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Theory Summary

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Fermilab

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BEAUTY 2016

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Outline

- LHC (high √s) and B decays (rare processes)
  - Hitoshi Murayama - Theory in the LHC era
  - Joachim Brod - Higgs
- B Physics
  - Kristof De Bruyn - Penguins in $\phi_{(s,d)}$
  - Sebastien Descotes-Genon - BSM fits (B decays)
  - Paolo Gambino - Semileptonic Decays (Vxbll)
  - Andreas Crivellin - B-anomalies (LFUV)
  - Jorge Martin Camalich - Semileptonic B decays (hadronic uncertainties)
  - Jerome Charles - CP violation
  - Ruth Van de Water - Lattice QCD
  - Enrico Lunghi - Rare Decays (Lattice)
  - Mateusz Koren - $B_s \to K\, e\, \nu$ (Lattice HQET)
  - Andrew Lytle - B_c Decays (Lattice HISQ)
- Charm Physic, Kaons, EMD's, LFV
  - Alexey Petrov - D mixing and rare decays
  - Stefan Schacht - Non-leptonic D decays
  - Andrzej Buras - Rare K Decays
  - Martin Jung - EDM and LFV
- Serendipity
  - Richard Lebed - Hadron Spectroscopy
  - Yasuhiro Okada - Belle 2
- Summary

apéritif

LHC (high $\sqrt{s}$) and B decays (rare processes)

STATE OF THEORY (< 2012)

EBH (Era Before the Higgs)

Two theoretical arguments for new physics at the LHC and rare decays

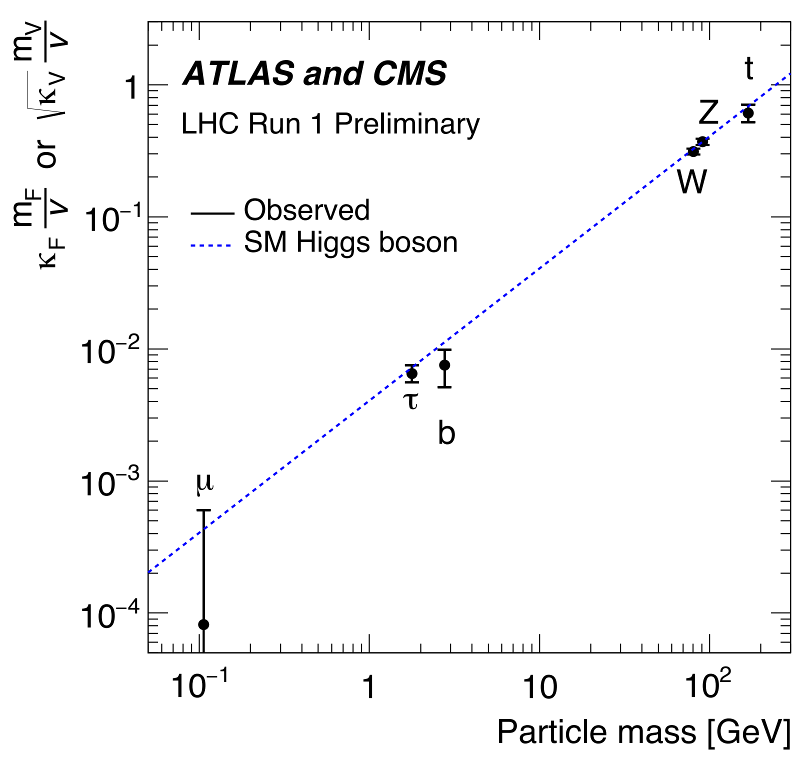
1. Unitarity argument set a scale in the TeV region:
    - Higgs, or
    - New strong dynamics, or
    - SUSY particles begin to appear.

2. Naturalness:
    - New strong dynamics at the TeV scale -> new spectrum of particles
    - SUSY -> supersymmetric partners begin to appear

- Higgs Discovered (4/7/2012)

m_H=125.09±0.21(stat)±0.11(scale)±0.02(other)±0.01(theory) GeV

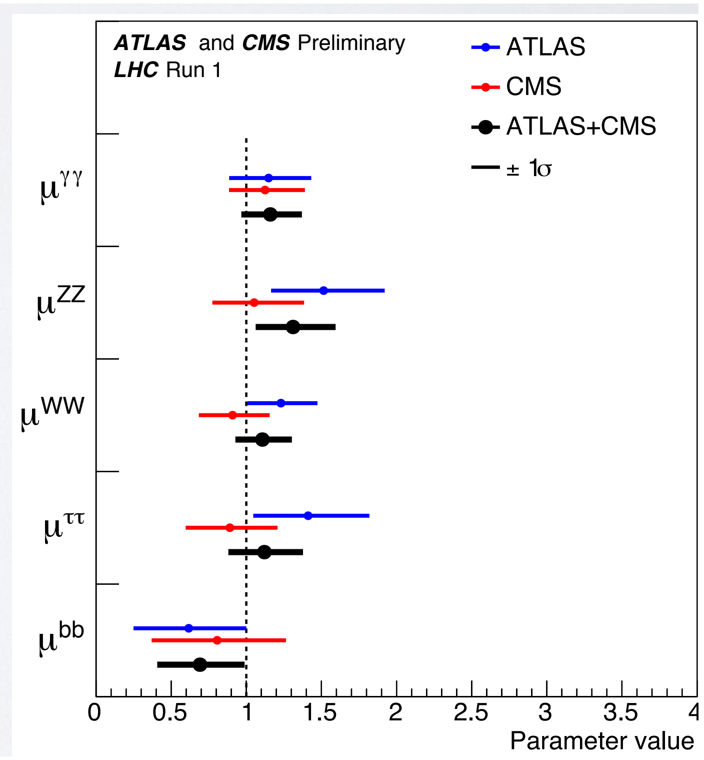
  - Spin 0
  - Couplings in SM completely determined by m_H
  - Couplings consistent with SM



- New Frontier for flavor physics

Joachim Brod

  - Measure charm coupling: total width, global fit, exclusive decays (h-> J/ψ ɣ), charm tagging
  - EDM constraints on Yukawa top, bottom couplings
  - New idea to calculate electron coupling in atomic systems [Delaunay et al. 1601.05087]
  - Hints of LFV decays:

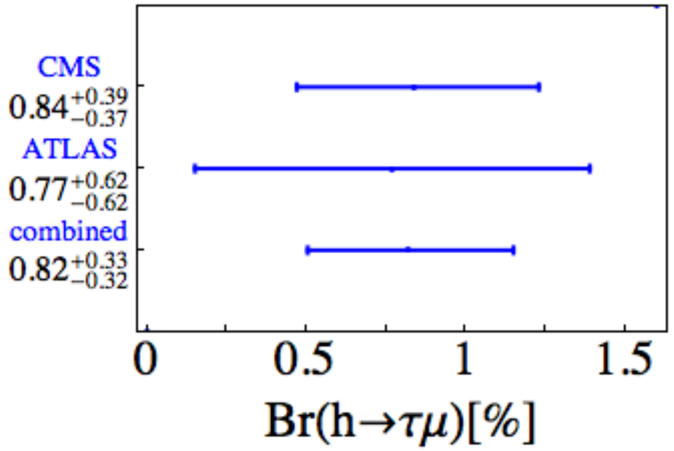


CMS

$$\mathrm{BR}(h \to \tau\mu) = (0.84^{+0.39}_{-0.37})\%$$

$$\Rightarrow \sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} = (2.6 \pm 0.6) \times 10^{-3}$$

[Altmannshofer et al. 1507.07927]



STATE OF THEORY (today)

ABH (Era After the Higgs):

One theoretical argument for new physics at the LHC and rare decays

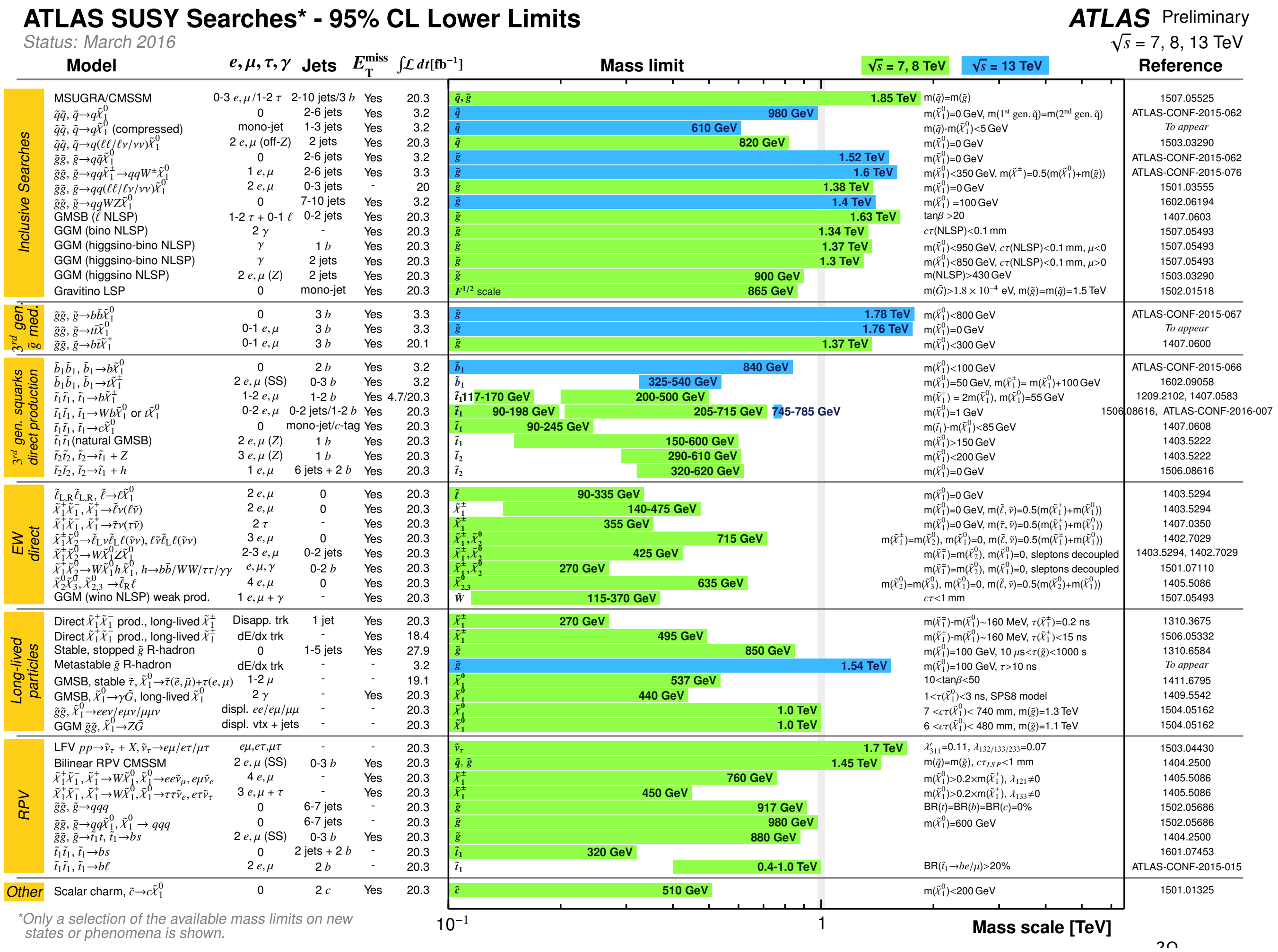
1. Unitarity argument set a scale in the TeV region:

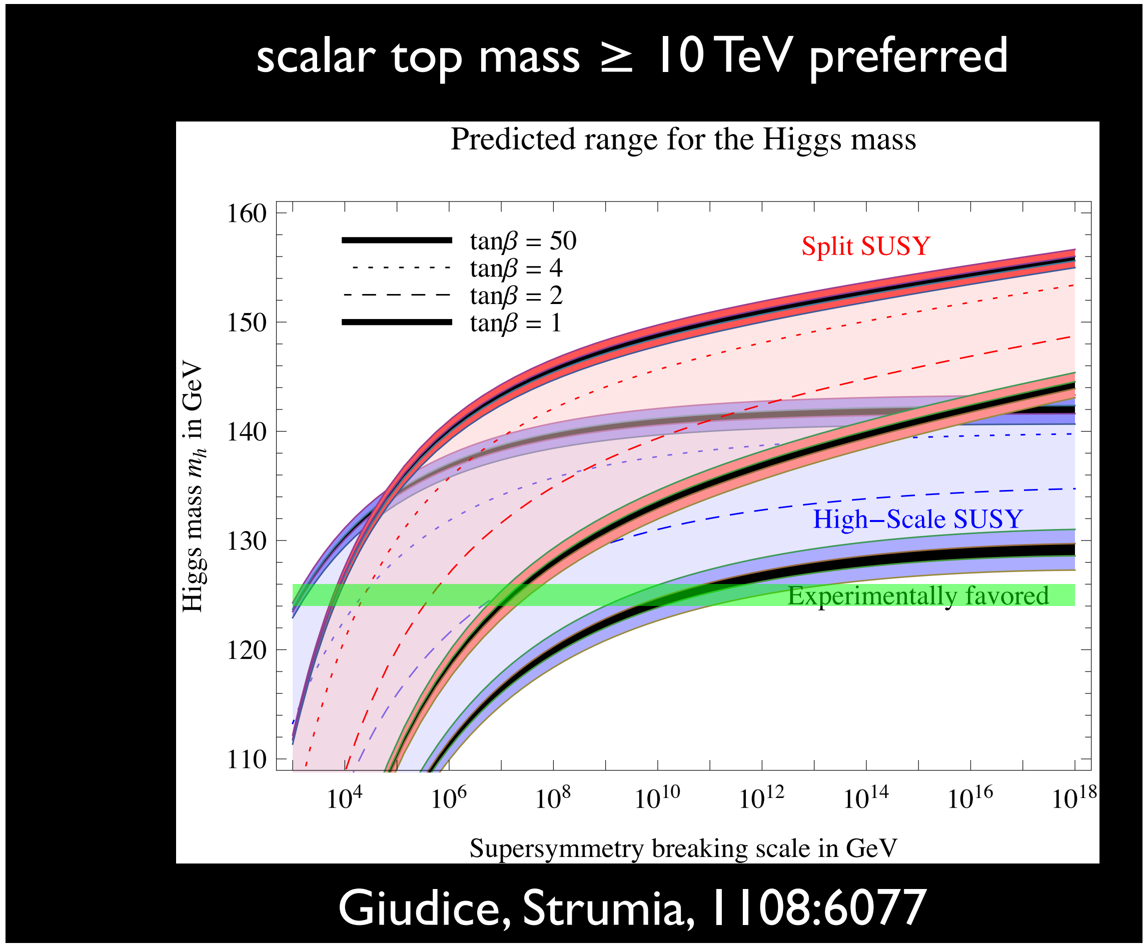
   - Higgs, or ✓ m_H = 125 GeV
   - New strong dynamics, or
   - SUSY particles begin to appear.

2. Naturalness:

   - Composite Higgs -> scale of new dynamics raised moderately
   - SUSY: ✗ MSSM -> More elaborate models - higher gluino masses - some fine tuning
   - New ideas bubbling about conformal theories

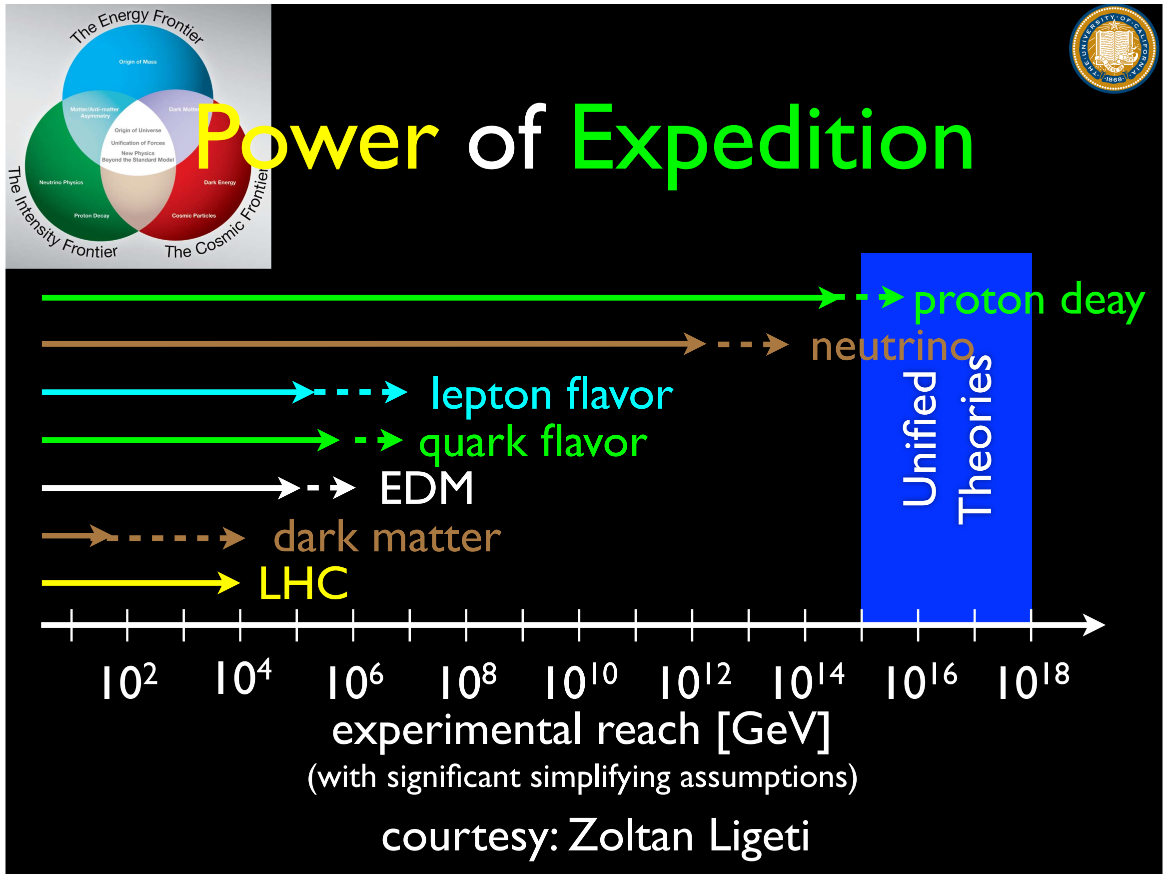
- The observed Higgs mass combined with the failure (to date) to find SUSY partners suggests that the SUSY scale postponed and there is fine tuning (~ 1%) (Murayama's Talk)




scalar top mass ≥ 10 TeV preferred

Giudice, Strumia, 1108:6077

- Standard Model completed with the discover of the Higgs
- Except: (1) Neutrino masses, mixing and CP violation -> new degrees of freedom or new interactions, (2) What is dark matter?, (3) How to explain observed baryon asymmetry, and (4) What is dark energy?
- We know of no nearby new physics scale. Only GUT, Planck, and seesaw [$M(\nu_R)$] scales.
- Discoveries of BSM physics at the LHC would guide the search for non SM effects in rare decays and help to distinguish among BSM models.
- But even if no new particles are found at the LHC there is still power to probe high scale physics in rare decays.



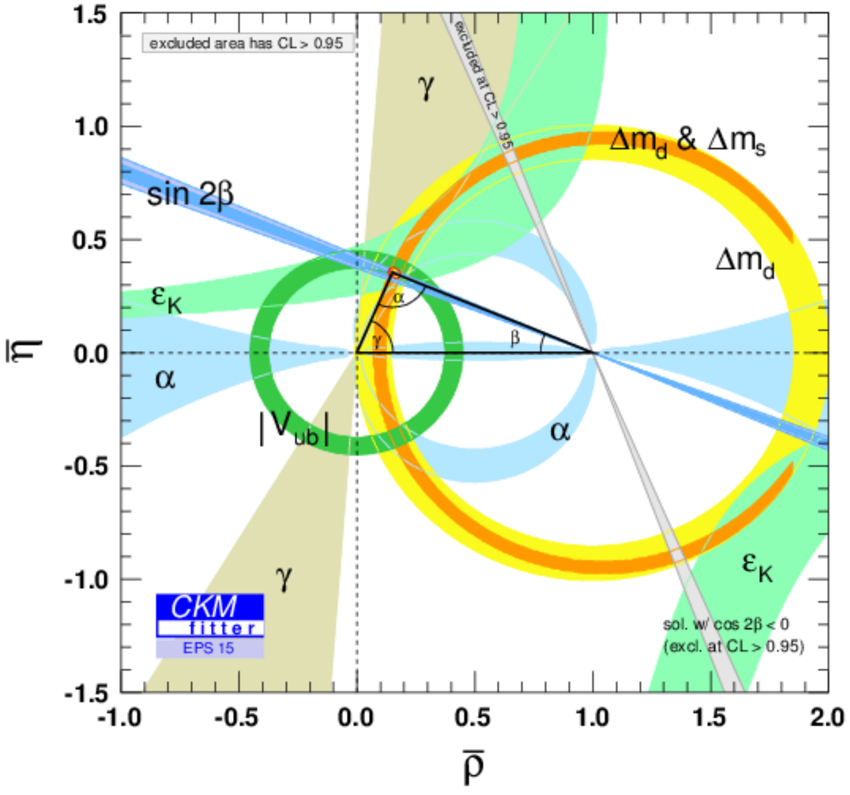
courtesy: Zoltan Ligeti

le plat principal

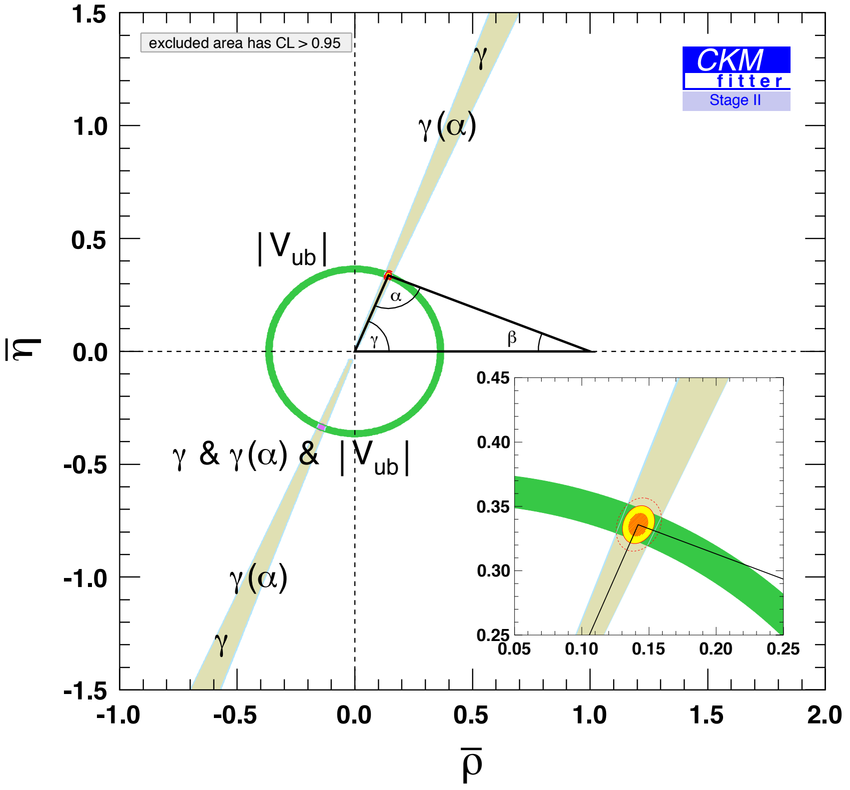
B physics

- Extraordinary improvements in understanding of the quark flavor physics. (The CKM matrix; production and decays of states with heavy quarks; the pattern of Higgs decays)

EPS 2015



Stage 2

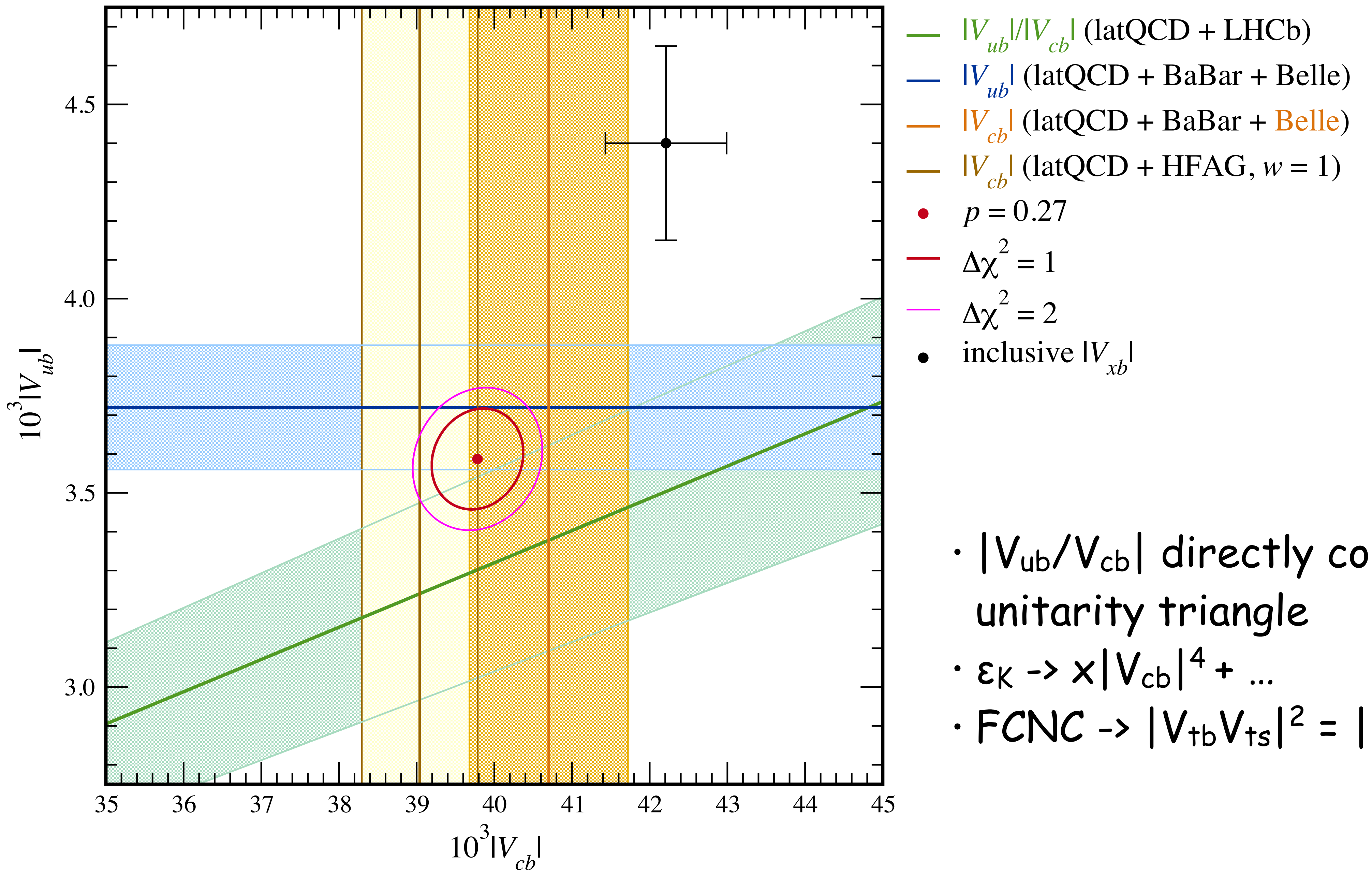


50 ab^{-1} Belle2
50 fb^{-1} LHCb

	2003	2013			Stage 2	
$\sin 2\beta$	0.726 ± 0.037	0.679 ± 0.020	0.679 ± 0.016	[17]	0.679 ± 0.008	[17]
α (mod π)	—	$(85.4^{+4.0}_{-3.8})^\circ$	$(91.5 \pm 2)^\circ$	[17]	$(91.5 \pm 1)^\circ$	[17]
γ (mod π)	—	$(68.0^{+8.0}_{-8.5})^\circ$	$(67.1 \pm 4)^\circ$	[17, 18]	$(67.1 \pm 1)^\circ$	[17, 18]
β_s	—	$0.0065^{+0.0450}_{-0.0415}$	0.0178 ± 0.012	[18]	0.0178 ± 0.004	[18]
$\mathcal{B}(B \to \tau\nu) \times 10^4$	—	1.15 ± 0.23	0.83 ± 0.10	[17]	0.83 ± 0.05	[17]
$\mathcal{B}(B \to \mu\nu) \times 10^7$	—	—	3.7 ± 0.9	[17]	3.7 ± 0.2	[17]
$A^d_{\rm SL} \times 10^4$	10 ± 140	23 ± 26	-7 ± 15	[17]	-7 ± 10	[17]
$A^s_{\rm SL} \times 10^4$	—	-22 ± 52	0.3 ± 6.0	[18]	0.3 ± 2.0	[18]

- Experimental results continue to sharpen the picture.
Theoretical efforts need to keep pace.

- Puzzle of inclusive versus exclusive measures of CKM?



$\Gamma(\Lambda_b \to p l \nu)/\Gamma(\Lambda_b \to \Lambda_c l \nu)$

$B \to \pi l \nu$

$B \to D l \nu$

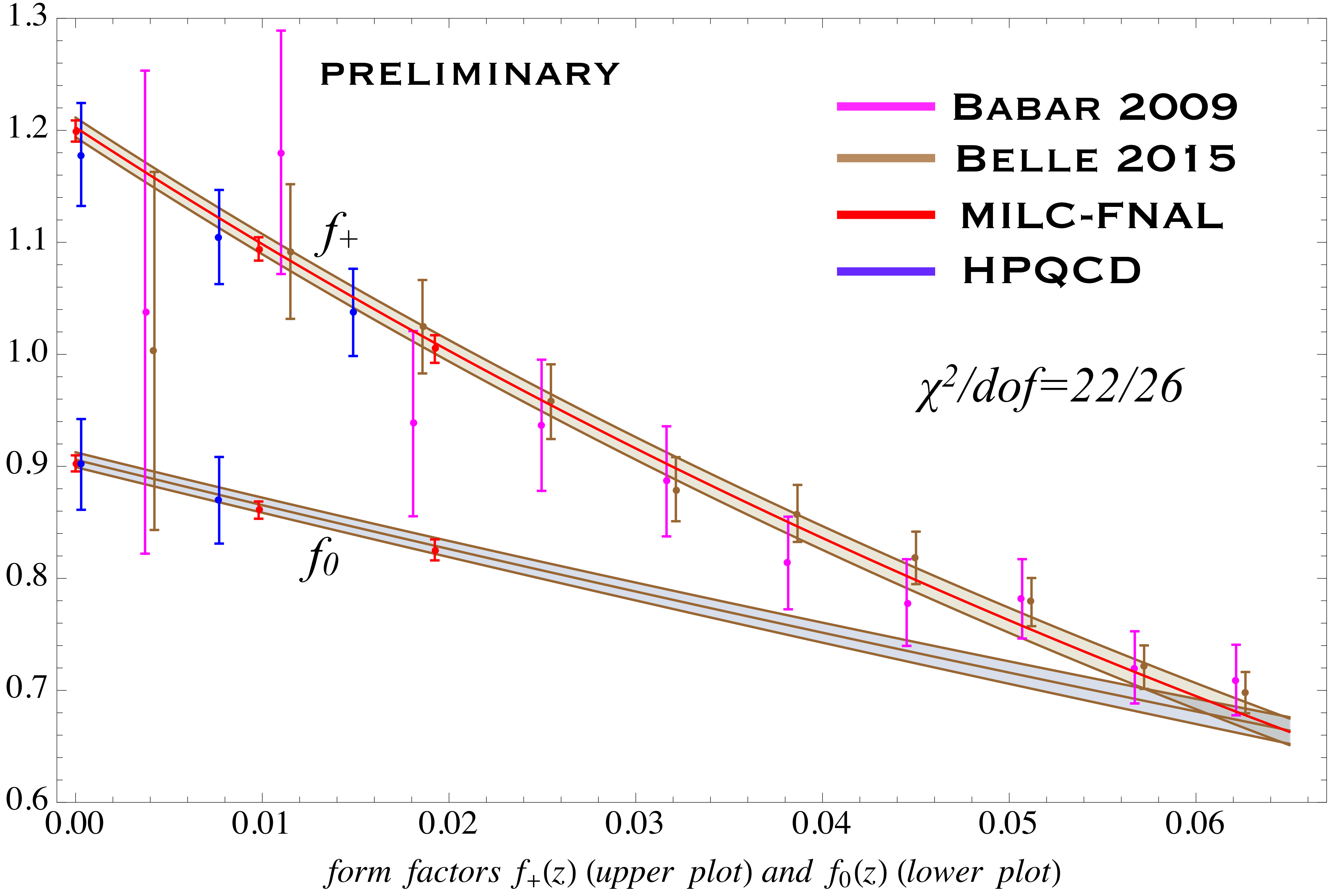
$B \to D^* l \nu$

C. DeTar [arXiv:1511.06884]
Updated A. Kronfeld

- $|V_{ub}/V_{cb}|$ directly constrains the unitarity triangle
- $\varepsilon_K \to x|V_{cb}|^4 + \ldots$
- FCNC -> $|V_{tb}V_{ts}|^2 = |V_{cb}|^2\,(1+\ O(\lambda^2))$

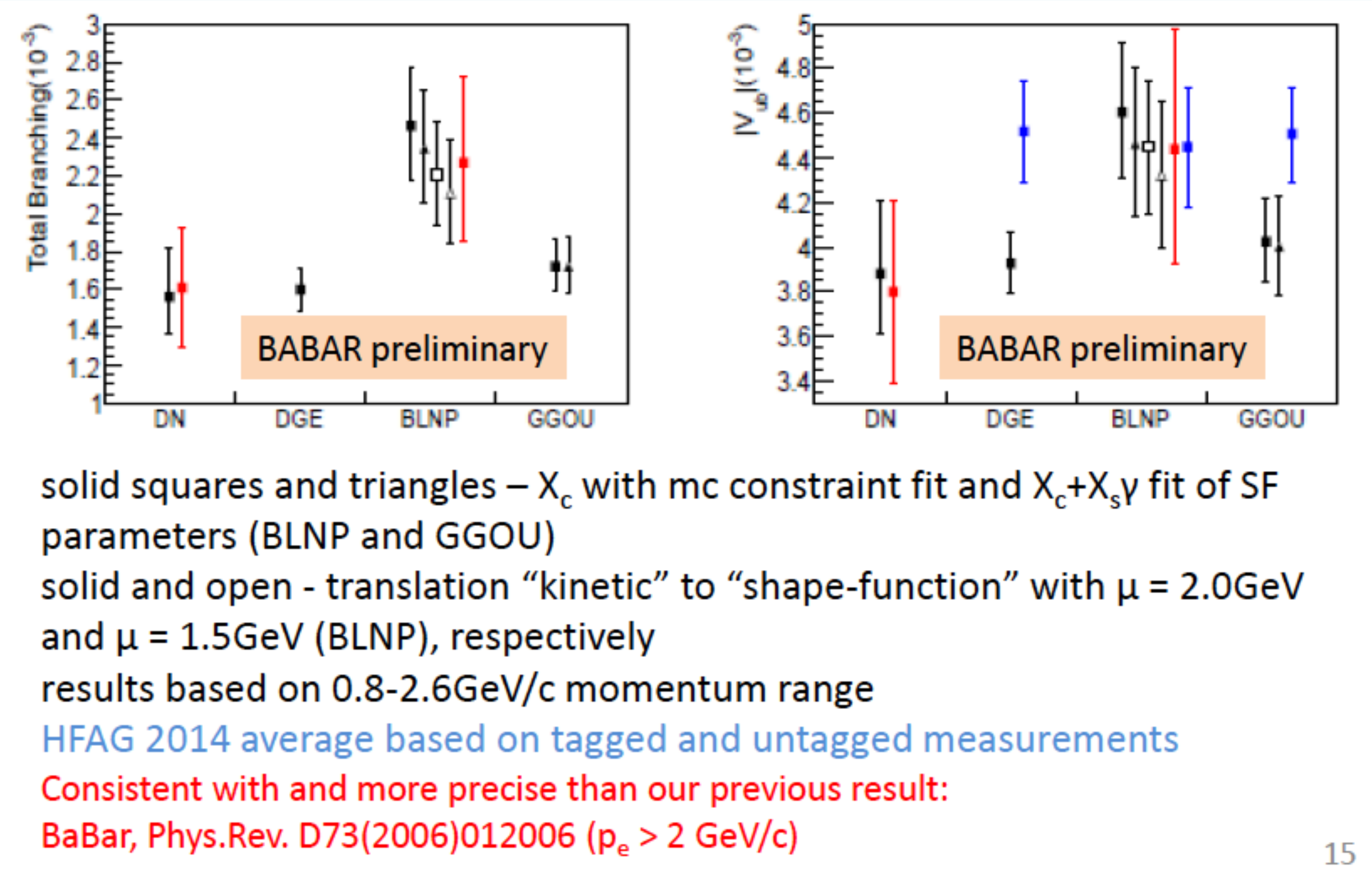
- Exclusive |Vcb| determinations:
  - Sensitive to LQCD calculations and experimental extrapolation to zero recoil.
    - Lattice D* and D results differ. Updates to the D* results might improve this. Particularly fitting to finite recoil as was recently done in the D case.
    - Different systematics in the baryon decays [Detmold, Lehner, & Meinel]. Agreement
- The extraction of $|V_{ub}|$ from inclusive decays have more theoretical challenges.
  - Has to be extracted in limited phase space range.
    - At and beyond endpoint of b->c decays.
    - Higher order contributions
    - Sensitivity to non perturbative contributions
    - Shape factors need to be determined
- Remaining issues are likely mostly in the extraction of the $|V_{ub}|$ inclusive results.

Global fit to B→Dlν D.Bigi, PG



NEW preliminary Babar endpoint analysis

High sensitivity of the BR on the shape of the signal in the endpoint region. GGOU: $|V_{ub}| = 4.03^{+0.20}_{-0.22} \times 10^{-3}$



solid squares and triangles – X_c with mc constraint fit and X_c+$X_s\gamma$ fit of SF parameters (BLNP and GGOU)

solid and open - translation “kinetic” to “shape-function” with μ = 2.0GeV and μ = 1.5GeV (BLNP), respectively

results based on 0.8-2.6GeV/c momentum range

HFAG 2014 average based on tagged and untagged measurements

Consistent with and more precise than our previous result:
BaBar, Phys.Rev. D73(2006)012006 (p_e > 2 GeV/c)

15

Y.SKOVPEN, EPS-PH 2015

SUMMARY

Paolo Gambino

- Improvements of OPE approach to s.l. decays continue. $O(\alpha_s\Lambda^2/m_b^2)$ effects implemented. **No sign of inconsistency in this approach so far**, **competitive m_b determination.**

- Exclusive/incl. tension in V_{cb} remains (3σ, 8%) only in the D^* channel. The **D channel is becoming competitive and is compatible with both**. The remaining tension calls for new lattice analyses and new data (ongoing Belle analysis, Belle-II)

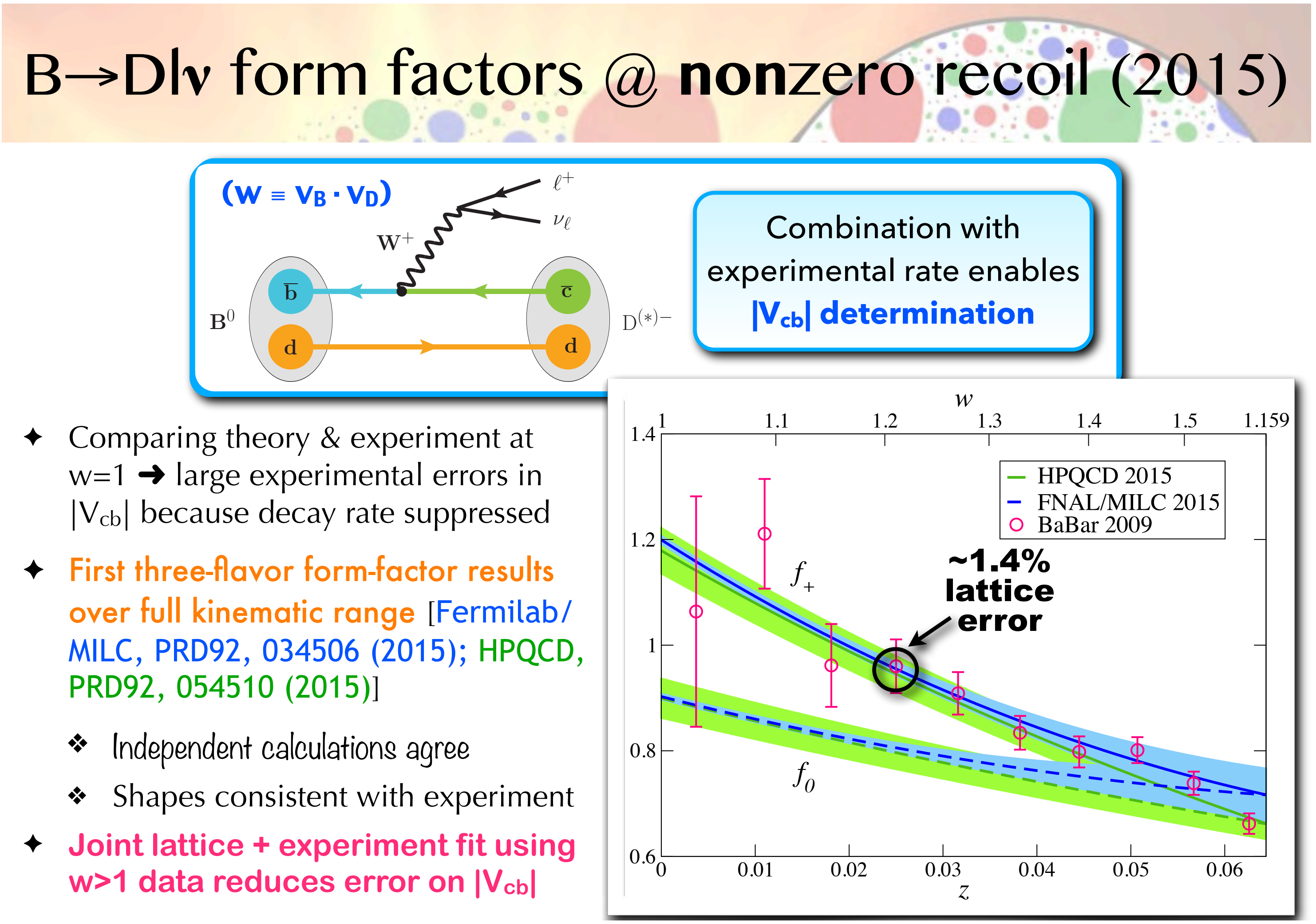
- Exclusive/incl tension in V_{ub} appears receding because of new FNAL/MILC and HPQCD results and of preliminary Babar results.

- New physics explanations less constrained for V_{ub} than for V_{cb}, but right handed current disfavoured. RH currents don't help.

- Belle-II will improve precision and allow for consistency checks of our methods, especially for inclusive V_{ub}. LHCb potential (for exclusives) greater than expected.

Combining All Approaches

- Lattice QCD provides essential non-perturbative information for the comparison of theory with experiment.
- Ruth Van de Water's talk
  - In the past year new results on B -> D, B -> π form factors and $B_{(d,s)}$ significantly improved precision.



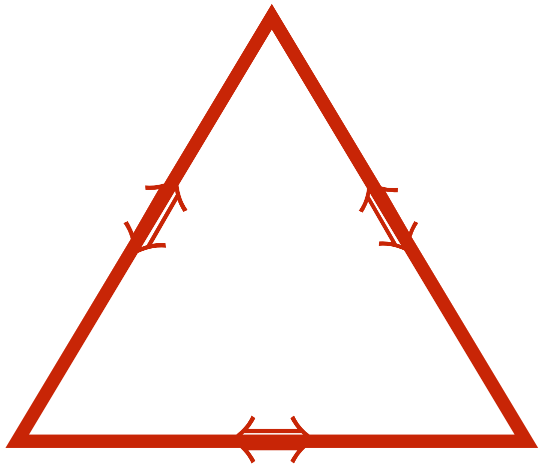
B→Dlν form factors @ **nonzero recoil** (2015)

($w \equiv v_B \cdot v_D$)

Combination with experimental rate enables **$|V_{cb}|$ determination**

- ✦ Comparing theory & experiment at w=1 ➔ large experimental errors in $|V_{cb}|$ because decay rate suppressed
- ✦ First three-flavor form-factor results over full kinematic range [Fermilab/MILC, PRD92, 034506 (2015); HPQCD, PRD92, 054510 (2015)]
  - ❖ Independent calculations agree
  - ❖ Shapes consistent with experiment
- ✦ **Joint lattice + experiment fit using w>1 data reduces error on $|V_{cb}|$**

- Tensions remain



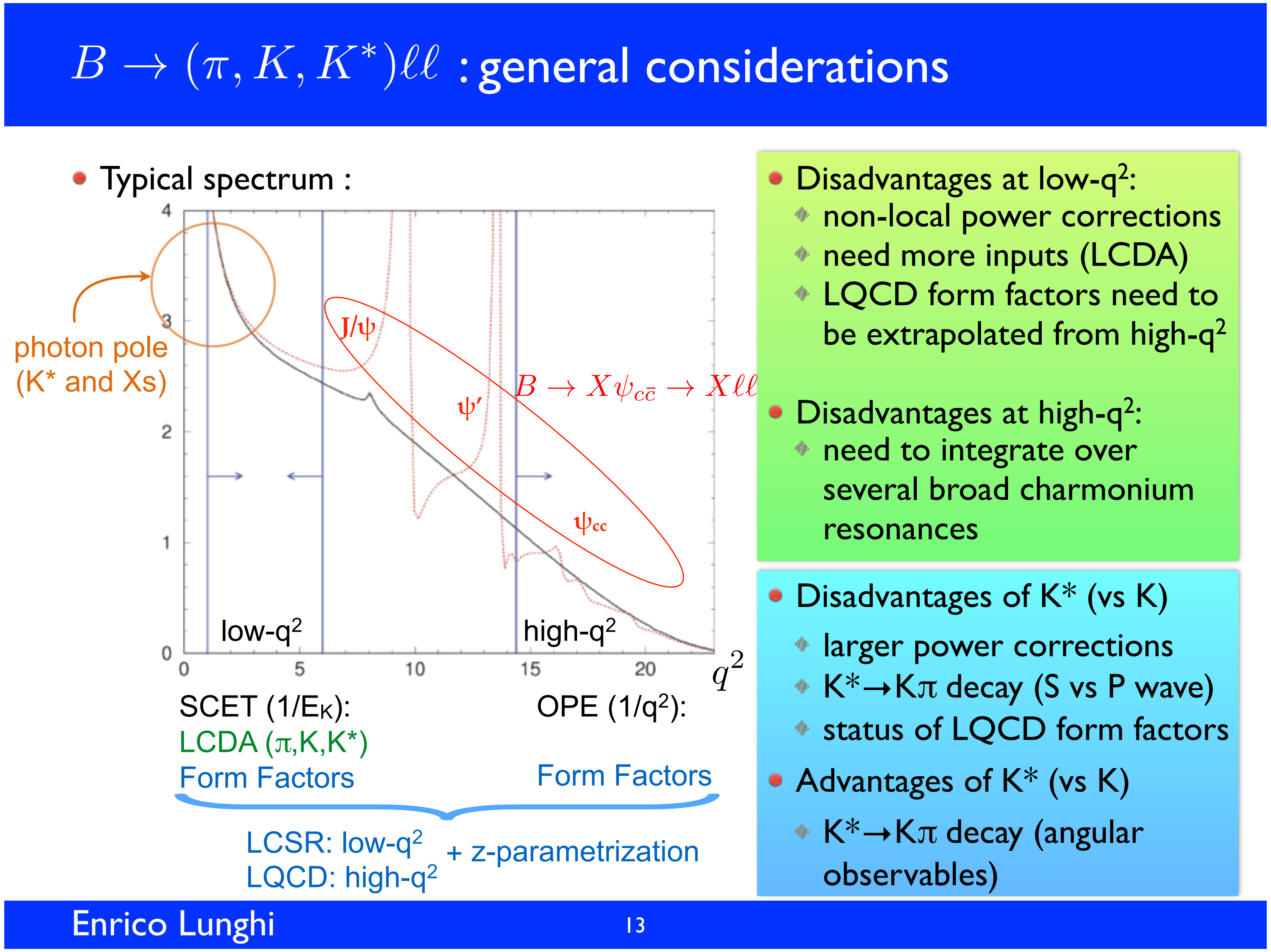
Experiment

Lattice QCD

Theoretical Tools

- In addition to Lattice QCD there are a wealth of theoretical tools
  - HQET/SCET$_{II}$, LCSR, pQCD, OPE
  - Applying these methods to semileptonic B decays — distinct regions of applicability

Enrico Lunghi



$B \to (\pi, K, K^*)\ell\ell$: general considerations

- Typical spectrum :

SCET (1/E$_K$):
LCDA (π,K,K*)
Form Factors

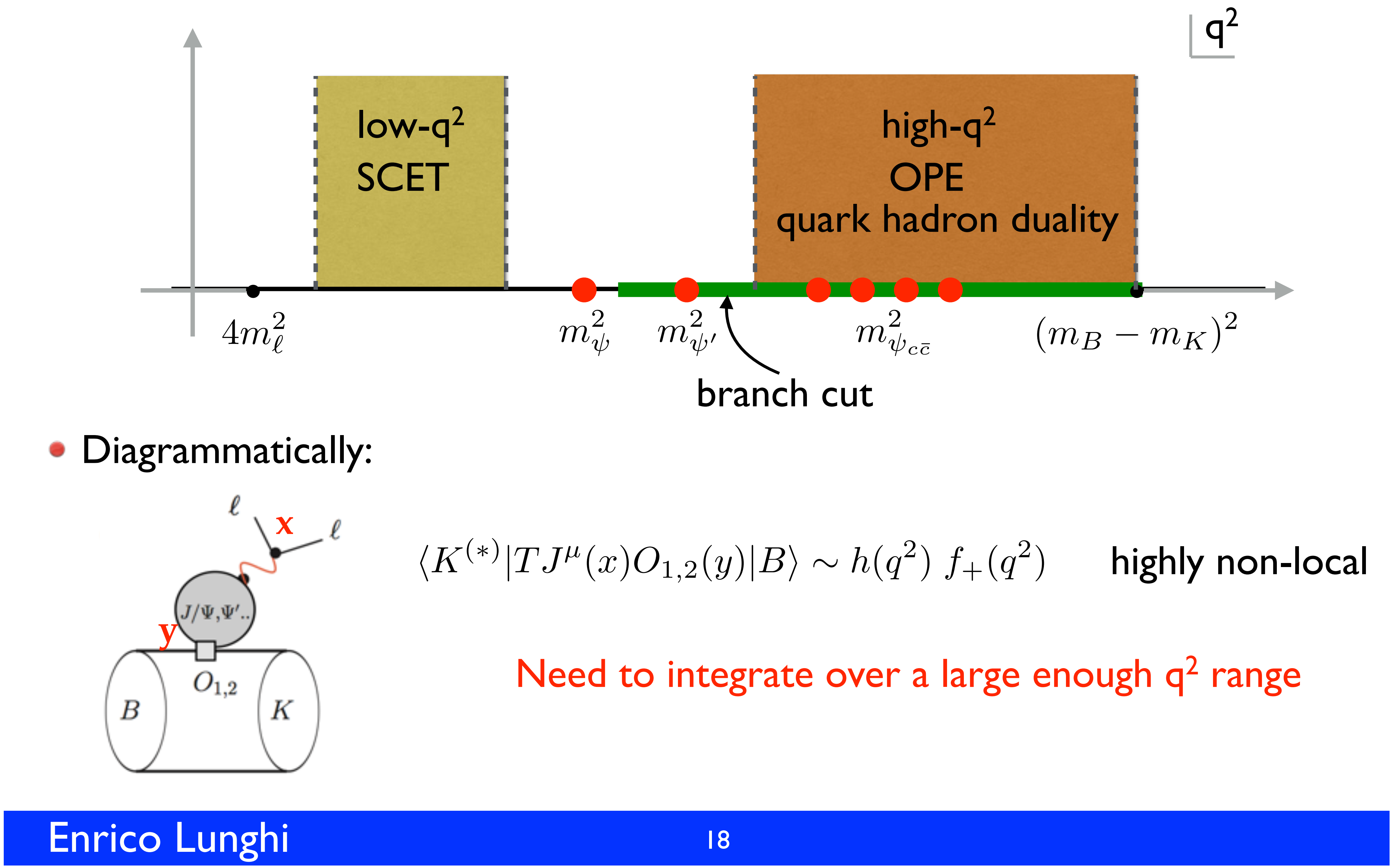
OPE (1/q^2):
Form Factors

LCSR: low-q^2
LQCD: high-q^2
+ z-parametrization

- Disadvantages at low-q^2:
  - non-local power corrections
  - need more inputs (LCDA)
  - LQCD form factors need to be extrapolated from high-q^2
- Disadvantages at high-q^2:
  - need to integrate over several broad charmonium resonances
- Disadvantages of K* (vs K)
  - larger power corrections
  - K*→Kπ decay (S vs P wave)
  - status of LQCD form factors
- Advantages of K* (vs K)
  - K*→Kπ decay (angular observables)

Enrico Lunghi 13

- Analytic structure in the q^2 plane



- Diagrammatically:

$$\langle K^{(*)}|TJ^\mu(x)O_{1,2}(y)|B\rangle \sim h(q^2)\ f_+(q^2)$$

highly non-local

Need to integrate over a large enough q^2 range

- We will return to this shortly.

- Many B decay measurements - Some hints of deviations {(3 ± 1) σ} from the standard model:

$$B_{(d,s)} \to \mu^+\mu^-$$

B -> $K^{(*)}$ μ^+ μ^- angular distributions

$$R_K = \frac{BR(B \to K\ \mu^+\ \mu^-)}{BR(B \to K\ e^+\ e^-)}$$

Bs -> ϕ μ^+ μ^-

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\ \tau\ \nu_\tau)}{BR(B \to D^{(*)}\ l\ \nu_l)}$$

- On the horns of a dilemma - 3σ deviations from the SM

BSM detectives

SUSY
Leptoquarks
Extended Higgs Sector
Little Higgs Models
Z'
331 models
…

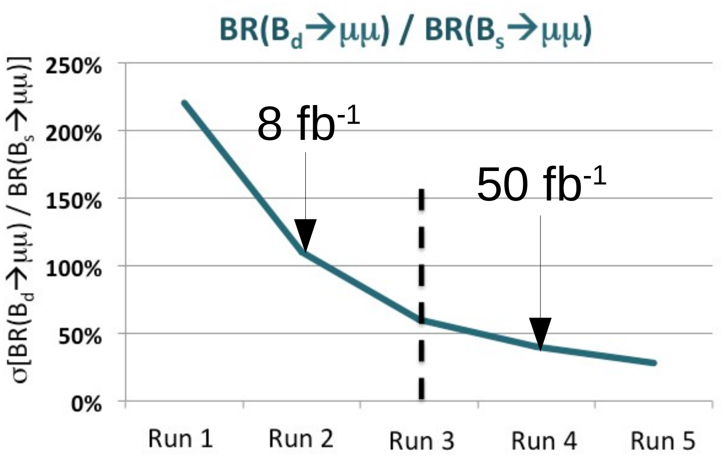
SM magistrats

HQET/SCET
Lattice QCD
OPE
Pert QCD
SCET
Sum Rules
…

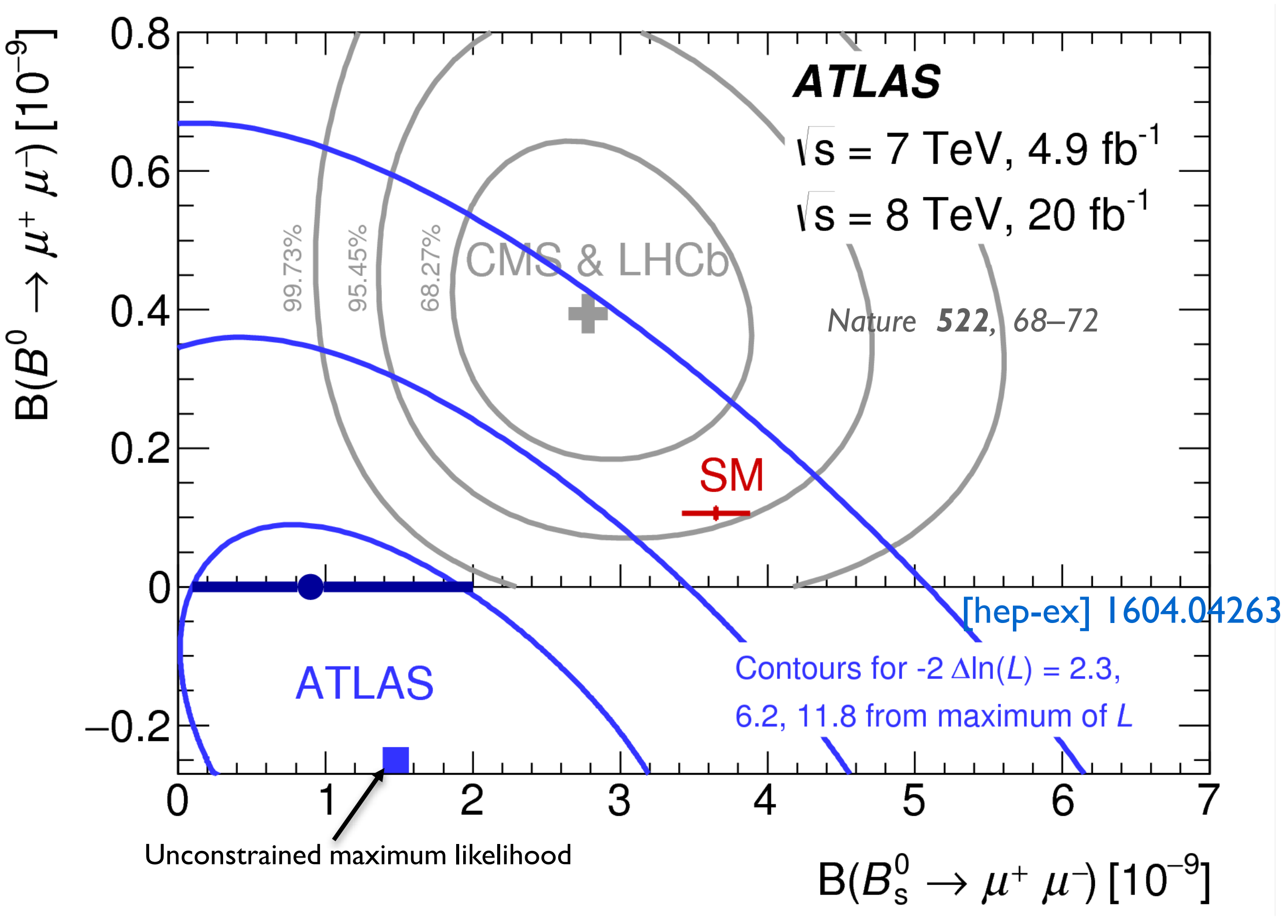
Engrenages - Will these clues lead to the unwinding of the Standard Model?

- Clean theoretically:
- BR(B_s->μμ) = (3.65 + 0.23)x10^{-9}

  BR(B_d->μμ) = (1.06 + 0.09) x10^{-10}
- With new Atlas results some tension with SM in B_s
- Await more data.
  - LHCb with 50 fb^{-1}
    - BR(B_s->μμ) to 5%
    - BR(B_d->μμ)/BR(B_s->μμ) to 35%

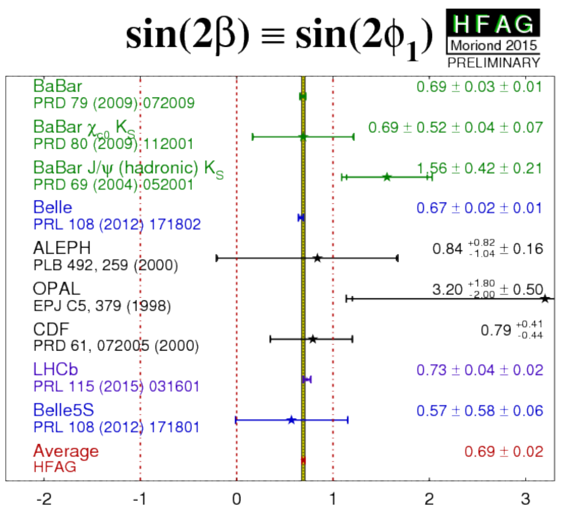


Inputs from LCHB-PUB2014-040



- Mixing and CP violation

B^0–$\overline{B}^0$ mixing phase ϕ_d

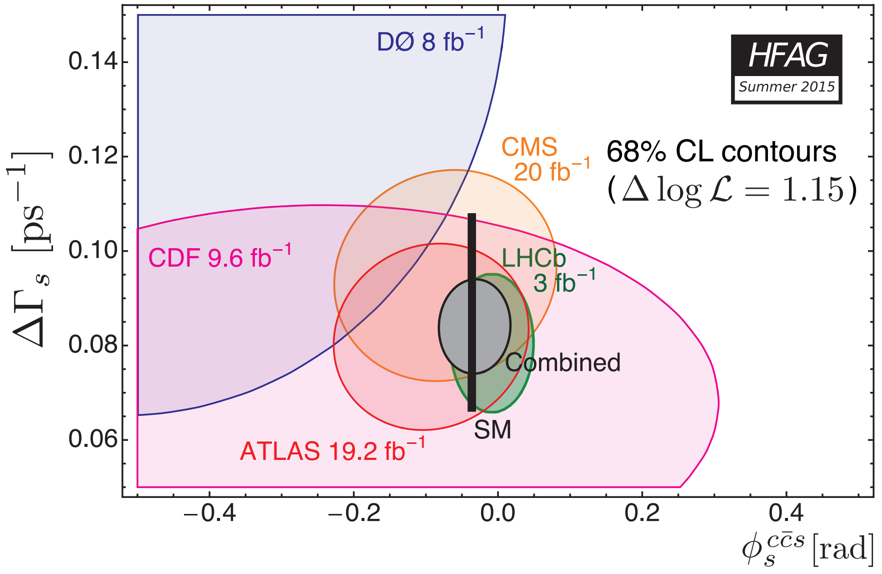


Golden Mode: $B^0 \to J/\psi\, K^0_S$

$$\phi^{\text{eff}}_{d,J/\psi K^0} = [42.2 \pm 1.5]^\circ$$

$$\phi^{\text{SM}}_d = [48.6 \pm 2.6]^\circ$$

B^0_s–$\overline{B}^0_s$ mixing phase ϕ_s



Golden Mode: $B^0_s \to J/\psi\, \phi$

$$\phi^{\text{eff}}_s = -0.034 \pm 0.033 = [-1.9 \pm 1.9]^\circ$$

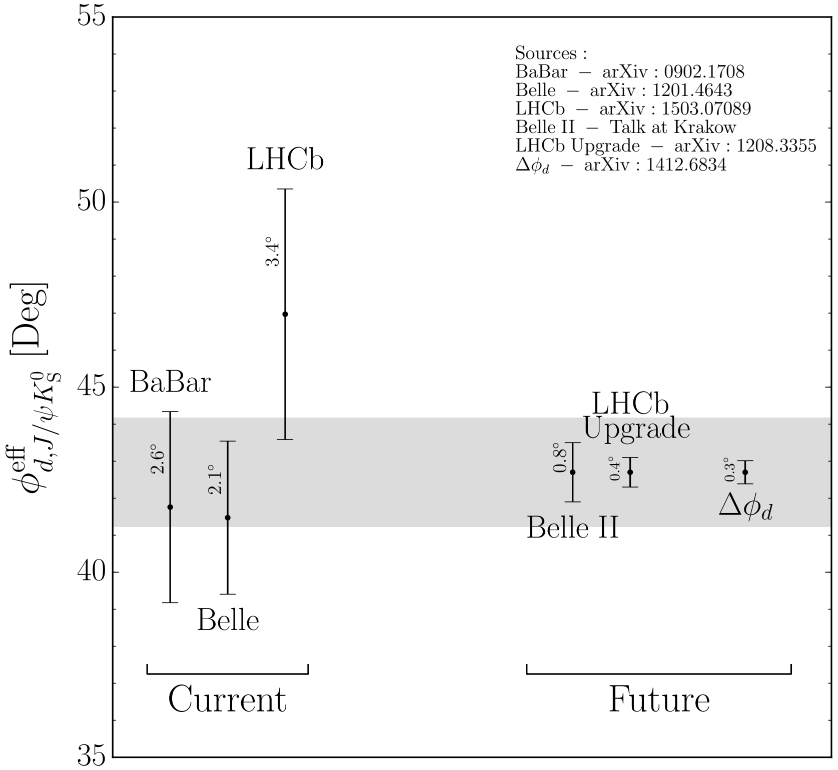
$$\phi^{\text{SM}}_s = -0.03761^{+0.00073}_{-0.00082} = [-2.155^{+0.042}_{-0.047}]^\circ$$

[HFAG] & [CKMFitter]

- Need a strategy to systematically improve the theoretical calculations of penguins contributions to ϕ_d and ϕ_s K. De Bruyn and R. Fleischer JHEP 1503 (2015) 145
- Strategy to control penguins :

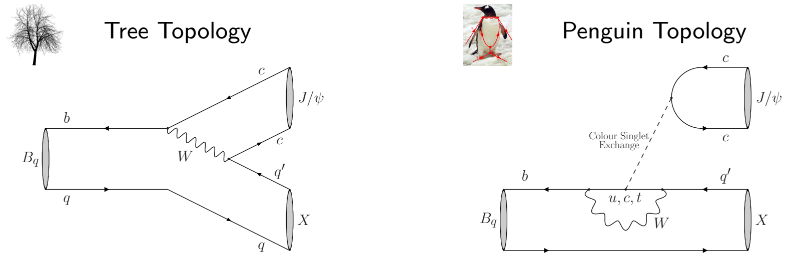
$$\frac{\mathcal{A}_{CP}^{\text{mix}}(B_q^0 \to f)}{\sqrt{1-\left(\mathcal{A}_{CP}^{\text{dir}}(B_q^0 \to f)\right)^2}} = \sin\left(\phi_q^{\text{eff}}\right) = \sin\left(\phi_q^{\text{SM}} + \phi_q^{\text{NP}} + \Delta\phi_q\right)$$

  - $\Delta\phi_q$ small so need accurate method to determine them.



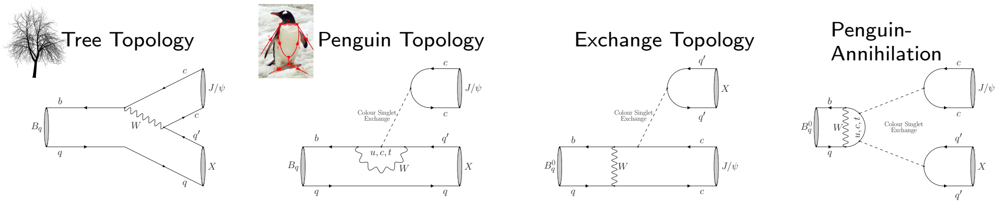
  - Strategies to get these corrections directly from data using SU(3) flavor symmetry.

Kristof De Bruyn



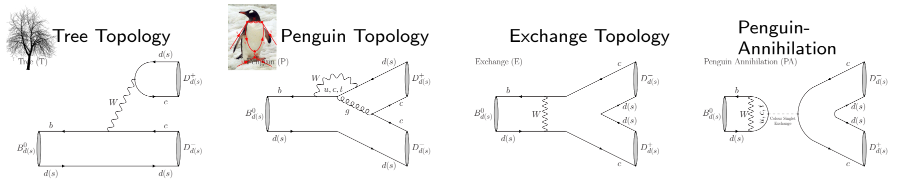
Golden Mode $B^0 \to J/\psi K_S^0$:

$$A(B^0 \to J/\psi K_S^0) = \left(1 - \frac{1}{2}\lambda^2\right)\mathcal{A}'\left[1 + \epsilon a' e^{i\theta'} e^{i\gamma}\right], \qquad \epsilon \equiv \frac{\lambda^2}{1-\lambda^2} \approx 0.053$$



Amplitude:

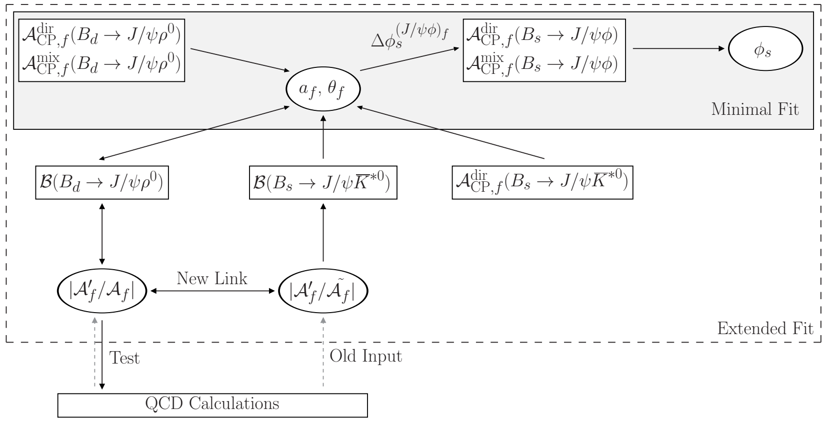
$$A(B_s^0 \to J/\psi\,\phi) = \left(1 - \frac{1}{2}\lambda^2\right)\mathcal{A}'_f\left[1 + \epsilon a'_f e^{i\theta'_f} e^{i\gamma}\right], \qquad \epsilon \equiv \frac{\lambda^2}{1-\lambda^2} \approx 0.053$$

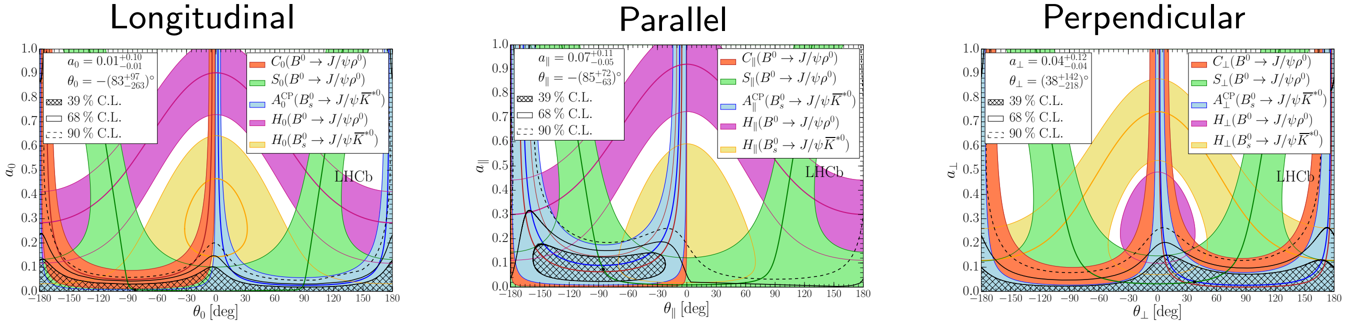


Amplitude:

$$A(B_s^0 \to D_s^- D_s^+) = \left(1 - \frac{1}{2}\lambda^2\right)\mathcal{A}'\left[1 + \epsilon a' e^{i\theta'} e^{i\gamma}\right], \qquad \epsilon \equiv \frac{\lambda^2}{1-\lambda^2} \approx 0.053$$

- $B_s \to J/\psi\,\phi$





Results from χ^2 fit:

$$a_0 = 0.01^{+0.10}_{-0.01}\,,\quad \theta_0 = -\left(82^{+98}_{-262}\right)^\circ,\quad \Delta\phi_s^{(J/\psi\,\phi)_0} = -\left(0.000^{+0.011}_{-0.009}\,(\text{stat.})^{+0.009}_{-0.004}\,(SU(3))\right)^\circ$$

$$a_\parallel = 0.07^{+0.11}_{-0.05}\,,\quad \theta_\parallel = -\left(85^{+71}_{-63}\right)^\circ,\quad \Delta\phi_s^{(J/\psi\,\phi)_\parallel} = \left(0.001^{+0.014}_{-0.010}\,(\text{stat.}) \pm 0.008\,(SU(3))\right)^\circ$$

$$a_\perp = 0.04^{+0.12}_{-0.04}\,,\quad \theta_\perp = \left(38^{+142}_{-218}\right)^\circ,\quad \Delta\phi_s^{(J/\psi\,\phi)_\perp} = \left(0.003^{+0.014}_{-0.010}\,(\text{stat.}) \pm 0.008\,(SU(3))\right)^\circ$$

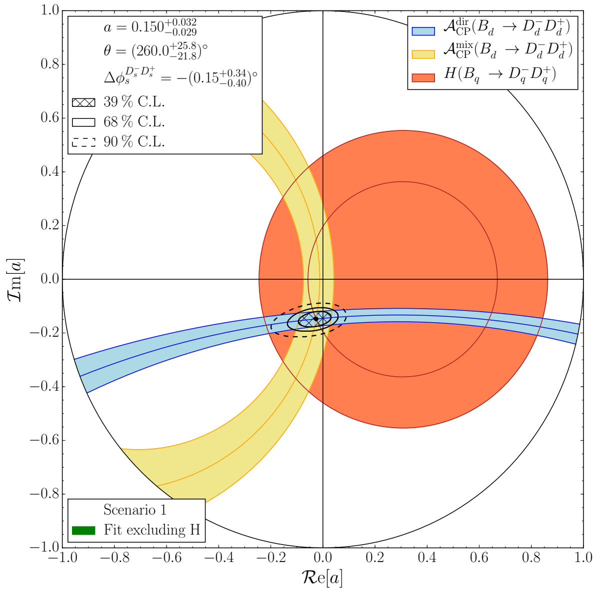
[LHCb, `arxiv:1509.00400 [hep-ex]`]

We can control the penguin effects!

- $B_s \to D_s^+ D_s^-$

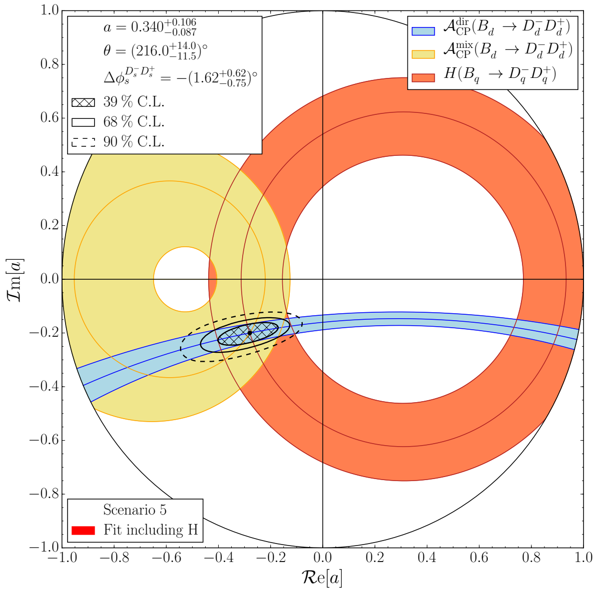
$$H = \left|\frac{V_{cs}}{V_{cd}}\right|^2 \left[\frac{R_{D_d}}{R_{D_s}}\right]\left[\frac{f_{D_s}}{f_{D_d}}\right]^2\left[\frac{X_{D_s}}{X_{D_d}}\right]\left|\frac{a^{(s)}_{\rm NF}}{a^{(d)}_{\rm NF}}\right|^2$$

Favourable Strategy:



- The use of the H observable can be avoided

Less Favourable Strategy:



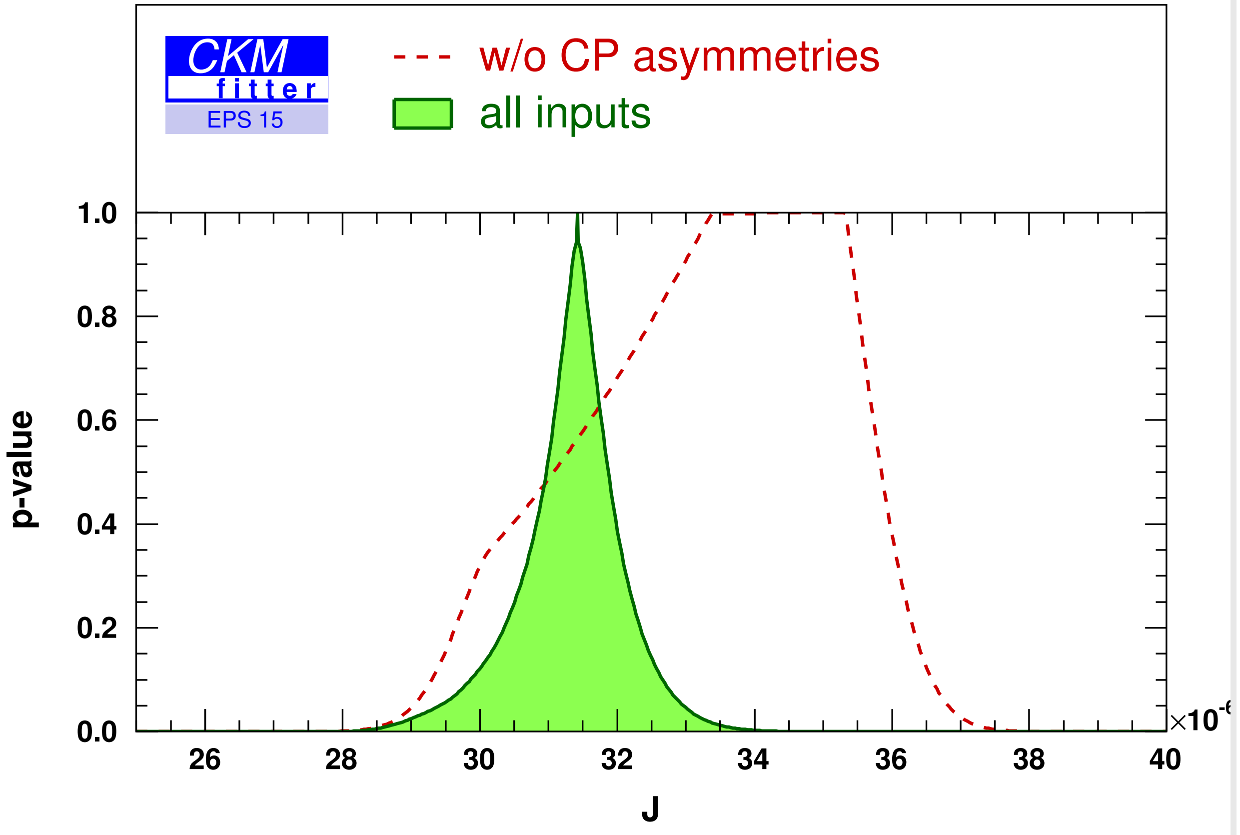
- The use of the H observable is necessary to determine a and θ

Jerome Charles

- Jarlskog invariant

$$\begin{aligned}\mathrm{Im}\left(V_{ij}V_{kl}V_{il}^{*}V_{kj}^{*}\right) &= J\sum_{m,n=1}^{3}\varepsilon_{ikm}\varepsilon_{jln}\\ J &= c_{12}c_{23}c_{13}^{2}s_{12}s_{23}s_{13}\sin\delta\end{aligned}$$

  - Can determine from CP conserving observables. Special feature of the three generation standard model.



- Accuracy of predictions of CP asymmetries in quark sector depends on the possibility to get rid of hadronic effects or compute them.

Theoretical cleanliness

***	γ	exact at LO of weak int.
***	$A_{\mathrm{SL,(d,s)}}$ [if null test]	SM pred. vanishingly small
**	α, β, β_s	penguins may show up
*	ε_K, $A_{\mathrm{SL,(d,s)}}$ [if finite value]	non trivial had. input
*/?	ε'/ε, rare B, D system, direct CP ...	requires further progress

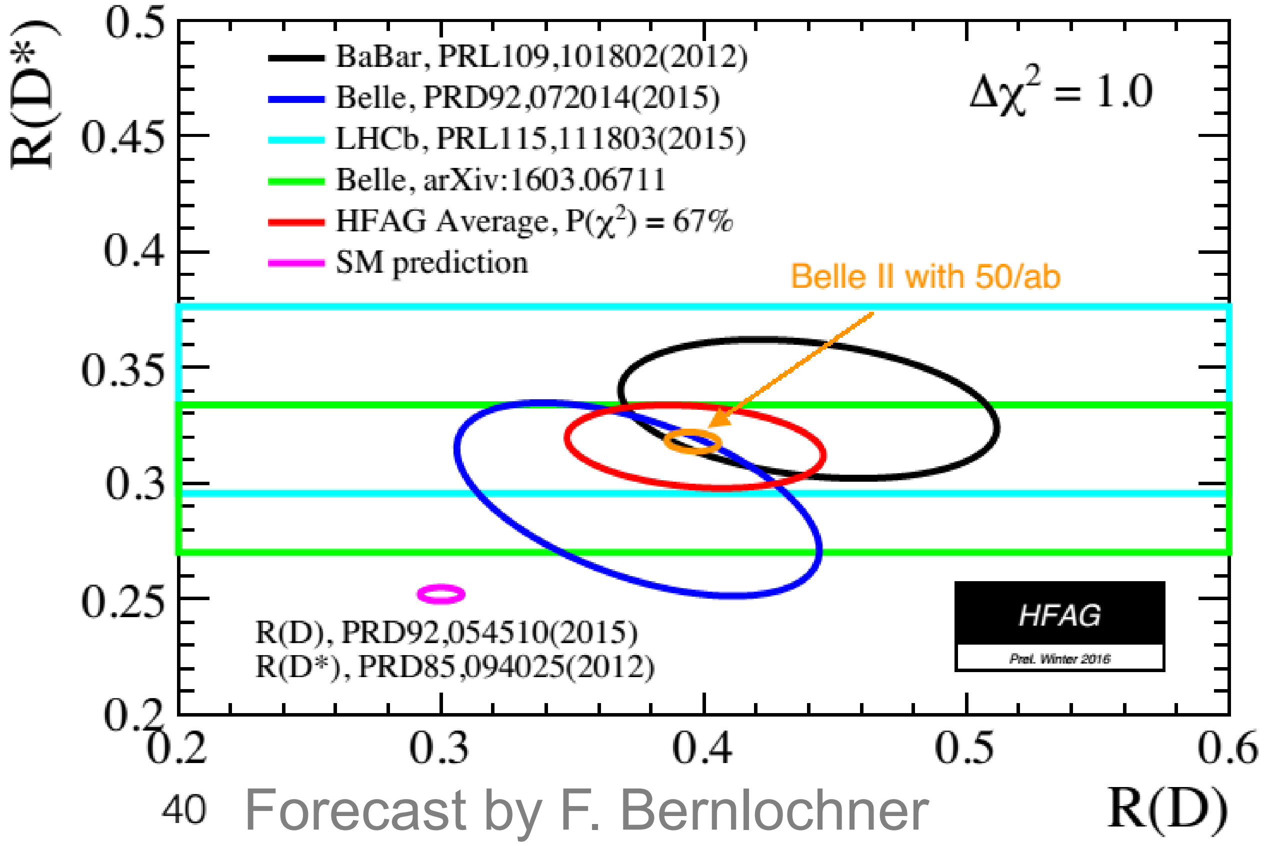
Exclusive Semileptonic Decays

- R_D and R_{D^*}

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\ \tau\ \nu_\tau)}{BR(B \to D^{(*)}\ l\ \nu_l)}$$

New Belle arXiv:1603.06711
$R(D^*)=0.302\pm0.030(stat)\pm0.011(syst)$
within 1.6σ of SM

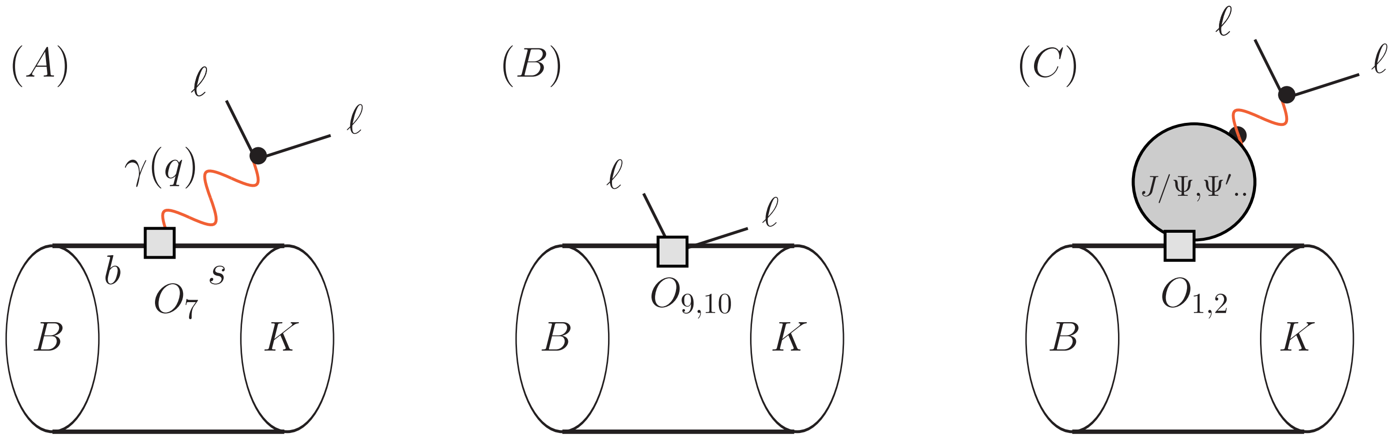
HPQCD [arXiv:1505.03925]
R(D)=0.300 (8) LQCD



- Depends on form factor shape. Dependence on CKM and m_b cancels.
- Lattice QCD computes this form factor shape.

HFAG fit:4σ disagreement with SM

- b -> s transitions



$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}}\left(\sum_{i=1}^{2}(\lambda_u C_i \mathcal{O}_i^u + \lambda_c C_i \mathcal{O}_i^c) - \lambda_t \sum_{i=3}^{10} C_i \mathcal{O}_i\right), \qquad \lambda_i \equiv V_{is}^* V_{ib} \qquad \lambda_u + \lambda_c + \lambda_t = 0.$$

$$\mathcal{O}_1^q = (\bar{s}_i q_j)_{V-A}(\bar{q}_j b_i)_{V-A} \qquad \mathcal{O}_2^q = (\bar{s}_i q_i)_{V-A}(\bar{q}_j b_j)_{V-A}$$

$$\mathcal{O}_3 = (\bar{s}_i b_i)_{V-A}\sum_q (\bar{q}_j q_j)_{V-A} \qquad \mathcal{O}_4 = (\bar{s}_i b_j)_{V-A}\sum_q (\bar{q}_j q_i)_{V-A}$$

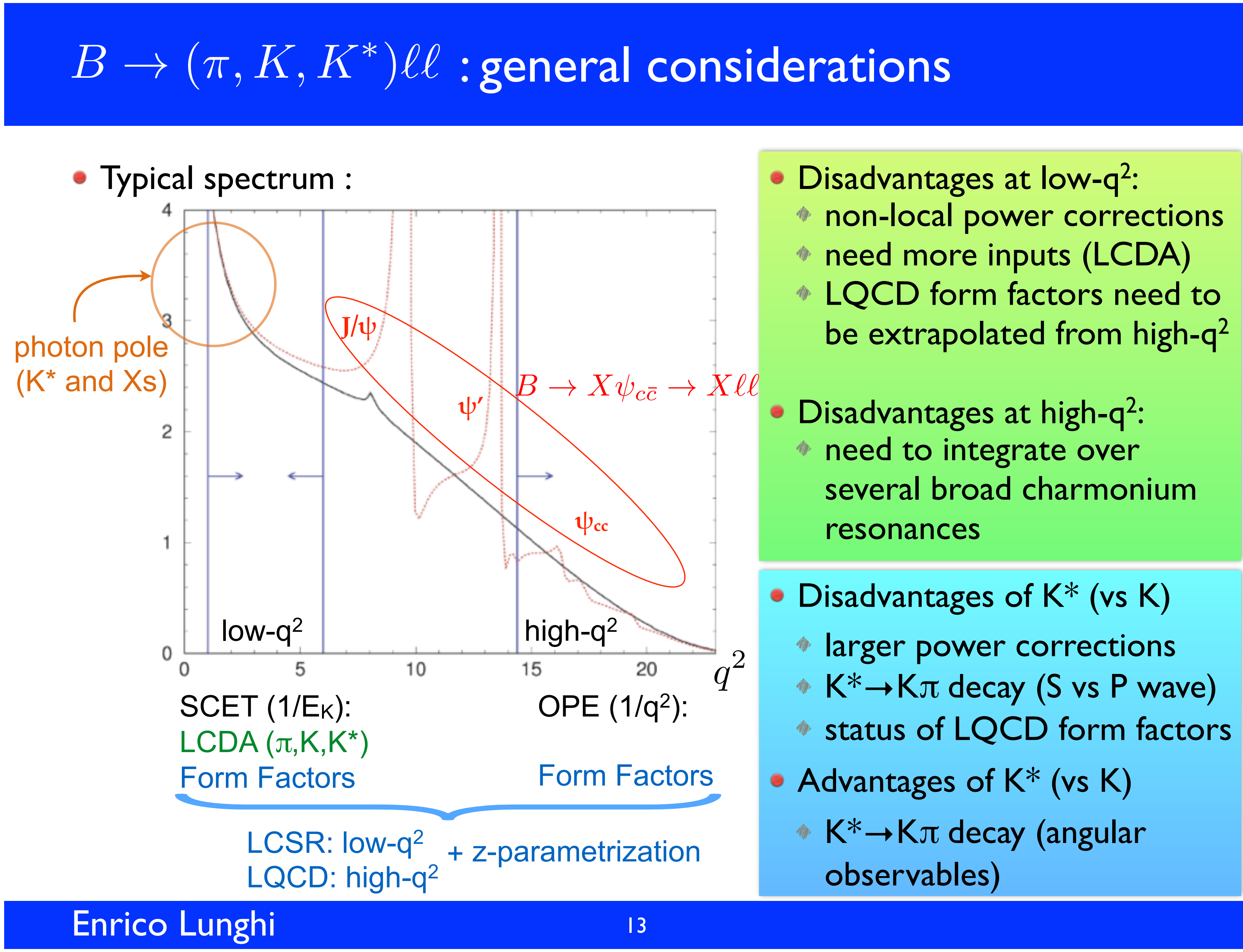
$$\mathcal{O}_5 = (\bar{s}_i b_i)_{V-A}\sum_q (\bar{q}_j q_j)_{V+A} \qquad \mathcal{O}_6 = (\bar{s}_i b_j)_{V-A}\sum_q (\bar{q}_j q_i)_{V+A}$$

$$\mathcal{O}_7 = -\frac{e m_b}{8\pi^2}\bar{s}\sigma\cdot F(1+\gamma_5)b \qquad \mathcal{O}_8 = -\frac{g_s m_b}{8\pi^2}\bar{s}\sigma\cdot G(1+\gamma_5)b$$

$$\mathcal{O}_9 = \frac{\alpha}{2\pi}(\bar{\ell}\gamma^\mu \ell)(\bar{s}\gamma_\mu(1-\gamma_5)b) \qquad \mathcal{O}_{10} = \frac{\alpha}{2\pi}(\bar{\ell}\gamma^\mu\gamma_5 \ell)(\bar{s}\gamma_\mu(1-\gamma_5)b)$$

prime (L⟷R)

- $B_d \to K^{(*)}\mu^+\mu^-$



$B \to (\pi, K, K^*)\ell\ell$: general considerations

- Typical spectrum :

SCET (1/EK):
LCDA (π,K,K*)
Form Factors

OPE (1/q²):
Form Factors

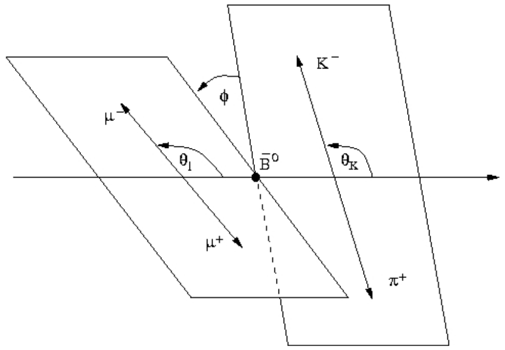
LCSR: low-q²
LQCD: high-q²
+ z-parametrization

- Disadvantages at low-q²:
  - non-local power corrections
  - need more inputs (LCDA)
  - LQCD form factors need to be extrapolated from high-q²
- Disadvantages at high-q²:
  - need to integrate over several broad charmonium resonances

- Disadvantages of K* (vs K)
  - larger power corrections
  - K*→Kπ decay (S vs P wave)
  - status of LQCD form factors
- Advantages of K* (vs K)
  - K*→Kπ decay (angular observables)

Enrico Lunghi 13

- Amplitudes (L,R): $A_0, A_{||}, A_\perp$
  - **4-body decay**

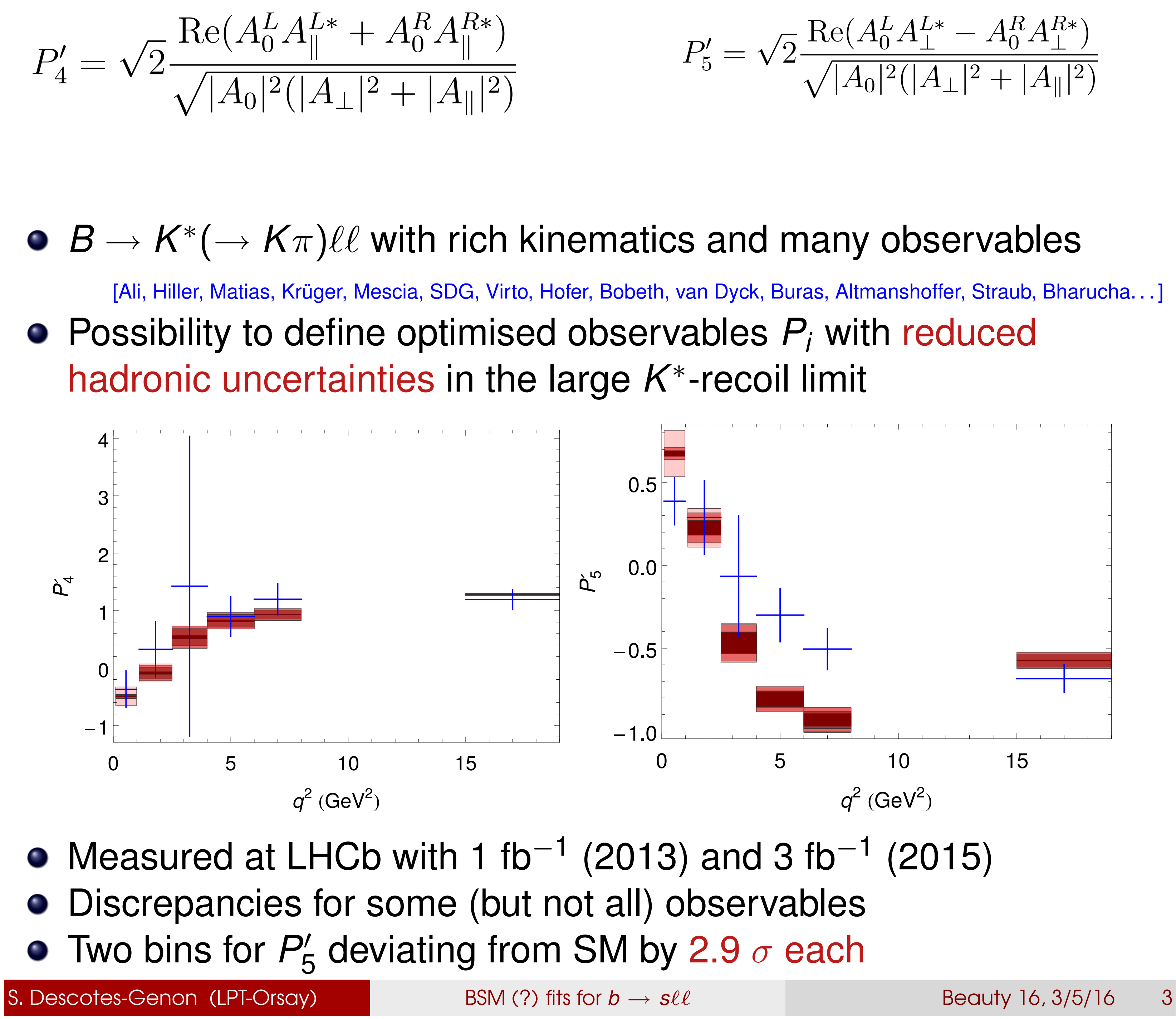


$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l)\, d(\cos\theta_k)\, d\phi} = \frac{9}{32\pi}\,(I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k$$

$$+ \quad (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k)\cos 2\theta_l + I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi$$

$$+ \quad I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi + \mathbf{I_5} \sin 2\theta_k \sin\theta_l \cos\phi + I_6 \sin^2\theta_k \cos\theta_l$$

$$+ \quad I_7 \sin 2\theta_k \sin\theta_l \sin\phi + I_8 \sin 2\theta_k \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_k \sin^2\theta_l \sin 2\phi)$$



$$P_4' = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\parallel^{L*} + A_0^R A_\parallel^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_\parallel|^2)}} \qquad P_5' = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_\parallel|^2)}}$$

- $B \to K^*(\to K\pi)\ell\ell$ with rich kinematics and many observables

  [Ali, Hiller, Matias, Krüger, Mescia, SDG, Virto, Hofer, Bobeth, van Dyck, Buras, Altmanshoffer, Straub, Bharucha. . .]
- Possibility to define optimised observables P_i with reduced hadronic uncertainties in the large K^*-recoil limit

- Measured at LHCb with 1 fb^{-1} (2013) and 3 fb^{-1} (2015)
- Discrepancies for some (but not all) observables
- Two bins for P_5' deviating from SM by 2.9 σ each

- $B_s^0 \to \phi\, \mu^+\mu^-$
  - untagged B
  - angular distributions consistent with SM expectations
  - but differential branching ratio in the low q^2 bins is 3σ below the SM expectations.

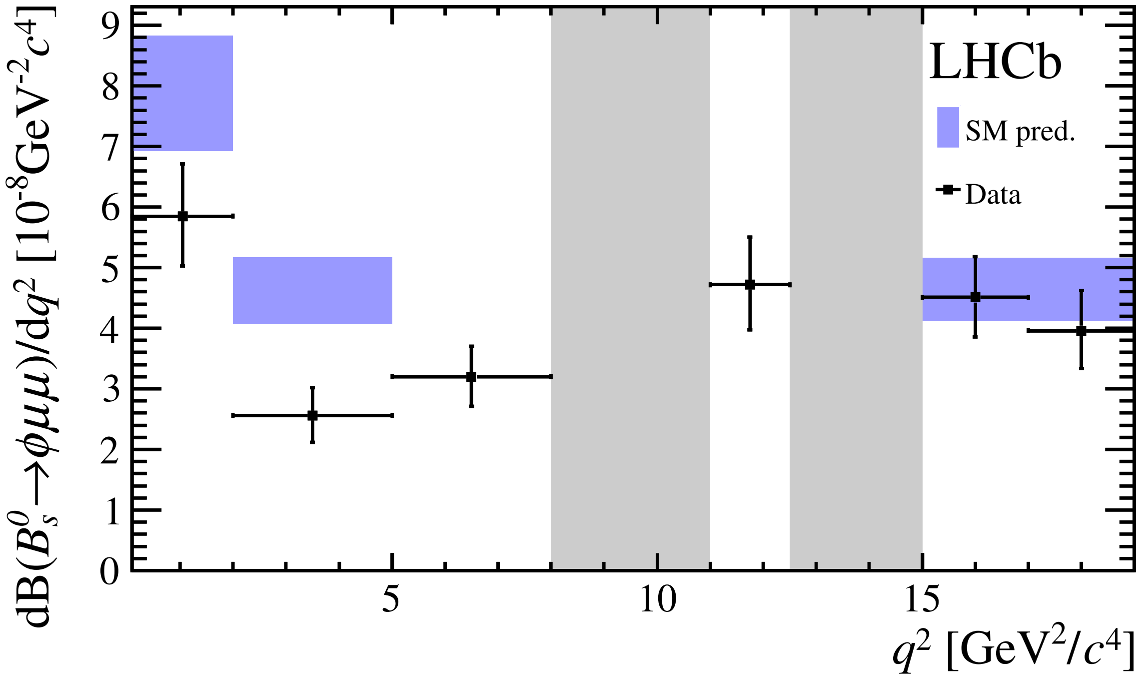
Light Cone Sum Rules:

W. Altmannshofer and D. M. Straub

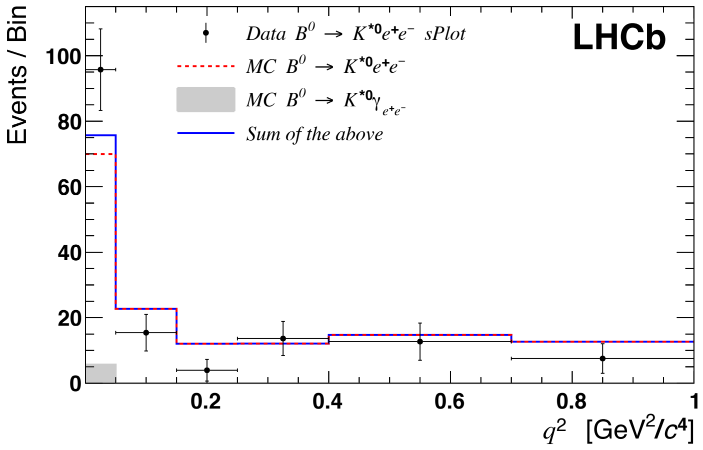
[Eur. Phys. J. C75 (2015) 382, arXiv:1411.3161]

A. Bharucha, D. M. Straub, and R. Zwicky [arXiv:1503.05534]

$$\begin{aligned}\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^3\Gamma}{\mathrm{dcos}\theta_l\,\mathrm{dcos}\theta_K\,\mathrm{d}\Phi} = \frac{9}{32\pi}\Big[&\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K \\ &+\tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_l - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_l \\ &+S_3\sin^2\theta_K\sin^2\theta_l\cos 2\Phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\Phi \\ &+A_5\sin 2\theta_K\sin\theta_l\cos\Phi + A_6\sin^2\theta_K\cos\theta_l \\ &+S_7\sin 2\theta_K\sin\theta_l\sin\Phi + A_8\sin 2\theta_K\sin 2\theta_l\sin\Phi \\ &+A_9\sin^2\theta_K\sin^2\theta_l\sin 2\Phi\Big].\end{aligned}$$



- $B \to K^*\, e^+ e^-$
  - Can reach very low q^2 ($0.02 < |q| < 1.0$ (GeV/c^2))
  - Measure angular observables.
  - No large disagreements with SM expectations



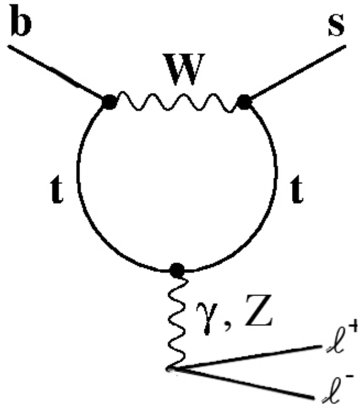
- Global analysis of b -> s l$^+$ l$^-$ transitions

Sebastien Descotes-Genon

Sebastien Descotes-Genon, Lars Hofer, Joaquim Matias, Javier Virto arXiv:1510.04239

- $b \to s\gamma$ and $b \to s\ell^+\ell^-$ Flavour-Changing Neutral Currents
- enhanced sensitivity to New Physics effects
- analysed in model-independent approach effective Hamiltonian

$$b \to s\gamma(^*) : \mathcal{H}^{SM}_{\Delta F=1} \propto \sum V^*_{ts} V_{tb} \mathcal{C}_i \mathcal{O}_i + \ldots$$



- $\mathcal{O}_7 = \frac{e}{g^2} m_b \, \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ [real or soft photon]
- $\mathcal{O}_9 = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b \; \bar{\ell}\gamma^\mu\ell$ [$b \to s\mu\mu$ via Z/hard $\gamma\ldots$]
- $\mathcal{O}_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b \; \bar{\ell}\gamma^\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]

$$\mathcal{C}_7^{\mathrm{SM}} = -0.29,\ \mathcal{C}_9^{\mathrm{SM}} = 4.1,\ \mathcal{C}_{10}^{\mathrm{SM}} = -4.3 \text{ @ } \mu_b = m_b$$

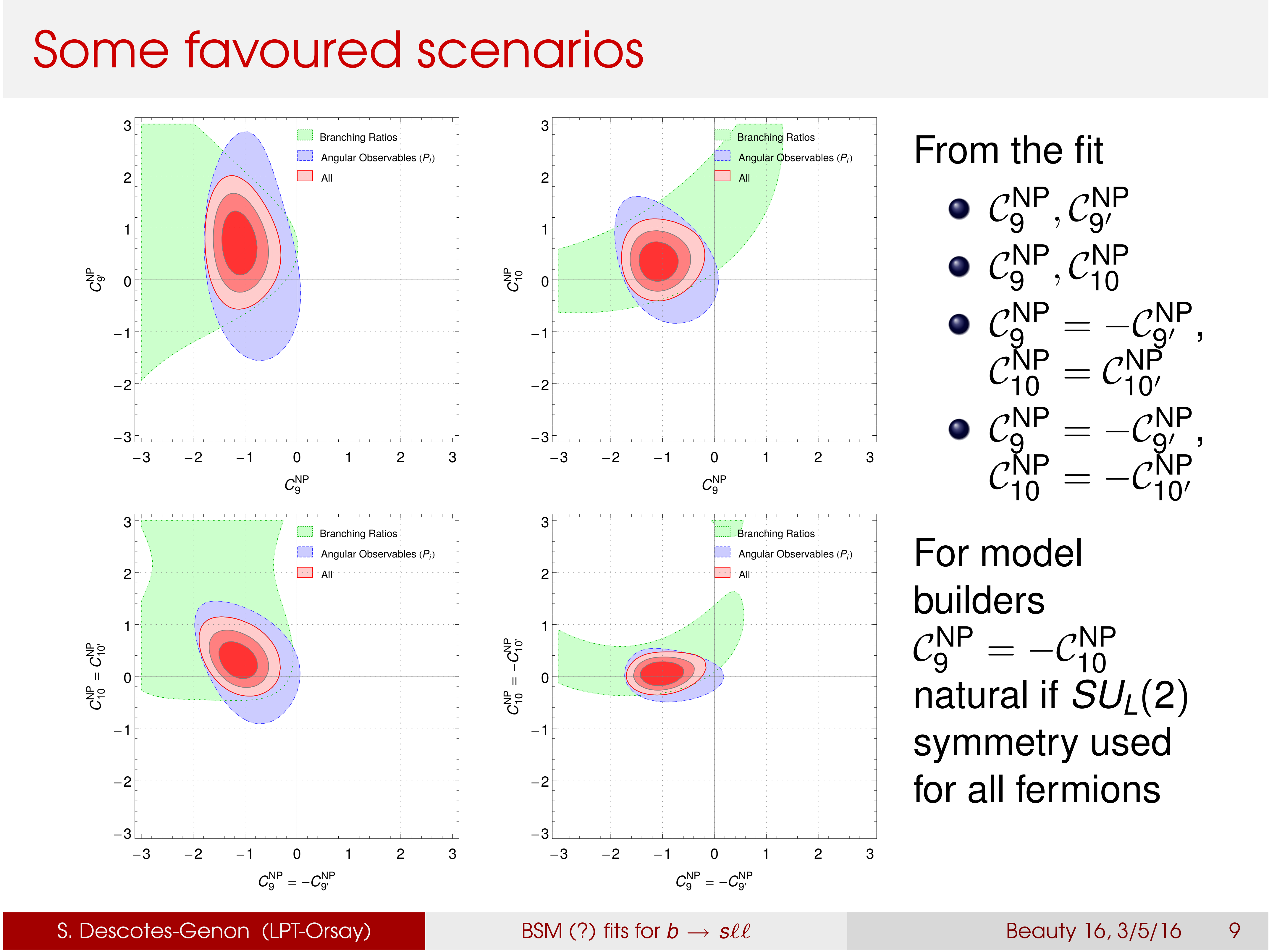
NP changes short-distance $\mathcal{C}_i$ for SM or new long-distance ops $\mathcal{O}_i$

- Chirally flipped ($W \to W_R$) $\mathcal{O}_7 \to \mathcal{O}_{7'} \propto \bar{s}\sigma^{\mu\nu}(1-\gamma_5)F_{\mu\nu}\, b$
- (Pseudo)scalar ($W \to H^+$) $\mathcal{O}_9, \mathcal{O}_{10} \to \mathcal{O}_S \propto \bar{s}(1+\gamma_5)b\bar{\ell}\ell, \mathcal{O}_P$
- Tensor operators ($\gamma \to T$) $\mathcal{O}_9 \to \mathcal{O}_T \propto \bar{s}\sigma_{\mu\nu}(1-\gamma_5)b\; \bar{\ell}\sigma_{\mu\nu}\ell$

$b \to s\mu\mu$: 1D hypotheses

- SM pull: $\chi^2(\mathcal{C}_i = 0) - \chi^2_{\rm min}$ (metrology, how far best fit from SM ?)
- p-value: $\chi^2_{\rm min}$ and N_{dof} (goodness of fit, how good is best fit ?)
- contribution to $\mathcal{C}_9$ always favoured

Coefficient	Best Fit Point	3σ	Pull$_{\rm SM}$	p-value (%)
SM	–	–	–	16.0
$\mathcal{C}_7^{\rm NP}$	-0.02	$[-0.07, 0.03]$	1.2	17.0
$\mathcal{C}_9^{\rm NP}$	-1.09	$[-1.67, -0.39]$	4.5	63.0
$\mathcal{C}_{10}^{\rm NP}$	0.56	$[-0.12, 1.36]$	2.5	25.0
$\mathcal{C}_9^{\rm NP} = \mathcal{C}_{10}^{\rm NP}$	-0.22	$[-0.74, 0.50]$	1.1	16.0
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}$	-0.68	$[-1.22, -0.18]$	4.2	56.0
$\mathcal{C}_{9'}^{\rm NP} = \mathcal{C}_{10'}^{\rm NP}$	-0.07	$[-0.86, 0.68]$	0.3	14.0
$\mathcal{C}_{9'}^{\rm NP} = -\mathcal{C}_{10'}^{\rm NP}$	0.19	$[-0.17, 0.55]$	1.6	18.0
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}$	-1.06	$[-1.60, -0.40]$	4.8	72.0
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}$ $= -\mathcal{C}_{9'}^{\rm NP} = -\mathcal{C}_{10'}^{\rm NP}$	-0.69	$[-1.37, -0.16]$	4.1	53.0
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}$ $= \mathcal{C}_{9'}^{\rm NP} = -\mathcal{C}_{10'}^{\rm NP}$	-0.19	$[-0.55, 0.15]$	1.7	19.0



Some favoured scenarios

From the fit

- $\mathcal{C}_9^{NP}, \mathcal{C}_{9'}^{NP}$
- $\mathcal{C}_9^{NP}, \mathcal{C}_{10}^{NP}$
- $\mathcal{C}_9^{NP} = -\mathcal{C}_{9'}^{NP}$, $\mathcal{C}_{10}^{NP} = \mathcal{C}_{10'}^{NP}$
- $\mathcal{C}_9^{NP} = -\mathcal{C}_{9'}^{NP}$, $\mathcal{C}_{10}^{NP} = -\mathcal{C}_{10'}^{NP}$

For model builders $\mathcal{C}_9^{NP} = -\mathcal{C}_{10}^{NP}$ natural if $SU_L(2)$ symmetry used for all fermions

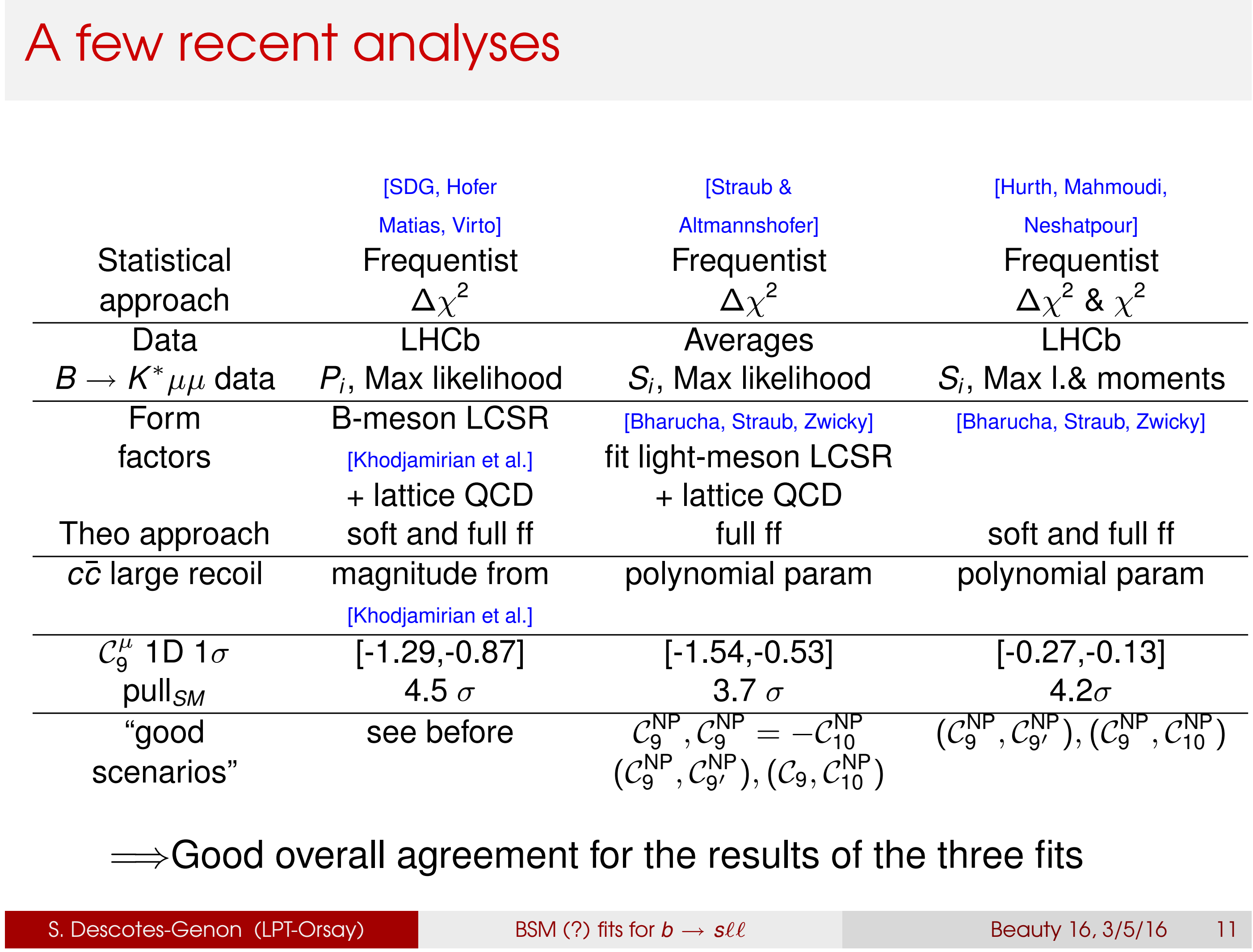
S. Descotes-Genon (LPT-Orsay) BSM (?) fits for $b \to s\ell\ell$ Beauty 16, 3/5/16 9

- Other groups' fits agree well
- Belle agrees with LHCb
- What is causing the NP contribution to (principally) C_9 ?

NEW PHYSICS

or

Large power corrections, Nonperturbative QCD effects (charmonium),...

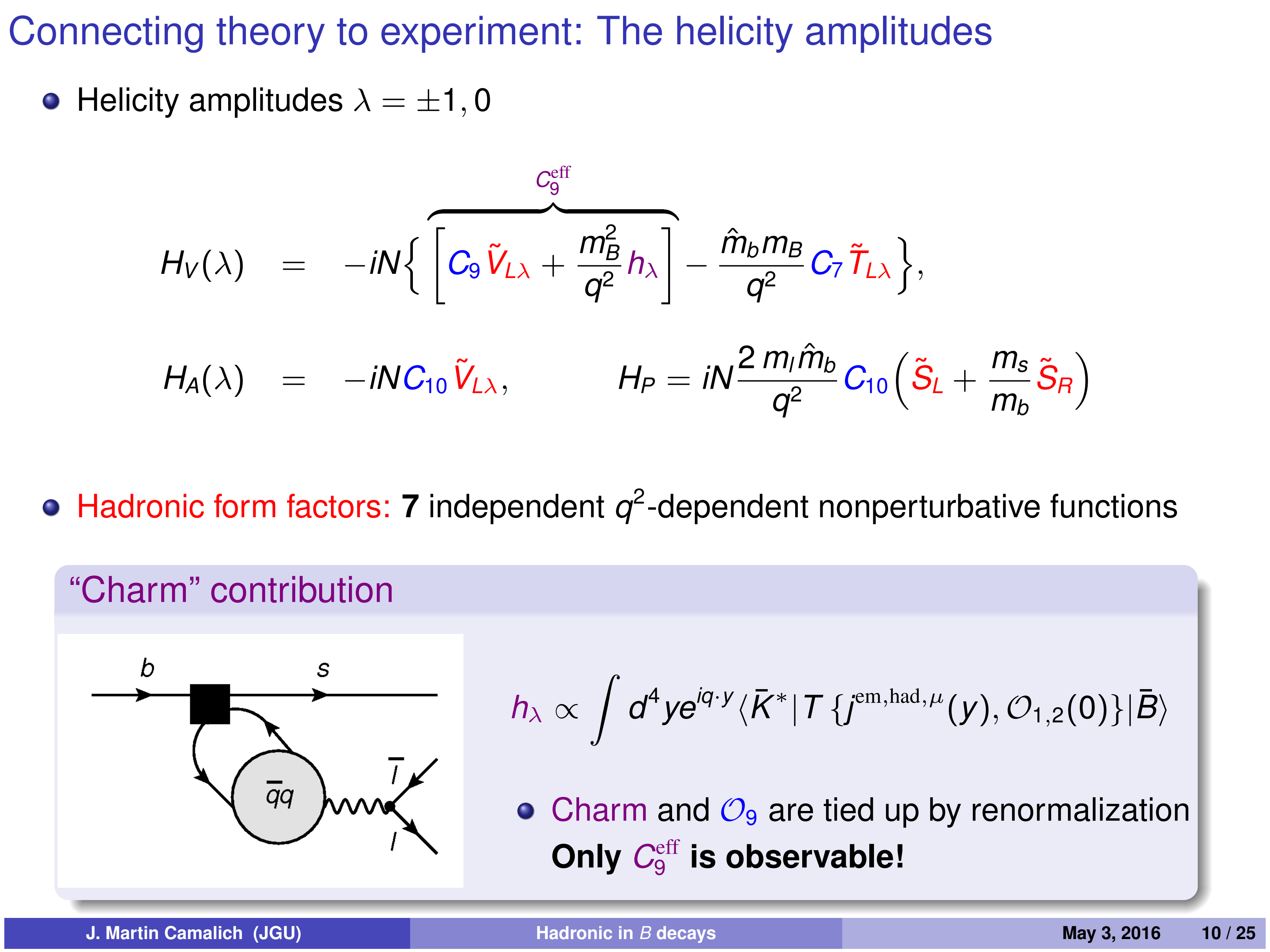


A few recent analyses

Statistical approach	[SDG, Hofer Matias, Virto] Frequentist $\Delta\chi^2$	[Straub & Altmannshofer] Frequentist $\Delta\chi^2$	[Hurth, Mahmoudi, Neshatpour] Frequentist $\Delta\chi^2$ & χ^2
Data $B \to K^*\mu\mu$ data	LHCb P_i, Max likelihood	Averages S_i, Max likelihood	LHCb S_i, Max l.& moments
Form factors	B-meson LCSR [Khodjamirian et al.] + lattice QCD	[Bharucha, Straub, Zwicky] fit light-meson LCSR + lattice QCD	[Bharucha, Straub, Zwicky]
Theo approach	soft and full ff	full ff	soft and full ff
$c\bar{c}$ large recoil	magnitude from [Khodjamirian et al.]	polynomial param	polynomial param
$\mathcal{C}_9^\mu$ 1D 1σ	[-1.29,-0.87]	[-1.54,-0.53]	[-0.27,-0.13]
pull$_{SM}$	4.5 σ	3.7 σ	4.2σ
"good scenarios"	see before	$\mathcal{C}_9^{NP}, \mathcal{C}_9^{NP} = -\mathcal{C}_{10}^{NP}$ $(\mathcal{C}_9^{NP}, \mathcal{C}_{9'}^{NP}), (\mathcal{C}_9, \mathcal{C}_{10}^{NP})$	$(\mathcal{C}_9^{NP}, \mathcal{C}_{9'}^{NP}), (\mathcal{C}_9^{NP}, \mathcal{C}_{10}^{NP})$

$\Longrightarrow$Good overall agreement for the results of the three fits

S. Descotes-Genon (LPT-Orsay) BSM (?) fits for $b \to s\ell\ell$ Beauty 16, 3/5/16 11



Connecting theory to experiment: The helicity amplitudes

- Helicity amplitudes $\lambda = \pm 1, 0$

$$H_V(\lambda) = -iN\left\{\overbrace{\left[C_9\tilde{V}_{L\lambda} + \frac{m_B^2}{q^2}h_\lambda\right]}^{C_9^{\rm eff}} - \frac{\hat{m}_b m_B}{q^2}C_7\tilde{T}_{L\lambda}\right\},$$

$$H_A(\lambda) = -iNC_{10}\tilde{V}_{L\lambda}, \qquad H_P = iN\frac{2\,m_l\hat{m}_b}{q^2}C_{10}\left(\tilde{S}_L + \frac{m_s}{m_b}\tilde{S}_R\right)$$

- Hadronic form factors: **7** independent q^2-dependent nonperturbative functions

"Charm" contribution

$$h_\lambda \propto \int d^4y e^{iq\cdot y}\langle \bar{K}^*|T\{j^{\rm em,had,\mu}(y), \mathcal{O}_{1,2}(0)\}|\bar{B}\rangle$$

- Charm and $\mathcal{O}_9$ are tied up by renormalization

Only $C_9^{\rm eff}$ is observable!

J. Martin Camalich (JGU) Hadronic in B decays May 3, 2016 10 / 25

Jorge Martin Camalich

$b \to s\ell\ell$

- Many observables, more or less sensitive to hadronic unc.
- Confirmation of LHCb results for $B \to K^*\mu\mu$, supporting $\mathcal{C}_9^{\rm NP} < 0$ with large significance and room for NP in other Wilson coeffs
- Several discrepancies in $b \to s\mu\mu$ require more global viewpoint
- Global fit does not seem to favour hadronic explanations

Sebastien Descotes-Genon

Jorge Martin Camalich

- The observable P_5' Matias *et al.*'12

$$P_5'|_\infty = \frac{I_5}{2\sqrt{-I_{2s}I_{2c}}} \simeq \frac{C_{10}\left(C_{9,\perp}+C_{9,\parallel}\right)}{\sqrt{(C_{9,\parallel}^2+C_{10}^2)(C_{9,\perp}^2+C_{10}^2)}}, \qquad \left\{ \begin{array}{l} C_{9,\perp}=C_9^{\rm eff}(q^2)+\frac{2\,m_b\,m_B}{q^2}\,C_7^{\rm eff} \\ C_{9,\parallel}=C_9^{\rm eff}(q^2)+\frac{2\,m_b\,E}{q^2}\,C_7^{\rm eff} \end{array} \right.$$

- **"Factorizable power corrections"** $(\Lambda_{\rm QCD}/m_b)$**:** Jäger&JMC, JHEP1305(2013)043

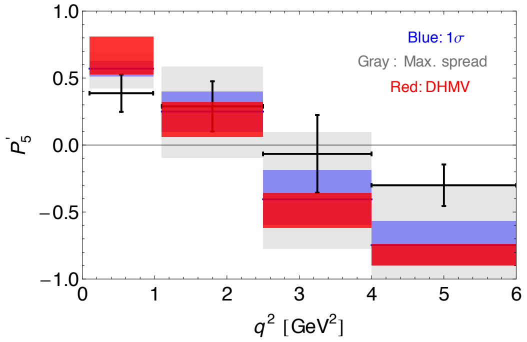
$$F^{\rm p.c.} = \pm a_F \pm b_F \frac{q^2}{m_B^2}$$

1. **Identify soft- with QCD-FFs:** E.g. $[T_-(q^2),\ S(q^2)]$ or $[V_-(q^2),\ V_0(q^2)]$ (Scheme dependence?) Hofer *et al.*, JHEP1412(2014)125
2. **QCD exact relations** $\Longrightarrow a_{T_+} = 0$ and $a_{V_0} = a_S$
3. **PC's estimated dim. analysis:** $\Lambda/m_b = 10\%$

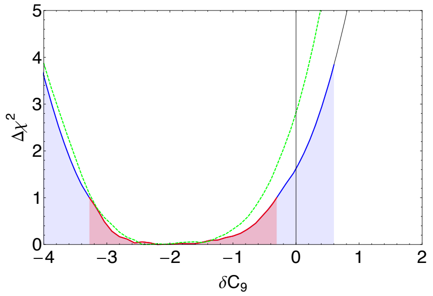
$$P_5'=P_5'|_\infty\left(1+\frac{a_{V_-}-a_{T_-}}{\xi_\perp}\,\frac{m_B}{|\vec{k}|}\,\frac{m_B^2}{q^2}\,C_7^{\rm eff}\,\frac{C_{9,\perp}C_{9,\parallel}-C_{10}^2}{(C_{9,\perp}^2+C_{10}^2)(C_{9,\perp}+C_{9,\parallel})}+\frac{a_{V_0}-a_{T_0}}{\xi_\parallel}\,2\,C_7^{\rm eff}\,\frac{C_{9,\perp}C_{9,\parallel}-C_{10}^2}{(C_{9,\parallel}^2+C_{10}^2)(C_{9,\perp}+C_{9,\parallel})}\right.$$
$$\left.+8\pi^2\,\frac{\tilde{h}_-}{\xi_\perp}\,\frac{m_B}{|\vec{k}|}\,\frac{m_B^2}{q^2}\,\frac{C_{9,\perp}C_{9,\parallel}-C_{10}^2}{C_{9,\perp}+C_{9,\parallel}}+\ldots\right)+\mathcal{O}(\Lambda^2/m_B^2)$$

Jäger and JMC, PRD93(2016)no.1,014028

- **Predictions** for P_5'



- **R-fit** to 1 fb^{-1} $P_i^{(\prime)}$'s [1, 6] GeV^2



Green line: Different FF scheme

Better understanding of had. uncert. desirable!

- **Scheme dependence?** Hofer *et al.*
- **Use LCSR?** Bharucha, Straub and Zwicky, arXiv: 1503.05534
- **Charm under control?** Lyon&Zwicky arXiv:1406.0566, Ciuchini *et al.* arXiv:1512.07157

Jorge Martin Camalich

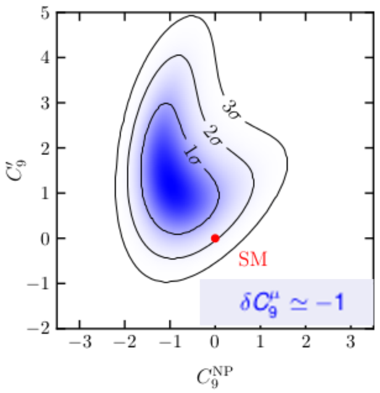
What about the high q^2 region?

- Theoretical approach based on **OPE+HQET** Lunghi's talk

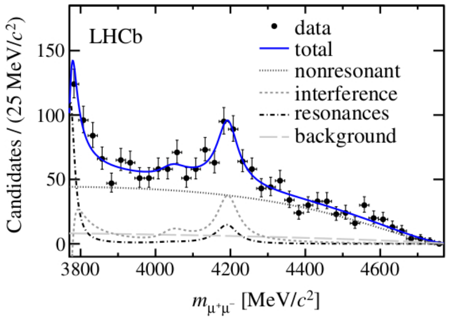
$$\lim_{x\to 0}\int d^4x\, \frac{e^{iq\cdot x}}{q^2}\, T\{j^{\mathrm{em,had},\mu}(x), \mathcal{H}^{\mathrm{had}}(0)\} = \sum_n C_{3,n}\,\mathcal{O}_{3,n}(q^2) + 0 + \mathcal{O}(\mathrm{dim}{>}4)$$

Grinstein *et al.* PRD70(2004)114005, Bobeth *et al.* JHEP1007(2010)098, Beylich *et al* EPJC71(2011)1635

- Up to $\mathcal{O}(\Lambda^2/m_b^2)$ $\sim$ 1% **"charm"** described by **form factors**
  - FFs in **LQCD**!! Horgan *et al.* PRL112(2014)212003



- **However:** Duality violations!!

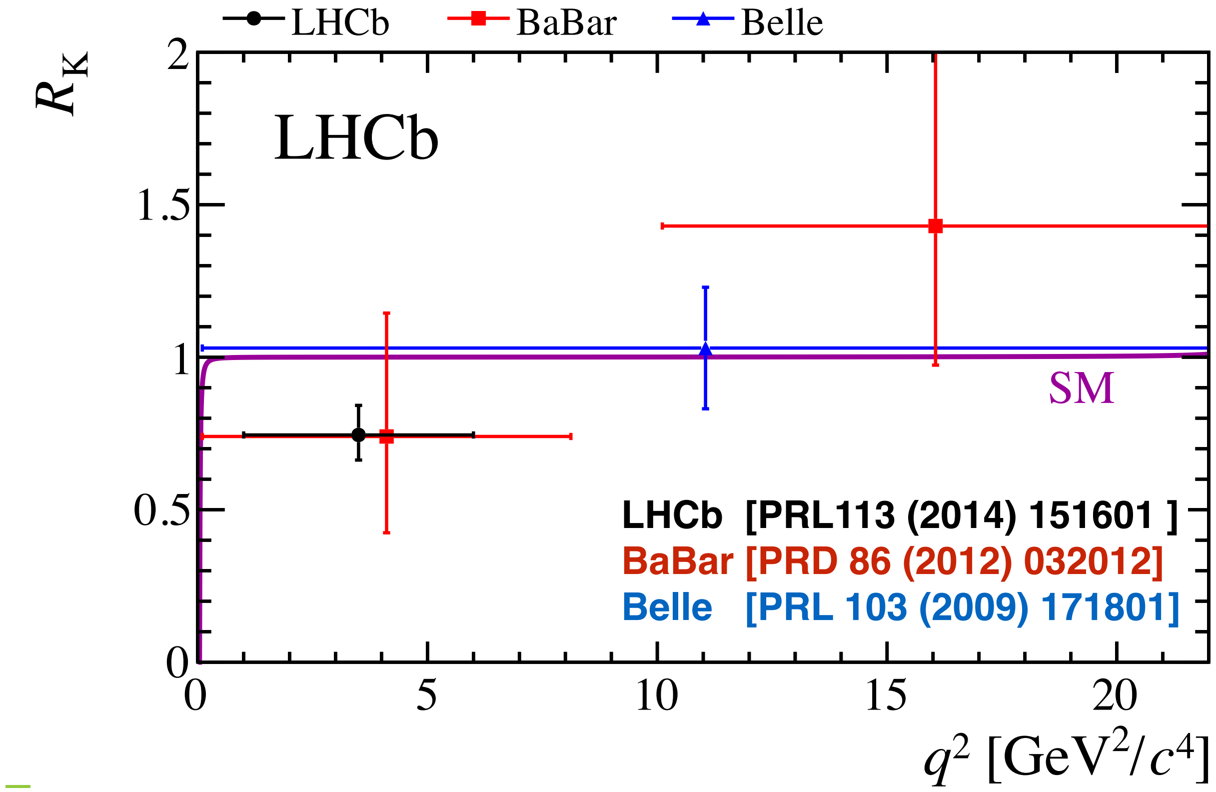


No satisfactory (model-independent) solution (yet?)

- Lepton Flavor Universality Violation
  - With full 3 fb^{-1} of LHCb

$$R_K = \frac{BR(B \to K\ \mu^+\ \mu^-)}{BR(B \to K\ e^+\ e^-)} = 0.745\ ^{+0/090}_{-0.074}(\ \mathrm{stat}) \pm 0.036(\ \mathrm{syst})$$

2.6 σ from SM $R_K = 1$



BSM Explanations

- We have considered the flavor anomalies in b -> s μ+μ- , B -> $D^{(*)}$ τ ν and h-> τμ
- Possible New Physics to explain these anomalies

Andreas Crivellin

  - Z '

    U. Haisch et al. arXiv:1308.1959;
    W. Altmannshofer et al. arXiv:1403.1269;
    A. Crivellin et al. arXiv:1501.00993; …

  - Extended Higgs Sector

    J. Heeck et al. arXiv:1412.3671;
    A. Greljo et al. arXiv:1502.07784;
    A. Crivellin et al. arXiv:1501.00993; …

  - Leptoquarks

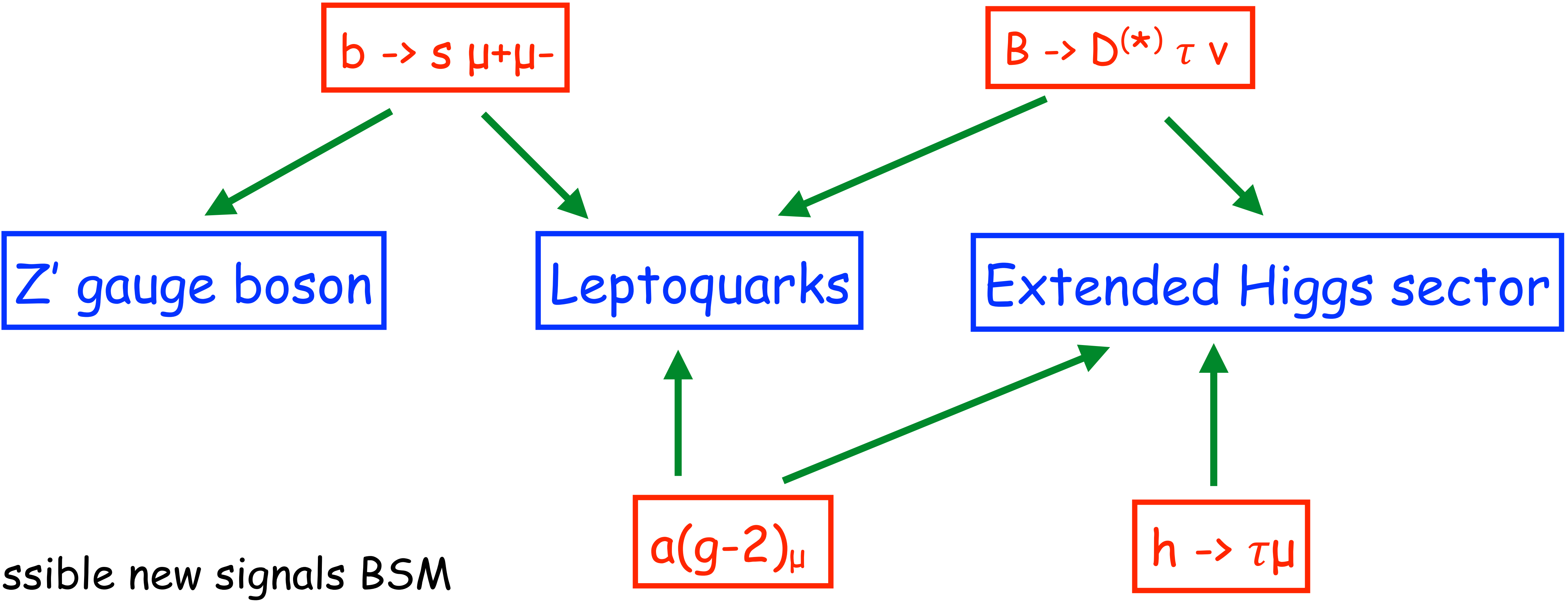
    M. Bauer, M. Neubert arXiv:1511.01900;
    L. Calibbi, A. Cruvellin, T. Ota arXiv:1506.02661

  - More complete models:
    - 2HDM with gauged Lτ -Lμ
    - 2HDM-X: one higgs couples to quarks, one to leptons
      Crivellin, J. Heck, P. Stoffer arXiv:1507.07567

Andreas Crivellin

BSM Explanations

- Concludes:



$b \to s\, \mu^+\mu^-$

$B \to D^{(*)}\, \tau\, \nu$

Z' gauge boson

Leptoquarks

Extended Higgs sector

$a(g-2)_\mu$

$h \to \tau\mu$

- Possible new signals BSM
  - $b \to s\, \mu^+\mu^- \oplus R(D^{(*)}) \Rightarrow$ Leptoquarks $\Rightarrow B_s \to \mu\mu,\ b \to s\, \tau\tau$
  - $a_\mu \oplus R(D^{(*)}) \Rightarrow$ 2HDM-X $\Rightarrow t \to H c,\ B_s \to \mu\mu,\ \tau \to \mu\nu\nu$
  - $b \to s\, \mu^+\mu^- \oplus h \to \tau\mu \Rightarrow$ Z' $\Rightarrow \tau \to \mu\mu\mu$

plats d'accompagnement

Charm physics, kaons, EDM's, LFV

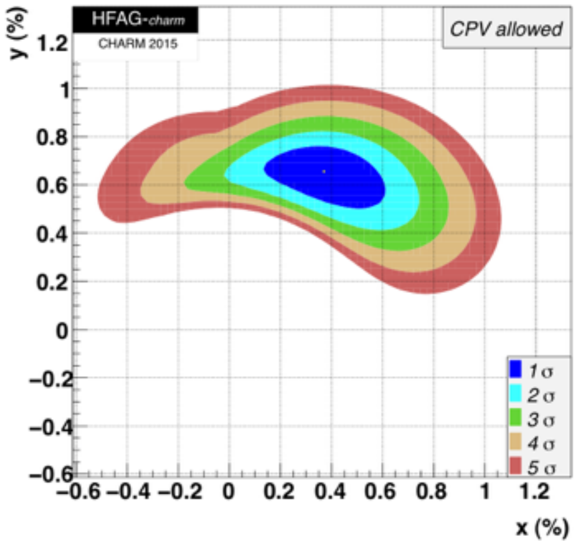
Charm Physics

Alexey Petrov

- Generic restrictions on NP from $D\bar{D}$-mixing

★ Comparing to experimental value of x, obtain constraints on NP models

- assume x is dominated by the New Physics model
- assume no accidental strong cancellations b/w SM and NP



$$\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} z_i(\mu) Q_i'$$

$$\begin{aligned} Q_1^{cu} &= \bar{u}_L^\alpha \gamma_\mu c_L^\alpha \bar{u}_L^\beta \gamma^\mu c_L^\beta, \\ Q_2^{cu} &= \bar{u}_R^\alpha c_L^\alpha \bar{u}_R^\beta c_L^\beta, \\ Q_3^{cu} &= \bar{u}_R^\alpha c_L^\beta \bar{u}_R^\beta c_L^\alpha, \end{aligned} \quad + \left\{ \begin{matrix} L \\ \updownarrow \\ R \end{matrix} \right\} + \quad \begin{aligned} Q_4^{cu} &= \bar{u}_R^\alpha c_L^\alpha \bar{u}_L^\beta c_R^\beta, \\ Q_5^{cu} &= \bar{u}_R^\alpha c_L^\beta \bar{u}_L^\beta c_R^\alpha, \end{aligned}$$

★ ... which are

$$\begin{aligned} |z_1| &\lesssim 5.7 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV} \right)^2, \\ |z_2| &\lesssim 1.6 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV} \right)^2, \\ |z_3| &\lesssim 5.8 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV} \right)^2, \\ |z_4| &\lesssim 5.6 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\ TeV} \right)^2, \\ |z_5| &\lesssim 1.6 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV} \right)^2. \end{aligned}$$

New Physics is either at a very high scales

tree level: $\Lambda_{NP} \geq (4-10) \times 10^3$ TeV

loop level: $\Lambda_{NP} \geq (1-3) \times 10^2$ TeV

or have highly suppressed couplings to charm!

Gedalia, Grossman, Nir, Perez
Phys.Rev.D80, 055024, 2009

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
Phys. Rev. D76:095009, 2007

★ Constraints on particular NP models available

- Rare leptonic/semileptonic decays of charm

Alexey Petrov

- These decays also proceed at one loop in the SM; GIM is very effective
  - SM rates are expected to be small

★ Rare decays D →$e^+e^-/\mu^+\mu^-$ are mediated by c→u ll, but helicity suppressed: Br ~ m^2_l .

★ Rare decays D → M $e^+e^-/\mu^+\mu^-$ just like D → $e^+e^-/\mu^+\mu^-$ are mediated by c→u ll

Burdman, Golowich, Hewett, Pakvasa;
Fajfer, Prelovsek, Singer

$$\mathcal{L}_{\rm eff}^{\rm SD} = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{ub} \sum_{i=7,9,10} C_i Q_i,$$

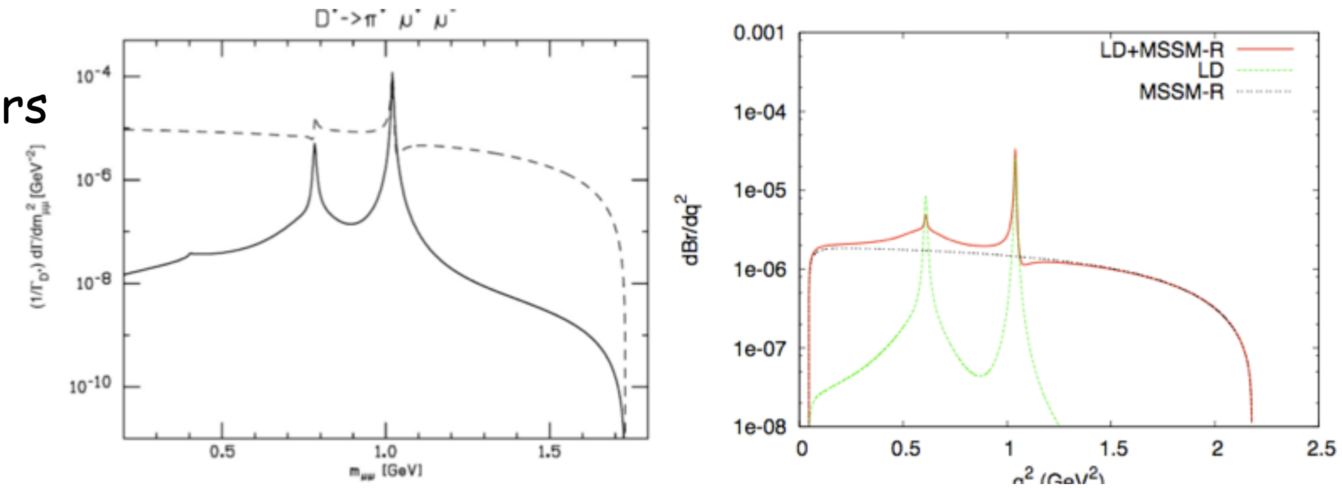
$$Q_9 = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \ell, \quad Q_{10} = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \gamma_5 \ell,$$

Mode	LD	Extra heavy q	LD + extra heavy q
$D^+ \to \pi^+ e^+ e^-$	2.0×10^{-6}	1.3×10^{-9}	2.0×10^{-6}
$D^+ \to \pi^+ \mu^+ \mu^-$	2.0×10^{-6}	1.6×10^{-9}	2.0×10^{-6}
Mode	MSSM$\not{R}$	LD + MSSM$\not{R}$	
$D^+ \to \pi^+ e^+ e^-$	2.1×10^{-7}	2.3×10^{-6}	
$D^+ \to \pi^+ \mu^+ \mu^-$	6.5×10^{-6}	8.8×10^{-6}	

- SM contribution is dominated by LD effects
- could be used to study NP effects

★ Example: R-parity-violating SUSY
- operators with the same parameters contribute to D-mixing
- feed results into rare decays

Fajfer, Kosnik, Prelovsek

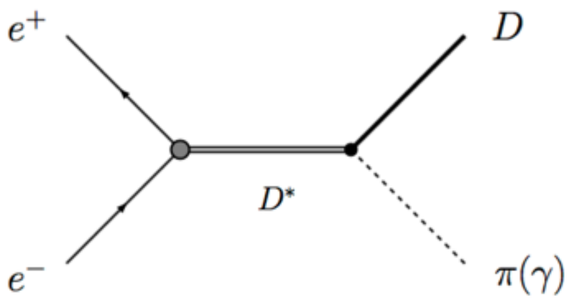


• Studies of D*(B*) -> e^+ e^- in resonance production

Alexey Petrov

➢ Is it at all possible and feasible experimentally???

$$\mathcal{B}^{SD}_{D^*\to e^+e^-} = \frac{\Gamma(D^*\to e^+e^-)}{\Gamma_0} \approx 2.0\times 10^{-19}$$



★ D* has a small width defined by strong and radiative decays

$$\begin{aligned}\Gamma_0 &= \Gamma(D^{*0}\to D^0\pi^0)+\Gamma(D^{*0}\to D^0\gamma)\\ &\simeq \frac{\Gamma_+\mathcal{B}_{D^{*+}\to D^0\pi^+}}{2}\left(\frac{\lambda(m^2_{D^{*0}},m^2_{D^0},m^2_{\pi^0})}{\lambda(m^2_{D^{*+}},m^2_{D^0},m^2_{\pi^+})}\right)^{3/2}\left(1+\frac{\mathcal{B}_{D^{*0}\to D^0\gamma}}{\mathcal{B}_{D^{*0}\to D^0\pi^0}}\right)\simeq 60\text{ keV}\end{aligned}$$

★ … with contributions from higher excitations being highly suppressed

$$\left|\frac{f_{D^{0*\prime}}\, g_{D^{*\prime 0}D^0\pi^0}\, m_{D^{*0\prime}}}{f_{D^{0*}}\, g_{D^{*0}D^0\pi^0}\, m_{D^{*0}}}\right| \times \left|\frac{i\Gamma_0}{2\Delta - i\Gamma_{D^{*\prime}}}\right| \sim 5.0\cdot 10^{-5}$$

★ … thus running for a “Snowmass year” (~10^7 s) with $L \approx 1.0\times 10^{32}\ cm^{-2}s^{-1}$

$$\mathcal{B}_{D^*\to e^+e^-} \ge \left(\frac{1}{\epsilon\int L dt}\right)\times\frac{m^2_{D^*}}{12\pi\ \mathcal{B}_{D^*\to D\pi}}.$$ probes $$\mathcal{B}_{D^*\to e^+e^-} > 4\times 10^{-13}$$

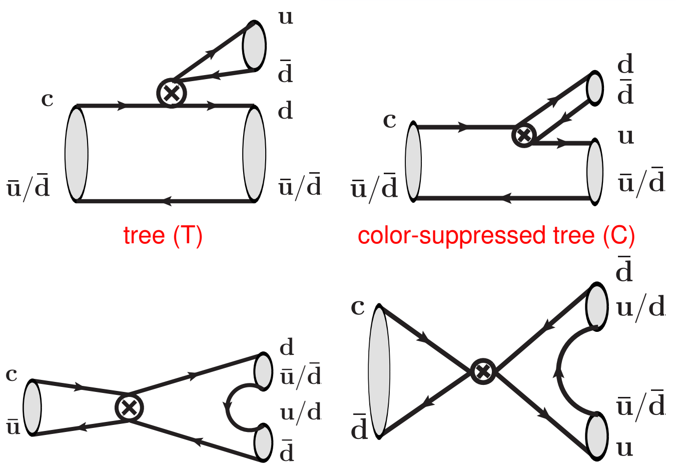
★ SM LD contributions are of the same order of magnitude or less compared to SD!!!

★ Great probe of NP contributions, wider reach than D -> ll with NO helicity suppression

Stefan Schacht

- Non Leptonic D decays
  - 4 Topological amplitudes in $SU(3)_F$ limit
  - 14 new topological amplitudes in general
  - can use $1/N_c$ arguments to order contributions
  - Summary

SU(3)$_F$-limit topologies



tree (T) color-suppressed tree (C)

exchange (E) annihilation (A)

[Chau 1980,1982; Zeppenfeld 1981, Buras Silvestrini 1998]

- Global fit of $D \to PP'$ branching ratios to topological amplitudes:
  $\Rightarrow$ multiple degenerate best-fit solutions.
- Likelihood ratio test of e.g. size of ~~$SU(3)_F$~~ and $P_{\text{break}} \neq 0$ (GIM).
- Branching ratio predictions:
  $\mathcal{B}(D_s^+ \to K_L K^+) = 0.012^{+0.007}_{-0.002}$ at 3σ
  $\mathcal{B}(D^0 \to K_L \pi^0) < \mathcal{B}(D^0 \to K_S \pi^0)$ at 4σ
- CP asymmetries involve topological amplitudes not constrained by the fit. These can be eliminated by forming judicious combinations of several CP asymmetries $\to$ sum rules .
- Sum rules test $SU(3)_F$ in penguin amplitudes and/or new physics.
- $D^0 \to K_S K_S$: $R = \sqrt{a_{CP}^{\text{dir}\,2} + \left(\phi - \phi_{\text{mix}} + \text{Im}\frac{\lambda_b}{\lambda_{sd}}\right)^2} \leq 1.1\%$ @95% CL.
- Violation of bound: New physics or enhancement of the penguin annihilation amplitude by QCD dynamics.
  ➥Would be visible also in other decays.

Renaissance of Kaon Flavour Physics

Andrzej Buras

1.

ε'/ε strikes back after new Lattice QCD results
from RBC-UKQCD and upper bounds $B_6 < B_8 < 1$
from dual QCD approach (Buras, Gérard) 1507.06326
1603.05686

New Anomaly
in
Flavour Physics

$$(\varepsilon'/\varepsilon)_{SM} = (1.9 \pm 4.5) \cdot 10^{-4}$$

$$(\varepsilon'/\varepsilon)_{exp} = (16.6 \pm 2.3) \cdot 10^{-4}$$

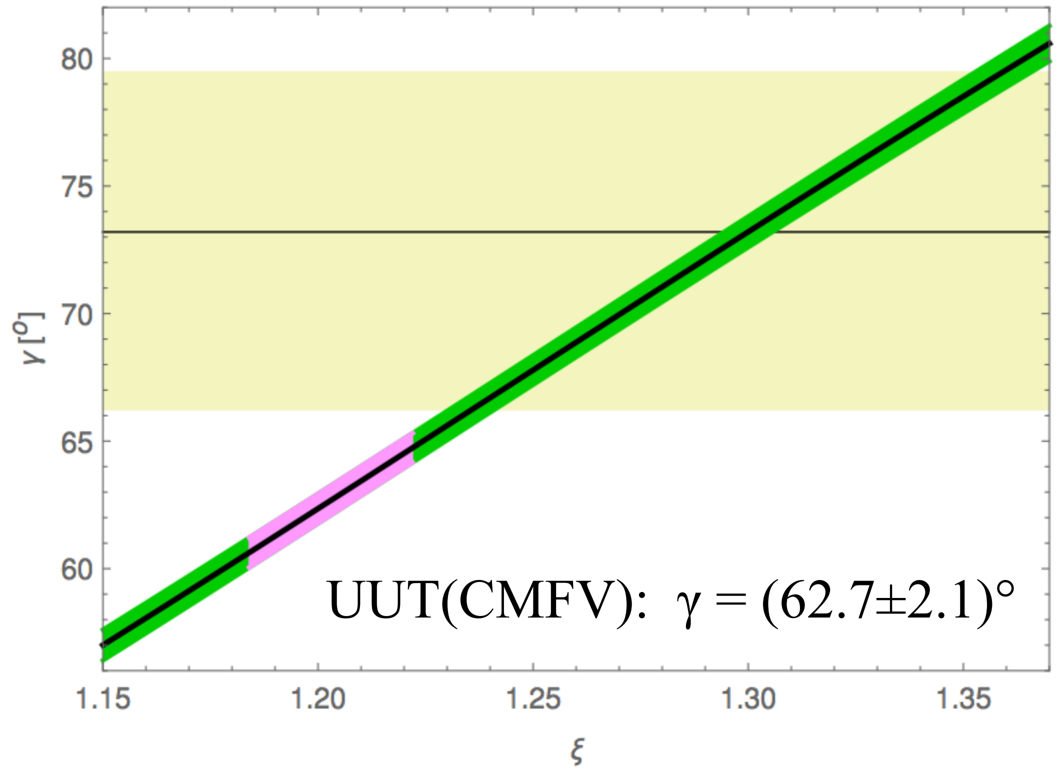
(Buras, Gorbahn, Jäger, Jamin)
(1507.06345)
(Buras, Gérard) (1507.06326)

2.

$\varepsilon_K \leftrightarrow \Delta M_{s,d}$ tension in SM and CMFV after new results
from Fermilab-MILC Collaboration (Blanke, Buras, 1602.04020)

Universal Unitarity Triangle 2016 ($\gamma = (62.7 \pm 2.1)^\circ$)

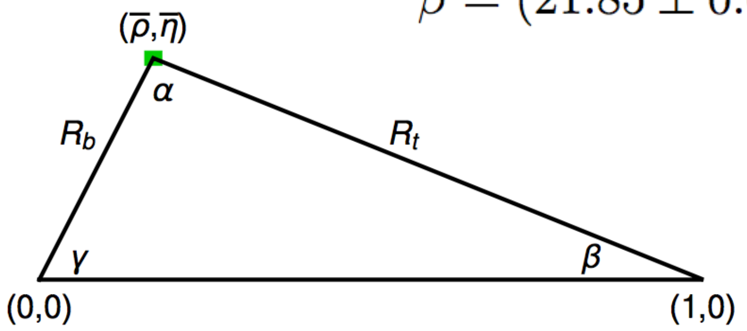
- LHCb: $\gamma = 70.9\,^{+7.1}_{-8.5}$



UUT(CMFV): γ = (62.7±2.1)°

$$\cot\gamma = \frac{1 - R_t\cos\beta}{R_t\sin\beta}$$

$$\beta = (21.85 \pm 0.67)^\circ$$



$$R_t = 0.741\,\xi = 0.893 \pm 0.013$$

$$\xi = \frac{F_{B_s}\sqrt{\hat{B}_{B_s}}}{F_{B_d}\sqrt{\hat{B}_{B_d}}} = 1.203 \pm 0.019$$

(Fermilab-MILC `arXiv:1602.03560`)

Andrzej Buras

3. **New Strategy :**

$$\underset{\text{Anomalies}}{(\varepsilon'/\varepsilon,\ \varepsilon_K)} \rightarrow \overset{\text{New Physics in}}{\begin{pmatrix} K \rightarrow \pi\nu\bar{\nu} \\ \Delta M_K \end{pmatrix}} \overset{\text{NP}}{\begin{pmatrix} \text{Effects} \\ \text{can be} \\ \text{large} \end{pmatrix}}$$

(Buras, 1601.00005)

Correlations between $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and $K_L \rightarrow \pi^0\nu\bar{\nu}$ and the sign of $(\Delta M_K)^{NP}$ can distinguish between $(\varepsilon'/\varepsilon)_{NP}$ from QCD Penguins and Electroweak Penguins.

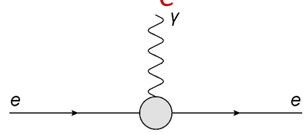
4.

Z, Z´ tree-level exchanges, LHT model, 331 models and MSSM provide solutions to ε'/ε - anomaly and ε_K - $\Delta M_{s,d}$ tensions with different implications for $K^+ \rightarrow \pi^+\nu\bar{\nu}$, $K_L \rightarrow \pi^0\nu\bar{\nu}$, $B_s \rightarrow \mu^+\mu^-$ and $B \rightarrow K(K^*)l^+l^-$.

Martin Jung

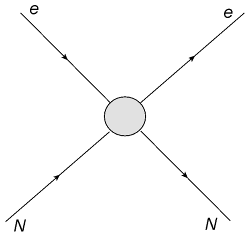
- EDMs

d_e



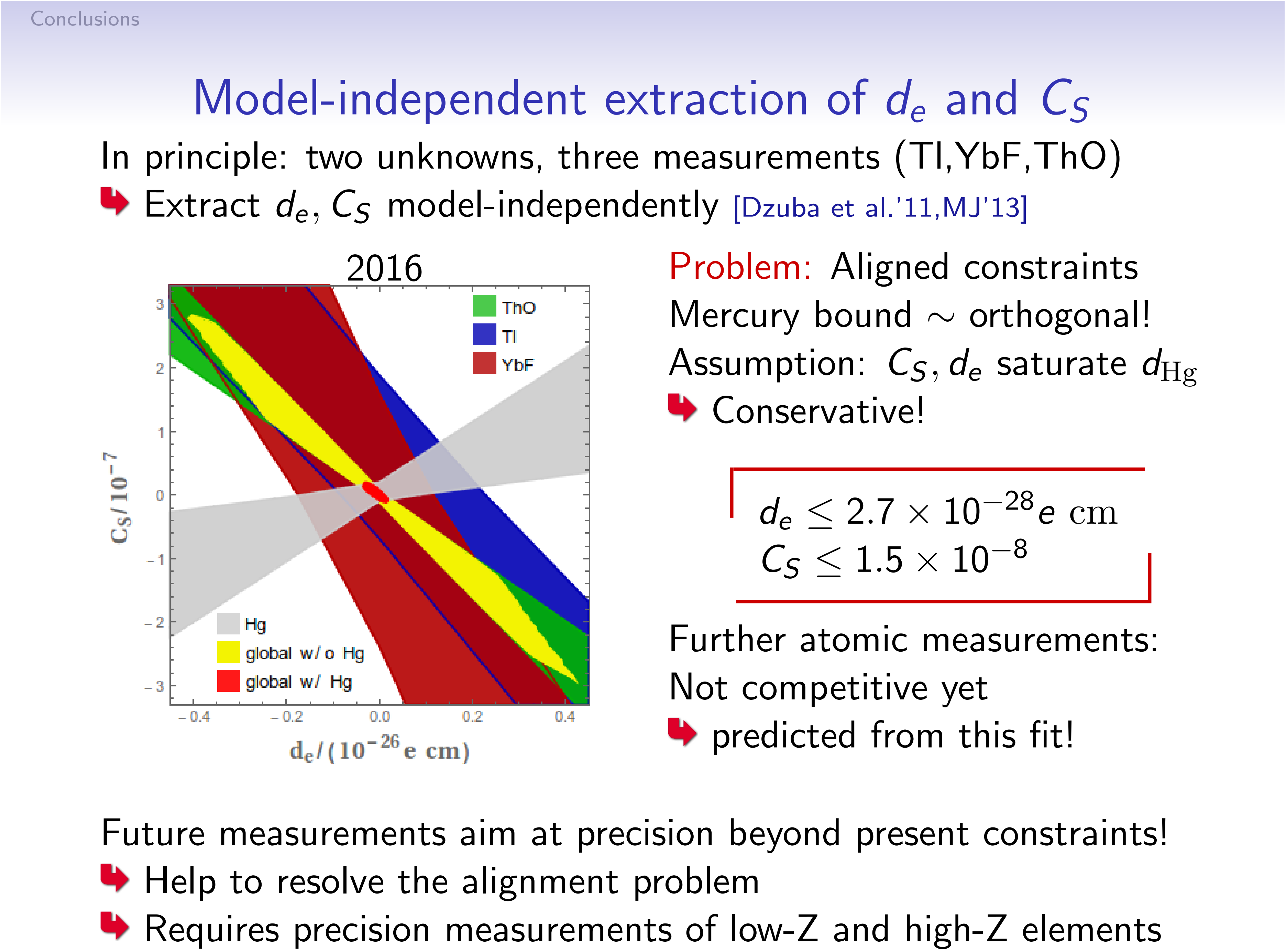
$\bar{e}F_{\mu\nu}\sigma^{\mu\nu}\gamma_5 e$

C_S



$(\bar{e}i\gamma_5 e)(\bar{N}N)$

$$\boxed{\omega = 2\pi\left(\frac{W_d^M}{2}d_e + \frac{W_c^M}{2}C_S\right) .}$$



Conclusions

Model-independent extraction of d_e and C_S

In principle: two unknowns, three measurements (Tl,YbF,ThO)

➥ Extract d_e, C_S model-independently [Dzuba et al.'11,MJ'13]

2016

Problem: Aligned constraints

Mercury bound ∼ orthogonal!

Assumption: C_S, d_e saturate $d_{\rm Hg}$

➥ Conservative!

$$\boxed{\begin{aligned} d_e &\leq 2.7\times10^{-28}e\ \mathrm{cm}\\ C_S &\leq 1.5\times10^{-8}\end{aligned}}$$

Further atomic measurements:

Not competitive yet

➥ predicted from this fit!

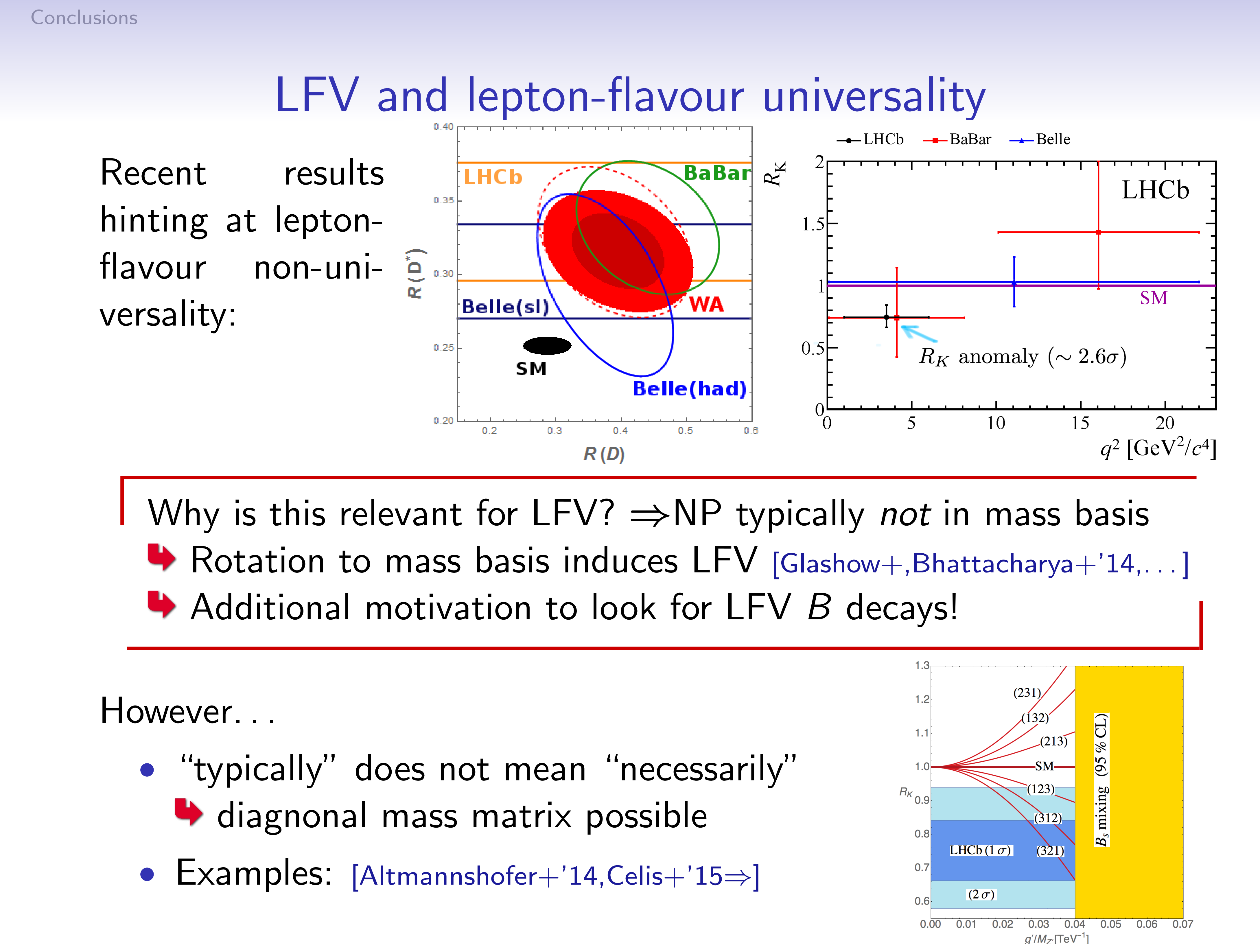
Future measurements aim at precision beyond present constraints!

➥ Help to resolve the alignment problem

➥ Requires precision measurements of low-Z and high-Z elements

- Lepton Flavor Violation

Martin Jung



Conclusions

LFV and lepton-flavour universality

Recent results hinting at lepton-flavour non-universality:

Why is this relevant for LFV? ⇒NP typically *not* in mass basis

➥ Rotation to mass basis induces LFV [Glashow+,Bhattacharya+'14,. . .]

➥ Additional motivation to look for LFV B decays!

However. . .

- "typically" does not mean "necessarily"
  - ➥ diagnonal mass matrix possible
- Examples: [Altmannshofer+'14,Celis+'15⇒]

Martin Jung

Conclusions

- EDMs and LFV observables unique tests of NP models
- Model-independent constraints on NP parameters difficult
    - ➥ Need (at least) as many experiments as (eff.) parameters
- Differentiation between (classes of) NP models possible!
    - ➥ model-dependent combination with $g-2, m_\nu, \dots$
- Quantitative results require close look at theory uncertainties
    - ➥ Use conservative limits, allowing for cancellations
    - ➥ For *e.g.* $d_n, d_{\rm Hg}$ bottleneck!
- Robust, model-independent limit on electron EDM (C_S not model-independently negligible):

$$|d_e| \leq 2.7 \times 10^{-28} e\,\mathrm{cm} \quad (95\%\,\mathrm{CL}, \mathrm{Hg})$$

- Violation of LFU motivation for search of LFV in B decays...
    - ➥ ...but not guaranteed!
- Plethora of new results to come
    - ➥ Might turn limits into determinations!

dessert

Serendipity

Serendipity

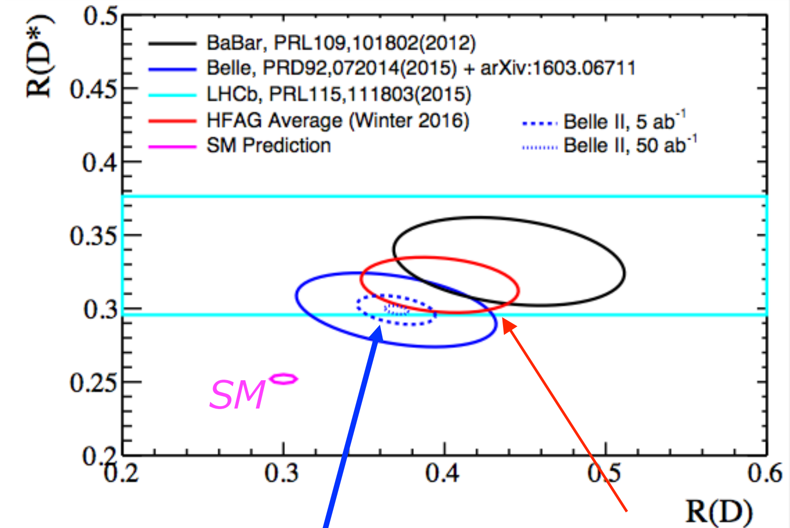
- Tau Physics from ISR at B factories:
  - Belle 2 will be not only a superb facility for studying B physics

Yasuhiro Okada

Example of B->D(*)τν

Currently the deviation is ~3σ…

K. Hara and S. Mishima for B2TiP LAL NP-workshop



~3σ deviation?

Belle II prospect

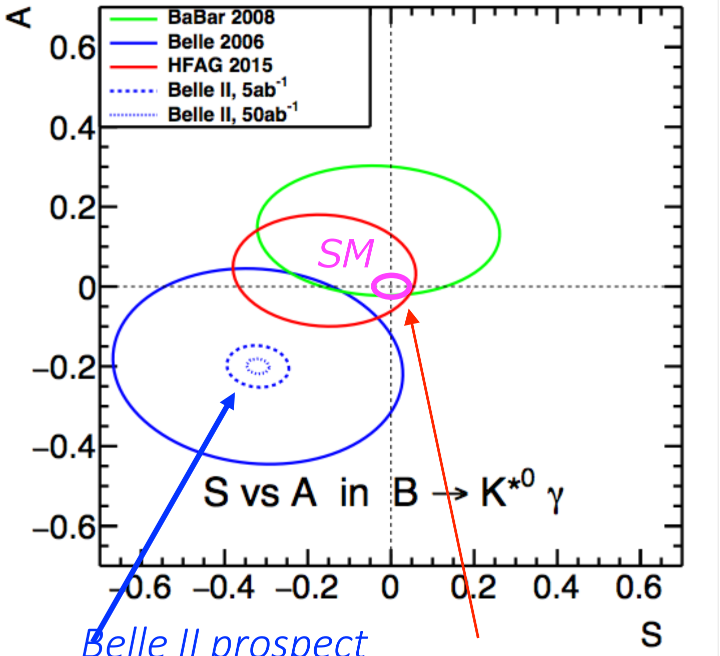
(with the current Belle central value)

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

Example of CPV in B->K*γ

Currently SM (#) consistent…

A. Ishikawa for B2TiP LAL NP-workshop



SM consistent?

Belle II prospect

(with the current Belle central value)

~16(6)σ deviation with 50(5)ab^{-1} of data!

(SM uncertainty to be included)

*(#) SM prediction of CPV in B->K*γ is still under discussion in B2TiP…*

Serendipity

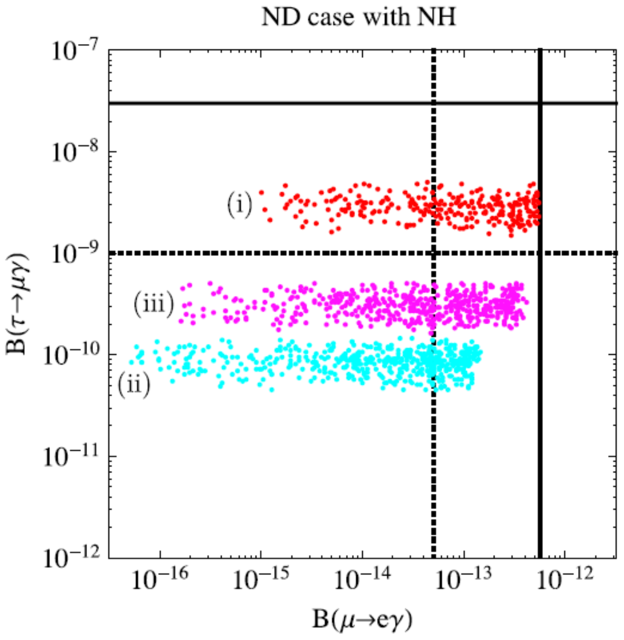
- *Also can study LFV decays in taus.*

Yasuhiro Okada

LFV in SUSY seesaw model

T. Goto. Y. Okada. T.Sindou. M.Tanaka and R.Wataanabe. 2015

μ-eγ vs. τ->μγ



SUSY parameter:

$M_{1/2} = 1.5\,\mathrm{TeV}, \ \mu > 0,$

(i) $A_0 = -2, \ M_0 = 2\,\mathrm{TeV}, \ \tan\beta = 30$

(ii) $A_0 = 0, \ M_0 = 6\,\mathrm{TeV}, \ \tan\beta = 30$

(iii) $A_0 = 0, \ M_0 = 6\,\mathrm{TeV}, \ \tan\beta = 50$

Neutrino Yukawa:

$0 \le \theta \le \pi/2,$

$1.5 < y_{2,3} < 2.0,$

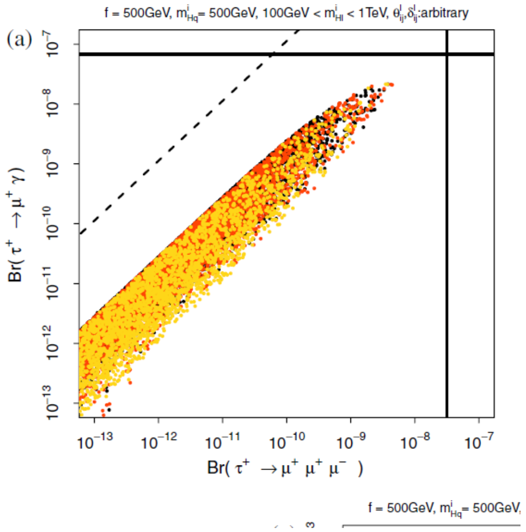
$0.01 < y_1 < 0.1$

LFV in the little Higgs model with T-parity

T. Goto, Y.Okada and Y.Yamamoto 2011

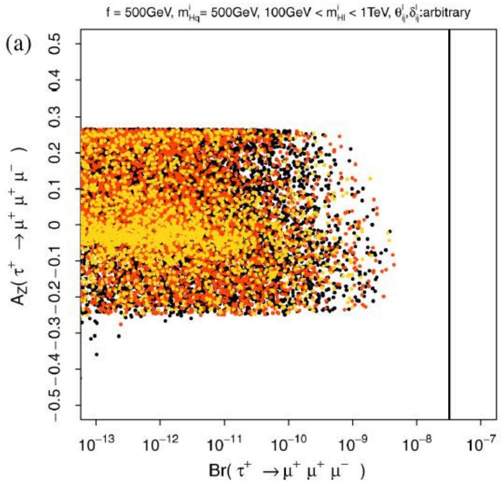
T-odd ferimions can induce large FCNC and LFV.

t->μγ vs. τ-3μ



Branching ratios of t->μγ and τ-3μ can be similar.

Z(μ-direction)-Asymmetry with respect to the tau polarization



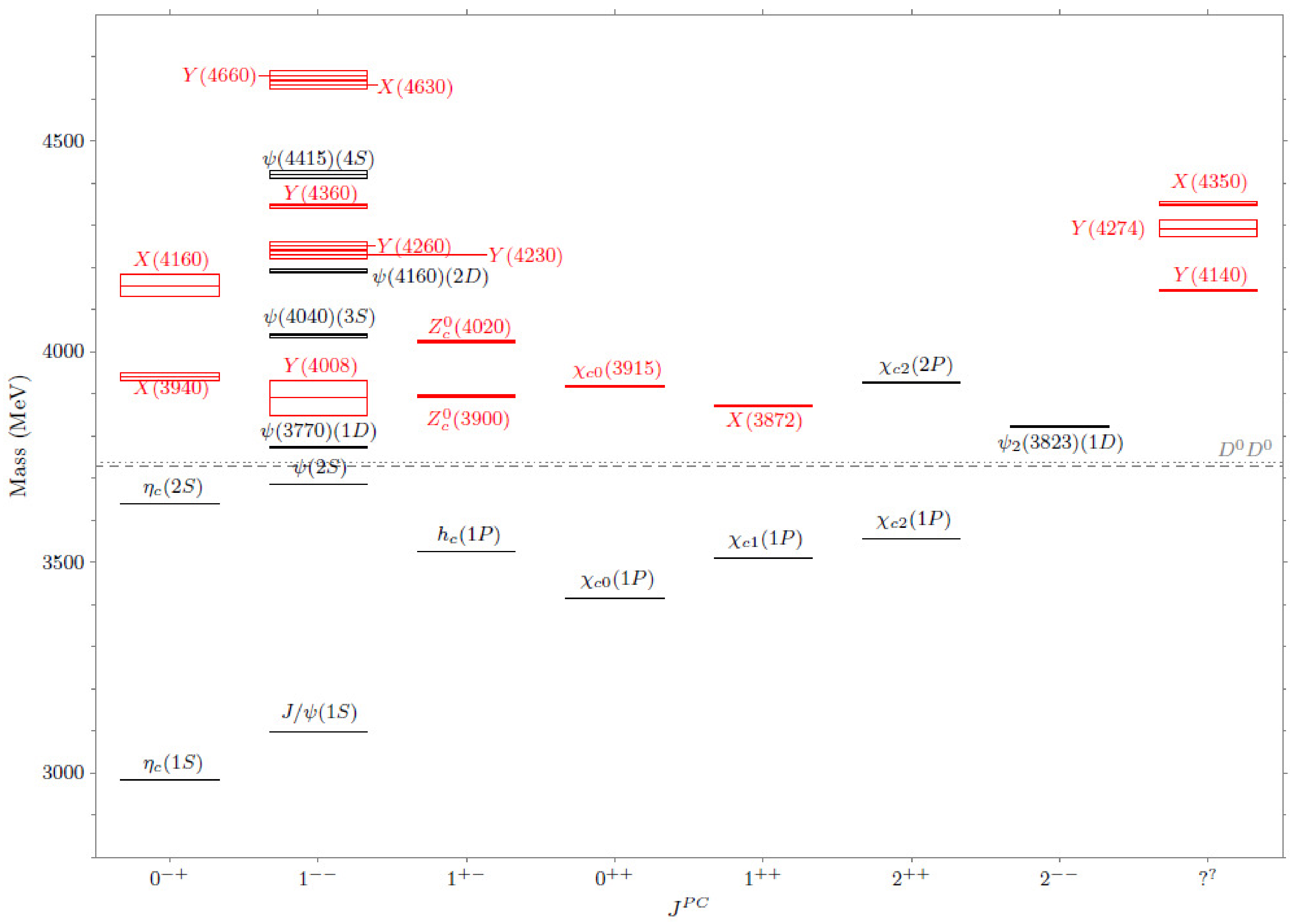
Asymmetries with respect to the tau polarization can give information of the LFV Interaction.

- Angular correlation at Belle II
- Tau from W decays at LHC

- Insights into QCD dynamics:
  - New hadronic states involving heavy quarks.
    - X(3872)
    - Many have followed: Y(4260), …
    - $Z^{+}_{(b,c)}$ I=1 $J^{PC} = 1^{+-}$
      - Two states observed in the charmonium (bottomonium) system just above the DD* (BB*) and D*D* (B*B*) thresholds
      - Impossible to interpreted as just a heavy quark - antiquark quarkonium state.
  - First discovered in the B decay products. But now found by hadronic production (LHCb, CMS, Atlas) and $e^{+}e^{-}$ (BES, Belle).
  - Tetraquarks and Pentaquarks
    - Threshold states
    - At or just above the opening of a conventional two hadron state in a relative S-wave.
    - Much remains to be understood about the dynamics of these states.
    - Both models and Lattice QCD can be employed to disentangle this QCD dynamics.
  - Spectroscopy explored here by Lebed and new experimental findings presented.

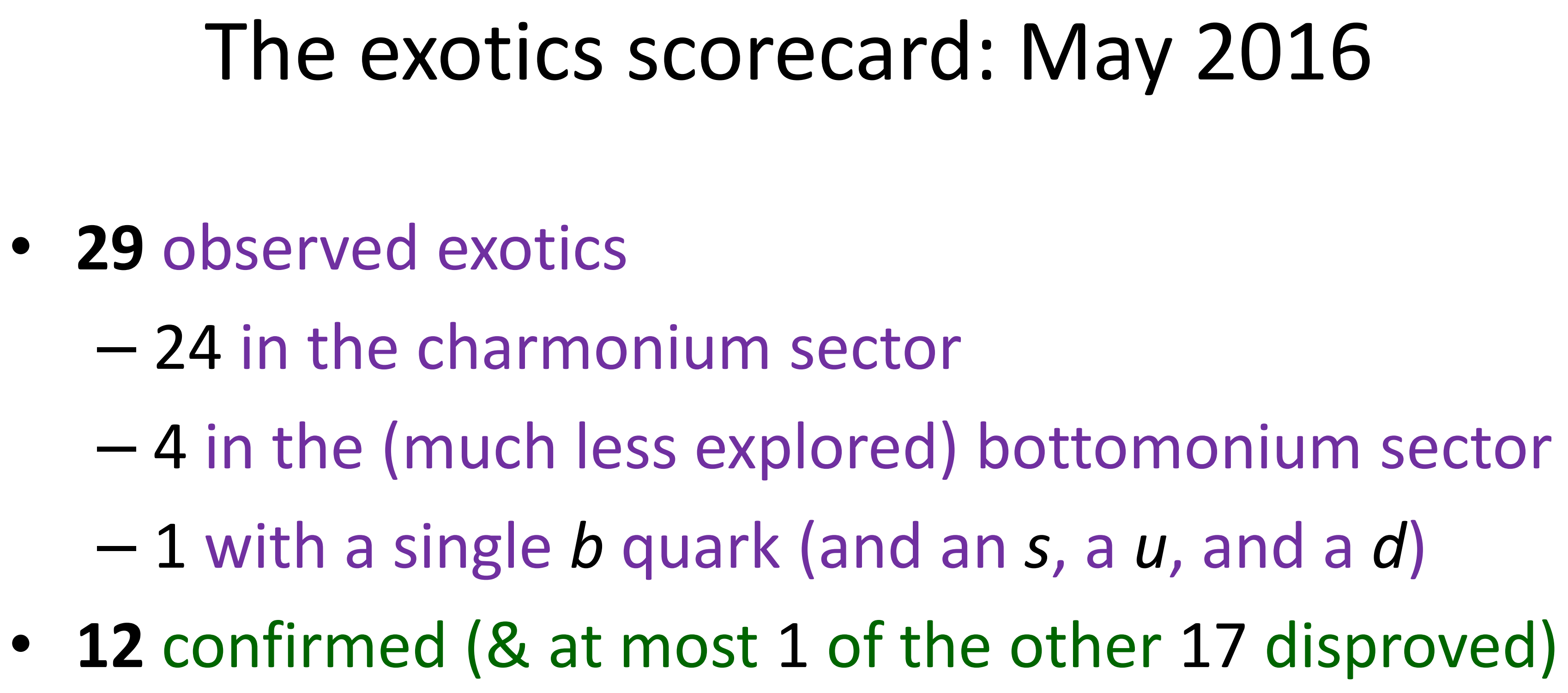
Neutral states in the charmonium region

Richard Lebed



- Below threshold the spectrum and decays are very well described by the conventional charmonium NRQCD.
- Above threshold additional states are observed.

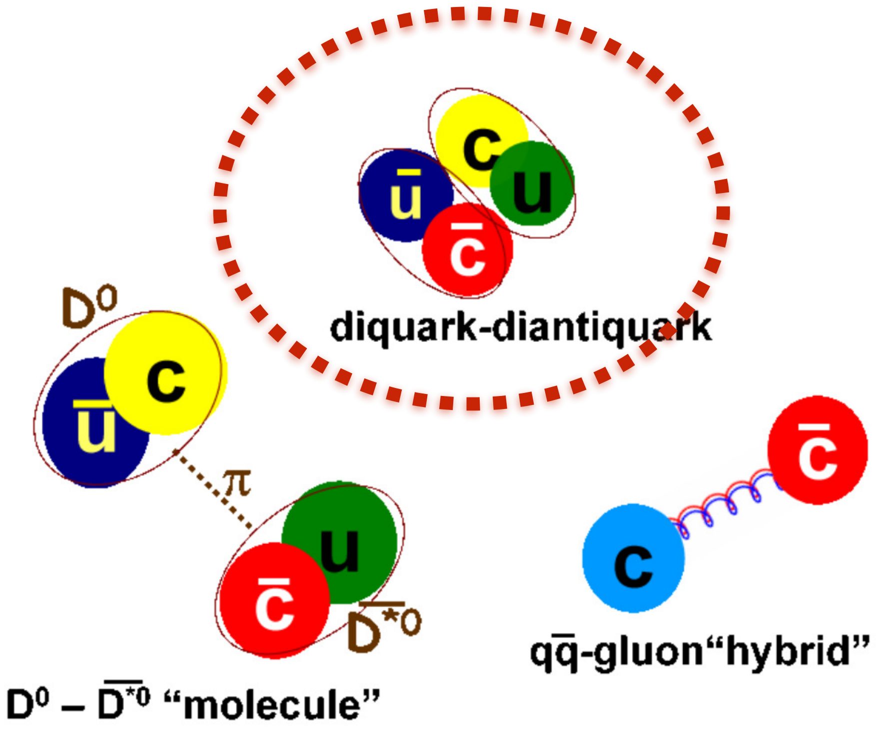
Richard Lebed

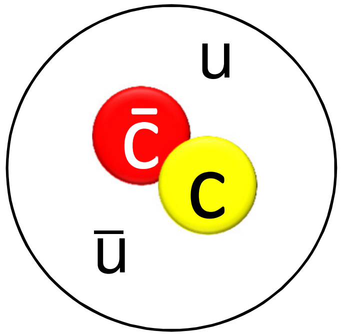


The exotics scorecard: May 2016

- **29** observed exotics
  - 24 in the charmonium sector
  - 4 in the (much less explored) bottomonium sector
  - 1 with a single *b* quark (and an *s*, a *u*, and a *d*)
- **12** confirmed (& at most 1 of the other 17 disproved)

How are tetraquarks assembled?





hadrocharmonium

cusp effect:
Resonance created by rapid
opening of meson-meson threshold

Image from Godfrey & Olsen,
Ann. Rev. Nucl. Part. Sci. **58** (2008) 51

- Lebed argues for a major role for the diquark-antidiquark dynamics
- Others argue for different pictures
- The physical states are likely to be a cocktail of these simple pictures.
- In the end this question is QCD dynamics and will need Lattice QCD calculations to disentangle the states.

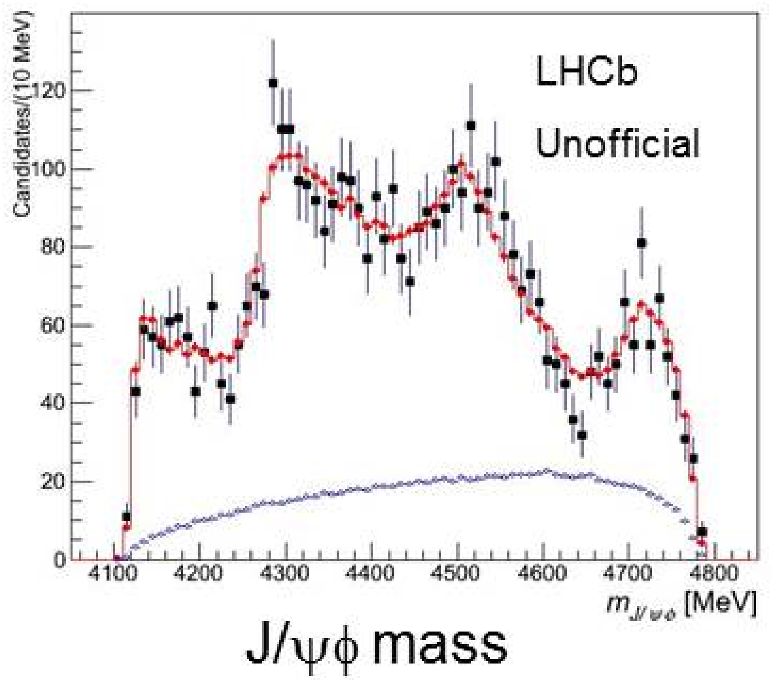
The Present and the Future

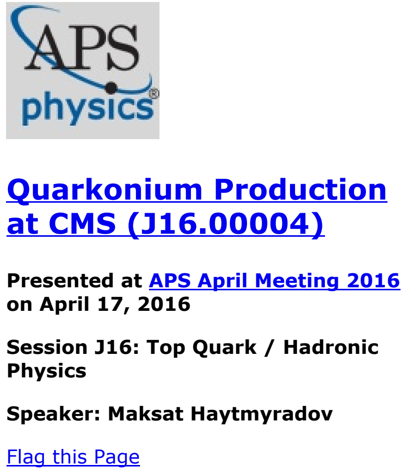
Richard Lebed

- The past two years have provided confirmation of the existence of the *tetraquark* and observation of the *pentaquark*, the third and fourth classes of hadron
- Almost 30 such states (X, Y, Z, P_C) have thus far been observed
- All of the popular physical pictures for describing their structure seem to suffer some difficulty
- We propose an entirely new dynamical picture based on a diquark-antidiquark (or triquark) pair rapidly separating until forced to hadronize due to confinement
- Exotics is a **data-driven** field. Many more exotics remain to be discovered, **especially in the beauty sector**

- Four quark states with heavier light quarks should also be observed.
  - (cscs) X(4140) and others?
- CMS at $\sqrt{s} = 8$ TeV observes double Υ production in the $\mu^+ \mu^- \mu^+ \mu^-$ final state:
  - $\sigma(pp \to \Upsilon\Upsilon) = 68.8 \pm 12.7\,(\mathrm{stat}) \pm 7.4\,(\mathrm{syst})$ pb for $|y| < 2.0$ and $p_T^{\Upsilon} < 50$ GeV
  - Possible to search for heavy quark hadrons (cccc), (cbcb), (bbbb)

Thomas Britton: APS April meetin





Quarkonium Production at CMS (J16.00004)

Presented at APS April Meeting 2016 on April 17, 2016

Session J16: Top Quark / Hadronic Physics

Speaker: Maksat Haytmyradov

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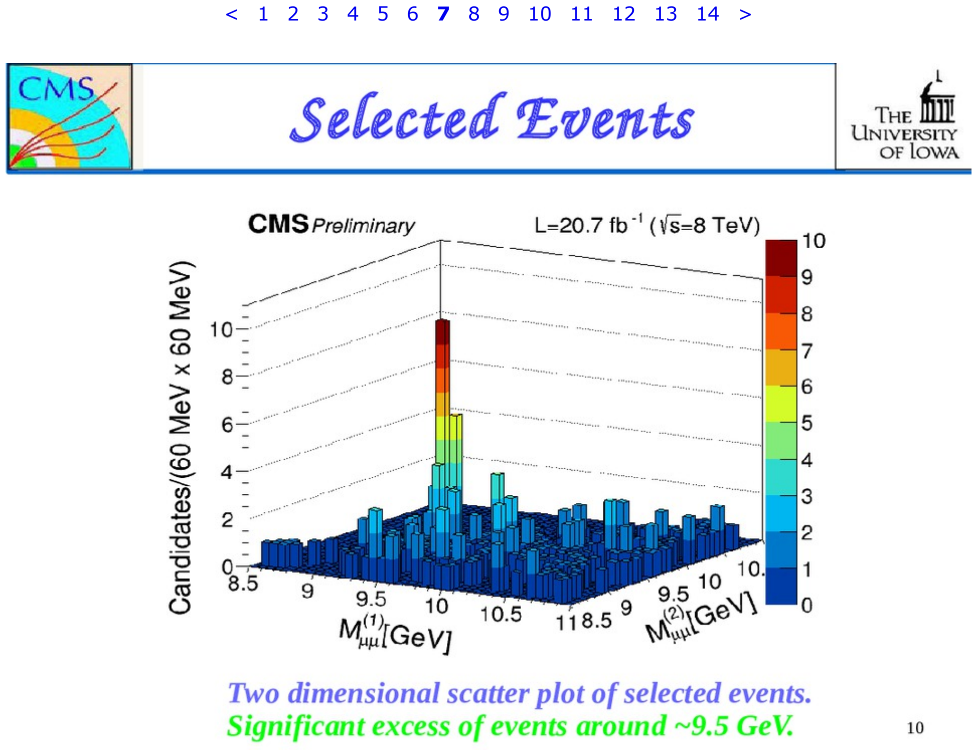
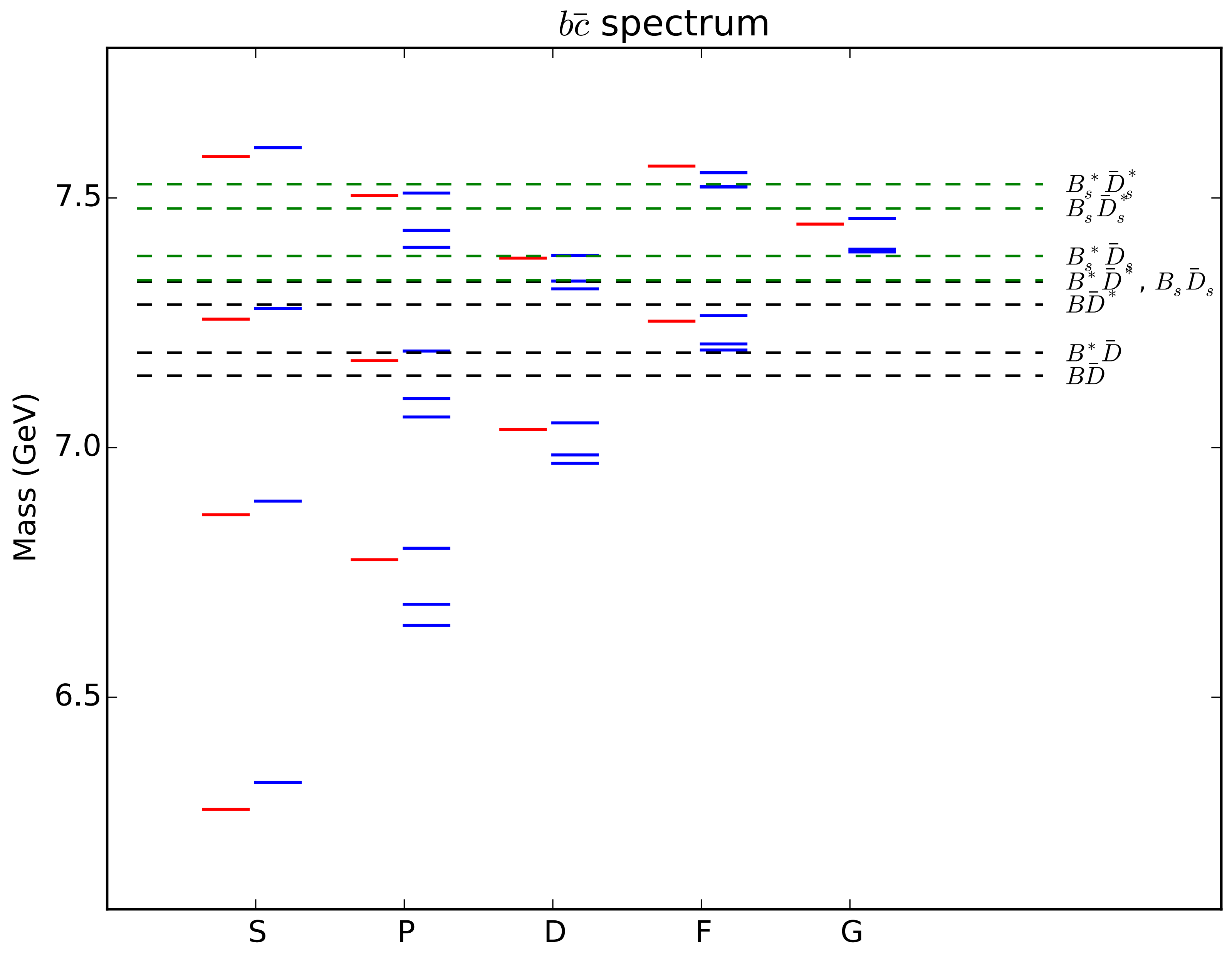


Selected Events

Two dimensional scatter plot of selected events.
Significant excess of events around ~9.5 GeV.

More distant future

- B_c - a rich excitation spectrum of states.
  - Atlas observed: Bc(2S) -> Bc(1S) +ππ. The first radially excited state.
  - Many states observable at the LHC and a future TevaZ factory.



- B_c is the only heavy-heavy meson that only has weak decays.
- Many opportunities to study CKM and BSM physics.

Andrew Lytle (poster)

First lattice calculations

Bc -> η_c and Bc -> J/ψ

weak form factors

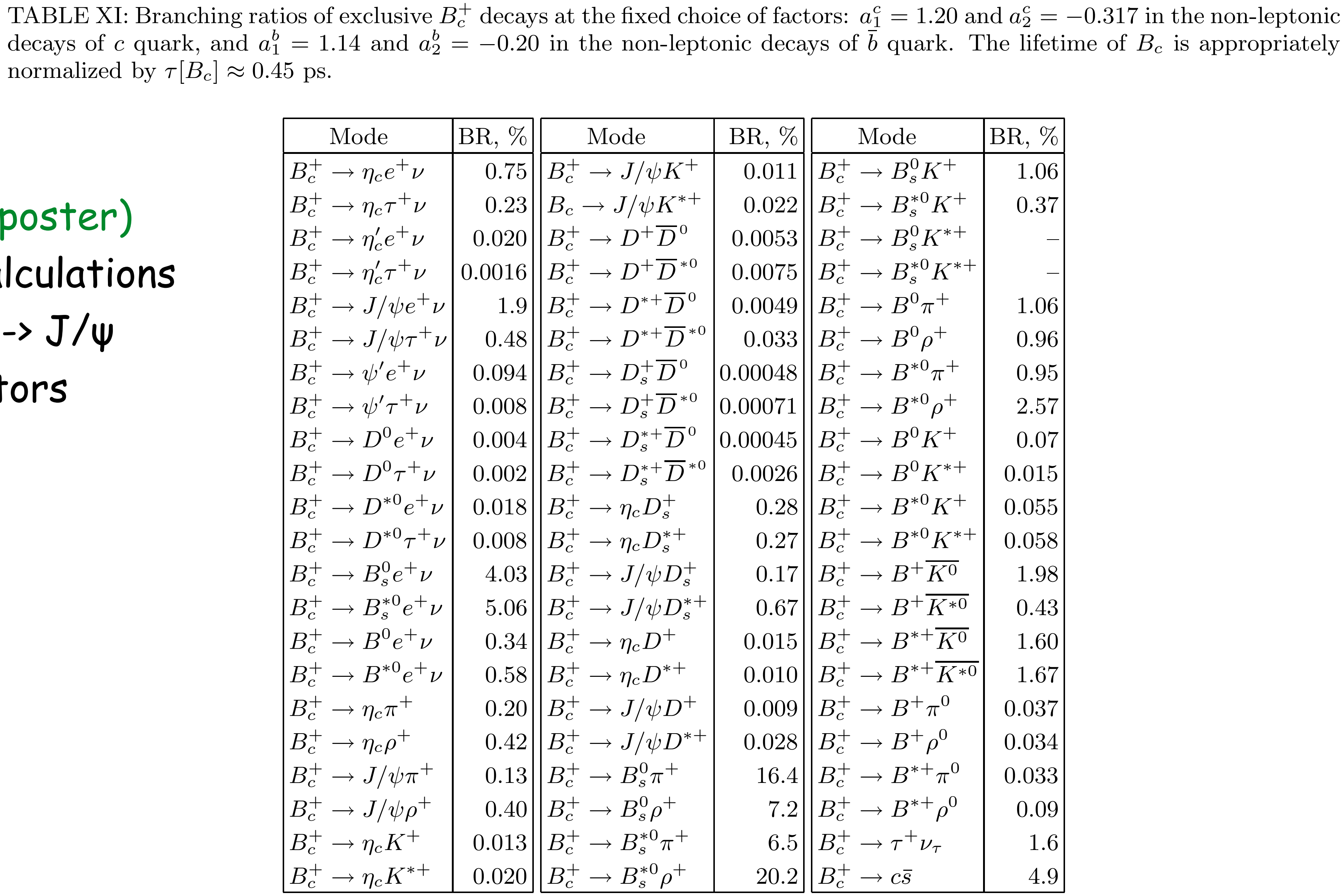


TABLE XI: Branching ratios of exclusive B_c^+ decays at the fixed choice of factors: $a_1^c = 1.20$ and $a_2^c = -0.317$ in the non-leptonic decays of c quark, and $a_1^b = 1.14$ and $a_2^b = -0.20$ in the non-leptonic decays of $\bar{b}$ quark. The lifetime of B_c is appropriately normalized by $\tau[B_c] \approx 0.45$ ps.

Mode	BR, %	Mode	BR, %	Mode	BR, %
$B_c^+ \to \eta_c e^+ \nu$	0.75	$B_c^+ \to J/\psi K^+$	0.011	$B_c^+ \to B_s^0 K^+$	1.06
$B_c^+ \to \eta_c \tau^+ \nu$	0.23	$B_c \to J/\psi K^{*+}$	0.022	$B_c^+ \to B_s^{*0} K^+$	0.37
$B_c^+ \to \eta_c' e^+ \nu$	0.020	$B_c^+ \to D^+ \overline{D}^0$	0.0053	$B_c^+ \to B_s^0 K^{*+}$	–
$B_c^+ \to \eta_c' \tau^+ \nu$	0.0016	$B_c^+ \to D^+ \overline{D}^{*0}$	0.0075	$B_c^+ \to B_s^{*0} K^{*+}$	–
$B_c^+ \to J/\psi e^+ \nu$	1.9	$B_c^+ \to D^{*+} \overline{D}^0$	0.0049	$B_c^+ \to B^0 \pi^+$	1.06
$B_c^+ \to J/\psi \tau^+ \nu$	0.48	$B_c^+ \to D^{*+} \overline{D}^{*0}$	0.033	$B_c^+ \to B^0 \rho^+$	0.96
$B_c^+ \to \psi' e^+ \nu$	0.094	$B_c^+ \to D_s^+ \overline{D}^0$	0.00048	$B_c^+ \to B^{*0} \pi^+$	0.95
$B_c^+ \to \psi' \tau^+ \nu$	0.008	$B_c^+ \to D_s^+ \overline{D}^{*0}$	0.00071	$B_c^+ \to B^{*0} \rho^+$	2.57
$B_c^+ \to D^0 e^+ \nu$	0.004	$B_c^+ \to D_s^{*+} \overline{D}^0$	0.00045	$B_c^+ \to B^0 K^+$	0.07
$B_c^+ \to D^0 \tau^+ \nu$	0.002	$B_c^+ \to D_s^{*+} \overline{D}^{*0}$	0.0026	$B_c^+ \to B^0 K^{*+}$	0.015
$B_c^+ \to D^{*0} e^+ \nu$	0.018	$B_c^+ \to \eta_c D_s^+$	0.28	$B_c^+ \to B^{*0} K^+$	0.055
$B_c^+ \to D^{*0} \tau^+ \nu$	0.008	$B_c^+ \to \eta_c D_s^{*+}$	0.27	$B_c^+ \to B^{*0} K^{*+}$	0.058
$B_c^+ \to B_s^0 e^+ \nu$	4.03	$B_c^+ \to J/\psi D_s^+$	0.17	$B_c^+ \to B^+ \overline{K^0}$	1.98
$B_c^+ \to B_s^{*0} e^+ \nu$	5.06	$B_c^+ \to J/\psi D_s^{*+}$	0.67	$B_c^+ \to B^+ \overline{K^{*0}}$	0.43
$B_c^+ \to B^0 e^+ \nu$	0.34	$B_c^+ \to \eta_c D^+$	0.015	$B_c^+ \to B^{*+} \overline{K^0}$	1.60
$B_c^+ \to B^{*0} e^+ \nu$	0.58	$B_c^+ \to \eta_c D^{*+}$	0.010	$B_c^+ \to B^{*+} \overline{K^{*0}}$	1.67
$B_c^+ \to \eta_c \pi^+$	0.20	$B_c^+ \to J/\psi D^+$	0.009	$B_c^+ \to B^+ \pi^0$	0.037
$B_c^+ \to \eta_c \rho^+$	0.42	$B_c^+ \to J/\psi D^{*+}$	0.028	$B_c^+ \to B^+ \rho^0$	0.034
$B_c^+ \to J/\psi \pi^+$	0.13	$B_c^+ \to B_s^0 \pi^+$	16.4	$B_c^+ \to B^{*+} \pi^0$	0.033
$B_c^+ \to J/\psi \rho^+$	0.40	$B_c^+ \to B_s^0 \rho^+$	7.2	$B_c^+ \to B^{*+} \rho^0$	0.09
$B_c^+ \to \eta_c K^+$	0.013	$B_c^+ \to B_s^{*0} \pi^+$	6.5	$B_c^+ \to \tau^+ \nu_\tau$	1.6
$B_c^+ \to \eta_c K^{*+}$	0.020	$B_c^+ \to B_s^{*0} \rho^+$	20.2	$B_c^+ \to c\bar{s}$	4.9

Summary

- Tremendous progress in the detailed measurements of B decays and other flavor sensitive systems.
- Theoretical expectations have also been tightened. Particularly important Lattice QCD inputs combined with analytic approaches: OPE, HQET, SCET, …
- In spite of a number of ~3σ deviations from the SM expectations, no smoking gun for BSM physics yet.
- Rich program in flavor physics for many years to come. LHCb, Belle2,…
  - "No Lose" Theorem:
    - If LHC discovers new physics in future running -> focussed searches for the effects in B decays.
    - If no new physics discovered at LHC -> leading probe for detecting BSM effect.
  - Surprises even in QCD.

– All this will require continual improvements in theoretical SM expectations.

"One more thing..." ... I mean, little things bother me.
I'm a ... It's just one of those things that gets in my head
and keeps rolling around in there like a marble.
Peter Falk - as Detective Columbo