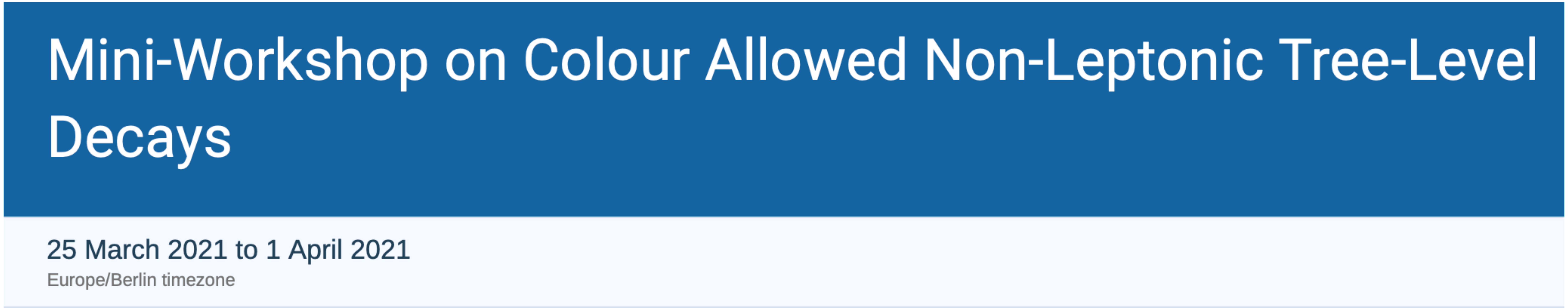
$b \to c\bar{u}d, s$ **puzzle**

Alexander Lenz, Siegen

Beyond the Anomalies
Zoomland, Durham 20.4.2021


ALL ANOMALIES ARE EQUAL
BUT SOME ANOMALIES
ARE MORE EQUAL
THAN OTHERS

Report from mini workshop



Mini-Workshop on Colour Allowed Non-Leptonic Tree-Level Decays

25 March 2021 to 1 April 2021
Europe/Berlin timezone

14:00

Introduction *Alexander Lenz*
14:00 - 14:05

Measurement of colour allowed tree-level decays *Mick Mulder*
14:05 - 14:35

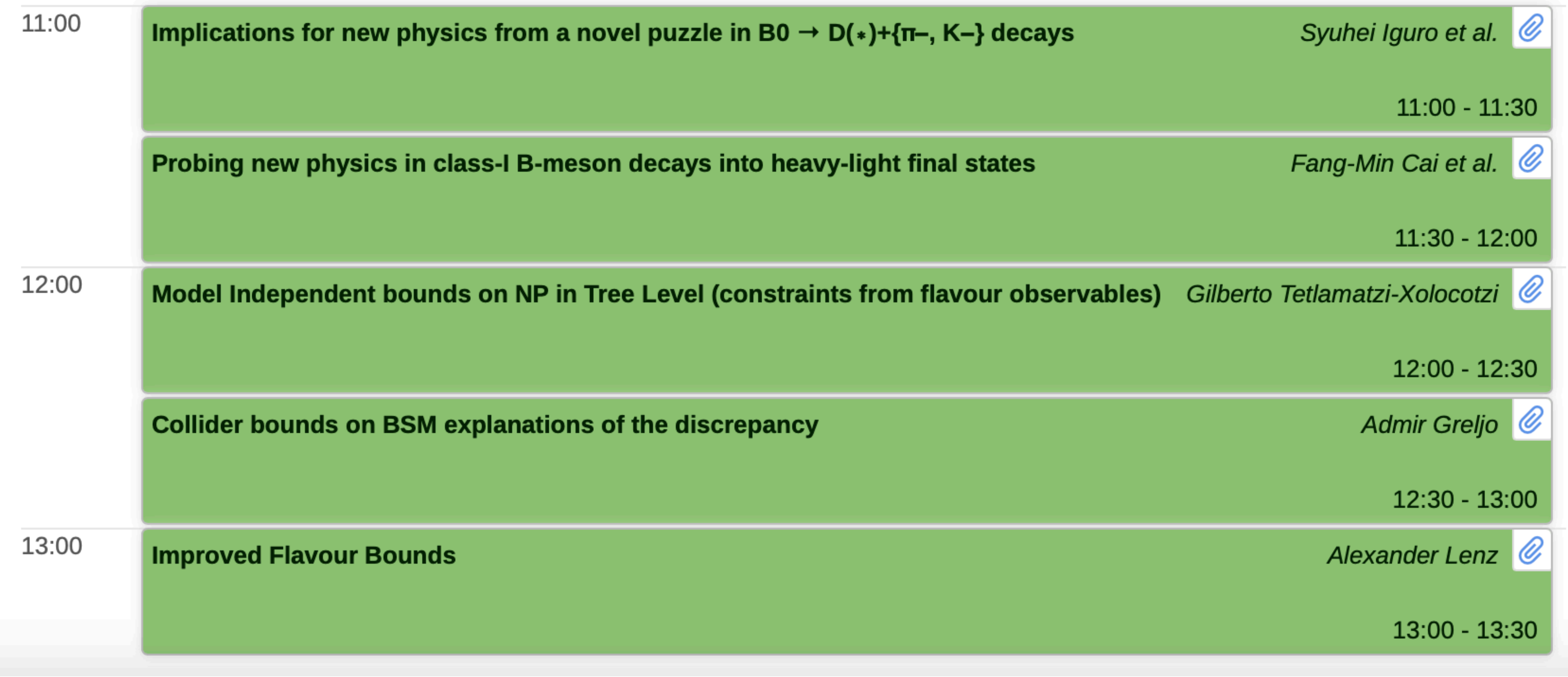
QCDf predictions for B_s to Ds^- pi^+ and friends *Nico Gubernari*
14:35 - 15:05

15:00

Scrutinizing SM predictions *Guido Bell*
15:05 - 15:33

Scrutinizing SM predictions *Alexander Khodjamirian*
15:33 - 16:00

16:00



11:00

Implications for new physics from a novel puzzle in B0 → D(∗)+{π−, K−} decays *Syuhei Iguro et al.*
11:00 - 11:30

Probing new physics in class-I B-meson decays into heavy-light final states *Fang-Min Cai et al.*
11:30 - 12:00

12:00

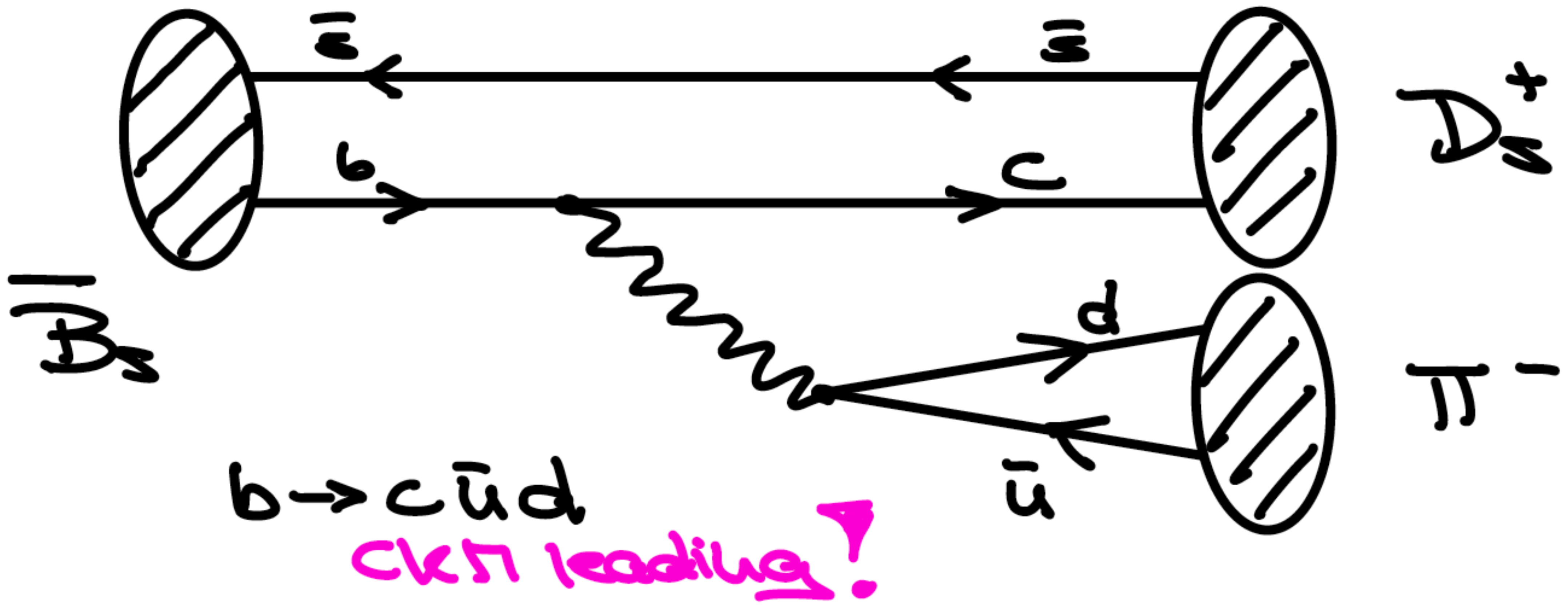
Model Independent bounds on NP in Tree Level (constraints from flavour observables) *Gilberto Tetlamatzi-Xolocotzi*
12:00 - 12:30

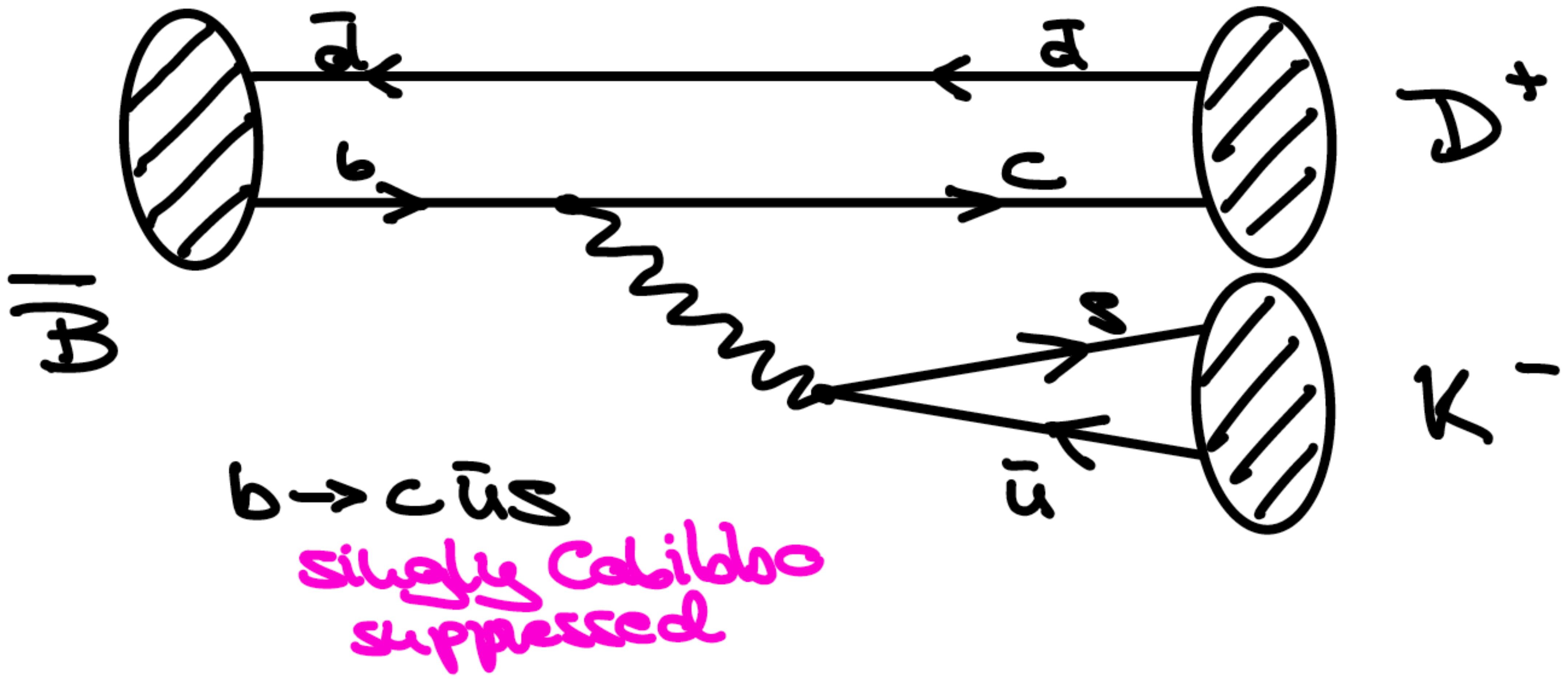
Collider bounds on BSM explanations of the discrepancy *Admir Greljo*
12:30 - 13:00

13:00

Improved Flavour Bounds *Alexander Lenz*
13:00 - 13:30

Colour-allowed Tree-level Decays



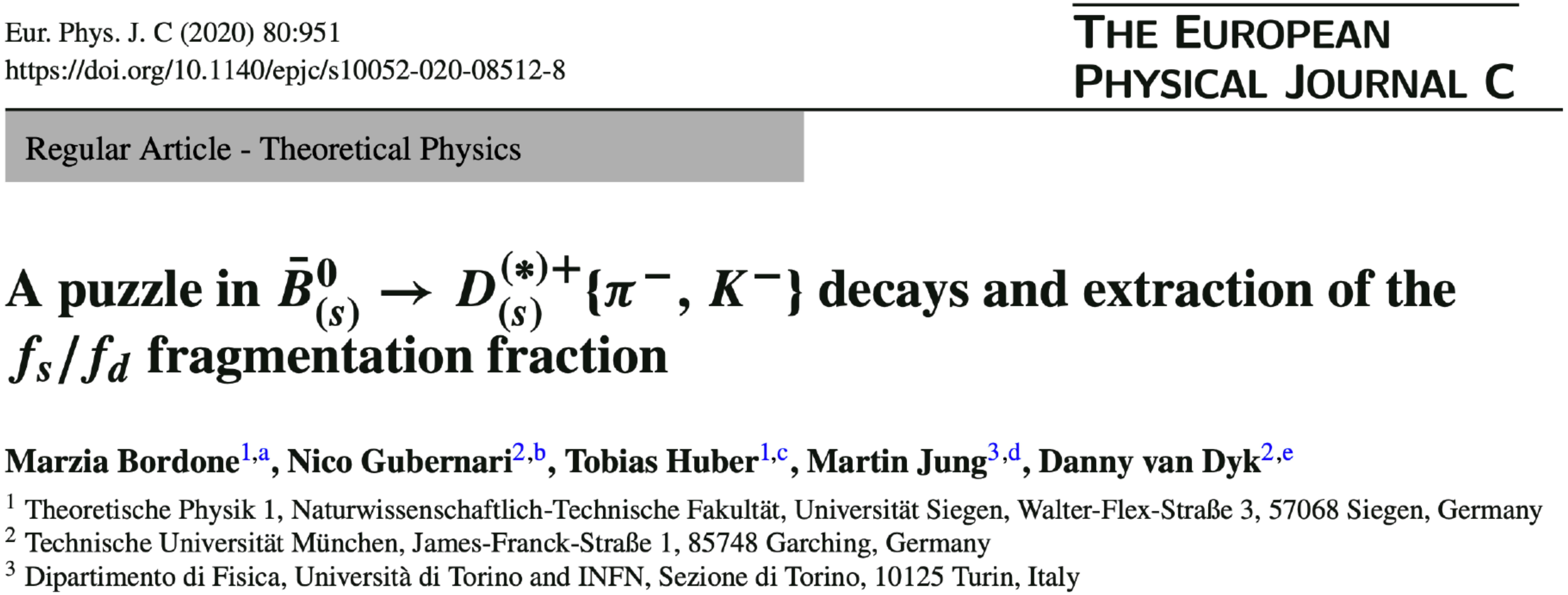


- CKM leading decays
- The are no annihilation, penguins,…
- QCDf should work at its best!

Beneke, Buchalla, Neubert, Sachrajda 1999…

$$\langle D_q^{(*)+} L^- | \mathcal{Q}_i | \bar{B}_q^0 \rangle = \sum_j F_j^{\bar{B}_q \to D_q^{(*)}}(M_L^2) \times \int_0^1 du\, T_{ij}(u) \phi_L(u) + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{m_b}\right)$$

Colour-allowed Tree-level Decays



Eur. Phys. J. C (2020) 80:951
https://doi.org/10.1140/epjc/s10052-020-08512-8

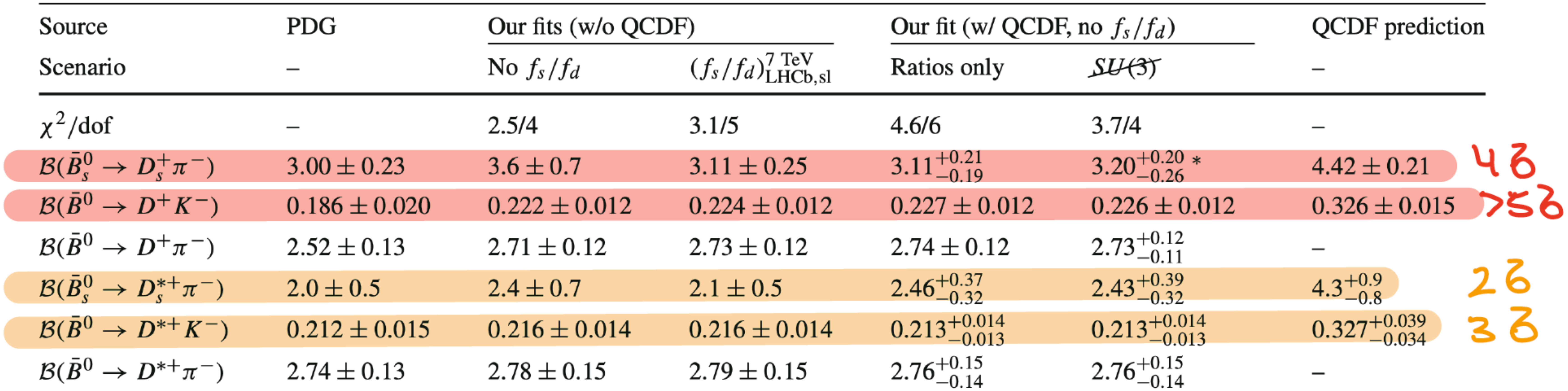
THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

A puzzle in $\bar{B}^0_{(s)} \to D^{(*)+}_{(s)}\{\pi^-, K^-\}$ decays and extraction of the f_s/f_d fragmentation fraction

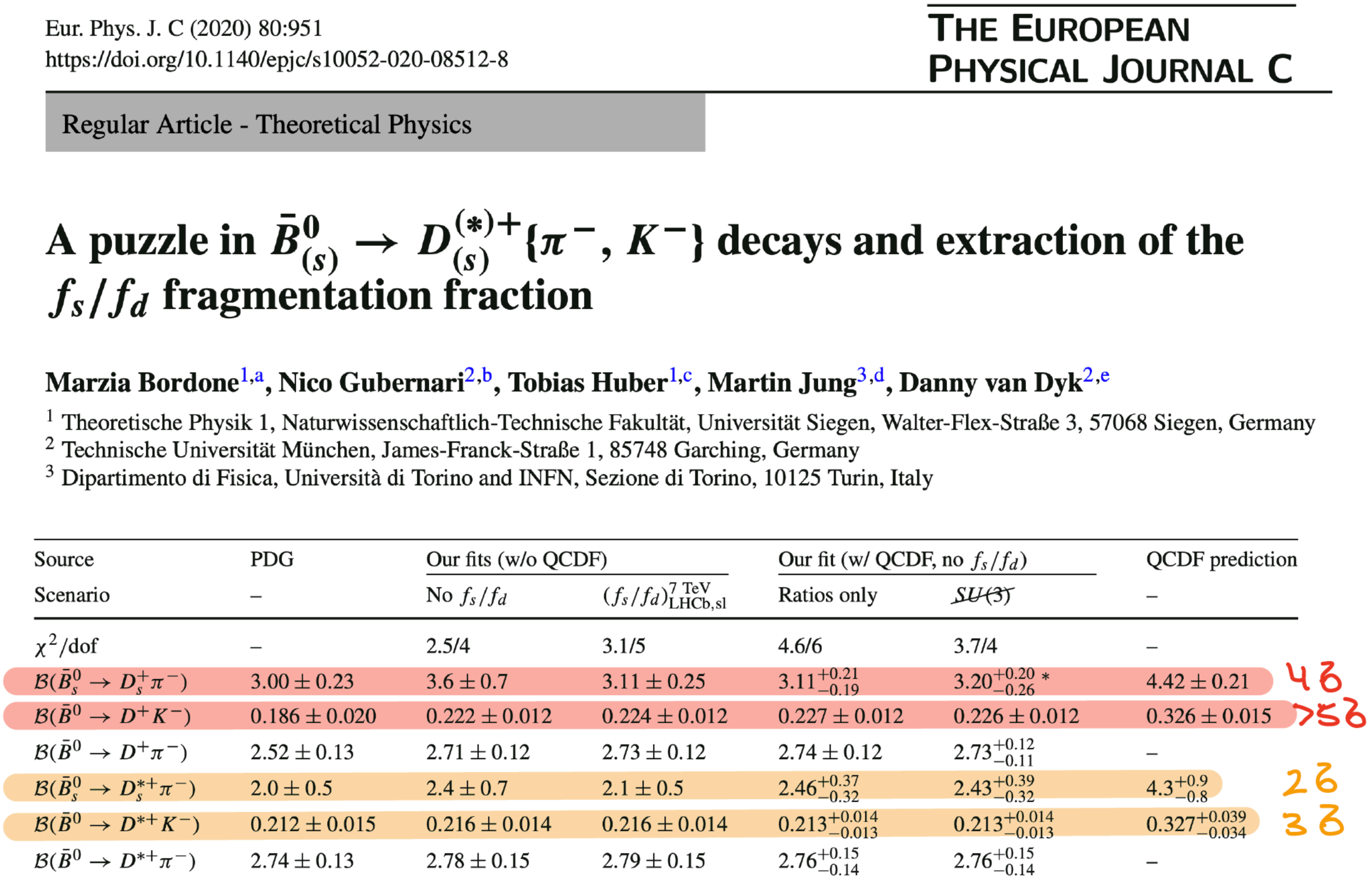
Marzia Bordone[1,a], **Nico Gubernari**[2,b], **Tobias Huber**[1,c], **Martin Jung**[3,d], **Danny van Dyk**[2,e]

[1] Theoretische Physik 1, Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany
[2] Technische Universität München, James-Franck-Straße 1, 85748 Garching, Germany
[3] Dipartimento di Fisica, Università di Torino and INFN, Sezione di Torino, 10125 Turin, Italy



Source	PDG	Our fits (w/o QCDF)		Our fit (w/ QCDF, no f_s/f_d)		QCDF prediction	
Scenario	–	No f_s/f_d	$(f_s/f_d)^{7\ \text{TeV}}_{\text{LHCb,sl}}$	Ratios only	~~$SU(3)$~~	–	
χ^2/dof	–	2.5/4	3.1/5	4.6/6	3.7/4	–	
$\mathcal{B}(\bar{B}^0_s \to D^+_s\pi^-)$	3.00 ± 0.23	3.6 ± 0.7	3.11 ± 0.25	$3.11^{+0.21}_{-0.19}$	$3.20^{+0.20}_{-0.26}$ *	4.42 ± 0.21	4σ
$\mathcal{B}(\bar{B}^0 \to D^+K^-)$	0.186 ± 0.020	0.222 ± 0.012	0.224 ± 0.012	0.227 ± 0.012	0.226 ± 0.012	0.326 ± 0.015	>5σ
$\mathcal{B}(\bar{B}^0 \to D^+\pi^-)$	2.52 ± 0.13	2.71 ± 0.12	2.73 ± 0.12	2.74 ± 0.12	$2.73^{+0.12}_{-0.11}$	–	
$\mathcal{B}(\bar{B}^0_s \to D^{*+}_s\pi^-)$	2.0 ± 0.5	2.4 ± 0.7	2.1 ± 0.5	$2.46^{+0.37}_{-0.32}$	$2.43^{+0.39}_{-0.32}$	$4.3^{+0.9}_{-0.8}$	2σ
$\mathcal{B}(\bar{B}^0 \to D^{*+}K^-)$	0.212 ± 0.015	0.216 ± 0.014	0.216 ± 0.014	$0.213^{+0.014}_{-0.013}$	$0.213^{+0.014}_{-0.013}$	$0.327^{+0.039}_{-0.034}$	3σ
$\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-)$	2.74 ± 0.13	2.78 ± 0.15	2.79 ± 0.15	$2.76^{+0.15}_{-0.14}$	$2.76^{+0.15}_{-0.14}$	–	

Colour-allowed Tree-level Decays



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THE EUROPEAN
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Regular Article - Theoretical Physics

A puzzle in $\bar{B}^0_{(s)} \to D^{(*)+}_{(s)}\{\pi^-, K^-\}$ decays and extraction of the f_s/f_d fragmentation fraction

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Source	PDG	Our fits (w/o QCDF)		Our fit (w/ QCDF, no f_s/f_d)		QCDF prediction	
Scenario	–	No f_s/f_d	$(f_s/f_d)^{7\ \text{TeV}}_{\text{LHCb,sl}}$	Ratios only	~~$SU(3)$~~	–	
χ^2/dof	–	2.5/4	3.1/5	4.6/6	3.7/4	–	
$\mathcal{B}(\bar{B}^0_s \to D^+_s\pi^-)$	3.00 ± 0.23	3.6 ± 0.7	3.11 ± 0.25	$3.11^{+0.21}_{-0.19}$	$3.20^{+0.20}_{-0.26}$ *	4.42 ± 0.21	4σ
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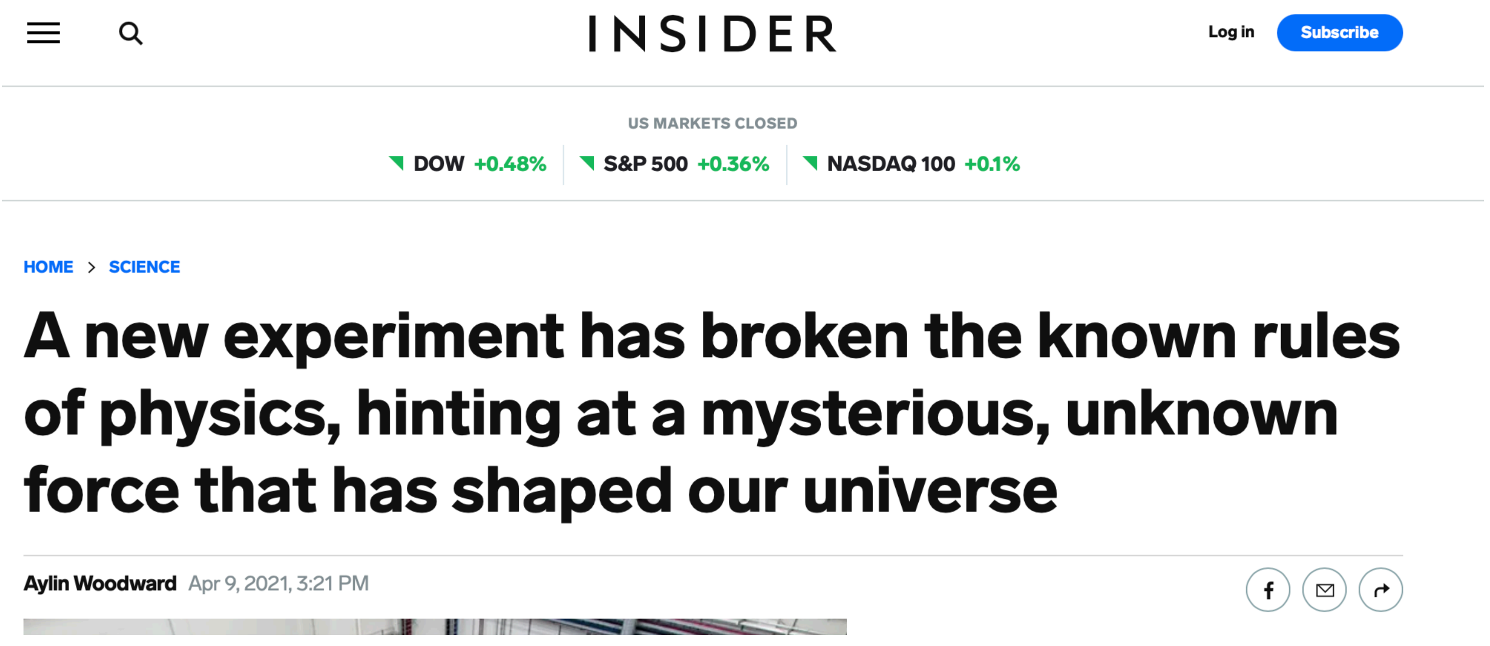
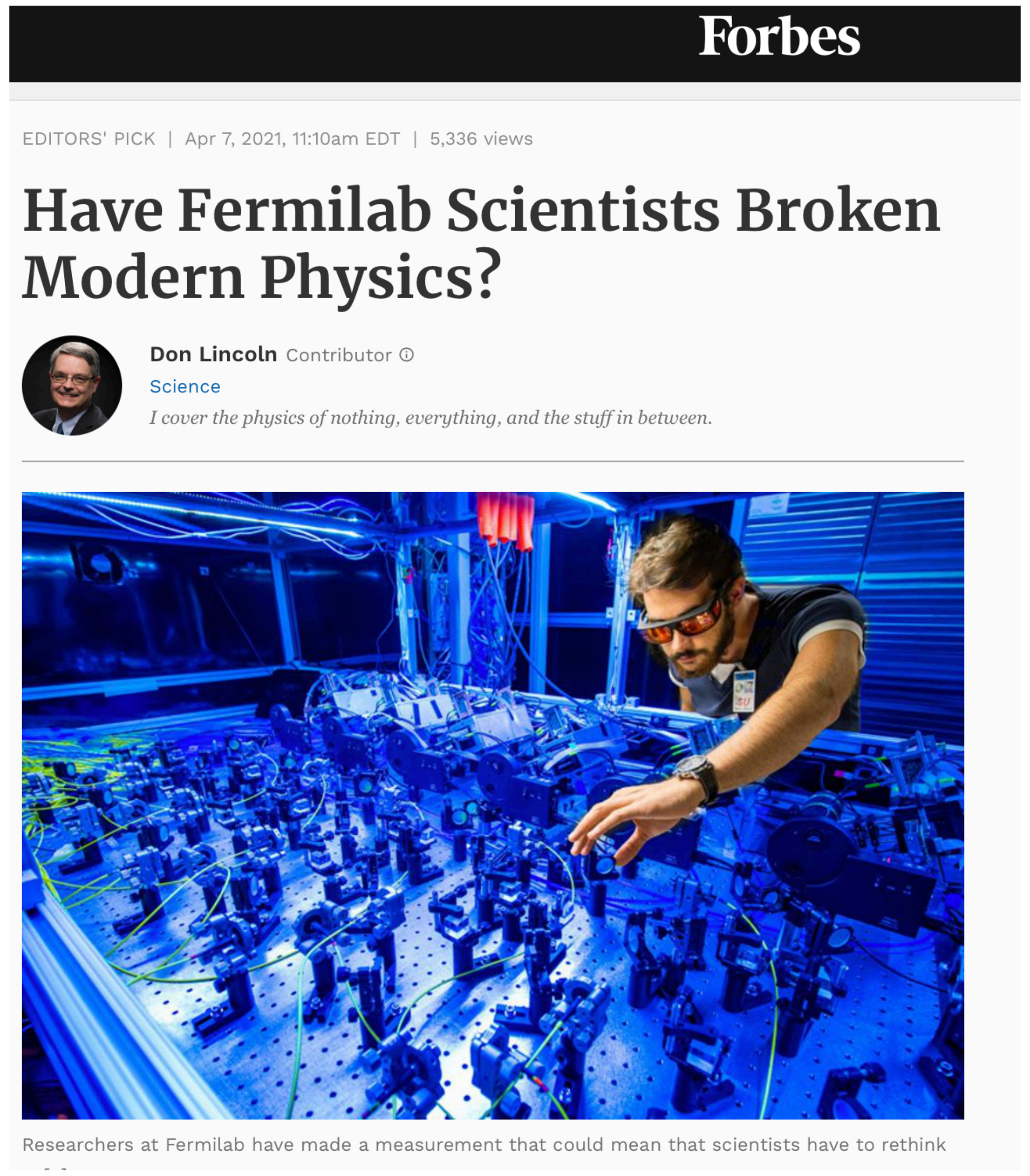


A new experiment has broken the known rules of physics, hinting at a mysterious, unknown force that has shaped our universe

Aylin Woodward Apr 9, 2021, 3:21 PM



EDITORS' PICK | Apr 7, 2021, 11:10am EDT | 5,336 views

Have Fermilab Scientists Broken Modern Physics?

Don Lincoln Contributor
Science
I cover the physics of nothing, everything, and the stuff in between.

Researchers at Fermilab have made a measurement that could mean that scientists have to rethink

PHYSICS | OPINION

Is the Standard Model of Physics Now Broken?

Colour-allowed Tree-level Decays

Theory update by Danny, Martin, Marzia, Nico and Tobias 2007.10338

Beneke, Buchalla, Neubert, Sachrajda 1999…

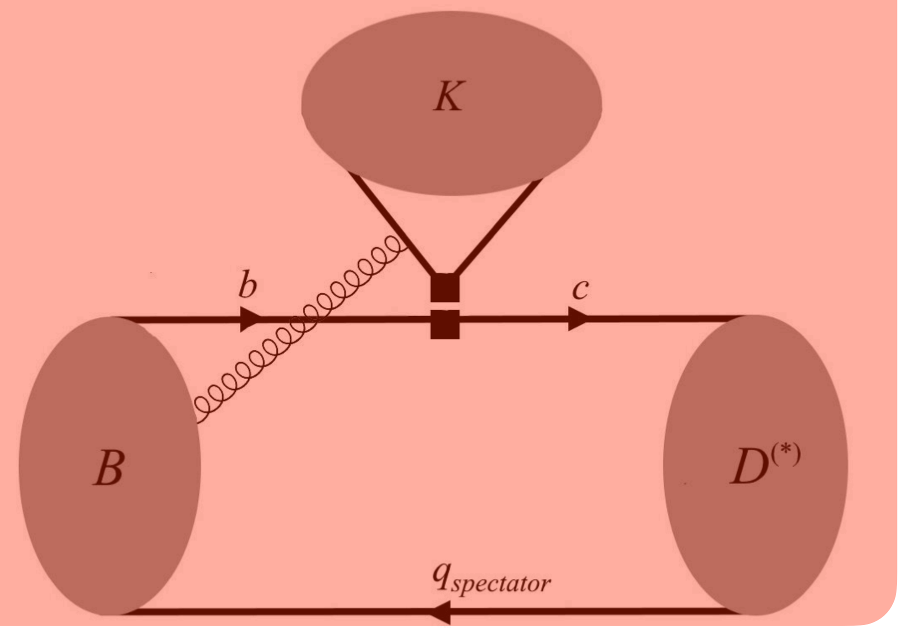
NNLO
T. Huber, S. Kränkl, X.-Q. Li
1606.02888

power-counting $\varepsilon \sim \Lambda_{\rm QCD}/E_L \sim \Lambda_{\rm QCD}/m_b$

$$\langle D_q^{(*)+} L^- |\, \mathcal{Q}_i \,| \bar{B}_q^0 \rangle = \sum_j F_j^{\bar{B}_q \to D_q^{(*)}}(M_L^2) \times \int_0^1 du\, T_{ij}(u) \phi_L(u) + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{m_b}\right)$$

- higher-twist corrections to the light-meson LCDA
  Enters only at order $\alpha_s \epsilon^2$ or higher

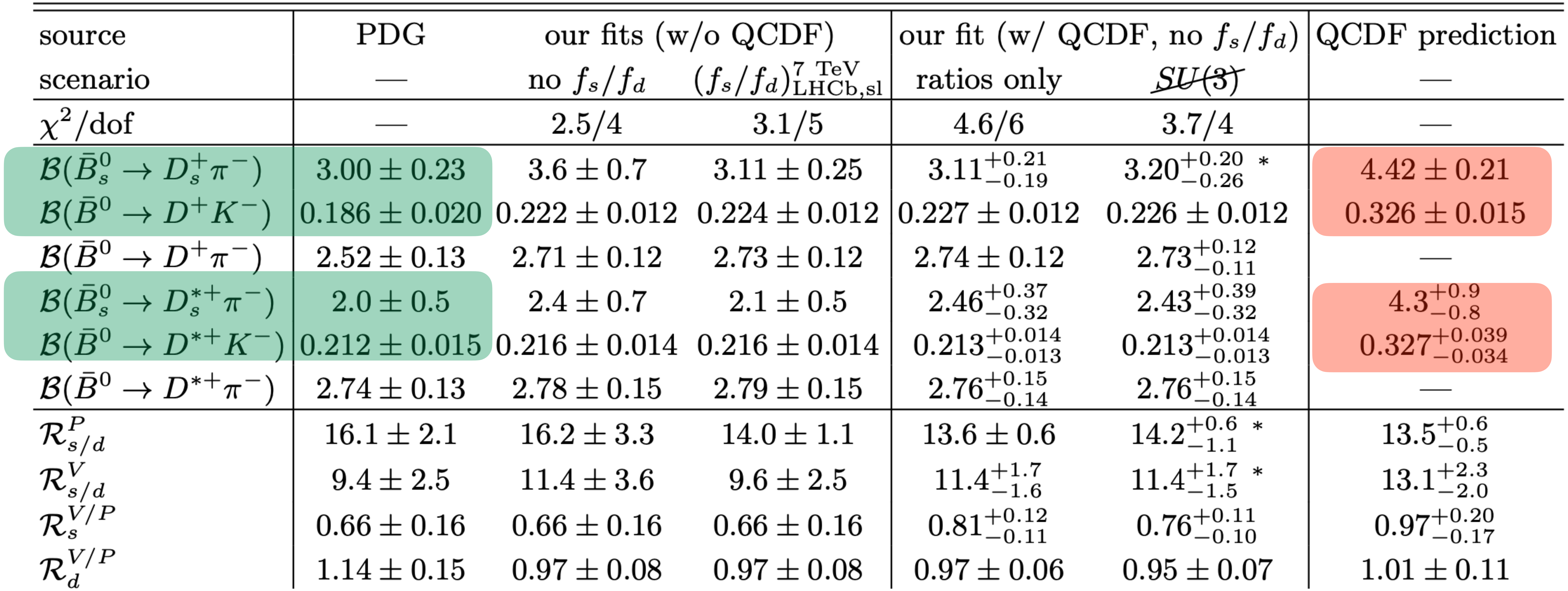
1. use form factors in terms of the QCD fields $\Longrightarrow$ no $\frac{\Lambda_{\rm QCD}}{m_c}$ corrections
2. hard-gluon between b or c quarks and the light meson is included in the WC
3. no hard-collinear gluon between spectator quark and the light meson (spectator is soft)
4. soft-gluon exchange between the $\bar{B}^0_{(s)} D^{(*)+}_{(s)}$ system and the light meson L
   we estimate this contribution
   with light-cone sum rules (LCSRs)



Update Form factors for B to D
Bordone, Gubernari, Jung, van Dyk, 1912.09335
Lattice, QCD-SR, LCSR with Bs-DA

Colour-allowed Tree-level Decays

Theory update by Danny, Martin, Marzia, Nico and Tobias 2007.10338



source	PDG	our fits (w/o QCDF)		our fit (w/ QCDF, no f_s/f_d)		QCDF prediction	**Naiv**
scenario	—	no f_s/f_d	$(f_s/f_d)^{7\,\mathrm{TeV}}_{\mathrm{LHCb,sl}}$	ratios only	$\cancel{SU(3)}$	—	$\frac{Exp - Theo}{\sqrt{\delta^2_{Exp} + \delta^2_{Theo}}}$
χ^2/dof	—	2.5/4	3.1/5	4.6/6	3.7/4	—	
$\mathcal{B}(\bar{B}^0_s \to D_s^+ \pi^-)$	3.00 ± 0.23	3.6 ± 0.7	3.11 ± 0.25	$3.11^{+0.21}_{-0.19}$	$3.20^{+0.20}_{-0.26}$ *	4.42 ± 0.21	4.6σ
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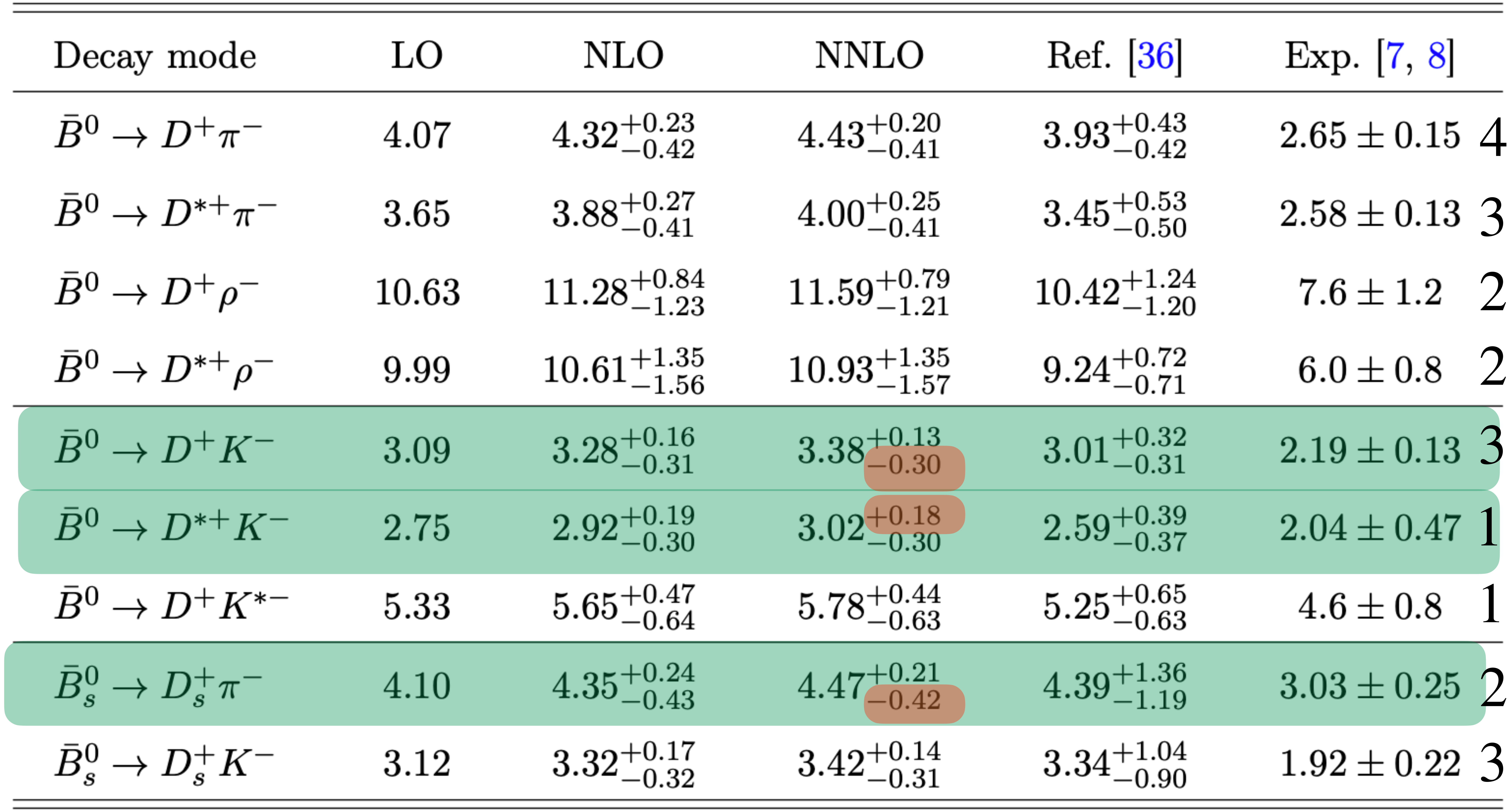
$\mathcal{B}(\bar{B}^0 \to D^+ \pi^-)$	2.52 ± 0.13	2.71 ± 0.12	2.73 ± 0.12	2.74 ± 0.12	$2.73^{+0.12}_{-0.11}$	—	
$\mathcal{B}(\bar{B}^0_s \to D_s^{*+} \pi^-)$	2.0 ± 0.5	2.4 ± 0.7	2.1 ± 0.5	$2.46^{+0.37}_{-0.32}$	$2.43^{+0.39}_{-0.32}$	$4.3^{+0.9}_{-0.8}$	2.4σ
$\mathcal{B}(\bar{B}^0 \to D^{*+} K^-)$	0.212 ± 0.015	0.216 ± 0.014	0.216 ± 0.014	$0.213^{+0.014}_{-0.013}$	$0.213^{+0.014}_{-0.013}$	$0.327^{+0.039}_{-0.034}$	3.1σ
$\mathcal{B}(\bar{B}^0 \to D^{*+} \pi^-)$	2.74 ± 0.13	2.78 ± 0.15	2.79 ± 0.15	$2.76^{+0.15}_{-0.14}$	$2.76^{+0.15}_{-0.14}$	—	
$\mathcal{R}^P_{s/d}$	16.1 ± 2.1	16.2 ± 3.3	14.0 ± 1.1	13.6 ± 0.6	$14.2^{+0.6}_{-1.1}$ *	$13.5^{+0.6}_{-0.5}$	
$\mathcal{R}^V_{s/d}$	9.4 ± 2.5	11.4 ± 3.6	9.6 ± 2.5	$11.4^{+1.7}_{-1.6}$	$11.4^{+1.7}_{-1.5}$ *	$13.1^{+2.3}_{-2.0}$	
$\mathcal{R}^{V/P}_s$	0.66 ± 0.16	0.66 ± 0.16	0.66 ± 0.16	$0.81^{+0.12}_{-0.11}$	$0.76^{+0.11}_{-0.10}$	$0.97^{+0.20}_{-0.17}$	
$\mathcal{R}^{V/P}_d$	1.14 ± 0.15	0.97 ± 0.08	0.97 ± 0.08	0.97 ± 0.06	0.95 ± 0.07	1.01 ± 0.11	

Huge and significant deviation

Colour-allowed Tree-level Decays

Confirmation of result by Fang-Min Cai, Wei-Jun Deng, Xin-Qiang Li, Ya-Dong Yang 2103.04138



Decay mode	LO	NLO	NNLO	Ref. [36]	Exp. [7, 8]		2007.10338
$\bar{B}^0 \to D^+\pi^-$	4.07	$4.32^{+0.23}_{-0.42}$	$4.43^{+0.20}_{-0.41}$	$3.93^{+0.43}_{-0.42}$	2.65 ± 0.15	4.1σ	
$\bar{B}^0 \to D^{*+}\pi^-$	3.65	$3.88^{+0.27}_{-0.41}$	$4.00^{+0.25}_{-0.41}$	$3.45^{+0.53}_{-0.50}$	2.58 ± 0.13	3.3σ	
$\bar{B}^0 \to D^+\rho^-$	10.63	$11.28^{+0.84}_{-1.23}$	$11.59^{+0.79}_{-1.21}$	$10.42^{+1.24}_{-1.20}$	7.6 ± 1.2	2.3σ	
$\bar{B}^0 \to D^{*+}\rho^-$	9.99	$10.61^{+1.35}_{-1.56}$	$10.93^{+1.35}_{-1.57}$	$9.24^{+0.72}_{-0.71}$	6.0 ± 0.8	2.8σ	
$\bar{B}^0 \to D^+K^-$	3.09	$3.28^{+0.16}_{-0.31}$	$3.38^{+0.13}_{-0.30}$	$3.01^{+0.32}_{-0.31}$	2.19 ± 0.13	3.6σ	3.26 ± 0.15
$\bar{B}^0 \to D^{*+}K^-$	2.75	$2.92^{+0.19}_{-0.30}$	$3.02^{+0.18}_{-0.30}$	$2.59^{+0.39}_{-0.37}$	2.04 ± 0.47	1.8σ	$3.27^{+0.39}_{-0.34}$
$\bar{B}^0 \to D^+K^{*-}$	5.33	$5.65^{+0.47}_{-0.64}$	$5.78^{+0.44}_{-0.63}$	$5.25^{+0.65}_{-0.63}$	4.6 ± 0.8	1.2σ	
$\bar{B}^0_s \to D^+_s\pi^-$	4.10	$4.35^{+0.24}_{-0.43}$	$4.47^{+0.21}_{-0.42}$	$4.39^{+1.36}_{-1.19}$	3.03 ± 0.25	2.9σ	4.42 ± 0.21
$\bar{B}^0_s \to D^+_s K^-$	3.12	$3.32^{+0.17}_{-0.32}$	$3.42^{+0.14}_{-0.31}$	$3.34^{+1.04}_{-0.90}$	1.92 ± 0.22	3.9σ	

Colour-allowed Tree-level Decays

Confirmation of result by Fang-Min Cai, Wei-Jun Deng, Xin-Qiang Li, Ya-Dong Yang 2103.04138

$$R^{(*)}_{(s)L} \equiv \frac{\Gamma(\bar{B}^0_{(s)} \to D^{(*)+}_{(s)} L^-)}{d\Gamma(\bar{B}^0_{(s)} \to D^{(*)+}_{(s)} \ell^- \bar{\nu}_\ell)/dq^2 \,|_{q^2=m_L^2}} = 6\pi^2 \, |V_{uq}|^2 \, f_L^2 \, |a_1(D^{(*)+}_{(s)} L^-)|^2 \, X_L^{(*)}$$

$R^{(*)}_{(s)L}$	LO	NLO	NNLO	Exp.	Deviation (σ)
R_π	1.01	$1.07^{+0.04}_{-0.04}$	$1.10^{+0.03}_{-0.03}$	0.74 ± 0.06	5.4
R_π^*	1.00	$1.06^{+0.04}_{-0.04}$	$1.10^{+0.03}_{-0.03}$	0.80 ± 0.06	4.5
R_ρ	2.77	$2.94^{+0.19}_{-0.19}$	$3.02^{+0.17}_{-0.18}$	2.23 ± 0.37	1.9
R_K	0.78	$0.83^{+0.03}_{-0.03}$	$0.85^{+0.01}_{-0.02}$	0.62 ± 0.05	4.4
R_K^*	0.72	$0.76^{+0.03}_{-0.03}$	$0.79^{+0.01}_{-0.02}$	0.60 ± 0.14	1.3
R_{K^*}	1.41	$1.50^{+0.11}_{-0.11}$	$1.53^{+0.10}_{-0.10}$	1.38 ± 0.25	0.6
$R_{s\pi}$	1.01	$1.07^{+0.04}_{-0.04}$	$1.10^{+0.03}_{-0.03}$	0.72 ± 0.08	4.4
R_{sK}	0.78	$0.83^{+0.03}_{-0.03}$	$0.85^{+0.01}_{-0.02}$	0.46 ± 0.06	6.3

World North America Science

'Tantalising' results of two experiments could break the known laws of physics

Colour-allowed Tree-level Decays

Confirmed by experiment LHCb [arXiv:2103.06810]

$$B_s \to D_s^+\pi^+ = (3.20 \pm 0.19)\cdot 10^{-3}\ (\text{PDG } 3.00 \pm 0.23)\ \ 4.6\sigma \to 4.3\sigma$$

$$B_s \to D_s^+K^+ = (2.41 \pm 0.16)\cdot 10^{-4}\ (\text{PDG } 1.92 \pm 0.22)\ \ 3.9\sigma \to 2.9\sigma$$

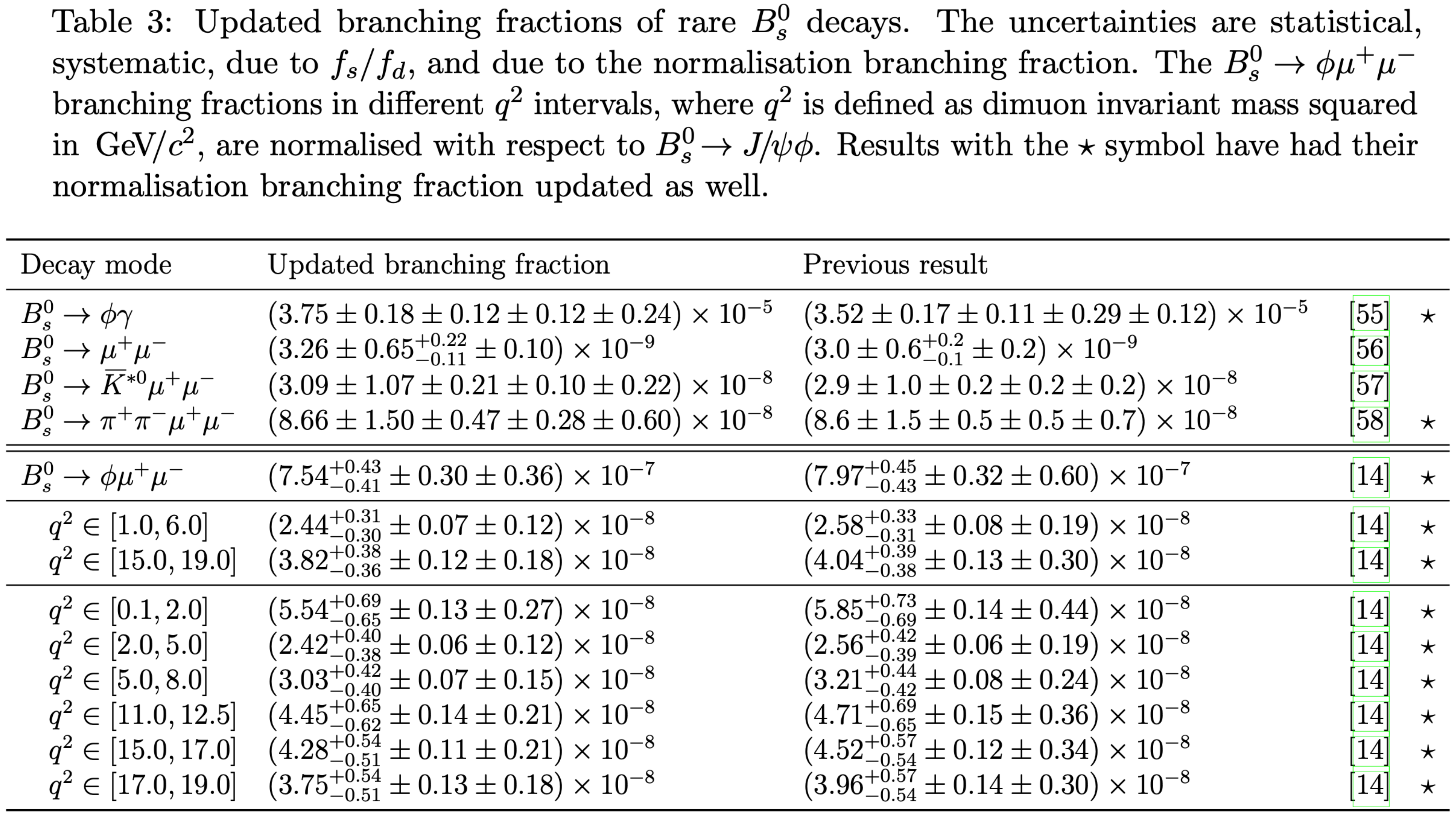


Table 3: Updated branching fractions of rare B_s^0 decays. The uncertainties are statistical, systematic, due to f_s/f_d, and due to the normalisation branching fraction. The $B_s^0 \to \phi\mu^+\mu^-$ branching fractions in different q^2 intervals, where q^2 is defined as dimuon invariant mass squared in GeV/c^2, are normalised with respect to $B_s^0 \to J/\psi\phi$. Results with the ⋆ symbol have had their normalisation branching fraction updated as well.

Decay mode	Updated branching fraction	Previous result		
$B_s^0 \to \phi\gamma$	$(3.75 \pm 0.18 \pm 0.12 \pm 0.12 \pm 0.24) \times 10^{-5}$	$(3.52 \pm 0.17 \pm 0.11 \pm 0.29 \pm 0.12) \times 10^{-5}$	[55]	⋆
$B_s^0 \to \mu^+\mu^-$	$(3.26 \pm 0.65^{+0.22}_{-0.11} \pm 0.10) \times 10^{-9}$	$(3.0 \pm 0.6^{+0.2}_{-0.1} \pm 0.2) \times 10^{-9}$	[56]	
$B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$	$(3.09 \pm 1.07 \pm 0.21 \pm 0.10 \pm 0.22) \times 10^{-8}$	$(2.9 \pm 1.0 \pm 0.2 \pm 0.2 \pm 0.2) \times 10^{-8}$	[57]	
$B_s^0 \to \pi^+\pi^-\mu^+\mu^-$	$(8.66 \pm 1.50 \pm 0.47 \pm 0.28 \pm 0.60) \times 10^{-8}$	$(8.6 \pm 1.5 \pm 0.5 \pm 0.5 \pm 0.7) \times 10^{-8}$	[58]	⋆
$B_s^0 \to \phi\mu^+\mu^-$	$(7.54^{+0.43}_{-0.41} \pm 0.30 \pm 0.36) \times 10^{-7}$	$(7.97^{+0.45}_{-0.43} \pm 0.32 \pm 0.60) \times 10^{-7}$	[14]	⋆
$q^2 \in [1.0, 6.0]$	$(2.44^{+0.31}_{-0.30} \pm 0.07 \pm 0.12) \times 10^{-8}$	$(2.58^{+0.33}_{-0.31} \pm 0.08 \pm 0.19) \times 10^{-8}$	[14]	⋆
$q^2 \in [15.0, 19.0]$	$(3.82^{+0.38}_{-0.36} \pm 0.12 \pm 0.18) \times 10^{-8}$	$(4.04^{+0.39}_{-0.38} \pm 0.13 \pm 0.30) \times 10^{-8}$	[14]	⋆
$q^2 \in [0.1, 2.0]$	$(5.54^{+0.69}_{-0.65} \pm 0.13 \pm 0.27) \times 10^{-8}$	$(5.85^{+0.73}_{-0.69} \pm 0.14 \pm 0.44) \times 10^{-8}$	[14]	⋆
$q^2 \in [2.0, 5.0]$	$(2.42^{+0.40}_{-0.38} \pm 0.06 \pm 0.12) \times 10^{-8}$	$(2.56^{+0.42}_{-0.39} \pm 0.06 \pm 0.19) \times 10^{-8}$	[14]	⋆
$q^2 \in [5.0, 8.0]$	$(3.03^{+0.42}_{-0.40} \pm 0.07 \pm 0.15) \times 10^{-8}$	$(3.21^{+0.44}_{-0.42} \pm 0.08 \pm 0.24) \times 10^{-8}$	[14]	⋆
$q^2 \in [11.0, 12.5]$	$(4.45^{+0.65}_{-0.62} \pm 0.14 \pm 0.21) \times 10^{-8}$	$(4.71^{+0.69}_{-0.65} \pm 0.15 \pm 0.36) \times 10^{-8}$	[14]	⋆
$q^2 \in [15.0, 17.0]$	$(4.28^{+0.54}_{-0.51} \pm 0.11 \pm 0.21) \times 10^{-8}$	$(4.52^{+0.57}_{-0.54} \pm 0.12 \pm 0.34) \times 10^{-8}$	[14]	⋆
$q^2 \in [17.0, 19.0]$	$(3.75^{+0.54}_{-0.51} \pm 0.13 \pm 0.18) \times 10^{-8}$	$(3.96^{+0.57}_{-0.54} \pm 0.14 \pm 0.30) \times 10^{-8}$	[14]	⋆

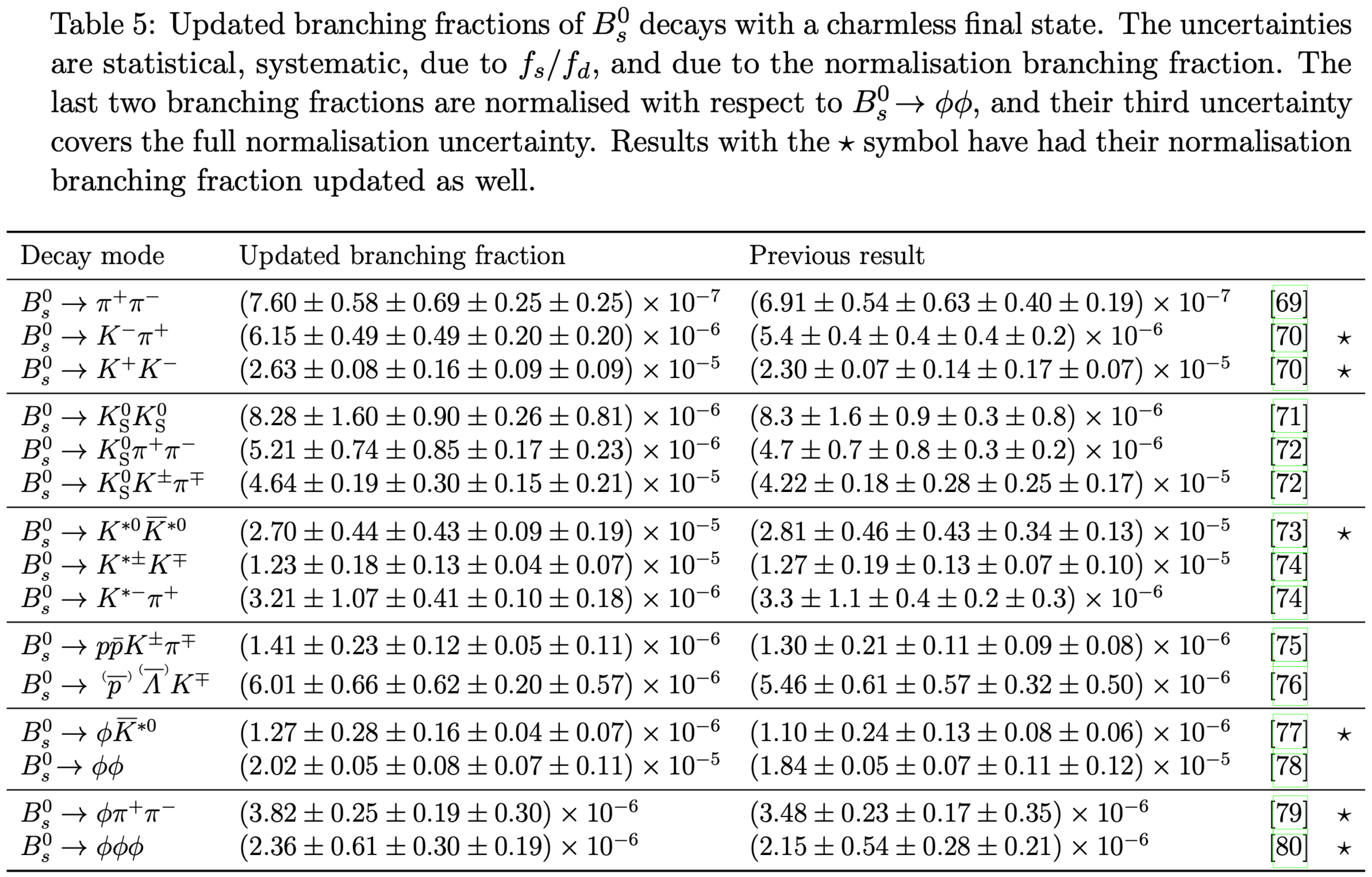


Table 5: Updated branching fractions of B_s^0 decays with a charmless final state. The uncertainties are statistical, systematic, due to f_s/f_d, and due to the normalisation branching fraction. The last two branching fractions are normalised with respect to $B_s^0 \to \phi\phi$, and their third uncertainty covers the full normalisation uncertainty. Results with the ⋆ symbol have had their normalisation branching fraction updated as well.

Decay mode	Updated branching fraction	Previous result		
$B_s^0 \to \pi^+\pi^-$	$(7.60 \pm 0.58 \pm 0.69 \pm 0.25 \pm 0.25) \times 10^{-7}$	$(6.91 \pm 0.54 \pm 0.63 \pm 0.40 \pm 0.19) \times 10^{-7}$	[69]	
$B_s^0 \to K^-\pi^+$	$(6.15 \pm 0.49 \pm 0.49 \pm 0.20 \pm 0.20) \times 10^{-6}$	$(5.4 \pm 0.4 \pm 0.4 \pm 0.4 \pm 0.2) \times 10^{-6}$	[70]	⋆
$B_s^0 \to K^+K^-$	$(2.63 \pm 0.08 \pm 0.16 \pm 0.09 \pm 0.09) \times 10^{-5}$	$(2.30 \pm 0.07 \pm 0.14 \pm 0.17 \pm 0.07) \times 10^{-5}$	[70]	⋆
$B_s^0 \to K_S^0K_S^0$	$(8.28 \pm 1.60 \pm 0.90 \pm 0.26 \pm 0.81) \times 10^{-6}$	$(8.3 \pm 1.6 \pm 0.9 \pm 0.3 \pm 0.8) \times 10^{-6}$	[71]	
$B_s^0 \to K_S^0\pi^+\pi^-$	$(5.21 \pm 0.74 \pm 0.85 \pm 0.17 \pm 0.23) \times 10^{-6}$	$(4.7 \pm 0.7 \pm 0.8 \pm 0.3 \pm 0.2) \times 10^{-6}$	[72]	
$B_s^0 \to K_S^0K^\pm\pi^\mp$	$(4.64 \pm 0.19 \pm 0.30 \pm 0.15 \pm 0.21) \times 10^{-5}$	$(4.22 \pm 0.18 \pm 0.28 \pm 0.25 \pm 0.17) \times 10^{-5}$	[72]	
$B_s^0 \to K^{*0}\overline{K}^{*0}$	$(2.70 \pm 0.44 \pm 0.43 \pm 0.09 \pm 0.19) \times 10^{-5}$	$(2.81 \pm 0.46 \pm 0.43 \pm 0.34 \pm 0.13) \times 10^{-5}$	[73]	⋆
$B_s^0 \to K^{*\pm}K^\mp$	$(1.23 \pm 0.18 \pm 0.13 \pm 0.04 \pm 0.07) \times 10^{-5}$	$(1.27 \pm 0.19 \pm 0.13 \pm 0.07 \pm 0.10) \times 10^{-5}$	[74]	
$B_s^0 \to K^{*-}\pi^+$	$(3.21 \pm 1.07 \pm 0.41 \pm 0.10 \pm 0.18) \times 10^{-6}$	$(3.3 \pm 1.1 \pm 0.4 \pm 0.2 \pm 0.3) \times 10^{-6}$	[74]	
$B_s^0 \to p\bar{p}K^\pm\pi^\mp$	$(1.41 \pm 0.23 \pm 0.12 \pm 0.05 \pm 0.11) \times 10^{-6}$	$(1.30 \pm 0.21 \pm 0.11 \pm 0.09 \pm 0.08) \times 10^{-6}$	[75]	
$B_s^0 \to \overset{(-)}{p}\,\overset{(-)}{\Lambda}K^\mp$	$(6.01 \pm 0.66 \pm 0.62 \pm 0.20 \pm 0.57) \times 10^{-6}$	$(5.46 \pm 0.61 \pm 0.57 \pm 0.32 \pm 0.50) \times 10^{-6}$	[76]	
$B_s^0 \to \phi\overline{K}^{*0}$	$(1.27 \pm 0.28 \pm 0.16 \pm 0.04 \pm 0.07) \times 10^{-6}$	$(1.10 \pm 0.24 \pm 0.13 \pm 0.08 \pm 0.06) \times 10^{-6}$	[77]	⋆
$B_s^0 \to \phi\phi$	$(2.02 \pm 0.05 \pm 0.08 \pm 0.07 \pm 0.11) \times 10^{-5}$	$(1.84 \pm 0.05 \pm 0.07 \pm 0.11 \pm 0.12) \times 10^{-5}$	[78]	
$B_s^0 \to \phi\pi^+\pi^-$	$(3.82 \pm 0.25 \pm 0.19 \pm 0.30) \times 10^{-6}$	$(3.48 \pm 0.23 \pm 0.17 \pm 0.35) \times 10^{-6}$	[79]	⋆
$B_s^0 \to \phi\phi\phi$	$(2.36 \pm 0.61 \pm 0.30 \pm 0.19) \times 10^{-6}$	$(2.15 \pm 0.54 \pm 0.28 \pm 0.21) \times 10^{-6}$	[80]	⋆

BSM in non-leptonic tree-level Decays

How much space is there for BSM effects in non-leptonic tree-level decays?

AL, Tetlalmatzi-Xolocotzi 1912.07621

$$\begin{aligned} C_1(M_W) &:= C_1^{\mathrm{SM}}(M_W) + \Delta C_1(M_W), \\ C_2(M_W) &:= C_2^{\mathrm{SM}}(M_W) + \Delta C_2(M_W), \end{aligned}$$

No new Dirac structures, $\Delta C_i \in \mathbb{C}$

$\Rightarrow$

$\Delta\Gamma_q, \Delta M_q, a_{sl}^q$

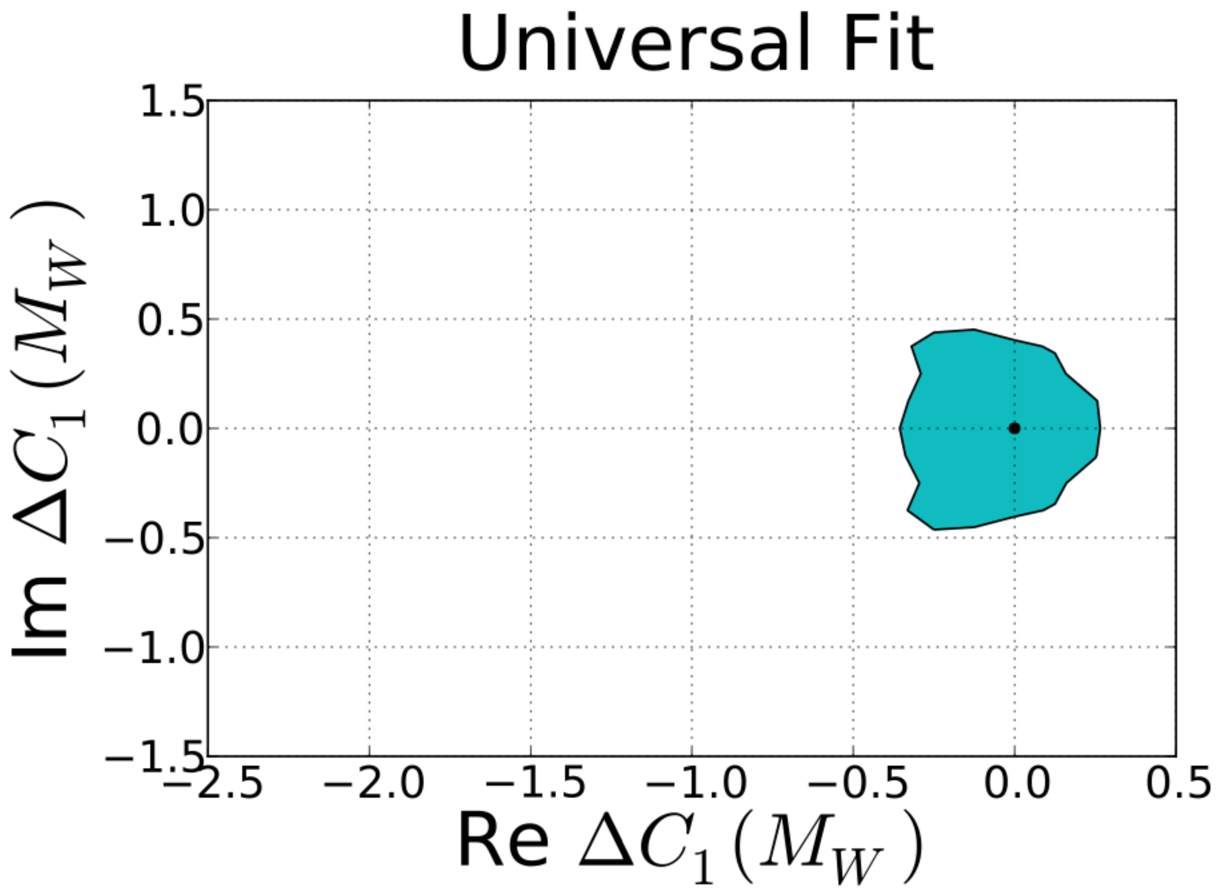
$B \to \pi\pi, D\pi, \ldots$

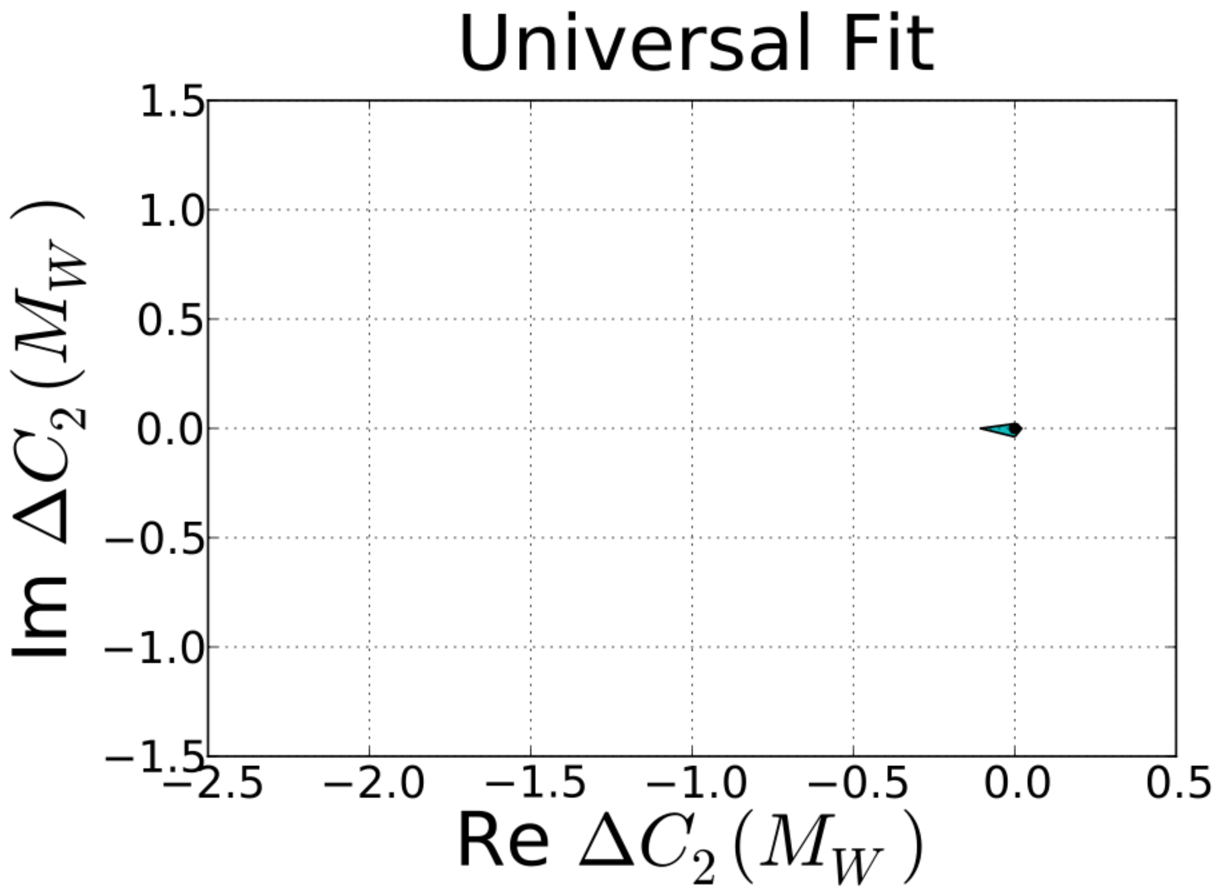
$b \to s\gamma, s\mu\mu$

$B \to J/\Psi K, \sin 2\beta, \ldots$

$\tau(B_s)/\tau(B_d), \ldots$

$\Rightarrow$





What consequences could this have?

- Enhancement of $\Delta\Gamma_d$ by several hundred %

Bobeth, Haisch, AL, Pecjak, Tetlalmatzi-Xolocotzi 1412.1446

- Deviation of the CKM angle γ by several degrees

Brod, AL, Tetlalmatzi-Xolocotzi 1404.2531

BSM in non-leptonic tree-level Decays

BSM effects in $b \to c\bar{c}s$ transitions?

Jäger, Kirk, AL, Leslie 1910.12924, 1701.09183

$$
\begin{aligned}
Q_1^c &= (\bar{c}_L^i \gamma_\mu b_L^j)(\bar{s}_L^j \gamma^\mu c_L^i), & Q_2^c &= (\bar{c}_L^i \gamma_\mu b_L^i)(\bar{s}_L^j \gamma^\mu c_L^j),\\
Q_3^c &= (\bar{c}_R^i b_L^j)(\bar{s}_L^j c_R^i), & Q_4^c &= (\bar{c}_R^i b_L^i)(\bar{s}_L^j c_R^j),\\
Q_5^c &= (\bar{c}_R^i \gamma_\mu b_R^j)(\bar{s}_L^j \gamma^\mu c_L^i), & Q_6^c &= (\bar{c}_R^i \gamma_\mu b_R^i)(\bar{s}_L^j \gamma^\mu c_L^j),\\
Q_7^c &= (\bar{c}_L^i b_R^j)(\bar{s}_L^j c_R^i), & Q_8^c &= (\bar{c}_L^i b_R^i)(\bar{s}_L^j c_R^j),\\
Q_9^c &= (\bar{c}_L^i \sigma_{\mu\nu} b_R^j)(\bar{s}_L^j \sigma^{\mu\nu} c_R^i), & Q_{10}^c &= (\bar{c}_L^i \sigma_{\mu\nu} b_R^i)(\bar{s}_L^j \sigma^{\mu\nu} c_R^j),
\end{aligned}
$$

New Dirac structures, $\Delta C_i \in \mathbb{C}$

$\Rightarrow$

$\Delta\Gamma_q, \Delta M_q, a_{sl}^q$

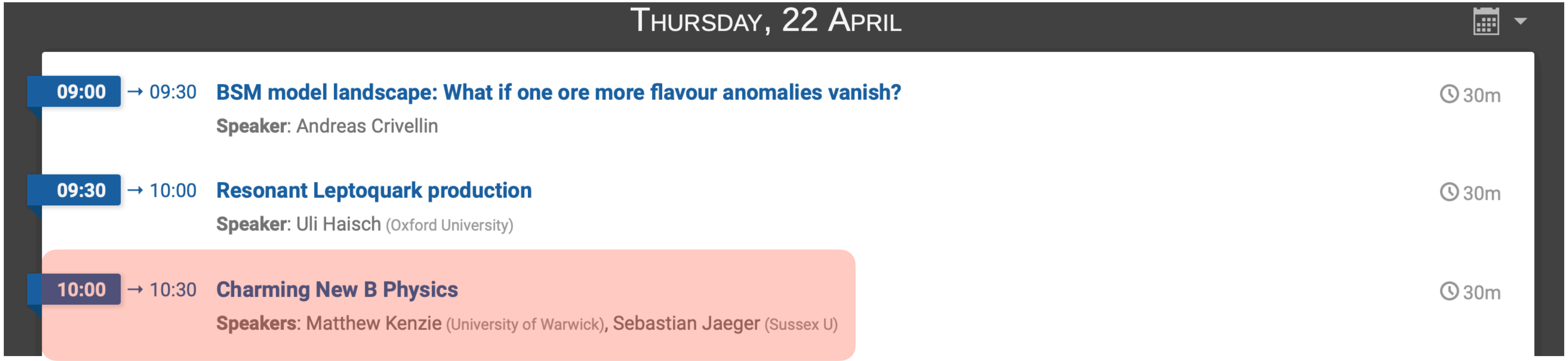
$b \to s\gamma, s\mu\mu$

$B \to J/\Psi K, \sin 2\beta, \ldots$

$\tau(B_s)/\tau(B_d), \ldots$

$\Rightarrow$

- You can create a q^2 dependent BSM effect to $b \to s\mu\mu$
- P5’ and friends can be explained, R_K clearly not
- Only part of a bigger picture: BSM in loop and tree-level



Thursday, 22 April

09:00 → 09:30 **BSM model landscape: What if one ore more flavour anomalies vanish?** 30m
Speaker: Andreas Crivellin

09:30 → 10:00 **Resonant Leptoquark production** 30m
Speaker: Uli Haisch (Oxford University)

10:00 → 10:30 **Charming New B Physics** 30m
Speakers: Matthew Kenzie (University of Warwick), Sebastian Jaeger (Sussex U)

BSM in non-leptonic tree-level Decays

Improvement of our studies: $\tau(B_s)/\tau(B_d)$ is a crucial constraint:

- ms corrections to **Bag parameter** for B_s and D_s^+ mesons

HQET sum rules King, AL, Rauh   **Lattice in Siegen! Black, Witzel**

- **Darwin term** turns out to be sizeable and has to be included!

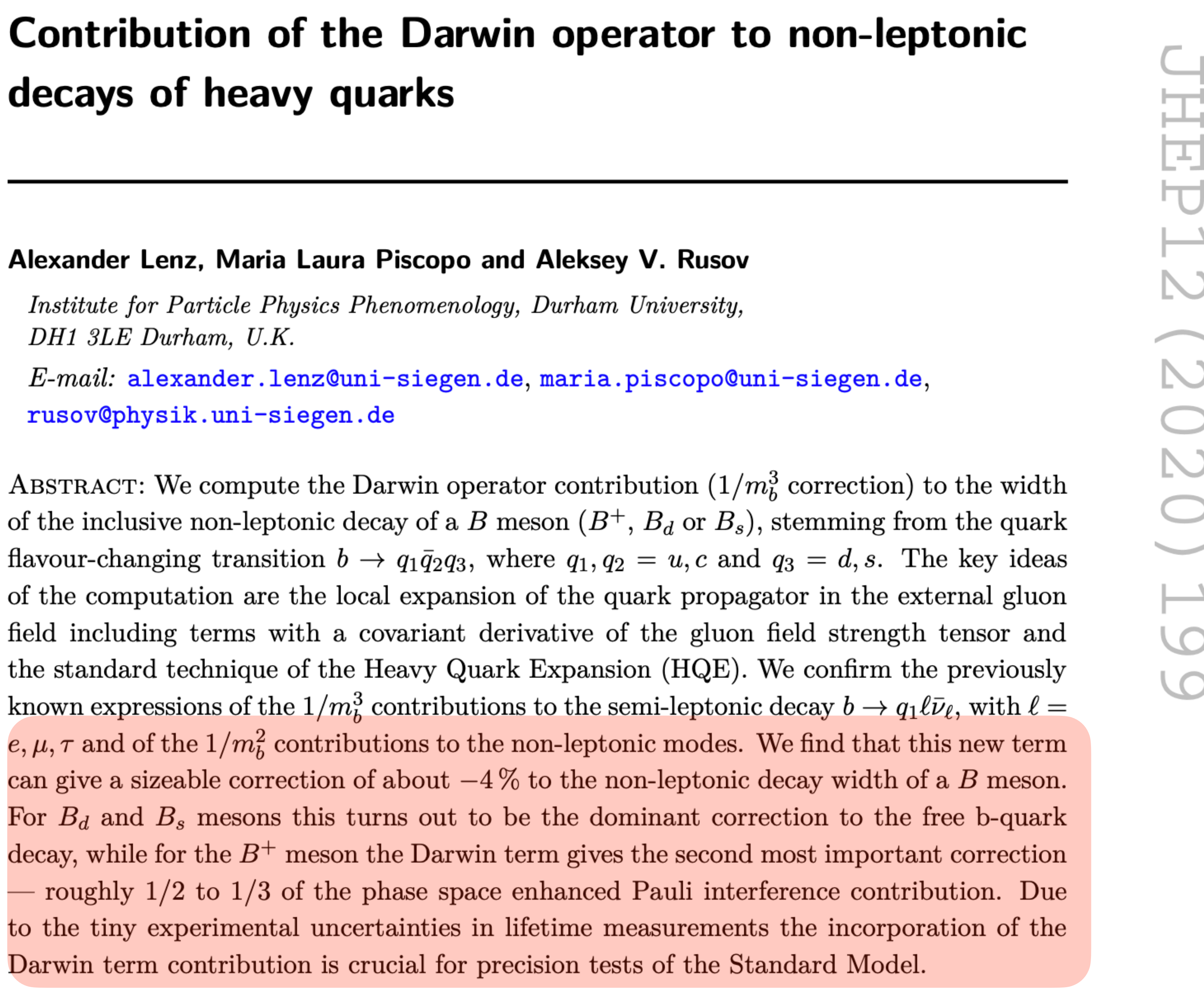
AL, Piscopo, Rusov   **Mannel, Moreno, Pivovarov**

Work in progress

update of charm meson lifetimes (test of convergence of HQE)

update of b meson lifetimes (phenomenology)

?size of SU(3)_F breaking in Darwin term?



Contribution of the Darwin operator to non-leptonic decays of heavy quarks

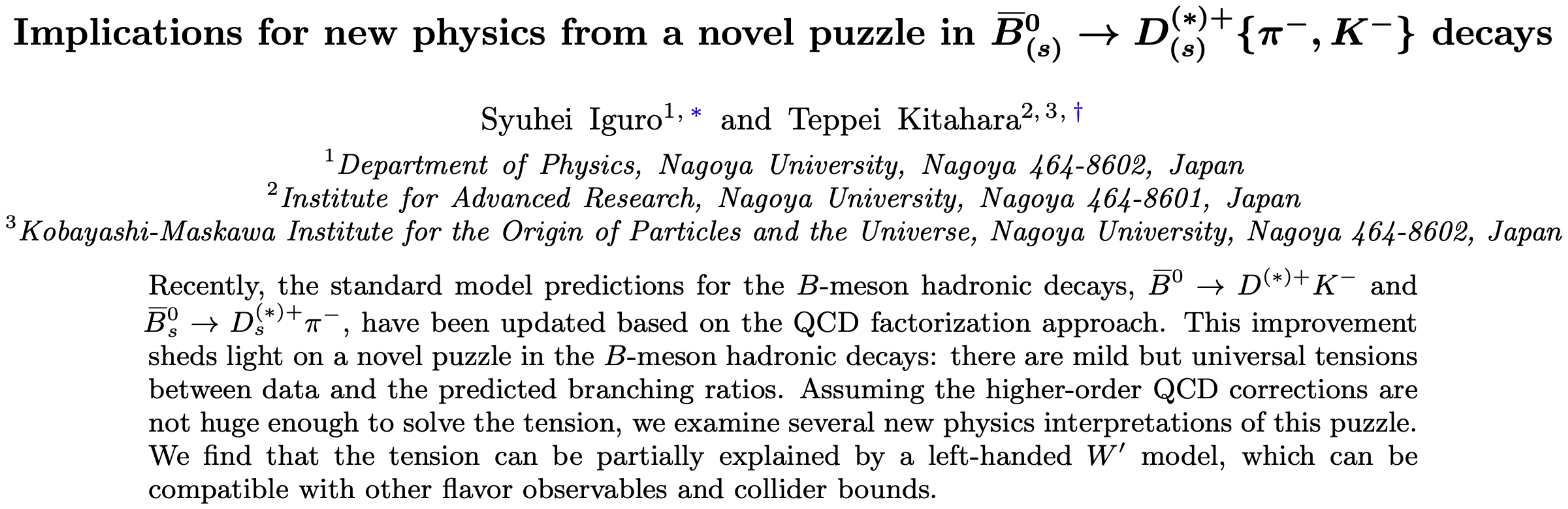
Alexander Lenz, Maria Laura Piscopo and Aleksey V. Rusov

Institute for Particle Physics Phenomenology, Durham University,
DH1 3LE Durham, U.K.
E-mail: alexander.lenz@uni-siegen.de, maria.piscopo@uni-siegen.de, rusov@physik.uni-siegen.de

ABSTRACT: We compute the Darwin operator contribution ($1/m_b^3$ correction) to the width of the inclusive non-leptonic decay of a B meson (B^+, B_d or B_s), stemming from the quark flavour-changing transition $b \to q_1\bar{q}_2q_3$, where $q_1, q_2 = u, c$ and $q_3 = d, s$. The key ideas of the computation are the local expansion of the quark propagator in the external gluon field including terms with a covariant derivative of the gluon field strength tensor and the standard technique of the Heavy Quark Expansion (HQE). We confirm the previously known expressions of the $1/m_b^3$ contributions to the semi-leptonic decay $b \to q_1\ell\bar{\nu}_\ell$, with $\ell = e, \mu, \tau$ and of the $1/m_b^2$ contributions to the non-leptonic modes. We find that this new term can give a sizeable correction of about $-4\,\%$ to the non-leptonic decay width of a B meson. For B_d and B_s mesons this turns out to be the dominant correction to the free b-quark decay, while for the B^+ meson the Darwin term gives the second most important correction — roughly 1/2 to 1/3 of the phase space enhanced Pauli interference contribution. Due to the tiny experimental uncertainties in lifetime measurements the incorporation of the Darwin term contribution is crucial for precision tests of the Standard Model.

JHEP12(2020)199

BSM in non-leptonic tree-level Decays



Implications for new physics from a novel puzzle in $\overline{B}^0_{(s)} \to D^{(*)+}_{(s)}\{\pi^-, K^-\}$ decays

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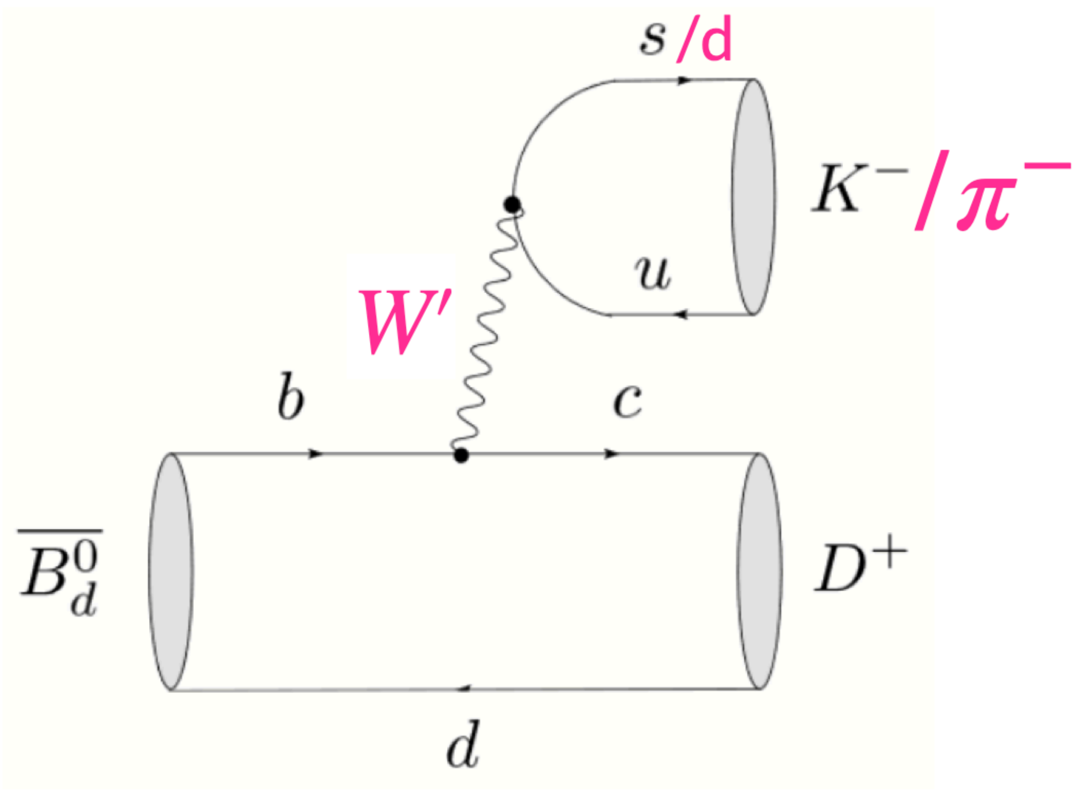
[3] *Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Nagoya 464-8602, Japan*

Recently, the standard model predictions for the B-meson hadronic decays, $\overline{B}^0 \to D^{(*)+}K^-$ and $\overline{B}^0_s \to D_s^{(*)+}\pi^-$, have been updated based on the QCD factorization approach. This improvement sheds light on a novel puzzle in the B-meson hadronic decays: there are mild but universal tensions between data and the predicted branching ratios. Assuming the higher-order QCD corrections are not huge enough to solve the tension, we examine several new physics interpretations of this puzzle. We find that the tension can be partially explained by a left-handed W' model, which can be compatible with other flavor observables and collider bounds.

2008.01086

Assume: BSM only in C_1 and C_2 (Colour-Singlett) ⇒

$$\boxed{\frac{C_2^{\mathrm{NP}}(m_b)}{C_2^{\mathrm{SM}}(m_b)} = -0.17 \pm 0.03\,.}$$



Just assuming no leptonic coupling

⇒

Flavour bounds

$K \to \pi\pi, \Delta M_{d,s}, b \to s\gamma, \ldots$

Collider dijet…

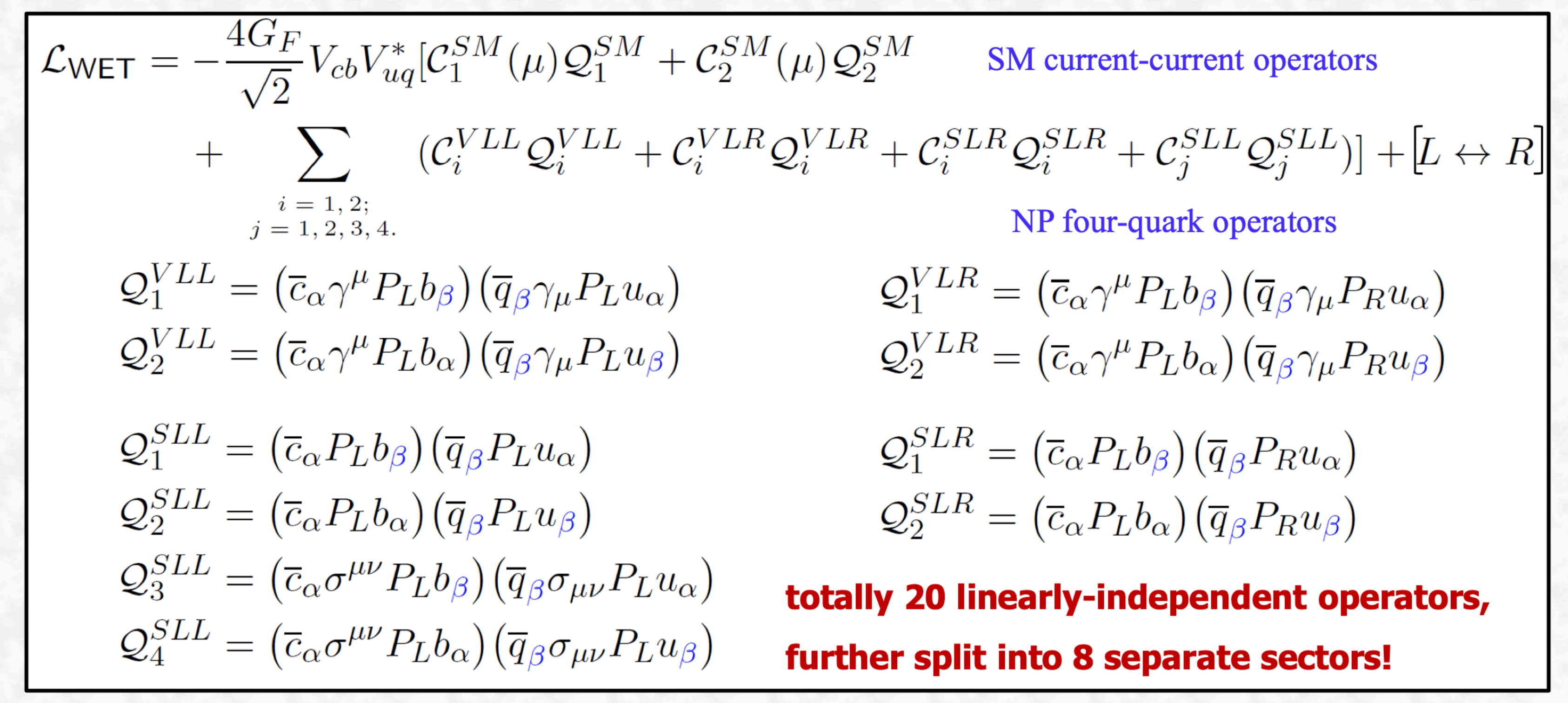
⇒

$C_2^{\mathrm{NP}}/C_2^{\mathrm{SM}} = -\mathcal{O}(10\%)$

possible

BSM in non-leptonic tree-level Decays

1. Update SM prediction
2. Investigate all possible new Dirac structures at NLO



$$\mathcal{L}_{\text{WET}} = -\frac{4G_F}{\sqrt{2}} V_{cb}V_{uq}^{*}[\mathcal{C}_1^{SM}(\mu)\mathcal{Q}_1^{SM} + \mathcal{C}_2^{SM}(\mu)\mathcal{Q}_2^{SM}$$

SM current-current operators

$$+ \sum_{\substack{i=1,2;\\ j=1,2,3,4.}} (\mathcal{C}_i^{VLL}\mathcal{Q}_i^{VLL} + \mathcal{C}_i^{VLR}\mathcal{Q}_i^{VLR} + \mathcal{C}_i^{SLR}\mathcal{Q}_i^{SLR} + \mathcal{C}_j^{SLL}\mathcal{Q}_j^{SLL})] + [L \leftrightarrow R]$$

NP four-quark operators

$$\mathcal{Q}_1^{VLL} = (\bar{c}_\alpha\gamma^\mu P_L b_\beta)(\bar{q}_\beta\gamma_\mu P_L u_\alpha) \qquad \mathcal{Q}_1^{VLR} = (\bar{c}_\alpha\gamma^\mu P_L b_\beta)(\bar{q}_\beta\gamma_\mu P_R u_\alpha)$$

$$\mathcal{Q}_2^{VLL} = (\bar{c}_\alpha\gamma^\mu P_L b_\alpha)(\bar{q}_\beta\gamma_\mu P_L u_\beta) \qquad \mathcal{Q}_2^{VLR} = (\bar{c}_\alpha\gamma^\mu P_L b_\alpha)(\bar{q}_\beta\gamma_\mu P_R u_\beta)$$

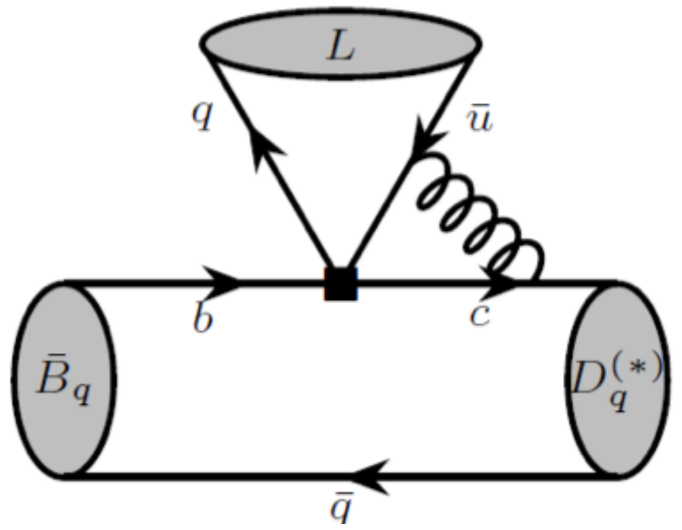
$$\mathcal{Q}_1^{SLL} = (\bar{c}_\alpha P_L b_\beta)(\bar{q}_\beta P_L u_\alpha) \qquad \mathcal{Q}_1^{SLR} = (\bar{c}_\alpha P_L b_\beta)(\bar{q}_\beta P_R u_\alpha)$$

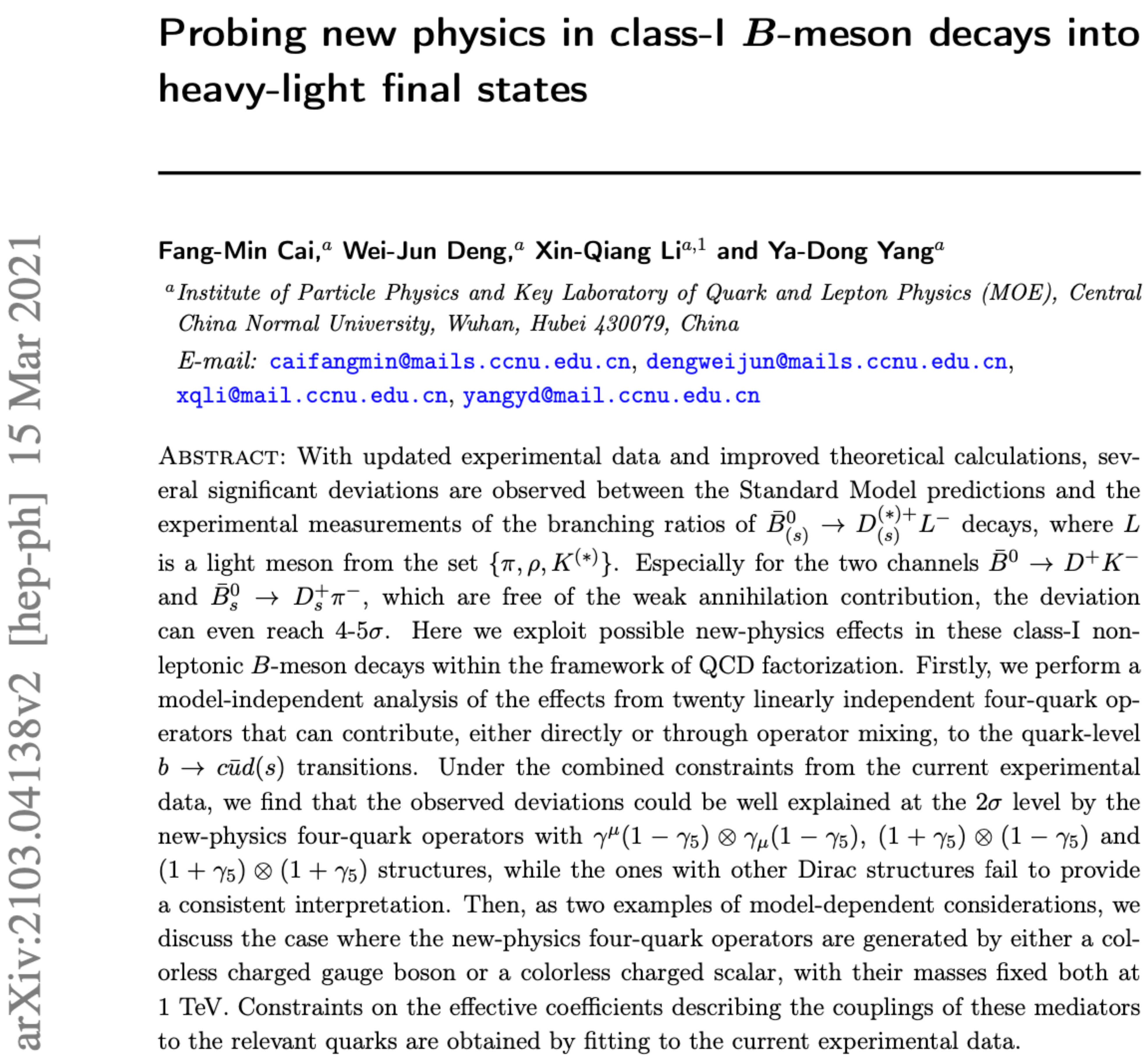
$$\mathcal{Q}_2^{SLL} = (\bar{c}_\alpha P_L b_\alpha)(\bar{q}_\beta P_L u_\beta) \qquad \mathcal{Q}_2^{SLR} = (\bar{c}_\alpha P_L b_\alpha)(\bar{q}_\beta P_R u_\beta)$$

$$\mathcal{Q}_3^{SLL} = (\bar{c}_\alpha\sigma^{\mu\nu} P_L b_\beta)(\bar{q}_\beta\sigma_{\mu\nu} P_L u_\alpha)$$

$$\mathcal{Q}_4^{SLL} = (\bar{c}_\alpha\sigma^{\mu\nu} P_L b_\alpha)(\bar{q}_\beta\sigma_{\mu\nu} P_L u_\beta)$$

totally 20 linearly-independent operators,
further split into 8 separate sectors!





Probing new physics in class-I B-meson decays into heavy-light final states

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Abstract: With updated experimental data and improved theoretical calculations, several significant deviations are observed between the Standard Model predictions and the experimental measurements of the branching ratios of $\bar{B}^0_{(s)} \to D^{(*)+}_{(s)} L^-$ decays, where L is a light meson from the set $\{\pi, \rho, K^{(*)}\}$. Especially for the two channels $\bar{B}^0 \to D^+K^-$ and $\bar{B}^0_s \to D^+_s\pi^-$, which are free of the weak annihilation contribution, the deviation can even reach 4-5σ. Here we exploit possible new-physics effects in these class-I non-leptonic B-meson decays within the framework of QCD factorization. Firstly, we perform a model-independent analysis of the effects from twenty linearly independent four-quark operators that can contribute, either directly or through operator mixing, to the quark-level $b \to c\bar{u}d(s)$ transitions. Under the combined constraints from the current experimental data, we find that the observed deviations could be well explained at the 2σ level by the new-physics four-quark operators with $\gamma^\mu(1-\gamma_5) \otimes \gamma_\mu(1-\gamma_5)$, $(1+\gamma_5) \otimes (1-\gamma_5)$ and $(1+\gamma_5) \otimes (1+\gamma_5)$ structures, while the ones with other Dirac structures fail to provide a consistent interpretation. Then, as two examples of model-dependent considerations, we discuss the case where the new-physics four-quark operators are generated by either a colorless charged gauge boson or a colorless charged scalar, with their masses fixed both at 1 TeV. Constraints on the effective coefficients describing the couplings of these mediators to the relevant quarks are obtained by fitting to the current experimental data.

arXiv:2103.04138v2 [hep-ph] 15 Mar 2021

☐ Model-indep. analysis reveals that only NP operators with 3 Dirac structures possible:

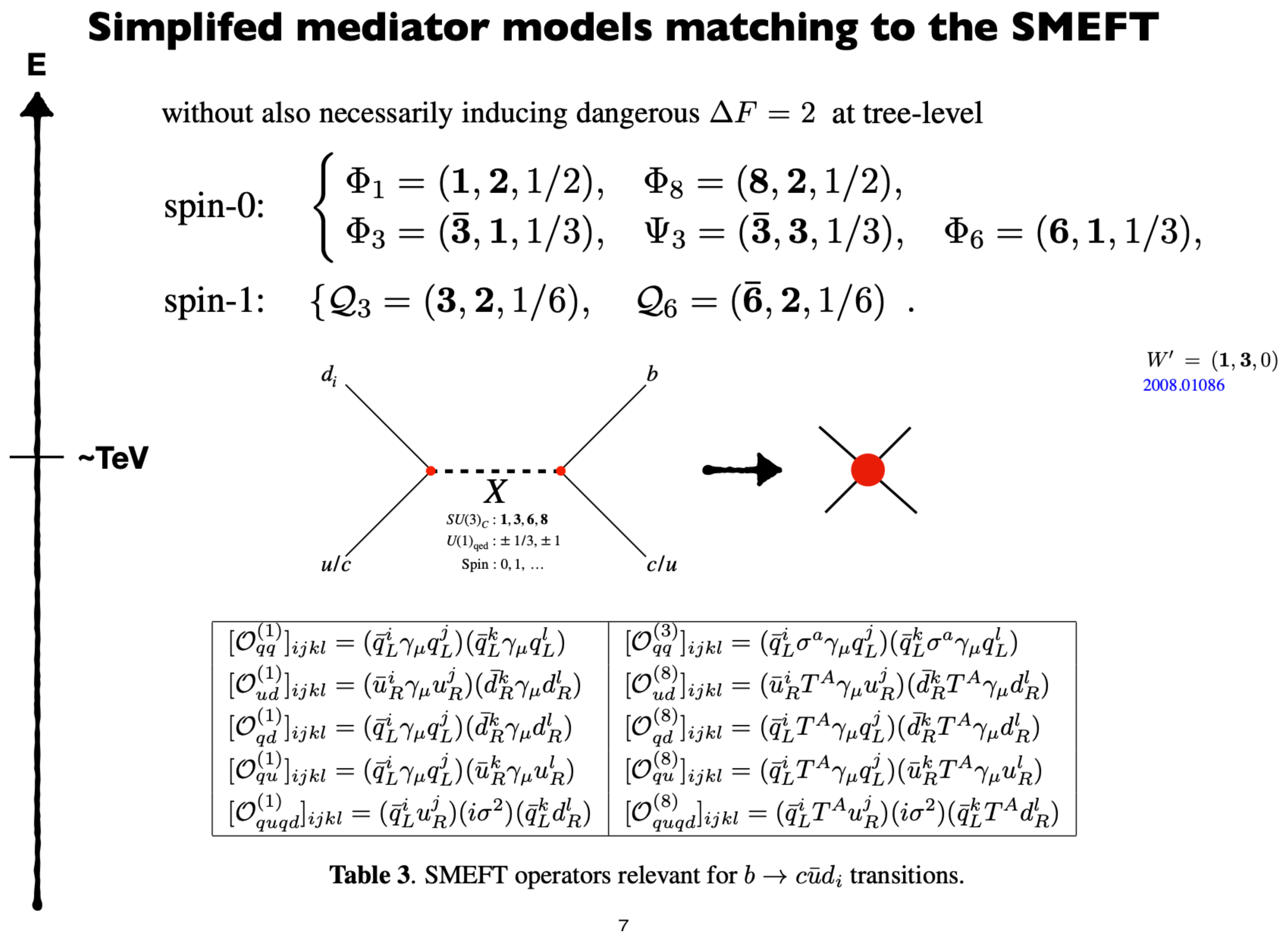
$$\boxed{\mathcal{Q}_{1,2}^{VLL} = \bar{c}_\alpha\gamma_\mu(1-\gamma_5)b_{\beta(\alpha)}\,\bar{q}_\beta\gamma^\mu(1-\gamma_5)u_{\alpha(\beta)}} \quad \boxed{\mathcal{Q}_{1,2}^{SRL} = \bar{c}_\alpha(1+\gamma_5)b_{\beta(\alpha)}\,\bar{q}_\beta(1-\gamma_5)u_{\alpha(\beta)}} \quad \boxed{\mathcal{Q}_{1,2}^{SRR} = \bar{c}_\alpha(1+\gamma_5)b_{\beta(\alpha)}\,\bar{q}_\beta(1+\gamma_5)u_{\alpha(\beta)}}$$

$$(\boldsymbol{V-A}) \otimes (\boldsymbol{V-A}) \qquad (\boldsymbol{S+P}) \otimes (\boldsymbol{S-P}) \qquad (\boldsymbol{S+P}) \otimes (\boldsymbol{S+P})$$

generated by a colorless charged gauge boson or by a colorless charged scalar.

BSM in non-leptonic tree-level Decays

- We focus on weakly-coupled extensions of the SM.
- TeV-scale physics, likely tree-level.



Simplifed mediator models matching to the SMEFT

without also necessarily inducing dangerous $\Delta F = 2$ at tree-level

$$\text{spin-0:} \quad \begin{cases} \Phi_1 = (\mathbf{1}, \mathbf{2}, 1/2), \quad \Phi_8 = (\mathbf{8}, \mathbf{2}, 1/2), \\ \Phi_3 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3), \quad \Psi_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3), \quad \Phi_6 = (\mathbf{6}, \mathbf{1}, 1/3), \end{cases}$$

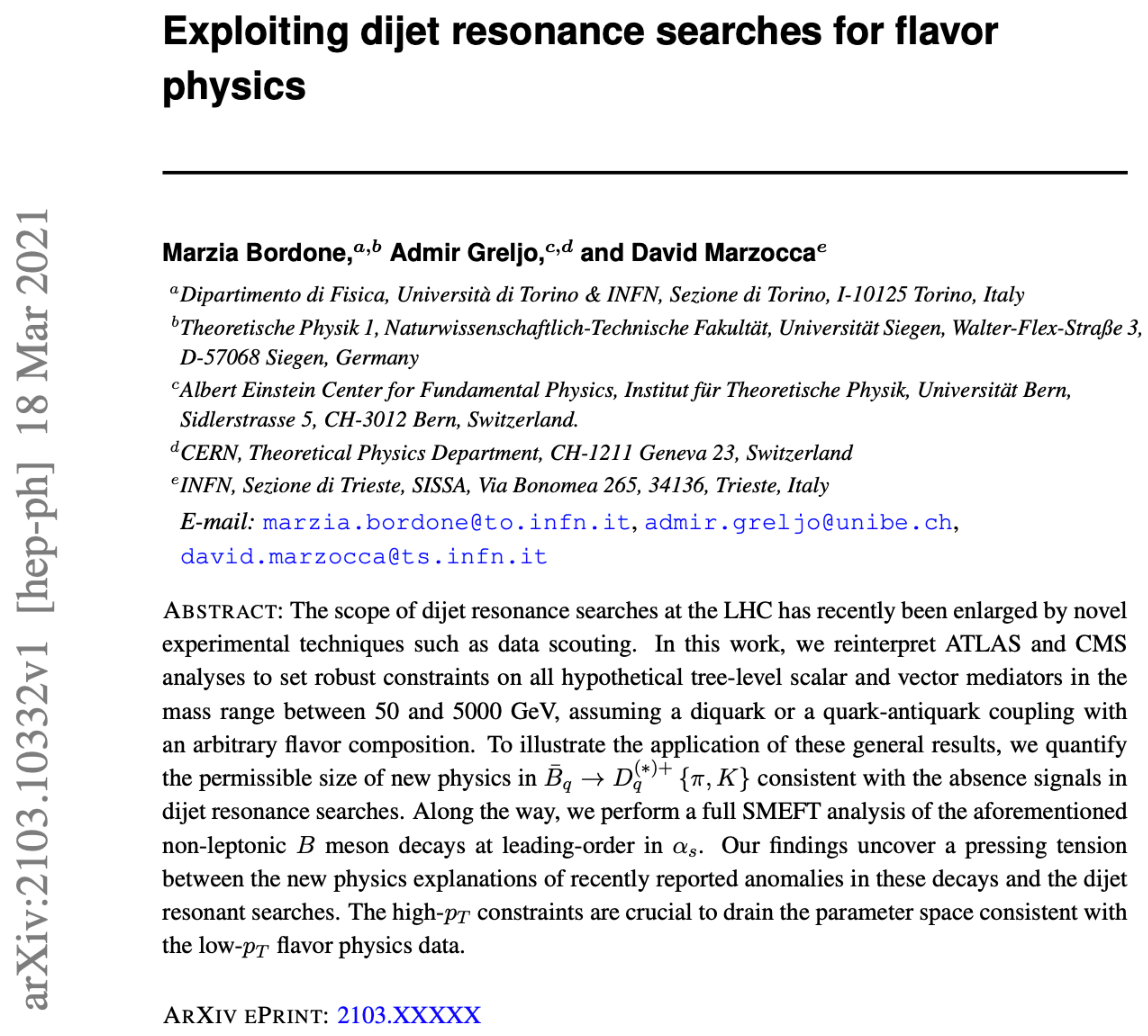
$$\text{spin-1:} \quad \{\mathcal{Q}_3 = (\mathbf{3}, \mathbf{2}, 1/6), \quad \mathcal{Q}_6 = (\bar{\mathbf{6}}, \mathbf{2}, 1/6) \ .$$

$W' = (\mathbf{1}, \mathbf{3}, 0)$
2008.01086

$[\mathcal{O}^{(1)}_{qq}]_{ijkl} = (\bar{q}^i_L \gamma_\mu q^j_L)(\bar{q}^k_L \gamma_\mu q^l_L)$	$[\mathcal{O}^{(3)}_{qq}]_{ijkl} = (\bar{q}^i_L \sigma^a \gamma_\mu q^j_L)(\bar{q}^k_L \sigma^a \gamma_\mu q^l_L)$
$[\mathcal{O}^{(1)}_{ud}]_{ijkl} = (\bar{u}^i_R \gamma_\mu u^j_R)(\bar{d}^k_R \gamma_\mu d^l_R)$	$[\mathcal{O}^{(8)}_{ud}]_{ijkl} = (\bar{u}^i_R T^A \gamma_\mu u^j_R)(\bar{d}^k_R T^A \gamma_\mu d^l_R)$
$[\mathcal{O}^{(1)}_{qd}]_{ijkl} = (\bar{q}^i_L \gamma_\mu q^j_L)(\bar{d}^k_R \gamma_\mu d^l_R)$	$[\mathcal{O}^{(8)}_{qd}]_{ijkl} = (\bar{q}^i_L T^A \gamma_\mu q^j_L)(\bar{d}^k_R T^A \gamma_\mu d^l_R)$
$[\mathcal{O}^{(1)}_{qu}]_{ijkl} = (\bar{q}^i_L \gamma_\mu q^j_L)(\bar{u}^k_R \gamma_\mu u^l_R)$	$[\mathcal{O}^{(8)}_{qu}]_{ijkl} = (\bar{q}^i_L T^A \gamma_\mu q^j_L)(\bar{u}^k_R T^A \gamma_\mu u^l_R)$
$[\mathcal{O}^{(1)}_{quqd}]_{ijkl} = (\bar{q}^i_L u^j_R)(i\sigma^2)(\bar{q}^k_L d^l_R)$	$[\mathcal{O}^{(8)}_{quqd}]_{ijkl} = (\bar{q}^i_L T^A u^j_R)(i\sigma^2)(\bar{q}^k_L T^A d^l_R)$

Table 3. SMEFT operators relevant for $b \to c\bar{u}d_i$ transitions.

7



Exploiting dijet resonance searches for flavor physics

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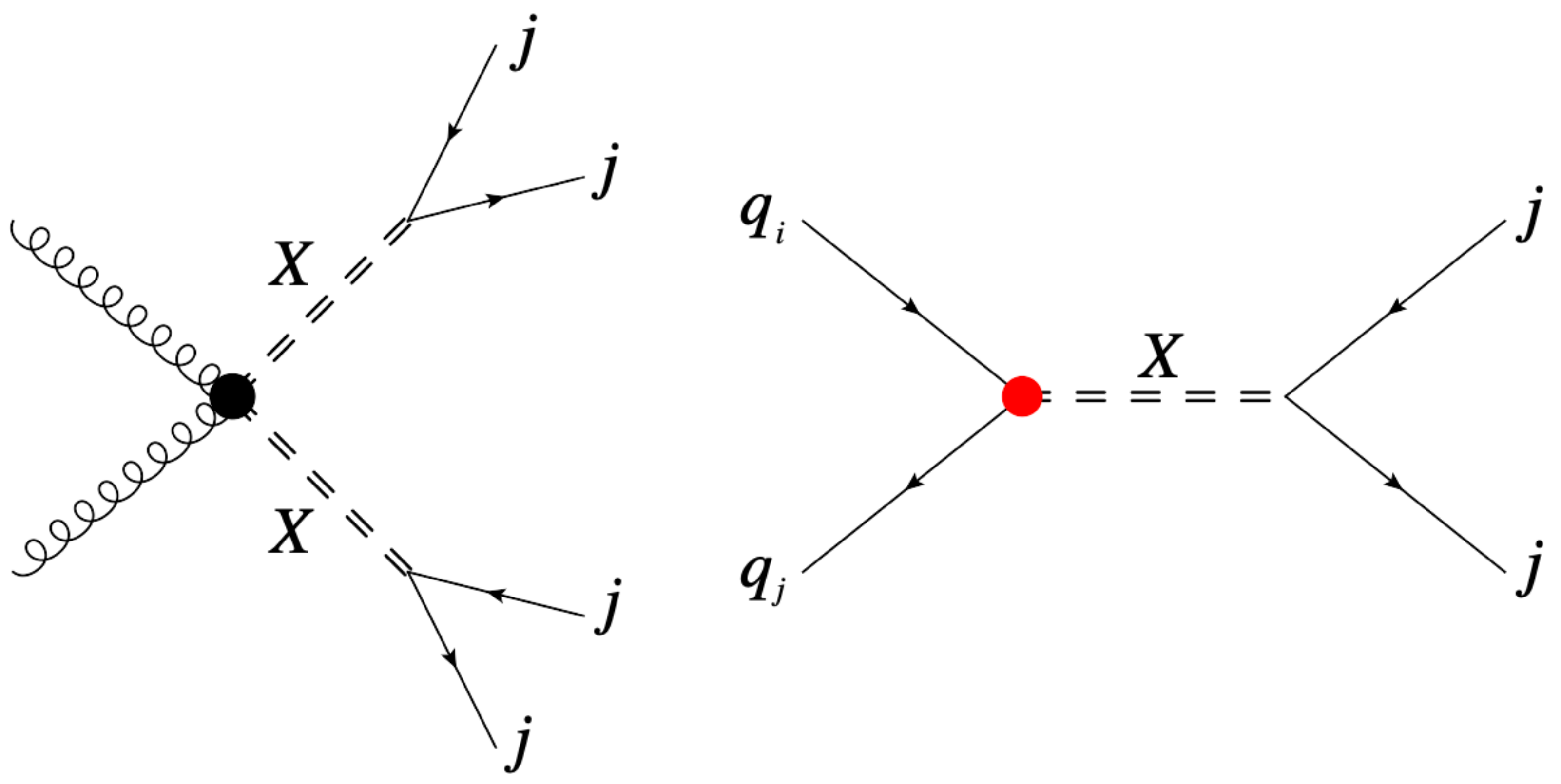
[c]*Albert Einstein Center for Fundamental Physics, Institut für Theoretische Physik, Universität Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland.*
[d]*CERN, Theoretical Physics Department, CH-1211 Geneva 23, Switzerland*
[e]*INFN, Sezione di Trieste, SISSA, Via Bonomea 265, 34136, Trieste, Italy*
E-mail: `marzia.bordone@to.infn.it`, `admir.greljo@unibe.ch`, `david.marzocca@ts.infn.it`

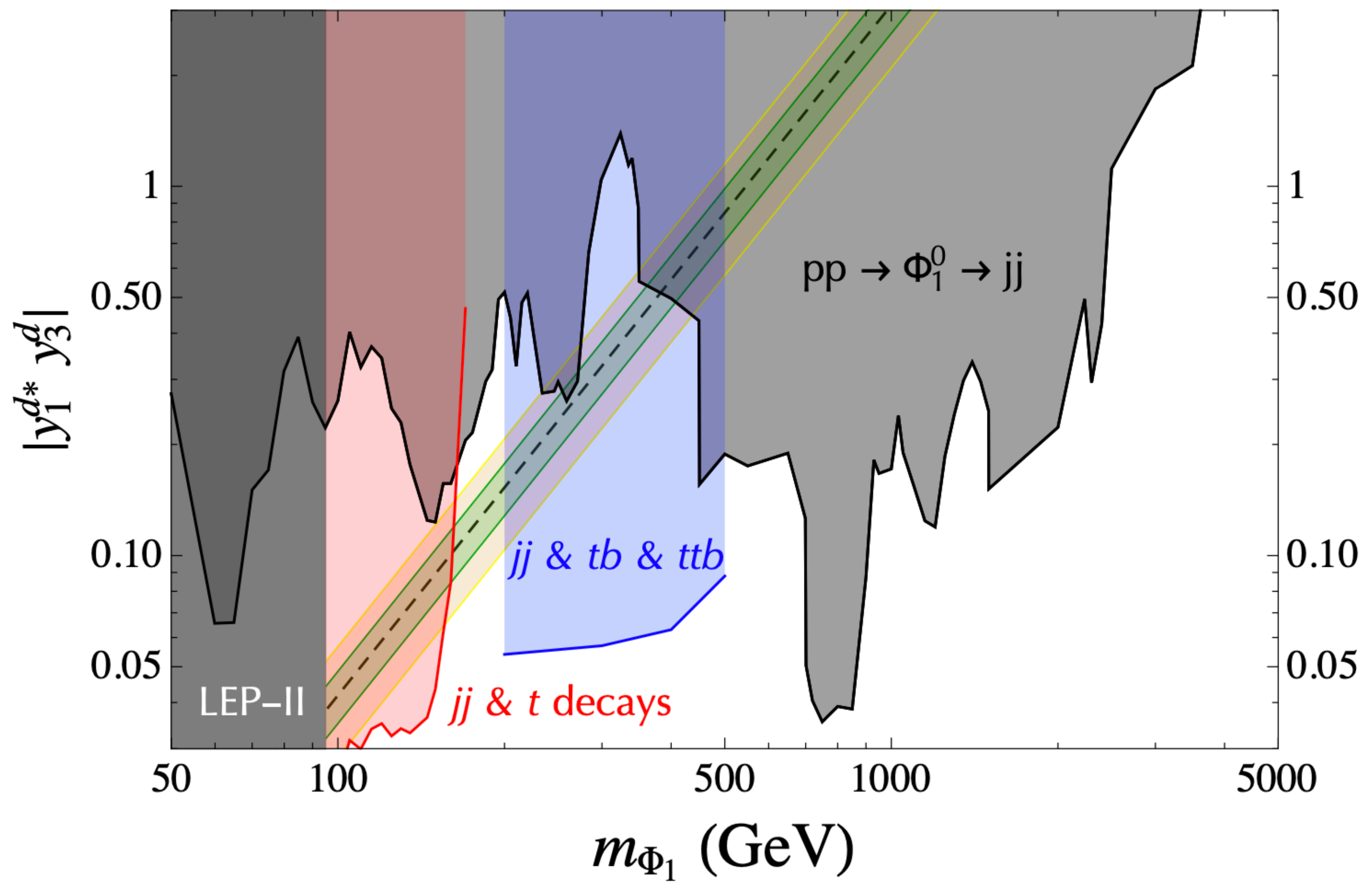
ABSTRACT: The scope of dijet resonance searches at the LHC has recently been enlarged by novel experimental techniques such as data scouting. In this work, we reinterpret ATLAS and CMS analyses to set robust constraints on all hypothetical tree-level scalar and vector mediators in the mass range between 50 and 5000 GeV, assuming a diquark or a quark-antiquark coupling with an arbitrary flavor composition. To illustrate the application of these general results, we quantify the permissible size of new physics in $\bar{B}_q \to D_q^{(*)+} \{\pi, K\}$ consistent with the absence signals in dijet resonance searches. Along the way, we perform a full SMEFT analysis of the aforementioned non-leptonic B meson decays at leading-order in α_s. Our findings uncover a pressing tension between the new physics explanations of recently reported anomalies in these decays and the dijet resonant searches. The high-p_T constraints are crucial to drain the parameter space consistent with the low-p_T flavor physics data.

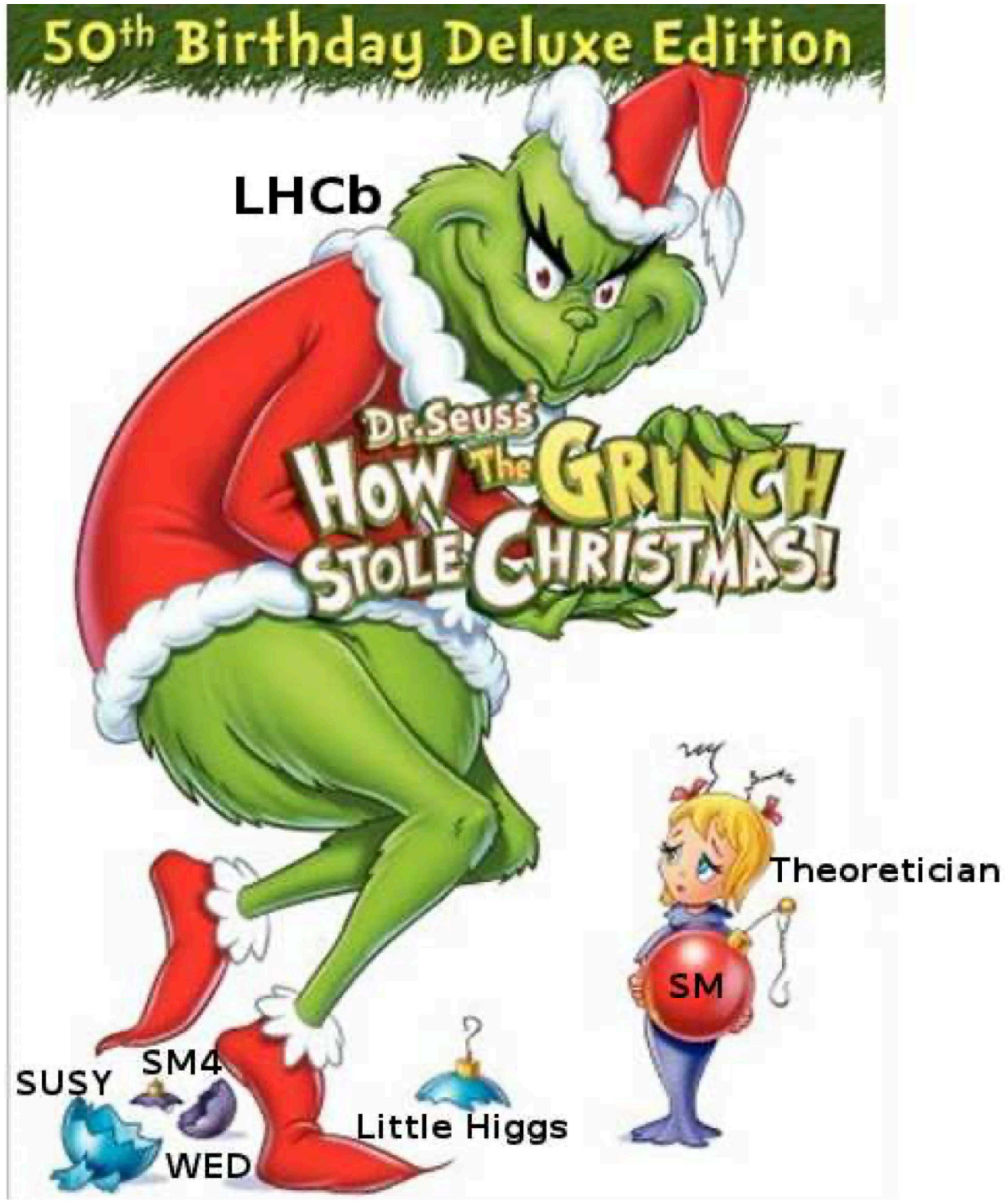
ARXIV EPRINT: 2103.XXXXX

BSM in non-leptonic tree-level Decays

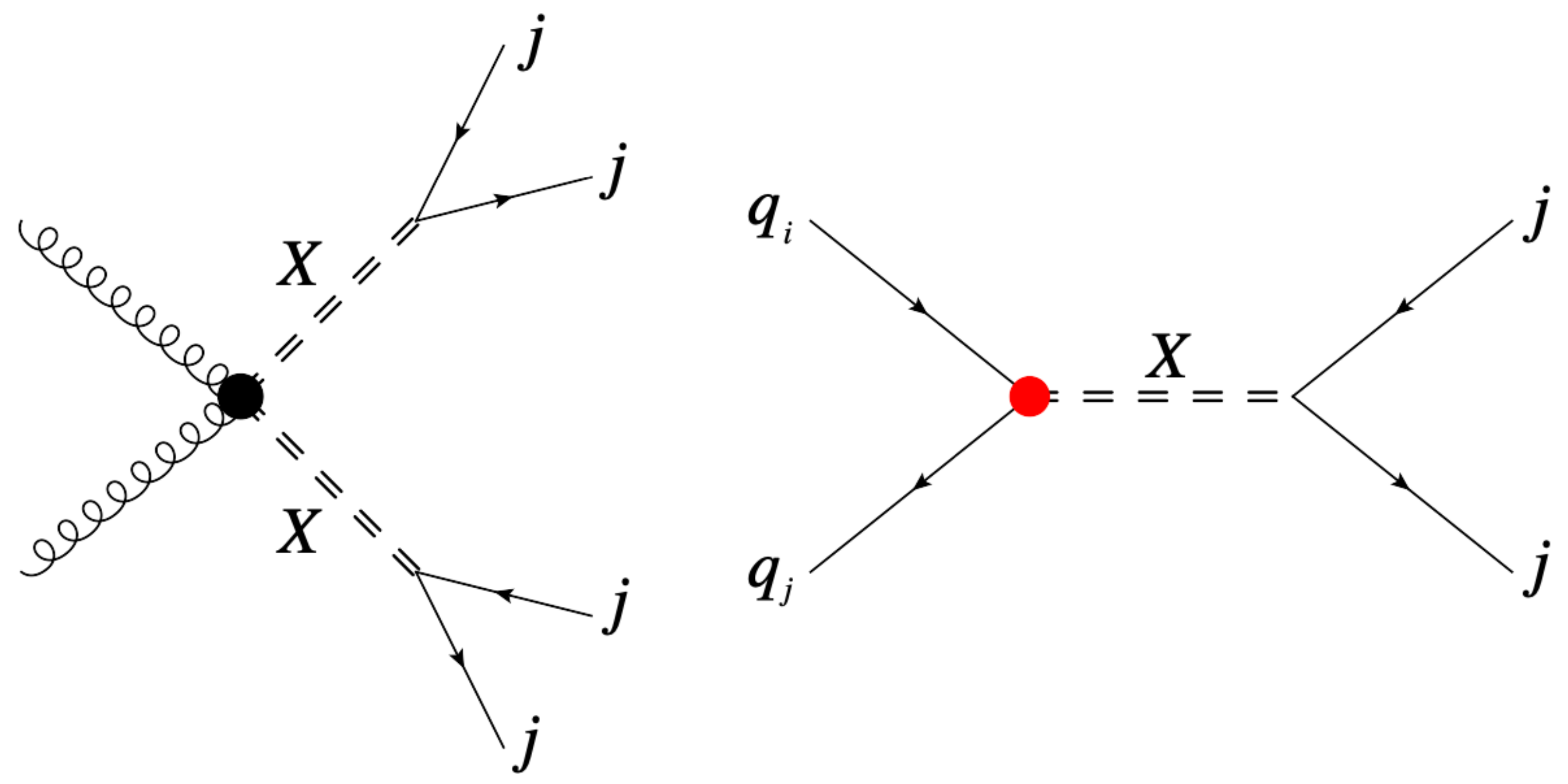


4.2 Colorless scalar doublet model $\Phi_1 = (\mathbf{1}, \mathbf{2}, 1/2)$





BSM in non-leptonic tree-level Decays



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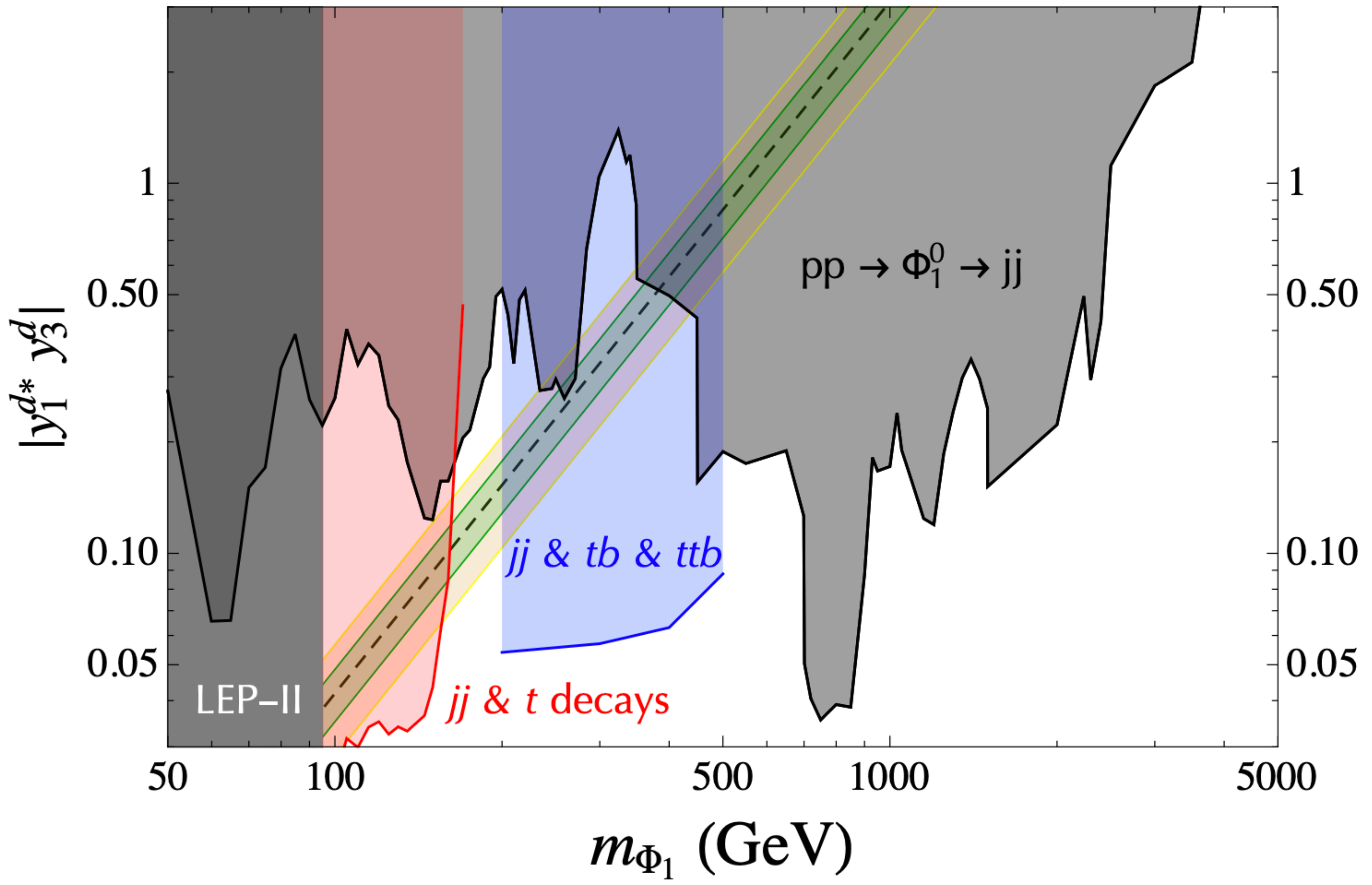

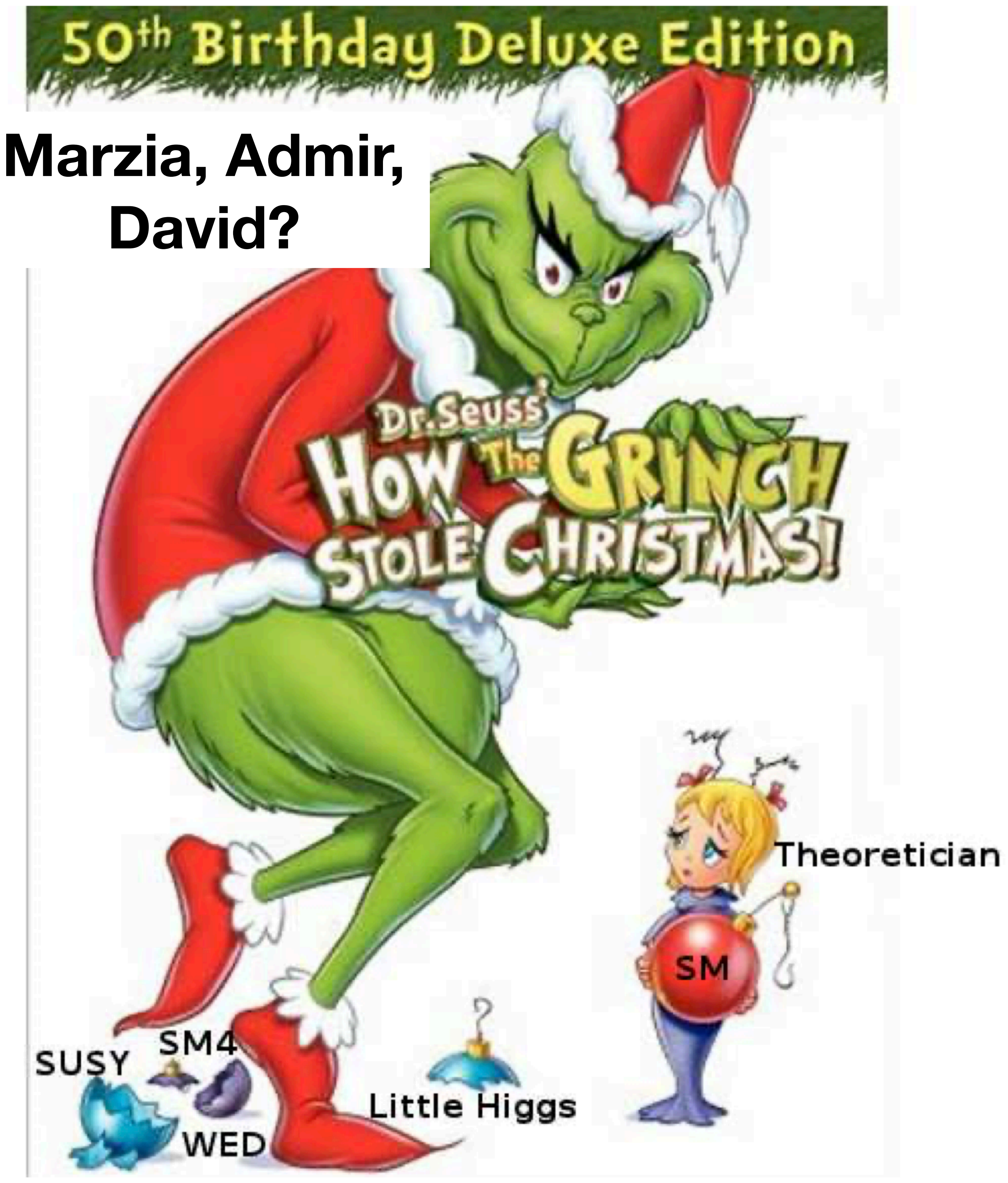

Marzia, Admir, David?

How to make it to the media?

1) Potential Improvements of estimates of power corrections

   Talks by Guido Bell and Alexander Khodjamirian

   Ideas how to further scrutinise the size of power corrections

2) Improved constraints from Flavour Physics

   Update lifetime bounds

3) To what extent is the work by Marzia, Admir and David a definite party spoiler?

   Are there any loopholes?


ALL ANOMALIES ARE EQUAL
BUT SOME ANOMALIES
ARE MORE EQUAL
THAN OTHERS