Prospects of Angular Analyses of $B \to D^* \ell \bar{\nu}_\ell$ at the B-Factories

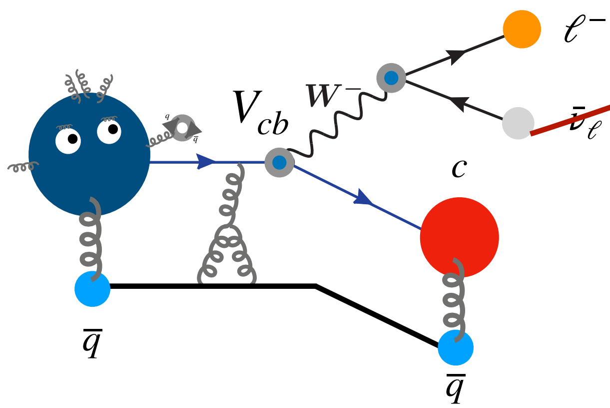
LHCb Open Workshop on Semileptonic Decays

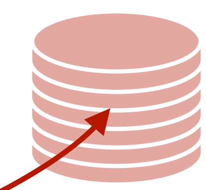
Florian Bernlochner (florian.bernlochner@uni-bonn.de)

UNIVERSITÄT BONN

Talk Overview

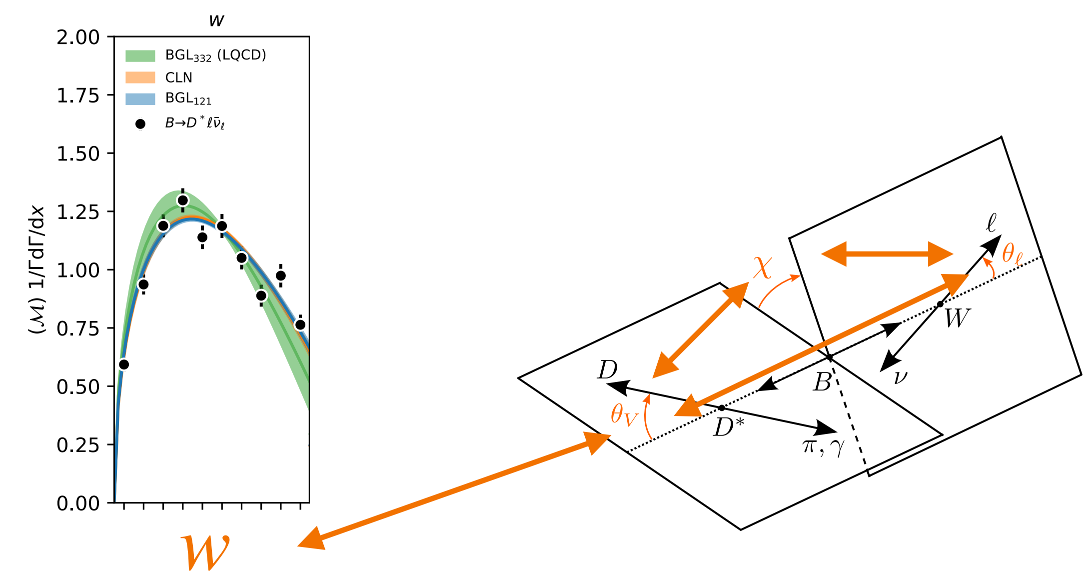
1. Why we need to do better to preserve our experimental Information





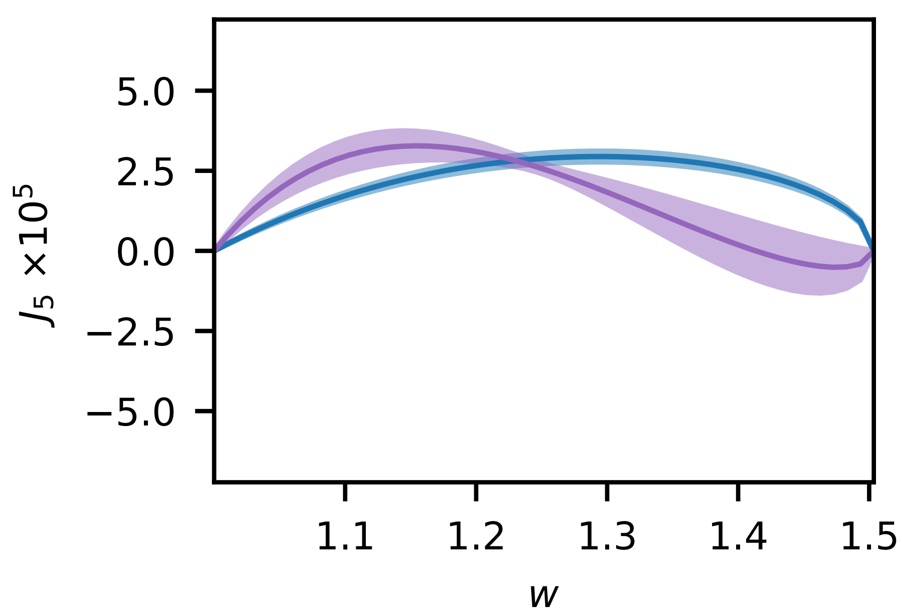
Idea range from **"Open Data"** to **"Reinterpretation friendly"** observables

2. From **1D projections** to full angular information



Working around the curse of dimensionality

3. Potential of full angular fits



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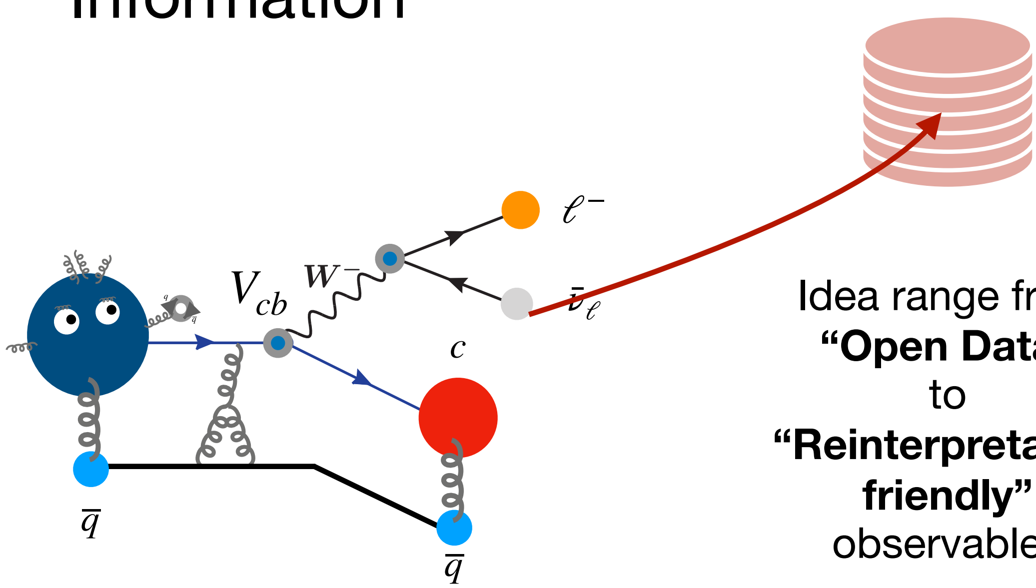

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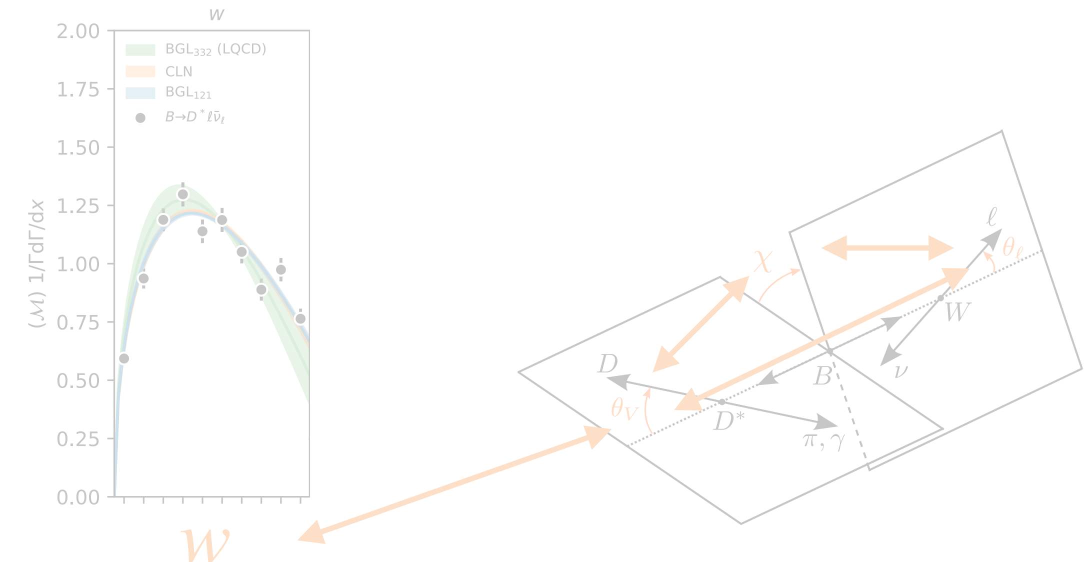

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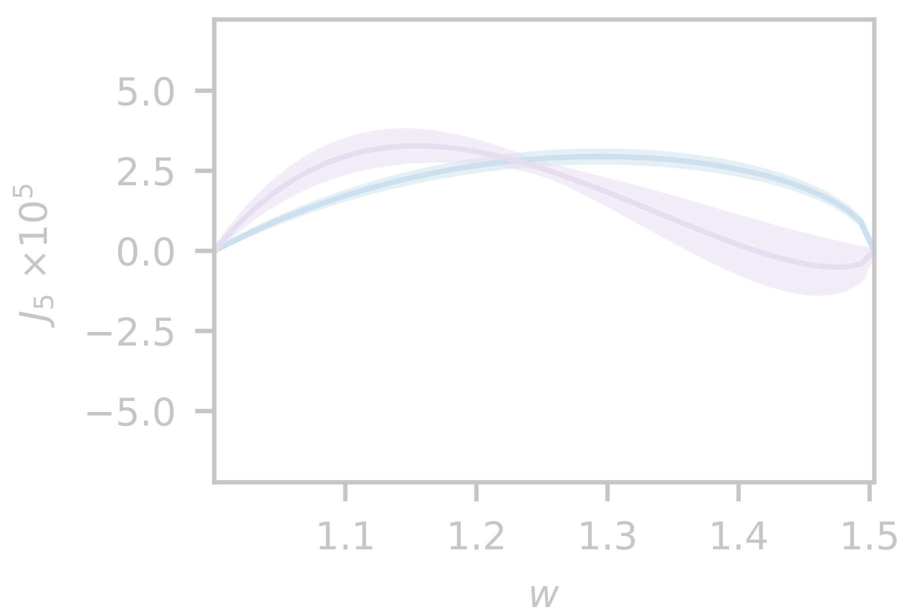


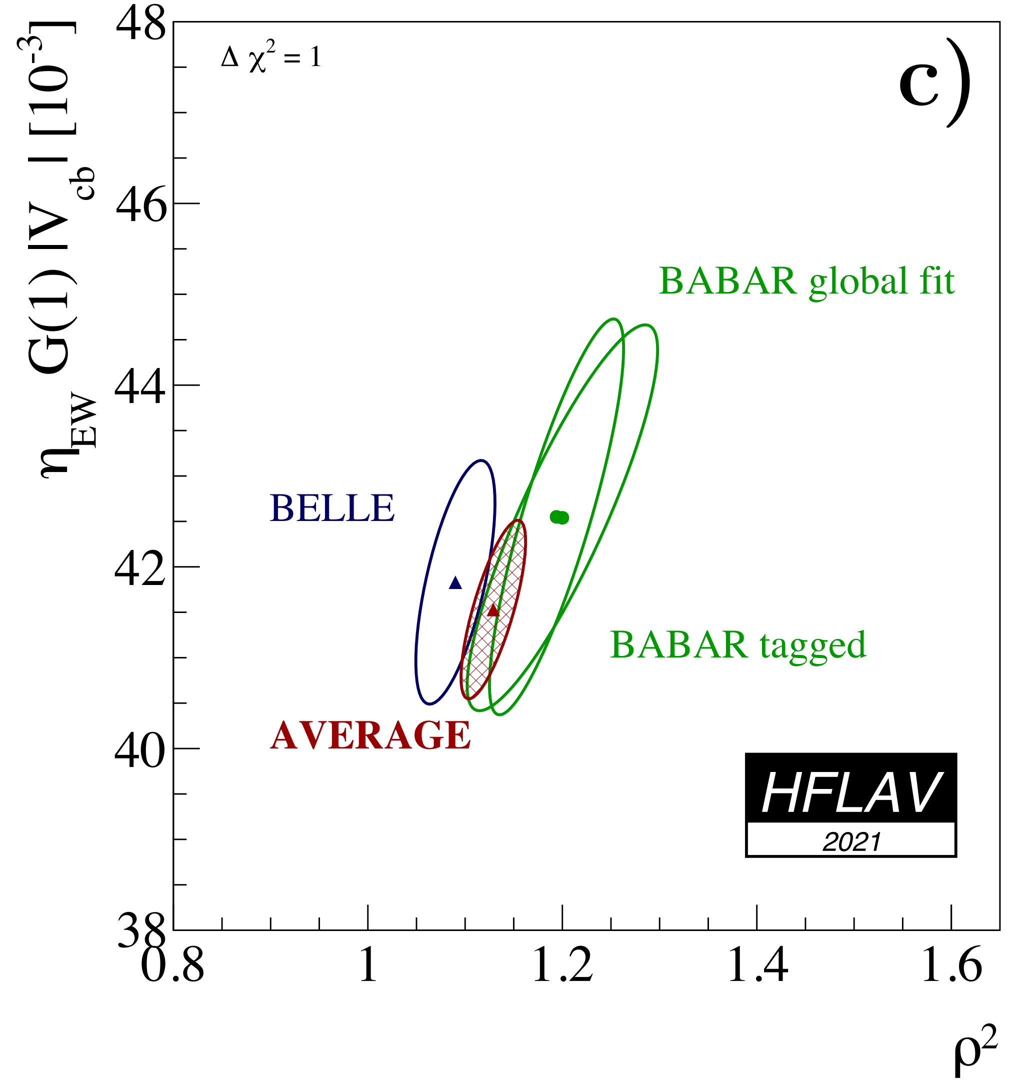
More than a decade of $B \to D^{(*)}\ell\bar{\nu}_\ell$ is "lost" :-(

For $B \to D^{(*)}\ell\bar{\nu}_\ell$ traditionally **single form factor** parametrization (Caprini-Lellouch-Neubert, **CLN**) was used. Nucl.Phys. B530 (1998) 153–181

Measurements directly determined the parameters and quoted these with correlations.

Problem: Theory knowledge advances; **today more** general parametrization are preferred (**BGL**, …)

Experiment	$\eta_{EW}\mathcal{F}(1)\vert V_{cb}\vert[10^{-3}]$ (rescaled) $\eta_{EW}\mathcal{F}(1)\vert V_{cb}\vert[10^{-3}]$ (published)	ρ^2 (rescaled) ρ^2 (published)
ALEPH [497]	$31.38 \pm 1.80_{stat} \pm 1.24_{syst}$ $31.9 \pm 1.8_{stat} \pm 1.9_{syst}$	$0.488 \pm 0.226_{stat} \pm 0.146_{syst}$ $0.37 \pm 0.26_{stat} \pm 0.14_{syst}$
CLEO [501]	$40.16 \pm 1.24_{stat} \pm 1.54_{syst}$ $43.1 \pm 1.3_{stat} \pm 1.8_{syst}$	$1.363 \pm 0.084_{stat} \pm 0.087_{syst}$ $1.61 \pm 0.09_{stat} \pm 0.21_{syst}$
OPAL excl [498]	$36.20 \pm 1.58_{stat} \pm 1.47_{syst}$ $36.8 \pm 1.6_{stat} \pm 2.0_{syst}$	$1.198 \pm 0.206_{stat} \pm 0.153_{syst}$ $1.31 \pm 0.21_{stat} \pm 0.16_{syst}$
OPAL partial reco [498]	$37.44 \pm 1.20_{stat} \pm 2.32_{syst}$ $37.5 \pm 1.2_{stat} \pm 2.5_{syst}$	$1.090 \pm 0.137_{stat} \pm 0.297_{syst}$ $1.12 \pm 0.14_{stat} \pm 0.29_{syst}$
DELPHI partial reco [499]	$35.52 \pm 1.41_{stat} \pm 2.29_{syst}$ $35.5 \pm 1.4_{stat}\ {}^{+2.3}_{-2.4 syst}$	$1.139 \pm 0.123_{stat} \pm 0.382_{syst}$ $1.34 \pm 0.14_{stat}\ {}^{+0.24}_{-0.22 syst}$
DELPHI excl [500]	$35.87 \pm 1.69_{stat} \pm 1.95_{syst}$ $39.2 \pm 1.8_{stat} \pm 2.3_{syst}$	$1.070 \pm 0.141_{stat} \pm 0.153_{syst}$ $1.32 \pm 0.15_{stat} \pm 0.33_{syst}$
Belle [502]	$34.82 \pm 0.15_{stat} \pm 0.55_{syst}$ $35.06 \pm 0.15_{stat} \pm 0.56_{syst}$	$1.106 \pm 0.031_{stat} \pm 0.008_{syst}$ $1.106 \pm 0.031_{stat} \pm 0.007_{syst}$
BABAR excl [503]	$33.37 \pm 0.29_{stat} \pm 0.97_{syst}$ $34.7 \pm 0.3_{stat} \pm 1.1_{syst}$	$1.182 \pm 0.048_{stat} \pm 0.029_{syst}$ $1.18 \pm 0.05_{stat} \pm 0.03_{syst}$
BABAR D^{*0} [507]	$34.55 \pm 0.58_{stat} \pm 1.06_{syst}$ $35.9 \pm 0.6_{stat} \pm 1.4_{syst}$	$1.124 \pm 0.058_{stat} \pm 0.053_{syst}$ $1.16 \pm 0.06_{stat} \pm 0.08_{syst}$
BABAR global fit [509]	$35.45 \pm 0.20_{stat} \pm 1.08_{syst}$ $35.7 \pm 0.2_{stat} \pm 1.2_{syst}$	$1.171 \pm 0.019_{stat} \pm 0.060_{syst}$ $1.21 \pm 0.02_{stat} \pm 0.07_{syst}$
Average	$\mathbf{35.00 \pm 0.11_{stat} \pm 0.34_{syst}}$	$\mathbf{1.121 \pm 0.014_{stat} \pm 0.019_{syst}}$



Old measurements **cannot be updated** the underlying distributions were not provided but only the result of the fit.

Obviously we should **avoid** this in the future.

The emergence of beyond zero-recoil lattice:

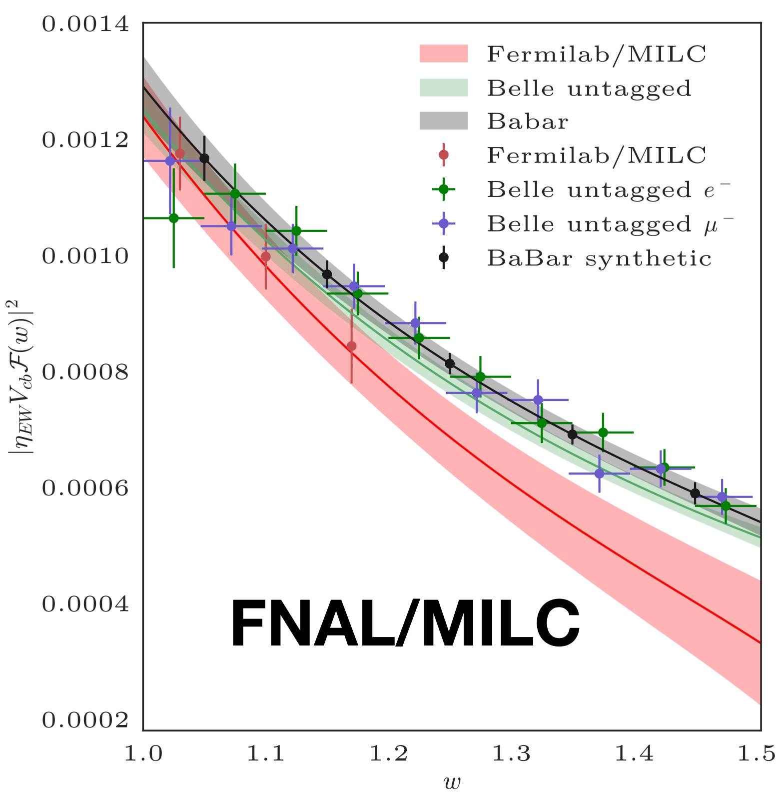
Very exciting times:

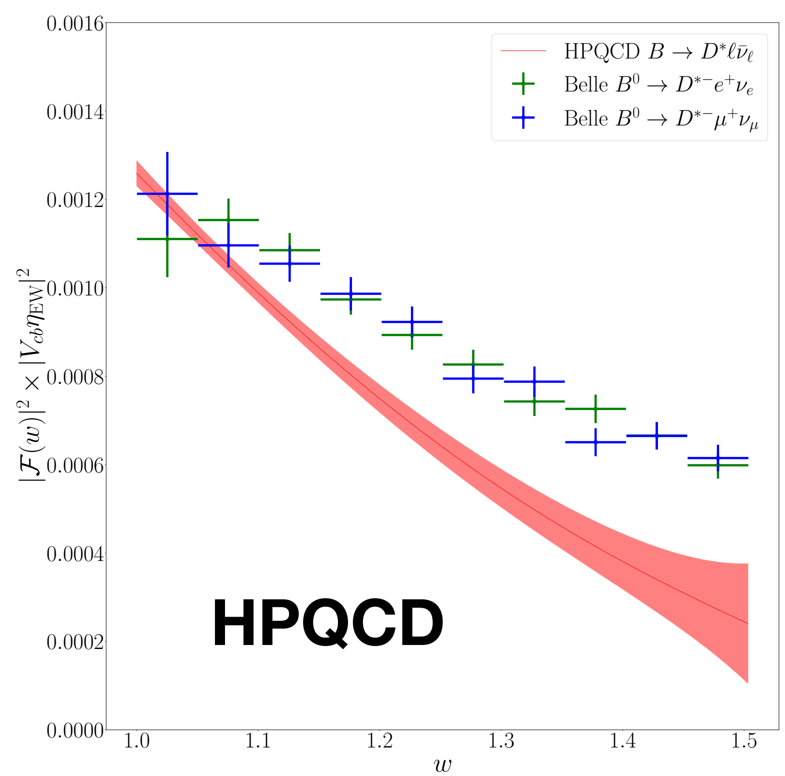
A. Bazavov et al. [FNAL/MILC] [Eur. Phys. J. C 82, 1141 (2022), arXiv:2105.14019]

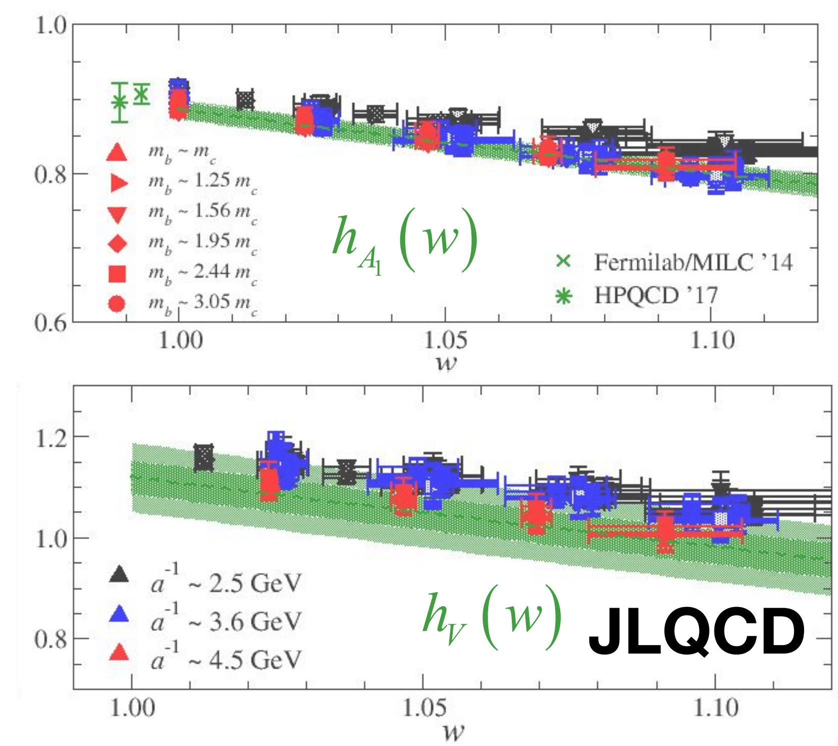
J. Harrison & T.H. Davies [HPQCD] [arXiv:2304.03137 [hep-lat]]

After more than 10 years in the making, we have beyond zero recoil LQCD predictions for $B \to D^* \ell \bar{\nu}_\ell$

Three groups: One published, One freshly on arxiv, One preliminary :







Tension with measured shapes …

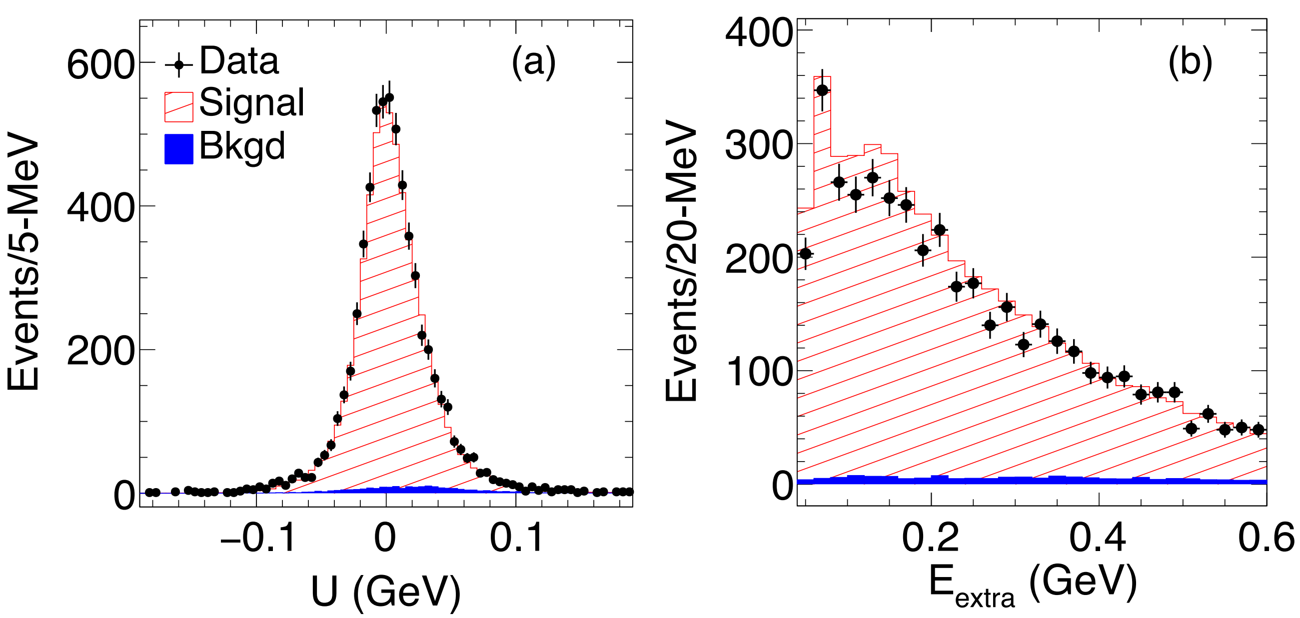
BGL is much better, model independent

So is it ok to just present results with Boyd Grinstein Lebed (**BGL**) ?

BGL looks great:

- it removes the relation between slope and curvature on the leading form factor; **data can pull it.**
- Slop and curvature of the form factor ratios $R_{1/2}$ are not constrained, **data can pull it.**

Beautiful **unbinned 4D fit (!)** from BaBar [Phys. Rev. Lett. 123, 091801 (2019)]



$a_0^f \times 10^2$	$a_1^f \times 10^2$	$a_1^{F_1} \times 10^2$	$a_0^g \times 10^2$	$a_1^g \times 10^2$	$\lvert V_{cb}\rvert \times 10^3$
1.29 ± 0.03	1.63 ± 1.00	0.03 ± 0.11	2.74 ± 0.11	8.33 ± 6.67	38.36 ± 0.90

TABLE I. The $N = 1$ BGL expansion results of this analysis, including systematic uncertainties.

$\rho^2_{D^*}$	$R_1(1)$	$R_2(1)$	$\lvert V_{cb}\rvert \times 10^3$
0.96 ± 0.08	1.29 ± 0.04	0.99 ± 0.04	38.40 ± 0.84

TABLE II. The CLN fit results from this analysis, including systematic uncertainties.

Truncation Order

Model independence is a **step forward**, but **choices have** to be **made** here as well..

$$g(z) = \frac{1}{P_g(z)\phi_g(z)} \sum_{n=0}^{N} a_n z^n, \qquad f(z) = \frac{1}{P_f(z)\phi_f(z)} \sum_{n=0}^{N} b_n z^n, \qquad \mathcal{F}_1(z) = \frac{1}{P_{\mathcal{F}_1}(z)\phi_{\mathcal{F}_1}(z)} \sum_{n=0}^{N} c_n z^n,$$

One Problem you face as an experimentalist: where do you truncate?

Truncate too soon:

- Model dependence in extracted result for $|V_{cb}|$?

Truncate too late:

- Unnecessarily increase variance on $|V_{cb}|$?

Is there an **ideal** truncation order?

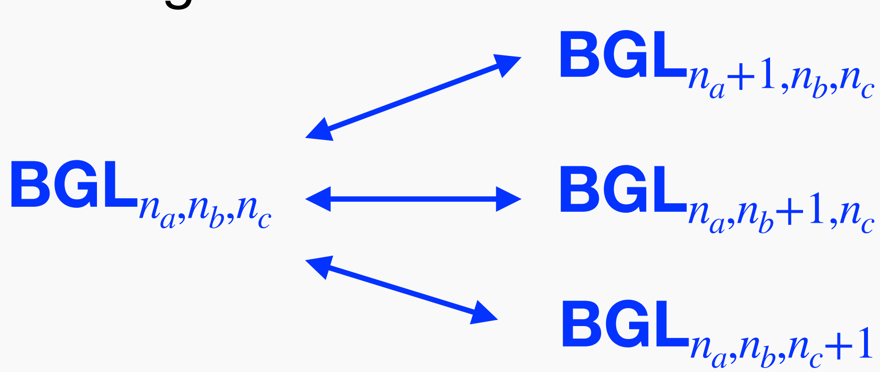
What about **additional constraints**?

Nested Hypothesis Tests or Saturation Constraints

Z. Ligeti, D. Robinson, M. Papucci, FB
[arXiv:1902.09553, PRD100,013005 (2019)]

Use a **nested hypothesis test (NHT)** to determine optimal truncation order

Challenge nested fits



Test statistics & Decision boundary

$$\Delta\chi^2 = \chi^2_N - \chi^2_{N+1} \qquad \Delta\chi^2 > 1$$

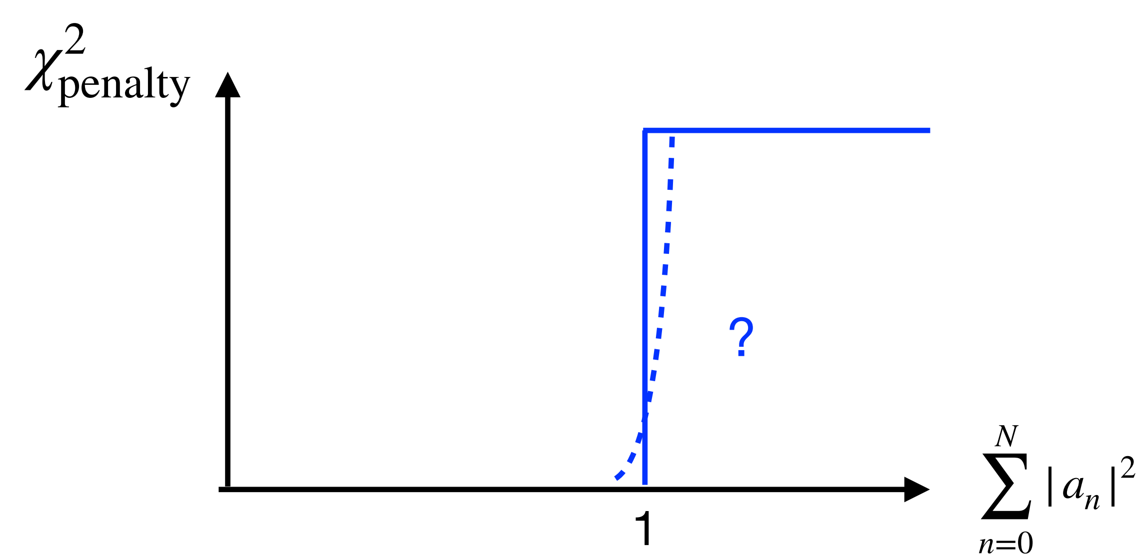
Distributed like a χ^2-distribution with 1 dof (Wilk's theorem)

Gambino, Jung, Schacht
[arXiv:1905.08209, PLB]

Constrain contributions from higher order coefficients using **unitarity bounds**

$$\sum_{n=0}^{N} |a_n|^2 \leq 1 \qquad \sum_{n=0}^{N} \left(|b_n|^2 + |c_n|^2 \right) \leq 1$$

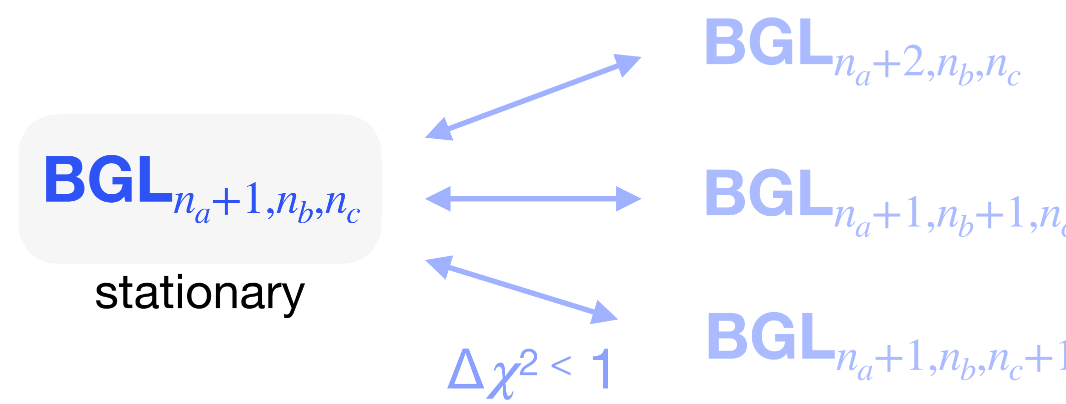
e.g. $\chi^2 \to \chi^2 + \chi^2_{\text{penalty}}$



Nesting Procedure

Steps:

1. Carry out nested fits with one parameter added
2. Accept descendant over parent fit, if $\Delta\chi^2 > 1$
3. Repeat 1 and 2 until you find **stationary** points
4. If multiple **stationary** points remain, choose the one with smallest N, then smallest χ^2
5. Reject scenarios that **produce strong correlations** (= blind directions)



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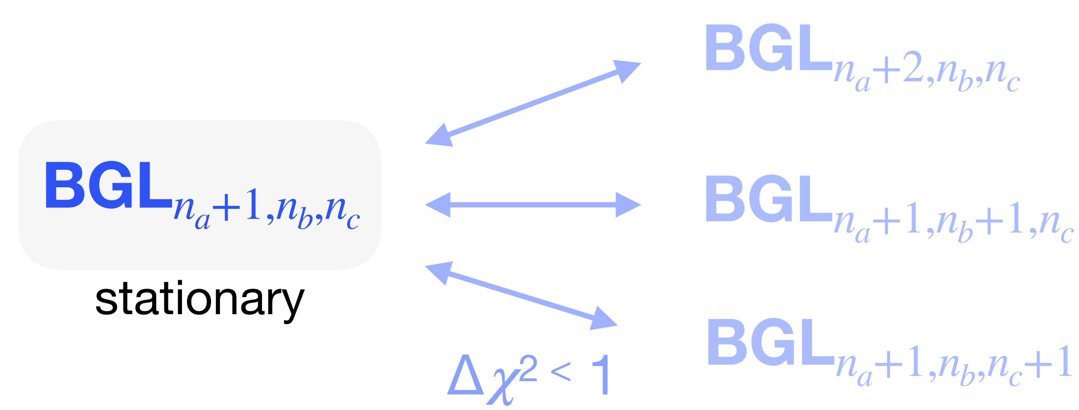

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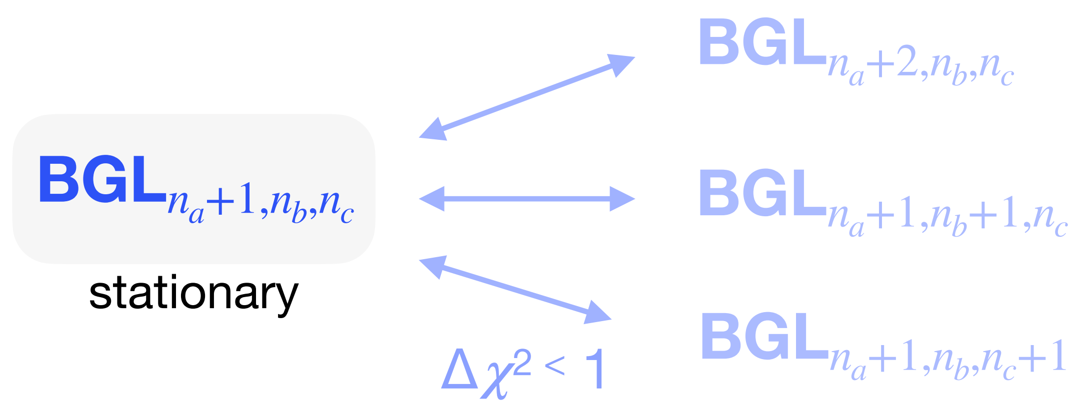

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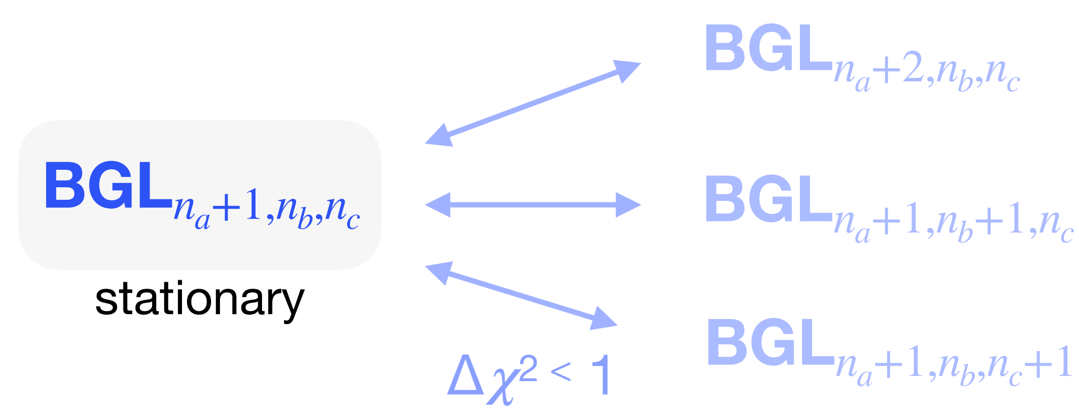

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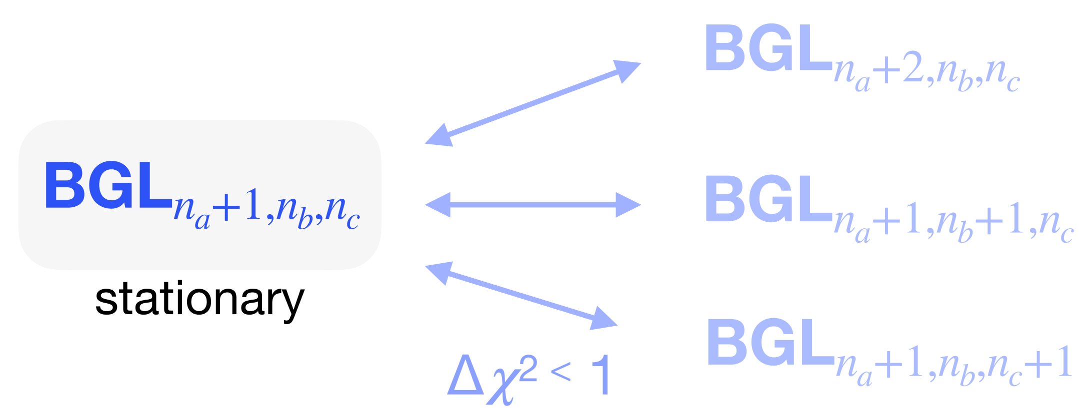


Toy study to illustrate possible bias

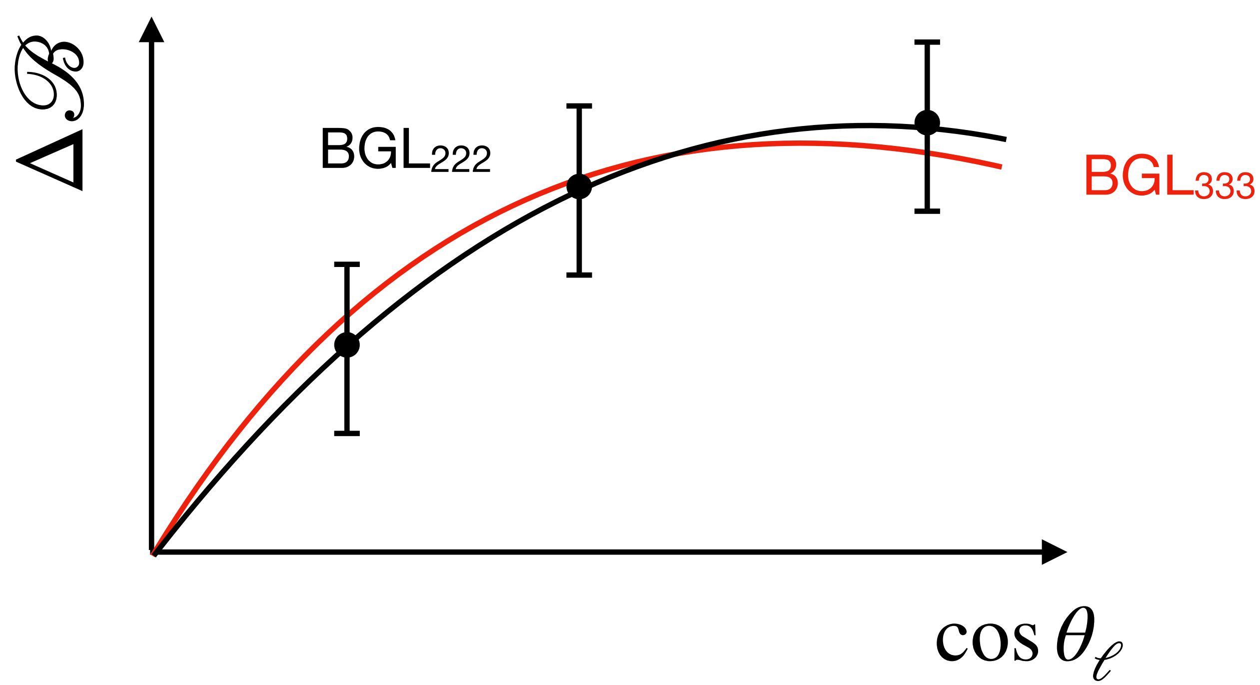
Use the central values of the **BGL_{222} fit** as a starting point to add **fine structure**

fit = fit to prel. 2017 Belle data

Parameter	'1-times' Value $\times\ 10^2$	'10-times' Value $\times\ 10^2$
$\tilde{a}_2$	2.6954	26.954
$\tilde{b}_2$	-0.2040	-2.040
$\tilde{c}_3$	0.5350	5.350

Create a "true" higher order Hypothesis of order **BGL_{333}**

Has fine structure element the **current data cannot resolve**



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Toy Test

Produce **ensemble** of toy measurements using **meas. covariance** & **BGL$_{333}$** central values

↓

Each toy is fitted to build the descendant tree and carry out a **NHT** to select its preferred **BGL$n_a n_b n_c$**

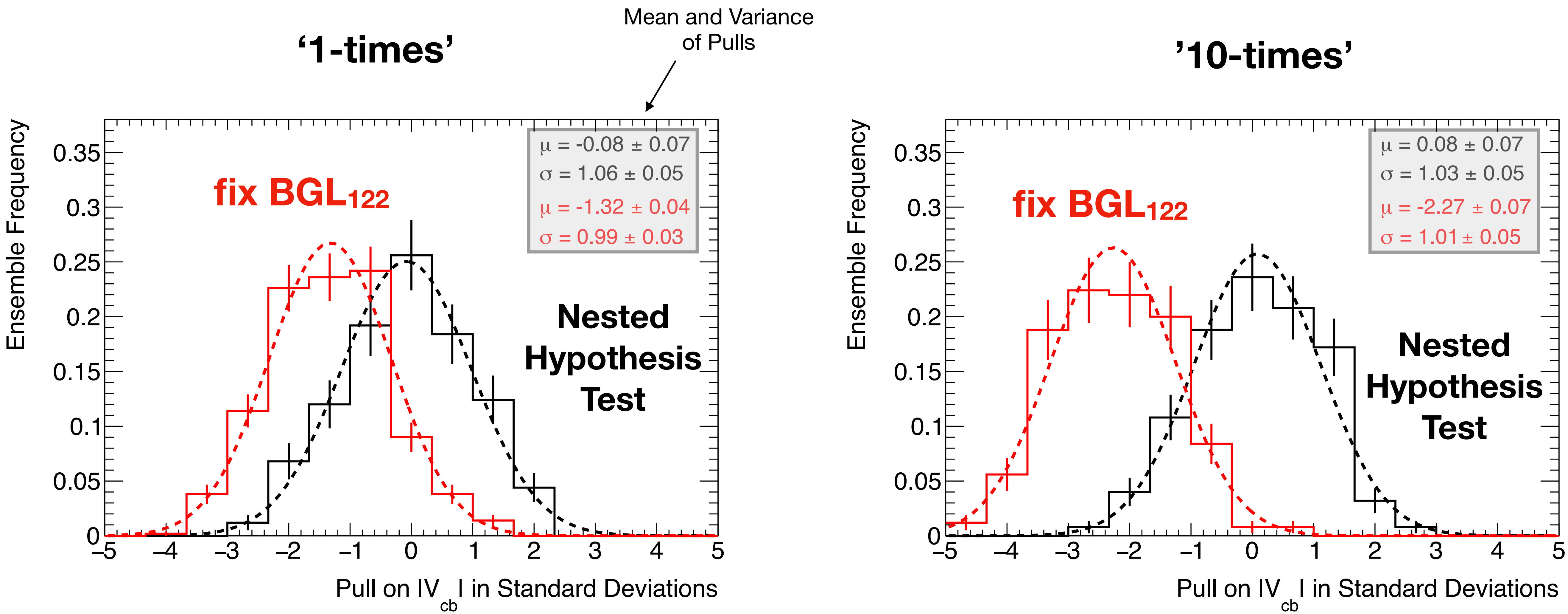
Construct Pulls →

$$\textbf{Pull} = \frac{|V_{cb}|_{\textbf{true}} - |V_{cb}|_{\textbf{toy}}}{\Delta |V_{cb}|_{\textbf{toy}}}$$

As calculated from selected BGL$n_a n_b n_c$ fit of each toy

If methodology unbiased, should follow a standard normal distribution (mean 0, width 1)

Bias



→ Procedure produces **unbiased** $|V_{cb}|$ values, just picking a given hypothesis (BGL_{122}) **does not**

Relative Frequency of selected Hypothesis:

	BGL_{122}	BGL_{212}	BGL_{221}	BGL_{222}	BGL_{223}	BGL_{232}	BGL_{322}	BGL_{233}	BGL_{323}	BGL_{332}	BGL_{333}
1-times	6%	0%	37%	27%	6%	6%	11%	0%	2%	4%	0.4%
10-times	0%	0%	8%	38%	14%	8%	16%	3%	4%	8%	1%

Paradigm shift

Publishing statistical models: Getting the most out of particle physics experiments
Kyle Cranmer, Sabine Kraml, Harrison B. Prosper, Philip Bechtle, Florian U. Bernlochner, Itay M. Bloch, Enzo Canonero, Marcin Chrzaszcz, Andrea Coccaro, Jan Conrad, Glen Cowan, Matthew Feickert, Nahuel Ferreiro Iachellini, Andrew Fowlie, Lukas Heinrich, Alexander Held, Thomas Kuhr, Anders Kvellestad, Maeve Madigan, Farvah Mahmoudi, Knut Dundas Morå, Mark S. Neubauer, Maurizio Pierini, Juan Rojo, Sezen Sekmen, Luca Silvestrini, Veronica Sanz, Giordon Stark, Riccardo Torre, Robert Thorne, Wolfgang Waltenberger, Nicholas Wardle, Jonas Wittbrodt
SciPost Phys. 12, 037 (2022) · published 25 January 2022

My three take-away points:

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BGL removes the (theory)-model dependent assumptions of **CLN**; great step forward

BUT

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What if someone comes along and wants to **fit something else** to the data with different assumptions?

BGL with updated pole masses?

DM from MNSL(*PoS* LATTICE2022 (2023) 298)
BGJD (*Eur.Phys.J.C* 80 (2020) 4, 347)
BLPR (*Phys. Rev. D 95, 115008 (2017)*)
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What if someone wants to **do something entirely else** with the **data** we have not thought of today?

E.g. look for a bump for a sterile neutrino at large MM2, search for RH currents in angular distributions

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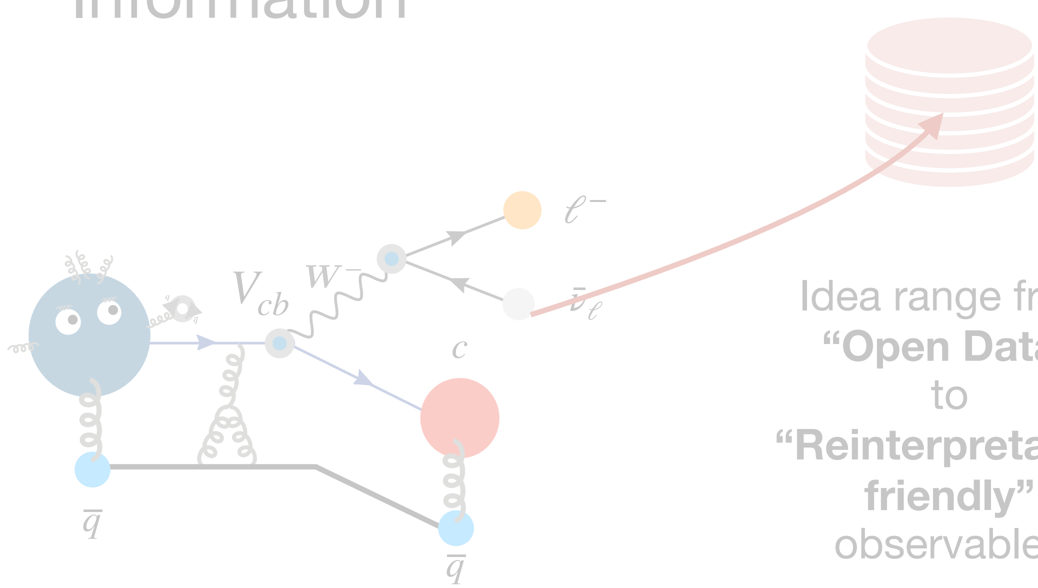

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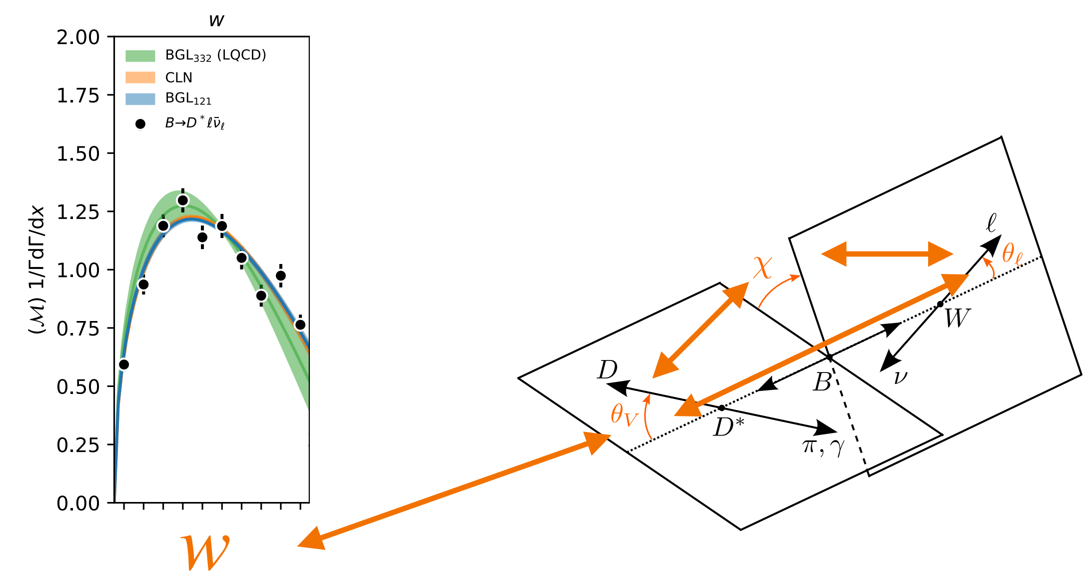

Working around the curse of dimensionality

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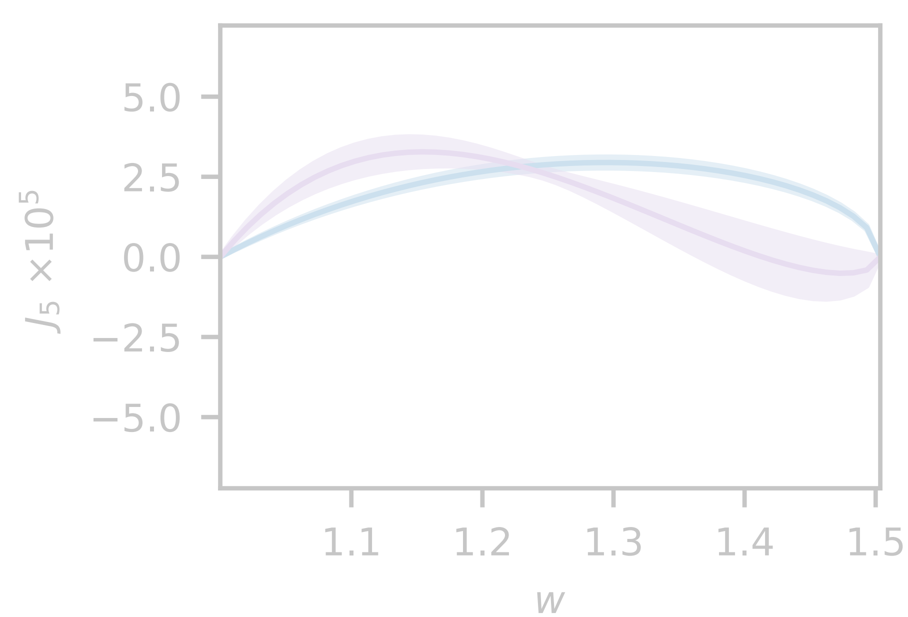


Possible Strategies

Publish either container that allows later reinterpretation

(includes final selected data, MC, etc.)

opendata CERN

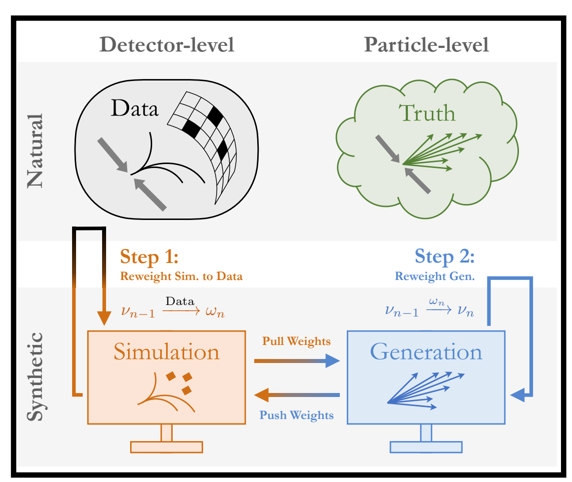
Very ambitious, but great goal!

- Not everybody agrees and not everybody agrees to what extend

Publish ND or unbinned unfolded measurements

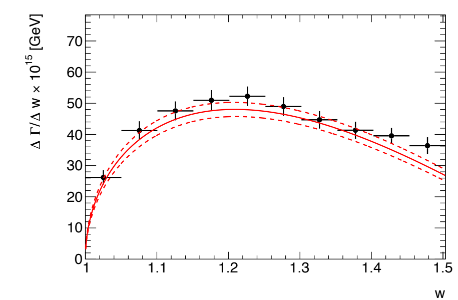
Very challenging, binned: curse of dimensionality (5D measurement essentially)

Unbinned unfolding cool new idea, beats high dimensionality



Omnifold: unbinned unfolding
Phys. Rev. Lett. 124, 182001 (2020)

Publish 1D Measurements of partial BFs



Belle started doing this in 2017

Followed up in 2018 and 2023

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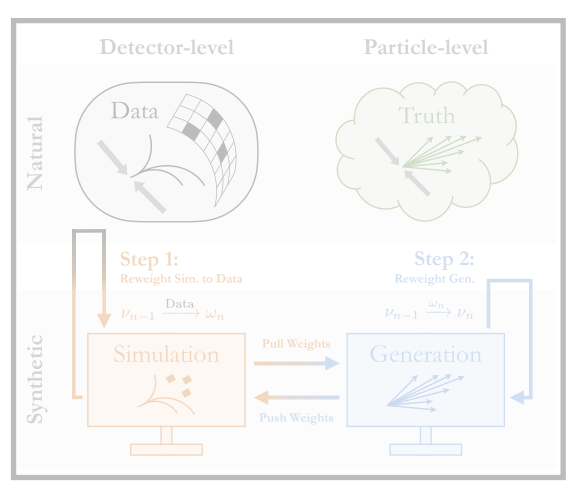

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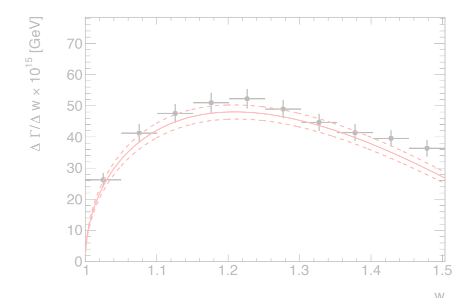
Somewhere in **between**?

Without loosing too much interesting information?

Publish 1D Measurements of partial BFs



Belle started doing this in 2017

Followed up in 2018 and 2023

Full Angular Information **without** going to 4D

Full angular information can be encoded into **12 coefficients** :

$$\frac{d\Gamma}{dq^2\, d\cos\theta_V\, d\cos\theta_\ell\, d\chi} = \frac{G_F^2 \left|V_{cb}\right|^2 m_B^3}{2\pi^4}$$
$$\times \Big\{ J_{1s} \sin^2\theta_V + J_{1c} \cos^2\theta_V$$
$$+ \left(J_{2s} \sin^2\theta_V + J_{2c} \cos^2\theta_V\right) \cos 2\theta_\ell$$
$$+ J_3 \sin^2\theta_V \sin^2\theta_\ell \cos 2\chi$$
$$+ J_4 \sin 2\theta_V \sin 2\theta_\ell \cos\chi + J_5 \sin 2\theta_V \sin\theta_\ell \cos\chi$$
$$+ \left(J_{6s} \sin^2\theta_V + J_{6c} \cos^2\theta_V\right) \cos\theta_\ell$$
$$+ J_7 \sin 2\theta_V \sin\theta_\ell \sin\chi + J_8 \sin 2\theta_V \sin 2\theta_\ell \sin\chi$$
$$+ J_9 \sin^2\theta_V \sin^2\theta_\ell \sin 2\chi \Big\} .$$

→ Each of these coefficients is a function of $q^2 \sim w$

↓

With some smart folding, one can "easily" determine them

Based on the ideas of:
JHEP 05 (2013) 043
JHEP 05 (2013) 137
Phys. Rev. D 90, 094003 (2014)
http://cds.cern.ch/record/1605179

8 Coefficients relevant in massless limit & SM

How can we measure these coefficients?

Step 1: bin up phase-space in $q^2 \sim w$ in however many bins you can afford

How can we measure these coefficients?

Step 1: bin up phase-space in $q^2 \sim w$ in however many bins you can afford

Step 2: Determine the # of signal events in specific phase-space regions

The coefficients are related to a weighted sun of events in a given q^2 bin

$$J_i = \frac{1}{N_i} \sum_{j=1}^{8} \sum_{k,l=1}^{4} \eta_{ij}^{\chi} \eta_{ik}^{\theta_\ell} \eta_{il}^{\theta_V} \left[\chi^i \otimes \theta_\ell^j \otimes \theta_V^k \right]$$

Normalization Factor — Weights — Phase space region

J_i	η_i^χ	$\eta_i^{\theta_\ell}$	$\eta_i^{\theta_V}$	normalization N_i
J_{1s}	$\{+\}$	$\{+,a,a,+\}$	$\{-,c,c,-\}$	$2\pi(1)2$
J_{1c}	$\{+\}$	$\{+,a,a,+\}$	$\{+,d,d,+\}$	$2\pi(1)(2/5)$
J_{2s}	$\{+\}$	$\{-,b,b,-\}$	$\{-,c,c,-\}$	$2\pi(-2/3)2$
J_{2c}	$\{+\}$	$\{-,b,b,-\}$	$\{+,d,d,+\}$	$2\pi(-2/3)(2/5)$
J_3	$\{+,-,-,+,+,-,-,+\}$	$\{+\}$	$\{+\}$	$4(4/3)^2$
J_4	$\{+,+,-,-,-,-,+,+\}$	$\{+,+,-,-\}$	$\{+,+,-,-\}$	$4(4/3)^2$
J_5	$\{+,+,-,-,-,-,+,+\}$	$\{+\}$	$\{+,+,-,-\}$	$4(\pi/2)(4/3)$
J_{6s}	$\{+\}$	$\{+,+,-,-\}$	$\{-,c,c,-\}$	$2\pi(1)2$
J_{6c}	$\{+\}$	$\{+,+,-,-\}$	$\{+,d,d,+\}$	$2\pi(1)(2/5)$
J_7	$\{+,+,+,+,-,-,-,-\}$	$\{+\}$	$\{+,+,-,-\}$	$4(\pi/2)(4/3)$
J_8	$\{+,+,+,+,-,-,-,-\}$	$\{+,+,-,-\}$	$\{+,+,-,-\}$	$4(4/3)^2$
J_9	$\{+,+,-,-,+,+,-,-\}$	$\{+\}$	$\{+\}$	$4(4/3)^2$

$a = 1 - 1/\sqrt{2}, b = a\sqrt{2}, c = 2\sqrt{2} - 1, d = 1 - 4\sqrt{2}/5$

E.g. for J_3: **Split** χ into **2 Regions**

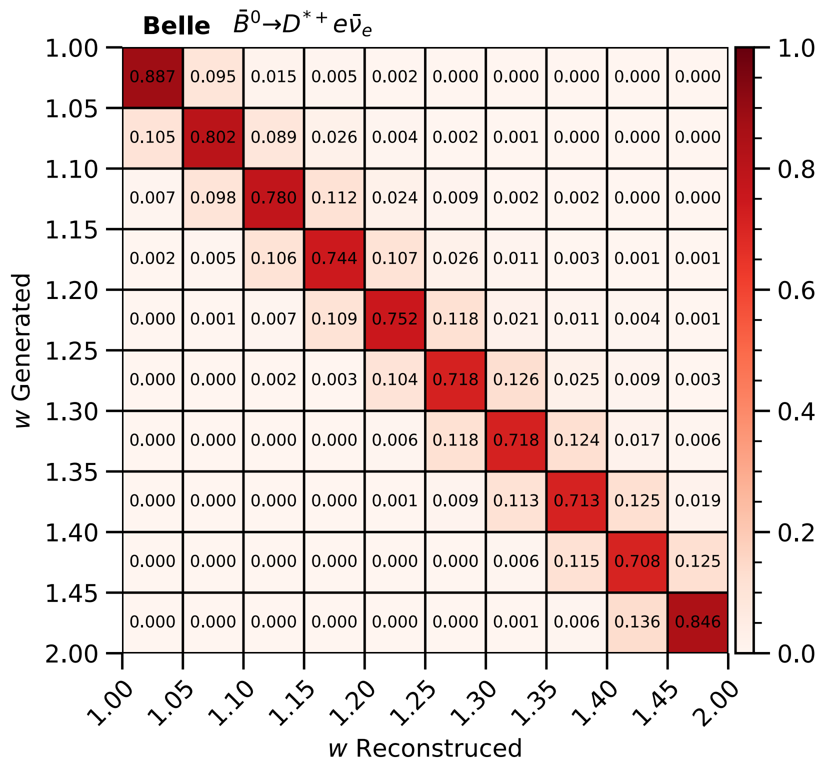
$'+' : \chi \in [0,\pi/4], [3/4\pi,5/4\pi], [7/4\pi,2\pi]$ — $\tilde{N}_+$

$'-' : \chi \in [\pi/4,3/4\pi], [5/4\pi,7/4\pi]$ — $\tilde{N}_-$

Step 3: Reverse Migration and Acceptance Effects

Resolution effects: events with a **given "true" value** of $\{q^2, \cos\theta_\ell, \cos\theta_V, \chi\}$ can **fall into different reconstructed** bins

E.g. w migration matrix



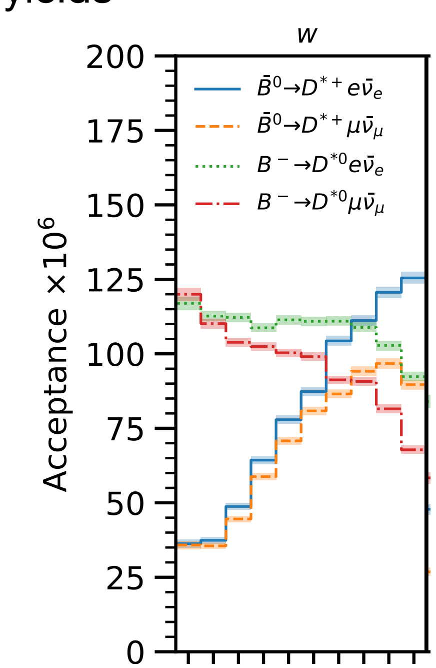
arXiv:2301.07529 **[hep-ex]**

$$\begin{pmatrix} \tilde{N}_+^{q_1^2} \\ \tilde{N}_-^{q_1^2} \\ \tilde{N}_+^{q_2^2} \\ \tilde{N}_-^{q_2^2} \\ \tilde{N}_+^{q_3^2} \\ \tilde{N}_-^{q_3^2} \\ \tilde{N}_+^{q_4^2} \\ \tilde{N}_-^{q_4^2} \\ \tilde{N}_+^{q_5^2} \\ \tilde{N}_-^{q_5^2} \end{pmatrix} = \mathscr{M} \begin{pmatrix} N_+^{q_1^2} \\ N_-^{q_1^2} \\ N_+^{q_2^2} \\ N_-^{q_2^2} \\ N_+^{q_3^2} \\ N_-^{q_3^2} \\ N_+^{q_4^2} \\ N_-^{q_4^2} \\ N_+^{q_5^2} \\ N_-^{q_5^2} \end{pmatrix}$$

← Unfolded yields

Migration matrix

Bkg subtracted yields



arXiv:2301.07529 **[hep-ex]**

Acceptance x Efficiency Corrections:

$$N_+^{q_i^2} \cdot e_{\mathrm{eff},+,q_i^2}^{-1} = n_+^{q_i^2}$$

$$N_-^{q_i^2} \cdot e_{\mathrm{eff},-,q_i^2}^{-1} = n_-^{q_i^2}$$

← Acceptance / Eff. corrected yields

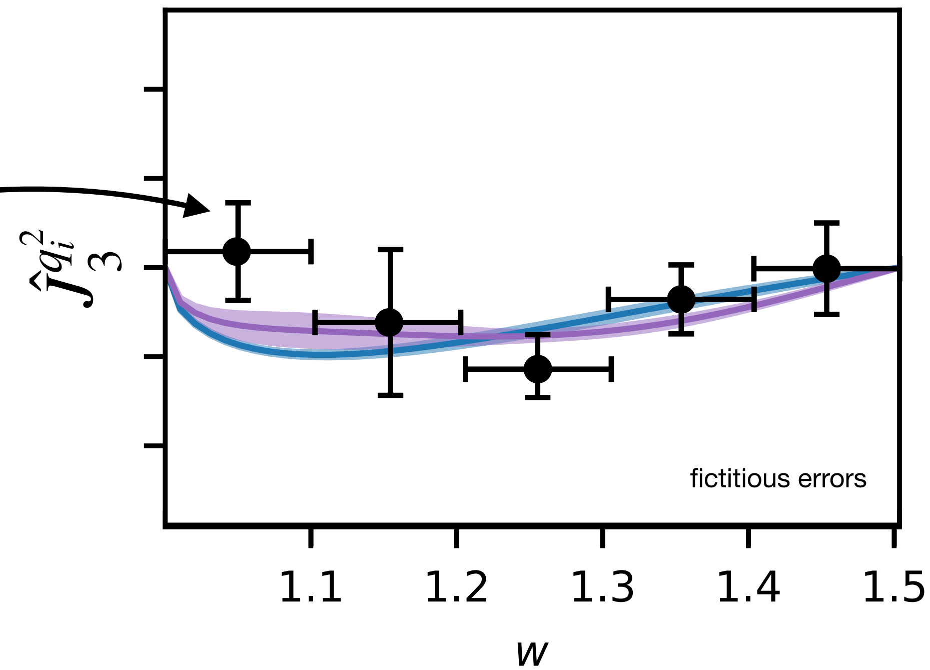
Unfolded yields

Step 4: Calculate J_i for a given w/q^2 bin

$$n_+^{q_i^2},\quad n_-^{q_i^2} \to \hat{J}_3^{q_i^2} = \frac{1}{\Gamma} \times \frac{n_+^{q_i^2} - n_-^{q_i^2}}{4(4/3)^2}$$

Normalization

$$\Gamma = \frac{8}{9}\pi \left(3 \sum_i J_{1c}^{q_i^2} + 6 \sum_i J_{1s}^{q_i^2} - \sum_i J_{2c}^{q_i^2} - 2 \sum_i J_{2s}^{q_i^2} \right)$$



More **involved** for the **other** coefficients: need full experimental covariance between all measured w/q^2 bins and coefficients
(statistical overlap, systematics)

SM:

$$\{J_{1s}^{q_i^2}, J_{1c}^{q_i^2}, J_{2s}^{q_i^2}, J_{2c}^{q_i^2}, J_{3}^{q_i^2}, J_{4}^{q_i^2}, J_{5}^{q_i^2}, J_{6s}^{q_i^2}\}$$

e.g. **5 x 8** = **40 coefficients**

or full thing (SM + NP)
with **5 x 12** = **60 coefficients**

J_i	η_i^χ	$\eta_i^{\theta_\ell}$	$\eta_i^{\theta_V}$	normalization N_i
J_{1s}	$\{+\}$	$\{+,a,a,+\}$	$\{-,c,c,-\}$	$2\pi(1)2$
J_{1c}	$\{+\}$	$\{+,a,a,+\}$	$\{+,d,d,+\}$	$2\pi(1)(2/5)$
J_{2s}	$\{+\}$	$\{-,b,b,-\}$	$\{-,c,c,-\}$	$2\pi(-2/3)2$
J_{2c}	$\{+\}$	$\{-,b,b,-\}$	$\{+,d,d,+\}$	$2\pi(-2/3)(2/5)$
J_3	$\{+,-,-,+,+,-,-,+\}$	$\{+\}$	$\{+\}$	$4(4/3)^2$
J_4	$\{+,+,-,-,-,-,+,+\}$	$\{+,+,-,-\}$	$\{+,+,-,-\}$	$4(4/3)^2$
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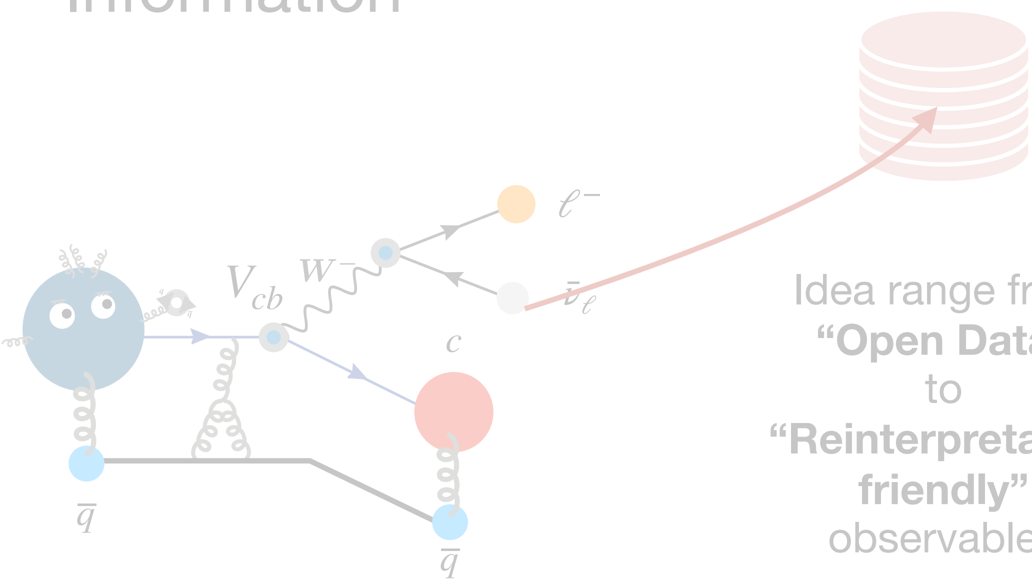
J_{6s}	$\{+\}$	$\{+,+,-,-\}$	$\{-,c,c,-\}$	$2\pi(1)2$
J_{6c}	$\{+\}$	$\{+,+,-,-\}$	$\{+,d,d,+\}$	$2\pi(1)(2/5)$
J_7	$\{+,+,+,+,-,-,-,-\}$	$\{+\}$	$\{+,+,-,-\}$	$4(\pi/2)(4/3)$
J_8	$\{+,+,+,+,-,-,-,-\}$	$\{+,+,-,-\}$	$\{+,+,-,-\}$	$4(4/3)^2$
J_9	$\{+,+,-,-,+,+,-,-\}$	$\{+\}$	$\{+\}$	$4(4/3)^2$

$$a = 1 - 1/\sqrt{2}, b = a\sqrt{2}, c = 2\sqrt{2} - 1, d = 1 - 4\sqrt{2}/5$$

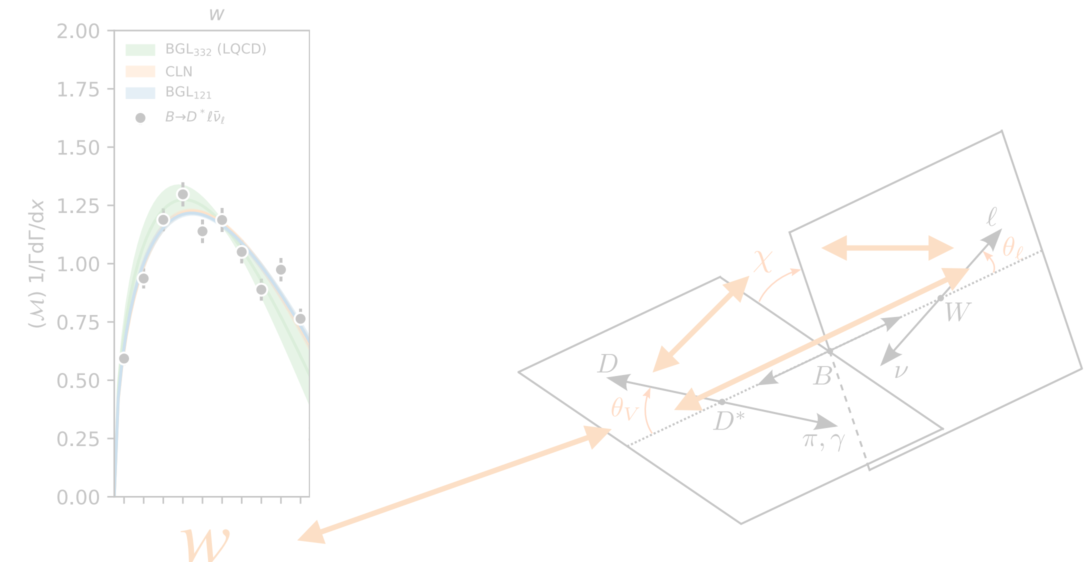
Talk Overview

1. Why we need to do better to preserve our experimental Information



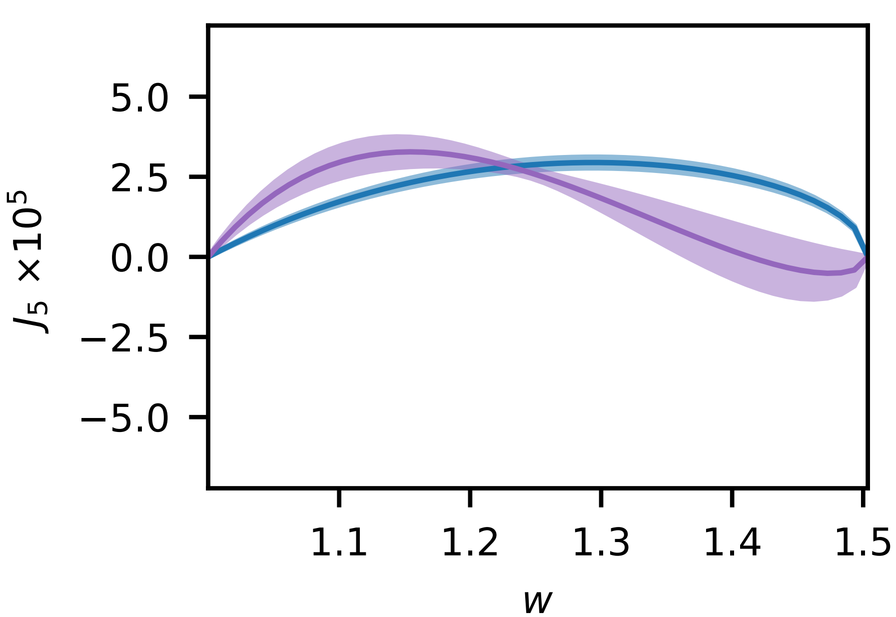
Idea range from **"Open Data"** to **"Reinterpretation friendly"** observables

2. From **1D projections** to full angular information



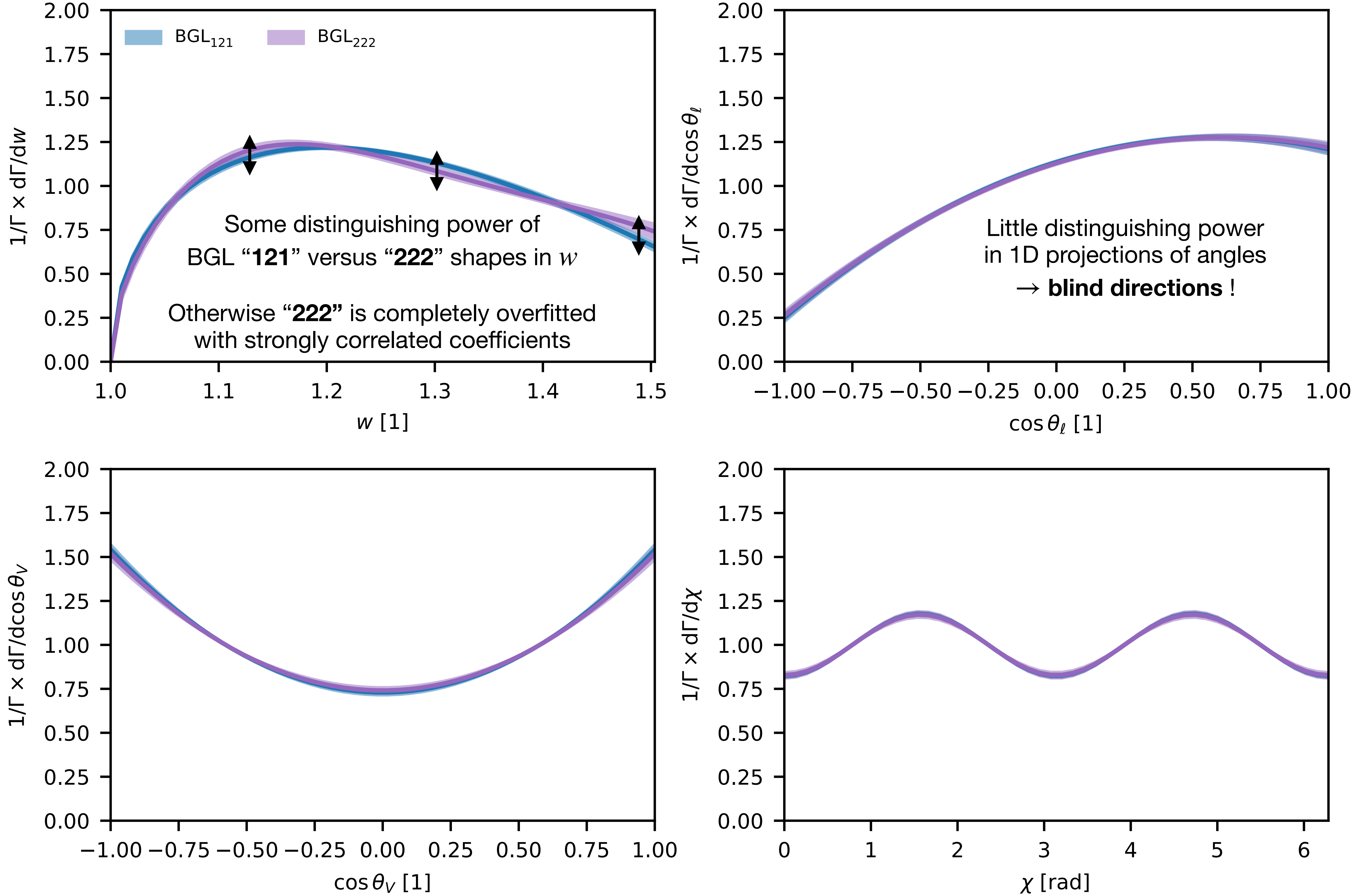
Working around the curse of dimensionality

3. Potential of full angular fits



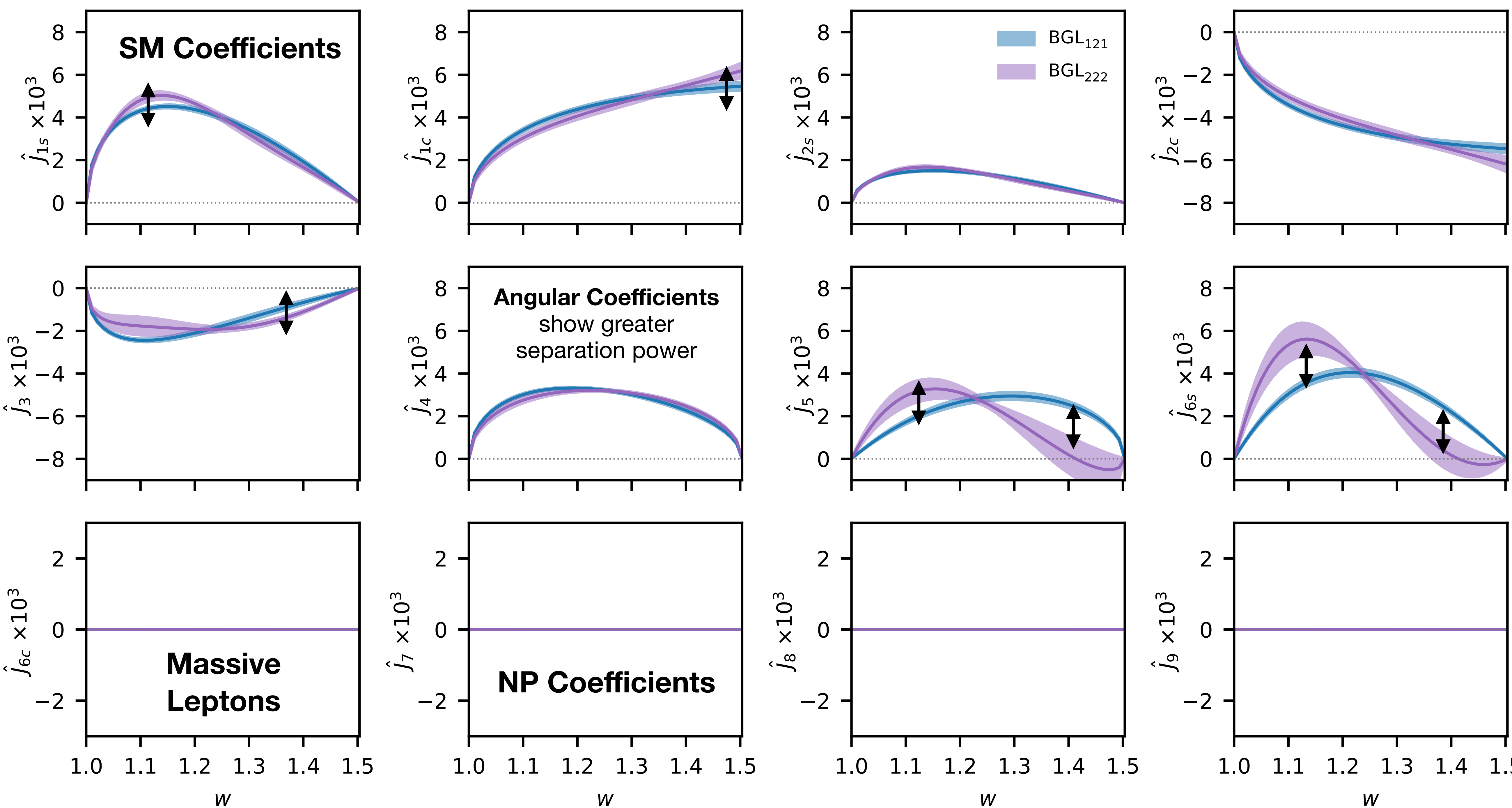
1D versus Full Angular Sensitivities

Errors and central values from 1D projection fits of arXiv:2301.07529 (Table XVI)



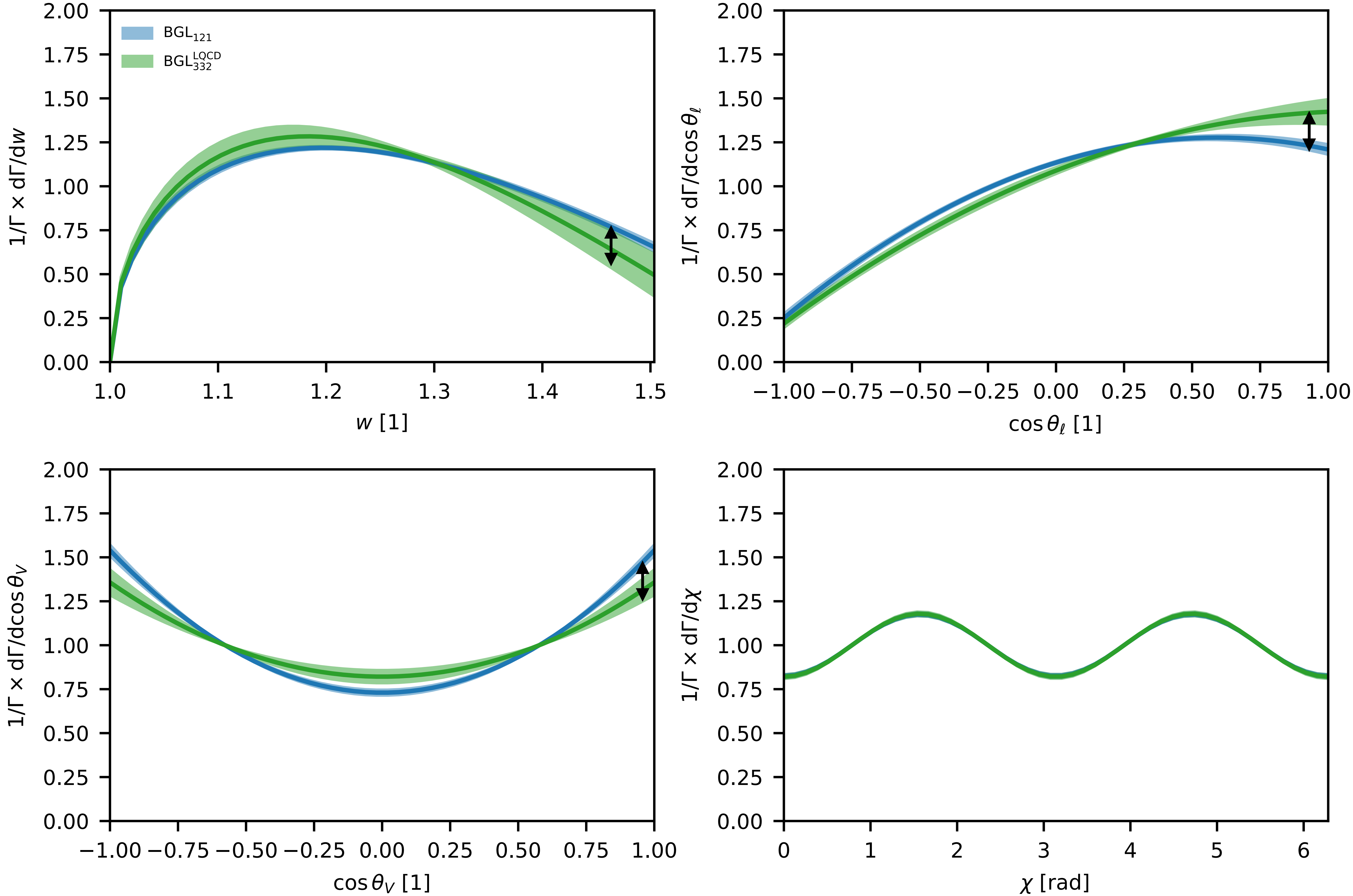
1D versus Full Angular Sensitivities

Errors and central values from 1D projection fit of arXiv:2301.07529 (Table XVI)



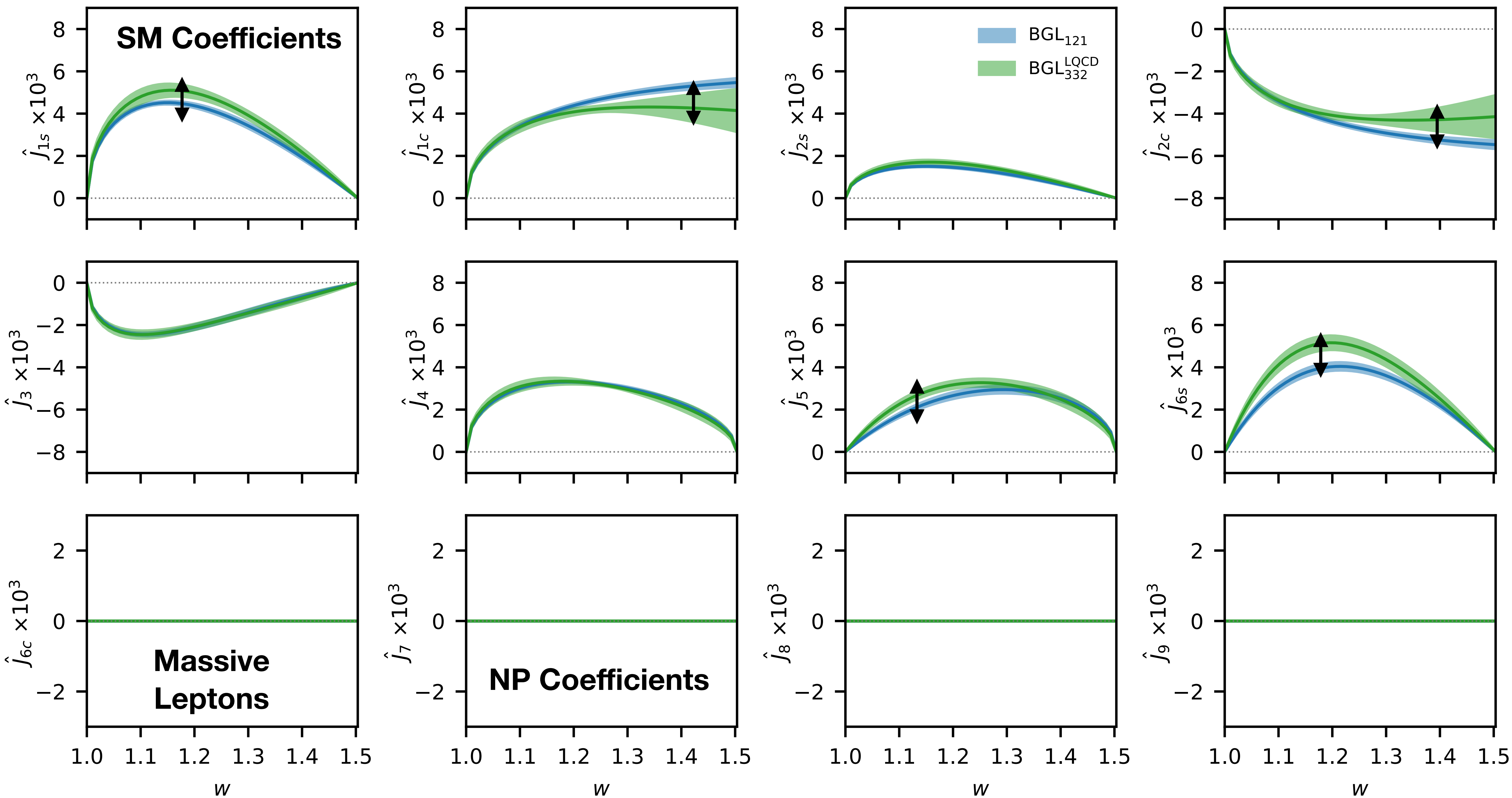
1D versus Full Angular Sensitivities

BGL121 1D projection fit of arXiv:2301.07529 (Table XVI) or **FNAL/MILC prediction** [arXiv:2105.14019]



1D versus Full Angular Sensitivities

BGL121 1D projection fit of arXiv:2301.07529 (Table XVI) or **FNAL/MILC prediction** [arXiv:2105.14019]



Angular Coefficients also will allow us to better **investigate** what is going on with **lattice** versus **data tensions**..

Summary

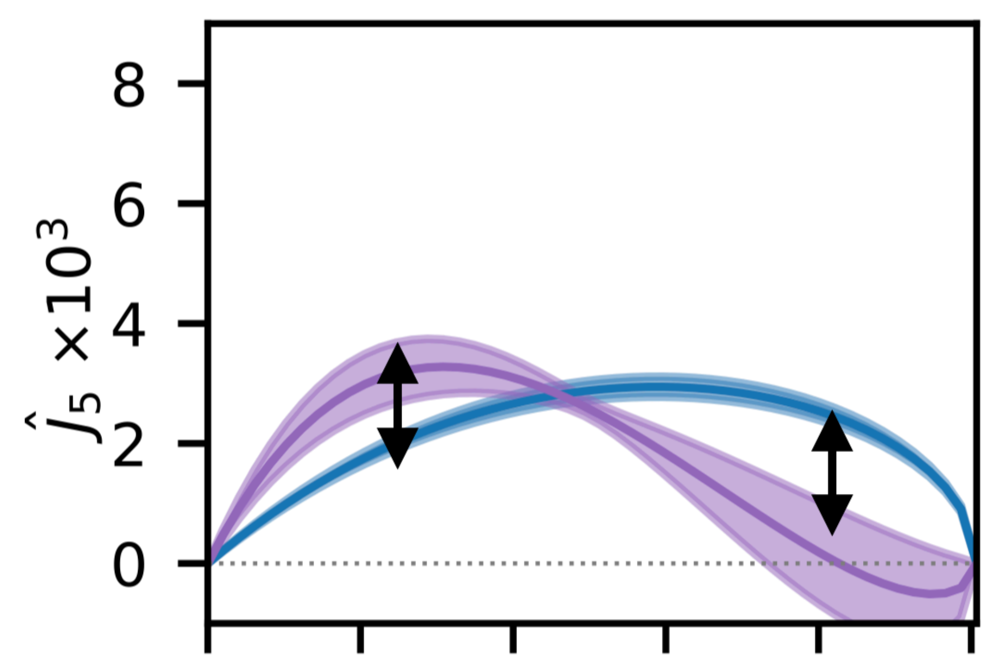
Angular information is crucial to better study $B \to D^* \ell \bar{\nu}_\ell$:

The **future** will hopefully go towards **open data** … but part of a longer discussion.

Unbinned unfolded data is a great new idea; best preserves the properties of the underlying data; but many details need to be ironed out

In the meantime: **Binned angular coefficients seem a very promising strategy to preserve our measurements.**

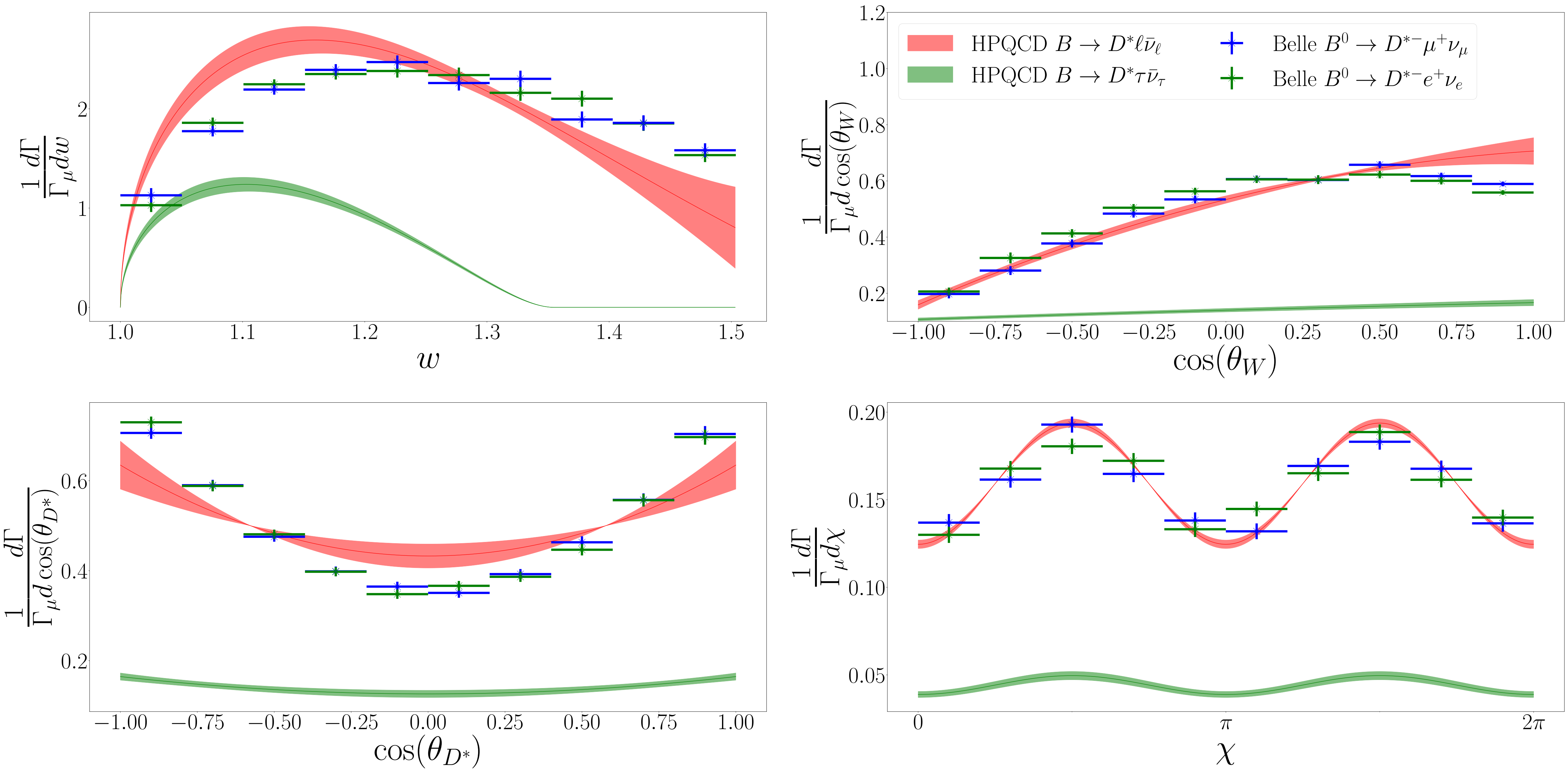
$$\frac{d\Gamma}{dq^2\, d\cos\theta_V\, d\cos\theta_\ell\, d\chi} = \frac{G_F^2 \left|V_{cb}\right|^2 m_B^3}{2\pi^4} \times \Big\{ J_{1s} \sin^2\theta_V + J_{1c}\cos^2\theta_V + (J_{2s}\sin^2\theta_V + J_{2c}\cos^2\theta_V)\cos 2\theta_\ell + J_3 \sin^2\theta_V \sin^2\theta_\ell \cos 2\chi + J_4 \sin 2\theta_V \sin 2\theta_\ell \cos\chi + J_5 \sin 2\theta_V \sin\theta_\ell \cos\chi + (J_{6s}\sin^2\theta_V + J_{6c}\cos^2\theta_V)\cos\theta_\ell + J_7 \sin 2\theta_V \sin\theta_\ell \sin\chi + J_8 \sin 2\theta_V \sin 2\theta_\ell \sin\chi + J_9 \sin^2\theta_V \sin^2\theta_\ell \sin 2\chi \Big\}.$$



Backup

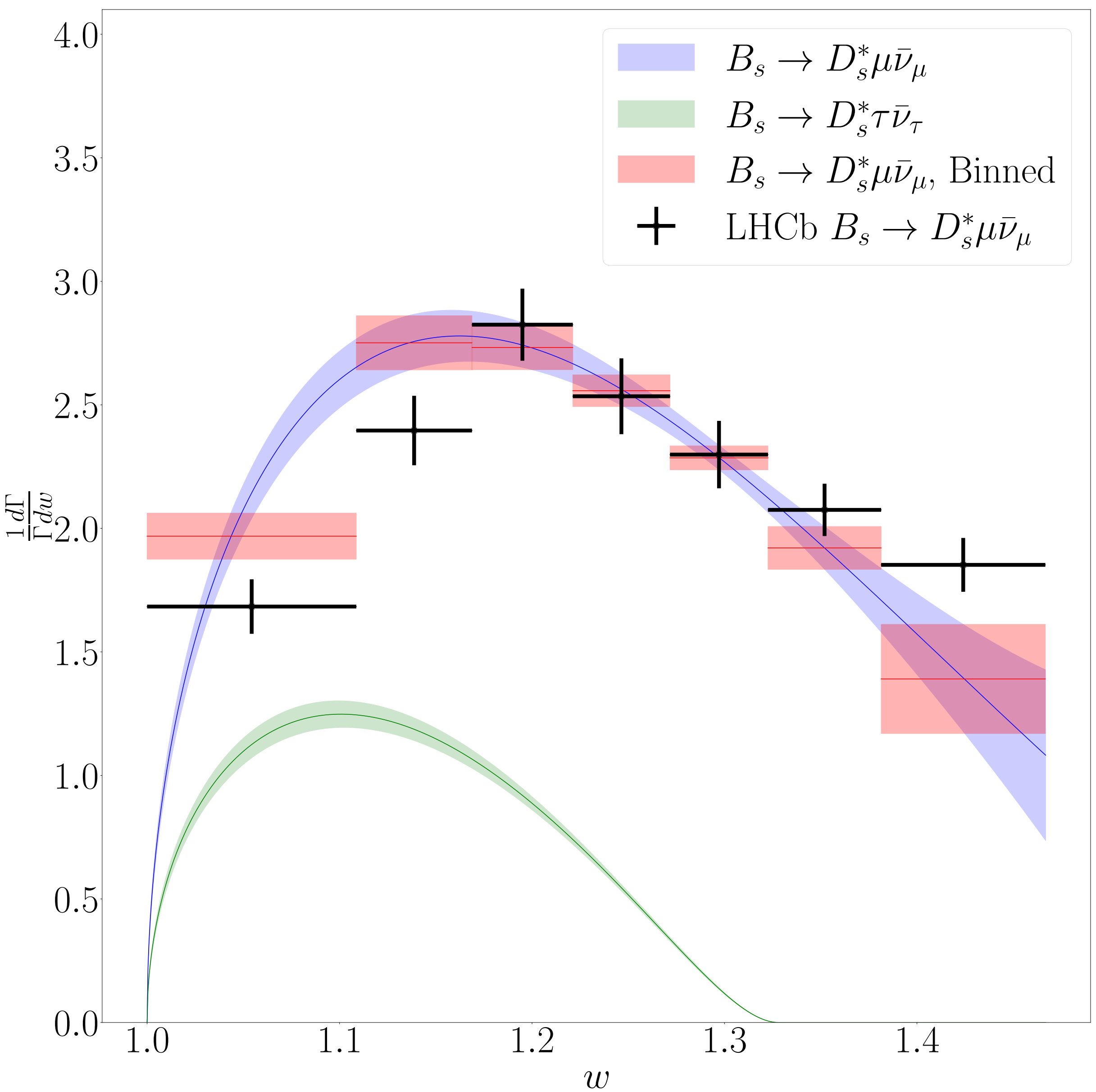
New HPQCD

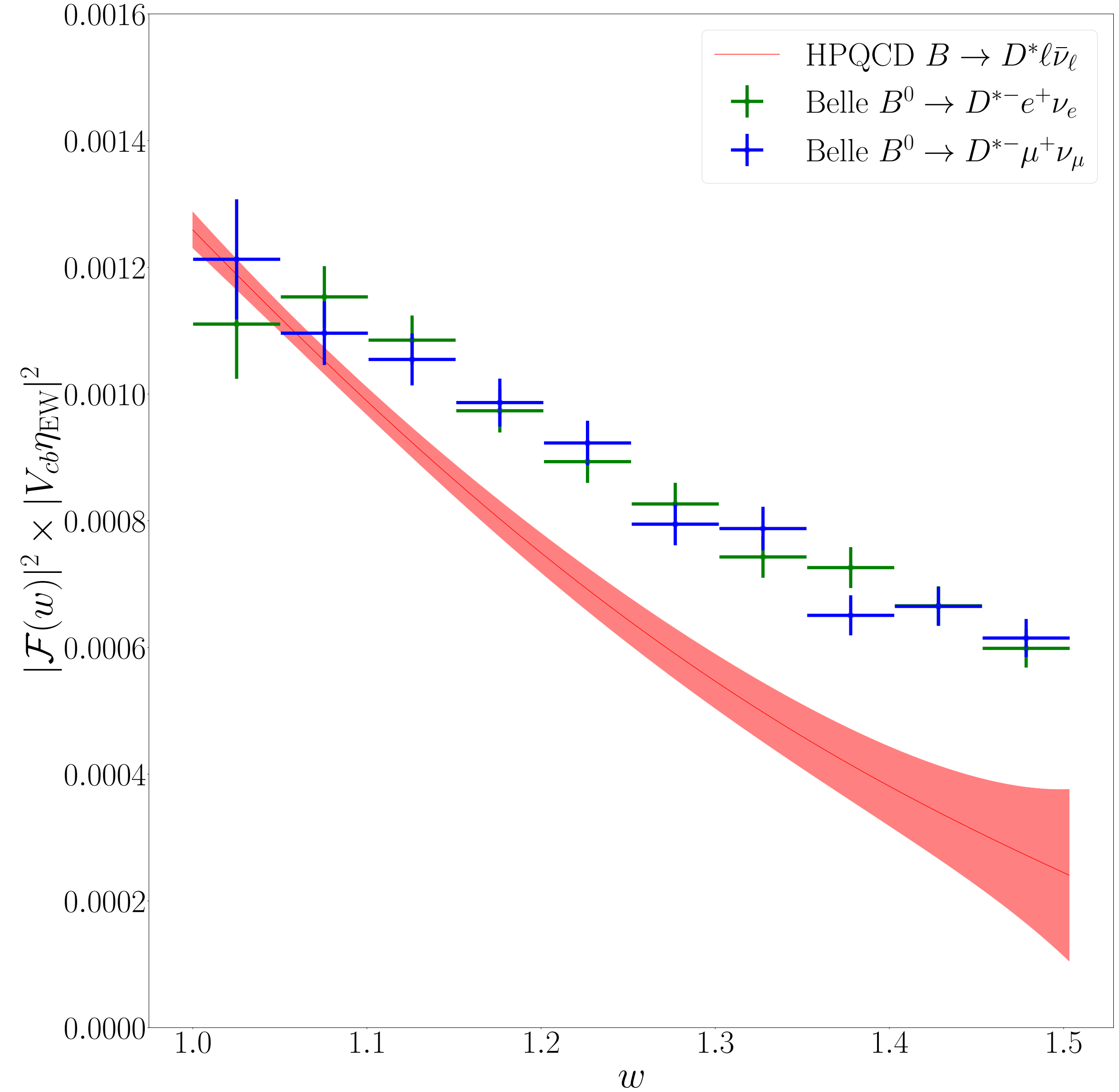
J. Harrison & T.H. Davies [HPQCD] [arXiv:2304.03137 [hep-lat]]



Is it meaningful to combine LQCD and data that do not agree in shape?

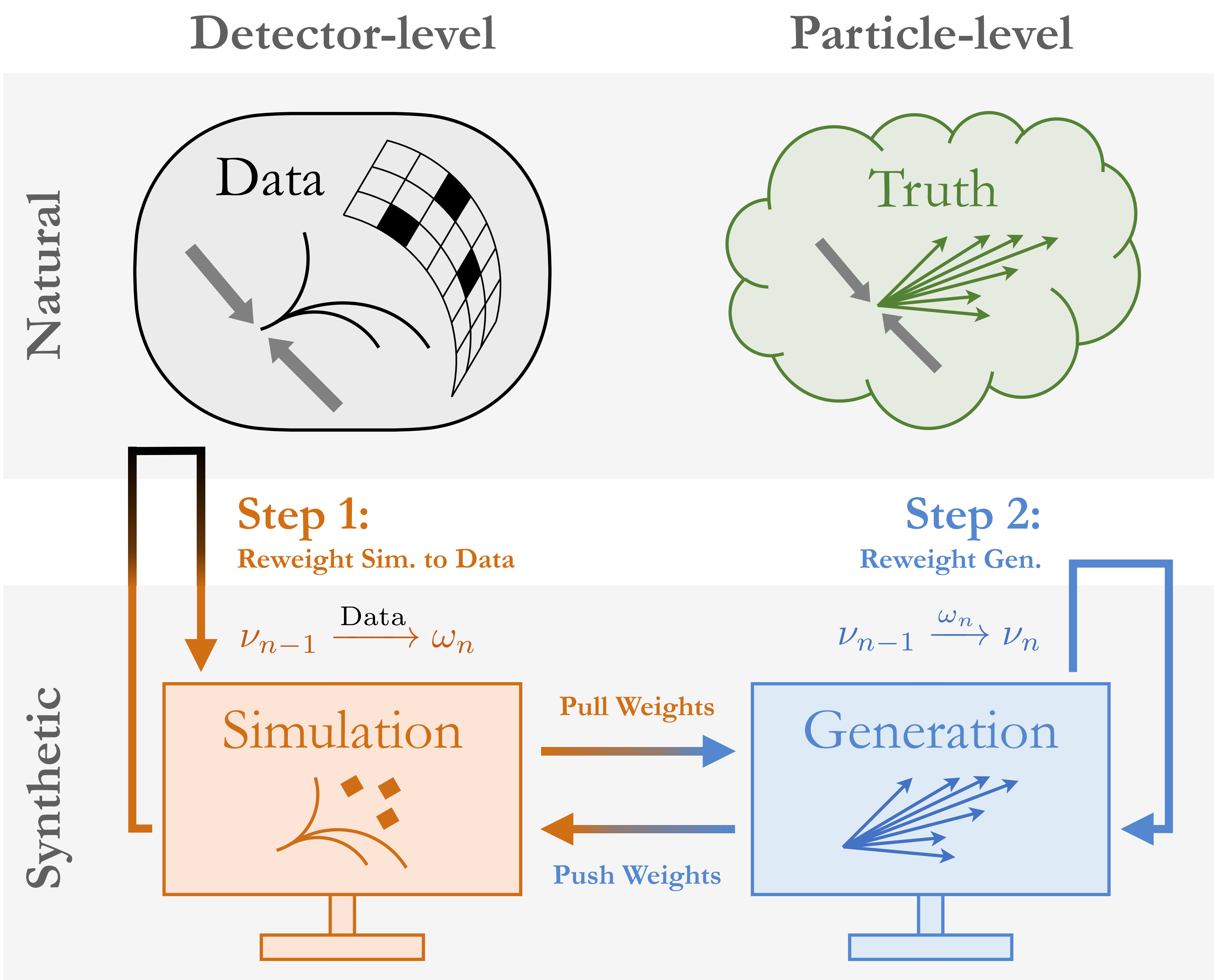
What does this mean for our $|V_{cb}|$ values? Can we trust $\mathscr{F}(1)$?





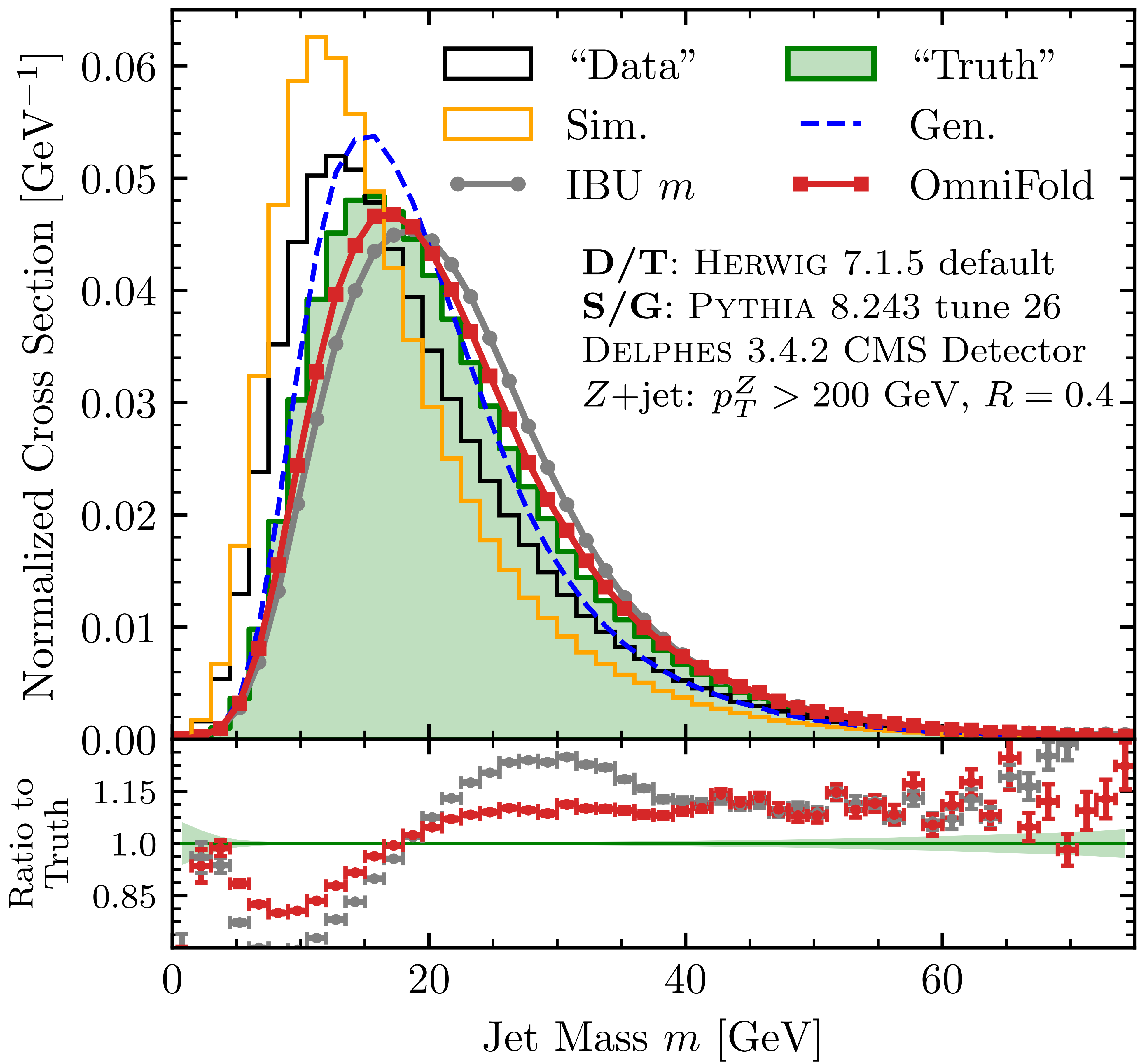
Same data / MC disagreement?

Omnifold



$$p^{(n)}_{\text{unfolded}}(t) = \nu_n(t)\, p_{\text{Gen.}}(t).$$

- UniFold: A single observable as input. This is an unbinned version of IBU.
- MultiFold: Many observables as input. Here, we use the six jet substructure observables in Fig. 2 to derive the detector response.
- OmniFold: The full event (or jet) as input, using the full phase space information.



"Data"
"Truth"
Sim.
Gen.
IBU m
OmniFold
D/T: Herwig 7.1.5 default
S/G: Pythia 8.243 tune 26
Delphes 3.4.2 CMS Detector
Z+jet: $p_T^Z > 200$ GeV, $R = 0.4$
Normalized Cross Section [GeV^{-1}]
0.00
0.01
0.02
0.03
0.04
0.05
0.06
Ratio to Truth
0.85
1.0
1.15
0
20
40
60
Jet Mass m [GeV]