	LHT	MSSM (dipole)	MSSM (Higgs)	SM4
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots 1$	$\sim 6\cdot 10^{-3}$	$\sim 6\cdot 10^{-3}$	$0.06\ldots 2.2$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots 0.4$	$\sim 1\cdot 10^{-2}$	$\sim 1\cdot 10^{-2}$	$0.07\ldots 2.2$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots 0.4$	$\sim 2\cdot 10^{-3}$	$0.06\ldots 0.1$	$0.06\ldots 2.2$
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots 0.3$	$\sim 2\cdot 10^{-3}$	$0.02\ldots 0.04$	$0.03\ldots 1.3$
$\frac{Br(\tau^-\to \mu^-e^+e^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots 0.3$	$\sim 1\cdot 10^{-2}$	$\sim 1\cdot 10^{-2}$	$0.04\ldots 1.4$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots 2$	~ 5	$0.3\ldots 0.5$	$1.5\ldots 2.3$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots 1.6$	~ 0.2	$5\ldots 10$	$1.4\ldots 1.7$
$\frac{R(\mu Ti\to e Ti)}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots 10^{2}$	$\sim 5\cdot 10^{-3}$	$0.08\ldots 0.15$	$10^{-12}\ldots 26$

⇨ Disentangle the *underlying dynamics* of NP

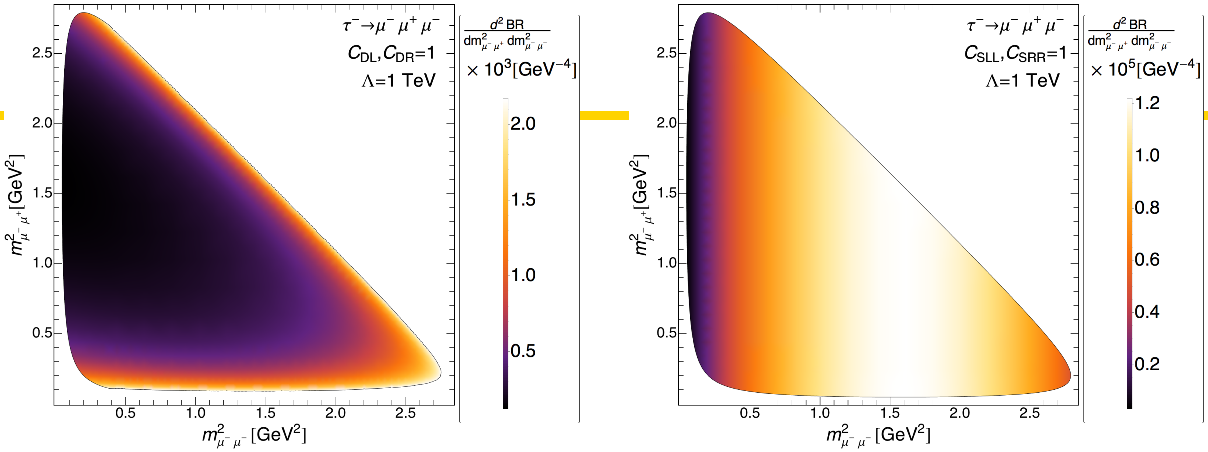


Figure 3: *Dalitz plot for $\tau^- \to \mu^-\mu^+\mu^-$ decays when all operators are assumed to vanish with the exception of $C_{DL,DR} = 1$ (left) and $C_{SLL,SRR} = 1$ (right), taking $\Lambda = 1$ TeV in both cases. Colors denote the density for $d^2BR/(dm^2_{\mu^-\mu^+} dm^2_{\mu^-\mu^-})$, small values being represented by darker colors and large values in lighter ones. Here $m^2_{\mu^-\mu^+}$ represents m^2_{12} or m^2_{23}, defined in Sec. 3.1.*

Dassinger, Feldman, Mannel, Turczyk' 07
Celis, Cirigliano, E.P.'14

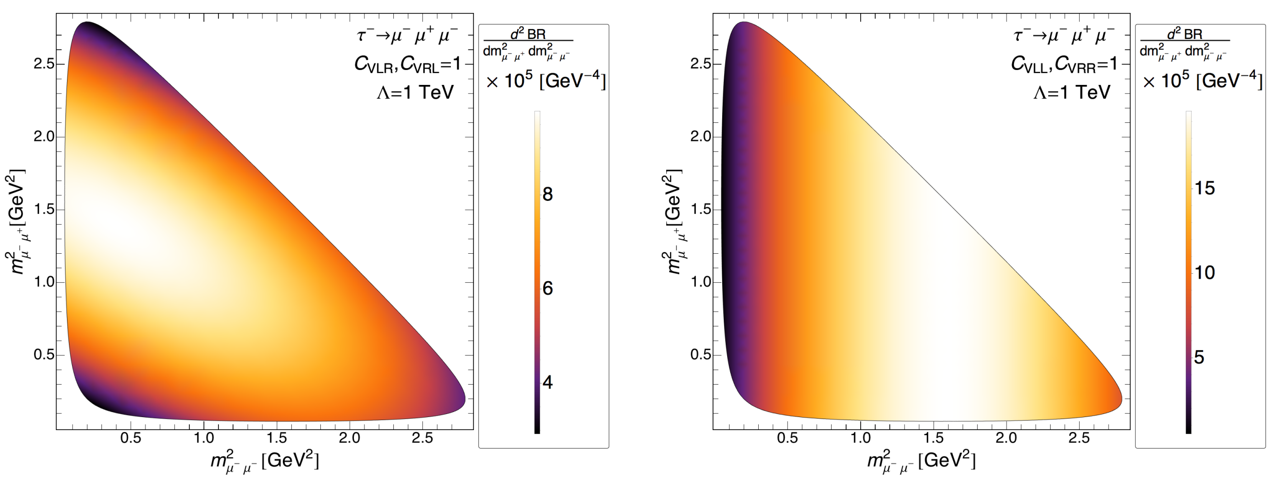


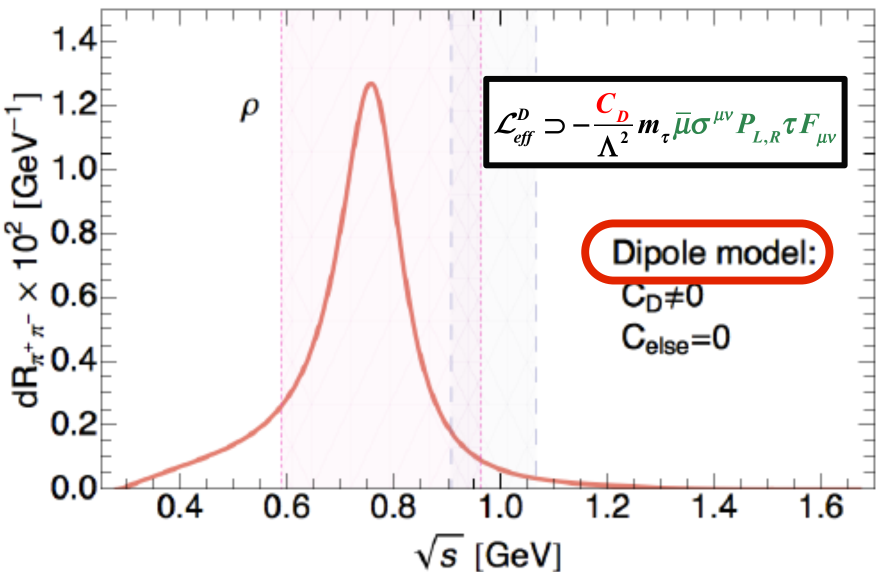
Figure 4: *Dalitz plot for $\tau^- \to \mu^-\mu^+\mu^-$ decays when all operators are assumed to vanish with the exception of $C_{VRL,VLR} = 1$ (left) and $C_{VLL,VRR} = 1$ (right), taking $\Lambda = 1$ TeV in both cases. Colors are defined as in Fig. 3.*

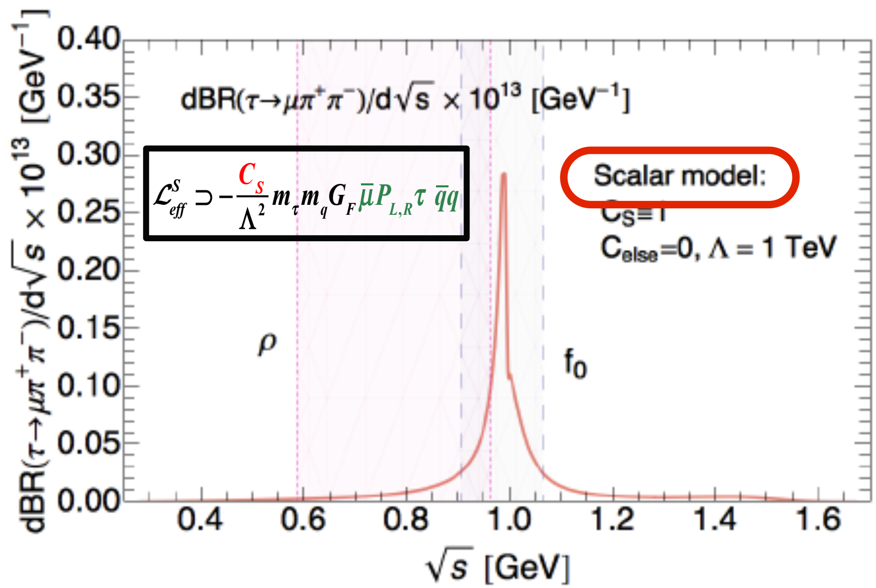
Angular analysis with polarized taus

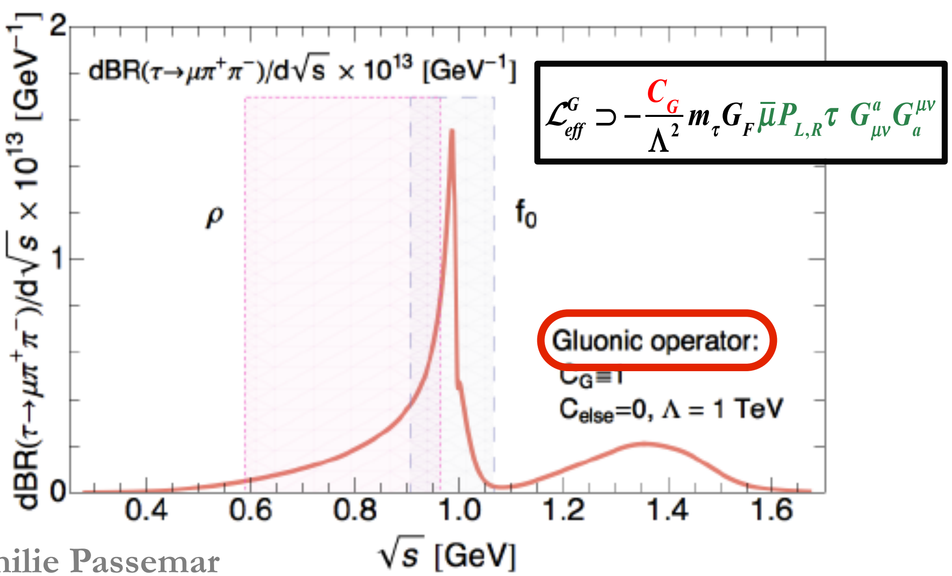
Dassinger, Feldman, Mannel, Turczyk' 07

2.7 Model discriminating of Spectra: $\tau \to \mu\pi\pi$

Celis, Cirigliano, E.P.'14







Very different distributions according to the *final hadronic state!*

NB: See also Dalitz plot analyses for $\tau \to \mu\mu\mu$

Dassinger et al.'07