(Re)interpretation of Flavour Constraints

Marcin Chrząszcz
University of Zurich & Polish Academy of Sciences

Nazila Mahmoudi
Lyon University & CERN TH

In Collaboration with:
F. Bernlochner, P. Jackson, P.Scott, M.White, N.Serra

(Re)interpreting the results of new physics searches at the LHC
CERN, December 12, 2016

Outline

- ⇛ Theoretical framework for B decays
- ⇛ $B \to K^* \ell^+ \ell^-$ observables and calculations
- ⇛ Numerical approach
- ⇛ Which data do Flavour factories publish
- ⇛ New Physics searches
- ⇛ What would be the best way to exchange the information?
- ⇛ Questions for discussion

Theoretical framework for B decays

A multi-scale problem

- new physics: $\Lambda_{\text{NP}} \gtrsim$ TeV
- electroweak interactions: $M_W \sim 80$ GeV
- hadronic effects: $m_b \sim 5$ GeV
- QCD interactions: $\Lambda_{\text{QCD}} \sim 0.2$ GeV

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$\Rightarrow$ Effective field theory approach:

separation between low and high energies using Operator Product Expansion

- short distance: Wilson coefficients, computed perturbatively
- long distance: local operators

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\sum_{i=1\cdots 10,S,P} \left(C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu) \right) \right)$$

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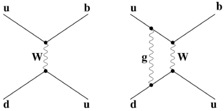
New physics:

- Corrections to the Wilson coefficients: $C_i \to C_i + \Delta C_i^{NP}$
- Additional operators: $\sum_j C_j^{NP} \mathcal{O}_j^{NP}$

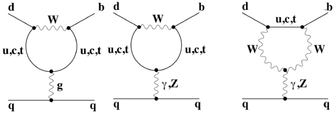
$\mathcal{O}$perators

$$\mathcal{O}_1 = (\bar{s}\gamma_\mu T^a P_L c)(\bar{c}\gamma^\mu T^a P_L b)$$
$$\mathcal{O}_2 = (\bar{s}\gamma_\mu P_L c)(\bar{c}\gamma^\mu P_L b)$$



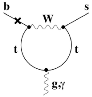
Current

$$\mathcal{O}_3 = (\bar{s}\gamma_\mu P_L b)\sum_q(\bar{q}\gamma^\mu q)$$
$$\mathcal{O}_4 = (\bar{s}\gamma_\mu T^a P_L b)\sum_q(\bar{q}\gamma^\mu T^a q)$$
$$\mathcal{O}_5 = (\bar{s}\gamma_{\mu_1}\gamma_{\mu_2}\gamma_{\mu_3} P_L b)\sum_q(\bar{q}\gamma^{\mu_1}\gamma^{\mu_2}\gamma^{\mu_3} q)$$
$$\mathcal{O}_6 = (\bar{s}\gamma_{\mu_1}\gamma_{\mu_2}\gamma_{\mu_3} T^a P_L b)\sum_q(\bar{q}\gamma^{\mu_1}\gamma^{\mu_2}\gamma^{\mu_3} T^a q)$$



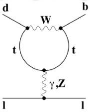
QCD penguins
Electroweak penguins

$$\mathcal{O}_7 = \frac{e}{16\pi^2}\left[\bar{s}\sigma^{\mu\nu}(m_s P_L + m_b P_R)b\right]F_{\mu\nu}$$
$$\mathcal{O}_8 = \frac{g}{16\pi^2}\left[\bar{s}\sigma^{\mu\nu}(m_s P_L + m_b P_R)T^a b\right]G^a_{\mu\nu}$$



Magnetic operators

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{l}\gamma_\mu l)$$
$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{l}\gamma_\mu\gamma_5 l)$$



Semileptonic operators

Wilson coefficients

Two main steps:

- Calculating $C_i^{eff}(\mu)$ at scale $\mu \sim M_W$ by requiring matching between the effective and full theories

$$C_i^{eff}(\mu) = C_i^{(0)eff}(\mu) + \frac{\alpha_s(\mu)}{4\pi} C_i^{(1)eff}(\mu) + \cdots$$

- Evolving the $C_i^{eff}(\mu)$ to scale $\mu \sim m_b$ using the RGE:

$$\mu \frac{d}{d\mu} C_i^{eff}(\mu) = C_j^{eff}(\mu) \gamma_{ji}^{eff}(\mu)$$

driven by the anomalous dimension matrix $\hat{\gamma}^{eff}(\mu)$

SM contributions to $C_i(\mu_b)$ are known to NNLO QCD and NLO EW/QED

Hadronic quantities

To compute the amplitudes:

$$\mathcal{A}(A \to B) = \langle B|\mathcal{H}_{\rm eff}|A\rangle = \frac{G_F}{\sqrt{2}} \sum_i \lambda_i C_i(\mu)\langle B|\mathcal{O}_i|A\rangle(\mu)$$

$\langle B|\mathcal{O}_i|A\rangle$: hadronic matrix element

How to compute matrix elements?

$\longrightarrow$ Model building, Lattice simulations, Light flavour symmetries, Heavy flavour symmetries, ...

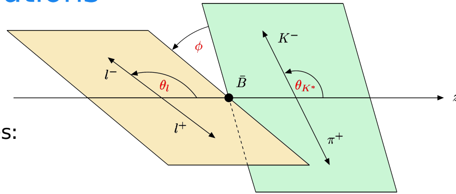
$\longrightarrow$ Describe hadronic matrix elements in terms of **hadronic quantities**

Two types of hadronic quantities:

- **Decay constants**: Probability amplitude of hadronising quark pair into a given hadron
- **Form factors**: Transition from a meson to another through flavour change

$B \to K^* \ell^+ \ell^-$ – Angular distributions

Angular distributions



The full angular distribution of the decay $\bar{B}^0 \to \bar{K}^{*0} \ell^+ \ell^-$ ($\bar{K}^{*0} \to K^- \pi^+$) is completely described by four independent kinematic variables: q^2 (dilepton invariant mass squared), θ_ℓ, θ_{K^*}, ϕ

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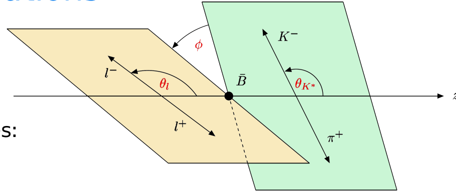
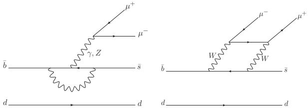


Main operators:

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell), \quad \mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$



F. Kruger et al., Phys. Rev. D 61 (2000) 114028;
W. Altmannshofer et al., JHEP 0901 (2009) 019; U. Egede et al., JHEP 1010 (2010) 056

Differential decay distribution:

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_V\, d\phi} = \frac{9}{32\pi} J(q^2, \theta_\ell, \theta_V, \phi)$$

$J(q^2, \theta_\ell, \theta_V, \phi) = \sum_i J_i(q^2)\, f_i(\theta_\ell, \theta_V, \phi)$

↘ angular coefficients J_{1-9}

↘ functions of the transversity amplitudes A_0, $A_\parallel$, $A_\perp$, A_t, and A_S, Transversity amplitudes: functions of Wilson coefficients and form factors

$B \to K^* \ell^+ \ell^-$ – Amplitudes

A closer look to the Effective Hamiltonian:

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$$

$$\mathcal{H}_{\rm eff}^{\rm sl} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Big[\sum_{i=7,9,10} C_i^{(\prime)} O_i^{(\prime)} \Big]$$

$\langle \bar{K}^* | \mathcal{H}_{\rm eff}^{\rm sl} | \bar{B} \rangle$: $B \to K^*$ form factors $V, A_{0,1,2}, T_{1,2,3}$

Transversity amplitudes:

$$A_\perp^{L,R} \simeq N_\perp \left\{ (C_9^+ \mp C_{10}^+) \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} C_7^+ T_1(q^2) \right\}$$

$$A_\parallel^{L,R} \simeq N_\parallel \left\{ (C_9^- \mp C_{10}^-) \frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} C_7^- T_2(q^2) \right\}$$

$$A_0^{L,R} \simeq N_0 \Big\{ (C_9^- \mp C_{10}^-) \left[(\ldots) A_1(q^2) + (\ldots) A_2(q^2) \right] + 2m_b C_7^- \left[(\ldots) T_2(q^2) + (\ldots) T_3(q^2) \right] \Big\}$$

$$A_S = N_S (C_S - C_S') A_0(q^2)$$

$$\left(C_i^\pm \equiv C_i \pm C_i' \right)$$

$B \to K^* \ell^+ \ell^-$ – Amplitudes

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$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$$

$$\mathcal{H}_{\rm eff}^{\rm had} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1\dots6} C_i O_i + C_8 O_8 \right]$$

$$\mathcal{A}_\lambda^{\rm (had)} = -\, i \frac{e^2}{q^2} \int d^4 x e^{-iq\cdot x} \langle \ell^+ \ell^- | j_\mu^{\rm em, lept}(x) | 0 \rangle$$

$$\times \int d^4 y\, e^{iq\cdot y} \langle \bar{K}_\lambda^* | T\{ j^{\rm em, had, \mu}(y) \mathcal{H}_{\rm eff}^{\rm had}(0) \} | \bar{B} \rangle$$

$$\equiv \frac{e^2}{q^2} \epsilon_\mu L_V^\mu \Big[\underbrace{{\rm LO\ in\ } \mathcal{O}\left(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}}\right)}_{\text{Non-Fact., QCDf}} + \underbrace{h_\lambda(q^2)}_{\text{power corrections}} \Big]$$

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$\rightarrow$ **unknown**

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Non-Fact., QCDf

power corrections

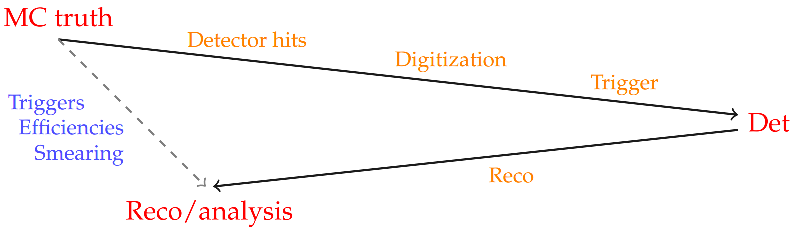
$\rightarrow$ **unknown**

Anomalies can be explained with 20-50% non-factorisable power corrections at the observable level in the critical bins (Ciuchini et al., 1512.07157)

This corresponds to more than 150% error at the amplitude level for the critical bins!

Detector effects 1/2

⇛ In Flavour factories because we usually measure the properties of a B meson decay we can provided the measurements that are corrected for the detector effects!



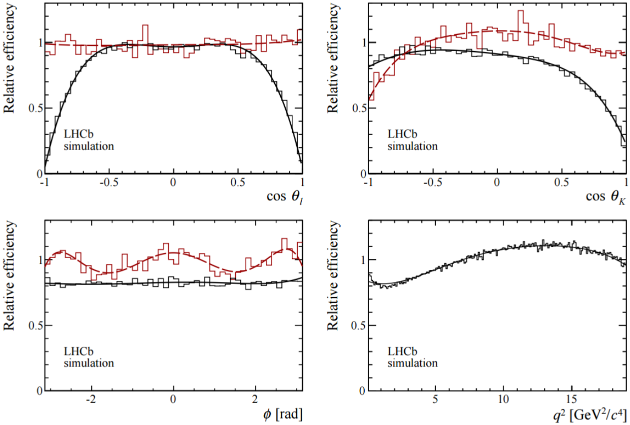
⇛ The differences that "Reco recovery" doesn't recover are recovered at the analysis stage.

⇛ Some imperfections (usually small), are assigned as systematics!

Thanks to Andy Buckley for the plot.

Detector effects 2/2

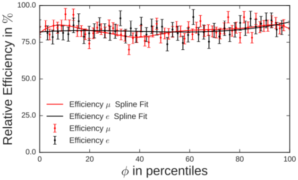
⇛ For example: measurement of angular coefficients of $B \to K^* \mu\mu$, arXiv::1512.04442, arXiv::1604.04042



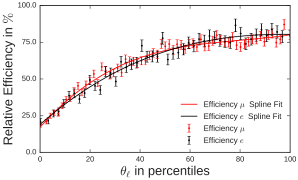
⇛ In Flavour physics we have ways to ensure we control our detector effects.

Detector effects 2/2

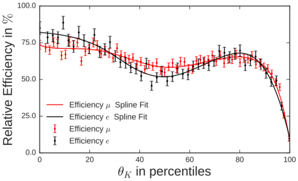
⇛ For example: measurement of angular coefficients of $B \to K^* \mu\mu$, arXiv::1512.04442, arXiv::1604.04042



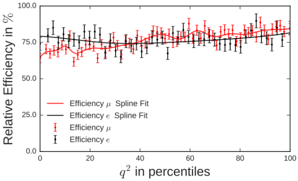
(a)Efficiency in ϕ



(b)Efficiency in θ_ℓ



(c)Efficiency in θ_K

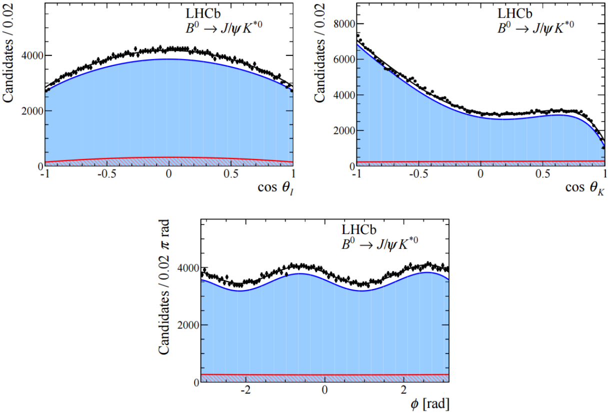


(d)Efficiency in q^2

⇛ In Flavour physics we have ways to ensure we control our detector effects.

Detector effects 2/2

⇛ For example: measurement of angular coefficients of $B \to K^{*}\mu\mu$, arXiv::1512.04442, arXiv::1604.04042



⇛ In Flavour physics we have ways to ensure we control our detector effects.

Published data format

- ⇛ There are number of ways the B-factories publish their results.
- ⇛ Most of the time the information to links are on the collaboration web pages:

Belle Journal Publications
The Belle Collaboration

- Physics Publications

471. **"Measurement of the τ lepton polarization and $R(D^*)$ in the decay $\overline{B} \to D^* \tau^- \bar{\nu}_\tau$"**
S.Hirose, et al. (Belle Collaboration), submitted to PRL
Belle preprint 2016-14, KEK Preprint 2016-53, arXiv:1612.00529 [hep-ex]

470. **"Search for D^0 decays to invisible final states at Belle"**
Y.Lai, et al. (Belle Collaboration), submitted to PRD
Belle preprint 2016-13, KEK Preprint 2016-51, arXiv:1611.09455 [hep-ex]

469. **"Search for the 0^{--} Glueball in Y(1S) and Y(2S) decays"**
S.Jia, et al. (Belle Collaboration), submitted to PRD
Belle preprint 2016-12, KEK Preprint 2016-50, arXiv:1611.07131 [hep-ex]

468. **"Observation of $D^0 \to \rho^0 \gamma$ and search for CP violation inradiative charm decays"**
T.Nanut, et al. (Belle Collaboration), submitted to PRL
Belle preprint 2016-11, KEK Preprint 2016-24, arXiv:1603.03257 [hep-ex]

467. **"Search for a dark vector gauge boson decaying to $\pi^+\pi^-$ using $\eta \to \pi^+\pi^-\gamma$ decays"**
E.Won, et al. (Belle Collaboration), published in PRD94, 092006 (2016 Nov 29)
Belle preprint 2016-10, KEK Preprint 2016-19, arXiv:1609.05599 [hep-ex]

466. **"Measurement of the branching ratio of $\overline{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ relative to $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays with a semileptonic tagging method"**
Y.Sato, T.Iijima, K.Adamczyk, et al. (Belle Collaboration), published in PRD 94, 072007 (2016 Oct 27)
Belle preprint 2016-08, KEK Preprint 2016-8, arXiv:1607.07923 [hep-ex]

465. **"Study of Excited Ξ_c States Decaying into Ξ_c^0 and Ξ_c^+ Baryons"**
J.Yelton, et al. (Belle Collaboration), published in PRD 94, 052011 (2016 Sep 23)
Belle preprint 2016-07, KEK Preprint 2016-7, arXiv:1607.07123 [hep-ex]

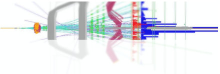
464. **"Measurement of the CKM angle φ_1 in $B^0 \to \overline{D}^{(*)0} h^0$, $\overline{D}^0 \to K_S^0\pi^+\pi^-$ decays with time-dependent binned Dalitz plot analysis"**
V.Vorobiev, et al. (Belle Collaboration), published in PRD 94, 052004 (2016 Sep 6)
Belle preprint 2016-09, KEK Preprint 2016-10, arXiv:1607.05813 [hep-ex]

463. **"Energy scan of the $e^+e^- \to h_b(nP)\,\pi^+\pi^-$ (n=1,2) cross sections and evidence for $\Upsilon(11020)$ decays into charged bottomonium-like states"**
R.Mizuk, A.Bondar, et al. (Belle Collaboration), published in PRL 117, 142001 (2016 Sep 28)
Belle preprint 2016-06, KEK Preprint 2016-6, arXiv:1508.06562 [hep-ex]

462. **"Studies of charmed strange baryons in the Λ D final state at Belle"**
Y.Kato, T.Iijima, et al. (Belle Collaboration), published in PRD 94, 032002 (2016 August 8)
Belle preprint 2016-05, KEK Preprint 2016-4, arXiv:1605.09103 [hep-ex]

461. **"Search for a massive invisible particle X^0 in $B^+ \to e^+ X^0$ and $B^+ \to \mu^+ X^0$ decays"**
C.-S. Park, Y.-J. Kwon, et al. (Belle Collaboration), published in PRD 94, 012003 (2016 July 18)
Belle preprint 2016-03, KEK Preprint 2016-2, arXiv:1605.04430 [hep-ex] [Fig]

The LHCb Public results



LHCb publications

[to restricted-access page]

PUBLICATIONS PER WORKING GROUP
- IONS AND FIXED TARGET
- FLAVOUR TAGGING
- b-HADRONS AND QUARKONIA
- B DECAYS TO CHARMONIUM
- DETECTOR PERFORMANCE
- CHARMLESS b-HADRON DECAYS
- QCD, ELECTROWEAK AND EXOTICA
- RARE DECAYS
- CHARM PHYSICS
- SEMILEPTONIC B DECAYS
- LUMINOSITY
- B DECAYS TO OPEN CHARM

List of papers (Total of 348 papers and 14676 citations)

TITLE	DOCUMENT NUMBER	JOURNAL	SUBMITTED ON	CITED
Observation of the decay $\Xi_b^- \to pK^-K^-$	PAPER-2016-050	PRL	07 Dec 2016	
Search for massive long-lived particles decaying semileptonically in the LHCb detector	PAPER-2016-047	EPJC	03 Dec 2016	
Evidence for the two-body charmless baryonic decay $B^+ \to p\overline{\Lambda}$	PAPER-2016-048	JHEP	23 Nov 2016	
Search for decays of neutral beauty mesons into four muons	PAPER-2016-043	JHEP	23 Nov 2016	
Measurements of charm mixing and CP violation using $D^0 \to K^\pm\pi^\mp$ decays	PAPER-2016-033	PRD	18 Nov 2016	
Measurement of the CKM angle γ from a combination of LHCb results	PAPER-2016-032	JHEP	09 Nov 2016	1
Measurement of CP asymmetry in $D^0 \to K^-K^+$ decays	PAPER-2016-035	PLB	29 Oct 2016	
Observation of the annihilation decay mode $B^0 \to K^+K^-$	PAPER-2016-036	PRL	26 Oct 2016	
Measurement of forward $t\bar{t}$, $W + b\bar{b}$ and $W + c\bar{c}$ production in pp collisions at $\sqrt{s} = 8$ TeV	PAPER-2016-038	PLB	26 Oct 2016	
New algorithms for identifying the flavour of B^0 mesons using pions and protons	PAPER-2016-039	EPJC	19 Oct 2016	
Observation of the decay $B_s^0 \to \phi\pi^+\pi^-$ and evidence for $B^0 \to \phi\pi^+\pi^-$	PAPER-2016-028	PRD	17 Oct 2016	
Search for the CP-violating strong decays $\eta \to \pi^+\pi^-$ and $\eta'(958) \to \pi^+\pi^-$	PAPER-2016-046	PLB	12 Oct 2016	

CERN document server

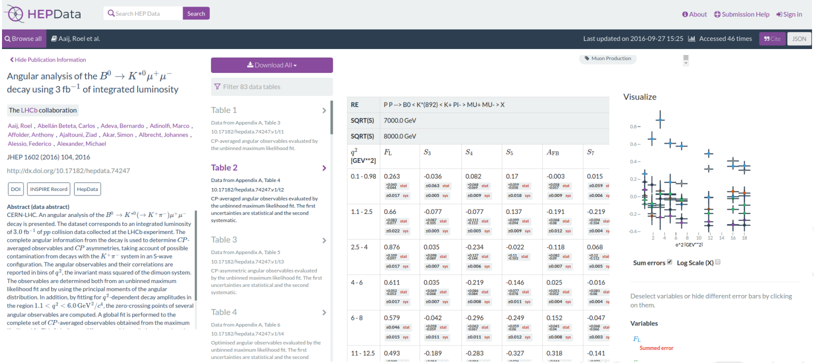
⇛ Figure on CDS and `LHCb publications` page available in many formats: `.pdf`, `.eps`, `.png`, `ROOT_.C`

⇛ No need to read the numbers from the plot any more!

⇛ Supplementary material not included in the paper (usually material that did not fit paper due to space constraints)

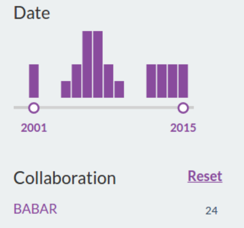
Unification of format

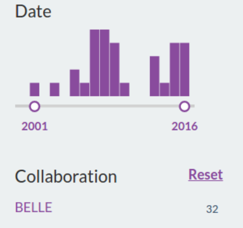
⇛ More and more results are being published on HepData make them "one clic away" to get.



Unification of format

⇛ More and more papers from Flavour community are appearing on `HepData`.





This is not the end of the story!!

$\Rrightarrow$ Even if experimentalist publish a number there is always a chance that the data might be misinterpreted by theorists.

This is not the end of the story!!

⇛ Even if experimentalist publish a number there is always a chance that the data might be misinterpreted by theorists.
⇛ Many times the error gets symmetrized, the correlation neglected, or worse...

Publish likelihood?

⇛ The proposal that I would like to make for discussion is that HepData portal (or similar) would have a possibility that experiments could publish the whole multidim. likelihood function.
⇛ In this way we ensure that the function will be used as the experiment intended to.

GAMBIT: a *second-generation* global fit code

GAMBIT: The Global And Modular BSM Inference Tool

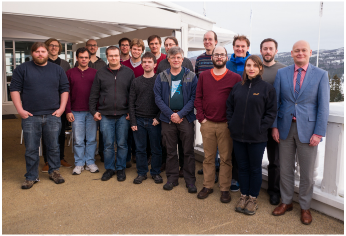
Overriding principles of GAMBIT: flexibility and modularity

- General enough to allow fast definition of new datasets and theoretical models
- Plug and play scanning, physics and likelihood packages
- Extensive model database – not just small modifications to constrained MSSM (NUHM, etc), and not just SUSY!
- Extensive observable/data libraries (likelihood modules)
- Many statistical options – Bayesian/frequentist, likelihood definitions, scanning algorithms
- A smart and *fast* LHC likelihood calculator
- Massively parallel
- Full open-source code release soon!
- Hear more in Anders Kvellestad tmr!

The GAMBIT Collaboration

30 Members, 16 institutions, 10 countries, 11 Experiments, 4 major theory codes

ATLAS	A. Buckley, P. Jackson, C. Rogan, M. White,
Flavour exp.	F. Bernlochner, M. Chrzaszcz, N. Serra
Fermi-LAT	J. Conrad, J. Edsjö, G. Martinez P. Scott
CTA	C. Balázs, T. Bringmann, J. Conrad, M. White
HESS	J. Conrad
IceCube	J. Edsjö, P. Scott
AMS-02	A. Putze
CDMS, DM-ICE	L. Hsu
XENON/DARWIN	J. Conrad
Theory	P. Athron, C. Balázs, T. Bringmann, J. Cornell, L. Dal, J. Edsjö, B. Farmer, A. Krislock, A. Kvellestad, M. Pato, F. Mahmoudi, A. Raklev, P. Scott, C. Weniger, M. White



+recently joined: T. Gonzales, J. McKay, R. Ruiz, R. Trotta
-recently retired: A. Saavedra, C. Savage

Global Analysis with Gambit

- Wilson coefficients and $b \to s\ell^+\ell^-$ observables implemented in **SuperIso**

- **SuperIso**: public code for calculating flavour physics observables

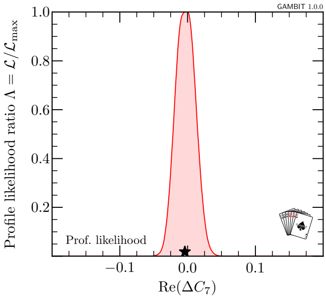
  Mahmoudi, CPC 178 (2008) 745; CPC 180 (2009) 1579, CPC 180 (2009) 1718
  available from http://superiso.in2p3.fr/

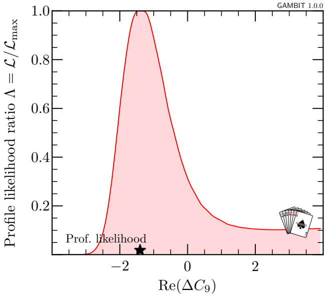
- **SuperIso** interfaced into **GAMBIT** through the flavour physics module **FlavBit**

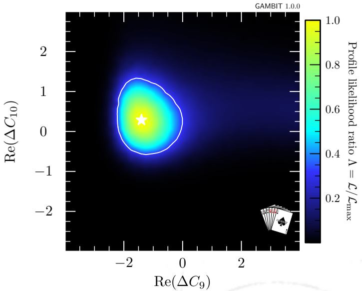
  GAMBIT: The Global And Modular BSM Inference Tool
  Web page: http://gambit.hepforge.org/

- **FlavBit** determines the likelihoods by comparing the theoretical evaluations and the experimental results taking into account the experimental and theoretical correlations.

Global Analysis with Gambit - Results







⇛ Tension if ΔC_9 observed!
⇛ Other coefficients within SM predictions.
⇛ C_{10} still has a big uncertainty.

Conclusions

$\Rrightarrow$ Flavour physics is a powerful tool to constrain NP models!
$\Rrightarrow$ Measurements are becoming more complex!
$\Rrightarrow$ Ability to publish the full multidim. likelihoods soon will be needed!
$\Rrightarrow$ **GAMBIT** is the new player for fitting Flavour observables and will be made public soon.
$\Rrightarrow$ $3-4\,\sigma$ deviations are present and Run2 data should clear the picture where it's NP or not.

Backup

$B \to K^*\mu^+\mu^-$ – Optimized observables

$$\langle P_1\rangle_{\rm bin} = \frac{1}{2}\frac{\int_{\rm bin} dq^2[J_3+\bar{J}_3]}{\int_{\rm bin} dq^2[J_{2s}+\bar{J}_{2s}]} \qquad \langle P_2\rangle_{\rm bin} = \frac{1}{8}\frac{\int_{\rm bin} dq^2[J_{6s}+\bar{J}_{6s}]}{\int_{\rm bin} dq^2[J_{2s}+\bar{J}_{2s}]}$$

$$\langle P_4'\rangle_{\rm bin} = \frac{1}{\mathcal{N}'_{\rm bin}}\int_{\rm bin} dq^2[J_4+\bar{J}_4] \qquad \langle P_5'\rangle_{\rm bin} = \frac{1}{2\mathcal{N}'_{\rm bin}}\int_{\rm bin} dq^2[J_5+\bar{J}_5]$$

$$\langle P_6'\rangle_{\rm bin} = \frac{-1}{2\mathcal{N}'_{\rm bin}}\int_{\rm bin} dq^2[J_7+\bar{J}_7] \qquad \langle P_8'\rangle_{\rm bin} = \frac{-1}{\mathcal{N}'_{\rm bin}}\int_{\rm bin} dq^2[J_8+\bar{J}_8]$$

with

$$\mathcal{N}'_{\rm bin} = \sqrt{-\int_{\rm bin} dq^2[J_{2s}+\bar{J}_{2s}]\int_{\rm bin} dq^2[J_{2c}+\bar{J}_{2c}]}$$

+ CP violating clean observables and other combinations

U. Egede et al., JHEP 0811 (2008) 032, JHEP 1010 (2010) 056

J. Matias et al., JHEP 1204 (2012) 104

S. Descotes-Genon et al., JHEP 1305 (2013) 137

Numerical approach