New Results on Semileptonic Decays from Belle

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Recent Results from Belle

Inclusive

1. Measurement of **partial** branching fractions of inclusive $B \to X_u \ell \bar{\nu}_\ell$ decays with hadronic tagging [PRD 104, 012008 (2021), arXiv:2102.00020]

2. Measurement of **differential** branching fractions of inclusive $B \to X_u \ell \bar{\nu}_\ell$ decays with hadronic tagging [Phys. Rev. Lett. 127, 261801 (2021), arXiv:2107.13855]

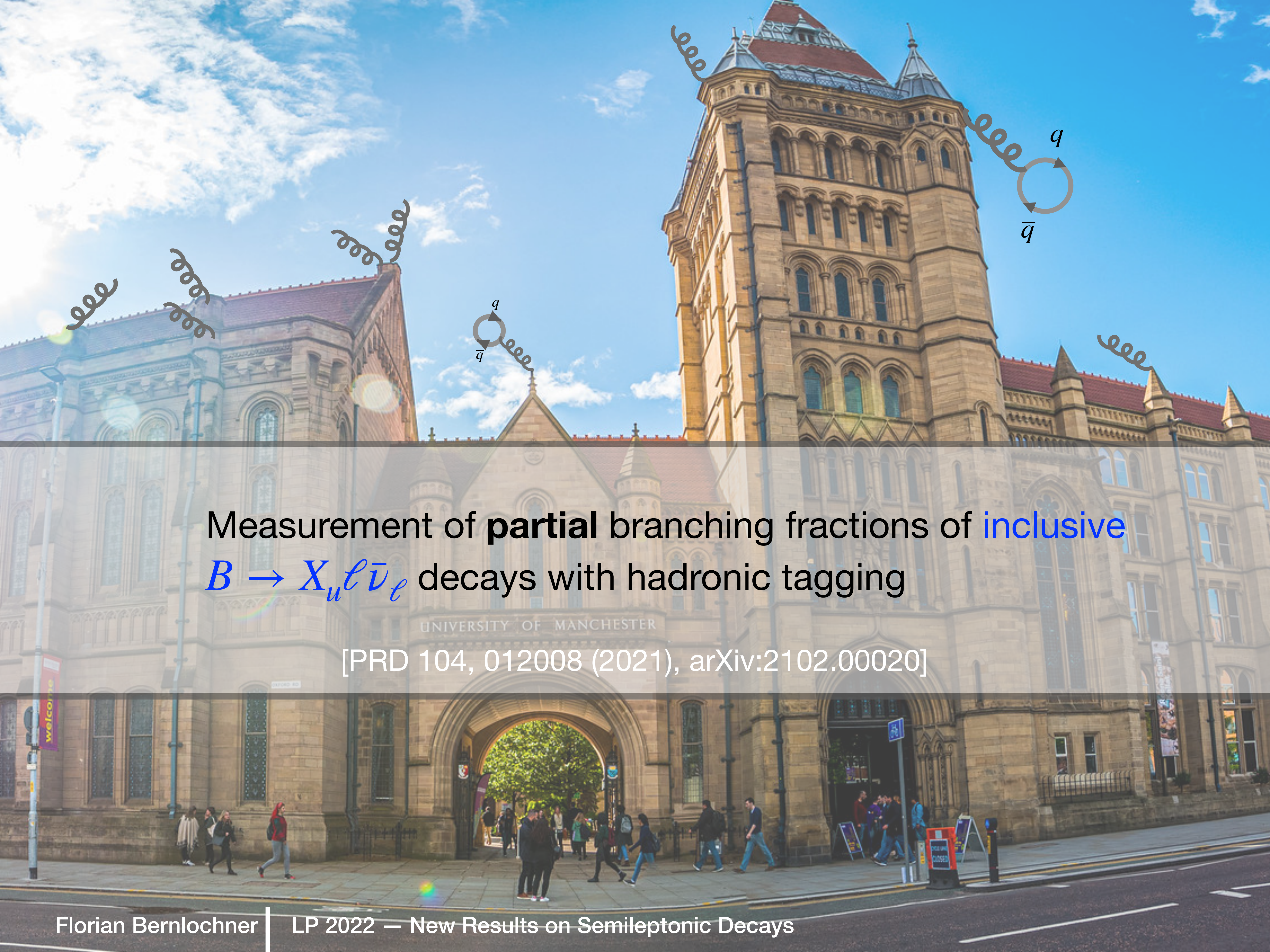
3. Measurements of q^2 **moments** of inclusive $B \to X_c \ell \bar{\nu}_\ell$ decays with hadronic tagging [PRD 104, 112011 (2021), arXiv:2109.01685

Exclusive

4. Measurement of the **branching fraction** of the decay $B^+ \to \pi^+ \pi^- \ell^+ \nu$ in fully reconstructed events at Belle [PRD 103, 112001 (2021), arXiv:2005.07766]

5. Measurement of the **branching fraction** of the $B^+ \to \eta \ell^+ \nu$ and $B^+ \to \eta' \ell^+ \nu$ decays with signal-side only reconstruction in the full q^2 range [Submitted to PRD, arXiv:2104.13354]

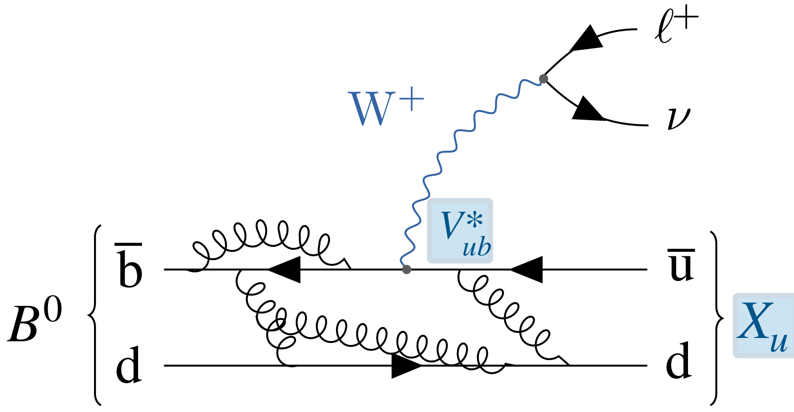
6. First test of **lepton flavor universality** in the charmed baryon decays $\Omega_c^0 \to \Omega^- \ell^+ \nu_\ell$ using data of the Belle experiment [Submitted to PRL, arXiv:2112.10367]

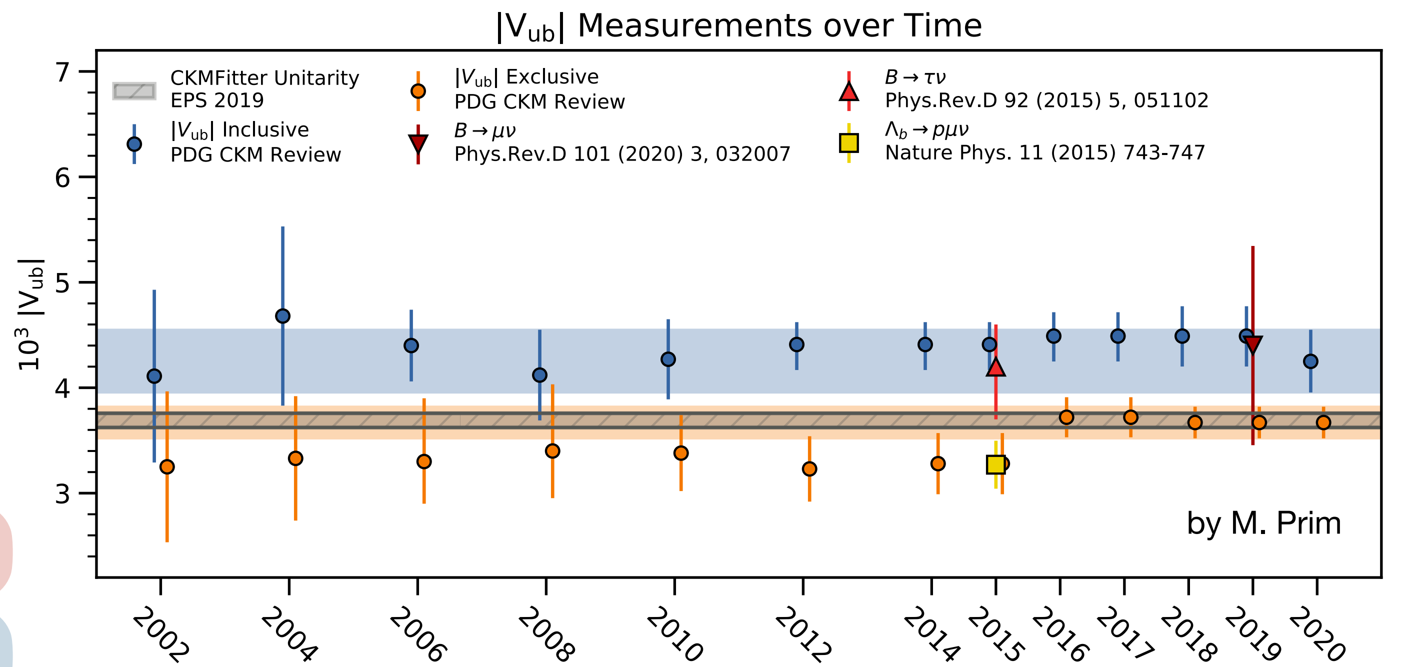


Measurement of **partial** branching fractions of inclusive $B \to X_u \ell \bar{\nu}_\ell$ decays with hadronic tagging

[PRD 104, 012008 (2021), arXiv:2102.00020]

Introduction





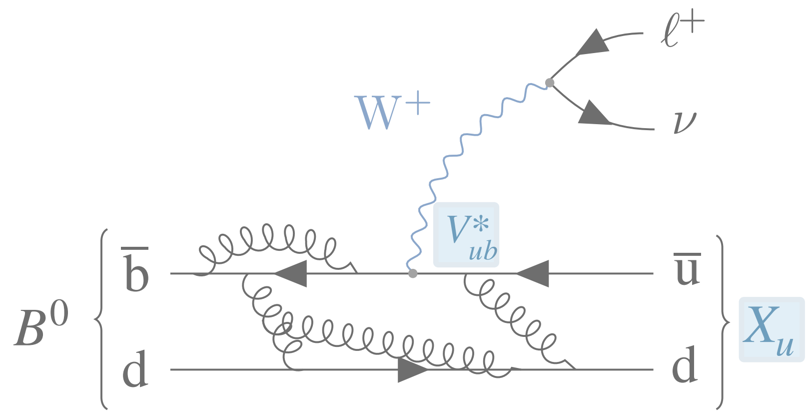
$\approx 3.3\,\sigma$

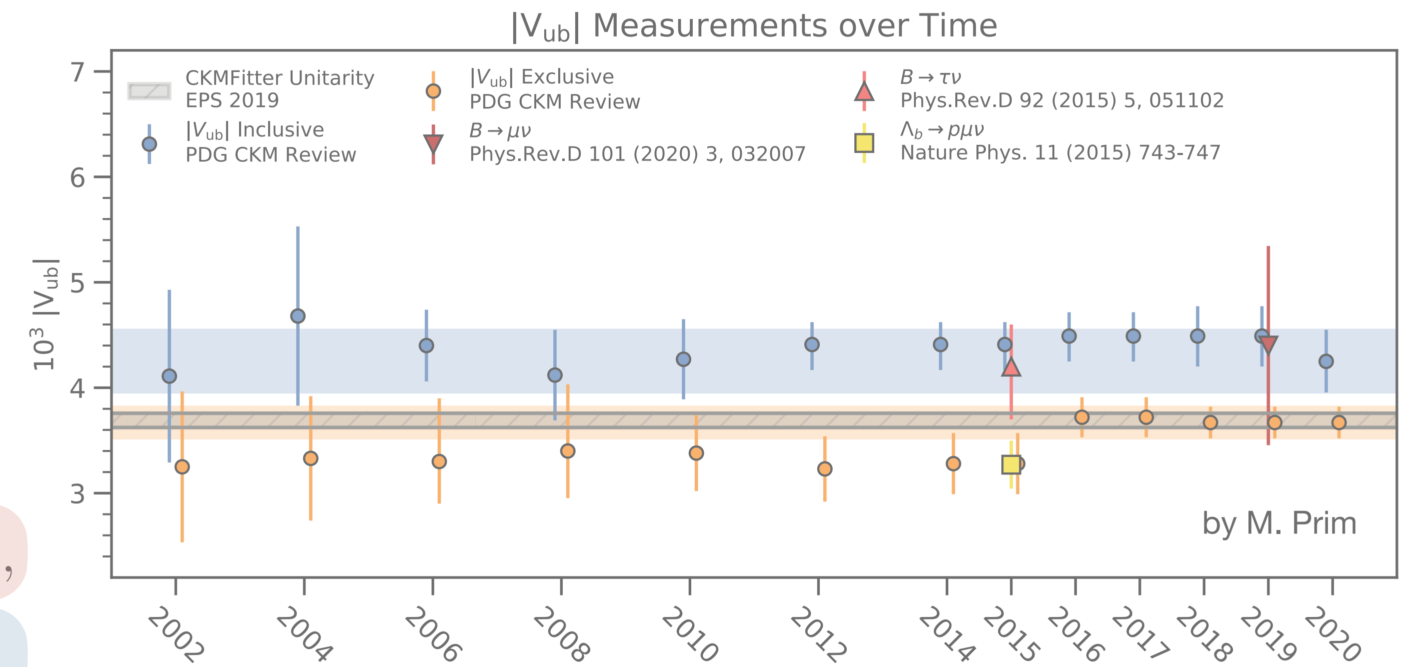
$$|V_{ub}^{\text{excl.}}| = (3.67 \pm 0.09 \pm 0.12) \times 10^{-3}\,,$$

$$|V_{ub}^{\text{incl.}}| = \left(4.32 \pm 0.12^{+0.12}_{-0.13}\right) \times 10^{-3}\,.$$

(HFLAV)

Introduction





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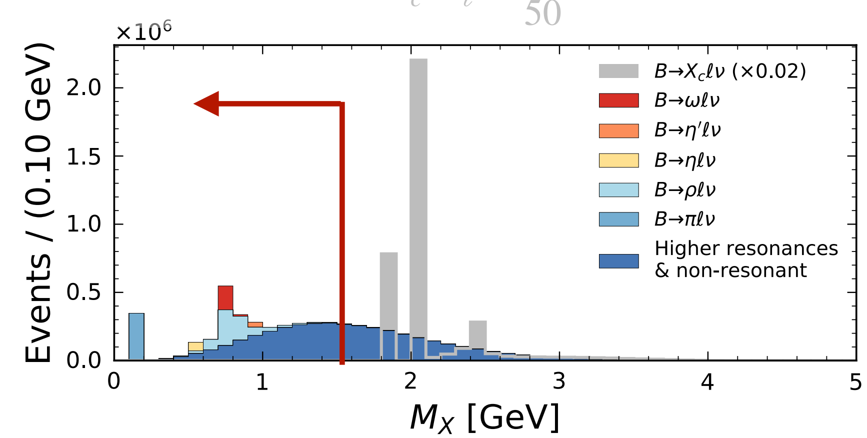
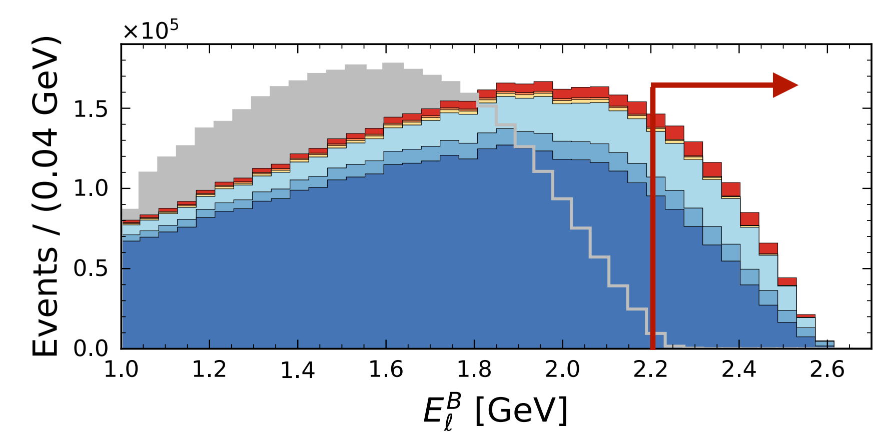
(HFLAV)

Inclusive $B \to X_u \ell \bar{\nu}_\ell$ measurements are extremely challenging due to dominant $B \to X_c \ell \bar{\nu}_\ell$ background

$B \to X_c \ell \bar{\nu}_\ell \times \frac{1}{50}$



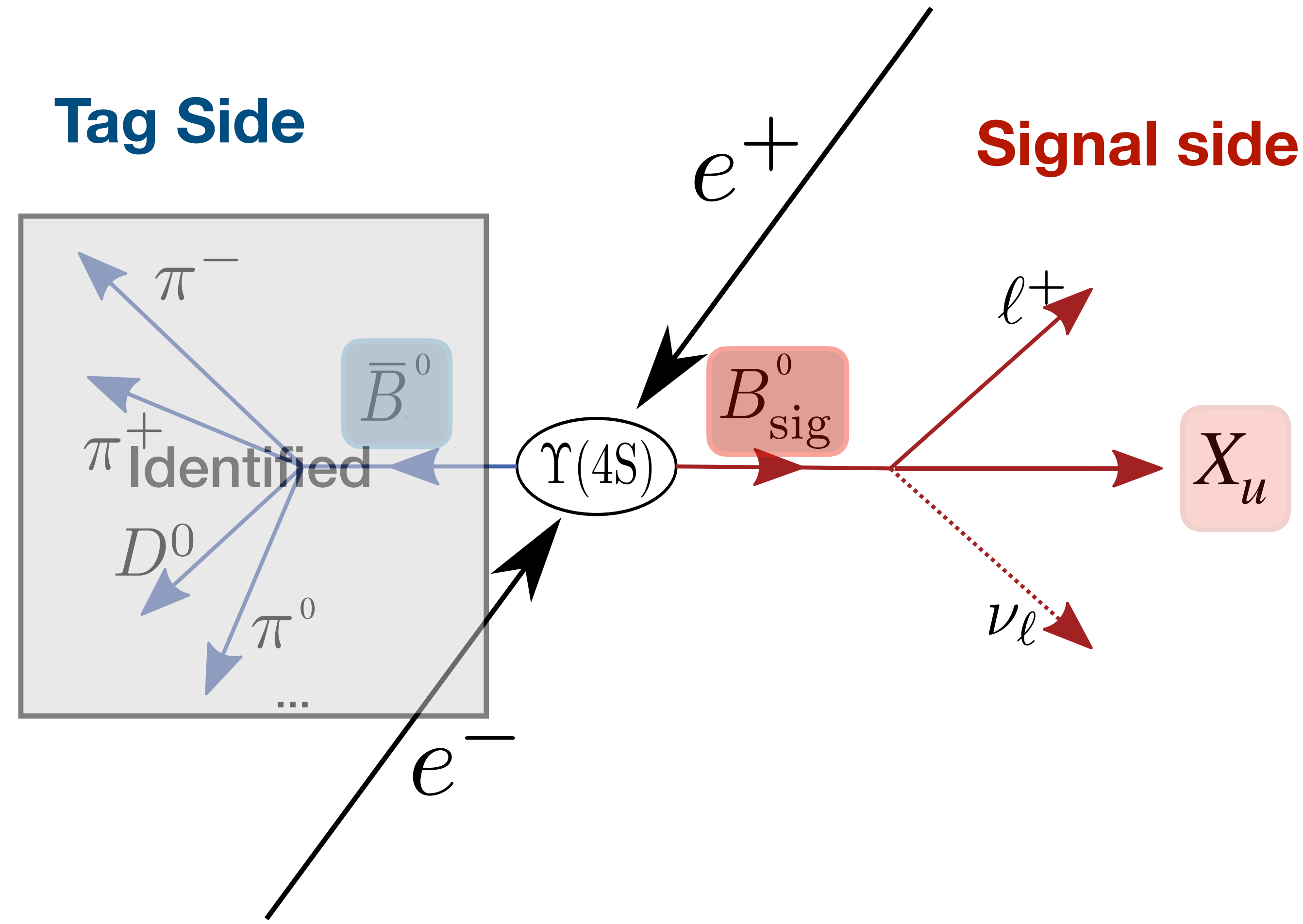
Clear **separation** only **possible** in certain **kinematic regions**, e.g. **lepton endpoint** or **low M_X**



Analysis Strategy

Use **full Belle** data set of **711/fb**

Hadronic tagging with neural networks (ca. 0.2-0.3% efficiency)



$$p_X = \sum_i \Big(\overset{\text{Charged Tracks}}{\sqrt{m_\pi^2 + |\mathbf{p}_i|^2}}, \mathbf{p}_i \Big) + \sum_j \overset{\text{Neutral Clusters}}{(E_j, \mathbf{k}_j)}$$

$$q^2 = (p_{\mathrm{sig}} - p_X)^2$$

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

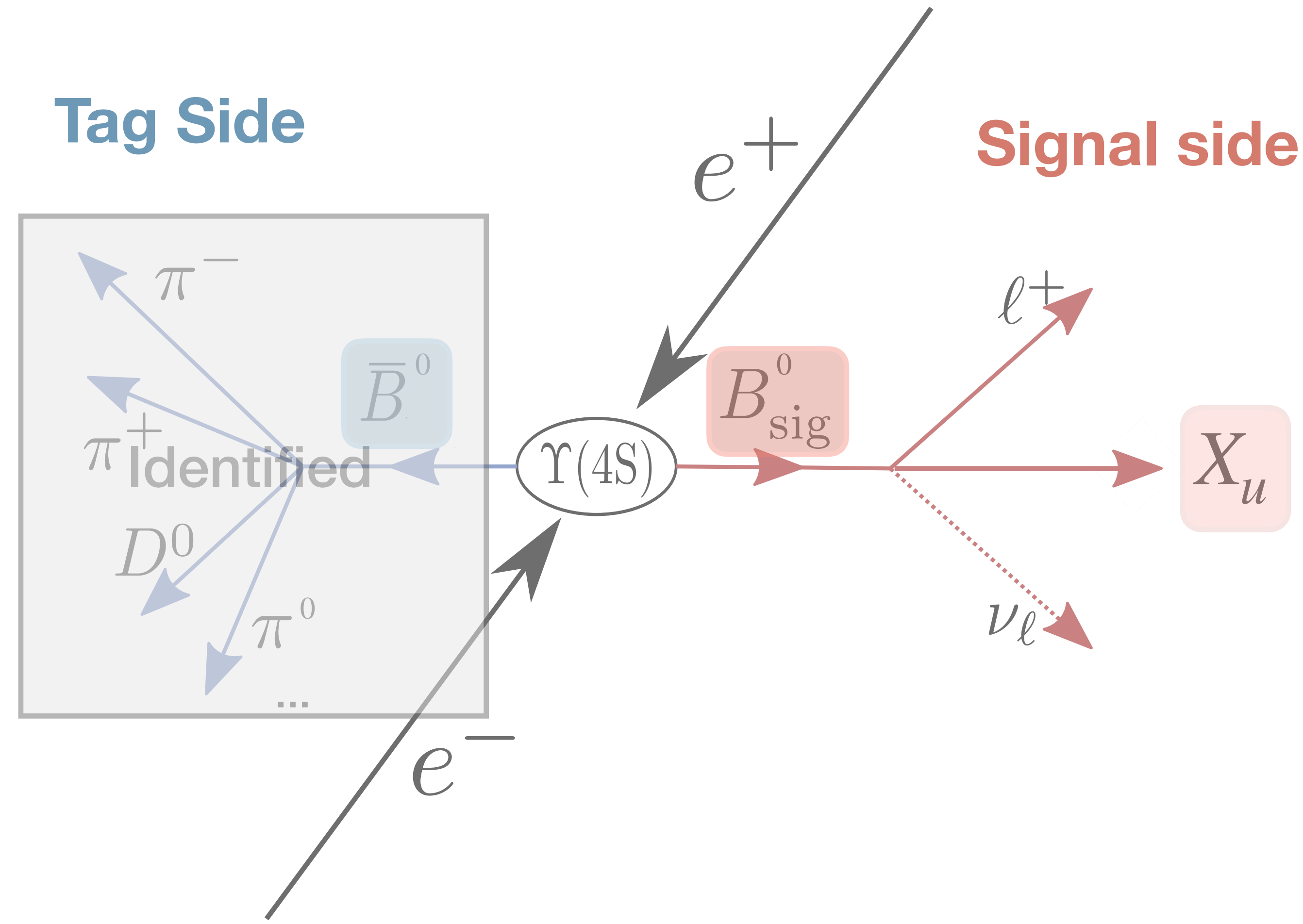
$$m_{\mathrm{miss}}^2 = \left(p_{\mathrm{sig}} - p_X - p_\ell\right)^2 \approx m_\nu^2 = 0\,\mathrm{GeV}^2$$

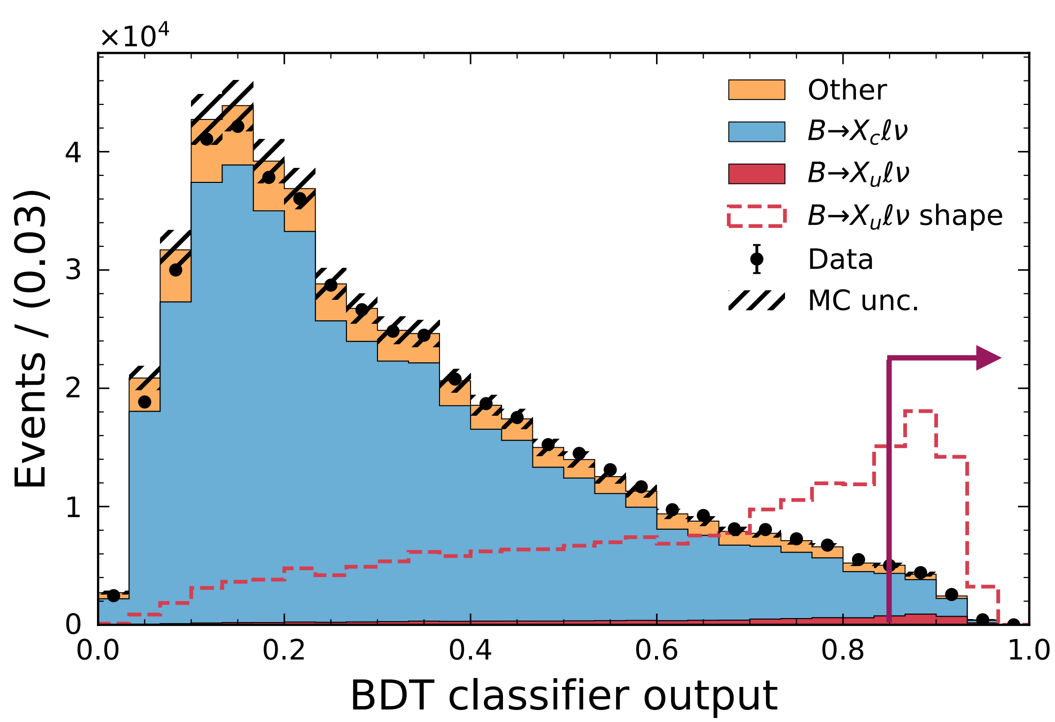
Analysis Strategy

Use **full Belle** data set of **711/fb**

Hadronic tagging with neural networks (ca. 0.2-0.3% efficiency)

Use **machine learning** (BDTs) to suppress backgrounds with 11 training features, e.g. m^2_{miss}, #K±, #Ks, etc.





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

$$q^2 = (p_{\text{sig}} - p_X)^2 \qquad M_X = \sqrt{(p_X)^\mu (p_X)_\mu}$$

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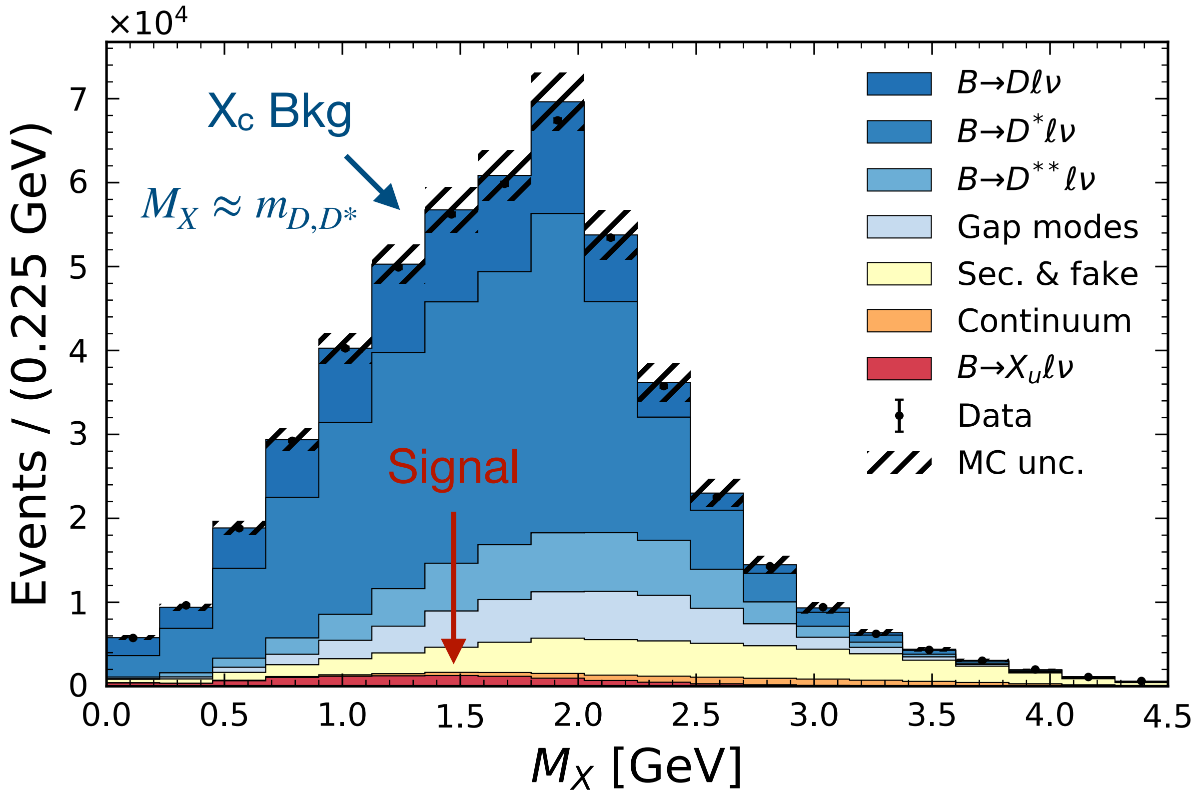
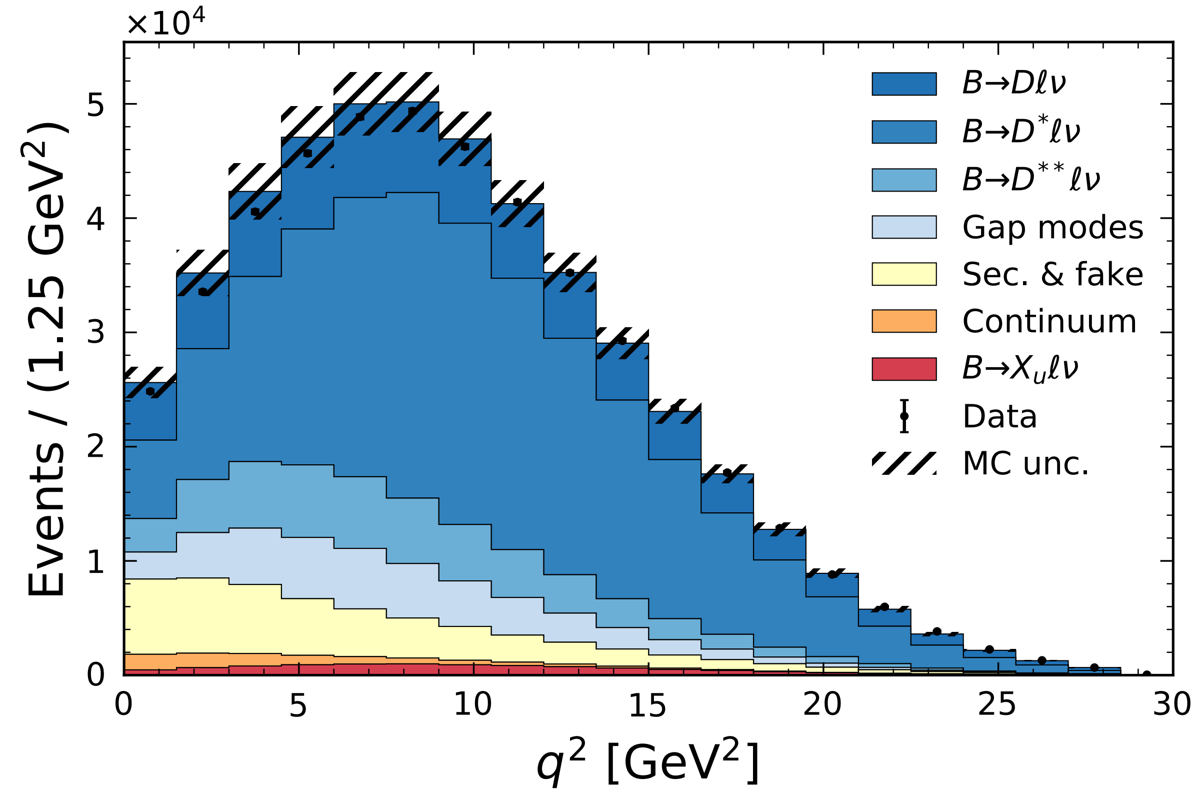
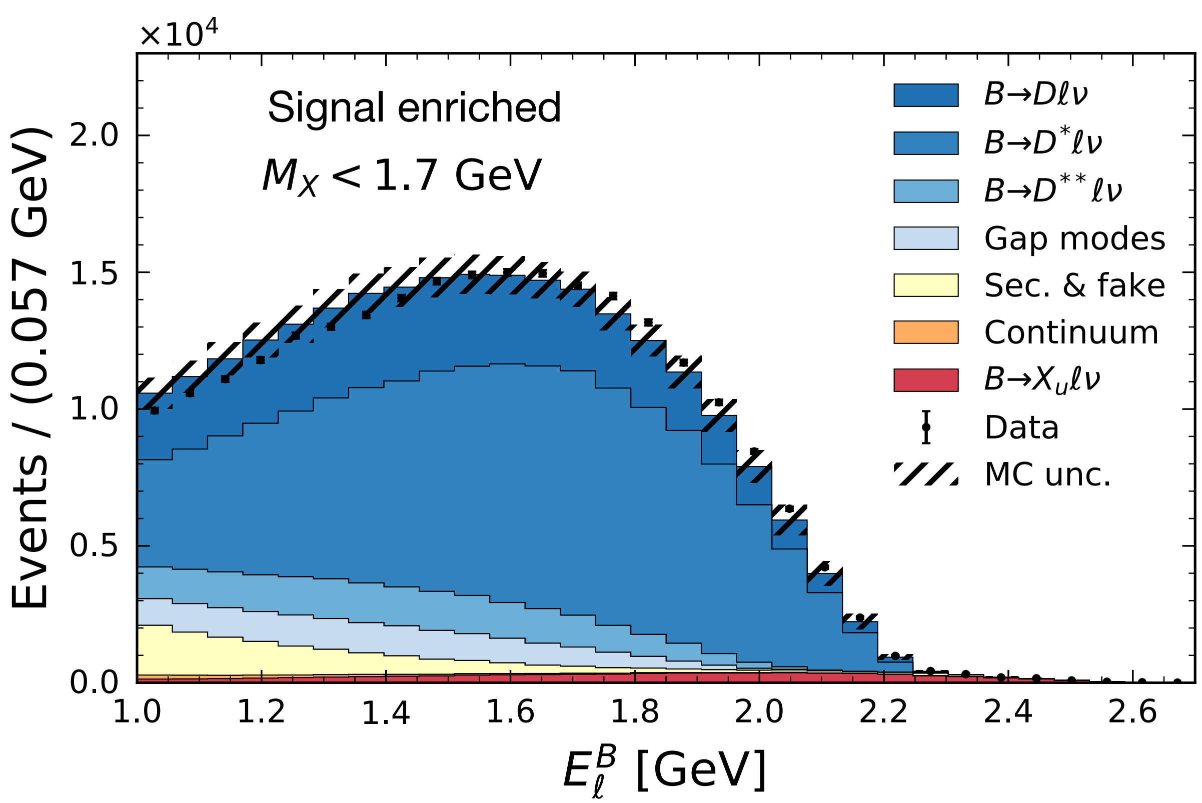
Before BDT selection

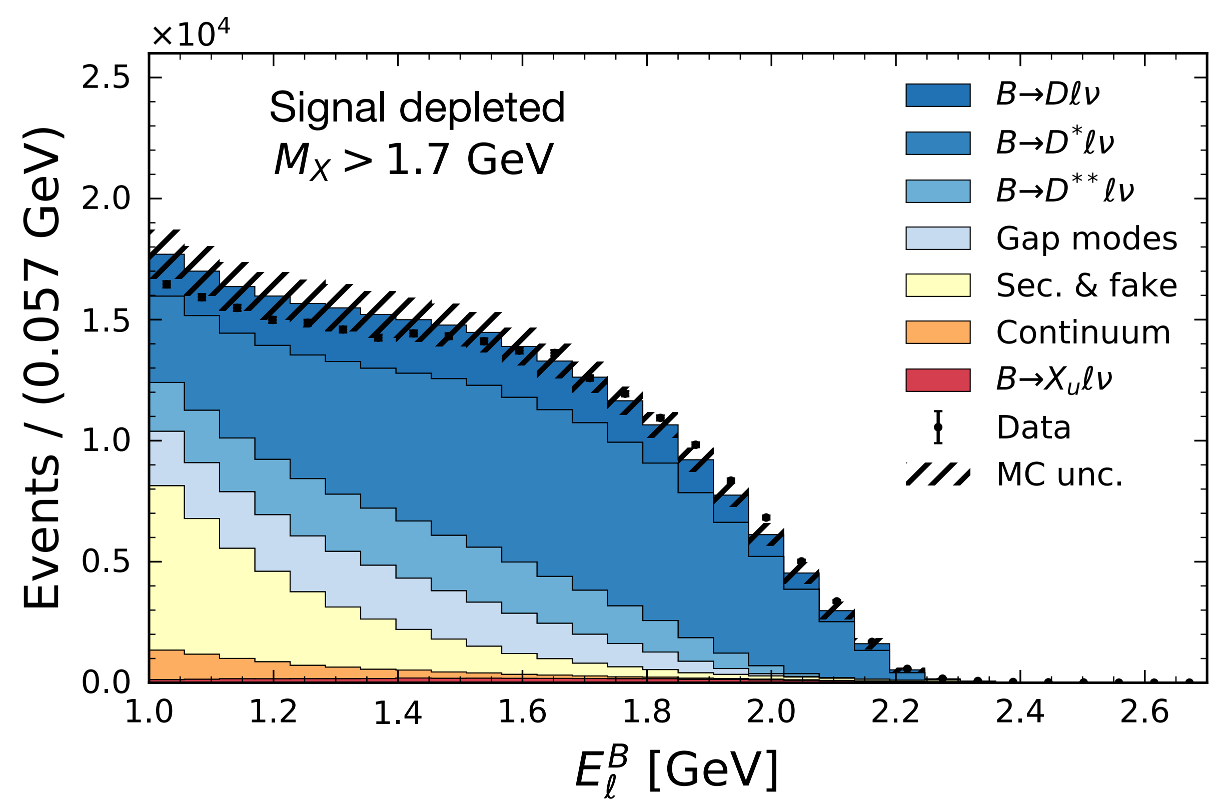
Hadronic Mass $M_X = \sqrt{p_X^2}$

Four-momentum transfer squared $q^2 = (p_B - p_X)^2$









Lepton Energy in signal B restframe E_ℓ^B

After BDT selection

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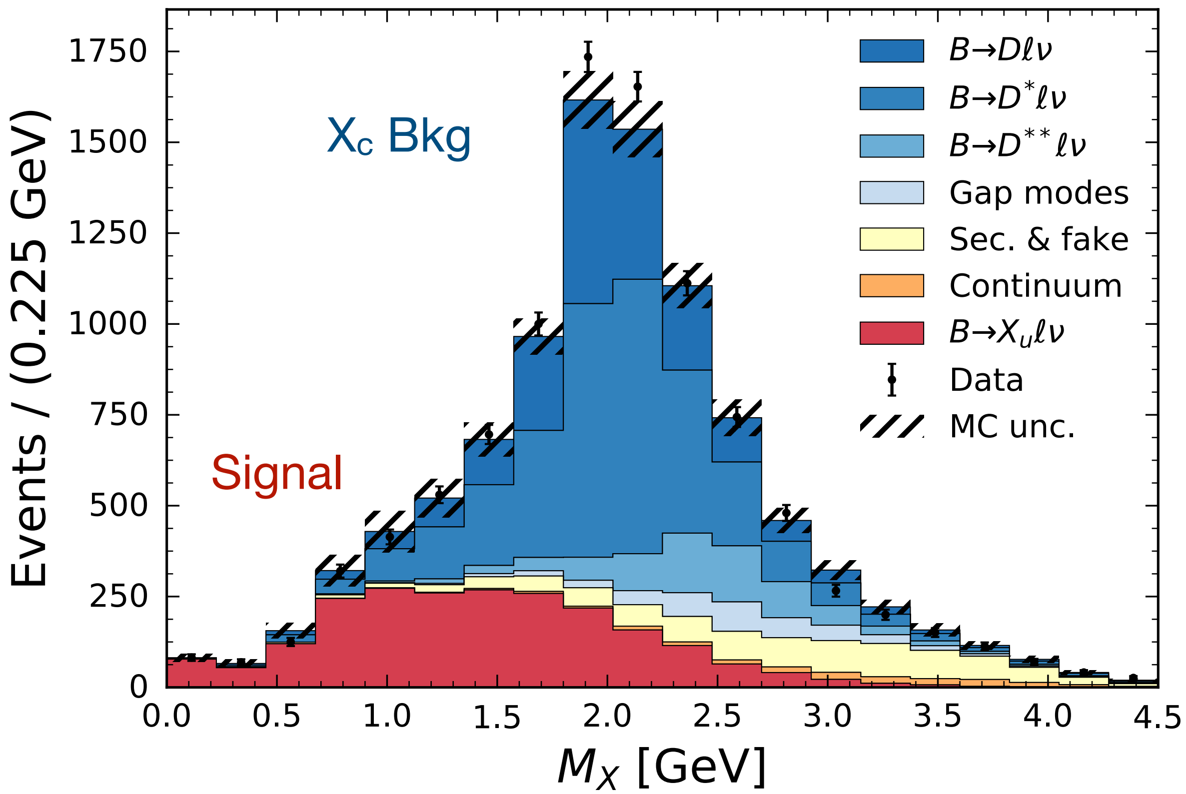
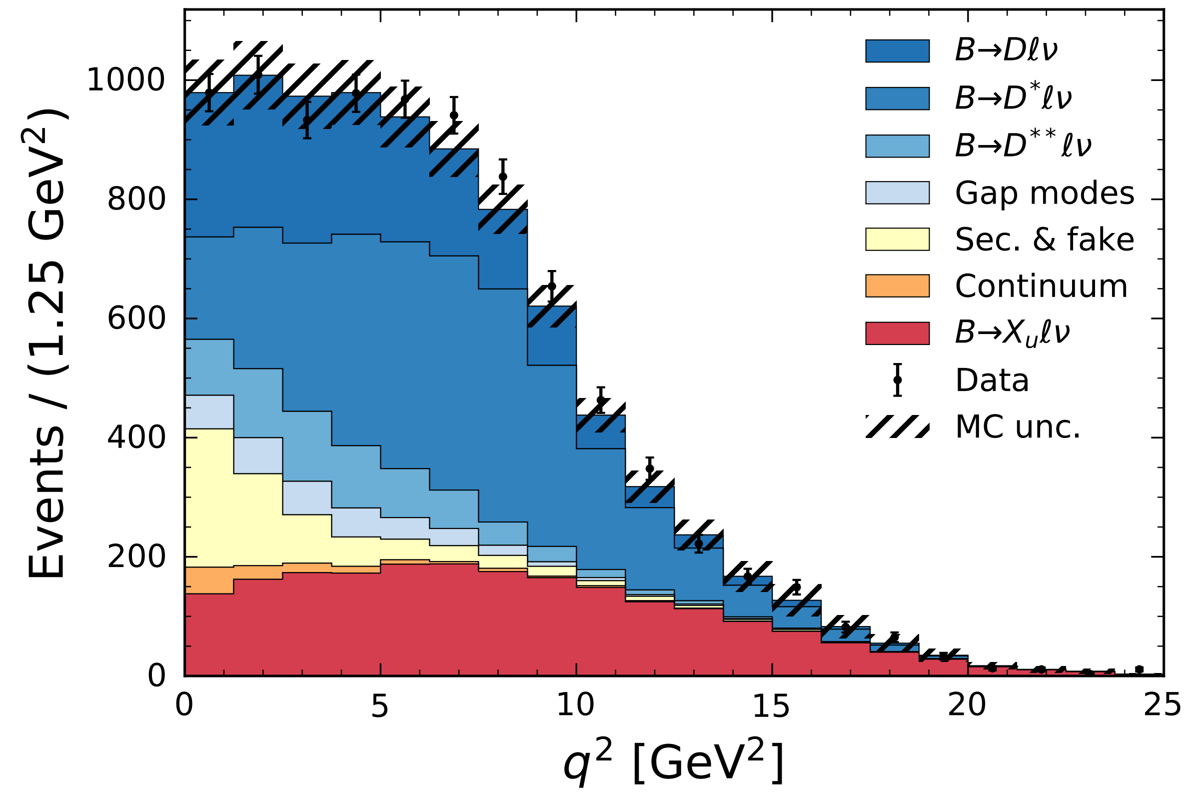
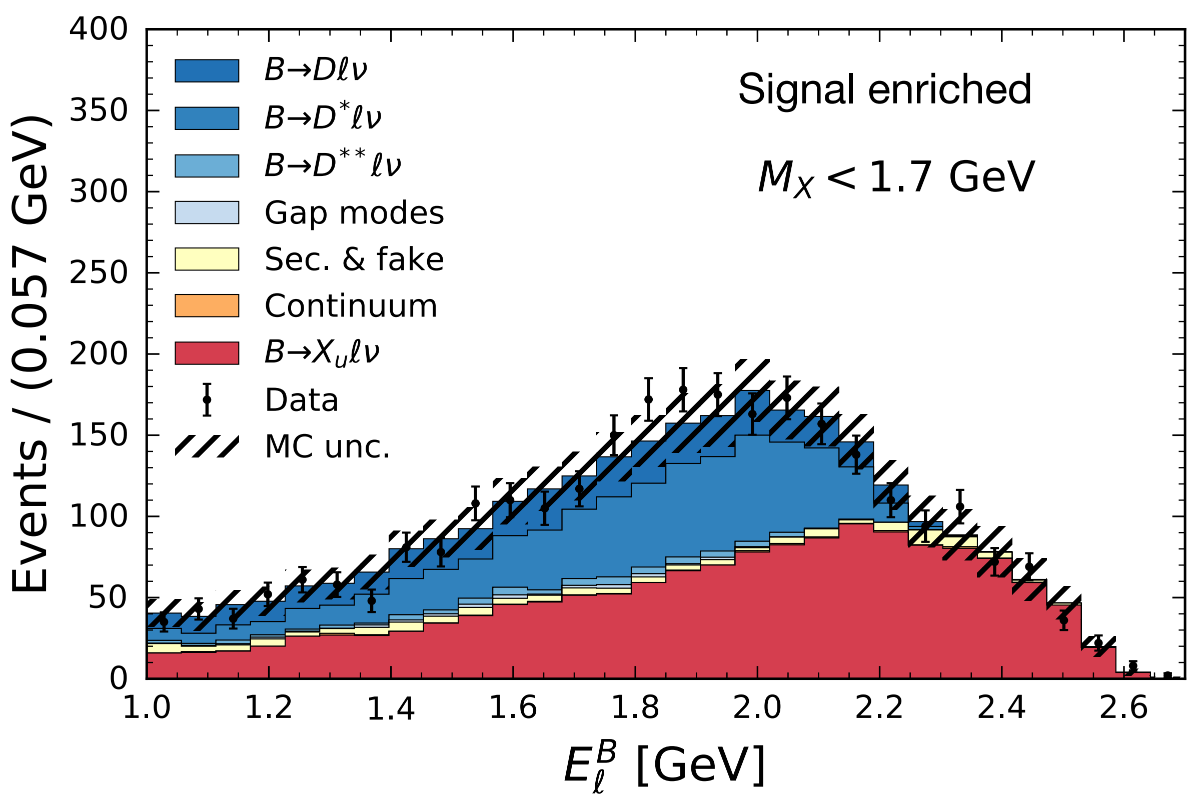
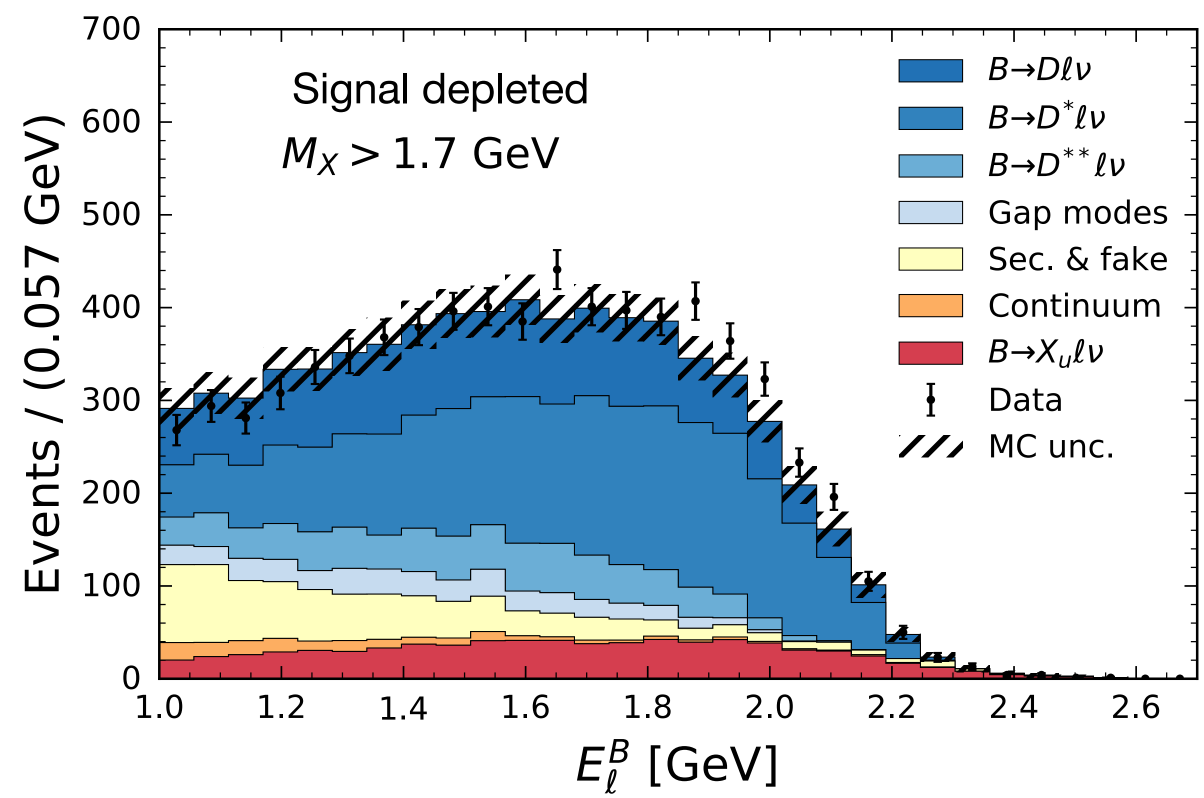
Four-momentum transfer squared $q^2 = (p_B - p_X)^2$









Lepton Energy in signal B restframe E_ℓ^B

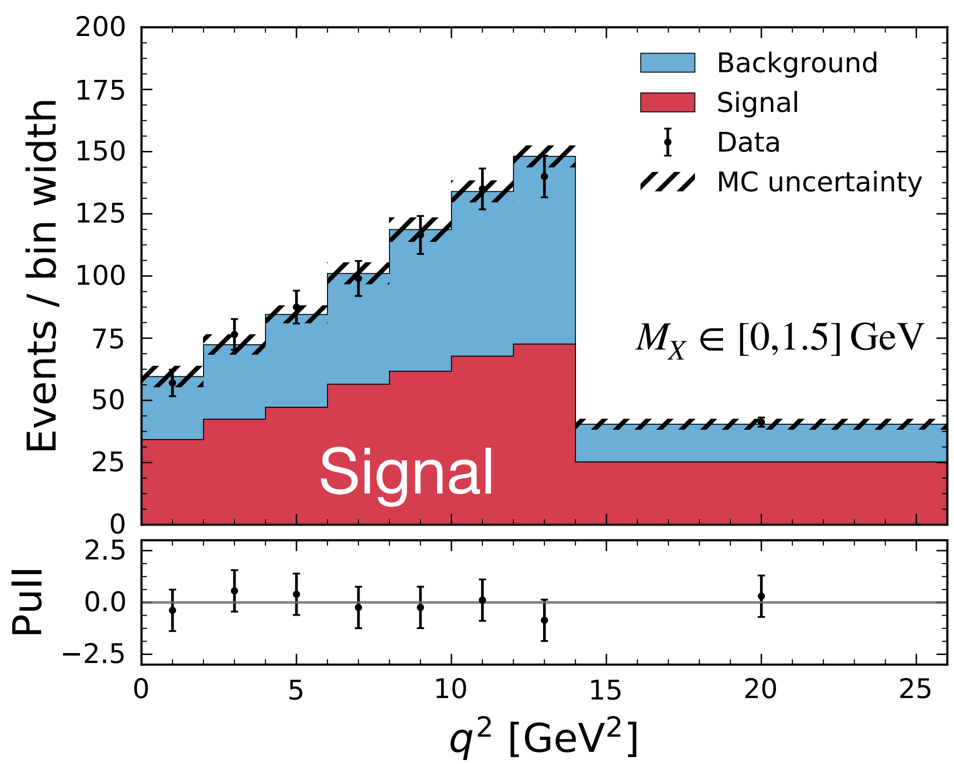
Fit kinematic distributions and measure partial BF

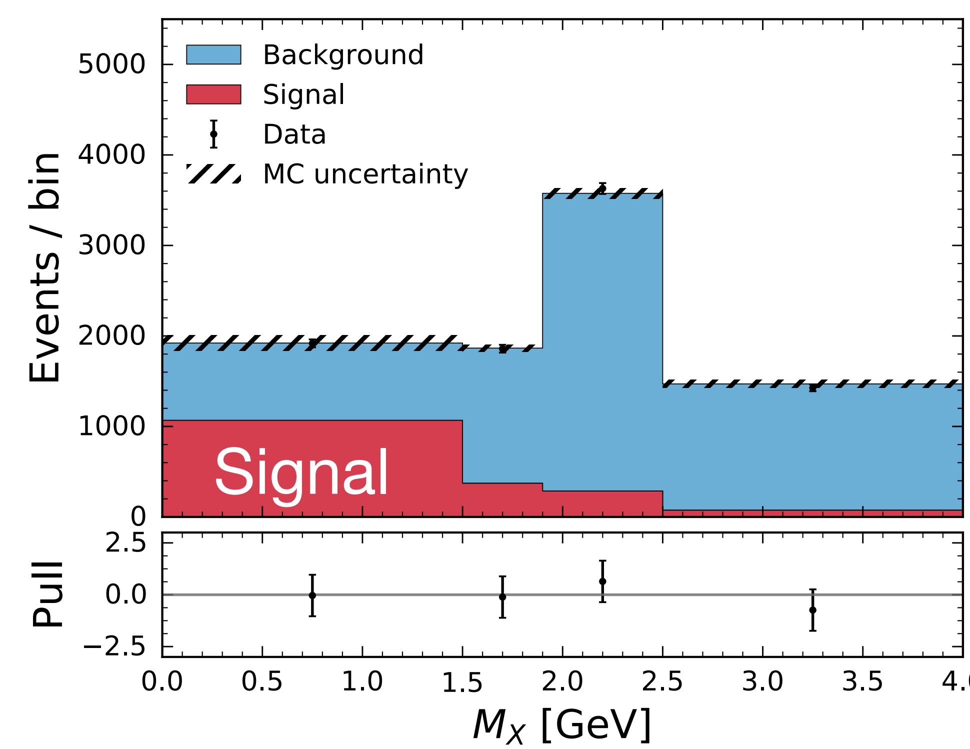
$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u\, \ell^+\, \nu_\ell)}{\tau_B \cdot \Delta\Gamma(B \to X_u\, \ell^+\, \nu_\ell)}}$$

3 phase-space regions

Phase-space region
$M_X < 1.7\,\mathrm{GeV}$
$M_X < 1.7\,\mathrm{GeV},\ q^2 > 8\,\mathrm{GeV}^2$
$E_\ell^B > 1\,\mathrm{GeV}$

Example projections of 2D fit:





2D binning

$M_X : q^2$	$[0, 1.5]\,\mathrm{GeV} \times [0, 2, 4, 6, 8, 10, 12, 14, 26]\,\mathrm{GeV}^2$
	$[1.5, 1.9]\,\mathrm{GeV} \times [0, 2, 4, 6, 26]\,\mathrm{GeV}^2$
	$[1.9, 2.5]\,\mathrm{GeV} \times [0, 2, 4, 26]\,\mathrm{GeV}^2$
	$[2.5, 4.0]\,\mathrm{GeV} \times [0, 2, 26]\,\mathrm{GeV}^2$

Fit kinematic distributions and measure partial BF

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u\, \ell^+\, \nu_\ell)}{\tau_B \cdot \Delta\Gamma(B \to X_u\, \ell^+\, \nu_\ell)}}$$

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Phase-space region
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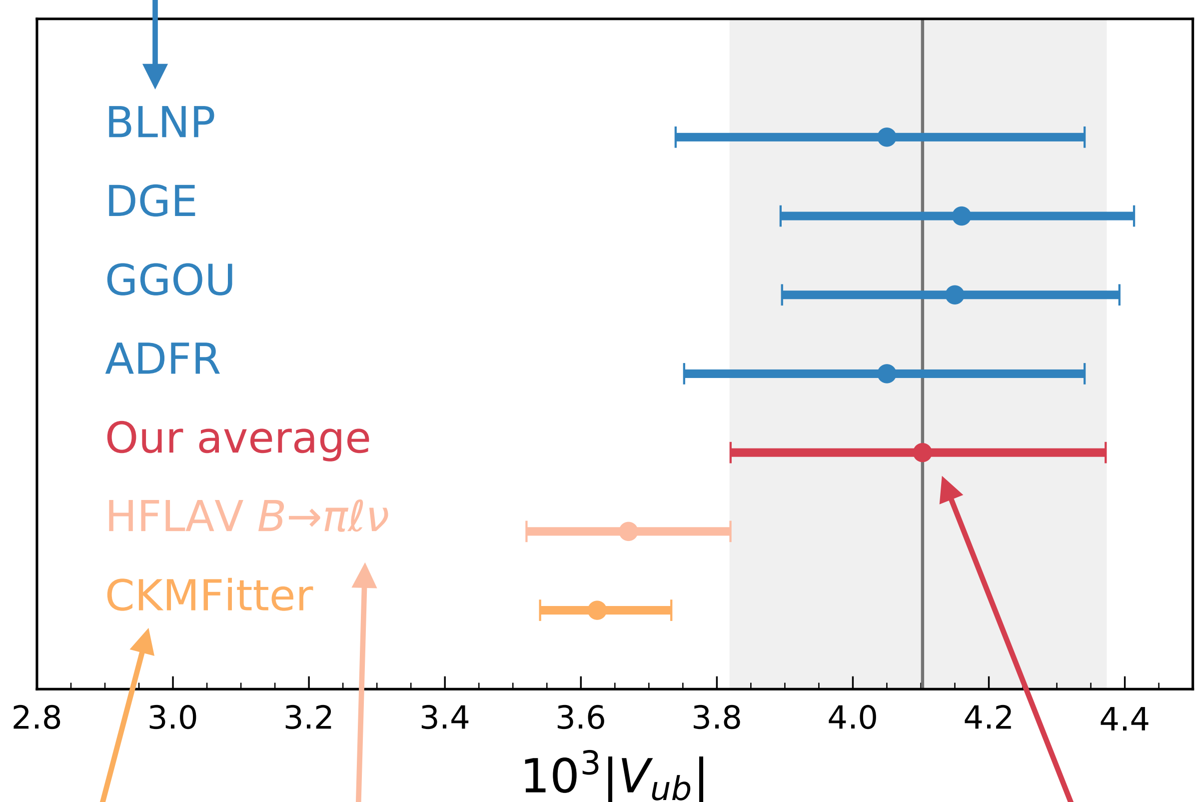
$M_X < 1.7\,\mathrm{GeV},\ q^2 > 8\,\mathrm{GeV}^2$
$E_\ell^B > 1\,\mathrm{GeV}$

4 predictions of the partial rate

Result for most inclusive region with $E_\ell^B > 1\,\mathrm{GeV}$

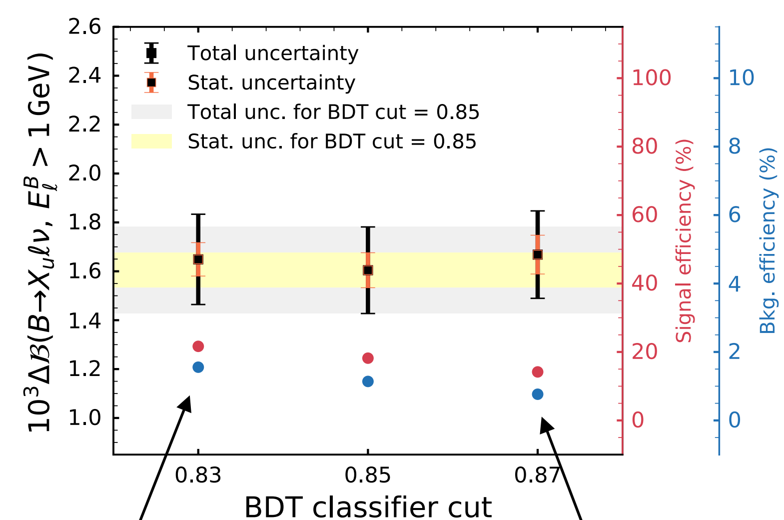


Exclusive Average for $B \to \pi \ell \bar{\nu}_\ell$:
$|V_{ub}| = (3.67 \pm 0.09 \pm 0.12) \times 10^{-3}$

CKM Unitarity:
$|V_{ub}| = \left(3.62^{+0.11}_{-0.08}\right) \times 10^{-3}$

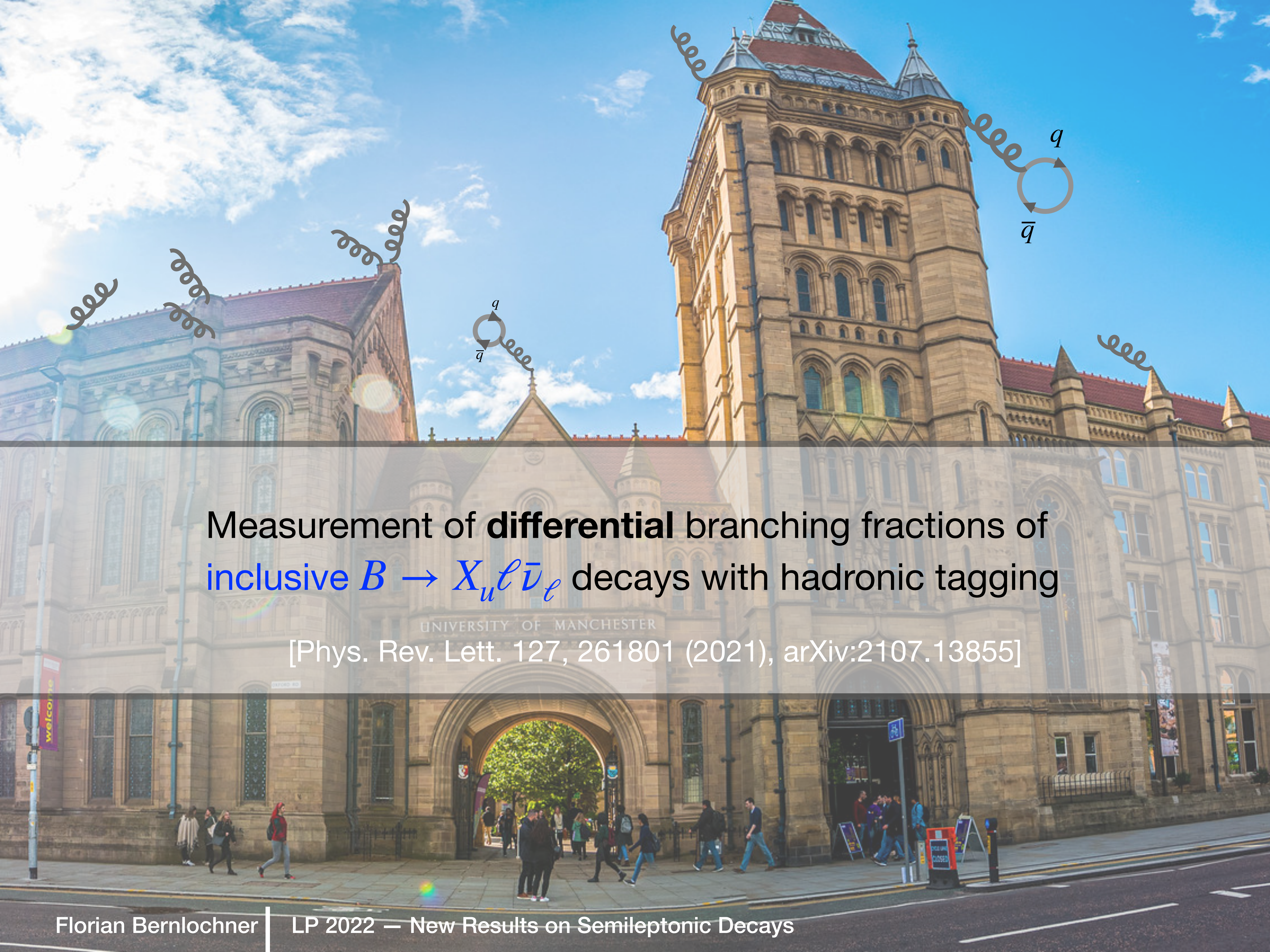
Arithmetic average:
$|V_{ub}| = \left(4.10 \pm 0.09 \pm 0.22 \pm 0.15\right) \times 10^{-3}$

Stability as a function of BDT cut:



33% more Bkg

37% less Bkg



Measurement of **differential** branching fractions of inclusive $B \to X_u \ell \bar{\nu}_\ell$ decays with hadronic tagging

[Phys. Rev. Lett. 127, 261801 (2021), arXiv:2107.13855]

Differential BF of inclusive $B \to X_u \ell \bar{\nu}_\ell$

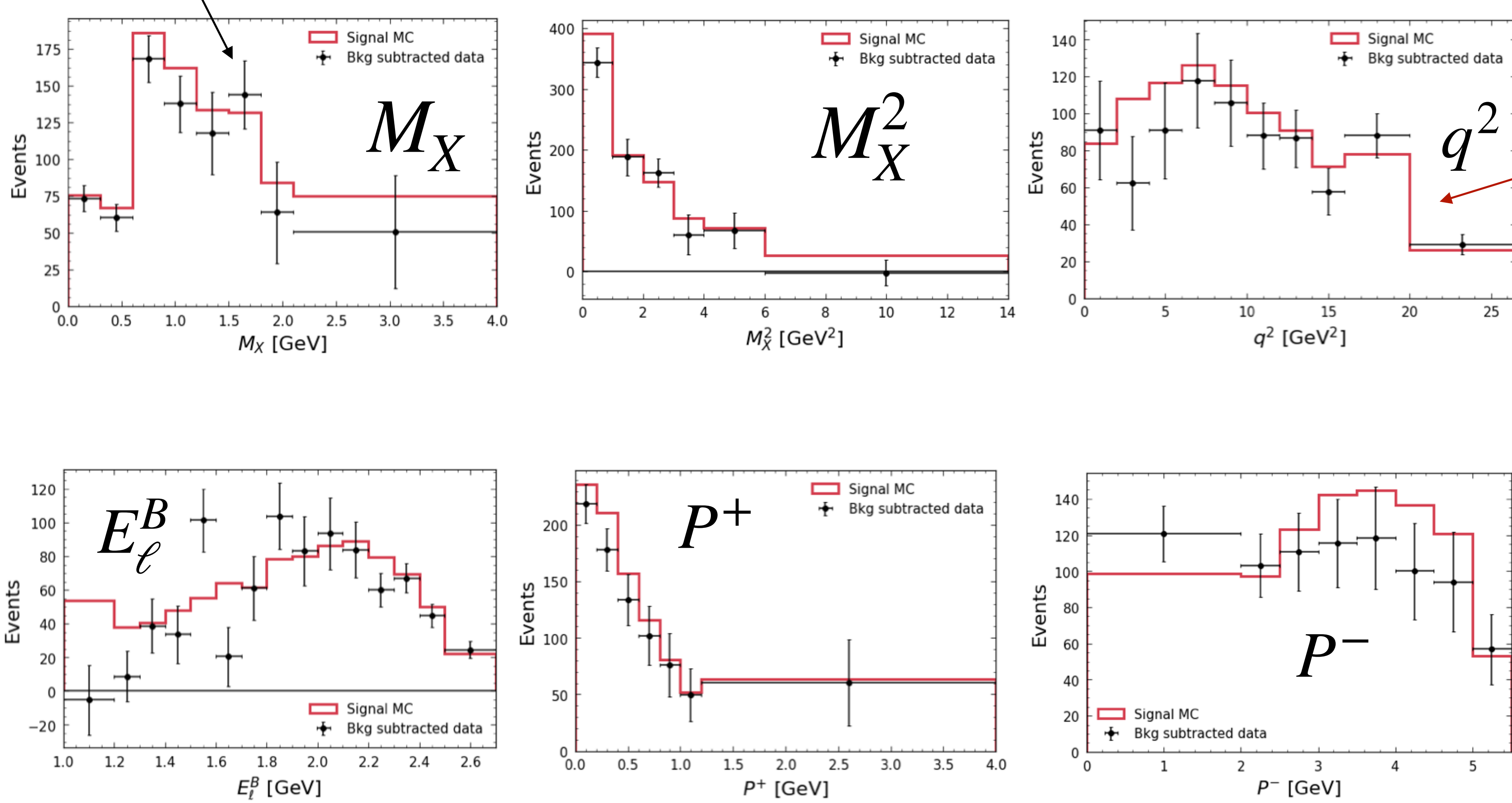
Measurement of **6 kinematic** variables **characterizing** $B \to X_u \ell \bar{\nu}_\ell$ in $E_\ell^B > 1\,\mathrm{GeV}$ region of PS

Selection and reconstruction **analogous** to **partial BF** measurement

Apply **additional selections** to **improve resolution and background shape uncertainties**

Bkg. subtracted data

Background subtraction via coarse M_X fit:



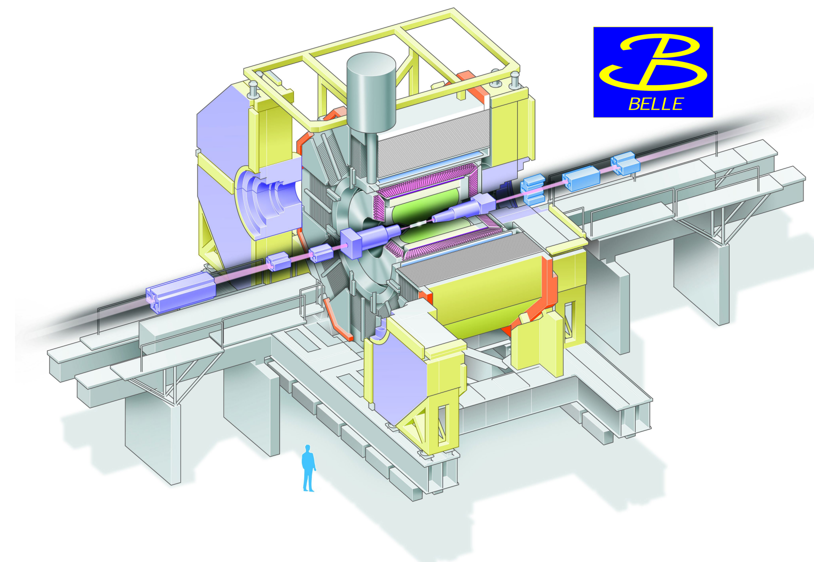
Overlaid **signal MC** (hybrid $B \to X_u \ell \bar{\nu}_\ell$)

light-cone momenta: $P_\pm = E_X \mp |P_X|$

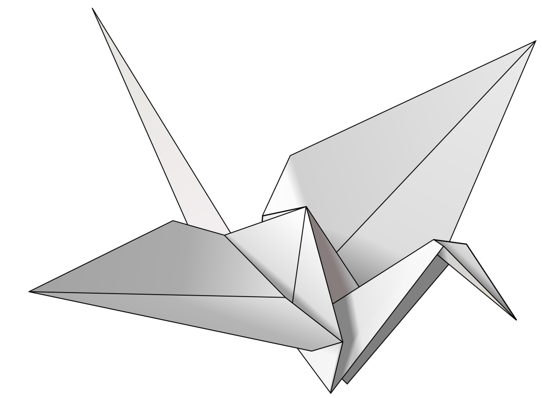
Unfolding

by L. Cao

X: True distribution



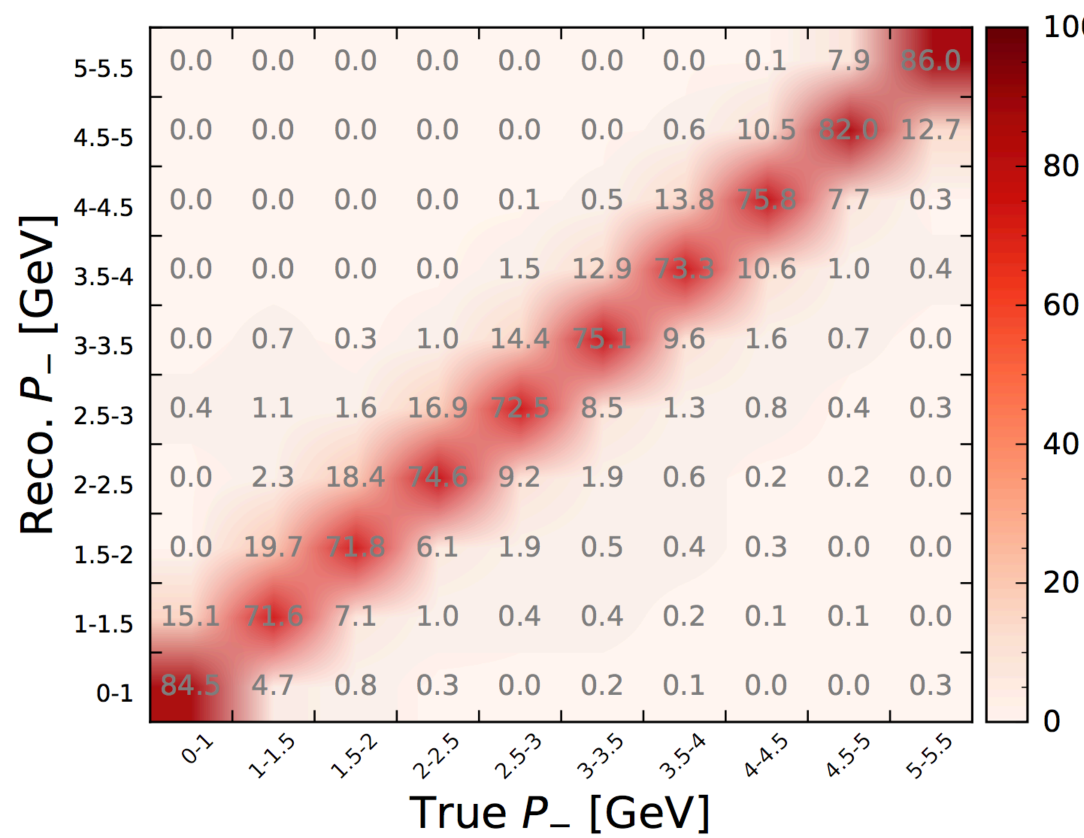
M: Detector response



Y: Measured distribution

Detector response is represented by migration matrix **M**

M(i,j) indicate probability to **reconstruct** event in **bin i** if it had **generator-level** value in **bin j**



Reco. \ True	0-1	1-1.5	1.5-2	2-2.5	2.5-3	3-3.5	3.5-4	4-4.5	4.5-5	5-5.5
5-5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	7.9	86.0
4.5-5	0.0	0.0	0.0	0.0	0.0	0.0	0.6	10.5	82.0	12.7
4-4.5	0.0	0.0	0.0	0.0	0.1	0.5	13.8	75.8	7.7	0.3
3.5-4	0.0	0.0	0.0	0.0	1.5	12.9	73.3	10.6	1.0	0.4
3-3.5	0.0	0.7	0.3	1.0	14.4	75.1	9.6	1.6	0.7	0.0
2.5-3	0.4	1.1	1.6	16.9	72.5	8.5	1.3	0.8	0.4	0.3
2-2.5	0.0	2.3	18.4	74.6	9.2	1.9	0.6	0.2	0.2	0.0
1.5-2	0.0	19.7	71.8	6.1	1.9	0.5	0.4	0.3	0.0	0.0
1-1.5	15.1	71.6	7.1	1.0	0.4	0.4	0.2	0.1	0.1	0.0
0-1	84.5	4.7	0.8	0.3	0.0	0.2	0.1	0.0	0.0	0.3

Direct solution to obtain **X**:

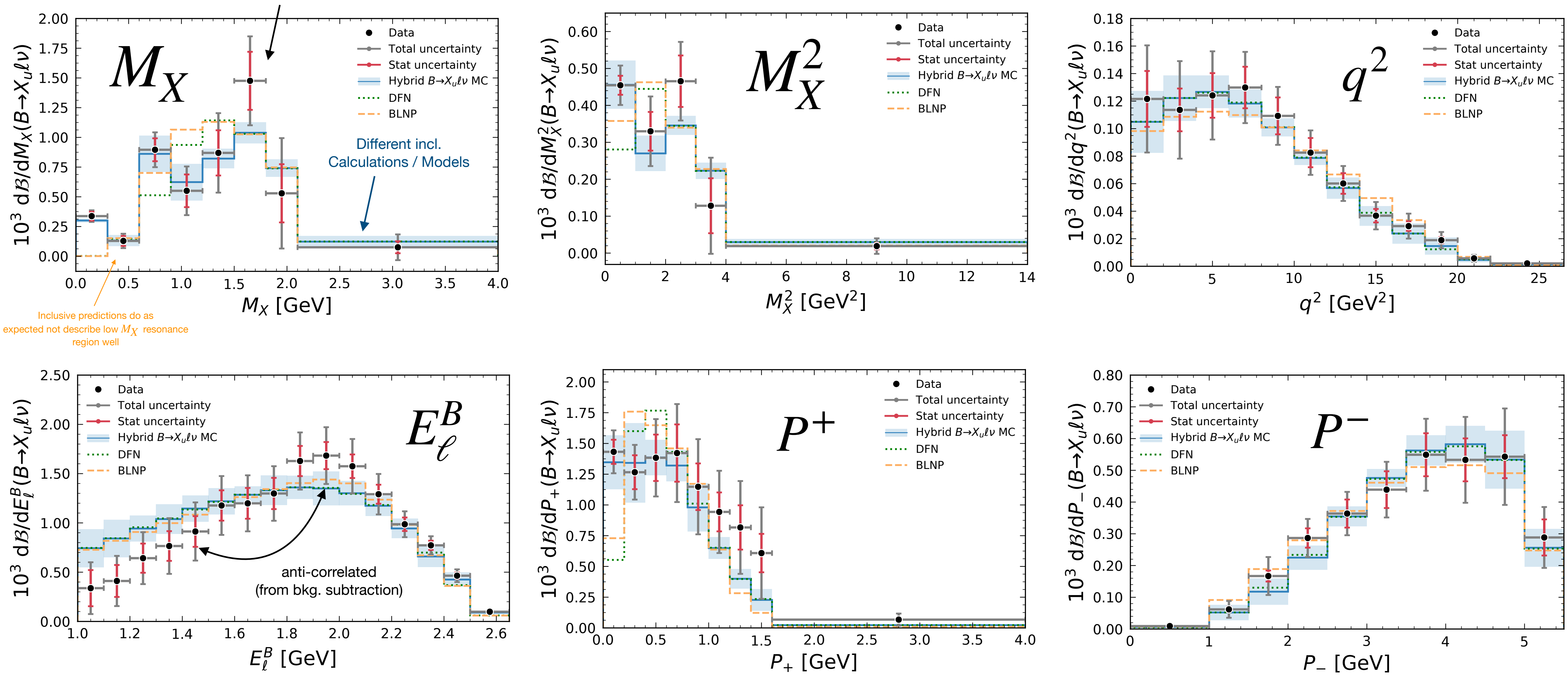
$$X = M^{-1} Y$$

Use Singular-Value-Decomposition (SVD) unfolding

[NIMA 372:469 (1996)]

Differential Spectra

Unfolded + acceptance corrected distributions with total Error / Stat. Error

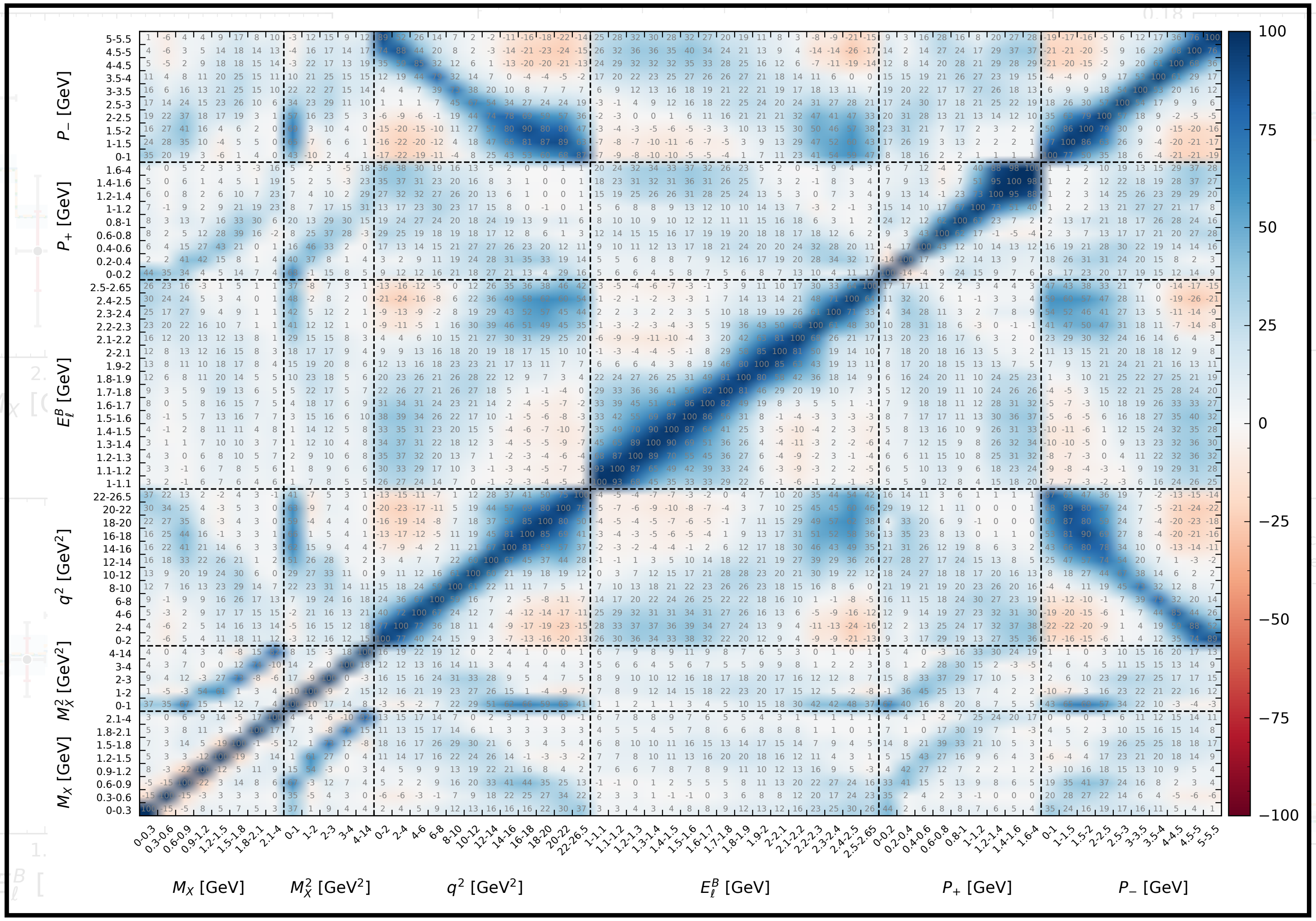


Agreement
(w/o theory uncertainties)

χ^2	E_ℓ^B	M_X	M_X^2	q^2	P_+	P_-
n.d.f.	16	8	5	12	9	10
Hybrid	13.5	2.5	2.6	4.5	1.7	5.2
DFN	16.2	63.2	13.1	18.5	29.3	6.1
BLNP	16.5	61.0	6.3	20.6	23.6	13.7

Differential Spectra

Full **experimental correlations**

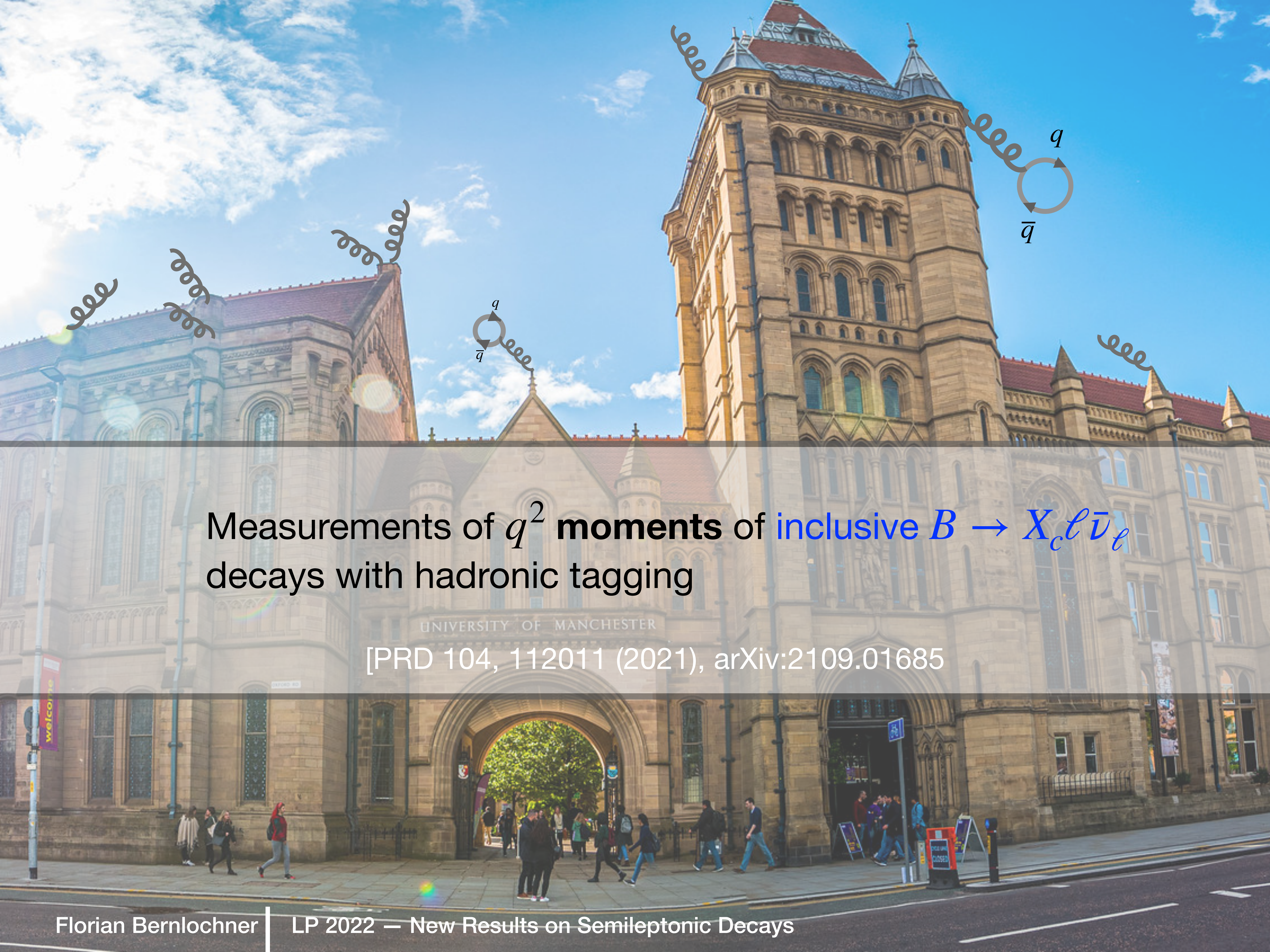


Can be used for future shape-function independent $|V_{ub}|$ determinations

NNVub

P. Gambino, K. Healey, C. Mondino, Phys. Rev. D 94, 014031 (2016), [arXiv:1604.07598]

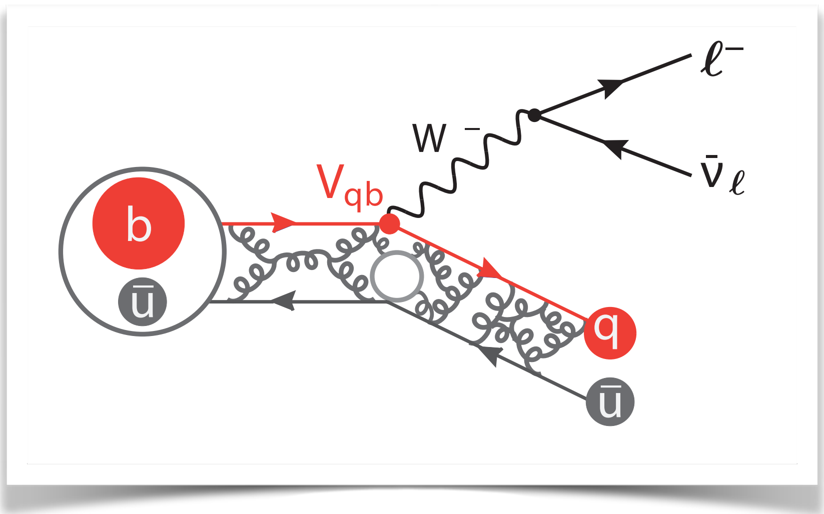
F. Bernlochner, H. Lacker, Z. Ligeti, I. Stewart, F. Tackmann, K. Tackmann Phys. Rev. Lett. 127, 102001 (2021) [arXiv:2007.04320]



Measurements of q^2 **moments** of inclusive $B \to X_c \ell \bar{\nu}_\ell$ decays with hadronic tagging

[PRD 104, 112011 (2021), arXiv:2109.01685]

Measurement of q^2 moments of $B \to X_c \ell \bar{\nu}_\ell$



Inclusive $|V_{cb}|$

$$\bar{B} \to X_c \, \ell \, \bar{\nu}_\ell$$

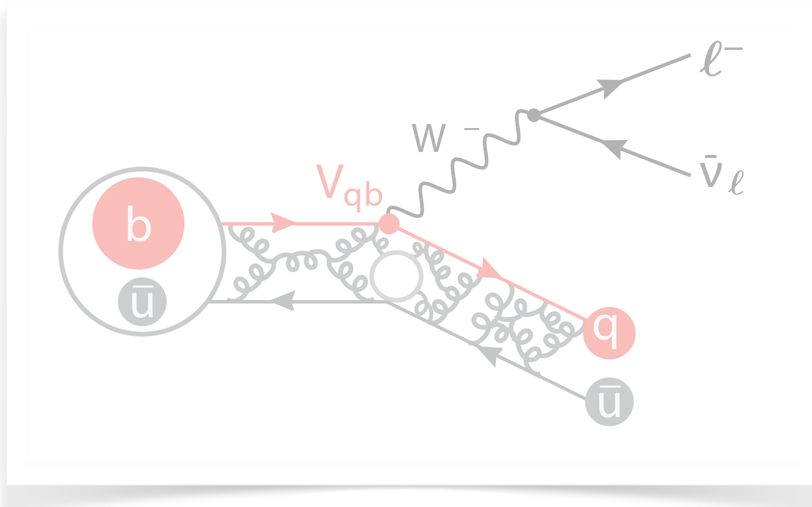
Operator Product Expansion (OPE)

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

Traditional approach: Use hadronic mass moments, lepton energy moments etc. to determine non-perturbative matrix elements (ME) of OPE and extract $|V_{cb}|$

Bad news: number of these matrix elements increases if one increases expansion in $1/m_{b,c}$

Measurement of q^2 moments of $B \to X_c \ell \bar{\nu}_\ell$



Inclusive $|V_{cb}|$

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Bad news: number of these matrix elements increases if one increases expansion in $1/m_{b,c}$

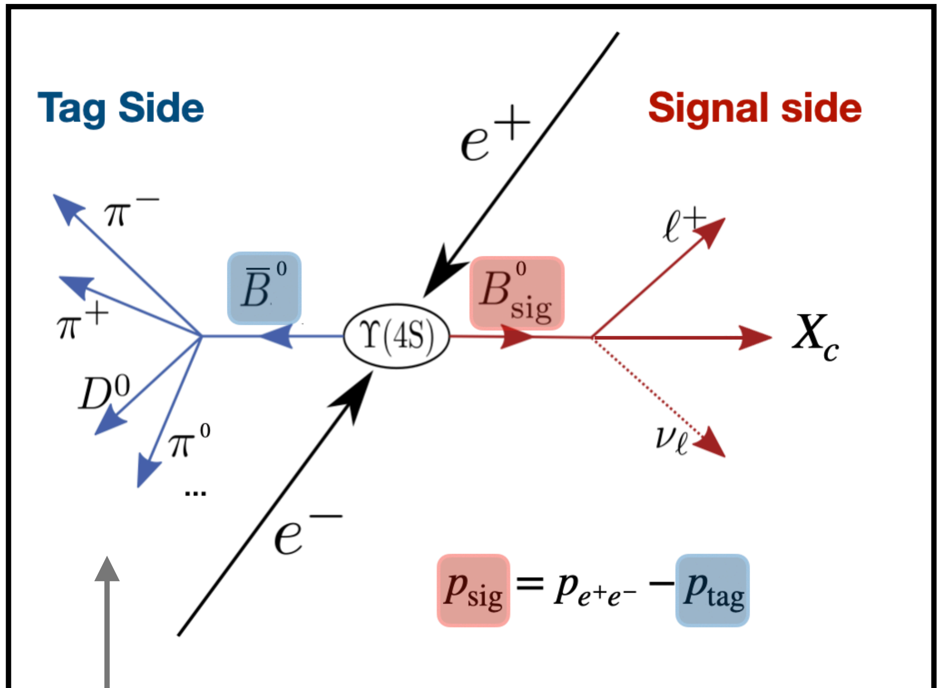
Fresh idea from [arXiv:1812.07472] (M. Fael, T. Mannel, K. Vos)

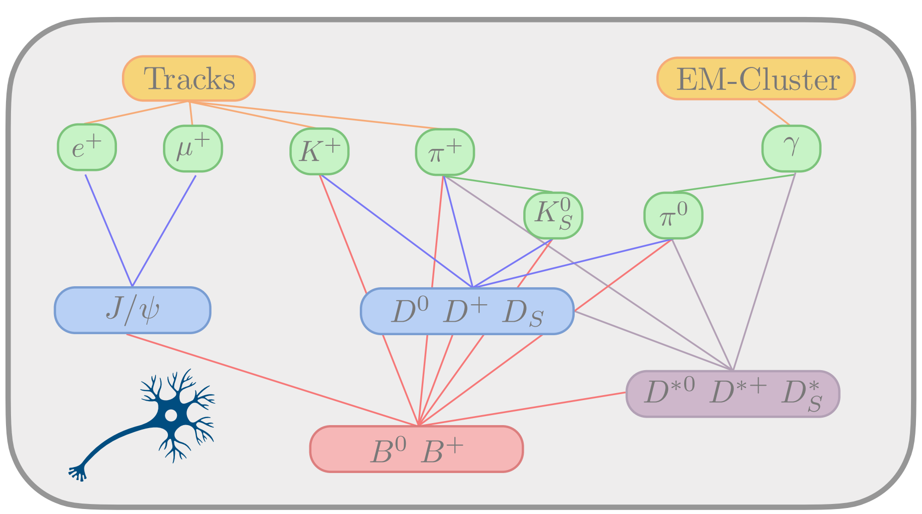
→ Number of ME reduce by exploiting reparametrization invariance, but **not true for every observable** (e.g. not for $\langle M_X \rangle$)

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

Measurement of q^2 moments of $B \to X_c \ell \bar{\nu}_\ell$

Key-technique: hadronic tagging

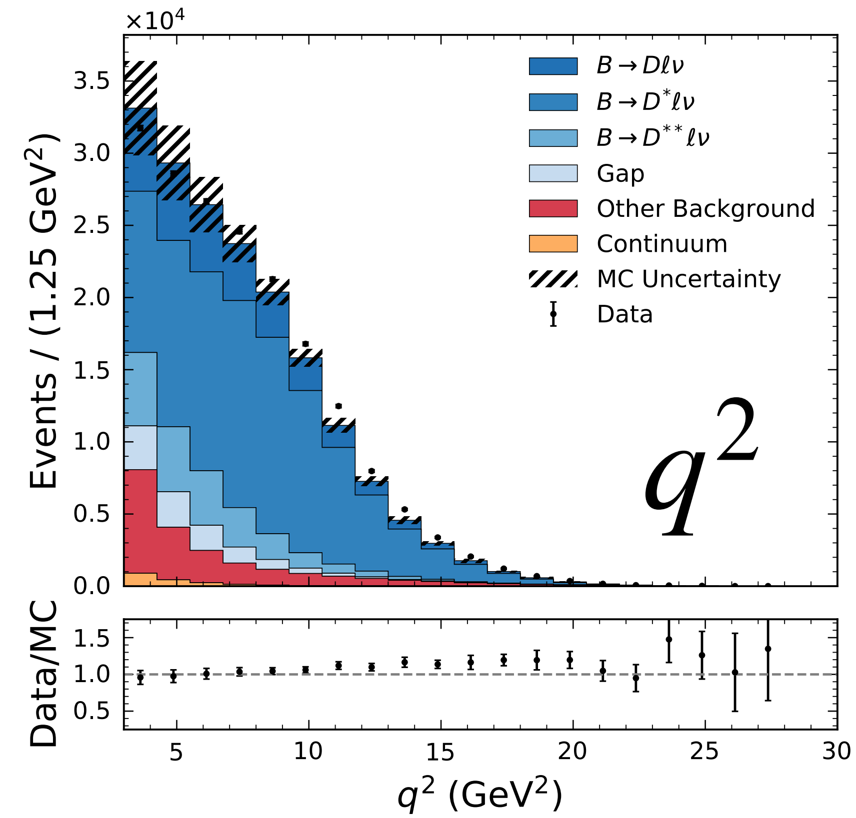


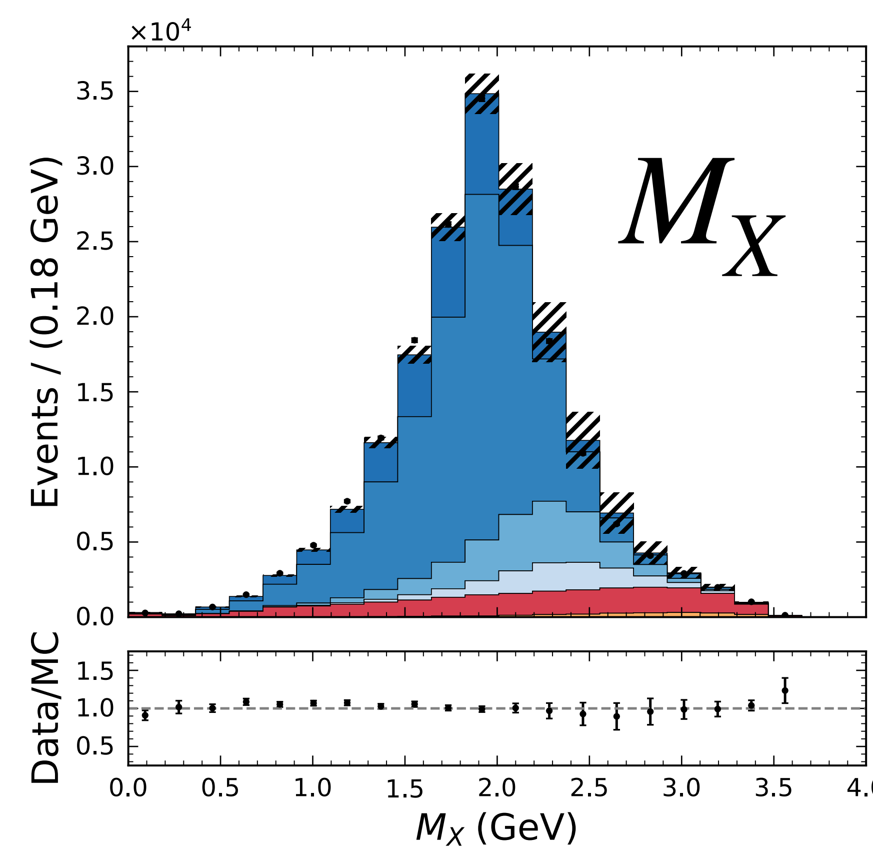


Can identify X_c constituents

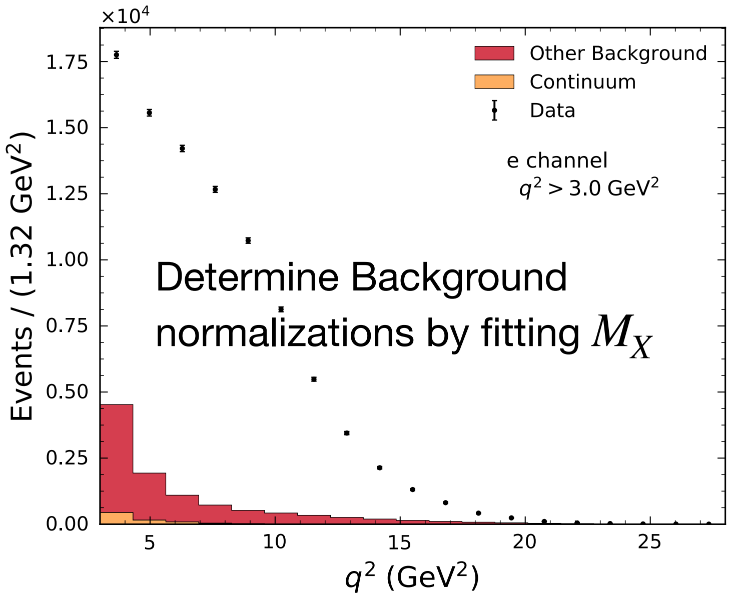
$$q^2 = \left(p_{\rm sig} - p_{X_c}\right)^2$$

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

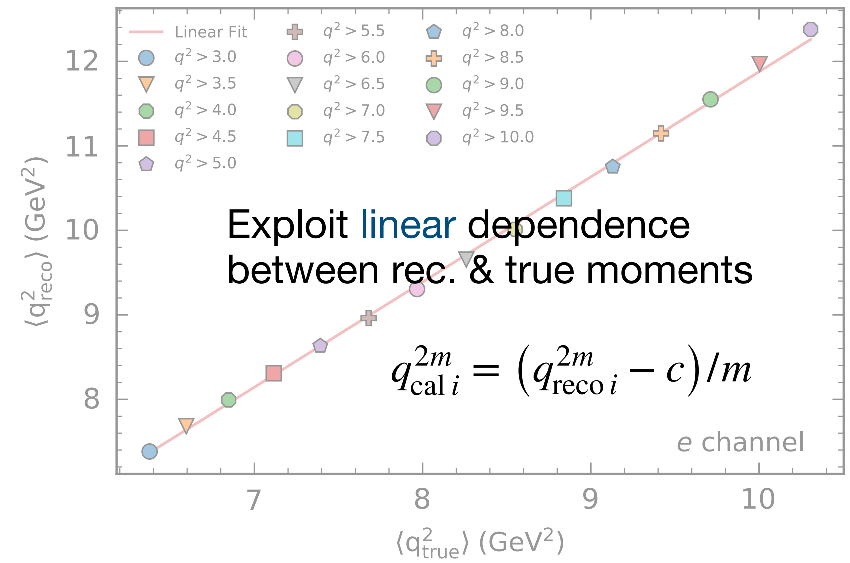




Moment determination



Step #1: Subtract Background

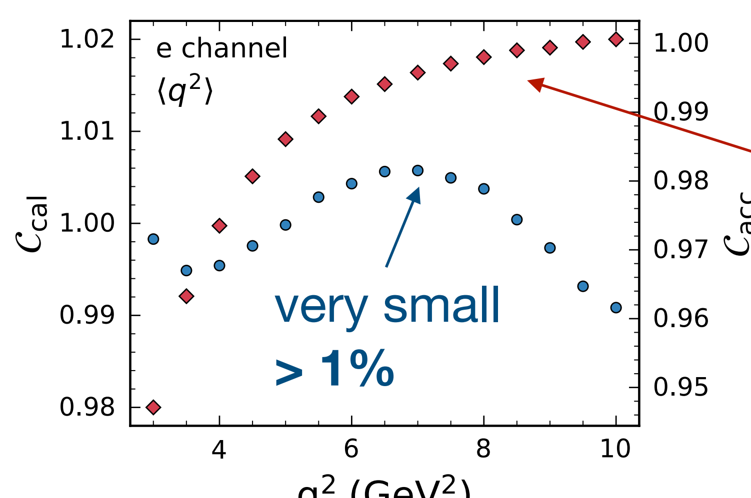


Step #2: Calibrate moment

Event-wise **Master-formula**

$$\langle q^{2m} \rangle = \frac{\boxed{C_{\mathrm{cal}}} \cdot \boxed{C_{\mathrm{acc}}}}{\sum_i^{\mathrm{events}} \boxed{w(q_i^2)}} \times \sum_i^{\mathrm{events}} \boxed{w(q_i^2)} \cdot \boxed{q^{2m}_{\mathrm{cal}\,i}}$$

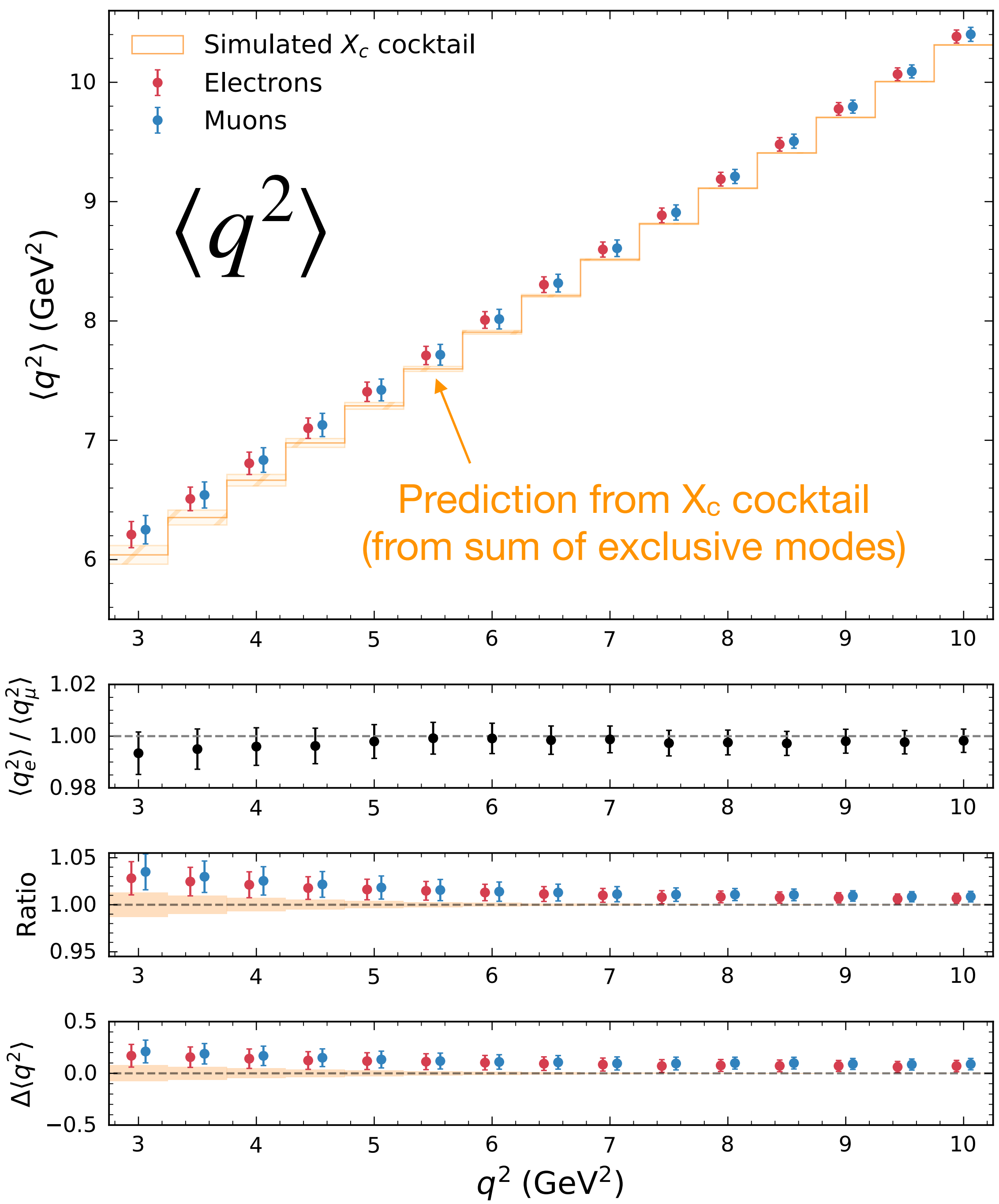
Step #3: If you fail, try again

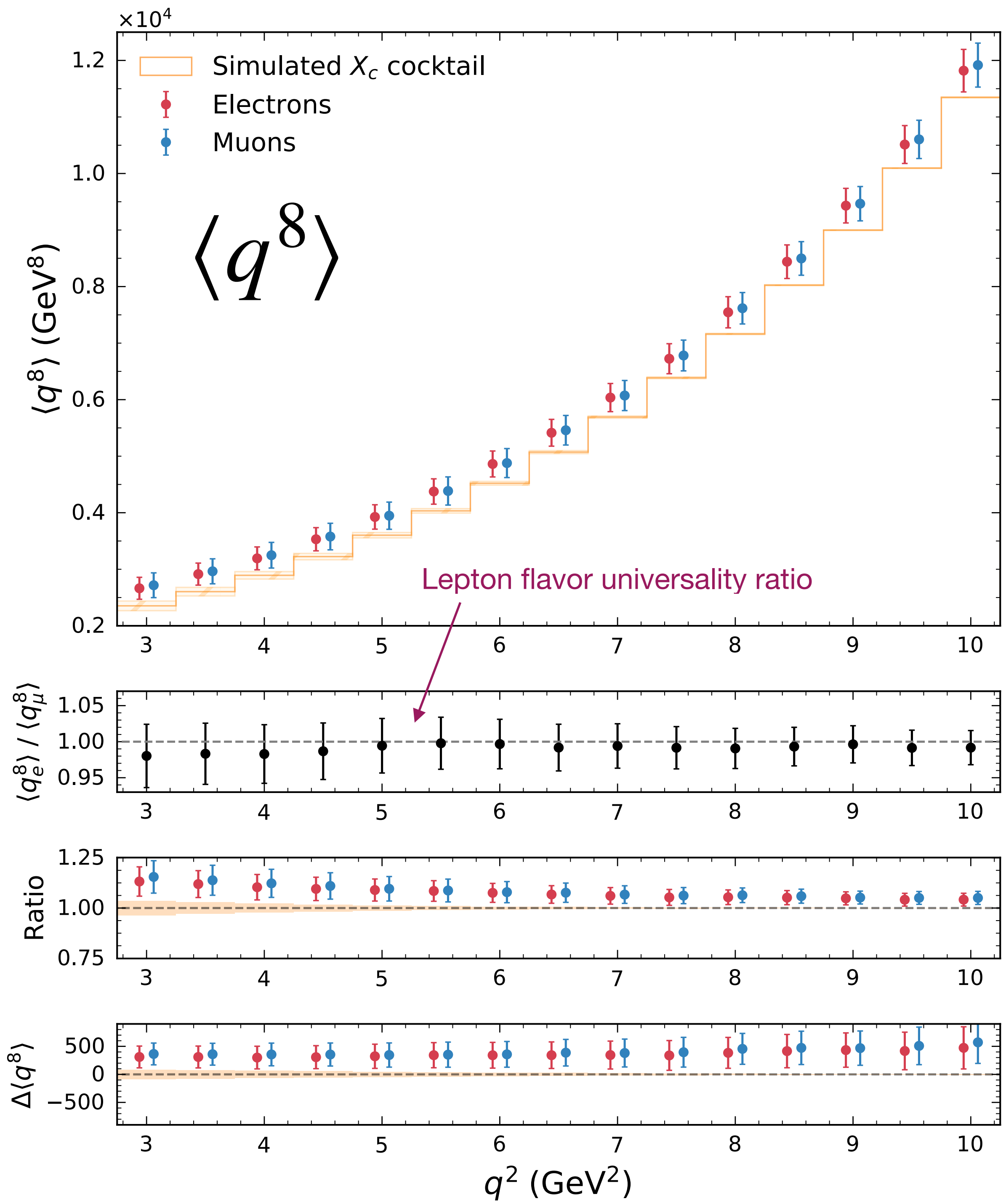


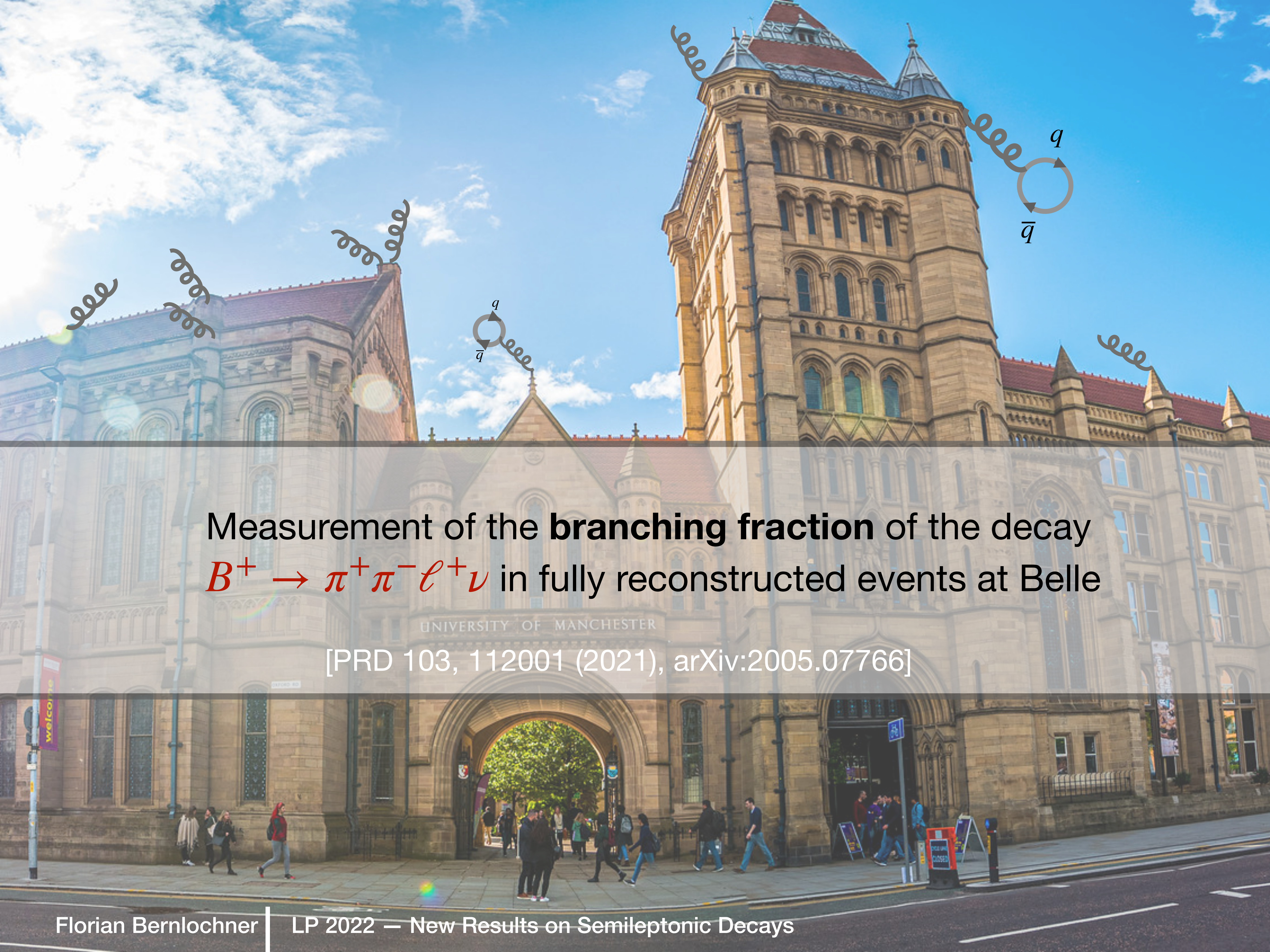
Step #4: Correct for selection effects

Overall event reconstruction itself also **biases** measured moment by **1-2%**

Measured Moments: $\langle q^2 \rangle - \langle q^8 \rangle$







Measurement of the **branching fraction** of the decay $B^+ \to \pi^+\pi^-\ell^+\nu$ in fully reconstructed events at Belle

[PRD 103, 112001 (2021), arXiv:2005.07766]

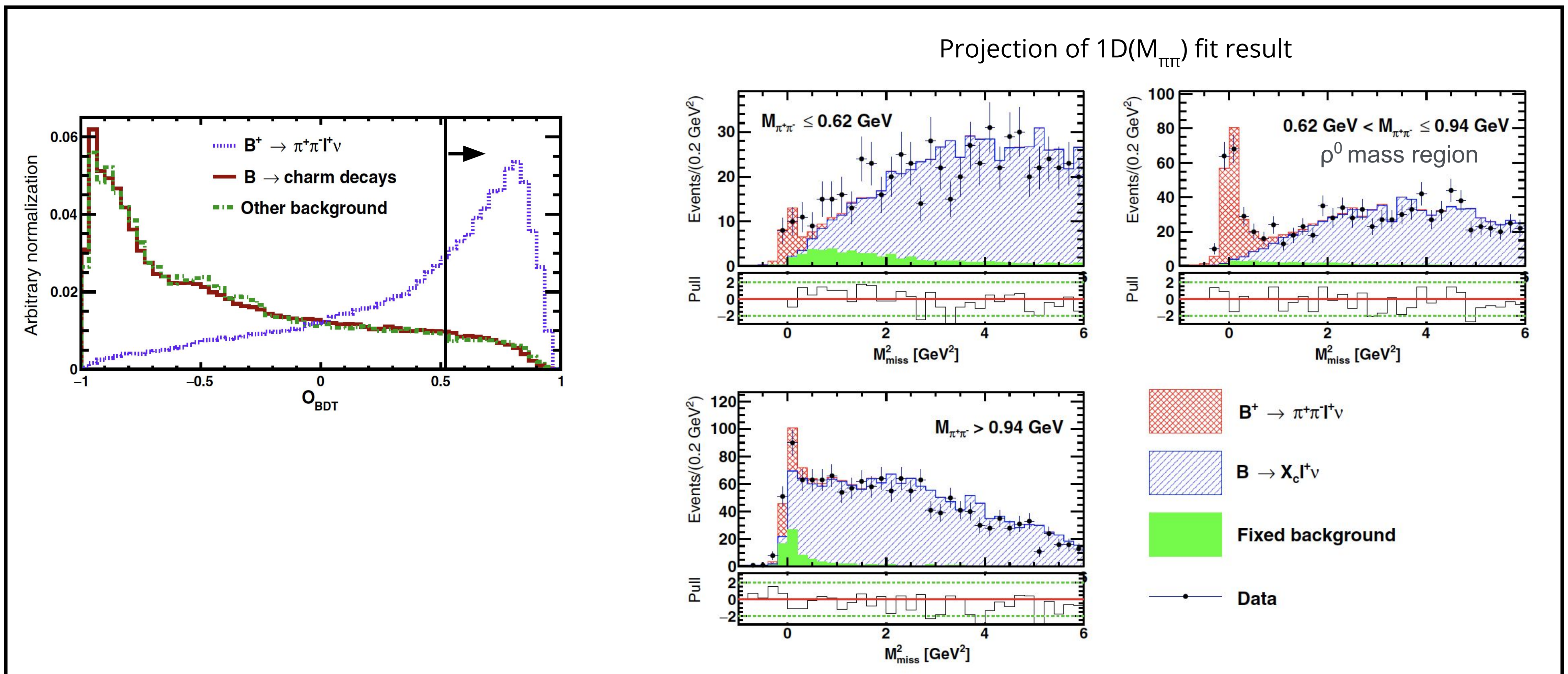
Event selection

Use **full Belle** data set & **hadronic tagging** with neural networks

Select $B^{\pm}_{\text{tag}}$ candidates and reconstruct $P_{\text{miss}} = P_{e^+e^-} - p_{B_{\text{tag}}} - P_\ell - P_{\pi^+} - P_{\pi^-}$

Suppress background via BDT trained on 6 features, e.g. $\Delta E, \theta_{\text{miss}}$, etc.

Signal yield extracted via $m^2_{\text{miss}} = P^2_{\text{miss}}$ in **bins** of $M_{\pi\pi}$ and q^2 (as projections and in 2D)



Result

First measurement of **differential** $B^+ \to \pi^+\pi^-\ell\bar{\nu}_\ell$ **BF** with full mass spectrum:

→ includes **resonant** (ρ, f_2,..) and **non-resonant** $\pi\pi$-contributions

→ Measured as a function of $M_{\pi\pi}$, q^2 and $M_{\pi\pi}$: q^2

Systematically **dominated** due to large **signal modelling uncertainties**

Clear evidence for additional **resonant** & **non-resonant contributions**, i.e. observe excess over $B^+ \to \rho^0\ell^+\nu_\ell$

$$\mathscr{B}(B^+ \to \rho^0\ell^+\nu_\ell) = (18.3 \pm 1.0 \pm 1.0) \times 10^{-3}$$

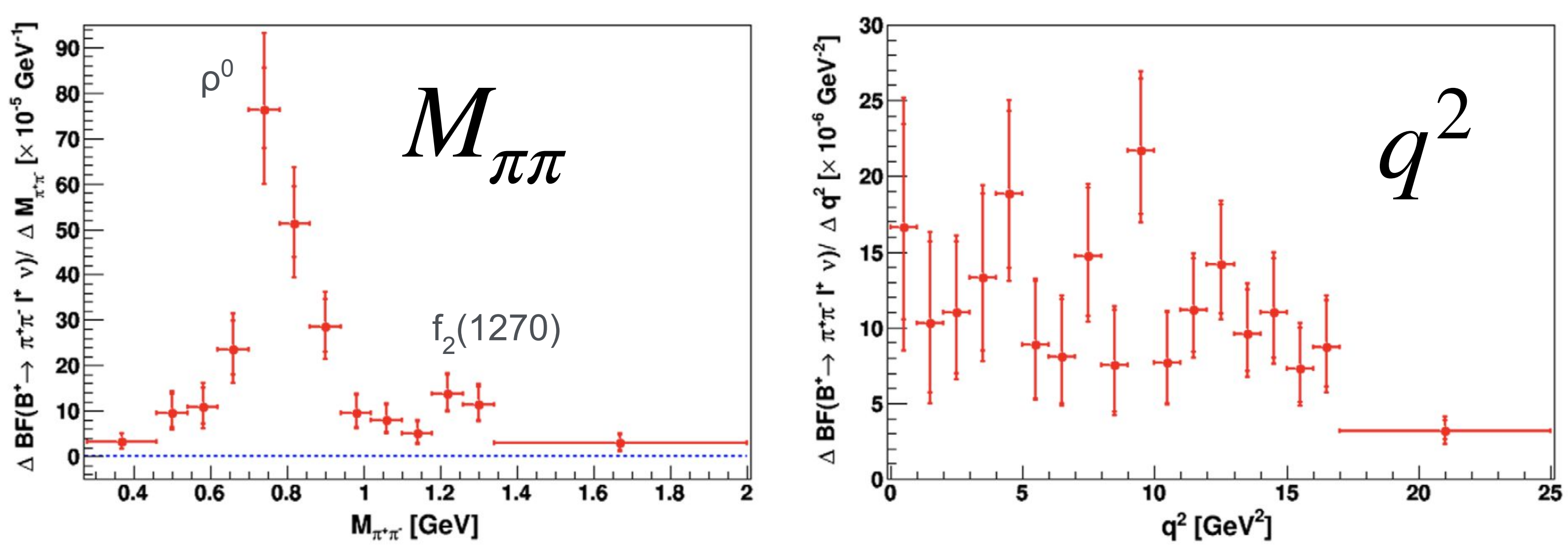
$$\mathscr{B}(B^+ \to \pi^+\pi^-\ell^+\nu_\ell) = \left(22.7 \pm 1.9 \pm 3.5\right) \times 10^{-3}$$

$$\mathcal{B}(B^+ \to \pi^+\pi^-\ell^+\nu_\ell)[\mathrm{1D}(M_{\pi\pi})] = [22.3^{+2.0}_{-1.8}(\mathrm{stat}) \pm 4.0(\mathrm{syst})] \times 10^{-5}$$

$$\boxed{\mathcal{B}(B^+ \to \pi^+\pi^-\ell^+\nu_\ell)[\mathrm{1D}(q^2)] = [22.7^{+1.9}_{-1.6}(\mathrm{stat}) \pm 3.5(\mathrm{syst})] \times 10^{-5}}$$

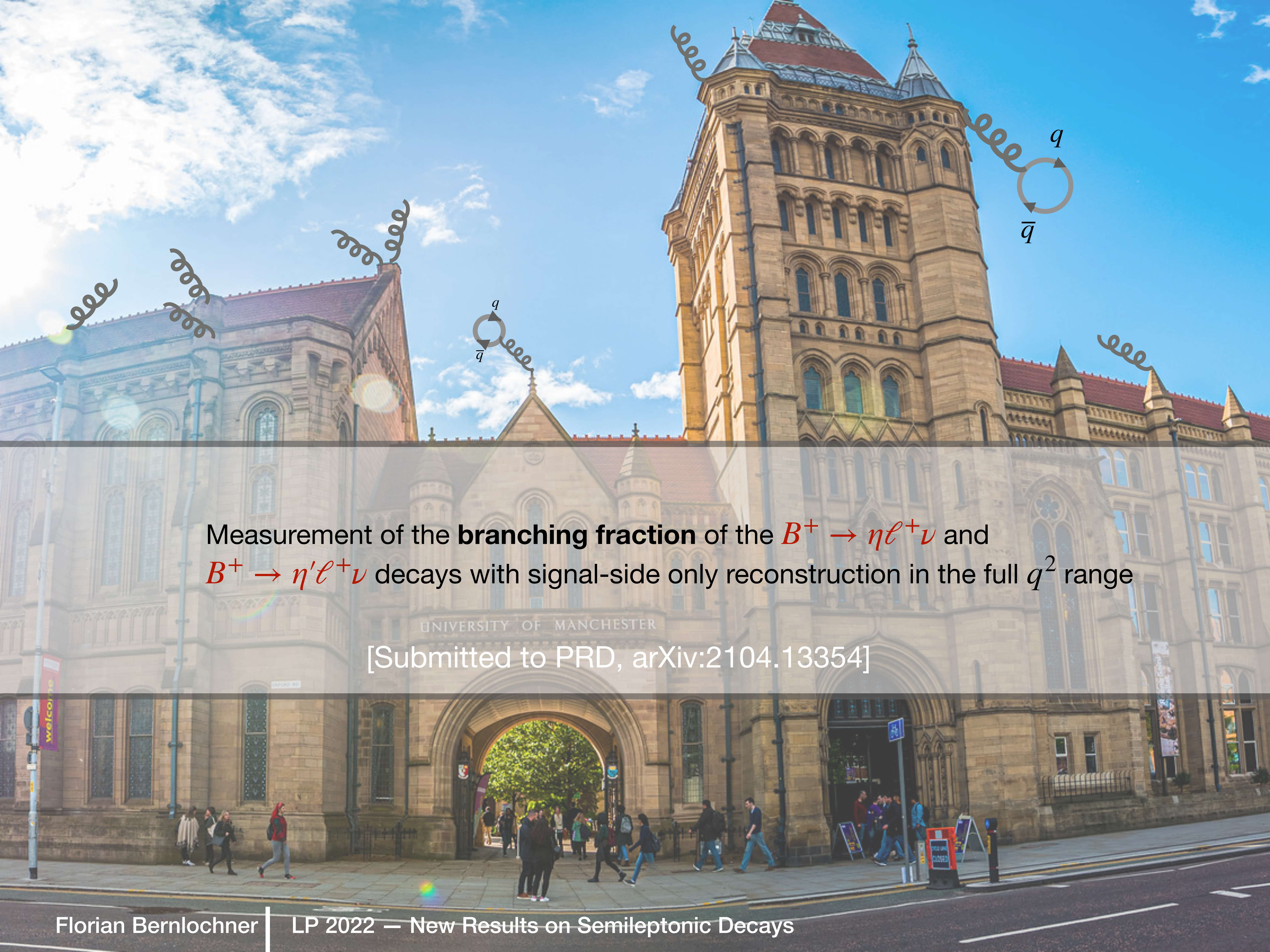
$$\mathcal{B}(B^+ \to \pi^+\pi^-\ell^+\nu_\ell)[\mathrm{2D}] = [23.0^{+2.0}_{-1.8}(\mathrm{stat}) \pm 3.0(\mathrm{syst})] \times 10^{-5}$$

Partial banching fractions with 1D($M_{\pi\pi}$) and 1D(q^2) config.



Measurement of the **branching fraction** of the $B^+ \to \eta \ell^+ \nu$ and $B^+ \to \eta' \ell^+ \nu$ decays with signal-side only reconstruction in the full q^2 range

[Submitted to PRD, arXiv:2104.13354]



Results

$$\cos\theta_{B-\eta\ell} = \frac{2E_B E_{\eta\ell} - m_B^2 - m_{\eta\ell}^2}{2|p_B||p_{\eta\ell}|}$$

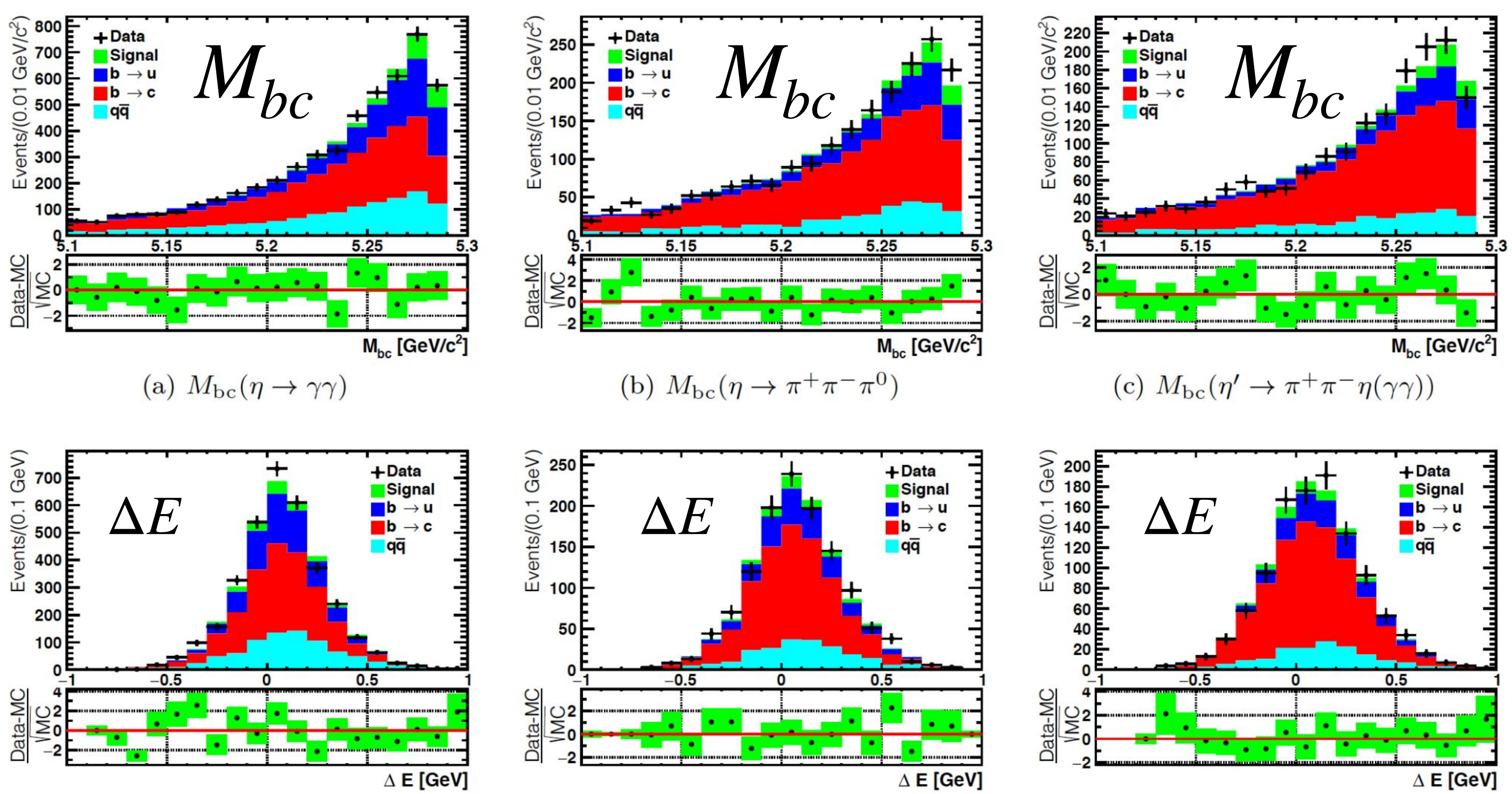
Use **full Belle** data set without tagging in 3 channels: $\eta \to \gamma\gamma, \eta \to \pi^+\pi^-\pi^0, \eta' \to \pi^+\pi^-\eta$

Suppress background via two BDTs and select events with $|\cos\theta_{B-\eta\ell}| < 1$

Signal yield extracted via ML fit in 2D with $M_{bc} : \Delta E$

Preliminary

Post-fit projections

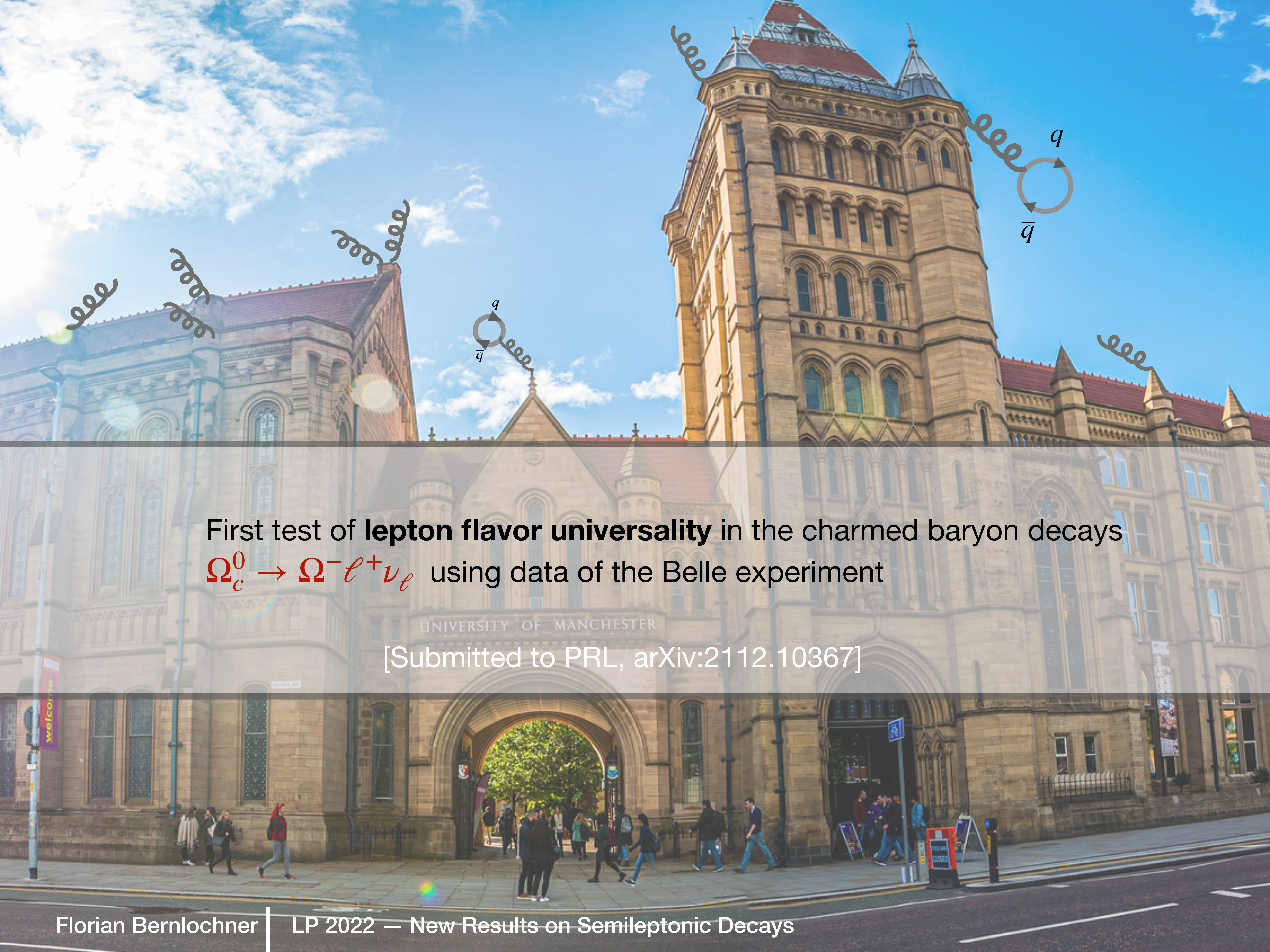


(a) $M_{bc}(\eta \to \gamma\gamma)$ (b) $M_{bc}(\eta \to \pi^+\pi^-\pi^0)$ (c) $M_{bc}(\eta' \to \pi^+\pi^-\eta(\gamma\gamma))$

(d) $\Delta E(\eta \to \gamma\gamma)$ (e) $\Delta E(\eta \to \pi^+\pi^-\pi^0)$ (f) $\Delta E(\eta' \to \pi^+\pi^-\eta(\gamma\gamma))$

$$\mathscr{B}(B^+ \to \eta\ell\bar{\nu}_\ell) = \left(2.83 \pm 0.55 \pm 0.34\right) \times 10^{-5}$$

$$\mathscr{B}(B^+ \to \eta'\ell\bar{\nu}_\ell) = (2.79 \pm 1.29 \pm 0.30) \times 10^{-5}$$



First test of **lepton flavor universality** in the charmed baryon decays $\Omega_c^0 \to \Omega^- \ell^+ \nu_\ell$ using data of the Belle experiment

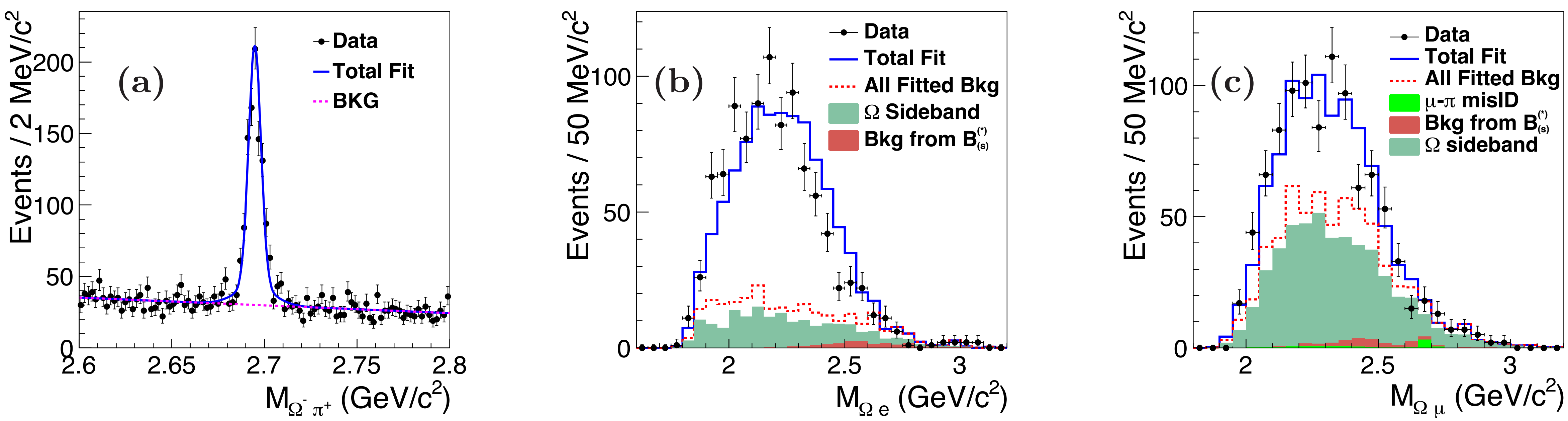
[Submitted to PRL, arXiv:2112.10367]

Results

Use **full Belle** data set of on-resonance and off-resonance data;
Production process is $e^+e^- \to c\bar{c} \to \Omega_c^0$ + anything

Signal yield extracted via ML fit of $M_{\Omega\ell}$ and normalized to $\Omega_c^- \to \Omega^-\pi^+$

First observation of $\Omega_c^- \to \Omega^-\mu\bar{\nu}_\mu$



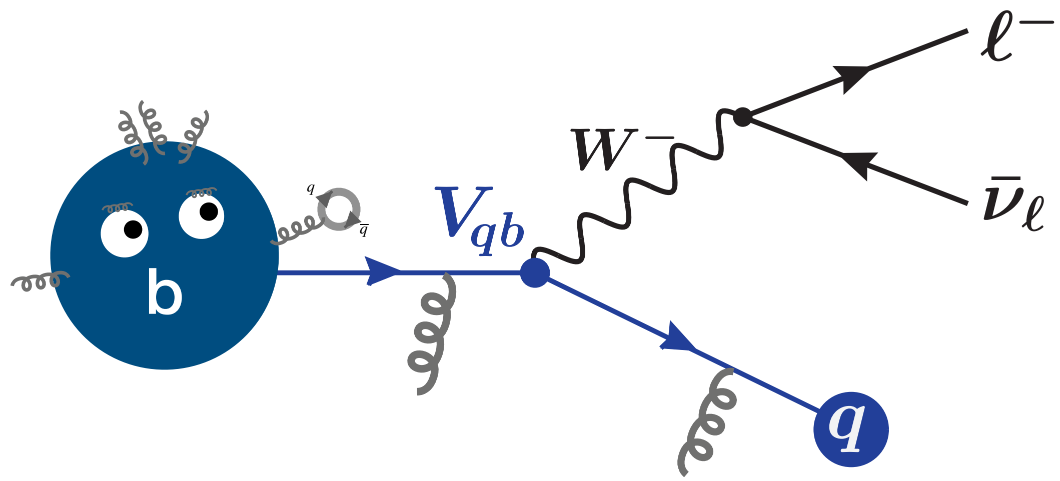
Observe ratio of $$\frac{\mathscr{B}(\Omega_c^0 \to \Omega^- e^+ \nu_e)}{\mathscr{B}(\Omega_c^0 \to \Omega^- \mu^+ \nu_\mu)} = 1.02 \pm 0.10 \pm 0.02$$

$$\frac{\mathscr{B}(\Omega_c^0 \to \Omega^- e^+ \nu_e)}{\mathscr{B}(\Omega_c^0 \to \Omega^- \mu^+ \nu_\mu)} = 1.03$$

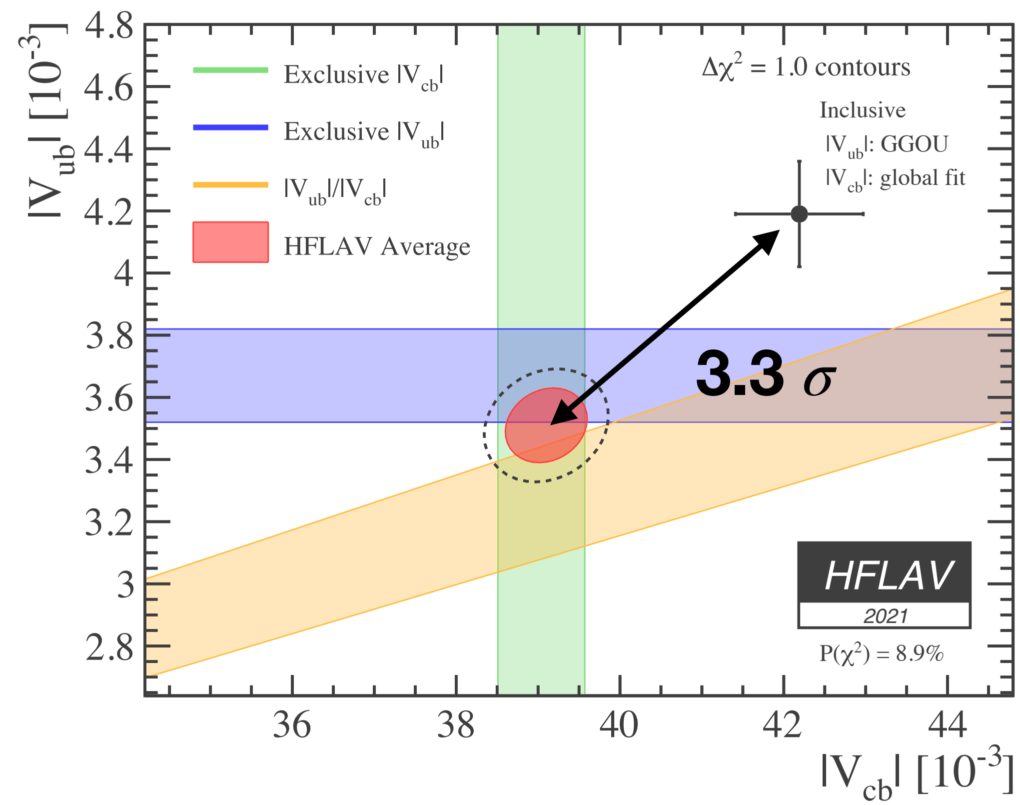
F. Huang, Q-A Zang
[arXiv:2108.06110]

Summary

He may look cute, but that might be deceiving…



… Long-standing discrepancy since about a decade



Belle very active and produced several recent results:

- Discrepancy between exclusive & inclusive $|V_{ub}|$ is reduced by recent BF measurements
- First systematic measurements of differential $B \to X_u \ell \bar{\nu}_\ell$ branching fractions provide input for future, less model-independent $|V_{ub}|$ determinations
- First measurement of $B \to X_c \ell \bar{\nu}_\ell$ q^2 moments; new observable for inclusive $|V_{cb}|$
- First measurements of $B \to \pi\pi \ell \bar{\nu}_\ell$ mass spectrum and q^2 distribution; potentially new channel for exclusive $|V_{ub}|$
- New measurements of $B \to \eta^{(')} \ell \bar{\nu}_\ell$ and LFU test with $\Omega_C \to \Omega \ell \bar{\nu}_\ell$