Theory

(flavour and lattice)

the latest news

Aoife Bharucha, CPT Marseille

Séminaire thématique GT01 "Physique des particules"

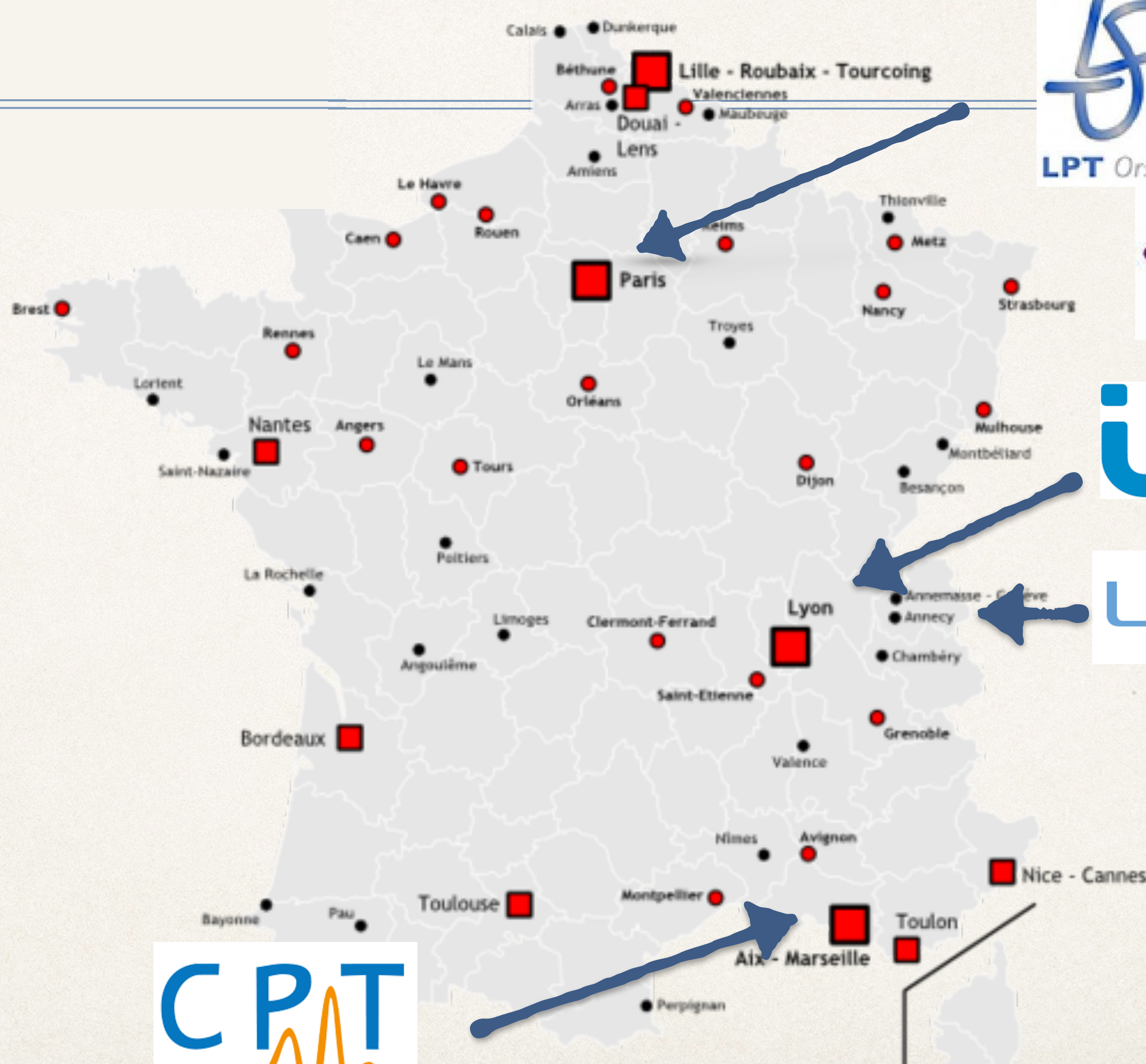
Prospectives nationales 2020-2030.

13/3/2020

Overview

- Neutral currents searches for BSM
- Charged currents/ high precision CKM
- $(g\text{-}2)_\ell$
- Further Lattice QCD activities

Neutral current BSM searches



LPT Orsay

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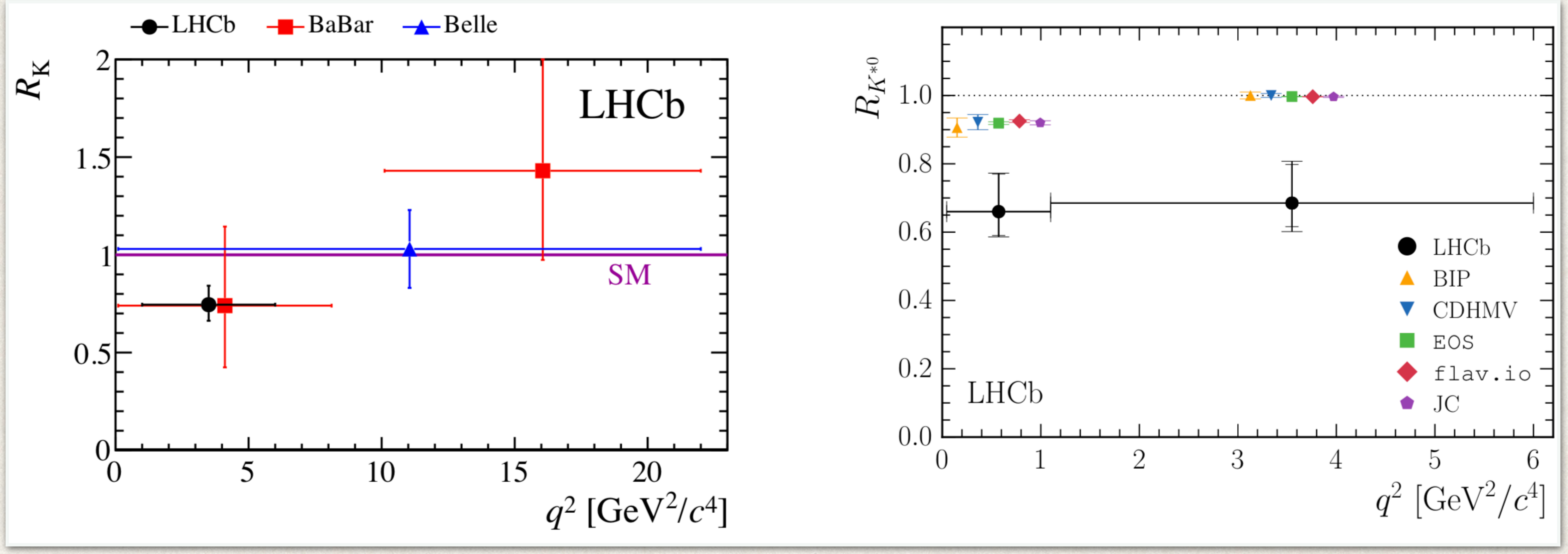
History of the anomalies part I:

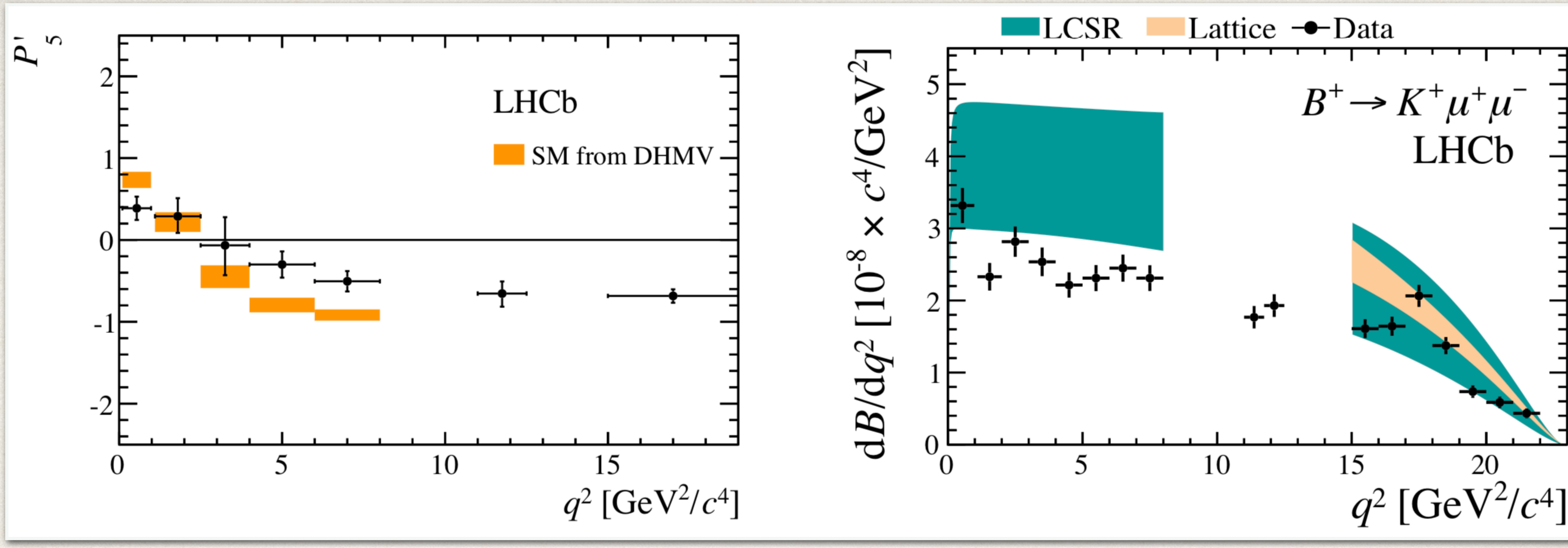
Several LHCb measurements deviate from Standard model (SM) predictions by 2-3σ

Measurements of lepton flavour universality (LFU) ratios R_K and R_{K^*} showed deviations from SM by about 2.5σ each.

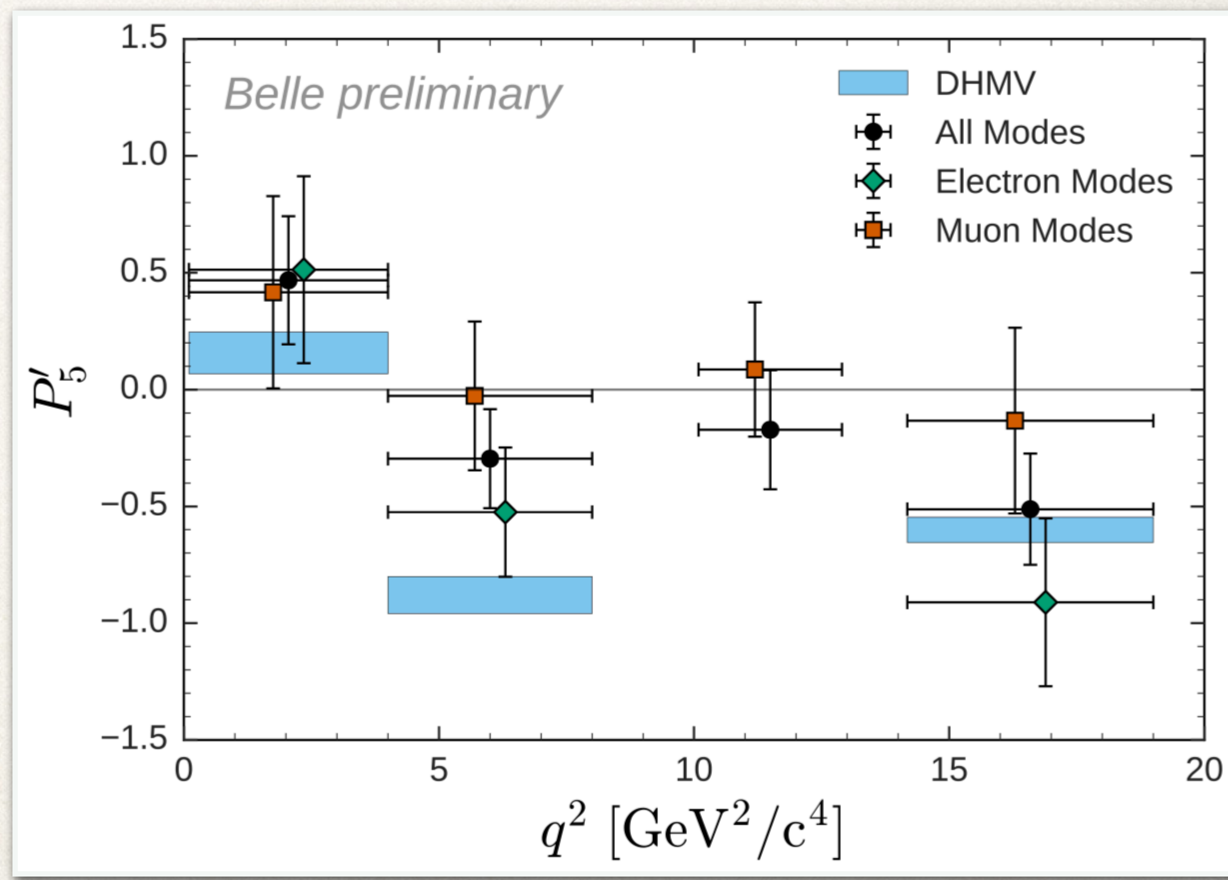
[LHCb arXiv:1406.6482, arXiv:1705.05802]

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$





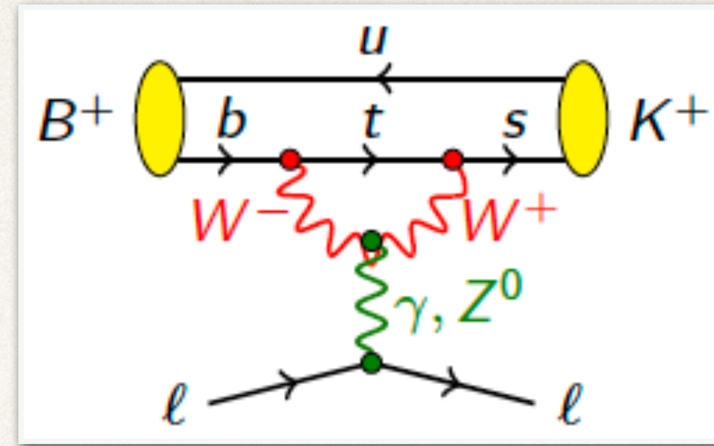
- Angular observable $P_{5'}$ in $B \to K^*\mu^+\mu^-$:
  - 2013: 1fb^{-1} LHCb found 3.7σ.
  - 2015: 3fb^{-1} LHCb found 3σ in 2 bins [arXiv: 1512.04442]
  - 2016: Belle found a similar result in the bin



- LHCb found several tensions in the Branching ratios of $B \to K^{(*)}\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$ [arXiv: 1403.8044, arXiv:1506.08777, arXiv:1606.04731]

Introduction to FCNC processes

$B \to K\, l^+ l^-$

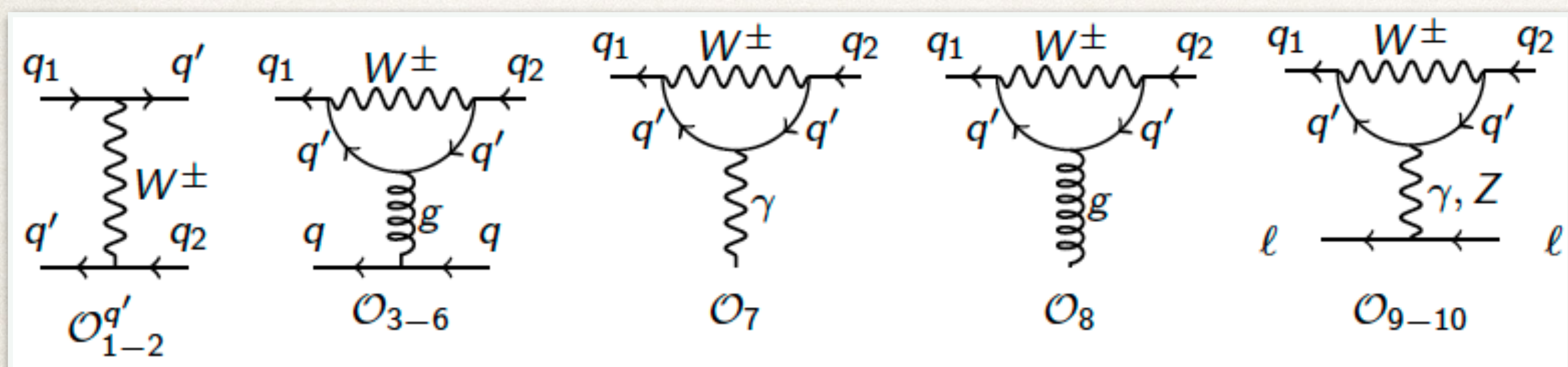


$$d\Gamma \propto \underbrace{\left|\langle K^* \ell\ell | \mathcal{H} | B\rangle\right|^2}_{\text{decay amplitude}} \overbrace{d\Phi}^{\text{phase space factor}}$$

$$\langle K^* \ell\ell | \mathcal{H} | B\rangle \sim \langle K^* \ell\ell | \mathcal{H}_{\text{eff}} | B\rangle = \frac{G_F}{\sqrt{2}} \sum_i \mathcal{C}_i \underbrace{\langle K^* \ell\ell | \mathcal{O}_i | B\rangle}_{\text{matrix element}}$$

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_i \mathcal{C}_i \mathcal{O}_i$$

Operator basis:



Focus on:

$$\mathcal{O}_{9\ell} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

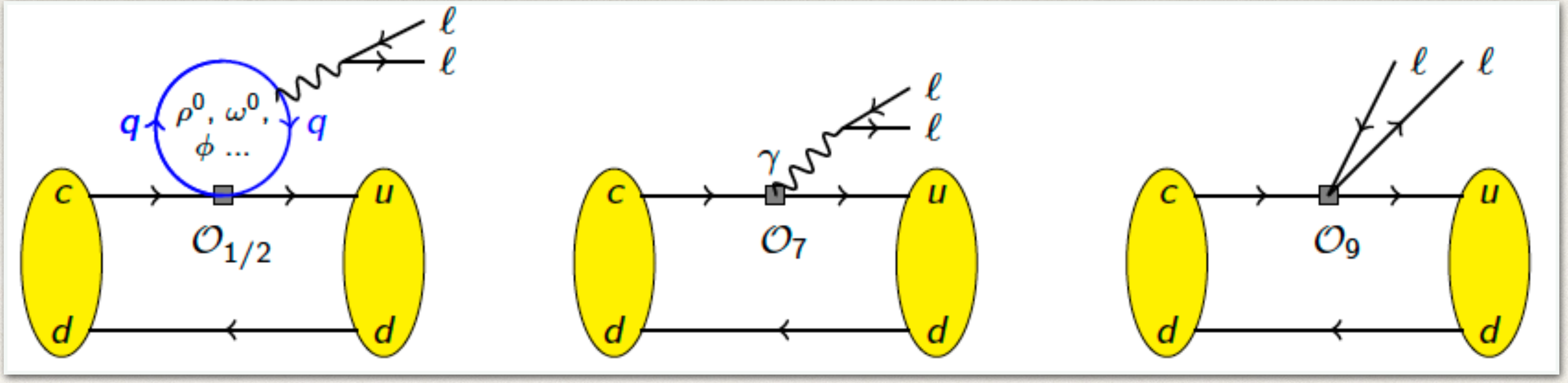
$$\mathcal{O}_{10\ell} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

Factorization:

$$\langle \ell\ell K^* | \mathcal{O}_i | B\rangle \sim \langle \ell\ell | j_\ell | 0\rangle \cdot \underbrace{\langle K^* | j_q | B\rangle}_{FF(q^2)} + \textbf{Resonances} + \textbf{QCDf corrections}$$

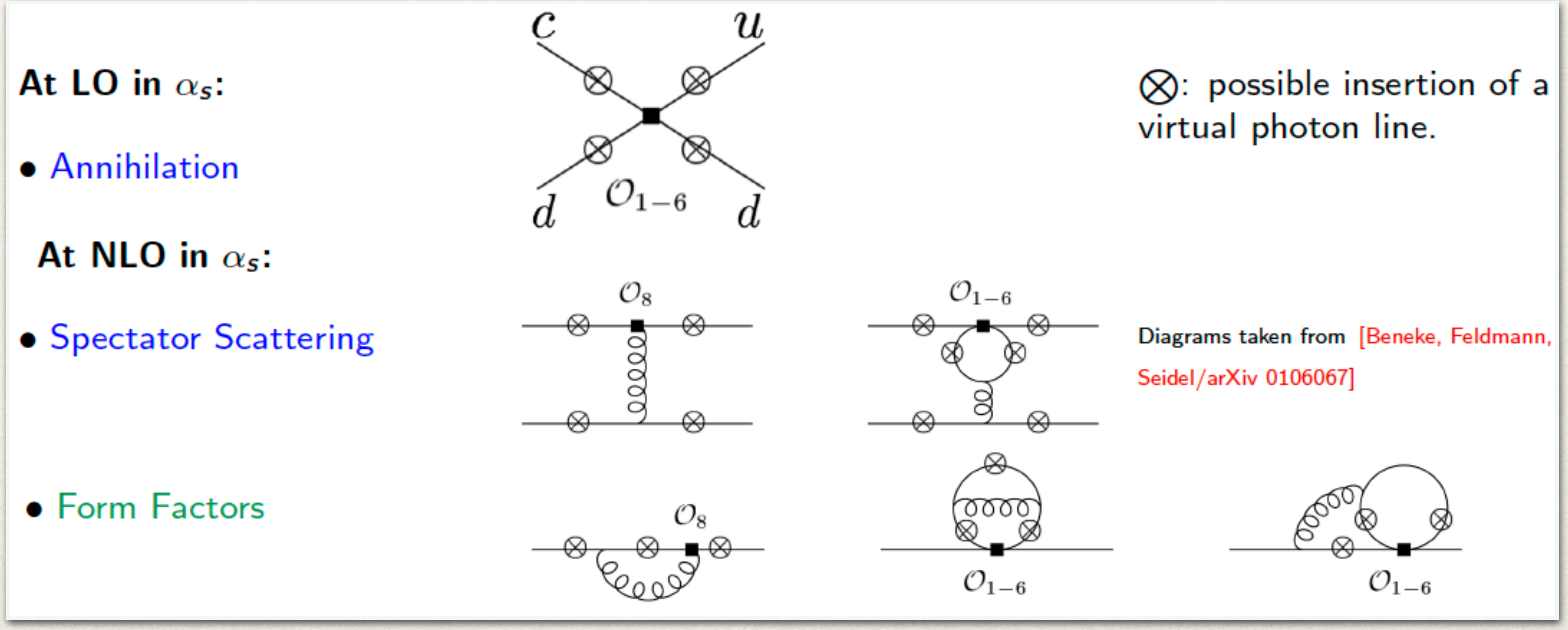
$$\mathcal{O}_i = j_q \cdot j_\ell$$

$FF(q^2)$ ← Form Factors calculated in LCSR [AB, Straub, Zwicky arXiv:1503.05534] or LQCD [Horgan et al arXiv:1310.3887]



Naive factorization (leading order): $\langle \ell\ell\pi|\mathcal{O}_i|D\rangle \sim \langle \ell\ell|j_\ell|0\rangle \cdot \underbrace{\langle \pi|j_q|D\rangle}_{FF(q^2)}$

QCDf (NLO): $\langle \pi\ell\ell|\mathcal{H}_{\text{eff}}|D\rangle \sim P(s)ff(s) + \overbrace{\phi_D}^{\text{LCDA}} \otimes \underbrace{T(s)}_{\text{pert. QCD}} \otimes\phi_\pi + \mathcal{O}\left(\frac{\Lambda_{QCD}}{m_c}\right)$



Observables: What is P_5'??

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} I(q^2, \theta_l, \theta_{K^*}, \phi)$$

← Differential Decay rate

$$I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K + (I_2^s \sin^2\theta_K + I_2^c \cos^2\theta_K)\cos 2\theta_l + I_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi$$
$$+ I_4 \sin 2\theta_K \sin 2\theta_l \cos\phi + I_5 \sin 2\theta_K \sin\theta_l \cos\phi + (I_6^s \sin^2\theta_K + I_6^c \cos^2\theta_K)\cos\theta_l$$
$$+ I_7 \sin 2\theta_K \sin\theta_l \sin\phi + I_8 \sin 2\theta_K \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi$$

$$S_i^{(a)} = \left(I_i^{(a)} + \bar{I}_i^{(a)}\right) \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

← Set of CP averaged angular observables

[Ball, AB et al arXiv:0811.1214]

$$S_5 = -\frac{4}{3}\left[\int_{\pi/2}^{3\pi/2} - \int_0^{\pi/2} - \int_{3\pi/2}^{2\pi}\right] d\phi \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_K \frac{d^3(\Gamma - \bar{\Gamma})}{dq^2\, d\cos\theta_K d\phi} \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}.$$

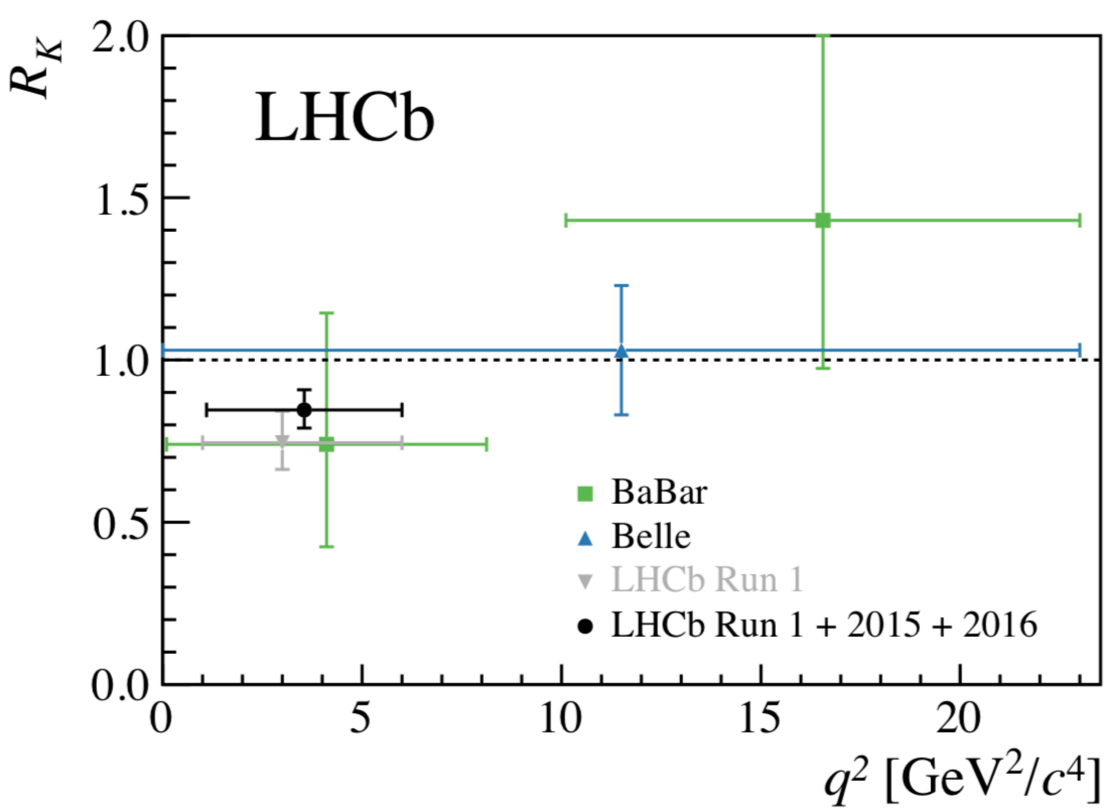
$$P_5' = \frac{S_5}{\sqrt{-S_2^c(1 + S_2^c)}}$$

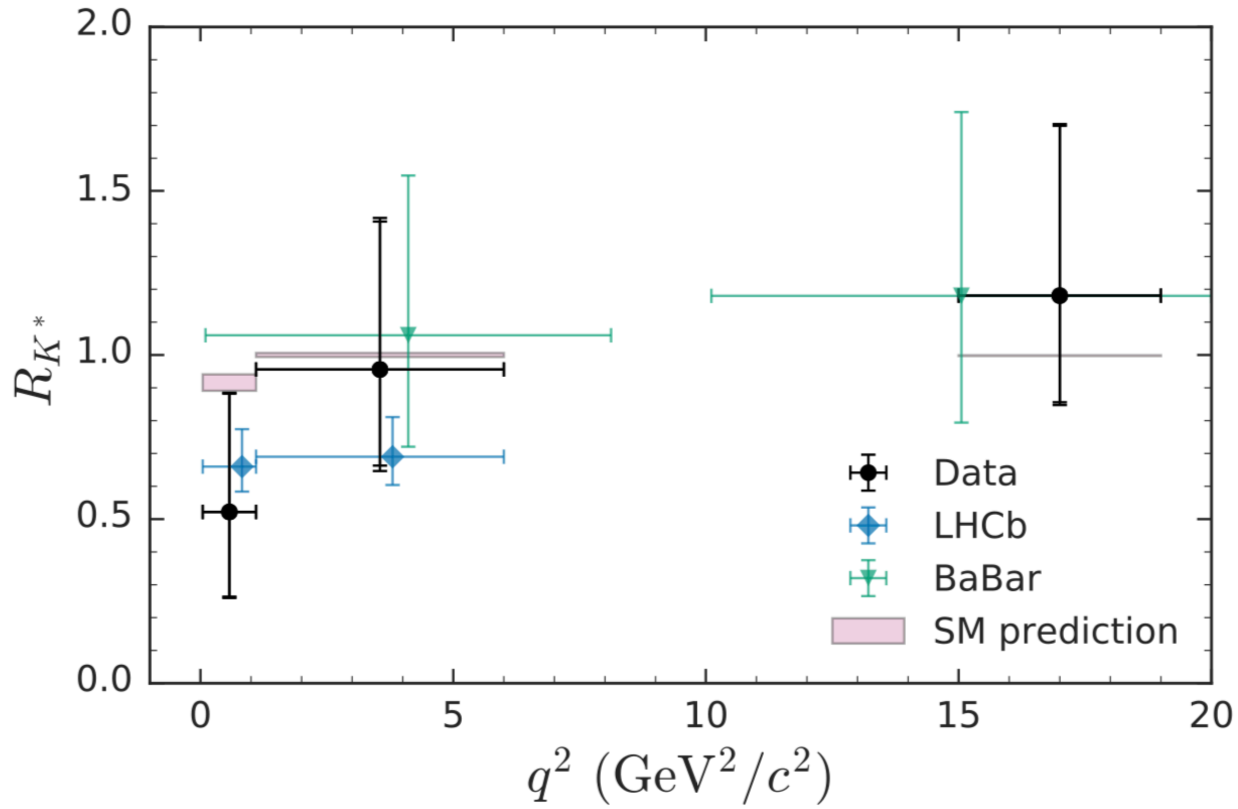
← "Optimised" observables to minimise the hadronic dependence and maximise experimental sensitivity

[Descotes-Genon et al arXiv: 1207.2753]

Update from Moriond 2019

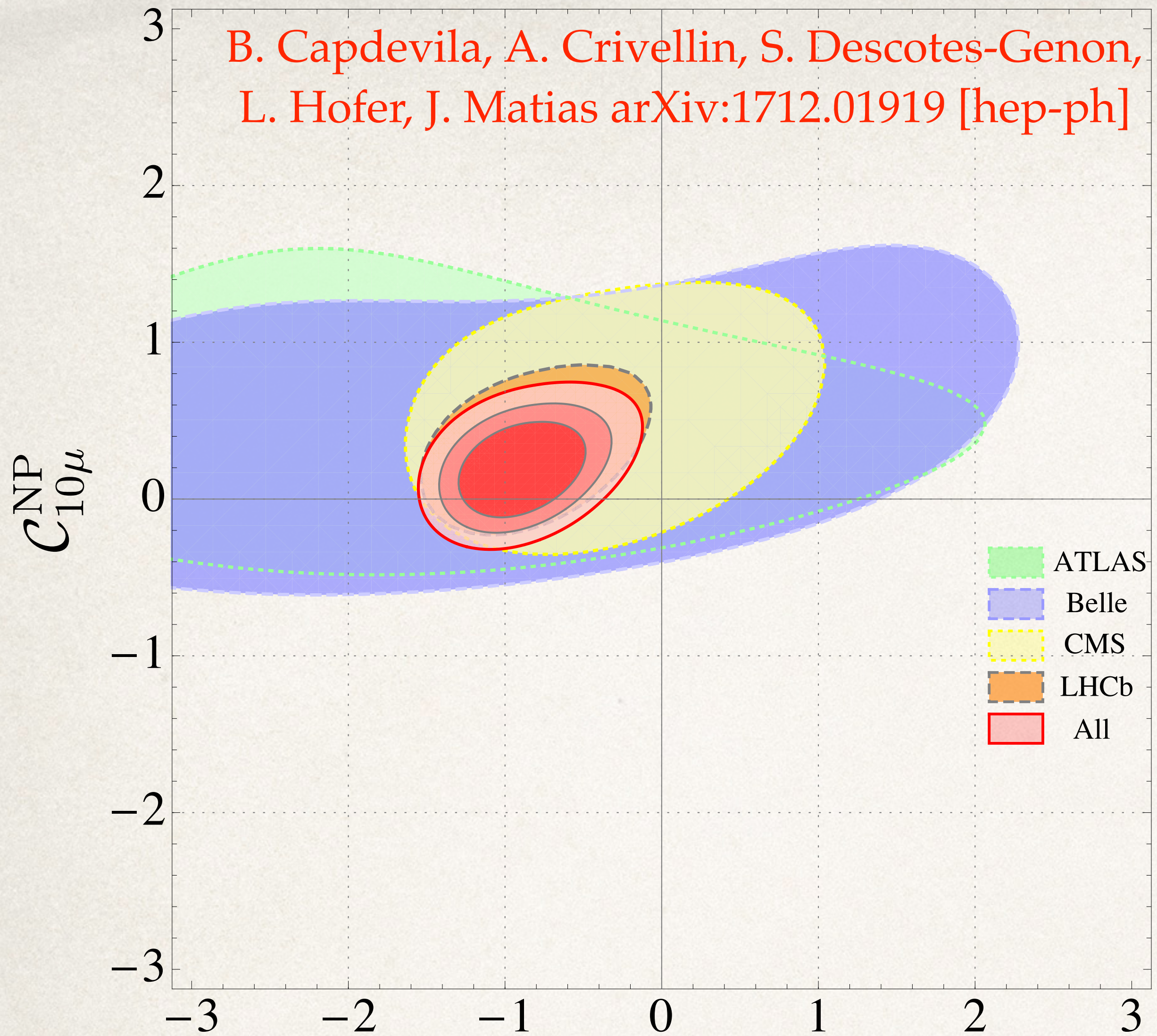
- Updated measurement of R_K by LHCb [LHCb, arXiv:1903.09252]
- New measurement of R_{K*} by Belle [Belle, arXiv:1904.02440]

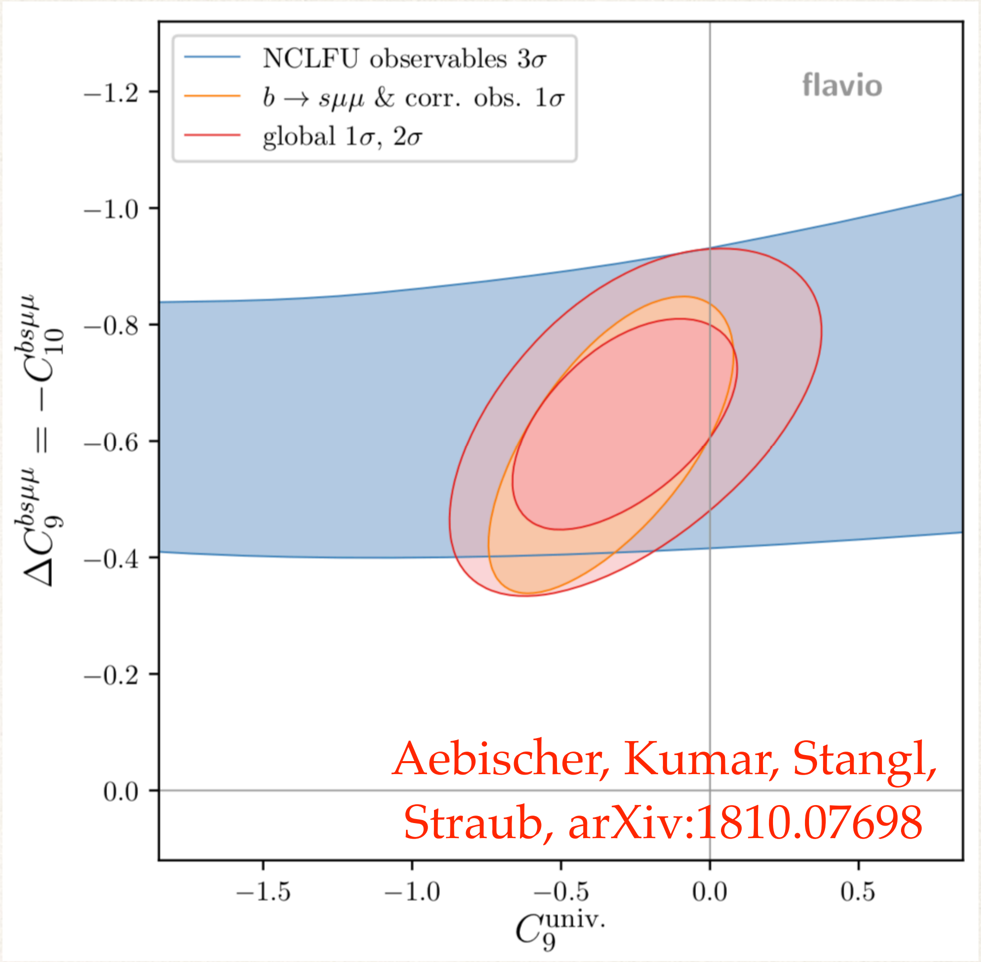


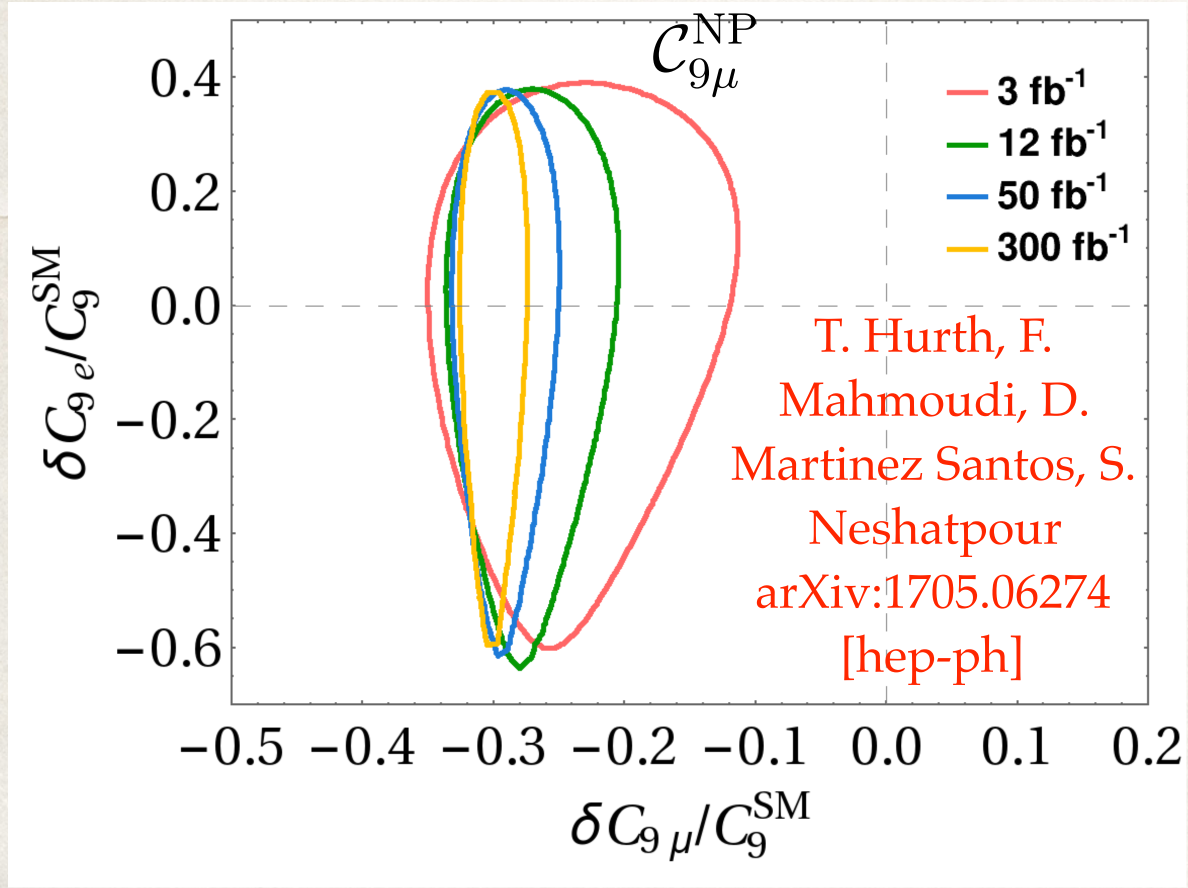


Talk by David Straub

Global fits for BSM







Introduce univ. NP contribution in C_9

$$C_9^{bsee} = C_9^{\rm univ} \qquad C_{10}^{bsee} = 0$$
$$C_9^{bs\mu\mu} = C_9^{\rm univ} + \Delta C_9^{bs\mu\mu} \qquad C_{10}^{bs\mu\mu} = -\Delta C_9^{bs\mu\mu}$$
$$C_9^{bs\tau\tau} = C_9^{\rm univ} \qquad C_{10}^{bs\tau\tau} = 0$$

Software development and statistical analysis (N Mahmoudi):

Need to include RGE running from UV scale to mb (SMEFT): non-trivial issues e.g. operator mixing/large logs. Need automated methods to reliably explore parameter space and tools to recast the constraints from LHC high-pT searches

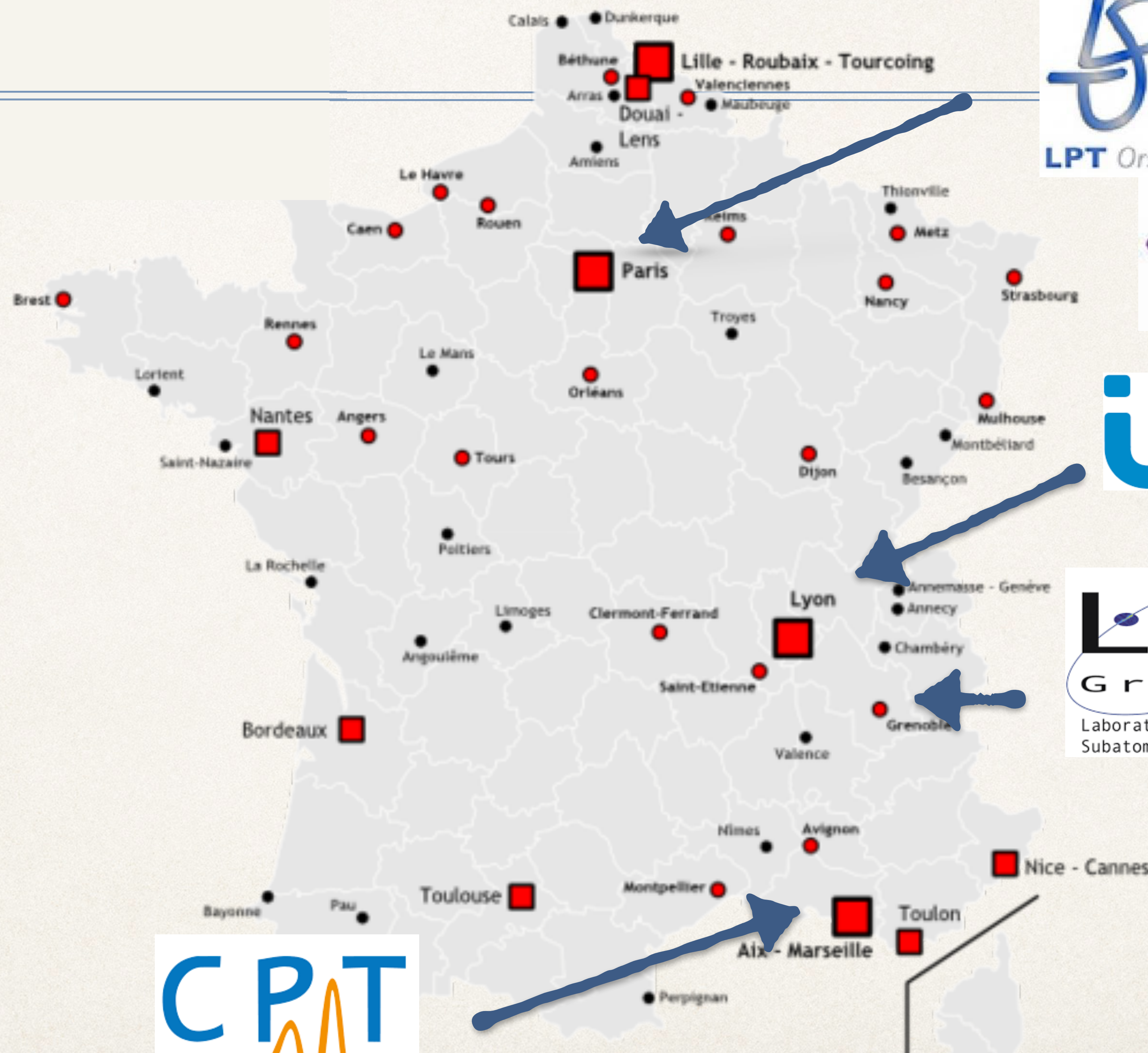
Link to direct searches for LUV (A Iyer/B Fuks):

e.g. for incl. $\ell^+\ell^-$ measurements, acceptance and reconstruction efficiencies important, to separate `physical' non-universality, induced by different couplings, from the detector-induced LFUV

Future prospects

- Main challenge comes from hadronic effects in QCD: calculation of form factors via LCSR (AB,SDG) or LQCD (see later); additional non-perturbative effects when factorization breaks down due to hadronic (charmonium) contributions to the quark loop mediating the decay.
- Form factors for the non-resonant channels (e.g. $B \to K\pi$) which contribute to the background [Sébastien Descotes-Genon et al arXiv:1908.02267 [hep-ph]].
- Study as many related channels as possible, e.g. baryon decays [S. Descotes-Genon, M. Novoa Brunet, arXiv:1903.00448 [hep-ph]] subject of GDR workshop (b-baryon fest, 14-15 May 2020, IJCLab Orsay) or $D \to \pi\ell\ell$ [AB , Diogo Boito, Cedric Méaux, to appear] Improve global analyses (Sebastien Descotes-Genon)
- B decays with τ(s) in the final state (Exp/theory network in France being established including AB, Damir Becirevic, Jérôme Charles, Sebastien Descotes-Genon)/studying τ decays (Sebastien Descote-Genon, Emi Kou)
- $b \to s\gamma$ photon polarisation measurement with $B \to K\pi\pi\gamma$ angular distribution (Emi Kou in collaboration with Belle II-LAL, writing MC generator with many kaonic resonances)
- Theory predictions for $B_s \to \gamma\ell\ell$ [Diego Guadanoli]
- Non-factorisable contribution to the radiative $B \to K_{res}\gamma$ (K_res being the kaonic resonance) to compute charm penguin effects to the photon polarisation measurement (Emi Kou in collaboration with D. Melikhov (Moscow) and H. Sazdjian (IJCLab)),

Charged currents-high precision CKM



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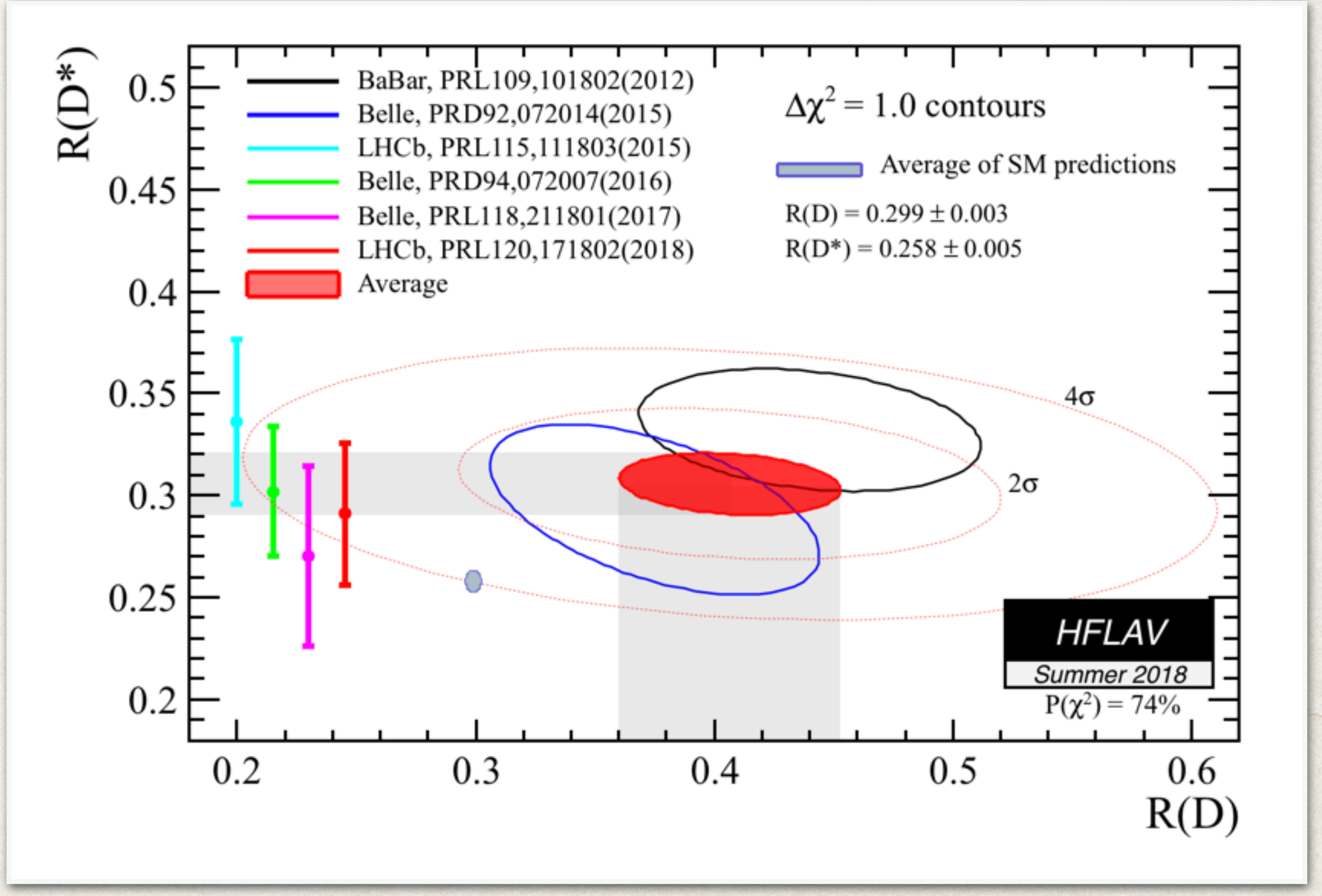
History of the anomalies part II:

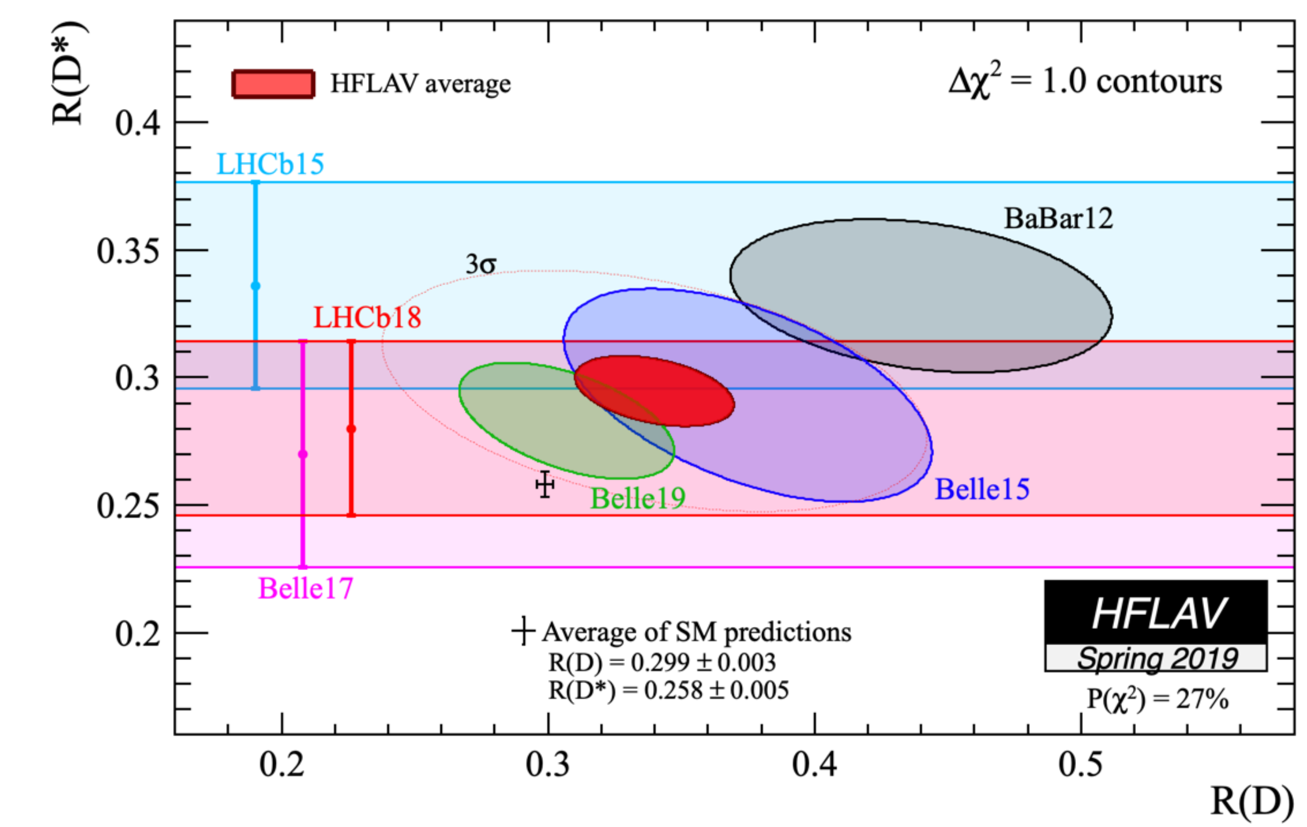
Charged Current anomalies

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

- B-factory measurements with leptonic τ decays:
  - BaBar: 2D fit [PRD 88, 072012 (2013)] $R_D = 0.440 \pm 0.058 \pm 0.042$ $R_{D*} = 0.332 \pm 0.024 \pm 0.018$
  - Belle: simultaneous 1D fits [PRD 92, 072014 (2015)] $R_D = 0.375 \pm 0.064 \pm 0.029$ $R_{D*} = 0.293 \pm 0.038 \pm 0.015$
- LHCb measurements with muonic τ decays:
  - $R_{D*} = 0.336 \pm 0.027 \pm 0.030$ [PRL 115, 112001 (2015)]
  - $R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$ [PRL 120, 121801 (2018)]
- Measurements with hadronic τ decays
  - Belle R_{D*} 1-prong [PRL 118, 211801 (2017)] [PRD 97, 012004 (2018)] $R_{D*} = 0.270 \pm 0.035{+}0.028$
  - LHCb R_{D*} 3-prong [PRL 120, 171802 (2018)] [PRL 120, 171802 (2018)] $R_D = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$



Charged semi-leptonic processes



Update from Belle, arXiv:1904.08794, Plot by HFLAV

- The process $B \to D^* l\nu$, where $l=e,\mu$ is used to measure the CKM matrix element V_{cb}, as the branching ratio is
  $BR \sim |V_{cb}\, FF\, G_F|^2$

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

- In the ratio R(D*), the form factor uncertainty is greatly reduced
- Huge 15% discrepancy with the SM prediction, tree-level process
- Need to be sure about SM prediction, i.e. the form factors.
- Exclusive-Inclusive discrepancy for V_{cb}
- Lattice at the high q^2 endpoint
- Extrapolation used to fit data
- BGl vs CLN, need more Lattice results

[PLB 353, 306 (1995), Nucl.Phys.B 530, 153 (1998), arXiv:1908.09398, PLB 353, 306 (1995), JHEP 12, 060 (2017), PRD 92, 034506 (2015), PRD 93, 119906 (2015),PRD 97, 054502 (2018),PRD 98, 114504 (2014),EPJC 77, 112 (2017)]

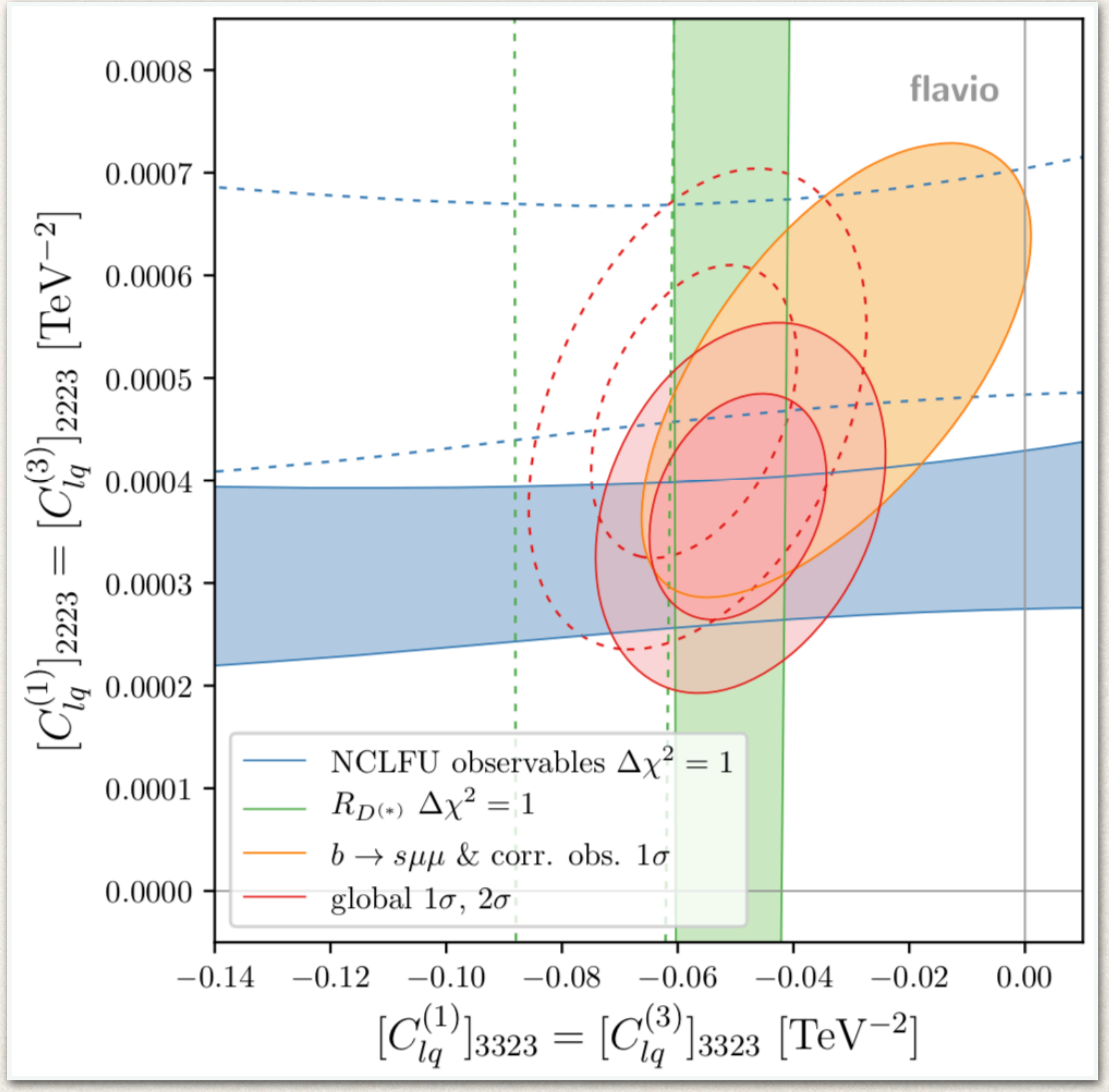
Global fits including $R_{D^{(*)}}$

Aebischer et al, arXiv:1903.10434

The following operators with ii=22 match onto C_9 and C_{10} at the EW scale:

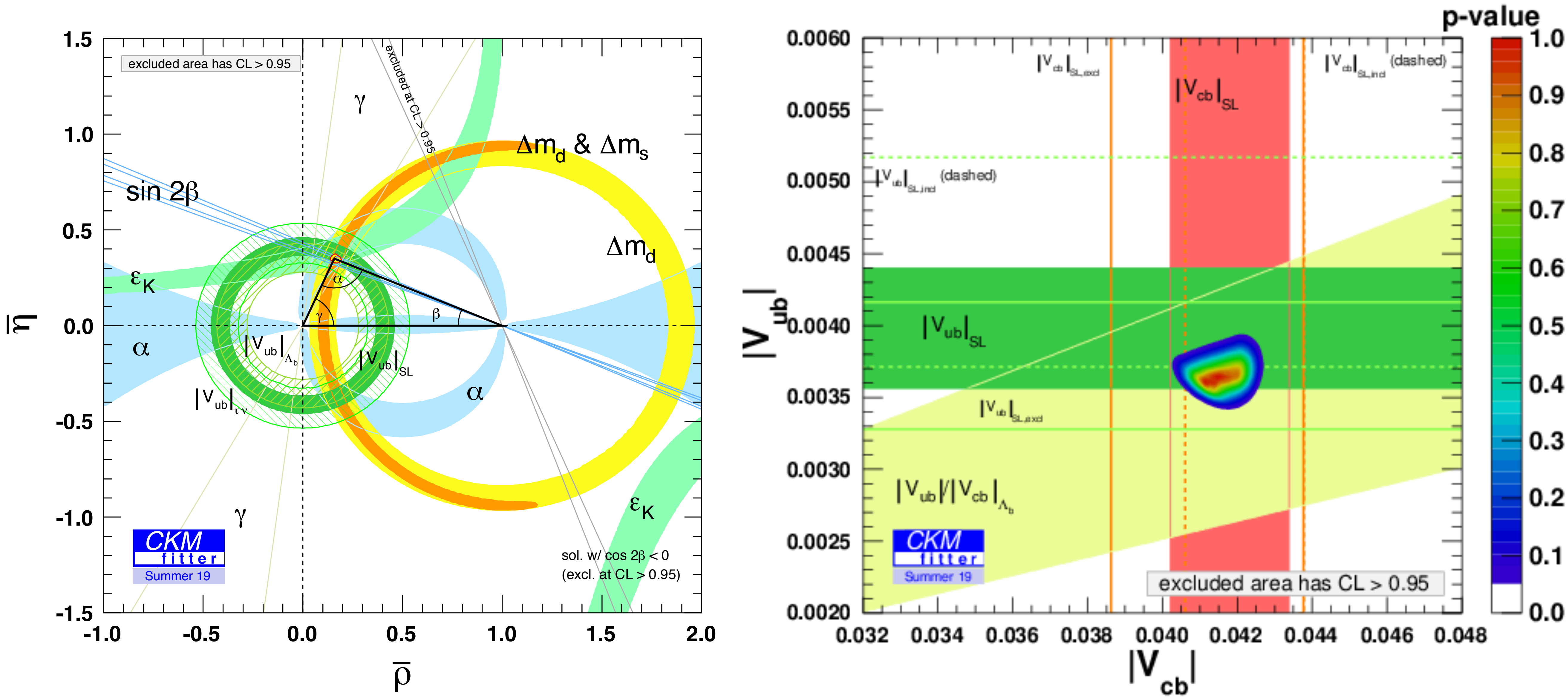
$$[O_{lq}^{(1)}]_{ii23} = (\bar{l}_i \gamma_\mu l_i)(\bar{q}_2 \gamma^\mu q_3)\,,$$
$$[O_{lq}^{(3)}]_{ii23} = (\bar{l}_i \gamma_\mu \tau^I l_i)(\bar{q}_2 \gamma^\mu \tau^I q_3)$$

- From semitauonic operators, a LFU RG contribution can be obtained by running above and below the EW scale
- The singlet/triplet Wilson coefficients should be approx. equal to avoid $B \to K\nu\nu$ constraints
- Before Moriond best-fit point of the NCLFU and $b \to s\mu\mu$ data was for vanishing semi-tauonic WCs
- Including the $R_{K^{(*)}}$ updates, this point moves to non-zero semi-tauonic WCs, as required to explain the $R_{D^{(*)}}$ anomalies, with the agreement improving with the Belle 2019 update, and a pull of ~8σ
- Only particle which can produce such operators: U1 LQs, transforming as (3,1)2/3 under the SM (Loop suppression of B mixing, Loop suppression of $B \to K\nu\nu$, singlet and triplet WCs are naturally equal)



CKM Fitter results 2019

CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184], updated results and plots available at: http://ckmfitter.in2p3.fr

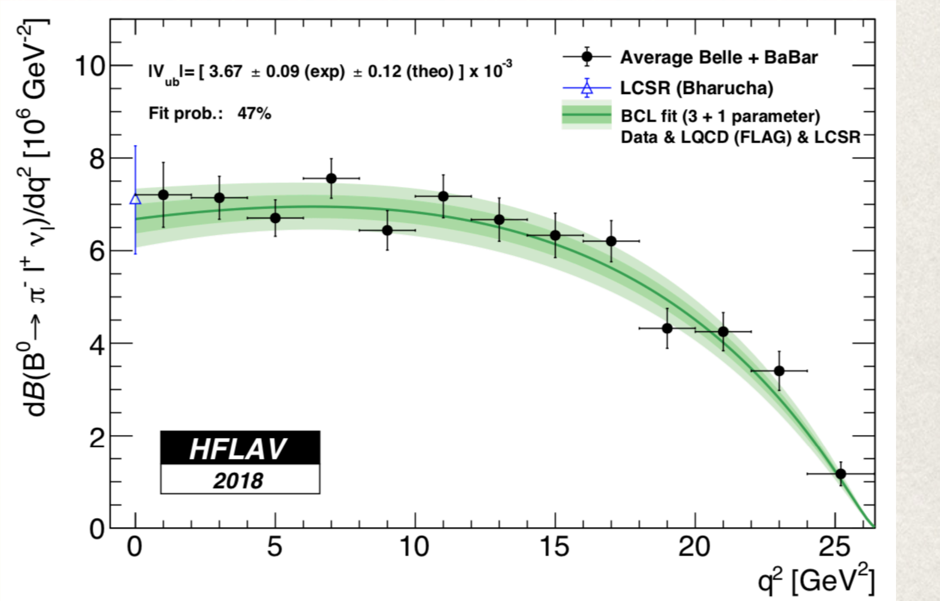


Looking closer at V_{ub} and V_{cb}

V_{ub}

$$|V_{cb}^{\rm excl}| = (3.67 \pm 0.09({\rm exp}) \pm 0.12({\rm theo})) \cdot 10^{-3} \quad ({\rm data + LQCD + LCSR})$$ (HFLAV 2018)

$$|V_{cb}^{\rm excl}| = (3.70 \pm 0.10({\rm exp}) \pm 0.12({\rm theo})) \cdot 10^{-3} \quad ({\rm data + LQCD})$$



- Exclusive result from B $\to \pi \ell \upsilon$: LQCD and Lattice agrees well.

- Inclusive result: 3 σ from excl, very model dependent, imprvs at Belle II

V_{cb}

$$|V_{cb}^{\rm excl}| = 40.3(0.8) \cdot 10^{-3}$$ (Bordone/Jung/vDyk'19)

$$|V_{cb}^{\rm incl}| = 42.00(64) \cdot 10^{-3}$$ (Gambino, Beauty 2019)

- Including (NNLO) uncertainties properly and with more Belle/BelleII data now fits give compatible results. Lattice FNAL-MILC and JLQCD preliminary results for FF ratio/slope, important constraint on fit. Important also for R(D*) and R(D).

- Inclusive result: Theory uncertainties dominant: further calculations in progress with aim to obtain 1% uncertainty, new observables for B factories, Lattice QCD information on local matrix elements is the next frontier

Future Prospects

- Aim to study the ratios linked to b→c anomalies: $R_{D^*_s}$, $R_{J/\psi}$ and R_{Λ_b} (B. Blossier)

- CKM V_{cb} element determination and new physics effects in b→c transition (Emi Kou with postdoc, KEK-lattice (JLQCD) + Belle II (Melbourne)) Form factors for particular b→c decays, B→ π and B_s→K decays in order to extract V_{cb} and V_{ub} (Antoine Gerardin/Benoit Blossier)

- Improved parameterisations for V_{cb} and V_{ub} to take into account higher order HQET contributions and combine more channels (AB, Laurent, Lellouch)

- Improved LCSR results for B to π and B_s to K form factors (AB)

- Probing meson DAs with B/D/K to 3l υ (AB, Marc Knecht with Emilie Passemar, Alexey Petrov)

- CKM gamma angle determination and D→K$\pi\pi$ decay in dispersive method (Emi Kou with B. Moussallam (IJCLab))

LQCD input for flavour physics

Vincent Morenas, Mariane Brinet, Benoit Blossier, Antoine Gerardin, Savvas Zafeiropolous

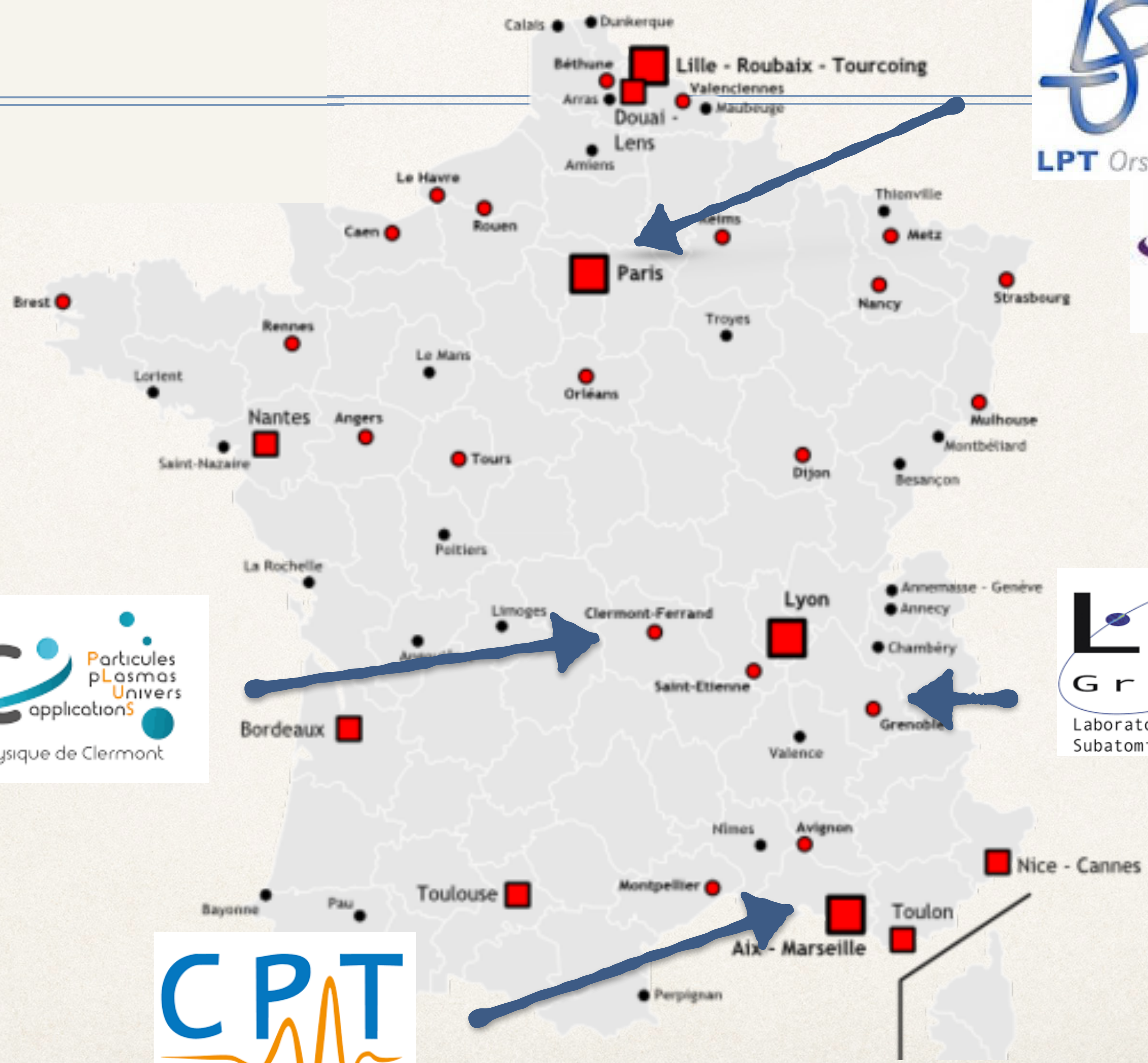
Progress over last ten years:

- Take into account u=d quarks as well as s and c quarks in the sea (dynamical quarks).
- We can include, in our simulations, strong and electromagnetic effects of the isospin symmetry breaking.
- A wide range of observables have been computed (hadron masses, decay constants, form factors, mixing parameters which characterise weak-decay amplitudes, PDFs, quark masses, etc.)
- As an example, LQCD provides the heavy flavour decay constants for the D, Ds, B and Bs mesons with sub percent precision, and the most precise determination of α_s.

Future prospects:

- Study of bottomium states to probe dynamics of the strong interaction and provide constraints for some BSM scenarios.
- Meson distribution amplitudes (DAs), important universal quantities, appearing in many factorization theorems, which allow for the description of exclusive processes at large momentum transfers., e.g. $B \to \pi l \nu$, $\eta l \nu$ giving $|Vub|$, $B \to D\pi$ used for tagging, and $B \to \pi\pi$, $K\pi$, KKbar, $\pi\eta$,...which are important channels for measuring CP violation.

Anomalous magnetic moments



$(g\text{-}2)_\mu$ today

- $(g\text{-}2)_\ell$, i.e. deviation of gyromagnetic ratio of ℓ with respect to classical value, promising NP search
- Calculated with impressive accuracy in SM
- Since E821 experiment of the Brookhaven National Laboratory in the early 2000s, 3:5 sigma disagreement theory and exp
- While exp/th uncertainties close, new Fermilab exp (E989) currently taking data and another planned (E34) at J-PARC in Japan, both will reduce the error by a factor four, i.e. down to 0.15 ppm.
- Reduction of the theory uncertainties (factor 10) is therefore essential to fully exploit the new experimental results.

	$a_\mu \times 10^{10}$	
QED 5-loops	11658471.8853 ± 0.0036	Aoyama, et al, 2012
Weak 2-loops	15.36 ± 0.10	Gnendiger et al, 2013
HVP (LO)	692.5 ± 2.7	RBC-UKQCD and FJ17 combined
	693.26 ± 2.46	KNT18
	693.9 ± 4.0	DHMZ19
HVP (NLO)	-9.93 ± 0.07	Fred Jegerlehner, 2017
HVP (NNLO)	1.22 ± 0.01	Fred Jegerlehner, 2017
HLbL	10.3 ± 2.9	Fred Jegerlehner, 2017
	10.5 ± 2.6	Glasgow Consensus, 2007
SM Theory	11659181.3 ± 4.0	
BNL E821 Exp	11659208.9 ± 6.3	
Exp − SM	27.6 ± 7.5	

Theoretical challenges

Theory uncertainty limited by two hadronic contributions: hadronic vacuum polarization (HVP) and hadronic light-by-light scattering (HLbL). 4 French teams significantly contributed to the calculation of both and more work ongoing.

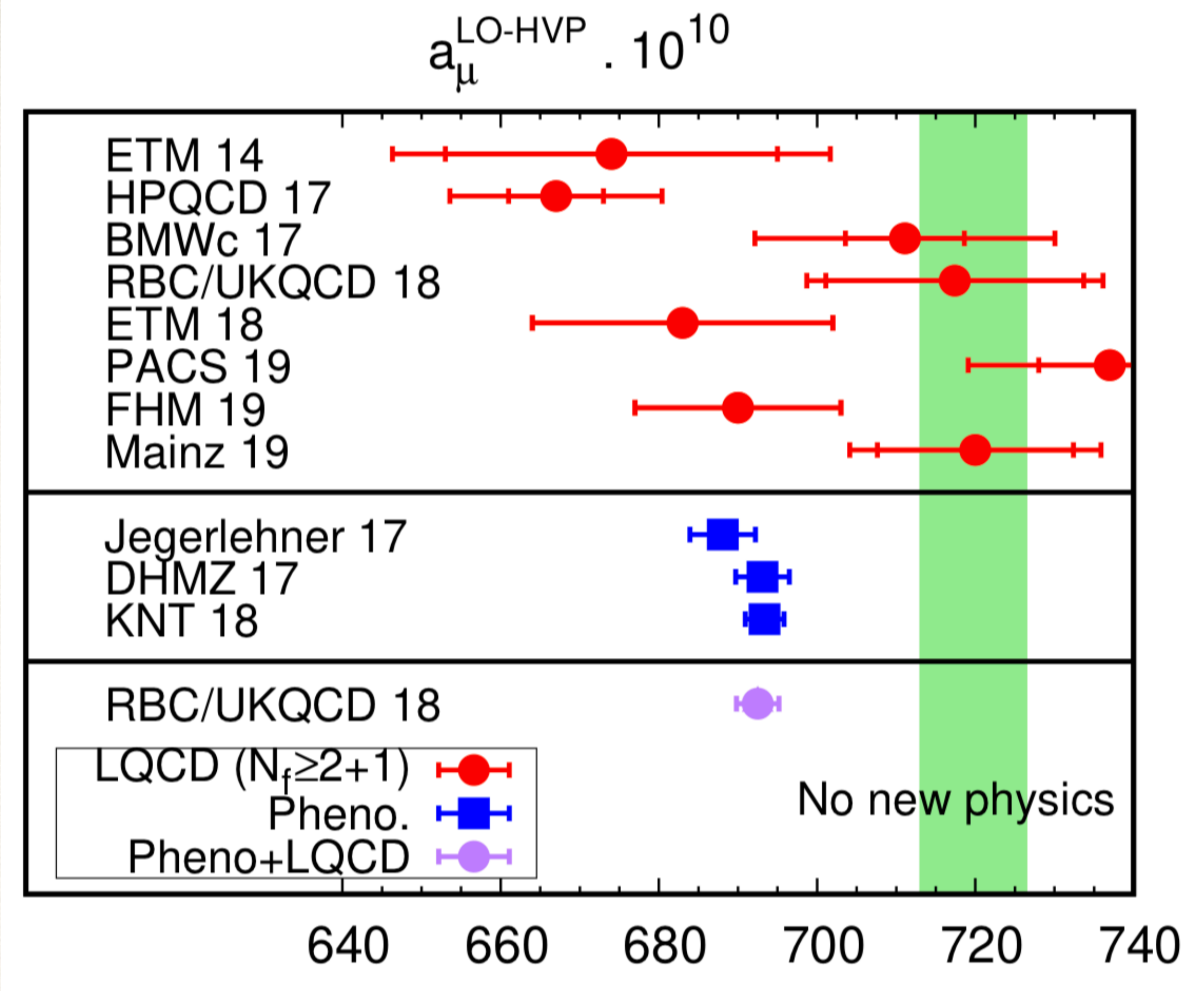
HVP contribution:

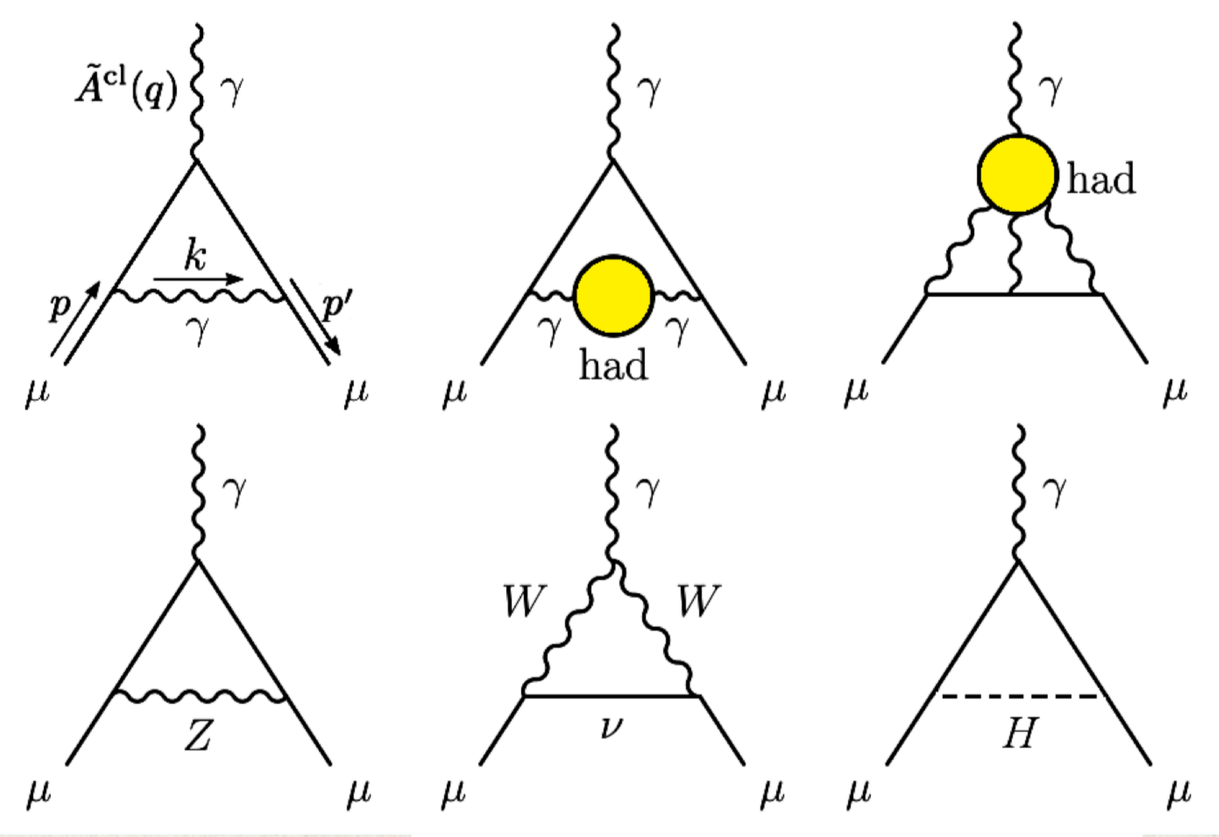
- Pheno: dispersion relations applied to data for the cross section of e+e- to hadrons. (most precise and to improve with data e.g. from Belle II.)
- LQCD: 1st complete result BMWc 17), uncertainties ~ 6 times> pheno.

MUonE project: proposes to determine the HVP contribution by directly measuring the eff. EM coupling in spacelike region via e scattering data.

HLbL contribution:

- Model based calculation computing contributions of individual hadronic states. (Knecht, Nyffler 2002)
- More recently, using LQCD (aim at O(10%) uncertainty) (N. Asmussen, E. H. Chao, A. Gerardin, J. R. Green, R. J. Hud, spith, H. B. Meyer and A. Nyffeler,arXiv:1911.05573 [hep-lat].)



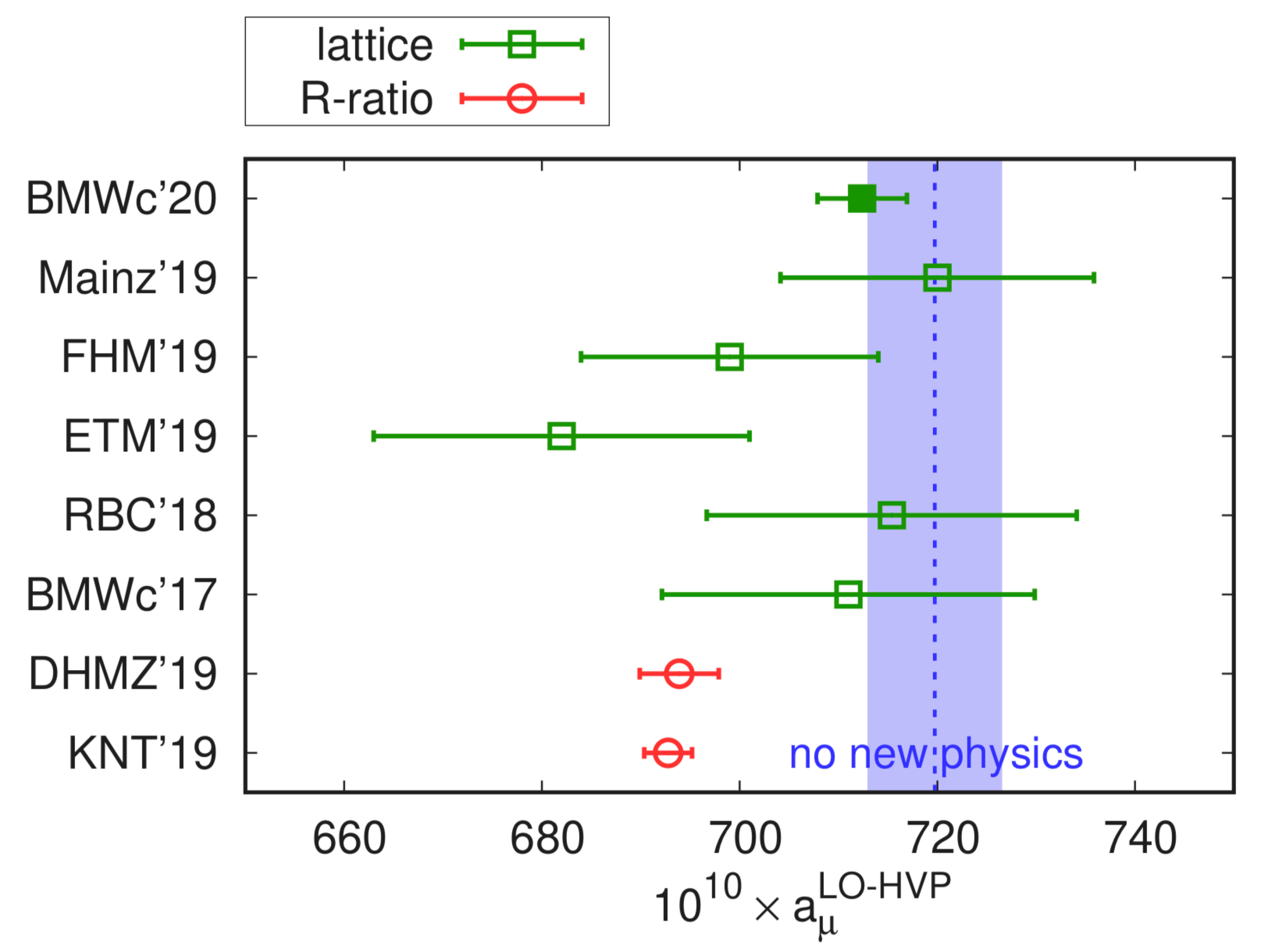


Latest news from BMWc

- BMWc’17 consistent with both pheno and “no new physics” scenario
- BMWc’20 clearly agrees with SM and disagrees with pheno result
- Question remains why pheno inconsistent with exp, supposing that E989 confirms previous measurements.

Improving the uncertainty on HVP needs:

- advanced noise reduction techniques
- the inclusion of electromagnetic and strong-isospin breaking effects
- much larger statistics, simulations in larger volumes



Leading-order hadronic vacuum polarization contribution to the muon magnetic momentfrom lattice QCD, Sz. Borsanyi et al.. arXiv:2002.12347 [hep-lat].

Additional themes in LQCD

Vincent Morenas, Mariane Brinet, Benoit Blossier, Savvas Zafeiropolous

- **Hadron structure:** PDFs and generalised GPDFs and meson DAs will be under deep investigation in future experiments at J-Lab (JLEIC). Lattice results in regions complementary to that accessible via exp.

- **Neutron EDM:** Upper bound $|d_n| < 3\ 10^{-26}$ e·cm (90% C.L.) stringent constraint on NP. In SM, mediated by the strong CP-violating term/topological charge. Estimates from the lattice challenging but good hope to remain competitive with respect to the new experiment led at nEDM@PSI.

- **Higgs Physics and PDFs:** for hadronic initial states (e.g. pp), a complete high-precision determination of the PDFs, is crucial for measurements e.g. of the Higgs sector, multi-TeV SM/BSM cross sections.

- **Algorithmic aspects:** large vol. simulations need extremely large computer time, (~O(10^8) core hrs) on Tier-0 and Tier-1 high-performance systems. Developing new paradigms is potentially mandatory to optimize the cost of acceptance/rejection test in hybrid Monte-Carlo algorithms.

Summary

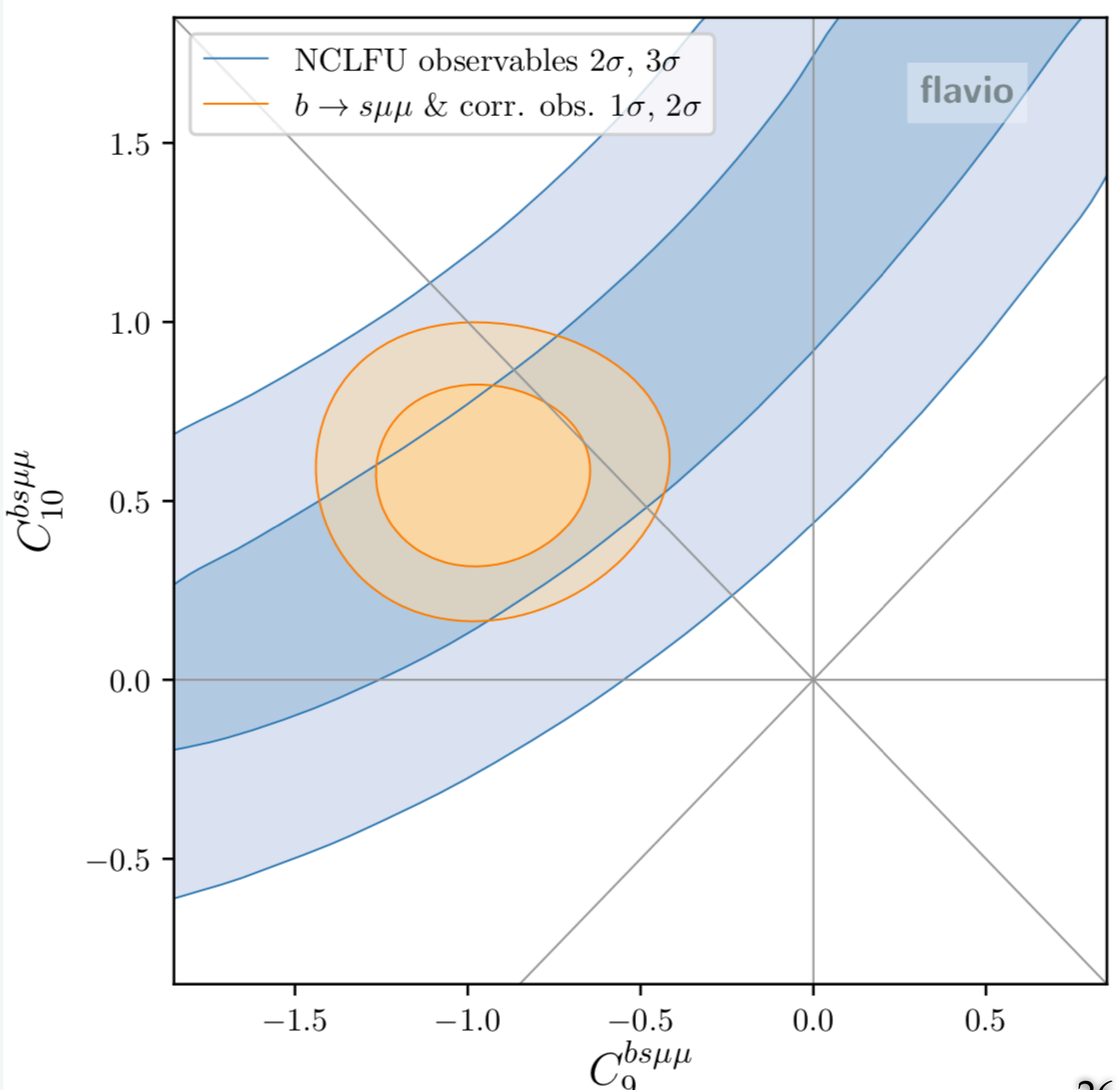
- **Neutral currents searches for BSM:** Anomalies, global fits, deeper understanding of related uncertainties, related channels, tau physics
- **Charged currents/ high precision CKM:** Anomalies and related ratios on the Lattice, improved determinations of Vcb and Vub (Lattice form factors/new parameterisations)
- **$(g\text{-}2)_\ell$:** HPV (lattice-new result from BMWc-and pheno), HLbL…
- **Further Lattice QCD activities:** PDFs, nEDM, algorithmic aspects

Observables and Sensitivity to Wilson Coefficients and Fits

- Angular observables in $B \to K^*\mu^+\mu^-$ (CDF, LHCb, ATLAS, CMS)
- BR($B \to K^*\mu^+\mu^-$) (CDF, LHCb, CMS)
- BR($B \to K\mu^+\mu^-$) (CDF, LHCb)
- BR($B_s \to \phi\mu^+\mu^-$) (CDF, LHCb)
- $B_s \to \phi\mu^+\mu^-$ angular observables (LHCb)
- BR($B \to X_s\, \mu^+\mu^-$) (BaBar)

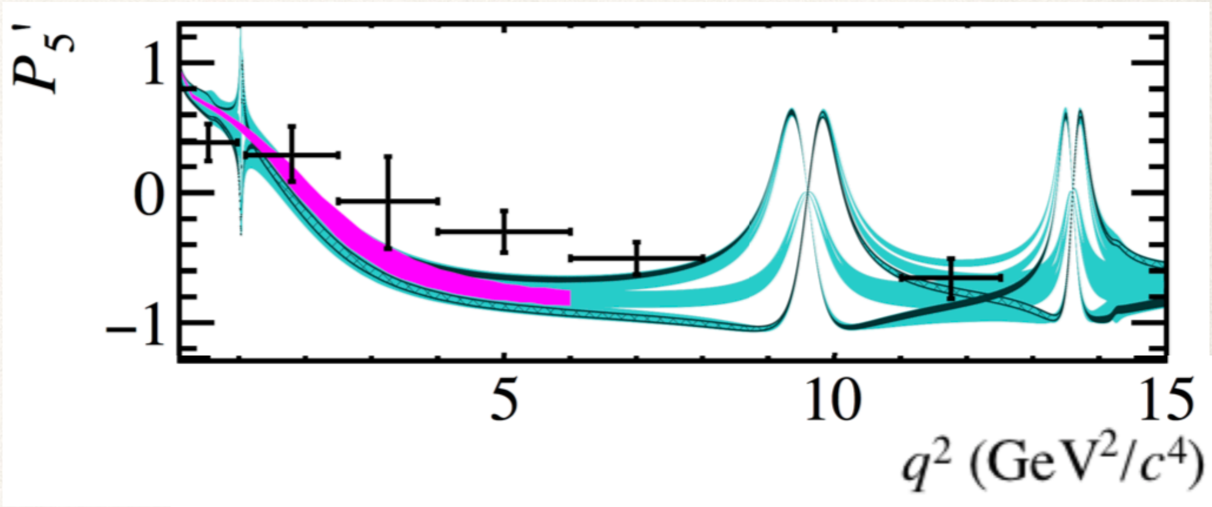
Aebischer, Kumar, Stangl, Straub, arXiv:1810.07698

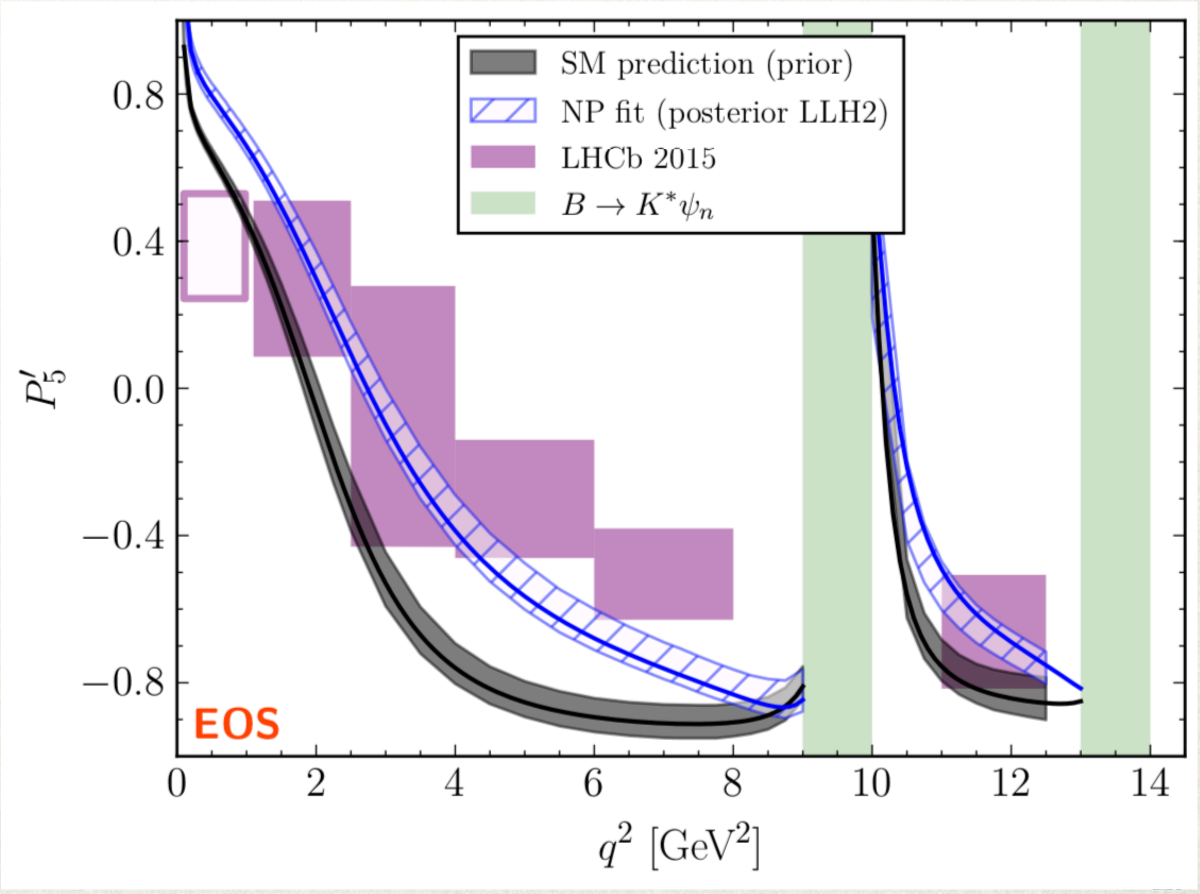
Decay	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$B \to X_s\gamma$	X			
$B \to K^*\gamma$	X			
$B \to X_s\ell^+\ell^-$	X	X	X	
$B \to K^{(*)}\ell^+\ell^-$	X	X	X	
$B_s \to \mu^+\mu^-$			X	X



Further checks: NP or QCD?

- Fit resonance contribution to e+e- data [Lyons and Zwicky arXiv:1406.0566]
- Breit-Wigner description of resonances fit to hadronic decays [Blake et al arXiv:1709.03921]
- Long-distance effects in $B \to K^*ll$ from Analyticity [Bobeth, Chrzaszcz,,van Dyk and Virto arXiv:1707.07305, Chrzaszcz et al, arXiv:1805.06378]





BGL vs CLN

Boyd, Grinstein,Lebed [arXiv:hep-ph/9705252]

$$z = \frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w+1}+\sqrt{2}} \qquad w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}},$$

$$g = h_V / \sqrt{m_B m_D^*}$$
$$f = \sqrt{m_B m_D^*}(1+w)\, h_{A_1} \qquad f(z) = \frac{1}{P_{1+}(z)\phi_f(z)} \sum_{n=0}^{\infty} a_n^f z^n$$
$$\mathcal{F}_1 = (1+w)(m_B - m_{D^*})\sqrt{m_B m_{D^*}} A_5$$

$$R_1(w) = (w+1)\, m_B m_{D^*} \frac{g(w)}{f(w)}, R_2(w) = \frac{w-r}{w-1} - \frac{\mathcal{F}_1(w)}{m_B(w-1)f(w)}.$$

Three form factors. Series expansion, impose dispersive bounds on coefficients using unitarity. Construct useful ratios in terms of form factors. Fit to data to obtain V(cb).

Caprini, Lellouch, Neubert [arXiv:hep-ph/9712417]

$$h_{A_1}(w) = h_{A_1}(1)\left[1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3\right],$$
$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2,$$
$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2$$

Use HQET+combine bounds from B to D, B to D*, B* to D* and B* to D to obtain shape of form factors and ratios. Theory uncertainties on slope and curvature ignored.

Uncertainties from NNLO can be up to 10-20%. In exp fits never included. At current precision cannot be ignored.

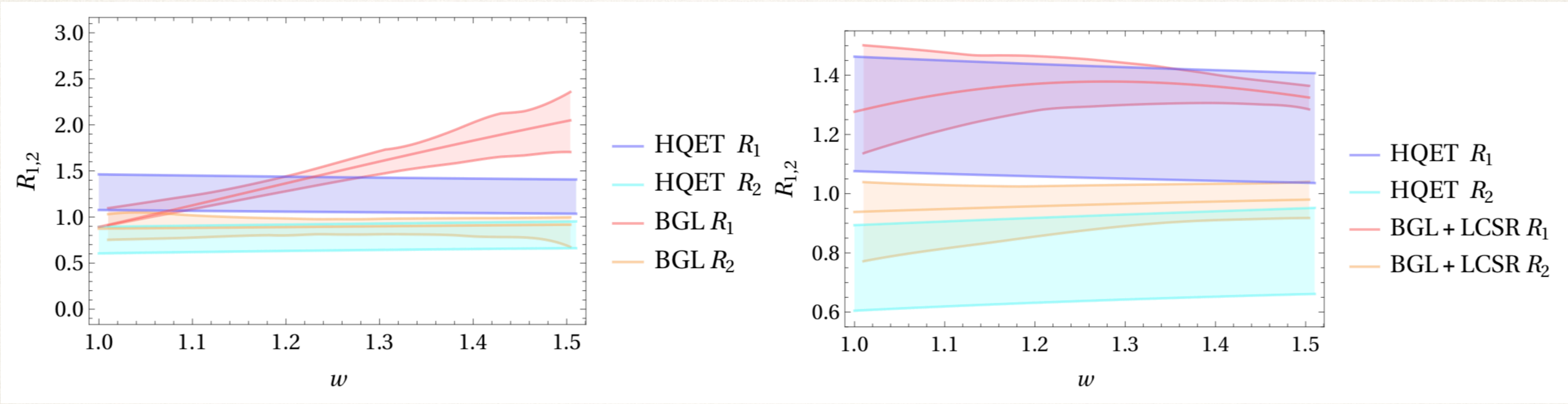
Role of HQET relations in V_{cb} extraction

(preliminary Belle data only)

STRONG HQET INPUT	SMALL V_{cb}	Refs.
"practical" CLN:	$\lvert V_{cb}\rvert = 38.2(1.5)\cdot 10^{-3}$	[1,5,6,7,8]
CLN+QCD sumrule errors + $B \to D$	$\lvert V_{cb}\rvert = 38.5(1.1)\cdot 10^{-3}$	[2]
same + lattice at non-zero recoil	$\lvert V_{cb}\rvert = 39.3(1.0)\cdot 10^{-3}$	[2]
BGL,HQET,LCSR,$B \to D$,nuisance	$\lvert V_{cb}\rvert = 40.9(0.9)\cdot 10^{-3}$	[3]
BGL + strong unitarity	$\lvert V_{cb}\rvert = 40.8(1.5)\cdot 10^{-3}$	[4]
BGL + weak unitarity	$\lvert V_{cb}\rvert = 41.7(2.0)\cdot 10^{-3}$	[5,6,7,8]
NO HQET INPUT	LARGE V_{cb}	

[1] [Belle 1702.01521] [2] [Bernlochner Ligeti Papucci Robinson 1703.05330]
[3] [Jaiswal Nandi Patra 1707.09977] [4] [Bigi Gambino Schacht 1707.09509]
[5] [Bigi Gambino Schacht 1703.06124] [6] [HPQCD 1711.11013]
[7] [Bernlochner Ligeti Papucci Robinson 1708.07134] [8] [Grinstein Kobach 1703.08170]

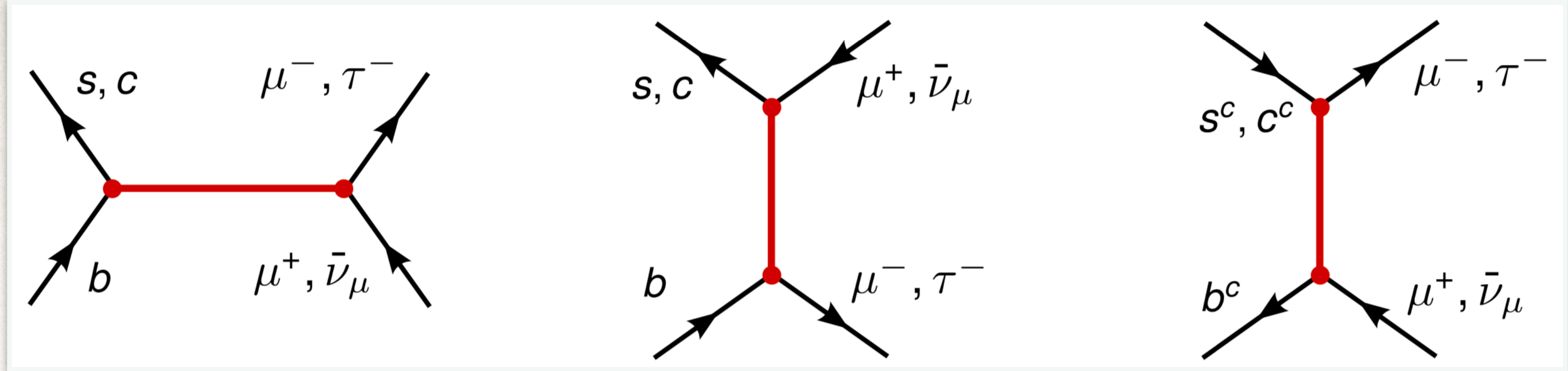
Effect of HQET on R1 and R2



- Fits for R2 in good agreement with HQET+QCDSR.
- Same goes for R1 with LCSR. R1 without LCSR well compatible with HQET only at small/moderate recoil. At large w clear tension with both HQET and LCSR.
- Fit without LCSR appears somewhat disfavored.

Lattice will compute A1 and R1,2 and settle the story

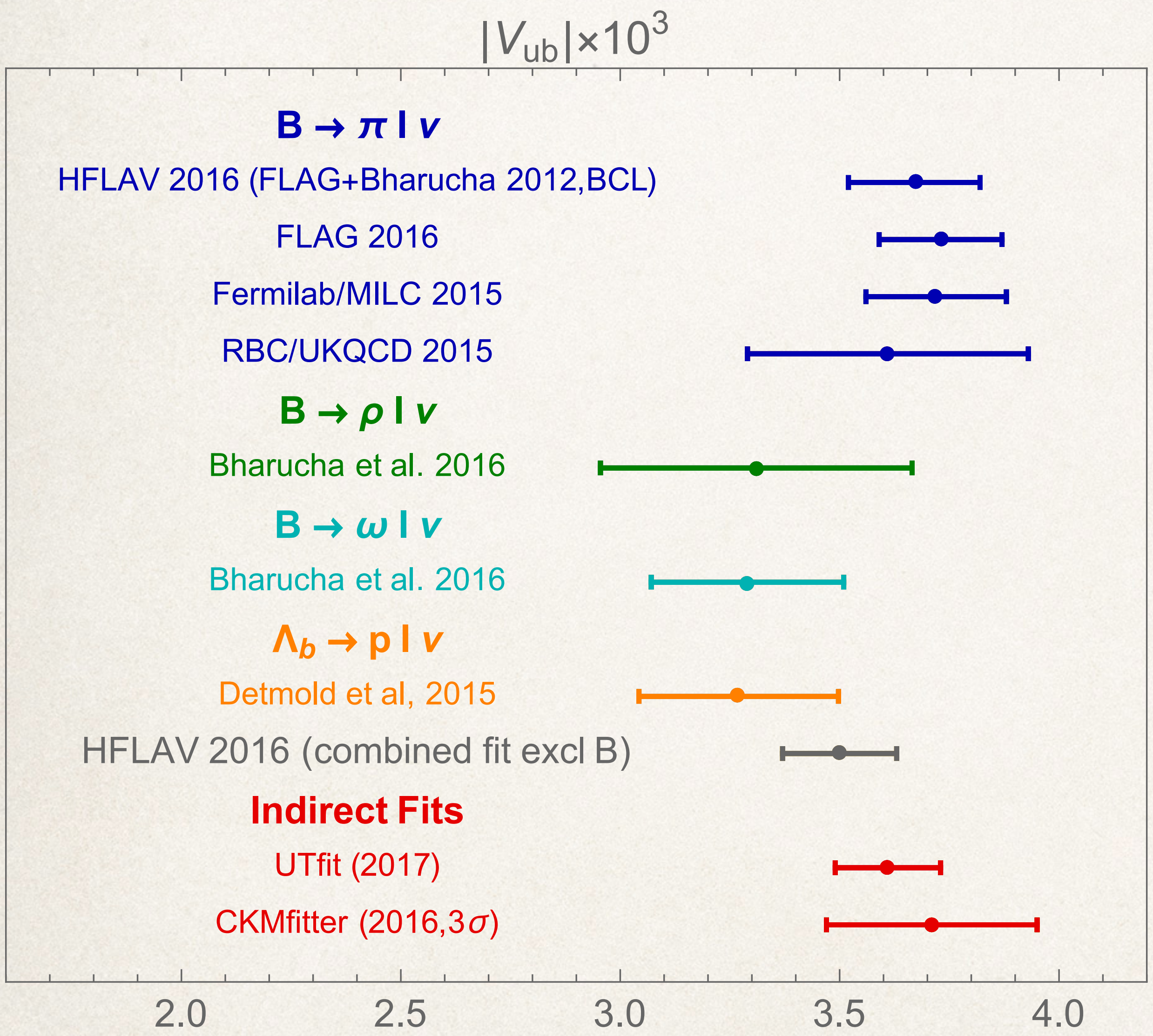
Tree-level solutions



With help from David Straub

- Only particle which can produce such operators: U_1 LQs, transforming as $(3,1)_{2/3}$ under the SM
  - Loop suppression of B mixing
  - Loop suppression of B → Kνν, singlet and triplet WCs are naturally equal
- Vector leptoquarks require a UV completion. Several model building attempts are underway, most based on Pati-Salam (PS) gauge group, SU(4) × SU(2) × SU(2)
  - Composite PS leptoquark Barbieri et al. 1611.04930, Barbieri and Tesi 1712.06844
  - SU(4) × SU(3) × SU(2) × U(1) Di Luzio et al. 1708.08450, cf. v2 of Assad et al. 1708.06350
  - PS with additional vector-like fermions Calibbi et al. 1709.00692
  - Three-site PS Bordone et al. 1712.01368
  - PS in warped extra dimensions Blanke and Crivellin 1801.07256

Summary of V_{ub} and Future Prospects



inclusive (BLNP): (4.44 +/- 0.15 +0.21/-0.22) 10^{-3}

Summary:

2012 NNLO calculation B → π (AB)

2014 Bayesian uncertainty analysis for the B → π form factor (Imsong, Khodjamirian, Mannel van Dyk)

2015 Update for B to V form factors (AB, Straub, Zwicky)

2017 Calculation of f_+ and f_T for $B_{(s)}$ to K form factors (Khodjamirian and Rusov)

Future Prospects:

- Find higher twist (i.e. 5,6) terms in the factorizable approximation are small, but still would be good to check the full NNLO twist 2 and twist 3 contributions
- Bayesian uncertainty analysis of all B → P, D → P LCSRs (for B → π in [Imsong,AK,Mannel,van Dyk (2013)])
- B_s→Klν measurement at LHCb/Belle II
- Future Belle-2 data on the q^2-shape of B → πlν will provide additional constraints on the DA parameters