Inclusive Charmless Decays at Belle (II)

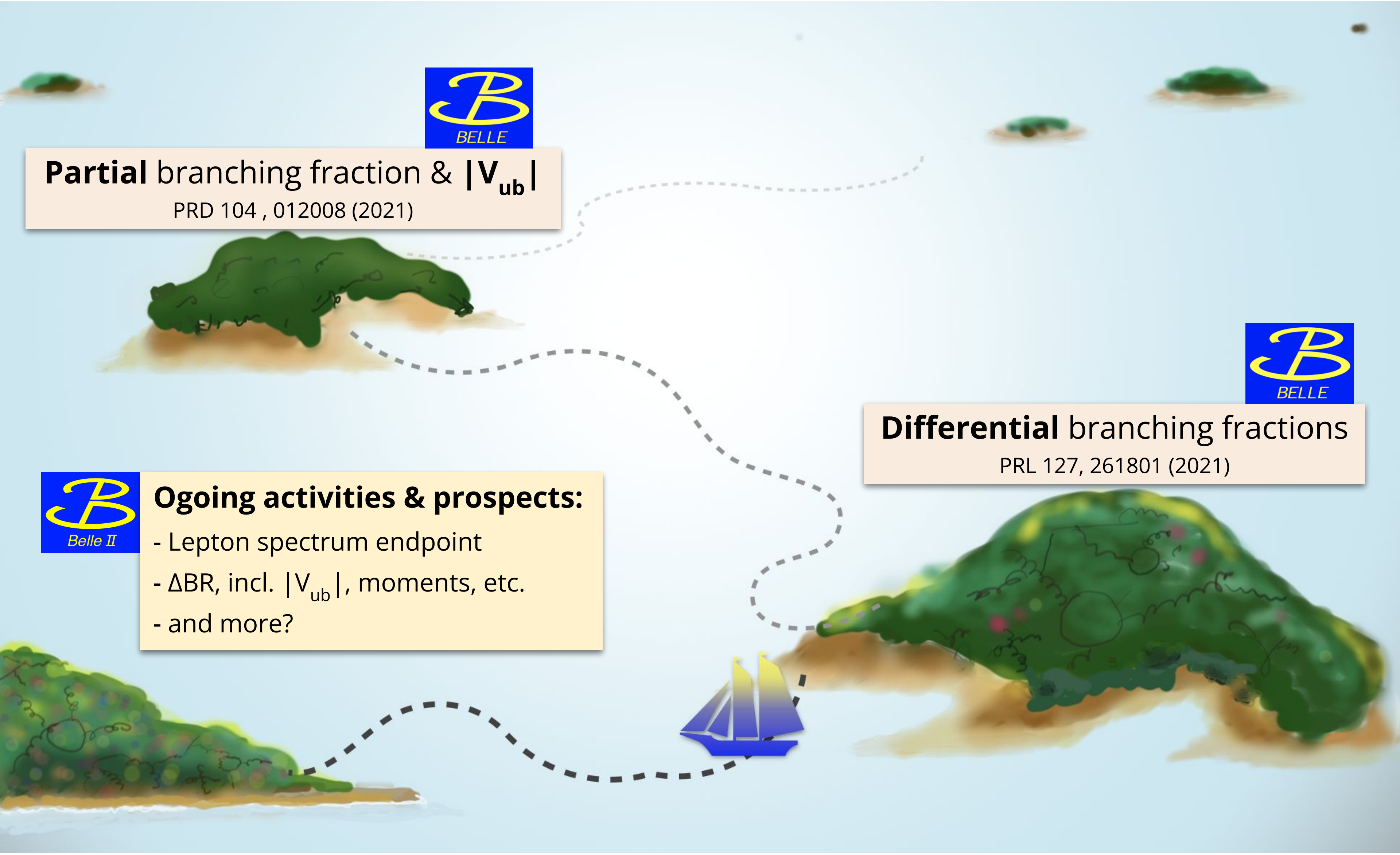
Lu Cao

for the Belle & Belle II Collaboration

"Challenges in Semileptonic B Decays" workshop @ Barolo, Italy
22 April 2022

lu.cao@desy.de

Adventure of Inclusive $B \rightarrow X_u \ell \nu$



Partial branching fraction & $|V_{ub}|$

PRD 104 , 012008 (2021)

Differential branching fractions

PRL 127, 261801 (2021)

Ogoing activities & prospects:

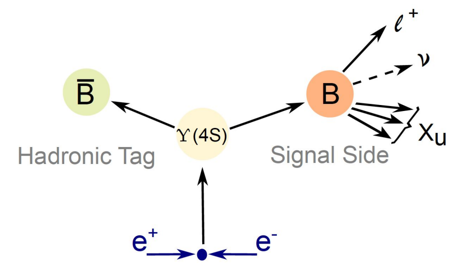
- Lepton spectrum endpoint
- ΔBR, incl. $|V_{ub}|$, moments, etc.
- and more?

$\Delta\mathcal{B}(B \to X_u \ell^+ \nu)$ and $|V_{ub}^{\text{incl.}}|$

PRD 104 , 012008 (2021)

Reconstruction of $B \to X_u \ell \nu$

- Using **full Belle** dataset of **711 fb^{-1}**
- **Hadronic tagging** with Neural Networks (~ 0.2-0.3% efficiency)
- Use **machine learning (BDT)** to suppress backgrounds with 11 trainning features, e.g. MM^2,#$K^{\pm}$, #K_s, etc.



Can fully assign each final state particle to either the tag or signal side

→ Allows to reconstruct X_u

Reconstructed kinematic variables

- Hadronic system X:

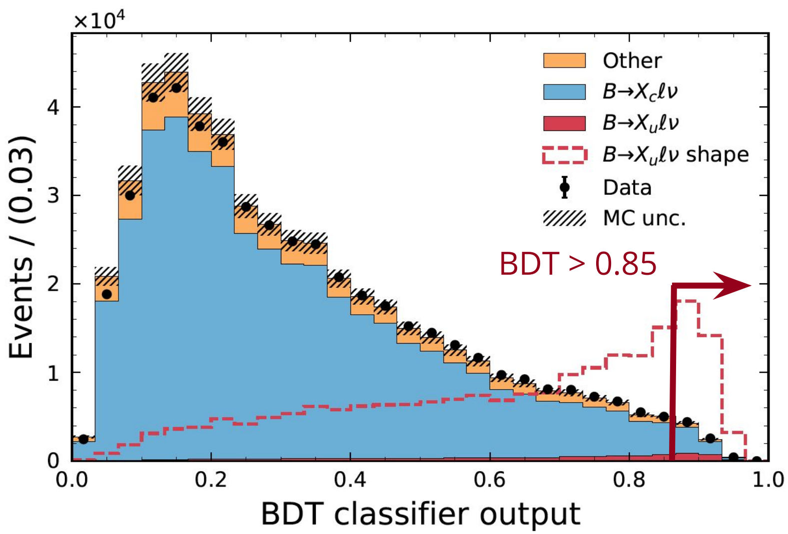
$$p_X = \sum_i \left(\sqrt{m_\pi^2 + |\mathbf{p_i}|^2}, \mathbf{p_i}\right) + \sum_i (E_i, \mathbf{k_i})$$

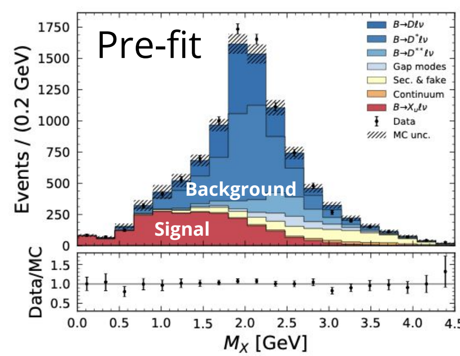
- Missing mass squared:

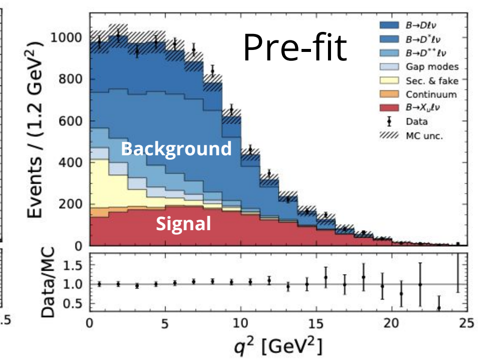
$$MM^2 = \left(P_{\Upsilon(4S)} - P_{\text{tag}} - P_X - P_\ell\right)^2$$

- Leptonic system:

$$q^2 = (P_B - P_X)^2 = (P_l + P_\nu)^2$$





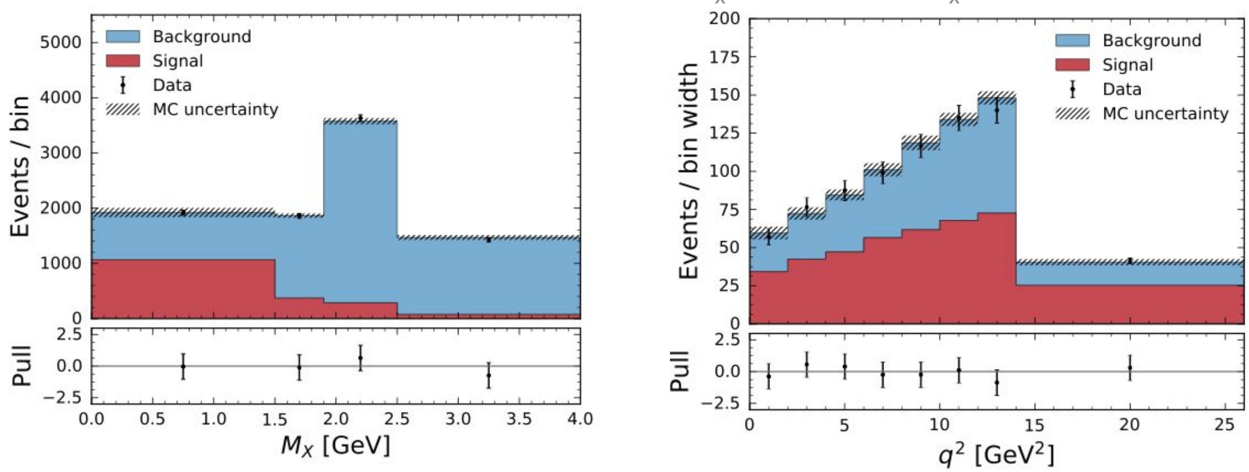


Partial Branching Fractions of $B \to X_u \ell \nu$

- Extract signal using binned likelihood in **3 phase space (PS) regions:**
  - $E_\ell^B > 1$ GeV **(covers 86% of available signal PS)**
  - $E_\ell^B > 1$ GeV, $M_X < 1.7$ GeV **(56%)**
  - $E_\ell^B > 1$ GeV, $M_X < 1.7$ GeV, $q^2 > 8$ GeV^2 **(31%)**

  → Fit either E_ℓ^B , M_X , q^2 or 2D (M_X : q^2)
- Signal yields further corrected for efficiency & acceptance in 3 PS regions
- Split results on e, μ, B^0, B^+ modes are provided for $E_\ell^B > 1$ GeV region

Projection of 2D fit result on M_X and q^2(in 1st M_X bin)



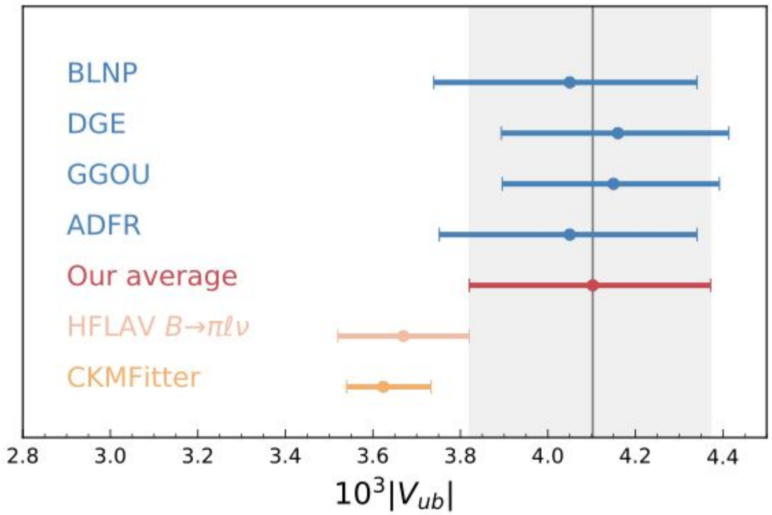
$$\Delta\mathcal{B}(E_\ell^B > 1\text{ GeV}) = (1.59 \pm 0.07_{stat} \pm 0.16_{sys}) \times 10^{-3}$$

based on 2D fit

Inclusive $|V_{ub}|$

- Convert partial BF in $E_\ell^B > 1$ GeV of 2D fit result to $|V_{ub}|$
- Based on **four** calculations of the **decay rate**

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

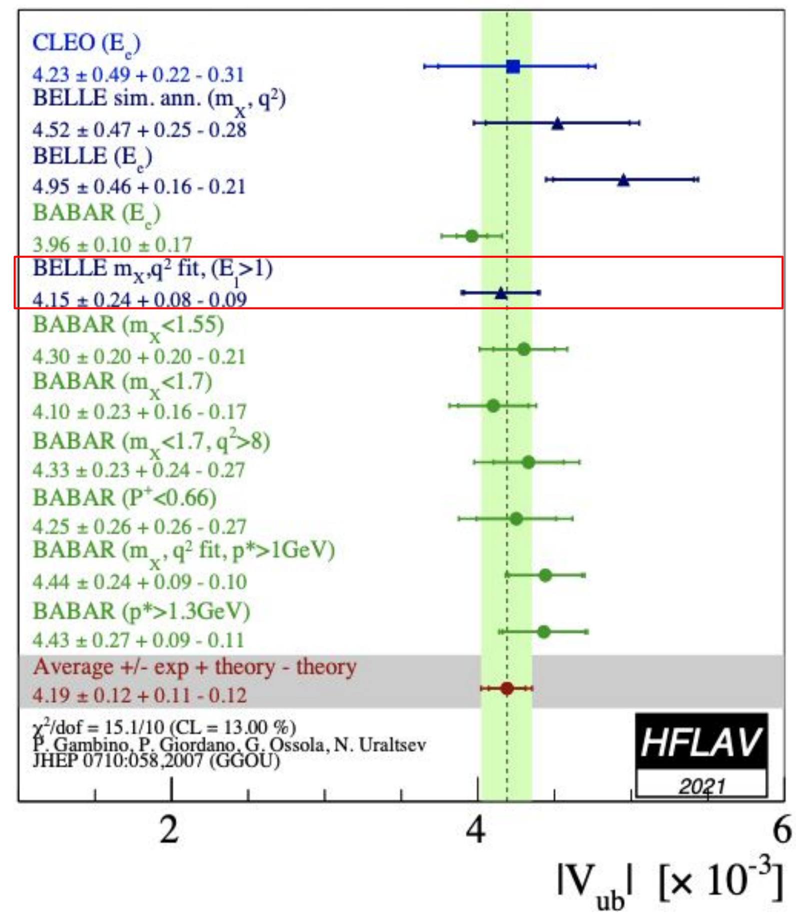


Our average:

$|V_{ub}| = (4.10 \pm 0.09_{stat} \pm 0.22_{sys} \pm 0.15_{theo}) \times 10^{-3}$

compatible with excl. and CKM expectation within **1.3σ** and **1.6σ** respectively

Comparions based on GGOU



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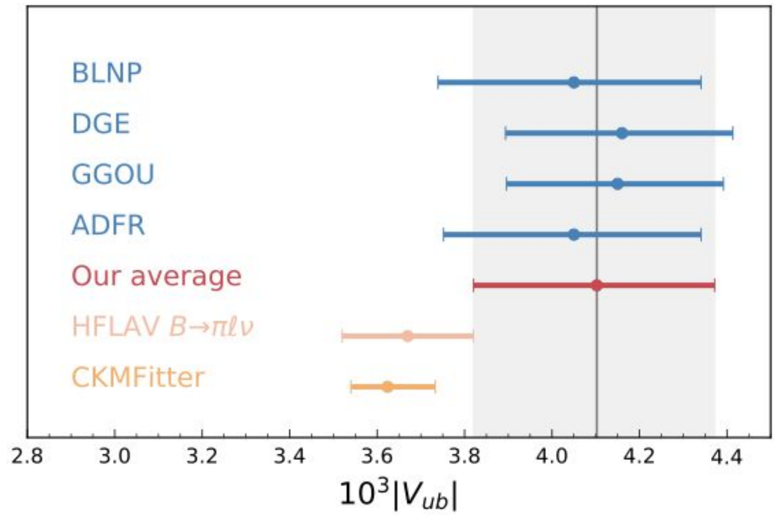

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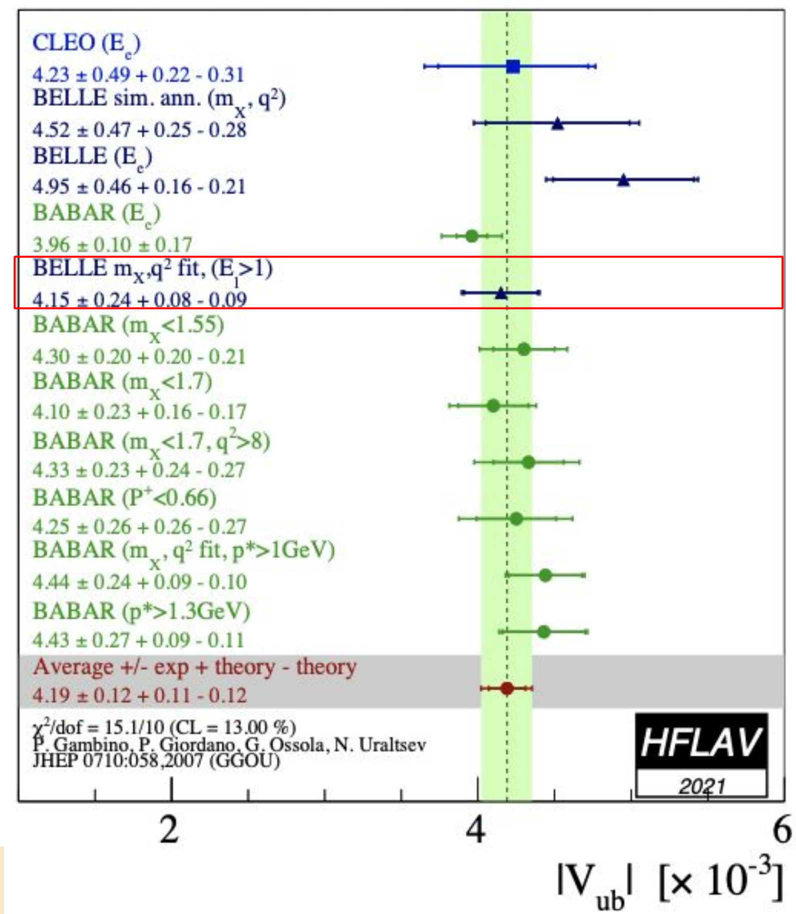

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1.1σ wrt new **LCSR** calculation [JHEP 07 (2021) 036]

0.6σ wrt new **JLQCD** result [arXiv:2203.04938]

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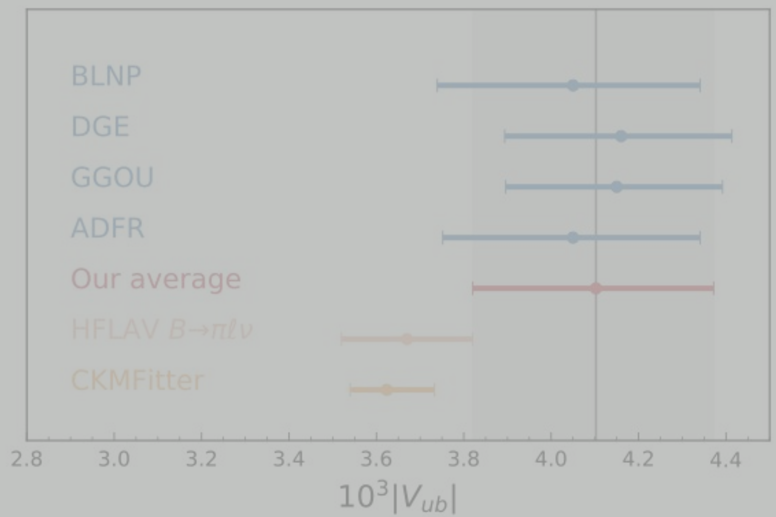

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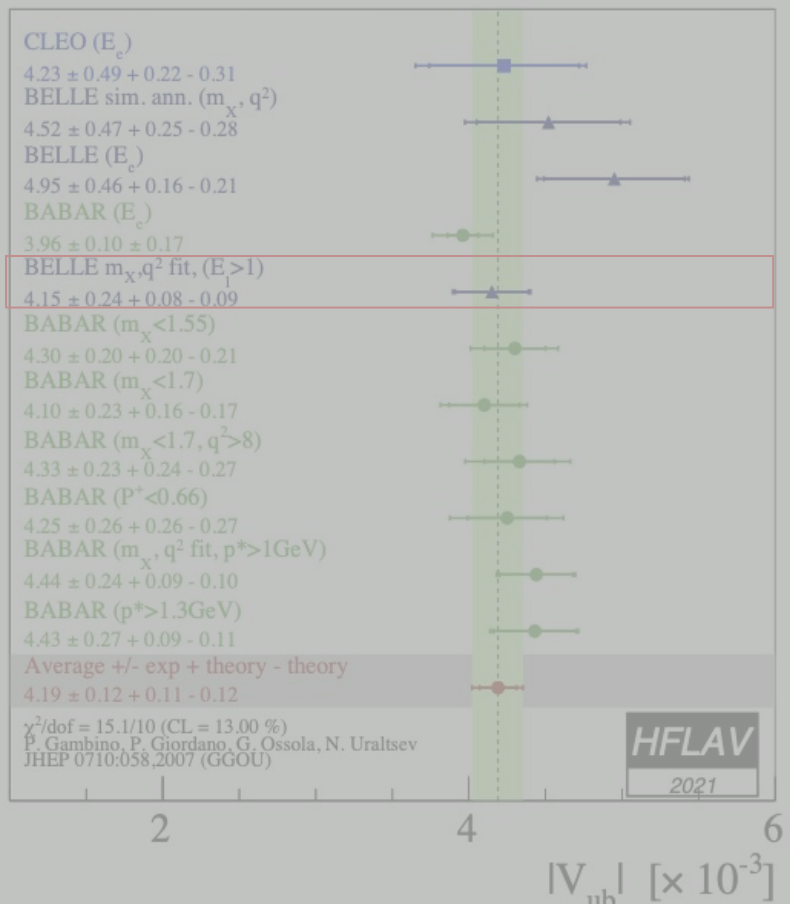

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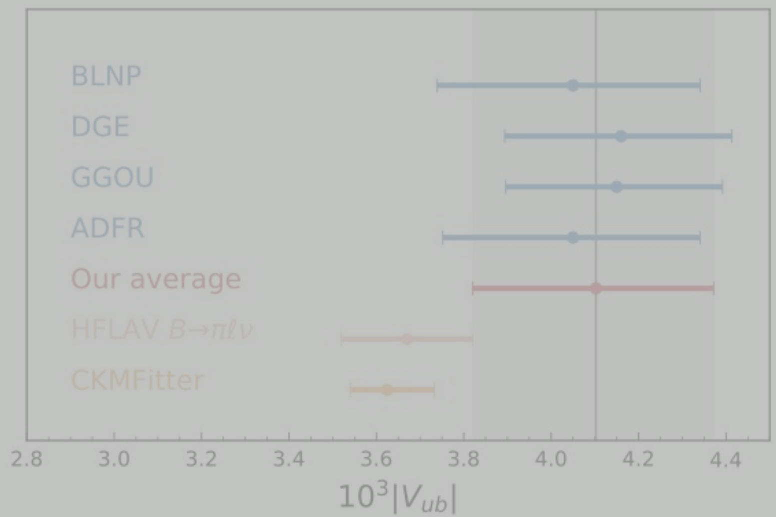
In the traditional way, all kinematic information of this decay is wrapped into **normalization: decay rate** as input for determining $|V_{ub}|$

→ **model-dependent extraction of $|V_{ub}|$**



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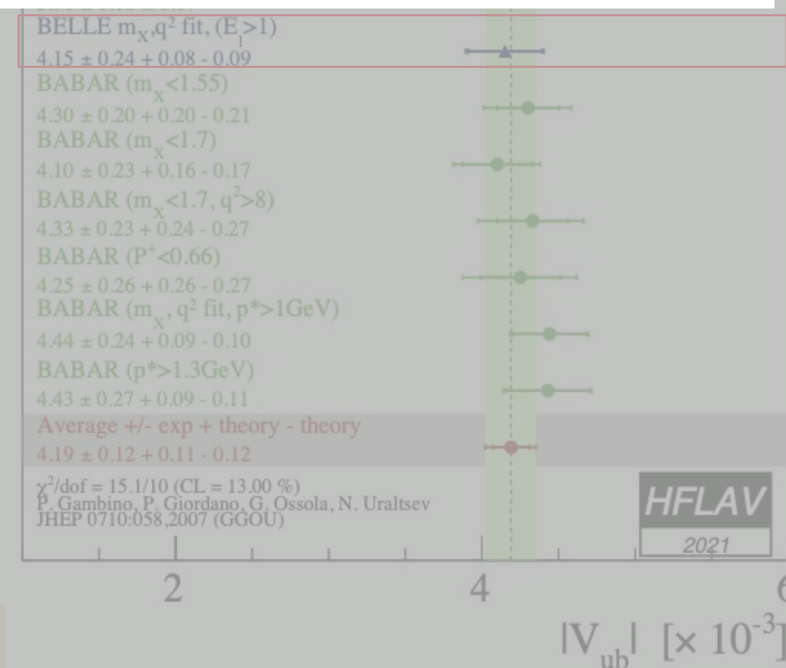

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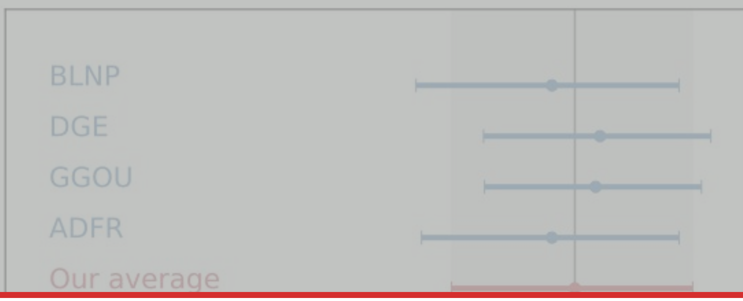

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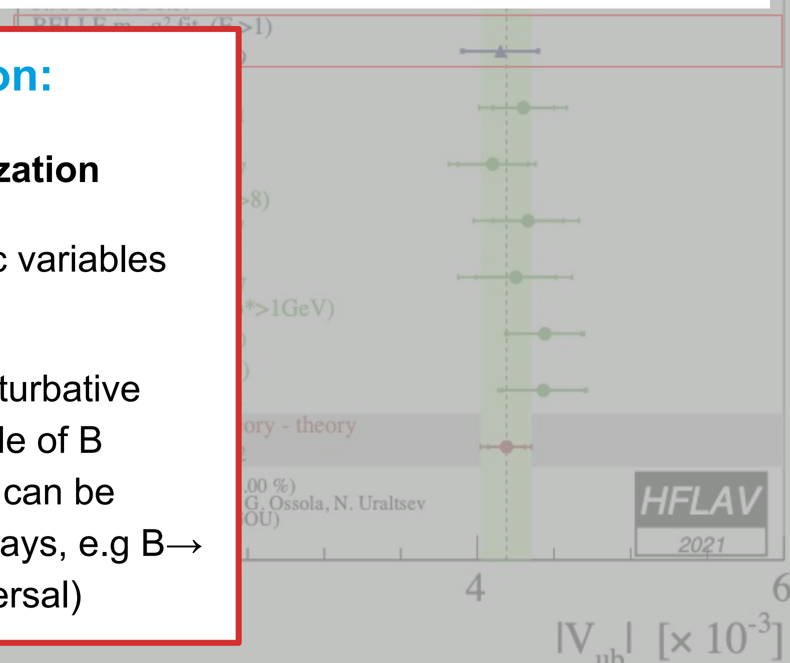

Direct & more model-independent extraction:

normalization ⇒ kinematic shapes + normalization

- **Exp:** measure differential spectra of key kinematic variables and provide full covariance information for them
- **Theo+Exp:** directly extract coefficients of non-perturbative shape functions (Fermi motion of the b quark inside of B meson) in a global fit and obtain $|V_{ub}|$; uncertainty can be further shrinked by including other inclusive B decays, e.g B→ $X_s\gamma$, B→ $X_c\ell\nu$ (as the shape function in LO is universal)

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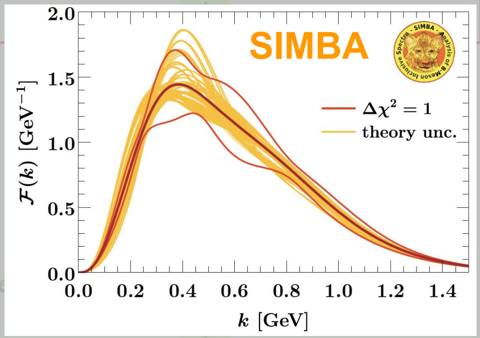

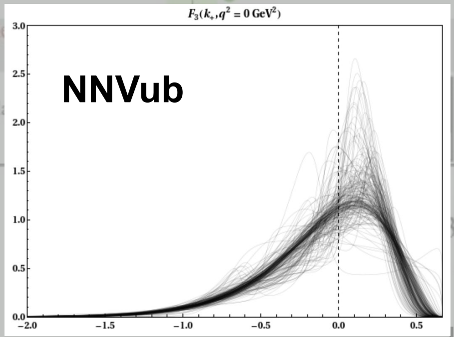

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Differential $\Delta\mathcal{B}(B \to X_u \ell^+ \nu)$

PRL 127, 261801 (2021)

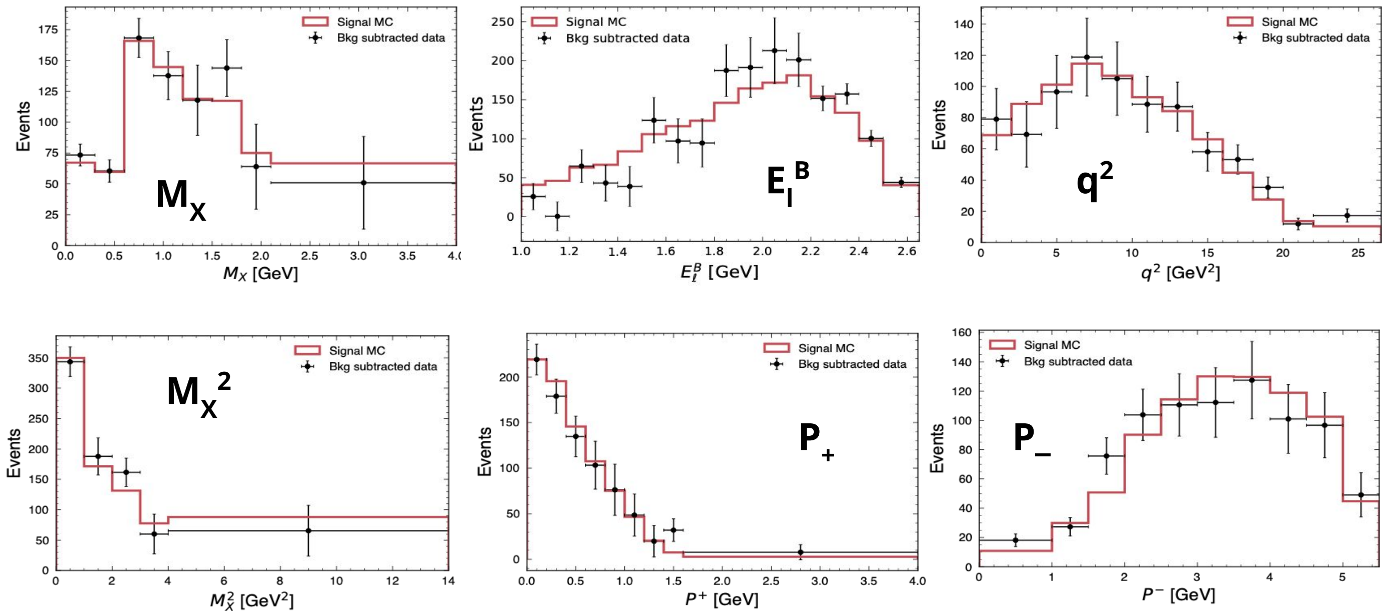
Differential BF of $B \to X_u \ell^+ \nu$

Background-subtracted spectra

- We measure the following 6 kinematic variables in the phase space of $E_l^B > 1$ GeV:

  q^2, E_l^B, M_X, M_X^2, P_+, P_- (light-cone momenta: $P_\pm = E_X \mp |p_X|$)

- Selection and reconstruction inherited from the partial BR measurement presented previously
- Additional selections on **$|E_{miss} - P_{miss}| < 0.1$ GeV** and reconstructed **$M_X < 2.4$ GeV** to improve resolution and reduce background shape uncertainty
- Background subtraction done via **M_X fit;** subtracted spectra are shown as below

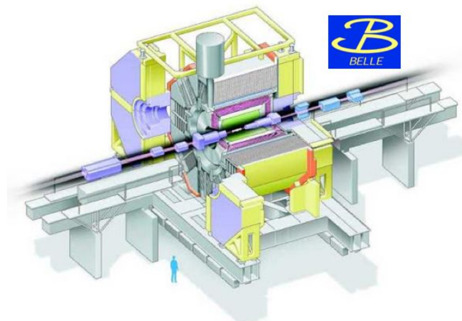


- **Full bkg-sub. uncertainties** are propagated

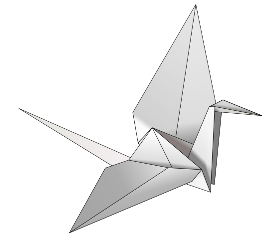
- **Overlaid MC** signal hybrid X_u (& normalised to fitted signal yields)

Unfolding

***X*: true distribution**

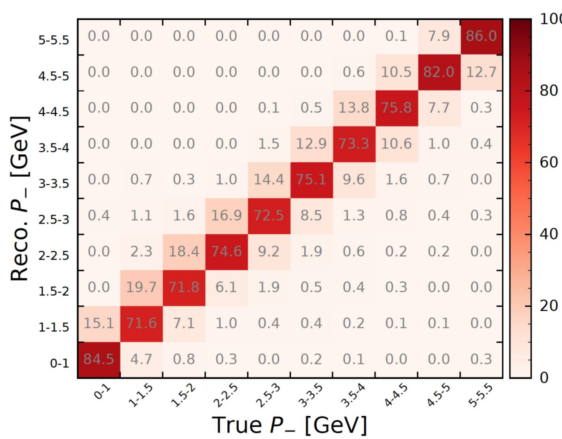


***M*: detector response**



***Y*: measured distribution**

- The detector response is represented by a migration matrix ***M***
- *M*(*i*, *j*) indicates the probability (%) to observe an event in bin *i* if it had a generator-level value in bin *j*



$$MX = Y$$

Direct solution for X is

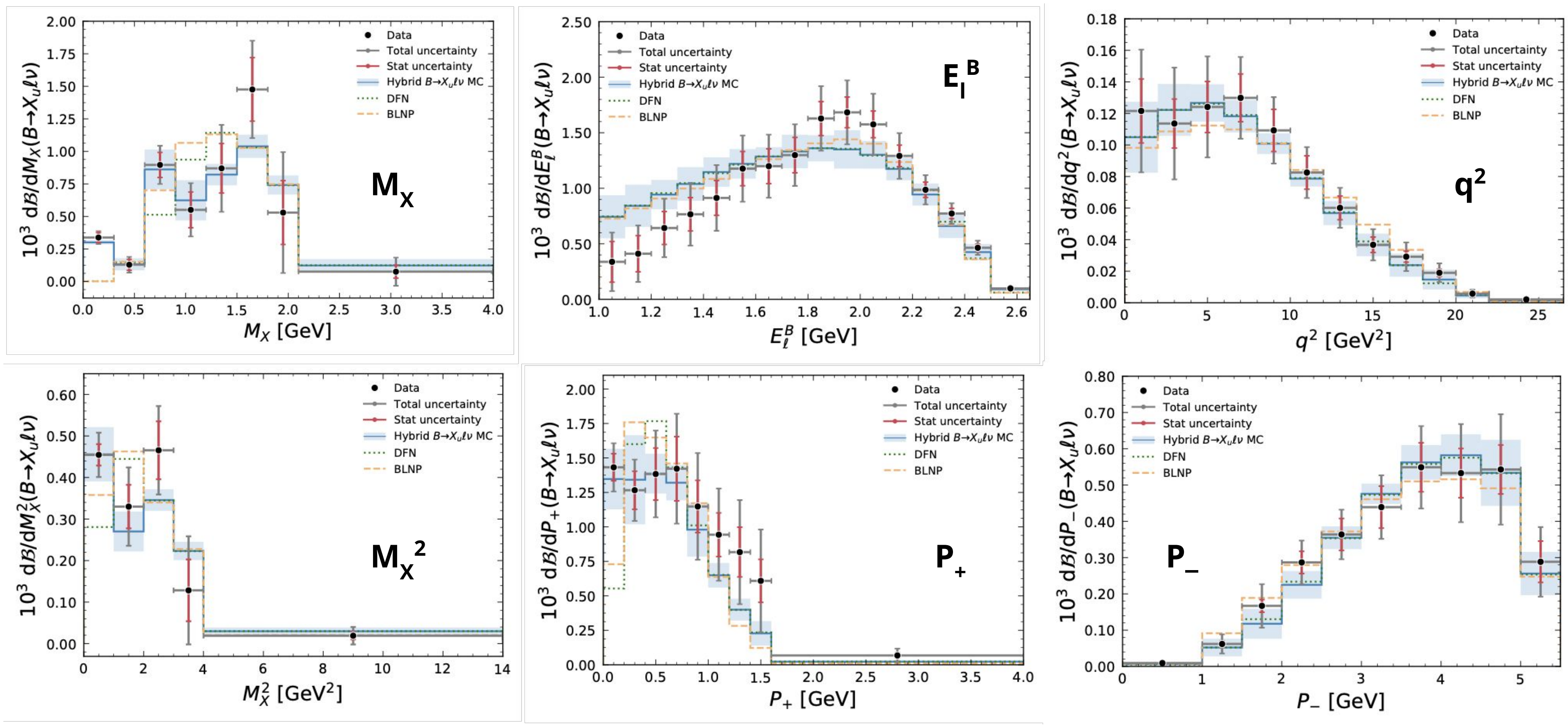
$$X = M^{-1}Y$$

- **Singular-Value-Decomposition (SVD)** [NIMA 372:469(1996)] is used in this analysis

Differential Spectra of $B \to X_u \ell^+ \nu$

$$\Delta^i\mathcal{B}\left(B \to X_u \ell^+ \nu_\ell;\ \mathrm{PS}\right) = \frac{\hat{\eta}^i_{\mathrm{unfolded}} \cdot \left(\epsilon^i_{\mathrm{tag}} \cdot \epsilon^i_{\mathrm{sel}}\right)^{-1} \cdot \epsilon^i_{\Delta\mathcal{B}(\mathrm{PS})}}{4 \cdot N_{B\bar{B}}}$$

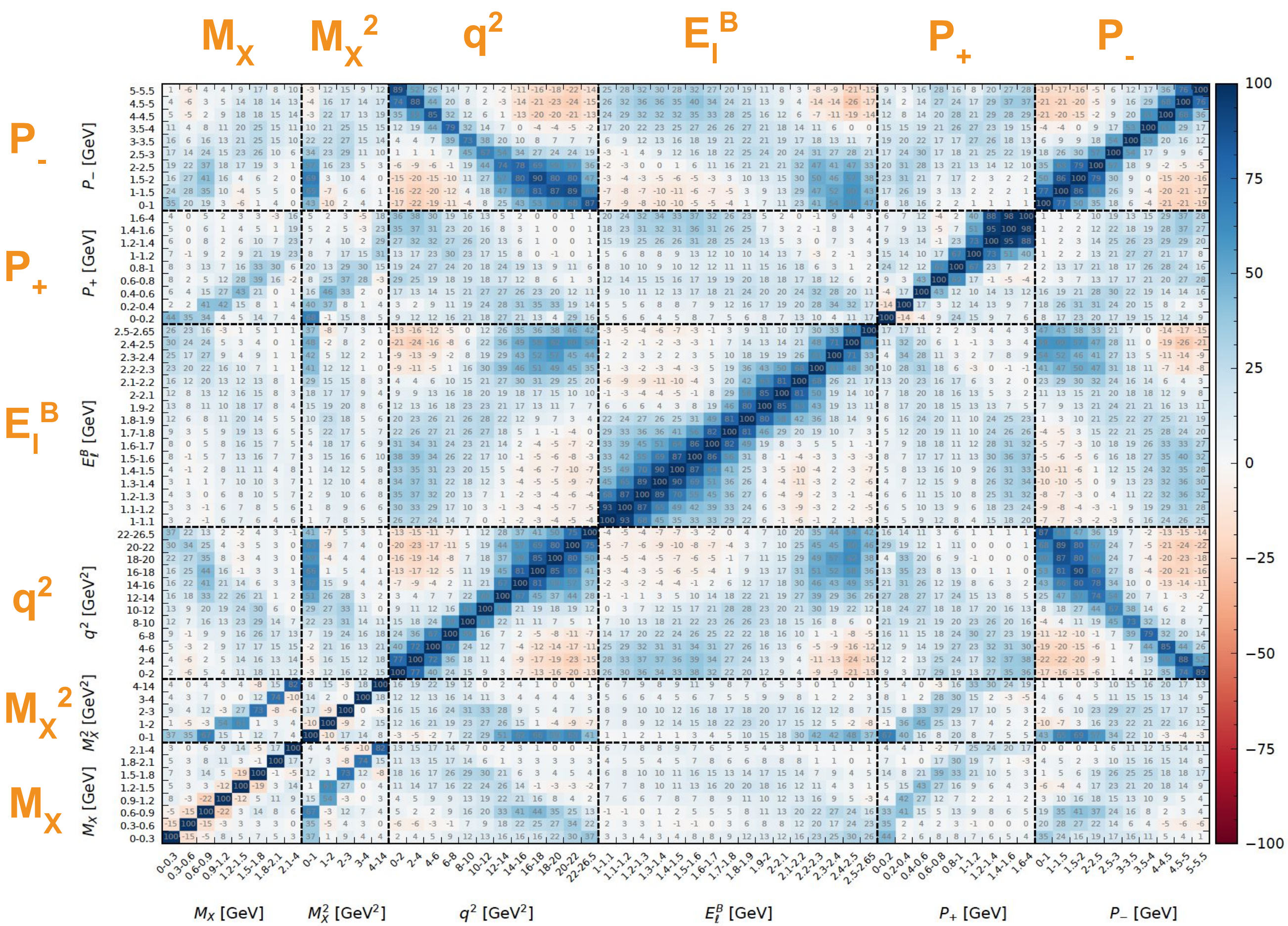
- Differential branching fractions ($E_\ell^B > 1$ GeV) are measured **for the first time**
- Necessary input for future **model-independent** determinations of **$|V_{ub}|$** (e.g. NNVub, SIMBA)

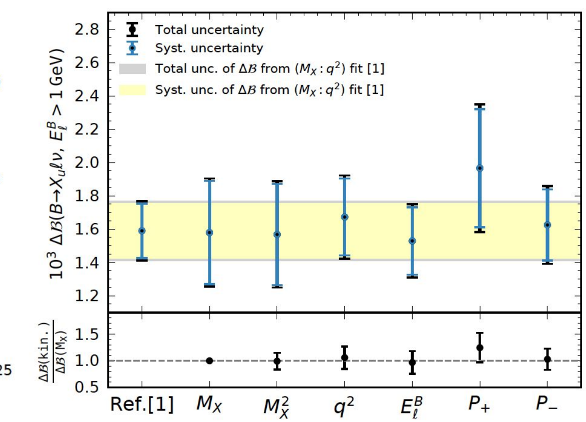


All MC shapes are normalised to 1.59×10^{-3} [Belle, PRD 104 , 012008 (2021)]

Correlations of All Measured $\Delta\mathcal{B}$

- Full experimental correlations of differential $\Delta\mathcal{B}$ are extracted (important for global fit)
- Summed $\Delta\mathcal{B}$ agree well with $(1.59 \pm 0.07 \pm 0.16)\times10^{-3}$ from $(M_X : q^2)$ fit result of [1]

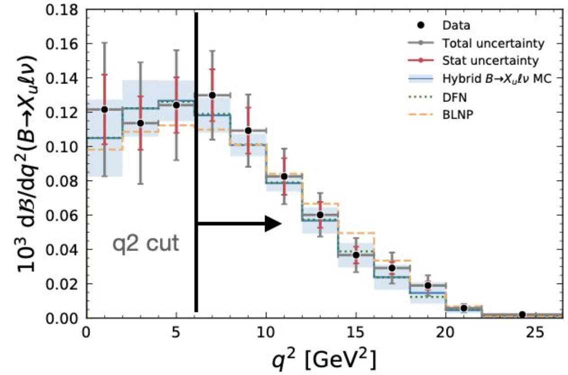




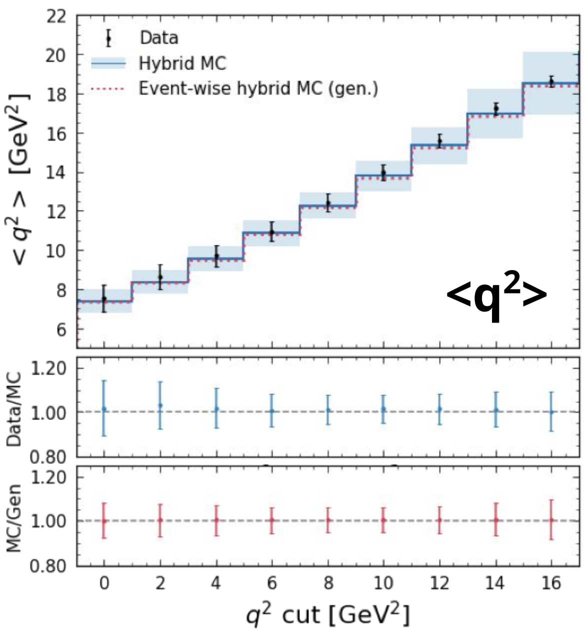
[1] Belle, PRD 104 , 012008 (2021)

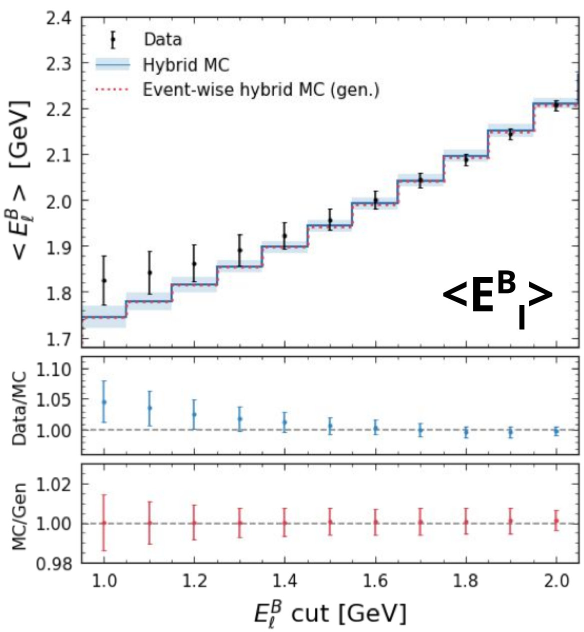
Extracted Moments

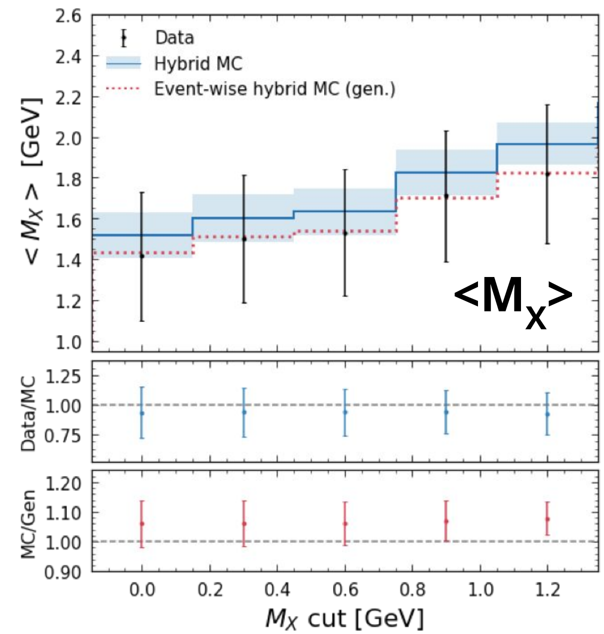
- The **first to third moments** of all measured kinematic varialbes are provided in suppl. material
- Accuracy of using **binned spectra** is checked by comparing with unbinned treatment
- Biases are found negligible, resulting biases seen in M_X are included in total uncertainty (due to fine peaks of resonances)



$$\langle k^n \rangle_{k>k^{\mathrm{cut}}} = \frac{\int_{k>k^{\mathrm{cut}}} \mathrm{d}k \cdot k^n \cdot \frac{\mathrm{d}\mathscr{B}}{\mathrm{d}k}}{\int_{k>k^{\mathrm{cut}}} \mathrm{d}k \frac{\mathrm{d}\mathscr{B}}{\mathrm{d}k}}, \quad n = [1,2,3], \quad k = \text{kin. variable}$$







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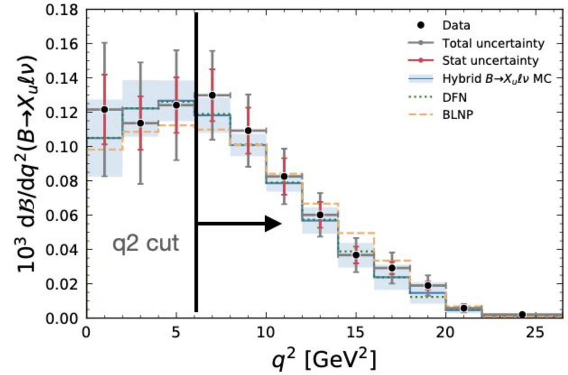

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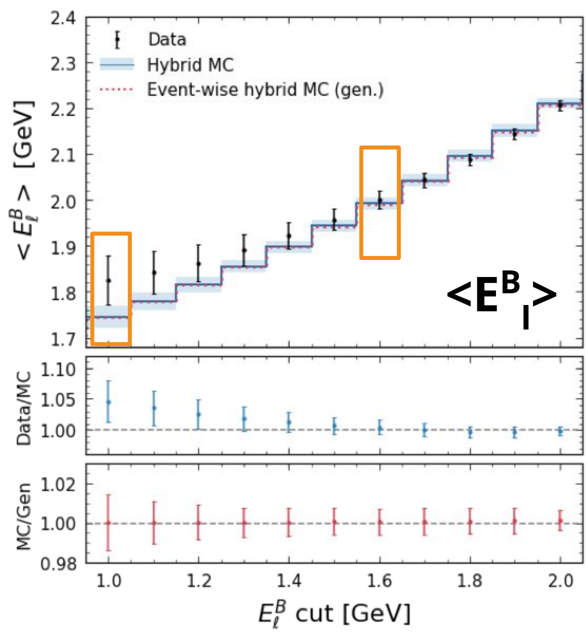
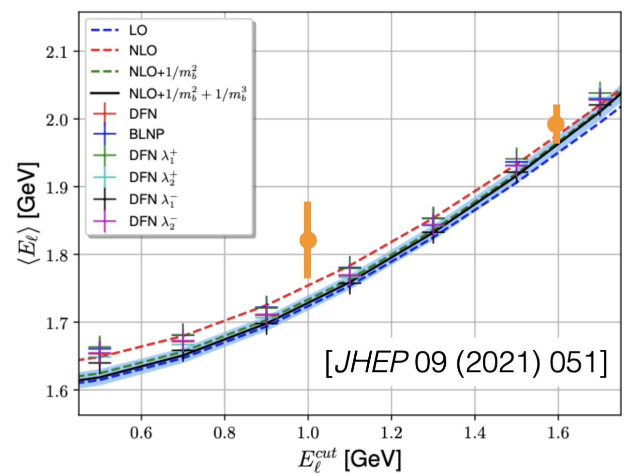
A quick look at the comparision of recent HQE prediction [*JHEP* 09 (2021) 051]



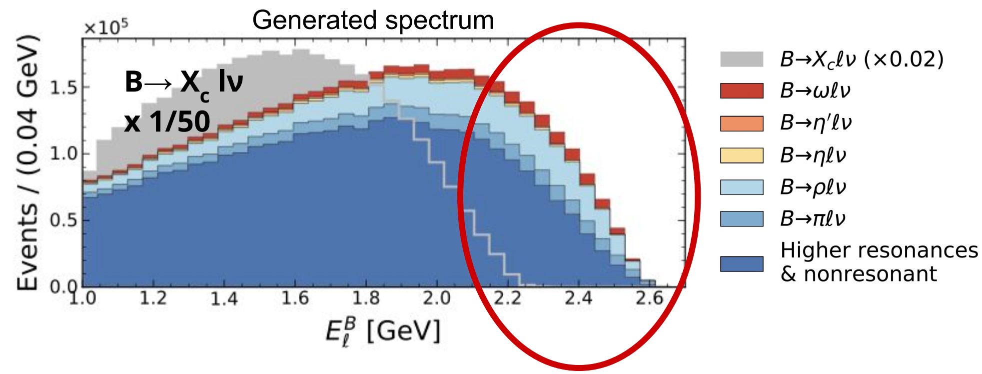


Lepton Momentum Endpoint

arXiv:2103.02629, shown in Beauty2020 & EPS-HEP2021

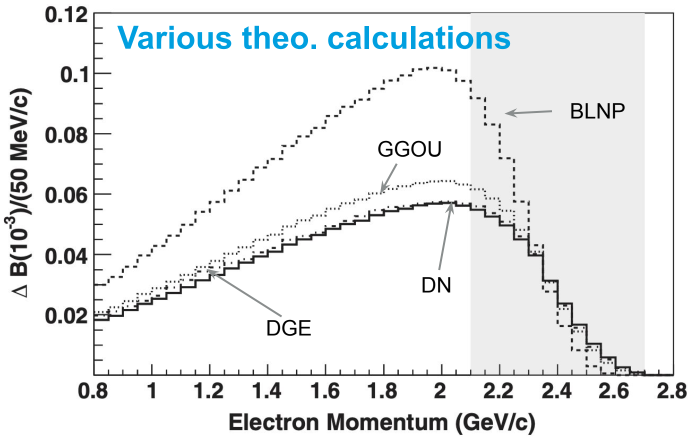
Why endpoint?

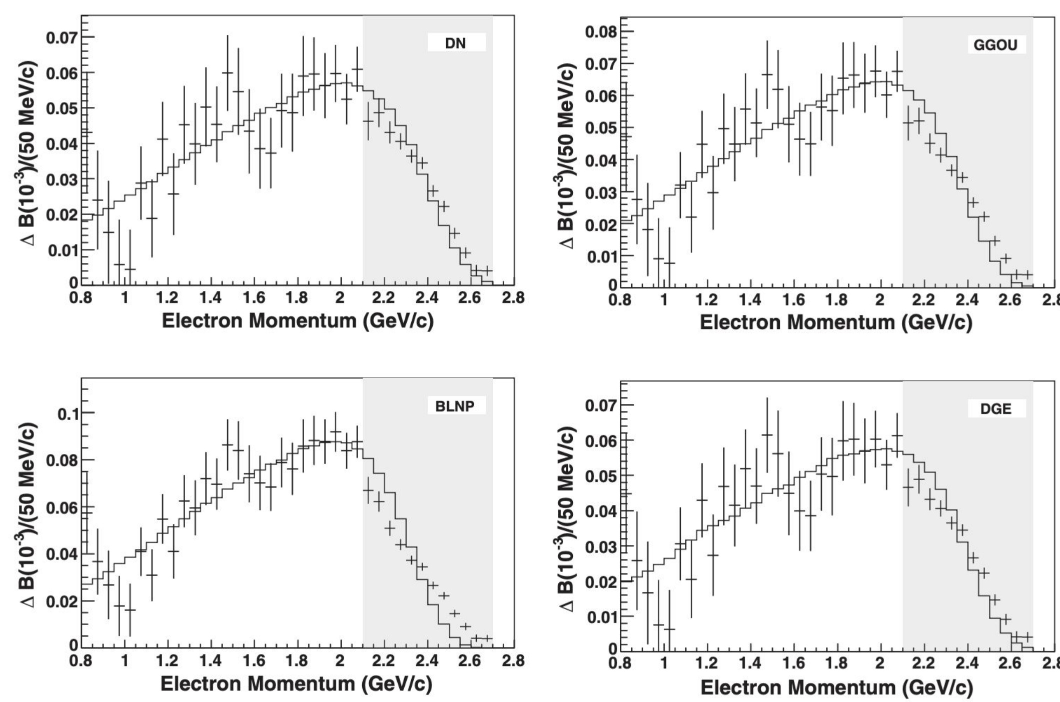
- Clear separation only possible in certain kinematic regions, e.g. **lepton endpoint** or low M_X
- Excellent resolution for lepton momentum/energy
- Sensitive to the shape of inclusive decays in this phase space



BaBar: PRD 95, 072001 (2017)

Electron momentum in c.m.s frame



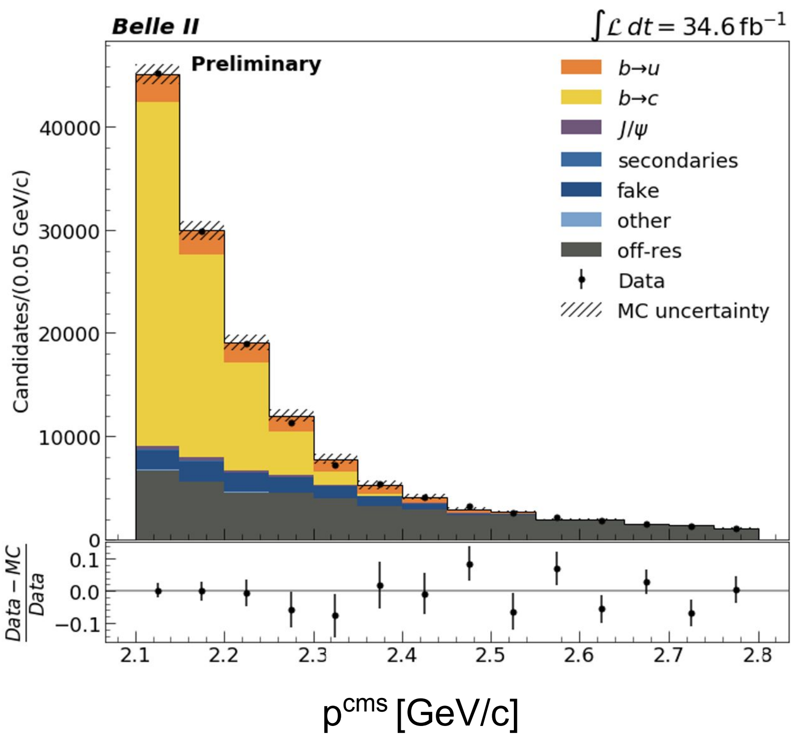


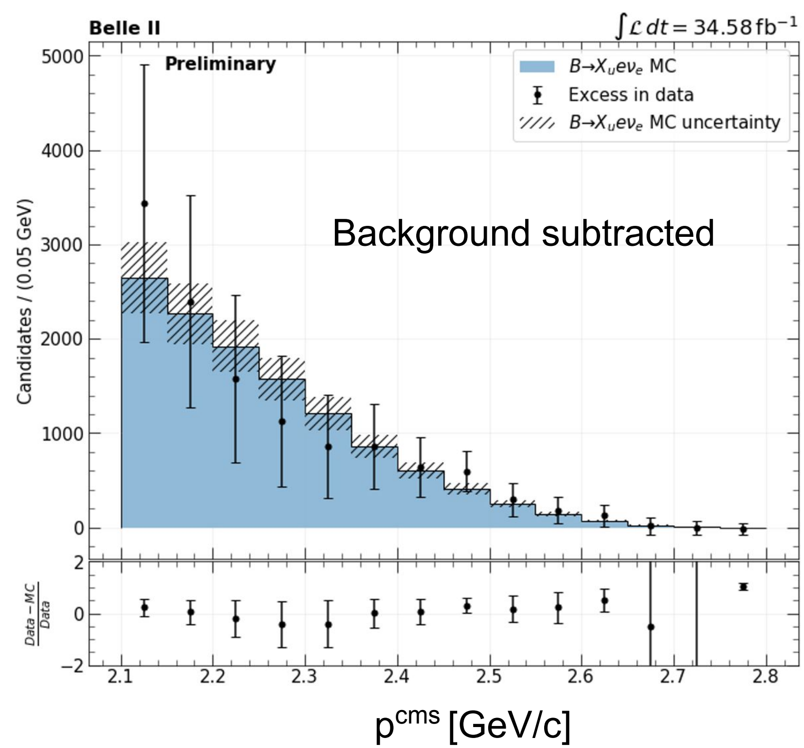
$B \to X_u e\nu$ Endpoint @ Belle II

with early data 34.6 fb^{-1}

arXiv:2103.02629

- Untagged measurement
- Reconstruct signal with one energetical electron based on particle identification
- Significance of the yield is found as 3σ





Further Ongoing Studies @ Belle II

Belle II Prospects

- Inherit successful recipe from the recent Belle measurements
- Potential to benefit from higher tagging eff. with FEI algorithm (arXiv:1807.08680)
- Implementation of GGOU into EvtGen is planned (collaborating with Paolo and Bernat)
- Further improvements are on track (signal selection scheme, unfolding, etc.)

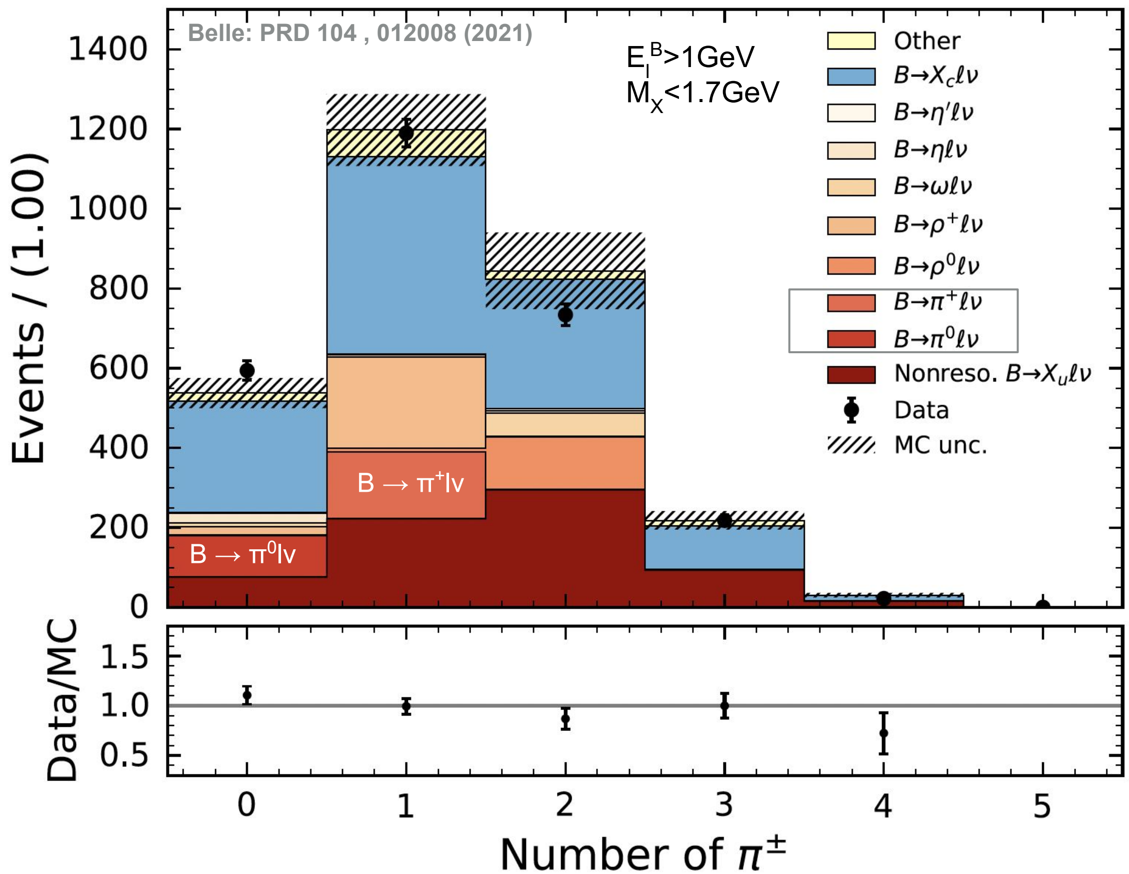
Observations Menu

- Partial & differential branching ratios
- Kinematic moments (event-wise treatment)
- Pion multiplicity (links excl. & incl. information, see next slide)
- A_FB in $B \to X_u \ell^+ \nu$
- $B \to X_u \tau^+ \nu$, LFU test, $R(X_u)$,...
- *… tell us your wishlist*

Combined Exclusive/Inclusive $|V_{ub}|$

ongoing, very preliminary

- Charged pion multiplicity measured by Belle shows a good agreement in data/MC
- Final state with single pion is promising to be disentangled with the rest of X_u



Combined Excl./Incl. $|V_{ub}|$

ongoing, very preliminary

- Extract excl. /incl. $|V_{ub}|$ ratio in a simultaneous fit on **b→ u components** yields and **B→ πℓν form factor** (q^2 shape)
- Several syst. uncertainties cancelled in ratio (e.g. tagging, lepID, etc)
- Attempt to demystify "Vub puzzle" from a new perspective

Fermilab/MILC:
PRD 92, 014024 (2015)

$$\chi^2 = \chi^2_{\text{exp}} + \chi^2_{\text{LQCD}}$$

$$\Delta\mathscr{B}(B \to X_u^{\text{other}}\ell\bar{\nu}_\ell) + \mathscr{B}(B \to \pi^{+,0}\ell\bar{\nu}_\ell) = \Delta\mathscr{B}(B \to X_u\ell\bar{\nu}_\ell)$$

$$\frac{|V_{ub}^{\text{excl}}|}{|V_{ub}^{\text{incl}}|} = \frac{\sqrt{\dfrac{\mathscr{B}(B \to \pi^{+,0}\ell^+\nu_\ell)}{\tau_B^{0,+}\cdot\Gamma(B \to \pi^{+,0}\ell^+\nu_\ell)}}}{\sqrt{\dfrac{\Delta\mathscr{B}(B \to X_u\ell^+\nu_\ell)}{\tau_B\cdot\Delta\Gamma(B \to X_u\ell^+\nu_\ell)}}}$$

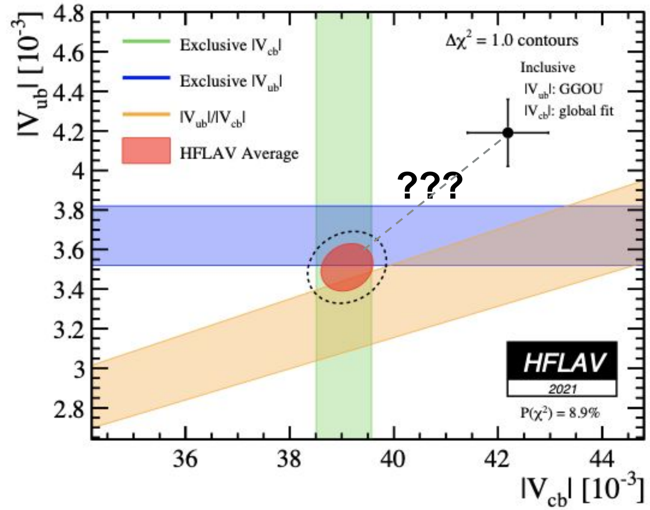
← FF

Postfit correlation in Asimov test

π^0	$\pi^\pm$	X_u other	bkg	FF: $b+_{0\text{-}3}$				FF: $b0_{0\text{-}3}$			
1.00	0.22	0.06	0.11	-0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.22	1.00	-0.00	0.17	0.00	0.01	-0.01	-0.01	0.00	0.00	0.00	0.00
0.06	-0.00	1.00	-0.06	-0.01	-0.02	0.02	0.02	0.00	-0.00	-0.00	-0.00
0.11	0.17	-0.06	1.00	0.00	0.01	-0.01	-0.01	-0.00	0.00	0.00	-0.00
-0.00	0.00	-0.01	0.00	1.00	0.14	-0.45	-0.34	0.22	0.17	0.05	-0.03
0.00	0.01	-0.02	0.01	0.14	1.00	-0.78	-0.87	-0.07	0.14	0.02	-0.01
0.00	-0.01	0.02	-0.01	-0.45	-0.78	1.00	0.87	-0.05	-0.25	0.10	0.23
0.00	-0.01	0.02	-0.01	-0.34	-0.87	0.87	1.00	0.08	0.04	0.02	-0.20
0.00	0.00	0.00	-0.00	0.22	-0.07	-0.05	0.08	1.00	-0.04	-0.60	-0.39
0.00	0.00	-0.00	0.00	0.17	0.14	-0.25	0.04	-0.04	1.00	-0.41	-0.75
0.00	0.00	-0.00	0.00	0.05	0.02	0.10	0.02	-0.60	-0.41	1.00	0.45
0.00	0.00	-0.00	-0.00	-0.03	-0.01	0.23	-0.20	-0.39	-0.75	0.45	1.00

Summary

- New results imply a smaller **excl. & incl. tension**, continuous efforts and futher confirmation from experiment and theory are still needed
- Recent Belle measurement provided important input for more model-independent extraction
- Beyond these important results, the accumulated knowledge on MC modelling, analysis techniques, etc. will be beneficial for future measurements by e.g. Belle II or LHCb
- Many exciting studies from Belle II are on the way!!



Vxb puzzle: ~3σ tension between excl. & incl. determinations

Thank You

lu.cao@desy.de

More Details

Expected Exp. Uncertainty for $|V_{ub}|$

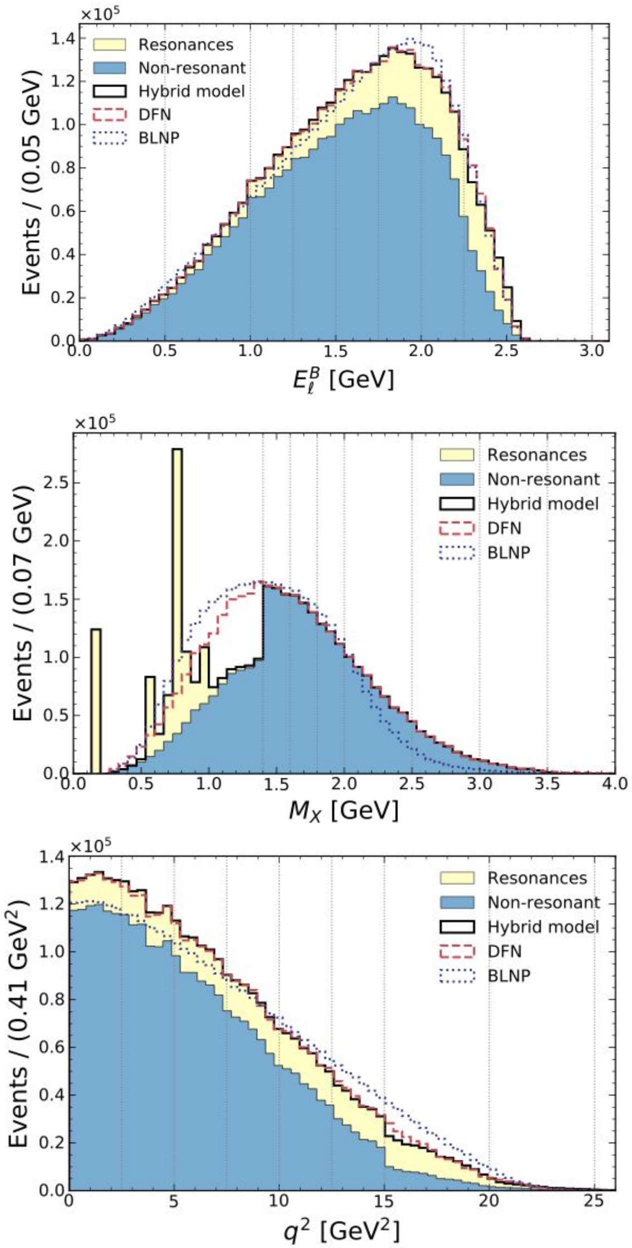
	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$5\ ab^{-1}$	1.1	$(1.3, 1.6)$	2.3	$2.5 - 4.5$	$3.4 - 5.1$
$50\ ab^{-1}$	0.4	$(0.4, 1.6)$	1.7	$2.5 - 4.5$	$3.0 - 4.8$

The expected relative uncertainties (in percent) for inclusive |Vub| measurements at Belle II

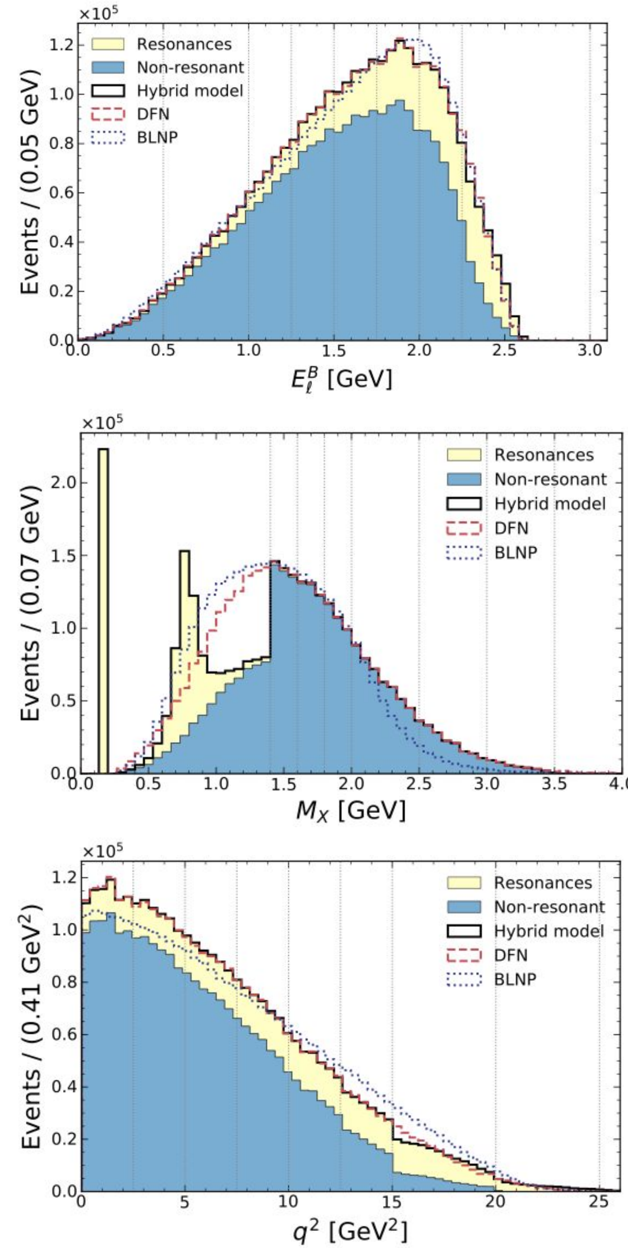
[The Belle II Physics Book, PTEP 2019 (2019)596 123C01, arXiv:1808.10567]

Hybrid modeling of B→ $X_u l\nu$

$B^{\pm}$



B^0



Efficiency & Acceptance Corrections

- Correct spectra for tagging & selection efficiency and phase-space acceptance in of $E_l^B > 1$ GeV
- Propagate full uncertainty to final result

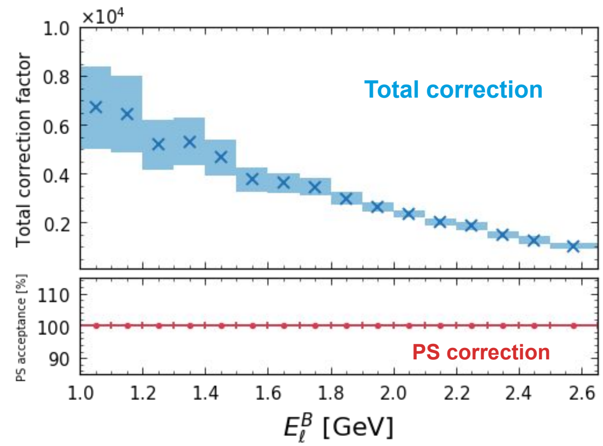
efficiency of tagging and signal selections

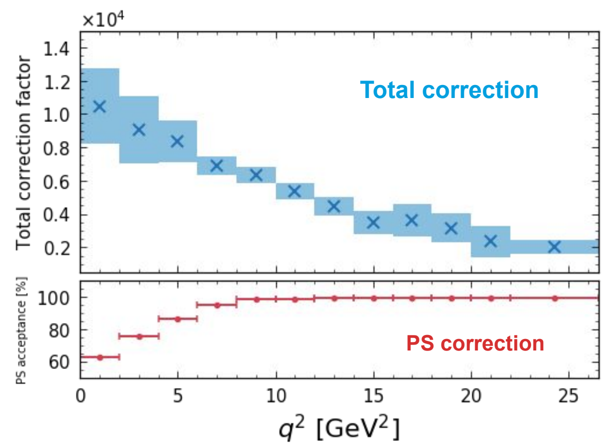
$$\Delta^i \mathscr{B}(B \to X_u \ell^+ \nu_\ell;\ \mathrm{PS}) = \frac{\hat{\eta}^i_{\mathrm{unfolded}} \cdot \left(\epsilon^i_{\mathrm{tag}} \cdot \epsilon^i_{\mathrm{sel}}\right)^{-1} \cdot \epsilon^i_{\Delta\mathscr{B}(\mathrm{PS})}}{4 \cdot N_{B\bar{B}}}$$

ratio of phase-space region

$$\epsilon^i_{\mathrm{tag}} \cdot \epsilon^i_{\mathrm{sel}} = \frac{N^{\mathrm{sel}}_{\mathrm{true,i}}}{N^{\mathrm{tot}}_{\mathrm{gen,i}}}$$

$$\epsilon^i_{\Delta\mathscr{B}(\mathrm{PS})} = \frac{N^{\mathrm{PS}}_{\mathrm{gen,i}}}{N^{\mathrm{tot}}_{\mathrm{gen,i}}}$$





Systematic uncertainties of the correction factors due to signal modelling are extracted simultaneously for selection eff. & PS acceptance

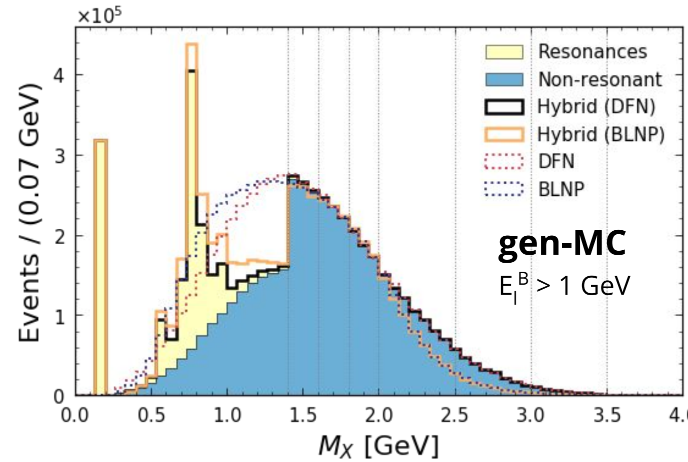
Systematics for M_X

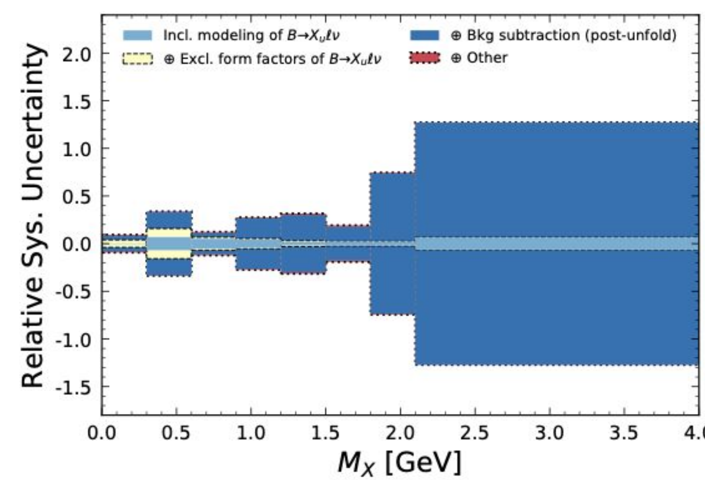
Relative uncertainty (%):

M_X [GeV]	0-0.3	0.3-0.6	0.6-0.9	0.9-1.2	1.2-1.5	1.5-1.8	1.8-2.1	2.1-4.0
Tracking efficiency	0.55	0.56	0.82	0.86	0.95	1.05	1.15	1.19
Tagging calibration	3.69	3.69	3.65	3.64	3.64	3.57	3.79	3.66
Slow pion efficiency	0.00	0.07	0.04	0.05	0.04	0.04	0.06	0.04
K_s^0	0.04	0.05	0.04	0.02	0.04	0.03	0.02	0.05
eID	0.72	0.83	0.74	0.69	0.73	0.74	0.94	1.22
μID	1.59	1.25	1.34	1.29	1.44	1.35	1.09	0.70
K/π ID	0.39	0.67	0.68	0.74	0.81	1.02	1.27	1.24
$\mathcal{B}(B \to X_u \ell \nu)$	0.18	0.44	0.07	0.59	0.82	0.69	0.73	0.46
$\mathcal{B}(B \to \pi \ell \nu)$	0.42	0.45	0.45	0.14	0.05	0.04	0.05	0.05
$\mathcal{B}(B \to \rho \ell \nu)$	0.42	1.00	0.61	0.56	0.33	0.16	0.22	0.15
$\mathcal{B}(B \to \omega \ell \nu)$	0.42	0.39	0.65	0.12	0.11	0.06	0.11	0.10
$\mathcal{B}(B \to \eta \ell \nu)$	0.41	1.16	0.46	0.11	0.06	0.03	0.03	0.14
$\mathcal{B}(B \to \eta' \ell \nu)$	0.42	0.39	0.46	0.24	0.30	0.03	0.14	0.11
$B \to \pi \ell \nu$ FF	0.98	3.08	1.52	0.53	1.05	0.37	0.36	0.38
$B \to \rho \ell \nu$ FF	2.77	8.54	3.96	2.94	1.65	0.59	0.83	0.89
$B \to \omega \ell \nu$ FF	2.40	9.71	1.10	0.90	1.41	0.70	0.65	1.32
$B \to \eta \ell \nu$ FF	0.71	3.58	0.09	0.09	0.51	0.28	0.27	0.07
$B \to \eta' \ell \nu$ FF	0.69	3.65	0.16	0.27	0.48	0.29	0.32	0.15
Hybrid model	0.21	5.86	5.08	4.01	0.50	1.97	2.02	6.13
DFN parameters	0.18	3.66	1.01	1.38	1.64	0.87	0.50	1.35
γ_s	0.47	4.17	2.36	3.98	3.08	4.10	9.31	3.60
π^+ multiplicity modeling	0.57	0.42	0.45	4.15	7.98	4.78	3.98	2.34
$N_{B\bar{B}}$	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
Background subtraction	5.97	26.93	8.23	25.15	29.65	16.80	73.36	126.64
MC stat. (migration matrix)	4.04	11.22	3.54	6.85	4.30	4.71	6.85	8.22
Total syst. uncertainty	9.36	33.77	12.32	27.56	31.62	19.21	74.55	127.23
Total stat. uncertainty	11.11	32.64	10.77	24.99	21.88	16.54	46.24	66.76
Total uncertainty	14.53	46.97	16.36	37.20	38.45	25.35	87.73	143.68

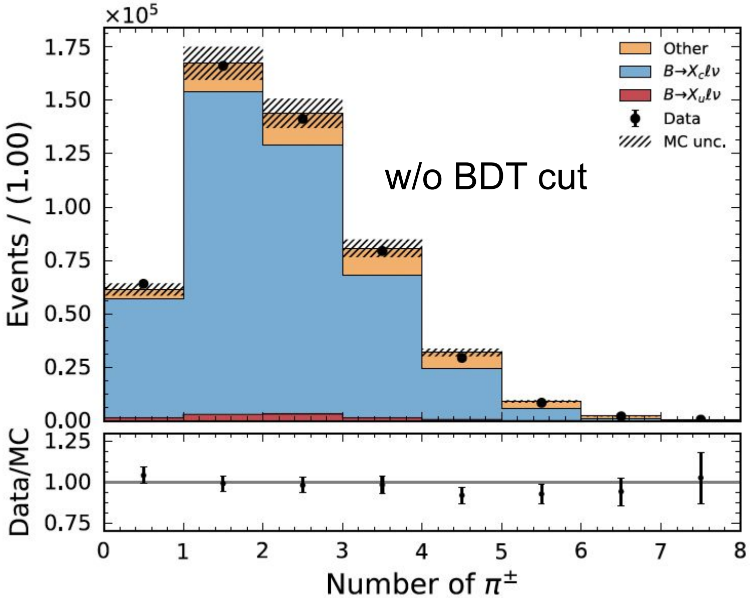
The generator-level MC illustrates the hybrid model of excl. and incl. components.

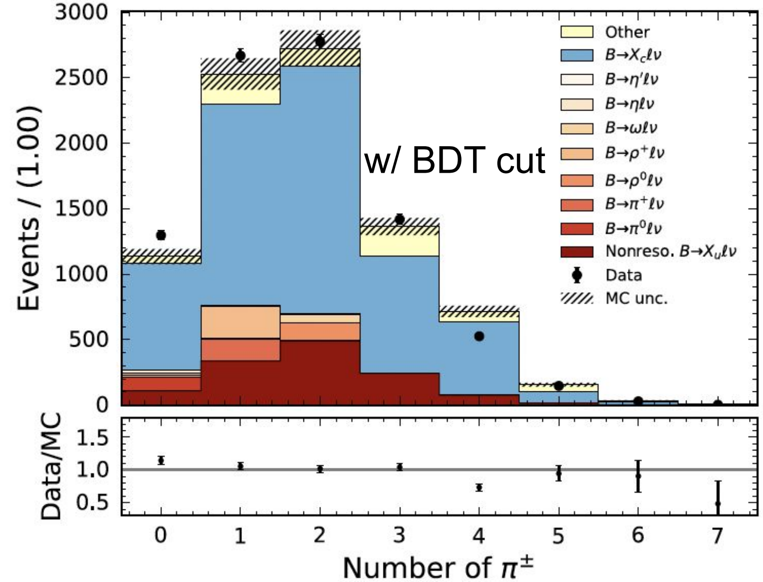
(providing some hints on sys., but keep in mind: the systematics is a combined effect of three parts....)

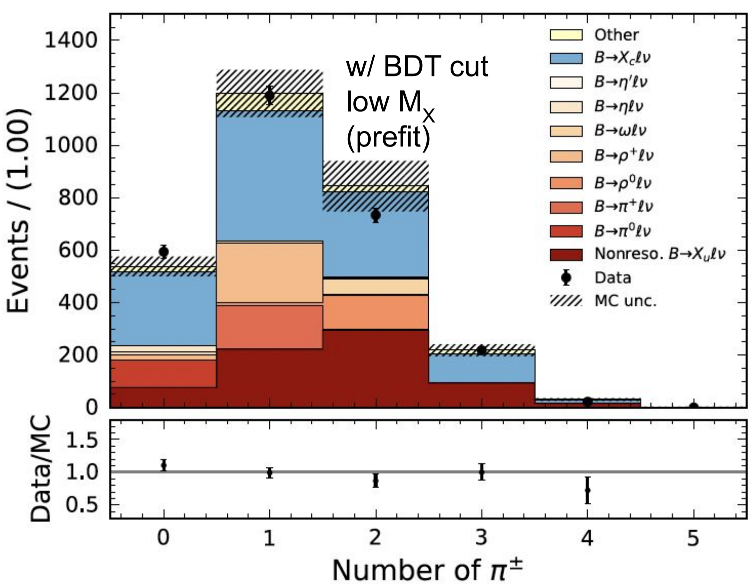


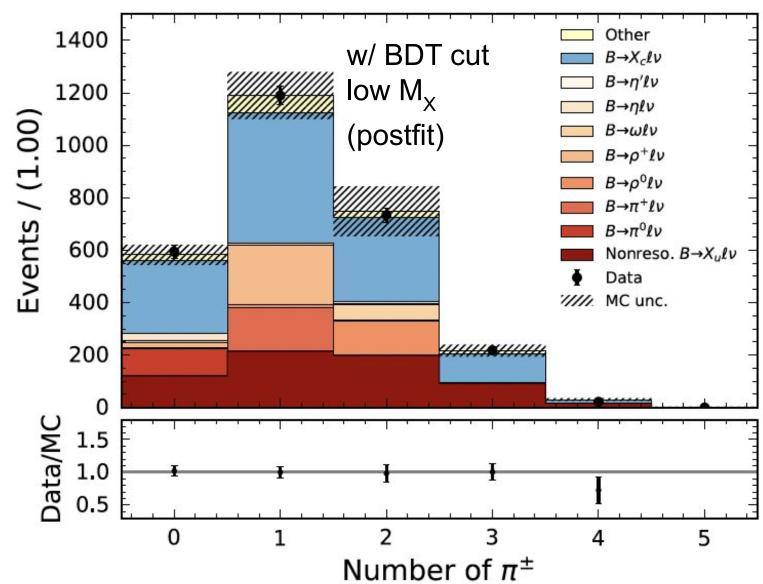


Pion Multiplicity









Status of $|V_{xb}|$