INTENSITY frontier

Non-perturbative aspects: Overview and Challenges

Aoife Bharucha, CPT (with help from Elisabeth Niel, EPFNL and Antoine Gerardin, CPT)

GDR-InF Annual Workshop, Mont Sainte-Odile 6-8 November 2023

Non-perturbative aspects WG

- Conveners: Aoife Bharucha, Antoine Gérardin, Elisabeth Niel
- Subjects:
  - Heavy-flavour production
  - Spectroscopy
  - Predictions and measurement of form factors
- Goals:
  - Test QCD predictions
  - Input needed for other measurements and interpretation of NP sensitive channels
  - Exotic bound states of quarks (tetra- and pentaquarks).
  - -> Overlap with GDR QCD

Heavy flavour production

- Heavy flavour production is a tool to test Quantum Chromodynamics QCD in high-energy hadronic collisions in different regimes:

- Production in pp:

  - (Open) heavy flavour production in pp collisions

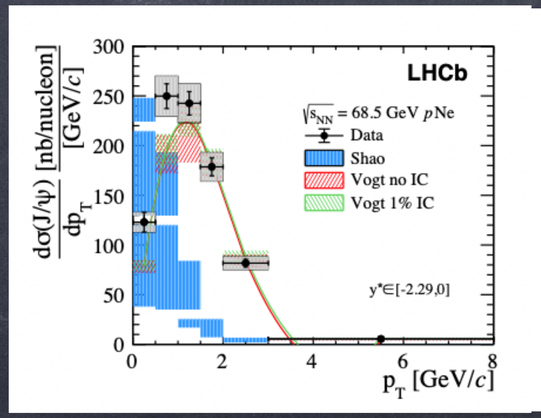
  - Quarkonium bound states

- In nucleus-nucleus and p-nucleus collisions:

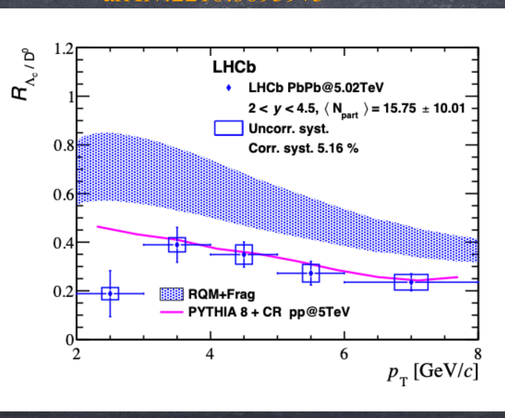
  - Hard scttering at early stage of collisions, before Quark Gluon Plasma forms.
  - Study Cold Nuclear Matter effects

Activities in France:
ALICE: charmonium production as a function of charged-particle multiplicity. Study multiparton interactions in a single hadron-hadron collisions
CMS: study of fragmentation of jets in PbPb and pp collisions
LHCb: charmonium production in pp collisions, open and hidden charm production in fixed-target collisions and baryon-to-meson ratio in PbPb collisions.
Belle II: bottomium spectroscopy

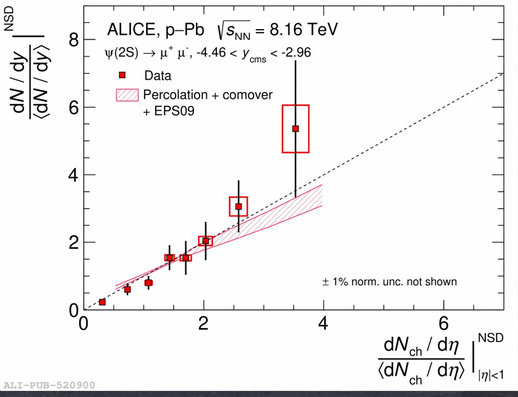
LHCb-PAPER-2022-015



arXiv:2210.06939v5



https://arxiv.org/abs/2204.10253



Spectroscopy

Conventional spectroscopy:

- production of doubly heavy baryons:
  - Observation $\Xi_{cc}^{+} \to \Xi_{c}^{'+}\pi^{+}$
  - Search for $\Xi_{bc}^{+} \to J/\Psi\,\Xi_{c}^{+}$

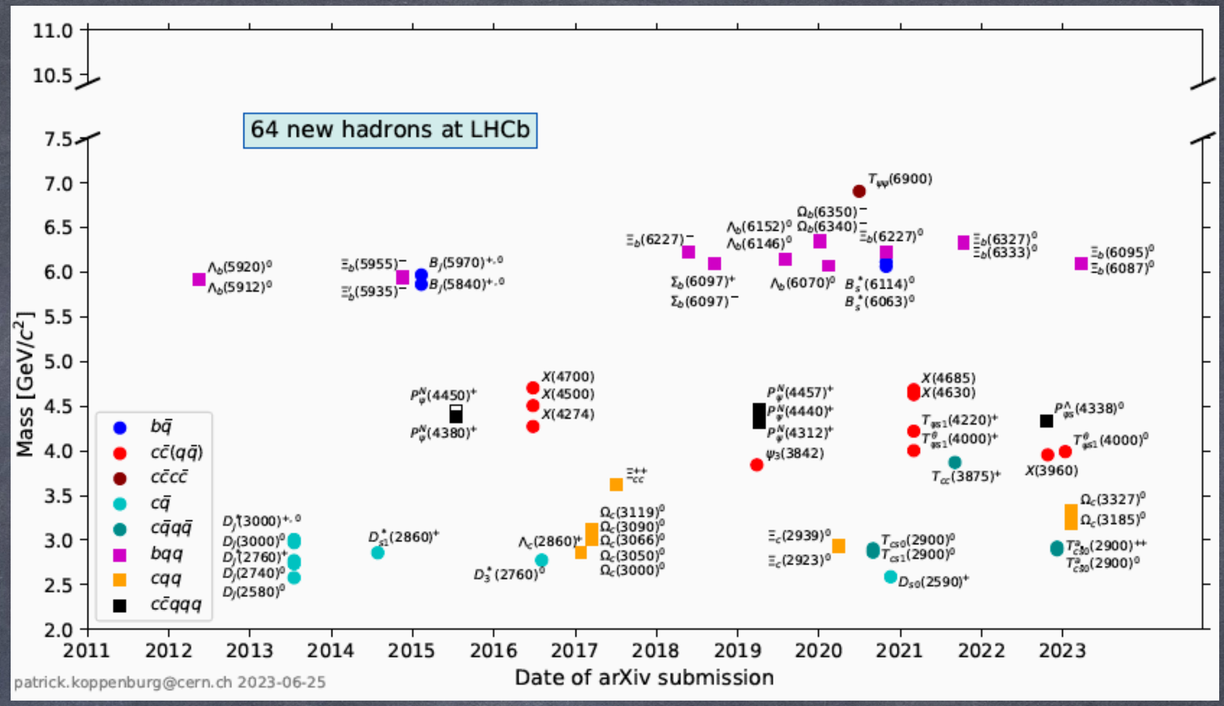
JHEP05(2022)038
arXiv: 2204.09541

- amplitude analysis of mesons and baryons multi-body decays:
  - $D_s^{+} \to \pi^{+}\pi^{-}\pi^{+}$
  - $D^{+} \to \pi^{+}\pi^{-}\pi^{+}$
  - $\Lambda_c^{+} \to p\,K^{-}\pi^{+}$
  - $\Lambda_b \to p\,K^{-}\gamma$

(on-going)

arXiv: 2208.03300
arXiv: 2209.09840

See also talk by Valerio Bertacchi on B to DKK and DDs decays at Belle II



Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G = 0^+,\ J^{PC} = 1^{++}$	$\chi_{c1}(3872)$
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G = 1^+,\ J^P = 1^+$	$T^b_{\psi 1}(3900)^+$
$c\bar{c}u\bar{d}$	$Z_c(4100)^+$	$I^G = 1^-$	$T_{\psi}(4100)^+$
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G = 1^+,\ J^P = 1^+$	$T^b_{\psi 1}(4430)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I = \frac{1}{2},\ J^P = 1^+$	$T^{\theta}_{\psi s1}(4000)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I = \frac{1}{2},\ J^P = 1^?$	$T_{\psi s1}(4220)^+$
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G = 0^+,\ J^{PC} = ?^{?+}$	$T_{\psi\psi}(6900)$
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P = 0^+$	$T_{cs0}(2900)^0$
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P = 1^-$	$T_{cs1}(2900)^0$
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G = 1^+,\ J^P = 1^+$	$T^b_{\Upsilon 1}(10610)^+$
$c\bar{c}uud$	$P_c(4312)^+$	$I = \frac{1}{2}$	$P^N_{\psi}(4312)^+$
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I = 0$	$P^{\Lambda}_{\psi s}(4459)^0$

Exotics

- Multiquark hadrons exotic:
  - Tetraquarks: $qq\bar{q}\bar{q}$
  - Pentaquark: $qqqq\bar{q}$
- Not in charmonium/bottonium spectrum
- New naming scheme proposed by LHCb:
  - ➢ T for **tetra** and P for **penta** arxiv2206.15233
  - ➢ Superscript: indicate isospin, parity and G-parity
  - ➢ Subscript: heavy quark content

Christine T.H. Davies 3
Martin Hoferichter 3
Christopher M. Bouchard 2
Javier Virto 2
Stefan Meinel 2
Andreas Crivellin 2
Antoine Gérardin 2
Jana Günther 2
Lukas Varnhorst 2
William Parrott 2
Show 90 more

Subject
Lattice 25
Phenomenology-HEP 25
Experiment-HEP 11
Theory-Nucl 6
Experiment-Nucl 2

arXiv Category
hep-lat 21
hep-ph 21
hep-ex 11
nucl-th 6
nucl-ex 2

Collaboration
Budapest-Marseille-Wuppertal 1
HPQCD 1

Lattice calculation of the D_s meson radiative form factors over the full kinematical range #5

R. Frezzotti (Rome U., Tor Vergata), N. Tantalo (Rome U., Tor Vergata), G. Gagliardi (Rome III U.), F. Sanfilippo (Rome III U.), S. Simula (Rome III U.) et al. (Jun 9, 2023)

Published in: *Phys.Rev.D* 108 (2023) 7, 074505 • e-Print: 2306.05904 [hep-lat]

pdf DOI cite claim reference search 2 citations

$B \to D^* \ell \nu_\ell$ semileptonic form factors from lattice QCD with Möbius domain-wall quarks #6

JLQCD Collaboration • Y. Aoki (RIKEN AICS, Kobe) et al. (Jun 8, 2023)

e-Print: 2306.05657 [hep-lat]

pdf cite claim reference search 9 citations

Discriminating $B \to D^* \ell \nu$ form factors via polarization observables and asymmetries #7

Marco Fedele (KIT, Karlsruhe, TTP), Monika Blanke (KIT, Karlsruhe, TTP and KIT, Karlsruhe, IKP), Andreas Crivellin (PSI, Villigen and Zurich U.), Syuhei Iguro (KIT, Karlsruhe, TTP and KIT, Karlsruhe, IKP), Ulrich Nierste (KIT, Karlsruhe, TTP) et al. (May 24, 2023)

Published in: *Phys.Rev.D* 108 (2023) 5, 5 • e-Print: 2305.15457 [hep-ph]

pdf DOI cite claim reference search 4 citations

Δ-Baryon axialvector and pseudoscalar form factors, and associated PCAC relations #8

Pei-Lin Yin (Nanjing U. Posts Telecom), Chen Chen (Hefei, CUST and PCFT, Hefei), Christian S. Fischer (Giessen U. and Helmholtz Res. Acad. Hesse for FAIR), Craig D. Roberts (Nanjing U.) (May 16, 2023)

Published in: *Eur.Phys.J.A* 59 (2023) 7, 163 • e-Print: 2305.09831 [hep-ph]

pdf DOI cite claim reference search 1 citation

Dispersive Analysis of $B \to K^{(*)}$ and $B_s \to \phi$ Form Factors #9

Nico Gubernari (Siegen U.), Méril Reboud (Durham U., IPPP and Durham U.), Danny van Dyk (Durham U., IPPP and Durham U.), Javier Virto (Barcelona U. and ICC, Barcelona U.) (May 10, 2023)

e-Print: 2305.06301 [hep-ph]

pdf cite claim reference search 12 citations

Lattice calculation of the π^0, η and η' transition form factors and the hadronic light-by-light contribution to the muon $g-2$ #10

Antoine Gérardin (Marseille, CPT), Willem E.A. Verplanke (Marseille, CPT), Gen Wang (Marseille, CPT), Zoltan Fodor (Wuppertal U. and Julich, NIC and Eotvos U. and Penn State U.), Jana N. Guenther (Wuppertal U.) et al. (May 8, 2023)

e-Print: 2305.04570 [hep-lat]

Overview of recent progress

b to c: Vcb, R(D)..

New results for B to D* from HPQCD, and JLQCD
(See slide 9 for more info)

b to u: Vub

arXiv:2203.04938

Recent B to pi FFs by JLQCD, Vub large but large uncertainties. JLQCD working on B→π update. HPQCD currently working on B(s)→π(K). Fermilab/MILC also working on B→π, Bs→K and Bs→Ds
(Judd Harrison, LHCb Implications, 2023)

arXiv:2301.09229

Form factors

b to s: BR, P(5)', R(K) ..

Story: LFU ratios probably SM-like
Still have to figure out why branching ratios and P5' not SM-like
(See next slide)

c to u, c to s

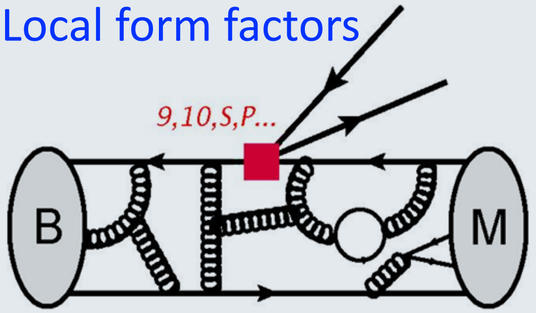
Lattice calculation of the Ds meson radiative form factors over the full kinematical range,
Frezzotti, Tantalo, Gagliardi, Sanfilipo Simula et al.

arXiv: 2306.05904

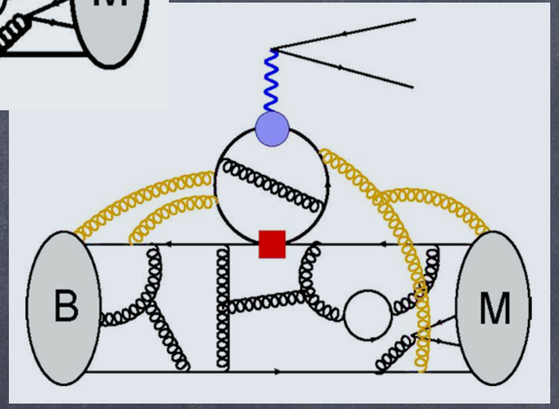
See also talk by Giuseppe Gagliardi

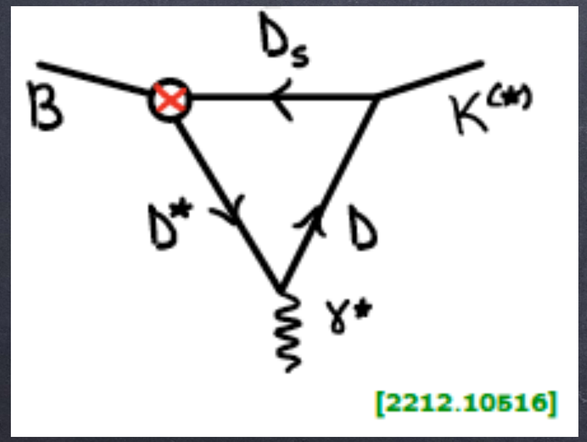
b to s

Local form factors



Non-local form factors





- Recent progress involve work on dispersive bounds for local form factors, and non-local hadronic matrix elements, N. Gubernari, M. Reboud, D. van Dyk and J. Virto, Also studied dispersive approach for baryonic decay $\Lambda_b \to \Lambda(1520)$ M. Reboud, Y. Amhis and M. Bordone

arXiv: 2305.06301

arXiv: 2206.03797

arXiv: 2208.08937

$$\mathcal{A}_\lambda^{L,R}(B \to M_\lambda \ell\ell) = \mathcal{N}_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

- After these results SM predictions can still not explain P5' anomaly

- S-wave form factors for $B \to K\pi$ by S. Descotes-Genon, A. Khodjamirian, J. Virto and K. Vos

arXiv: 2304.02973

- Continue exploring the high-q2 region, with e.g. from $D_s \to \gamma$ to $B_s \to \gamma\mu^+\mu^-$ at high q2

arXiv:2303.02174
arXiv:2308.00034

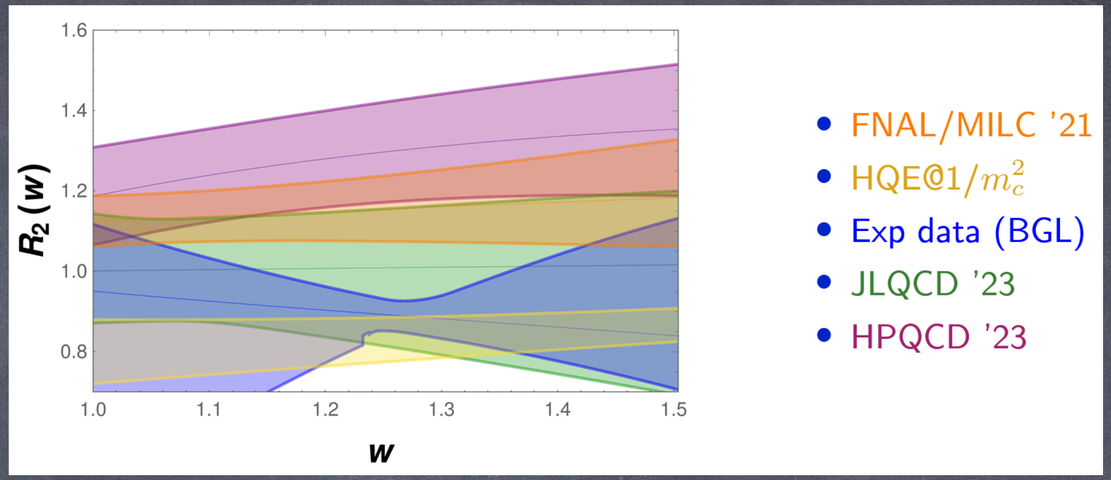
See talk by Irene Bachiller

- Open questions: 1) Can some anomalous branch cuts in charm loop be responsible? 2) Can Lattice QCD help? 3) Can we extract the q2 behavior from data?

See talks by Christina Agopopoulou, Salvador Rosauro-Alcaraz7

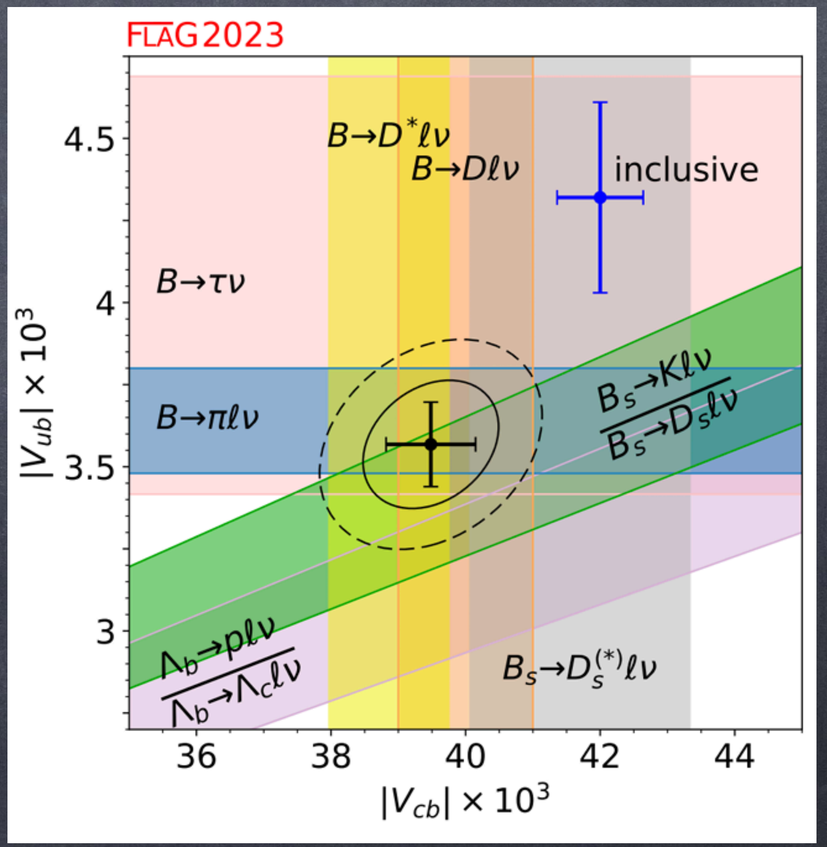
b to c

- Recent result for B→D∗ from HPQCD and JLQCD arXiv: 2306.05657 arXiv: 2304.03137



- New results for B to D* from Belle II inconsistent with Fermilab/MILC R1 and R2, and new HPQCD, new JLQCD in better agreement, but larger uncertainties

- Crucial to resolve this inclusive exclusive discrepancy, as mentioned earlier important quantity for: unitarity tests, ϵ_K, $\mathcal{B}(B_s \to \mu^+\mu^-)$, $\mathcal{B}(B \to K\nu\bar{\nu})$

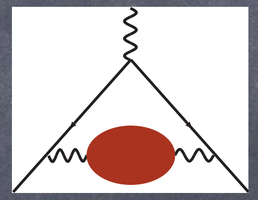


- On inclusive side, recent improvements involve QED effects in inclusive semi-leptonic B decays arXiv: 2309.02849 M. Bordone, D. Bigi, P. Gambino, U. Haisch and A. Piccione, Non-perturbative LQCD methods for inclusive decays in development (Gambino et al) arXiv: 2203.11762

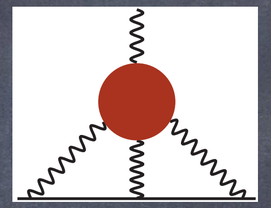
See talk by Ludovico Vittorio., Bogdan Dobrescu

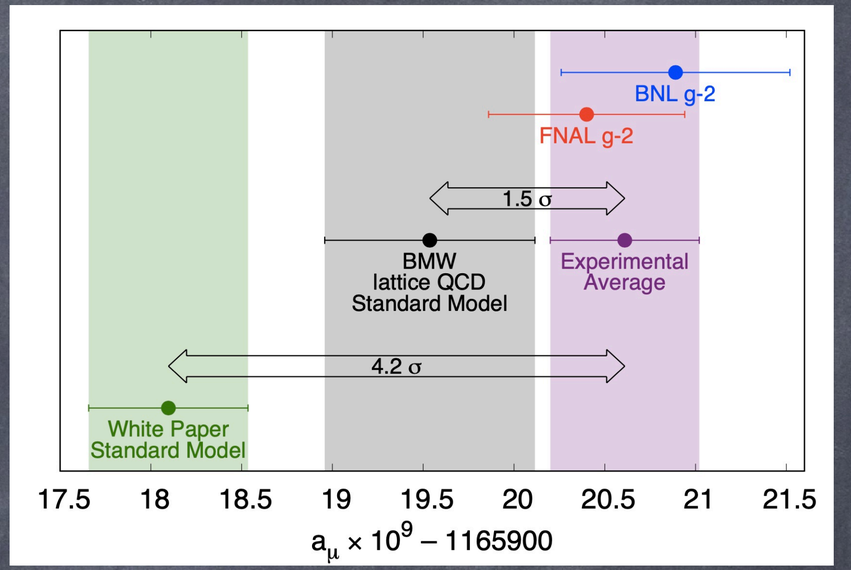
Recent g-2 progress

- Hadronic Vacuum Polarisation (HVP, α^2)
  - Target precision: ~0.2%
  - BMW' 21 : $a_\mu^{\mathrm{LO-HVP}} = (707.5 \pm 5.5) \times 10^{-10}$ arXiv:2002.12347

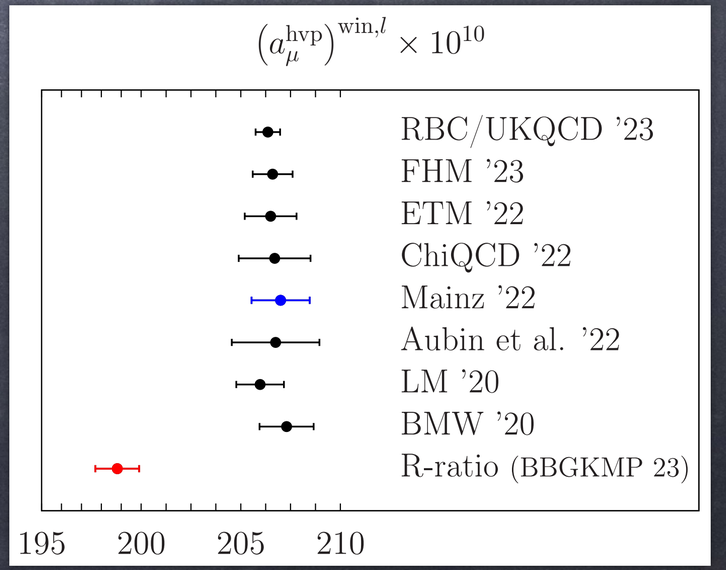


- Hadronic Light-by-Light scatt. (HLbL, α^3)
  - Target precision ~10%
  - LQCD π^0, η, η' form factors+g-2 LBL—> 6% precision by A. Gérardin, W. Verplanke, G. Wang, Z. Fodor, J. Guenther, L. Lellouch, K. K. Szabo, L. Varnhorst arXiv:2305.04570





- Intermediate window : ~30% of the total contribution
  - Easier to compute on lattice (and accessible from R-ratio data !) → small finite-volume effects, small electromagnetic correction
  - significant tension between lattice calculations vs data-driven approach



See talk by Marc Knecht

Exciting programme for the non-perturbative working group session:

14:00 → 16:00 **GDR-InF Annual Workshop: Non-perturbative aspects** — Mont Sainte Odile

Conveners: Aoife Bharucha (CPT, Marseille), Benjamin Audurier (CEA), Dorothea vom Bruch (Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France)

- 14:00 **Overview** — 20m
  Speaker: Aoife Bharucha (CPT, Marseille)
- 14:30 **g-2 overview** — 25m
  Speaker: Marc KNECHT (CNRS)
- 14:55 **QCD x QED on the lattice** — 20m
  Speaker: Giuseppe Gagliardi
- 15:15 **Unitarity constraints and hadronic form factors within the Dispersive Matrix approach** — 20m
  Speaker: Ludovico Vittorio (LAPTh, Université Savoie Mont-Blanc and CNRS, Annecy, France)

16:00 → 16:30 **Coffee break** — 30m

16:30 → 18:30 **GDR-InF Annual Workshop: Non-perturbative aspects** — Mont Sainte Odile

Conveners: Aoife Bharucha (CPT, Marseille), Benjamin Audurier (CEA), Dorothea vom Bruch (Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France)

- 16:30 **Measurement of the branching fractions of $B \to D^{(*)}KK^{(*)}$ decays in Belle II** — 20m
  Speaker: Valerio Bertacchi (Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France)
- 17:00 **Studies in non-leptonic B meson decays through flavour symmetries and some little puzzles** — 20m
  Speaker: Gilberto Tetlalmatzi-Xolocotzi
- 17:30 **Overview PIXEL workshop** — 20m
  Speaker: Benjamin Audurier (CEA)

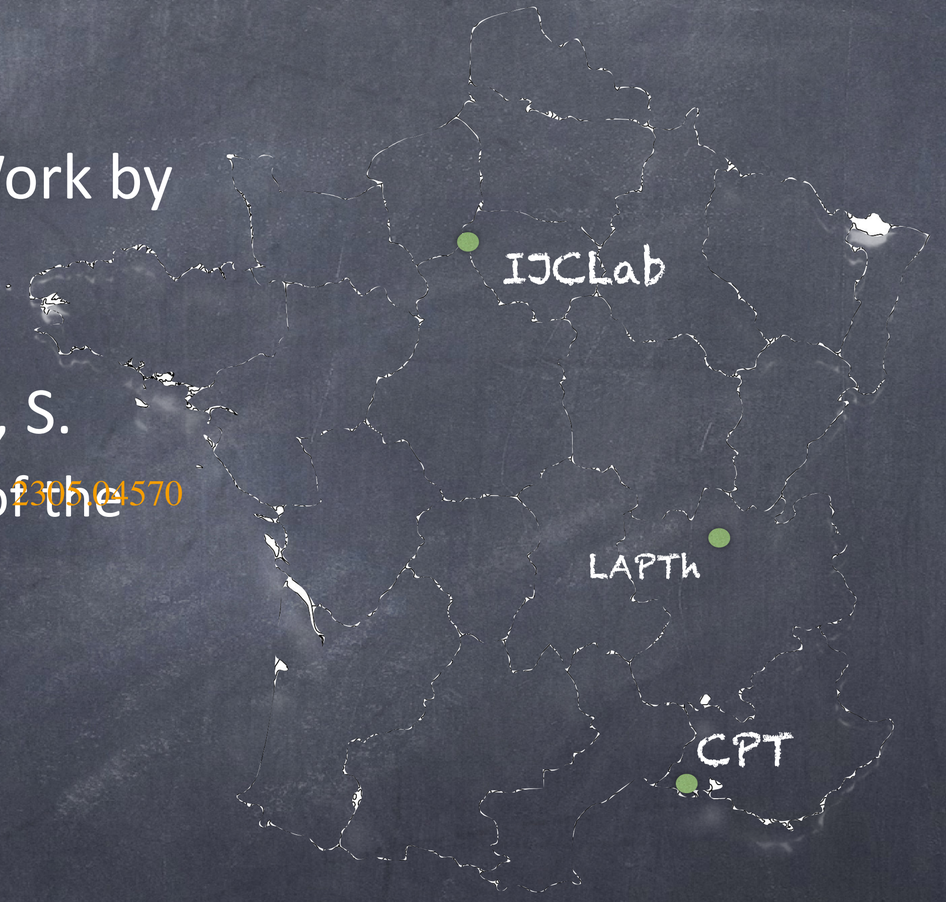
Recent work in France

- IJCLab (B. Blossier, S. Descotes-Genon, M. Reboud) : Work by SDG and MR on b to s, see next slide
- CPT (AB, J. Charles, A. Gerardin, M. Knecht, L. Lellouch, S. Zafeiropolous) : Work on g-2, see slide 10. Determination of the structure of the K→πππ amplitudes from recent data G. D'Ambrosio, M. Knecht, S. Neshatpour

arXiv: 2305.04570

- LAPTh (D. Guadagnoli): $B_s \to \gamma\mu^+\mu^-$,

arXiv: 2209.02143



arXiv:2303.02174
arXiv:2308.00034

See also talks by Ludovico Vittorio (LAPTh) and Marc Knecht (CPT) !!

New results in heavy flavour spectroscopy

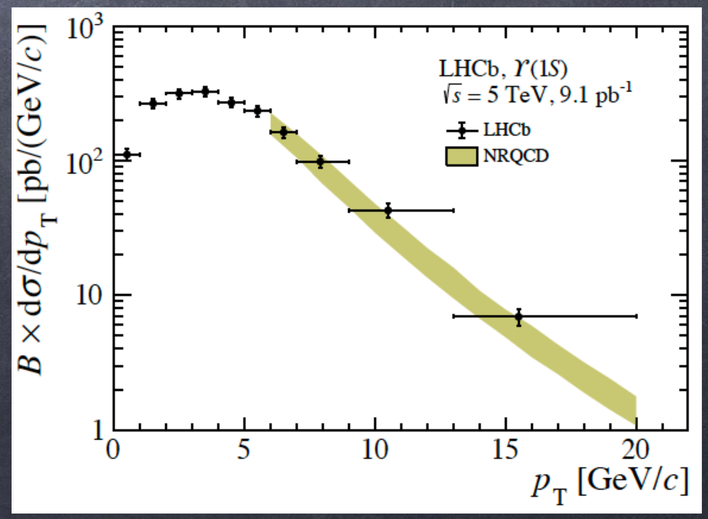
- First observation of two new excited Ωc states near ΞD and ΞD* thresholds, confirmed by Belle 2302.04733 5 new narrow states observed by LHCb in 2017, 4 of them confirmed by Belle Use full Run1+Run2 data [9 fb-1] All previous states confirmed with improved masses and widths precision, Two new states (near ΞD and ΞD* thresholds) Ωc(3185)0, Ωc(3327)
- Search for new Ξ**b states in m(Ξb π+π-) with Run1+Run2 data Ξ-/0b → Ξ0/+c π- and Ξ0/+c π-π+π- (max. 9 tracks!) First observation of Ξb(6087) and Ξb(6095) – LHCb-PAPER-2023-008 (In preparation)
- Most precise measurement of mass difference and production ratio of Ω-b and Ξ-b arXiv:2305.15329
- Cross-sections of Υ mesons measured with improved precision arXiv:2212.12664
- First measurement of prompt J/ψ – Υ associated production, effective cross-section was found compatible with other hadro-production measurements arXiv:2305.15580

new

Resonance	m (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.44 \pm 0.07\ ^{+0.07}_{-0.13} \pm 0.23$	$3.83 \pm 0.23\ ^{+1.59}_{-0.29}$
$\Omega_c(3050)^0$	$3050.18 \pm 0.04\ ^{+0.06}_{-0.07} \pm 0.23$	$0.67 \pm 0.17\ ^{+0.64}_{-0.72}$
		< 1.8 MeV, 95% C.L.
$\Omega_c(3065)^0$	$3065.63 \pm 0.06\ ^{+0.06}_{-0.06} \pm 0.23$	$3.79 \pm 0.20\ ^{+0.38}_{-0.47}$
$\Omega_c(3090)^0$	$3090.16 \pm 0.11\ ^{+0.06}_{-0.10} \pm 0.23$	$8.48 \pm 0.44\ ^{+0.61}_{-1.62}$
$\Omega_c(3119)^0$	$3118.98 \pm 0.12\ ^{+0.09}_{-0.23} \pm 0.23$	$0.60 \pm 0.63\ ^{+0.90}_{-1.05}$
		< 2.5 MeV, 95% C.L.
$\Omega_c(3185)^0$	$3185.1 \pm 1.7\ ^{+7.4}_{-0.9} \pm 0.2$	$50 \pm 7\ ^{+10}_{-20}$
$\Omega_c(3327)^0$	$3327.1 \pm 1.2\ ^{+0.1}_{-1.3} \pm 0.2$	$20 \pm 5\ ^{+13}_{-1}$

New

	Value [MeV]
Q_0 $[\Xi_b(6100)^-]$	$23.60 \pm 0.11 \pm 0.02$
Γ $[\Xi_b(6100)^-]$	$0.94 \pm 0.30 \pm 0.08$
m_0 $[\Xi_b(6100)^-]$	$6099.74 \pm 0.11 \pm 0.02 \pm 0.6\ (\Xi_b^-)$
Q_0 $[\Xi_b(6087)^0]$	$16.20 \pm 0.20 \pm 0.06$
Γ $[\Xi_b(6087)^0]$	$2.43 \pm 0.51 \pm 0.10$
m_0 $[\Xi_b(6087)^0]$	$6087.24 \pm 0.20 \pm 0.06 \pm 0.5\ (\Xi_b^0)$
Q_0 $[\Xi_b(6095)^0]$	$24.32 \pm 0.15 \pm 0.03$
Γ $[\Xi_b(6095)^0]$	$0.50 \pm 0.33 \pm 0.11$
m_0 $[\Xi_b(6095)^0]$	$6095.36 \pm 0.15 \pm 0.03 \pm 0.5\ (\Xi_b^0)$



From Lepton Photon 23 talk by Yixiong Zhou