FLAVOUR PHYSICS @ IPPP

Alexander Lenz, 29.3.2017

CONTENT

- People
- Science
- Interaction with the community
- International comparison

PEOPLE

PEOPLE –STAFF

Past:

2001 - 2010

Patricia Ball

retired

2011

Thorsten Feldmann

University of Siegen

Present:

since 2005

Silvia Pascoli

representing

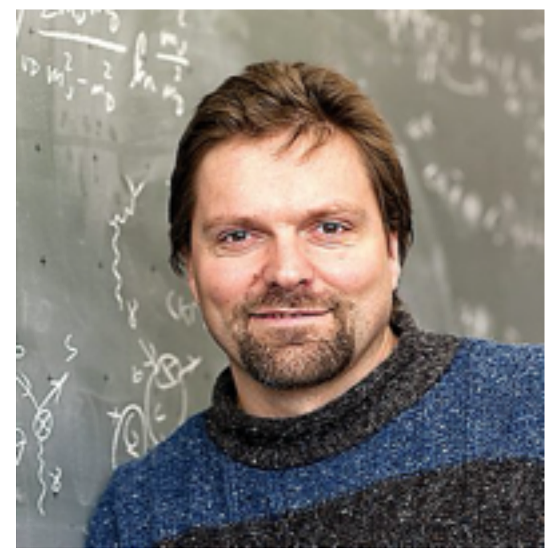
leptons - not covered

since 2012

Ben Pecjak

representing

top physics



since 2012

Alexander Lenz

representing

beauty +charm

since 2001

Valery Khoze

part-time flavour

exclusive processes

Future: *2017 new lecturer in neutrino physics*

PEOPLE – WHO DO THE REAL WORK

Past:

2013-'15:PD

Martin Wiebusch

Private Sector

2014-'16:PD

Rhorry Gauld

Zurich

2012-'16:PhD Lenz

Gilberto Tetlalmatzi

Nikhef

Present:

since 2016 PD

Thomas Rauh

Higher orders

since 2013 PhD

Darren Scott

Pecjak

since 2013 PhD

Tom Jubb

Lenz

since 2014 PhD

Matthew Kirk

Lenz

since 2016 PhD

Jonathan Cullen

Pecjak

SCIENCE

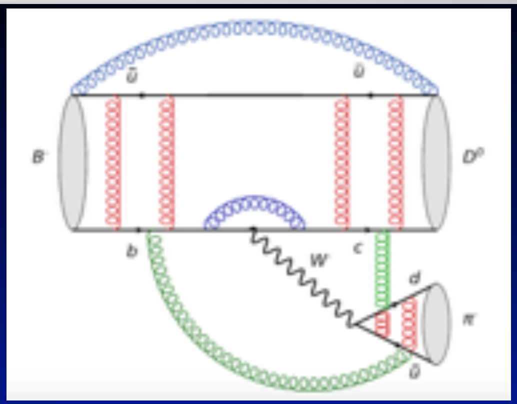
MOTIVATION FOR FLAVOUR PHYSICS

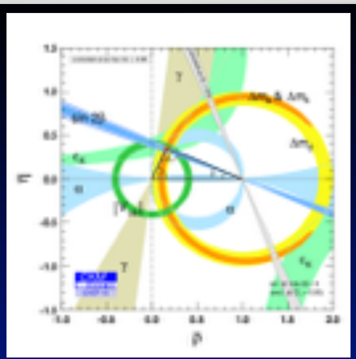
Baryon Asymmetry in the Universe:
A violation of the CP symmetry - which causes matter and anti-matter to evolve differently with time - seems to be necessary to explain the existence of matter in the Universe.
CP violation has so far only been found in hadron decays, which are experimentally investigated at LHCb and NA62 (CERN), SuperBelle (Japan),...

Indirect Search for New Physics:
To find hints for New Physics beyond the Standard Model we can either use brute force (= higher energies) or more subtle strategies like high precision measurements.
New contributions to an observable f are identified via:

$$f^{\mathrm{SM}} + f^{\mathrm{NP}} = f^{\mathrm{Exp}}$$

Understanding QCD:
Hadron decays are strongly affected by QCD (strong interactions) effects, which tend to overshadow the interesting fundamental decay dynamics. Theory tools like effective theories, Heavy Quark Expansion, HQET, SCET ,...enable a control over QCD-effects and they are used in other fields like Collider Physics, Higgs Physics, DM searches...



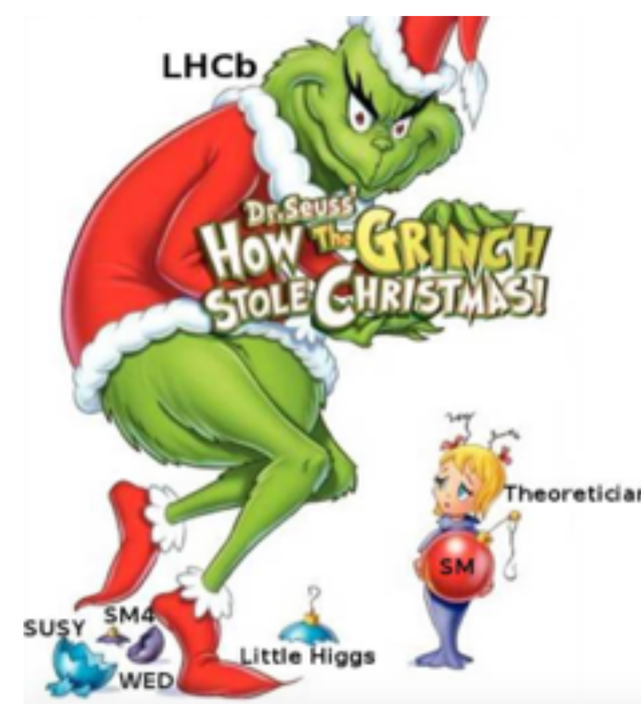


Standard Model parameters:
Hadron decays depend strongly on Standard Model parameters like quark masses and CKM couplings (which are the only known source of CP violation in the SM). A precise knowledge of these parameters is needed for all branches of particle physics.

STATUS OF FLAVOUR PHYSICS IN 2017

- **Huge** experimental progress: B-factories, Tevatron and LHC
- **LHCb**: 370 papers
  16841 citations
  till 2016 5fb-1

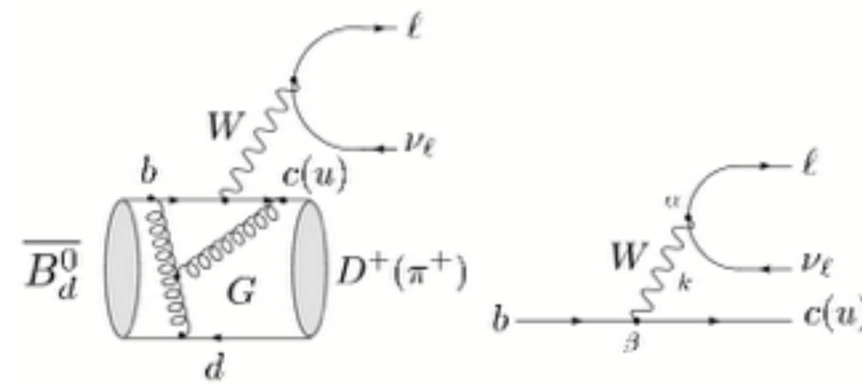
- SM and CKM mechanism work perfectly
- Experimental errors often smaller than theory ones
- Textbook wisdom might have to be re-considered
- Several interesting deviations
- Bounds on NP/DM models



FLAVOUR DEVIATIONS IN 2017 $2\,\sigma - 5\,\sigma$

- Tree-level semi leptonic

$$V_{ub},\ V_{cb} \quad R_{D^{(*)}} = \frac{Br(\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau)}{Br(\bar{B} \to D^{(*)} l^- \bar{\nu}_l)}$$



- Loop-level leptonic

$$B_d \to \mu\mu$$

- Loop-level semi leptonic

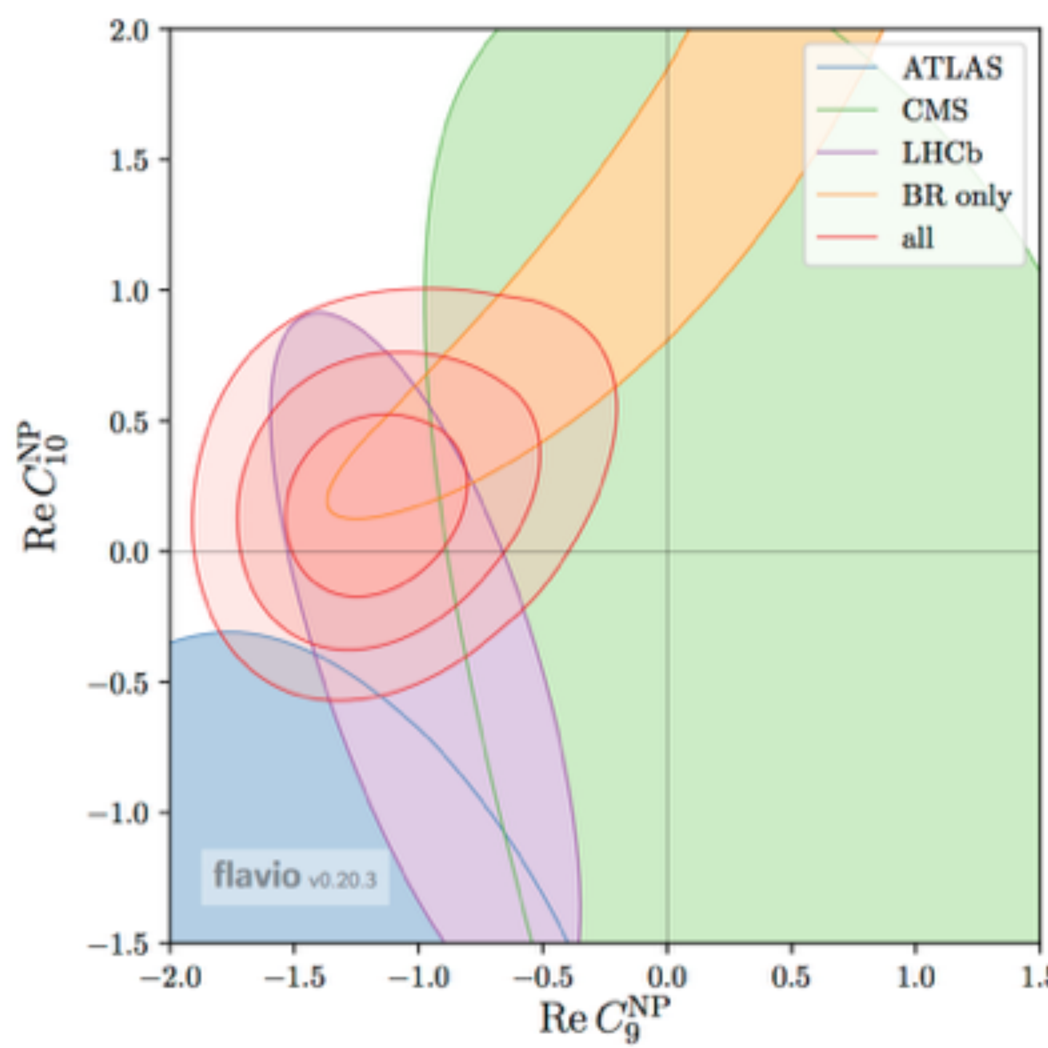
$$R_K = \frac{Br(B^+ \to K^+ \mu^- \mu^+)}{Br(B^+ \to K^+ e^- e^+)}$$

$$Br(B \to K^* \mu^+ \mu^-),\ P5',\ Br(B_s \to \phi \mu^+ \mu^-)$$

- Mixing: kaons ϵ'/ϵ

  B-mixing ΔM $A_{\text{di-muon}}$

- Non-leptonic: $K\pi$ puzzle

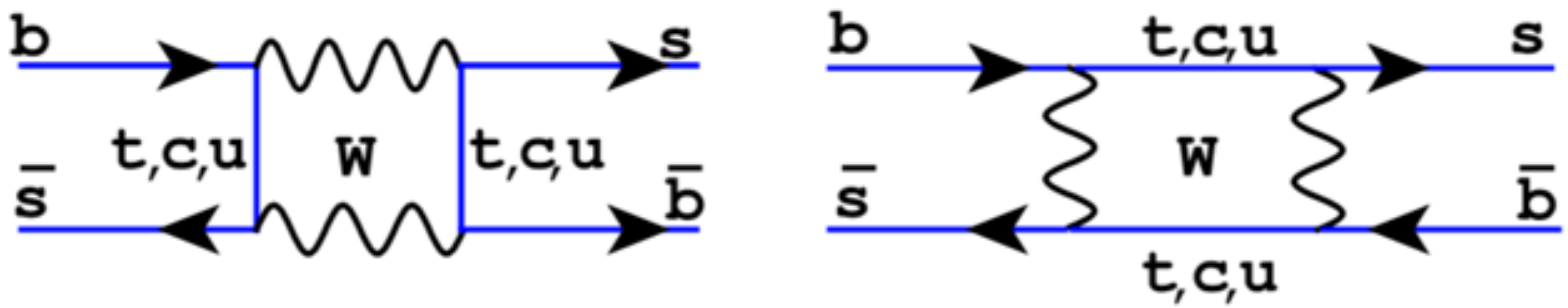


arXiv:1703.09189 [pdf, other]

Status of the $B \to K^* \mu^+ \mu^-$ anomaly after Moriond 2017

Wolfgang Altmannshofer, Christoph Niehoff, Peter Stangl, David M. Straub

THEORY UNCERTAINTIES IN MIXING



B-mixing observables:

$$\Delta M_s = 2|M_{12}^s|\,, \qquad \Delta\Gamma_s = 2|\Gamma_{12}^s|\cos\phi_{12}^s\,, \qquad a_{sl}^s = \left|\frac{\Gamma_{12}^s}{M_{12}^s}\right|\sin\phi_{12}^s$$

Observable	SM – conservative	SM – aggressive	Experiment
ΔM_s	(18.3 ± 2.7) ps^{-1}	(20.11 ± 1.37) ps^{-1}	(17.757 ± 0.021) ps^{-1}
$\Delta\Gamma_s$	(0.088 ± 0.020) ps^{-1}	(0.098 ± 0.014) ps^{-1}	(0.082 ± 0.006) ps^{-1}
a_{sl}^s	$(2.22 \pm 0.27) \cdot 10^{-5}$	$(2.27 \pm 0.25) \cdot 10^{-5}$	$(-7.5 \pm 4.1) \cdot 10^{-3}$

Ideal for NP searches - experimental precision higher than theory

On the ultimate precision of meson mixing observables
Thomas Jubb, Matthew Kirk, Alexander Lenz, Gilberto Tetlalmatzi-Xolocotzi
Published in Nucl.Phys. B915 (2017) 431-453

THEORY UNCERTAINTIES IN MIXING

$\Delta\Gamma_s^{SM}$	This work
Central value	0.088 ps^{-1}
$\delta(B_{\tilde{R}_2})$	14.8%
$\delta(f_{B_s}\sqrt{B})$	13.9%
$\delta(\mu)$	8.4%
$\delta(V_{cb})$	4.9%
$\delta(\tilde{B}_S)$	2.1%
$\delta(B_{R_0})$	2.1%
$\delta(\bar{z})$	1.1%
$\delta(m_b)$	0.8%
$\delta(B_{\tilde{R}_1})$	0.7%
$\delta(B_{\tilde{R}_3})$	0.6%
$\delta(B_{R_1})$	0.5%
$\delta(B_{R_3})$	0.2%
$\delta(m_s)$	0.1%
$\delta(\gamma)$	0.1%
$\delta(\alpha_s)$	0.1%
$\delta(\lvert V_{ub}/V_{cb}\rvert)$	0.1%
$\delta(\bar{m}_t(\bar{m}_t))$	0.0%
$\sum\delta$	22.8%

Dominant uncertainties from hadronic MEs:

$$\langle R_2\rangle = -\frac{2}{3}\left[\frac{M_{B_s}^2}{m_b^{\text{pow2}}} - 1\right] M_{B_s}^2 f_{B_s}^2 B_{R_2},$$

$$R_2 = \frac{1}{m_b^2}\,\bar{s}_\alpha \overleftarrow{D}_\rho \gamma^\mu(1-\gamma_5)D^\rho b_\alpha\,\bar{s}_\beta\gamma_\mu(1-\gamma_5)b_\beta$$

Dim 7 is has never been done

-**Wingate** works on lattice

-**Rauh, Kirk, Lenz** with QCD sum rules

$$\langle Q\rangle \equiv \langle \bar{B}_s^0|Q|B_s^0\rangle = \tfrac{8}{3}M_{B_s^0}^2 f_{B_s}^2 B(\mu)$$

$$Q = \bar{s}^\alpha\gamma_\mu(1-\gamma_5)b^\alpha \times \bar{s}^\beta\gamma^\mu(1-\gamma_5)b^\beta$$

Dim 6 is done on the lattice

newest results (**Fermilab MILC 1602:03560**)

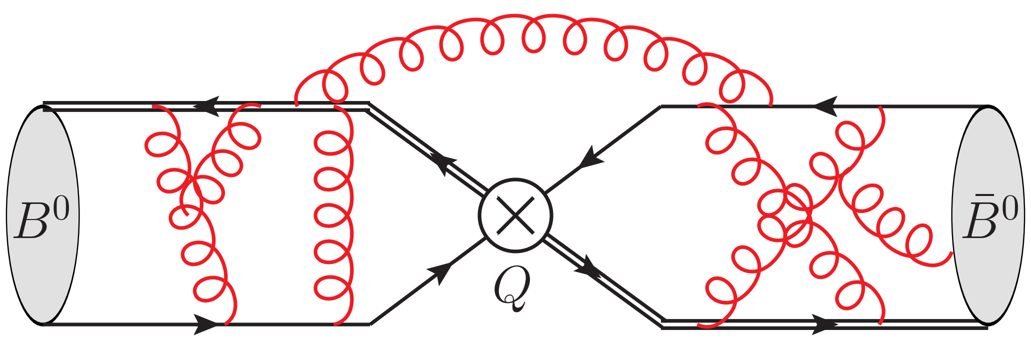
indicate a small tension with experiment

CP violation in the Bs system

Marina Artuso, Guennadi Borissov, Alexander Lenz

Rev.Mod.Phys. 88 (2016) no.4,045002

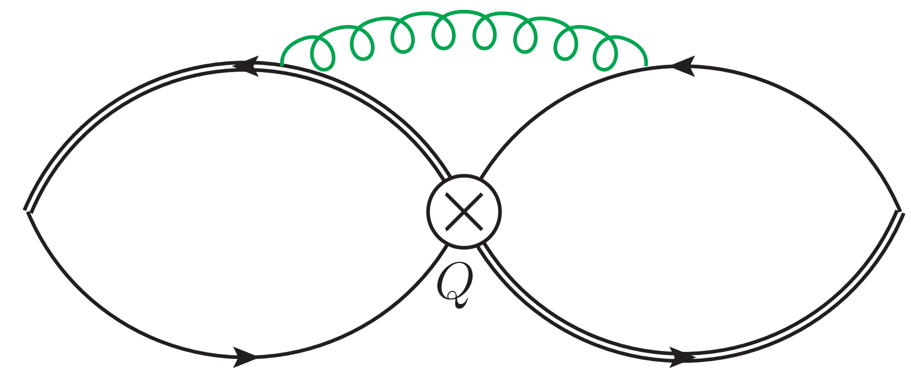
THEORY UNCERTAINTIES IN MIXING



Sum rule

Quark-hadron duality

Analyticity



Hadronic matrix element

Characteristic scale: Λ_{QCD}

$\alpha_s\left(\Lambda_{\text{QCD}}\right) \sim \mathcal{O}(1)$

$\Rightarrow$ non-perturbative

Correlation function

Characteristic scale: 'virtuality' ω

Choose ω s.t. $\alpha_s(\omega) \ll 1$

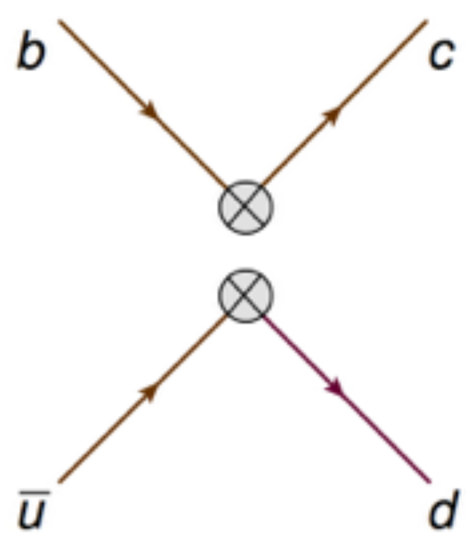
$\Rightarrow$ perturbatively calculable

- Do all dim 6 and dim 7 operators (operator Q done by Siegen group)
- 3 loop diagrams with FIRE reduced
- Master integrals known
- Expect to reduce uncertainty by a factor of up to two!

NP IN TREE-LEVEL DECAYS

Common lore: tree-level decays are not affected by NP

$$\hat{\mathcal{H}}_{eff} = \frac{V_{cb} V_{ud}^*}{\sqrt{2}} \left(C_1 \hat{Q}_1 + C_2 \hat{Q}_2 \right)$$

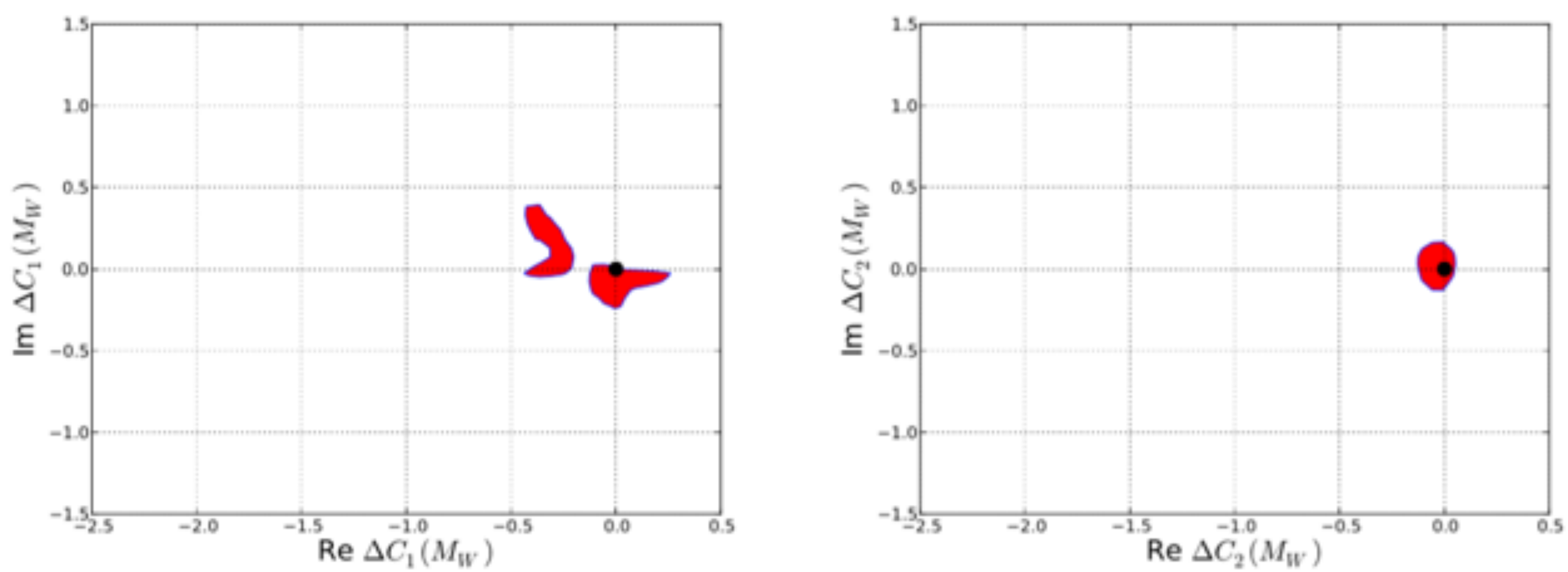


Do a systematic study of tree-level observables

that are both well known in experiment and theory

$$C_{1,2}^{SM} \to C_{1,2}^{SM} + \Delta C_{1,2}$$

Result: what does this mean?



NP IN TREE-LEVEL DECAYS

- Decay rate difference of neutral Bd mesons, $\Delta\Gamma_d$, can be enhanced by several 100%

  work triggered by D0 di-muon asymmetry - **Borissov**

  work triggered ATLAS measurement of $\Delta\Gamma_d$ - **Borissov**

On new physics in $\Delta\Gamma_d$
Bobeth, Haisch, Lenz, Pecjak, Tetlalmatzi-Xolocotzi
JHEP 1406 (2014) 040

- Extraction of CKM angle γ can be modified by several degrees

  SM precision: 1 ppm

  Experimental precision: now 6deg, future 1 deg

NP effects in tree-level decay and the precision of γ
Brod, Lenz, Tetlamatzi-Xolocotzi Alexander Lenz
Rev.Mod.Phys. 88 (2016) no.4,045002

- More profound analysis in progress **Tetlalmatzi-Xolocotzi**

till now only SM Dirac structures

NP IN RARE B DECAYS

Is there a connection between mixing and rare decays?

Charming new physics in rare B-decays and mixing
Jaeger, Kirk, Lenz, Leslie
arXiv: 1701.09183

Consider NP in tree-level b -> ccs traditions with general Dirac structures

$$\mathcal{H}_{\text{eff}}^{c\bar{c}} = \frac{4G_F}{\sqrt{2}} V_{cs}^* V_{cb} \sum_{i=1}^{10} (C_i^c Q_i^c + C_i^{c\prime} Q_i^{c\prime})$$

$$Q_1^c = (\bar{c}_L^i \gamma_\mu b_L^j)(\bar{s}_L^j \gamma^\mu c_L^i), \qquad Q_2^c = (\bar{c}_L^i \gamma_\mu b_L^i)(\bar{s}_L^j \gamma^\mu c_L^j),$$
$$Q_3^c = (\bar{c}_R^i b_L^j)(\bar{s}_L^j c_R^i), \qquad Q_4^c = (\bar{c}_R^i b_L^i)(\bar{s}_L^j c_R^j). \quad (2)$$

This affects rare decays and mixing/lifetimes:

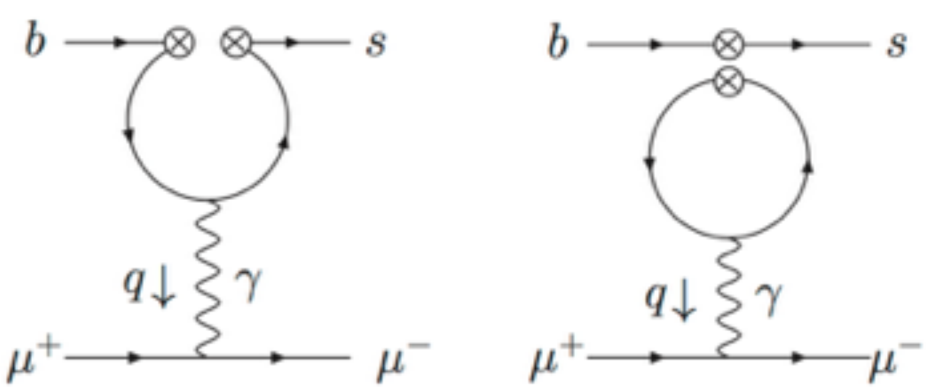


FIG. 1. Leading Feynman diagrams for CBSM contributions to rare and semileptonic decays. With our choice of Fierz-ordering, only the diagram on the left is relevant.

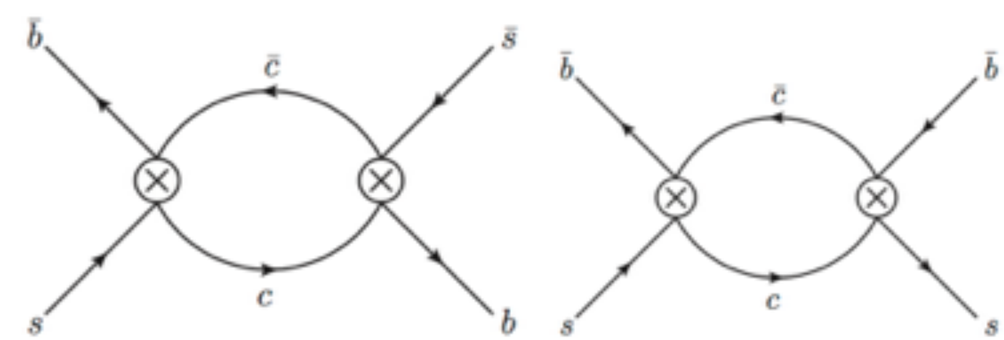
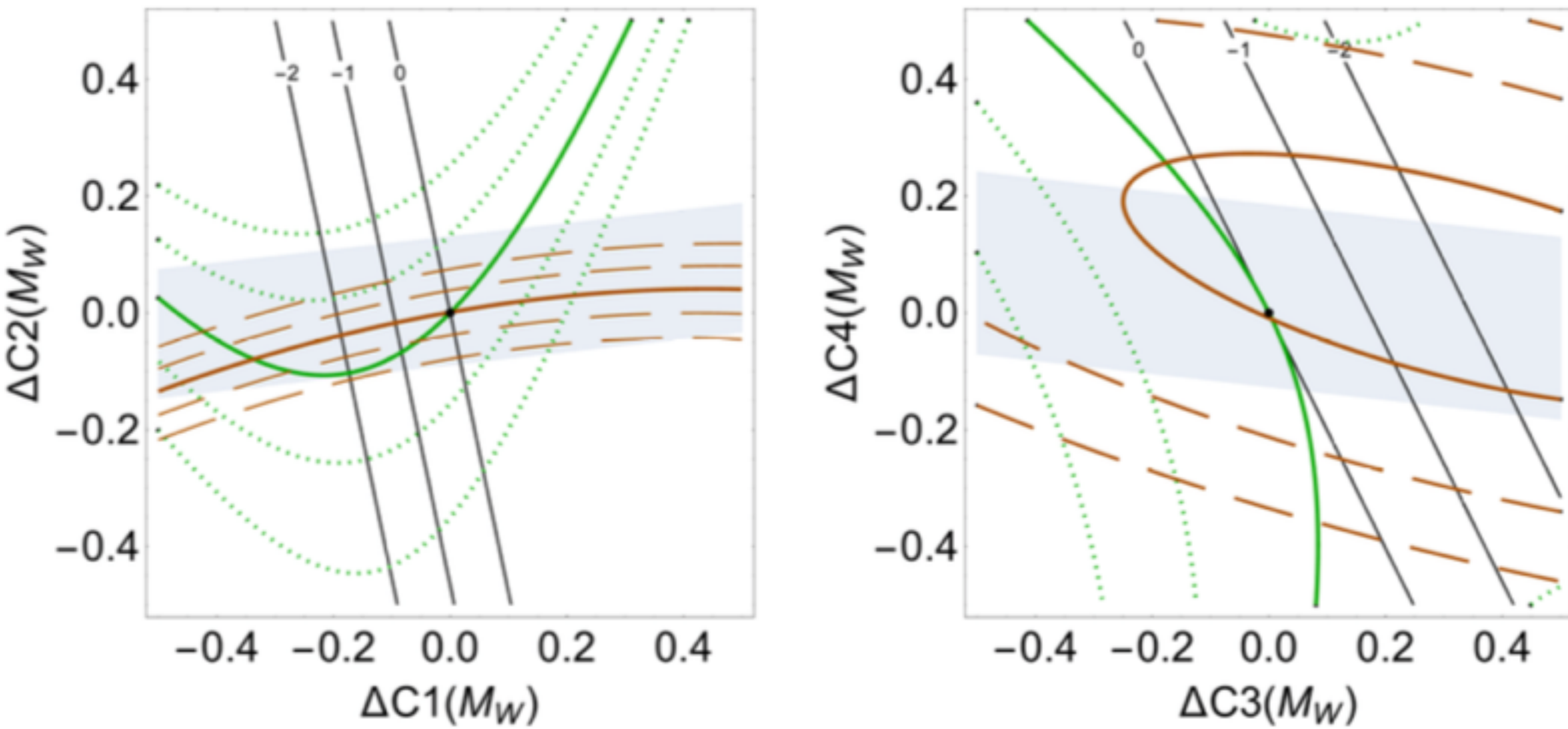


FIG. 2. Leading Feynman diagrams for CBSM contributions to the width difference $\Delta\Gamma_s$ (left) and the lifetime ratio $\tau(B_s)/\tau(B_d)$ (right).

NP IN RARE B DECAYS

- Deviation in rare B-decays can be explained without violation other bounds



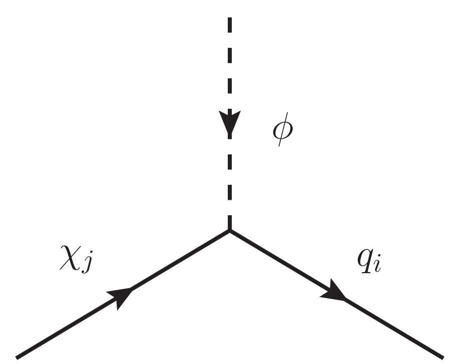
- it is possible that NP in rare decays is q^2 dependent!
- more profound study in progress: **Jaeger, Kirk, Lenz, Leslie**

CHARMING DM

DM coupling to b-quark has been studied several times

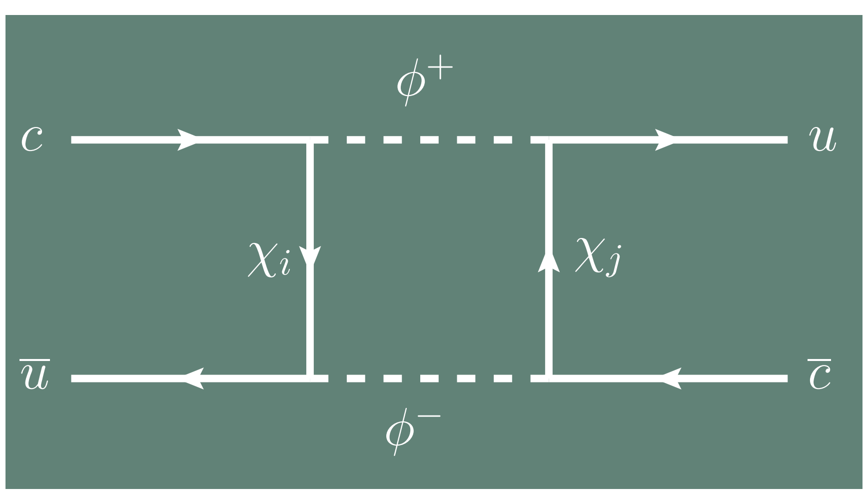
charm has peculiar features e.g. extreme GIM cancellation

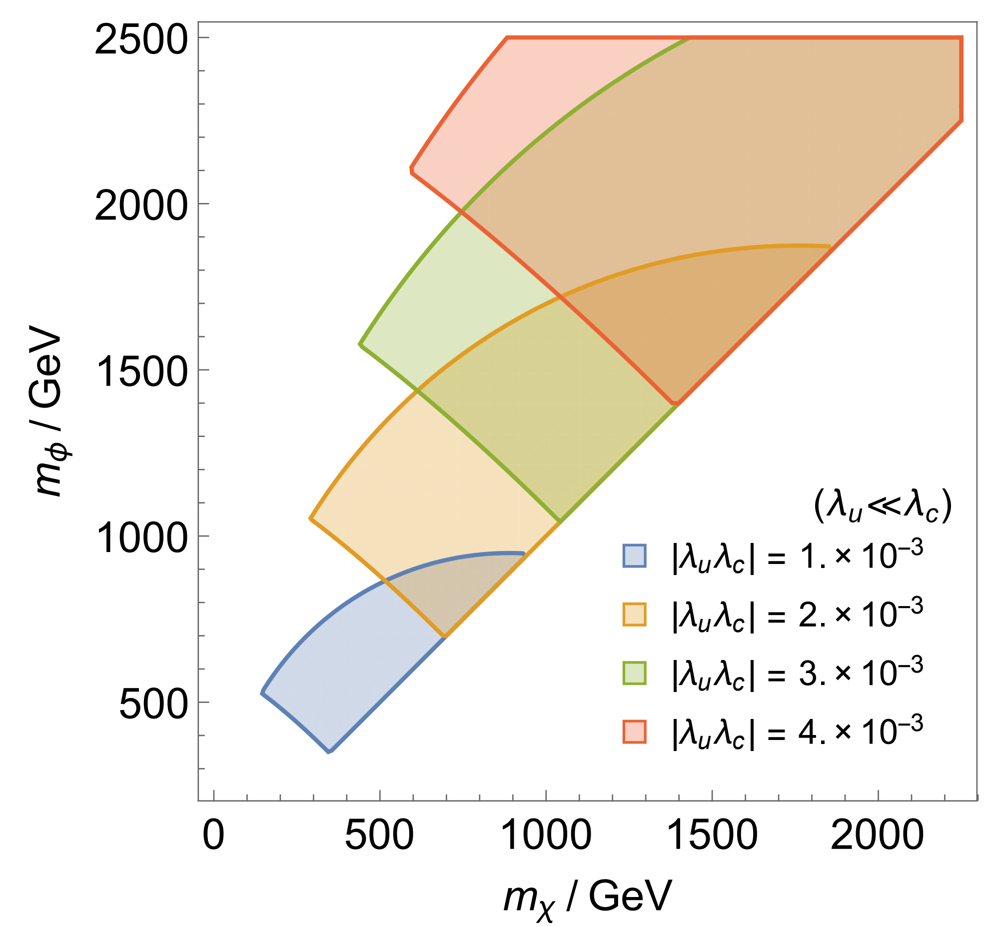
Consider:



$: (\lambda)_{ij}$

Flavour constraints:

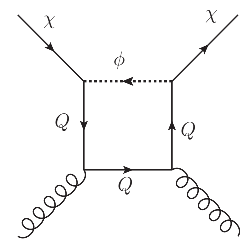


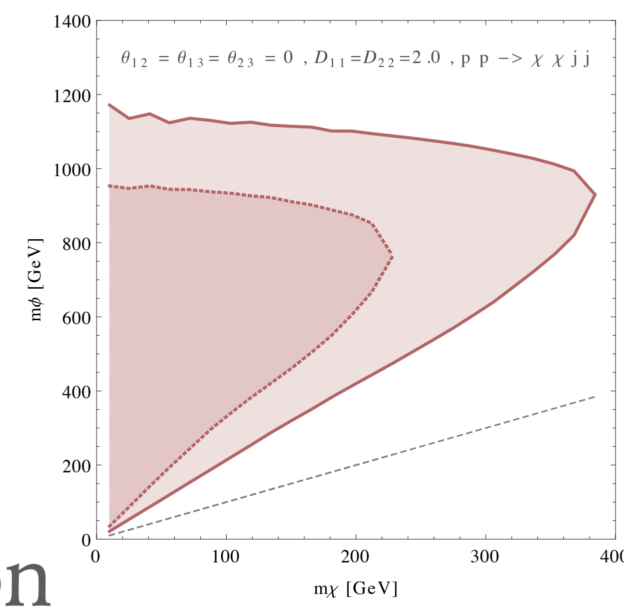


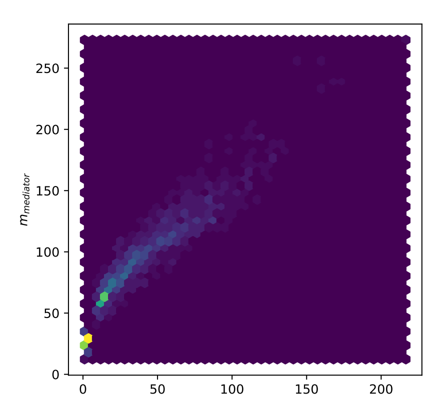
CHARMING DM

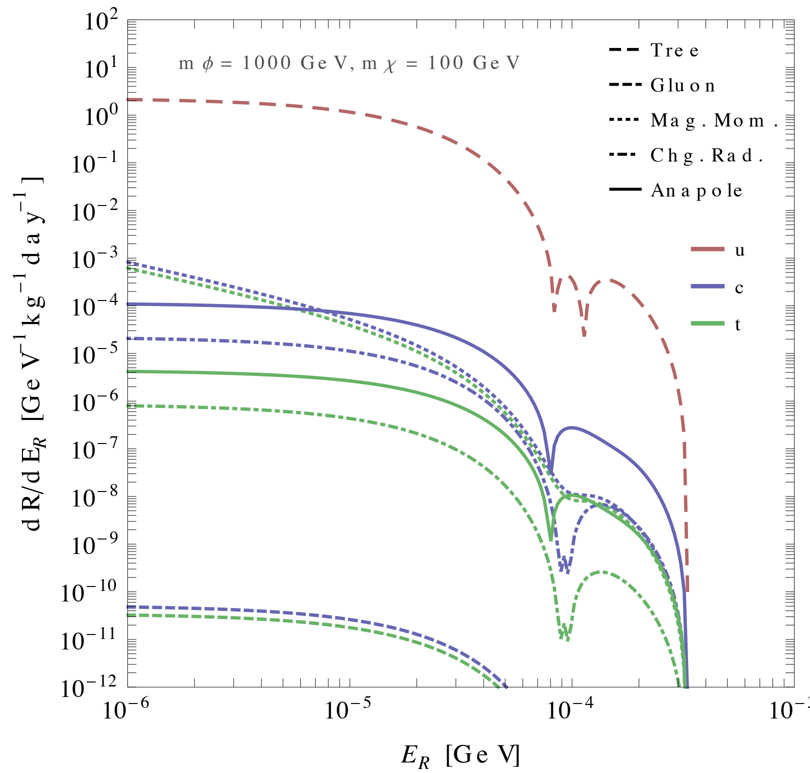
Try to do all possible constraints:

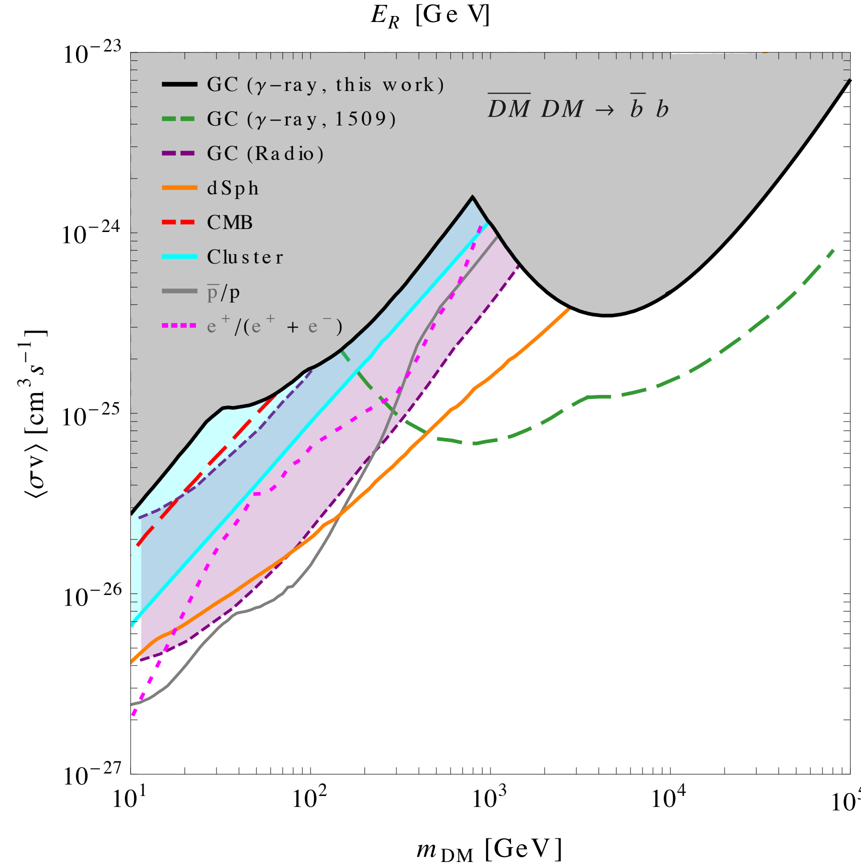
1. Direct detection
2. Collider constraints
3. EW precision
4. Relic density
5. Gamma lines
6. Indirect detection











study in progress: **Jubb, Kirk**

TOP+EXCLUSIVE REACTIONS

➤ Ben Pecjak: QCD resummation for boosted top pair production

1. Energetic (boosted) top-quark production (p_T >>mt) important for new physics searches.
2.Resummation effects beyond NLO important due to multiple scales
[**Pecjak, Scott et. al.** Phys.Rev.Lett. 116 (2016) no.20, 202001]
3.work in progress on matching NNLO with resummed result
[**Pecjak, Scott, Czakon, Mitov** et. al. to appear]
4.similar techniques apply to top-pair + (Z,W, or Higgs production)
[**Broggio, Ferroglia** et al JHEP 1702 (2017) 126, JHEP 1609 (2016) 089 + others]

➤ Valery Khoze: Exclusive processes

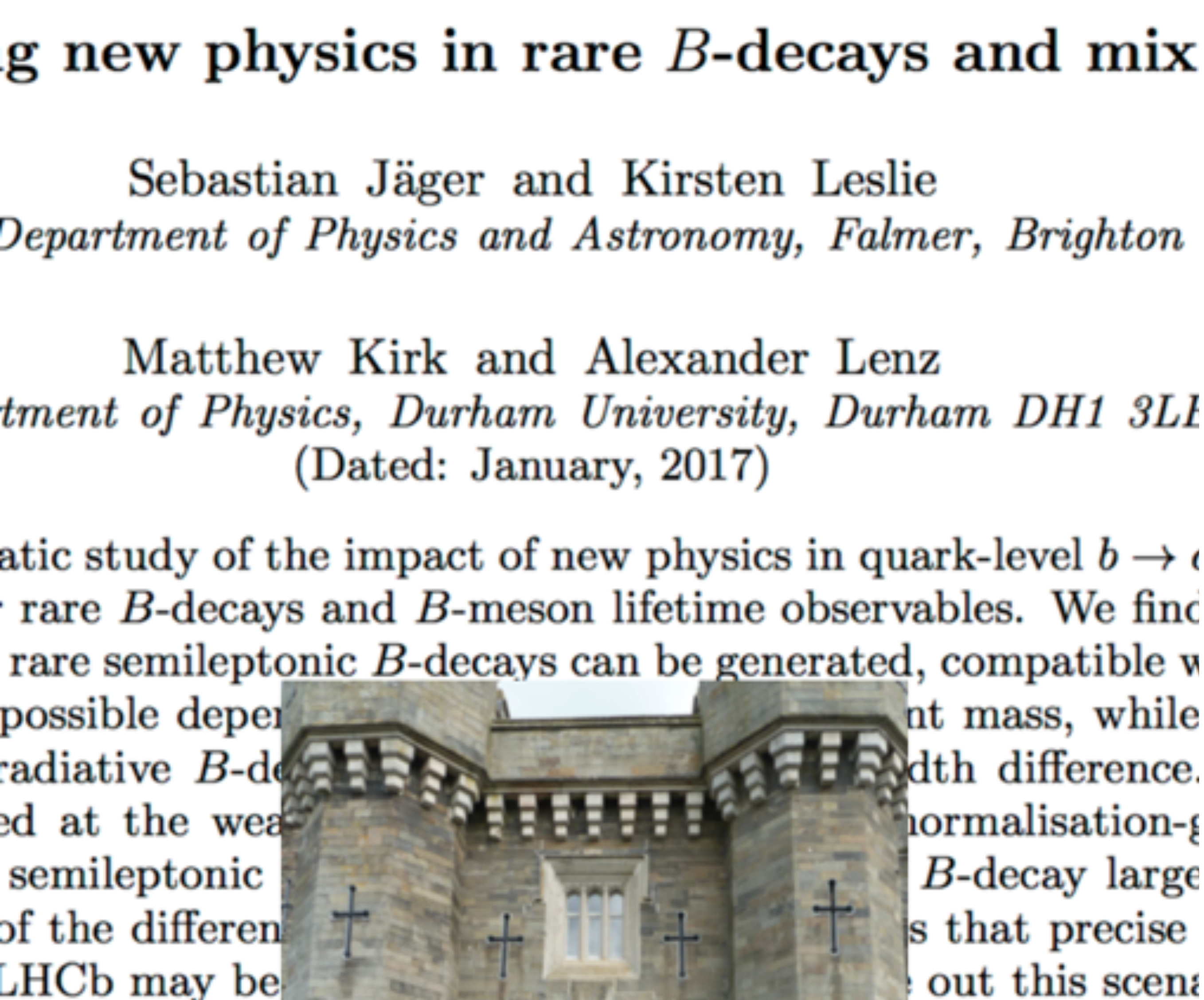
1. **Harland-Lang, Khoze and Ryskin** χc decays and the gluon content of the η', η mesons
arXiv:1703.04682
This paper addresses a long-standing problem of how to explain the existing data on $\chi c(0,2)\to\eta(')\eta(')$ branching ratios and the current understanding of the size of the gluon component of the η', η1.
2. **Harland-Lang, Khoze and Ryskin**, Exclusive physics at the LHC with SuperChic 2,
Eur. Phys.J.C76 016 no.1, 9
We presented a range of physics results for central exclusive production processes at the LHC, using the new SuperChic 2 Monte Carlo event generator.In parrticular J /ψ, ψ(2S), Y(1S)) photoproduction, χc,b and ηc,b quarkonia, production are discussed and compared with the recent results from LHCb.SuperChic2 is systematically used by all experimental groups at the LHC.
3. **Harland-Lang, Khoze and Ryskin**, Exclusive production of double J/ψ mesons in hadronic collisions,
J.Phys.G42 no. 5, 055001 (2015)
We presented the first (and the only one) calculation of exclusive double J/ψ production in hadronic collisions. Our predicted cross sections appear to be in good agreement with the LHCb Run–I measurement of exclusive double J/ψ production.

INTERACTION WITH THE COMMUNITY

CONFERENCES/WORKSHOPS

- 2013,’17 UK Flavour Durham
  bring together UK experts from experiment, lattice and pheno
- 2014 LHCbUK meeting Durham
  2015,16,17 organisation of theory part for that meeting
- 2014 YETI Flavour Durham
- 2013 Charm Manchester
- 2013 UK HEP Forum
- 2014 BEACH Birmingham
- 2014 BEAUTY Edinburgh
- 2014 Rare B decays ICL
- 2016 Kaon Birmingham
- 2016 Heavy Flavour-Quo vadis?Ardbeg
- 2017 D-mixing Peak District

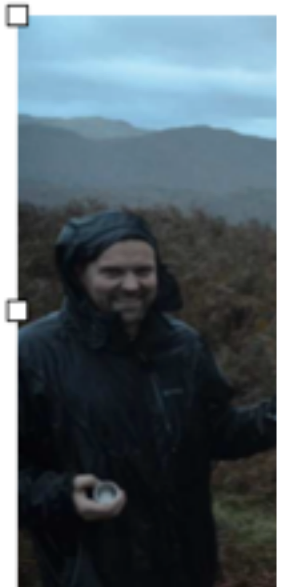
S.E.X. FELLOWS, ASSOCIATESHIPS


g new physics in rare B-decays and mix

Sebastian Jäger and Kirsten Leslie
Department of Physics and Astronomy, Falmer, Brighton

Matthew Kirk and Alexander Lenz
tment of Physics, Durham University, Durham DH1 3LI
(Dated: January, 2017)

atic study of the impact of new physics in quark-level $b \to$
rare B-decays and B-meson lifetime observables. We find
rare semileptonic B-decays can be generated, compatible w
possible deper ... nt mass, while
radiative B-de ... dth difference.
ed at the wea ... ormalisation-
semileptonic ... B-decay large
of the differen ... s that precise
LHCb may be ... out this scena



- **2013,’14 Egede**
  Workshop at Imperial
- **2015,’16 Muheim**
  Workshop at Ardbeg Distillery
- 2012,’13 Gersabeck, Parkes
  Meeting in Lake District
- 2013,’14 Borissov
  Meeting in Lake District, Review of Modern Physics; ATLAS
- 2015,’16 Lazzeroni
  KAON 2016
- 2015,’16 Wingate
  Talk at LHCbUK
- 2015,’16,’17 Jaeger
  First paper in January, visits
- 2016,’17 Gersabeck
  D-mixing workshop in Peak District,
- 2016,’17 Cowan
  Exotics workshop planned

FP SEMINARS IN UK

- 2012 Manchester, Abingdon
- 2013 Lancaster, Edinburgh, Cavendish, DAMTP, Southampton, Manchester, Birmingham,Warwick
- 2014 Plymouth, Bristol, Liverpool, Lancaster, ICL, Edinburgh, Sussex
- 2015 , Edinburgh, Liverpool, Sussex, Glasgow
- 2016 Oxford, Sussex
- 2017 Oxford, Edinburgh

INTERNATIONAL COMPARISON

UK

EXPERIMENT

- University of Birmingham (LHCb)
- University of Bristol (LHCb)
- University of Cambridge (LHCb)
- University of Edinburgh (LHCb)
- University of Glasgow (LHCb)
- Imperial College London (LHCb)
- University of Liverpool (LHCb)
- University of Manchester (LHCb)
- University of Oxford (LHCb)
- STFC Rutherford (LHCb)
- University of Warwick (LHCb)

PHENOMENOLOGY

- IPPP: **Lenz** (Deputy Director), (Pecjak, Khoze)
- Edinburgh: **Zwicky**
- Liverpool: **Gorbahn**
- Sussex: **Jaeger**
- Oxford/CERN: **Haisch**

11 experimental groups vs 5 staff in pheno

Germany

EXPERIMENT

- Aachen (LHCb)
- Dortmund (LHCb)
- MPI Heidelberg (LHCb)
- Heidelberg (LHCb)
- Rostock (LHCb)
- Bonn (BELLE II)
- DESY (BELLE II)
- Giessen (BELLE II)
- Goettingen (BELLE II)
- Hamburg (BELLE II)
- Karlsruhe (BELLE II)
- Mainz (BELLE II)
- Munich: MPI, LMU, TU (BELLE II)

PHENOMENOLOGY

- Siegen: **Mannel, Feldmann, Khodjamirian, Bell, Huber, Pivovarov, (**Lange)
- Munich: **Beneke, Buras, Buchalla,** Straub, (Weiler)
- Mainz: **Neubert, Hurth**,
- KIT: **Nierste, Blanke**, (Steinhauser)
- Dortmund : **Hiller**, Brod (C1)
- MPI Heidelberg: **Goertz**
- DESY: Ali (em.)
- Hamburg: Kramer (em.)
- Heidelberg: Westhoff (C1)
- Aachen: (Czakon)

16 experimental groups vs 15 staff in pheno