Update on (Heavy) Flavour Physics

Rencontres de Physique des Particules 2019

Aoife Bharucha
CPT Marseille

11 April 2018

Contents

- Introduction to the GDR: Intensity Frontier

  Aims, structure, workshops organised and programme 2019

- Prospects for (Semi)leptonic decays

  Update on tensions in Vub and Vcb

- Models explaining the anomalies

  Search for Leptoquark(s) explaining both charged and neutral current anomalies

- Dark sectors at LHCb and Belle II

  Latest news on searches for dark photons, scalar mediators and ALPs

The GDR-InF Community

- GDR-InF created on January 2017
- 61 senior physicists+ many students/postdocs
- 14 laboratories of IN2P3, INP, CEA
- New members welcome!

Allocated budget:
Initially 15000 euros per year
Increased to 18000 euros in 2018 and 23000 euros in 2019

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CNRS IN2P3 — Les deux infinis

LPNHE Paris

LAL — Laboratoire de l'Accélérateur Linéaire

IPHC — Institut Pluridisciplinaire Hubert Curien Strasbourg

LPC Caen — Laboratoire de physique corpusculaire

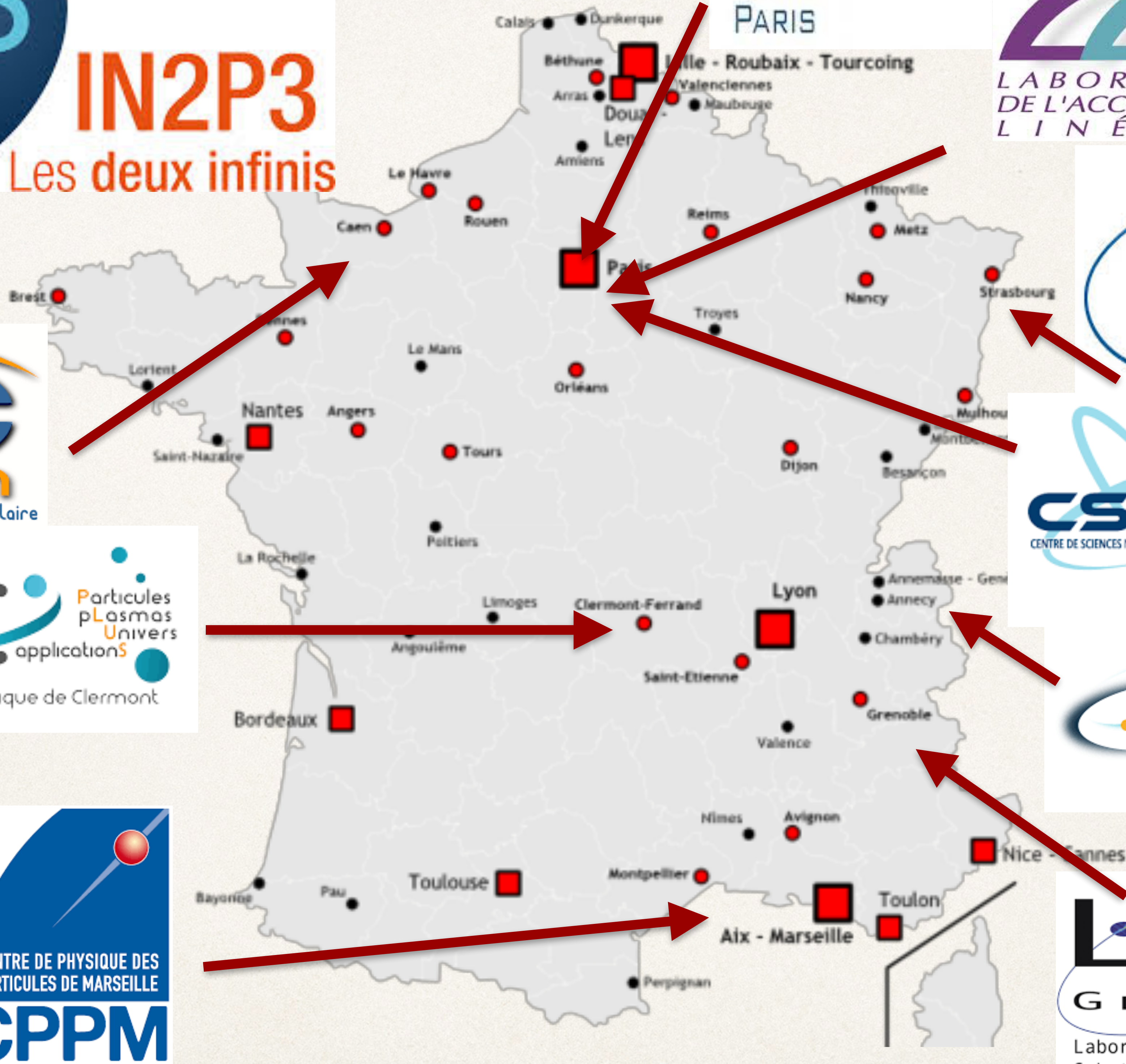
CSNSM — Centre de Sciences Nucléaires et de Sciences de la Matière

LPC — Laboratoire de Physique de Clermont

LAPP — Laboratoire d'Annecy-le-Vieux de Physique des Particules

CPPM — Centre de Physique des Particules de Marseille

LPSC Grenoble — Laboratoire de Physique Subatomique et de Cosmologie



CNRS INP

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

IPhT SACLAY

LPT Orsay

IPN ORSAY

IPNL

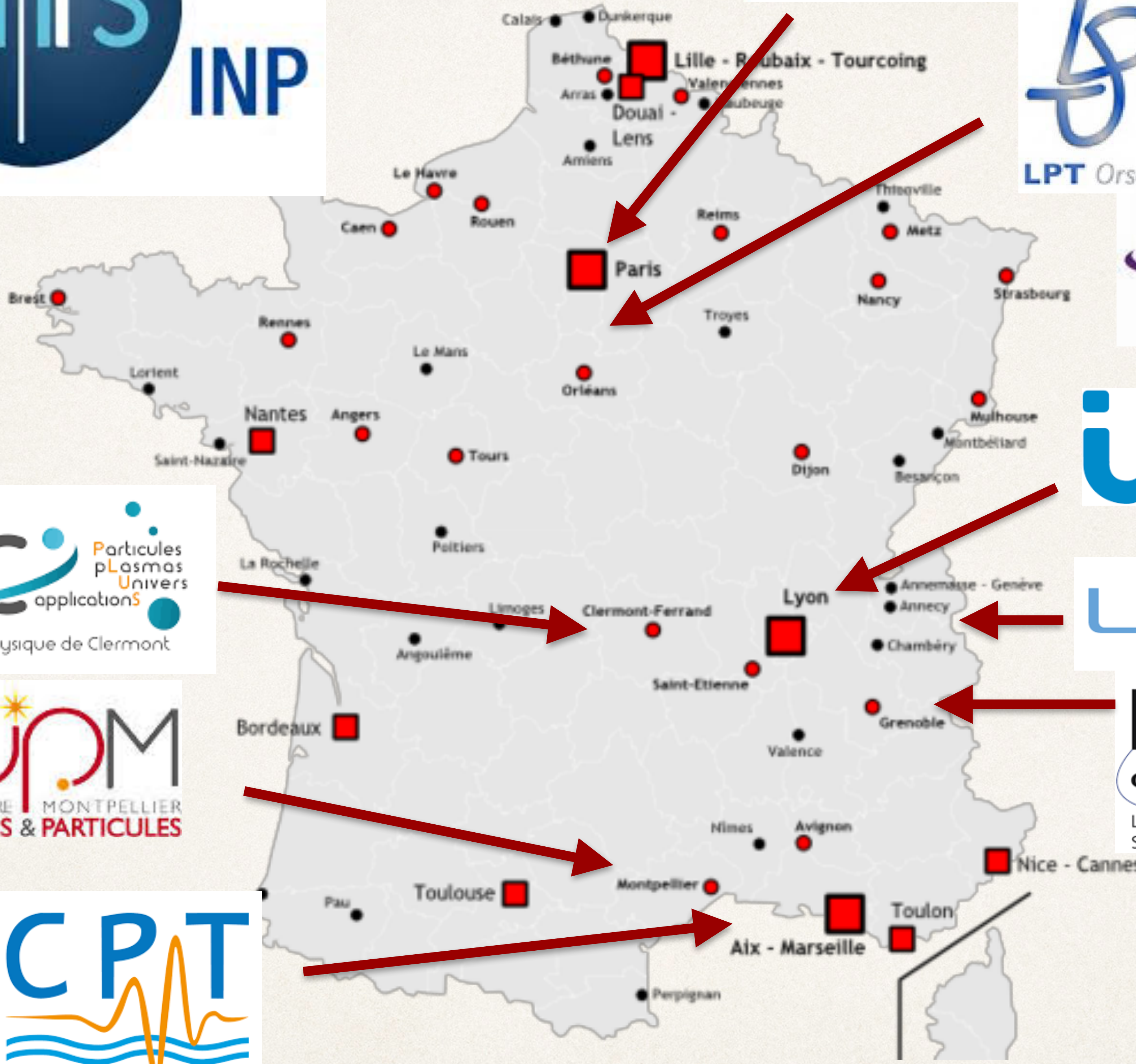
LPC
Particules pLasmas Univers applicationS
Laboratoire de Physique de Clermont

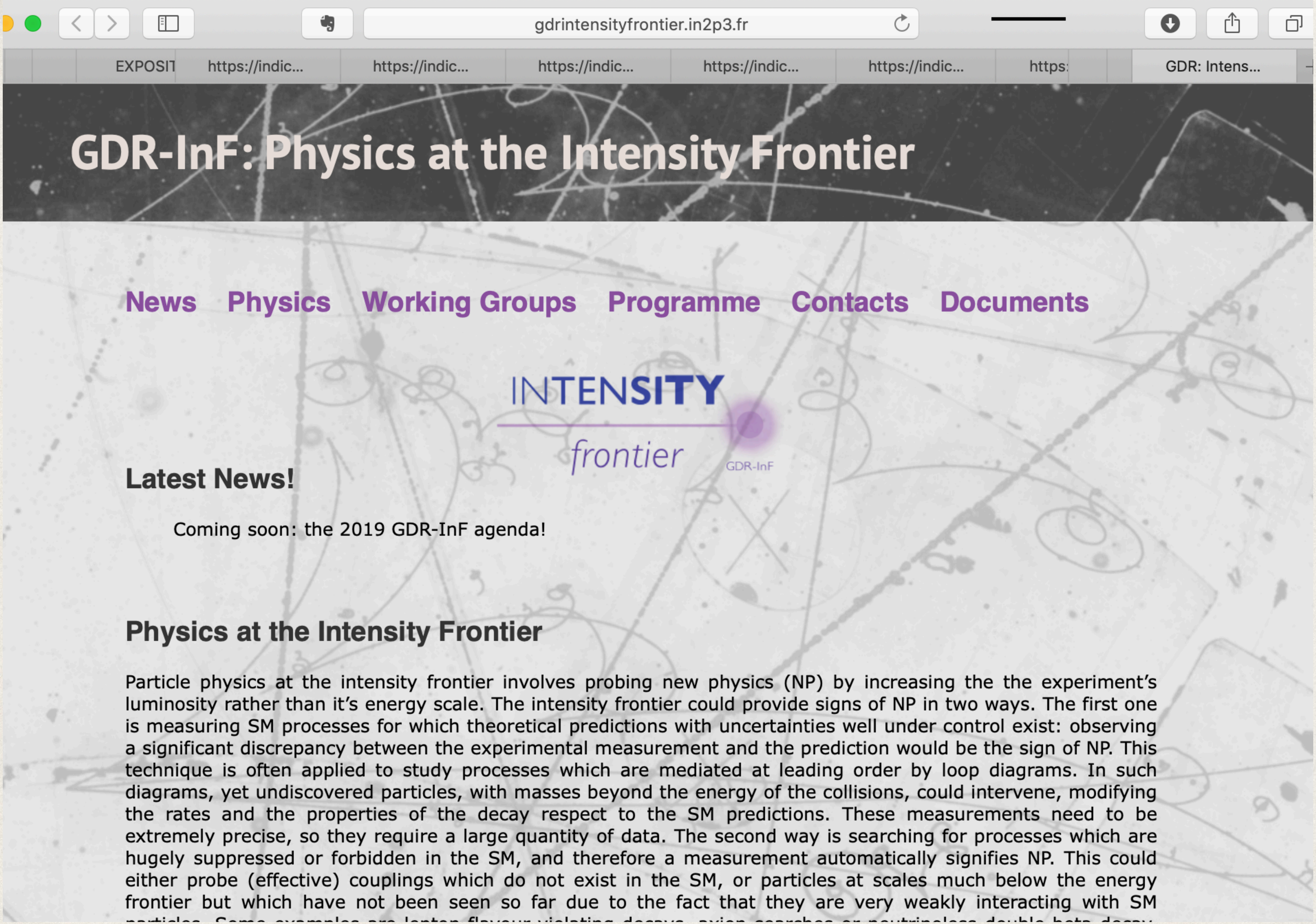
LAPTh

LPSC
Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

LUPM
LABORATOIRE MONTPELLIER UNIVERS & PARTICULES

CPT





for the latest news go to gdrintensityfrontier.in2p3.fr

Contact persons for laboratories involved

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Stephane T'Jampens (LAPP)
Diego Guadagnoli (LAPTh)
Marie-Helene Schune (LAL)
Christopher Smith (LPSC)
Sebastien Descotes-Genon (LPT)
Mark Goodsell (LPTHE)
Jérôme Charles (CPT)

Working groups/Conseil scientifique

- WG1: CP violation in fermonic processes, CKM triangle including semi-leptonic decays (Christopher Smith, Jean-Francois Marchand, Stephanie Roccia)
- WG2: Searches for new physics via neutral FCNC processes (Diego Guadagnoli, Carla Marin-Benito, Justine Serrano)
- WG3: Heavy flavour production and Spectroscopy (include heavy ion community) (Emi Kou, Michel Winn)
- WG4: Interplay of quark and lepton flavour (including all R ratios) (Ana Teixeira, Yasmine Amhis, Peter Stangl)
- WG5: Future experiments (Mark Goodsell, Stephane Monteil, Giulio Dujany)

Types of GDR Meetings

With the aim of bringing our community together via events taking non-traditional formats, we have come up with the followings types of meetings:

- Intensity lectures: Lectures on a blackboard, theory and experiment alternated, recorded, possibly published
- Intensity brainstorming: Following the model white cards + roundtable
- Topical workshops: To sit down and work on a specific subject
- Supported workshops: Not directly organized by GDR-InF, but of interest for our community
- Annual general GDR meeting: To report on the activities, present the ongoing work in our community, hear from external speakers on topics/experiments on which we are not directly implied

Keeping the door open to any other desired format!

Previous Meetings

All GDR-InF events are linked from the GDR-InF indico page.

- Novel aspects of b to s transitions: investigating new channels, St Charles Campus de l'Université Aix-Marseille (Marseille), 5-7 October 2015
- LFV/LFUV: why and how?, Institut Henri Poincaré (Paris), 7-9 November 2016
- GDR-InF Kickoff meeting: current trends in flavor physics, Institut Henri Poincaré (Paris), 29-31 March 2017
- Rencontres de Physique des Particules, CPPM (Marseille), 24-26 April 2017
- The 2nd LHCb open semitauonic workshop, LAL (Orsay), 13-15 November 2017
- Journée SHiP/Physique du secteur caché, LPNHE (Paris), 11 October 2017
- GDR-Intensity lectures: from theory to experiments and everything in between, "LF(U)V in B decays", by Martino Borsato and Diego Guadagnoli, Institut Henri Poincaré (Paris), 26-27 October 2017
- GDR-InF workshop: The future of the intensity frontier?, CERN, 1-2 February 2018
- GDR-Intensity lectures: from theory to experiments and everything in between, "LF(U)V in B decays-II", by Lucia Grillo and Diego Guadagnoli, Institut Henri Poincaré (Paris), 13-14 February 2018
- Workshop on the Strong CP puzzle and Axions, organised by Christopher Smith, Diego Guadagnoli, Guillaume Pignol, Jeremie Quevillon and Stephanie Roccia, LPSC (Grenoble), 14-16 May 2018
- Workshop on multibody charmless B-hadron decays, organised by Eli Ben-Haim and Mat Charles, LPNHE (Paris), 6-7 June 2018
- Workshop on singly and doubly charmed baryons, organised by Emi Kou, Mat Charles, Jean-Marc Richard, Patrick Robbe, Yanxi Zhang, LPNHE (Paris), 26-27 June 2018
- GDR Intensity lectures: "Vcb", by Giulia Ricciardi and Marcello Rotondo, Paris, 2-3 July 2018
- École de Gif on Heavy Flavour physics, Clermont Ferrand, 10-14 September 2018
- Annual meeting of the GDR-InF , Arles, 5-7 November 2018

Tentative programme for 2019

- Lectures on Vub, Gamma extraction from 3-body decays/Daltiz plot analyses
- 5th force workshop, ~October, Annecy as follow up to Strong CP violation workshop in Grenoble in 2018.
- QED corrections to B decays, Paris, Spring
- Workshop with neutrino GDR: Interface between lepton flavour and quark flavour
- Workshop with Terascale IRN (top/Higgs): Connection between Indirect measurements at ATLAS/CMS and LHCb/Belle II/low energy experiments
- D spectroscopy-Vcb-R(D(*)) Event on future experiments/FCC
- Annual General Meeting: Meeting to be held in November (week of the 4th).

Submitted proposal to CNRS 80 ans tour for photo exhibition in Paris, Marseille, Clermont-Ferrand, Lyon, Grenoble…

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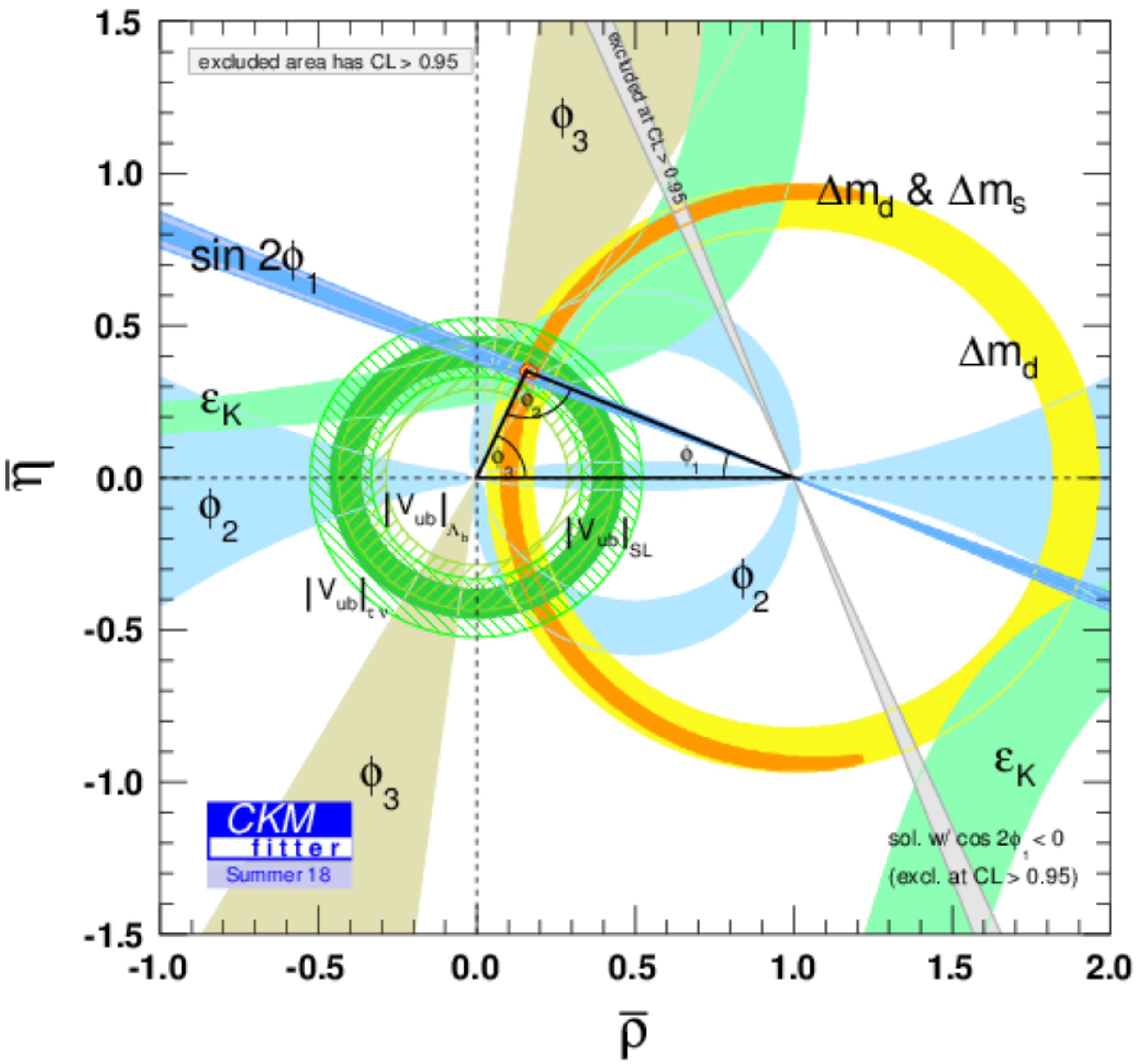
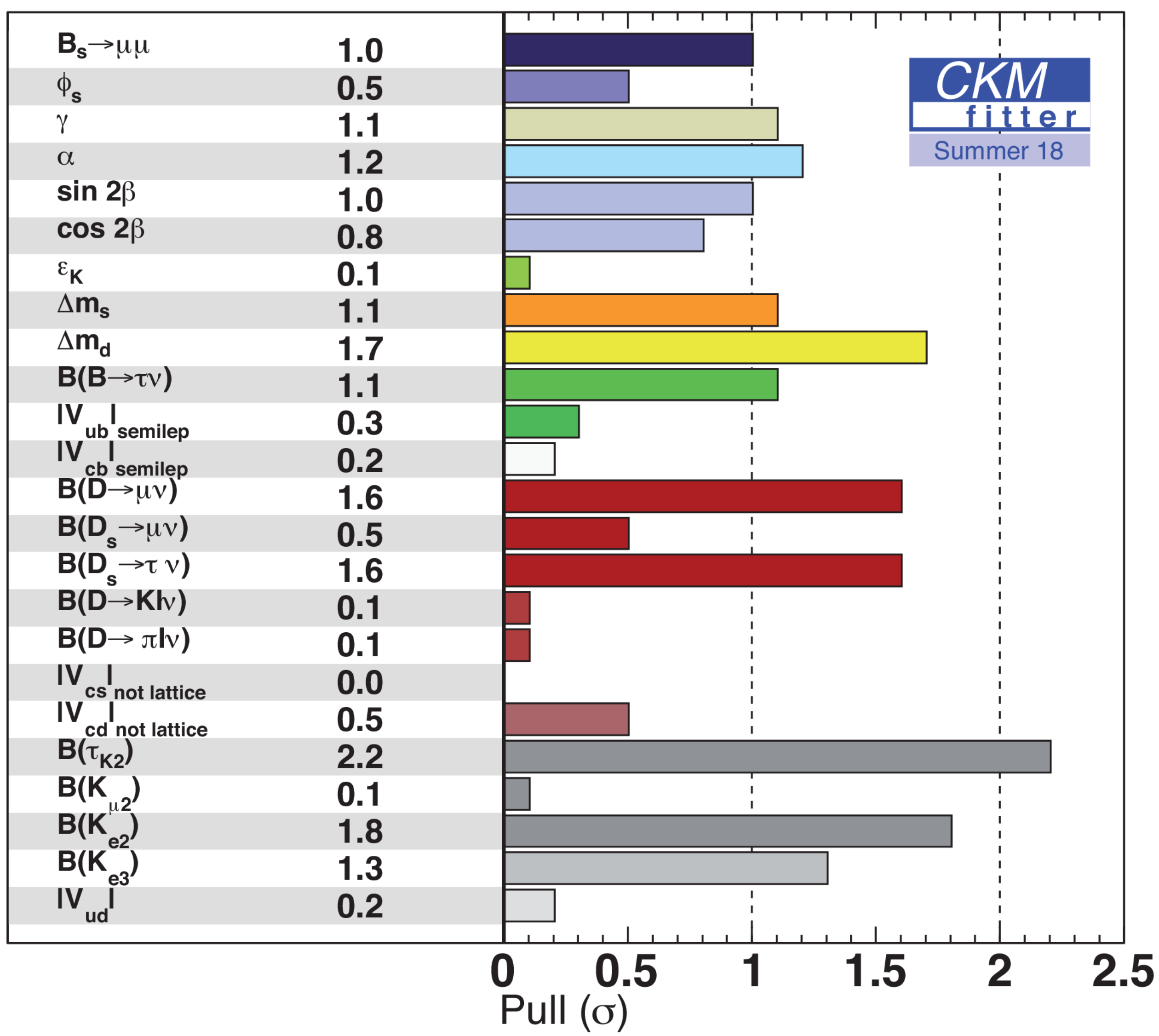
CKM Fitter results 2018





Looking closer at Vub and Vcb

- $|V_{cb}|$
  - 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

Christoph Schwanda, CKM2018

BGL vs CLN

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

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

$$g = h_V / \sqrt{m_B m_D^*}$$
$$f = \sqrt{m_B m_D^*}(1+w)\, h_{A_1}$$
$$\mathcal{F}_1 = (1+w)(m_B - m_{D^*})\sqrt{m_B m_{D^*}} A_5$$

$$f(z) = \frac{1}{P_{1+}(z)\phi_f(z)} \sum_{n=0}^{\infty} a_n^f z^n$$

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

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

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

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

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

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

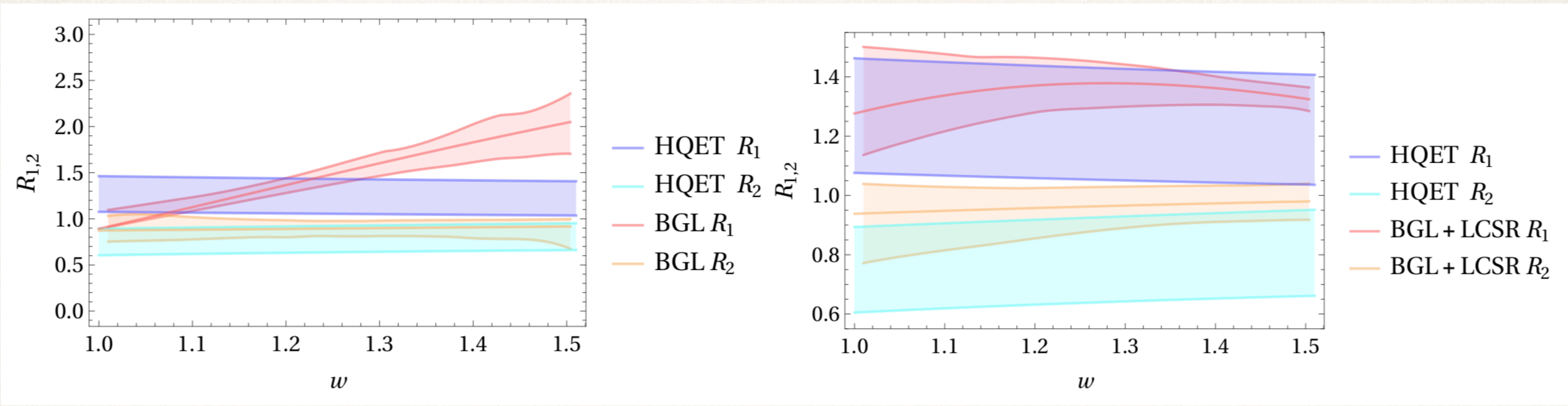
Role of HQET relations in V_{cb} extraction

(preliminary Belle data only)

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

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

Effect of HQET on R1 and R2



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

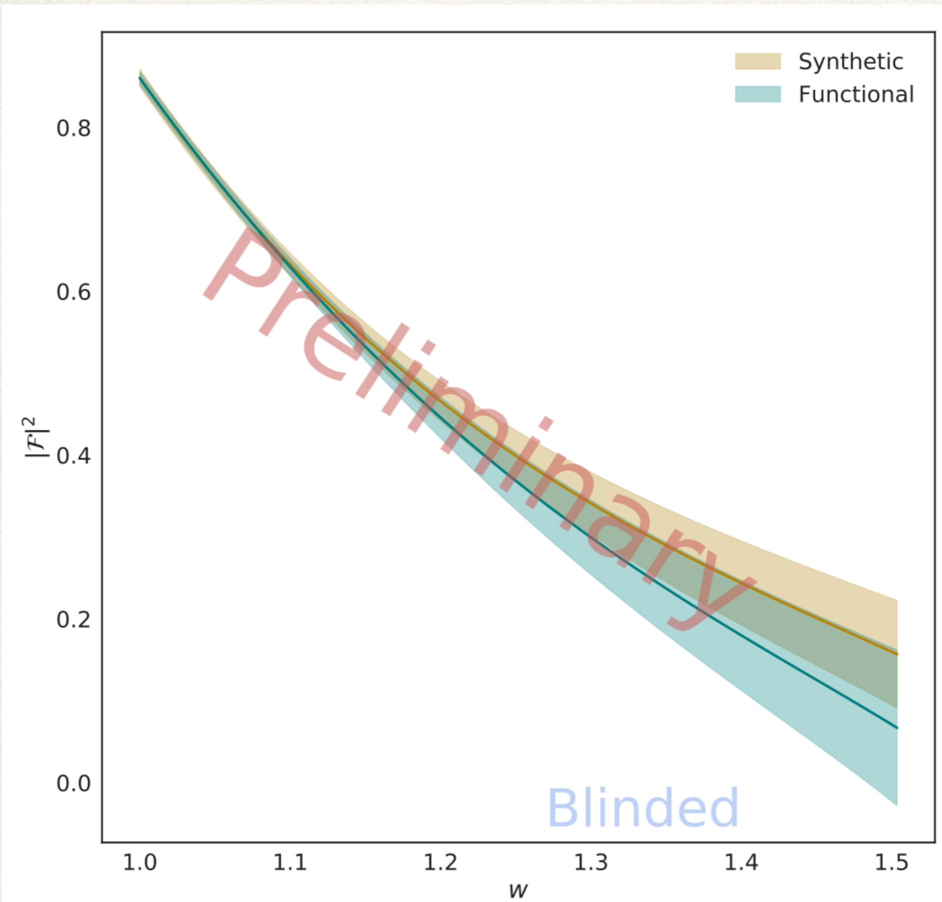
Lattice will compute A1 and R1,2 and settle the story

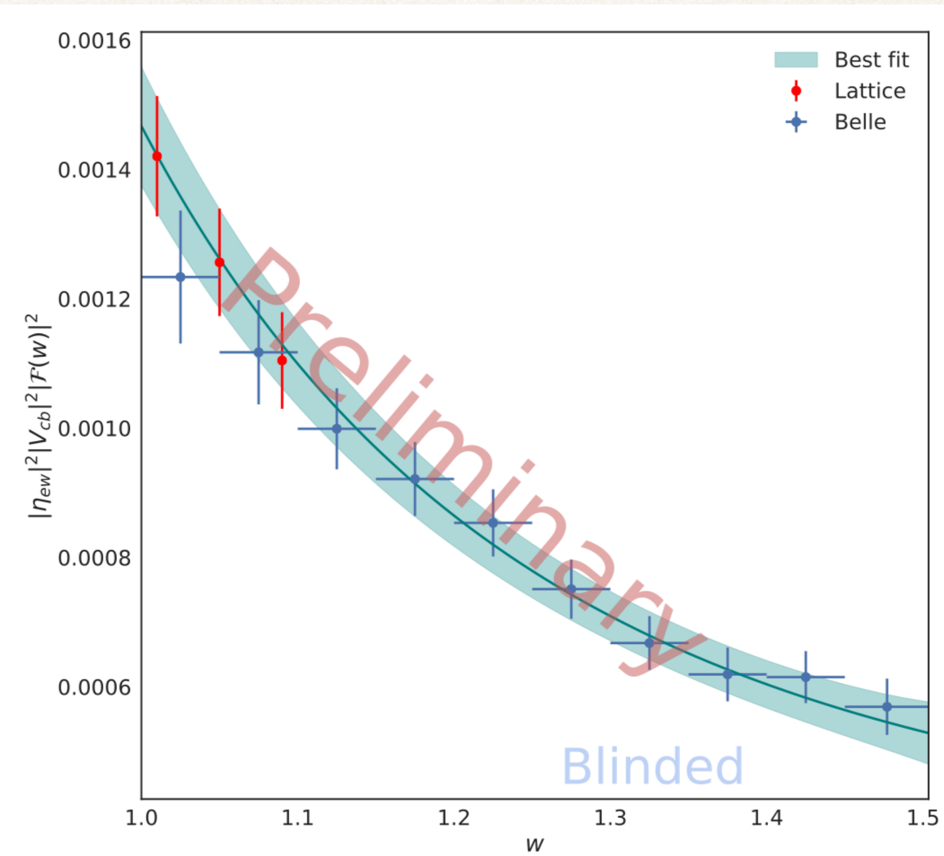
Update at CKM September 2018

Results and Outlook @Belle

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		

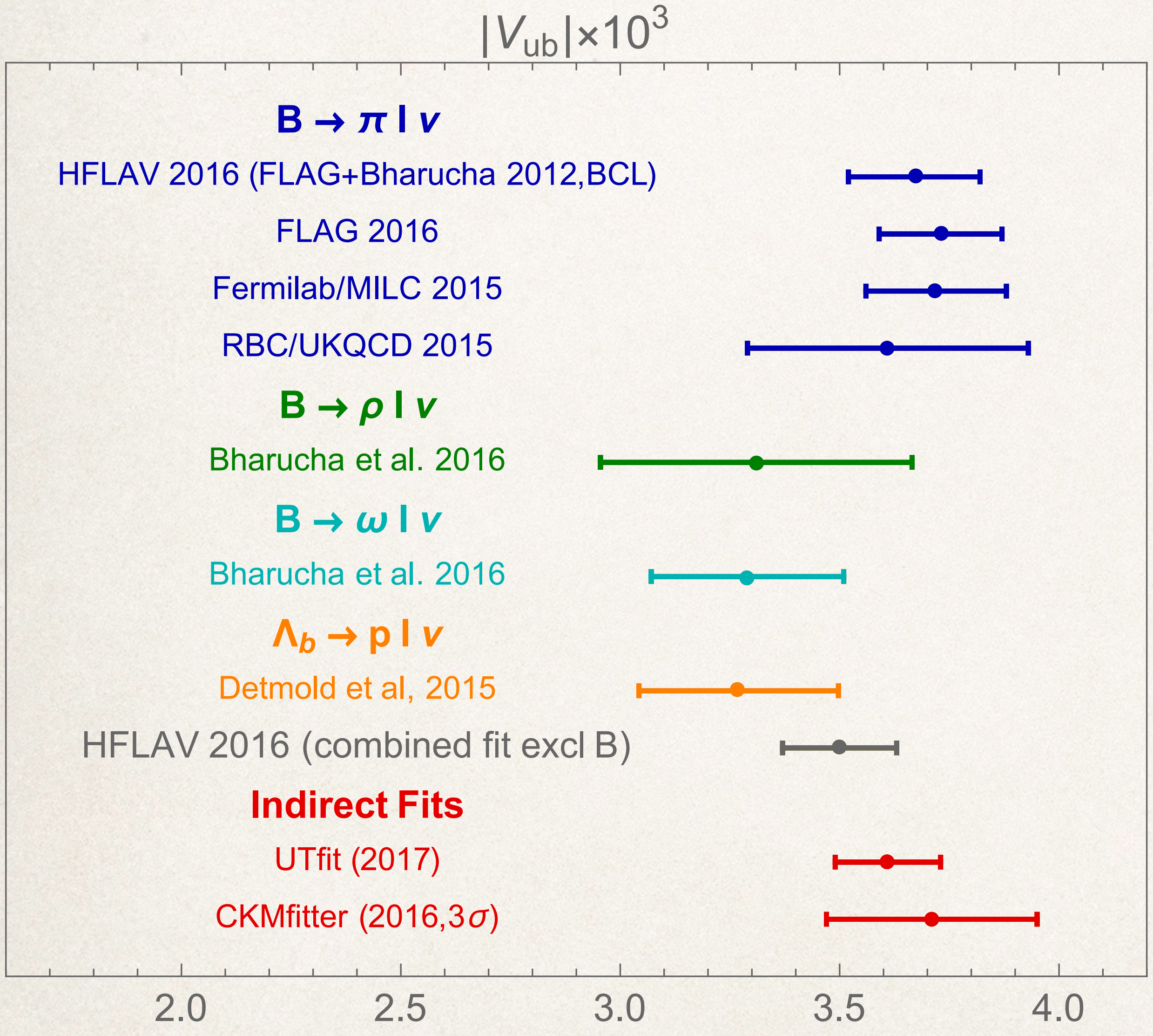
cf. current PDG: $V_{cb,\text{incl.}} = (42.2 \pm 0.8) \times 10^{-3}$





Lattice preliminary results from FermiLab/MILC presented by A. Vaquero. Results promised soon.

Summary of V_{ub} and Future Prospects



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

Summary:

2012 NNLO calculation $B \to \pi$ (AB)

2014 Bayesian uncertainty analysis for the $B \to \pi$ form factor (Imsong, Khodjamirian, Mannel van Dyk)

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

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

Future Prospects:

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

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Shaping our future(?): The anomalies

from Peter Stangl's talk, GDR Annual Meeting, Arles 2018

Neutral Current:

Anomalies observed in:

Angular obs. $P5'$ in $B \to K^*\mu^+\mu^-$

LHCb,arXiv:1512.04442 [?]

BRs of $B \to K\,\mu^+\mu^-$, $B \to K^*\mu^+\mu^-$ and $B_s \to \varphi\mu^+\mu^-$

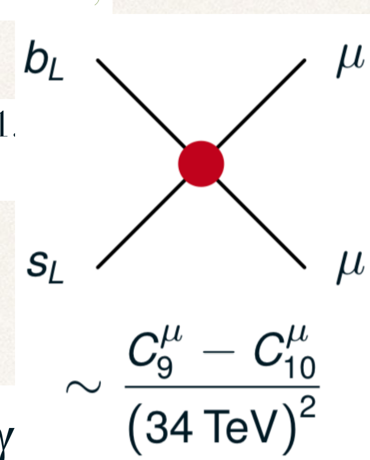
LHCb, arXiv:1403.8044, arXiv:1506.08777, arXiv:1606.04731, LHCb,arXiv:1406.6482 LHCb, arXiv:1705.05802

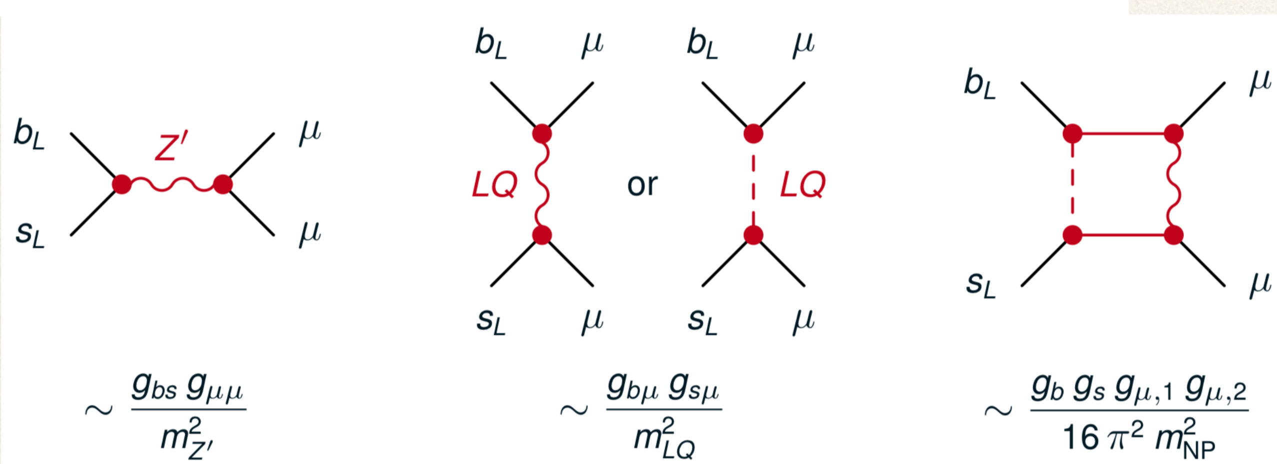
[?] LFU ratios $R_K^{[1,6]}$ and $R_{K^*}^{[0.045,1.1]}$ and [1.

Global fits suggest

$C_9^\mu - C_{10}^\mu \approx -1.3$, $0 > C_{10}^\mu / C_9^\mu > -1$

$O_9^\mu = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu\mu)$, $O_{10}^\mu = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu\gamma$





Charged Current:

Hints for LFU violation observed in :

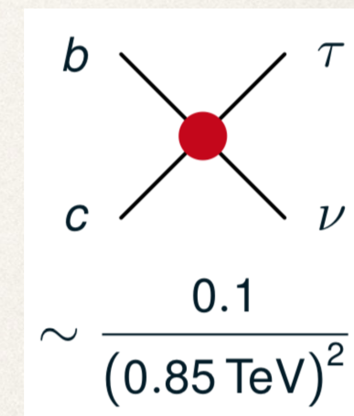
[?]LFU ratios R_D and R_{D^*}

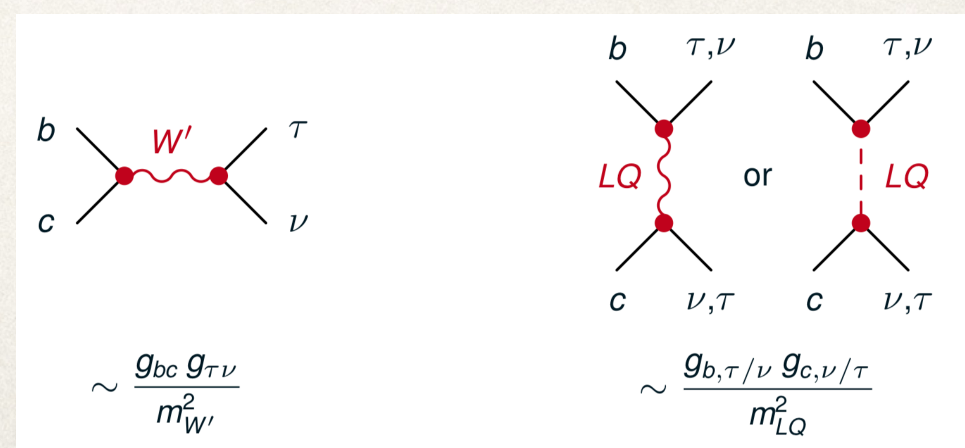
BaBar, arXiv:1205.5442, arXiv:1303.0571 LHCb, arXiv:1506.08614, arXiv:1708.08856 Belle, arXiv:1507.03233, arXiv:1607.07923, arXiv:1612.00529

Global fits suggest [?] [?]

$C_V^\tau \approx 0.1$, where

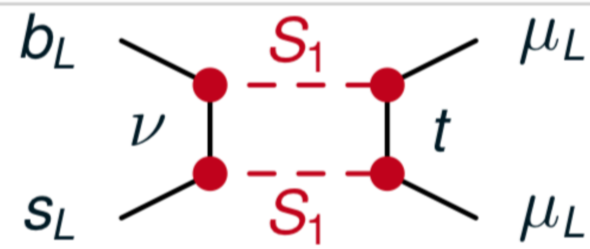
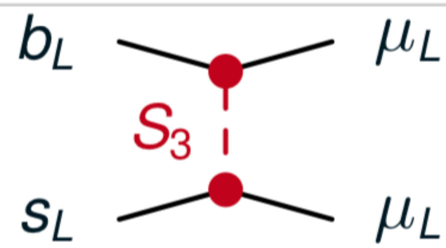
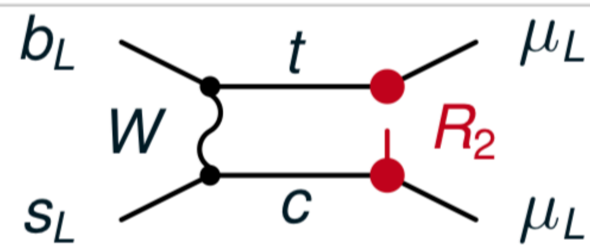
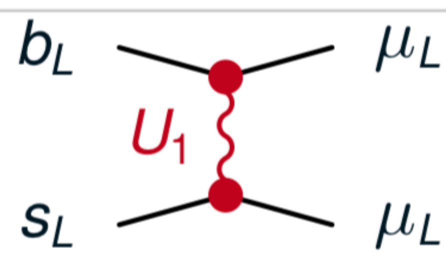
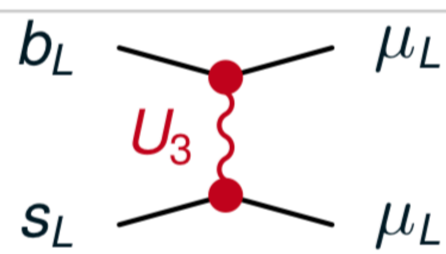
$O_V^\tau = (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$





LQ solutions for b to sll

cf. Angelescu, Becirevic, Faroughy, Sumensari, arXiv:1808.08179

Spin	G_{SM}	Name	Characteristic process	$R_{K^{(*)}}$	
0	$(\bar{3}, 1)_{1/3}$	S_1		✓X	requires very large couplings Bauer, Neubert, arXiv:1511.01900
0	$(\bar{3}, 3)_{1/3}$	S_3		✓	Hiller, Schmaltz, arXiv:1408.1627
0	$(3, 2)_{7/6}$	R_2		X	tension with LHC limits Becirevic et al arXiv:1704.05835
1	$(3, 1)_{2/3}$	U_1		✓	Barbieri et al., arXiv:1512.01560
1	$(3, 3)_{2/3}$	U_3		✓	Fajfer, Košnik, arXiv:1511.06024

LQ solutions for R_D and R_{D^*}

Spin	G_{SM}	Name	$R_{D^{(*)}}$	
0	$(\bar{3}, 1)_{1/3}$	S_1	✓	
0	$(\bar{3}, 3)_{1/3}$	S_3	X	wrong sign of contribution to $R_{D^{(*)}}$
0	$(3, 2)_{7/6}$	R_2	✓	
1	$(3, 1)_{2/3}$	U_1	✓	
1	$(3, 3)_{2/3}$	U_3	X	wrong sign of contribution to $R_{D^{(*)}}$

cf. Angelescu, Bečirević, Faroughy, Sumensari, arXiv:1808.08179

Combined explanations

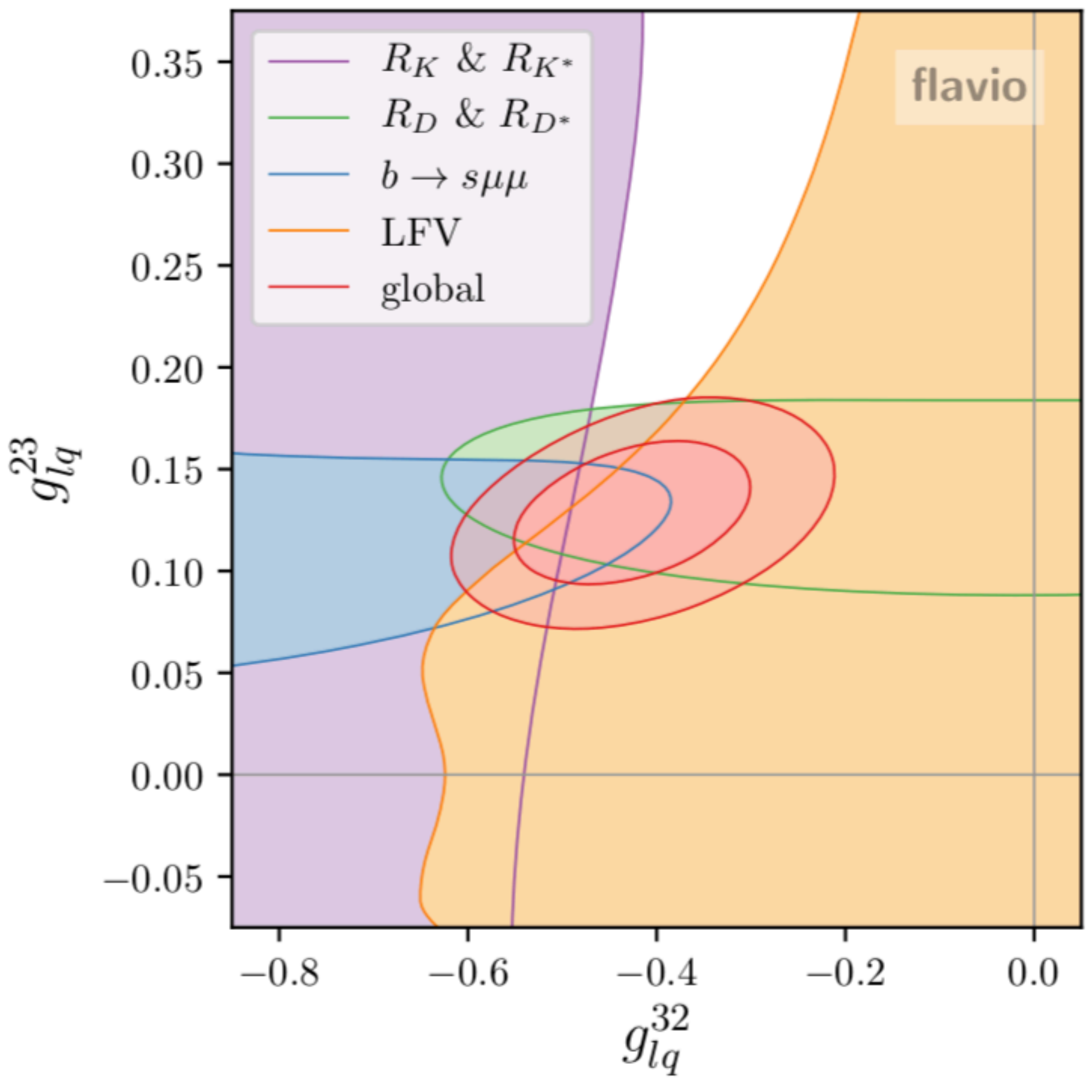
- Single mediator solution

Spin	G_{SM}	Name	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
0	$(\bar{3}, 1)_{1/3}$	S_1	✓✗	✓	✓✗
0	$(\bar{3}, 3)_{1/3}$	S_3	✓	✗	✗
0	$(3, 2)_{7/6}$	R_2	✗	✓	✗
1	$(3, 1)_{2/3}$	U_1	✓	✓	✓
1	$(3, 3)_{2/3}$	U_3	✓	✗	✗

cf. Angelescu, Bečirević, Faroughy, Sumensari, arXiv:1808.08179

- More complicated constructions possible
  - Combination of S_1 and S_3 e.g. Crivellin, Müller, Ota, arXiv:1703.09226; Marzocca, arXiv:1803.10972
  - ...

Vector U_1 solution to B-anomalies



Aebischer, Kumar, PS, Straub, arXiv:1810.07698

- Only truly viable single mediator solution
- Does not generate $B \to K\nu\nu$ at tree level

  Buras, Girrbach-Noe, Niehoff, Straub, arXiv:1409.4557
- Couplings:

$$\mathcal{L}_{U_1} \supset g_{lq}^{ij} \left(\bar{l}_L^i \gamma^\mu q_L^j\right) U_\mu + \text{h.c.}$$

  - $b \to s\mu\mu$ requires $g_{lq}^{22} g_{lq}^{23*}$
  - $b \to c\tau\nu$ requires $g_{lq}^{32} g_{lq}^{33*}$
  - $\tau \to \phi\mu$ constrains $g_{lq}^{32} g_{lq}^{22*}$

$$m_{U_1} = 1\,\text{TeV} \quad g_{lq}^{33} = 1 \quad g_{lq}^{22} = 0.04^2 \approx V_{cb}^2$$

▸ *Speculations on UV completions*

Two main approaches

Non-perturbative TeV-scale dynamics
[*non-renormalizable models*]

- Scalar LQ as PNG

  Gripaios, '10
  Gripaios, Nardecchia, Renner, '14
  Marzocca '18

- Vector LQ (or W',Z') as techni-fermion resonances

  Barbieri *et al.* '15, Buttazzo *et al.* '16
  Barbieri, Murphy, Senia, '17
  Blanke, Crivellin, '17

- W', Z' as Kaluza-Klein excitations [*e.g. from warped extra dim.*]

  Megias, Quiros, Salas '17
  Megias, Panico, Pujolas, Quiros '17

Perturbative TeV-scale dynamics
[*renormalizable models*]

- Renormalizable models with scalar mediators [*LQ, but also RPV-SUSY*]

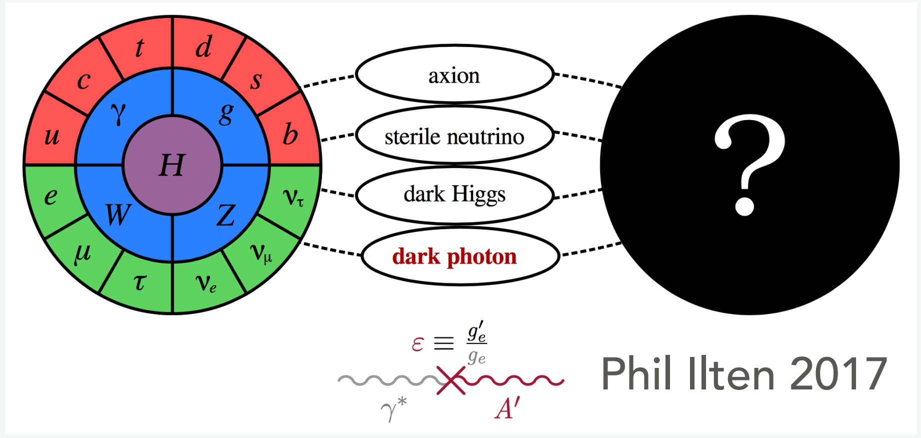
  Hiller & Schmaltz, '14
  Becirevic *et al.* '16, Fajfer *et al.* '15-'17
  Dorsner *et al.* '17
  Crivellin, Muller, Ota '17
  Altmannshofer, Dev, Soni, '17
  Becirevic *et al.* '18 + ...

- Gauge models

  Cline, Camalich '17
  Calibbi, Crivellin, Li, '17
  Assad, Fornal, Grinstein, '17
  Di Luzio, Greljo, Nardecchia, '17
  Bordone, Cornella, Fuentes-Martin, GI, '17

Dark Sector@LHCb

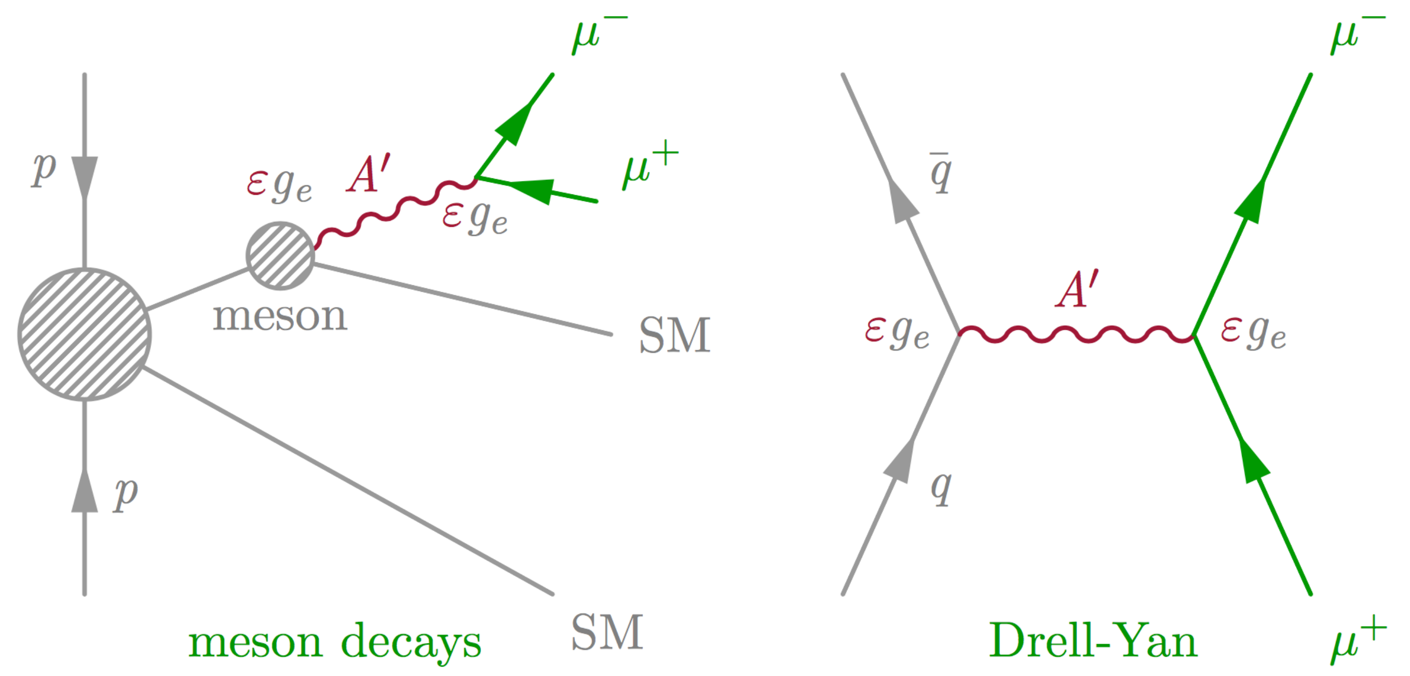
See Carlos Vazquez Sierra's talk, Franco-Italian B physics workshop Marseille 2018



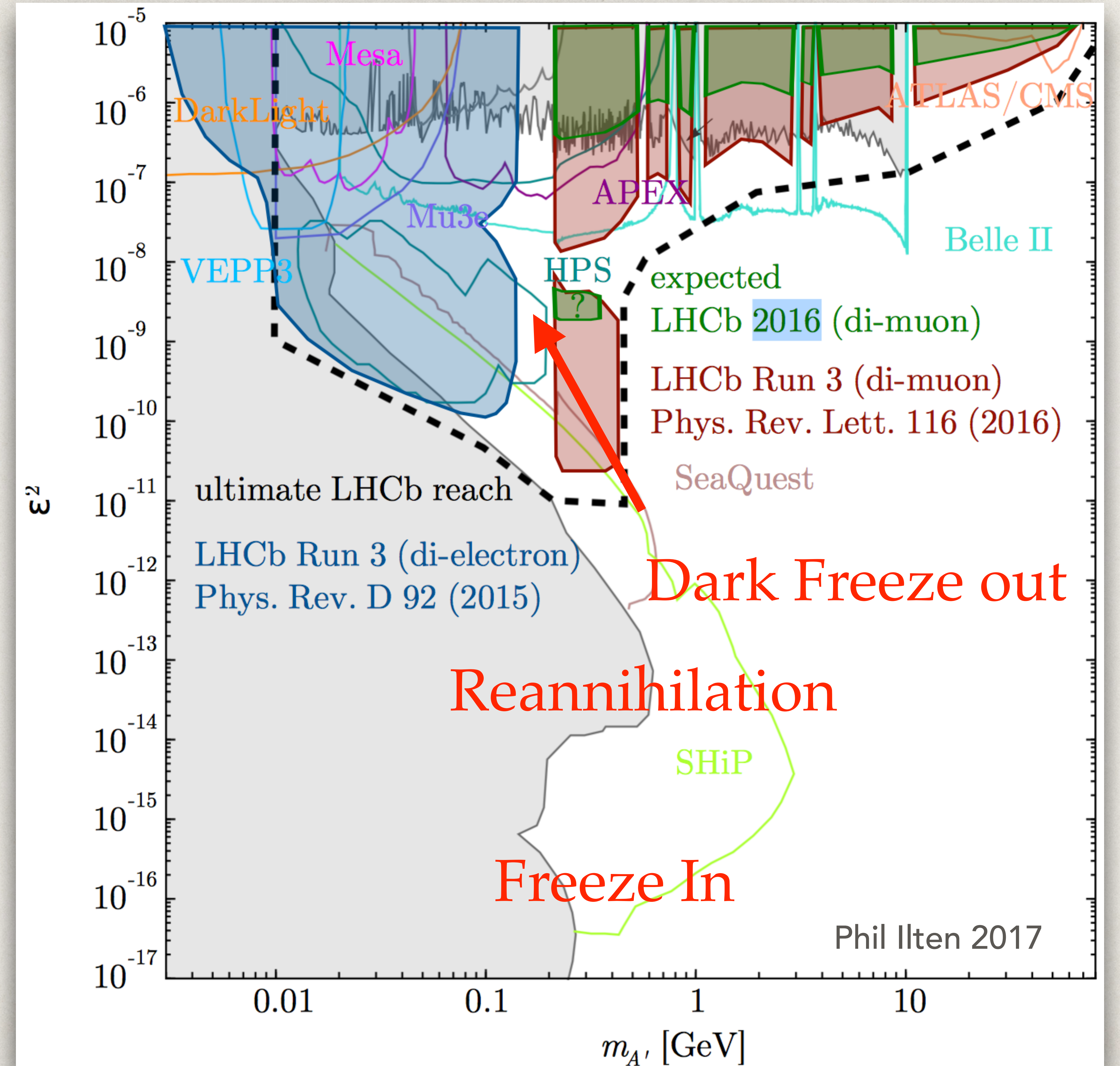
Ilten, (Soreq), Thaler, Williams and Xue, arXiv:1603.08926, arXiv:1509.06765

Dark photon searches proposed using inclusive di-muon production and $D^{*0} \to D^0 e^+e^-$

Prompt and displaced searches to be performed simultaneously, covering large region of parameter space with the full Run 3 LHCb dataset.



D^{*0} search (requires Run 3 triggers) will cover dark photon masses from the $2m_e$ to 1.9 GeV, and inclusive di-muon (possible with Run 2) above $2m_\mu$.



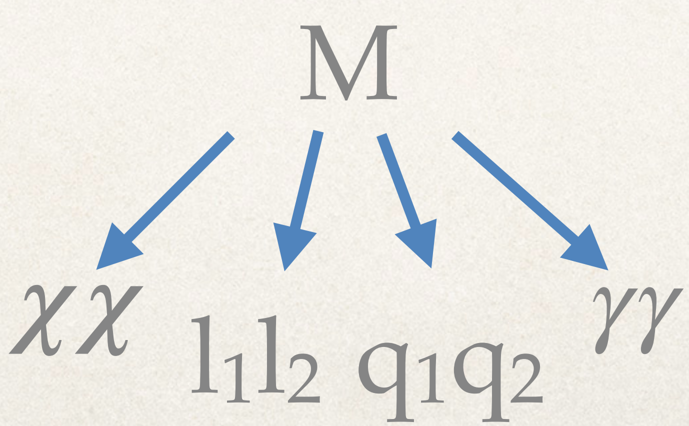
Mesa
DarkLight
APEX
Mu3e
ATLAS/CMS
Belle II
VEPP3
HPS
?
expected
LHCb 2016 (di-muon)
LHCb Run 3 (di-muon)
Phys. Rev. Lett. 116 (2016)
SeaQuest
ultimate LHCb reach
LHCb Run 3 (di-electron)
Phys. Rev. D 92 (2015)
Dark Freeze out
Reannihilation
SHiP
Freeze In
Phil Ilten 2017
ε²
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
0.01
0.1
1
10
m_A' [GeV]

Production and decay modes at B factories

Three fundamentally different ways to produce light mediators (M):

- Non-resonant annihilation of an electron-positron pair: $\mathbf{e^+e^- \rightarrow M + X}$
- Resonant production from tree-level decay, e.g. $\mathbf{e^+e^- \rightarrow \Upsilon(nS) \rightarrow M+X}$.
- Resonant production from loop-level rare decay, e.g. $\mathbf{e^+e^- \rightarrow B+X \rightarrow K+M+X}$.

Once produced, the mediator can have four different types of decays:

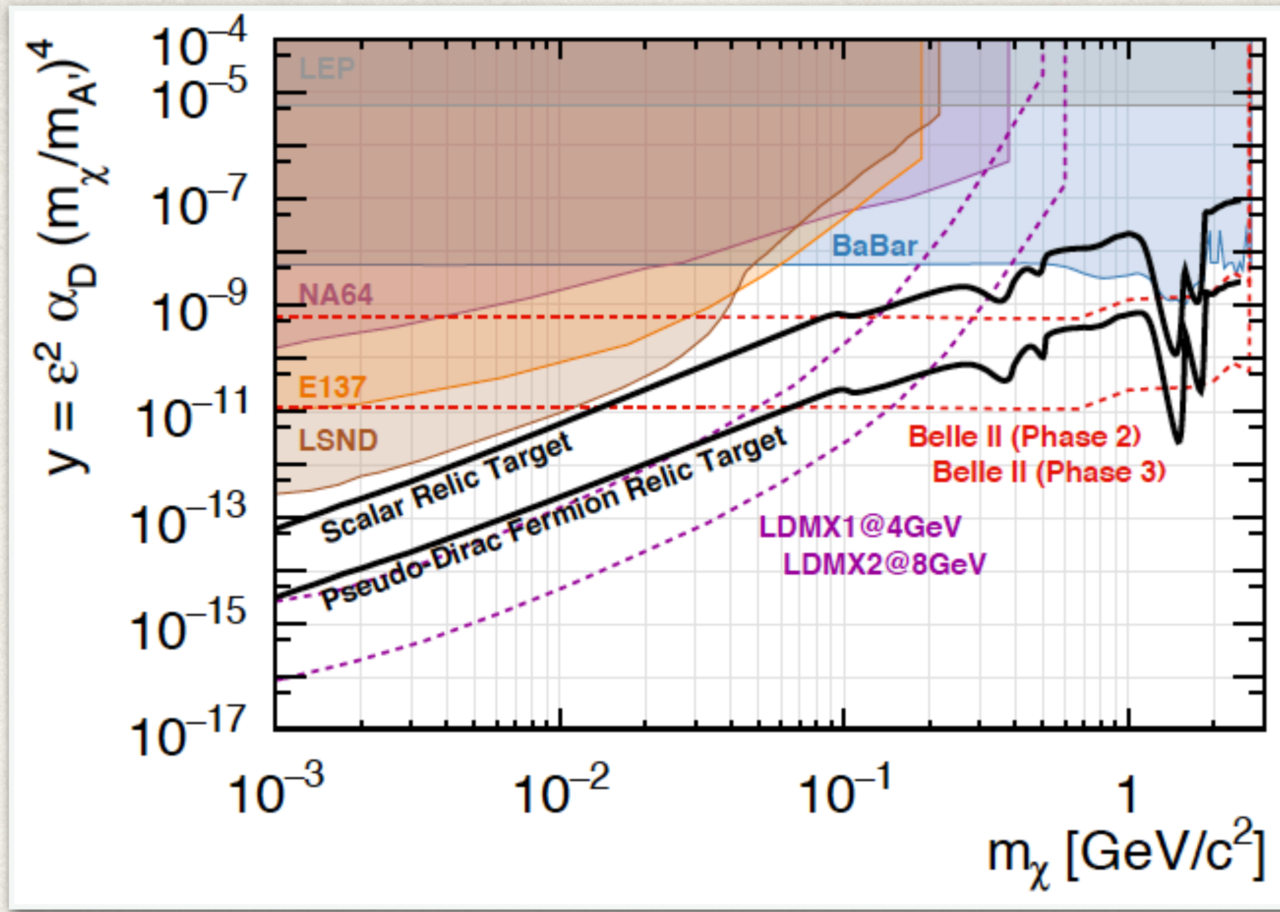


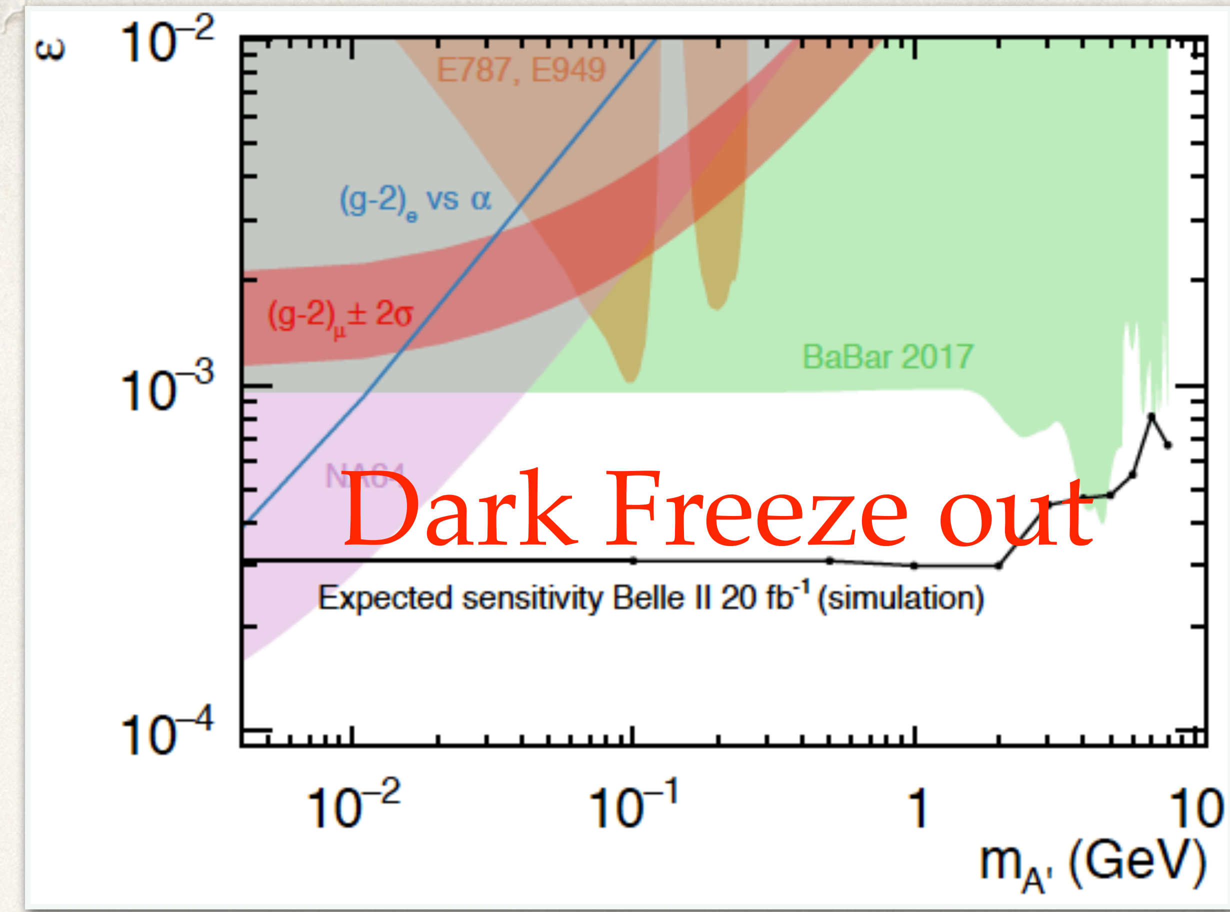
Promising search channels at Belle II

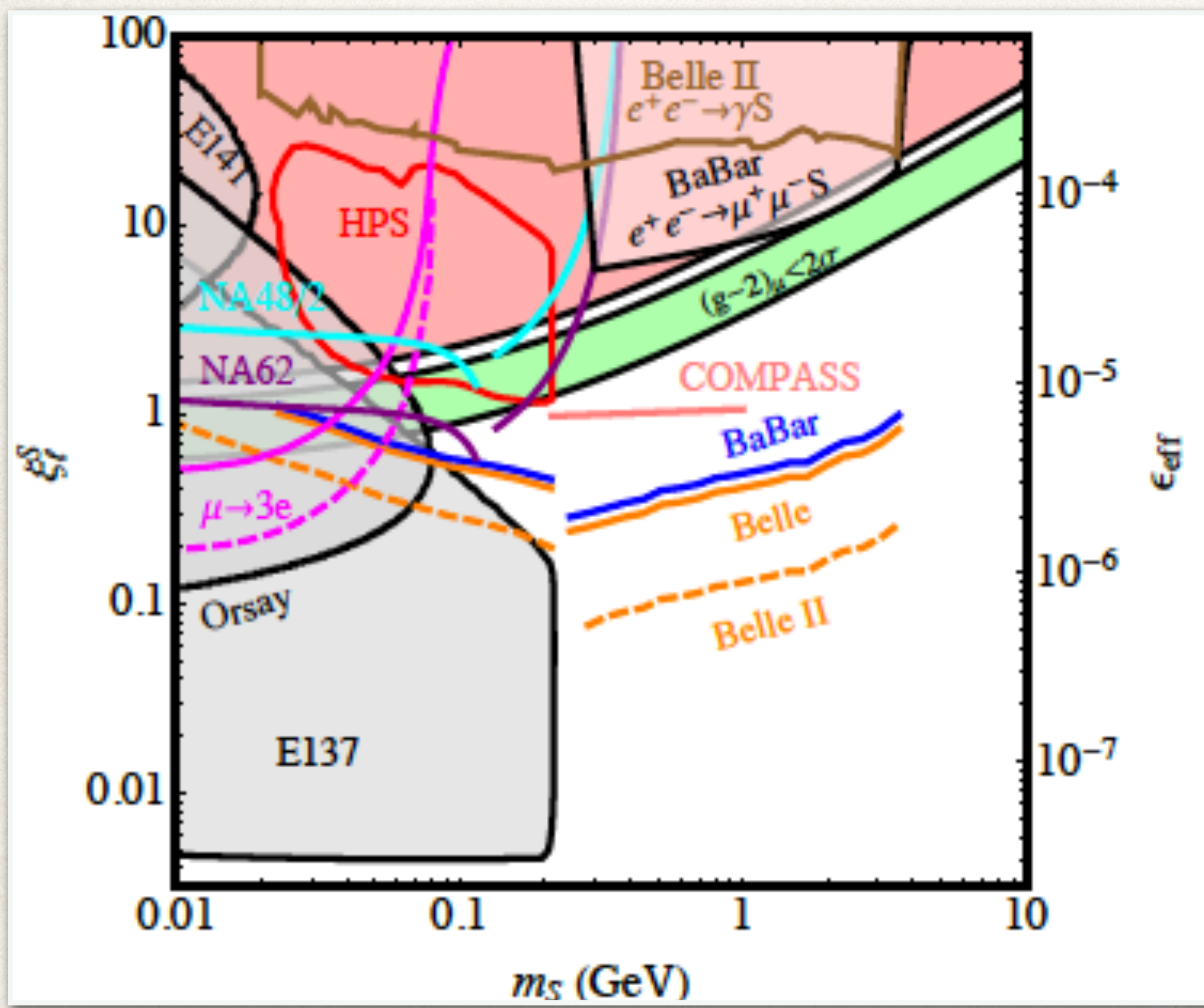
For more information see Belle II physics book.

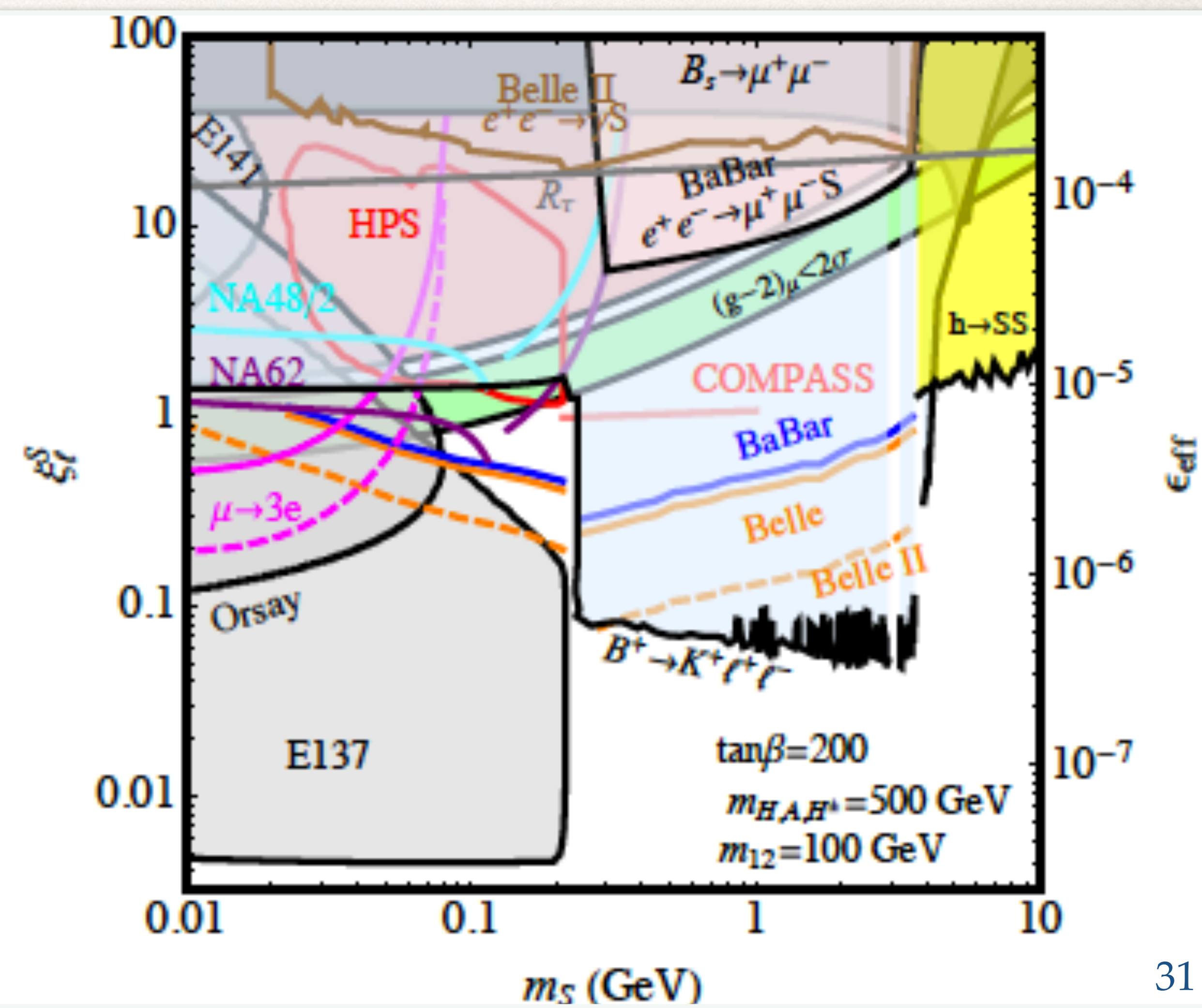
- **$e^+e^- \to M + X$:**
  - Relies on e-coupling, best for vector, if pseudoscalar via alpsstrahlung $e^+e^- \to \gamma^* \to \gamma M$, or photon fusion $e^+e^- \to M + e^+e^- \to \gamma\gamma + e^+e^-$). or $e^+e^- \to \gamma^* \to \tau\tau \to M + \tau\tau$,
  - If invisible, γ needed for triggering ($e^+e^- \to M + \gamma$), if leptonic, γ can also help enhance trigger acceptance (Displaced vertices also possible.)
- **$e^+e^- \to \Upsilon(2S/3S) \to \Upsilon(1S) + \pi\pi \to M + \gamma + \pi\pi$:**
  - For spin-0 or axial-vector mediators $\Upsilon(1S) \to M\gamma$, (bump in photon spectrum). $M \to \ell\ell$, leptonic invariant mass shows peak.
  - $\tau\tau$, gg, hh final states also possible. Triggering on $\pi\pi$ allows $M \to$inv, even if γ off shell.
- **$e^+e^- \to B + X \to K + M + X$:**
  - $M \to$inv (like B to K$\nu\nu$ but diff. K distribution), $\gamma\gamma$ (good for pseudo-scalar with mass near $2m_\mu$) or $\mu\mu$ (strongest limit for spin-0).
  - Displaced vertices can also be identified.

See Laura Zani's talk, Franco-Italian B physics workshop Marseille 2018


LEP
NA64
E137
LSND
BaBar
Scalar Relic Target
Pseudo-Dirac Fermion Relic Target
Belle II (Phase 2)
Belle II (Phase 3)
LDMX1@4GeV
LDMX2@8GeV
$y = \varepsilon^2 \alpha_D (m_\chi/m_{A'})^4$
m_χ [GeV/c^2]

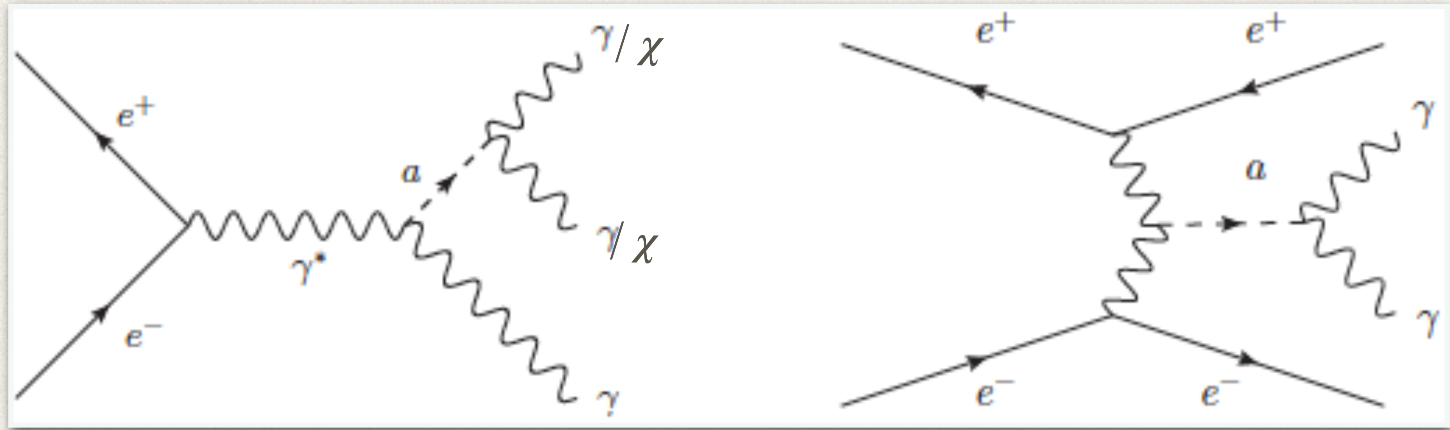

ε
E787, E949
(g-2)$_e$ vs α
(g-2)$_\mu$ ± 2σ
BaBar 2017
NA64
Dark Freeze out
Expected sensitivity Belle II 20 fb^{-1} (simulation)
$m_{A'}$ (GeV)

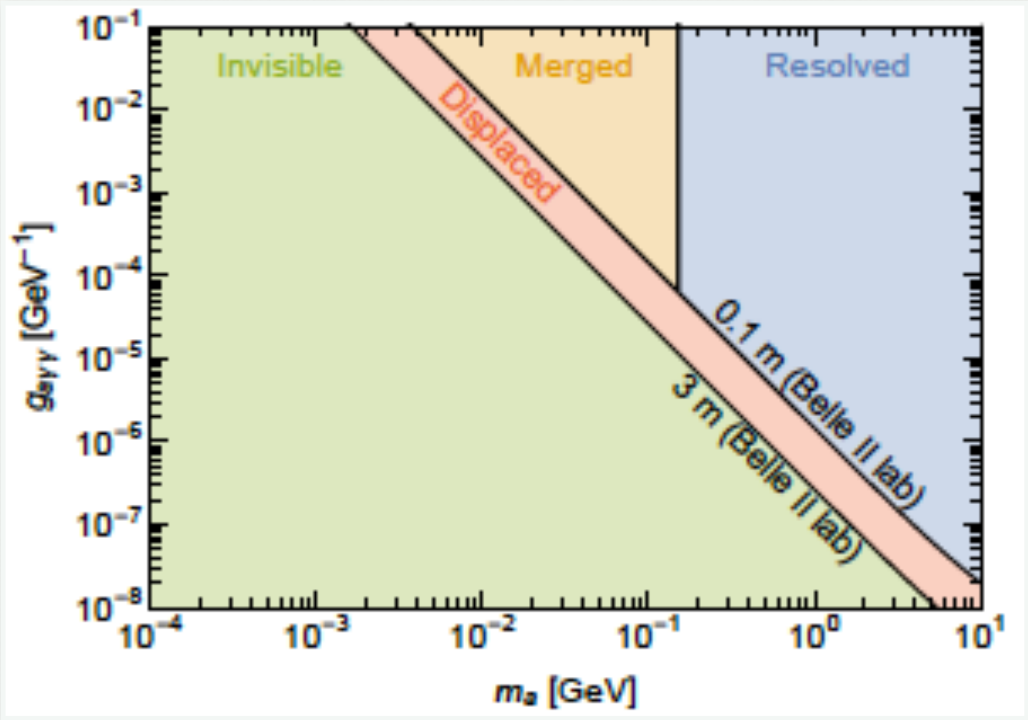

Belle II
$e^+e^- \to \gamma S$
BaBar
$e^+e^- \to \mu^+\mu^- S$
E141
HPS
NA48/2
NA62
$(g-2)_\mu < 2\sigma$
COMPASS
BaBar
Belle
Belle II
$\mu \to 3e$
Orsay
E137
ξ_ℓ^S
ϵ_{eff}
m_S (GeV)

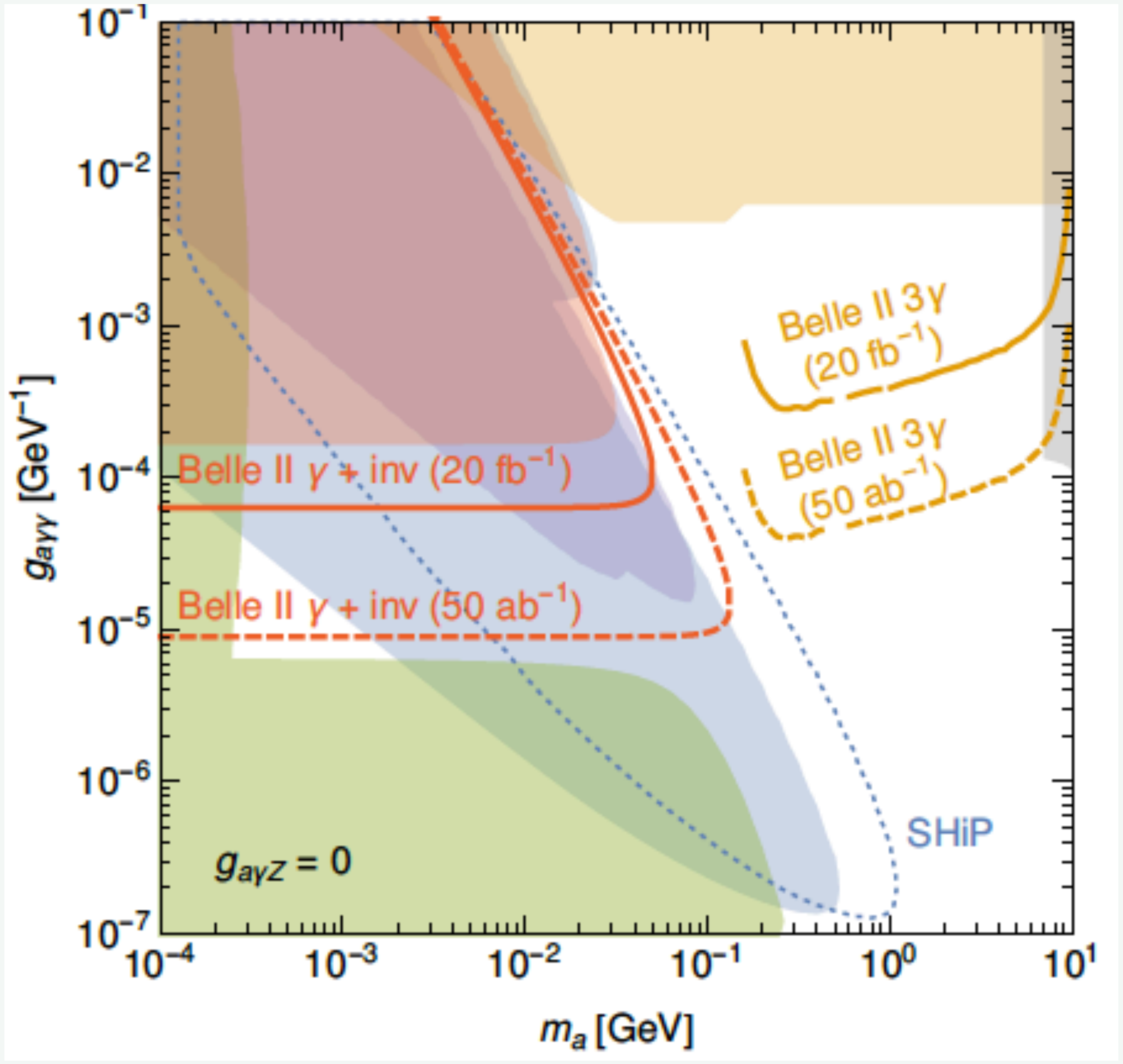

$B_s \to \mu^+\mu^-$
Belle II
$e^+e^- \to \gamma S$
BaBar
$e^+e^- \to \mu^+\mu^- S$
R_τ
E141
HPS
NA48/2
NA62
$(g-2)_\mu < 2\sigma$
COMPASS
h→SS
BaBar
Belle
Belle II
$\mu \to 3e$
$B^+ \to K^+ \ell^+ \ell^-$
Orsay
E137
tanβ=200
$m_{H,A,H^\pm}$=500 GeV
m_{12}=100 GeV
ξ_ℓ^S
ϵ_{eff}
m_S (GeV)

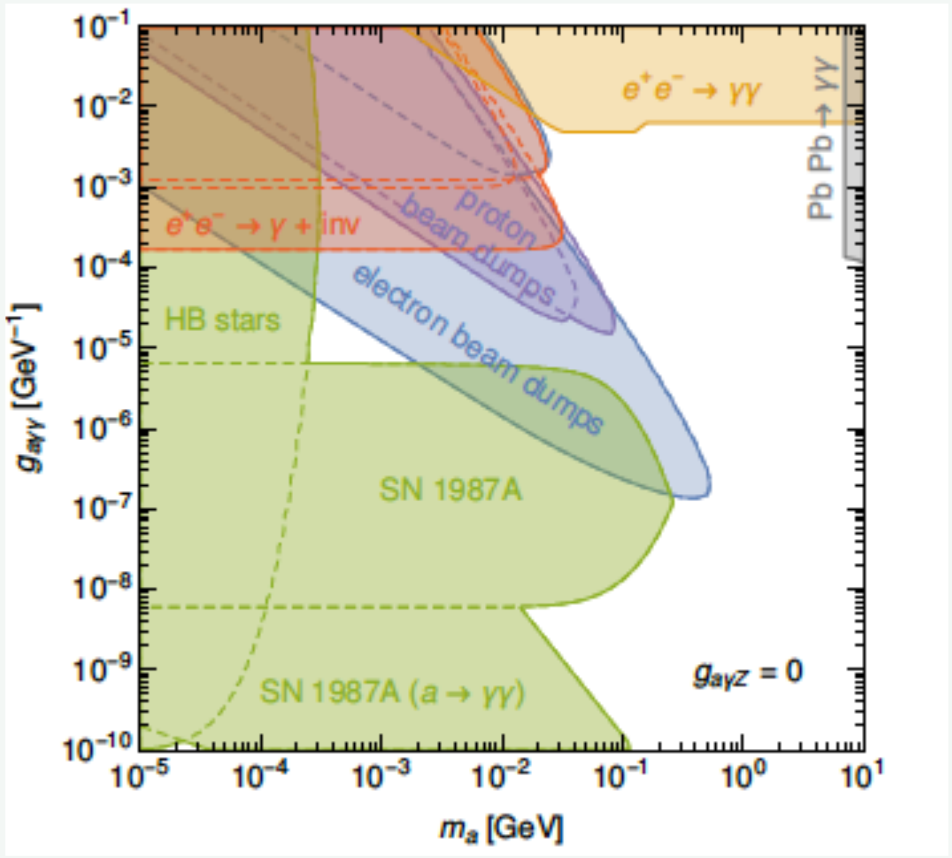
ALPs searches at Belle II

Dolan, Ferber, Hearty, Kahlhoefer and Schmidt-Hoberg arXiv:1709.00009









Important future experimental searches

LHCb

- **Vub/Vcb**
  - $BR(\Lambda_b \to pl\nu)/BR(\Lambda_b \to \Lambda_c l\nu)$
  - $BR(B_s \to Kl\nu)/BR(B_s \to D_s l\nu)$
  - $B \to \mu\mu\mu\nu$
- **LFU Anomalies**
  - $B \to K^{(*)}\tau\tau$, $B \to K^{(*)}\tau\mu$, $R_{J/\psi}$, R_{D^*}
  - $R(D^+)$, $R(D^0)$, $R(D_s^{+(*)})$, $R(\Lambda_c^{+(*)})$
  - $\Lambda_b \to p\tau\upsilon$, $B \to pp\tau\upsilon$
- **Dark sector**
  - $D^* \to De^+e^-$

Belle II

- **Vub/Vcb**
  - $B \to \pi l\nu$, $B \to \rho l\nu$
  - Inclusive $B \to X_u l\nu$
  - $B^+ \to l^+\nu_l\gamma$
- **LFU Anomalies**
  - R_K, R_{K^*},$R_{Xs,,}$ R_D, R_{D^*}
  - $B \to K^*ll$ angular obs. for e/μ
  - $B(B \to Xsll)$ $B \to K^{(*)}\nu\nu$, $B \to K\tau l$
- **Dark sector**
  - $e^+e^- \to \gamma$+inv or $e^+e^- \to 3\gamma$

Back up slides

Form factors for B to V: Definitions

Express hadronic matrix elements via:

$$\langle K^*(p)|\bar{s}\gamma^\mu(1 \mp \gamma_5)b|\bar{B}(p_B)\rangle = P_1^\mu\, \mathcal{V}_1(q^2) \pm P_{2,3}^\mu\, \mathcal{V}_{2,3}(q^2) \pm P_P^\mu \mathcal{V}_P(q^2)$$

$$\langle K^*(p)|\bar{s}iq_\nu\sigma^{\mu\nu}(1 \pm \gamma_5)b|\bar{B}(p_B)\rangle = P_1^\mu\, T_1(q^2) \pm P_{2,3}^\mu\, T_{2,3}(q^2)$$

where the Lorentz structures P_i^μ are

$$P_P^\mu = i(\eta^* \cdot q)q^\mu\,,$$

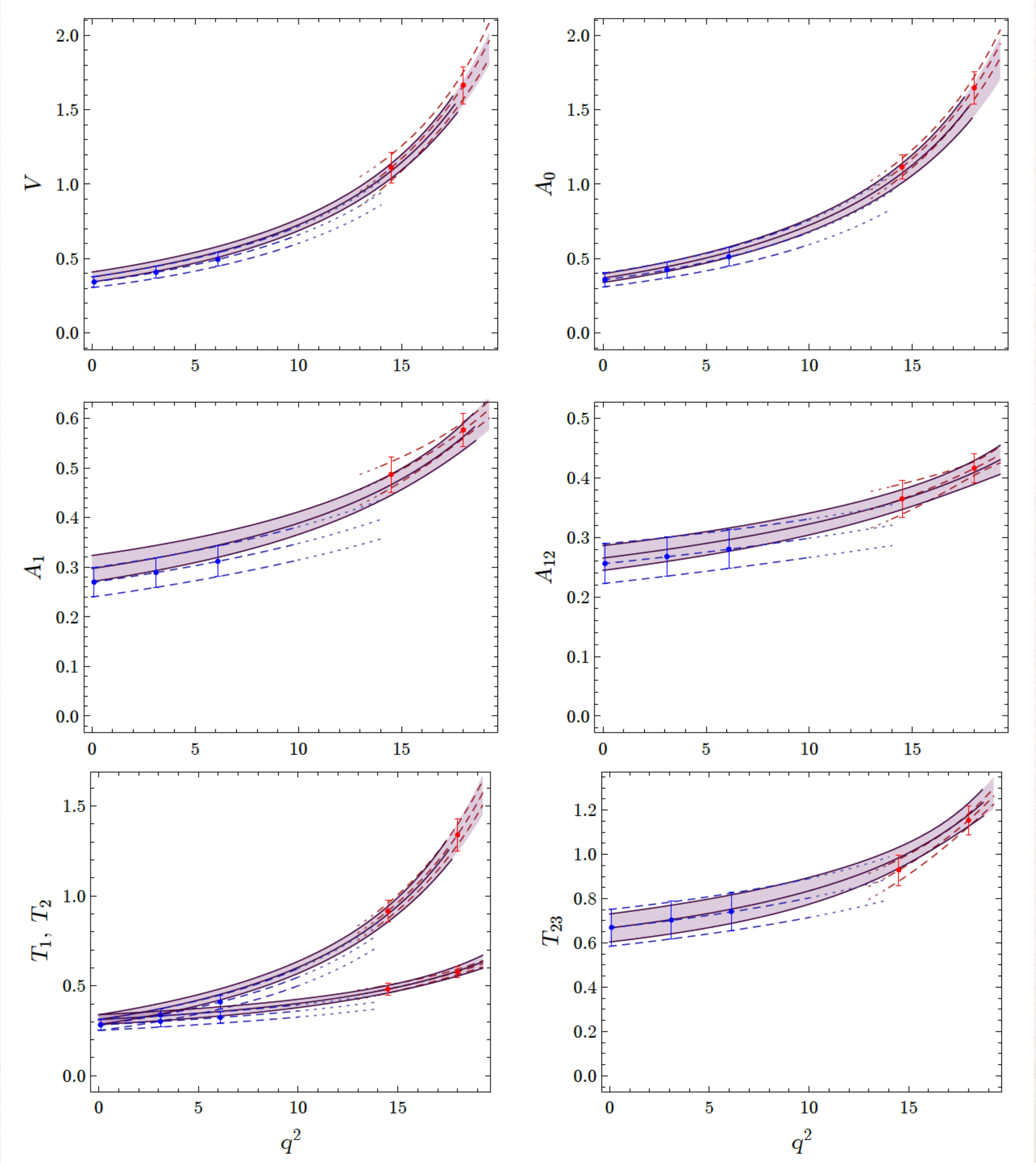
$$P_1^\mu = 2\epsilon^\mu{}_{\alpha\beta\gamma}\eta^{*\alpha}p^\beta q^\gamma\,,$$

$$P_2^\mu = i\{(m_B^2 - m_{K^*}^2)\eta^{*\mu} - (\eta^* \cdot q)(p + p_B)^\mu\}\,,$$

$$P_3^\mu = i(\eta^* \cdot q)\{q^\mu - \frac{q^2}{m_B^2 - m_{K^*}^2}(p + p_B)^\mu\}$$

- Bjorken & Drell convention for the Levi-Civita tensor $\epsilon_{0123} = +1$
- η is the polarization of K^*
- Only 7 independent FFs

Results for the B to K* form factors



Quantity	Published value	Reference	error (to be published)	2025
f_K	155.7 ± 0.7 MeV	$N_f = 2+1$ [1]	0.4%	
$f_+^{K\to\pi}(0)$	0.9706(27)	$N_f = 2+1+1$ [1]	0.28% (0.19% [2])	0.12%
B_K	0.7625(97)	$N_f = 2+1$ [1]	1.3%	0.7%
f_{B_s}	228.4(3.7)	$N_f = 2+1$ [1]	1.6%(0.56% [3])	
f_{B_s}/f_{B^+}	1.205(7)	$N_f = 2+1+1$ [1]	0.6%(0.4% [3])	
B_{B_s}	1.32(5)/1.35(6)	$N_f = 2/N_f = 2+1$ [1]	$\sim 4\%$	0.8%
B_{B_s}/B_{B_d}	1.007(21)/1.032(28)	$N_f = 2/N_f = 2+1$ [1]	2.1%/2.7%	0.5%
ξ	1.206(17)	$N_f = 2+1$ [1]	1.4%	0.3%
$\overline{m}_c(\overline{m}_c)$	1.275(8) GeV	$N_f = 2+1$ [1]	0.6%	0.4%
$f_{K^\pm}/f_{\pi^\pm}$	1.193(3)	$N_f = 2+1+1$ [1]	0.25%(0.15%, symmet. [3])	
f_{D_s}	248.83(1.27)	$N_f = 2+1+1$ [1]	0.5%(0.16% [3])	
f_{D_s}/f_{D^+}	1.1716(32)	$N_f = 2+1+1$ [1]	0.27%(0.14% [3])	
$B \to \pi$ for $\lvert V_{ub}\rvert_{\text{theor}}$		$N_f = 2+1$ [1]	2.9%	1%(1.4%)
$B \to D$ for $\lvert V_{cb}\rvert_{\text{theor}}$		$N_f = 2+1$ [1]	1.4%	0.3%(1%)
(first param. BCL z-exp.)		$N_f = 2+1$ [1]	1.5%	0.5%(1.1%)
$B \to D^*$ for $\lvert V_{cb}\rvert_{\text{theor}}$	-	$N_f = 2+1$ [1]	1.4%	0.4%(0.7%)
$h_{A_1}^{B\to D^*}(\omega = 1)$			=	=
$P_1^{B\to D^*}(\omega = 1)$		No LQCD available		1-1.5%
$\Lambda_b \to p(\Lambda_c)$ for $\lvert V_{ub}/V_{cb}\rvert_{\text{theor}}$		[4]	4.9%	1.2%(1.6%)
$B \to K$		$N_f = 2+1$ [1]	2%	0.7%(1.2%)
(first param. BCL z-exp.)				
$B_s \to K$		$N_f = 2+1$ [1]	4%	1.3%(1.7%)
(first param. BCL z-exp.)				

Introduction to exclusive V_{ub}

- Uncertainty on $|V_{ub}|^{\mathbf{incl}} \sim 7\%$ ($< 2\%$ on $|V_{cb}|^{\mathbf{incl}}$) due to large $b \to c\ell\nu$ background

- Competitive $|V_{ub}|^{\mathbf{excl}}$ from $B \to \pi\ell\nu$, depends on $f_+(q^2)$ (as $m_l \to 0$) from Lattice QCD ($q^2 \gtrsim 15\,\mathrm{GeV}^2$) or QCD sum rules on the light-cone (LCSR) ($q^2 \lesssim 6-7\,\mathrm{GeV}^2$)

- Also possible via other B decays, e.g. recent progress in $B \to \rho\ell\nu$, $\Lambda_b \to p\ell\nu$, $B_s \to K\ell\nu$

Obtaining the form factor in Light-cone sum rules:

$$\Pi_\mu = i\, m_b \int d^D x e^{-i p_B \cdot x} \langle \pi(p)| T\{\bar{u}(0)\gamma_\mu b(0) \bar{b}(x) i\gamma_5 d(x)\}|0\rangle,$$
$$= (p_B + p)_\mu \Pi_+(p_B^2, q^2) + (p_B - p)_\mu \Pi_-(p_B^2, q^2).$$

into

$B \to \pi$ transition ($f_+(q^2)$)

$$\langle \pi(p)|\bar{u}\gamma_\mu b|B(p_B)\rangle = (p_B+p)_\mu f_+(q^2) + (p_B-p)_\mu f_-(q^2)$$

B meson decay (f_B)

$$m_b\langle 0|\bar{d} i\gamma_5 b|B\rangle = m_B^2 f_B$$

Leading to:

$$\Pi_+(p_B^2, q^2) = f_B m_B^2 \frac{f_+(q^2)}{m_B^2 - p_B^2} + \int_{s>m_B^2} ds \frac{\rho_{\rm had}}{s - p_B^2},$$

($\rho_{\rm had}$ is spectral density of the higher-mass hadronic states)

On the other hand:

Light-cone expand about $x^2 = 0 \;\; \Rightarrow$

$\Pi_+(p_B^2, q^2) = \sum_n \int du\, \mathcal{T}_+{}^{(n)}(u, p_B^2, q^2, \mu^2)\phi^{(n)}(u, \mu^2) = \int ds \frac{\rho_{\rm LC}}{s - p_B^2},$

$\mathcal{T}_+^{(n)}(u, \mu^2)$: perturbatively calculable hard kernels

$\phi^{(n)}(u, \mu^2)$: non-perturbative LCDAs at twist n

e.g. n=2, $\langle \pi(p)|\bar{u}(0)\gamma_\mu\gamma_5\, d(x)|0\rangle = -i f_\pi p_\mu \int_0^1 du\, e^{i\bar{u}p\cdot x}\phi(u, \mu^2) + \ldots,$

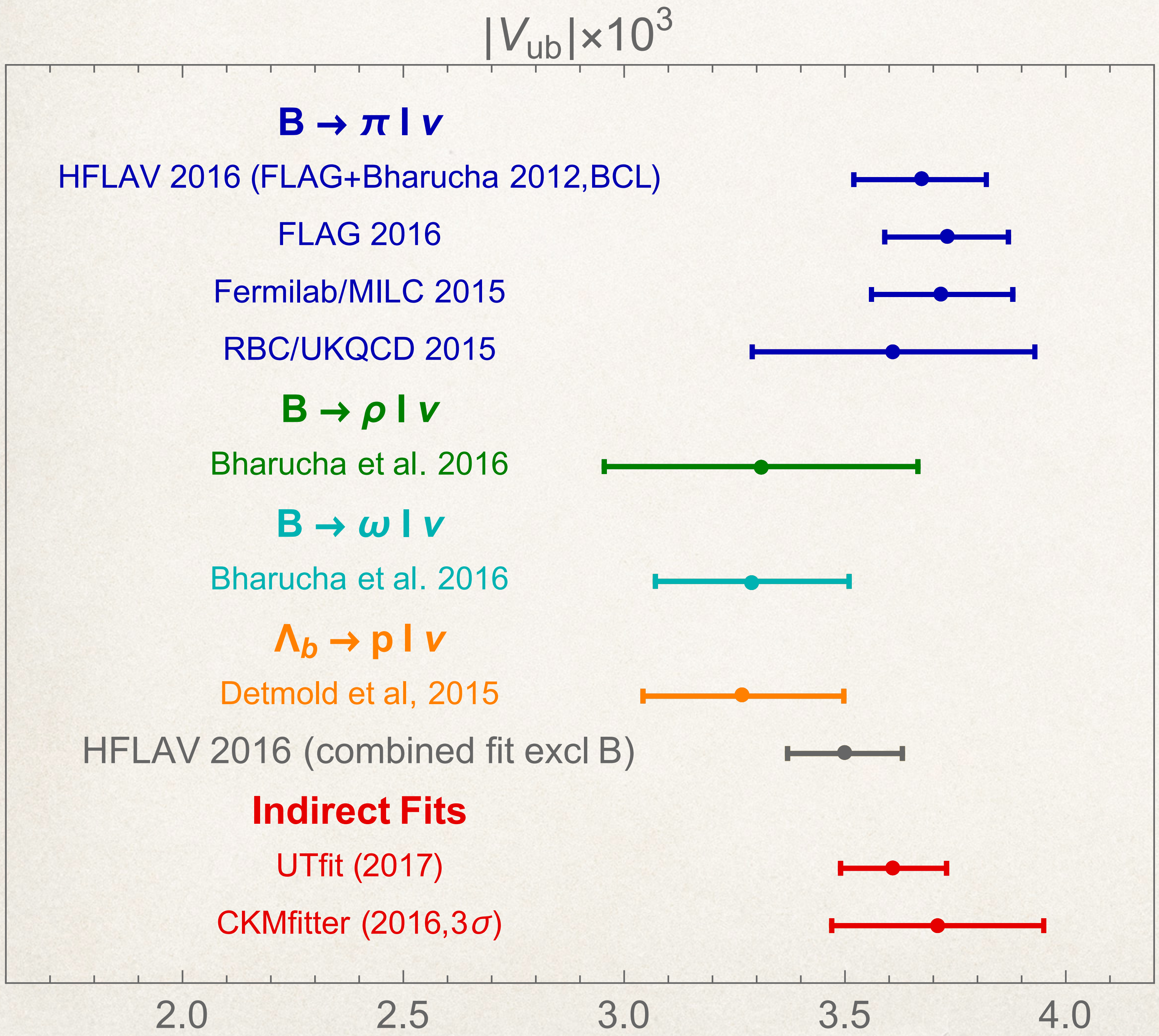
where $\phi(u, \mu^2) = 6u(1-u)\sum_{n=0}^{\infty} a_n(\mu^2) C_n^{3/2}(2u-1)$

Sum rule for $f_+(q^2)$: $f_+(q^2) = \frac{1}{f_B m_B^2}\int_{m_b^2}^{s_0} ds\, \rho_{\rm LC}\, e^{-(s-m_B^2)/M^2}$

Status of $f_+(q^2)$ for $B \to \pi$ < 2012

- 1997: NLO twist-2 corrections were calculated (A. Khodjamirian et al, [arXiv:hep-ph/9706303]; E. Bagan, P. Ball and V. M. Braun, [arXiv:hep-ph/9709243])
- 2000: LO corrections up to twist-4 were calculated (A. Khodjamirian et al, [arXiv:hep-ph/0001297])
- 2004: NLO twist-3 corrections (P. Ball and R. Zwicky, [arXiv:hep-ph/0406232])
- 2008: $\overline{\rm MS}$ m_b is used in place of the pole mass (G. Duplancic et al, 2008)
- 2011: Use a_2, a_4 from F_π, LCSR+new JLab, Extrapolate by fitting to BCL q^2 parameterisation (A. Khodjamirian, T. .Mannel, N. Offen, Y. -M. Wang, [arXiv:1103.2655])

Summary of exclusive V_{ub}



In this talk:

2012 NNLO calculation $B \to \pi$ (AB)

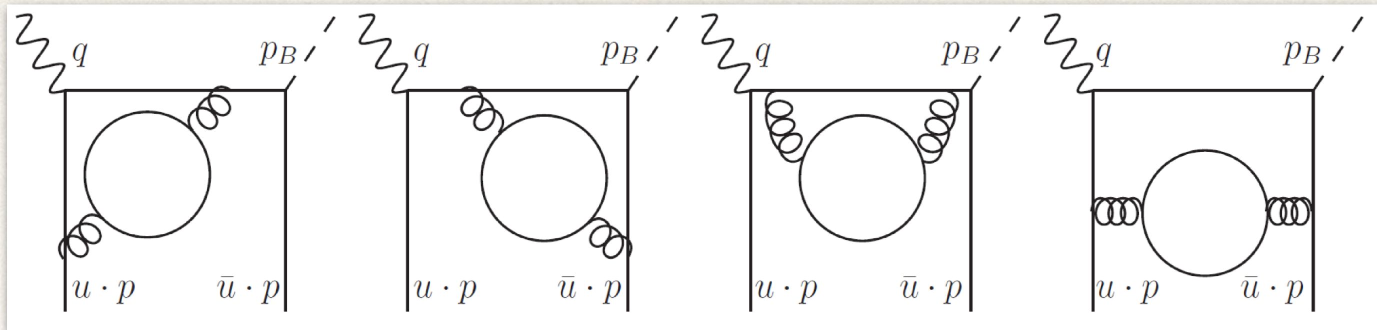
2014 Bayesian uncertainty analysis for the $B \to \pi$ form factor (Imsong, Khodjamirian, Mannel van Dyk)

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

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

Two-loop corrections

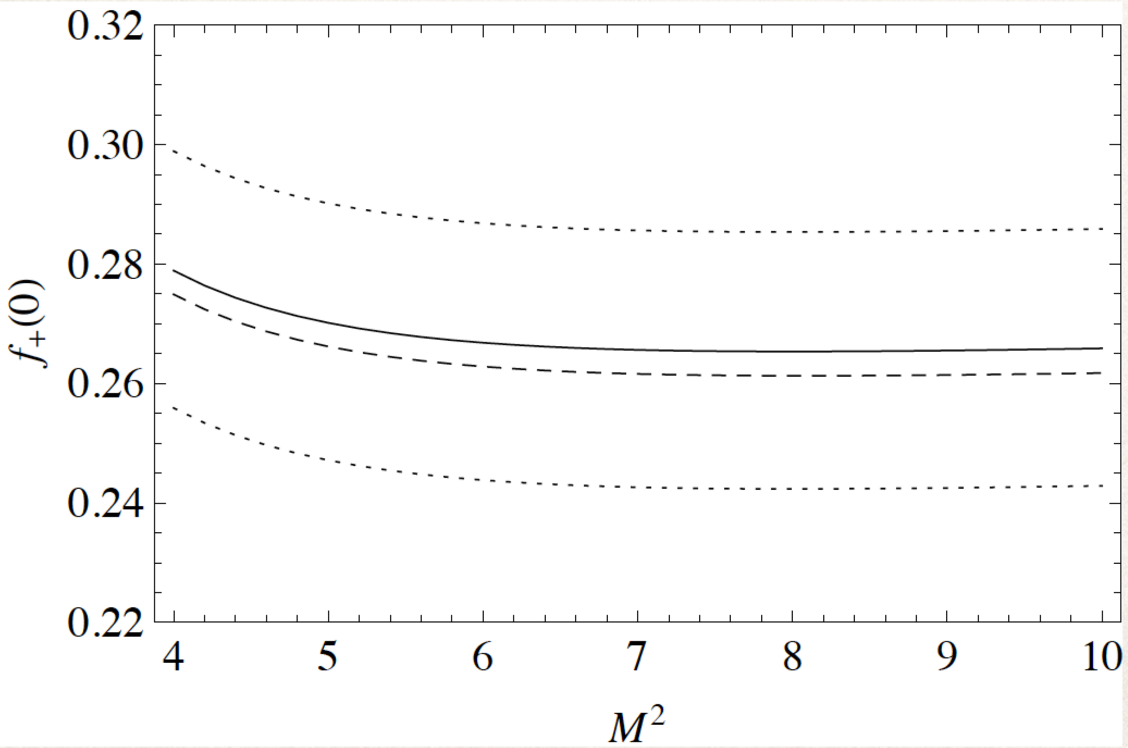
(AB 1203.1359)

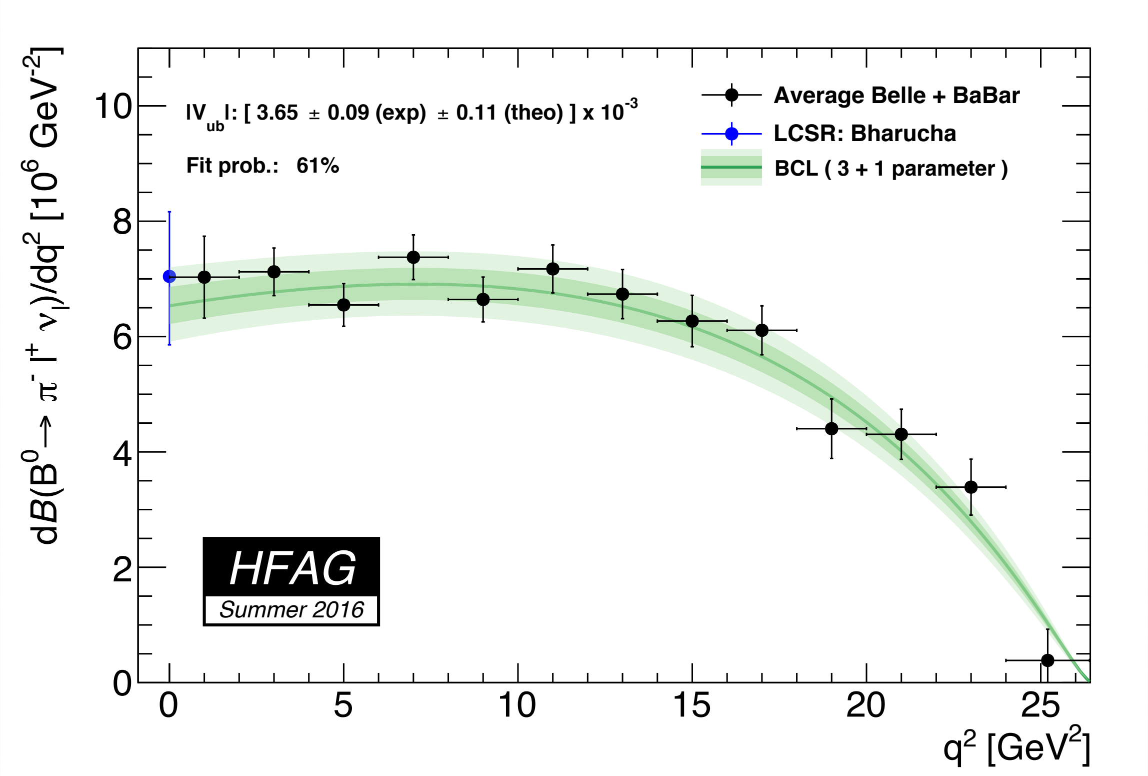


- Test argument that radiative corrections to $f_+ f_B$ and f_B should cancel when both calculated in sum rules (2-loop contribution to f_B in QCDSR sizeable) $\Rightarrow$ *Calculate subset of two-loop radiative corrections for twist-2 contribution to* $f_+(0) \propto \beta_0$

- $f_+(0)$ $(0.262^{+0.020}_{-0.023})$ at $\mathcal{O}(\alpha_s^2 \beta_0)$ (solid) with uncertainties$\lesssim 9\%$ (dotted), compared to $\mathcal{O}(\alpha_s)$ result (dashed), as a function of Borel parameter M^2

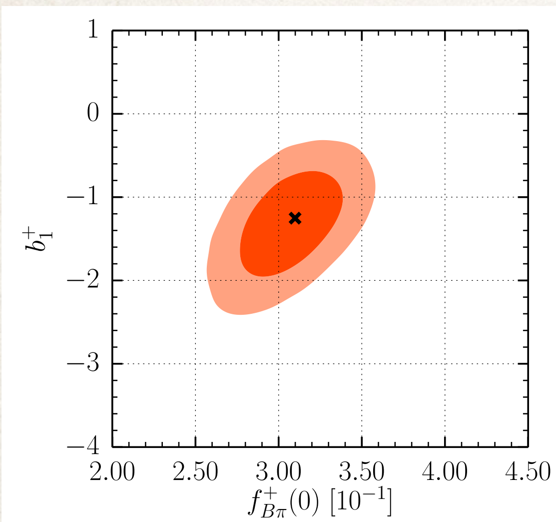
- Despite $\sim 9\%$ $\mathcal{O}(\alpha_s^2 \beta_0)$ corrections to f_B, change in $f_+(0)$, only $\sim 2\%$

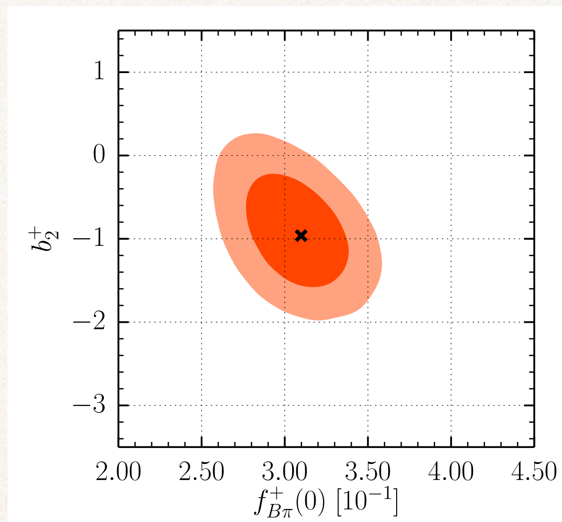




Extrapolation and unitarity bounds for the B → π form factor

(I. S. Imsong, A. Khodjamirian, T. Mannel, D. van Dyk, 1409.7816)





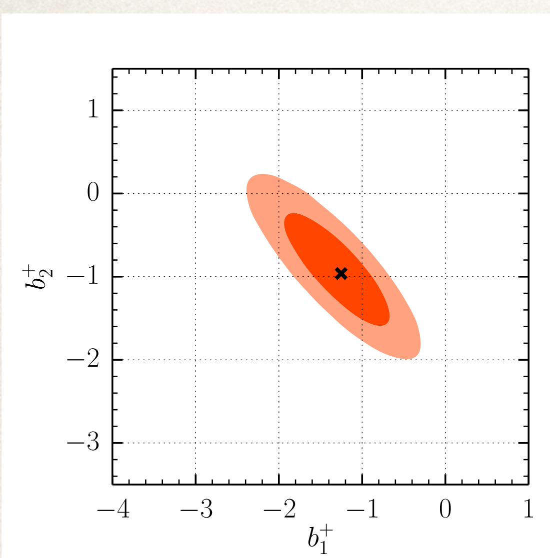


Figure 1. The regions with 68% probability (red) and 95% probability (orange) for all two-dimensional marginalisations of the posterior $P(\vec{\lambda}|\mathrm{LCSR})$. The cross marks the best-fit point.

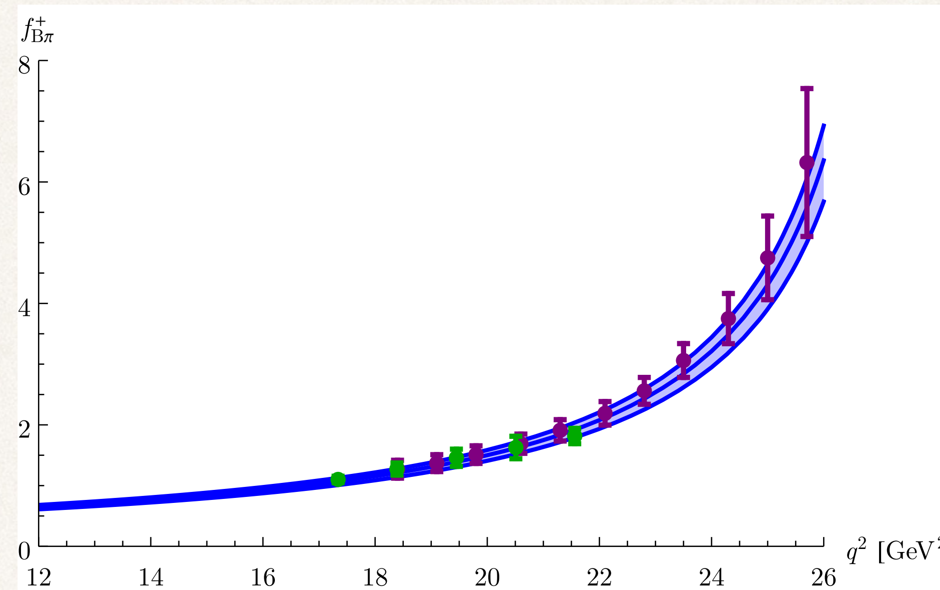


Figure 2. Form factor $f^+_{B\pi}(q^2)$ obtained at $q^2 < 12\mathrm{GeV}^2$ from the statistical analysis of LCSR, fitted to z-series representation and extrapolated to large q^2. The solid lines correspond to the 68% probability envelope and the best fit curve. The green (magenta) points are HPQCD [7] (Fermilab-MILC [8]) lattice QCD results.

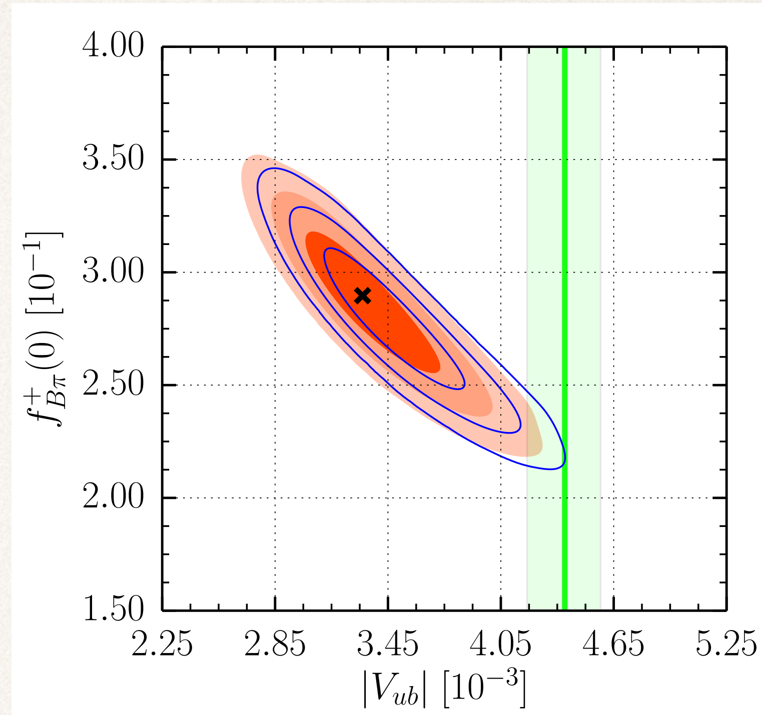
- Use Bayesian analysis: prior distributions for inputs, construct likelihood function based on SR fulfilling m_B to 1%, obtain posterior distributions using Bayes theorem
- Posterior distributions of inputs only different for s_0 : (41±4) GeV^2(~gaussian)
- Fit to BCl exp, find central value of $f_+(0) = 0.31 \pm 0.02$: raised due to value m_b, s_0, μ
- Obtaining $f_+(q_2)$ and first two derivatives at 0 and 10 GeV^2 allowed extrapolation to high q^2 using improved unitarity bounds

- Perform Bayesian analysis including experimental results to obtain $|V_{ub}|$

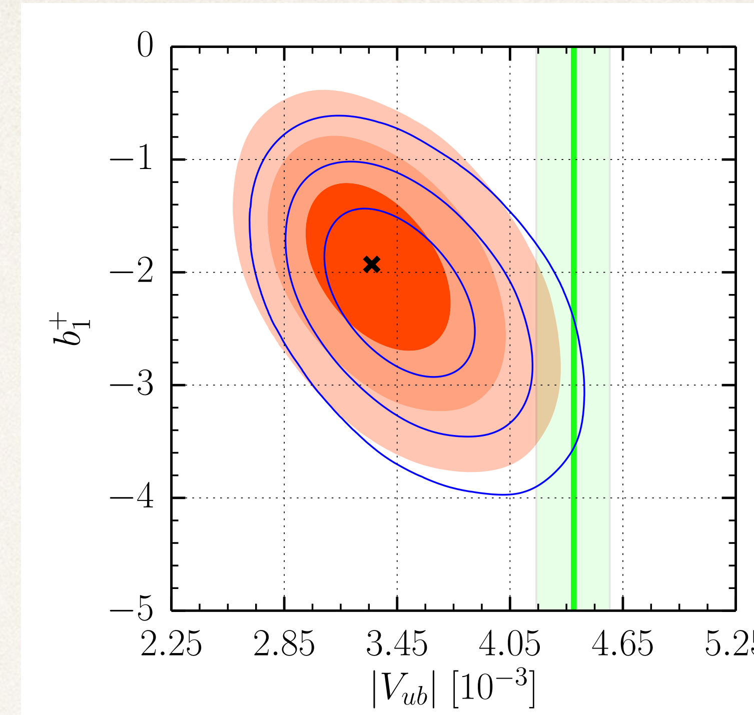
- Theory uncertainty on $|V_{ub}|$ obtained from analysis comparable to that of most accurate determinations from inclusive $b \to u$ transitions

- 2010 data set agrees better with inclusive than 2013

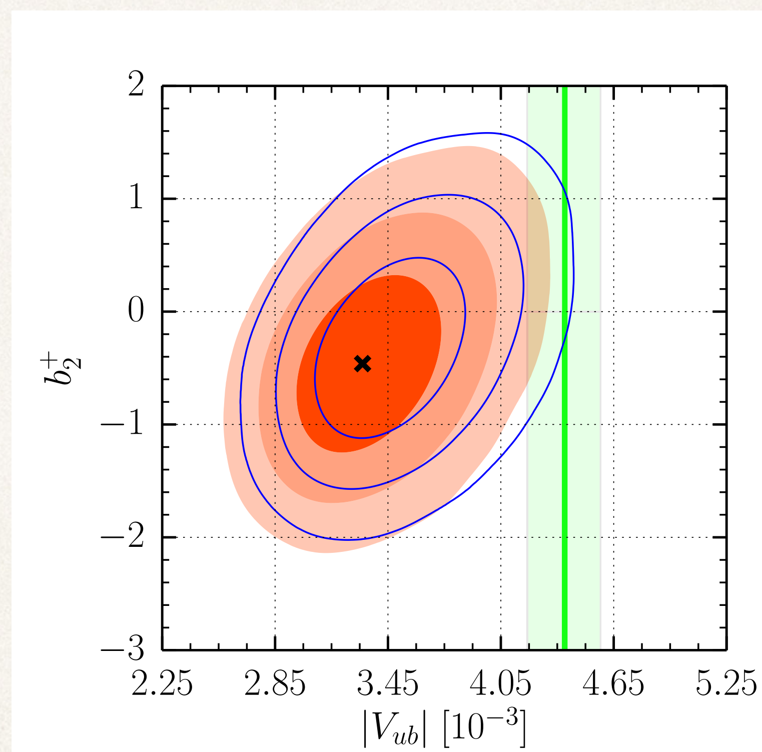
- Tension wrt GGOU determination seen beyond 99% C.L.



(a)



(b)



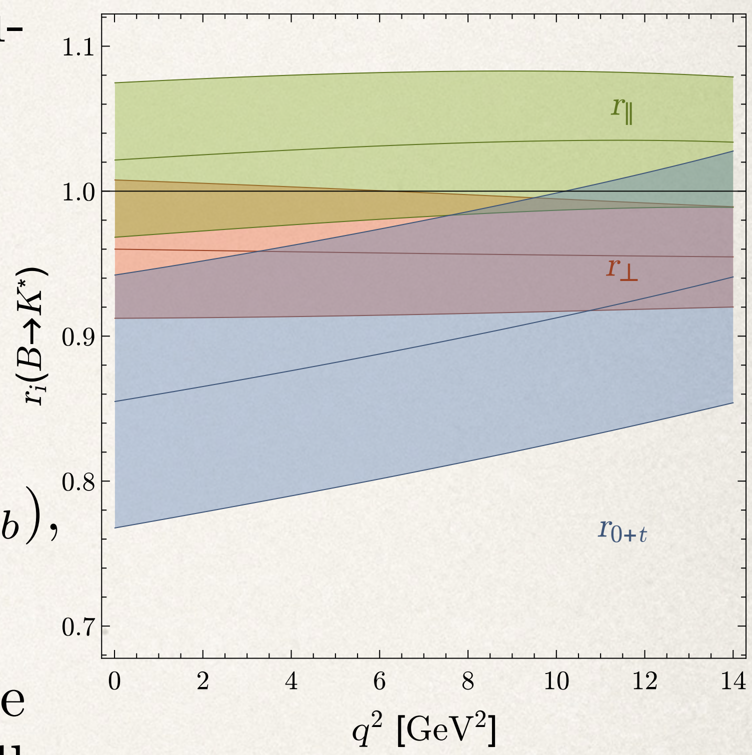
(c)

Figure 4. The two-dimensional marginal posteriors for $|V_{ub}|$ versus the BCL parameters (a) $f^+_{B\pi}(0)$, (b) b^+_1, and (c) b^+_2. The dark orange, orange, and light orange regions show, respectively, the 68%, 95% and 99% probability regions when using the "2013" data set. The blue contours delineate the corresponding probability regions of the "2010" data set. The green and light green vertical bands denote the central value and 68% CL interval of the HFAG world average [39] of the $|V_{ub}|$ determinations from inclusive decays $B \to X_u \ell \bar{\nu}$ according to the GGOU method [40].

(I. S. Imsong, A. Khodjamirian, T. Mannel, D. van Dyk, 1409.7816)

Update for B to V form factors
(AB, D. Straub and R. Zwicky 1503.05534)

- Largest uncertainty in calculation is from form factors
- Best coverage in q^2: fit to LCSR/Lattice using series expansion, coefficients satisfy dispersive bounds.(AB, T. Feldmann, M. Wick, arXiv:1004.3249)
- **Our Aim:** improve uncertainty by making correlations available
- We obtain the four equation of motion relations:
  e.g. $T_1(q^2) + (m_b + m_s)\mathcal{V}_1(q^2) + \mathcal{D}_1(q^2) = 0$
- Isgur-Wise relations at low recoil follow from $\mathcal{D}_\iota/(\mathcal{V}_\iota \text{ or } T_\iota) \sim \mathcal{O}(\Lambda_{\rm QCD}/m_b)$, $\mathcal{D}_\iota$ is derivative FF, breaking of I-W relations.
- Certain combinations of $\mathcal{D}_\iota$'s may be small at large recoil: $\iota = 1, 2$ are direct candidates, and combinations of $\iota = 3, P$ result in potentially small ratio of $\mathcal{D}/T$



In order to fulfil EOM, V_1, T_1 and D_1 should have same s_0. As D_1 small, difficult to compensate different s_0^{T1} and s_0^{V1} via s_0^{D1}. For $s_0^{T1} = s_0^{V1} \pm 0.5$ GeV^2, a 5 GeV^2 change in s_0^{D1} is required. Therefore correlation between s_0^{V1} and s_0^{T1} seems reasonable, ensuring s_0^{V1}-$s_0^{T1}<1$ GeV^2. Apply same sum rules parameters for related FFs +correlations (7/8), less correlated for 0+t case (1/2)

Update for B to V form factors
(AB, D. Straub and R. Zwicky 1503.05534)

We carefully choose the sum rules parameters using the following:

- SR depends little on, but is clear extremum as fn of s_0, M^2, SR for m_B fulfilled;
- the continuum and higher twist contributions should be under control $\lesssim 30\%, 10\%$ respectively;
- Correlate s_0 for EOM related FFs, and M^2 for $FF \times f_B$ and f_B 50%.

Other improvements in the calculation:

- computation of full twist-4 (+partial twist-5) 2-particle DA contribution to FFs, plus determination of certain so-far unknown twist-5 DAs in the asymptotic limit
- discussion of non-resonant background for vector meson final states,
- determination and usage of updated hadronic parameters, specifically the decay constants
- fits with full error correlation matrix for the z-expansion coefficients, as well as an interpolation to the most recent lattice computation.

Update for the $B_{(s)}$ to K form factors

$B_{(s)}$ to K ll and B to π ll decays at large recoil and CKM matrix elements, Alexander Khodjamirian, Aleksey V. Rusov, arXiv:1703.04765 [hep-ph], JHEP 1708 (2017) 112.

The OPE result, schematically:

$$F^{(T)}_{B_sK}(q^2)_{\mathrm{OPE}} = (T_0^{(2)} + (\alpha_s/\pi)T_1(2)) \otimes \phi^{(2)} + \frac{\mu_K}{m_b}(T_0^{(3)} + (\alpha_s/\pi)T_1^{(3)}) \otimes \phi_K^{(3)}$$
$$+ T_0^{(4)} \otimes \phi_K^{(4)} + \langle \bar{q}q \rangle \left(T_0^{(5)} \otimes \phi_k^{(2)} + \frac{\mu_K}{m_b} T_0^{(6)} \otimes \phi_K^{(3)} \right)$$

where $\phi_K(2,3,4) = \{\text{kaon DAs with non-asympt.terms}\}$, $\mu_K = \dfrac{m_K^2}{m_s + m_q}$

Include factorizable twist 5,6 contributions (Rusov 1705.01929) , find very small contribution

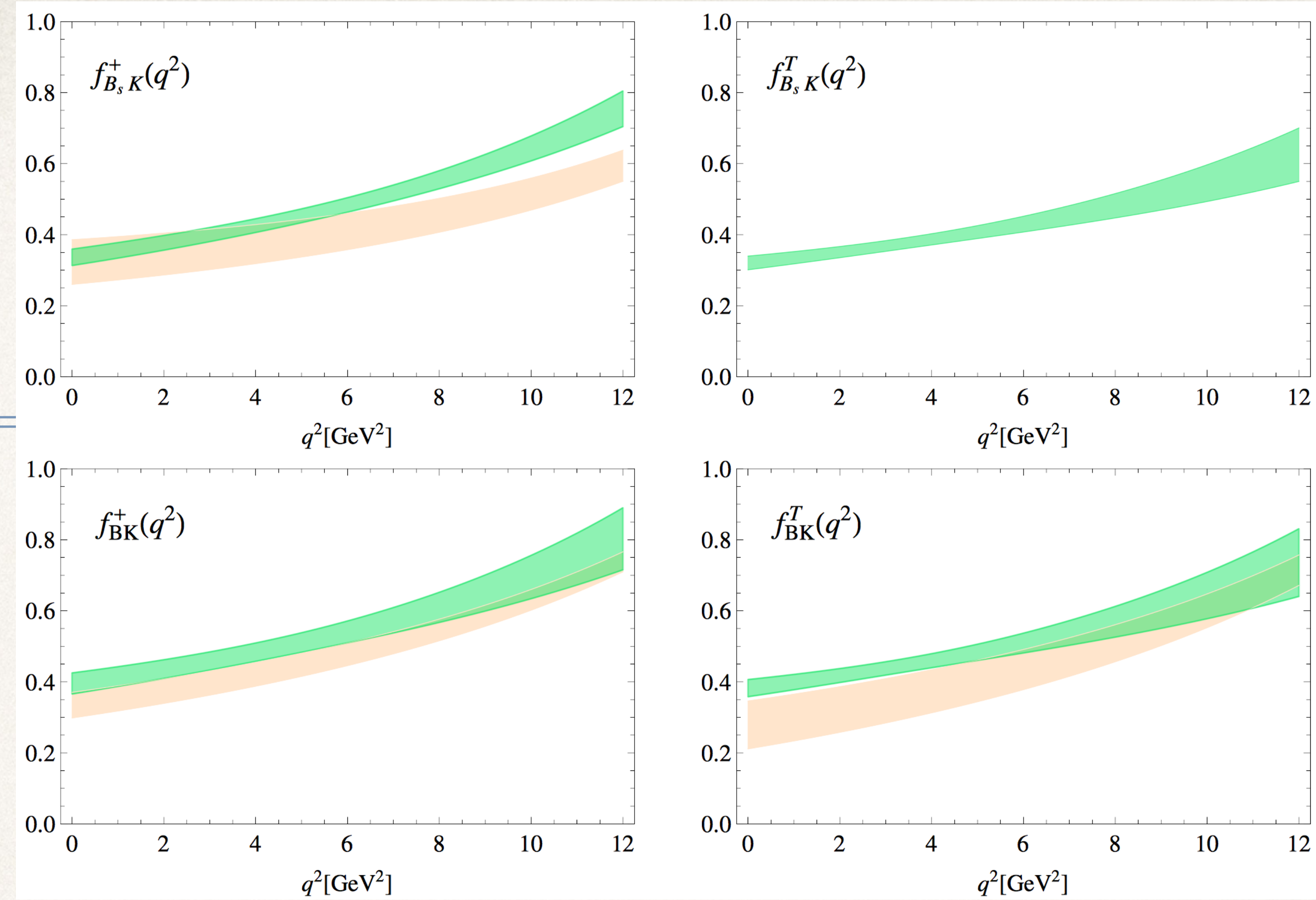
Additional improvements:

- Corrected subheading twist 3/4 contributions
- Use updated (smaller) QCDSR result for $f_{B(s)}$ from 2013
- Important update from LCSR for B_s to K

$f^+_{B_sK}(0)$	0.336
Tw2 LO	47.0%
Tw2 NLO	8.8%
Tw3 LO	47.1%
Tw3 NLO	−3.9%
Tw4 LO	1.0%
Tw5 LO-fact	−0.039%
Tw6 LO-fact	−0.005%

Results for $B_s \to K$ and $B \to K$ form factors and observables

Alexander Khodjamirian, Aleksey V. Rusov, arXiv: 1703.04765 [hep-ph], JHEP 1708 (2017) 112.



The vector (tensor) form factors of $B_s \to K$ and $B \to K$ from LCSRs with the dark-shaded (green) bands. Extrapolations of the lattice QCD results for $B_s \to K$ (HPQCD) and $B \to K$ (FermiLAB/MILC) form factors are shown with the light-shaded (orange) bands.

$$\Delta\zeta_{B_sK}\,[0, 12\,\mathrm{GeV}^2] \equiv \frac{1}{|V_{ub}|^2} \int_0^{12\,\mathrm{GeV}^2} dq^2 \frac{d\Gamma(\bar{B}_s \to K^+ \ell \bar{\nu}_\ell)}{dq^2} = 7.03^{+0.73}_{-0.69}\,\mathrm{ps}^{-1}$$

Decay mode	$B^- \to K^- \ell^+ \ell^-$	$B^- \to \pi^- \ell^+ \ell^-$	$\bar{B}_s \to K^0 \ell^+ \ell^-$
Measurement or calculation	$\mathcal{B}_{BK}[1.0\,, 6.0]$	$\mathcal{B}_{B\pi}[1.0\,, 6.0]$	$\mathcal{B}_{B_sK}[1.0, 6.0]$
Belle (2009)	$2.72^{+0.46}_{-0.42} \pm 0.16$	—	—
CDF (2011)	$2.58 \pm 0.36 \pm 0.16$	—	—
BaBar (2012)	$2.72^{+0.54}_{-0.48} \pm 0.06$	—	—
LHCb (2014,2015)	$2.42 \pm 0.7 \pm 0.12$	$0.091^{+0.021}_{-0.020} \pm 0.003$	—
HPQCD (2013)	3.62 ± 1.22	—	—
Fermilab/MILC (2015)	3.49 ± 0.62	0.096 ± 0.013	—
This work	$4.38^{+0.62}_{-0.57} \pm 0.28$	$0.131^{+0.023}_{-0.022} \pm 0.010$	$0.154^{+0.018}_{-0.017} \pm 0.011$

Binned branching fractions in units of 10^{-8} GeV^2 for the 1-6 GeV^2 bin. The first (second) error is due to the uncertainty of the input (only of the CKM parameters).