$B \to D^{(*)}$ Form Factors in HQET and using dispersive bounds

Martin Jung and **Florian Bernlochner**

UNIVERSITÀ DEGLI STUDI DI TORINO

UNIVERSITÄT BONN

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Beyond the Flavour Anomalies
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Form factor parametrizations

FFs parametrize mismatch: Theory (partons) $\leftrightarrow$ Experiment (hadrons)

$$\langle D_q(p')|\bar{c}\gamma^\mu b|\bar{B}_q(p)\rangle = (p+p')^\mu f_+^q(q^2) + (p-p')^\mu f_-^q(q^2)\,,\; q^2 = (p-p')^2$$

Issue: q^2 dependence $\rightarrow$ different parametrizations

Experiments should give information independent of this choice!

"BGL parametrization": [Boyd/Grinstein/Lebed'95]

- Analytic structure: account for cuts and poles explicitly
  - ➥ remainder can be expanded in simple power series in z
- Use quark-hadron-duality (+crossing sym., unitarity)
  - ➥ Absolute bounds on coefficients, rapid convergence ($z \lesssim 0.06$)

➥ Efficient expansion of individual FFs with few coefficients

"HQE parametrization" ($\rightarrow$ CLN): [Caprini/Lellouch/Neubert'97]

- Exploit heavy-quark spin-flavour symmetry for $m_{b,c} \rightarrow \infty$
  - ➥ All $B^{(*)} \rightarrow D^{(*)}$ FFs given by Isgur-Wise function $\xi(z)$
  - ➥ Systematic expansion in $1/m_{b,c}$ and α_s + approx. unitarity
  - ➥ z expansion, no bounds on individual coefficients

➥ Less parameters in total. Presently unavoidable for NP!

Higher orders I: BGL analysis of $B \to D^*$ [Gambino/MJ/Schacht'19]

Recent untagged analysis by Belle with 4 1D distributions [1809.03290]
Analysis of 2017+2018 Belle data with BGL form factors:

- Datasets compatible
- 2018: no parametrization dependence
- All FFs to z^2 to include uncertainties

➥ 50% larger uncertainties!

- CV including syst. uncertainties

➥ $\sim 1\sigma$ higher CV than Belle

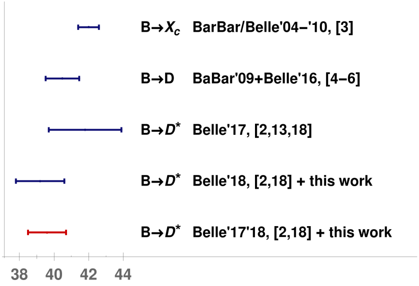
2017+2018:
$|V_{cb}^{D^*}| = 39.6^{+1.1}_{-1.0} \times 10^{-3}$
2018 only:
$|V_{cb}^{D^*}| = 39.1^{+1.5}_{-1.3} \times 10^{-3}$

Discussion topic 1:
Including "superfluous" parameters

- Averaging results from $B \to D$, $B \to X_c$ and $B \to D^*$:

➥ Tension down to $\sim 1.6\sigma$ ($\chi^2/\mathrm{dof} = 4.4/2$)

➥ V_{cb} puzzle reduced!



Higher order II: $1/m_c^2$ analysis of $B \to D^{(*)}$ FFs

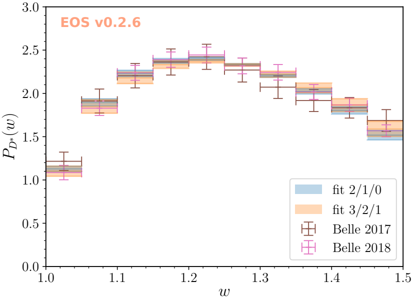
[Bordone/MJ/vDyk'19, Bordone/Gubernari/MJ/vDyk'20]

2 problems with CLN (as it has been used in analyses):

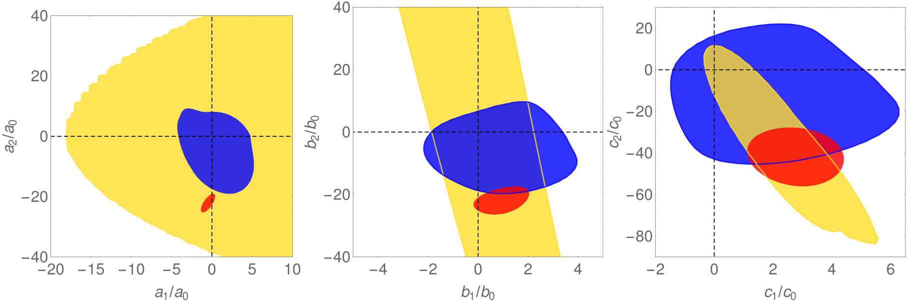
1. Missing uncertainties of numerical factors and correlations
   - Solved in [Bernlochner+'17] $\to$ improved description
2. Predictions @$1/m_c$ contradict lattice ($B \to D$ and $B \to D^*$)
   - Calculable parameters (at $1/m$, e.g. $h_{A_1}(1)$) varied
   - Not a systematic treatment of $1/m^2$, correlations missing
   - Uncertainty remains $\mathcal{O}[\Lambda^2/(2m_c)^2] \sim 5\%$, insufficient

- Include systematically $1/m_c^2$ corrections, using [Falk/Neubert'92]
  - use lattice + QCDSR + LCSR + unitarity [citations later]

- Theory-only fits match data
- k/l/m: z^n at $\mathcal{O}(1, 1/m, 1/m_c^2)$
- V_{cb} (Belle'17) consistent w/ BGL
- Good fit for 2/1/0
  - underestimates uncertainties
- Discussion topic 2 = topic 1



Predictions from 2/1/0 and 3/2/1 vs. data



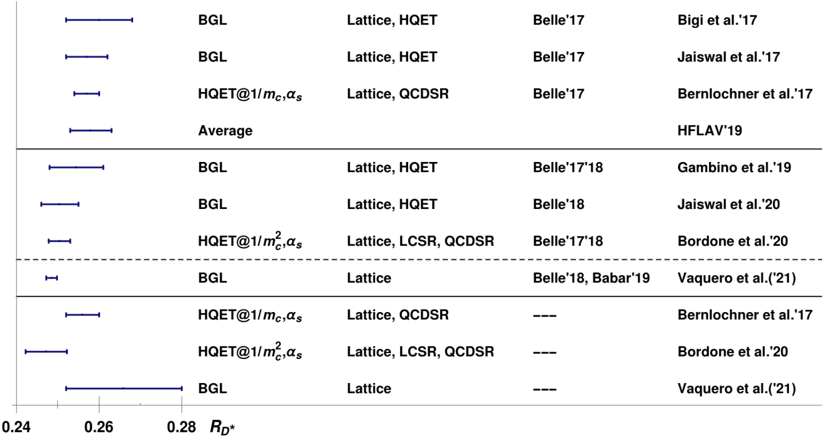
- $B \to D^*$ BGL coefficient ratios from:
  1. Data (Belle'17+'18) + weak unitarity (yellow)
  2. HQE theory fit 2/1/0 (red)
  3. HQE theory fit 3/2/1 (blue)

➥ Again compatibility of theory with data

➥ 2/1/0 underestimates the uncertainties massively

➥ For b_i, c_i ($\to f, \mathcal{F}_1$) data and theory complementary

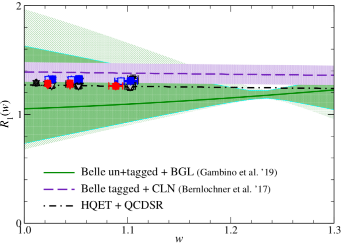
Overview over predictions for $R(D^*)$

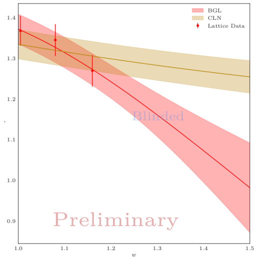


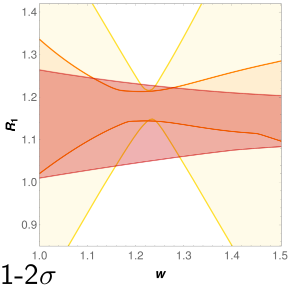
Lattice $B \to D^*$: $h_{A_1}(w=1)$ [FNAL/MILC'14,HPQCD'17]
Other lattice: $f_{+,0}^{B\to D}(q^2)$ [MILC,HPQCD'15]
QCDSR: [Ligeti/Neubert/Nir'93,'94] , LCSR: [Gubernari/Kokulu/vDyk'18]

Consistent SM predictions! Improvement expected from lattice FNAL/MILC('21) discussed in the following.

Preliminary lattice calculations

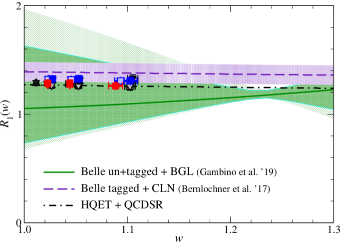


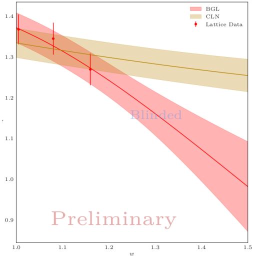


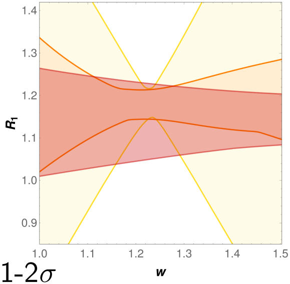


$R_1(w)$: FNAL slope surprising, compatible at 1-2σ

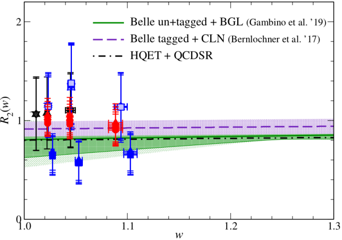
Preliminary lattice calculations

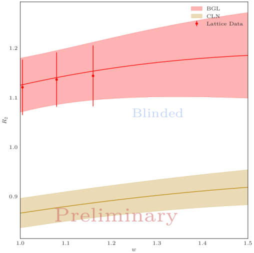


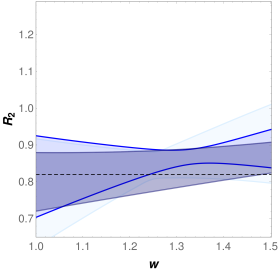




$R_1(w)$: FNAL slope surprising, compatible at 1-2σ







$R_2(w)$: Discrepancy FNAL (1.12 ± 0.06) vs. (HQE fit, experiment)!

HQE@$1/m_c^2$: $0.78^{+0.10}_{-0.06}$, BGL: 0.81 ± 0.11, HFLAV: 0.852 ± 0.018

Flavour universality in $B \to D^*(e,\mu)\nu$

[Bobeth/Bordone/Gubernari/MJ/vDyk'21]

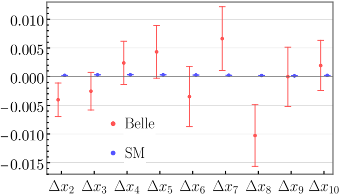
So far: Belle'18 data used in SM fits, flavour-averaged

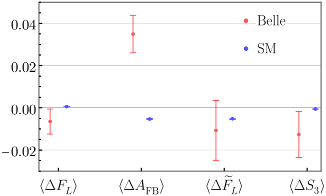
However: Bins 40 × 40 covariances given separately for $\ell = e, \mu$

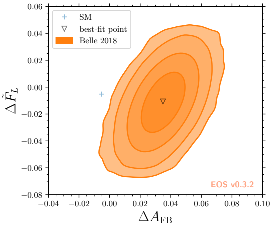
- Belle'18: $R_{e/\mu}(D^*) = 1.01 \pm 0.01 \pm 0.03$
- What can we learn about flavour-non-universality? $\to$ 2 issues:
  1. $e - \mu$ correlations not given $\to$ constructable from Belle'18
  2. 3 bins linearly dependent, but covariances not singular

Two-step analysis:

1. Extract 2 × 4 angular observables for 2 × 30 angular bins
   - Model-independent description including NP!
2. Compare with SM predictions, using FFs@$1/m_c^2$ [Bordone+'19]
   - $\sim 4\sigma$ discrepancy in $\Delta A_{\rm FB} = A^\mu_{\rm FB} - A^e_{\rm FB}$







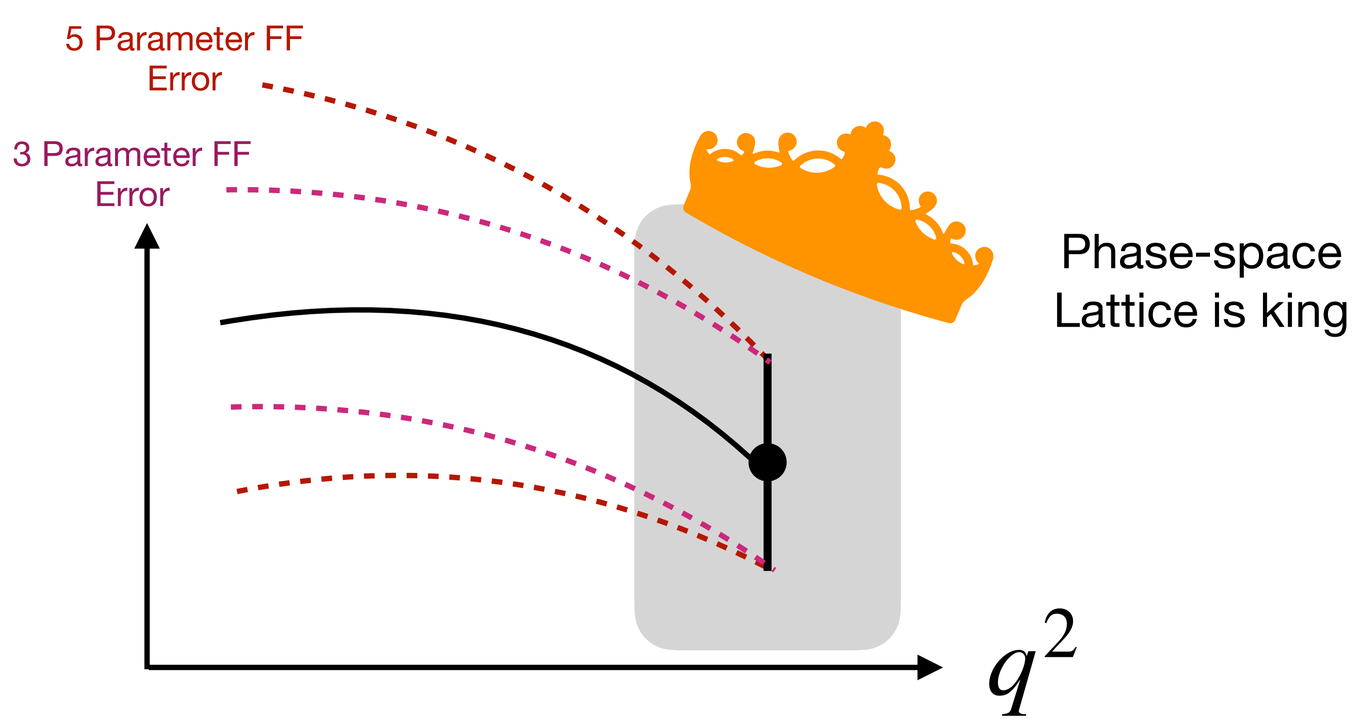
Thoughts on best practices on Lattice Data

Extend the shelf life

Present results in a FF model independent way

Preferred FFs change, so do use-cases

Sampling these out of a given parametrization can have caveats (cf. Sketch)



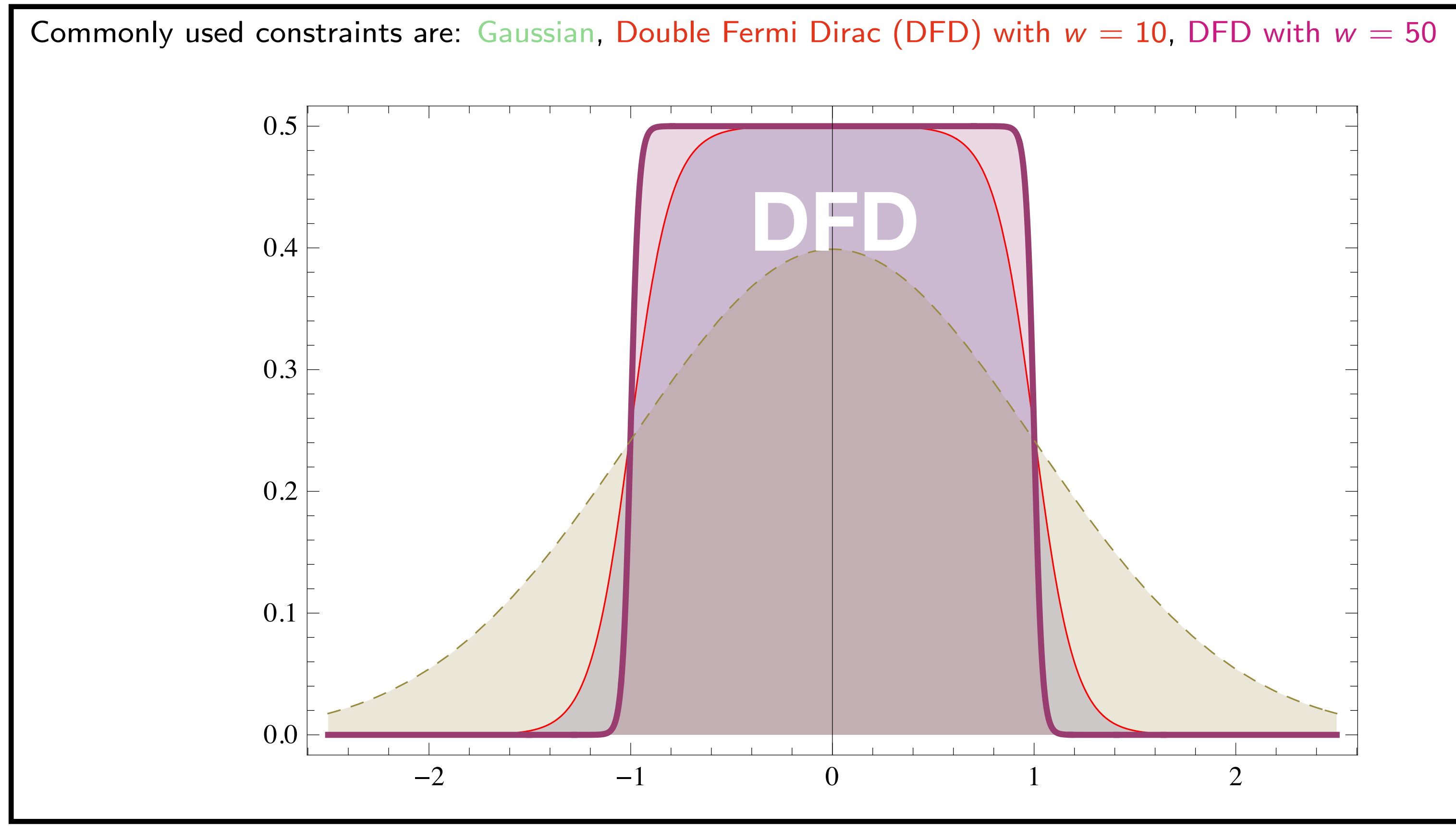
Thoughts on Unitarity Constraints

Obviously perfectly fine to consider such.

Some considerations:

Prior of such can have fairly huge impact on errors of higher order terms

i.e. DFD with high w
versus
Gaussian
versus hard-cut off can
result in very different errors



<u>But:</u> Lattice results should **always** reported FF bounds without such

E.g. imagine a situation like $\mathscr{L}_{\text{Lattice 1}} \times \mathscr{L}_{\text{Lattice 2}} \times \mathscr{L}_{\text{Data}} \times \mathscr{L}_{\text{UT Prior}}$

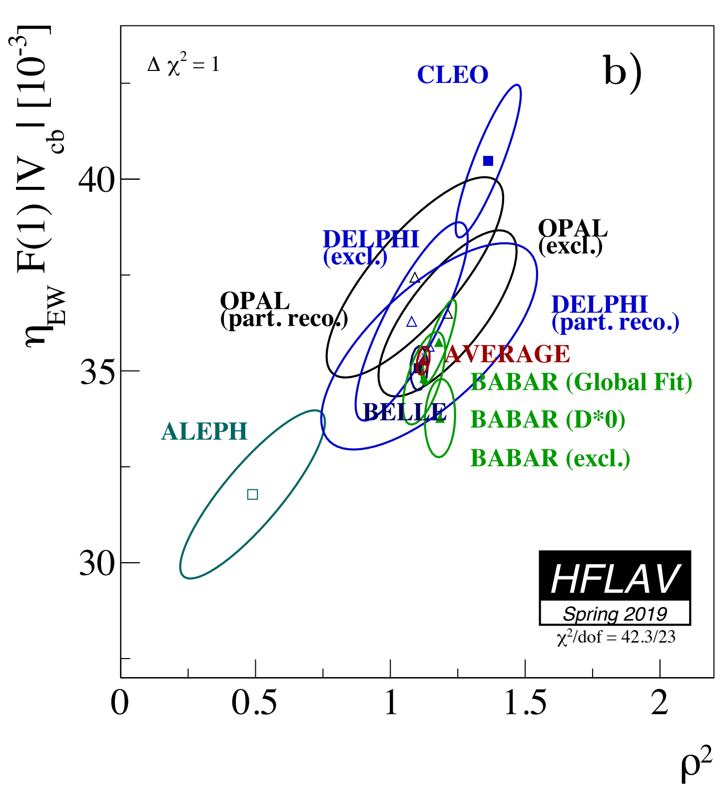
We only should apply such a **prior** *once* and not several times! Plus one might want to try different priors or FF parameterizations. Or fits without (the data is unitary by definition).

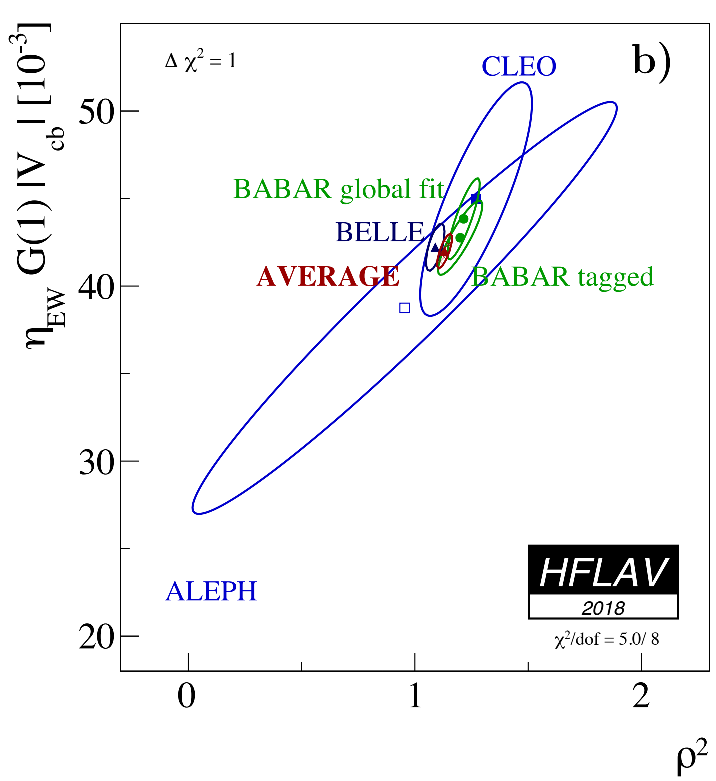
Thoughts on best practices on Experimental Data

Extend the shelf life

Present results in a FF model-independent way

This is I think the real tragedy of CLN
(note that this is not a critisim directed to CLN or at the experiments! In hindsight everythign is 20/20)





Experiment	$\eta_{\rm EW}\mathcal{F}(1)\lvert V_{cb}\rvert[10^{-3}]$ (rescaled) $\eta_{\rm EW}\mathcal{F}(1)\lvert V_{cb}\rvert[10^{-3}]$ (published)	ρ^2 (rescaled) ρ^2 (published)
ALEPH [486]	$31.78 \pm 1.83_{\rm stat} \pm 1.21_{\rm syst}$ $31.9 \pm 1.8_{\rm stat} \pm 1.9_{\rm syst}$	$0.489 \pm 0.226_{\rm stat} \pm 0.145_{\rm syst}$ $0.37 \pm 0.26_{\rm stat} \pm 0.14_{\rm syst}$
CLEO [490]	$40.47 \pm 1.25_{\rm stat} \pm 1.55_{\rm syst}$ $43.1 \pm 1.3_{\rm stat} \pm 1.8_{\rm syst}$	$1.363 \pm 0.084_{\rm stat} \pm 0.087_{\rm syst}$ $1.61 \pm 0.09_{\rm stat} \pm 0.21_{\rm syst}$
OPAL excl [487]	$36.50 \pm 1.60_{\rm stat} \pm 1.46_{\rm syst}$ $36.8 \pm 1.6_{\rm stat} \pm 2.0_{\rm syst}$	$1.212 \pm 0.209_{\rm stat} \pm 0.148_{\rm syst}$ $1.31 \pm 0.21_{\rm stat} \pm 0.16_{\rm syst}$
OPAL partial reco [487]	$37.44 \pm 1.20_{\rm stat} \pm 2.32_{\rm syst}$ $37.5 \pm 1.2_{\rm stat} \pm 2.5_{\rm syst}$	$1.091 \pm 0.138_{\rm stat} \pm 0.297_{\rm syst}$ $1.12 \pm 0.14_{\rm stat} \pm 0.29_{\rm syst}$
DELPHI partial reco [488]	$35.64 \pm 1.41_{\rm stat} \pm 2.29_{\rm syst}$ $35.5 \pm 1.4_{\rm stat}\ {}^{+2.3}_{-2.4\rm syst}$	$1.144 \pm 0.123_{\rm stat} \pm 0.381_{\rm syst}$ $1.34 \pm 0.14_{\rm stat}\ {}^{+0.24}_{-0.22\rm syst}$
DELPHI excl [489]	$36.29 \pm 1.71_{\rm stat} \pm 1.94_{\rm syst}$ $39.2 \pm 1.8_{\rm stat} \pm 2.3_{\rm syst}$	$1.079 \pm 0.142_{\rm stat} \pm 0.152_{\rm syst}$ $1.32 \pm 0.15_{\rm stat} \pm 0.33_{\rm syst}$
Belle [491]	$35.07 \pm 0.15_{\rm stat} \pm 0.56_{\rm syst}$ $35.06 \pm 0.15_{\rm stat} \pm 0.56_{\rm syst}$	$1.106 \pm 0.031_{\rm stat} \pm 0.008_{\rm syst}$ $1.106 \pm 0.031_{\rm stat} \pm 0.007_{\rm syst}$
BABAR excl [493]	$33.77 \pm 0.29_{\rm stat} \pm 0.98_{\rm syst}$ $34.7 \pm 0.3_{\rm stat} \pm 1.1_{\rm syst}$	$1.184 \pm 0.048_{\rm stat} \pm 0.029_{\rm syst}$ $1.18 \pm 0.05_{\rm stat} \pm 0.03_{\rm syst}$
BABAR D^{*0} [495]	$34.81 \pm 0.58_{\rm stat} \pm 1.06_{\rm syst}$ $35.9 \pm 0.6_{\rm stat} \pm 1.4_{\rm syst}$	$1.125 \pm 0.058_{\rm stat} \pm 0.053_{\rm syst}$ $1.16 \pm 0.06_{\rm stat} \pm 0.08_{\rm syst}$
BABAR global fit [497]	$35.75 \pm 0.20_{\rm stat} \pm 1.09_{\rm syst}$ $35.7 \pm 0.2_{\rm stat} \pm 1.2_{\rm syst}$	$1.180 \pm 0.020_{\rm stat} \pm 0.061_{\rm syst}$ $1.21 \pm 0.02_{\rm stat} \pm 0.07_{\rm syst}$
Average	$\mathbf{35.27 \pm 0.11_{\rm stat} \pm 0.36_{\rm syst}}$	$\mathbf{1.122 \pm 0.015_{\rm stat} \pm 0.019_{\rm syst}}$

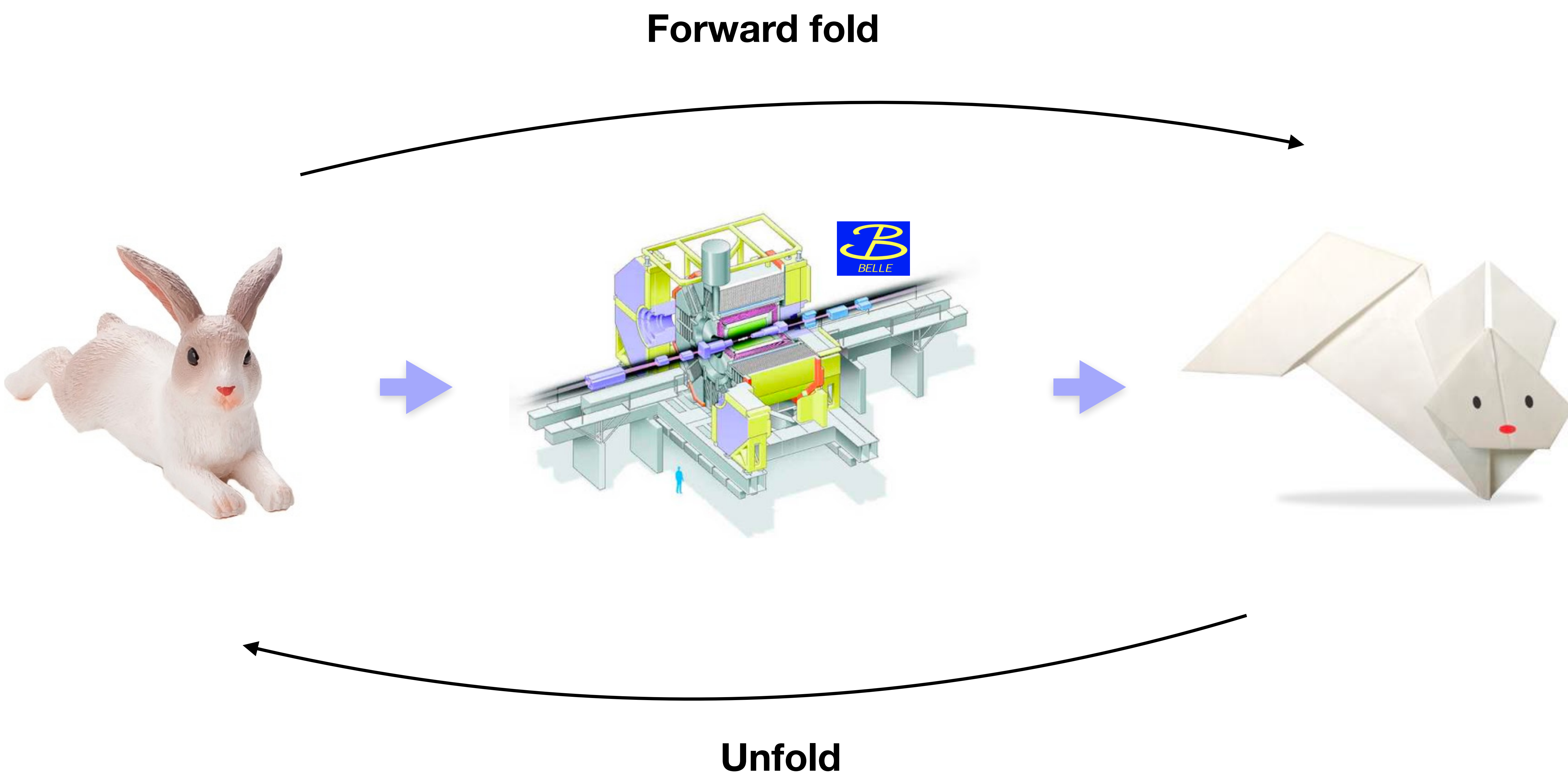


Image credit: Lu Cao

Thoughts on best practices on Experimental Data

Extend the shelf life

Present results in a FF model-independent way

If you can unfold, but also provide with the ingredients to forward-fold

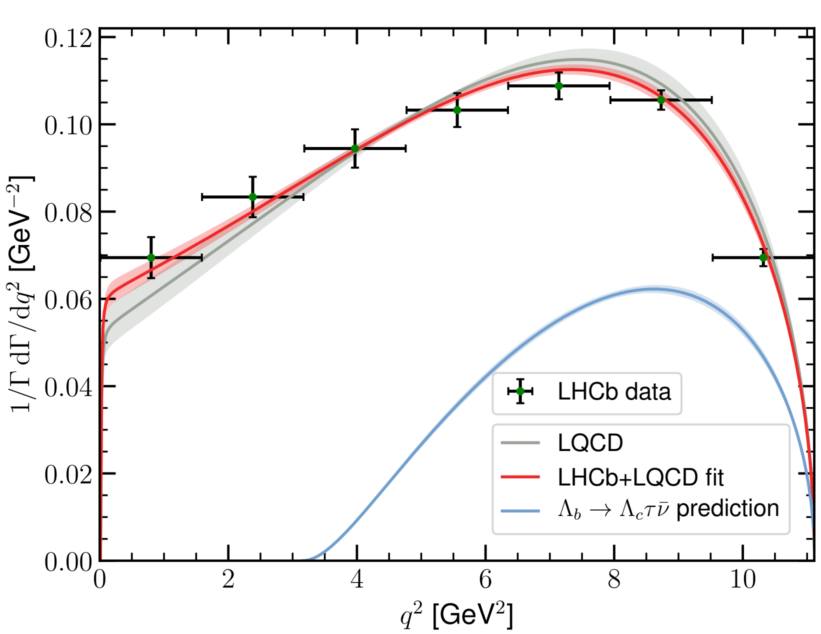
Acceptance Factors

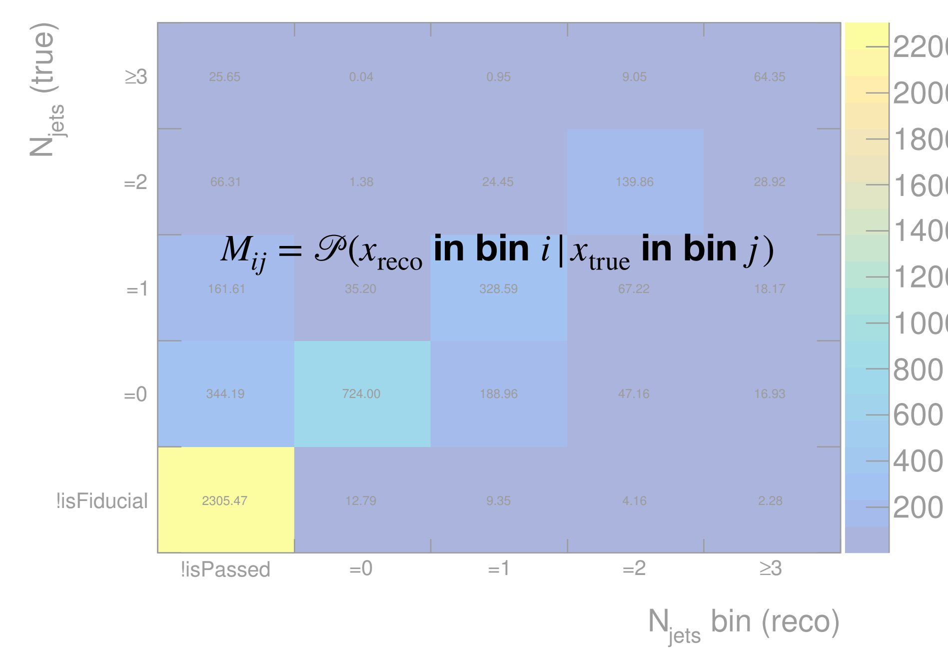
$$\epsilon_i = \frac{\#\,\textbf{Gen. Events in } x_{\text{true}} \textbf{ bin i}}{\#\,\textbf{Reco. Events in } x_{\text{true}} \textbf{ bin i}}$$

Full Systematic and Statistical Covariances

$$C_{\text{exp}}$$

Migration matrices





Further thoughts on combined fits

Sometimes weird stand-offs are happening these days:

* Experiments are holding back information as they are waiting for the lattice community to put out results.

* The lattice community is hesitant to show things, as they are worried that people are using things in preliminary fits.

I understand that there is no easy solution to this. Careers are obviously made based on individual work.

But: We are one community and I think I have not seen a single instance where collaborations have made science worse.

As an experimentalist my primary concern should be my measurement and to get this right.

As a theorist your primary concern is to get your lattice calculation right.

How we put things together is a common concern, so maybe more collaborative papers could emerge where this is done. Obviously HFLAV is doing some of this as soon as more than one experimental result is involved and HFLAG if more than one lattice calculation is involved.