Inclusive semileptonic $B \to X_c \ell \nu$ decays at Belle (II)

Raynette van Tonder | Challenges in Semileptonic *B* Decays 2022 | raynette.vantonder@mcgill.ca

Back in 2018…

Talk by C. Schwanda
Challenges in Semileptonic B decays 2018

Data used in b → c inclusive analyses

BaBar	$\langle E^n_l \rangle$: n=0,1,2,3 [PRD 69, 111104 (2004), PRD 81, 032003 (2010)] $\langle M^{2n}_X \rangle$: n=1,2, 3 [PRD 81, 032003 (2010)]
Belle	$\langle E^n_l \rangle$: n=0,1,2,3 [PRD 75, 032001 (2007)] $\langle M^{2n}_X \rangle$: n=1,2 [PRD 75, 032005 (2007)]
CDF	$\langle M^{2n}_X \rangle$: n=1,2 [PRD 71, 051103 (2005)]
CLEO	$\langle M^{2n}_X \rangle$: n=1,2 [PRD 70, 032002 (2004)] $\langle E^n_\gamma \rangle$: n=1 [PRL 87, 251807 (2001)]
DELPHI	$\langle E^n_l \rangle$: n=1,2,3 $\langle M^{2n}_X \rangle$: n=1,2 [EPJ C45, 35 (2006)]

- Newest measurement is from the year 2010!

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A brief recap

Manca's **awesome** introduction:

Ongoing $b \to c$ analyses at Belle(II)

Tagged and untagged
$B \to D^{**}\ell\nu_\ell$
(Göttingen, McGill)

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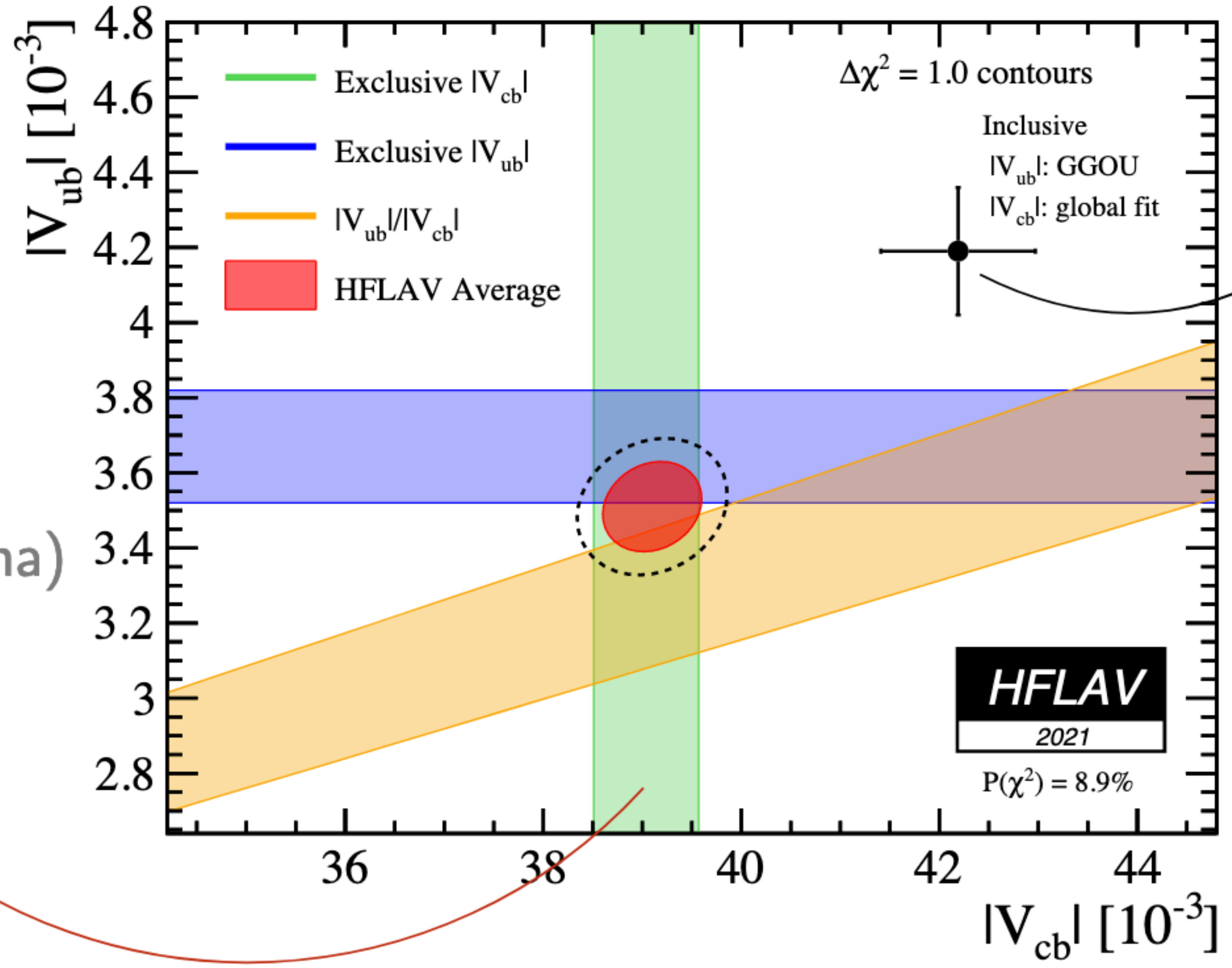
$B \to D^{*}\ell\nu_\ell$
(KEK, McGill, Bonn, Vienna)

Untagged
$B \to D\ell\nu_\ell$
(Vienna, Bonn)



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$B \to X_c\ell\nu_\ell$
Ray's talk on Wed.

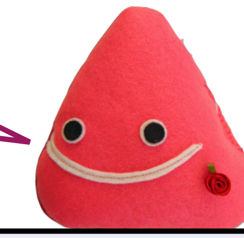
Untagged: only **signal** ***B* meson** is reconstructed

Tagged: **both *B* mesons** are reconstructed

A brief recap

Manca's **awesome** introduction:

Exciting, new
results
are on the way!



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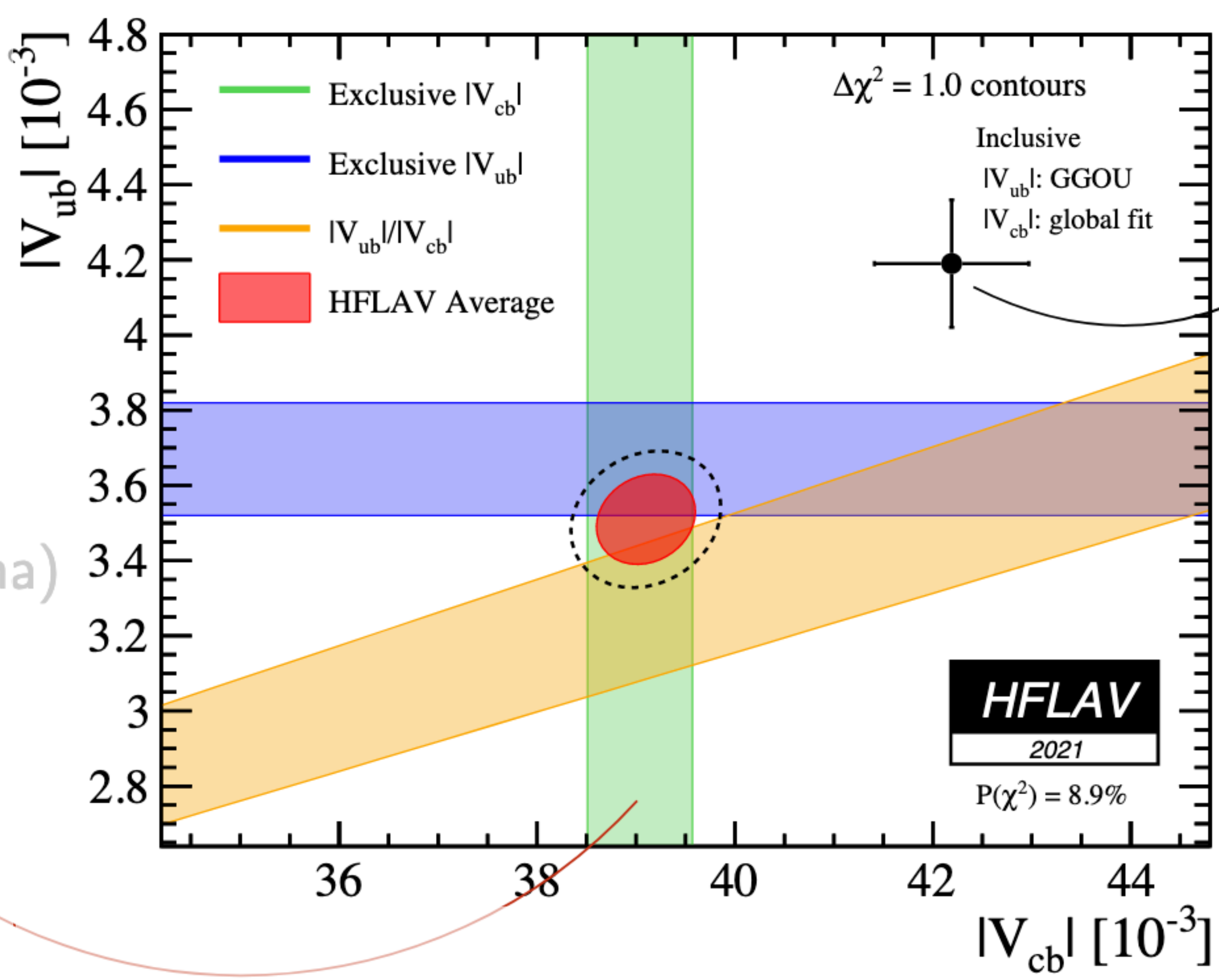

Untagged
$\mathcal{B}(B \to X_c \ell \nu_\ell)$
(Vienna)

Tagged
$\langle M_X^n \rangle$ moments
(Bonn)

Tagged and untagged
$\langle q^{2n} \rangle$ moments
(Bonn, Vienna)

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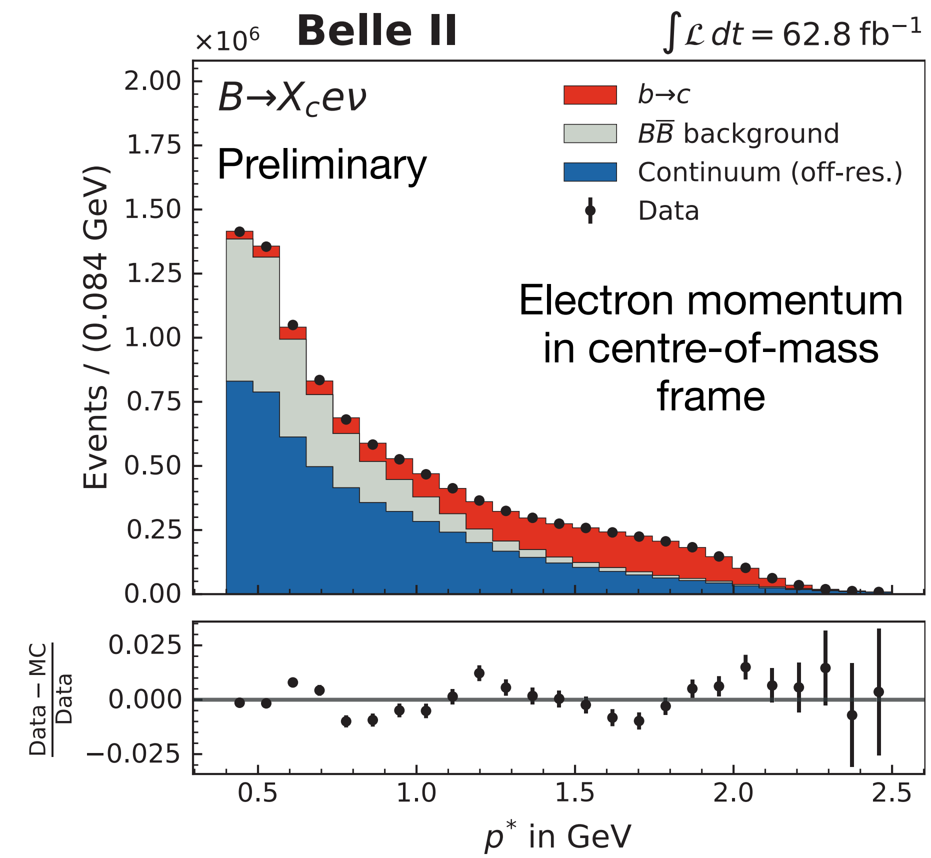
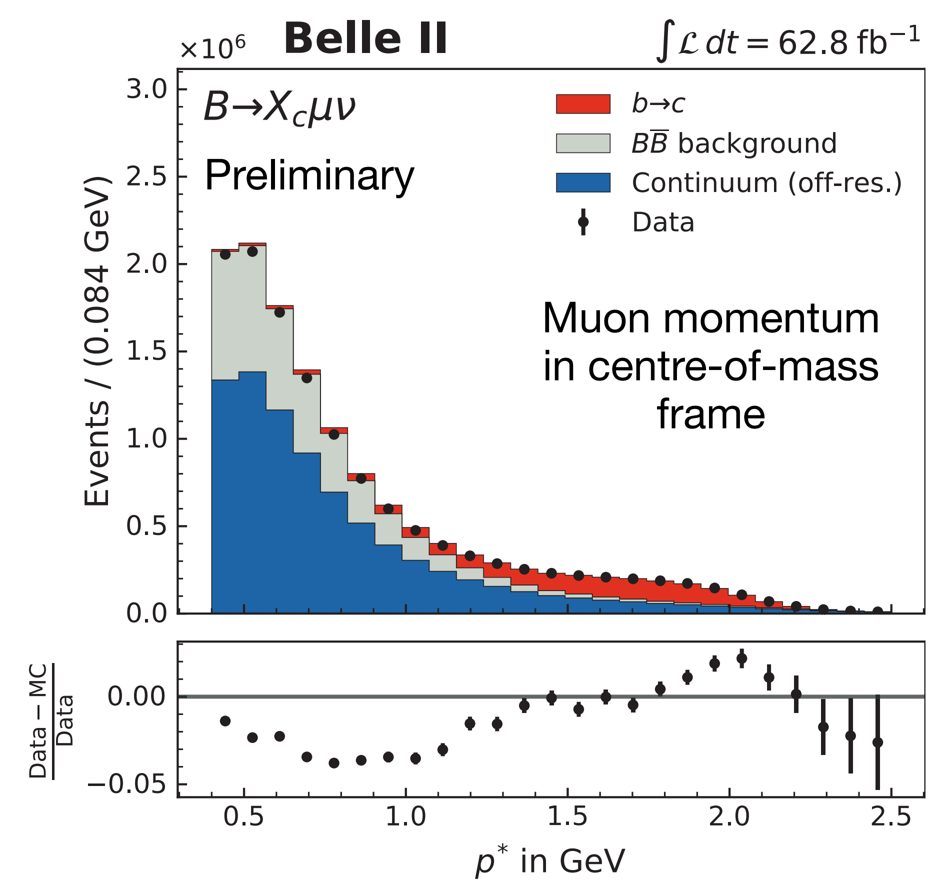
Belle II $\mathcal{B}(B \to X_c \ell \nu_\ell)$ meas.

arXiv:2111.09405

- First presented **in summer 2021**
- Belle II data sample: 62.8 fb^{-1}
- Requires one well identified **signal lepton**
- Exploits missing mass and momentum distributions to **reject backgrounds**
- Estimate **signal yield** with binned likelihood fit in p_ℓ^*
  - separates electron and muon channels

Yield	Electron mode	Muon mode
Signal	$(1.932 \pm 0.006) \times 10^6$	$(1.501 \pm 0.007) \times 10^6$





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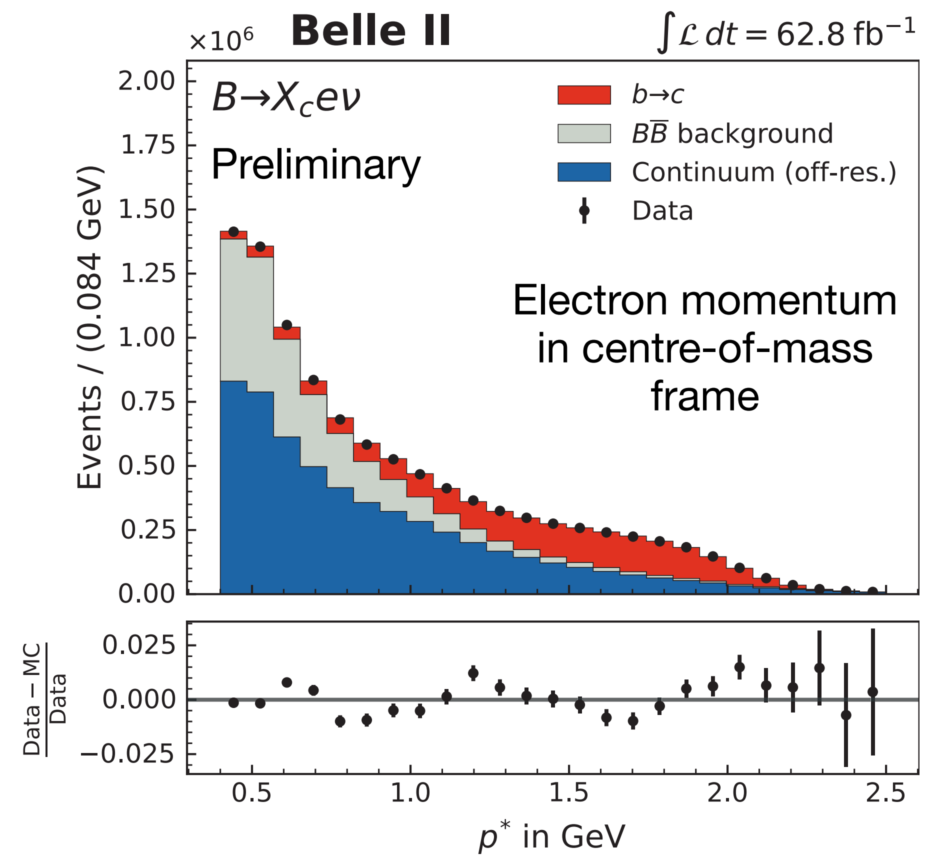
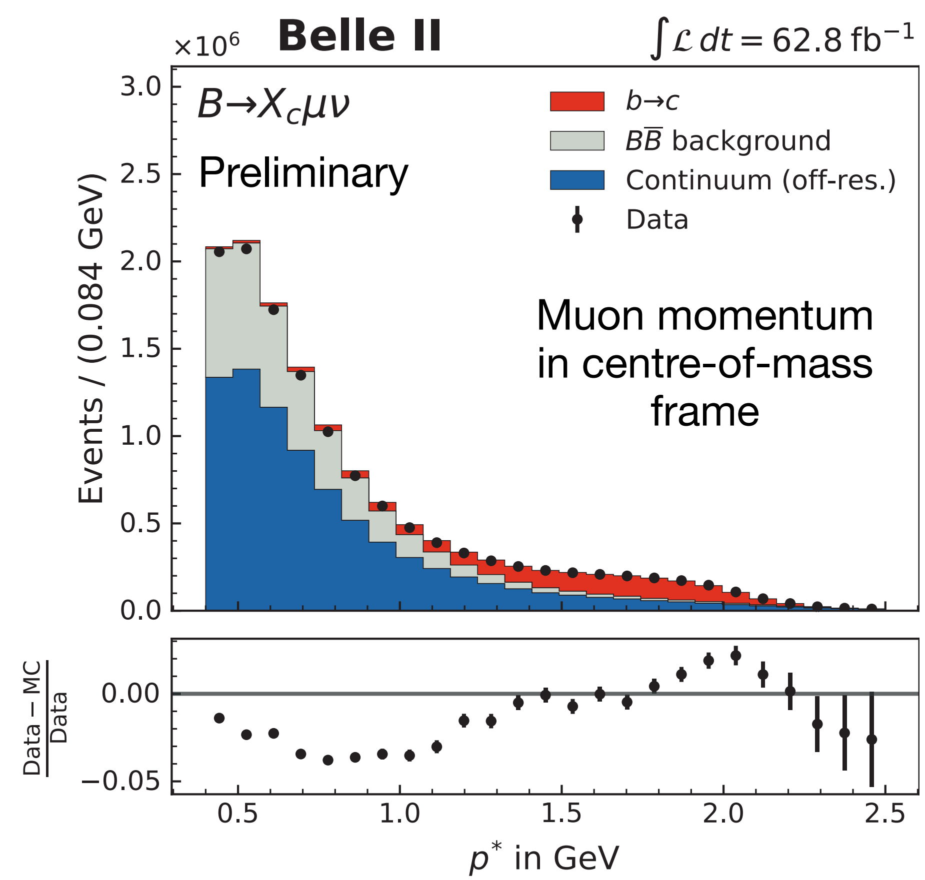
$$\mathcal{B}(B \to X_c \ell \nu) = (9.75 \pm 0.03(\text{stat}) \pm 0.47(\text{sys}))\%$$

Leading systematics:

$B \to X_c \ell \nu$ branching fractions + form factors





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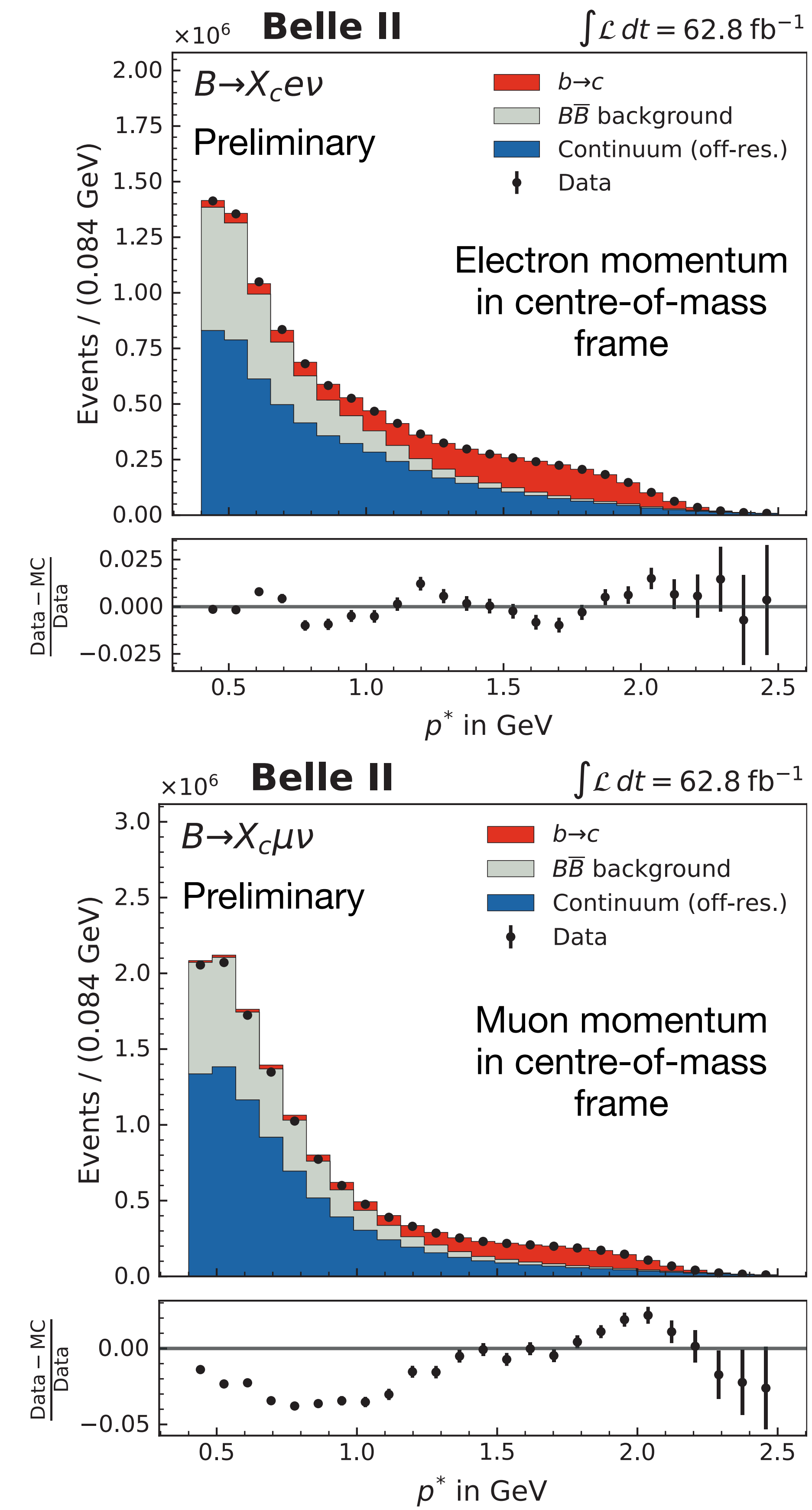
Analysis will be **extended** to measure moments of q^2



Recipe to bake moments

Event-wise **Key-formula**

$$\langle q^{2n} \rangle = \frac{\sum w_i(q^2)(q^{2n}_{\mathrm{calib},i})}{\sum_i w_i(q^2)} \times \mathcal{C}_{\mathrm{cal}} \times \mathcal{C}_{\mathrm{acc}}$$

Recipe to bake moments

Step #1: Subtract background

Estimate background **normalizations** by fitting M_X

Determine sets of signal prob. weights as a **progression of threshold selections on** q^2 (or p_ℓ for moments of M_X)

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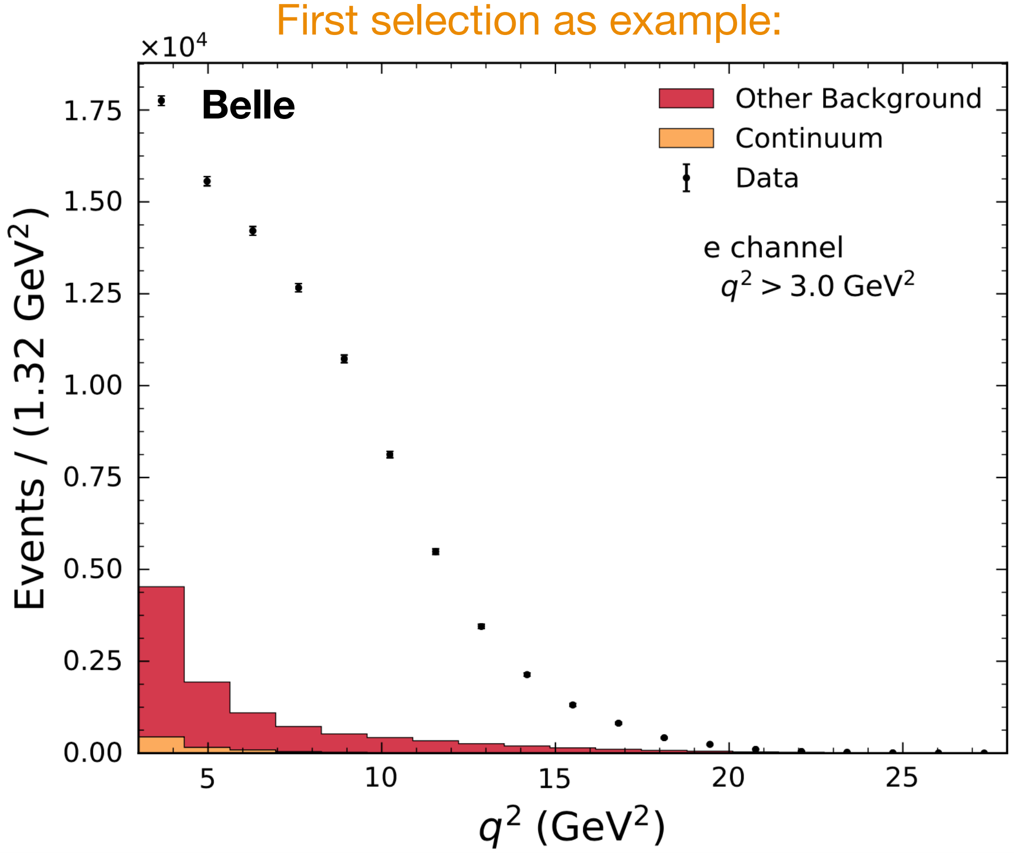

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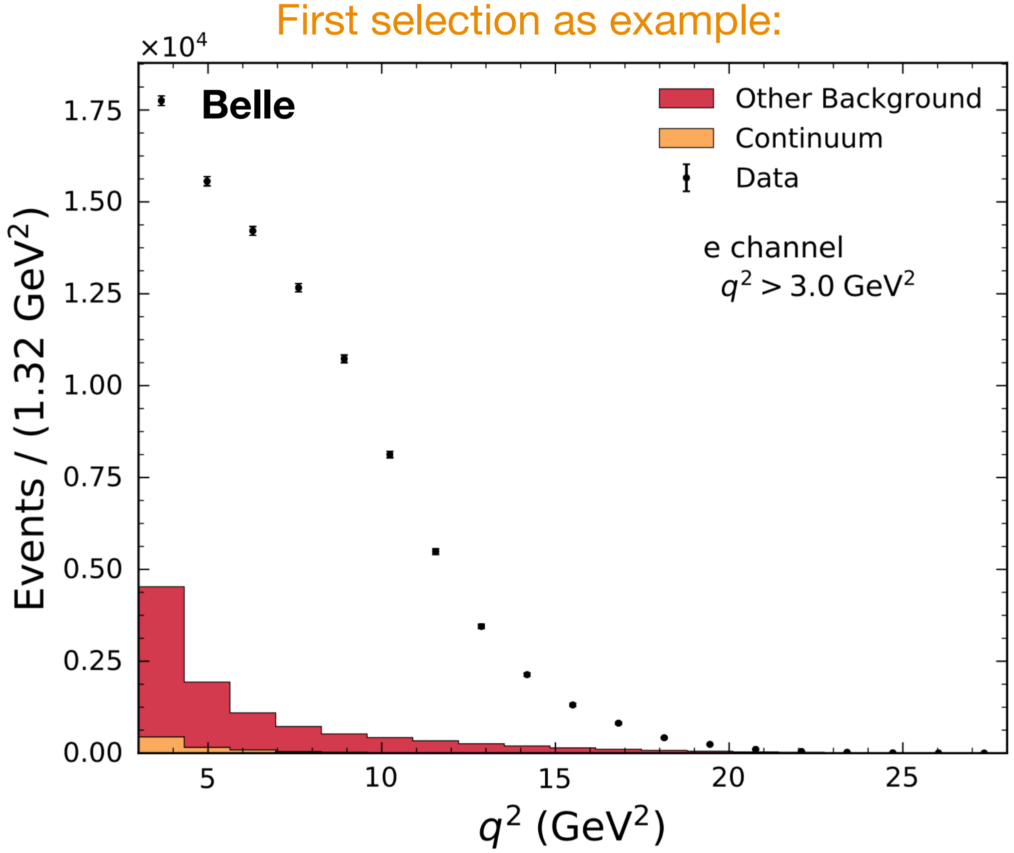
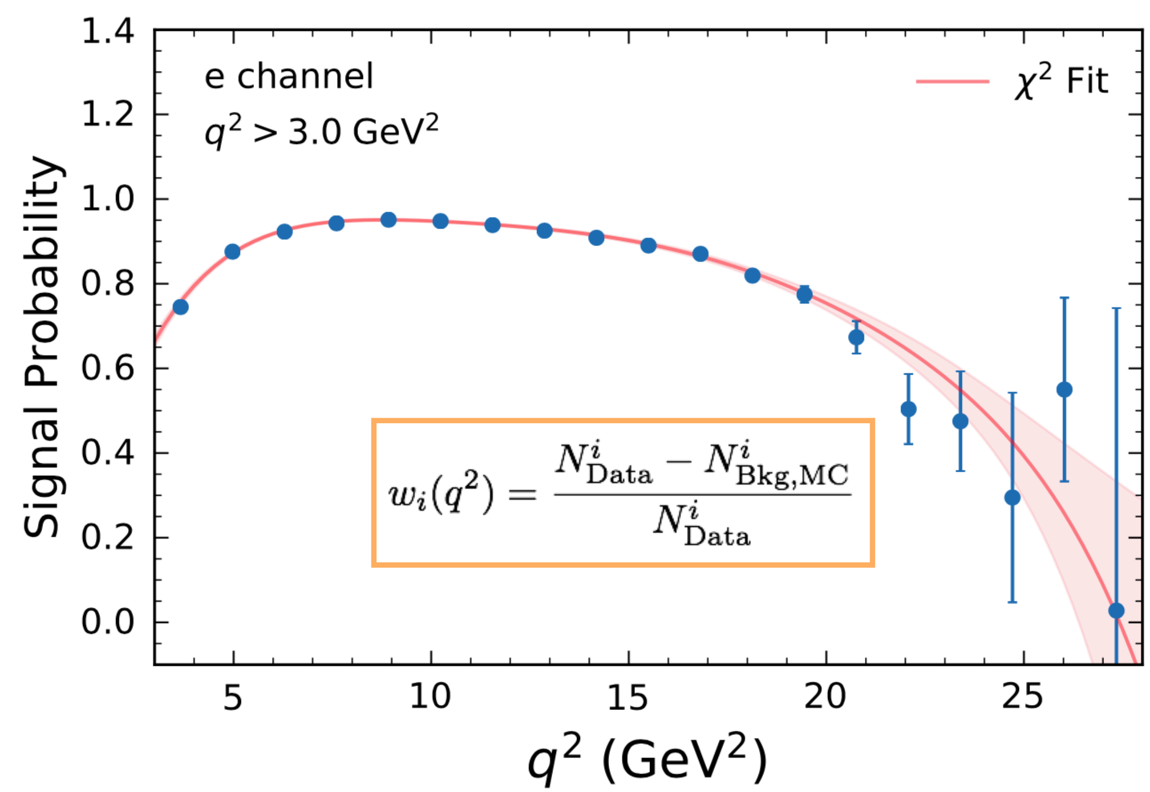


Smooth signal prob. Function $w_i(q^2)$



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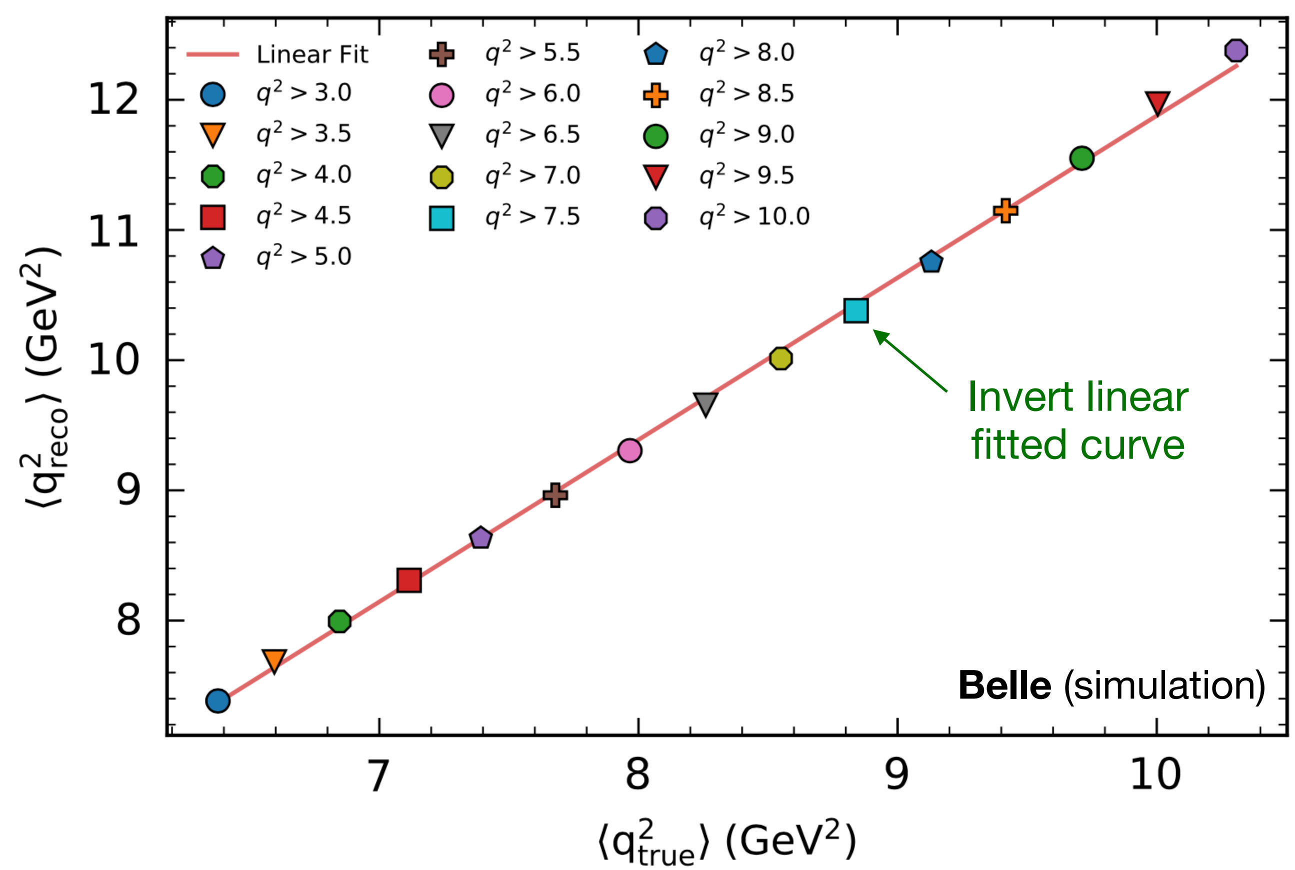
Linear dependence between reconstructed and true moments as a function of q^2

$$q^2_{\text{calib},i} = \left(q^2_{\text{reco},i} - c\right)/m$$

from simulation



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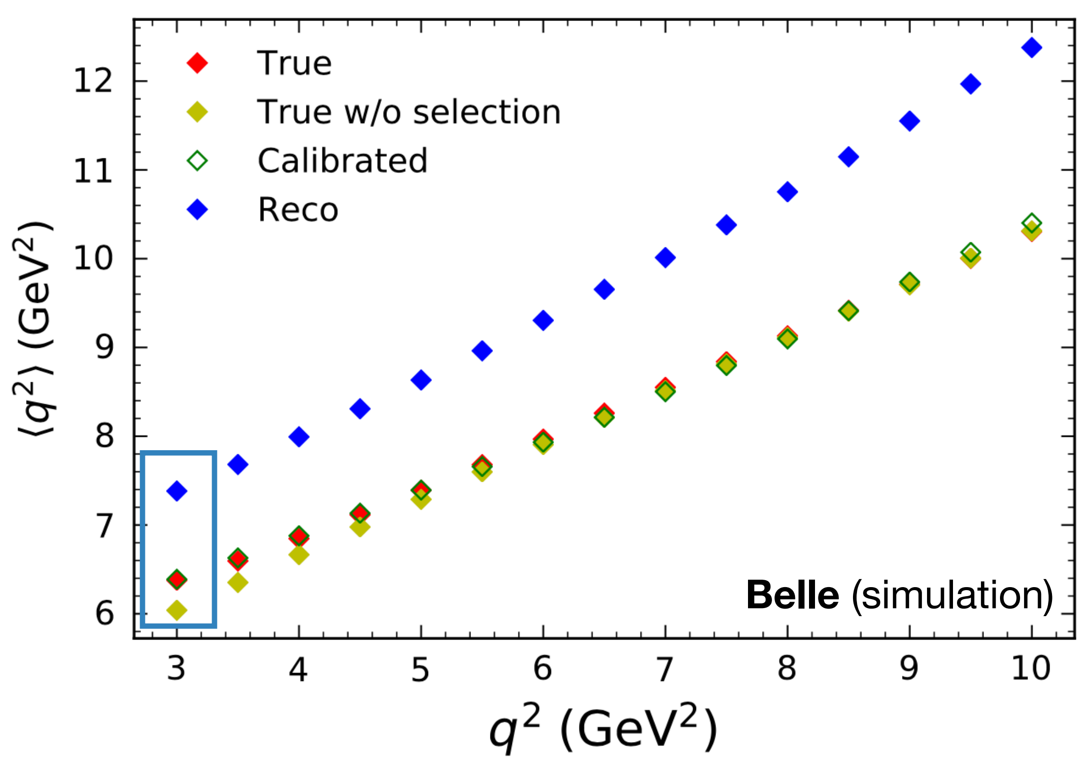
Step #3: If you fail, try, try again

Correct for residual calibration bias

Compare with expectation from simulated data



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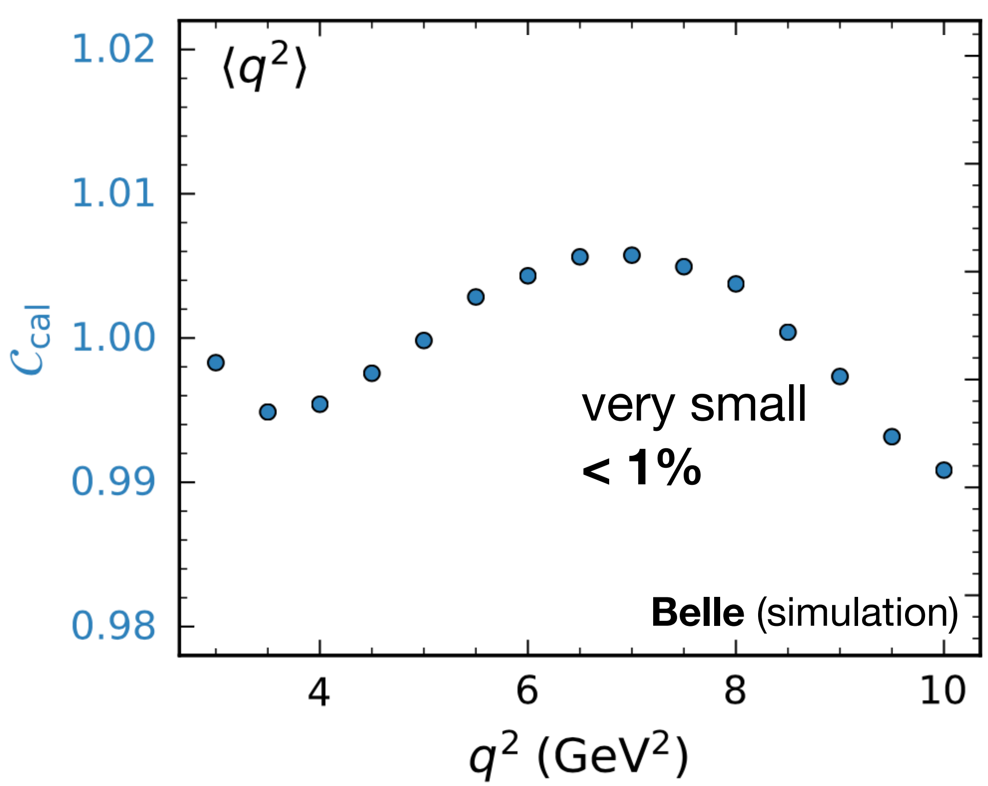

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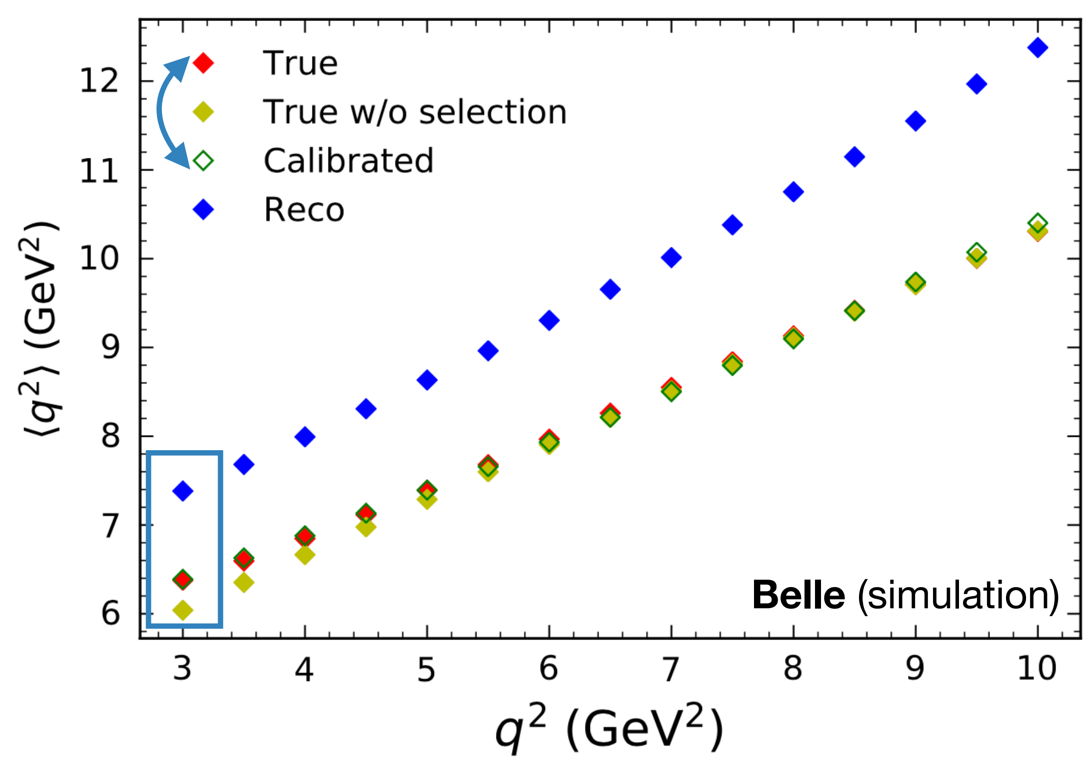

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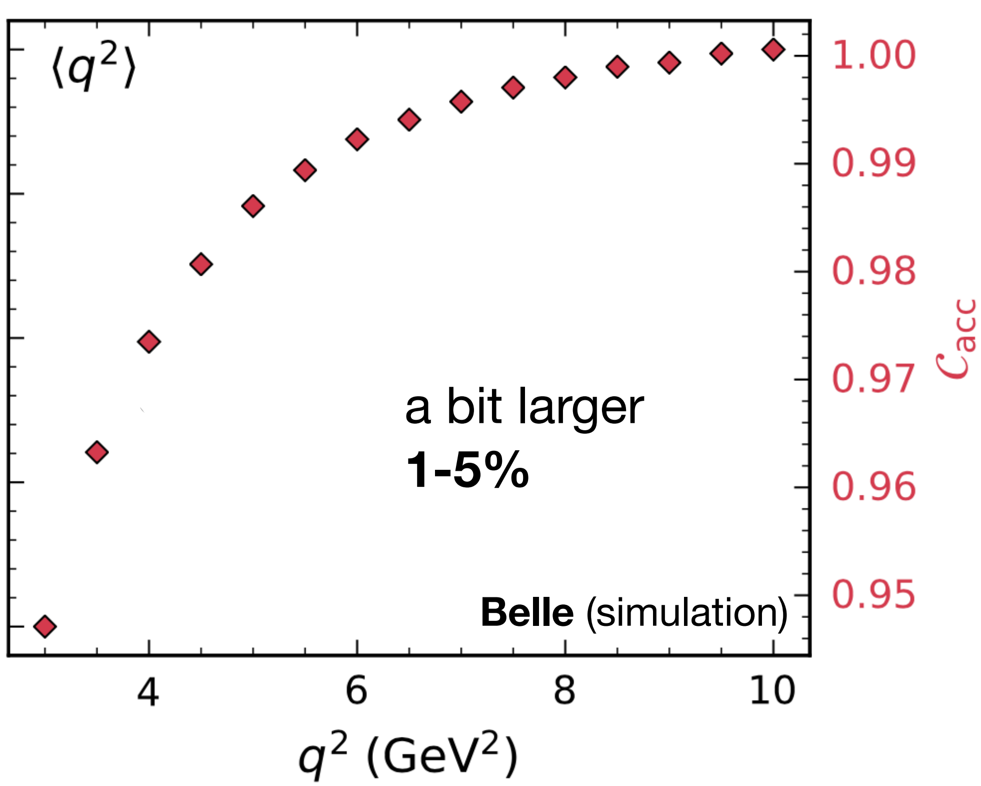
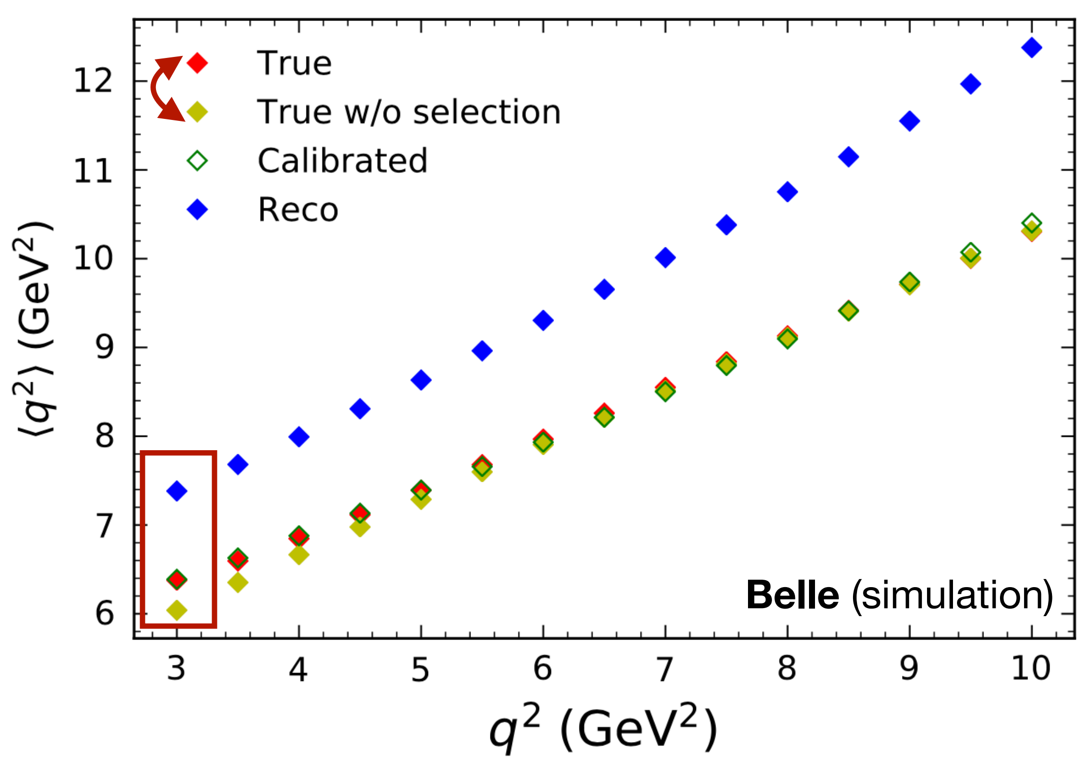
Correct for residual calibration bias

Step #4: Correct selection bias

Overall event reconstruction also **biases** measured moments

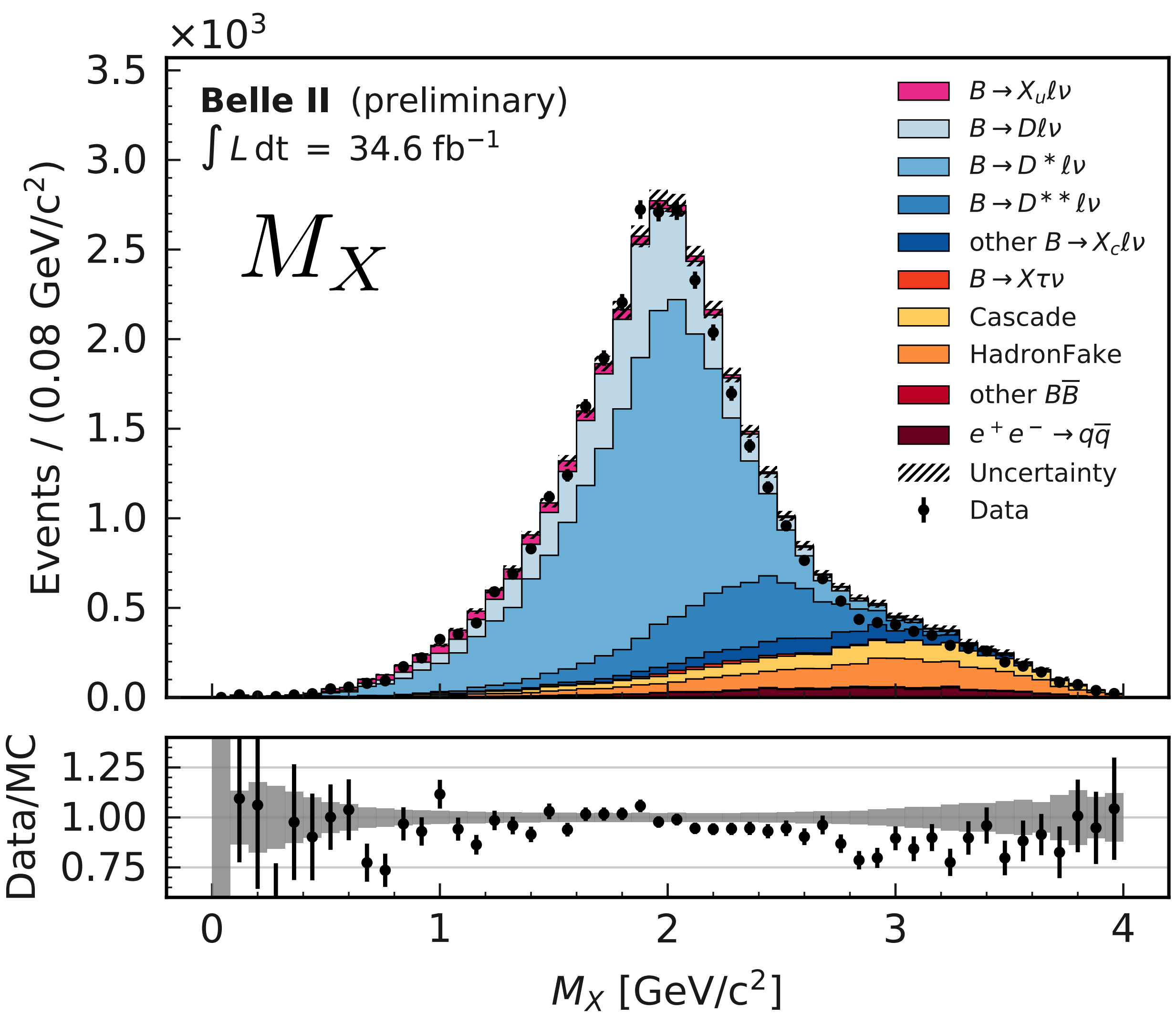


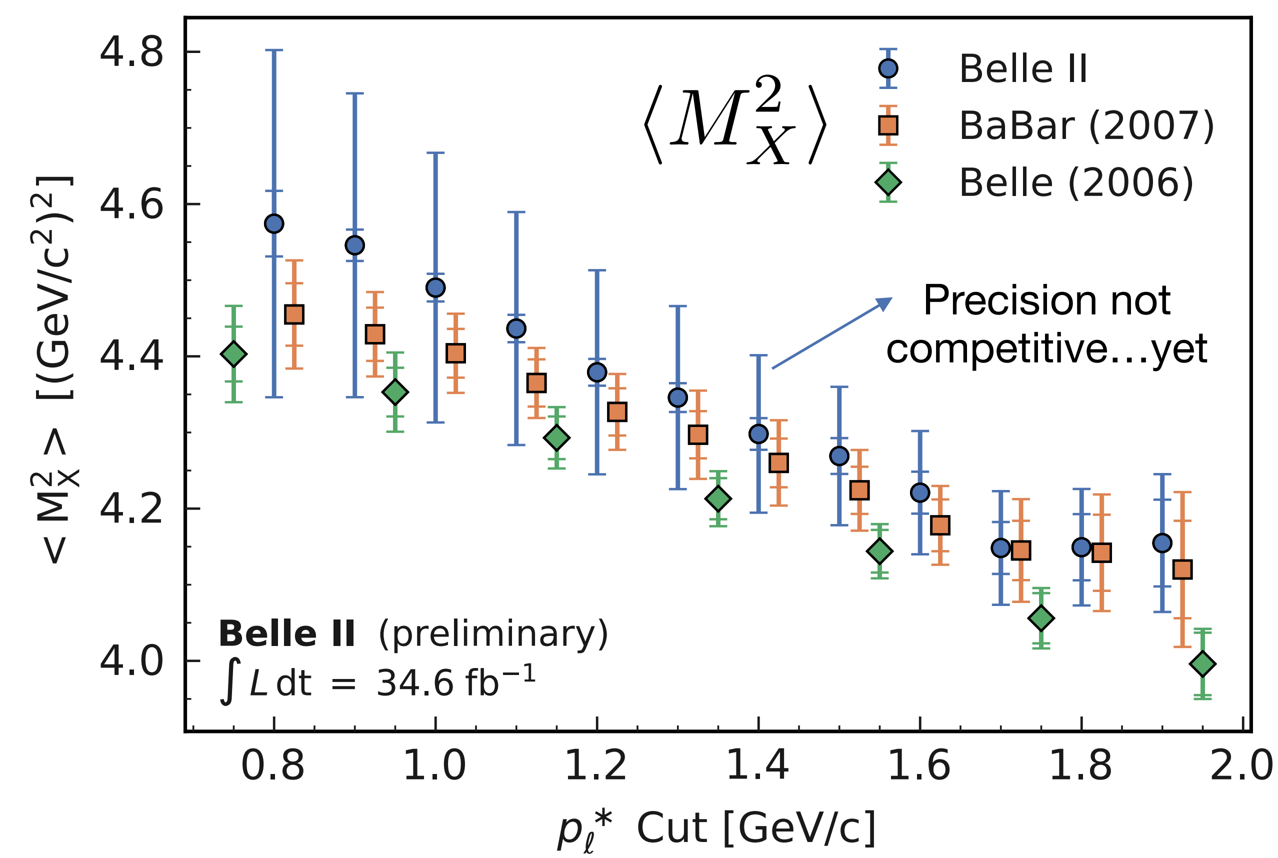


Belle II $\langle M_X^n \rangle$ moments

arXiv:2009.04493

- First presented **in summer 2020**
- Belle II data sample: 34.6 fb^{-1}
- Companion B meson reconstructed using the **Full Event Interpretation (FEI)**
- Requires one **high momentum** signal lepton
- Reduces background by exploiting **inclusive kinematic variables**
- Performs calibration as a function of: Missing energy and momentum, X system multiplicity, p_ℓ
- Leading systematics: $B \to X_c \ell \nu$ **composition + modelling**



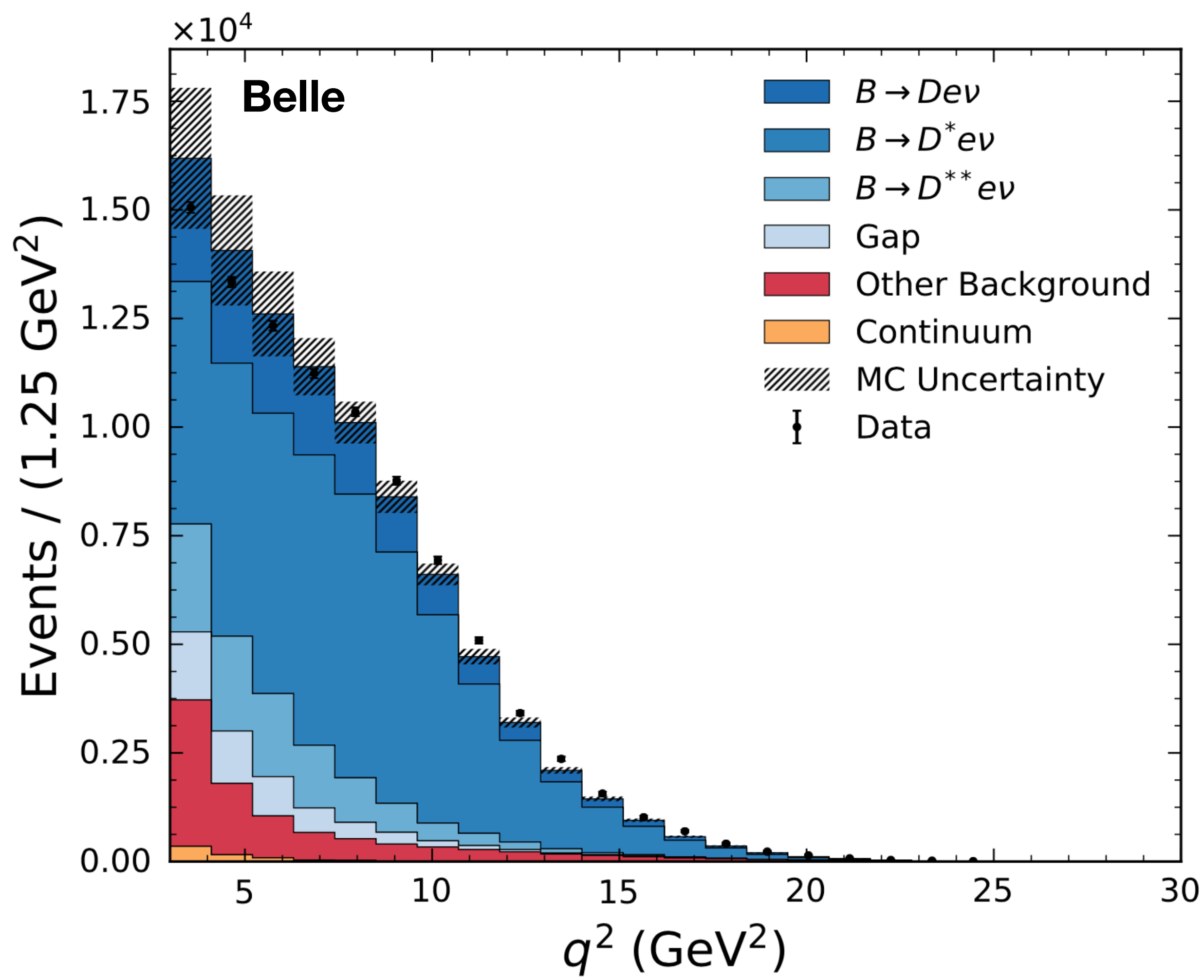


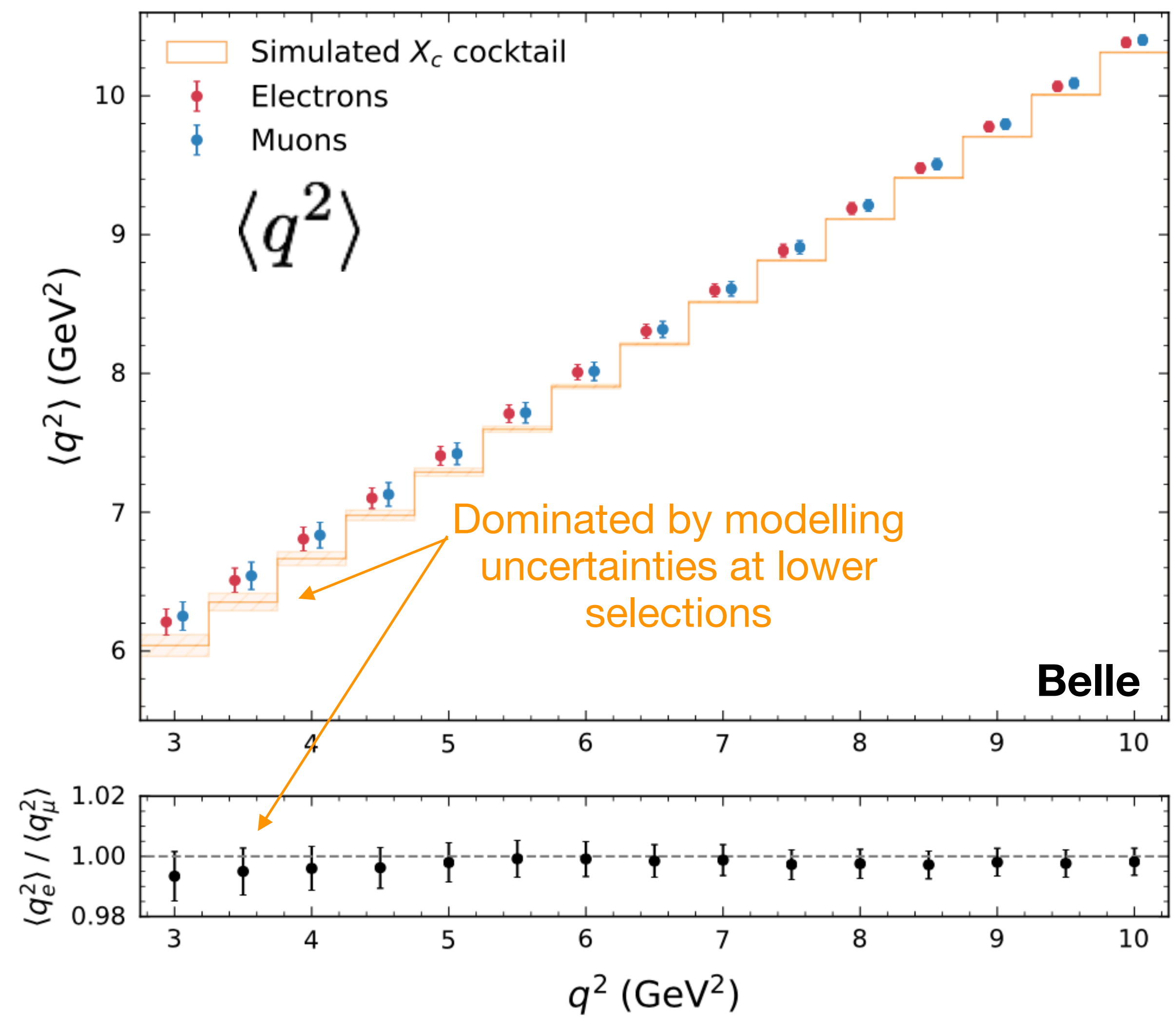
Belle $\langle q^{2n} \rangle$ moments

PRD 104, 112011 (2021)

Fresh idea from [JHEP 02, 177 (2019)] (see Keri's talk)

- First presented **in spring 2021**
- Complete Belle dataset: 711 fb^{-1}
- Companion B meson reconstructed using the **Full Reconstruction (FR)**
- Selects leptons at **detector acceptance** limit: $p_e^* > 0.3$ GeV, $p_\mu^* > 0.5$ GeV
- Separates **electron** and **muon** channels
- Exploits missing energy and momentum to **reject backgrounds**





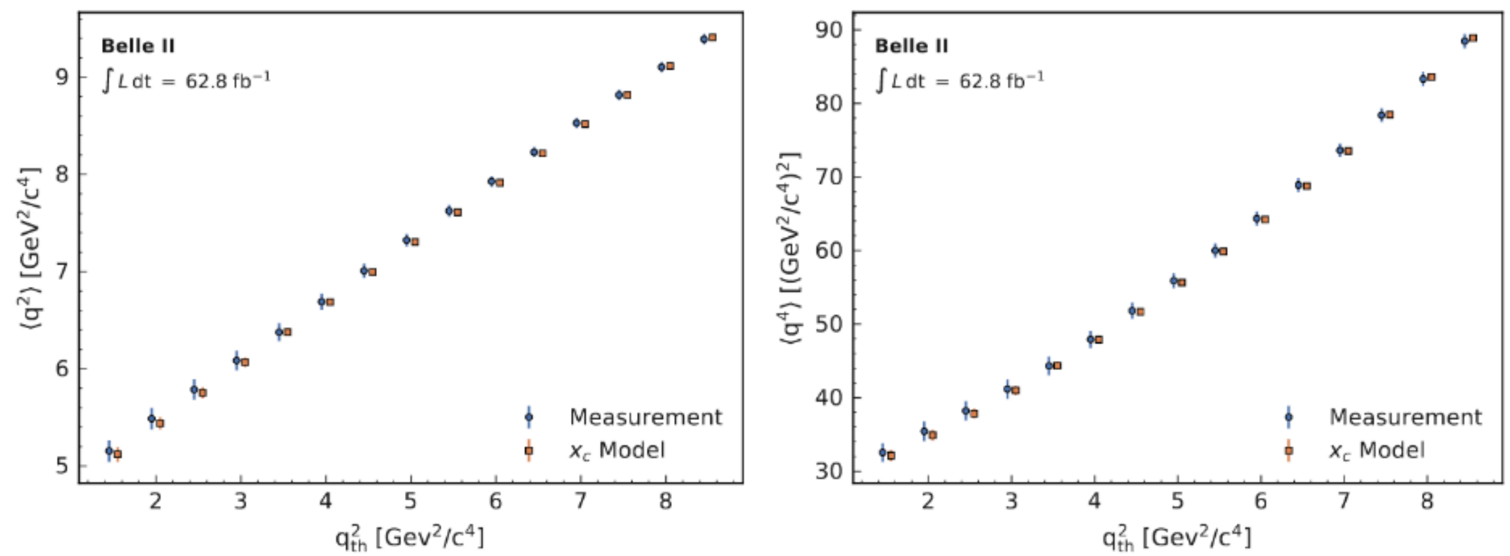
Hot off the press from Belle II!

Talk by W. Sutcliffe
Moriond EW 2022

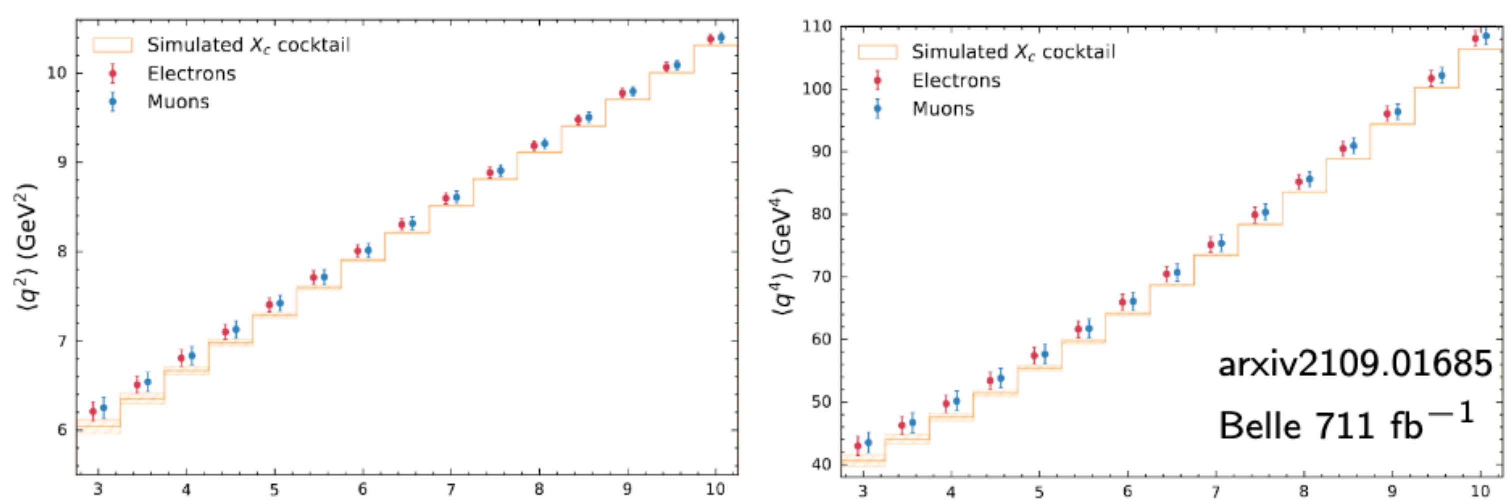
Measurements of inclusive $B \to X_c l \nu$ decays.

q^2 moments from $B \to X_c \ell \nu$ decays

- Here compare $n = 1, 2$ q^2 moments as a function of lower q^2 threshold between Belle II and Belle.



Paper soon!



- Expect global fits for inclusive $|V_{cb}|$ using the moments in the near future.

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

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

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

$\mathrm{D}^0 \ell^+ \nu_\ell$	$\mathrm{D}^{*0} \ell^+ \nu_\ell$	$\mathrm{D}^{**0} \ell^+ \nu_\ell$ + Other	Gap
$2.31\,\%$	$5.05\,\%$	$2.38\,\%$	$\sim 1.05\,\%$

Image credit: F. Metzner

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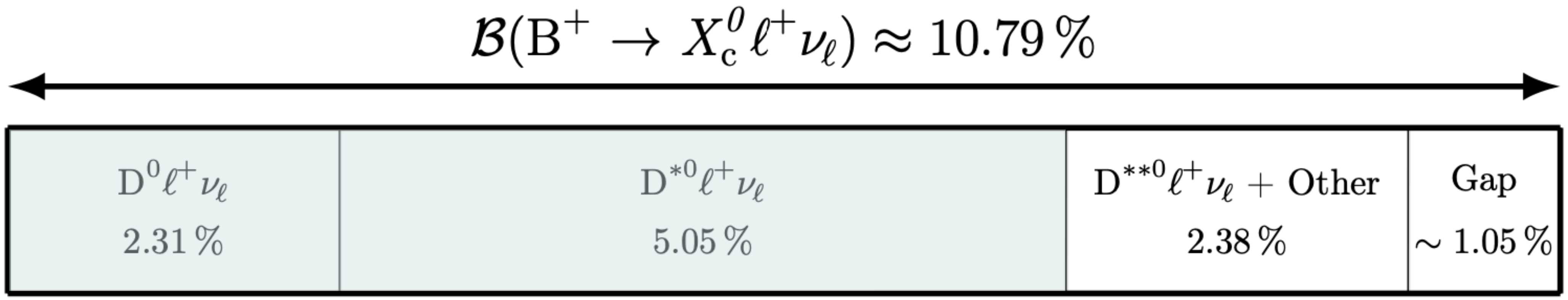

Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell^+\,\nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell^+\,\nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$

→ Fairly well known.
Some iso-spin tension.

Image credit: F. Metzner

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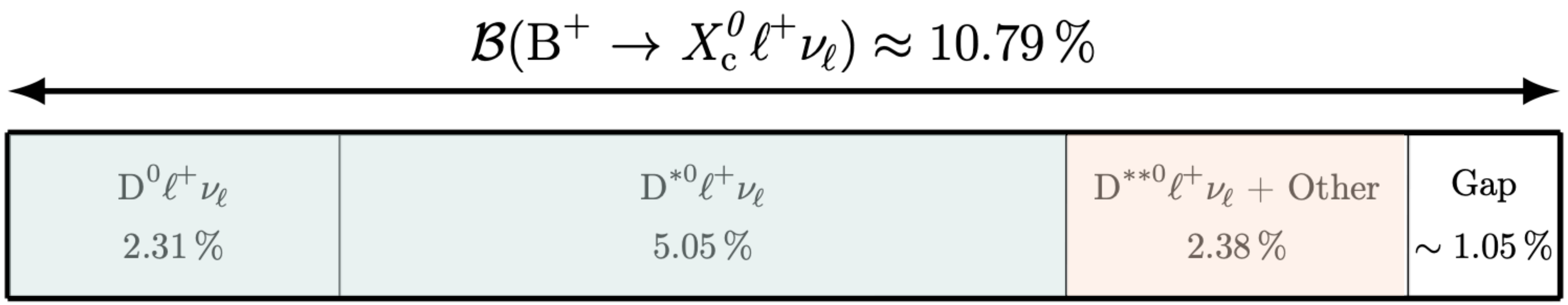

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$B \to D_1'\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.9) \times 10^{-3}$	$(3.9 \pm 0.8) \times 10^{-3}$

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

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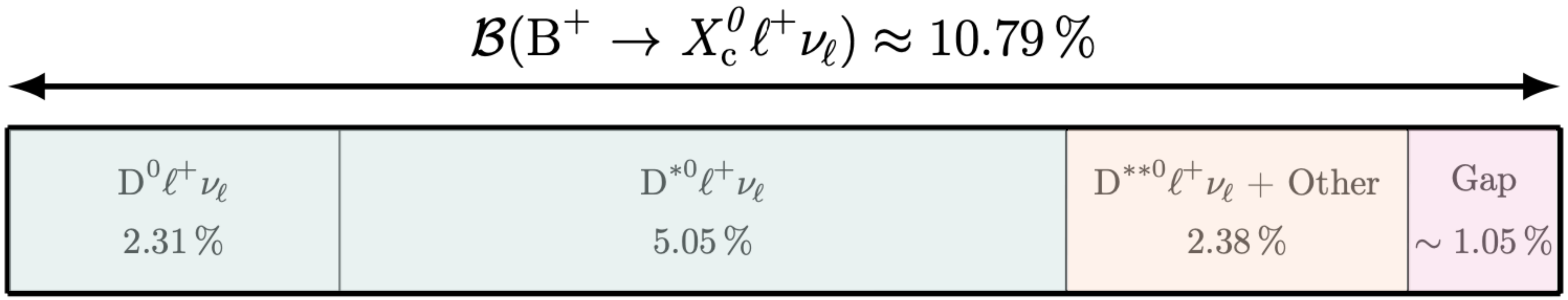

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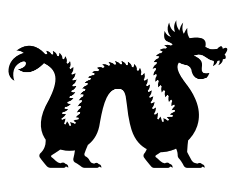

$B \to X_c \ell \nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$

Image credit: F. Metzner

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$B \to D\pi\pi\,\ell^+\,\nu_\ell$	$(0.6 \pm 0.9) \times 10^{-3}$	$(0.6 \pm 0.9) \times 10^{-3}$
$B \to D^*\pi\pi\,\ell^+\,\nu_\ell$	$(2.2 \pm 1.0) \times 10^{-3}$	$(2.0 \pm 1.0) \times 10^{-3}$
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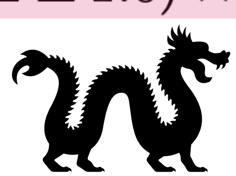

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→ Some hints from the BaBar result.

Image credit: F. Metzner

A tale of two 'gap' models

Model 1:
Equidistribution of all final state particles in phase space

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

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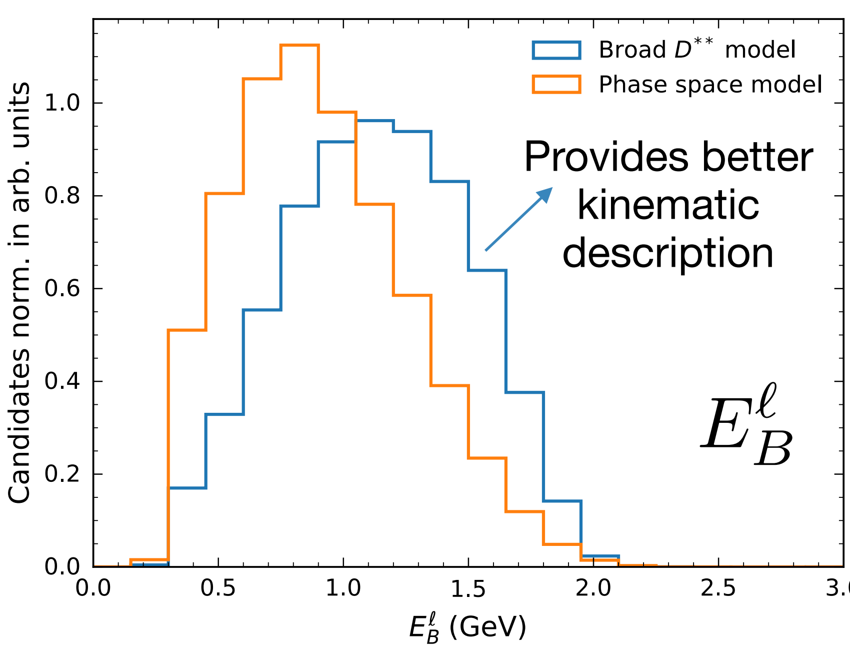
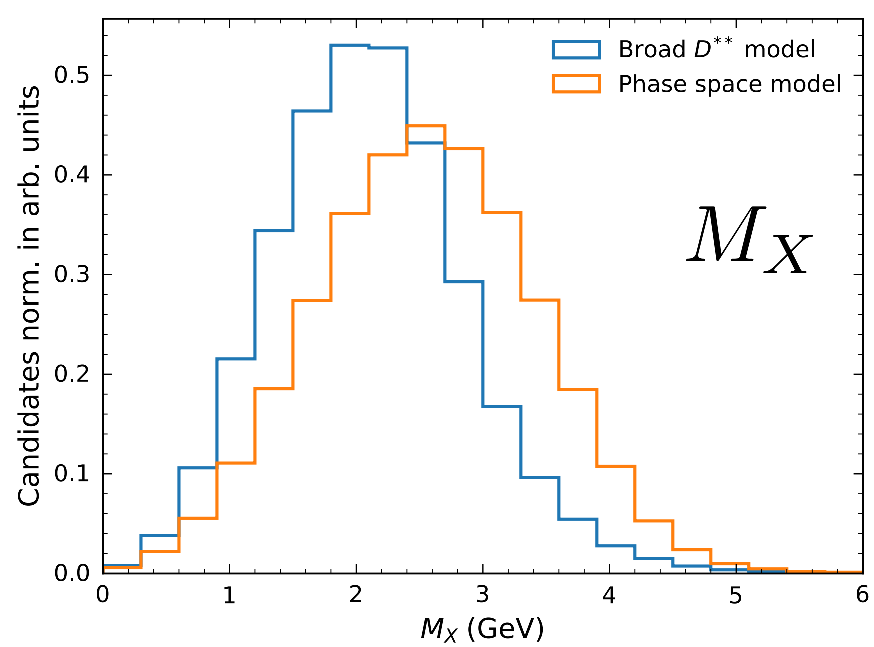
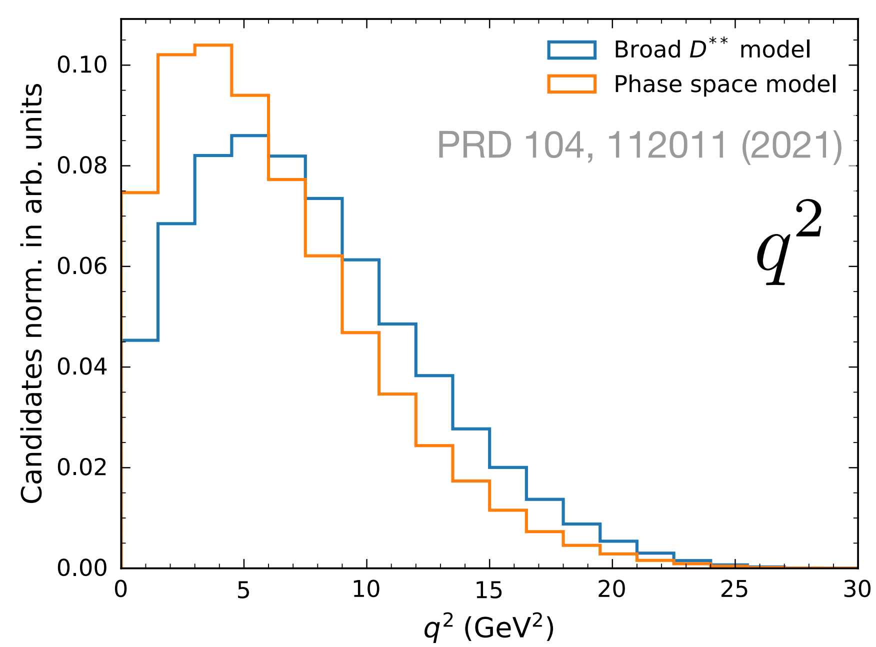




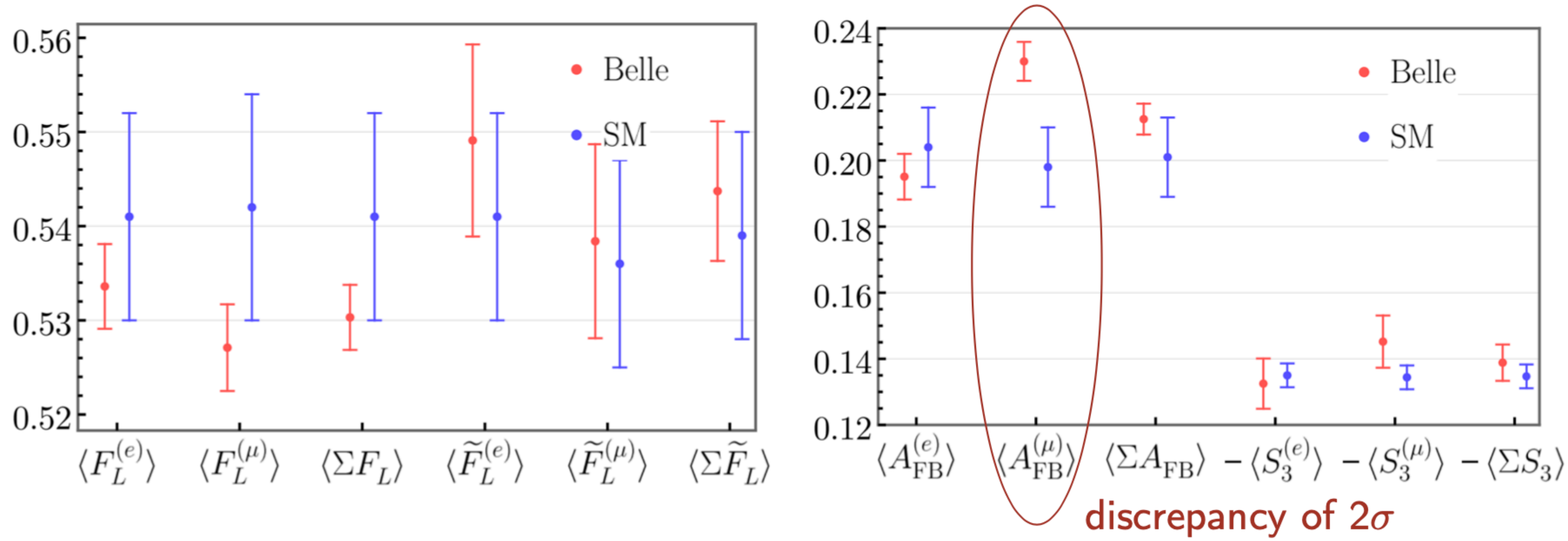


Recap: A_{FB} status

Manca's talk…again

A_{FB} from $B^0 \to D^{*-}\ell^+\nu_\ell$ (2021)

[arXiv:2104.02094v1]



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- Correlation matrices of the statistical uncertainties are incorrect

? Beyond the Standard Model physics scenario

? Wrong assumptions $\to$ But why no discrepancy in other parameters?

- **Further studies are needed**
- **e/μ flavours should be studied separately**

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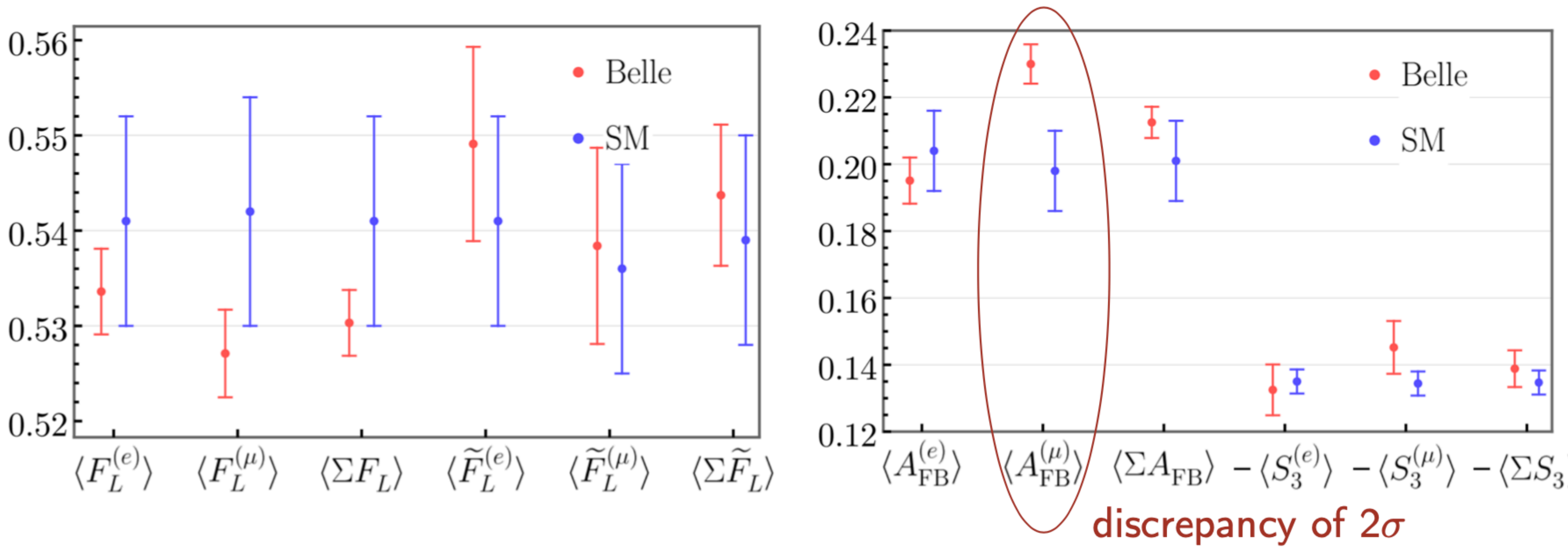

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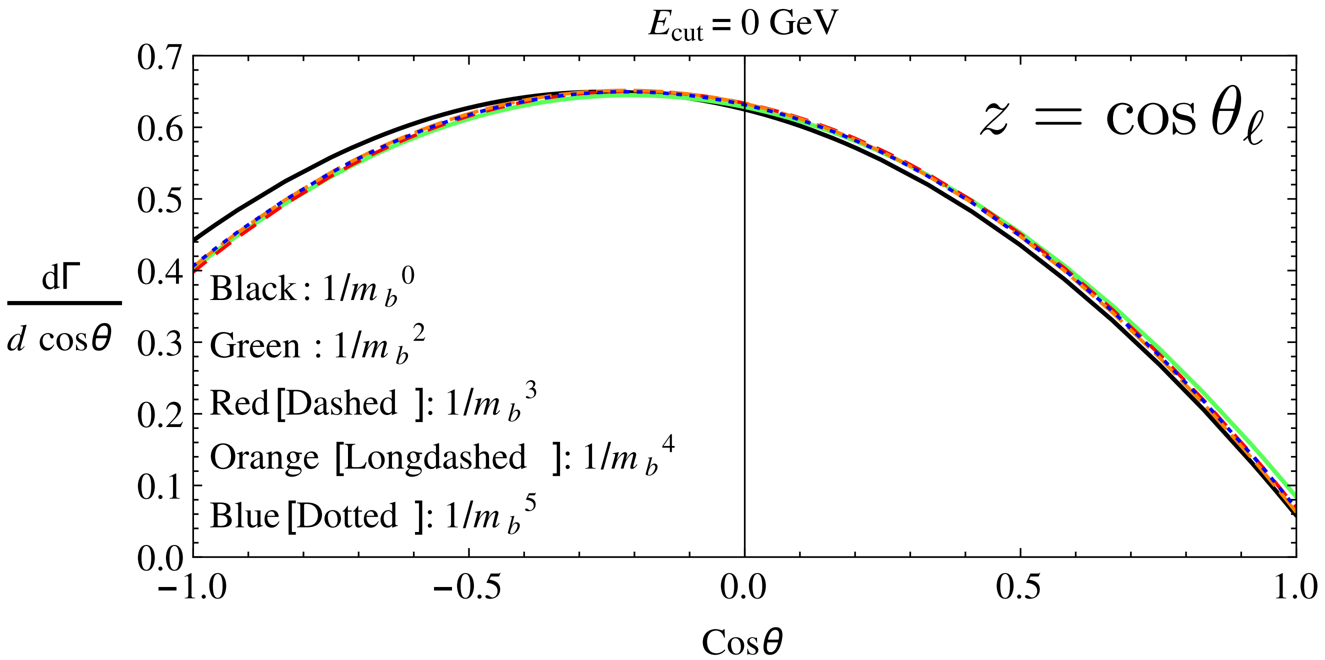
Measure A_{FB} from inclusive $B \to X_c\ell\nu$ decays for an **orthogonal, complementary study**, while also gaining **additional information** on HQE parameters. [JHEP 04 (2016) 131]

A_{FB} at Belle II

JHEP 04 (2016) 131

- Goal: Measure A_{FB} from **inclusive** $B \to X_c \ell \nu$ decays using **hadronic tagging**

$$\mathcal{A}_{FB} = \frac{1}{\Gamma}\left(\int_{-1}^{0} \mathrm{d}z \frac{\mathrm{d}\Gamma}{\mathrm{d}z} - \int_{0}^{1} \mathrm{d}z \frac{\mathrm{d}\Gamma}{\mathrm{d}z}\right)$$



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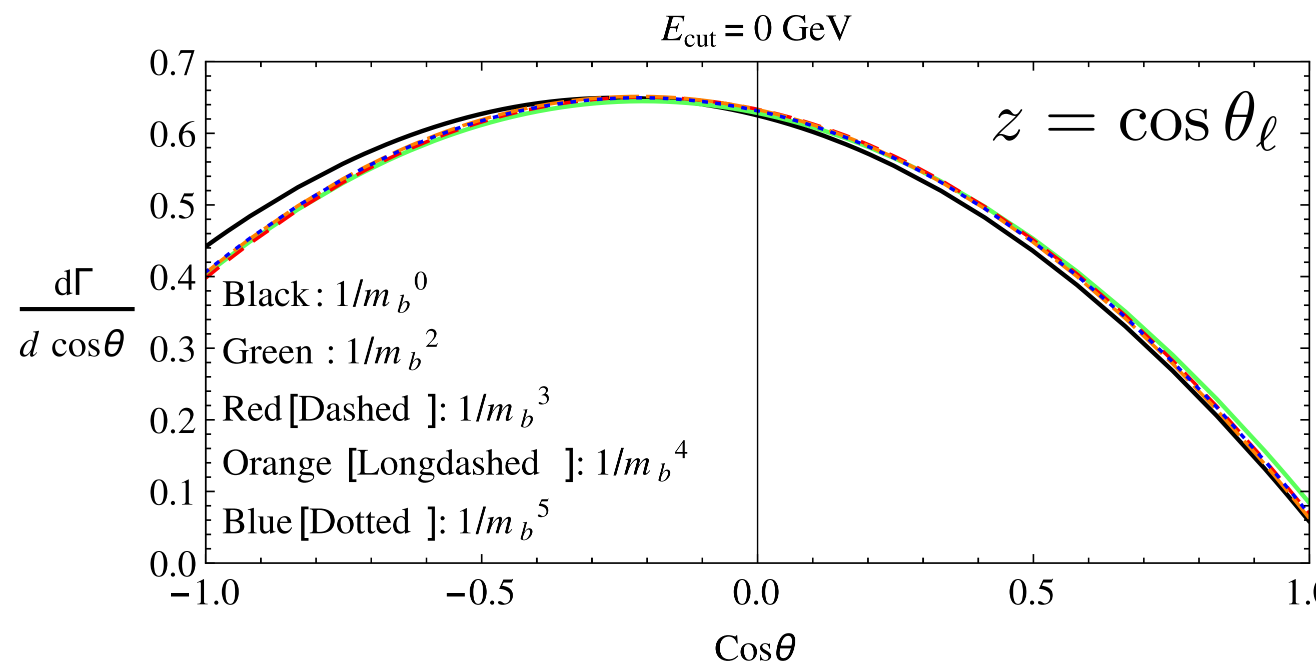
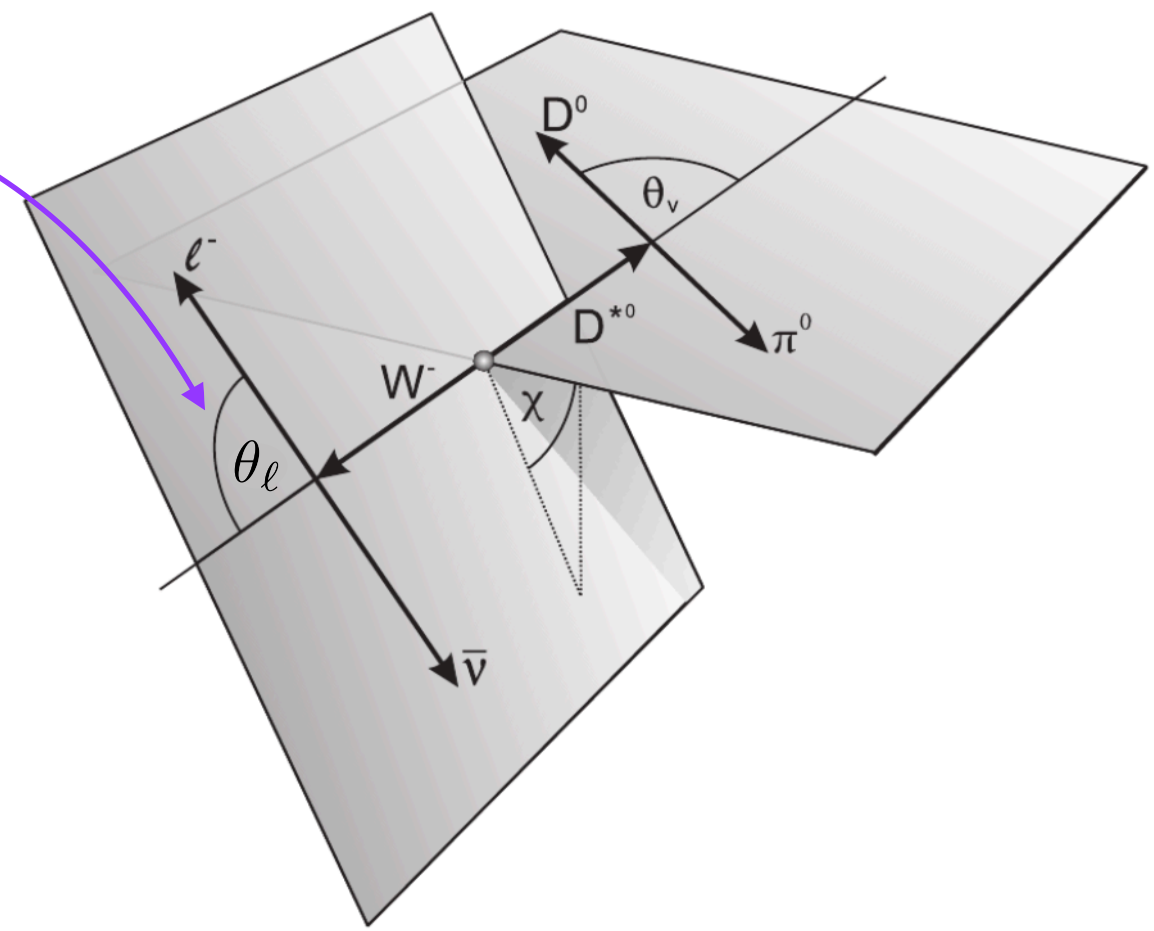


- Reconstruct:

$$z = \frac{E^B_{\nu_\ell} - E^B_\ell}{\sqrt{(E^B_{\nu_\ell} + E^B_\ell)^2 - q^2}}$$



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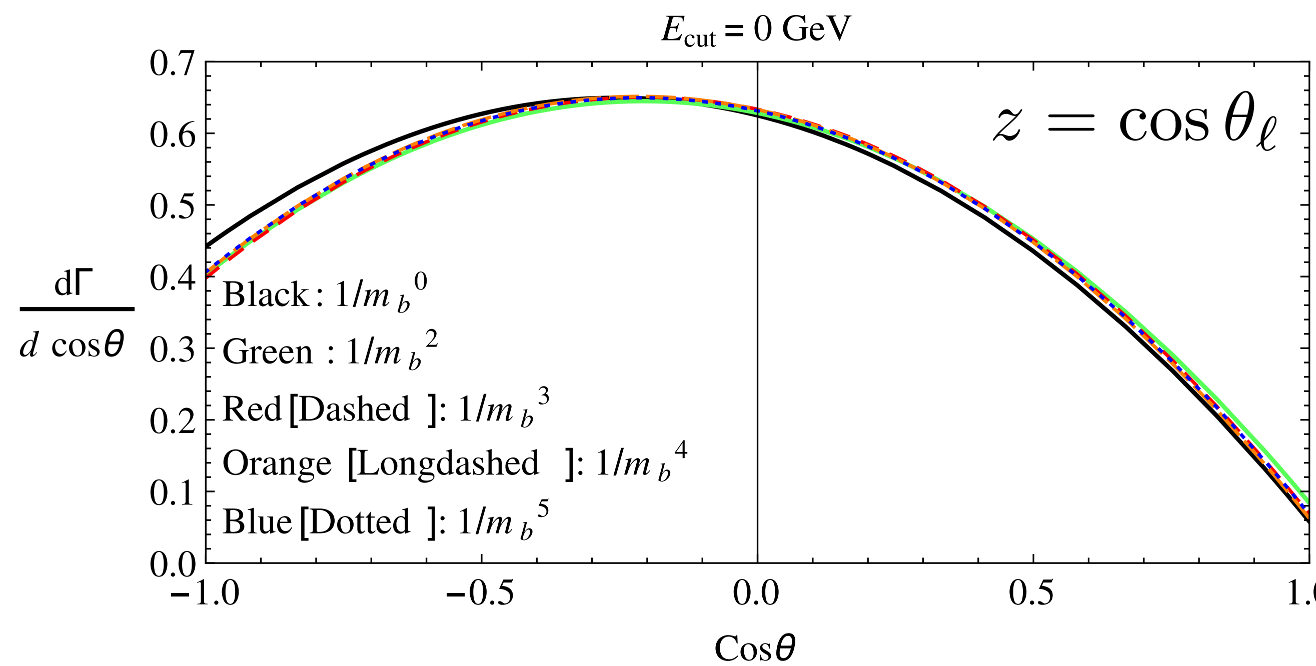

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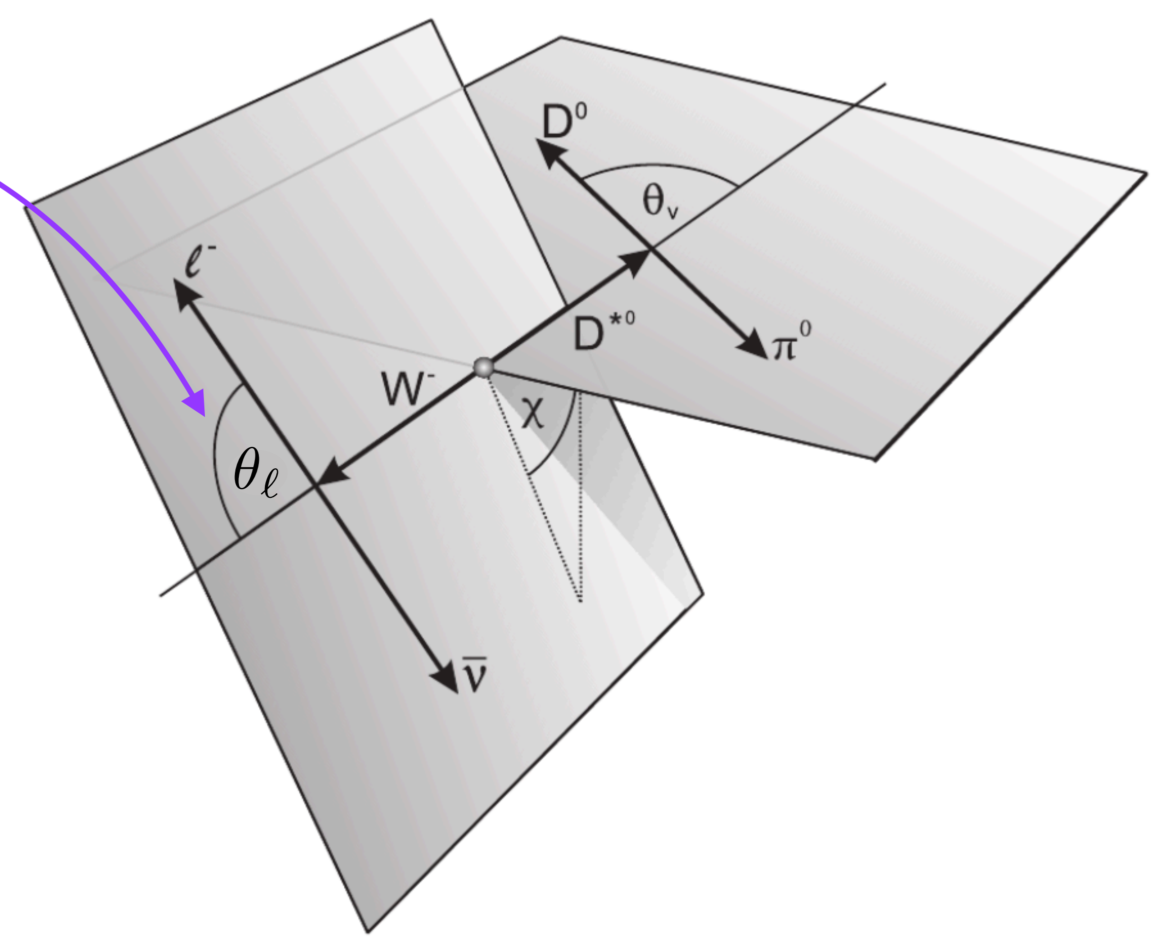

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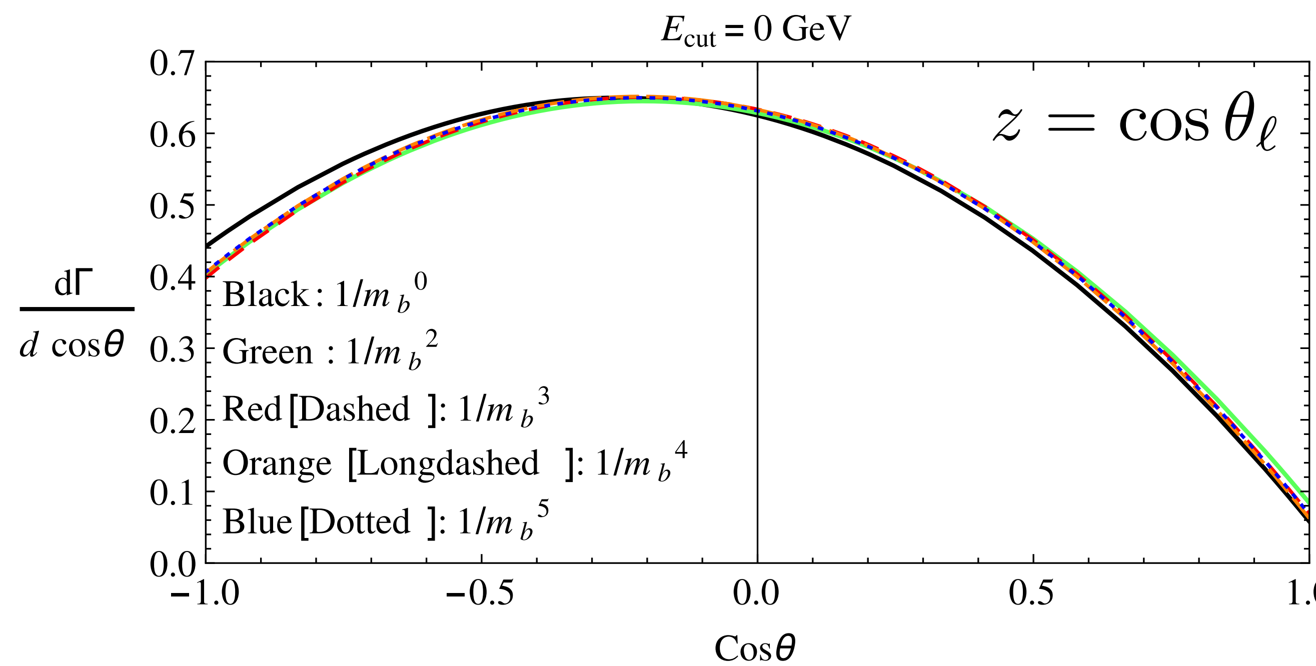

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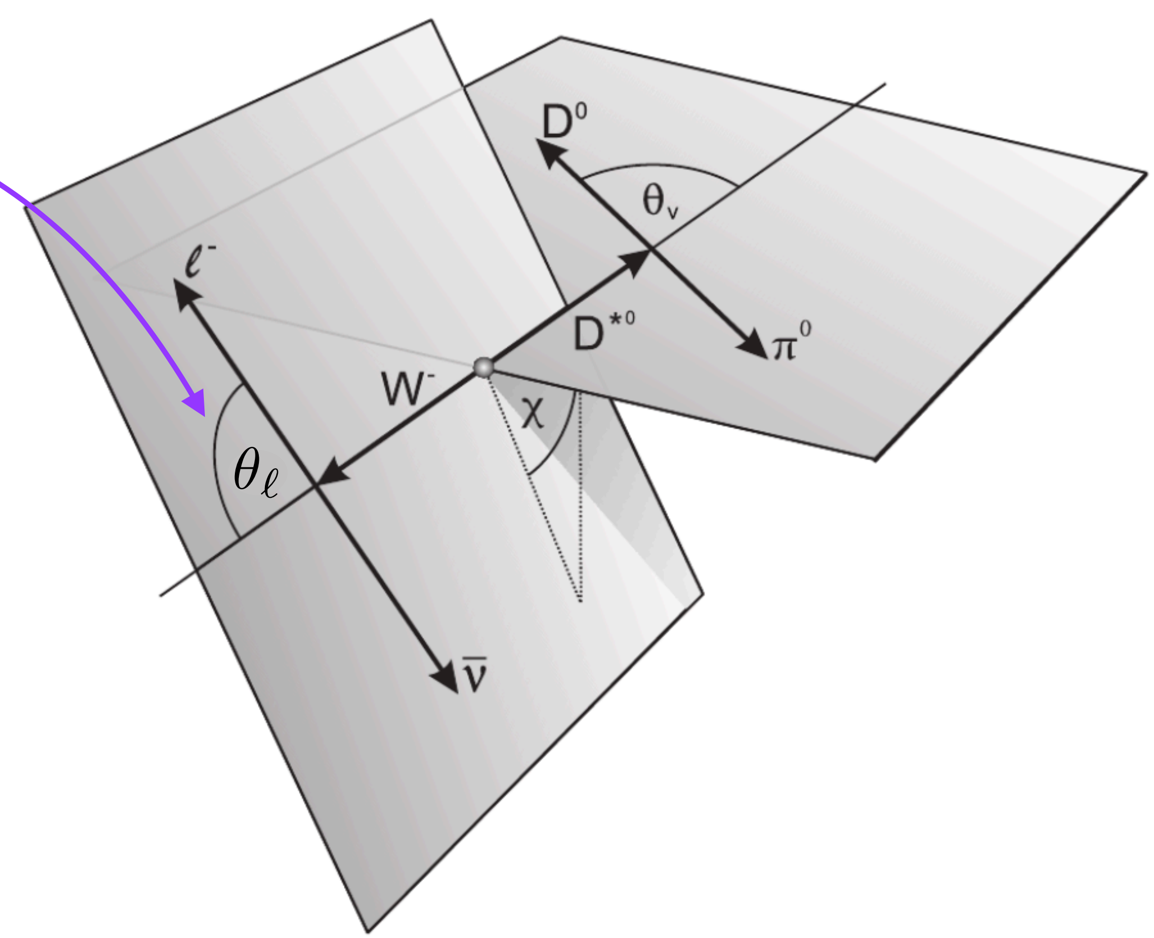

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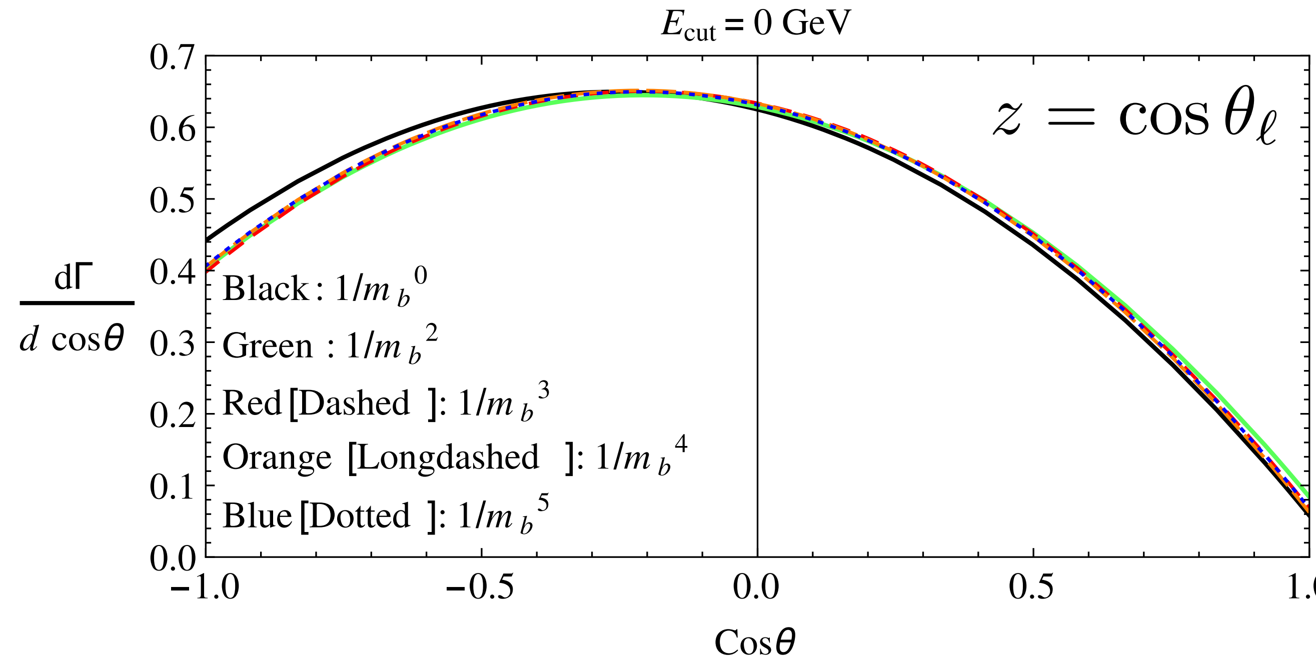

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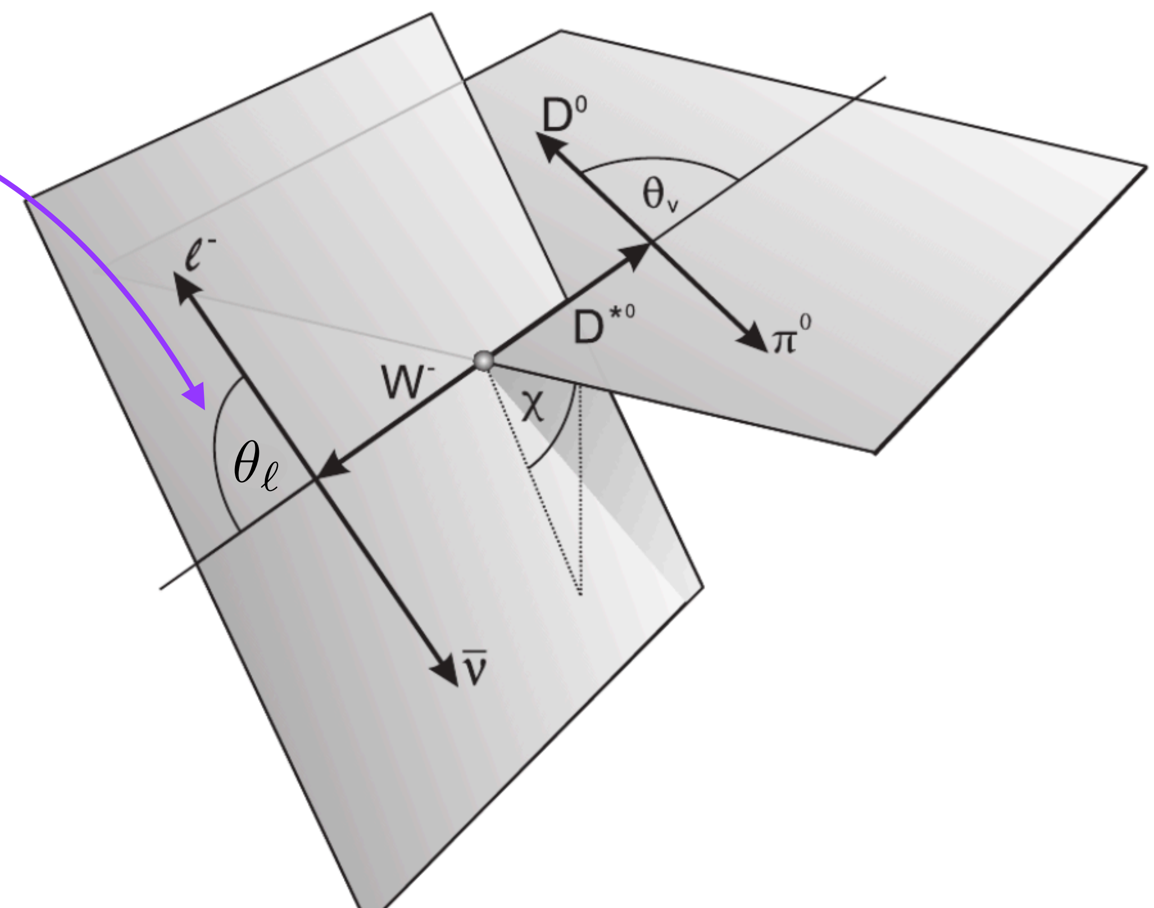

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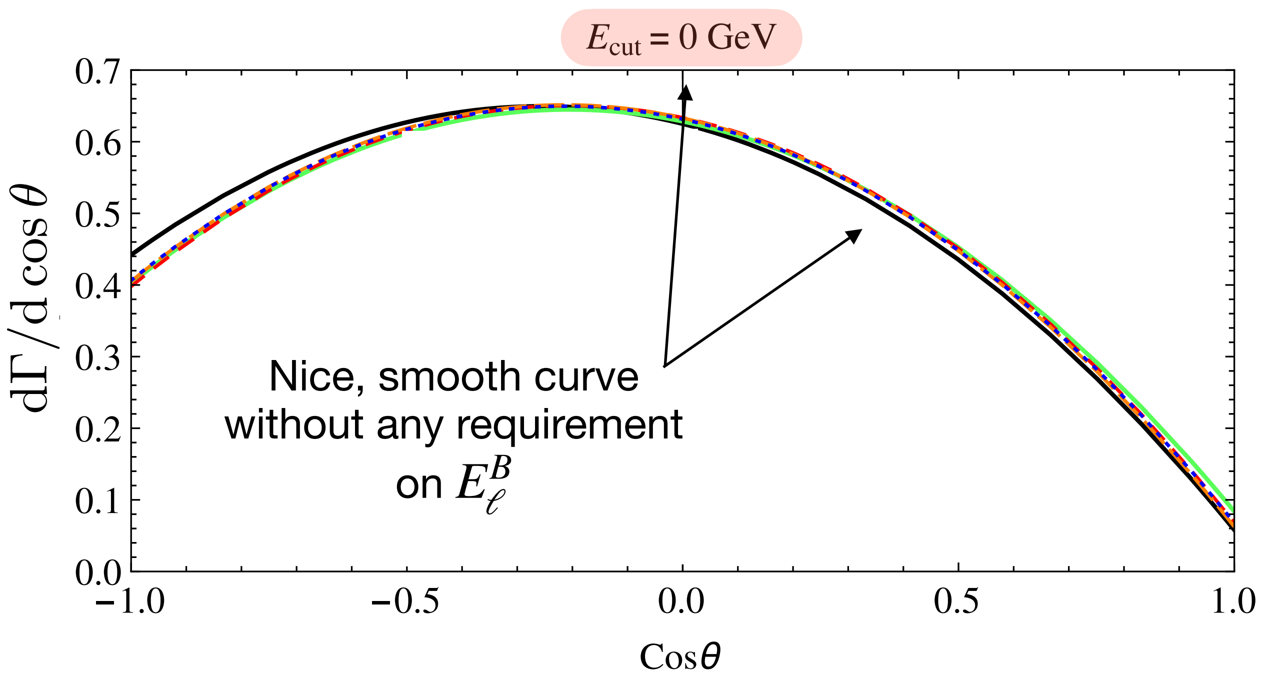
- Separate electron and muon channels for further **LFU tests**
- Additional information leads to **greater sensitivity** in global fits, particularly the HQE parameter $\hat{\mu}_G$

Impact of an E_ℓ requirement



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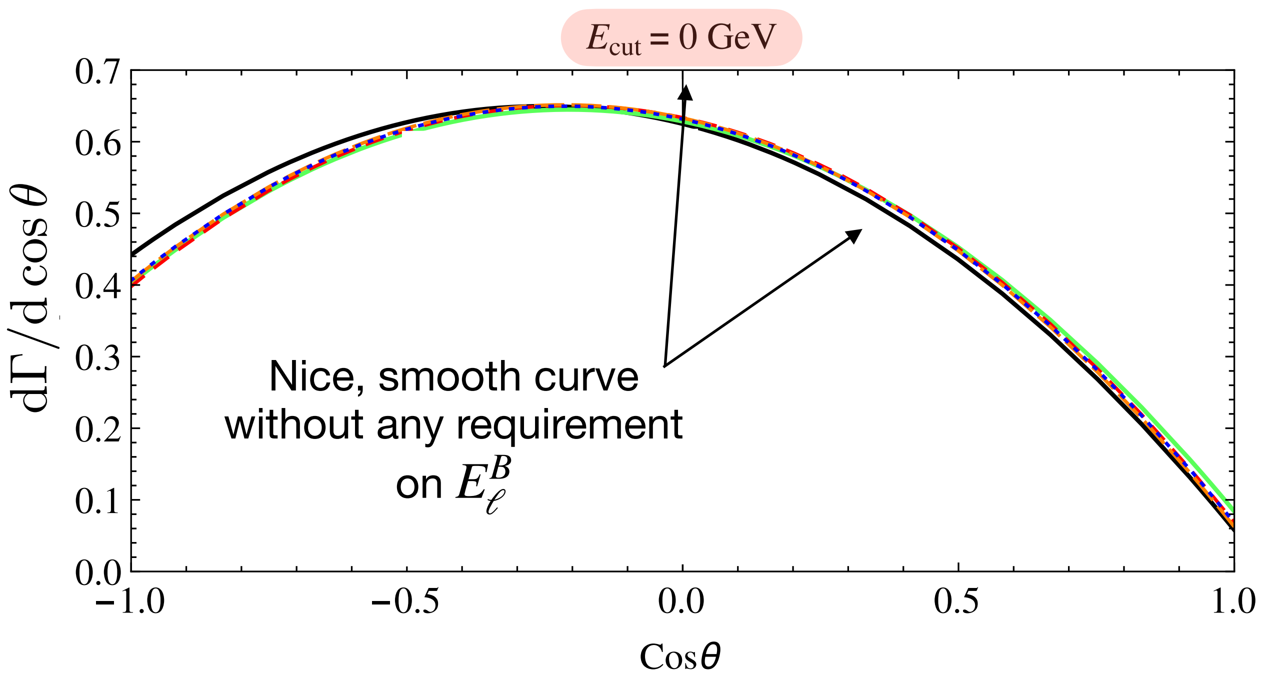
Impact of an E_ℓ requirement



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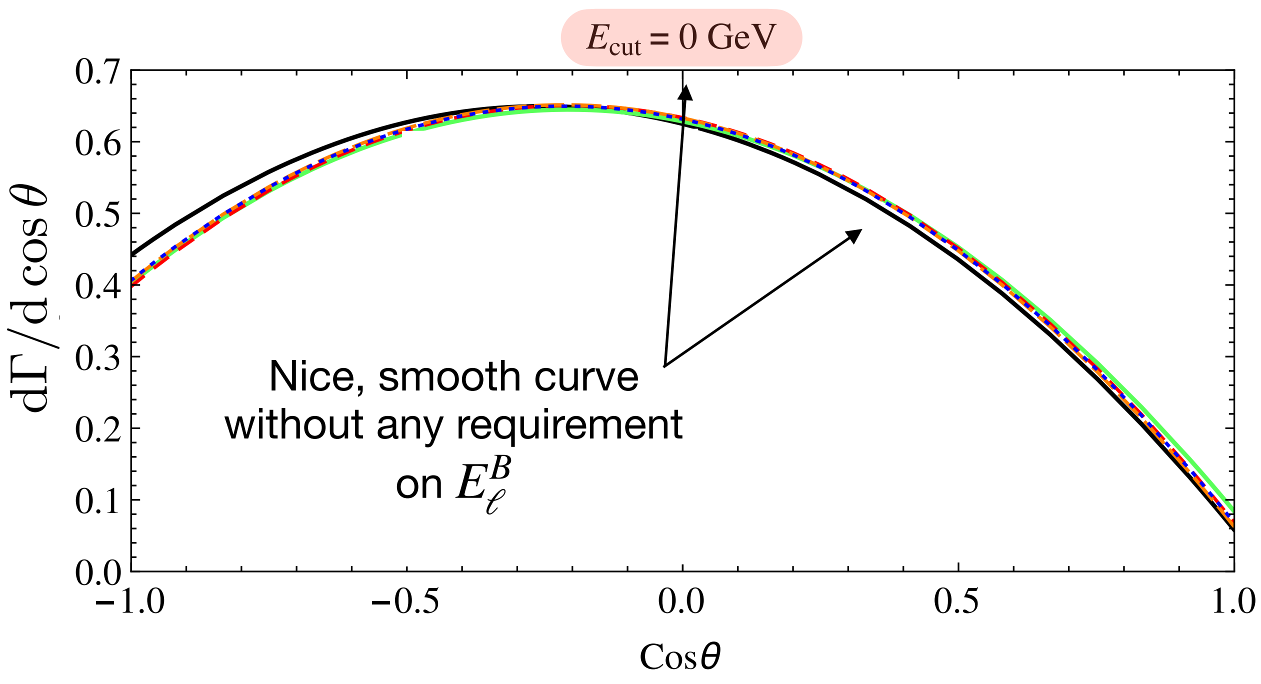

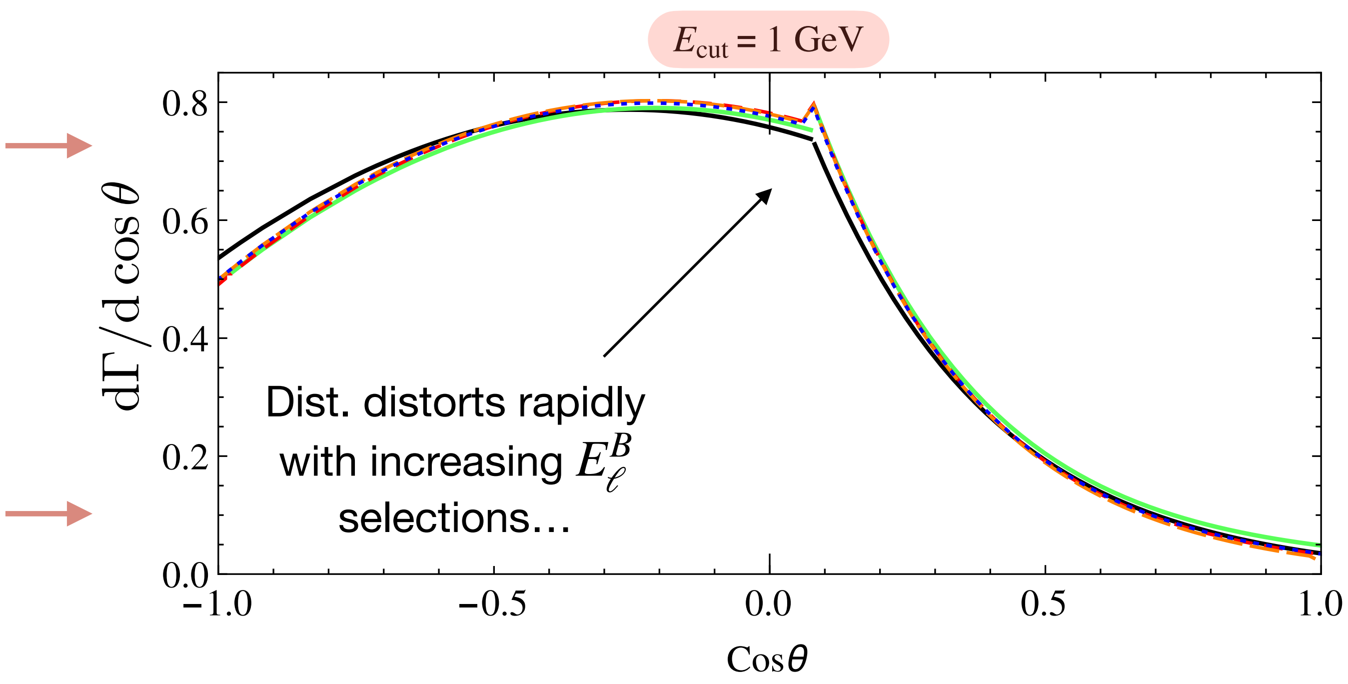

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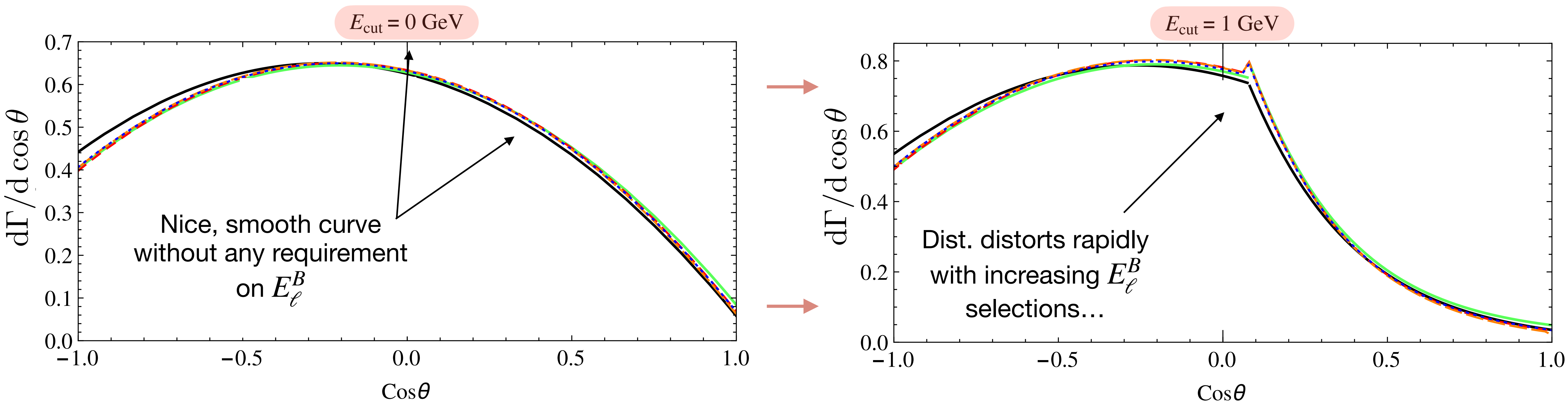

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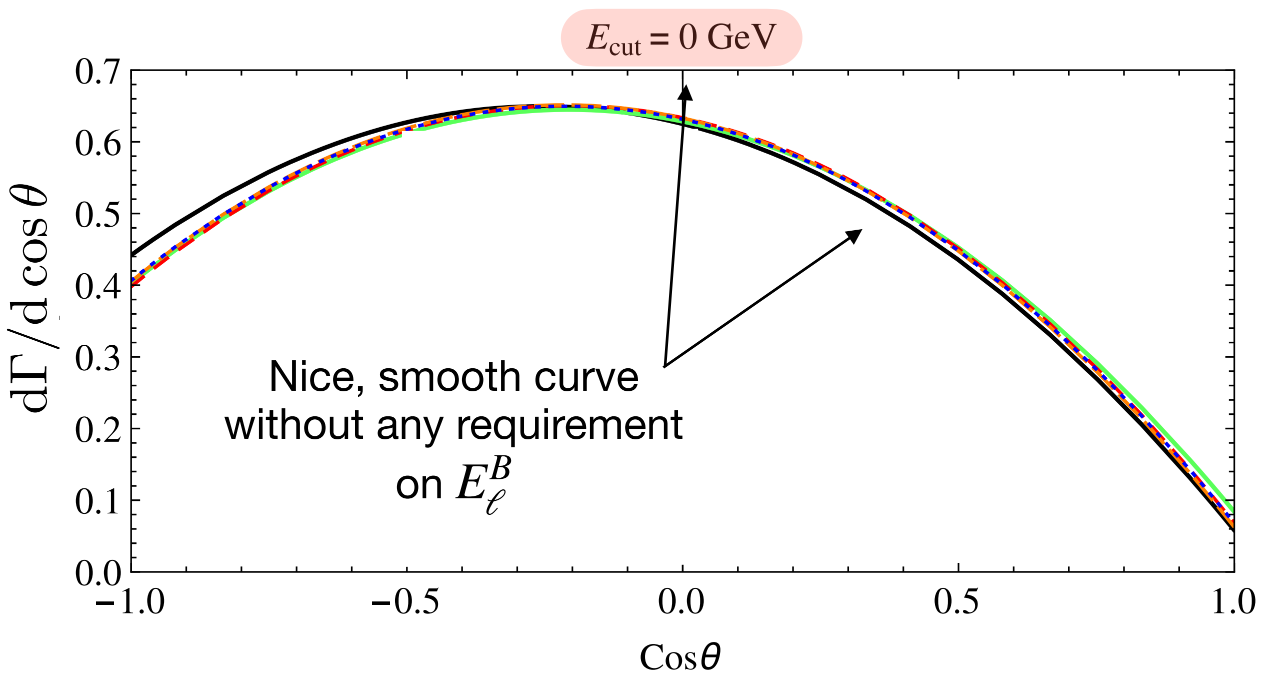
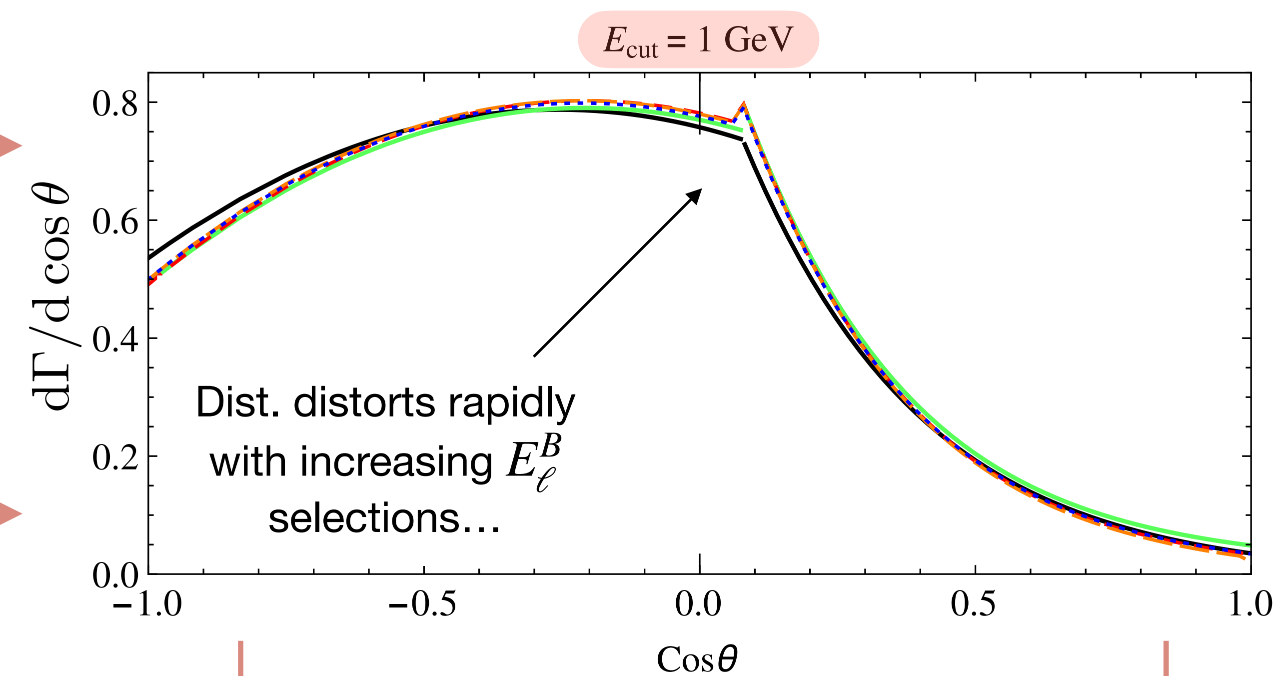
Publication in preparation





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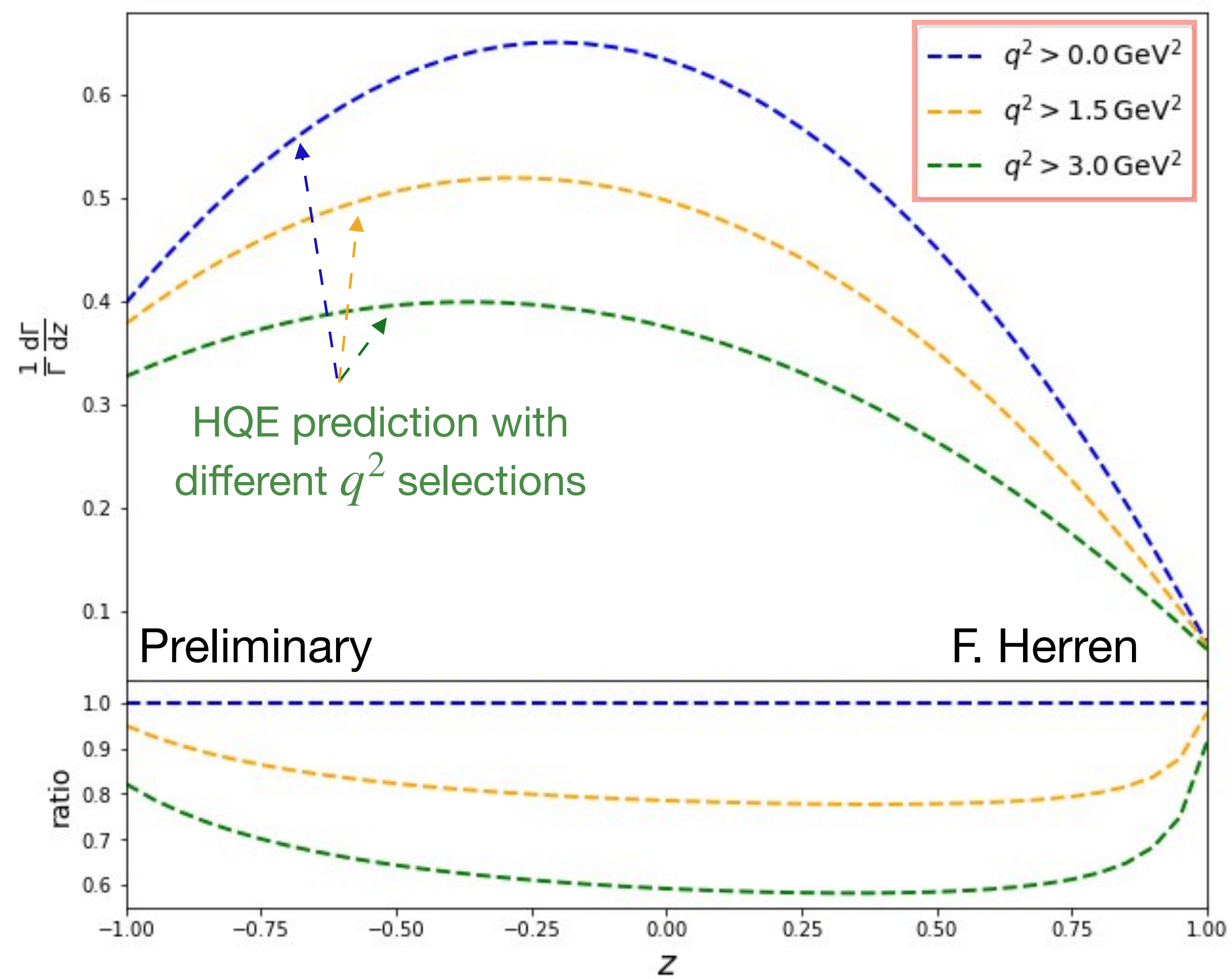

Suggestion:
Use a q^2 selection instead

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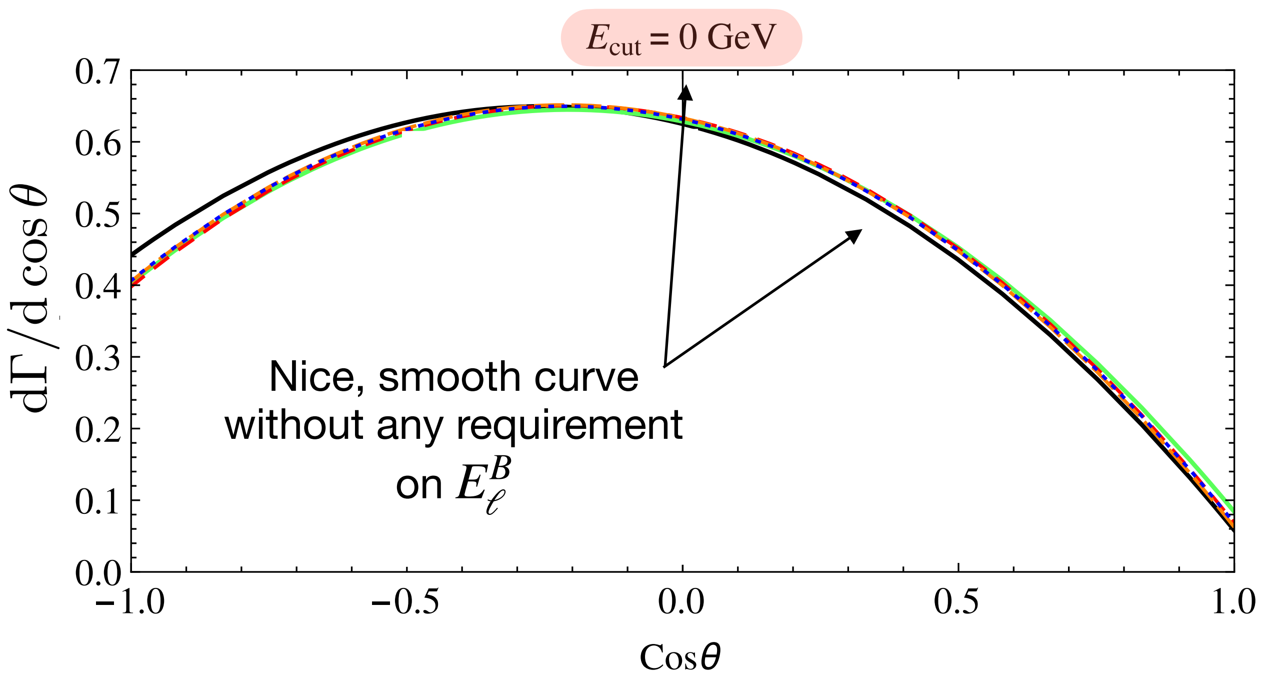

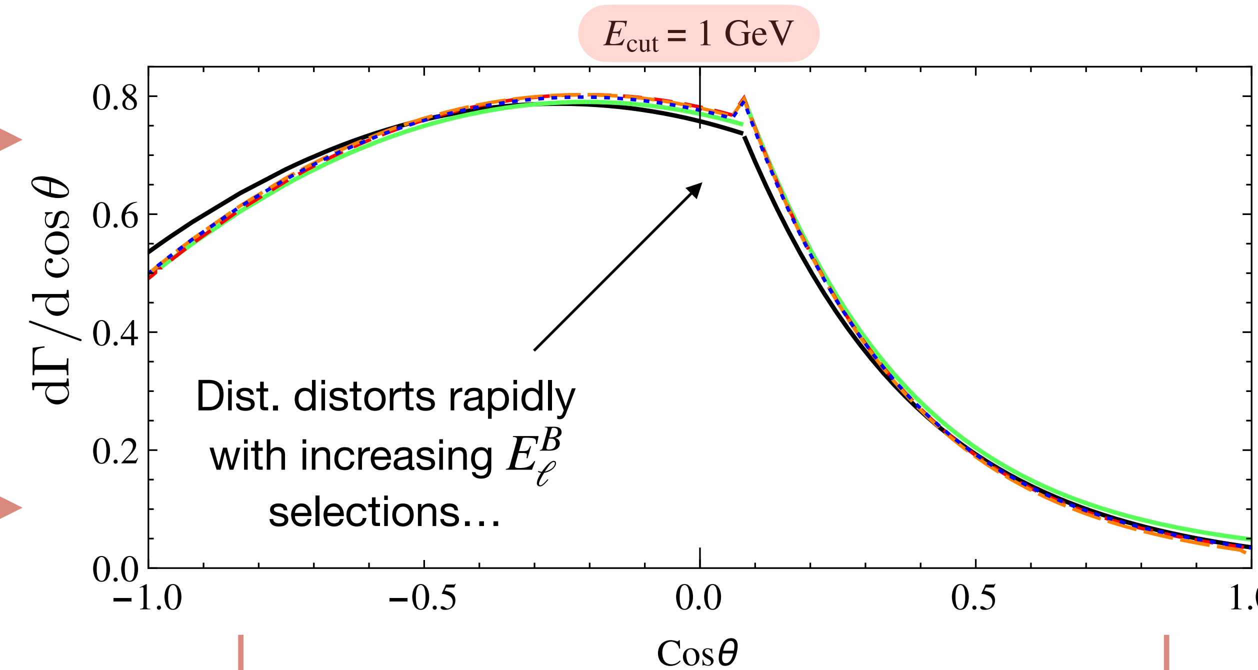

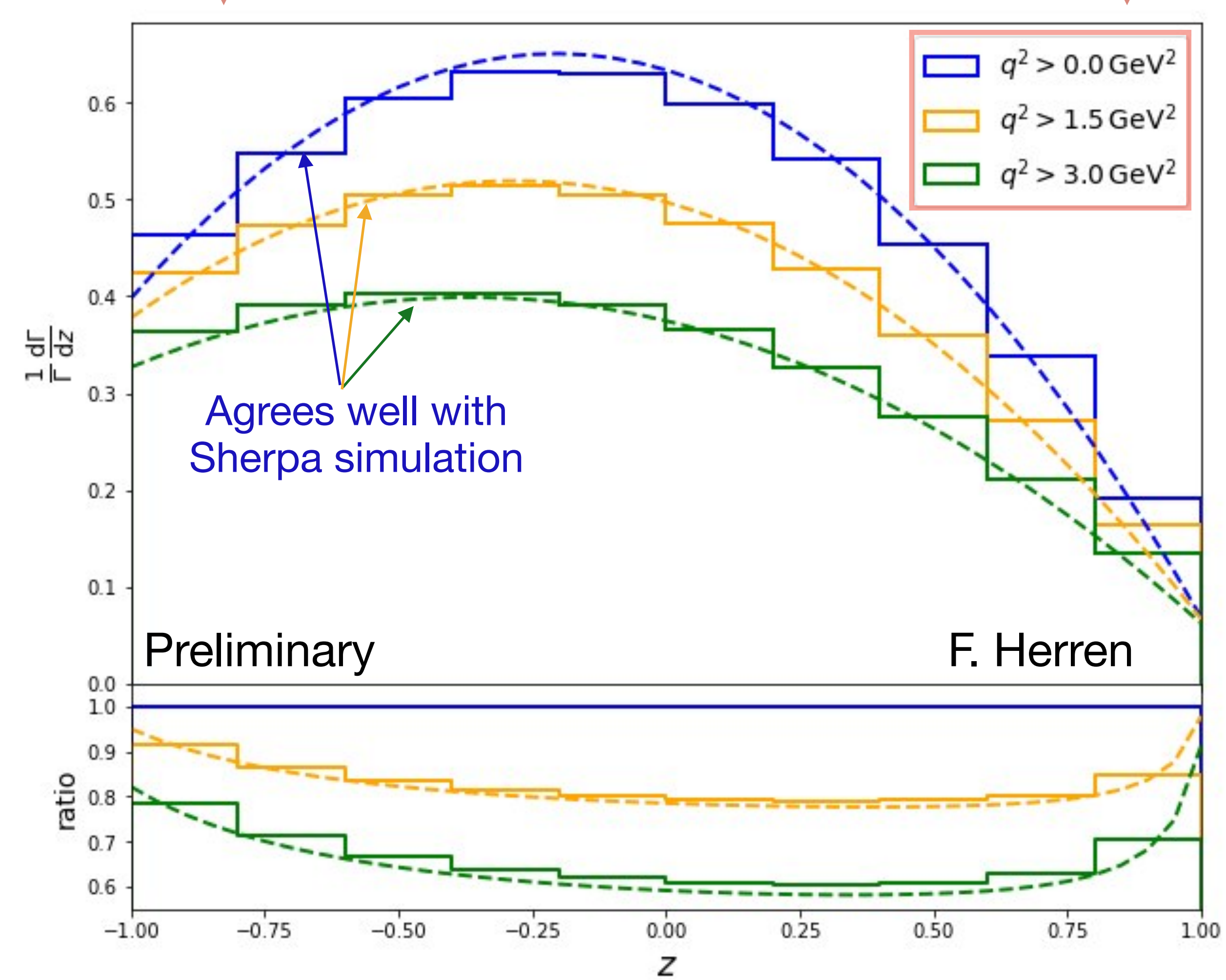

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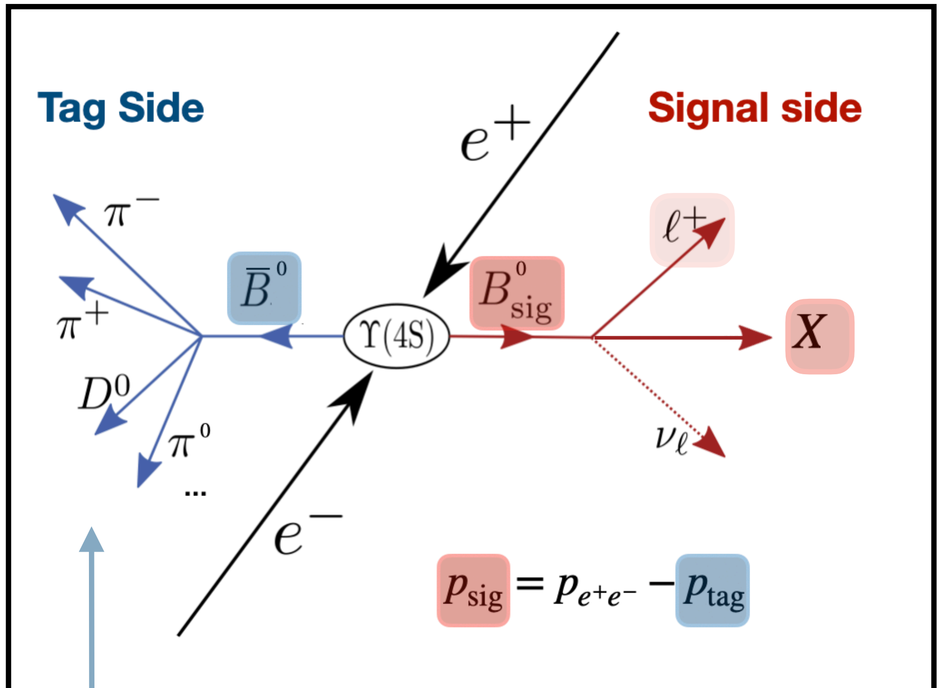
Conclusion & Outlook:

- Measurements generally used in $b \to c$ analyses are old and should be **systematically revisited** with Belle II and LHCb.
- Several **new results** on inclusive $B \to X_c \ell \nu$ decays at the B-factories: $\mathcal{B}$, moments of $\langle q^{2n} \rangle$ and $\langle M_X^n \rangle$…
- Modelling and composition of $B \to X_c \ell \nu$ decays are **leading systematics**. Steadily increasing dataset of Belle II will **improve our understanding** of the non-resonant contribution.
- **New observables** that could better constrain the OPE should be investigated. Analysis aiming to measure A_{FB} **already underway** —with help from theory friends! (…you?)

Reconstruction at B-Factories

Key-technique: hadronic tagging

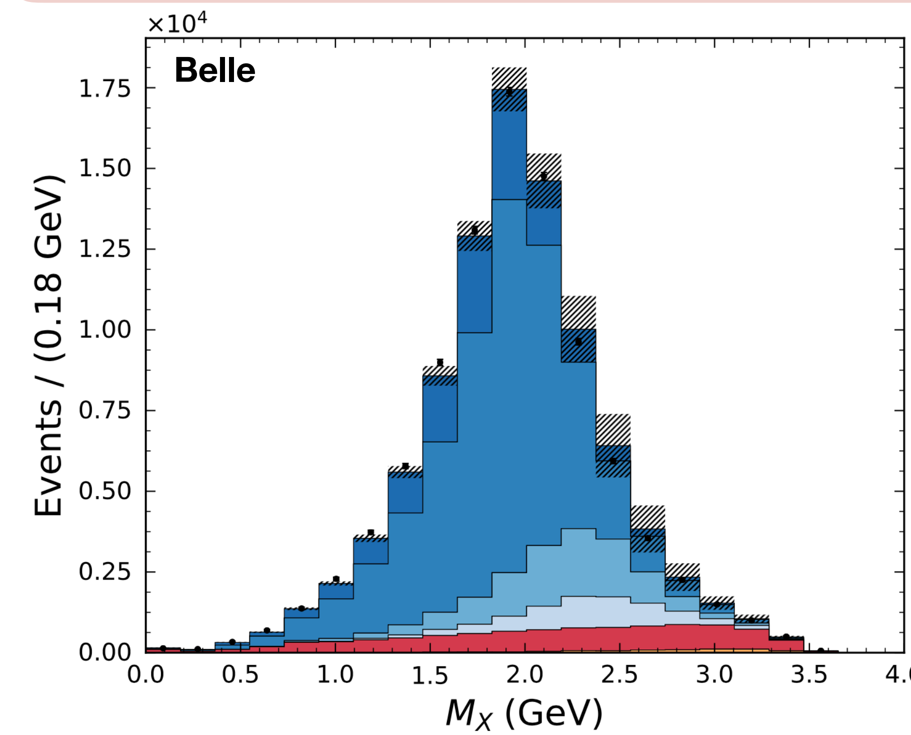


Can identify X constituents

$$M_X = \sqrt{(p_X)^\mu (p_X)_\mu}$$

Charged Tracks Neutral Clusters

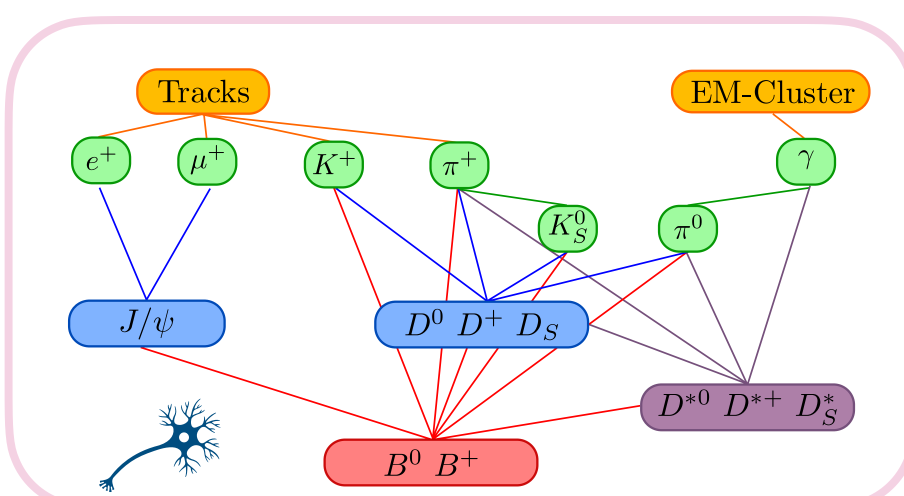
$$p_X = \sum_i \left(\sqrt{m_\pi^2 + |\mathbf{p}_i|^2}, \mathbf{p}_i \right) + \sum_j (E_j, \mathbf{k}_j)$$

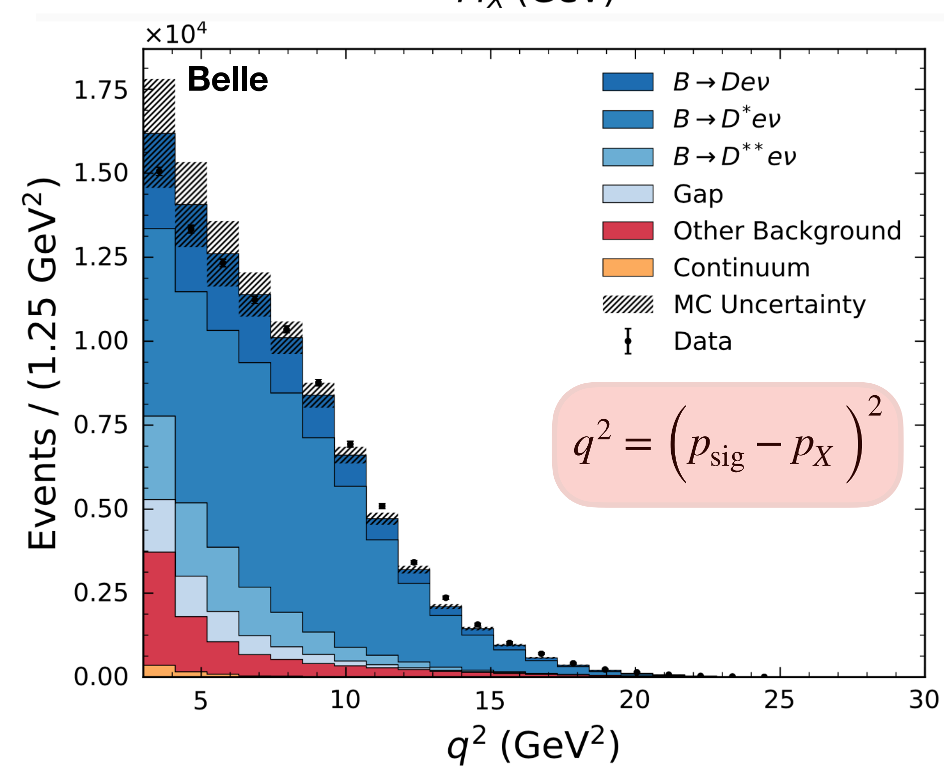


Full Reconstruction = Belle tagging algorithm

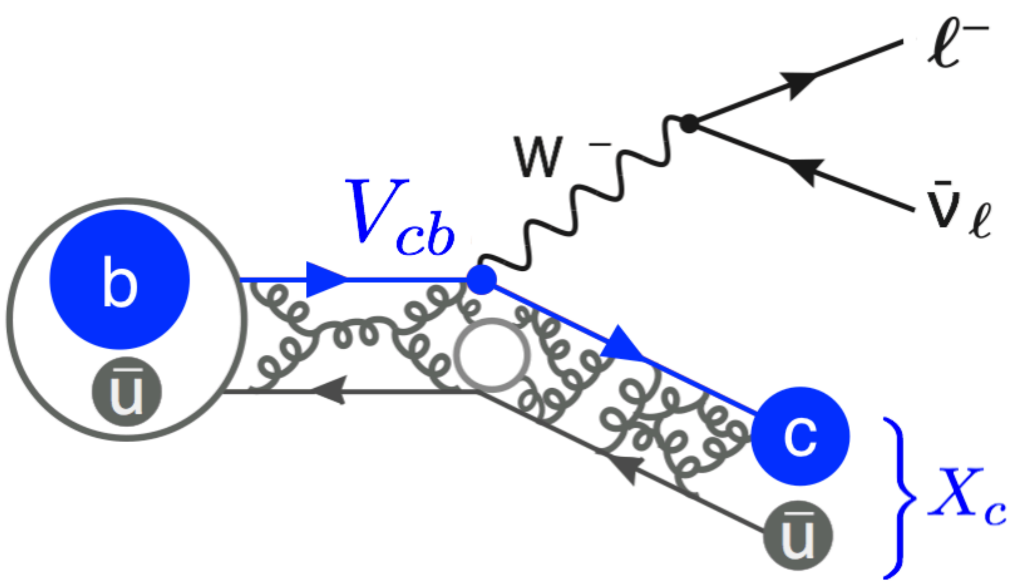
Candidates reconstructed using a **hierarchical** approach & **neural networks** in **hadronic modes**

1104 decay cascades used with an **efficiency** of **0.28% / 0.18%** for $B^\pm$ and $B^0/\bar{B}^0$





Determining incl. $|V_{cb}|$



Established approach: Use hadronic mass moments, lepton energy moments etc.

$$\Gamma(B \to X_c \ell \nu_\ell) \quad \langle M_X^n \rangle \quad \langle E_\ell^n \rangle$$

to determine non-perturbative matrix elements (ME) of HQE and extract $|V_{cb}|$

$$\mathcal{B} = |V_{qb}|^2 \left[\Gamma(b \to q\, \ell\, \bar{\nu}_\ell) + 1/m_{c,b} + \alpha_s + \ldots \right]$$

STOP The number ME increases if one increases expansion in orders of $1/m_{b,c}$

Novel theoretical approach introduced in [JHEP 02, 177 (2019)]

→ Exploits reparametrization invariance to **reduce** the # of ME, but **not true for every observable** (e.g. not for $\langle M_X \rangle$)

Holds for $\langle q^2 \rangle$ and at $1/m_b^4$ the # of ME reduces from **13 → 8(!)**

Complementary and fully data-driven approach!

→

Goal: Measure $\langle q^{2n} \rangle$ (n = 1 - 4) as a progression of cuts on q^2 with Belle & Belle II

Belle $\langle q^{2n} \rangle$ moments syst.

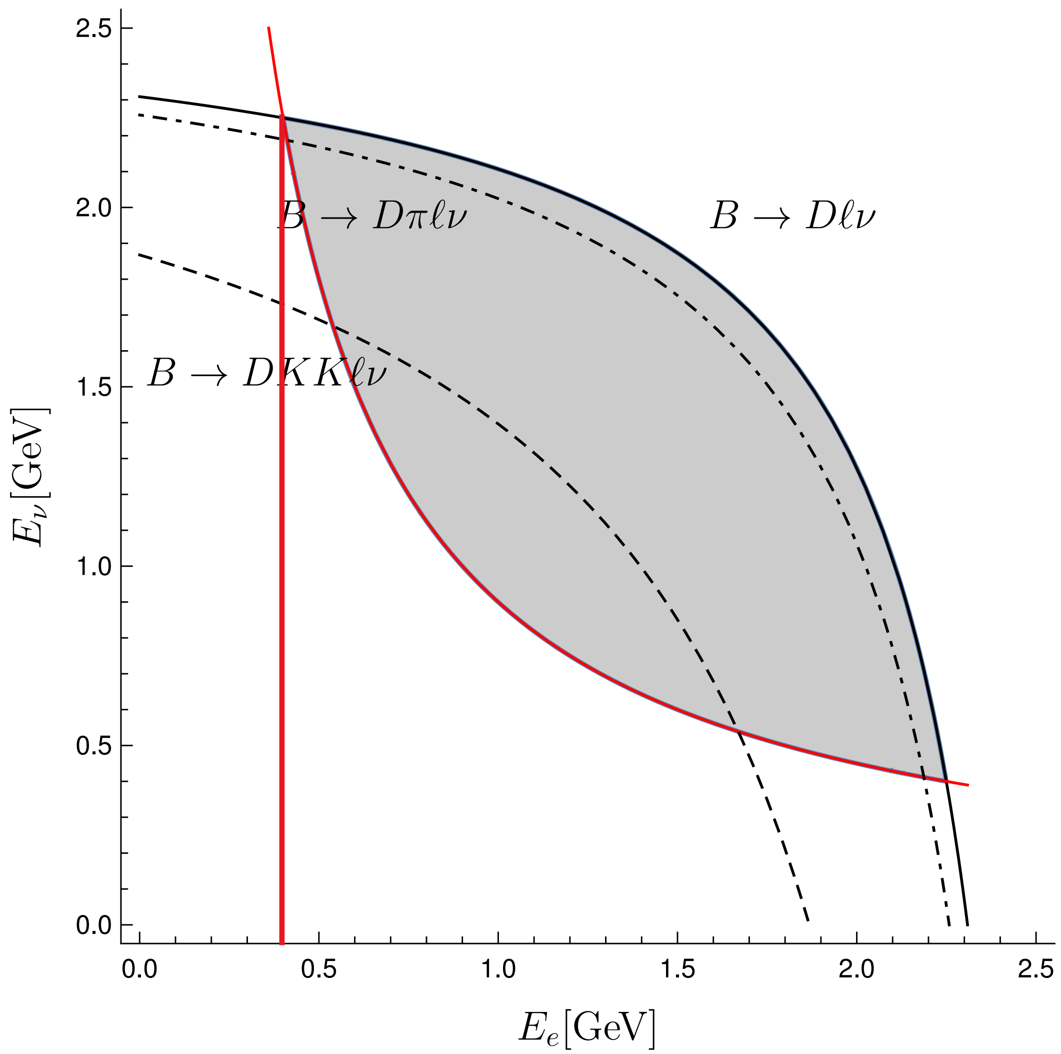
PRD 104, 112011 (2021)

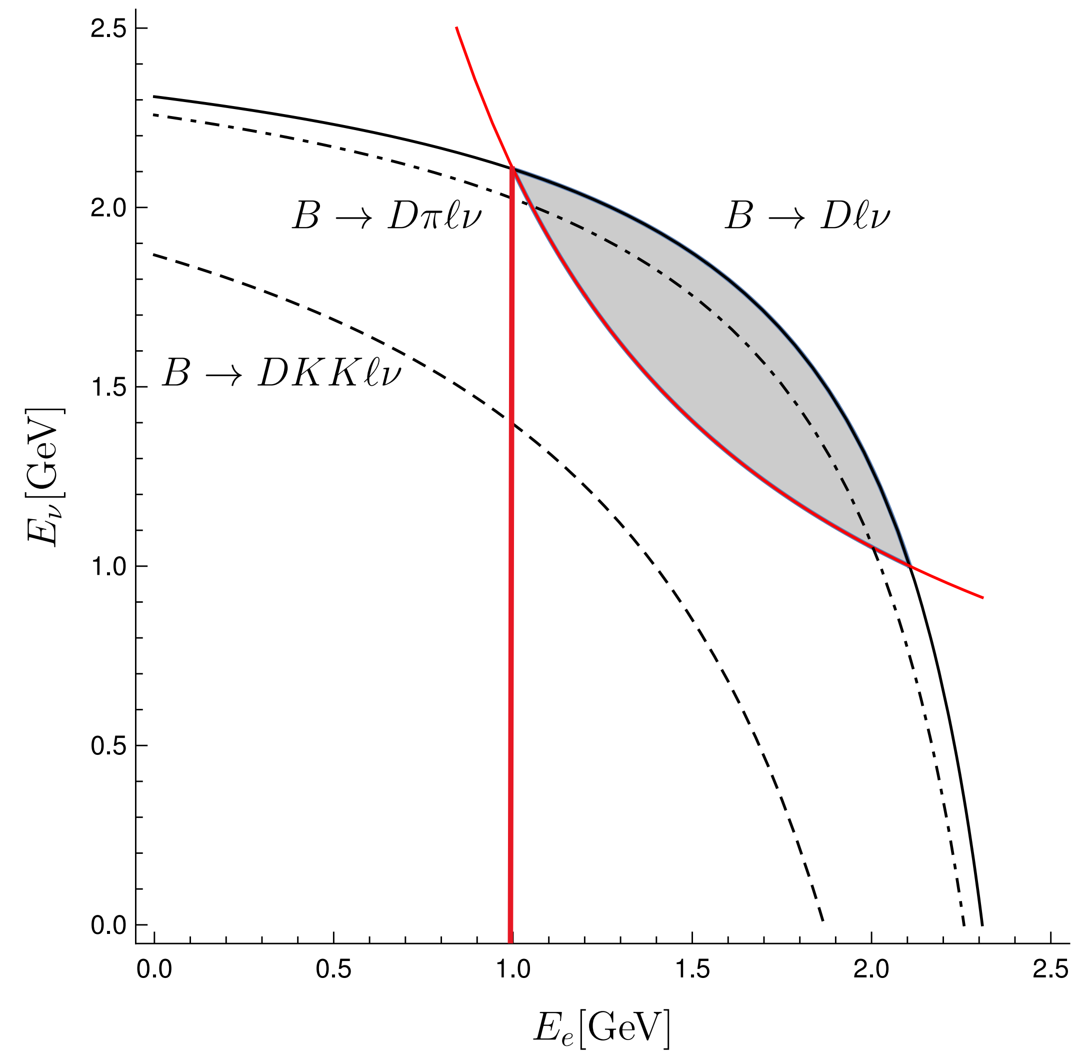
q^2 selection in GeV^2	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
$\langle q^2 \rangle$ in GeV^2	6.25	6.54	6.83	7.13	7.42	7.72	8.02	8.32	8.61	8.91	9.21	9.51	9.80	10.09	10.40
Stat. error (data)	1.51	1.45	1.39	1.34	1.30	1.27	1.24	1.22	1.21	1.20	1.20	1.22	1.23	1.26	1.29
Bkg. subtraction	1.34	1.12	0.90	0.71	0.59	0.53	0.49	0.49	0.57	0.63	0.65	0.70	0.76	0.77	0.82
$B \to X_u \ell \nu$ BF	2.18	2.04	1.75	1.48	1.35	1.04	0.76	0.54	0.38	0.29	0.19	0.16	0.12	0.05	0.05
$B \to X_c \ell \nu$ BF	4.82	5.02	5.14	5.14	5.05	5.00	4.67	4.05	3.51	3.11	2.66	2.21	1.75	1.36	1.16
Non-resonant model	14.25	12.72	11.04	9.28	7.83	6.62	5.42	4.00	3.02	2.28	1.65	1.43	1.04	0.86	0.78
$B \to X_c \ell \nu$ FF	1.43	1.30	1.16	1.03	0.91	0.85	0.82	0.74	0.69	0.62	0.54	0.48	0.42	0.39	0.35
N_{tracks} res.	5.66	5.31	4.96	4.65	4.36	4.06	3.78	3.52	3.29	3.06	2.85	2.66	2.51	2.38	2.20
N_γ res.	0.39	0.38	0.34	0.31	0.30	0.28	0.30	0.31	0.32	0.28	0.27	0.26	0.25	0.27	0.29
$E_{\text{miss}} - \lvert \mathbf{p}_{\text{miss}} \rvert$ shape	1.29	1.26	1.21	1.17	1.15	1.11	1.04	1.05	1.06	1.09	1.16	1.20	1.30	1.33	1.29
q^2 scale	9.48	7.15	6.65	6.65	6.12	5.91	5.83	5.48	5.26	4.69	4.27	4.42	3.91	3.94	4.38
MC non-closure	0.19	0.11	0.12	0.11	0.11	0.05	0.05	0.06	0.08	0.07	0.11	0.04	0.04	0.06	0.02
Cal. function	0.13	0.08	0.03	0.02	0.07	0.12	0.17	0.22	0.26	0.31	0.35	0.39	0.43	0.47	0.51
Stat. bias corr.	1.32	1.27	1.23	1.19	1.16	1.13	1.10	1.08	1.07	1.06	1.06	1.06	1.07	1.09	1.11
PID eff.	0.16	0.14	0.14	0.13	0.13	0.12	0.11	0.10	0.10	0.10	0.09	0.08	0.08	0.07	0.06
Track eff.	0.44	0.42	0.39	0.36	0.34	0.31	0.29	0.27	0.25	0.23	0.21	0.20	0.18	0.17	0.15
$B^0/B^\pm$ tag eff.	0.46	0.58	0.50	0.44	0.51	0.40	0.28	0.34	0.36	0.38	0.29	0.23	0.20	0.12	0.47
Sys. error (total)	18.99	16.65	15.03	13.62	12.22	11.19	10.17	8.86	7.97	7.06	6.30	6.09	5.44	5.27	5.50
Total rel. error in ‰	19.05	16.71	15.09	13.68	12.29	11.26	10.25	8.94	8.06	7.16	6.41	6.21	5.58	5.42	5.65

$\langle q^8 \rangle$ in GeV^8	2717.22	2963.88	3248.31	3578.45	3947.44	4384.73	4878.23	5458.95	6072.92	6780.95	7616.67	8497.60	9466.03	10603.31	11917.23
Stat. error (data)	10.35	10.07	9.78	9.47	9.19	8.89	8.63	8.36	8.19	8.05	7.94	7.91	7.94	7.95	7.99
Bkg. subtraction	5.57	5.25	4.98	4.80	4.99	5.23	5.02	5.06	5.51	5.71	5.58	6.00	5.96	5.81	6.02
$B \to X_u \ell \nu$ BF	11.94	11.10	9.61	7.82	7.00	5.31	3.66	2.53	1.76	1.30	0.79	0.69	0.59	0.20	0.16
$B \to X_c \ell \nu$ BF	21.51	22.91	23.24	23.14	22.84	22.14	20.76	18.50	16.31	14.53	12.43	10.40	8.44	6.74	5.74
Non-resonant model	49.93	45.52	40.56	35.22	30.45	26.13	21.80	16.75	13.12	10.26	7.73	6.66	5.10	4.25	3.79
$B \to X_c \ell \nu$ FF	4.91	4.76	4.60	4.40	4.23	4.12	4.03	3.75	3.52	3.23	2.88	2.59	2.31	2.09	1.89
N_{tracks} res.	29.72	28.51	27.15	25.82	24.47	22.99	21.54	20.09	18.76	17.40	16.09	14.89	13.83	12.86	11.73
N_γ res.	2.95	2.89	2.75	2.62	2.58	2.46	2.46	2.44	2.39	2.22	2.16	2.07	2.00	2.01	2.06
$E_{\text{miss}} - \lvert \mathbf{p}_{\text{miss}} \rvert$ shape	10.18	9.83	9.42	9.05	8.69	8.33	7.89	7.70	7.50	7.35	7.33	7.21	7.26	7.11	6.66
q^2 scale	46.61	41.26	39.53	39.00	36.70	35.23	33.82	32.22	30.11	27.83	25.47	25.28	23.04	24.16	25.90
MC non-closure	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cal. function	0.63	0.34	0.04	0.26	0.55	0.86	1.14	1.42	1.68	1.92	2.17	2.37	2.56	2.74	2.90
Stat. bias corr.	8.21	8.00	7.79	7.59	7.38	7.18	6.99	6.83	6.67	6.54	6.43	6.35	6.29	6.27	6.27
PID eff.	0.81	0.77	0.74	0.70	0.69	0.64	0.60	0.56	0.52	0.51	0.47	0.42	0.40	0.35	0.30
Track eff.	2.25	2.16	2.05	1.95	1.84	1.72	1.60	1.49	1.38	1.27	1.16	1.06	0.98	0.89	0.81
$B^0/B^\pm$ tag eff.	0.97	1.19	0.98	0.80	0.94	0.58	0.18	0.29	0.30	0.26	0.14	0.42	0.59	1.79	3.06
Sys. error (total)	79.98	73.90	69.18	64.95	60.23	56.09	51.86	47.19	43.06	39.32	35.61	34.06	31.06	30.93	31.65
Total rel. error in ‰	80.64	74.58	69.87	65.64	60.93	56.79	52.58	47.93	43.83	40.13	36.48	34.97	32.06	31.93	32.64

E_ℓ vs. q^2 selection criteria

[JHEP 02, 177 (2019)]





A requirement of $q^2 > 3.6\ \mathrm{GeV}^2$ is equivalent to imposing a selection of $E_\ell > 0.4\ \mathrm{GeV}$

A requirement of $q^2 > 8.43\ \mathrm{GeV}^2$ is equivalent to imposing a selection of $E_\ell > 1.0\ \mathrm{GeV}$