Summary of WG2:
V_{ub}, V_{cb} and (semi)leptonic B decays including tau

Chris Bouchard with Lu Cao and Patrick Owen

Tuesday

- Effect of QED corrections on R(D), ***Teppei Kitahara***
- Inclusive b to u l nu at Belle/Belle II, ***Raynette van Tonder***
- B to D(*) l nu at Belle/Belle II, ***Killian Lieret***
- B -> D* form factors at non-zero recoil, ***Alejandro Vaquero Aviles-Casco***

- Review of exclusive semileptonic B meson decays from lattice QCD, ***Christopher Monahan***
- Exclusive semileptonic baryonic b decays from lattice QCD, ***Stefan Meinel***
- Semileptonic Lb->Lc(*) decays (LHCb), ***Marcello Rotondo***
- A unified resolution to B anomalies with lepton mixing, ***Rusa Mandal***

Wednesday

- Review of |Vub| and |Vcb| measurements at the B-factories, ***Christoph Schwanda***
- |Vcb| determination from inclusive semileptonic decays, ***Paolo Gambino***
- New ideas for calculating inclusive semileptonic decays on the lattice, ***Shoji Hashimoto***

- B to semi-tauonic decays at Belle/Belle II, ***Karol Adamczyk***
- B to mu nu at Belle/Belle II, ***Alexei Sibidanov***
- B to l nu gamma at Belle, ***Moritz Gelb***
- B -> 3 mu nu at LHCb, S***vende Annelies Braun***

Thursday

- *(joint with WG1)* Semileptonic B and D decays from sum rules, ***Alexander Khodjamirian***
- *(joint with WG1)* Nonperturbative calculations of form factors for exclusive semileptonic Bs decays, ***Oliver Witzel***
- *(joint with WG1)* New physics in b -> c l nu, ***David Straub***
- *(joint with WG1)* Leptonic Decays of B and D Mesons from Lattice QCD, ***Javad Komijani***

- *(joint with WG3)* LFU tests with semitauonic decays at LHCb, ***Adam Morris***
- *(joint with WG3)* b->sll LFU measurements at LHCb, ***Vitalii Lisovskyi***
- *(joint with WG3)* BSM physics and lepton flavor nonuniversality in semileptonic b decays, ***Olcyr Sumensari***
- *(joint with WG3)* New directions in B-anomalies model building, ***Admir Greljo***

Summary

- $|V_{cb}|$
  - HFLAV 2016 results
    - exclusive ($D^*l\nu$): (39.05 +/- 0.47(exp) +/- 0.58(th)) x 10^{-3}
    - inclusive: (42.19 +/- 0.78) x 10^{-3}
  - Evidence has been mounting in the past two years that the CLN parameterization is biasing the exclusive result
    - On two independent $D^*l\nu$ data sets BGL results in $|V_{cb}|$ being ~2σ higher than CLN
- $|V_{ub}|$
  - HFLAV 2016 results
    - $\pi l\nu$: (3.70 +/- 0.10(exp) +/- 0.12(th)) x 10^{-3}
    - inclusive (BLNP): (4.44 +/- 0.15 +0.21/-0.22) x 10^{-3}
  - For $|V_{ub}|$ however, the ~3σ discrepancy remains to be understood

Belle data sets for B to D*
- hadronic tagging: arXiv:1702.01521
- untagged: arXiv:1809.032090

Vub and Vcb and semitauonic

Form factor parameterizations

- Caprini, Lellouch, Neubert [Nucl.Phys. B530, 153(1998)]

coeffs related via HQET

$B \to D^* l\nu$

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

$B \to D l\nu$

$$\mathcal{G}(z) = \mathcal{G}(1)(1 - 8\rho^2 z + (51\rho^2 - 10)z^2 - (252\rho^2 - 84)z^3)$$

Parameters: $F(1)$, ρ^2, $R_1(1)$, $R_2(1)$
$G(1)$, ρ^2

- Boyd, Grinstein, Lebed [Phys. Rev. Lett. 74, 4603 (1995)]

$$f_i(z) = \frac{1}{P_i(z)\phi_i(z)} \sum_{n=0}^{N} a_{i,n} z^n, \qquad z(w) = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

Parameters: coefficients $a_{i,n}$

Model-independent analysis of arXiv:1702.01521 data

- D.Bigi, P. Gambino, S.Schacht, Phys.Lett. B769 (2017) 441

BGL Fit:	Data + lattice	Data + lattice + LCSR
χ^2/dof	27.9/32	31.4/35
$\lvert V_{cb}\rvert$	$0.0417\,(^{+20}_{-21})$	$0.0404\,(^{+16}_{-17})$
a_0^f	0.01223(18)	0.01224(18)
a_1^f	$-0.054\,(^{+58}_{-43})$	$-0.052\,(^{+27}_{-15})$
a_2^f	$0.2\,(^{+7}_{-12})$	$1.0\,(^{+0}_{-5})$
$a_1^{\mathcal{F}_1}$	$-0.0100\,(^{+61}_{-56})$	$-0.0070\,(^{+54}_{-52})$
$a_2^{\mathcal{F}_1}$	0.12 (10)	$0.089\,(^{+96}_{-100})$
a_0^g	$0.012\,(^{+11}_{-8})$	$0.0289\,(^{+57}_{-37})$
a_1^g	$0.7\,(^{+3}_{-4})$	$0.08\,(^{+8}_{-22})$
a_2^g	$0.8\,(^{+2}_{-17})$	$-1.0\,(^{+20}_{-0})$

CLN Fit:	Data + lattice	Data + lattice + LCSR
χ^2/dof	34.3/36	34.8/39
$\lvert V_{cb}\rvert$	0.0382 (15)	0.0382 (14)
$\rho^2_{D^*}$	$1.17\,(^{+15}_{-16})$	1.16 (14)
$R_1(1)$	$1.391\,(^{+92}_{-88})$	1.372 (36)
$R_2(1)$	$0.913\,(^{+73}_{-80})$	$0.916\,(^{+65}_{-70})$
$h_{A_1}(1)$	0.906 (13)	0.906 (13)

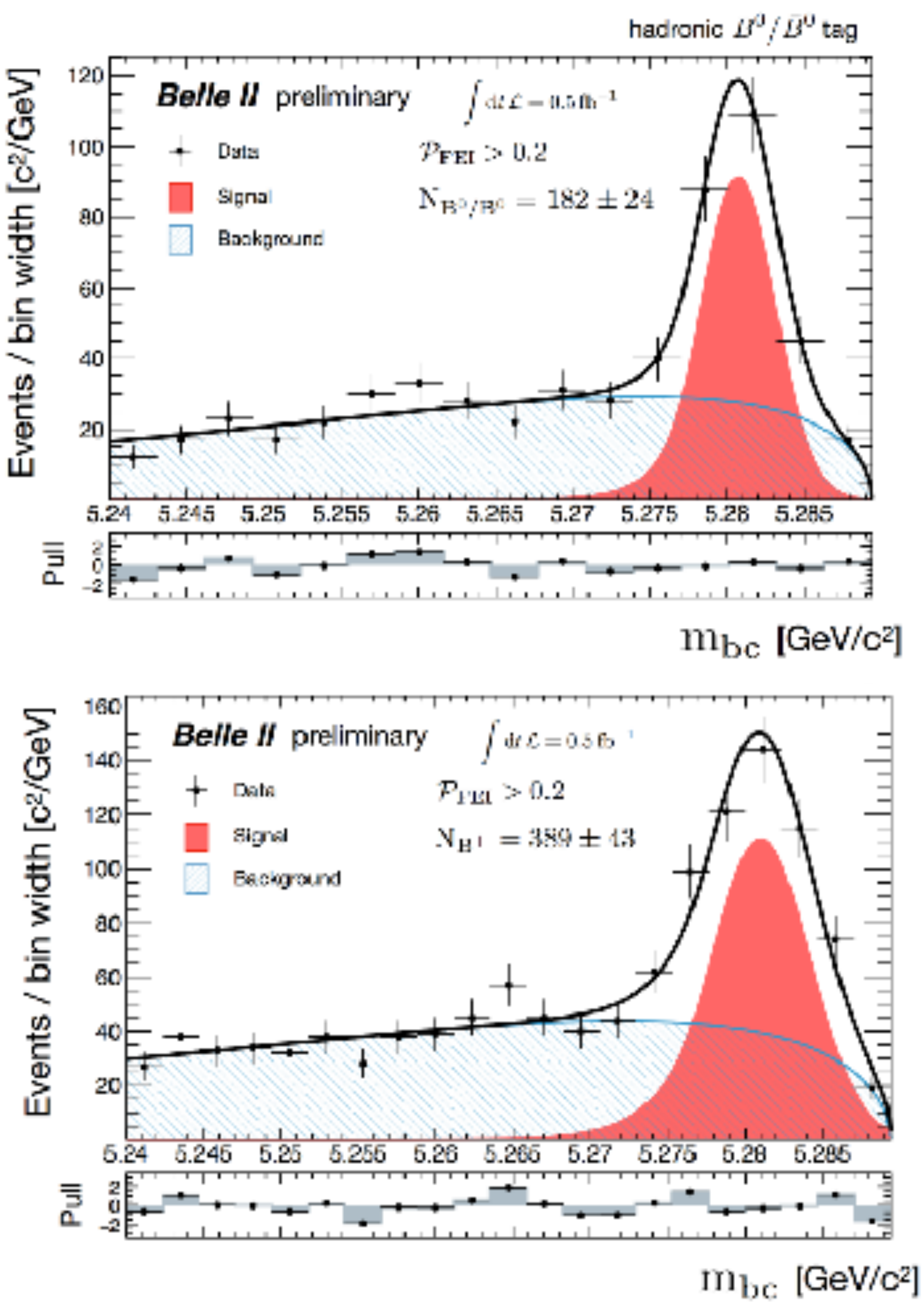
- B.Grinstein, A.Kobach, Phys.Lett. B771 (2017) 359

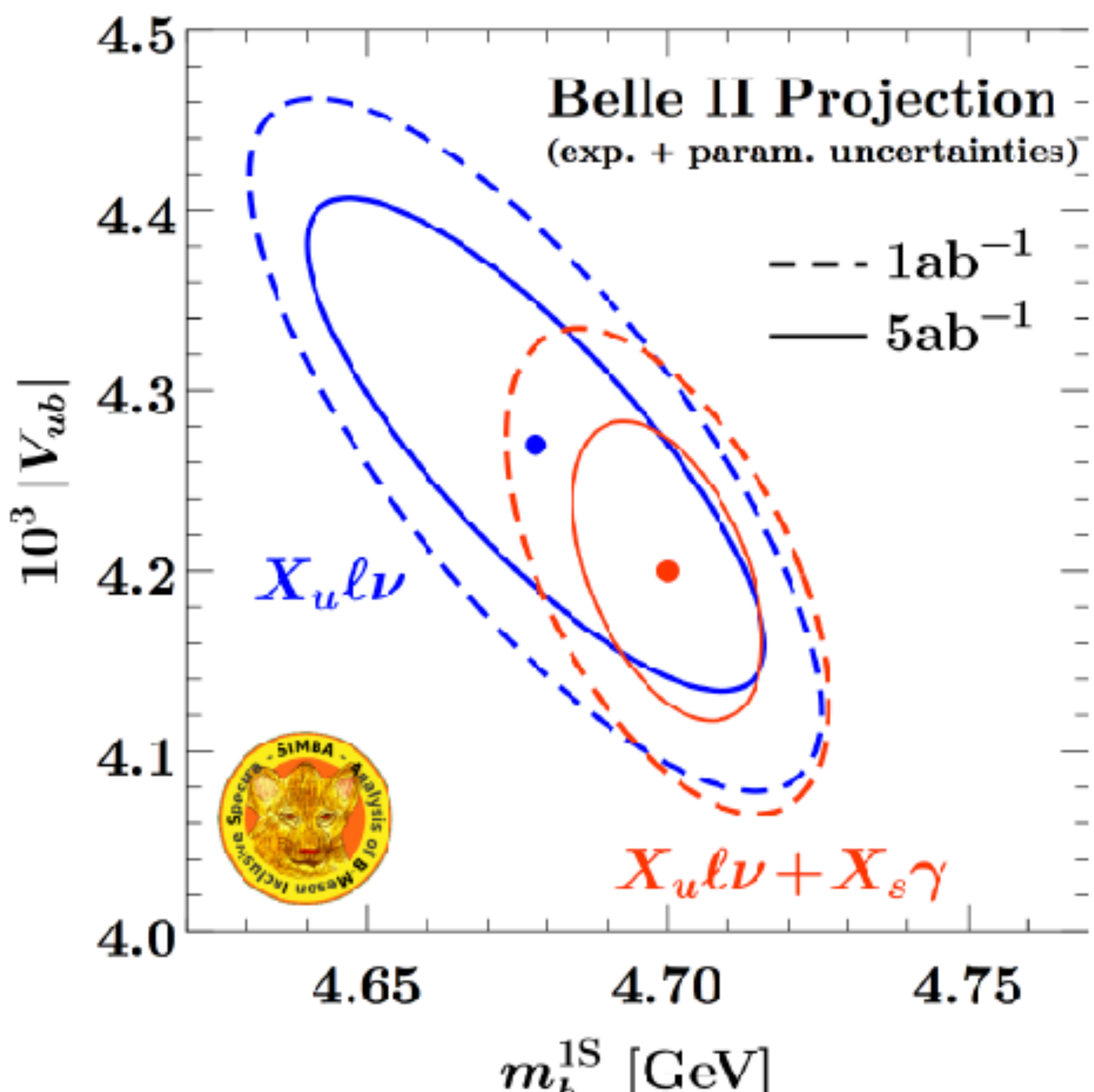
$$|V_{cb}| = (37.4 \pm 1.3) \times 10^{-3} \qquad \text{(CLN)}$$

$$|V_{cb}| = (41.9\ ^{+2.0}_{-1.9}) \times 10^{-3} \qquad \text{(BGL)}$$

Raynette Van Tonder, **Inclusive B -> Xu l nu at Belle II**

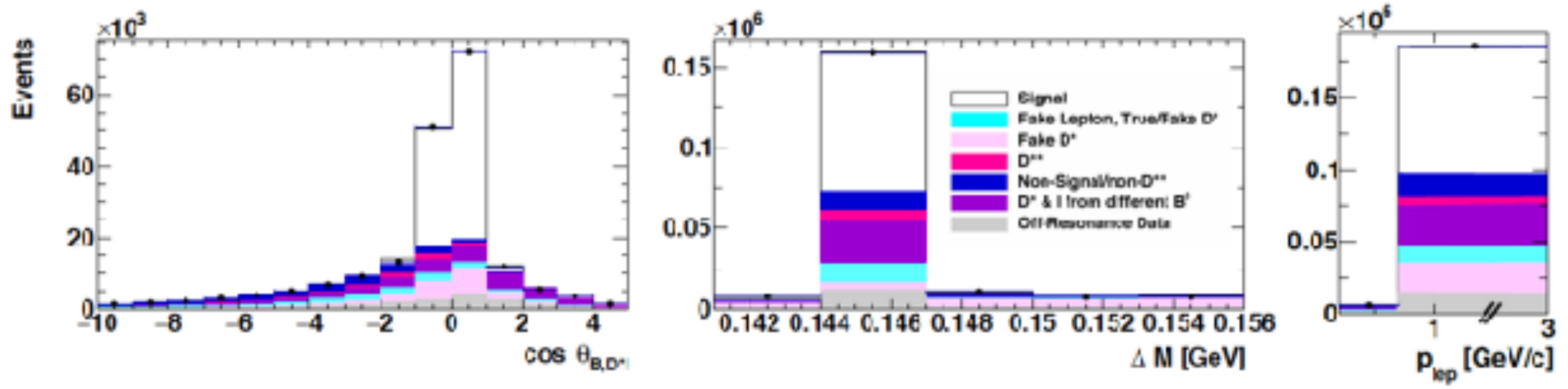
- aim to disentangle ~3.5σ tension between exclusive and inclusive Vub.
- Difficulty from large background coming from b -> clv decays.
- Need good tagging performance and reasonable B -> Xu lv MC modelling.
- Hadronic tagging performance with FEI using Belle2 phase II data is obtained.
- Global fit proposal by SIMBA, NNVub can be done to reduce error 2-3%.



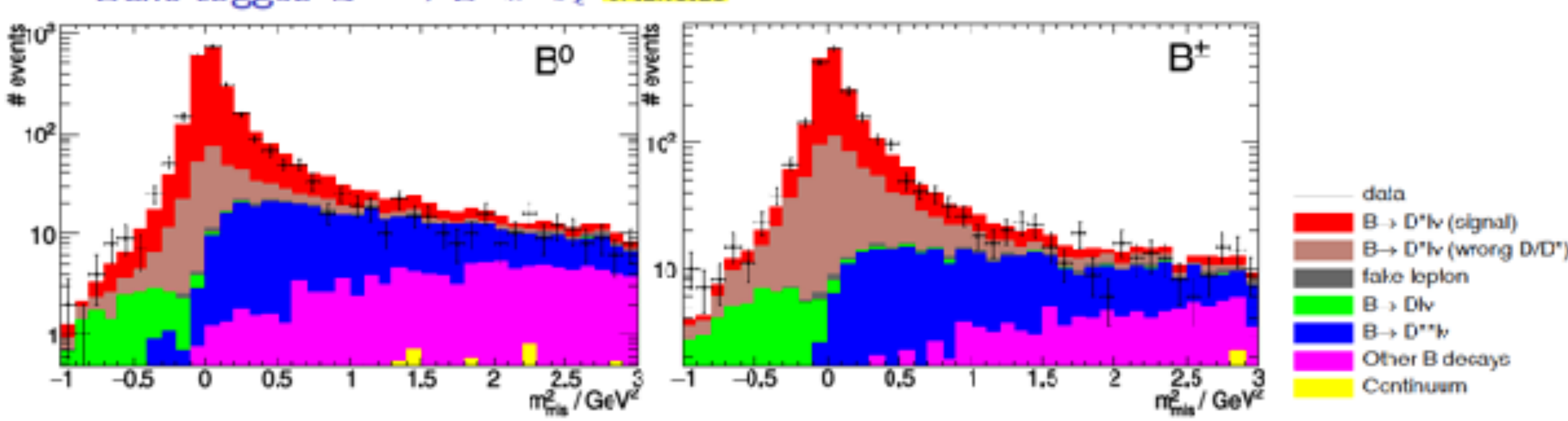


- aim to disentangle ~3σ tension between exclusive and inclusive Vcb. Hadronic tagging & untagged.
- CLN & BGL parameterisations used for form factor. Prospects for BelleII

Belle untagged $\bar{B} \longrightarrow D^*\ell^-\bar{\nu}_\ell$ (new) 1809.03290



Belle tagged $\bar{B} \longrightarrow D^*\ell^-\bar{\nu}_\ell$ 1702.01521



Link	Channel	Tag	$\lvert V_{cb}\rvert \times 10^3$ (CLN)	$\lvert V_{cb}\rvert \times 10^3$ (BGL)	Unfold	Notes
Phys.Rev. D82 112007	$D^*\ell^-\bar{\nu}_\ell$	No	35.5 ± 1.5			
1809.03290	$D^*\ell^-\bar{\nu}_\ell$	No	38.4 ± 0.9	42.5 ± 1.0	Soon	
1702.01521	$D^*\ell^-\bar{\nu}_\ell$	Had.	37.4 ± 1.3		Yes	Soon: Separate results $\ell = e$ and $\ell = \mu$
Phys.Rev. D93 no.3, 032006	$D\ell^-\bar{\nu}_\ell$	Had.	39.9 ± 1.3	40.8 ± 1.1		

cf. current PDG: $V_{cb,\text{incl.}} = (42.2 \pm 0.8) \times 10^{-3}$

Karol Adamczyk, **B to semi-tauonic decays at Belle/Belle II**

[Phys. Rev. Lett. 118, 211801 (2017)], [Phys. Rev. D 97, 012004 (2018)]

- first measurement of tau polarisation;
- combined P_τ and R(D*) consists with SM within 0.6 sigma.

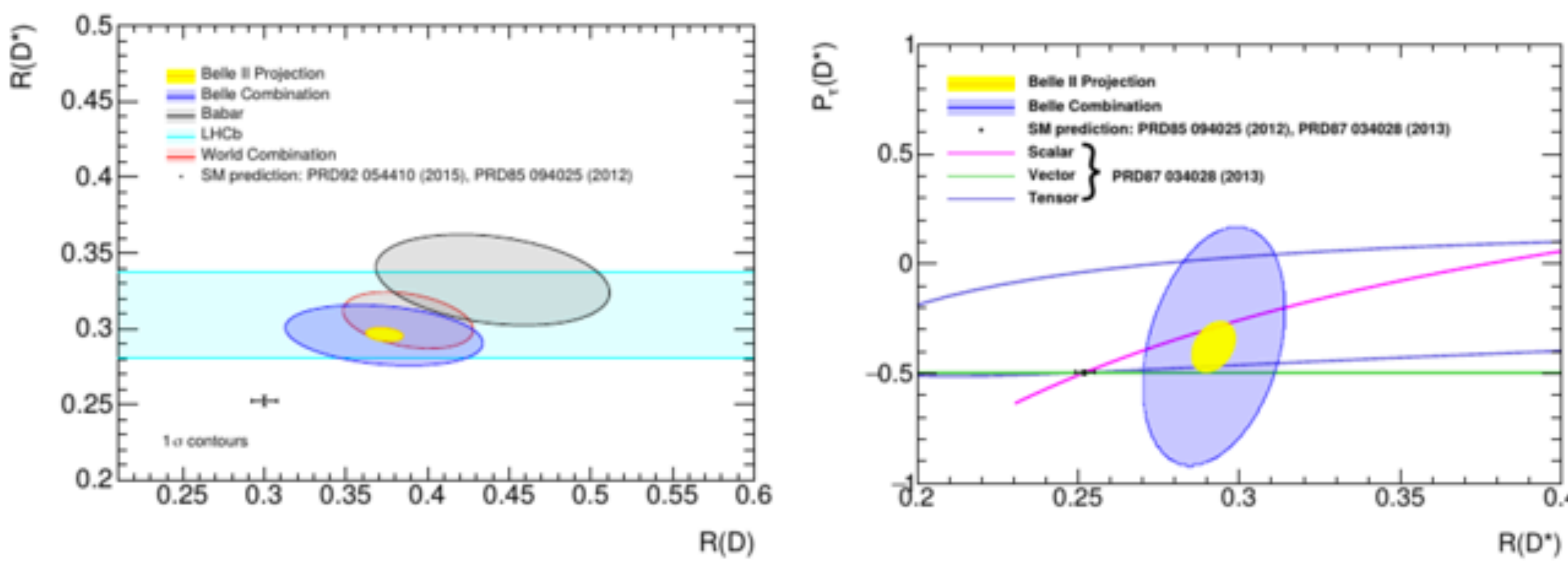
$$P_\tau(D^*) = -0.38 \pm 0.51(stat.)^{+0.21}_{-0.16}(syst.)$$
$$R(D^*) = 0.270 \pm 0.035(stat.)^{+0.028}_{-0.025}(syst.)$$

Prospects @ Belle II

Belle II

The Belle II Physics Book, arXiv:1808.10567

- expected constraints on R_D vs. R_{D^*}; R_{D^*} vs. $P_\tau^{D^*}$ compared to existing experimental constraints from Belle



Christopher Monahan, **Review of exclusive semileptonic B meson decays from lattice QCD**

- overview of B(s) semileptonic decay calculations on the lattice
- overview of lattice systematic uncertainties
- (many!) results since CKM 2018

B to π
- more groups now studying decay (3 -> 5)
- soon: 2+1+1 results at nonzero recoil

B_s to K
- more groups now studying decay (2 -> 3)
- soon: 2+1+1 results

B to D
- now: preliminary 2+1+1 results

B to D^*
- more groups now studying decay (1 -> 3)
- now: published 2+1+1 result [HPQCD] and new V_{cb}=0.00413(22)
- soon: 2+1 results at nonzero recoil

B_s to D_s
- more groups now studying decay (1 -> 3)
- now: published 2+1 result at nonzero recoil [HPQCD], inc. $R(D_s)$
- soon: 2+1+1 results

B_s to D_s^*
- ~~more~~ groups now studying decay (0 -> 2)
- now: published 2+1+1 result [HPQCD]

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- overview of B(s) semileptonic decay calculations on the lattice
- overview of lattice systematic uncertainties
- (many!) results since CKM 2018

Outlook

Next few years will see many more lattice results
- expect new Vub from ETMC, FNAL/MILC, HPQCD, JLQCD
- expect new Vcb from FNAL/MILC, HPQCD, SWME

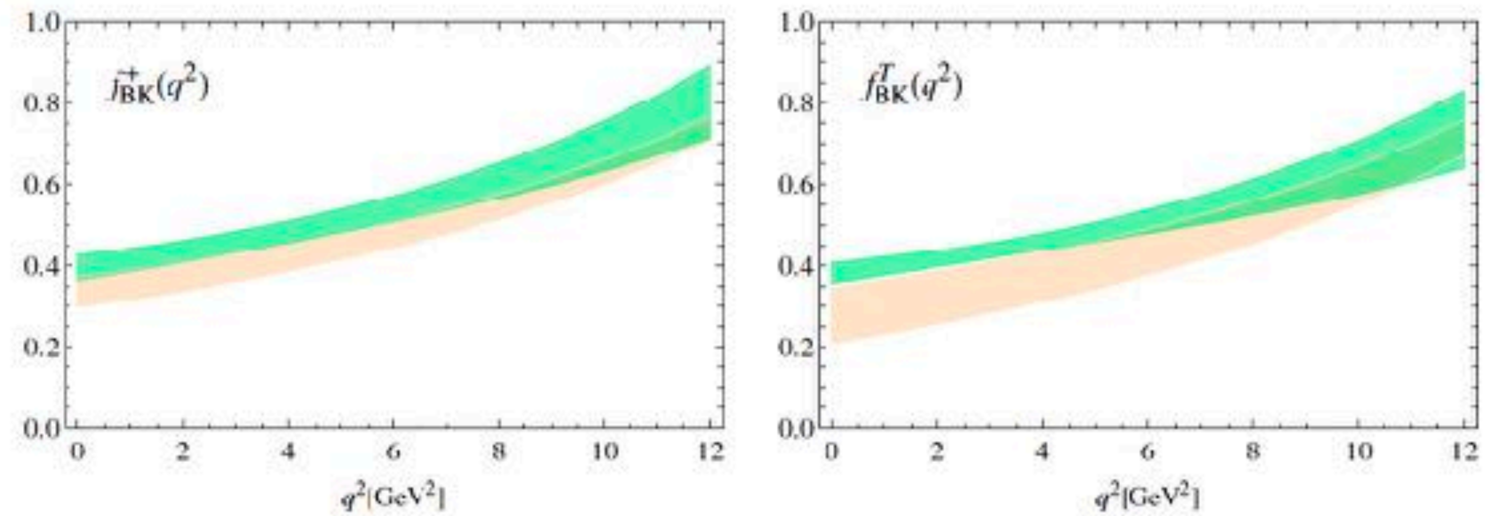
Heavy HISQ (and DWF) results are very promising
- allows entirely nonperturbative current renormalisation
- should facilitate sub-1% precision

Anticipating exp. results, B_s decays a real growth industry
- HPQCD, RBC/UKQCD, SWME
- but further progress really requires experimental data

Moving beyond ~0.5% precision will require
- isospin breaking effects
- QED effects

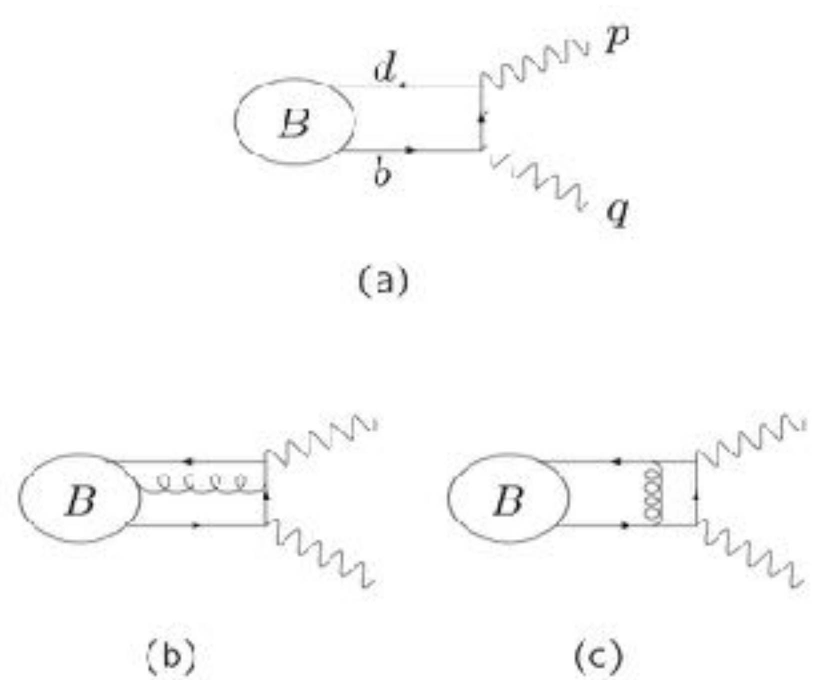
Alexander Khodjamirian, **Semileptonic B and D decays from sum rules** (joint with WG1)

- new results for Bs -> K [1703.04765]
- preliminary results for D -> π and D -> K

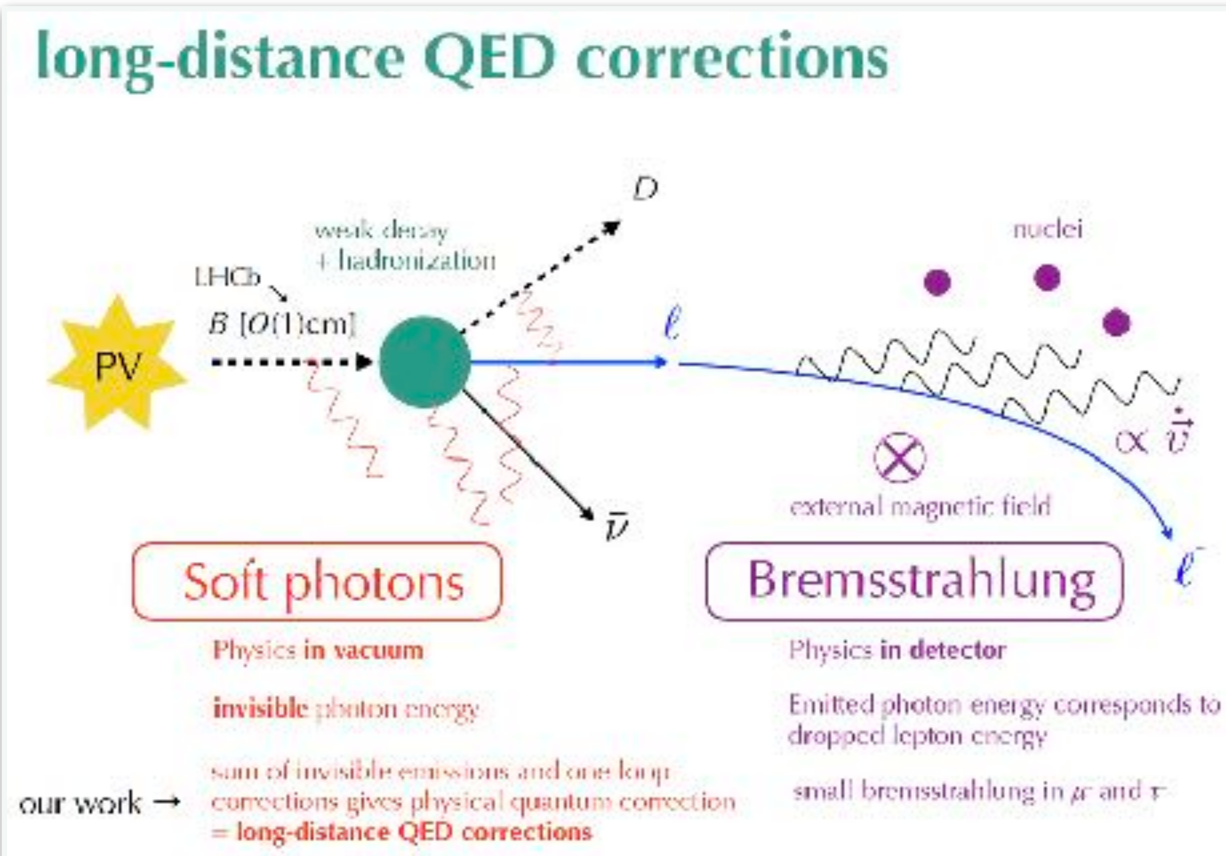


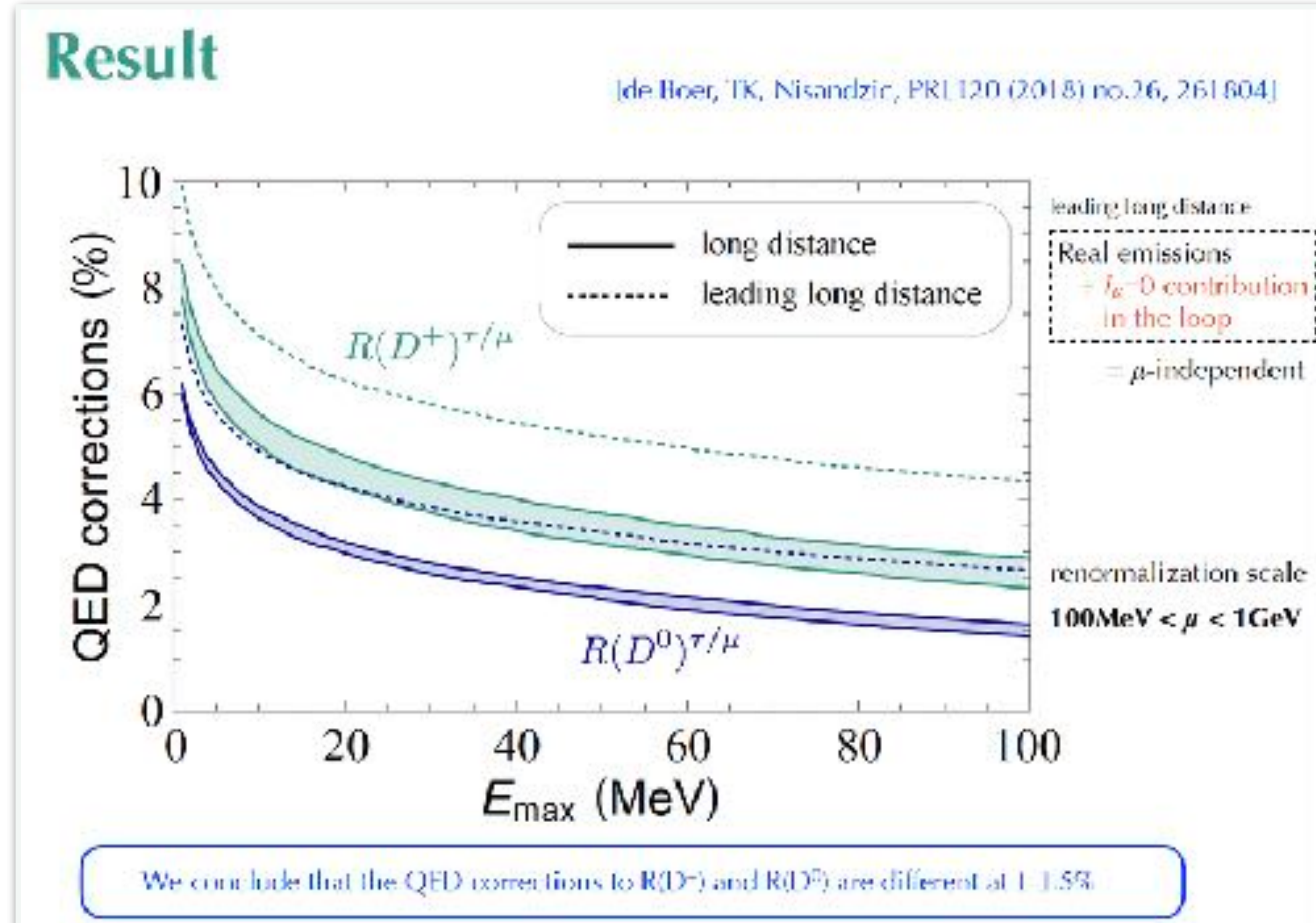
- improvements:
  - NNLO correction to twist 2
  - twist 5,6 terms
  - improved π, K distribution amplitudes & form factors (in progress)

- new approach using B meson DAs
  - valid for any B -> "light" form factor
  - need Belle-II B -> γ μ ν_μ
  - application to B -> ππ [1701.01633]



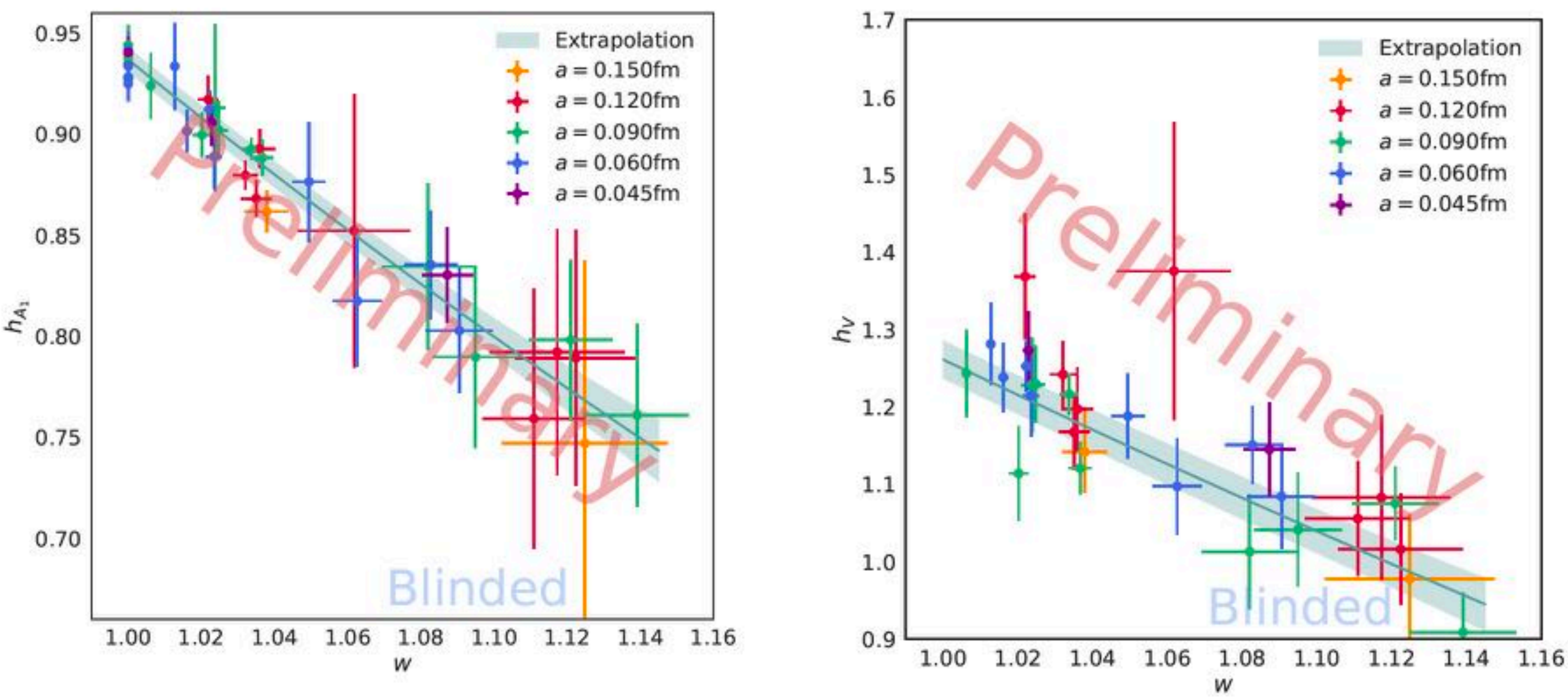
Teppei Kitahara, **Effect of QED corrections on R(D)**



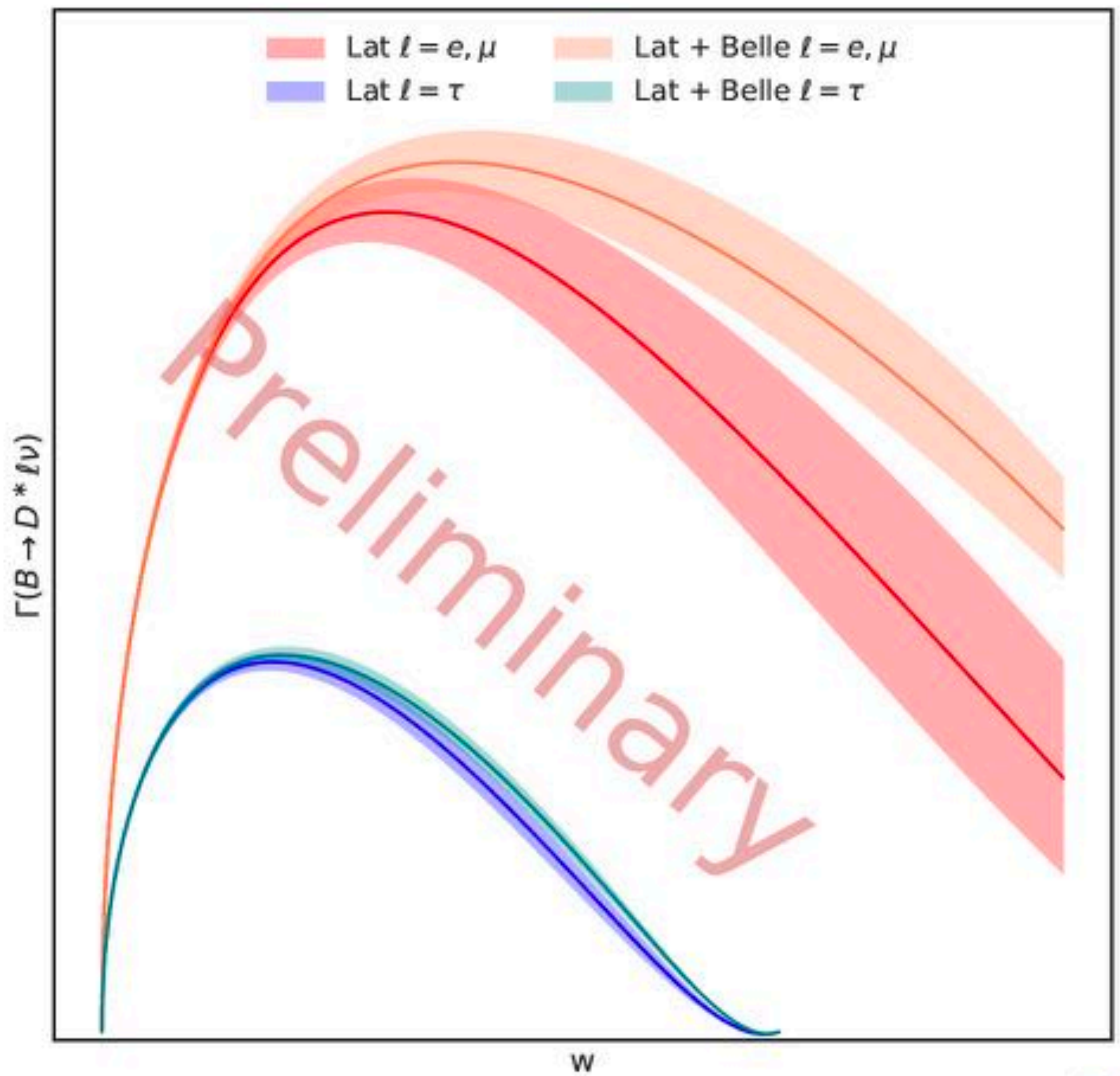


- 3-4% correction to R(D) based on soft (≲30 MeV) photon contributions
- important to understand how QED effects handled in experiment (PHOTOS)
- working on R(D*) and Vcb

- much anticipated, preliminary (still blinded) results over a small range of momentum transfer.
- do not anticipate signficant reduction in |Vcb| uncertainty, but slope at zero recoil (w=1) will weigh in on CLN vs BGL



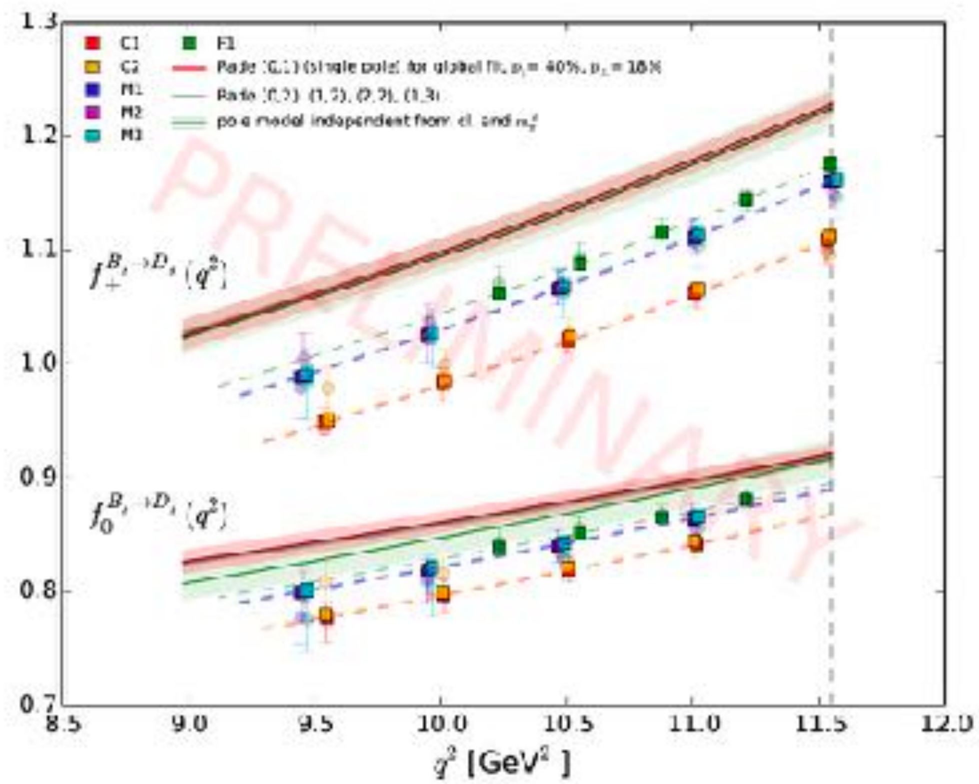
- Pure lattice QCD prediction of $R(D^*)$
- Probably underestimating errors (prepared last week)
- Lattice very reliable up to the point we have lattice data
- Sensitive to the slope in $\mathcal{F}$



Oliver Witzel,

Nonperturbative calculations of form factors for exclusive semileptonic Bs decays

(joint with WG1)



Conclusion

- Second (third) entirely independent analysis about to be completed
- In the final stages to complete $B_s \to K\ell\nu$ and $B_s \to D_s\ell\nu$ form factor calculation
  - → As usual, carefully estimating all systematic uncertainties is tedious
- Our lattice calculation also includes
  - → $B \to \pi\ell\nu$, $B \to \pi\ell^+\ell^-$
  - → $B \to K^*\ell^+\ell^-$
  - → $B \to D^{(*)}\ell\nu$
  - → $B_s \to K^*\ell^+\ell^-$
  - → $B_s \to D_s^*\ell\nu$
  - → $B_s \to \phi\ell^+\ell^-$
- Future
  - → Add $48^3 \times 96$ ensemble with physical pions

Paolo Gambino, **|Vcb| determination from inclusive semileptonic decays**

- reviewed inclusive approach
- continued effort to improve inclusive b -> clν
  - no signs of inconsistency
  - good understanding of higher power contributions

PROSPECTS for INCLUSIVE V_{cb}

- Theoretical uncertainties already dominant
- theoretical correlations between different moments?
- $O(\alpha_s/m_b^3)$ calculation under way
- $O(1/m_Q^{4,5})$ effects need further investigation but small effect on V_{cb}
- NNNLO corrections to total width feasible, needed for 1% uncertainty?
- Electroweak (QED) corrections require attention
- New observables in view of Belle-II: FB asymmetry proposed by S.Turczyk could be measured already by Babar and Belle now
- Lattice QCD information on local matrix elements is the next frontier, e.g.

Shoji Hashimoto, **New ideas for calculating inclusive semileptonic decays on the lattice**

- lattice QCD determination of 4pt correlator <Bl J J lB> at unphysical kinematics relevant to inclusive determinations of Vcb, coordination with Paolo
- exciting, exploratory study

Partial decay rate:

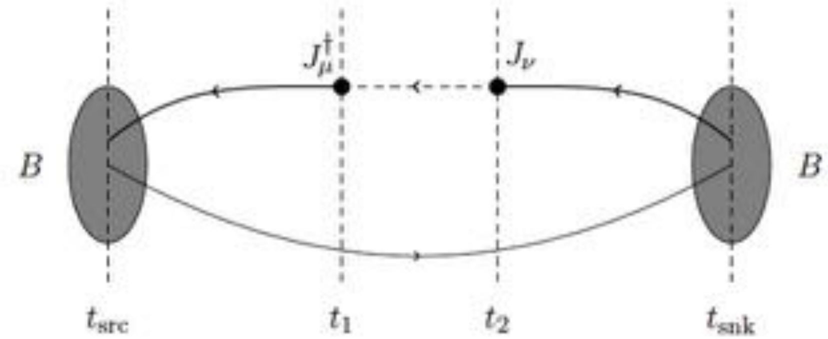
$$d\Gamma \sim |V_{cb}|^2 l^{\mu\nu} W_{\mu\nu}$$

$$W_{\mu\nu} = \sum_X (2\pi)^3 \delta^4(p_B - q - p_X) \frac{1}{2M_B} \langle B(p_B)|J_\mu^\dagger(0)|X\rangle\langle X|J_\nu(0)|B(p_B)\rangle$$

sum over all final states

optical theorem

$$T_{\mu\nu} = i\int d^4x e^{-iqx} \frac{1}{2M_B} \langle B|T\{J_\mu^\dagger(x) J_\nu(0)\}|B\rangle$$



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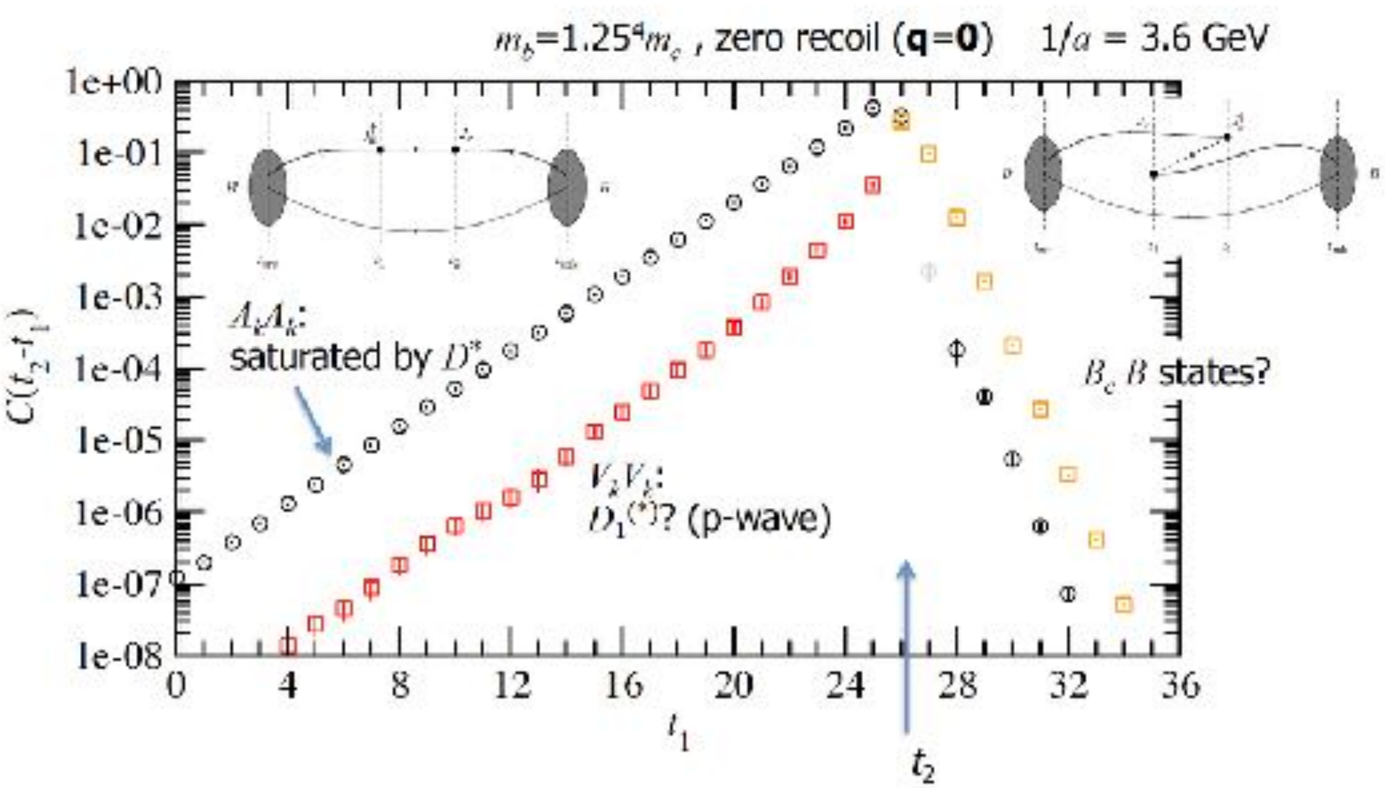
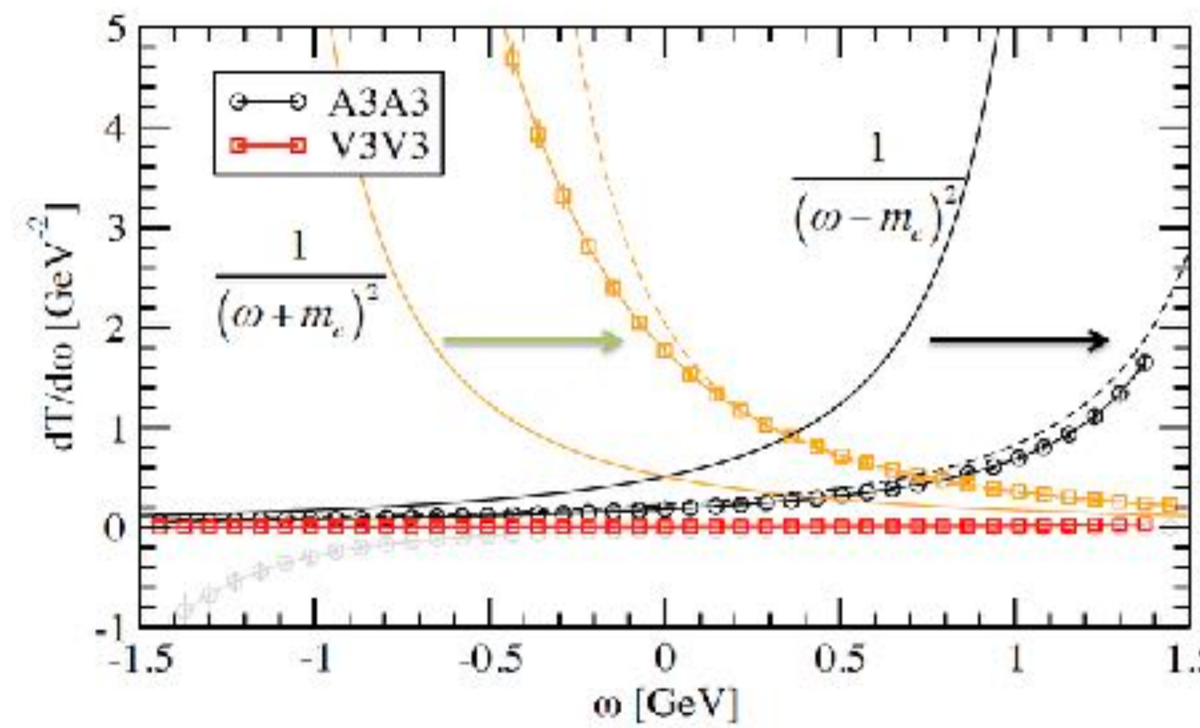




- possible appliation to nucleon structure

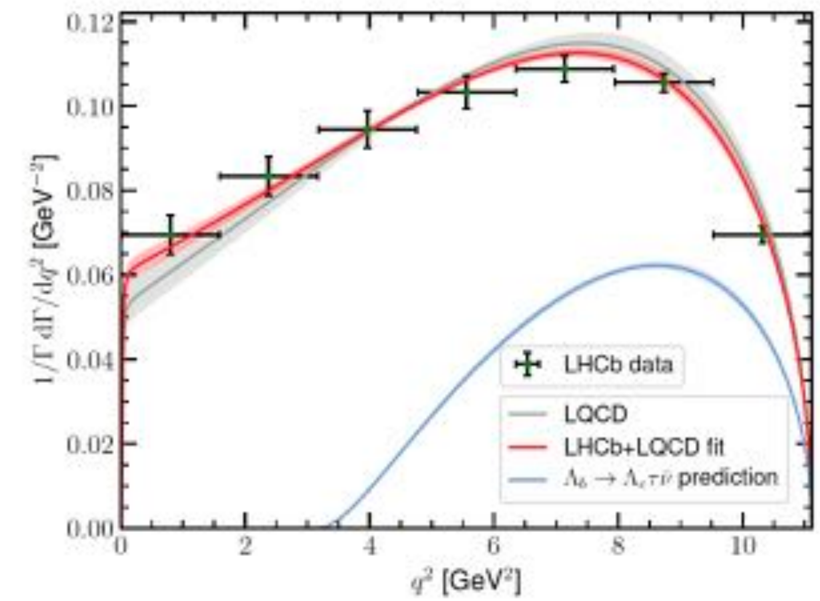
Vub and Vcb and semitauonic

* baryonic!

Stefan Meinel, **Exclusive semileptonic baryonic b decays from lattice QCD**

overview of b hadronic semileptonic decays
(Λb = bdu, Λc = cdu, Λ=sdu)

- Λb → p l ν (b → ulν)
- Λb → Λc l ν (b → clν)

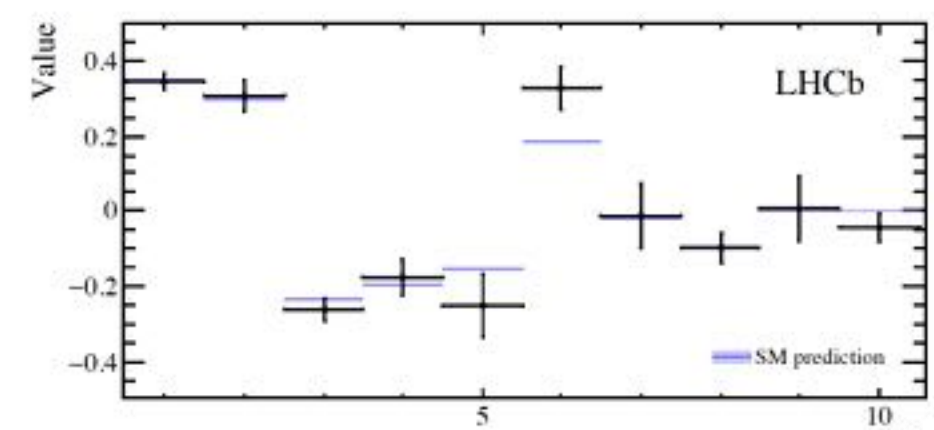


Heavy-quark symmetry provides stronger constraints for $\Lambda_b \to \Lambda_c \ell \bar{\nu}$ than for $B \to D^{(*)} \ell \bar{\nu}$

→ First determination of $\mathcal{O}(\Lambda^2/m_c^2)$ contributions to an exclusive decay

[F. Bernlochner, Z. Ligeti, D. Robinson, W. Sutcliffe, arXiv:1808.09464]

$\frac{d^5\Gamma}{d\vec{\Omega}} = \frac{3}{32\pi^2} \sum_i^{34} K_i f_i(\vec{\Omega})$ $\quad 15 < q^2 < 20\,\mathrm{GeV}^2$



[LHCb Collaboration, arXiv:1808.00264]

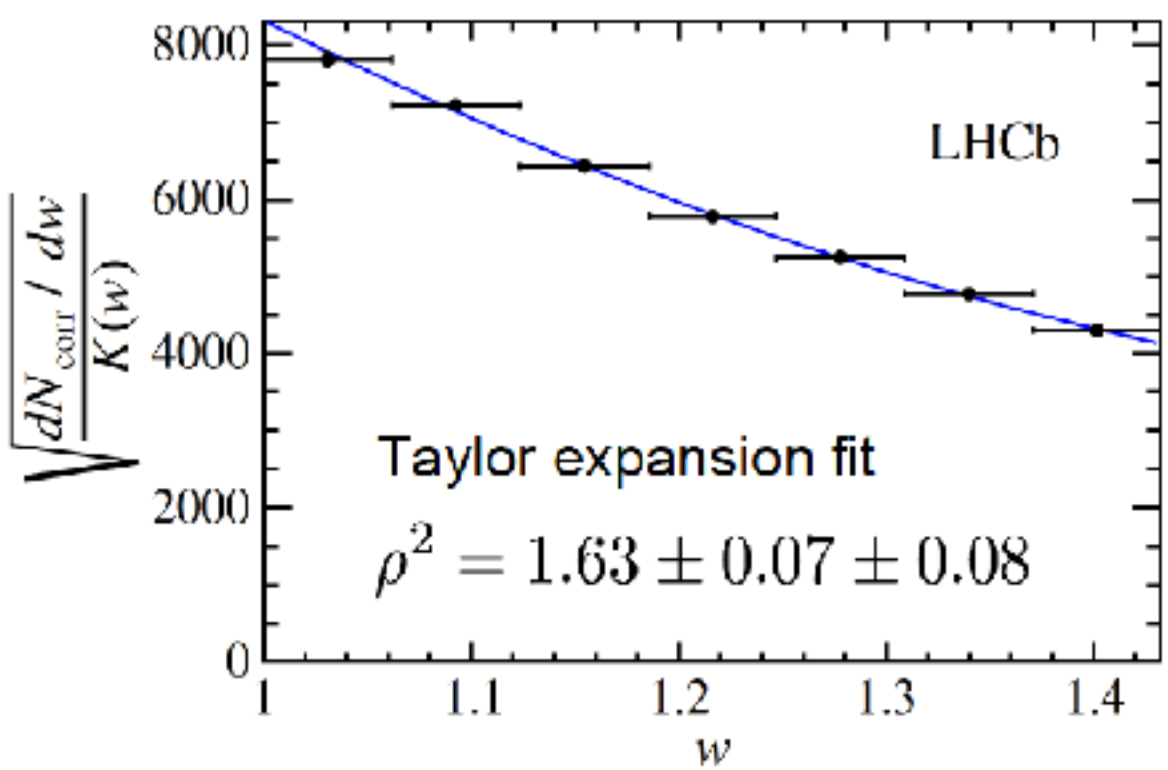
$A^{\ell}_{FB} = \frac{3}{2} K_3, \quad A^{h}_{FB} = K_4 + \frac{1}{2} K_5, \quad A^{\ell h}_{FB} = \frac{3}{4} K_6$

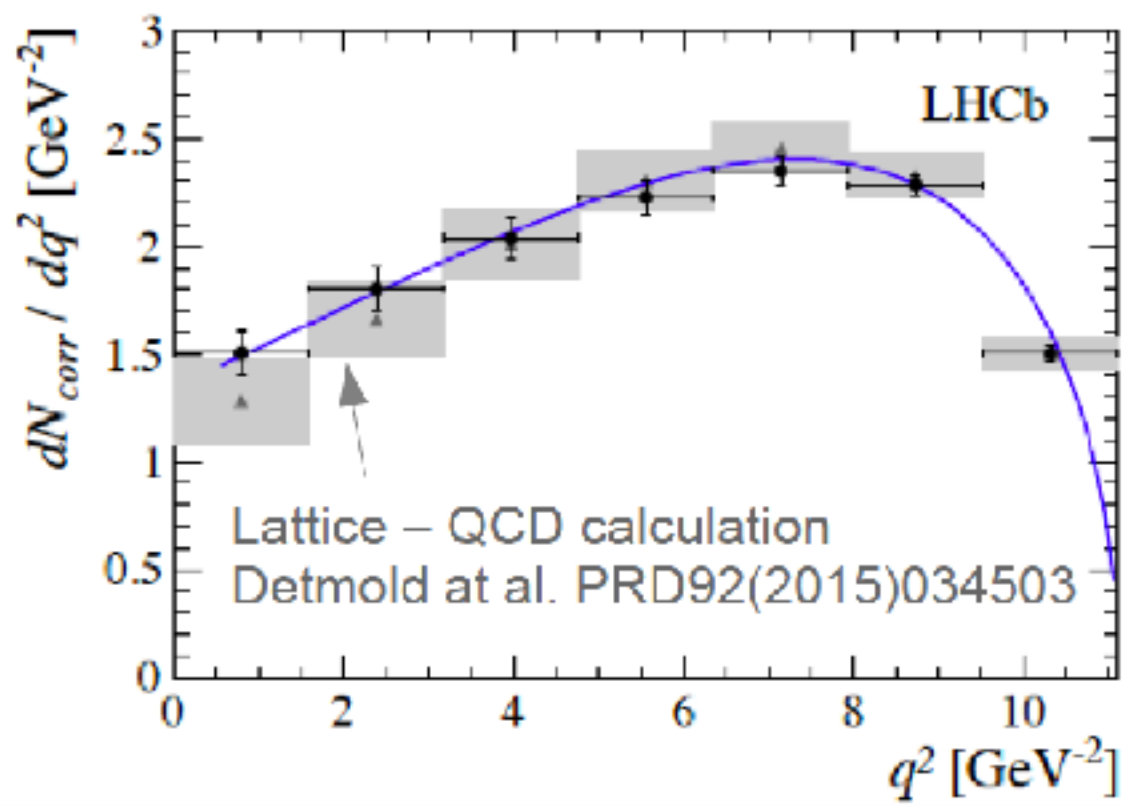
Note: the 2015 LHCb result for A^{ℓ}_{FB}, which deviated 3.4σ from our SM prediction, was incorrect (it was actually the CP asymmetry in A^{ℓ}_{FB}).

→ Our Wilson coefficient fits [S. Meinel and D. van Dyk, arXiv:1603.02974/PRD 2016] need to be redone.

- Λb → Λ ll (b → sll)
- New Λb → Λc* (negative parity)
  - Λb → Λc*(2595) l ν and Λb → Λc*(2625) l ν at large q2
  - Λb to Λ*(1520) ll at large q2

- Yield of Λb -> Λc μν from LHCb run 1 data 3fb^{-1} is 2.74(2) x 10^{6} [PRD 96, 112005, 2017]
- With the clean sample, w and q2 are extracted.
- Sensitivity study of Λb -> Λc* μν [JHEP 06, 155, 2018]
- properties of SL decays of b baryons can be studied at LHCb with high precision
  - CKM parameters
  - LFU tests
  - lattice QCD crucial
- Expect new results by early 2019.





other B/D decays

Alexei Sibidanov, **B -> μν at Belle/Belle II**

[Phys. Rev. Lett. 121, 031801 (2018), arXiv:1712.04123]

- full Belle data used
- measured 2.4 sigma excess
- corresponds to a branding fraction of B -> mu v

$$\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu) = (6.46 \pm 2.22_{\rm stat} \pm 1.6_{\rm syst}) \times 10^{-7}$$

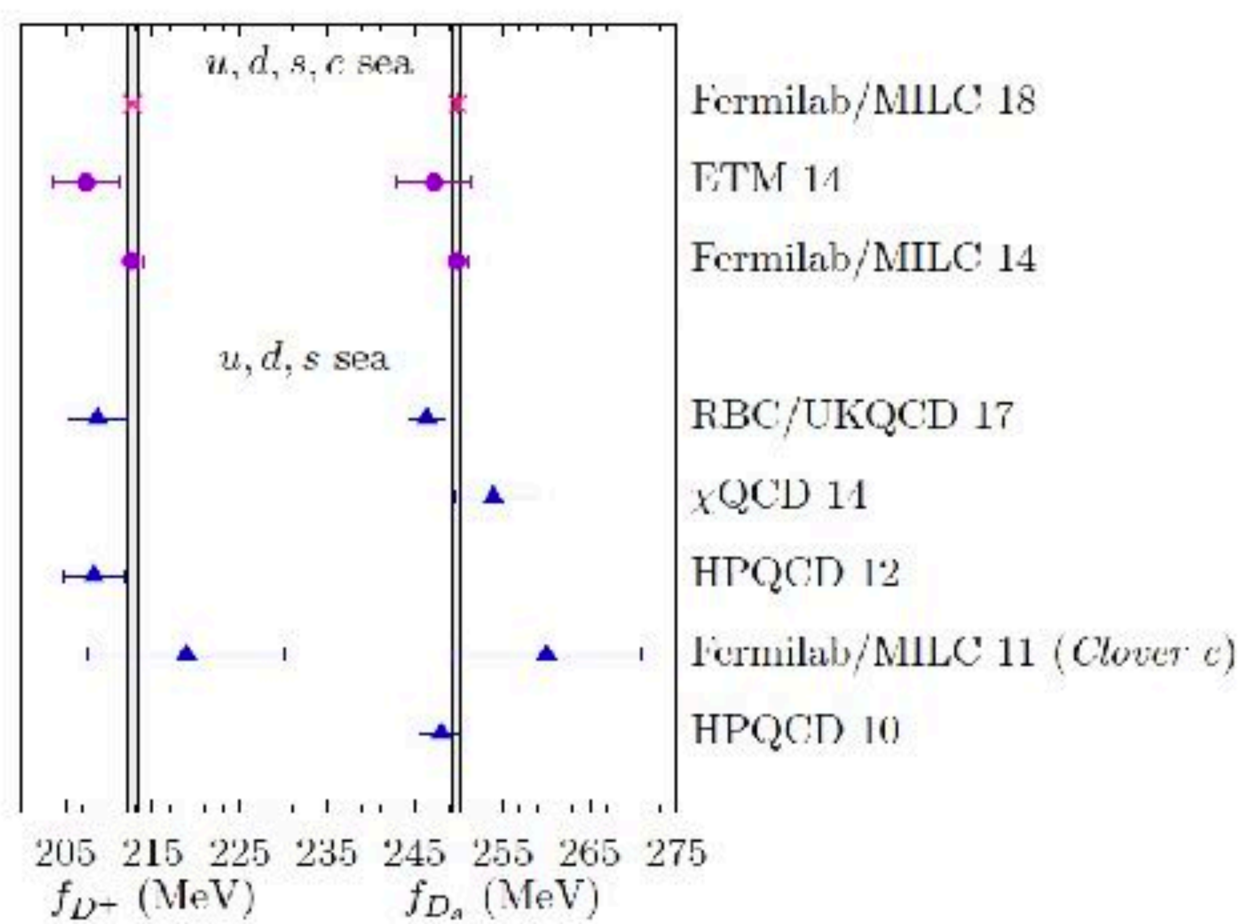
ℓ	$\mathcal{B}_{\rm SM}$	$N_{\rm SM}^{\rm Belle}(711/{\rm fb})$	$N_{\rm SM}^{\rm Belle2}(50/{\rm ab})$
τ	$(8.46 \pm 0.70) \times 10^{-5}$	67419 ± 5570	$(4.74 \pm 0.39) \times 10^{6}$
μ	$(3.80 \pm 0.31) \times 10^{-7}$	303 ± 25	21300 ± 1760
e	$(8.90 \pm 0.74) \times 10^{-12}$	0.0071 ± 0.0006	0.5 ± 0.04

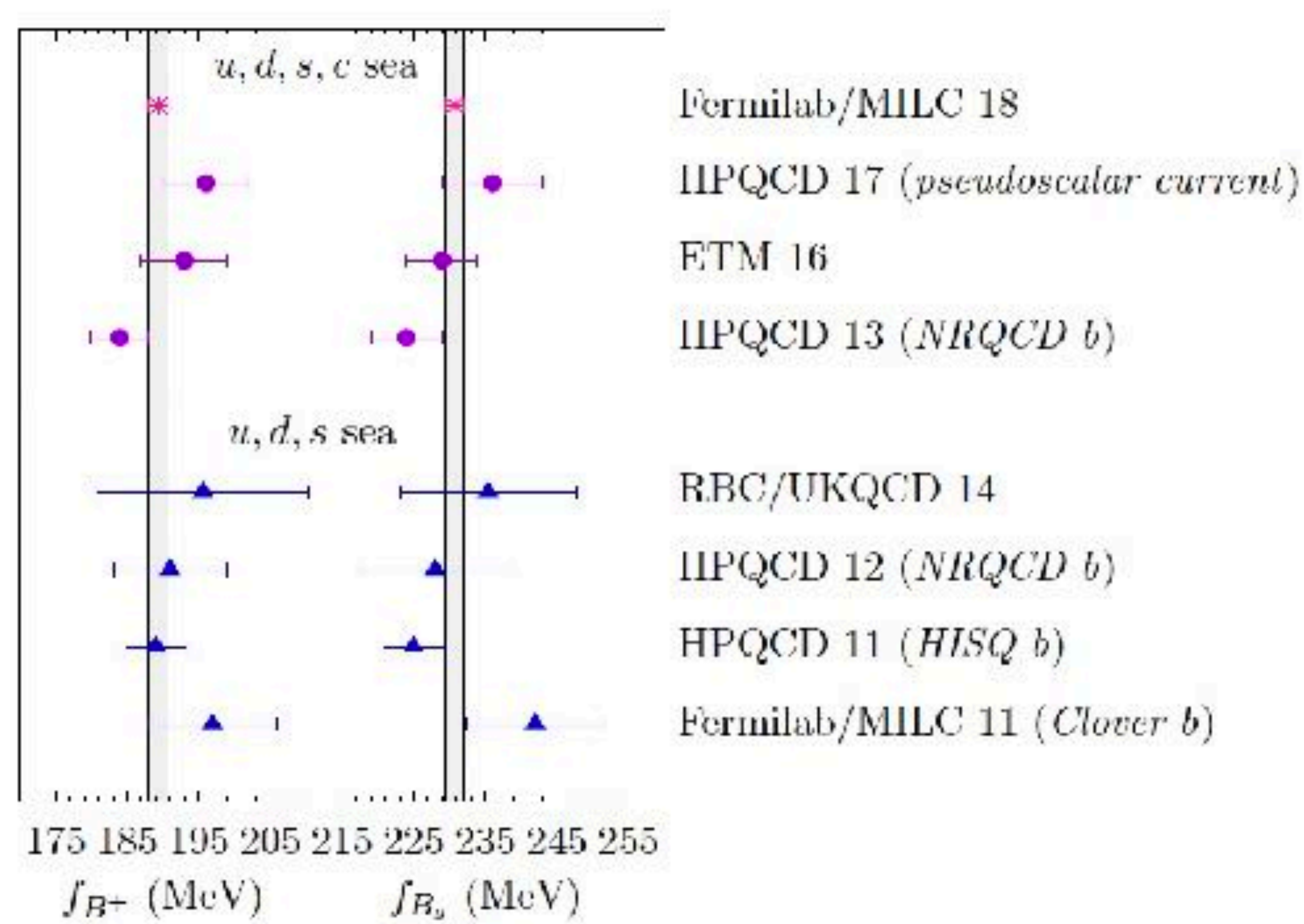
Adam Morris (joint with WG3) **LFU tests with semitauonic decays at LHCb**

- Hints of LFU violation in semitauonic B decays.
  - $R(D) - R(D^*)$: $3.8\,\sigma$ away from SM.
  - $R(J/\psi)$: $2\,\sigma$ above SM.
- LHCb results only use Run 1 data: Runs 2,3,4... will bring much larger statistics.
- Many systematics will reduce with more data and more MC
- Others will reduce with improved external measurements (BESIII, Belle II)
- Analyses of more modes:
  - $b \to c\tau^-\overline{\nu}_\tau$: $R(D^+)$, $R(D^0)$, $R(D_s^{+(*)})$, $R(\Lambda_c^{+(*)})$ ...
  - $b \to u\tau^-\overline{\nu}_\tau$: $\Lambda_b^0 \to p\tau^-\overline{\nu}_\tau$, $B^+ \to p\overline{p}\tau^+\nu_\tau$ ...
- New observables beyond ratios of branching fractions, *e.g.* angular analyses to discriminate between NP models.

Javad Komijani (joint with WG1) **Leptonic Decays of B and D Mesons from Lattice QCD**

- FNAL Lattice/MILC calc of B and D decay constants
- most precise decay constants to date





using Belle2 software framework for Belle data:

- new tagging algorithm FEI (Full Event Interpretation giving about 3 times higher efficiency than old Belle algorithm)
- using the extracted B+ -> pi0 l+ v as control sample allows to get λ_B independent with V_ub, and get R_pi in addition.

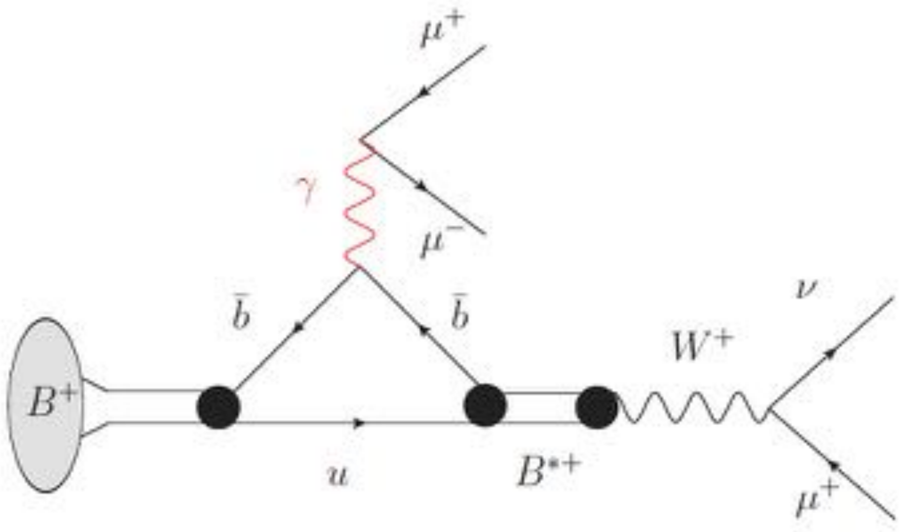
Form Factors (valid for large photon energies)

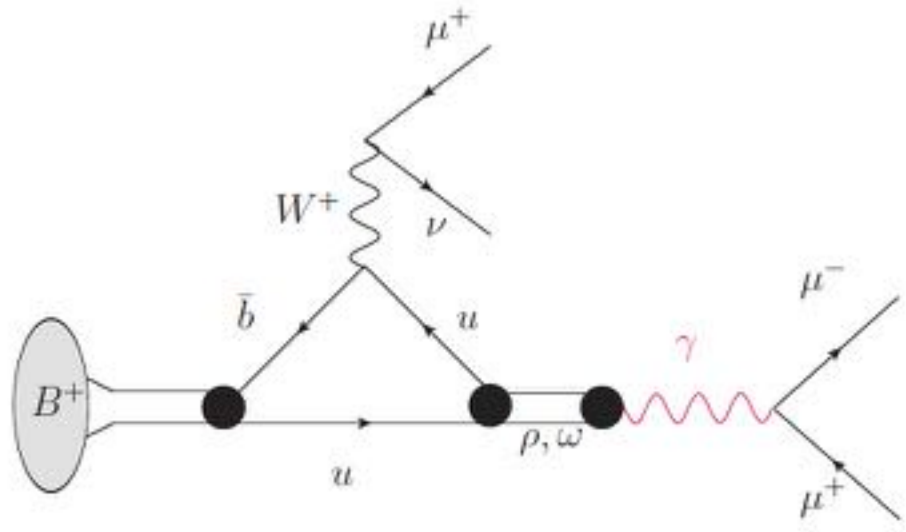
$$F_V(E_\gamma) = \frac{Q_u m_B f_B}{2E_\gamma \lambda_B} R(E_\gamma, \mu) + \left[\xi(E_\gamma) + \frac{Q_b m_B f_B}{2E_\gamma m_b} + \frac{Q_u m_B f_B}{(2E_\gamma)^2}\right]$$

$$F_A(E_\gamma) = \frac{Q_u m_B f_B}{2E_\gamma \lambda_B} R(E_\gamma, \mu) + \left[\xi(E_\gamma) - \frac{Q_b m_B f_B}{2E_\gamma m_b} - \frac{Q_u m_B f_B}{(2E_\gamma)^2} + \frac{Q_\ell f_B}{E_\gamma}\right]$$

	λ_B (GeV)
QCD factorization	≈ 0.2
QCD sum rules	0.46 ± 0.11
BaBar (90% C.L.)	> 0.115
Belle (2015) (90% C.L.)	> 0.238
This work (90% C.L.)	$> \mathbf{0.24}$

Svende Annelies Braun, **B -> 3 mu nu at LHCb**



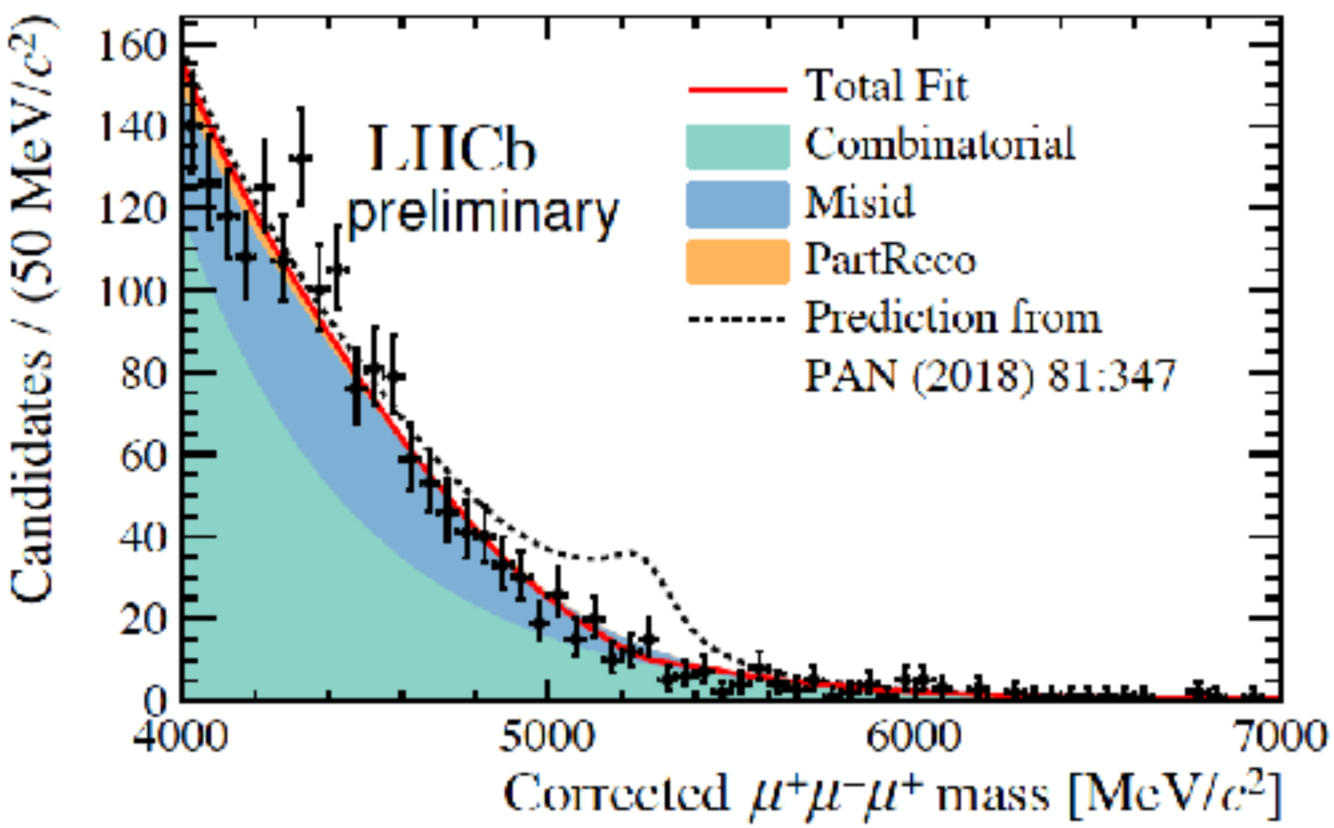


no signal found in 4.7 fb-1 LCHb data,

set upper limit of BF < 1.4 x 10e-8 at 95% C.L.,
poor agreement with recent theory prediction of 1.3X10e-7

largest sys. uncertainty due to decay model of single channel (PHSP used)

result prepared to be published.



Rusa Mandal, **A unified resolution to B anomalies with lepton mixing**

[PRL 119, 151801 (2018)] and [NPB 933 (2018) 433-45]

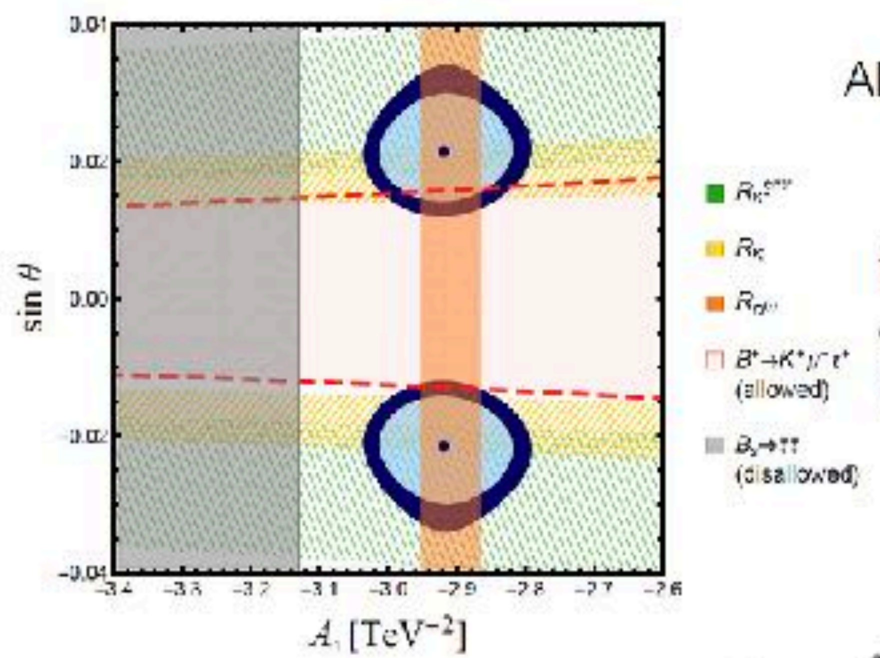
Effective operators

- NP operators with 2nd & 3rd generation fields

$$\mathcal{H}^{\rm NP} = A_1\,(\bar{Q}_{2L}\gamma_\mu L_{3L})\,(\bar{L}_{3L}\gamma^\mu Q_{3L}) + A_2\,(\bar{Q}_{2L}\gamma_\mu Q_{3L})\,(\bar{\tau}_R\gamma^\mu \tau_R)$$

- constraints from SM-consistent experimental results
  - Bs to μμ
  - B to K(*) νν
  - B to K μτ
  - Bs to ττ
  - Bc to τν
- try to explain
  - R(K(*))
  - R(D(*))

Results



Allowing 20% breaking

$A_2 = 4A_1/5$

from quantum corrections or unknown dynamics of the UV completion of the model

$\chi^2_{\rm SM}/{\rm d.o.f} \simeq 6.6$ → $\chi^2_{\rm allowed\ region}/{\rm d.o.f} \simeq 2$

✓ agreement within 1σ level

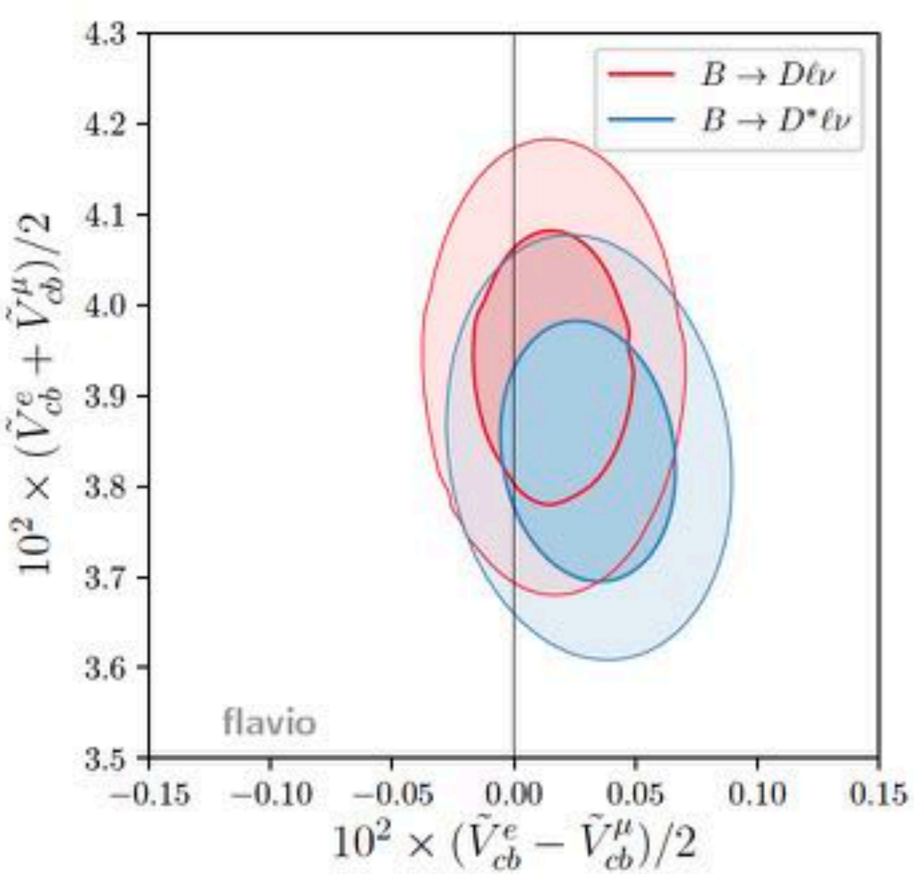
$R_K \simeq 0.80,\ R_{K^*}^{\rm cntr} \simeq 0.83,\ R_{K^*}^{\rm low} \simeq 0.88,$

$R(D^{(*)}) \sim 1.24 \times R(D^{(*)})_{\rm SM},\ \Phi \sim 3.8 \times 10^{-8}{\rm GeV}^{-2}$

David Straub (joint with WG1) **New physics in b -> c l nu (nu not tau!)**

[1801.01112]

- light leptons with e,mu split and unfolded distributions
  - LFUV in e vs mu
  - precision Vcb
  - importance of shape of dBr/dq2 vs integrated Br
- B to D* l nu precludes large right-handed current
- e-mu UV constrained at 1% level
- endpoints of B to D(*) l nu strongly constrains scalar (tensor) ops



$$\tilde{V}^\ell_{cb} = V_{cb}(1 + C^{\ell\ell}_{V_L})$$

- ▶ compatible with universality
- ▶ agreement between D and D^*
- ▶ strong constraint on models violating e-μ universality

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▸ At $q^2 \to 0$, SM contribution to $B \to D^* \ell \nu$ is fully longitudinal, tensor contribution isn't

$$\frac{d\Gamma_T(B \to D^* \ell \nu)}{dq^2} \propto q^2 C_{V_L}^2 \left(A_1(0)^2 + V(0)^2\right) + 16 m_B^2 C_T^2 T_1(0)^2 + O\left(\frac{m_{D^*}^2}{m_B^2}\right)$$

▸ First bin of Γ_T is extremely sensitive to C_T (much more than total rate!)