Heavy to heavy exclusive discussion session

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Challenges in Semileptonic B Decays 2022

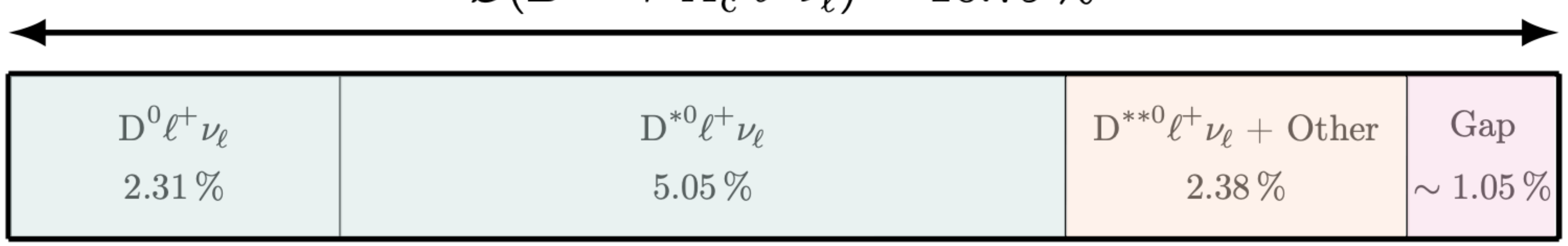
Barolo, Italy
April 2022

$B \to D^{**}\ell\bar{\nu}_\ell$ Decays and Friends

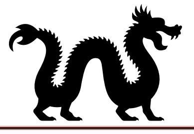
$B \to X_c\ell\nu$ modelling & composition

A **leading systematic** in all the discussed analyses:

$$\mathcal{B}(\mathrm{B}^+ \to X_c^0\,\ell^+\nu_\ell) \approx 10.79\,\%$$



Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell^+\,\nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell^+\,\nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
$B \to D_1\,\ell^+\,\nu_\ell$	$(6.6 \pm 0.1) \times 10^{-3}$	$(6.2 \pm 0.1) \times 10^{-3}$
$B \to D_2^*\,\ell^+\,\nu_\ell$	$(2.9 \pm 0.3) \times 10^{-3}$	$(2.7 \pm 0.3) \times 10^{-3}$
$B \to D_0^*\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.8) \times 10^{-3}$	$(3.9 \pm 0.7) \times 10^{-3}$
$B \to D_1'\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.9) \times 10^{-3}$	$(3.9 \pm 0.8) \times 10^{-3}$
$B \to D\pi\pi\,\ell^+\,\nu_\ell$	$(0.6 \pm 0.9) \times 10^{-3}$	$(0.6 \pm 0.9) \times 10^{-3}$
$B \to D^*\pi\pi\,\ell^+\,\nu_\ell$	$(2.2 \pm 1.0) \times 10^{-3}$	$(2.0 \pm 1.0) \times 10^{-3}$
$B \to X_c\ell\nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$



→ Fairly well known. Some iso-spin tension.

→ Broad states based on 3 measurements. (BaBar, Belle, DELPHI)

→ Some hints from the BaBar result.

Image credit: F. Metzner

Model 1:

Equidistribution of all final state particles in phase space

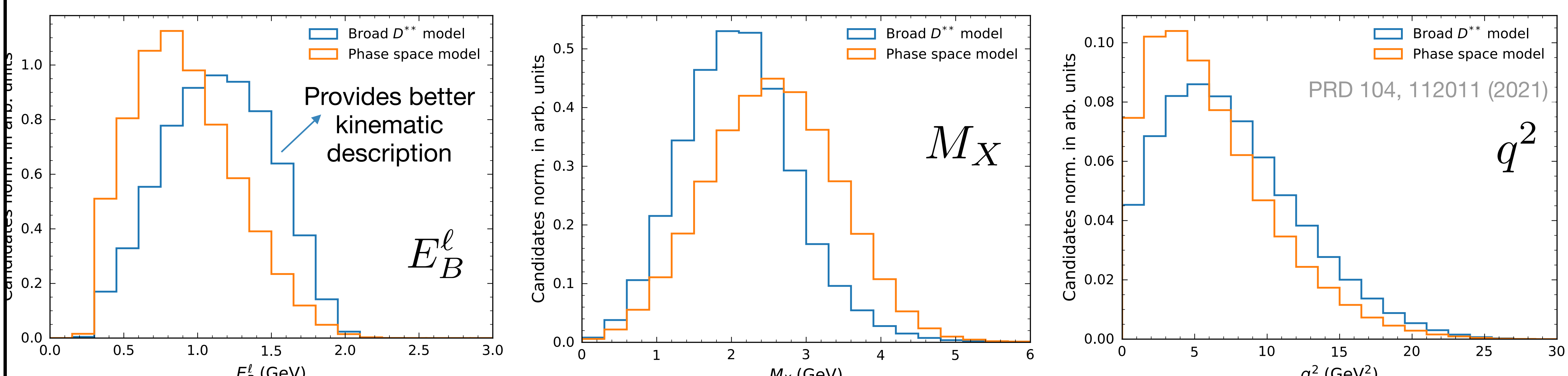
Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell^+\,\nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell^+\,\nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
$B \to D_1\,\ell^+\,\nu_\ell$	$(6.6 \pm 0.1) \times 10^{-3}$	$(6.2 \pm 0.1) \times 10^{-3}$
$B \to D_2^*\,\ell^+\,\nu_\ell$	$(2.9 \pm 0.3) \times 10^{-3}$	$(2.7 \pm 0.3) \times 10^{-3}$
$B \to D_0^*\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.8) \times 10^{-3}$	$(3.9 \pm 0.7) \times 10^{-3}$
$B \to D_1'\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.9) \times 10^{-3}$	$(3.9 \pm 0.8) \times 10^{-3}$
$B \to D\pi\pi\,\ell^+\,\nu_\ell$	$(0.6 \pm 0.9) \times 10^{-3}$	$(0.6 \pm 0.9) \times 10^{-3}$
$B \to D^*\pi\pi\,\ell^+\,\nu_\ell$	$(2.2 \pm 1.0) \times 10^{-3}$	$(2.0 \pm 1.0) \times 10^{-3}$
$B \to D\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to D^*\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to X_c \ell \nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$

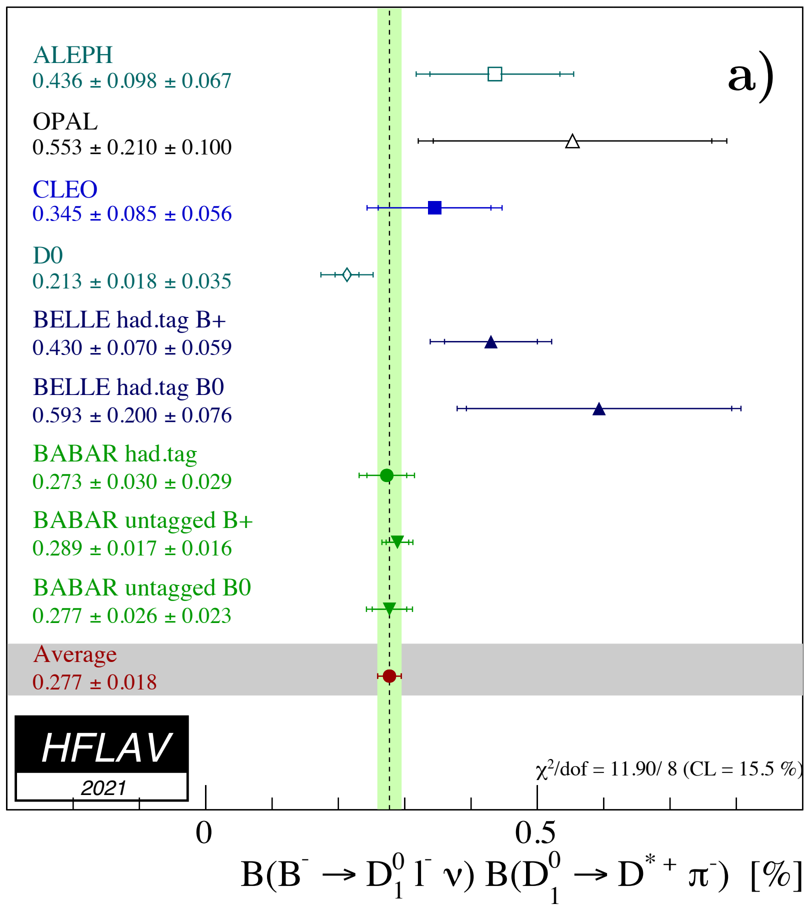
Model 2:

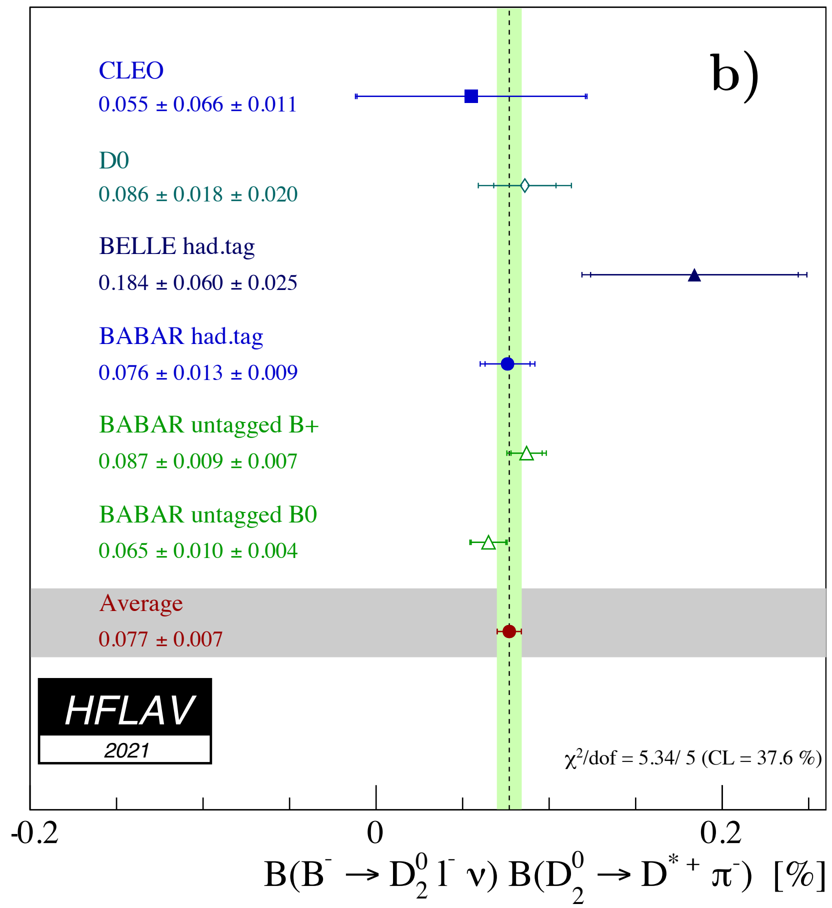
Decay via intermediate broad D^{**} state

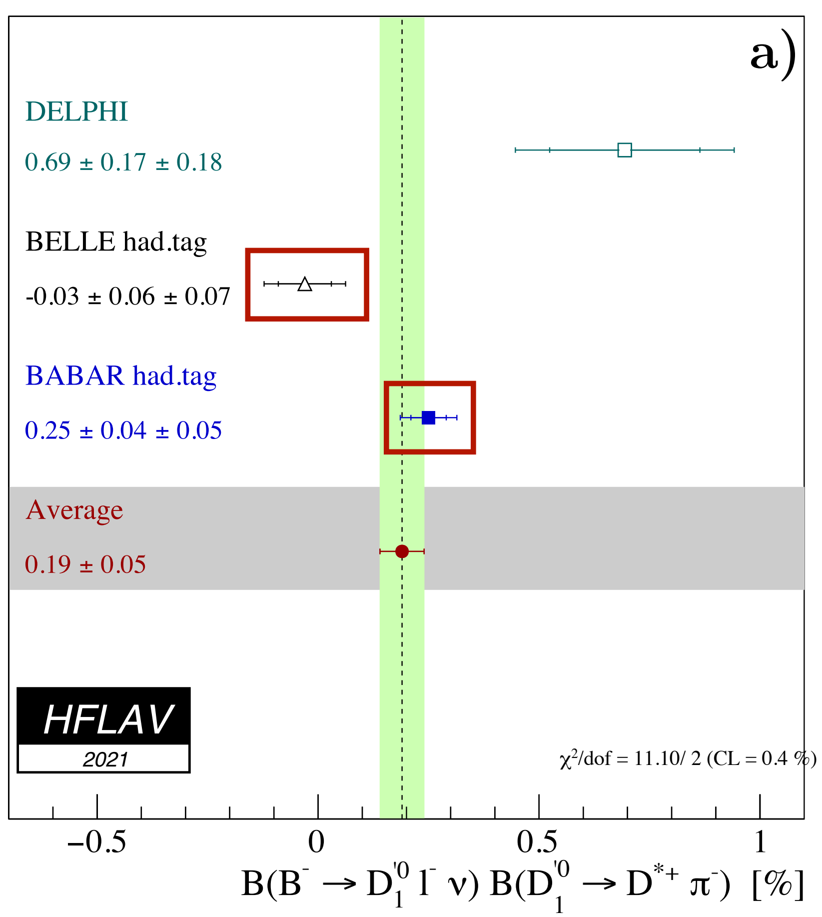
Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D_0^*\,\ell^+\,\nu_\ell$ $(\hookrightarrow D\pi\pi)$	$(0.03 \pm 0.03) \times 10^{-2}$	$(0.03 \pm 0.03) \times 10^{-2}$
$B \to D_1^*\,\ell^+\,\nu_\ell$ $(\hookrightarrow D\pi\pi)$	$(0.03 \pm 0.03) \times 10^{-2}$	$(0.03 \pm 0.03) \times 10^{-2}$
$B \to D_0^*\pi\pi\,\ell^+\,\nu_\ell$ $(\hookrightarrow D^*\pi\pi)$	$(0.108 \pm 0.051) \times 10^{-2}$	$(0.101 \pm 0.048) \times 10^{-2}$
$B \to D_1^*\pi\pi\,\ell^+\,\nu_\ell$ $(\hookrightarrow D^*\pi\pi)$	$(0.108 \pm 0.051) \times 10^{-2}$	$(0.101 \pm 0.048) \times 10^{-2}$
$B \to D_0^*\,\ell^+\,\nu_\ell$ $(\hookrightarrow D\eta)$	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$
$B \to D_1^*\,\ell^+\,\nu_\ell$ $(\hookrightarrow D^*\eta)$	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$

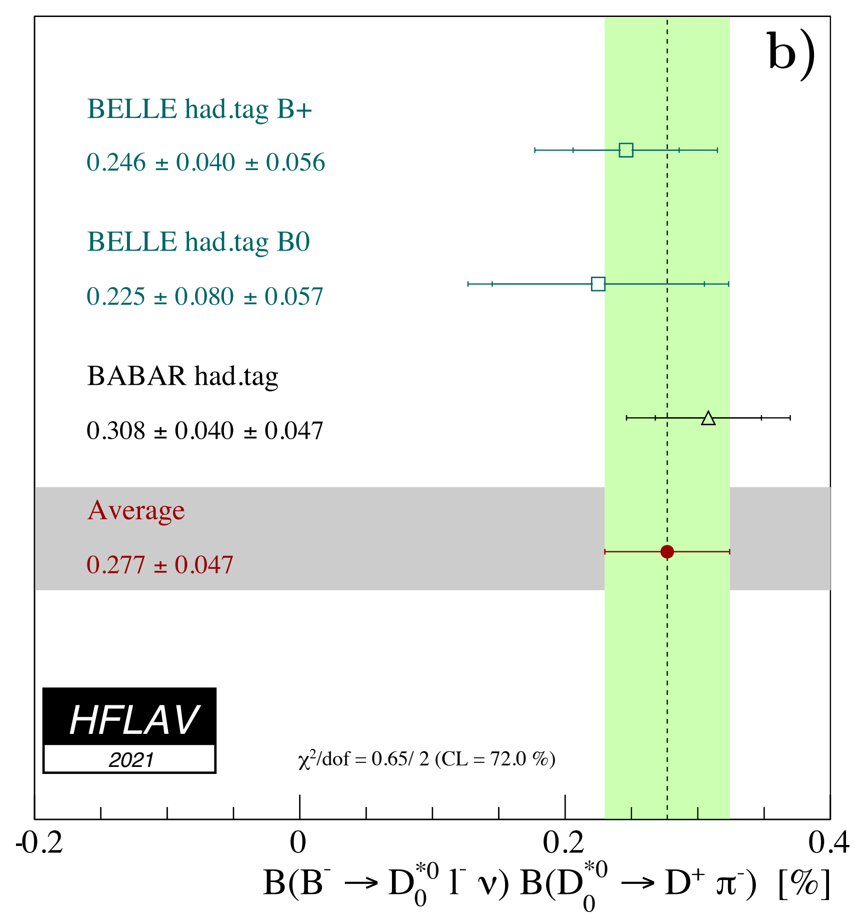
(Assign 100% BR uncertainty in systematics covariance matrix)




a)
ALEPH
0.436 ± 0.098 ± 0.067
OPAL
0.553 ± 0.210 ± 0.100
CLEO
0.345 ± 0.085 ± 0.056
D0
0.213 ± 0.018 ± 0.035
BELLE had.tag B+
0.430 ± 0.070 ± 0.059
BELLE had.tag B0
0.593 ± 0.200 ± 0.076
BABAR had.tag
0.273 ± 0.030 ± 0.029
BABAR untagged B+
0.289 ± 0.017 ± 0.016
BABAR untagged B0
0.277 ± 0.026 ± 0.023
Average
0.277 ± 0.018
HFLAV
2021
χ^2/dof = 11.90/ 8 (CL = 15.5 %)
0
0.5
$B(B^- \to D_1^0 l^- \nu)\, B(D_1^0 \to D^{*+} \pi^-)$ [%]


b)
CLEO
0.055 ± 0.066 ± 0.011
D0
0.086 ± 0.018 ± 0.020
BELLE had.tag
0.184 ± 0.060 ± 0.025
BABAR had.tag
0.076 ± 0.013 ± 0.009
BABAR untagged B+
0.087 ± 0.009 ± 0.007
BABAR untagged B0
0.065 ± 0.010 ± 0.004
Average
0.077 ± 0.007
HFLAV
2021
χ^2/dof = 5.34/ 5 (CL = 37.6 %)
-0.2
0
0.2
$B(B^- \to D_2^0 l^- \nu)\, B(D_2^0 \to D^{*+} \pi^-)$ [%]


a)
DELPHI
0.69 ± 0.17 ± 0.18
BELLE had.tag
-0.03 ± 0.06 ± 0.07
BABAR had.tag
0.25 ± 0.04 ± 0.05
Average
0.19 ± 0.05
HFLAV
2021
χ^2/dof = 11.10/ 2 (CL = 0.4 %)
−0.5
0
0.5
1
$B(B^- \to D_1'^0 l^- \nu)\, B(D_1'^0 \to D^{*+} \pi^-)$ [%]

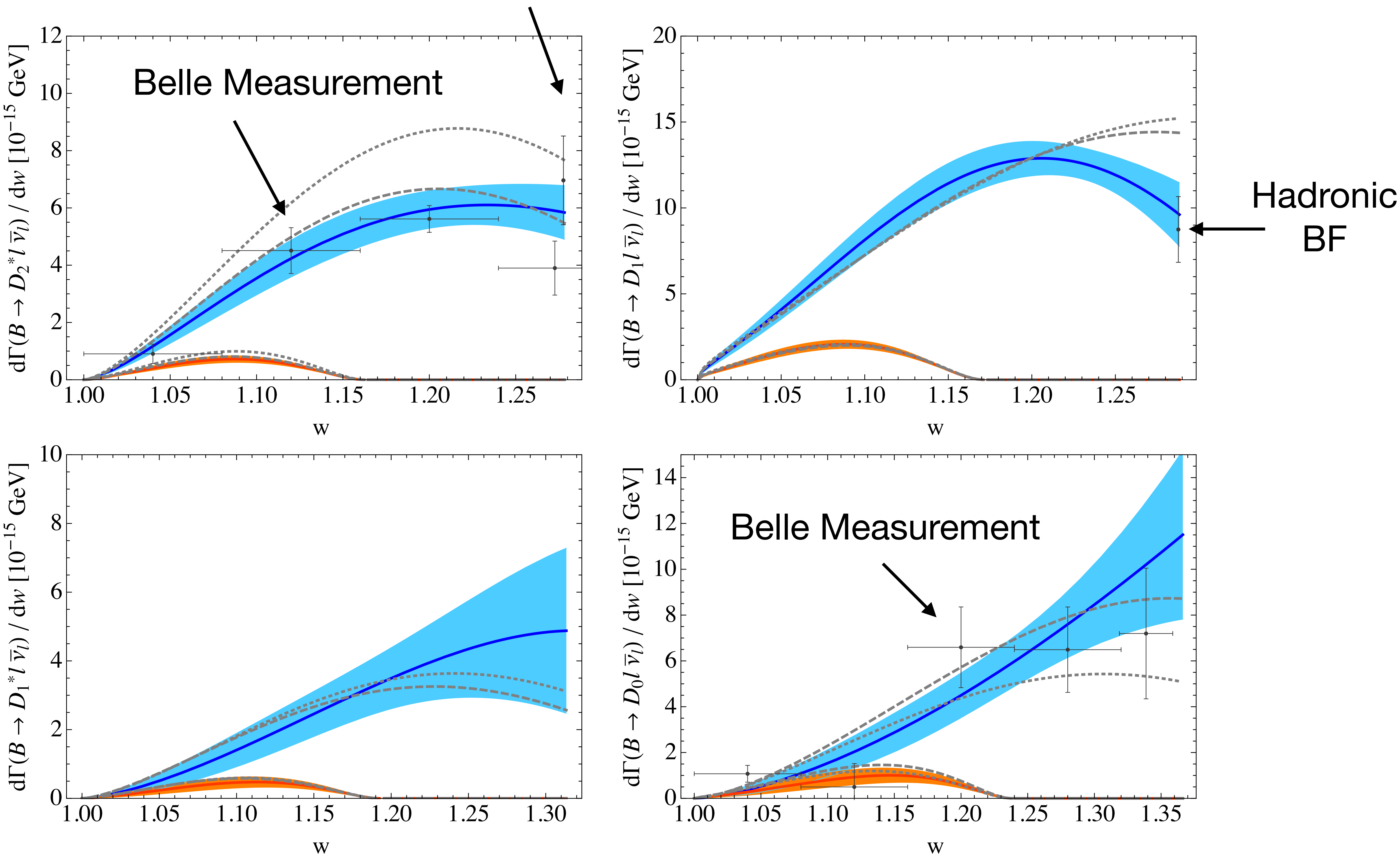

b)
BELLE had.tag B+
0.246 ± 0.040 ± 0.056
BELLE had.tag B0
0.225 ± 0.080 ± 0.057
BABAR had.tag
0.308 ± 0.040 ± 0.047
Average
0.277 ± 0.047
HFLAV
2021
χ^2/dof = 0.65/ 2 (CL = 72.0 %)
-0.2
0
0.2
0.4
$B(B^- \to D_0^{*0} l^- \nu)\, B(D_0^{*0} \to D^+ \pi^-)$ [%]

$B \to D^{**}\ell\bar{\nu}_\ell$ FFs

Decay mode	Branching fraction
$B^0 \to D_2^{*-}\pi^+$	$(0.59 \pm 0.13) \times 10^{-3}$
$B^0 \to D_1^-\pi^+$	$(0.75 \pm 0.16) \times 10^{-3}$

Decay mode	Branching fraction
$B^+ \to \bar{D}_2^{*0}\, l\,\bar{\nu}$	$(0.30 \pm 0.04) \times 10^{-2}$
$B^+ \to \bar{D}_1^0\, l\,\bar{\nu}$	$(0.67 \pm 0.05) \times 10^{-2}$
$B^+ \to \bar{D}_1^{*0}\, l\,\bar{\nu}$	$(0.20 \pm 0.05) \times 10^{-2}$
$B^+ \to \bar{D}_0^{*0}\, l\,\bar{\nu}$	$(0.44 \pm 0.08) \times 10^{-2}$

$$\Gamma_\pi = \frac{3\pi^2\,|V_{ud}|^2\,C^2 f_\pi^2}{m_B^2\,r}\left(\frac{\mathrm{d}\Gamma_{\mathrm{sl}}}{\mathrm{d}w}\right)_{w_{\max}}$$



Some validation

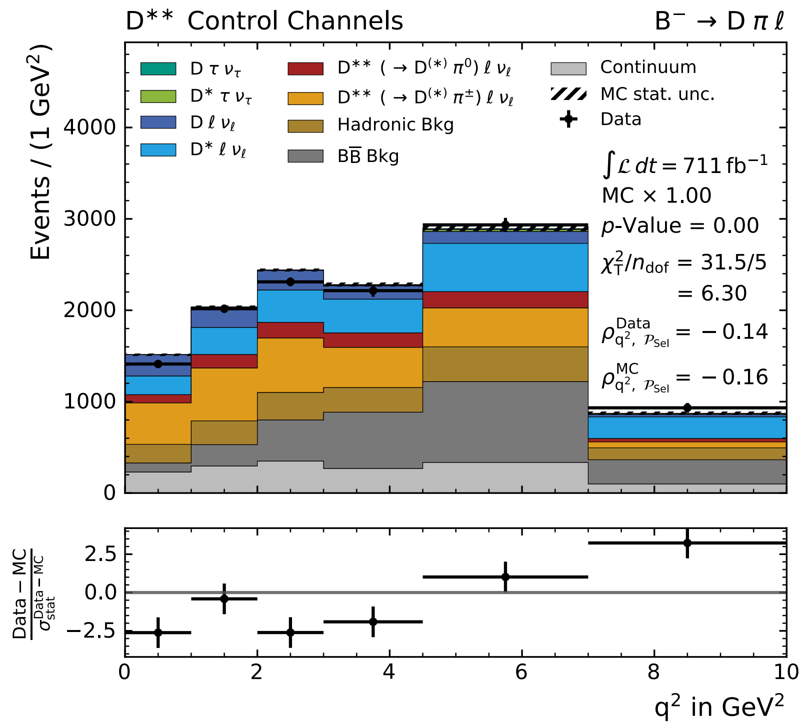
PhD thesis of Felix Metzner

D

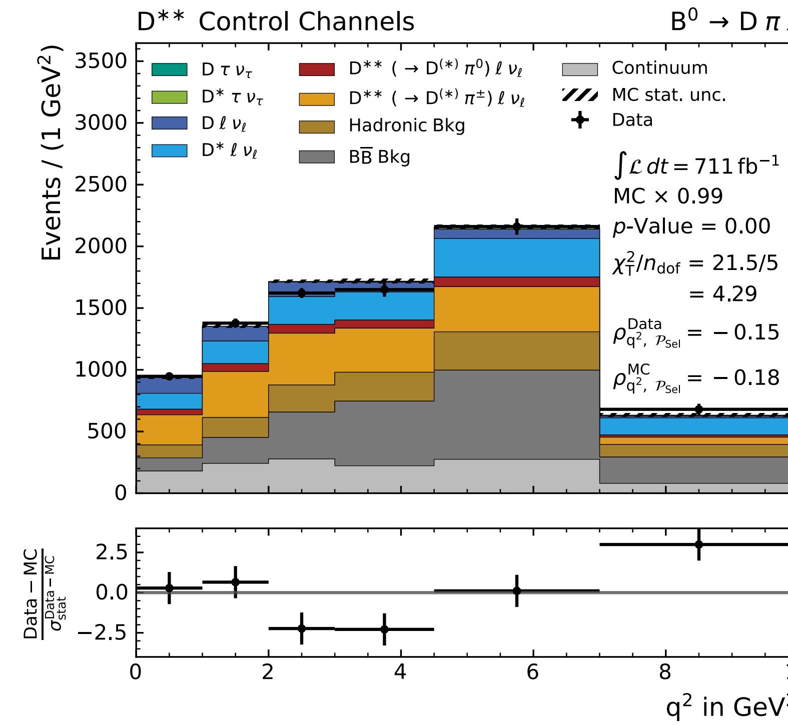
D*

D → D(*)π^0**

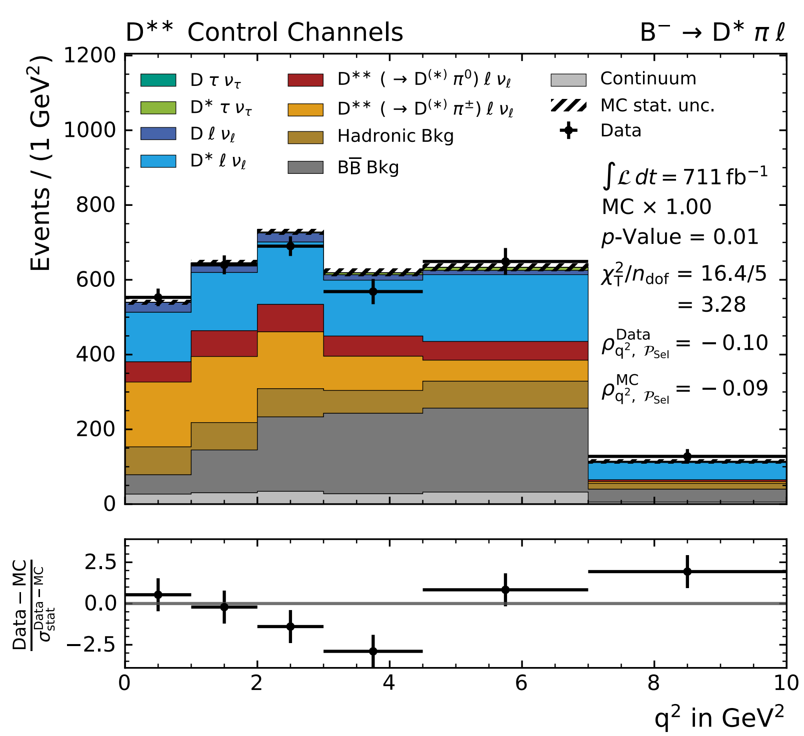
D → D(*)π^+**



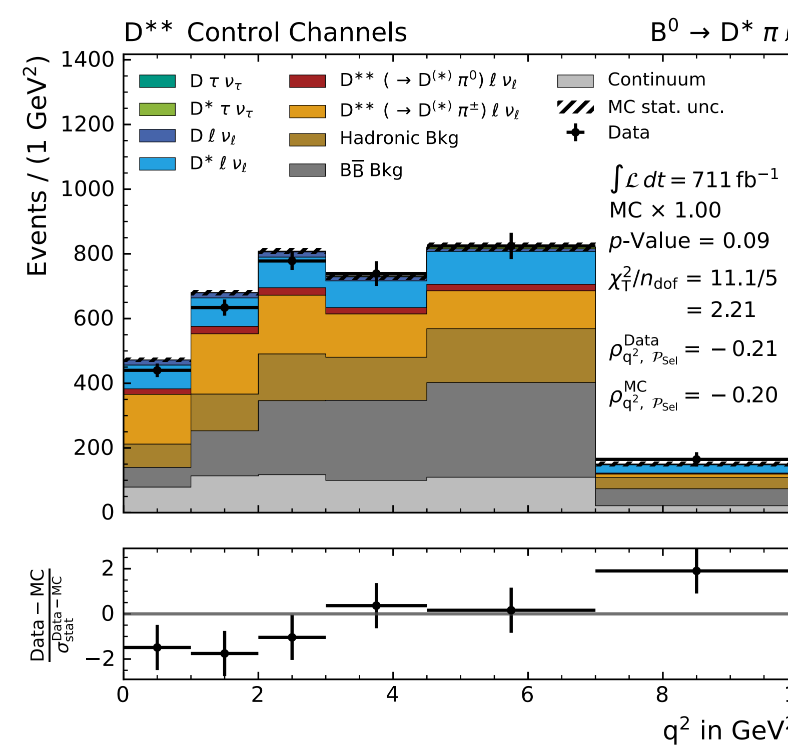
(a) $B^- \to D\pi\ell$



(b) $B^0 \to D\pi\ell$



(c) $B^- \to D^*\pi\ell$



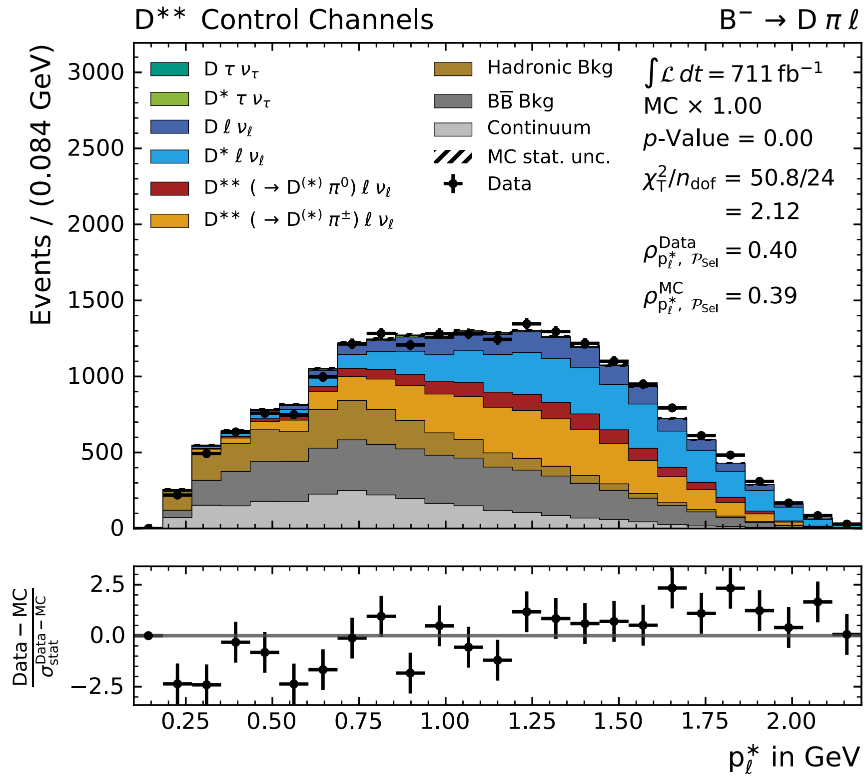
(d) $B^0 \to D^*\pi\ell$

D

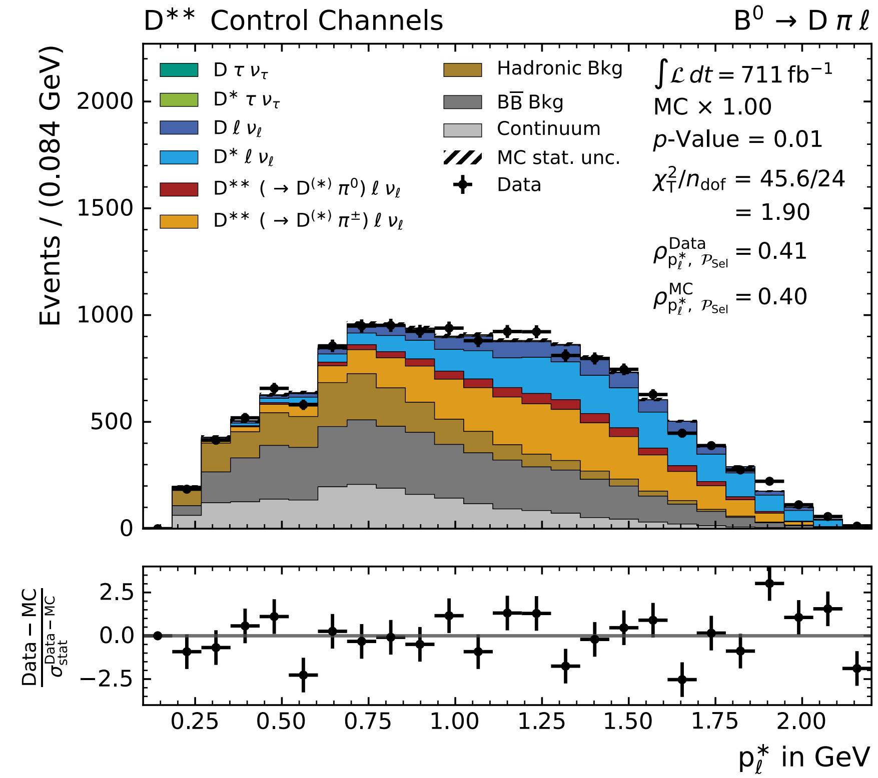
D*

D → D(*)π^0**

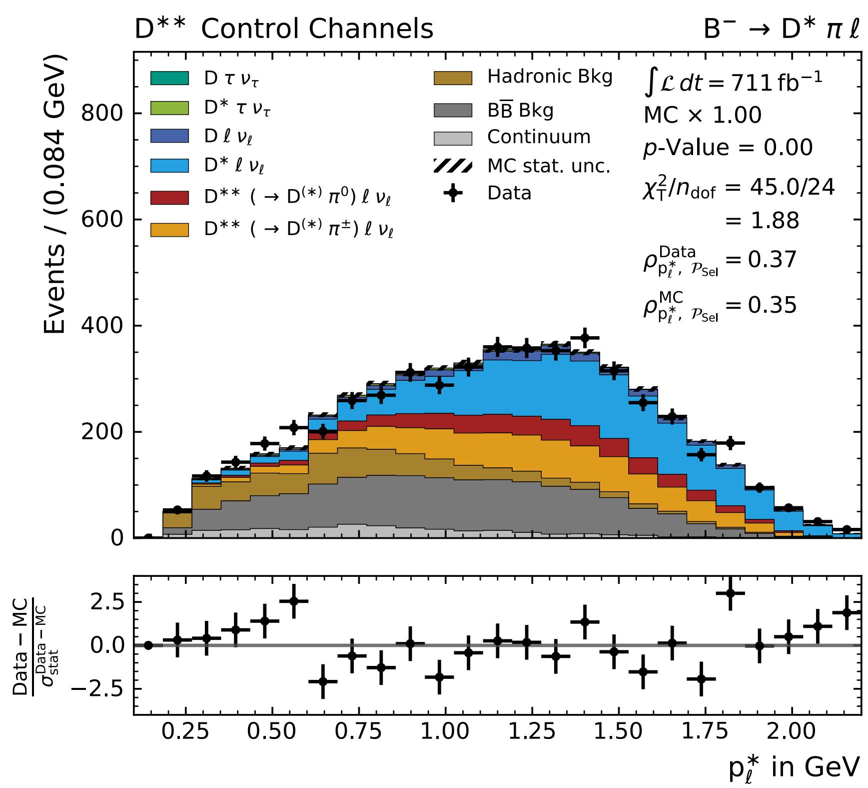
D → D(*)π^+**



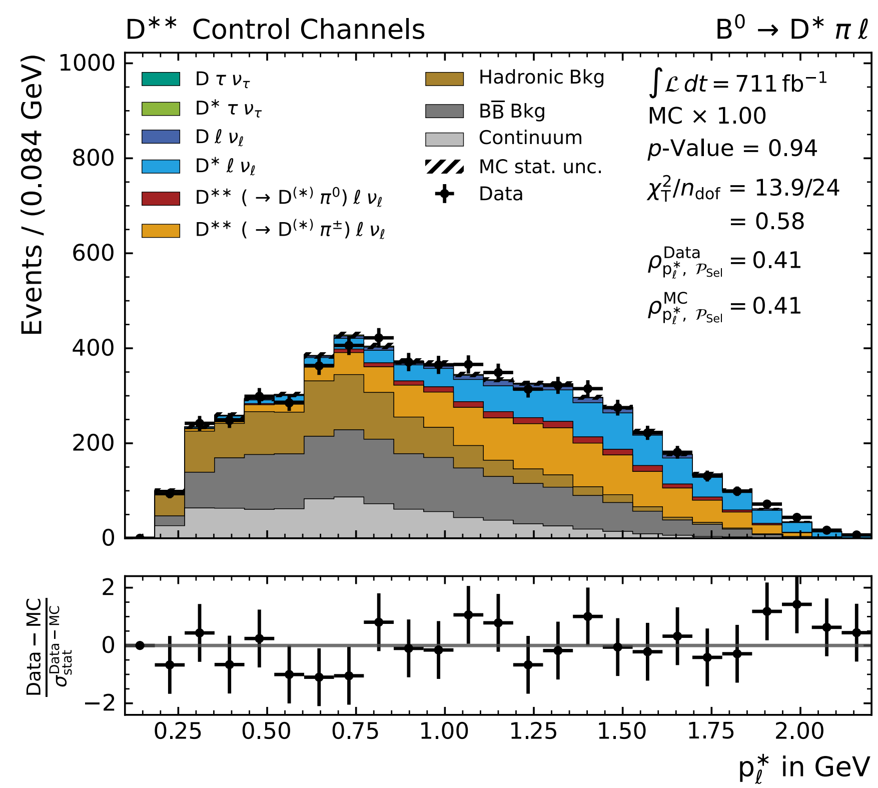
(a) $B^- \to D\pi\ell$



(b) $B^0 \to D\pi\ell$



(c) $B^- \to D^*\pi\ell$



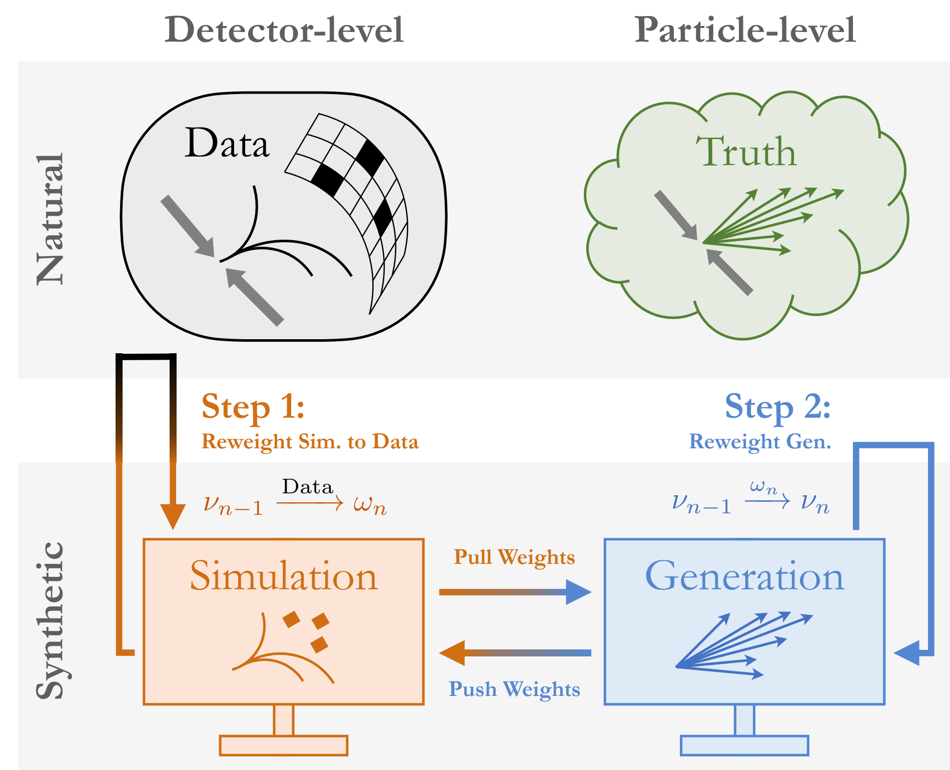
(d) $B^0 \to D^*\pi\ell$

Unfolding with neural networks

arXiv:1911.09107 [hep-ph]

OmniFold: A Method to Simultaneously Unfold All Observables

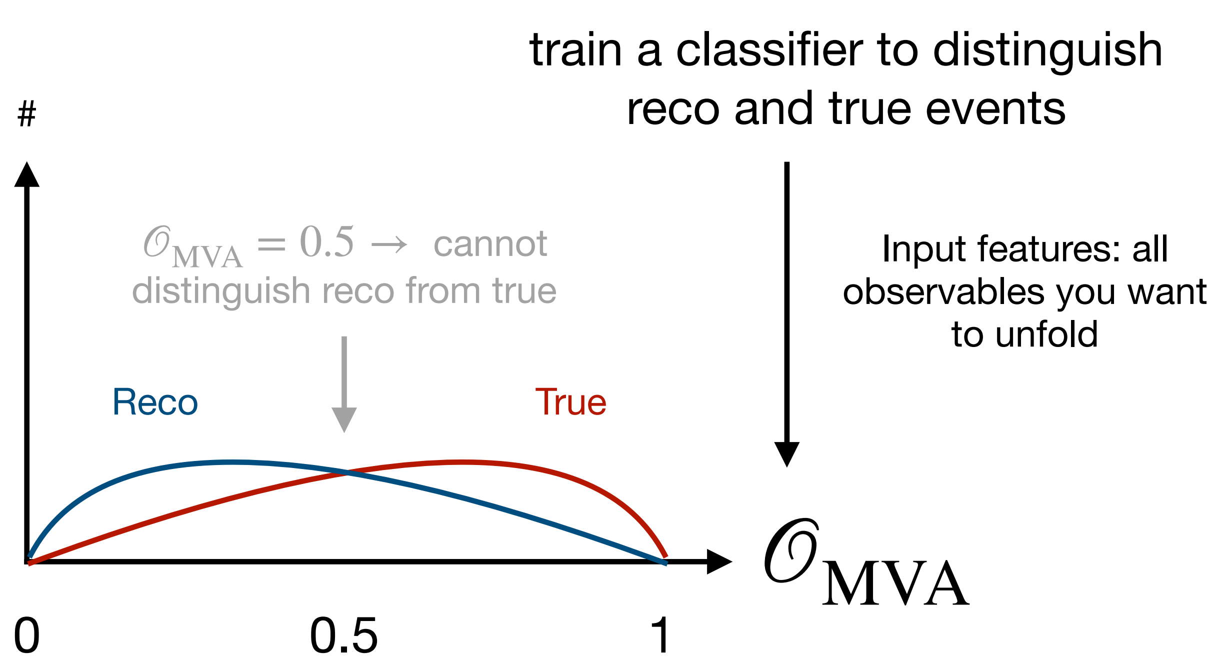
Anders Andreassen,[1,2,3,*] Patrick T. Komiske,[4,†] Eric M. Metodiev,[4,‡] Benjamin Nachman,[2,§] and Jesse Thaler[4,¶]
[1] *Department of Physics, University of California, Berkeley, CA 94720, USA*
[2] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[3] *Google, Mountain View, CA 94043, USA*
[4] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*



$$R_{ij} = \Pr(\text{measure } i \,|\, \text{truth is } j).$$

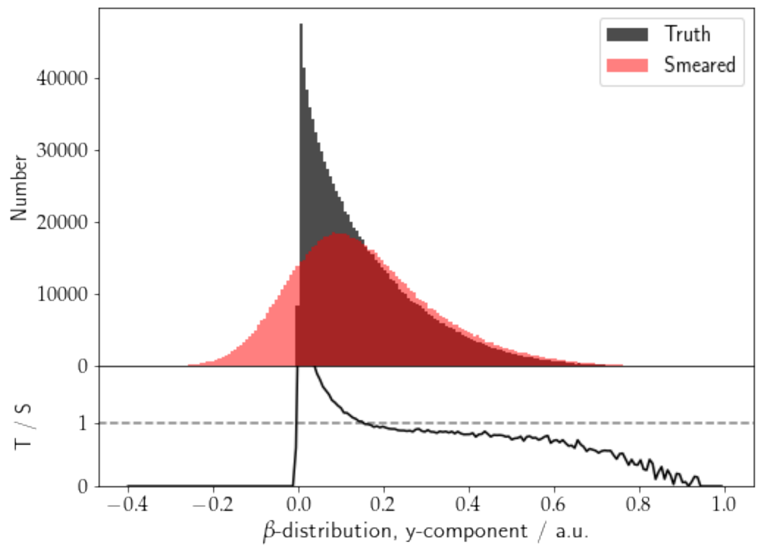
How does this work with a NN?

Basic principle simple actually:

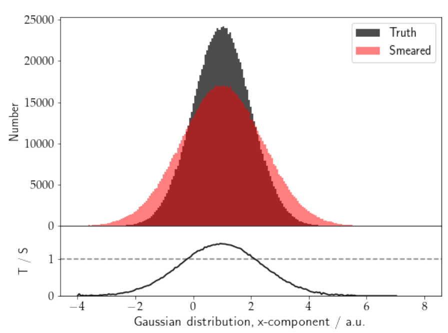


Event-wise unfolding:

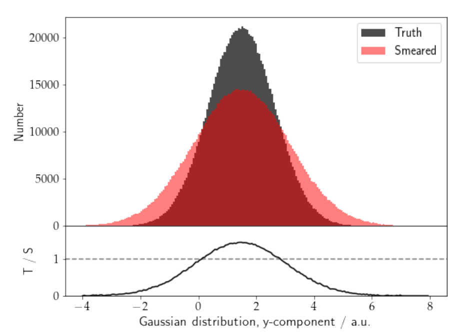
$$w = \frac{\mathcal{O}_{\text{MVA}}}{1 - \mathcal{O}_{\text{MVA}}}$$



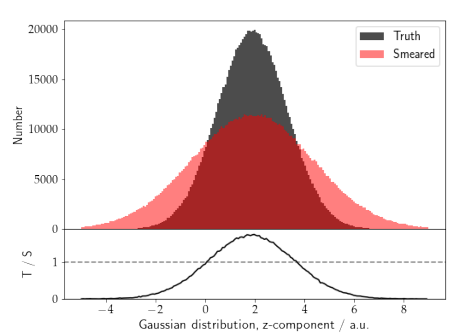
(b) The y-component of the β-distribution



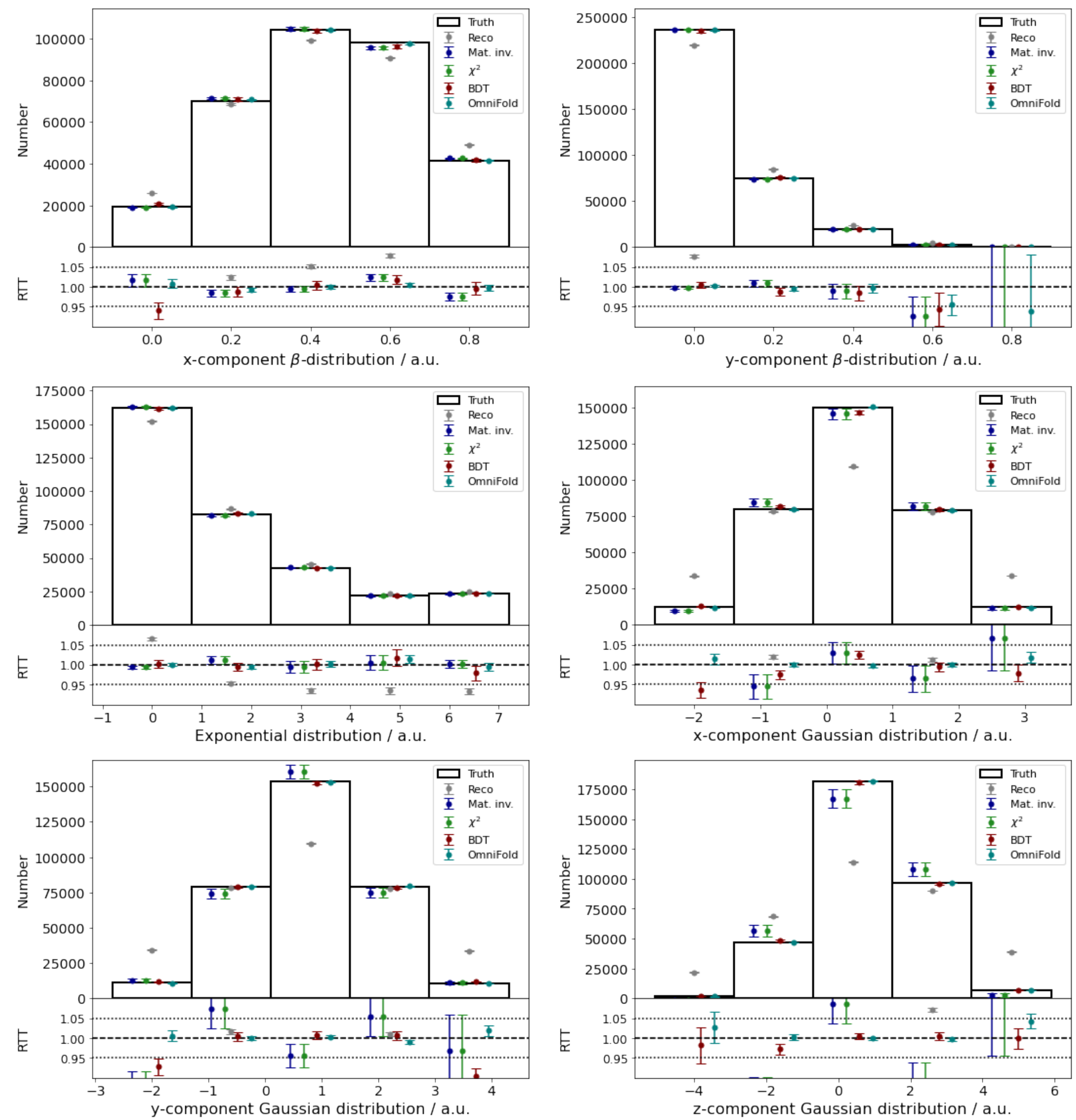
(a) The x-component of the Gaussian distribution

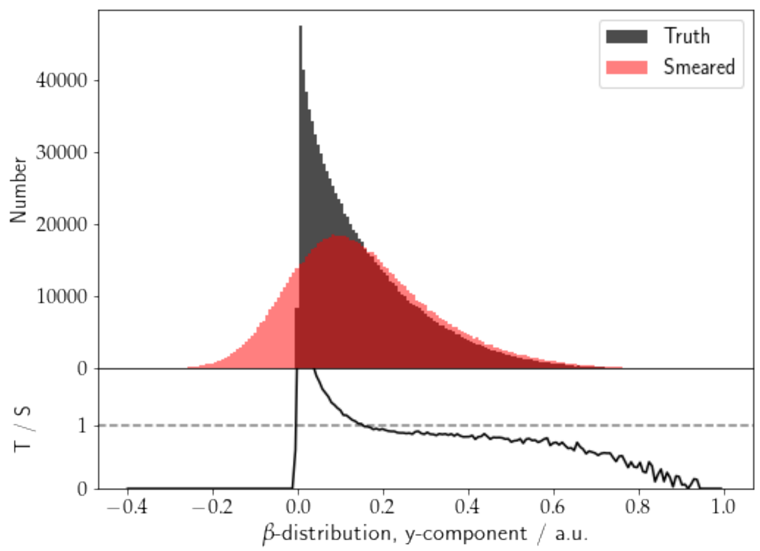


(b) The y-component of the Gaussian distribution



(c) The z-component of the Gaussian distribution





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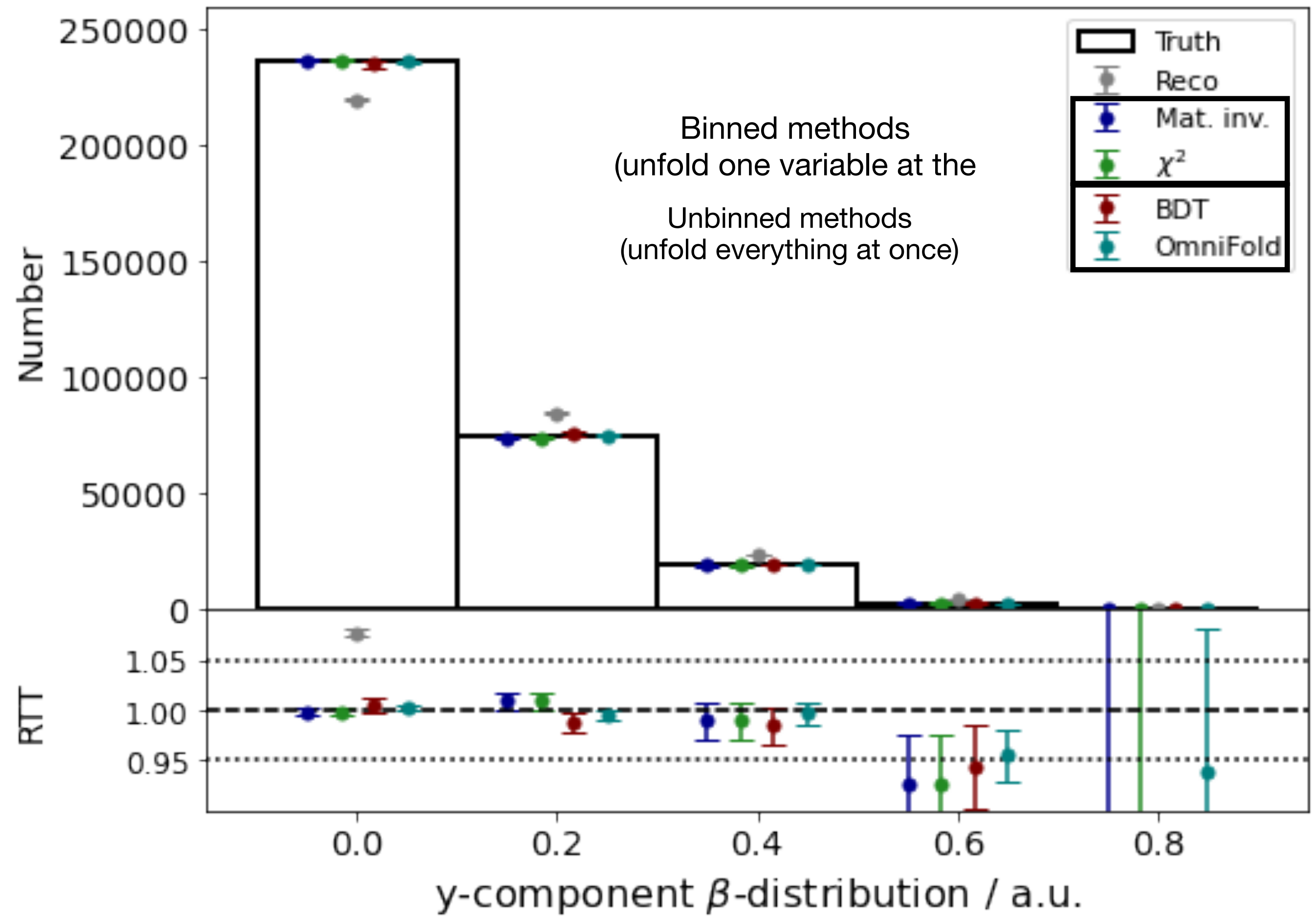

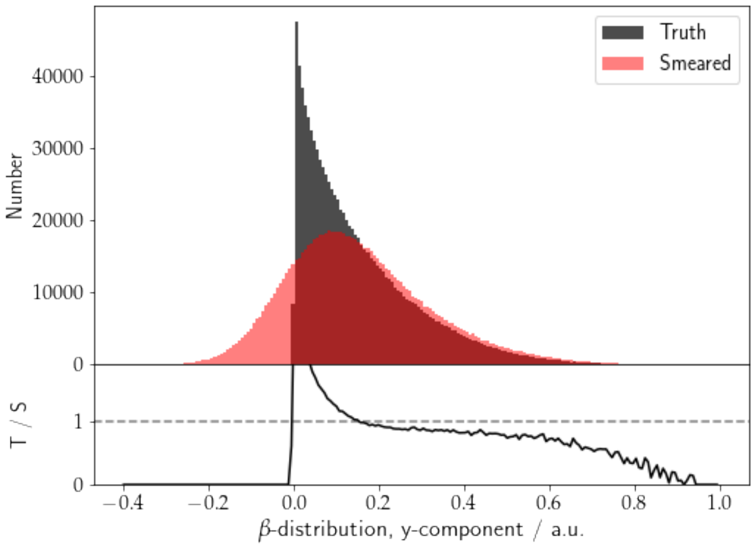

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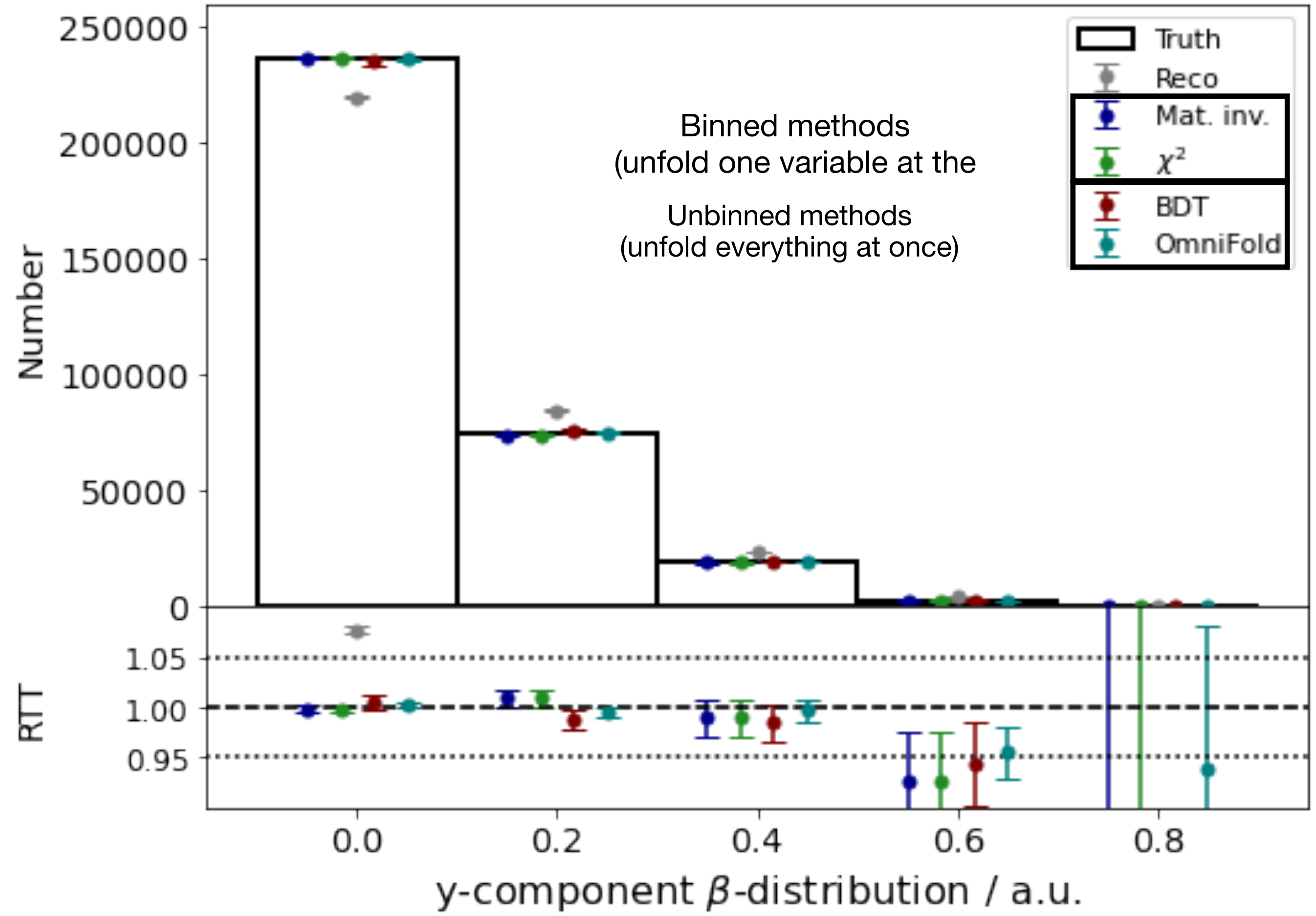
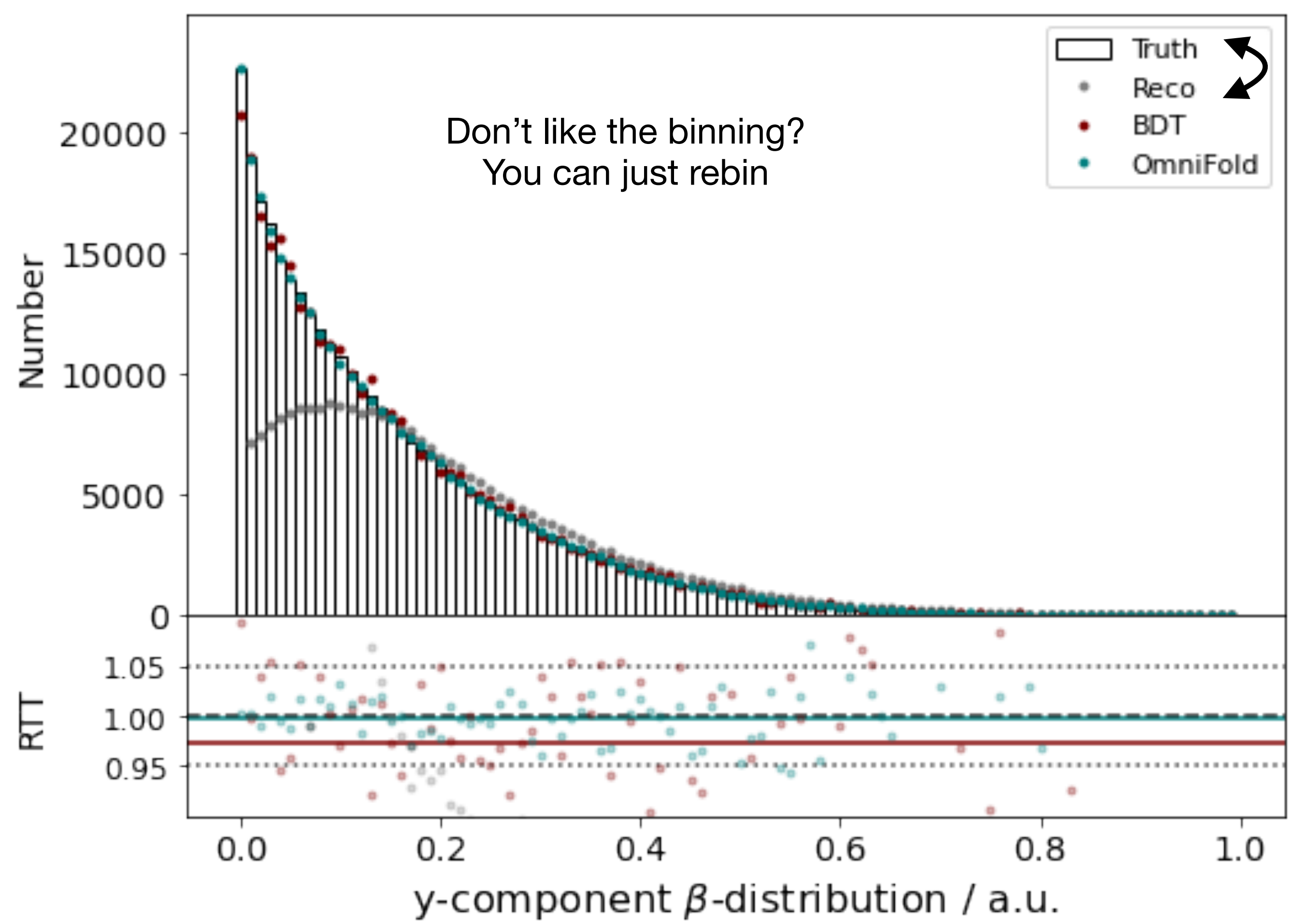




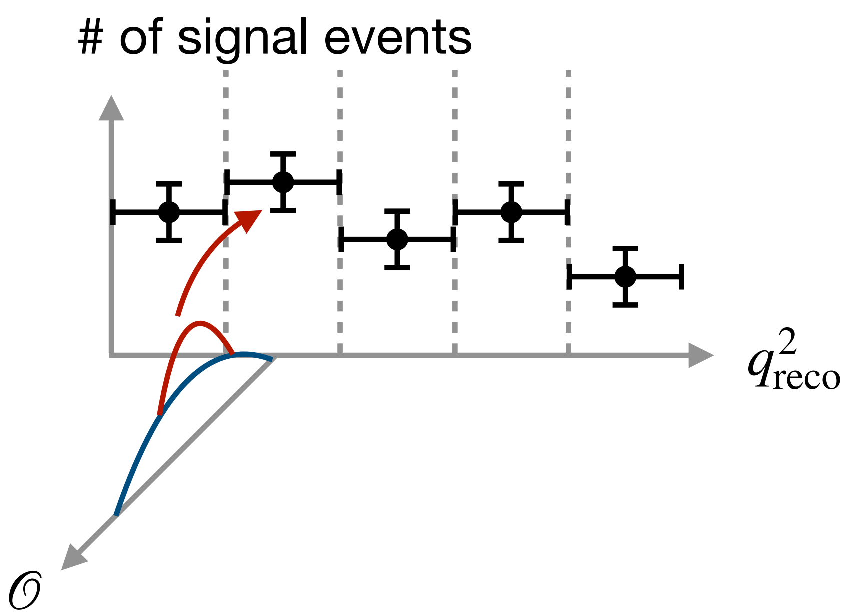
independent samples

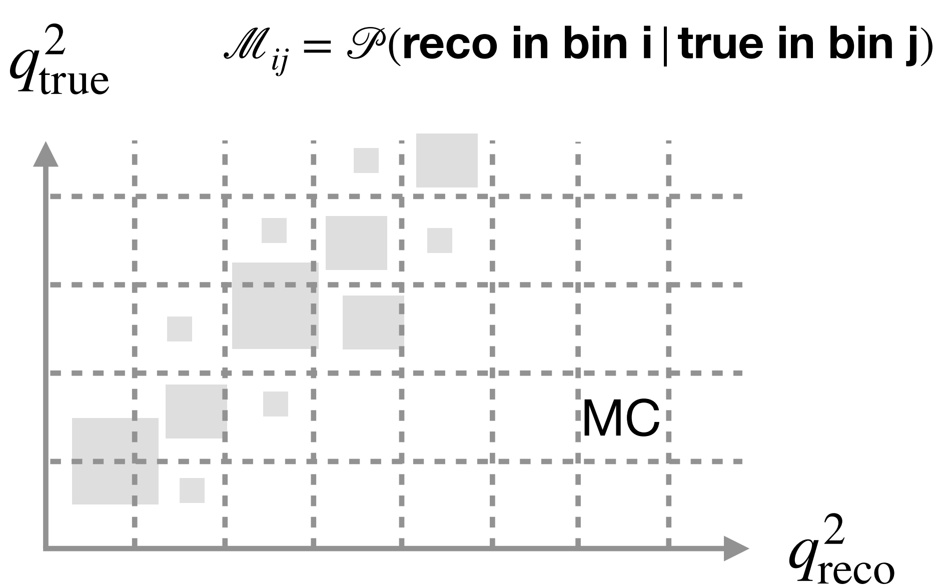
(plot is just cut off)

BaBar Approach versus Belle / LHCb

Binned (Belle, LHCb)

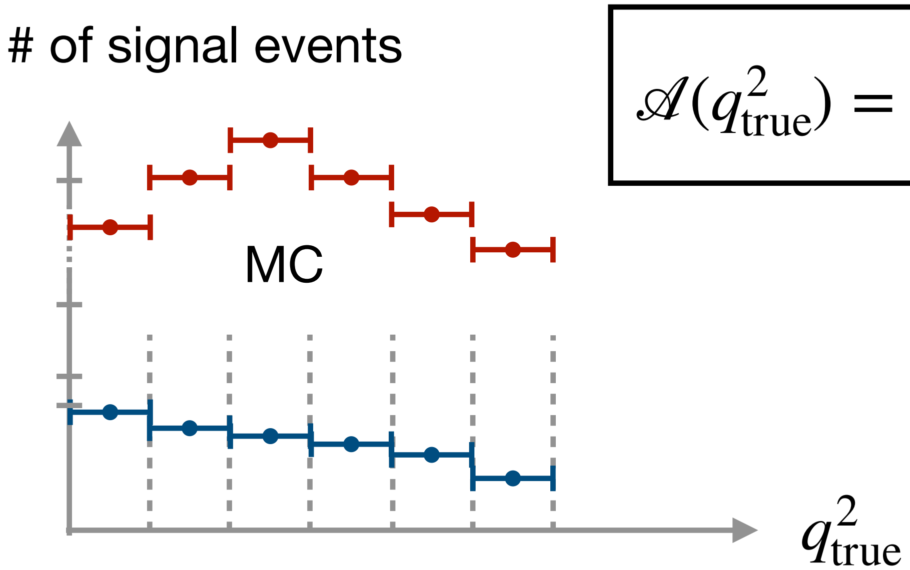
Determine # of signal events in a given bin in the observable of interest (e.g. q^2_{reco}) by fitting discriminating variables ($\mathcal{O}$)





BaBar Approach versus Belle / LHCb

...



$\mathscr{A}(q^2_{\text{true}}) =$

Final correction:

$$\mathscr{M}_{ij}^{-1} \times \text{diag}[\mathscr{A}^{-1}]$$

or

$$\mathscr{M}_{ij} \times \text{diag}[\mathscr{A}]$$

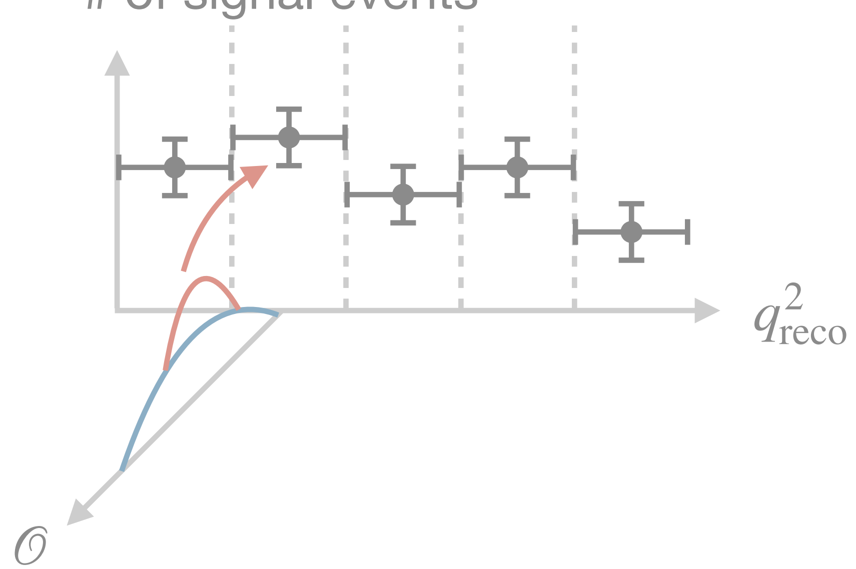
Fit Theory to unfolded or folded binned distributions

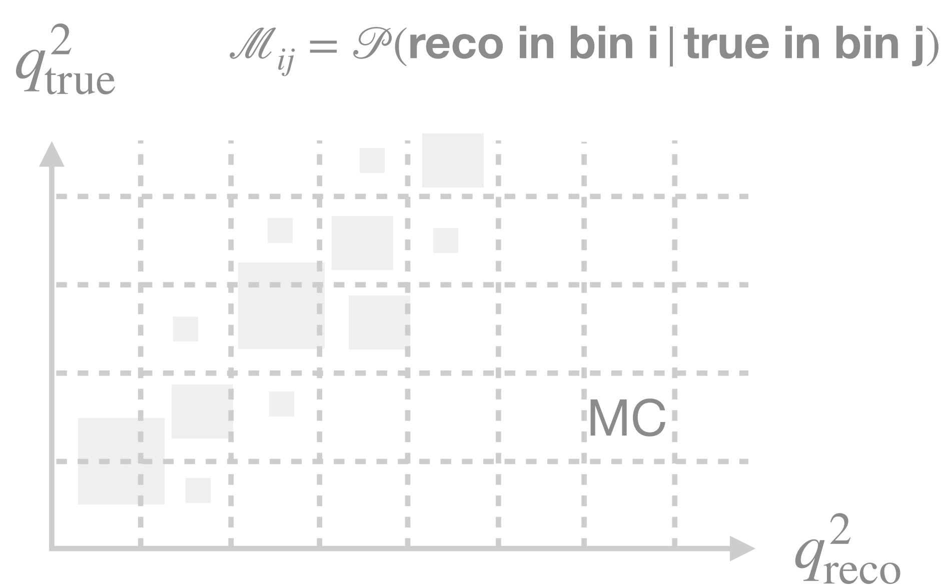
Need to evaluate uncertainties on migration matrix and acceptance from modelling. Are these under control?

BaBar Approach versus Belle / LHCb

Binned (Belle, LHCb)

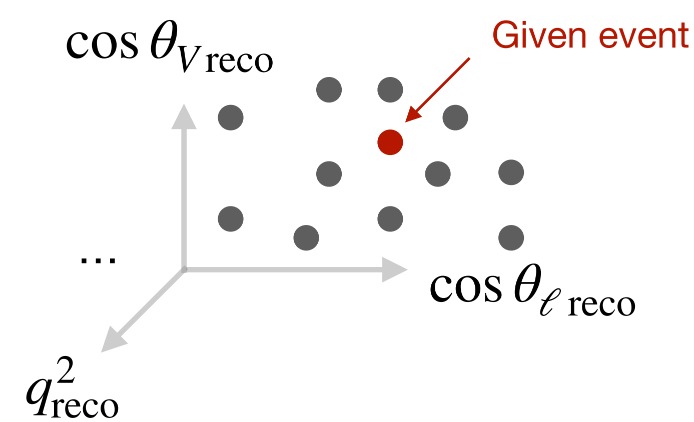
Determine # of signal events in a given bin in the observable of interest (e.g. q^2_{reco}) by fitting discriminating variables ($\mathcal{O}$)





Unbinned (BaBar)

Determine # of signal events in a given point of phase-space using properties of its closest neighbors (50-100)

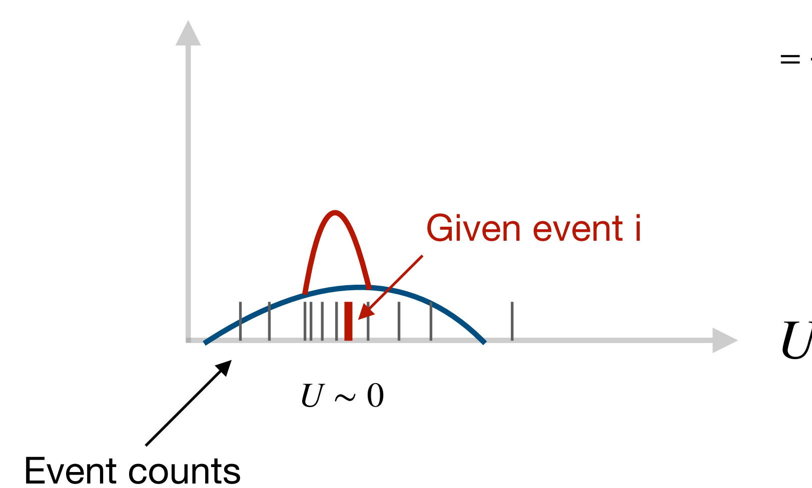


With these closest neighbors carry out an unbinned fit in $U = E_{\text{miss}} - p_{\text{miss}}$

From post-fit PDFs calculate

$$Q_i = \frac{S_i}{S_i + B_i}$$

$$= \frac{\mu_S\, f_S(\mathrm{m}^2_{\text{miss}\,i})}{\mu_S\, f_S(\mathrm{m}^2_{\text{miss}\,i}) + \mu_B\, f_B(\mathrm{m}^2_{\text{miss}\,i})}$$



BaBar Approach versus Belle / LHCb

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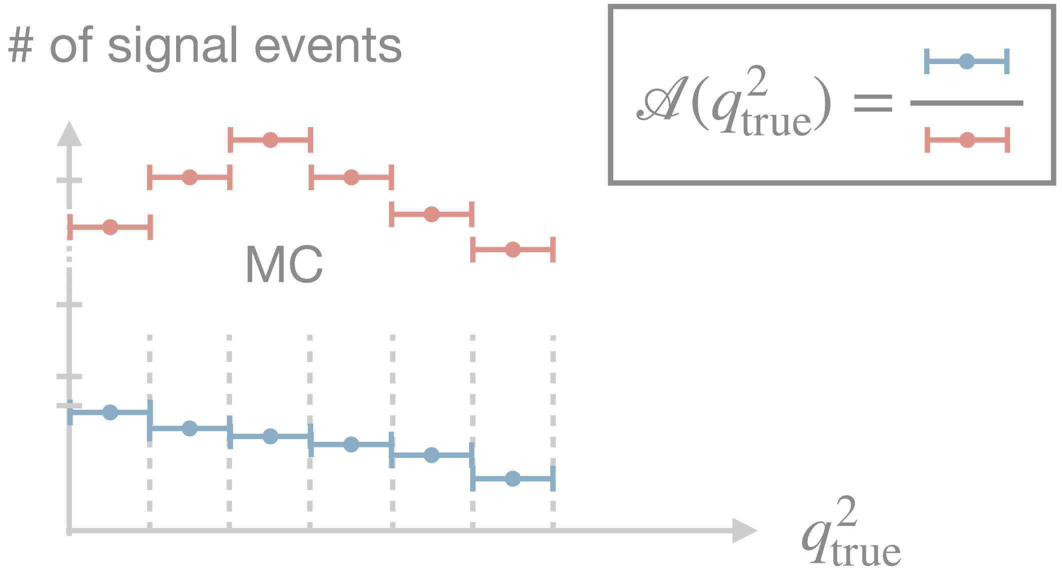


Final correction:

$$\mathscr{M}_{ij}^{-1} \times \text{diag}[\mathscr{A}^{-1}]$$

or

$$\mathscr{M}_{ij} \times \text{diag}[\mathscr{A}]$$

Fit Theory to unfolded or folded binned distributions

Need to evaluate uncertainties on migration matrix and acceptance from modelling. Are these under control?

…

To confront weighted events with theory, need to fold the latter:

$$\{Q, \mathscr{O}\}_i \quad \longleftrightarrow \quad f_{\text{res}} \otimes f_{\text{acc}} \otimes \mathrm{d}\Gamma/\mathrm{d}\mathscr{O}$$

Instead of doing a folding, this is done using MC events using a normalization integral:

$$-2\log \mathcal{L}|^{\text{sig}}_{\text{BABAR}} = -2\left[\sum_{k=0}^{N_{\text{data}}} \log(\mathcal{P}_k)\right] + 2N_{\text{data}} \log\left(\int \mathcal{P} d\Omega dq^2\right)$$

$$\int \mathcal{P} d\Omega dq^2 = \sum_{k=0}^{N^{\text{MC}}_{\text{acc}}} \mathcal{P}_k, \qquad \mathcal{P} \equiv d\Gamma/d\Omega dq^2$$

Normalization integral

In the PRL version the background was subtracted using MC expectation

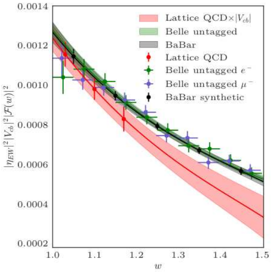
$$-2\log \mathcal{L}|^{\text{bkgd}}_{\text{BABAR}} = -2\left[\sum_{k=0}^{N_{\text{MC}}} w_k \log(\mathcal{P}_k)\right] + 2\left(\sum_{k=0}^{N_{\text{MC}}} w_k\right) \log\left(\int \mathcal{P} d\Omega dq^2\right),$$

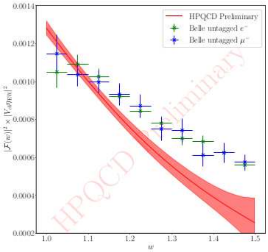
How to combine Belle II/LHCb?

- Should we agree on common tools?

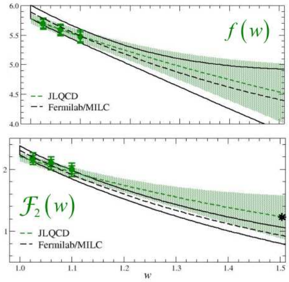
- Can we agree on common tools?

Tensions between Lattice and Experiment?





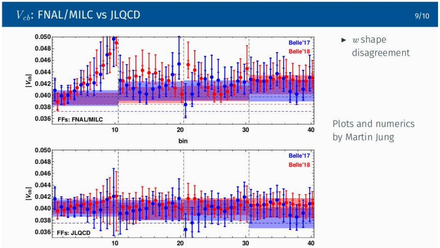
(PRELIMINARY)

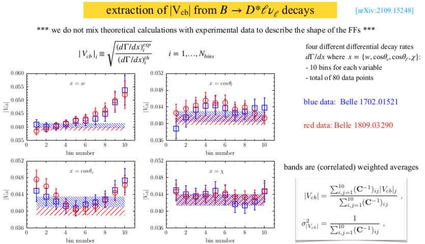


[Alejandro] [Judd] [Kaneko]

- Fermilab/MILC and HPQCD have similar shape, different from Belle; different from JLQCD.

Bin by bin analyses





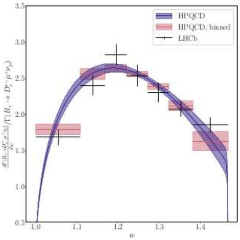
[Danny/Martin] [Silvano]

- Does/should averaging bin-wise V_{cb} agree with fitting all bins directly?
- How are the bins correlated? Do toy Monte Carlos change correlations?

Lattice for full q^2 range

$B_s \to D_s^*$ Shape

We can compare the binned experimental differential rate[12] for the $B_s \to D_s^*$ shape to our results



$\chi^2/\mathrm{dof} = 1.8$ (0.62 excluding third bin)

[Judd]

- Modified z expansion assumes BGL hold for all lattice spacings?
- What are further (hidden) assumptions?
  E.g., how is χPT M_π^2 dependence reflected in BGL coefficients?
  How, in practice, do the pole masses depend on m_h & M_π^2?