Inclusive and Exclusive $|V_{xb}|$ Discrepancies

— An attempt of a guided diagnostic tour —

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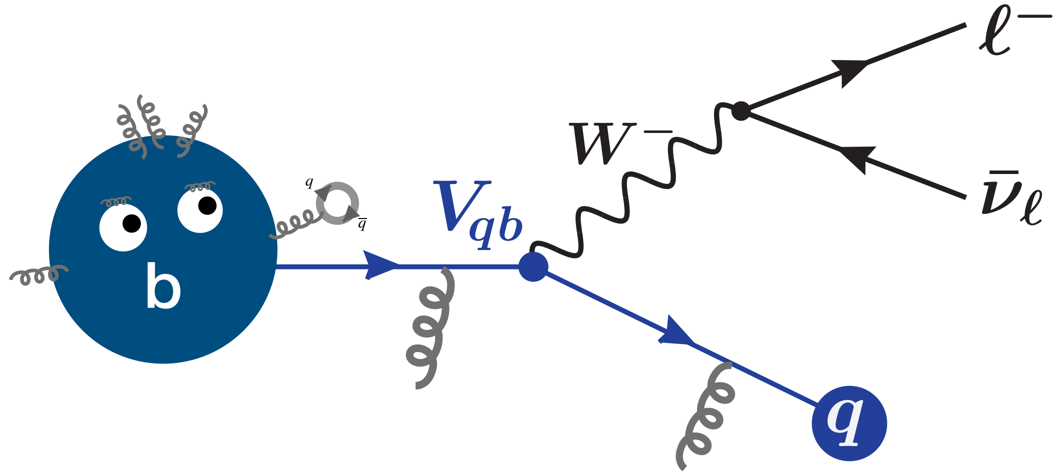
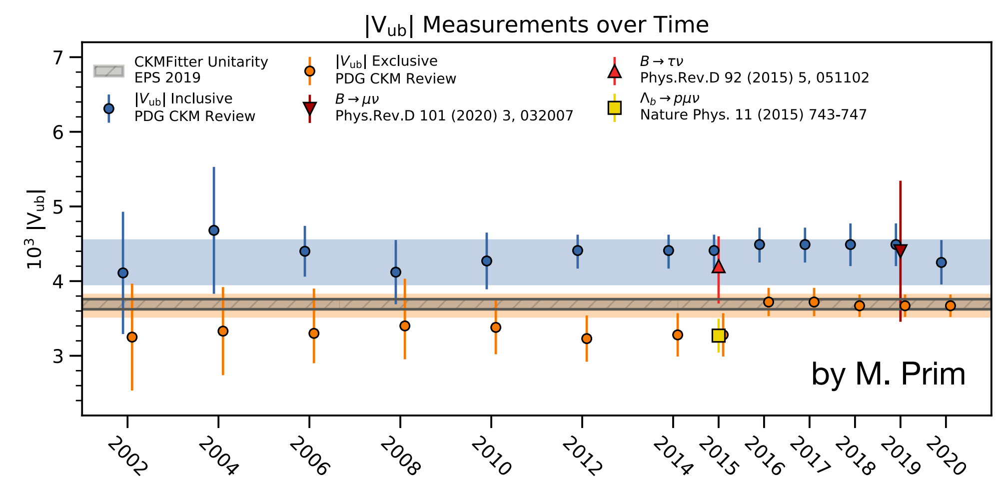
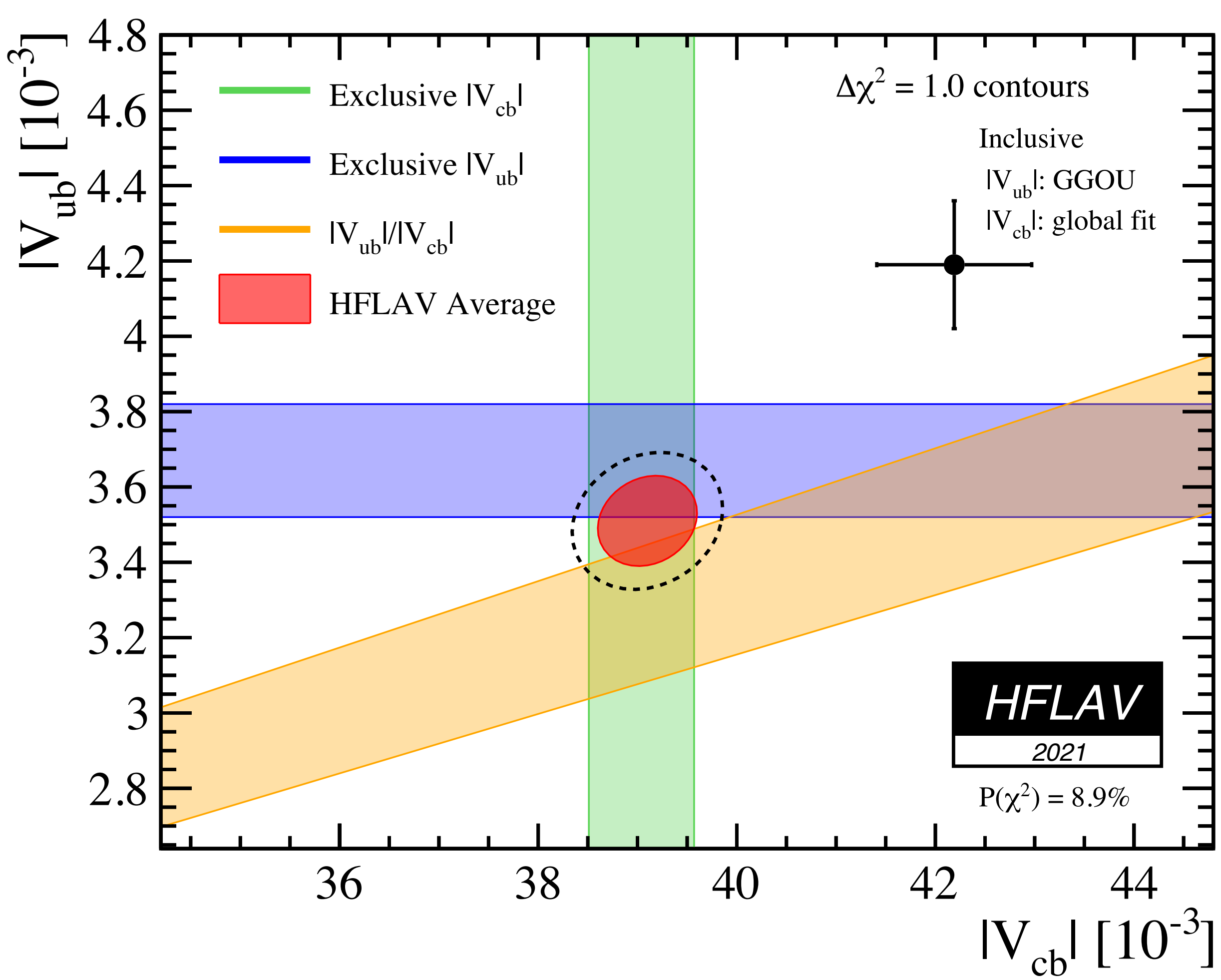
The |V_{xb}| puzzle

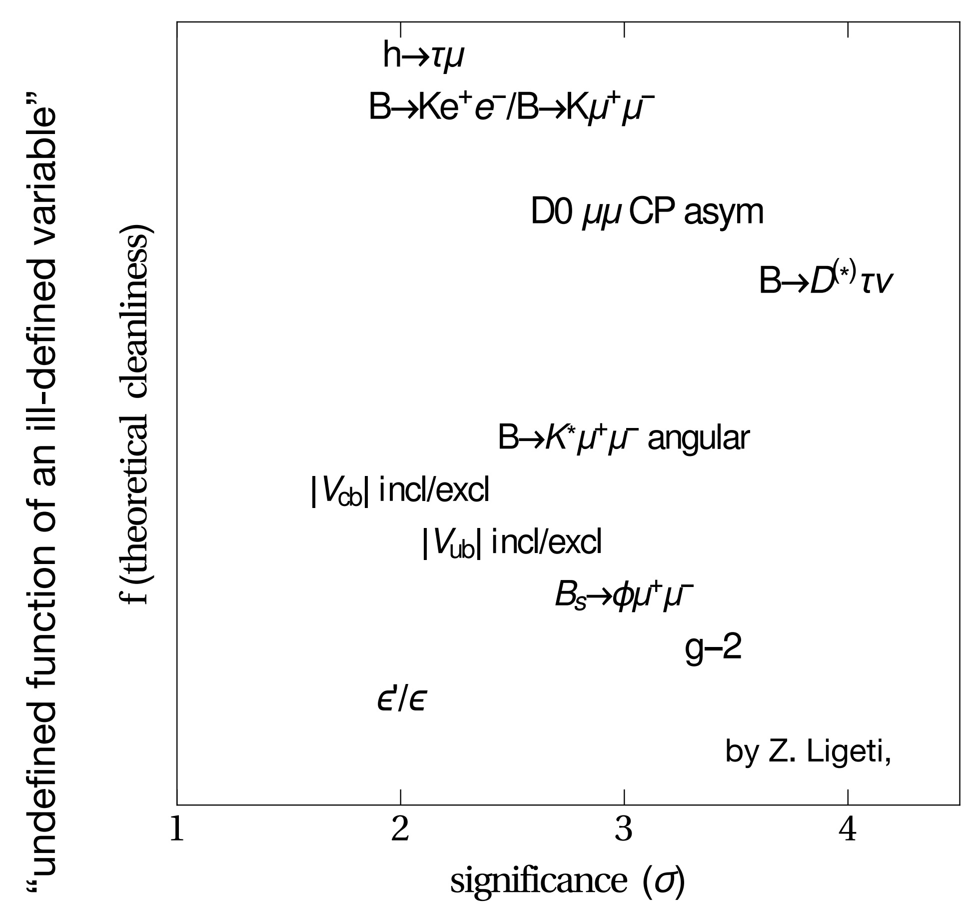
He may look cute, but that might be deceiving…



… Long-standing discrepancy since about a decade





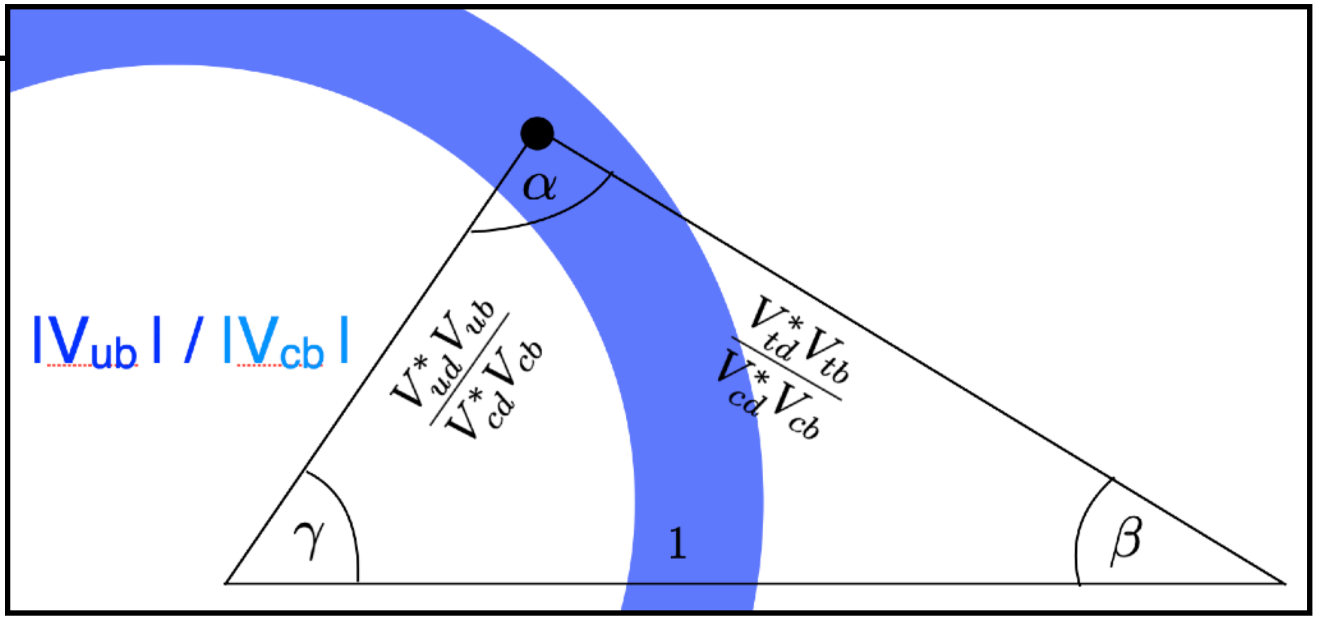


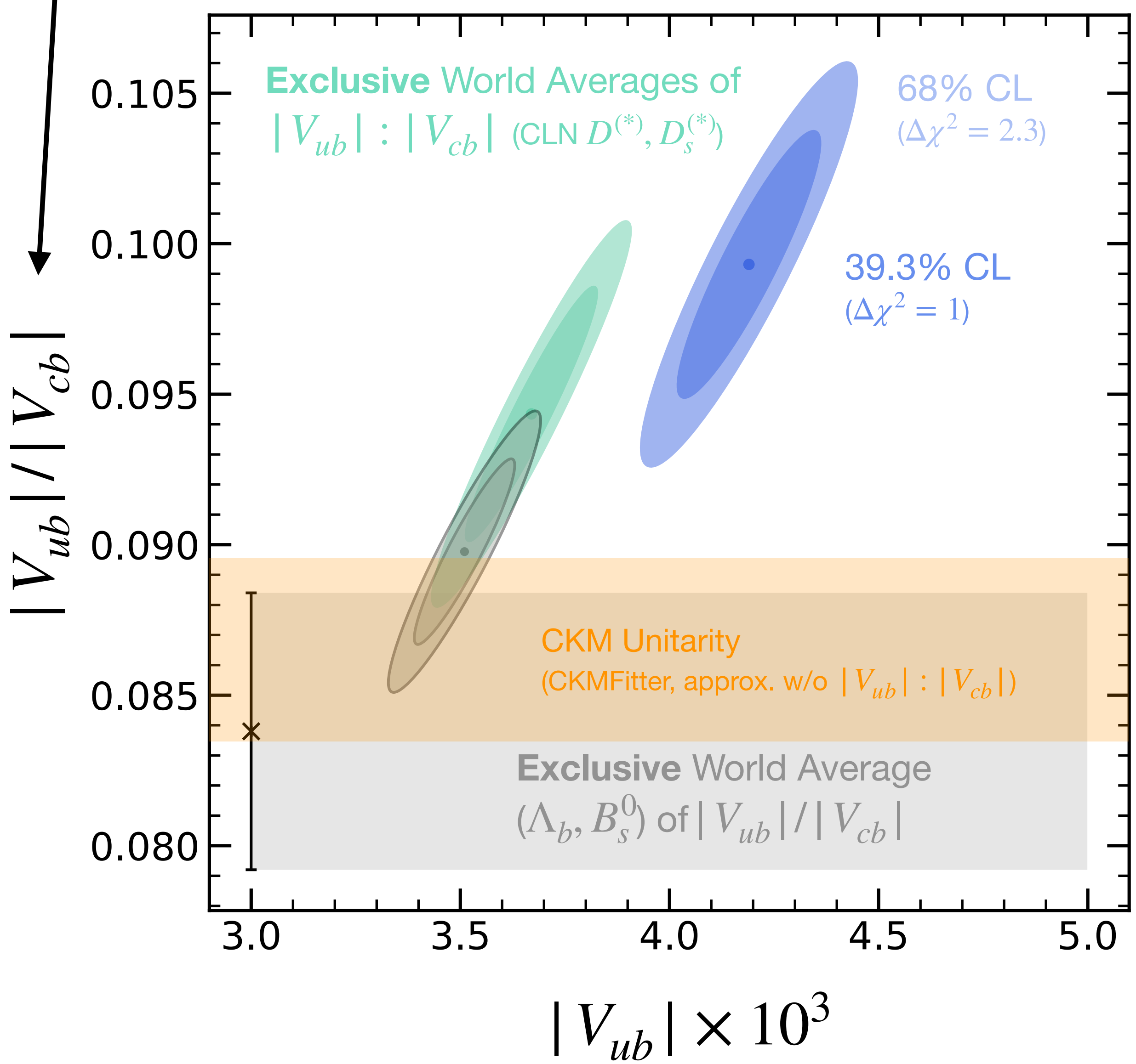
Maybe some change of perspective helps?

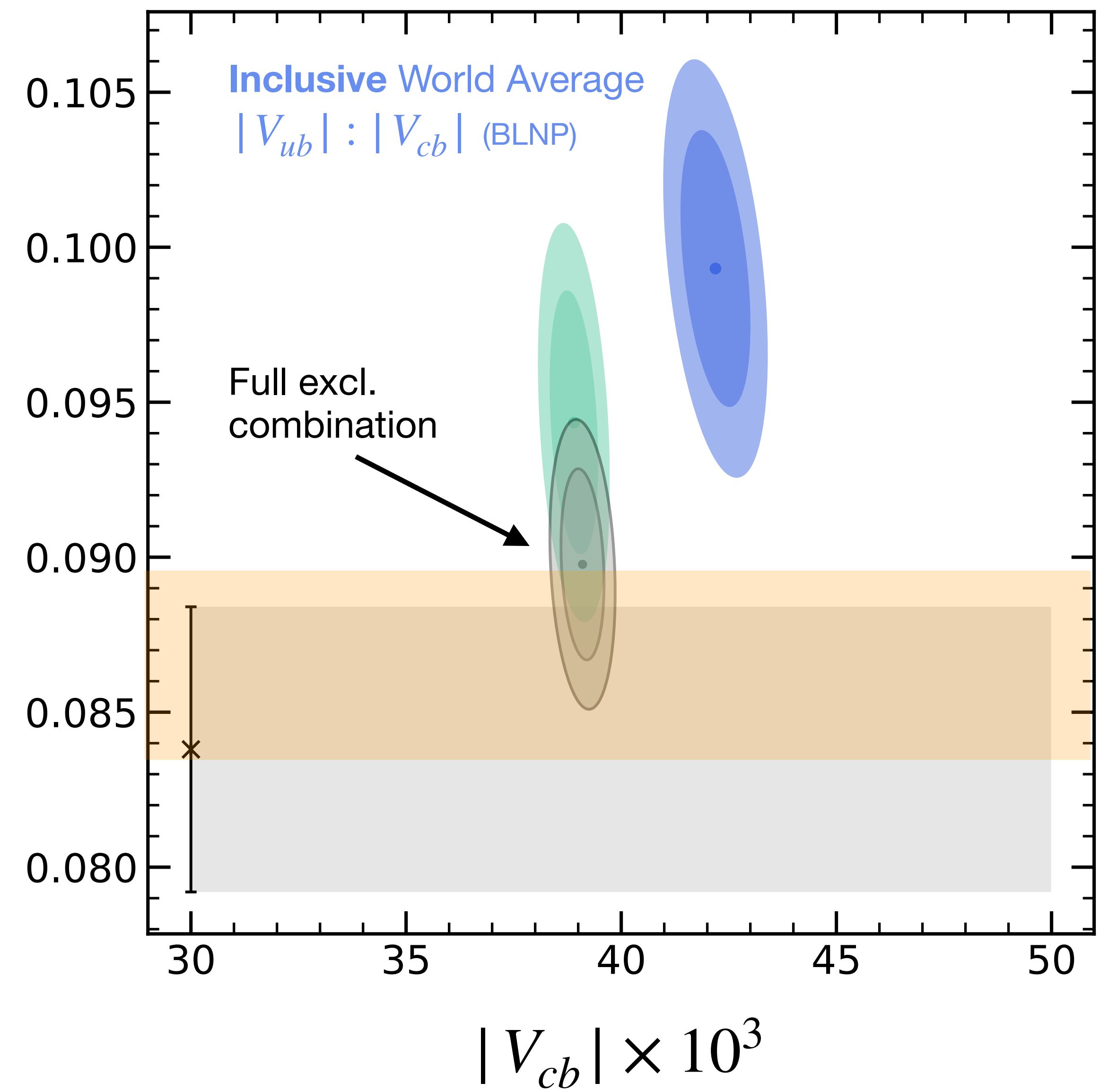
For global CKM fits we care about

$|V_{ub}|/|V_{cb}|$

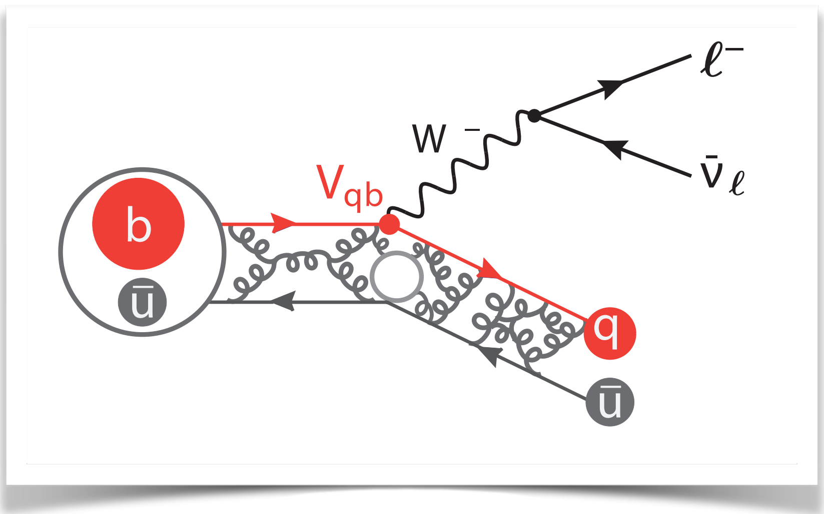
Well, a little. But still troublesome..







“red thread”



Inclusive $|V_{ub}|$

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

+ Fermi Motion / Shape Function

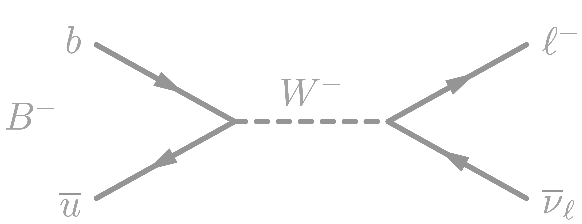
Inclusive $|V_{cb}|$

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

Operator Product Expansion

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

‘Leptonic’ $|V_{ub}|$



$$\boxed{\mathcal{B} \propto |V_{ub}|^2 \, f_B^2 \, m_\ell^2}$$

B-Meson decay constant

Exclusive $|V_{ub}|$

$$\bar{B} \to \pi \, \ell \, \bar{\nu}_\ell, \Lambda_b \to p \, \mu \, \bar{\nu}_\mu$$

Exclusive $|V_{cb}|$

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

$$B_s \to D_s^{(*)} \mu \bar{\nu}_\mu$$

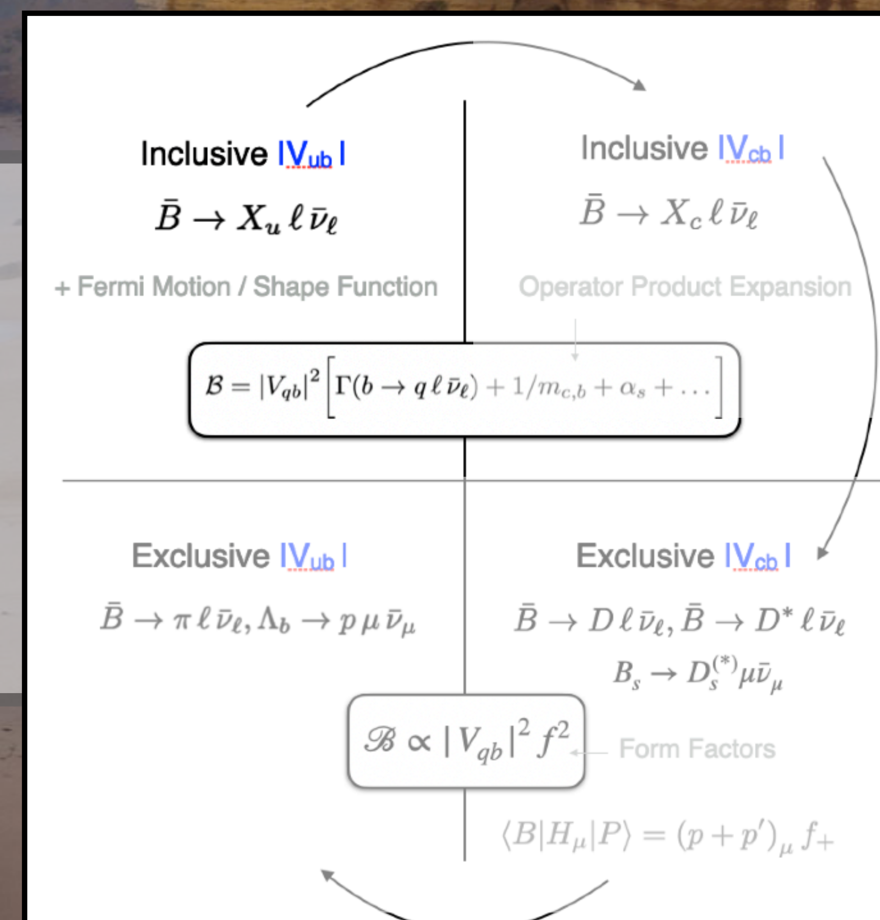
$$\boxed{\mathcal{B} \propto |V_{qb}|^2 \, f^2}$$

Form Factors

$$\langle B | H_\mu | P \rangle = (p + p')_\mu \, f_+$$

A brief tour with personal highlights and thoughts

Incl. $|V_{ub}|$

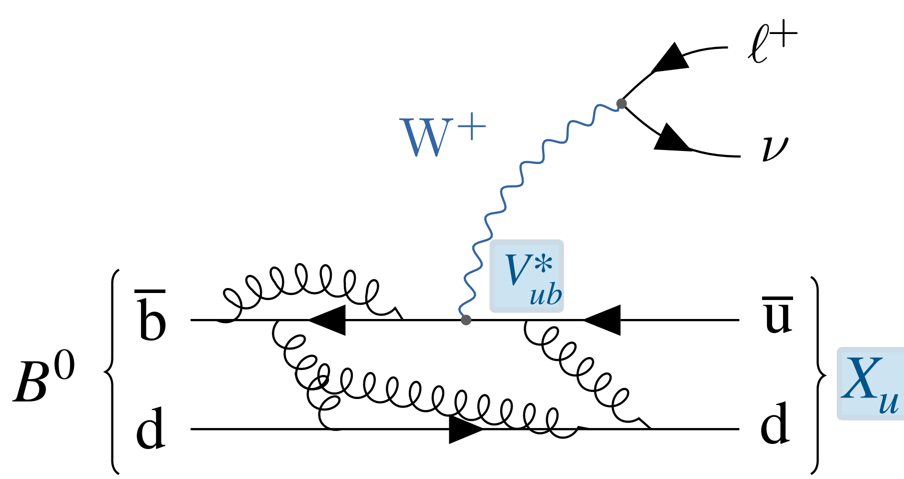


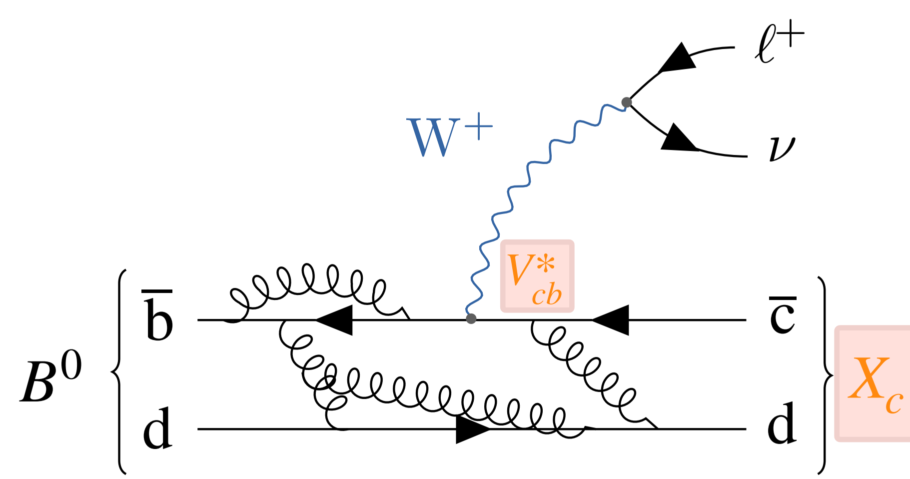
- Caveats on current (recent) results
- Era of Differential measurements

State-of-the-Art

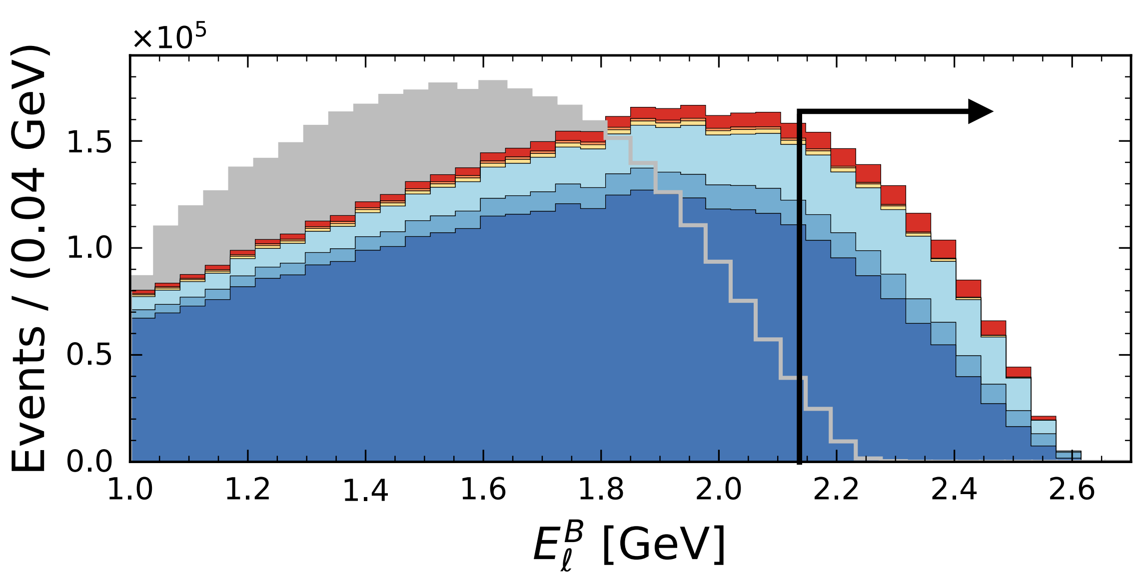
Measuring $|V_{ub}|$ is **hard** due to $B \to X_c \ell \bar{\nu}_\ell$

- x $\mathcal{O}(100)$ more abundant
- Very similar **signature**:
  - high momentum lepton, hadronic system
- Clear separation only in corners of phase space
  - high E_ℓ, low M_X





The experimenter's dilemma illustrated with E_ℓ^B:

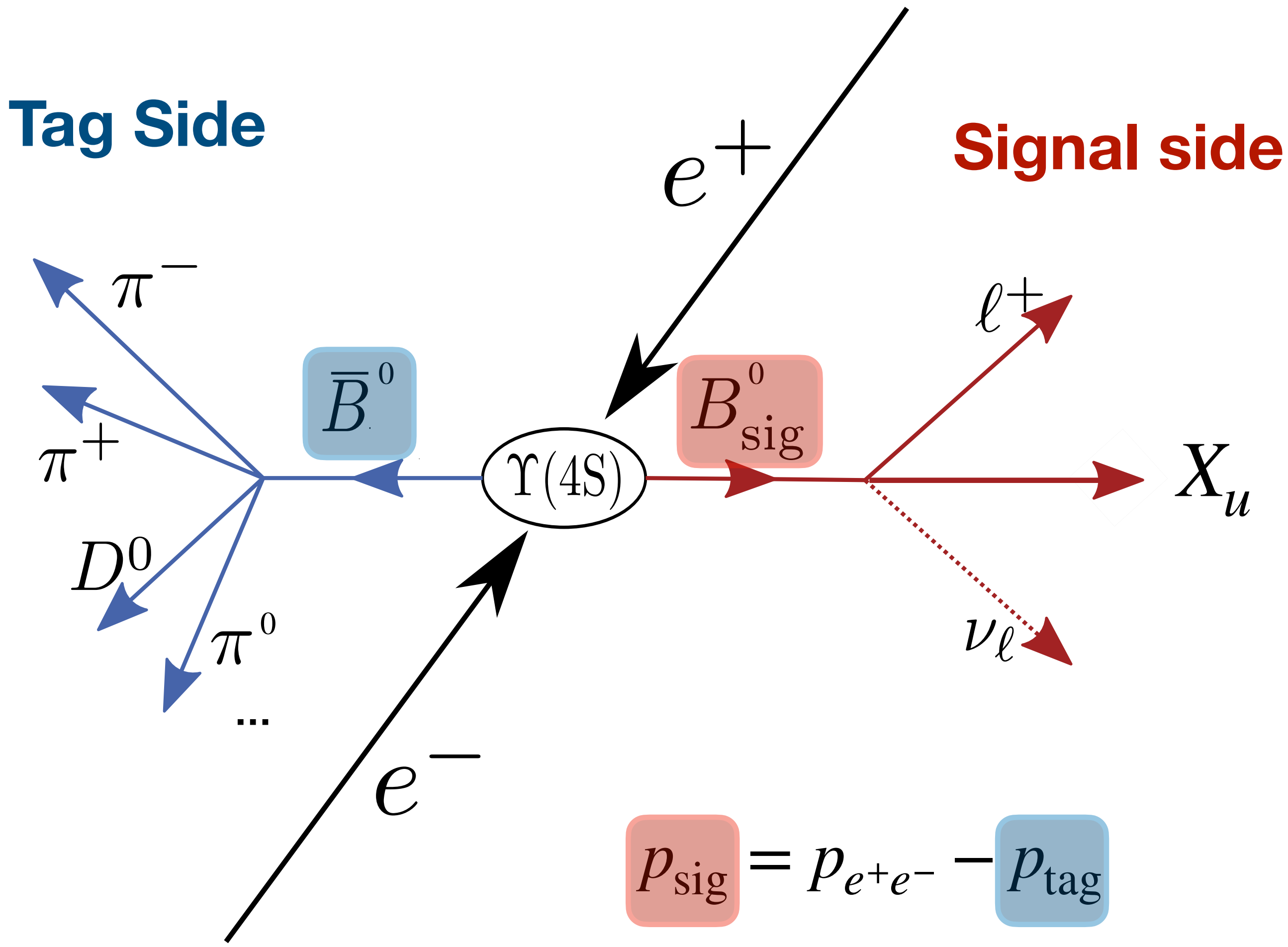


$$\left|V_{ub}\right| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u \ell \bar{\nu}_\ell)}{\tau\,\Delta\Gamma(B \to X_u \ell \bar{\nu}_\ell)}}$$

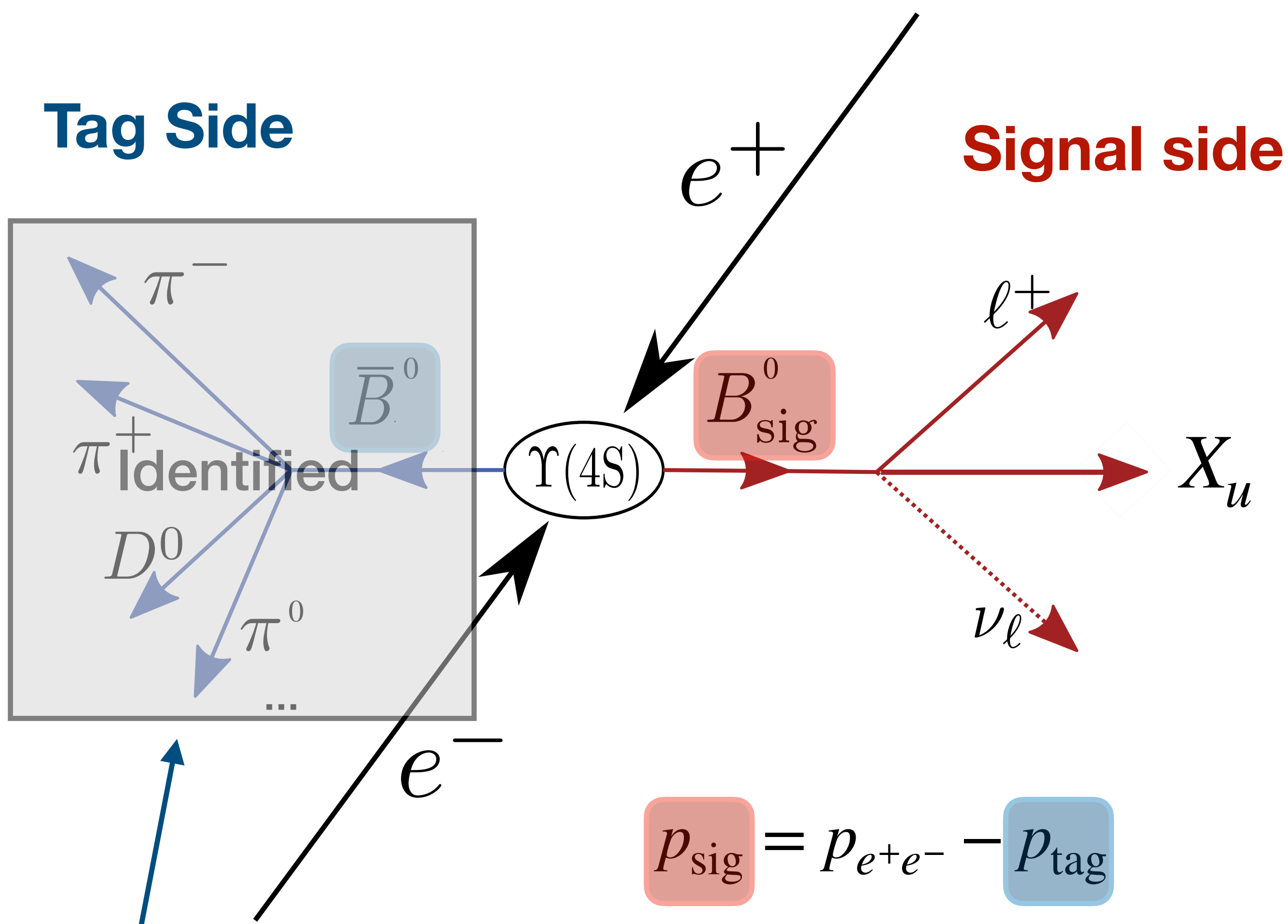
Theory error gets large
Experimental uncert. small
high cut

Theory error gets small
Experimental uncert. large
low cut

Hadronic Tagging



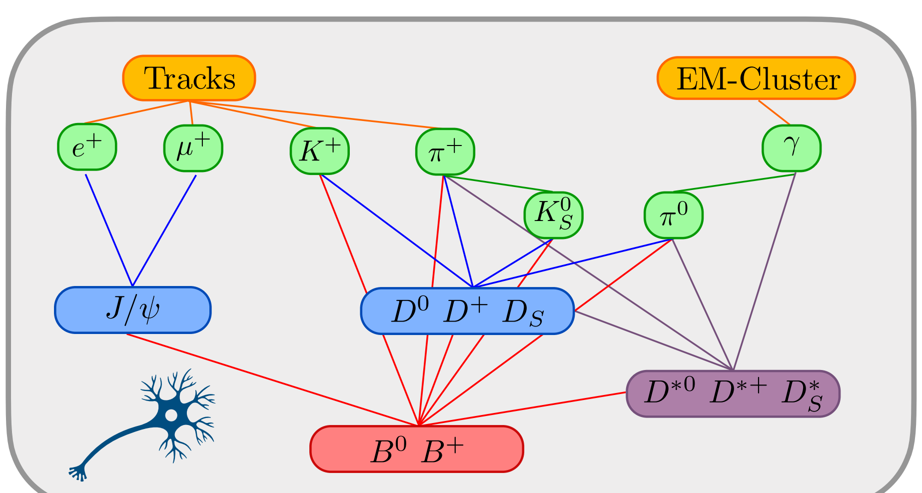
Hadronic Tagging



$$p_{\text{sig}} = p_{e^+e^-} - p_{\text{tag}}$$

Candidates reconstructed with **hierarchical** approach & **neural networks** in **hadronic modes**

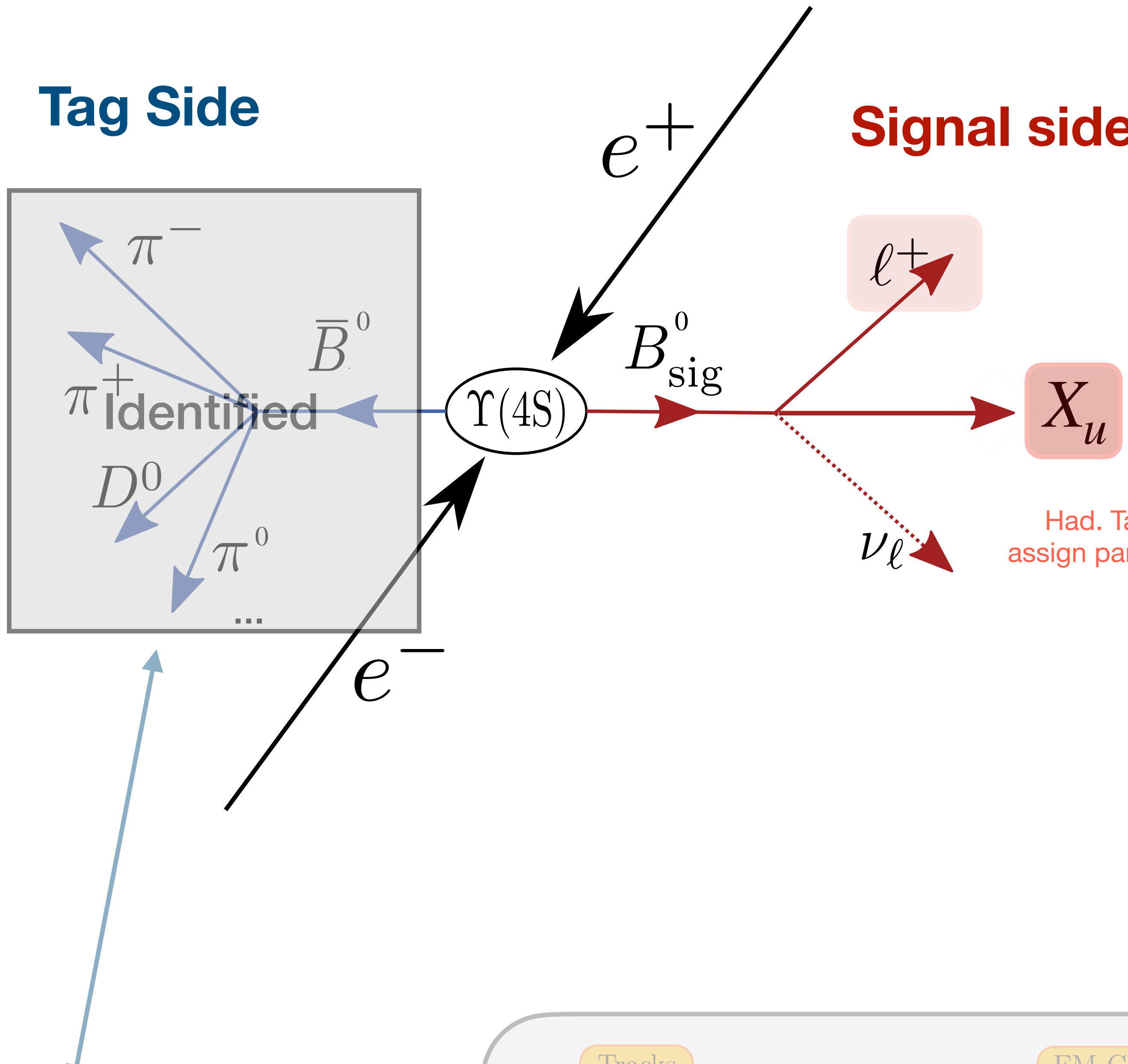
1104 decay cascades used with an **efficiency** of **0.28% / 0.18%** for $B^\pm$ and $B^0/\bar{B}^0$



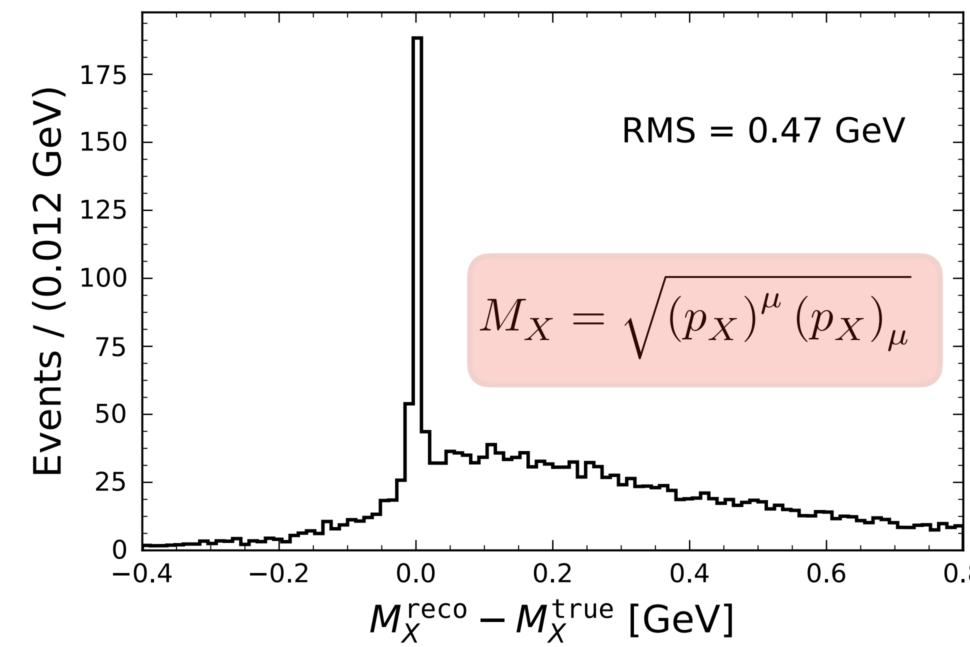
Hadronic Tagging

Charged Tracks — Neutral Clusters

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



Had. Tagging allows to assign particles to X_u system



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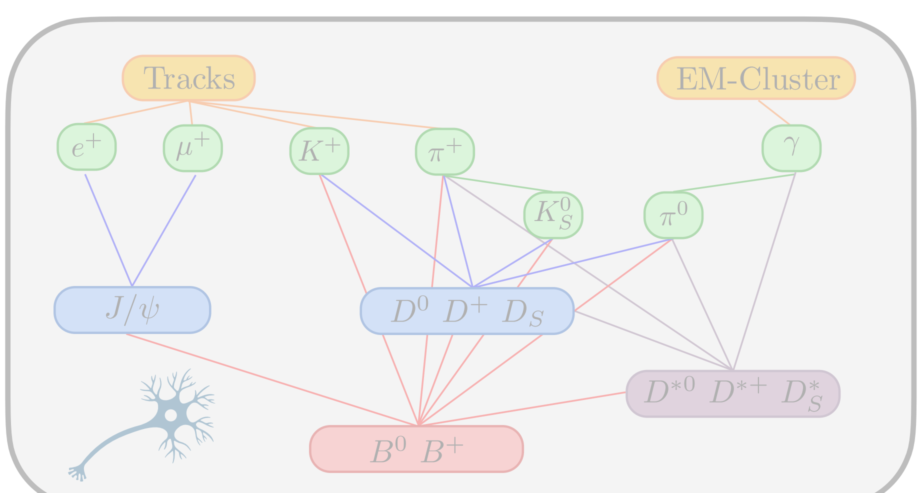
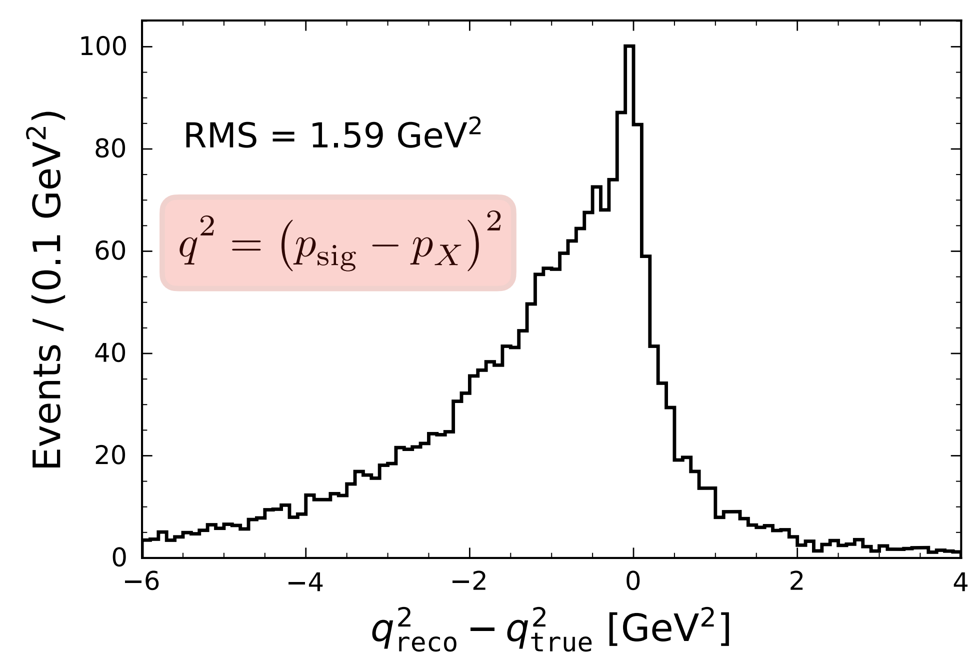
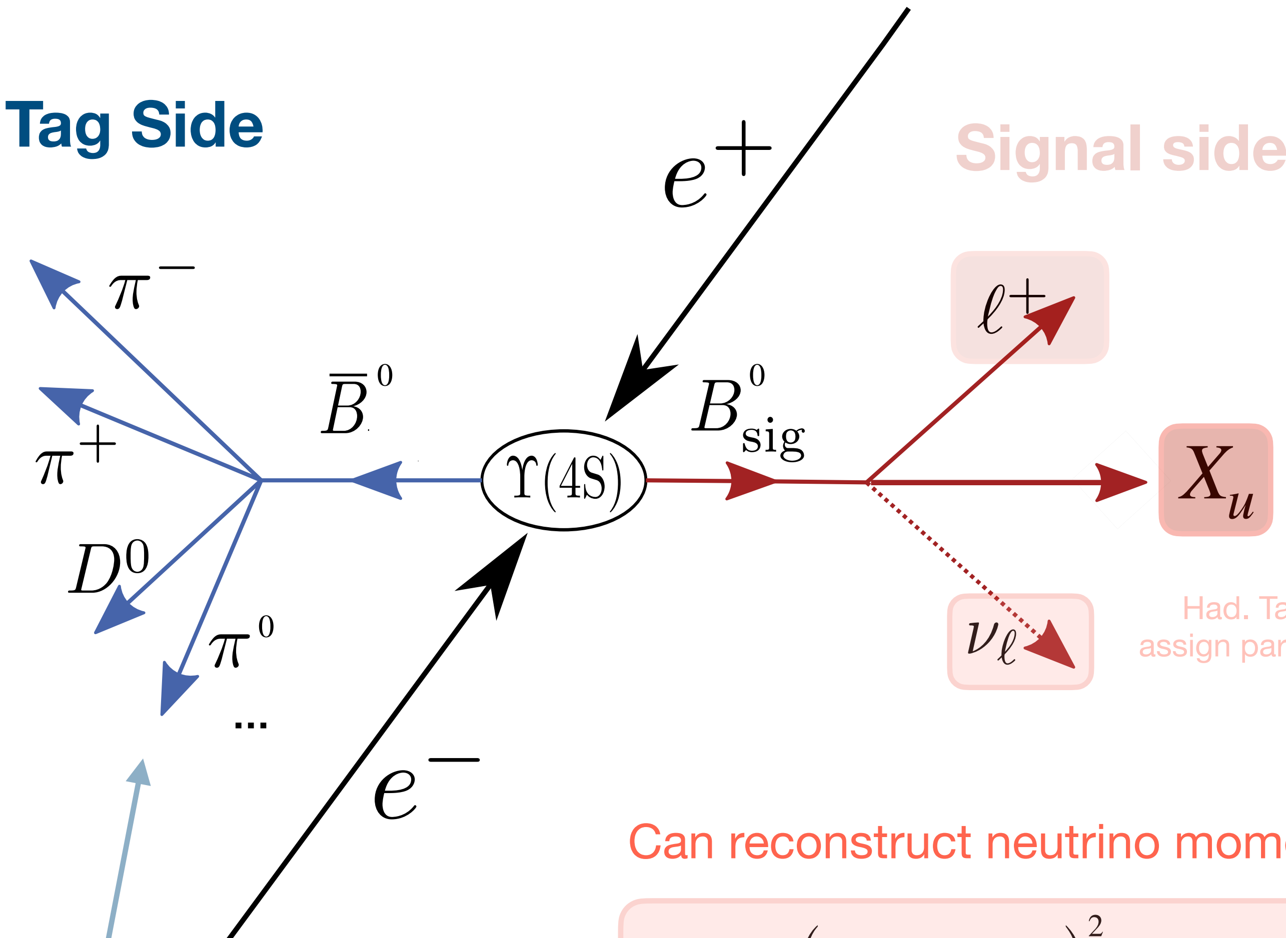




Hadronic Tagging

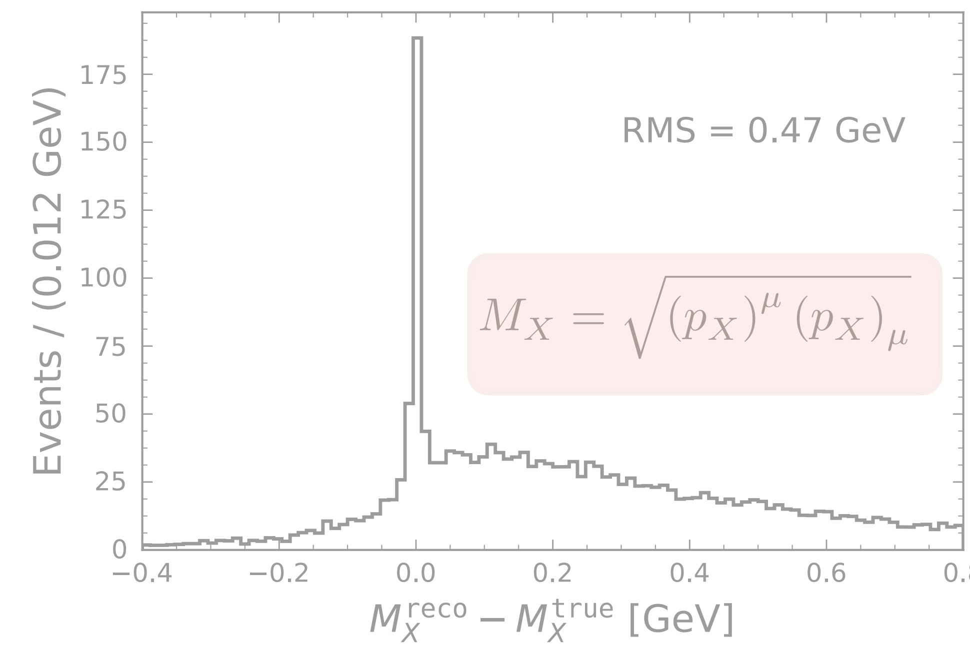
Tag Side

Signal side



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

Had. Tagging allows to assign particles to X_u system



Can reconstruct neutrino momentum:

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

Candidates reconstructed with **hierarchical** approach & **neural networks** in **hadronic modes**

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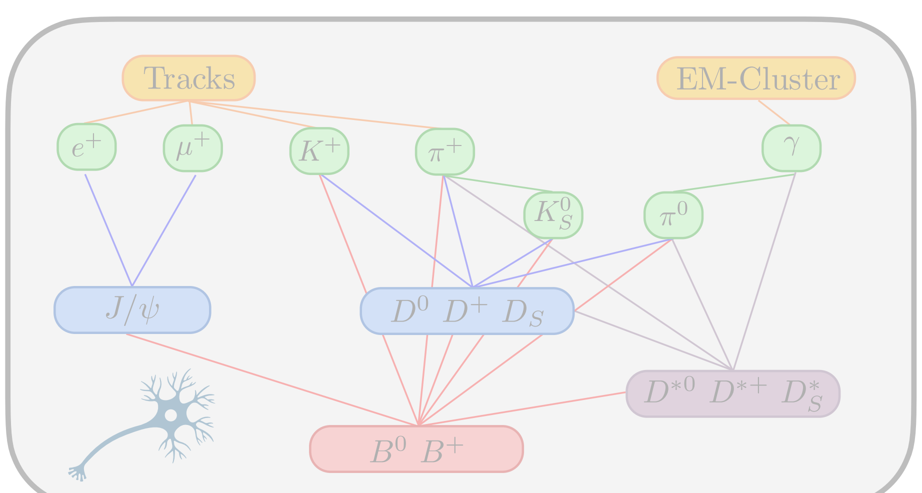
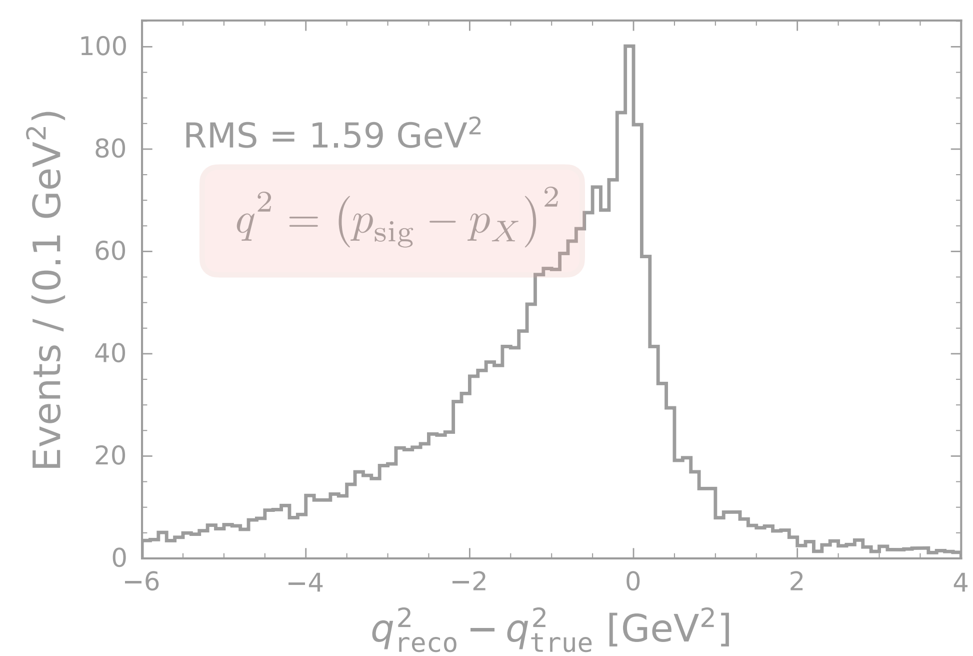




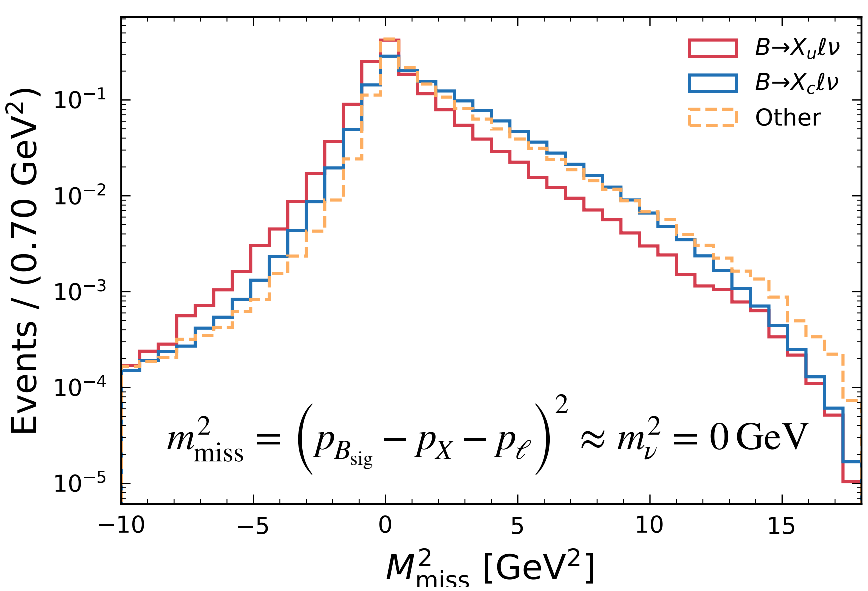
Multivariate Sledgehammer

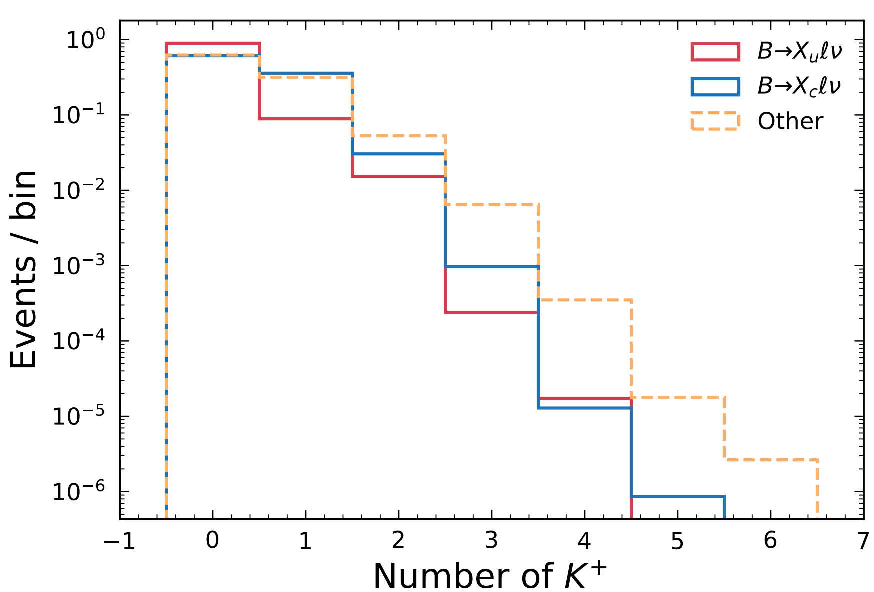
Can exploit that there are differences:

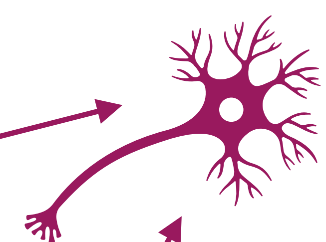
$X_u \longleftrightarrow X_c$

Direct cuts on m_X, E_ℓ **problematic**
(i.e. direct shape-function dependence)

Higher multiplicity
Often come with charged and neutral **Kaons**
D* decays (**slow pions**)
(**Slightly lower** E_ℓ)

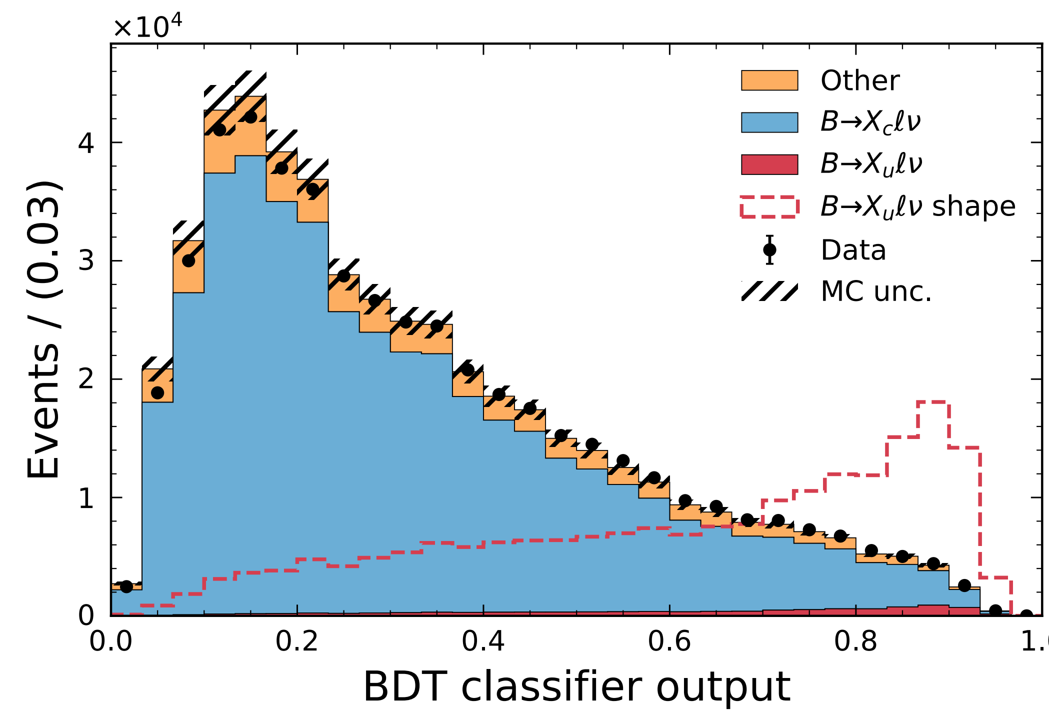






=

+ 9 other variables



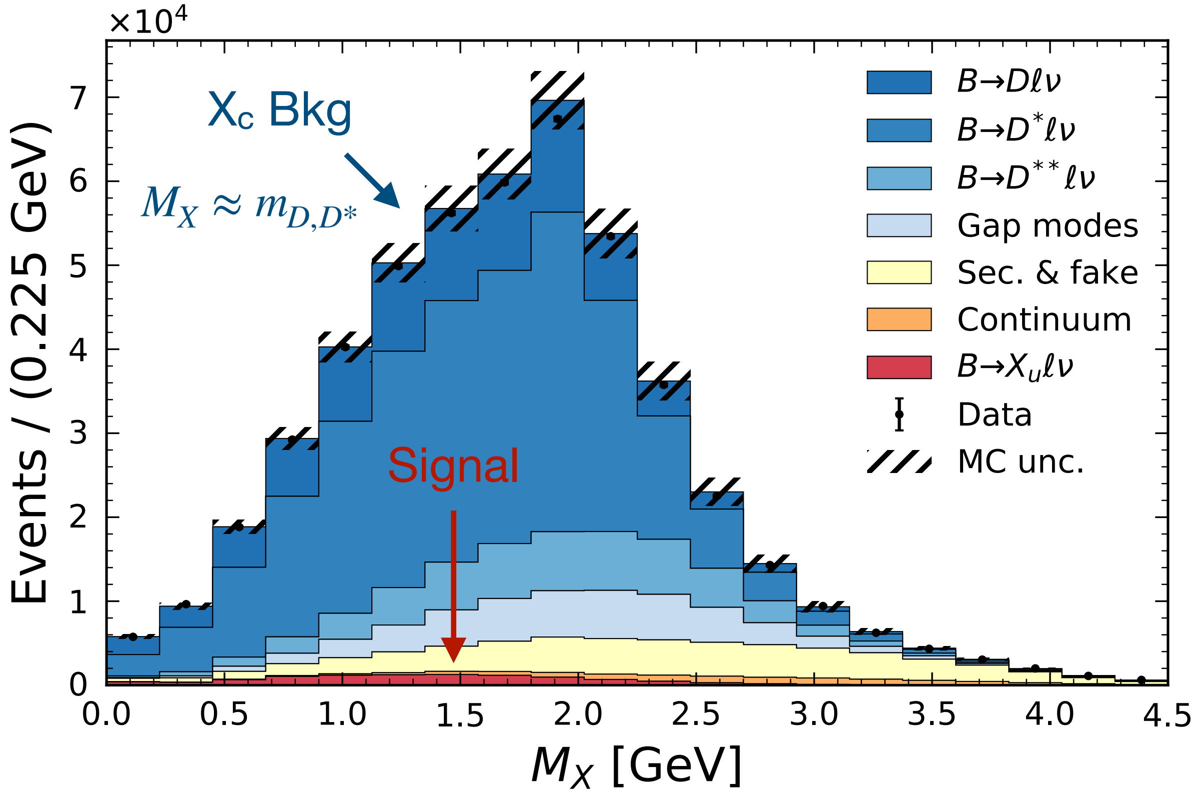
Can reject **98.7%** of X_c

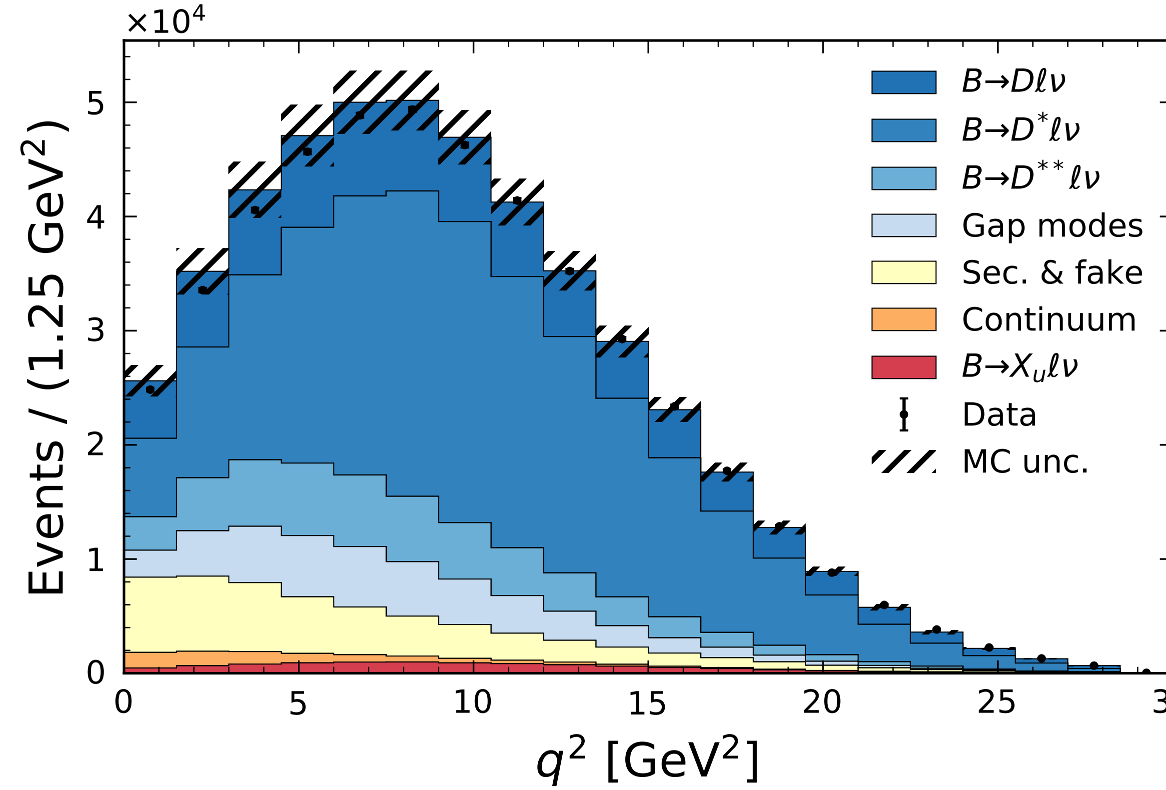
Selection	$B \to X_u\,\ell^+\,\nu_\ell$	$B \to X_c\,\ell^+\,\nu_\ell$	Data
$M_{\text{bc}} > 5.27\,\text{GeV}$	84.8%	83.8%	80.2%
$\mathcal{O}_{\text{BDT}} > 0.85$	18.5%	1.3%	1.6%
$\mathcal{O}_{\text{BDT}} > 0.83$	21.9%	1.7%	2.1%
$\mathcal{O}_{\text{BDT}} > 0.87$	14.5%	0.9%	1.1%

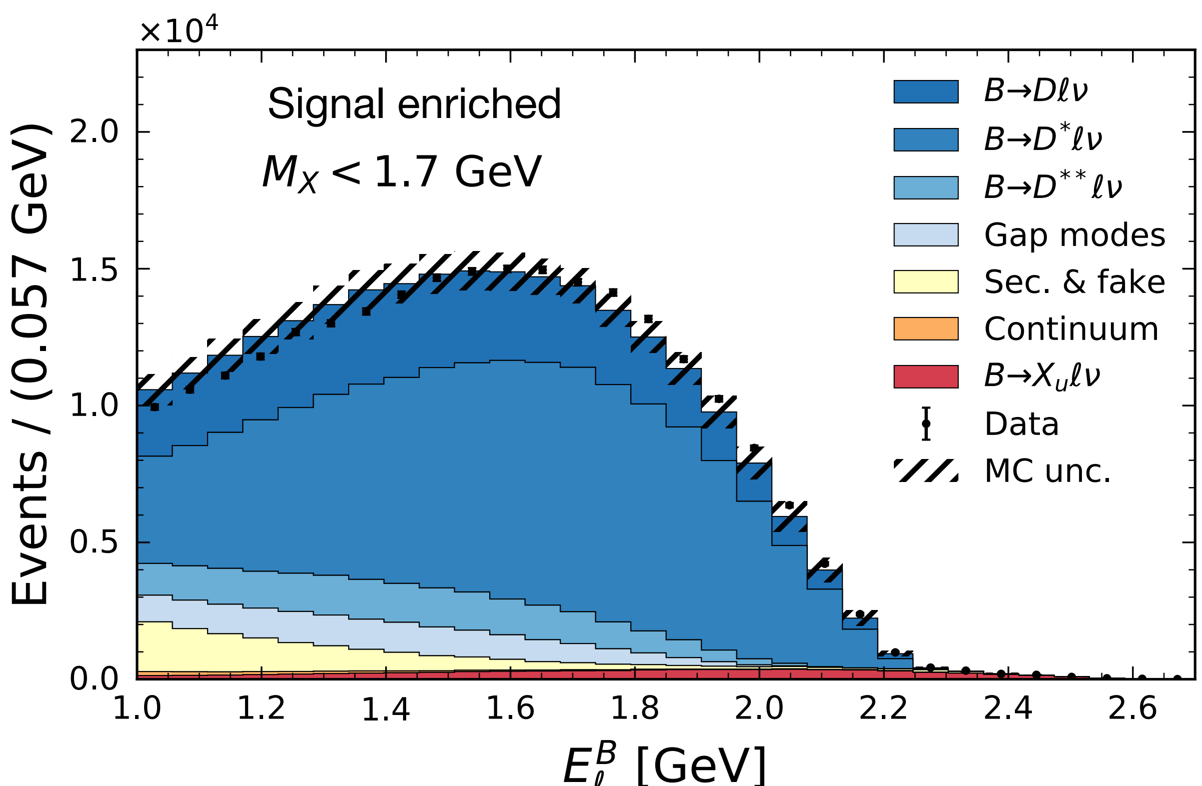
... and retain **18.5%** of X_u

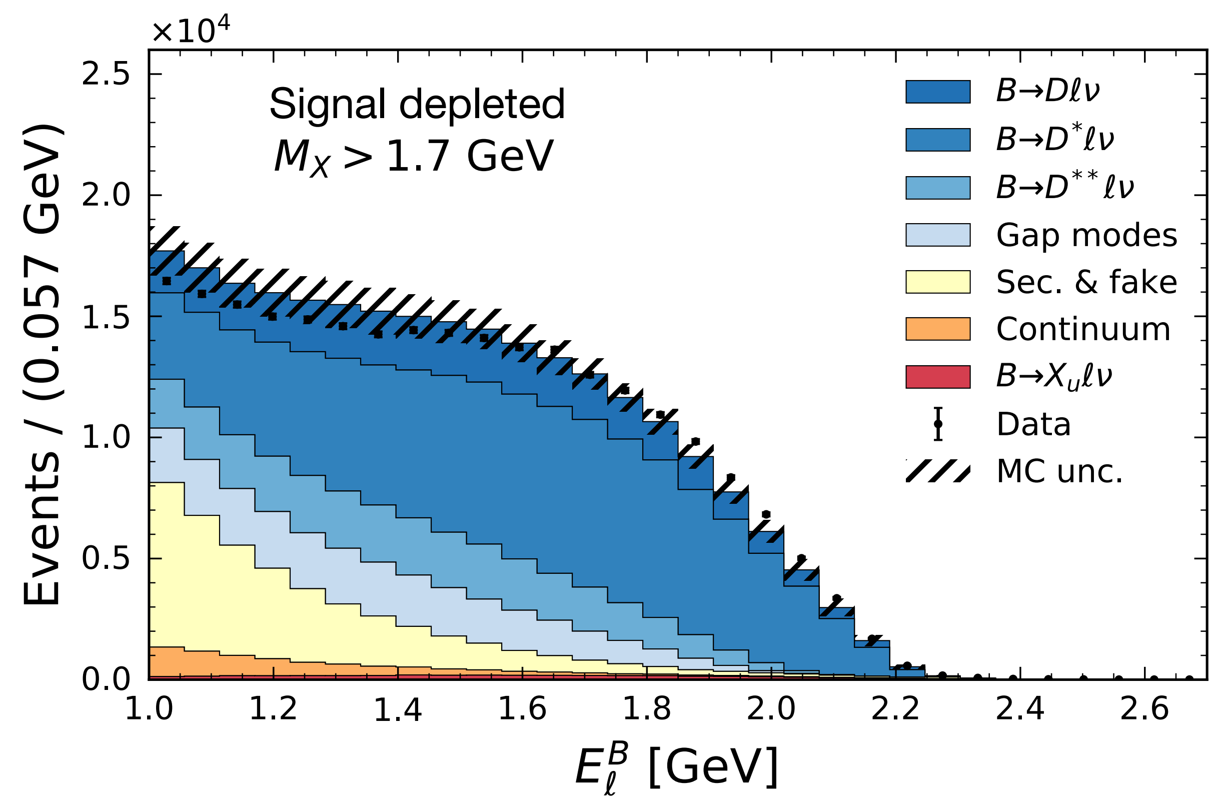
Hadronic Mass $M_X = \sqrt{p_X^2}$

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





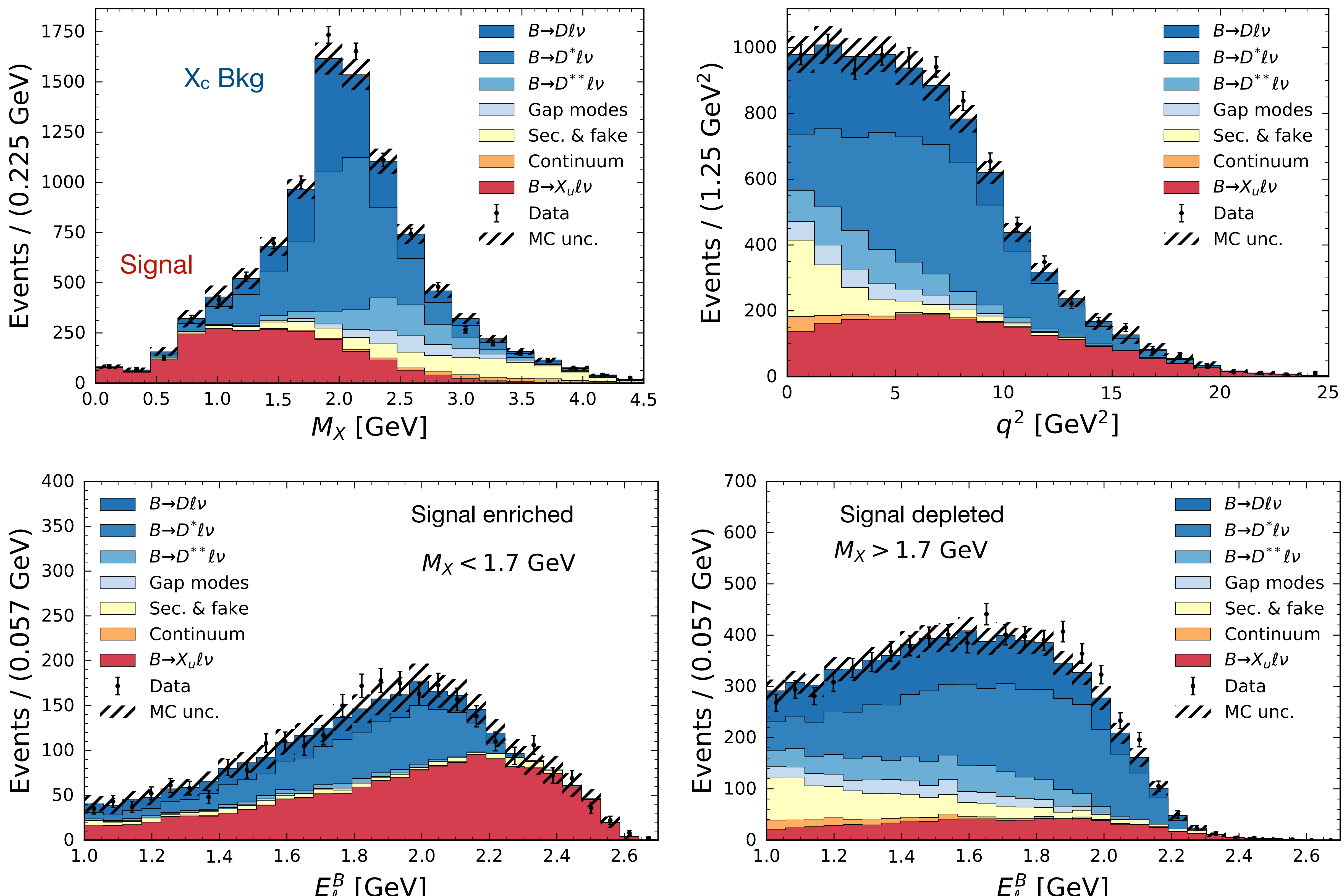




Lepton Energy in signal B frame

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

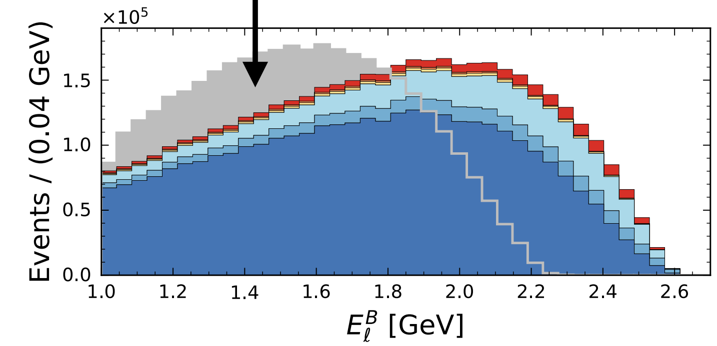
Four-momentum transfer squared $q^2 = (p_B - p_X)^2$



Lepton Energy in signal B frame

reduced
to an acceptable level

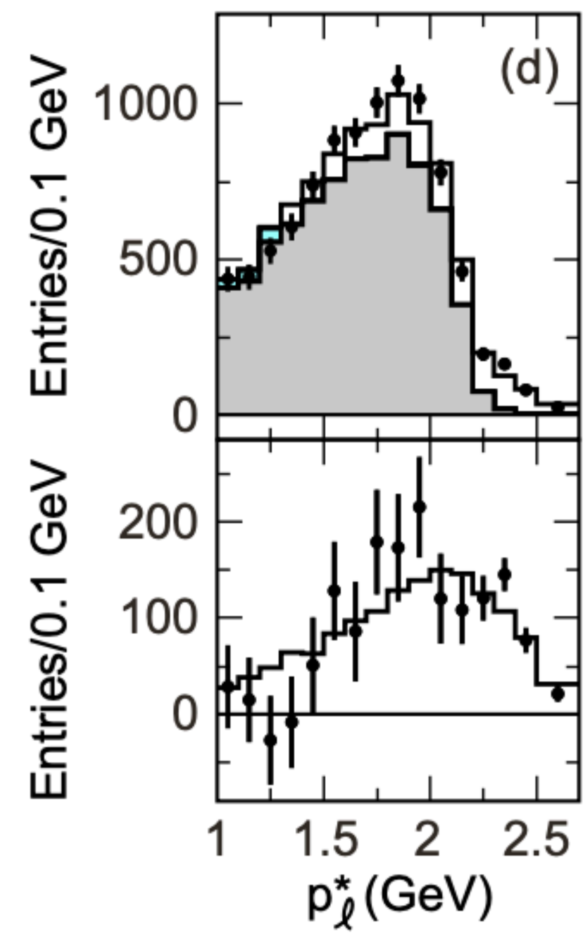
Ok, but what's the problem?



Abstract

We present the partial branching fraction for inclusive charmless semileptonic B decays and the corresponding value of the CKM matrix element $|V_{ub}|$, using a multivariate analysis method to access ~90% of the $B \to X_u \ell \nu$ phase space. This approach dramatically reduces the theoretical uncertainties from the b–quark mass and non-perturbative QCD compared to all previous inclusive measurements. The results are based on a sample of 657 million $B\bar{B}$ pairs collected with the Belle detector. We find that $\Delta\mathcal{B}(B \to X_u \ell \nu; p_\ell^{*B} > 1.0\ \mathrm{GeV}/c) = 1.963 \times (1 \pm 0.088_{\mathrm{stat.}} \pm 0.081_{\mathrm{sys.}}) \times 10^{-3}$. Corresponding values of $|V_{ub}|$ are extracted using several theoretical calculations.

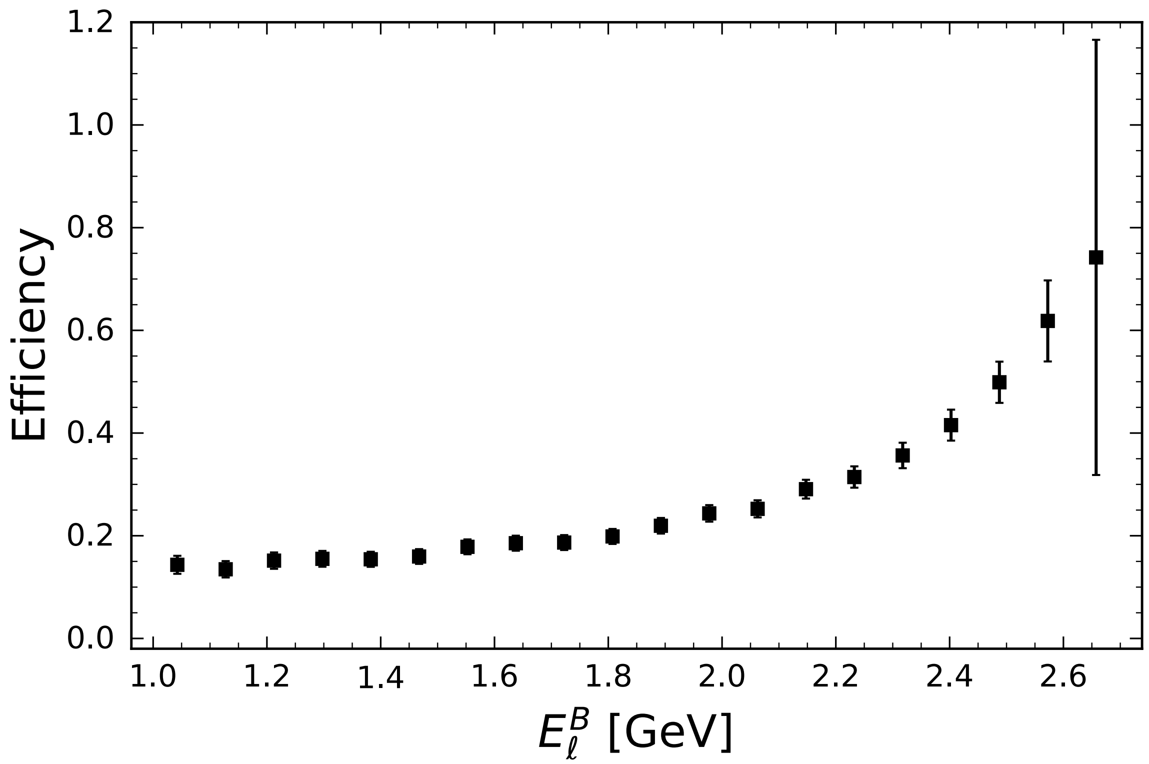
We report measurements of partial branching fractions for inclusive charmless semileptonic B decays $\overline{B} \to X_u \ell \bar{\nu}$, and the determination of the CKM matrix element $|V_{ub}|$. The analysis is based on a sample of 467 million $\Upsilon(4S) \to B\overline{B}$ decays recorded with the *BABAR* detector at the PEP-II e^+e^- storage rings. We select events in which the decay of one of the B mesons is fully reconstructed and an electron or a muon signals the semileptonic decay of the other B meson. We measure partial branching fractions $\Delta\mathcal{B}$ in several restricted regions of phase space and determine the CKM element $|V_{ub}|$ based on different QCD predictions. For decays with a charged lepton momentum $p_\ell^* > 1.0$ GeV in the B meson rest frame, we obtain $\Delta\mathcal{B} = (1.80 \pm 0.13_{\mathrm{stat.}} \pm 0.15_{\mathrm{sys.}} \pm 0.02_{\mathrm{theo.}}) \times 10^{-3}$ from a fit to the two-dimensional $M_X - q^2$ distribution. Here, M_X refers to the invariant mass of the final state hadron X and q^2 is the invariant mass squared of the charged lepton and neutrino. From this measurement we extract $|V_{ub}| = (4.33 \pm 0.24_{\mathrm{exp.}} \pm 0.15_{\mathrm{theo.}}) \times 10^{-3}$ as the arithmetic average of four results obtained from four different QCD predictions of the partial rate. We separately determine partial branching fractions for $\overline{B}^0$ and B^- decays and derive a limit on the isospin breaking in $\overline{B} \to X_u \ell \bar{\nu}$ decays.

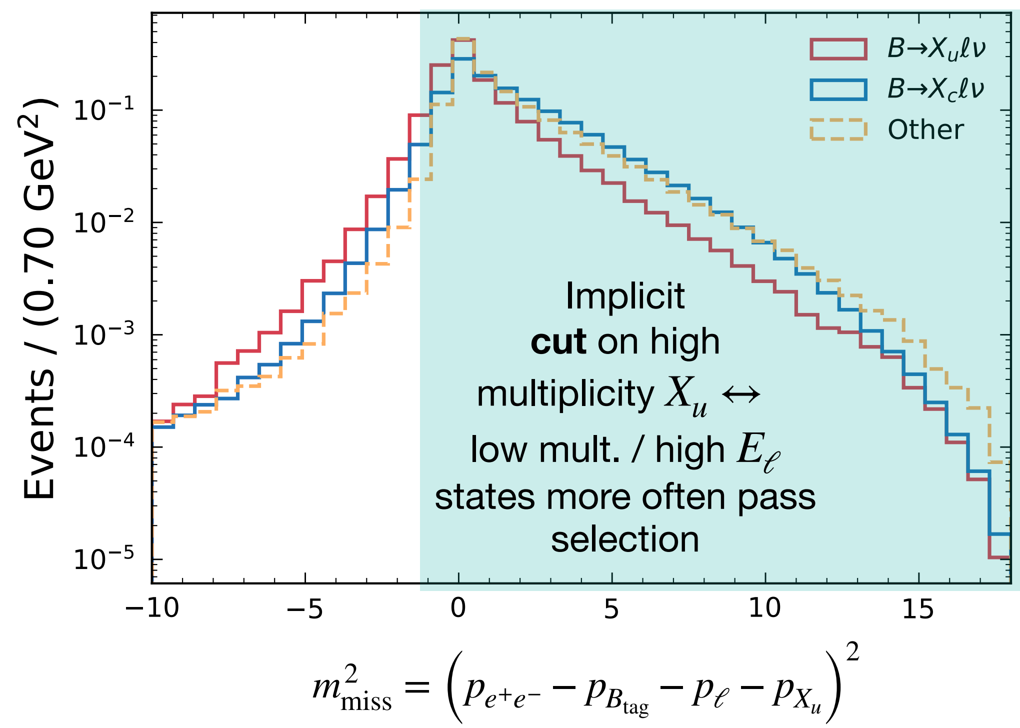


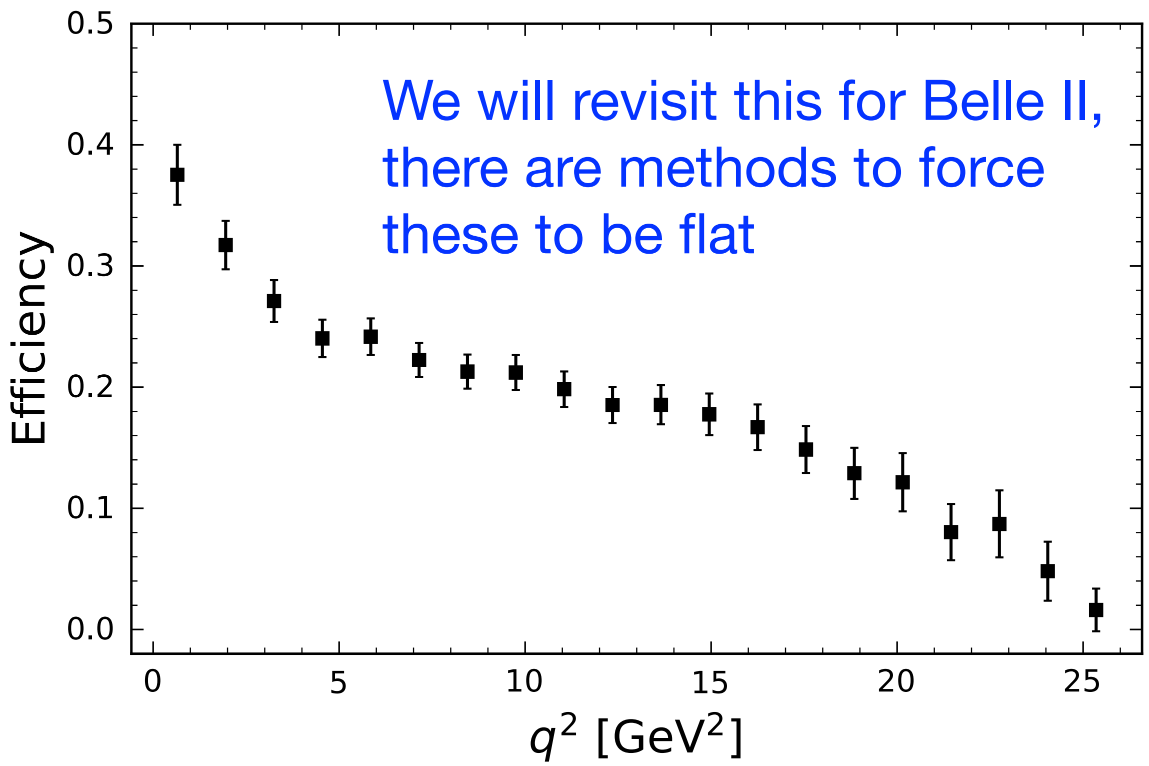
Comes at a cost

The Cost

Shaping in efficiencies, so some model dependence

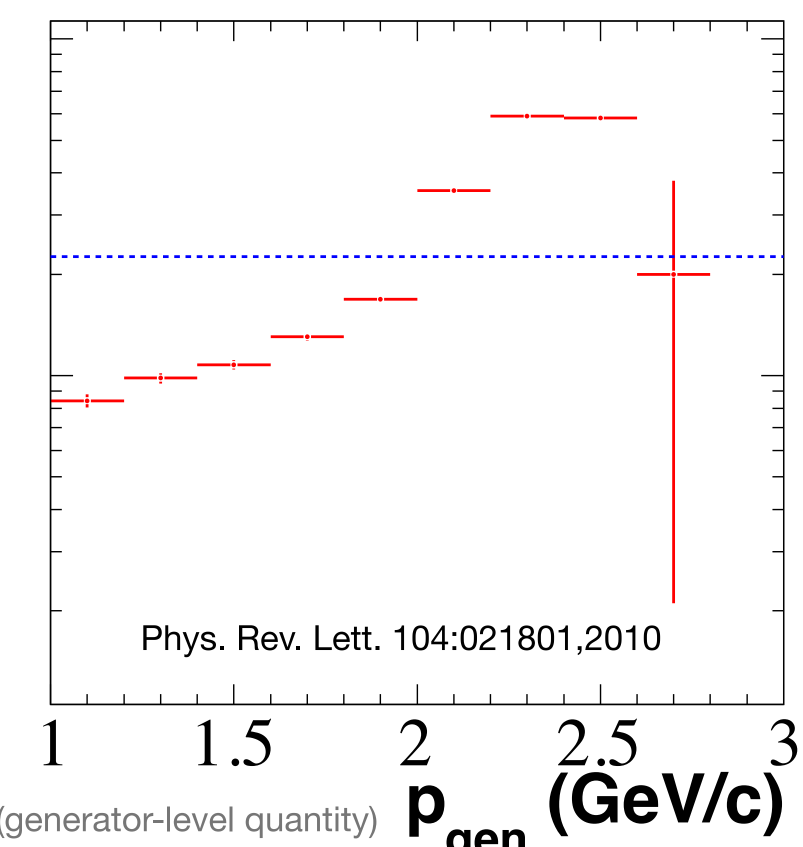






We will revisit this for Belle II, there are methods to force these to be flat

(reconstructed quantities)

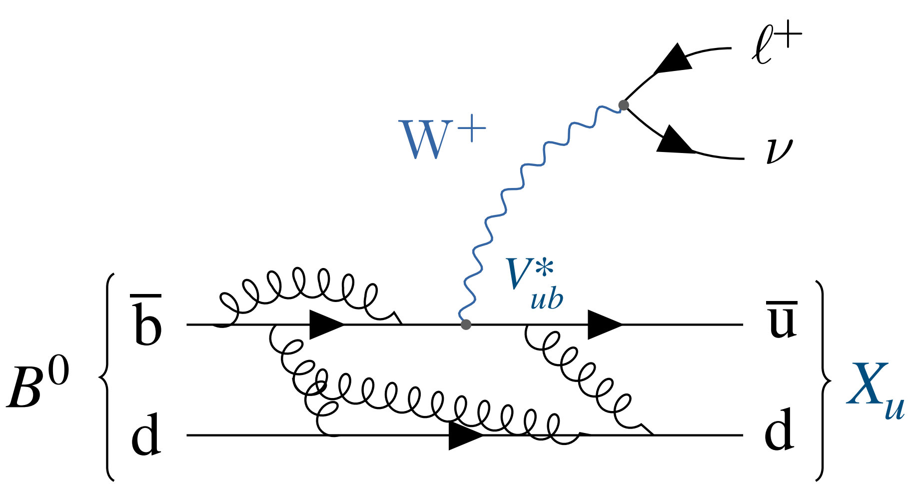


(generator-level quantity)

$B \to X_u \ell \bar{\nu}_\ell$ MC: Going Hybrid

Many measurements target inclusive decays

- $B \to X_u \ell \bar{\nu}_\ell$ with $X_u \in [\pi, \rho, \omega, \eta, \eta', \text{non-resonant decays}, \ldots]$
- $B \to X_s \gamma$ or $B \to X_s \ell \ell$ with $X_s \in [K^*, K\pi, \text{non-resonant}, \ldots]$



Simulated as mix of **exclusive** & **inclusive** processes

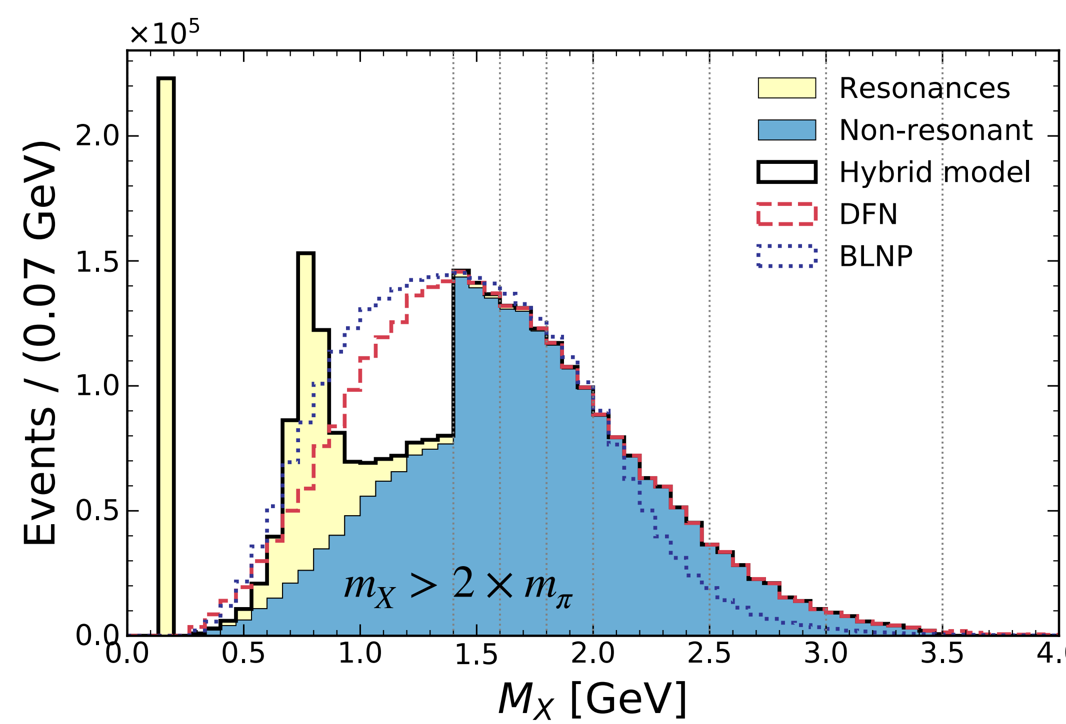
Inclusive: Simulate X system with kinematic properties following (N)NLO calculation w/ non-perturbative QCD input (e.g. from auxiliary measurements)

Hadronizied with Pythia / JETSET

Hybrid Approach: Originally proposed by Phys. Rev. D **41**, 1496

$$\Delta\mathcal{B}^{\text{incl}}_{ijk} = \Delta\mathcal{B}^{\text{excl}}_{ijk} + w_{ijk} \times \Delta\mathcal{B}^{\text{incl}}_{ijk} \,,$$

$$q^2 = [0, 2.5, 5, 7.5, 10, 12.5, 15, 20, 25]\,\text{GeV}^2 \,,$$
$$E^B_\ell = [0, 0.5, 1, 1.25, 1.5, 1.75, 2, 2.25, 3]\,\text{GeV} \,,$$
$$M_X = [0, 1.4, 1.6, 1.8, 2, 2.5, 3, 3.5]\,\text{GeV} \,.$$



Markus Prim, Lu Cao, FB

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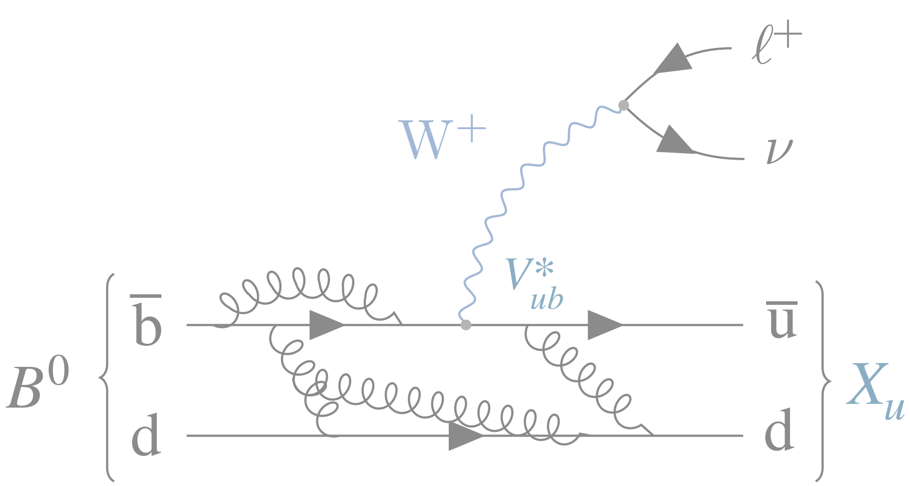

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Hadronizied with Pythia / JETSET

Hybrid Approach: Originally proposed by Phys. Rev. D **41**, 1496

Assessment of uncertainties:

* Change excl. FFs and incl. admixture
* Changes to underlying model parameters
* Vary Pythia / JETSET parameters that affect e.g. scalar vs. vector final states, suppression of s quark production, η-meson suppression

mesonUDvector, mesonSvector, mesonCvector	for the relative production ratio vector/pseudoscalar for light (u, d), s and c mesons
probStoUD	the suppression of s quark production relative to u or d production.
probQQtoQ	parameter for the suppression of diquark production relative to quark production, i.e. of baryon relative to meson production
etaSup	the η-meson suppression

Estimated by variations of **underlying theory assumptions** and **Hybrid** model parameters used to determine (and correct for) selection efficiencies

Phase space restriction	$M_X - q^2$
Data statistical uncertainty	7.1
MC statistical uncertainty	1.1
Track efficiency	0.7
Photon efficiency	1.0
π^0 efficiency	0.9
Particle identification	2.3
K_L production/detection	1.6
K_S production/detection	1.2
Shape function parameters	5.4
Shape function form	1.5
Exclusive $\overline{B} \to X_u \ell \bar{\nu}$	1.9
$s\bar{s}$ production	2.7
B semileptonic branching ratic	1.0
D decays	1.1
$B \to D\ell\nu$ form factor	0.4
$B \to D^*\ell\nu$ form factor	0.7
$B \to D^{**}\ell\nu$ form factor	0.9
$B \to D^{**}$ reweighting	1.9
m_{ES} background subtraction	1.9
combinatorial backg.	1.0
Total semileptonic BF	1.4
Total systematic uncertainty	8.4
Total experimental uncertainty	11.0

$p_\ell^{*B} > 1.0$ GeV	$\Delta\mathcal{B}/\mathcal{B}$ (%)
$\mathcal{B}(D^{(*)}\ell\nu)$	1.2
$(D^{(*)}\ell\nu)$ form factors	1.2
$\mathcal{B}(D^{**}e\nu)$ & form factors	0.2
$B \to X_u\ell\nu$ (SF)	3.6
$B \to X_u\ell\nu$ $(g \to s\bar{s})$	1.5
$\mathcal{B}(B \to \pi/\rho/\omega\ell\nu)$	2.3
$\mathcal{B}(B \to \eta,\ \eta'\ell\nu)$	3.2
$\mathcal{B}(B \to X_u\ell\nu)$ un-meas.	2.9
Cont./Comb.	1.8
Sec./Fakes/Fit.	1.0
PID/Reconstruction	3.1
BDT	3.1
Systematics	8.1
Statistics	8.8

Phase-space region	$E_\ell^B > 1\,\mathrm{GeV}$
Fit variable(s)	$(M_X : q^2$ fit)
Additive uncertainties	
$B \to X_u\,\ell^+\,\nu_\ell$ modeling	
$B \to \pi\,\ell^+\,\nu_\ell$ FFs	0.4
$B \to \rho\,\ell^+\,\nu_\ell$ FFs	0.7
$B \to \omega\,\ell^+\,\nu_\ell$ FFs	0.8
$B \to \eta\,\ell^+\,\nu_\ell$ FFs	0.3
$B \to \eta'\,\ell^+\,\nu_\ell$ FFs	1.6
$\mathcal{B}(B \to \pi\,\ell^+\,\nu_\ell)$	0.2
$\mathcal{B}(B \to \rho\,\ell^+\,\nu_\ell)$	0.4
$\mathcal{B}(B \to \omega\,\ell^+\,\nu_\ell)$	0.1
$\mathcal{B}(B \to \eta\,\ell^+\,\nu_\ell)$	<0.1
$\mathcal{B}(B \to \eta'\,\ell^+\,\nu_\ell)$	<0.1
$\mathcal{B}(B \to X_u\,\ell^+\,\nu)$	2.1
DFN parameters	5.0
Hybrid model	3.1
$B \to X_c\,\ell^+\,\nu_\ell$ modeling	
$B \to D\,\ell^+\,\nu_\ell$ FFs	<0.1
$B \to D^*\,\ell^+\,\nu_\ell$ FFs	1.1
$B \to D^{**}\,\ell^+\,\nu_\ell$ FFs	0.4
$\mathcal{B}(B \to D\,\ell^+\,\nu_\ell)$	0.2
$\mathcal{B}(B \to D^*\,\ell^+\,\nu_\ell)$	0.2
$\mathcal{B}(B \to D^{**}\,\ell^+\,\nu_\ell)$	0.5
Gap modeling	1.0
MC statistics	1.6
Tracking efficiency	0.4
$\mathcal{L}_{\ell\mathrm{ID}}$ shape	1.2
$\mathcal{L}_{\mathrm{K}/\pi\mathrm{ID}}$ shape	1.0
$D \to X\ell\,\nu_\ell$	0.1
π_s efficiency	0.1
Multiplicative uncertainties	
$B \to X_u\,\ell^+\,\nu_\ell$ modeling	
$B \to \pi\,\ell^+\,\nu_\ell$ FFs	0.2
$B \to \rho\,\ell^+\,\nu_\ell$ FFs	0.6
$B \to \omega\,\ell^+\,\nu_\ell$ FFs	1.1
$B \to \eta\,\ell^+\,\nu_\ell$ FFs	0.2
$B \to \eta'\,\ell^+\,\nu_\ell$ FFs	0.2
$\mathcal{B}(B \to \pi\,\ell^+\,\nu_\ell)$	0.3
$\mathcal{B}(B \to \rho\,\ell^+\,\nu_\ell)$	0.4
$\mathcal{B}(B \to \omega\,\ell^+\,\nu_\ell)$	<0.1
$\mathcal{B}(B \to \eta\,\ell^+\,\nu_\ell)$	<0.1
$\mathcal{B}(B \to \eta'\,\ell^+\,\nu_\ell)$	0.1
$\mathcal{B}(B \to X_u\,\ell^+\,\nu)$	3.8
DFN parameters	3.6
Hybrid model	2.8
π^+ multiplicity	1.7
γ_s ($s\bar{s}$ fragmentation)	0.8
$\mathcal{L}_{\ell\mathrm{ID}}$ efficiency	1.5
$\mathcal{L}_{\mathrm{K}/\pi\,\mathrm{ID}}$ efficiency	0.7
$N_{B\bar{B}}$	1.3
Tracking efficiency	0.9
Tagging calibration	3.6
Total syst. uncertainty	**10.4**

Tables from Phys. Rev. Lett. 104:021801,2010, Phys.Rev. D86 (2012) 032004, Phys. Rev. D 104, 012008 (2021)

Estimated by variations of **underlying theory assumptions** and **Hybrid** model parameters used to determine (and correct for) selection efficiencies

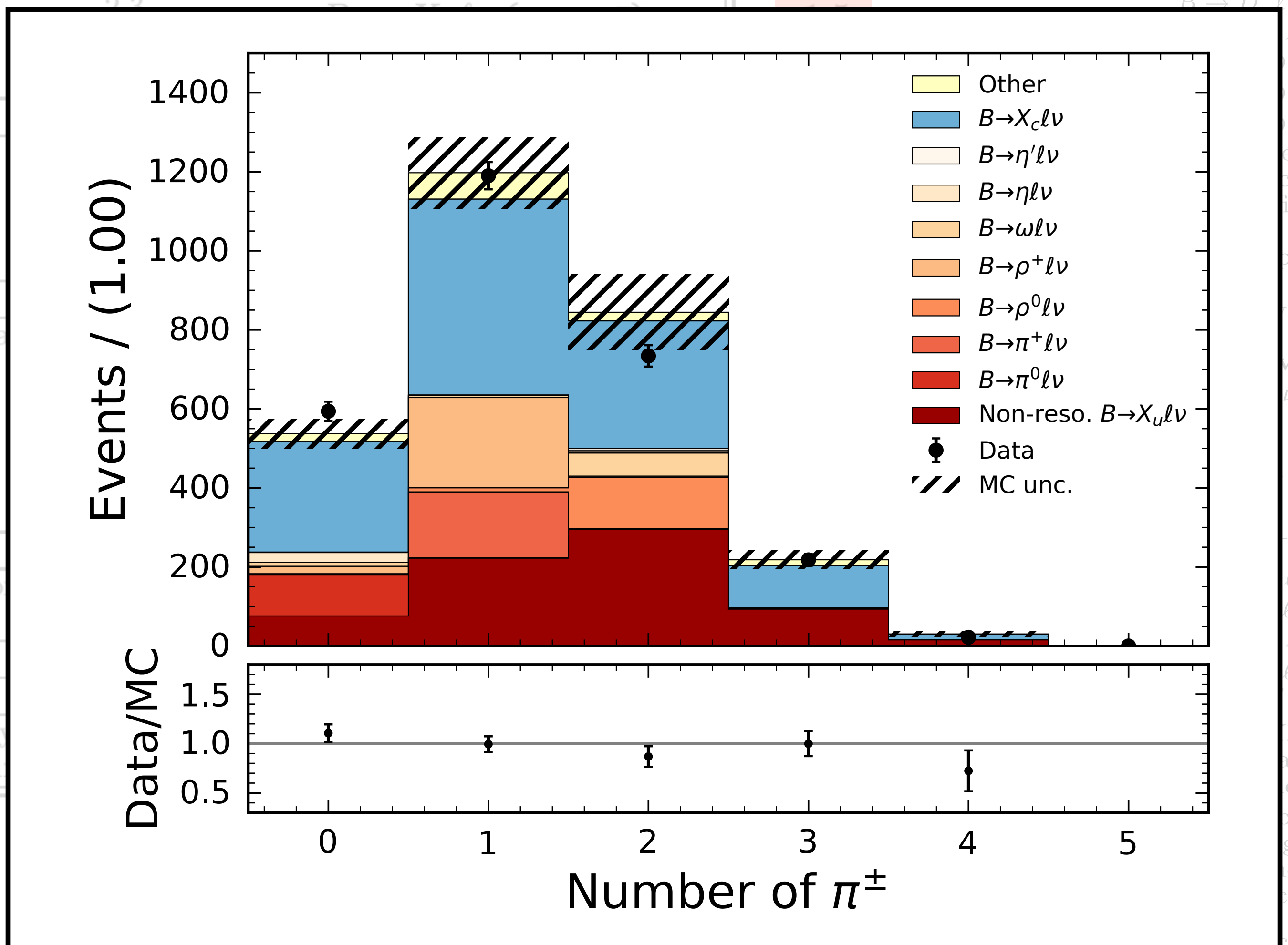
Phase space restriction	$M_X - q^2$
Data statistical uncertainty	7.1
MC statistical uncertainty	1.1
Track efficiency	0.7
Photon efficiency	1.0
π^0 efficiency	0.9
Particle identification	
K_L production/detection	
K_S production/detection	
Shape function parameters	
Shape function form	
Exclusive $\bar{B} \to X_u \ell \bar{\nu}$	
$s\bar{s}$ production	
B semileptonic branching ra	
D decays	
$B \to D\ell\nu$ form factor	
$B \to D^*\ell\nu$ form factor	
$B \to D^{**}\ell\nu$ form factor	
$B \to D^{**}$ reweighting	
m_{ES} background subtractio	
combinatorial backg.	
Total semileptonic BF	
Total systematic uncertaint	
Total experimental uncertai	

Can we do better?

Can data teach us more?

p_ℓ^*	
$\mathcal{B}(D^{(*)}\ell\nu)$	1.2
$(D^{(*)}\ell\nu)$ form factors	1.2
$\mathcal{B}(D^{**}e\nu)$ & form factors	0.2
$B \to X_u\ell\nu$ (SF)	3.6

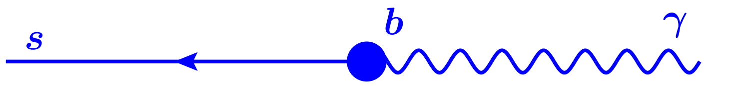
Phase-space region	$E_\ell^B > 1\,\mathrm{GeV}$
Fit variable(s)	($M_X : q^2$ fit)
Additive uncertainties	
$B \to X_u \ell^+ \nu_\ell$ modeling	
$B \to \pi \ell^+ \nu_\ell$ FFs	0.4
$B \to \rho \ell^+ \nu_\ell$ FFs	0.7
$B \to \omega \ell^+ \nu_\ell$ FFs	0.8
$B \to \eta \ell^+ \nu_\ell$ FFs	0.3
$B \to \eta' \ell^+ \nu_\ell$ FFs	1.6
$\mathcal{B}(B \to \pi \ell^+ \nu_\ell)$	0.2
$\mathcal{B}(B \to \rho \ell^+ \nu_\ell)$	0.4
$\mathcal{B}(B \to \omega \ell^+ \nu_\ell)$	0.1
$\mathcal{B}(B \to \eta \ell^+ \nu_\ell)$	<0.1
$\mathcal{B}(B \to \eta' \ell^+ \nu_\ell)$	<0.1
$\mathcal{B}(B \to X_u \ell^+ \nu)$	2.1
DFN parameters	5.0
Hybrid model	3.1
$B \to X_c \ell^+ \nu_\ell$ modeling	
$B \to D \ell^+ \nu_\ell$ FFs	<0.1
$B \to D^* \ell^+ \nu_\ell$ FFs	1.1
$\ell^+ \nu_\ell$ FFs	0.4
$\ell^+ \nu_\ell)$	0.2
$^* \ell^+ \nu_\ell)$	0.2
$^{**} \ell^+ \nu_\ell)$	0.5
eling	1.0
s	1.6
iciency	0.4
	1.2
pe	1.0
	0.1
	0.1
ve uncertainties	
ν_ℓ modeling	
ν_ℓ FFs	0.2
ν_ℓ FFs	0.6
ν_ℓ FFs	1.1
ν_ℓ FFs	0.2
ν_ℓ FFs	0.2
$\ell^+ \nu_\ell)$	0.3
$\ell^+ \nu_\ell)$	0.4
$\ell^+ \nu_\ell)$	<0.1
$\ell^+ \nu_\ell)$	<0.1
$\ell^+ \nu_\ell)$	0.1
$_u \ell^+ \nu)$	3.8
meters	3.6
odel	2.8
licity	1.7
gmentation)	0.8
cy	1.5
iency	0.7
	1.3
ciency	0.9
Tagging calibration	3.6
Total syst. uncertainty	10.4



Tables from Phys. Rev. Lett. 104:021801,2010, Phys.Rev. D86 (2012) 032004, Phys. Rev. D 104, 012008 (2021)

Going differential

Focus on experimental **most sensitive region** (e.g. high E_ℓ^B)

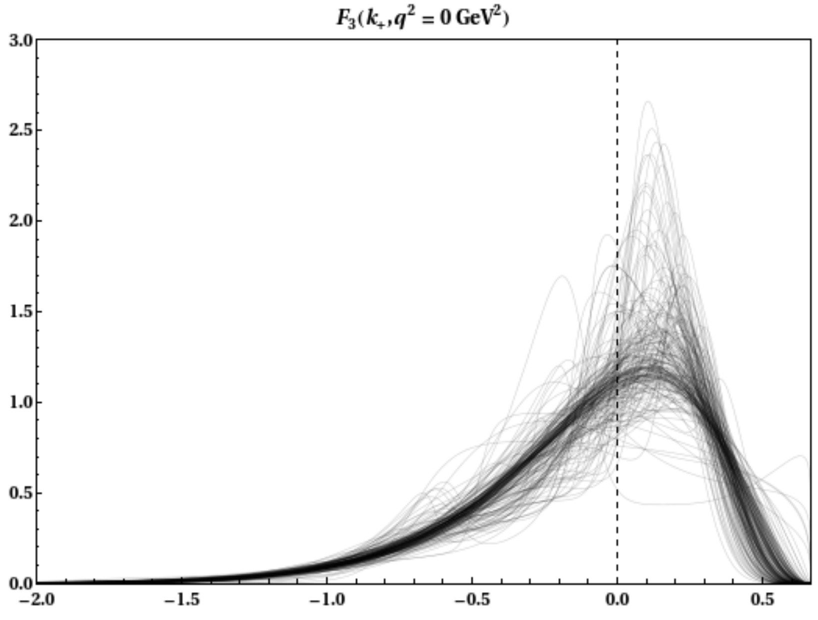


Determine Shape-Function in a data-driven way

Note: this is still not the NNVub Logo :-)

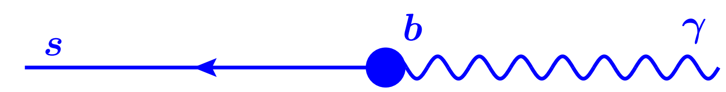
NNVub

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



Going differential

Focus on experimental **most sensitive region** (e.g. high E_ℓ^B)



Determine Shape-Function in a data-driven way

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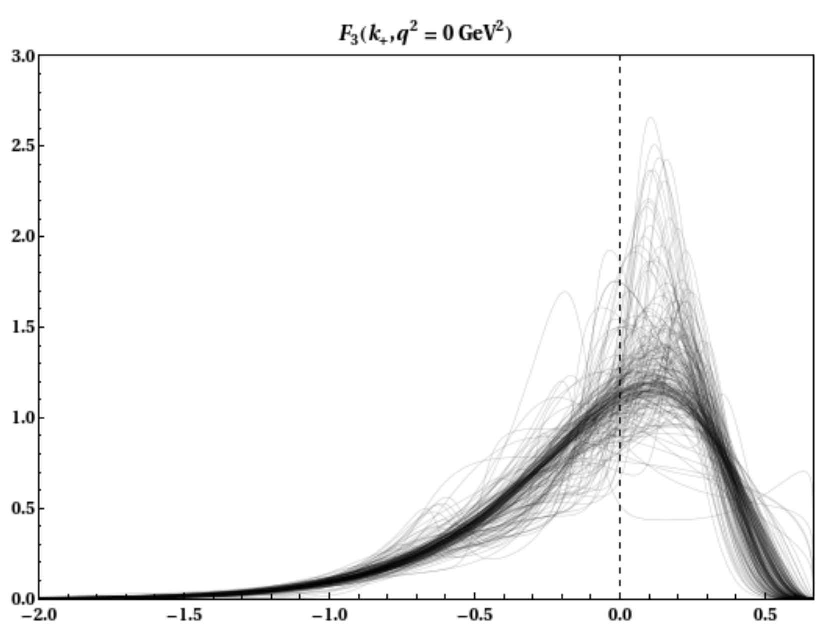
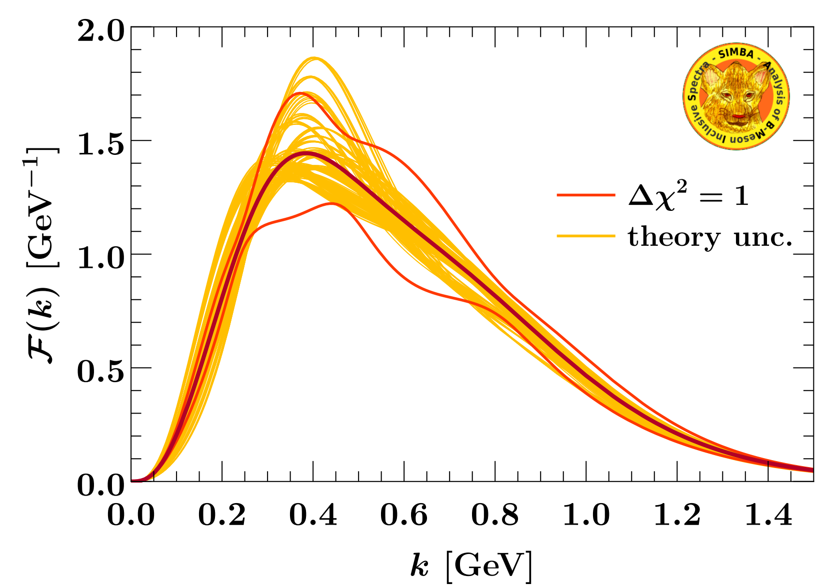
F. Bernlochner, H. Lacker, Z. Ligeti, I. Stewart, F. Tackmann, K. Tackmann Phys. Rev. Lett. 127, 102001 (2021) [arXiv:2007.04320]





~ Momentum Distribution of b-Quark in B Meson

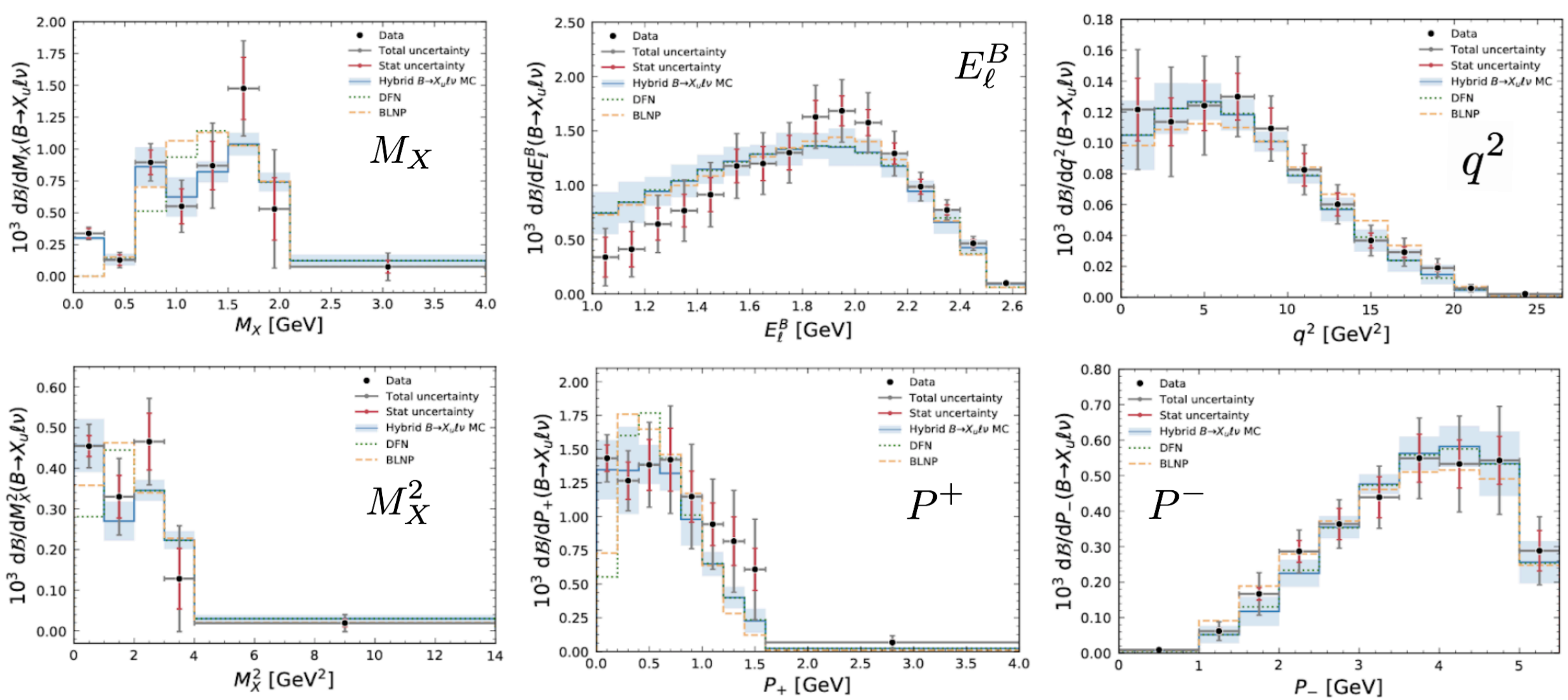
Going differential

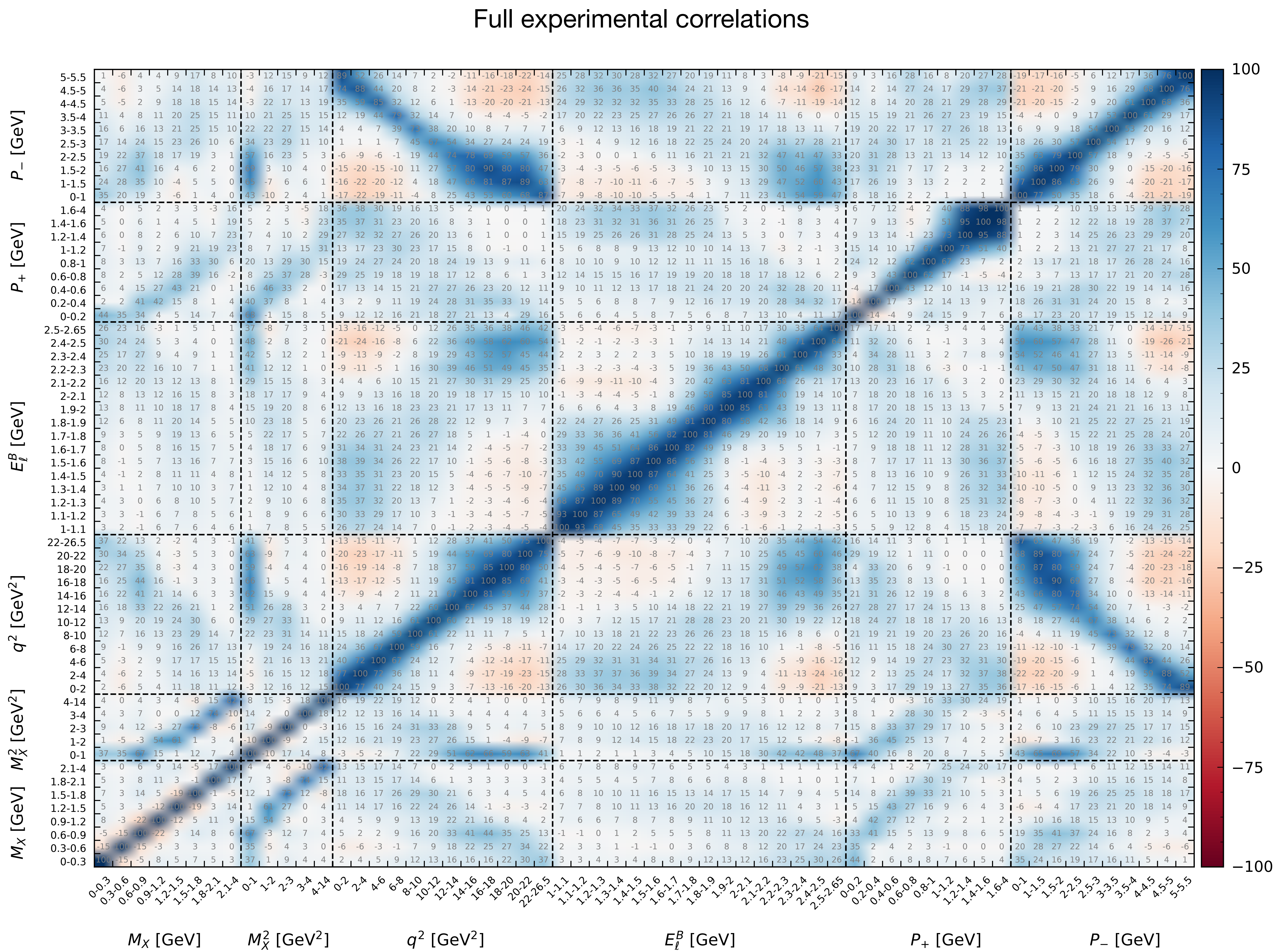
Raynette Van Tonder's talk

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

arXiv:2107.13855, accepted by PRL

- **Convert** unfolded yield to $\Delta\mathscr{B}$ in each bin considering reco. efficiency & acceptance
- **First measurement** of differential branching fractions in the E_ℓ^B > 1 GeV region of phase space
- Necessary input for future **model-independent** determinations of $|V_{ub}|$ (e.g. NNVub, SIMBA)

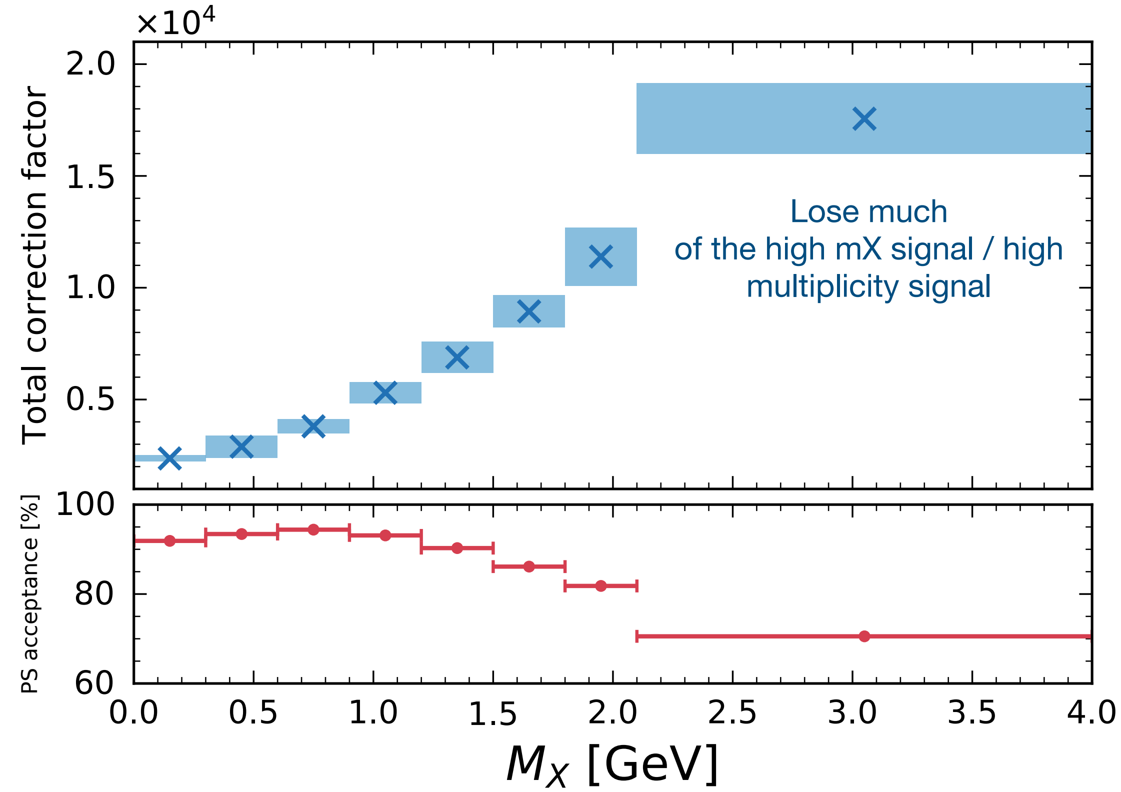


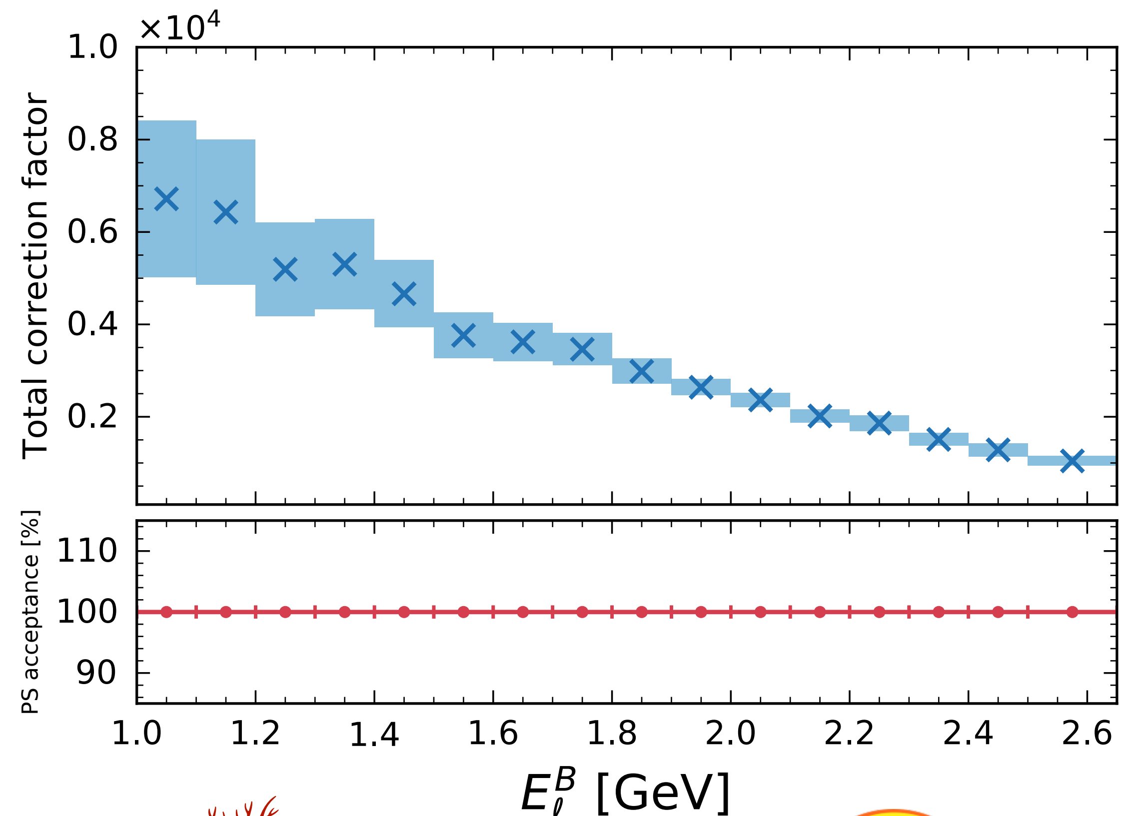

Full experimental correlations
P_- [GeV]
P_+ [GeV]
E_ℓ^B [GeV]
q^2 [GeV^2]
M_X^2 [GeV^2]
M_X [GeV]
0-0.3 0.3-0.6 0.6-0.9 0.9-1.2 1.2-1.5 1.5-1.8 1.8-2.1 2.1-4
0-1 1-2 2-3 3-4 4-14
0-2 2-4 4-6 6-8 8-10 10-12 12-14 14-16 16-18 18-20 20-22 22-26.5
1-1.1 1.1-1.2 1.2-1.3 1.3-1.4 1.4-1.5 1.5-1.6 1.6-1.7 1.7-1.8 1.8-1.9 1.9-2 2-2.1 2.1-2.2 2.2-2.3 2.3-2.4 2.4-2.5 2.5-2.65
0-0.2 0.2-0.4 0.4-0.6 0.6-0.8 0.8-1 1-1.2 1.2-1.4 1.4-1.6 1.6-4
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
100 75 50 25 0 −25 −50 −75 −100

M_X

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

background
dominated region

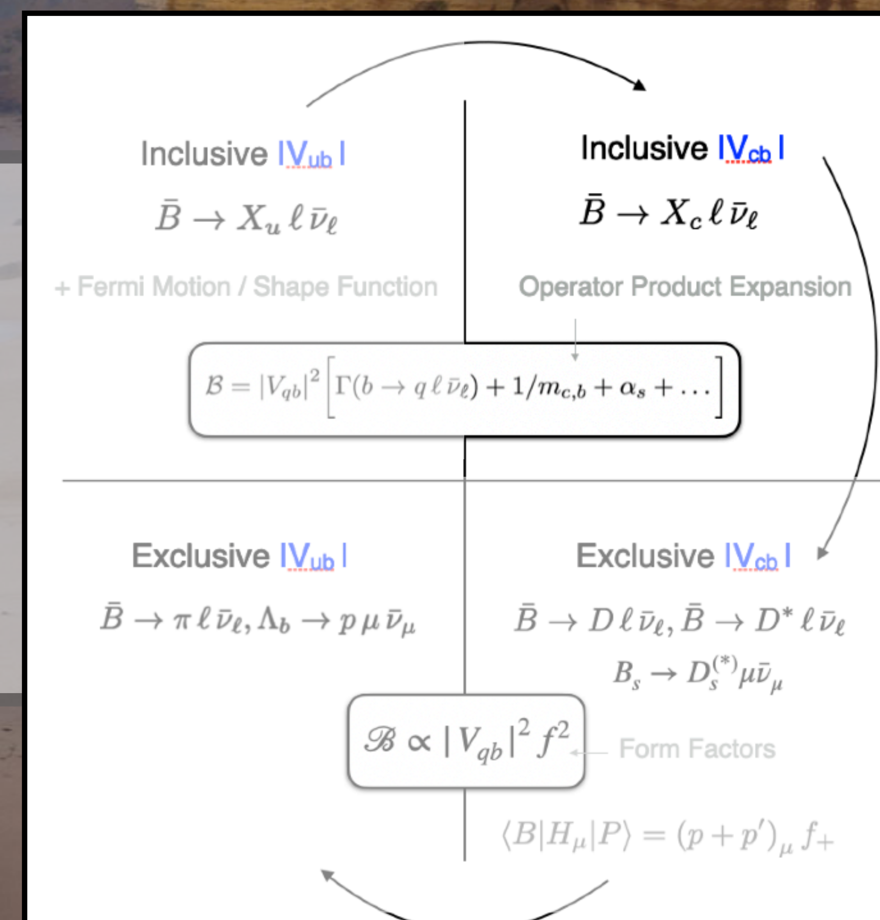




It will be exciting to get first fits with these done..

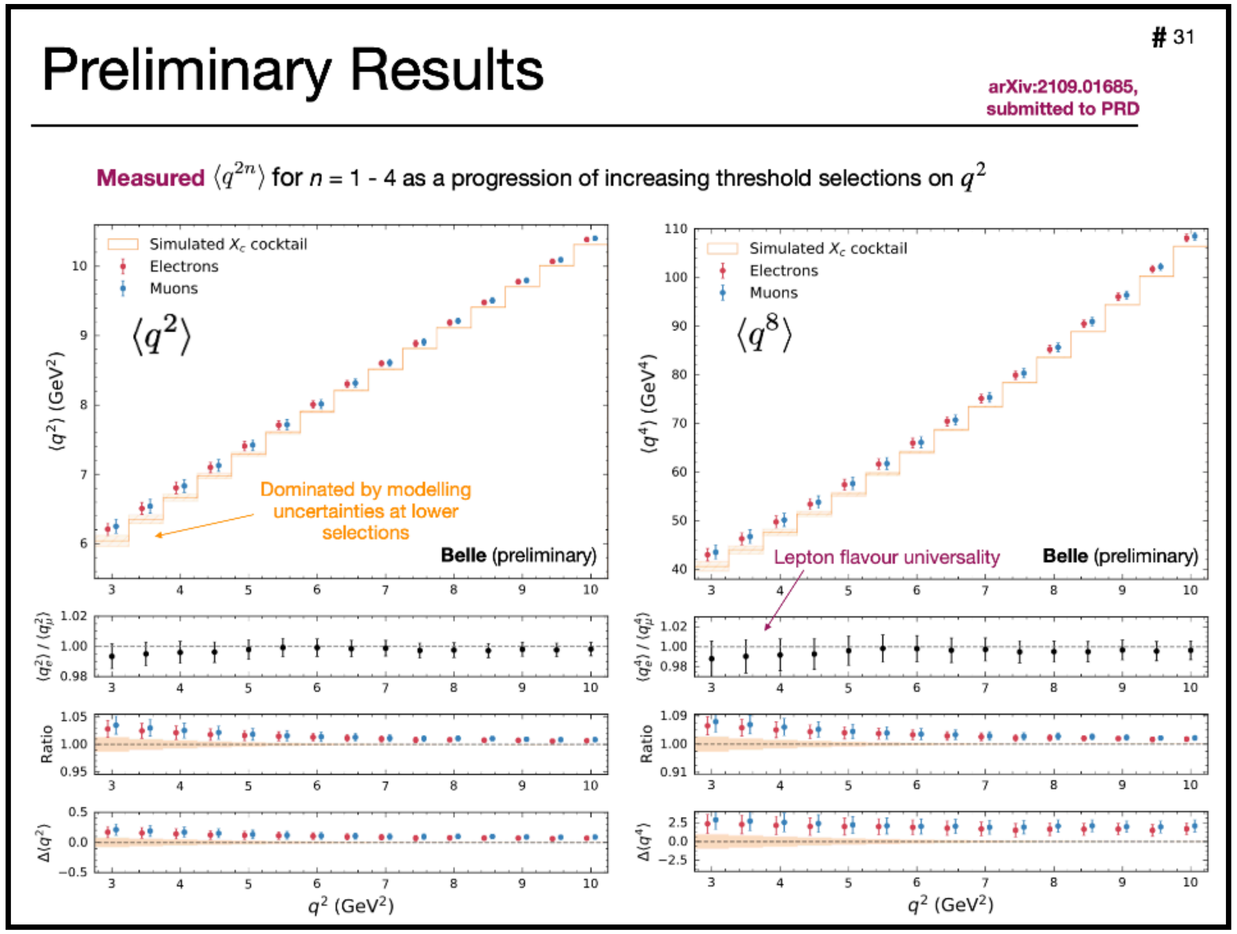
NNVub

Incl. $|V_{cb}|$



- Systematic covariances of inputs
- Theory correlations
- Role of lattice QCD

New results from Belle (soon also from Belle II)



Experiment	Hadron moments $<M^n_X>$	Lepton moments $<E^n_l>$	References
BaBar	n=2 c=0.9,1.1,1.3,1.5 n=4 c=0.8,1.0,1.2,1.4 n=6 c=0.9,1.3 [1]	n=0 c=0.6,1.2,1.5 n=1 c=0.6,0.8,1.0,1.2,1.5 n=2 c=0.6,1.0,1.5 n=3 c=0.8,1.2 [1,2]	[1] Phys.Rev. D81 (2010) 032003 [2] Phys.Rev. D69 (2004) 111104
Belle	n=2 c=0.7,1.1,1.3,1.5 n=4 c=0.7,0.9,1.3 [3]	n=0 c=0.6,1.4 n=1 c=1.0,1.4 n=2 c=0.6,1.4 n=3 c=0.8,1.2 [4]	[3] Phys.Rev. D75 (2007) 032005 [4] Phys.Rev. D75 (2007) 032001
CDF	n=2 c=0.7 n=4 c=0.7 [5]	.	[5] Phys.Rev. D71 (2005) 051103
CLEO	n=2 c=1.0,1.5 n=4 c=1.0,1.5 [6]	.	[6] Phys.Rev. D70 (2004) 032002
DELPHI	n=2 c=0.0 n=4 c=0.0 n=6 c=0.0 [7]	n=1 c=0.0 n=2 c=0.0 n=3 c=0.0 [7]	[7] Eur.Phys.J. C45 (2006) 35-59

Subset of currently used measurements in global fits from HFLAV

With Belle II (& LHCb via SEM-techniques?) we should **systematically remeasure** properties & actively investigate if other observables could be helpful

We learnt a fair bit in the last decade and should evaluate, how this propagates into our measurements, e.g.

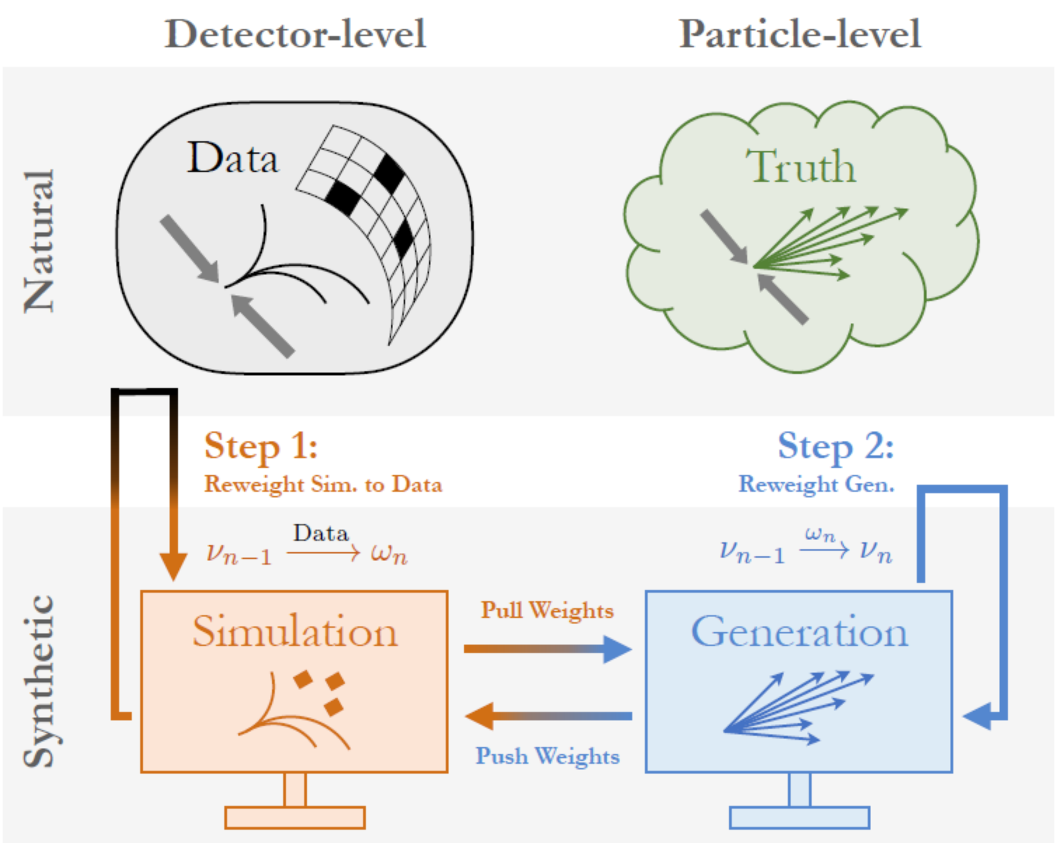
- $B \to X_c \ell \bar{\nu}_\ell$ composition and modeling
- Revisit most important systematic uncertainties, e.g. modelling of detector resolution
- New experimental techniques

Let’s get ambitious

Figure right: Lukas Reinarz, FB

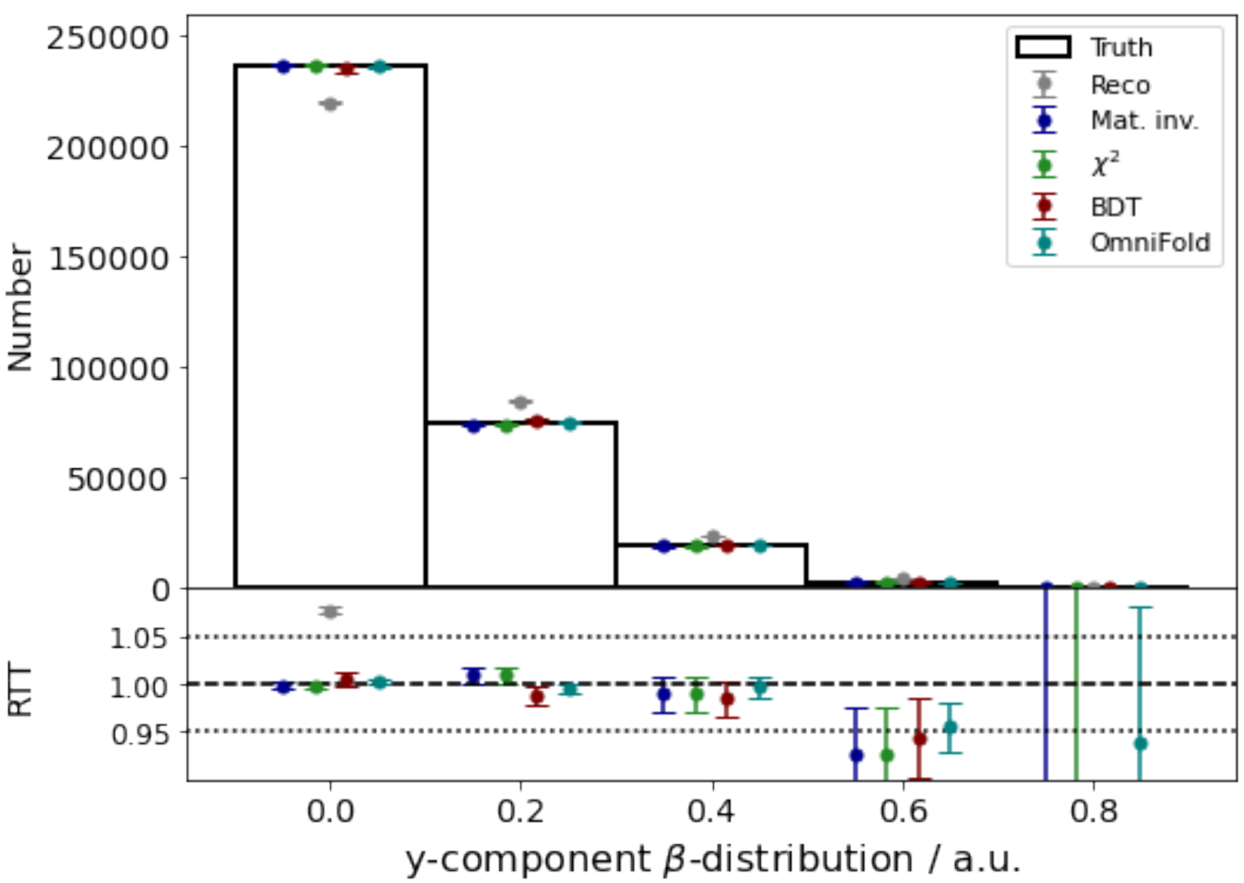
OmniFold: A Method to Simultaneously Unfold All Observables

Phys. Rev. Lett. 124, 182001 (2020)



6D Example:

(3D Gaussian, 2D beta distribution
1 exponential, all smeared with gaussian resolution)



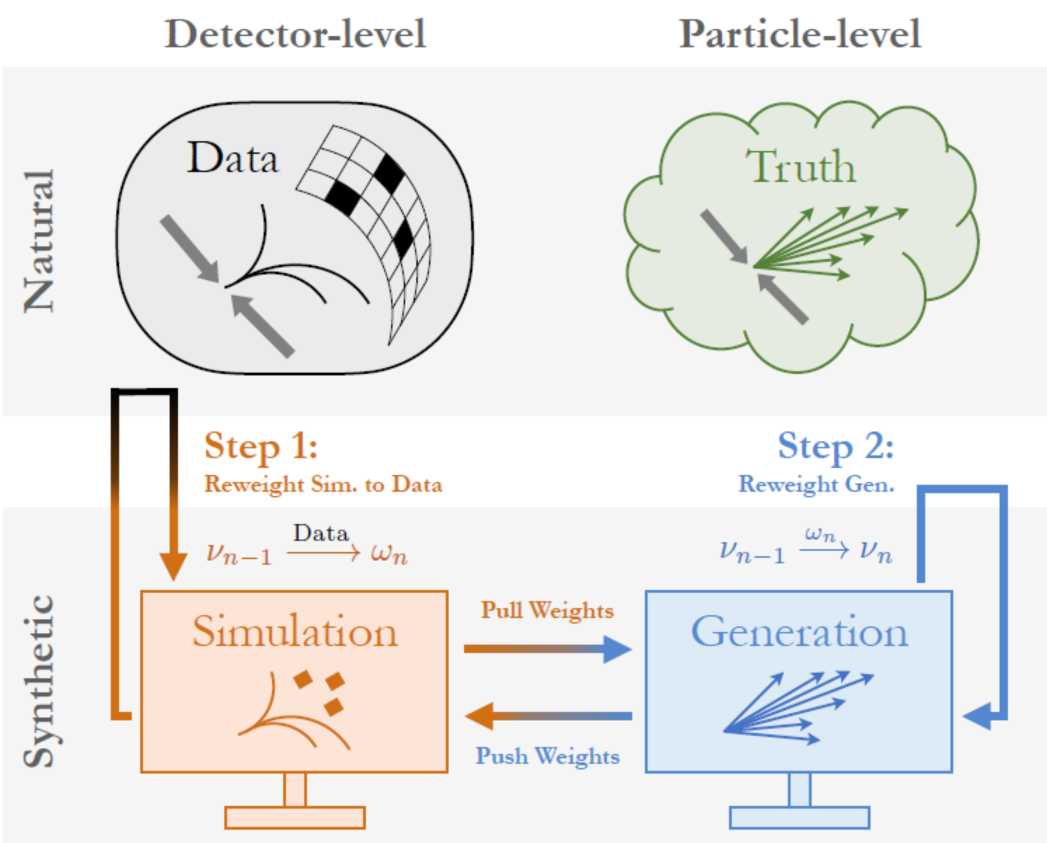
based on training a deep network to unfold detector distortions and effects

Let’s get ambitious

Figure right: Lukas Reinarz, FB

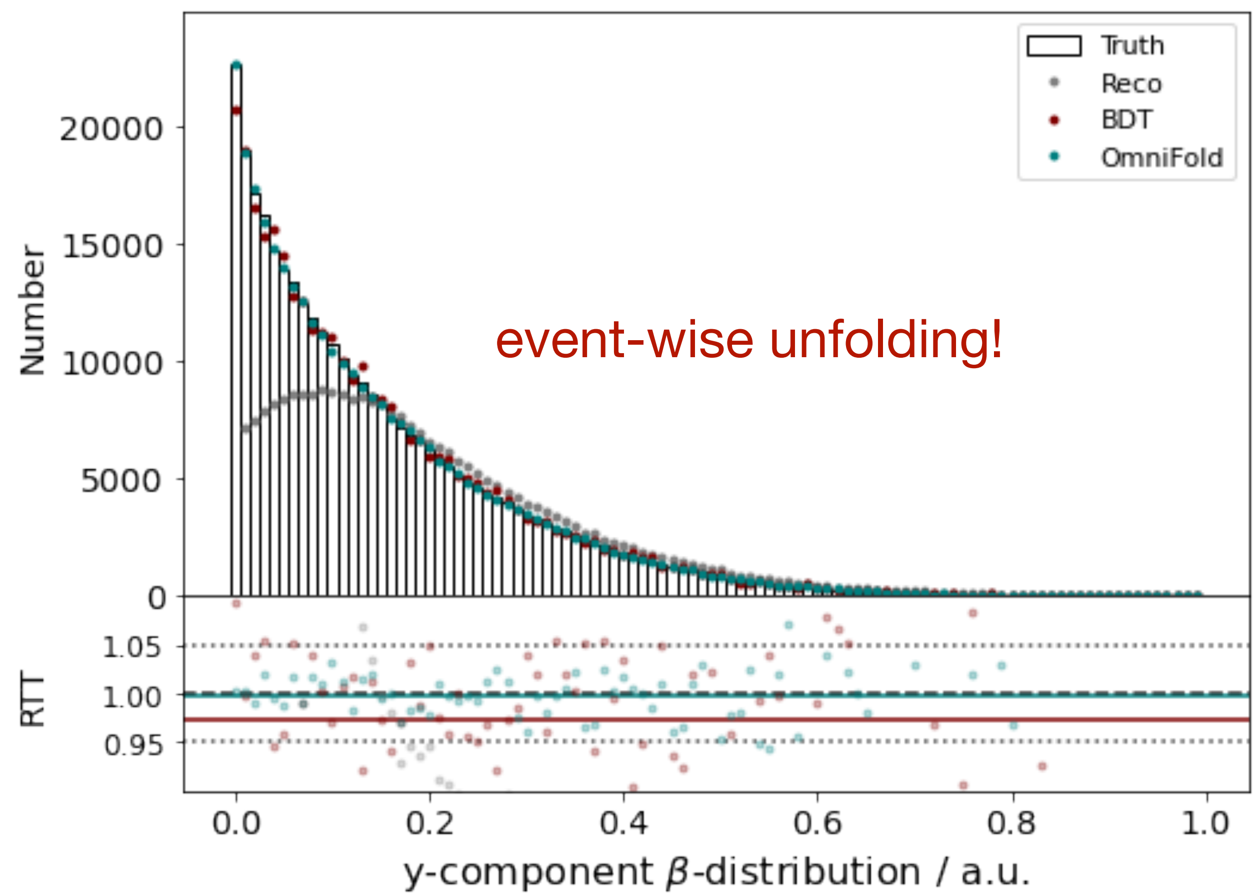
OmniFold: A Method to Simultaneously Unfold All Observables

Phys. Rev. Lett. 124, 182001 (2020)



6D Example:

(3D Gaussian, 2D beta distribution
1 exponential, all smeared with gaussian resolution)



based on training a deep network to unfold detector distortions and effects

Theory Correlations

$|V_{cb}|$ "extraction formula": $C = C_{\rm exp} + C_{\rm theo}$

Introduce theory correlations between moments of various cuts and orders

measured moments

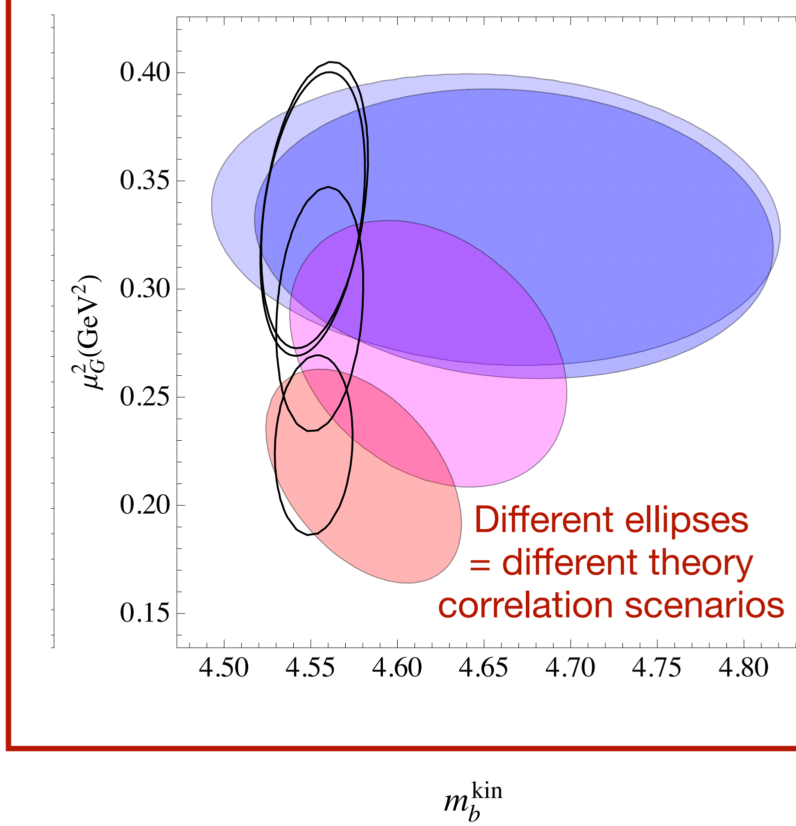
predicted moments

$$\chi^2(|V_{cb}|, \vec{\mu}_{\rm HQE}) = \left(\mathscr{M} - \mathscr{P}(\vec{\mu}_{\rm HQE})\right) C^{-1} \left(\mathscr{M} - \mathscr{P}(\vec{\mu}_{\rm HQE})\right)$$
$$+ \left(\mathscr{B} - |V_{cb}|^2 \tau_B \Gamma(\vec{\mu}_{\rm HQE})\right)^2 / \sigma^2_{\mathscr{B}}$$

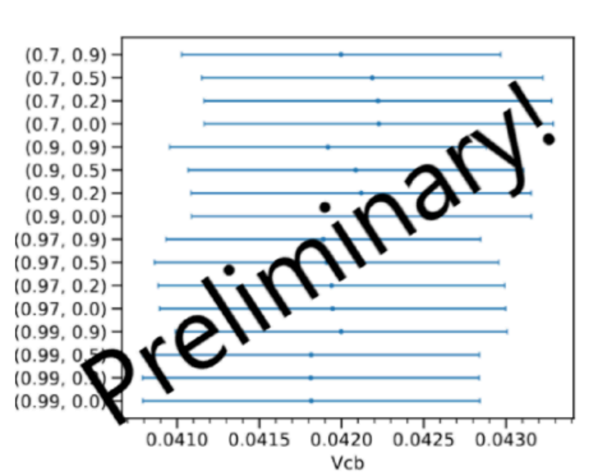
Precise choice of correlations entering $C_{\rm theo}$ introduce a large dependence on HQE parameters

$|V_{cb}|$ seems not to care so much

P. Gambino, C. Schwanda
Phys. Rev. D 89, 014022 (2014)



- Flexible theory covariance matrix:
  - V_{cb} rather insensitive dominated by $B \to X_c \ell \nu$ branchingratio
  - HQE parameters sensitive



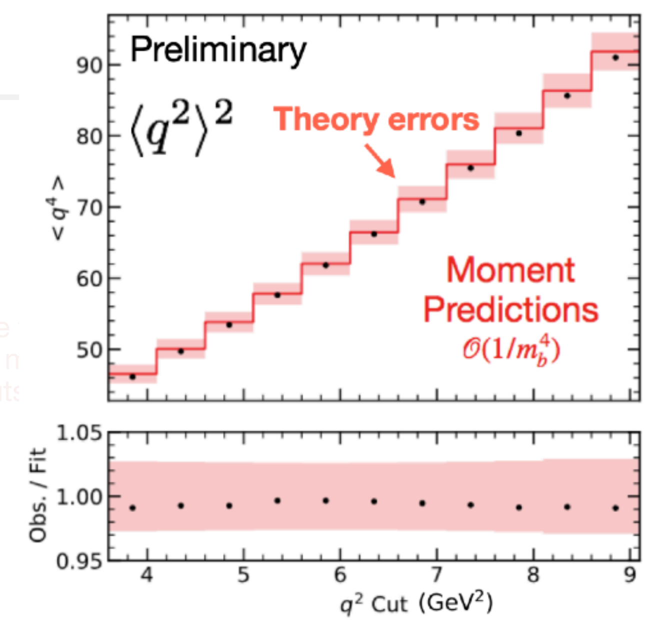
Keri's talk on Monday

Theory Correlations

Could e.g. **theory nuisance parameters** help?

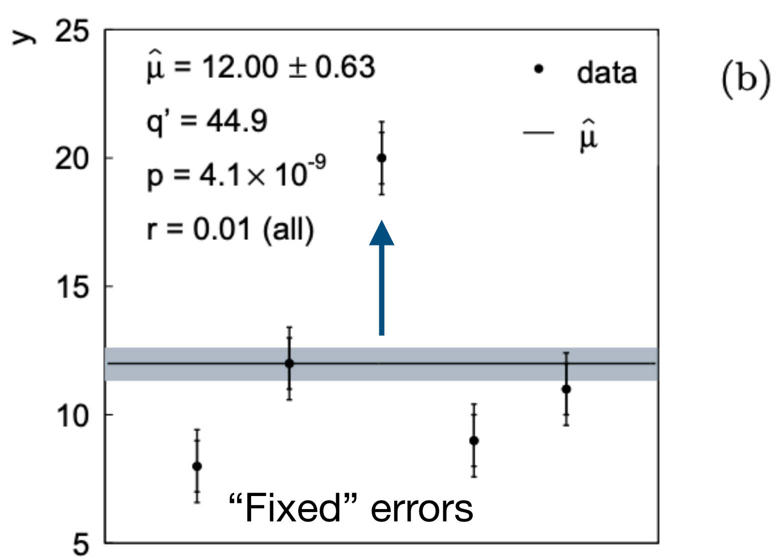
The data is so precise, it can tell us which theory variations are **too conservative**

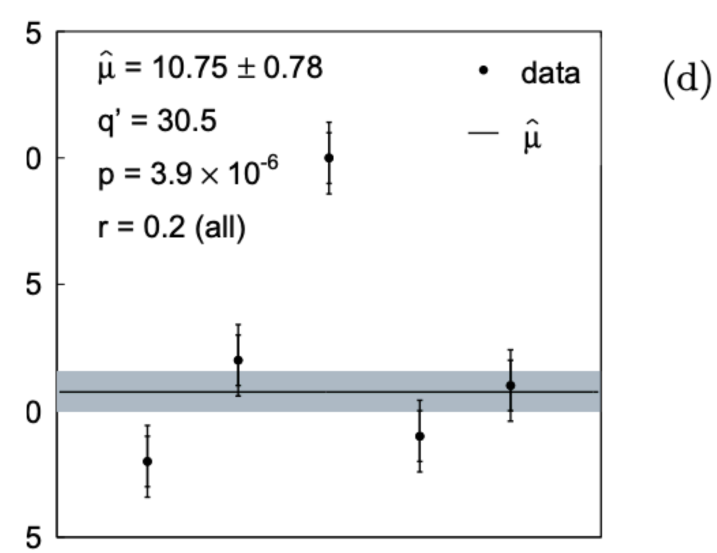
Can we **parametrize** our **ignorance**?



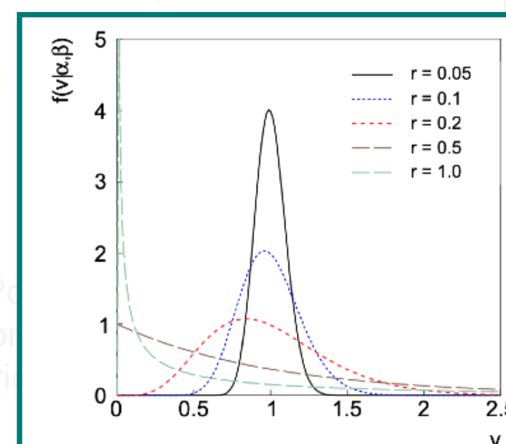
Usually we fix the size of theory errors, but are we certain we know them as precisely as we think we do? I.e. are they themselves uncertain?

Glen Cowan, Eur. Phys. J. C (2019) 79:133





Size or errors are constrained, but floating parameter in the average



Constraint: gamma distribution

Experimental correlations

Phys. Rev. D81:032003, 2010

C_{exp}

Many of the measurement are systematically limited

(with the notable exception of some high cut moments)

i.e. systematic correlations are important

Source-wise correlations well motivated scheme

Sum over independent uncertainties / eigendirections

$$C_{\text{exp}} = C_{\text{stat}} + \sum_{i}^{\text{Source}} C_i$$

Independent error source has a fully correlated effect over all measured quantities

$$C_i = \vec{\sigma}_i \otimes \vec{\sigma}_i$$

Note that there are other experimental errors that need a more careful treatment, e.g. Lepton ID (one can use replicas as there might be decorrelation effects across measured quantities)

$$(C_i)_{km} = (\sigma_i)_k \, (\sigma_i)_m \, \rho_{km}$$

BABAR-PUB-09/004
SLAC-PUB-13735

Measurement and Interpretation of Moments in Inclusive Semileptonic Decays $\overline{B} \to X_c \ell^- \overline{\nu}$

B. Aubert, Y. Karyotakis, J. P. Lees, V. Poireau, E. Prencipe, X. Prudent, and V. Tisserand
Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France

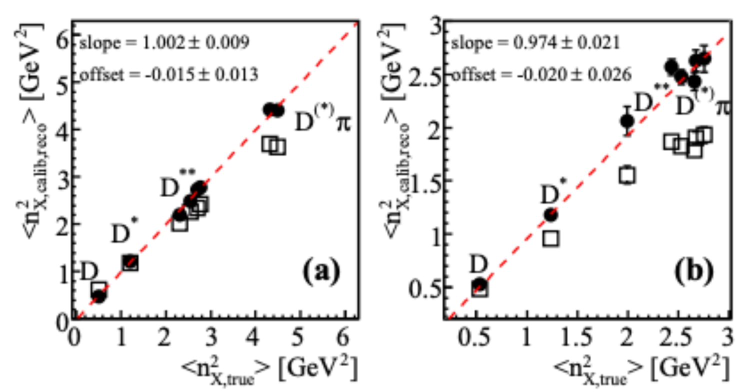


FIG. 7: Example of the calibration verification procedure for different minimum lepton momenta (a) $p^*_{\ell,\text{min}} = 0.8\,\text{GeV}/c$ and (b) $p^*_{\ell,\text{min}} = 1.7\,\text{GeV}/c$. Moments $\langle n_X^2 \rangle$ of exclusive modes on simulated events before (□) and after (•) calibration are plotted against the true moments for each mode. The dotted line shows the result of a fit to the calibrated moments, the resulting parameters are given.

The bias correction factors $\mathcal{C}(p^*_\ell, k)$, depending on the minimum lepton momentum and the order of the extracted moments, are determined by MC simulations; they combine the two factors $\mathcal{C}_{cal}$ and $\mathcal{C}_{true}$ as described in Section IV B.

Varying the branching fractions of the exclusive signal modes in the MC simulation has, in agreement with the mass-moment studies, a very small impact on the measured combined moments. Also, no significant variations of the results are observed when splitting the data sample into the same subsamples as for the mass moments.

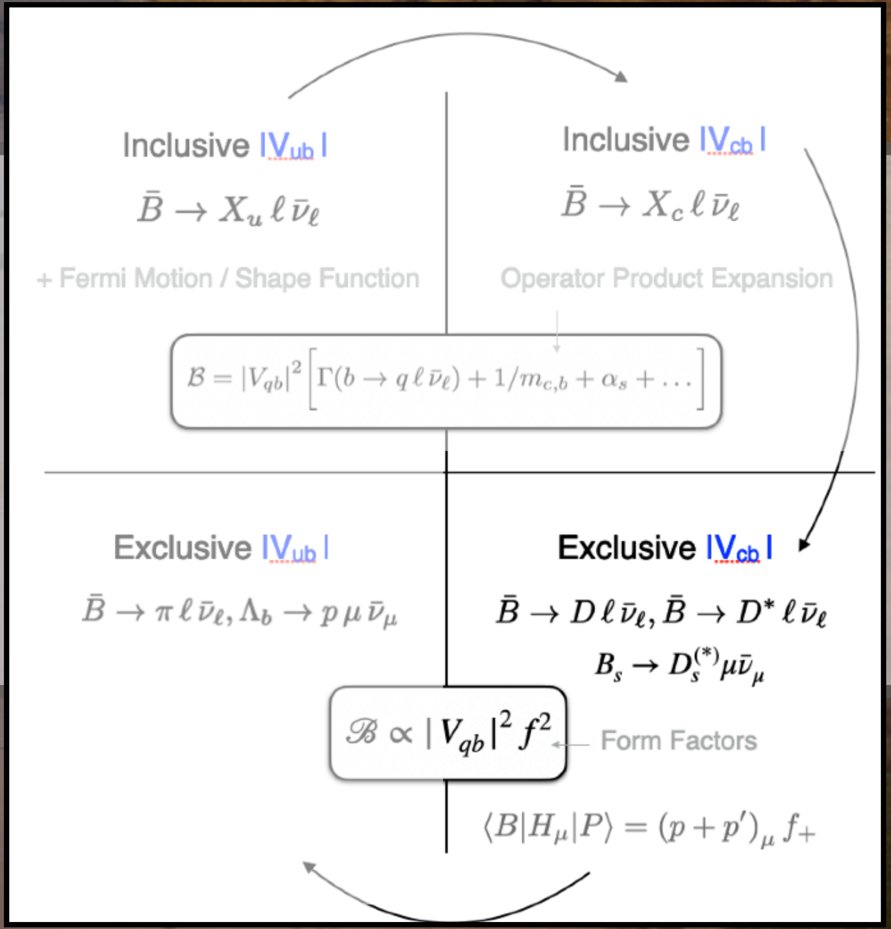
D. Results

Figure 8 shows the results for the moments $\langle n_X^2 \rangle$, $\langle n_X^4 \rangle$, and $\langle n_X^6 \rangle$ as a function of the minimum lepton momentum $p^*_{\ell,\text{min}}$. The moments are highly correlated due to the overlapping data samples. The full numerical results and the statistical and the estimated systematic uncertainties are given in Table A.III. The systematic covariance matrix for the moments of different order and with different cuts on $p^*_{\ell,\text{min}}$ is built using statistical correlations. This correlation matrix for the moments is given in the EPAPS document [43].

A clear dependence on the minimum lepton momentum is observed for all moments, due to the increasing contributions from higher-mass final states with decreasing lepton momentum. In most cases we obtain systematic uncertainties slightly exceeding the statistical uncertainty.

We should check the impact of alternative approaches

Excl. $|V_{cb}|$

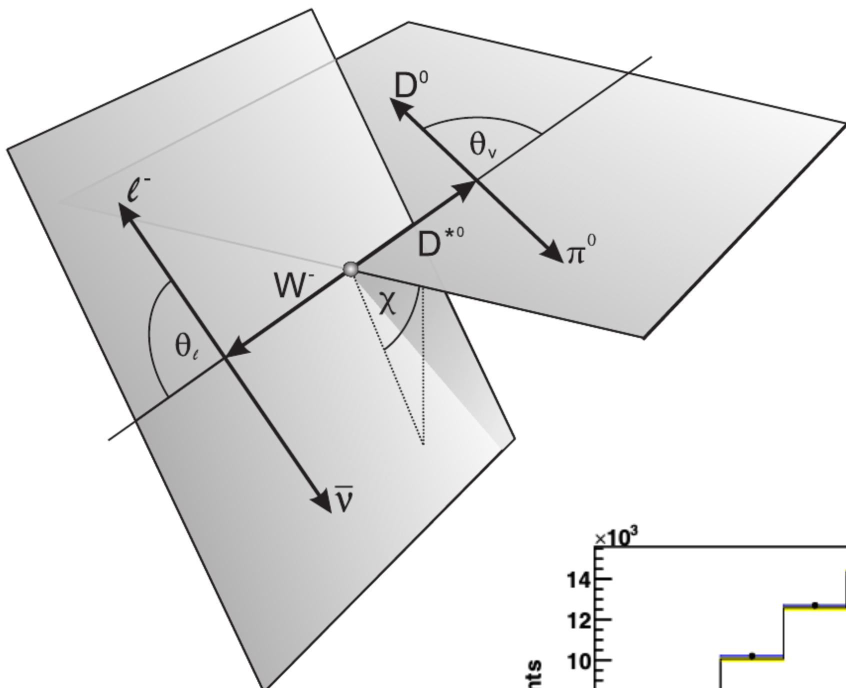


- 4 x 1D: Beware
- Recent Lattice QCD results
- New from LHCb & Belle II

4 x 1D Fits

See also Bordone, Jung, Van Dyk [arXiv:1908.09398]

$B \to D^*[\to D\pi]\ell\bar{\nu}_\ell$



Statistical correlation matrix of all 40 bins

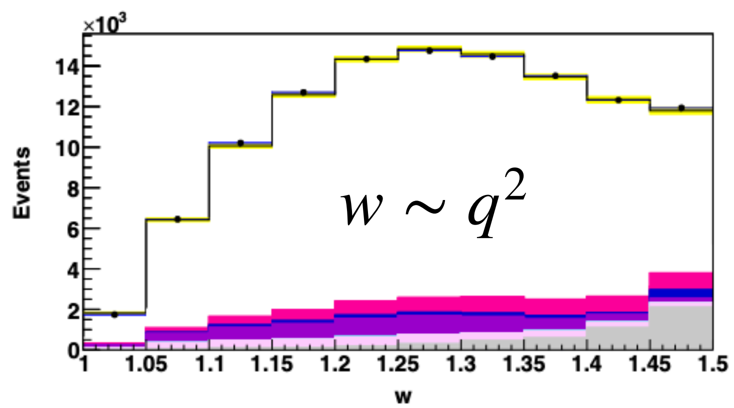
$C_{40x40} \to C_{4x4}$

Sum all 10 bins

$JC_{40x40}J^T = C_{4x4}$

$$J = \begin{pmatrix} 1,1,1,1,1,1,1,1,1,1 \\ 1,1,1,1,1,1,1,1,1,1 \\ 1,1,1,1,1,1,1,1,1,1 \\ 1,1,1,1,1,1,1,1,1,1 \end{pmatrix}$$

If there would be no *background*, C_{4x4} should be **singular**

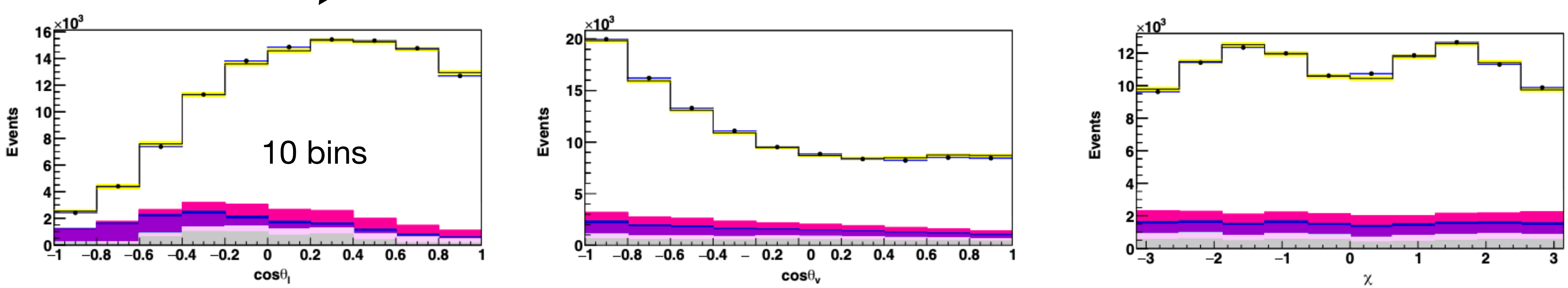


i.e. if you setup your $|V_{cb}|$ extraction by fitting all 40 bins, this could create problems

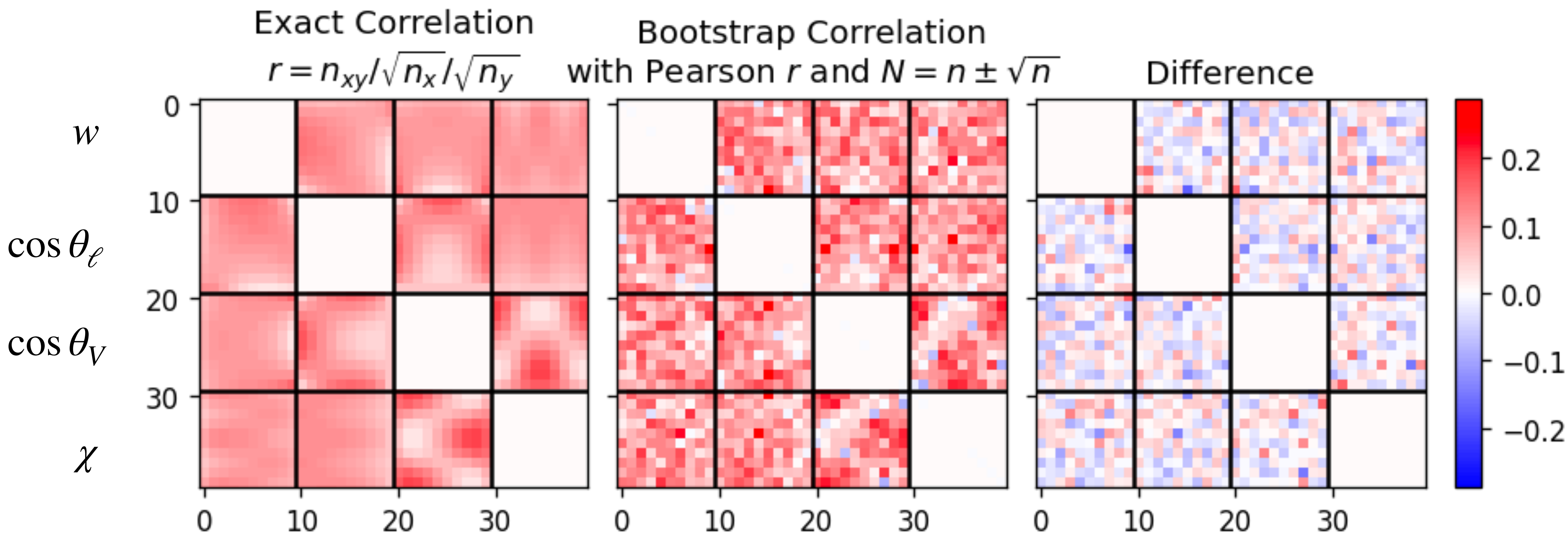
$$\chi^2(|V_{cb}|, \vec{\mu}_{\rm FF}) = \left(\Delta\mathcal{B} - |V_{cb}|^2 \tau_B \Gamma(\vec{\mu}_{\rm FF})\right) C^{-1}_{40\times 40} \left(\Delta\mathcal{B} - |V_{cb}|^2 \tau_B \Gamma(\vec{\mu}_{\rm FF})\right)$$

Projection of same Events

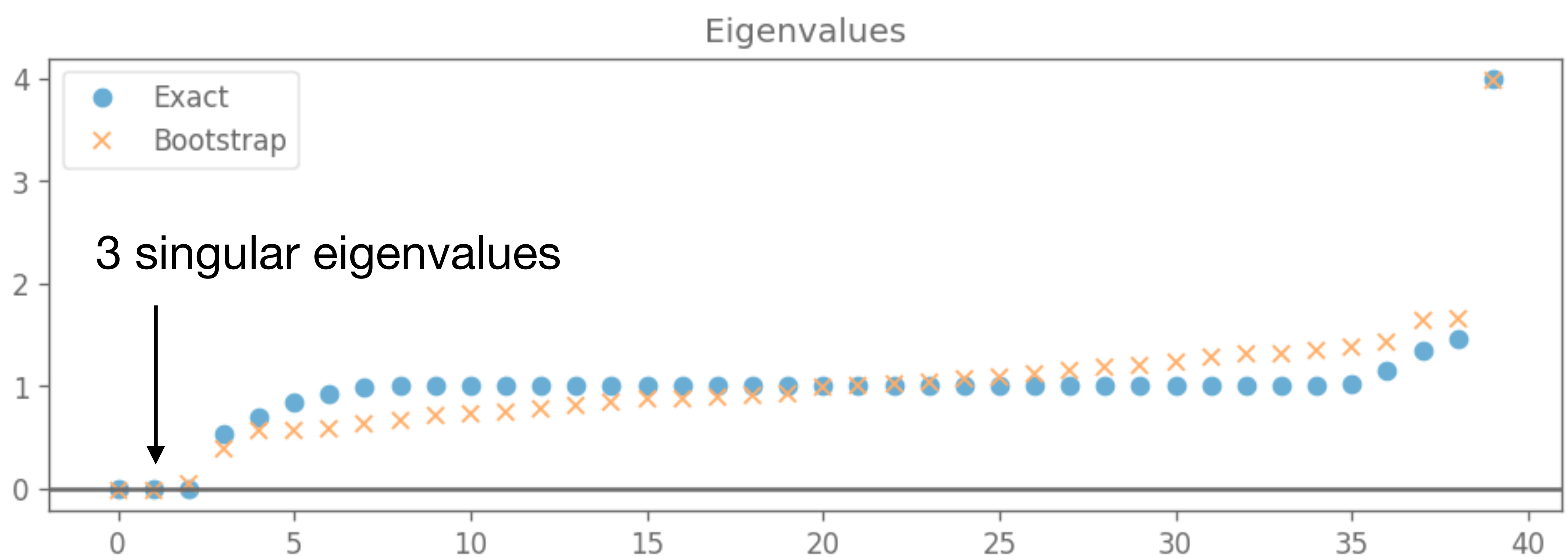
Helicity Angles



Toy example:



Exact Correlation
$r = n_{xy}/\sqrt{n_x}/\sqrt{n_y}$
Bootstrap Correlation
with Pearson r and $N = n \pm \sqrt{n}$
Difference
w
$\cos\theta_\ell$
$\cos\theta_V$
χ



Eigenvalues
Exact
Bootstrap
3 singular eigenvalues

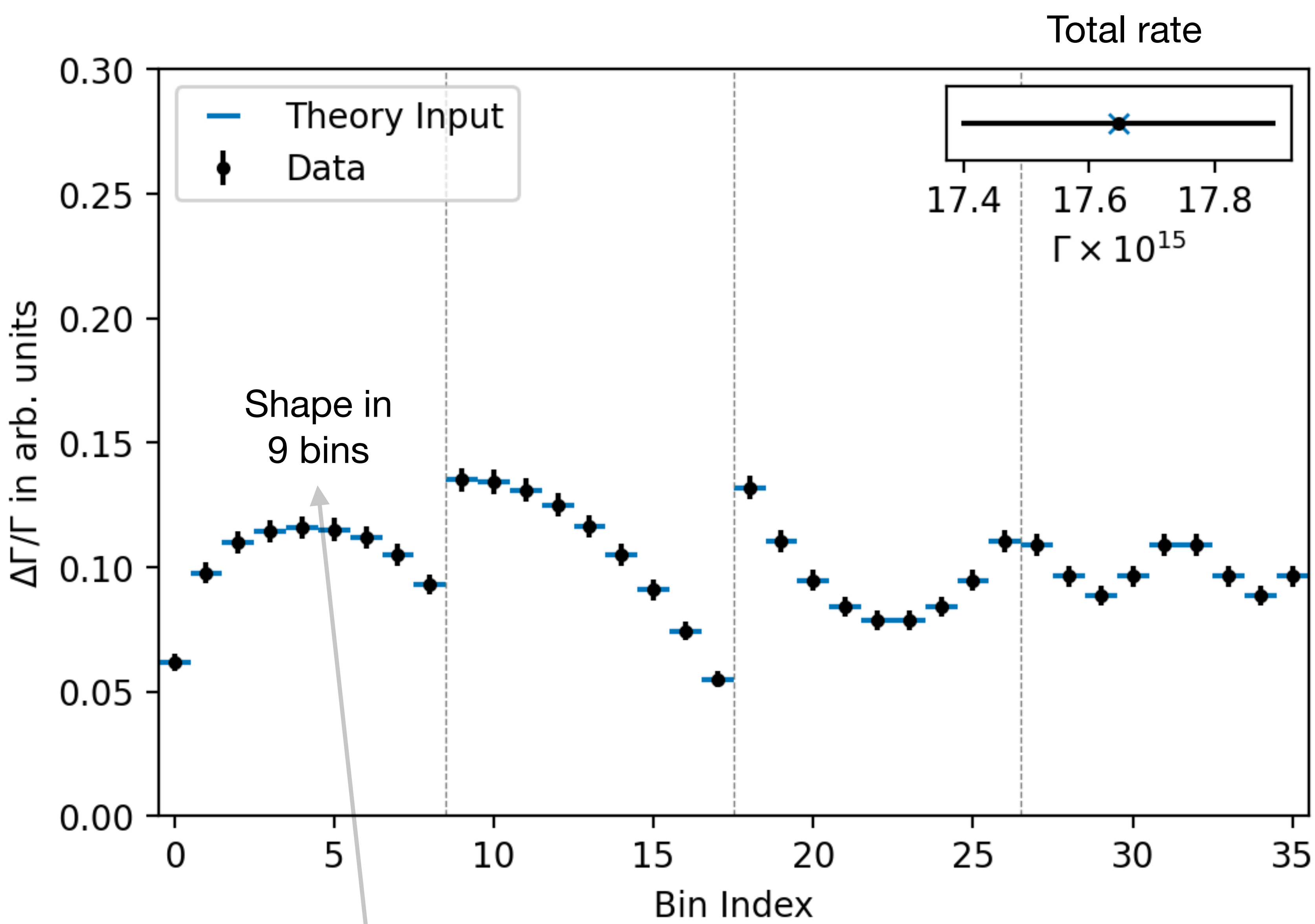
Toy example:

See **also** Bordone, Jung, Van Dyk [arXiv:1908.09398] (!)

Markus Prim, FB

Elegant Solution: Fit the total rate and 4 shapes

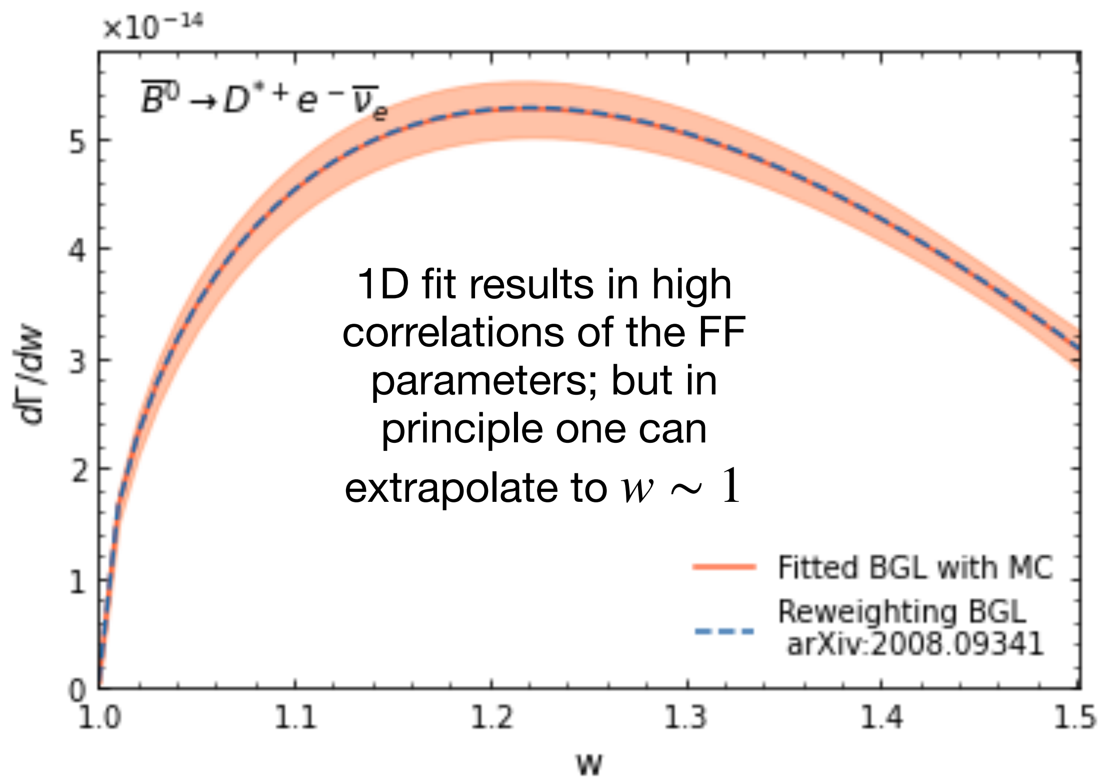
$$\chi^2(|V_{cb}|, \vec{\mu}_{\mathrm{FF}}) = \left(\Delta\mathscr{B}/\mathscr{B} - \Delta\Gamma(\vec{\mu}_{\mathrm{FF}})/\Gamma(\vec{\mu}_{\mathrm{FF}})\right) C^{-1}_{36\times 36} \left(\Delta\mathscr{B}/\mathscr{B} - \Delta\Gamma(\vec{\mu}_{\mathrm{FF}})/\Gamma(\vec{\mu}_{\mathrm{FF}})\right) + \left(\mathscr{B} - |V_{cb}|^2 \tau_B \Gamma(\vec{\mu}_{\mathrm{FF}})\right)^2 / \sigma^2_{\mathscr{B}}$$

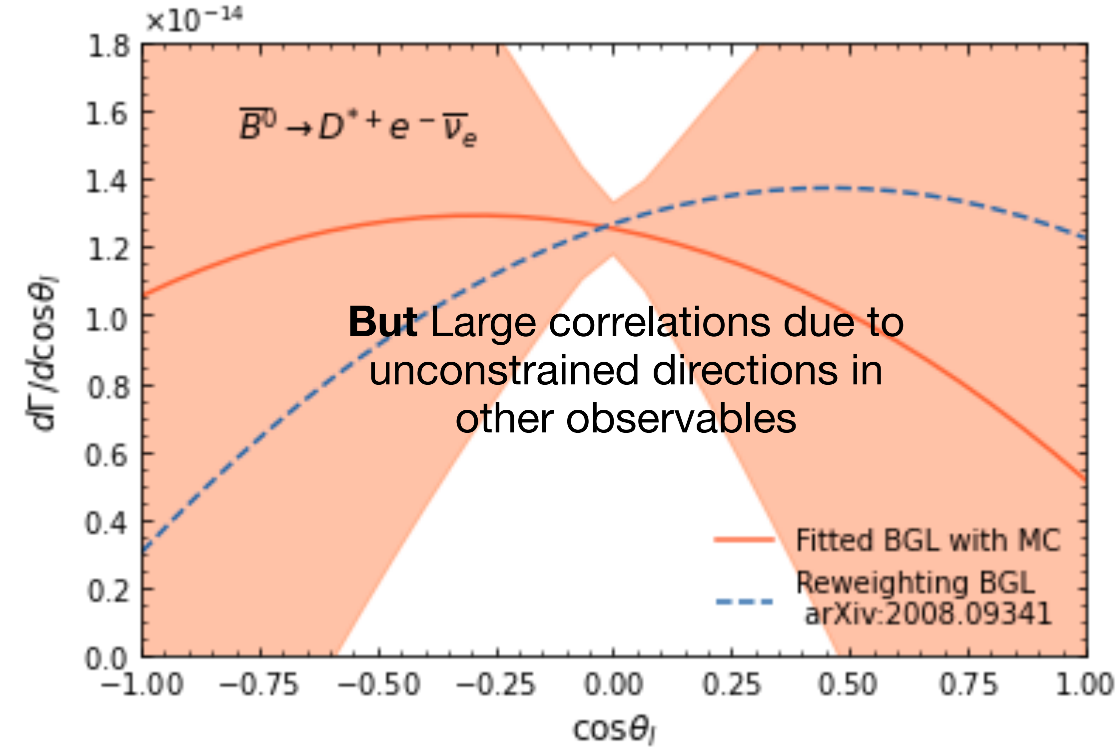


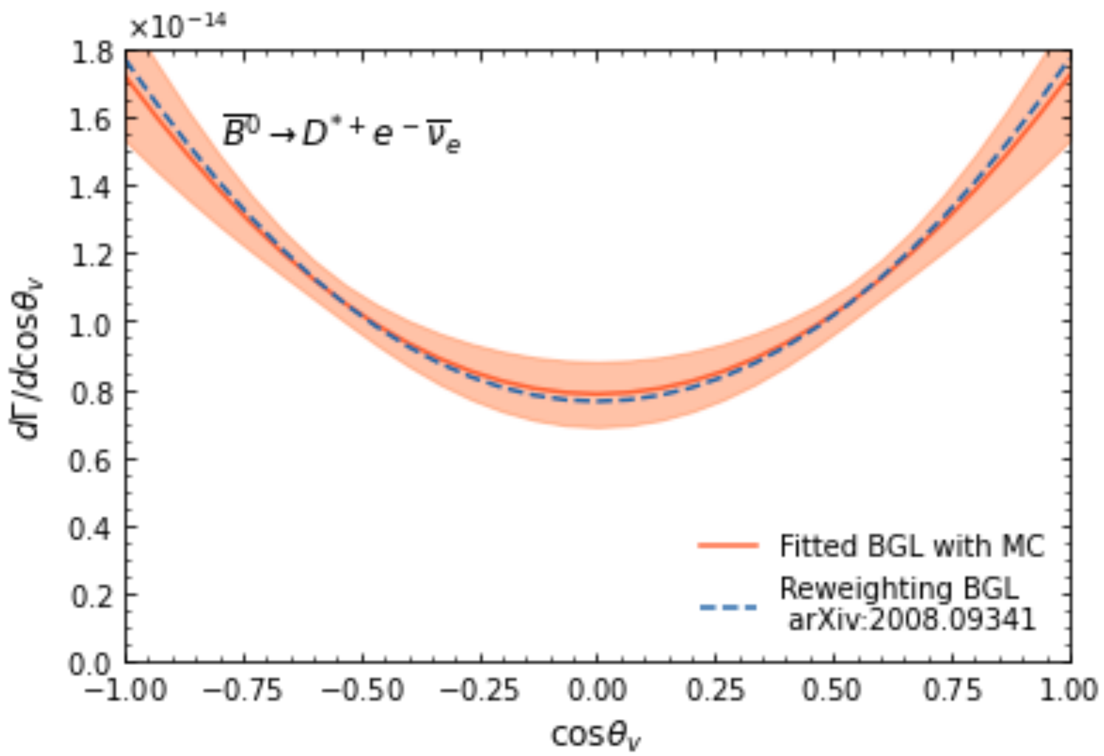
(last bin is fully determined by 1 - sum of all other bins)

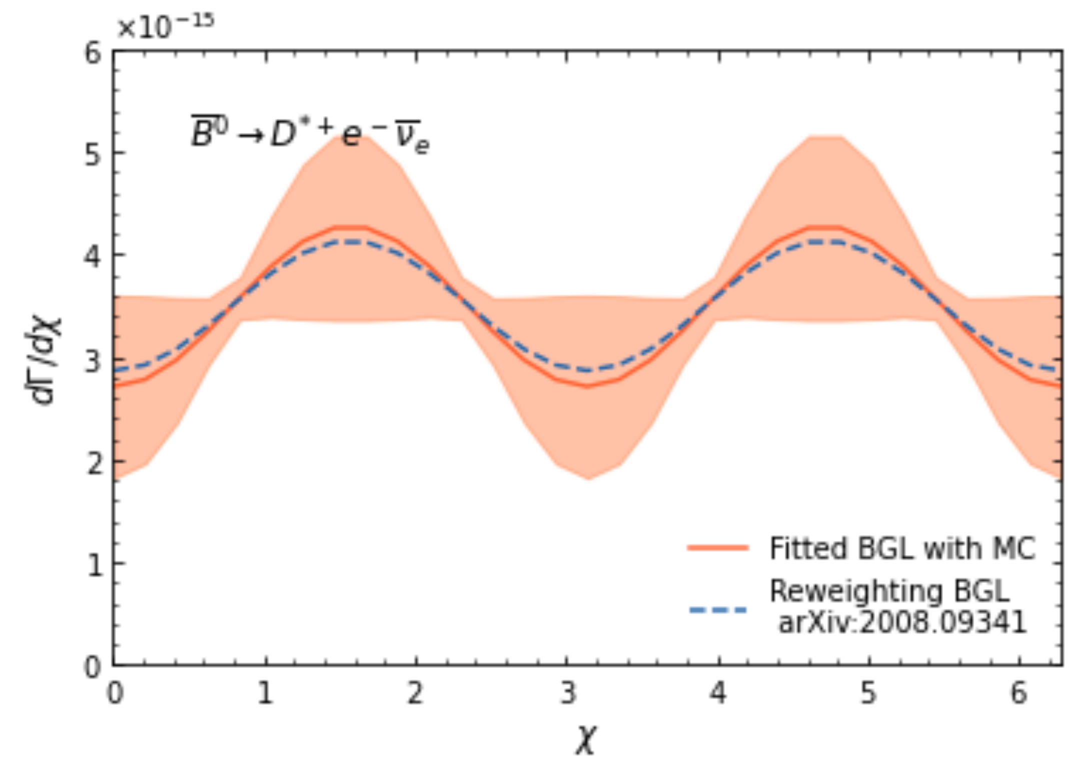
4 x 1D or 1D or 4D?

Chaoyi Lyu, FB









The future might be unbinned…

Un-binned Angular Analysis of $B \to D^* \ell \nu_\ell$ and the Right-handed Current

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Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

C.D. Lü‡ and R.Y. Tang§
Institute of High Energy Physics,
Chinese Academy of Sciences, Beijing 100049, China
and
School of Physics, University of Chinese Academy of Sciences, Beijing 100049, China
(Dated: June 29, 2021)

Experimentally challenging (solved e.g. by Phys. Rev. Lett. 123, 091801 (2019))

BABAR-PUB-19/001
SLAC-PUB-17420

Extraction of form factors from a four-dimensional angular analysis of $\overline{B} \to D^* \ell^- \overline{\nu}_\ell$

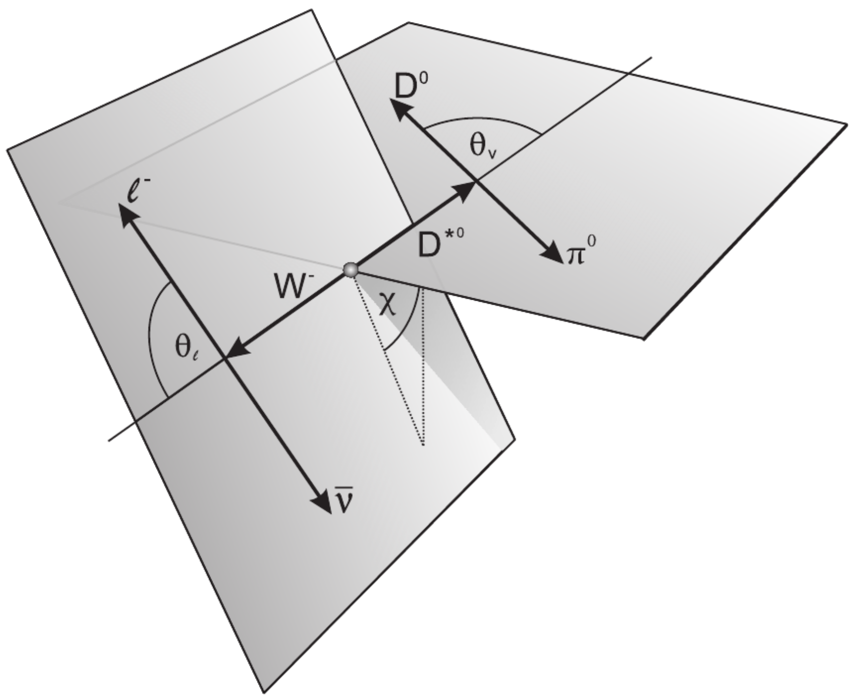
J. P. Lees,[1] V. Poireau,[1] V. Tisserand,[1] E. Grauges,[2] A. Palano,[3] G. Eigen,[4] D. N. Brown,[5] Yu. G. Kolomensky,[5] M. Fritsch,[6] H. Koch,[6] T. Schroeder,[6] C. Hearty[ab,7] T. S. Mattison[b,7] J. A. McKenna[b,7] R. Y. So[b,7] V. E. Blinov[abc,8] A. R. Buzykaev[a,8] V. P. Druzhinin[ab,8] V. B. Golubev[ab,8] E. A. Kozyrev[ab,8] E. A. Kravchenko[ab,8] A. P. Onuchin[abc,8] S. I. Serednyakov[ab,8] Yu. I. Skovpen[ab,8] E. P. Solodov[ab,8] K. Yu. Todyshev[ab,8] A. J. Lankford,[9] B. Dey,[10] J. W. Gary,[10] O. Long,[10] A. M. Eisner,[11] W. S. Lockman,[11] W. Panduro Vazquez,[11] D. S. Chao,[12] C. H. Cheng,[12] B. Echenard,[12] K. T. Flood,[12] D. G. Hitlin,[12] J. Kim,[12] Y. Li,[12] T. S. Miyashita,[12] P. Ongmongkolkul,[12] F. C. Porter,[12] M. Röhrken,[12] Z. Huard,[13] B. T. Meadows,[13] B. G. Pushpawela,[13] M. D. Sokoloff,[13] L. Sun,[13,*] J. G. Smith,[14] S. R. Wagner,[14] D. Bernard,[15] M. Verderi,[15] D. Bettoni[a,16] C. Bozzi[a,16] R. Calabrese[ab,16] G. Cibinetto[ab,16] E. Fioravanti[ab,16] I. Garzia[ab,16] E. Luppi[ab,16] V. Santoro[a,16] A. Calcaterra,[17] R. de Sangro,[17] G. Finocchiaro,[17] S. Martellotti,[17] P. Patteri,[17] I. M. Peruzzi,[17] M. Piccolo,[17]

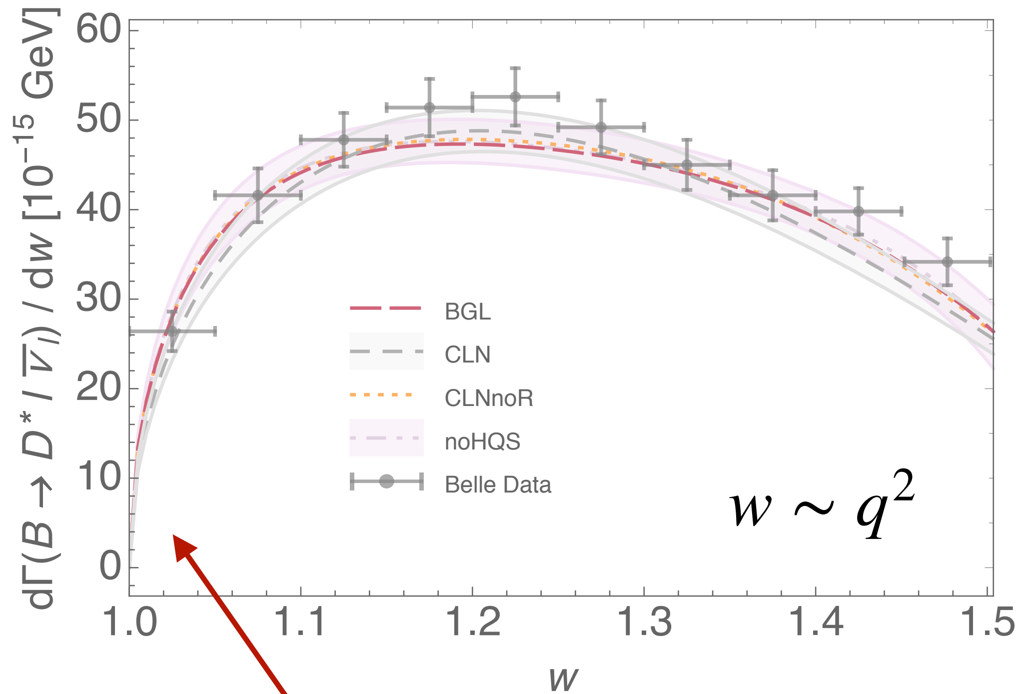
2019

Largest challenge: how to make this data accessible to others?
(also cf. Omnifold)

Slow pions

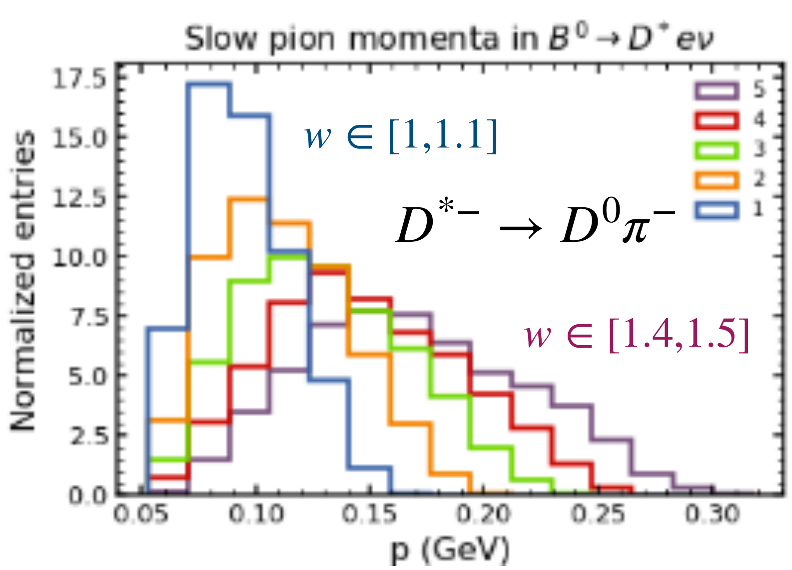
$B \to D^*[\to D\pi]\ell\bar{\nu}_\ell$



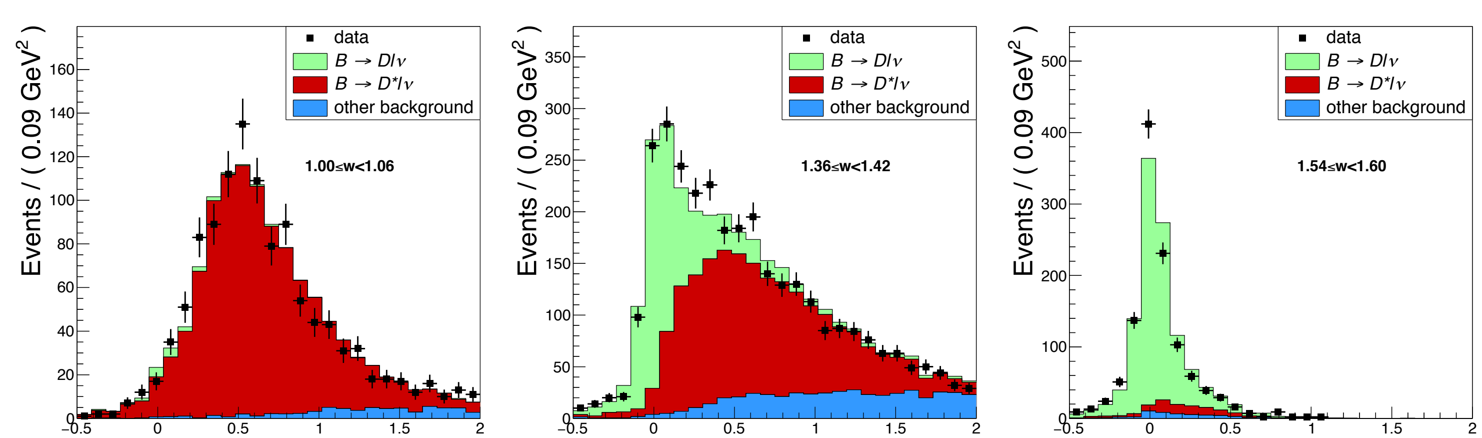


To determine $|V_{cb}|$ we extrapolate to rate near $w \sim 1$

Experimentally very challenging region:



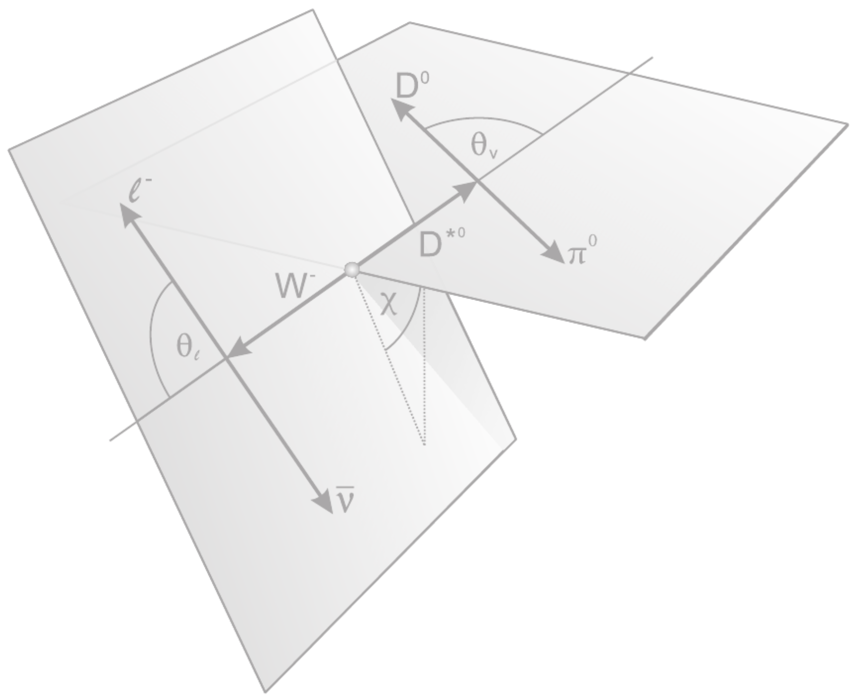
We see many of these events as down-feed in e.g. $B^+ \to D^0 e\bar{\nu}_e$

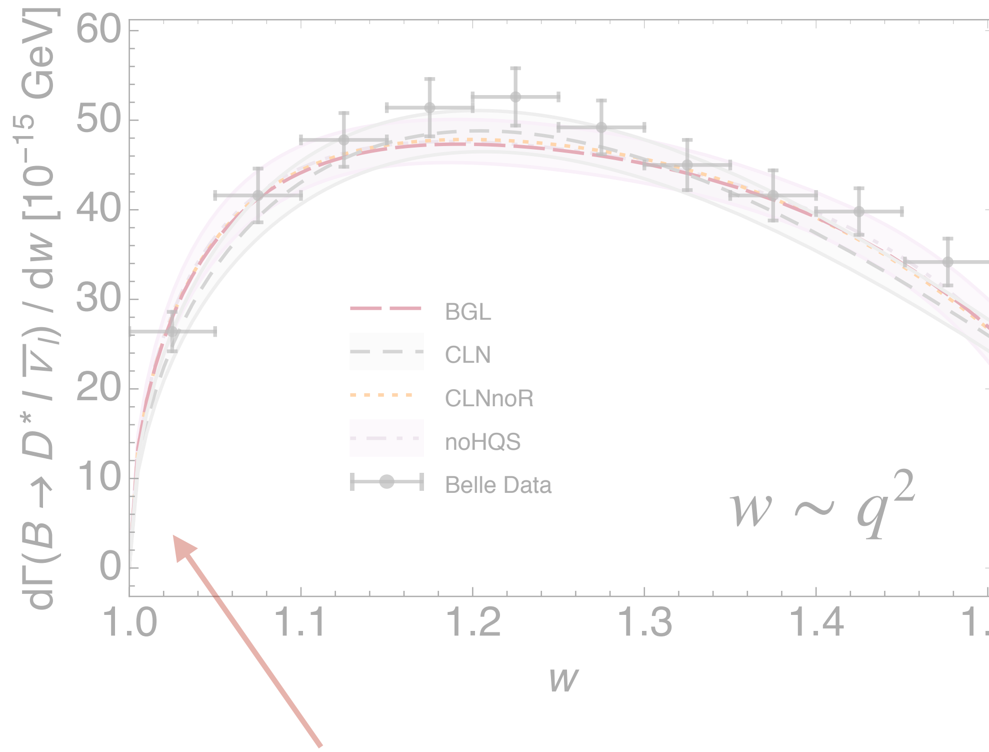


Slow pions

This has been exploited e.g. by the BaBar global analysis $|V_{cb}|$ [Phys. Rev. D79:012002, 2009]

$B \to D^*[\to D\pi]\ell\bar{\nu}_\ell$





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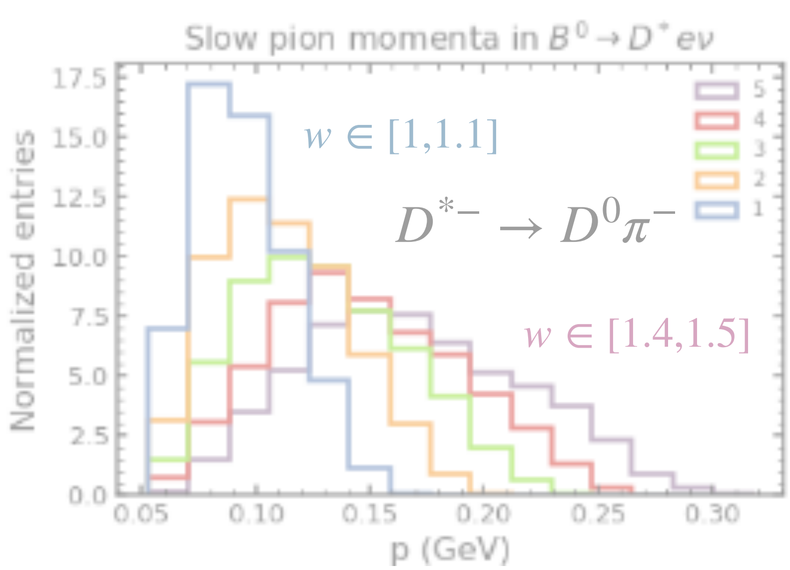
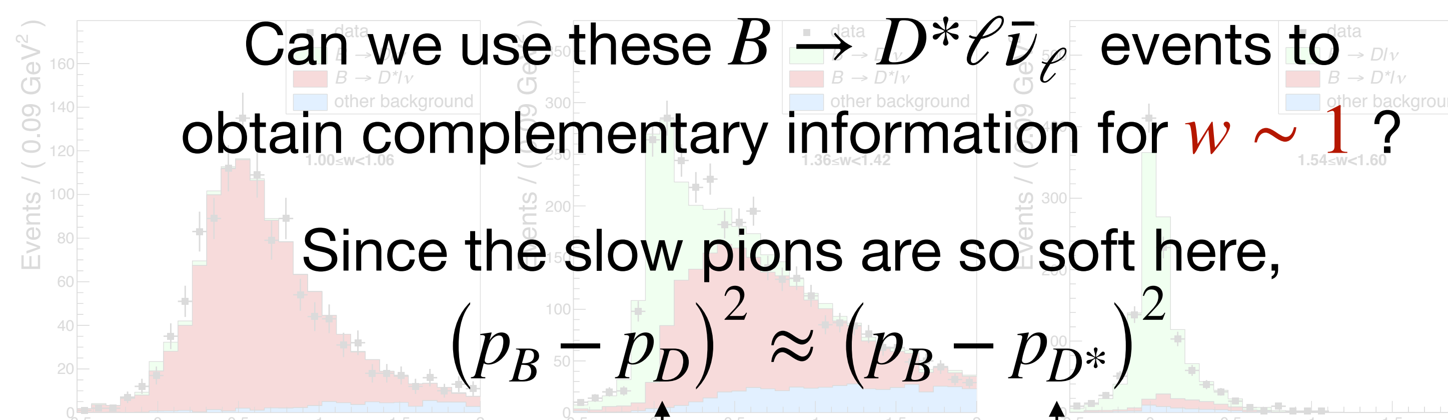


We see many of these events as down-feed in e.g. $B^+ \to D^0 e\bar{\nu}_e$



Can we use these $B \to D^*\ell\bar{\nu}_\ell$ events to obtain complementary information for $w \sim 1$?

Since the slow pions are so soft here,

$$(p_B - p_D)^2 \approx (p_B - p_{D^*})^2$$

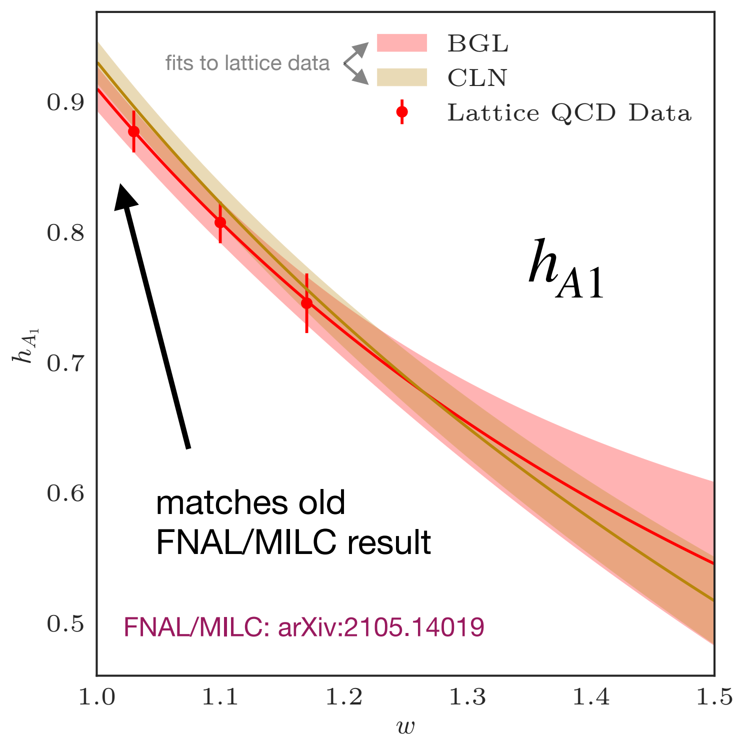
What is reconstructed

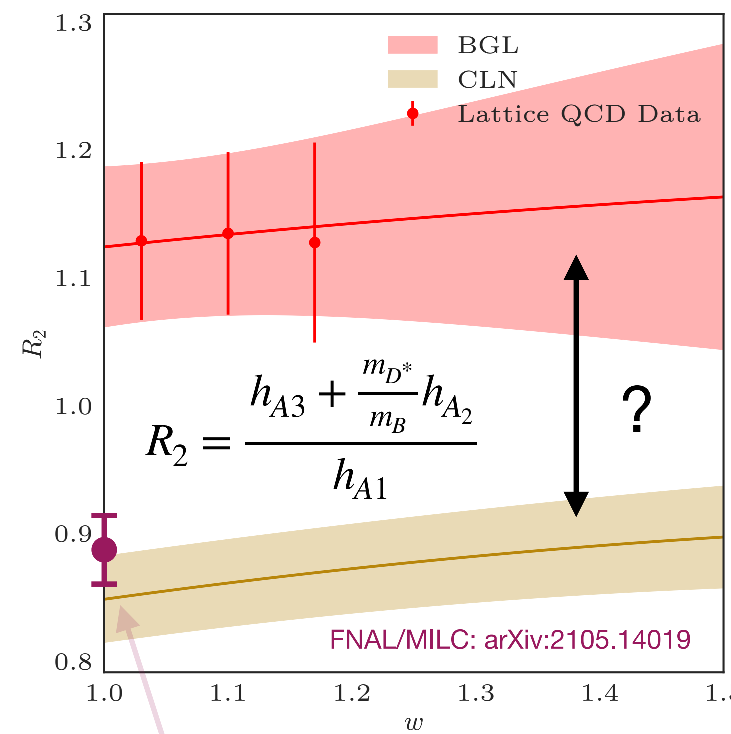
What you want

FNAL D^* Lattice Results

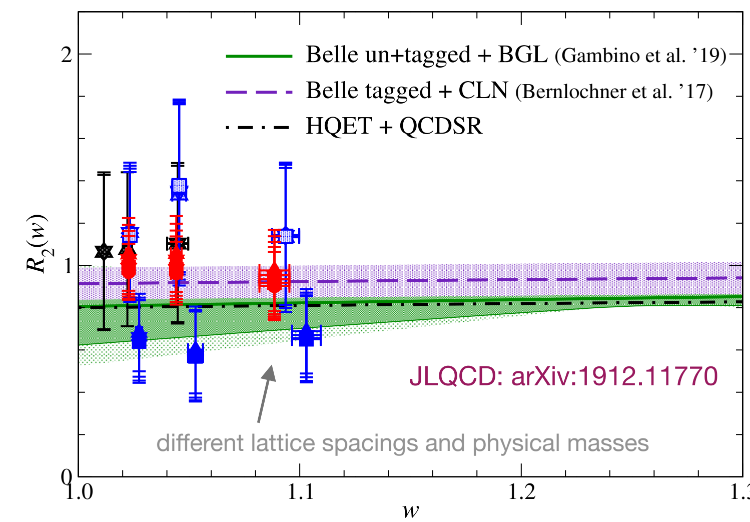
See also BGL fit to BaBar Data
Phys. Rev. Lett. 123, 091801 (2019)
and studies of Belle untagged D* spectrum
Phys. Rev. D 103, 073005 (2021)

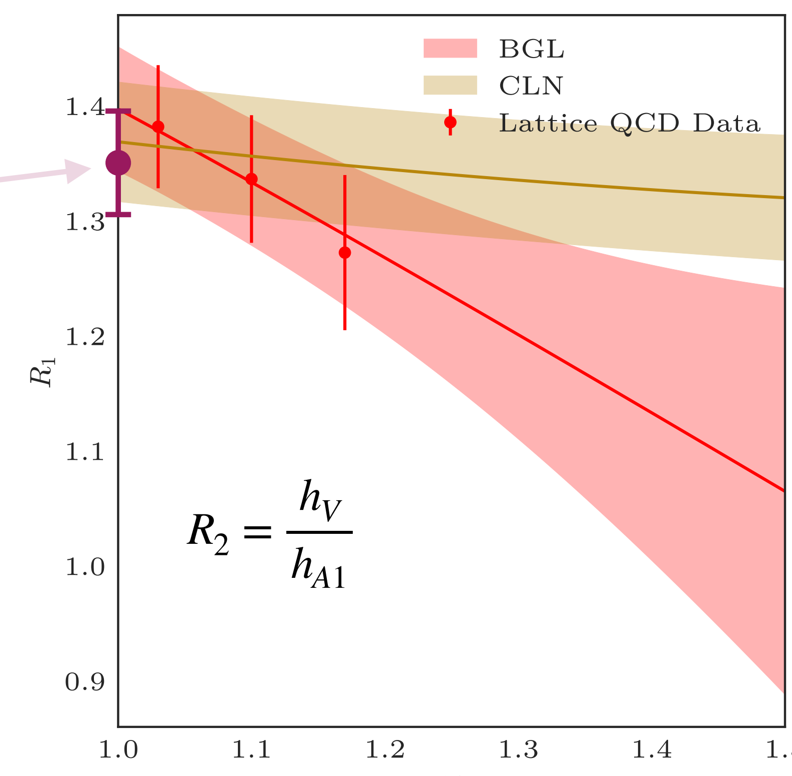
New results from **FNAL/MILC** on $B \to D^*$ form factors [FNAL/MILC: arXiv:2105.14019]





Intriguing deviation from HQET expectation!





HQET prediction: Based on Phys. Rev. D 95, 115008 (2017) fit results

$$R_1(1) = 1.34 - 0.12\eta(1) \approx 1.35 \pm 0.05$$

$$R_2(1) = 0.98 - 0.42\eta(1) - 0.54\hat{\chi}_2(1) \approx 0.89 \pm 0.03$$

To explain FNAL/MILC need negative $\eta(1), \hat{\chi}_2(1)$

$$\eta(1) \approx -0.5 \qquad \hat{\chi}_2(1) \approx -0.4$$

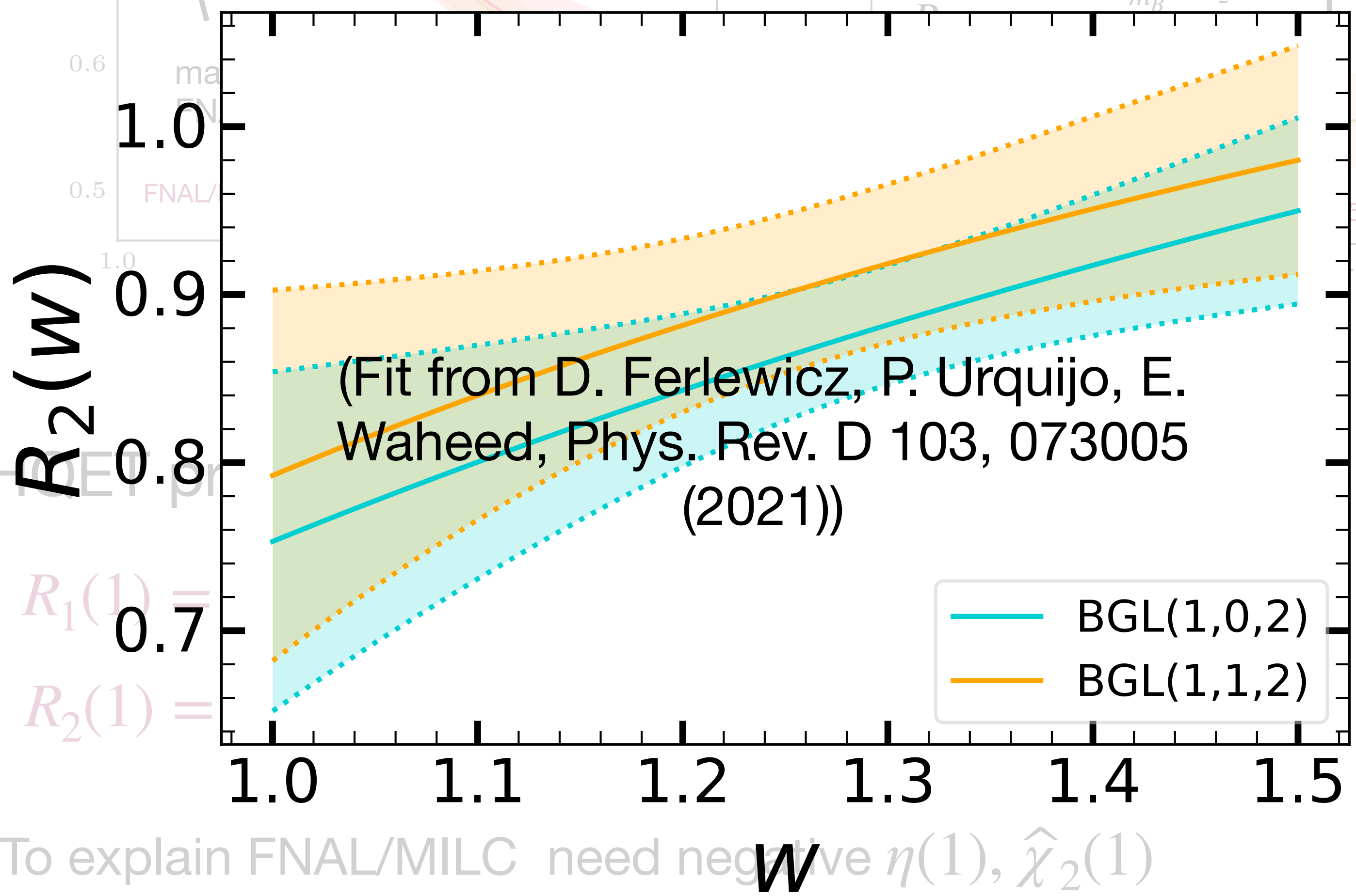
FNAL D^* Lattice Results

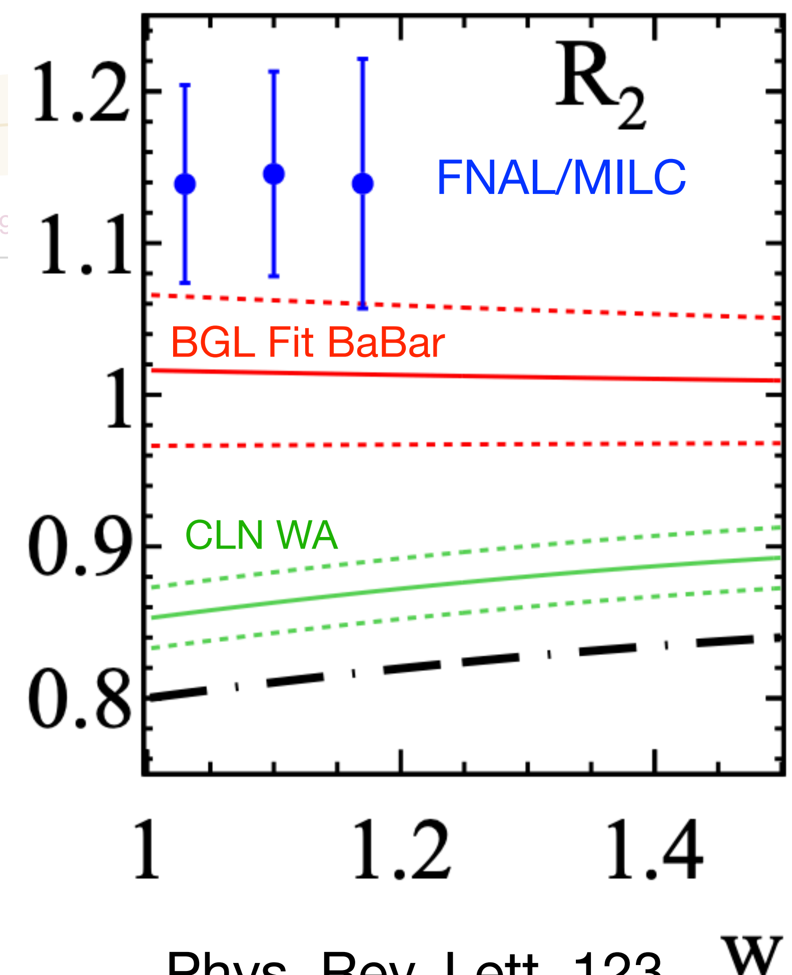
See also BGL fit to BaBar Data
Phys. Rev. Lett. 123, 091801 (2019)
and studies of Belle untagged D* spectrum
Phys. Rev. D 103, 073005 (2021)

New results from **FNAL/MILC** on $B \to D^*$ form factors [FNAL/MILC: arXiv:2105.14019]

Intriguing deviation from HQET expectation!

Belle Untagged ⟷ BaBar tagged





Phys. Rev. Lett. 123, 091801 (2019)

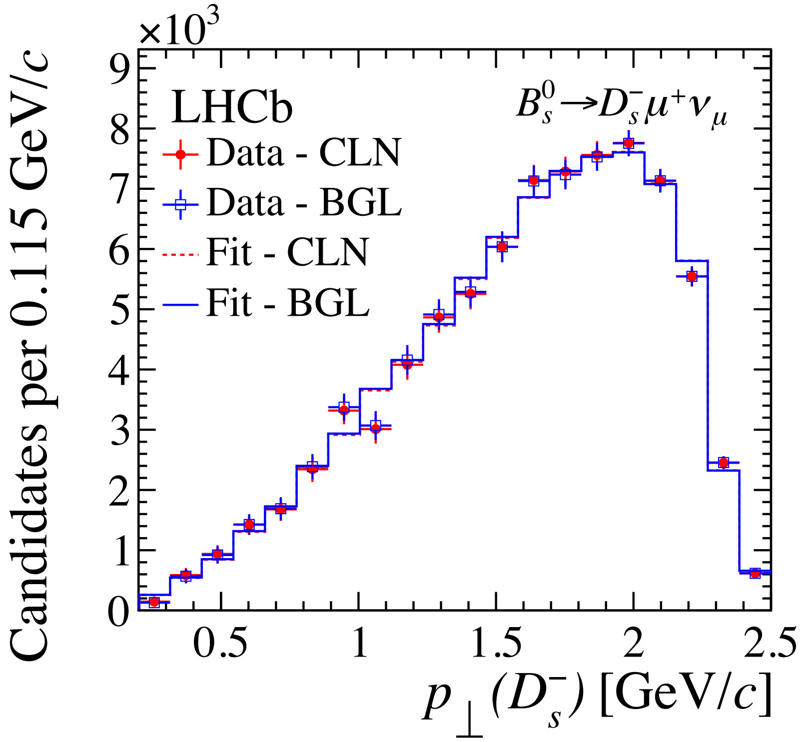
To explain FNAL/MILC need negative $\eta(1), \hat{\chi}_2(1)$

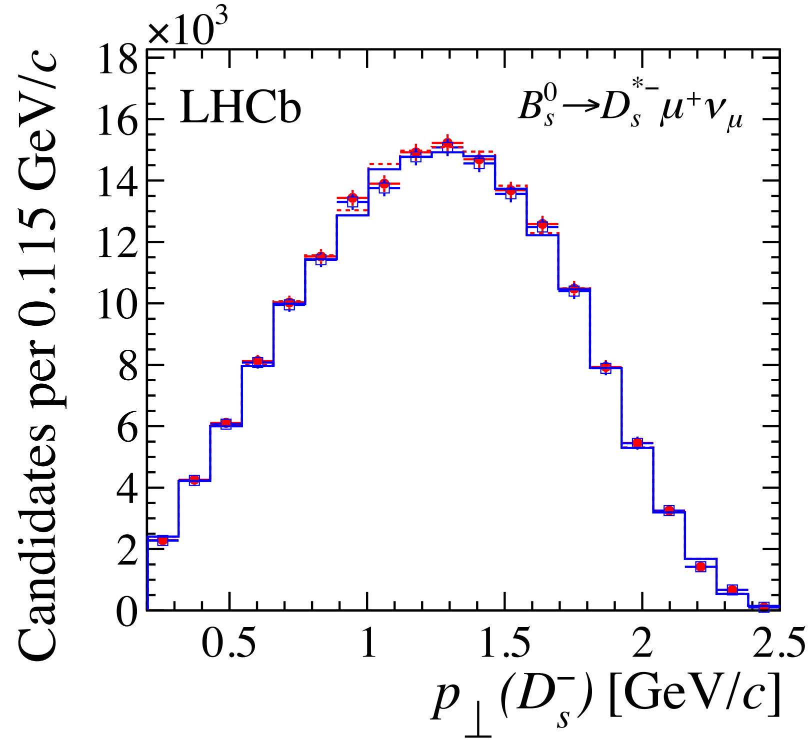
$\eta(1) \approx -0.5 \quad \hat{\chi}_2(1) \approx -0.4$

Also see Martin's talk

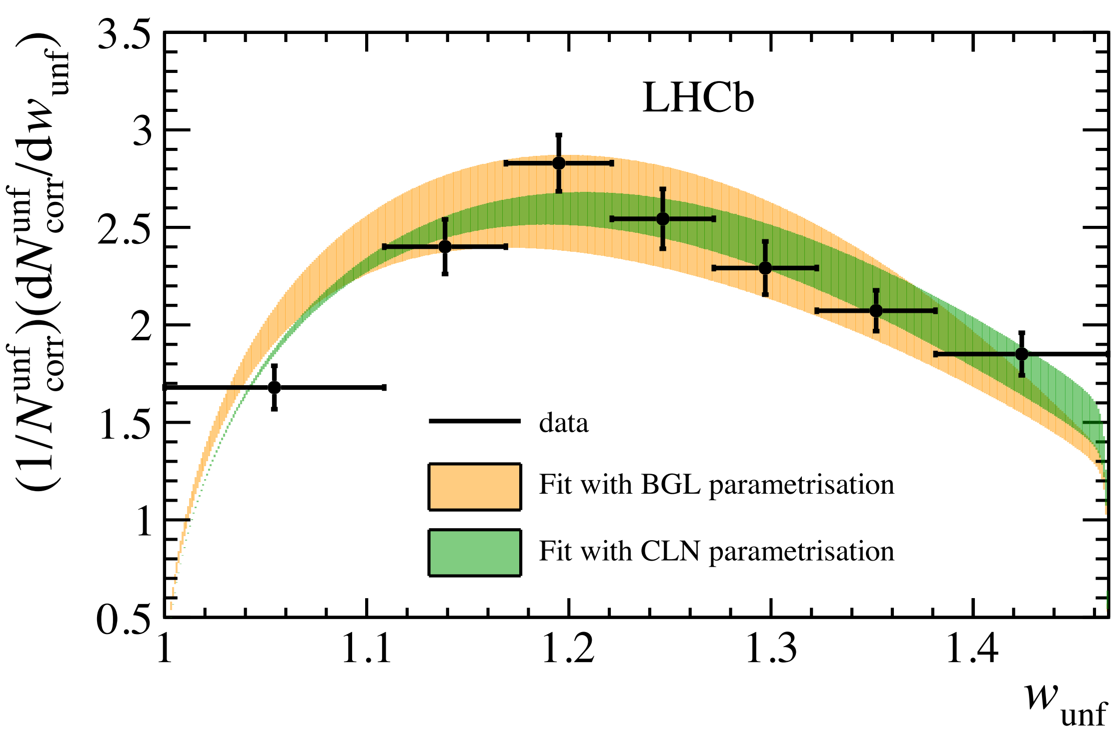
Great results from LHCb

JHEP 12 (2020) 144
Phys. Rev. D 101, 072004 (2020)



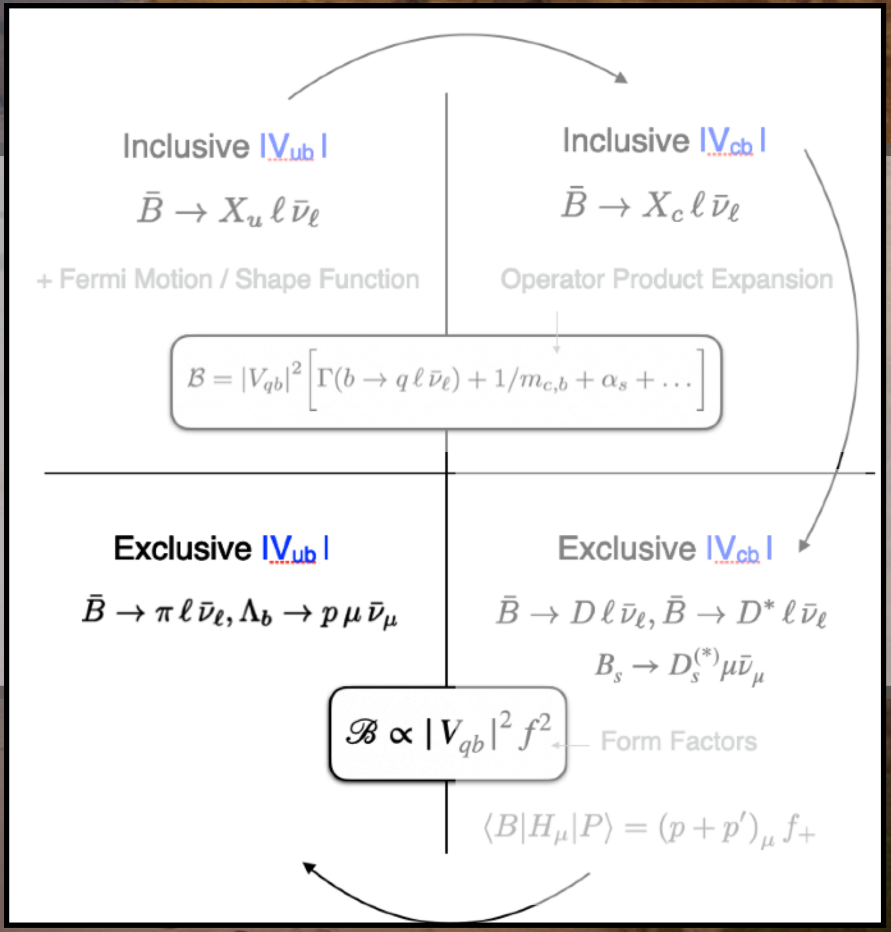


Parameter	Value
$\lvert V_{cb}\rvert$ $[10^{-3}]$	41.4 ± 0.6 (stat) ± 1.2 (ext)
$\mathcal{G}(0)$	1.102 ± 0.034 (stat) ± 0.004 (ext)
$\rho^2(D_s^-)$	1.27 ± 0.05 (stat) ± 0.00 (ext)
$\rho^2(D_s^{*-})$	1.23 ± 0.17 (stat) ± 0.01 (ext)
$R_1(1)$	1.34 ± 0.25 (stat) ± 0.02 (ext)
$R_2(1)$	0.83 ± 0.16 (stat) ± 0.01 (ext)



CLN fit	
Unfolded fit	$\rho^2 = 1.16 \pm 0.05 \pm 0.07$
Unfolded fit with massless leptons	$\rho^2 = 1.17 \pm 0.05 \pm 0.07$
Folded fit	$\rho^2 = 1.14 \pm 0.04 \pm 0.07$
BGL fit	
Unfolded fit	$a_1^f = -0.005 \pm 0.034 \pm 0.046$ $a_2^f = 1.00^{+0.00\,+0.00}_{-0.19\,-0.38}$
Folded fit	$a_1^f = 0.039 \pm 0.029 \pm 0.046$ $a_2^f = 1.00^{+0.00\,+0.00}_{-0.13\,-0.34}$

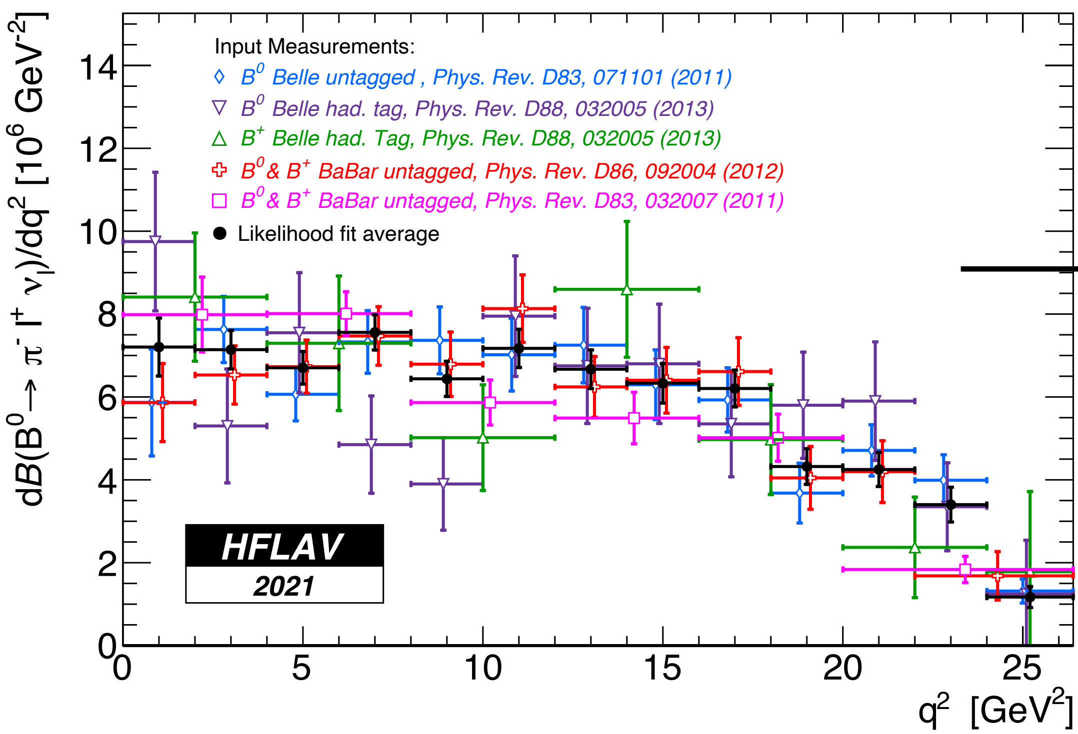
Excl. $|V_{ub}|$

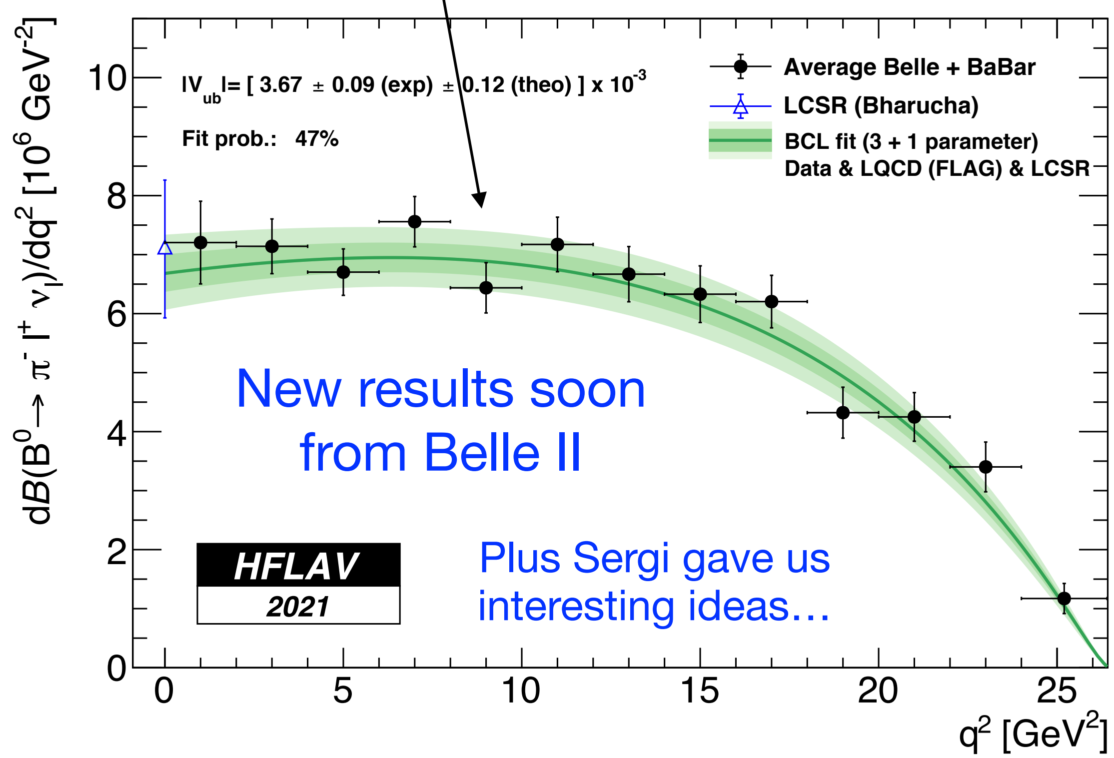


- State-of-the-Art
- New averages from HFLAV
- News from LHCb

State-of-the-Art

Likelihood combination with
systematic Nuisance Parameters
of all measurements



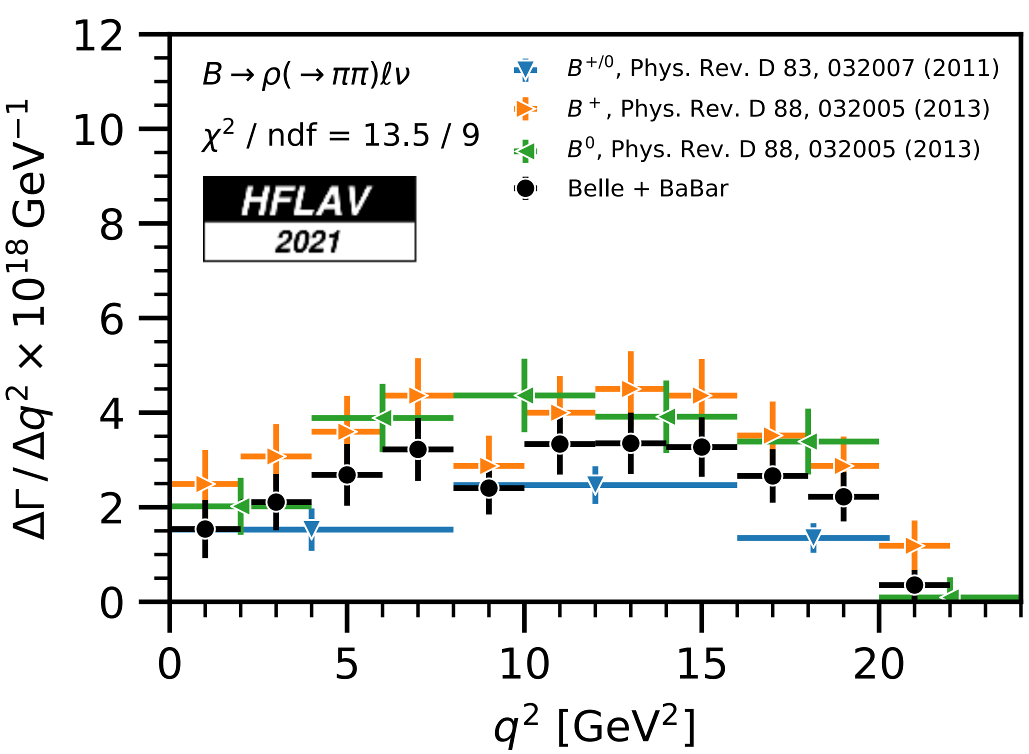


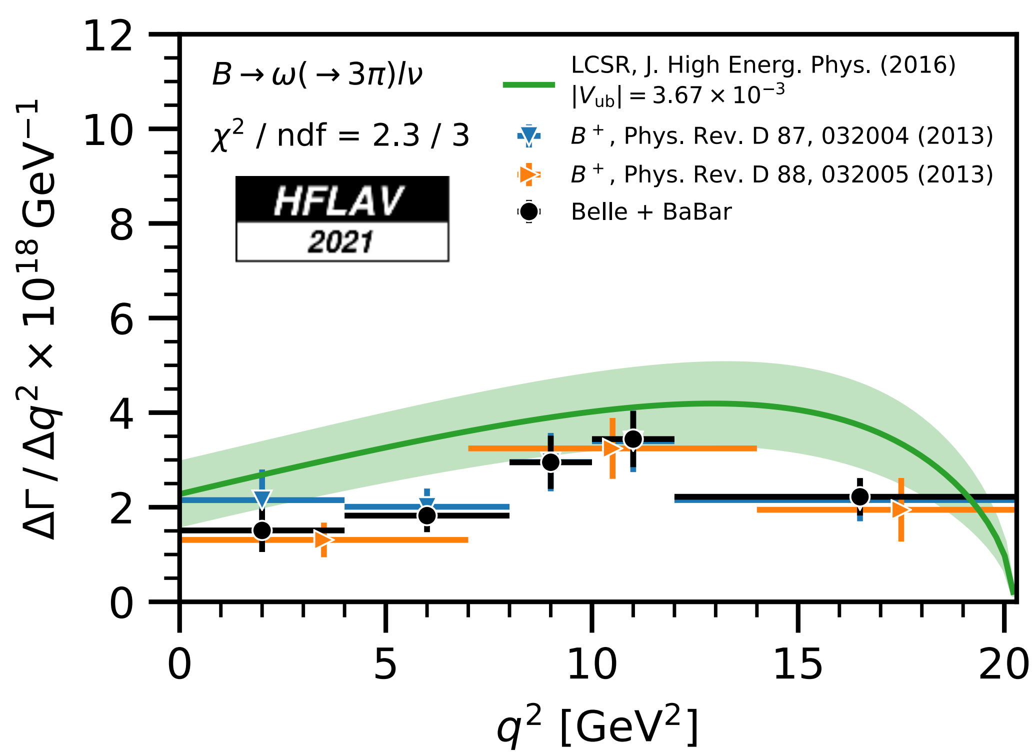
New results soon
from Belle II

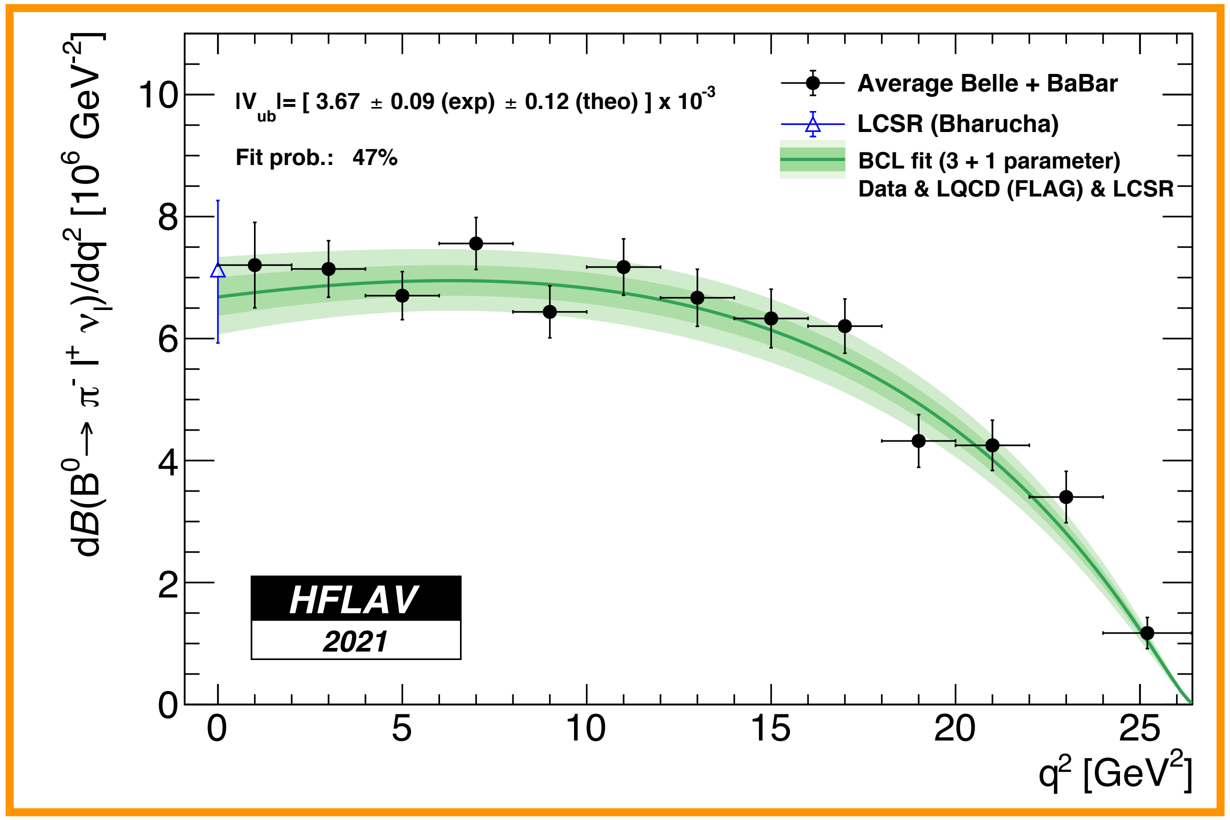
Plus Sergi gave us
interesting ideas…

Now also available for $B \to \rho/\omega \ell \bar{\nu}_\ell$:

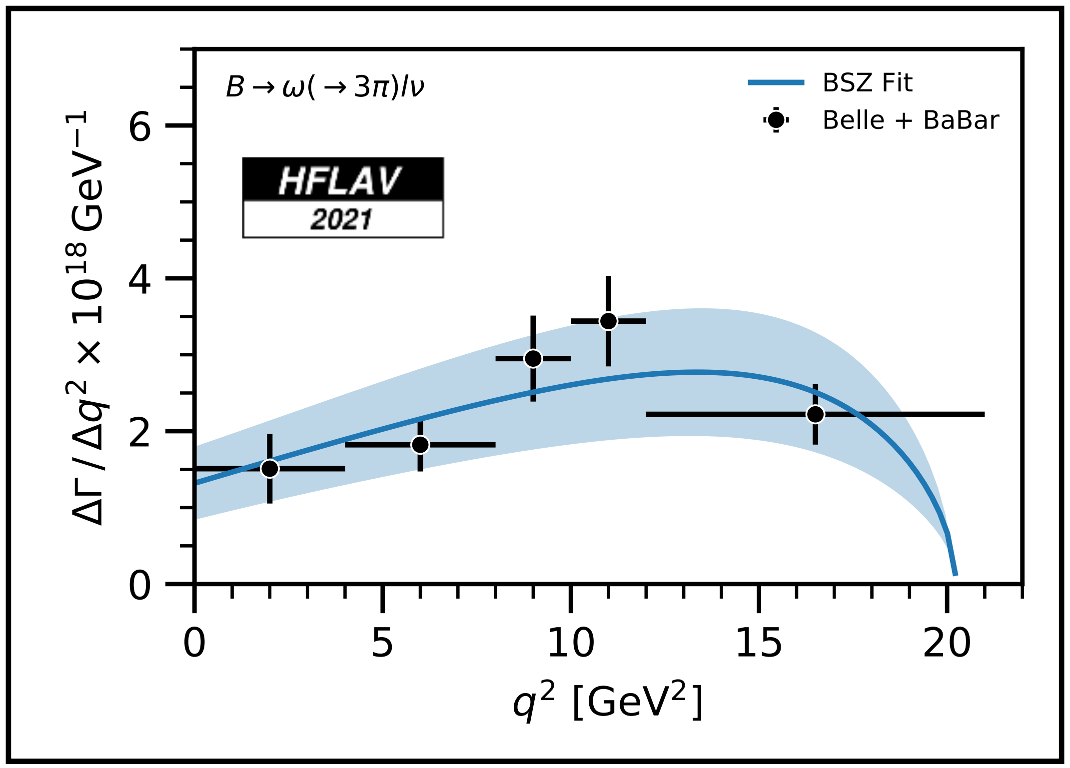
Plan to release public code for all of these

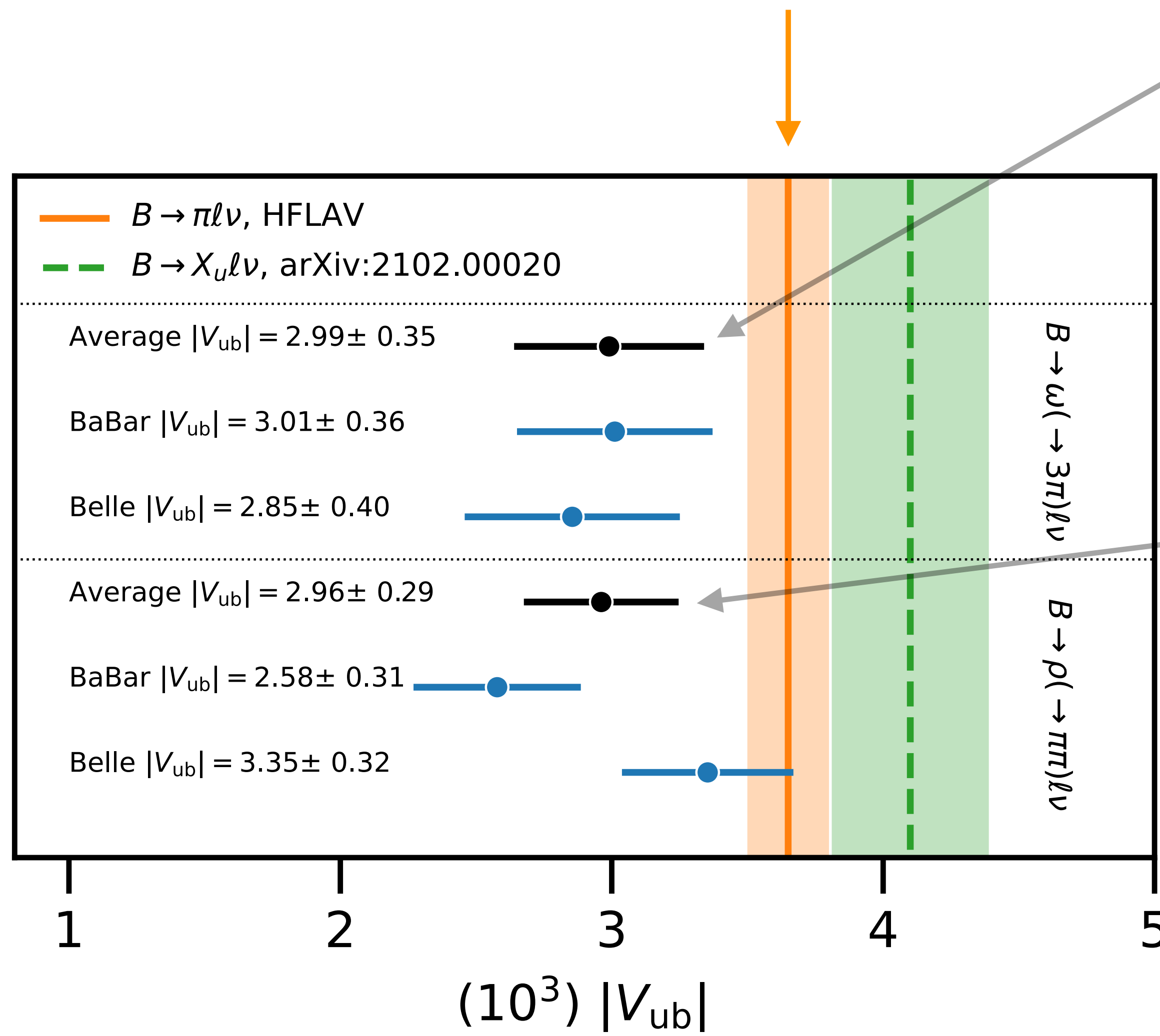


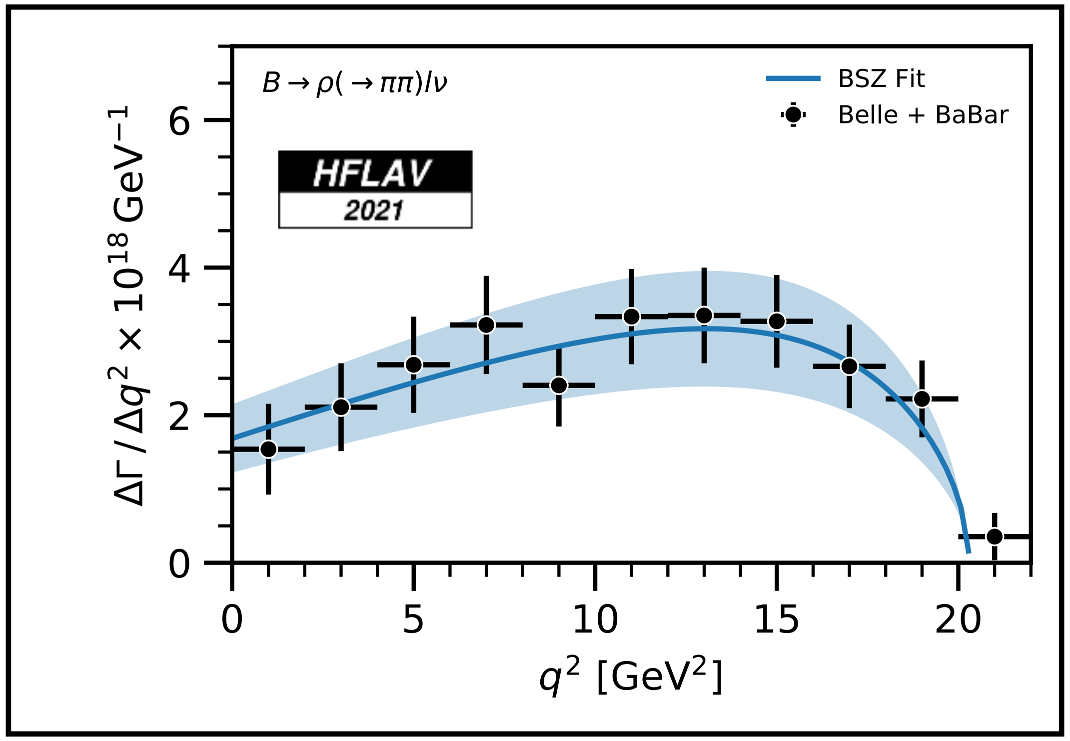




BSZ: J. High Energ. Phys. (2016) 2016: 98







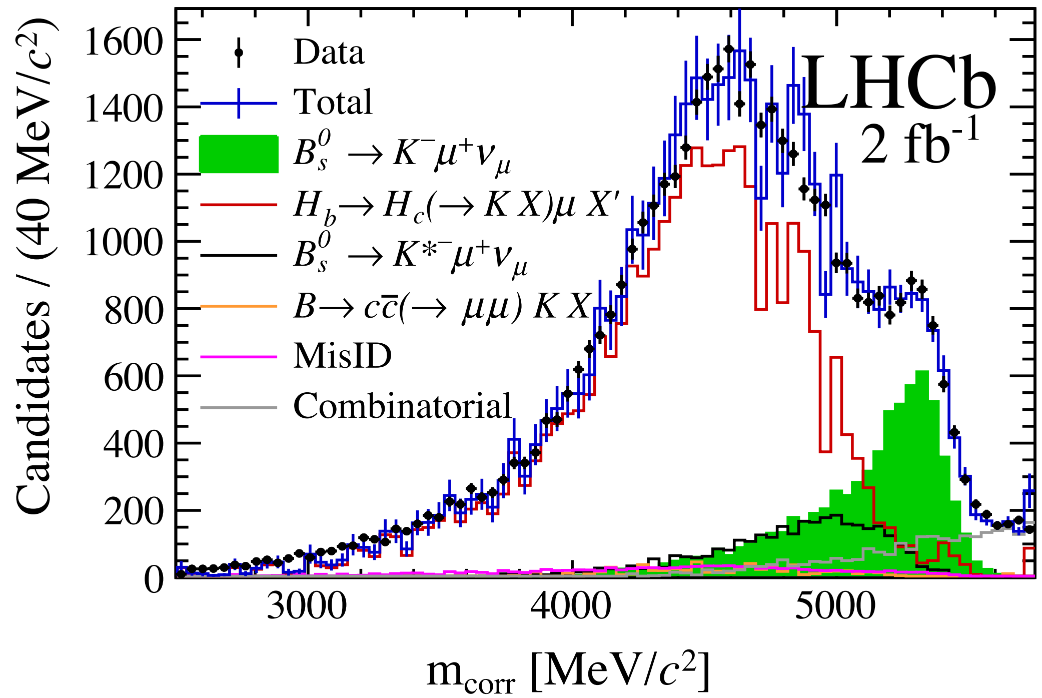
ρ/ω prefer much lower values of $|V_{ub}|$ …

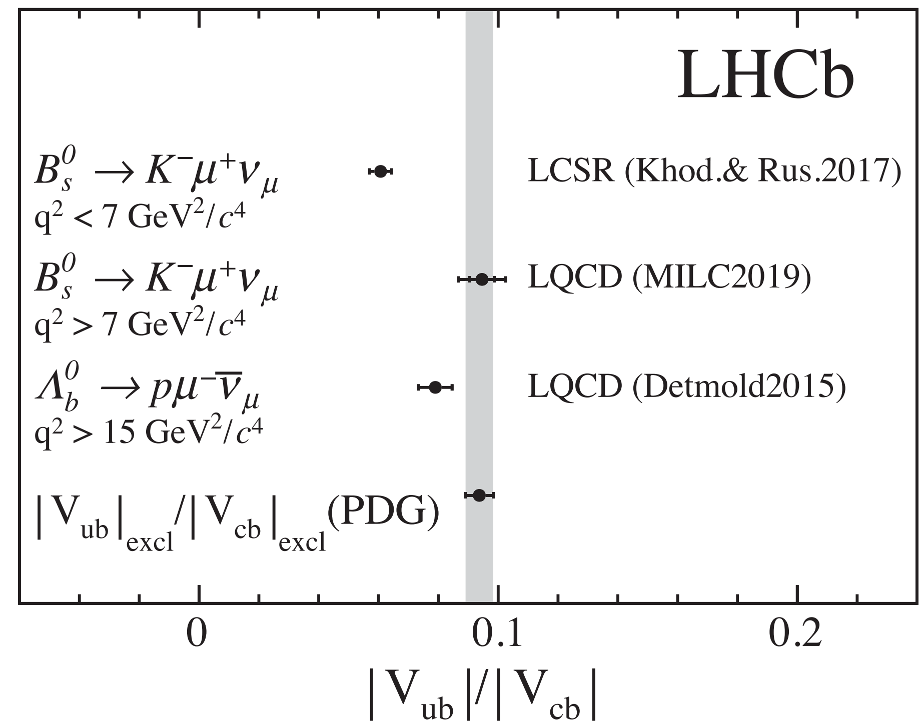
See also FB, Markus Prim, Dean Robinson, Phys. Rev. D 104, 034032 (2021)

Again: Great results from LHCb

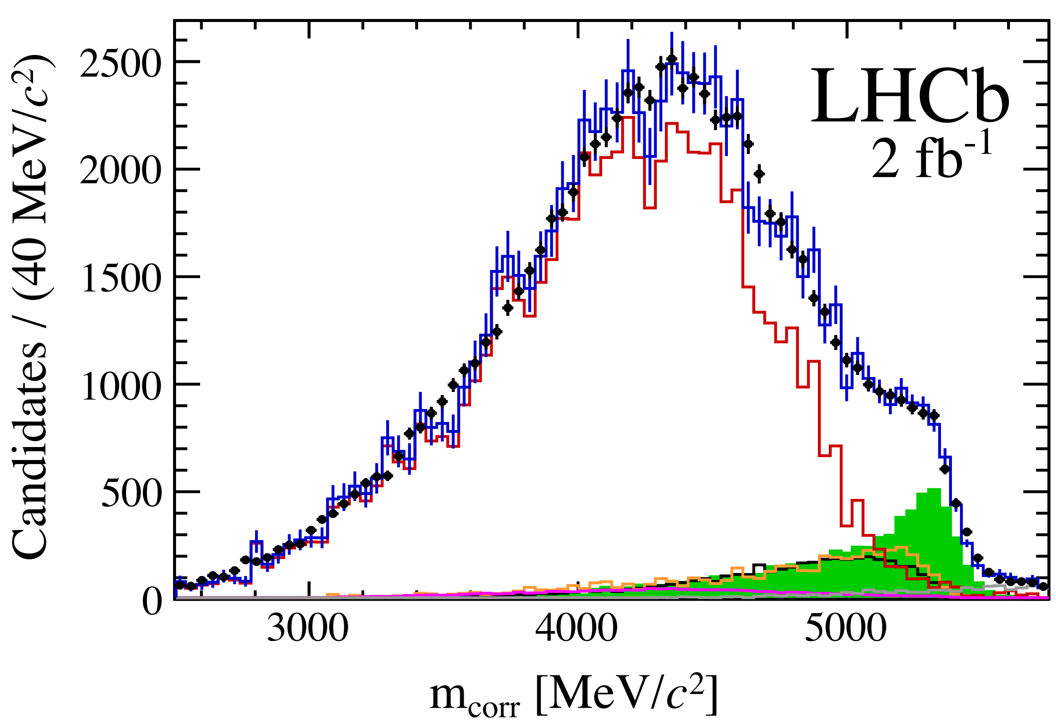
Phys. Rev. Lett. 126, 081804 (2021)

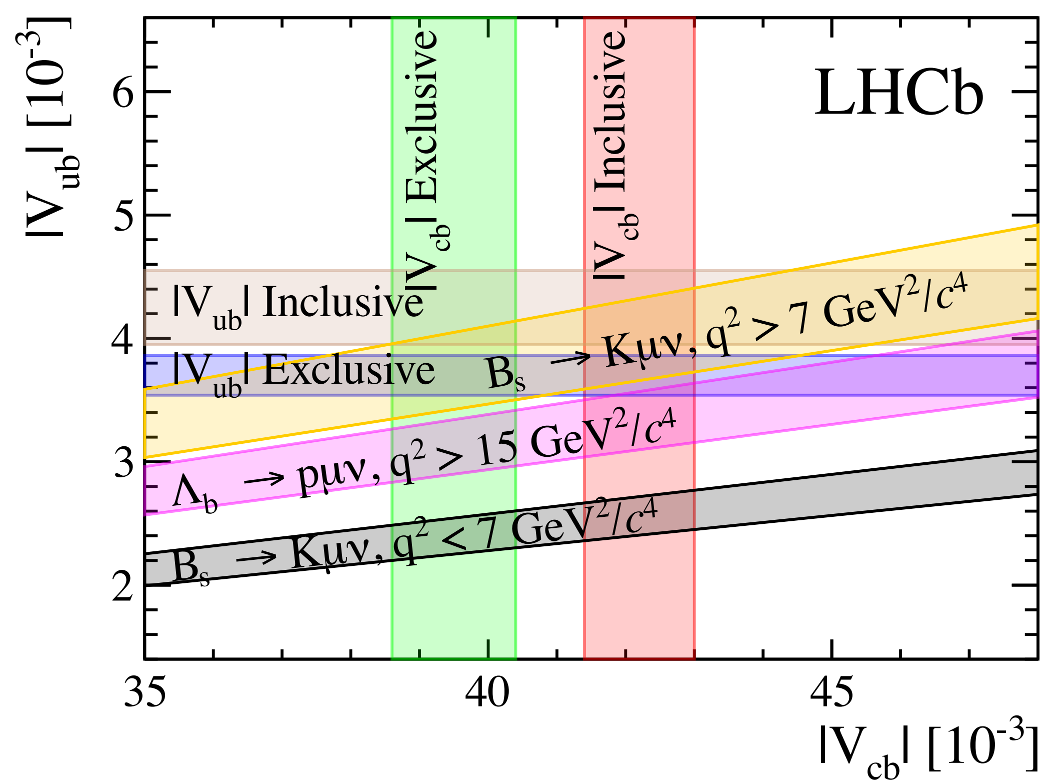
$q^2 < 7\,\mathrm{GeV}^2$





$q^2 > 7\,\mathrm{GeV}^2$





Quo vadis?

- Where should and where can we go?

Some closing thoughts

Number of exciting developments are happening:

Belle II has many exciting results in the making (stay tuned for Spring / Summer 2022)

→ Will revisit all inclusive and exclusive results of the B-factory era

We need to start an era of more accessible data

LHCb has evolved into a semileptonic results machine

→ Adds new perspectives and results form baryons, maybe also inclusive determinations?

Lattice QCD made impressive leaps forward

→ Some are puzzling and need to be understood; lattice role in understanding inclusive decays has just started and is exciting

LCSR for many decays available

→ Interesting orthogonal information for phase-space regions plus only input for decays for which we have no lattice information

Some closing thoughts

Number of exciting developments are happening:

Belle II has many exciting results in the making (stay tuned for Spring / Summer 2022)

→ Will revisit all inclusive and exclusive results of the B-factory era

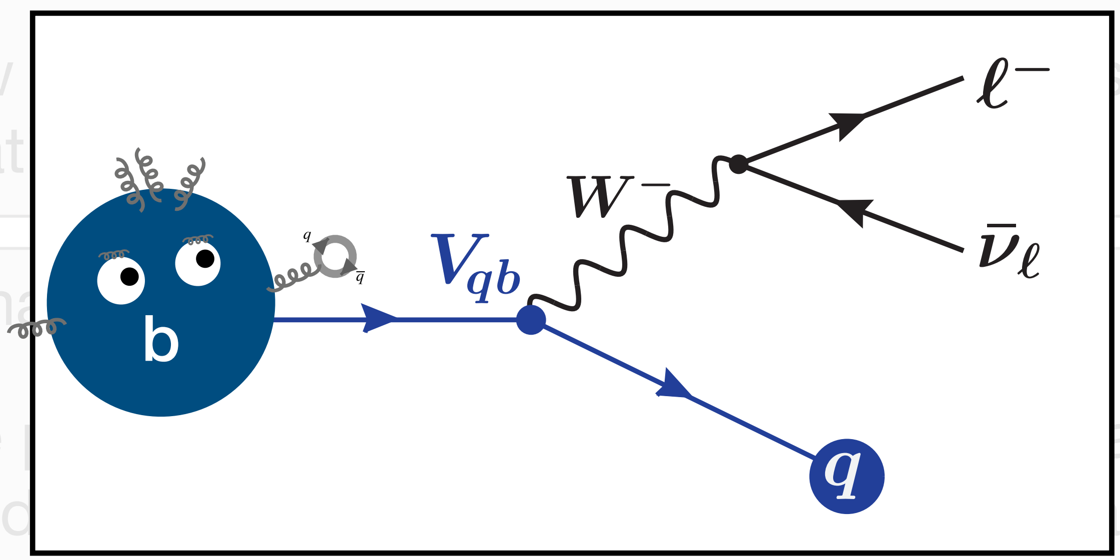
He may look cute, but that
might be deceiving…

LHCb has evolv… …nic results machine

→ Adds new … …, maybe also inclusive
determinat…

Lattice QCD m…

→ Some are … …attice role in
understand… …nd is exciting

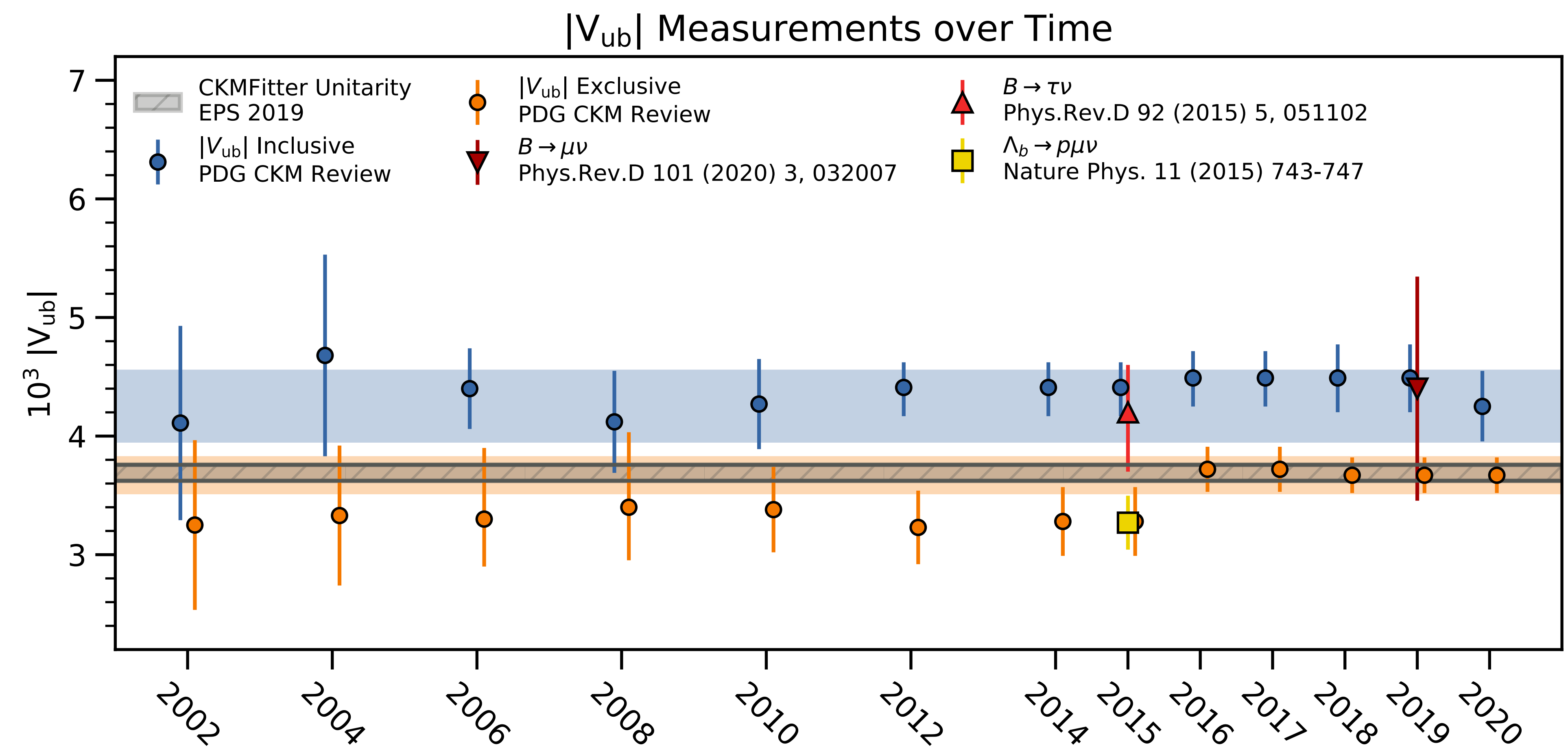


LCSR for many decays available

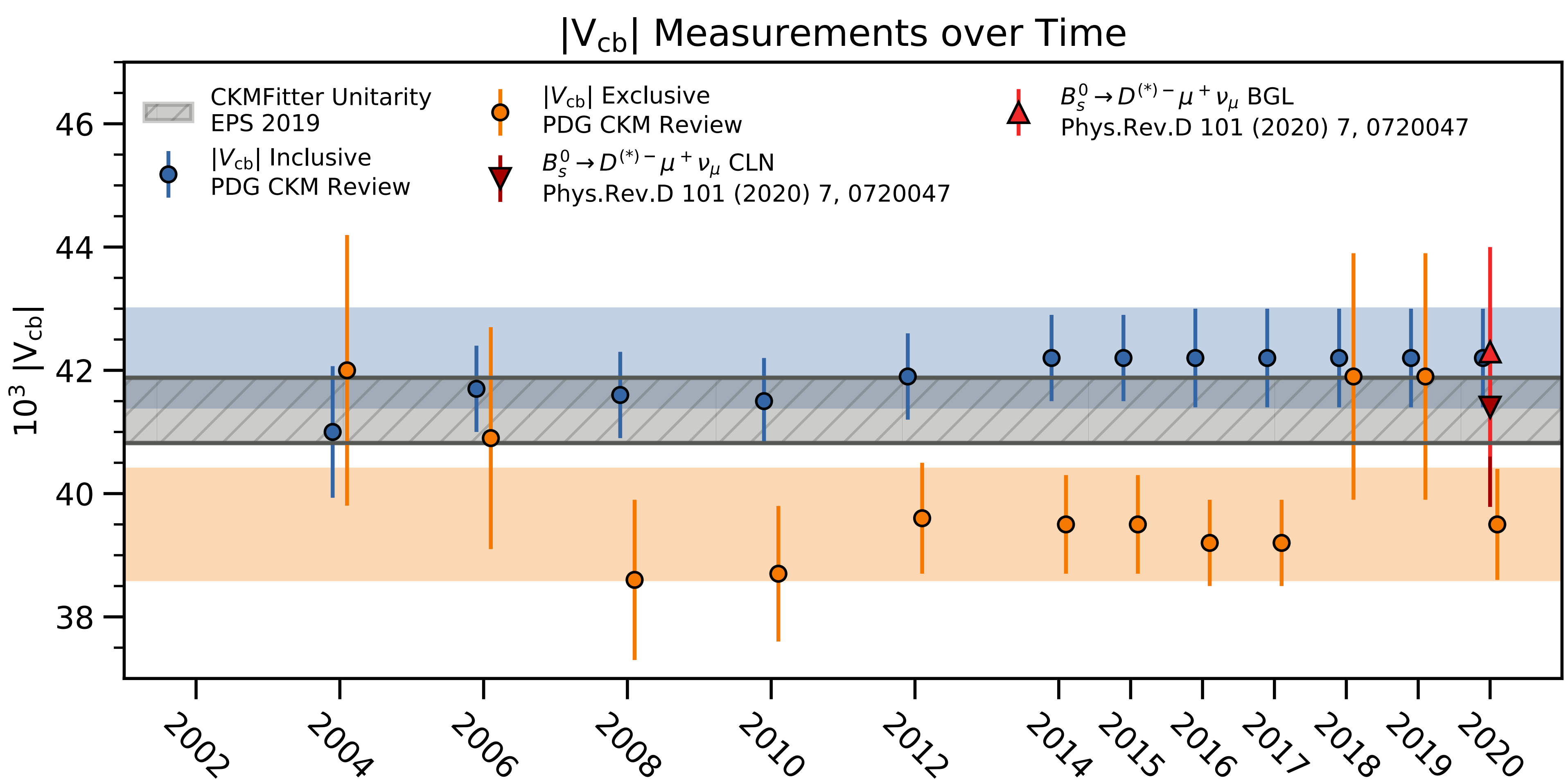
… but we are hot on his trail

→ Interesting orthogonal information for phase-space regions plus only input
for decays for which we have no lattice information

More Material



|Vub| Measurements over Time
CKMFitter Unitarity
EPS 2019
|Vub| Inclusive
PDG CKM Review
|Vub| Exclusive
PDG CKM Review
B → μν
Phys.Rev.D 101 (2020) 3, 032007
B → τν
Phys.Rev.D 92 (2015) 5, 051102
Λb → pμν
Nature Phys. 11 (2015) 743-747
10^3 |Vub|
7
6
5
4
3
2002
2004
2006
2008
2010
2012
2014
2015
2016
2017
2018
2019
2020

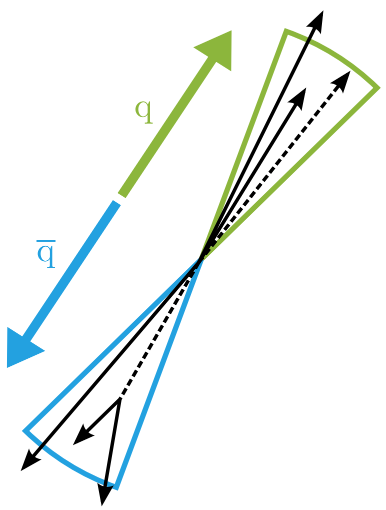


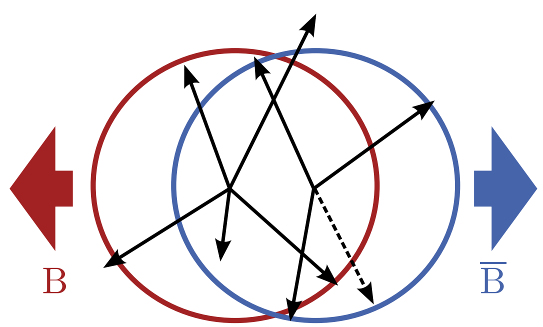
|Vcb| Measurements over Time
CKMFitter Unitarity
EPS 2019
|Vcb| Inclusive
PDG CKM Review
|Vcb| Exclusive
PDG CKM Review
B0s → D(*)− μ+ νμ CLN
Phys.Rev.D 101 (2020) 7, 0720047
B0s → D(*)− μ+ νμ BGL
Phys.Rev.D 101 (2020) 7, 0720047
10^3 |Vcb|
46
44
42
40
38
2002
2004
2006
2008
2010
2012
2014
2015
2016
2017
2018
2019
2020

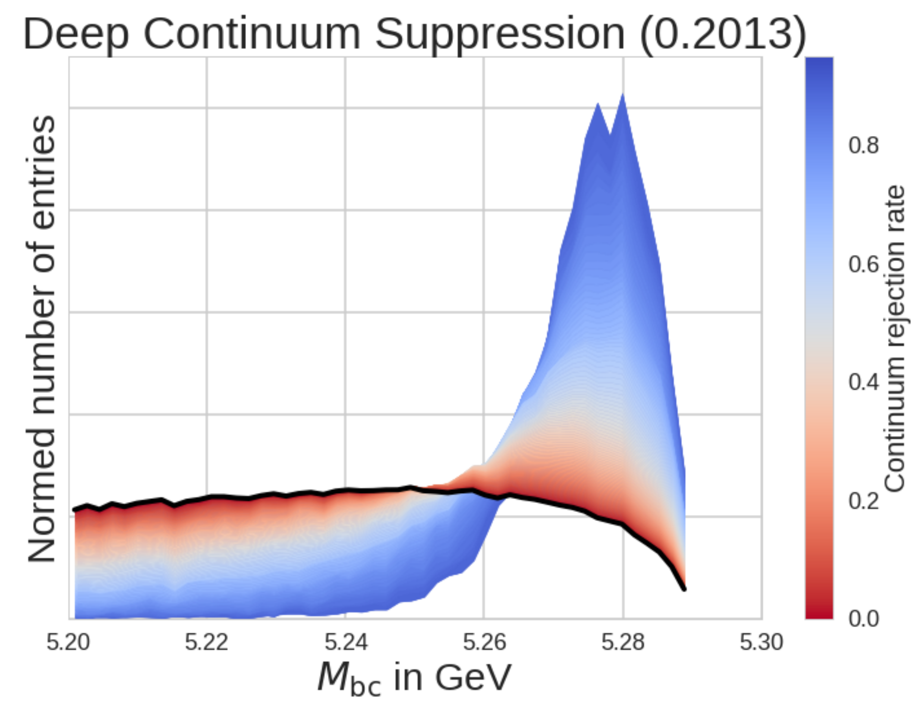
Future directions:

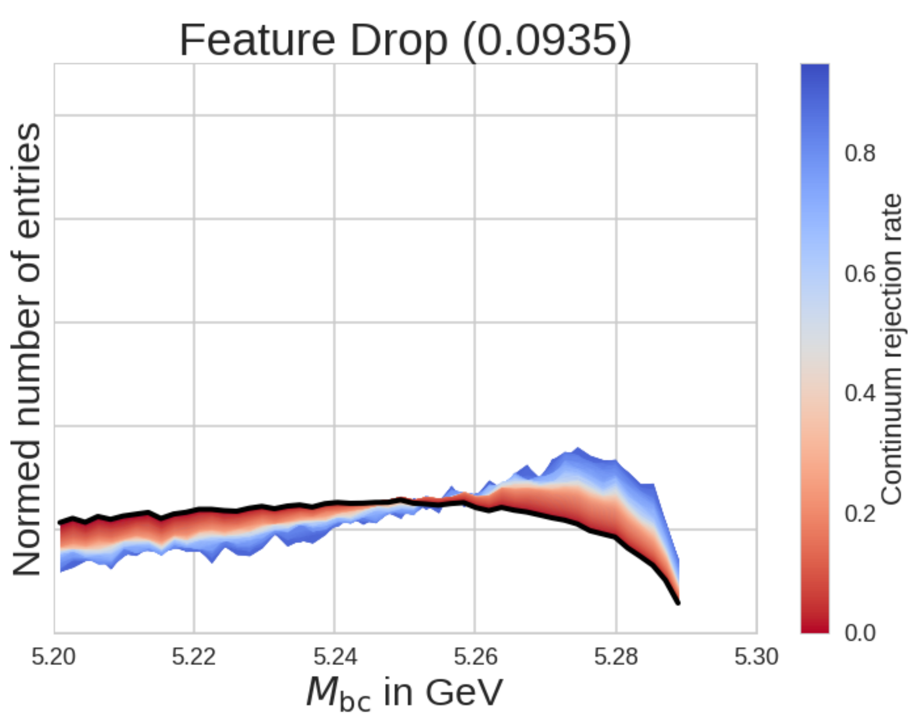
$$M_{\mathrm{bc}} = \sqrt{E_{\mathrm{beam}}^2 - p_B^2}$$

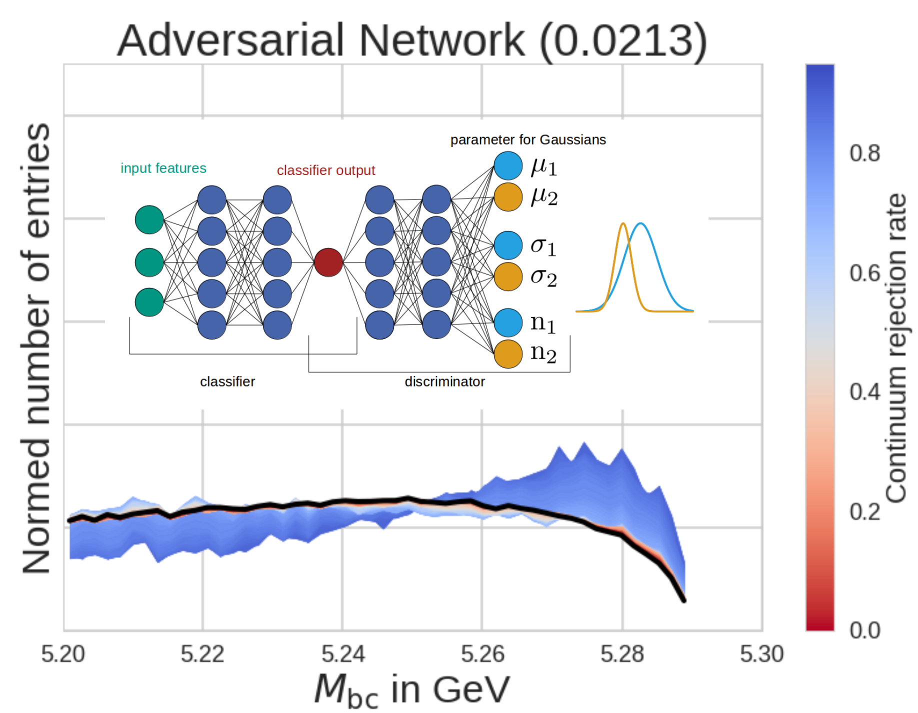
Avoid Efficiency shaping



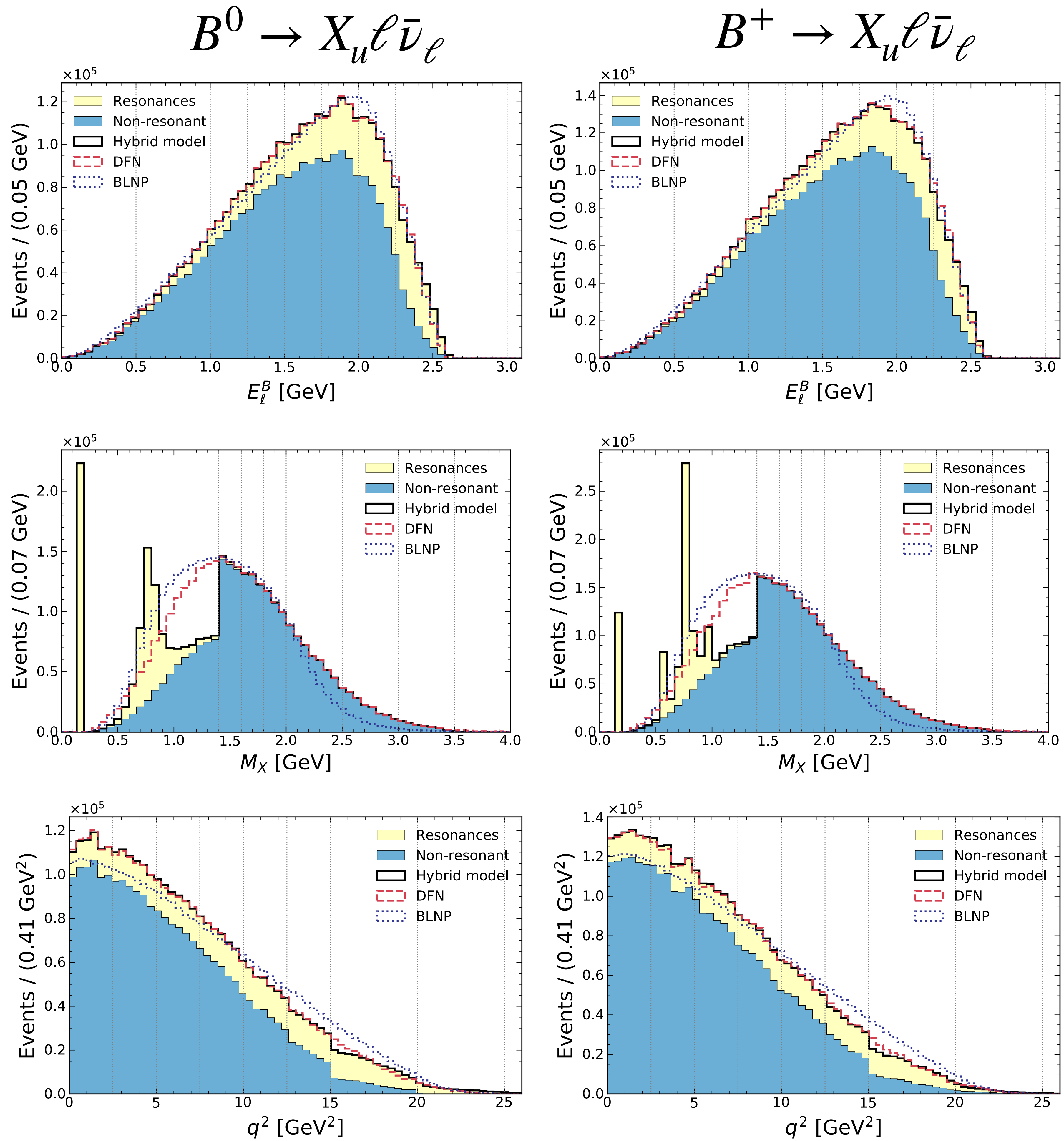








https://indico.cern.ch/event/655447/contributions/2742185/attachments/1552413/2439489/adversarial_networks_in_belle2-iml.pdf



$B^0 \to X_u \ell \bar{\nu}_\ell$
$B^+ \to X_u \ell \bar{\nu}_\ell$
Resonances
Non-resonant
Hybrid model
DFN
BLNP
Events / (0.05 GeV)
E_ℓ^B [GeV]
Events / (0.07 GeV)
M_X [GeV]
Events / (0.41 GeV^2)
q^2 [GeV^2]

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

- **Update** excl. branching ratios to PDG 2020 and the masses and widths of D** decays
- **Generate** additional MC samples to fill the **gap** between the exclusive & inclusive measurement (assign 100% BR uncertainty in systematics covariance matrix)

	BR	B+	B0
	$B \to X_c \ell^+ \nu_\ell$		
D, D*	$B \to D \ell^+ \nu_\ell$	$(2.5 \pm 0.1) \times 10^{-2}$	$(2.3 \pm 0.1) \times 10^{-2}$
	$B \to D^* \ell^+ \nu_\ell$	$(5.4 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
D**	$B \to D_0^* \ell^+ \nu_\ell$	$(0.420 \pm 0.075) \times 10^{-2}$	$(0.390 \pm 0.069) \times 10^{-2}$
	$(\hookrightarrow D\pi)$		
	$B \to D_1^* \ell^+ \nu_\ell$	$(0.423 \pm 0.083) \times 10^{-2}$	$(0.394 \pm 0.077) \times 10^{-2}$
	$(\hookrightarrow D^*\pi)$		
	$B \to D_1 \ell^+ \nu_\ell$	$(0.422 \pm 0.027) \times 10^{-2}$	$(0.392 \pm 0.025) \times 10^{-2}$
	$(\hookrightarrow D^*\pi)$		
	$B \to D_2^* \ell^+ \nu_\ell$	$(0.116 \pm 0.011) \times 10^{-2}$	$(0.107 \pm 0.010) \times 10^{-2}$
	$(\hookrightarrow D^*\pi)$		
	$B \to D_2^* \ell^+ \nu_\ell$	$(0.178 \pm 0.024) \times 10^{-2}$	$(0.165 \pm 0.022) \times 10^{-2}$
	$(\hookrightarrow D\pi)$		
	$\rho(D_2^* \to D^*\pi, D_2^* \to D\pi) = 0.693$		
Gap	$B \to D_1 \ell^+ \nu_\ell$	$(0.242 \pm 0.100) \times 10^{-2}$	$(0.225 \pm 0.093) \times 10^{-2}$
	$(\hookrightarrow D\pi\pi)$		
	$B \to D\pi\pi \ell^+ \nu_\ell$	$(0.06 \pm 0.06) \times 10^{-2}$	$(0.06 \pm 0.06) \times 10^{-2}$
	$B \to D^*\pi\pi \ell^+ \nu_\ell$	$(0.216 \pm 0.102) \times 10^{-2}$	$(0.201 \pm 0.095) \times 10^{-2}$
	$B \to D\eta \ell^+ \nu_\ell$	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$
	$B \to D^*\eta \ell^+ \nu_\ell$	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$
	$B \to X_c \ell^+ \nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$

BR	B+	B0
$B \to D_0^* \ell^+ \nu_\ell$	$(0.03 \pm 0.03) \times 10^{-2}$	$(0.03 \pm 0.03) \times 10^{-2}$
$(\hookrightarrow D\pi\pi)$		
$B \to D_1^* \ell^+ \nu_\ell$	$(0.03 \pm 0.03) \times 10^{-2}$	$(0.03 \pm 0.03) \times 10^{-2}$
$(\hookrightarrow D\pi\pi)$		
$B \to D_0^*\pi\pi \ell^+ \nu_\ell$	$(0.108 \pm 0.051) \times 10^{-2}$	$(0.101 \pm 0.048) \times 10^{-2}$
$(\hookrightarrow D^*\pi\pi)$		
$B \to D_1^*\pi\pi \ell^+ \nu_\ell$	$(0.108 \pm 0.051) \times 10^{-2}$	$(0.101 \pm 0.048) \times 10^{-2}$
$(\hookrightarrow D^*\pi\pi)$		
$B \to D_0^* \ell^+ \nu_\ell$	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$
$(\hookrightarrow D\eta)$		
$B \to D_1^* \ell^+ \nu_\ell$	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$
$(\hookrightarrow D^*\eta)$		

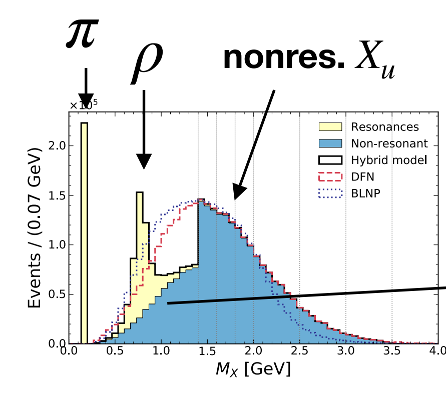
Fit for partial BFs

Subtraction of bkg in fit with coarse binning to minimize X_u modelling dependence

(low m_X, high q^2)

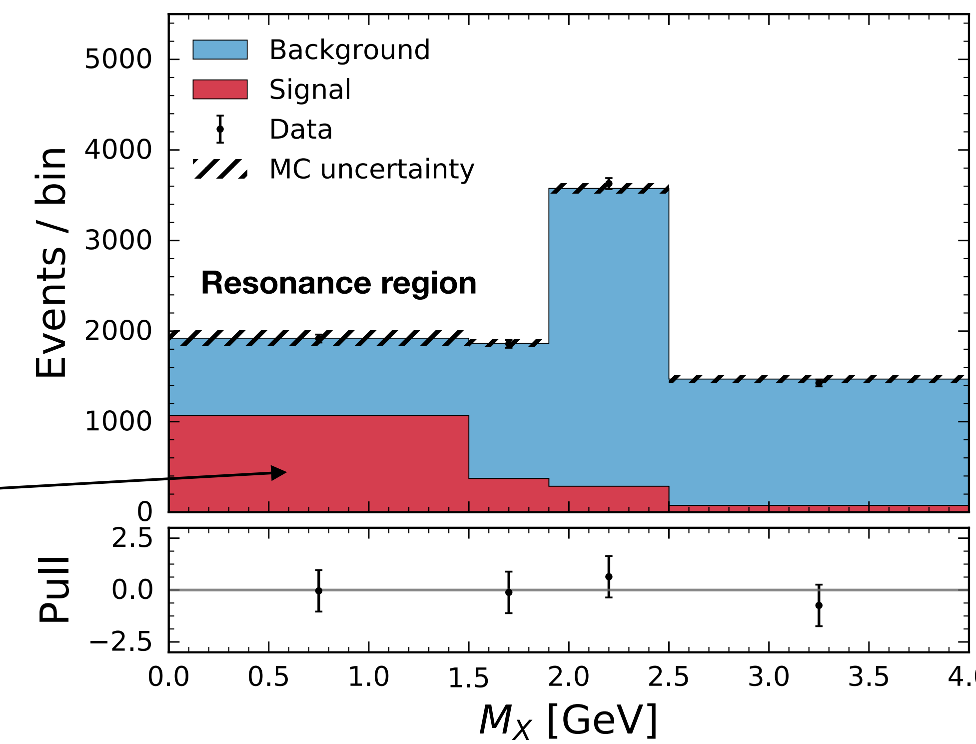
$$\mathcal{L} = \prod_i^{\text{bins}} \mathcal{P}(n_i; \nu_i) \times \prod_k \mathcal{G}_k ,$$

Signal and Bkg shape errors included in Fit via NPs



W/o detector smearing

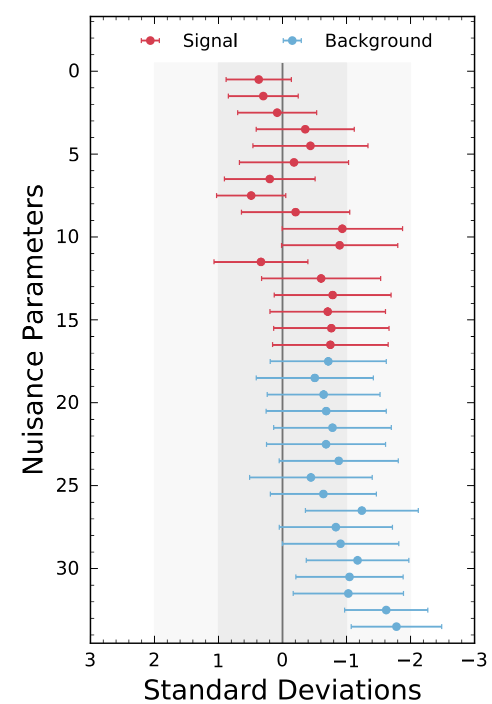
Projections of 2D fit in m_X : q^2

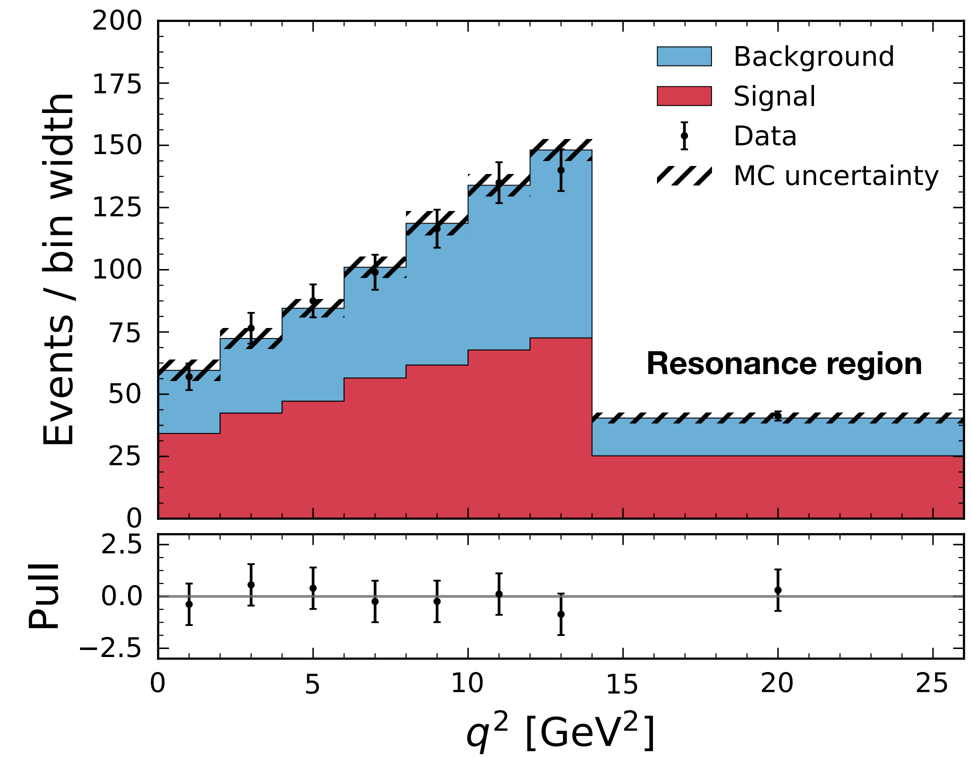


Unfold measured yields to **3 phase-space regions:**

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

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

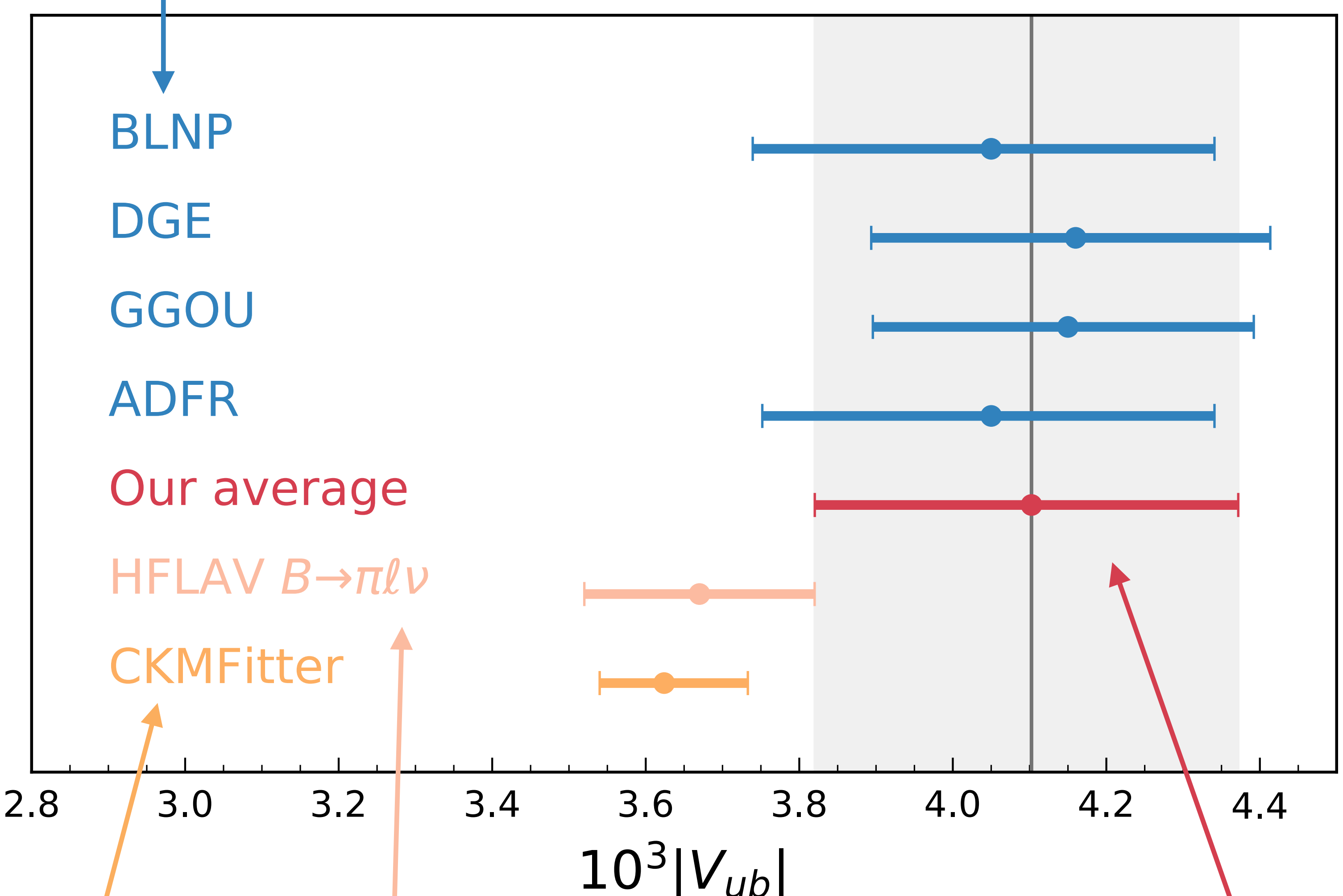




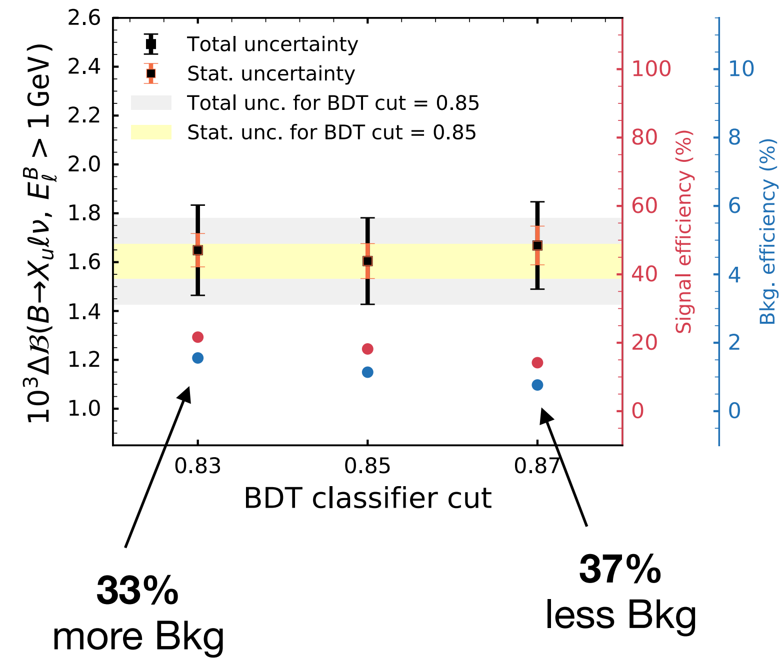
$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u \ell^+ \nu_\ell)}{\tau_B \cdot \Delta\Gamma(B \to X_u \ell^+ \nu_\ell)}}$$

Fit kinematic distributions and measure partial BF

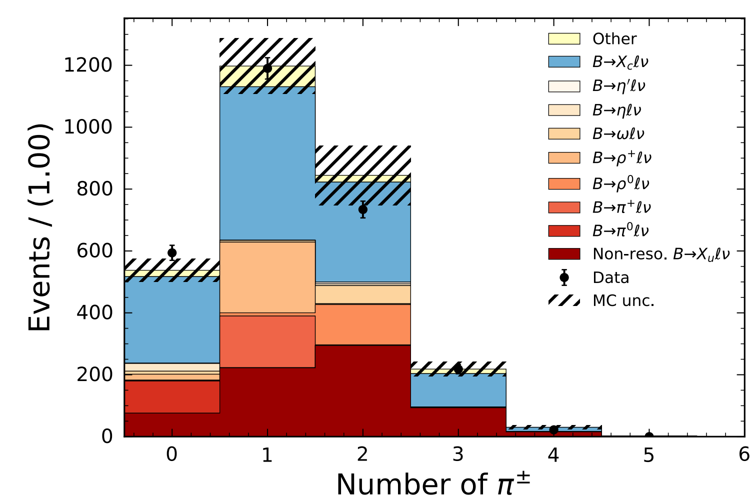
4 predictions of the partial rate



Stability as a function of BDT cut:



Post-fit N_{π^+} distribution:



Exclusive Average for $B \to \pi \ell \bar{\nu}_\ell$:

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

Arithmetic average:

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

CKM Unitarity:

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

Into the tool shed: EvtGen & Pythia8

Many analyses need generic B-Meson decay samples

* Pythia8 hadronized modes make up ca. **48%** (!) of all simulated decays

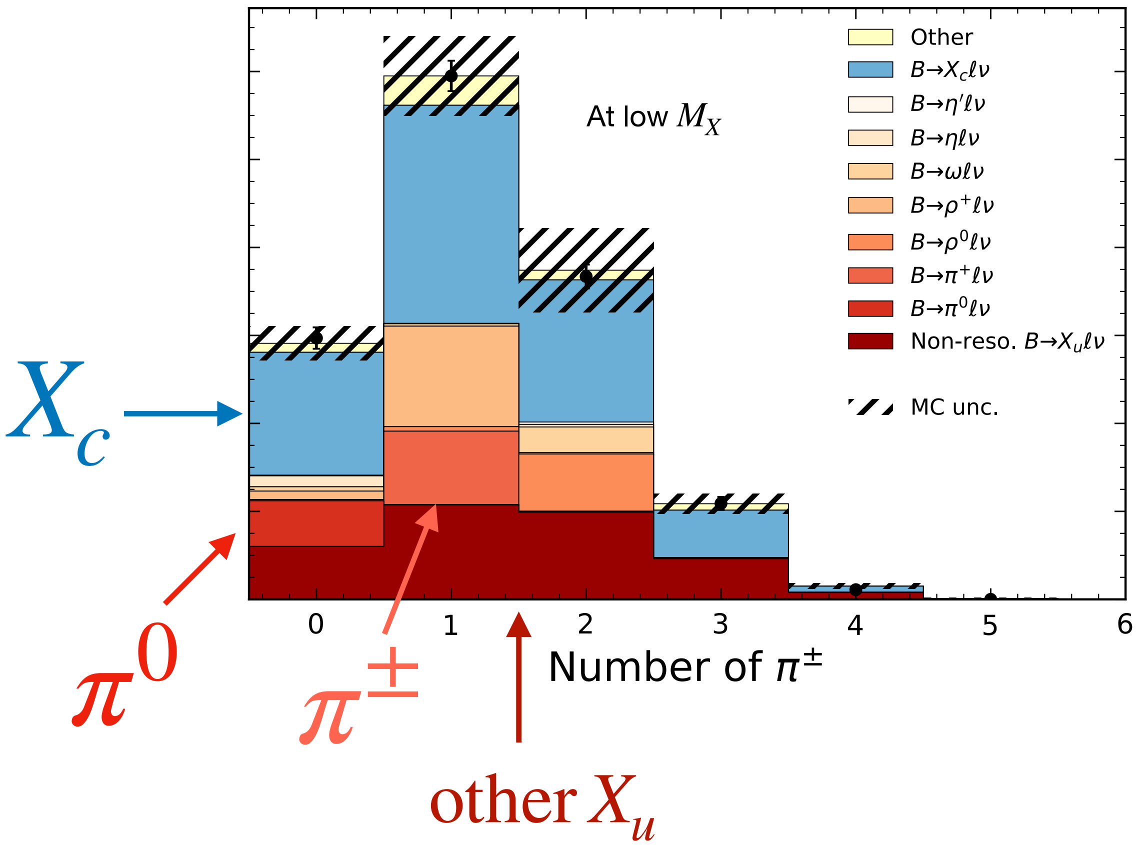
```
#  Lam_c X  / Sigma_c X      4.0 %
#
0.010520663 anti-cd_0 ud_0                              PYTHIA 23;
0.021041421 anti-cd_1 ud_1                              PYTHIA 23;

#  Xi_c X    2.5%
#
0.002869298 anti-cs_0 ud_0                              PYTHIA 23;
0.005738595 anti-cs_1 ud_1                              PYTHIA 23;

0.258091538 u       anti-d  anti-c  d                   PYTHIA 48;
0.043995612 u       anti-d  anti-c  d                   PYTHIA 13;
0.020084989 u       anti-s  anti-c  d                   PYTHIA 13;
0.017215691 u       anti-c  anti-d  d                   PYTHIA 48;
0.000860770 u       anti-c  anti-s  d                   PYTHIA 48;
#lange - try to crank up the psi production....
0.070775534 c       anti-s  anti-c  d                   PYTHIA 13;
0.005738595 c       anti-d  anti-c  d                   PYTHIA 13;
0.002869298 u       anti-d  anti-u  d                   PYTHIA 48;
0.003825730 c       anti-s  anti-u  d                   PYTHIA 48;
# JGS 11/5/02 This and similar a few lines above have been divided by two
# to solve a double-counting problem for this channel
0.001960649 u       anti-u  anti-d  d                   PYTHIA 48;
0.000066973 d       anti-d  anti-d  d                   PYTHIA 48;
0.000086068 s       anti-s  anti-d  d                   PYTHIA 48;
0.002104095 u       anti-u  anti-s  d                   PYTHIA 48;
0.001721541 d       anti-d  anti-s  d                   PYTHIA 48;
0.001434649 s       anti-s  anti-s  d                   PYTHIA 48;
0.004782163 anti-s  d                                   PYTHIA 32;
```

Modes for Matrix Element Processing

Some decays can be treated better than what pure phase space allows, by reweighting with appropriate matrix e
signaled by a nonvanishing `meMode()` value for a decay mode in the particle data table. The list of allowed poss
introduced, and most have been moved for better consistency. Here is the list of currently allowed `meMode()` co

- 0 : pure phase space of produced particles ("default"); input of partons is allowed and then the partonic con
- 1 : *omega* and *phi → pi+ pi- pi0*
- 2 : polarization in *V → PS + PS* (*V* = vector, *PS* = pseudoscalar), when *V* is produced by *PS → PS + V* or *P*
- 11 : Dalitz decay into one particle, in addition to the lepton pair (also allowed to specify a quark-antiquark pa
- 12 : Dalitz decay into two or more particles in addition to the lepton pair
- 13 : double Dalitz decay into two lepton pairs
- 21 : decay to phase space, but weight up *neutrino_tau* spectrum in *tau* decay
- 22 : weak decay; if there is a quark spectator system it collapses to one hadron; for leptonic/semileptonic d
- 23 : as 22, but require at least three particles in decay
- 31 : decays of type B → gamma X, very primitive simulation where X is given in terms of its flavour content spectrum is weighted up relative to pure phase space
- 42 - 50 : turn partons into a random number of hadrons, picked according to a Poissonian with average val new try with another multiplicity if the sum of daughter masses exceed the mother one
- 52 - 60 : as 42 - 50, with multiplicity between `code` - 50 and 10, but avoid already explicitly listed non-parto
- 62 - 70 : as 42 - 50, but fixed multiplicity `code` - 60
- 72 - 80 : as 42 - 50, but fixed multiplicity `code` - 70, and avoid already explicitly listed non-partonic channel
- 91 : decay to *q qbar* or *g g*, which should shower and hadronize
- 92 : decay onium to *g g g* or *g g gamma* (with matrix element), which should shower and hadronize
- 93 : decay of colour singlet to *q qbar* plus another singlet, flat in phase space (and arbitrarily ordered), whe
- 94 : same as 93, but weighted with *V-A* weak matrix element if the decay chain is of the type *neutrino \rarr;*
- 100 - : reserved for the description of partial widths of resonances

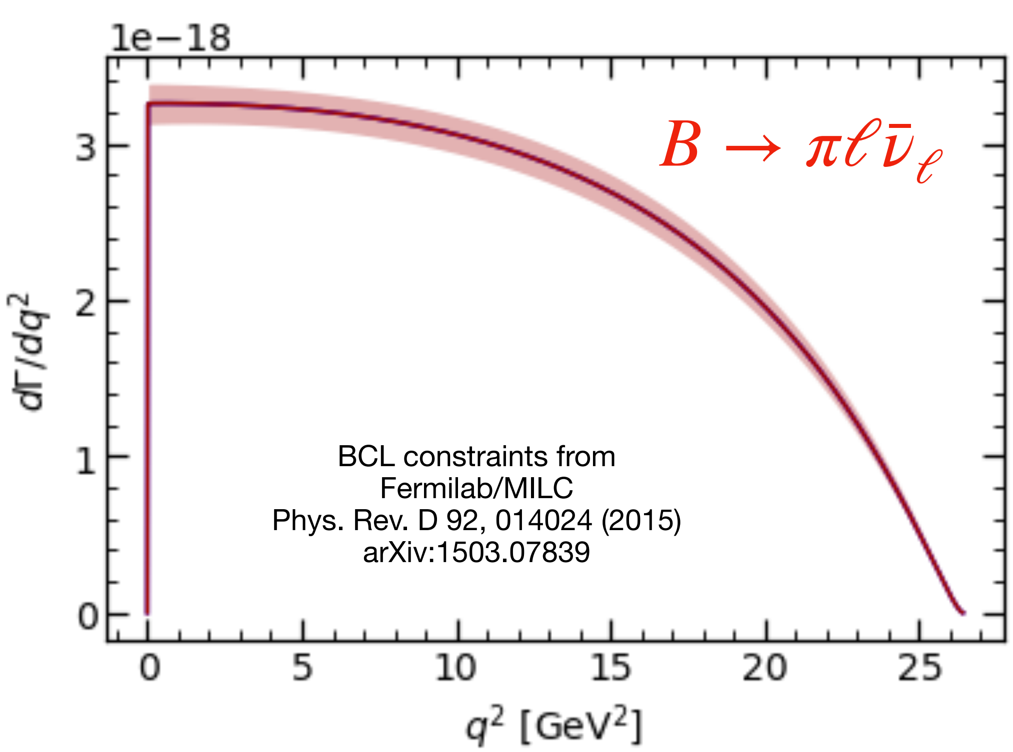
Can we measure incl. and excl. $|V_{ub}|$ at the same time?



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

$$\mathscr{B}(B \to \pi \ell \bar{\nu}_\ell)$$

$$\frac{|V_{ub}^{\text{excl.}}|}{|V_{ub}^{\text{incl.}}|} = \frac{\sqrt{\dfrac{\mathscr{B}(B \to \pi \ell \bar{\nu}_\ell)}{\Gamma(B \to \pi \ell \bar{\nu}_\ell)}}}{\sqrt{\dfrac{\Delta\mathscr{B}(B \to X_u \ell \bar{\nu}_\ell)}{\Delta\Gamma(B \to X_u \ell \bar{\nu}_\ell)}}}$$



Use $q^2 : N_{\pi^\pm}$ to separate

$B \to \pi^0 \ell \bar{\nu}_\ell$

$B \to \pi^\pm \ell \bar{\nu}_\ell$

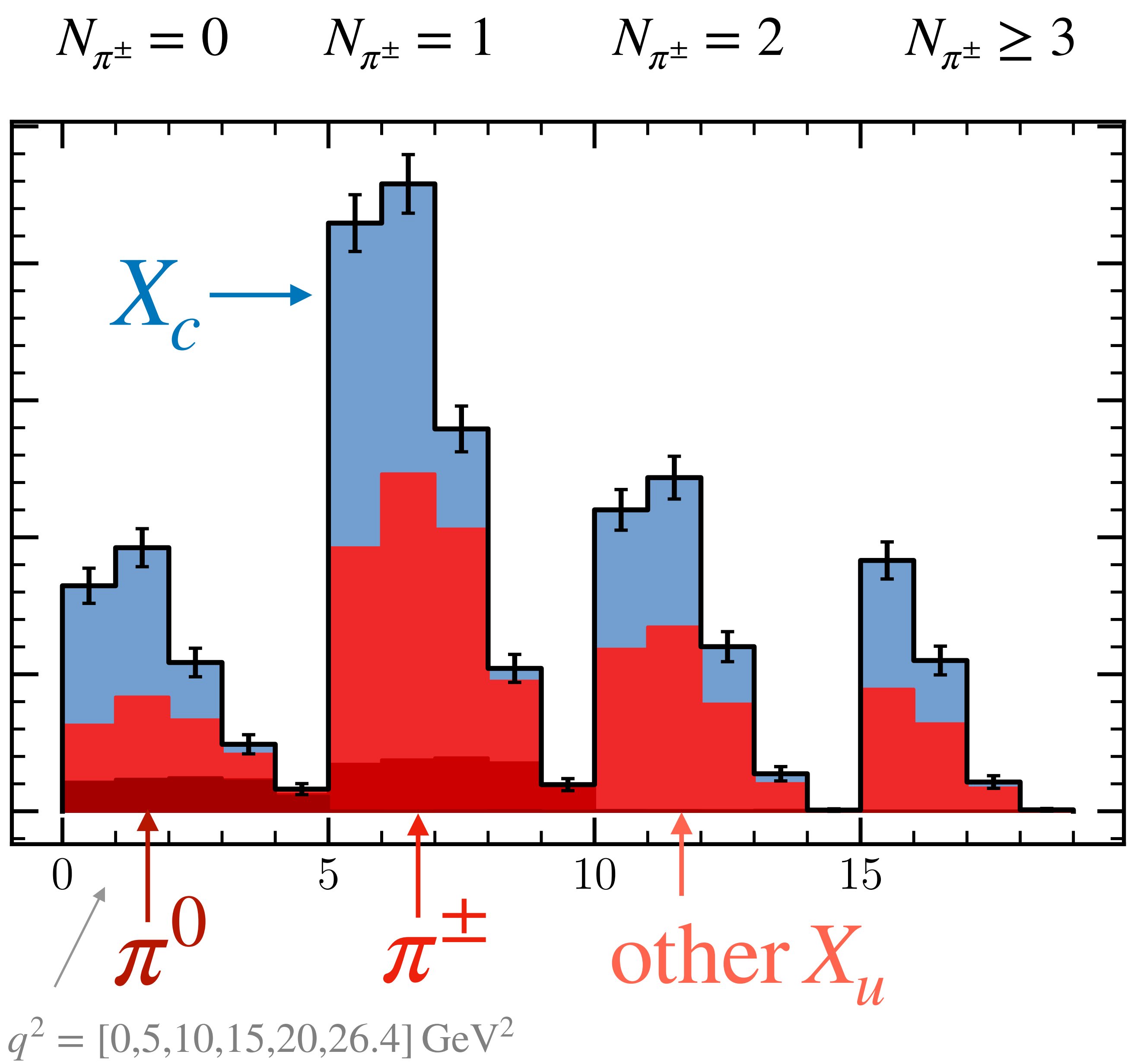
$B \to X_u^{\text{other}} \ell \bar{\nu}_\ell$

$B \to X_c \ell \bar{\nu}_\ell + \text{other Bkg}\,.$

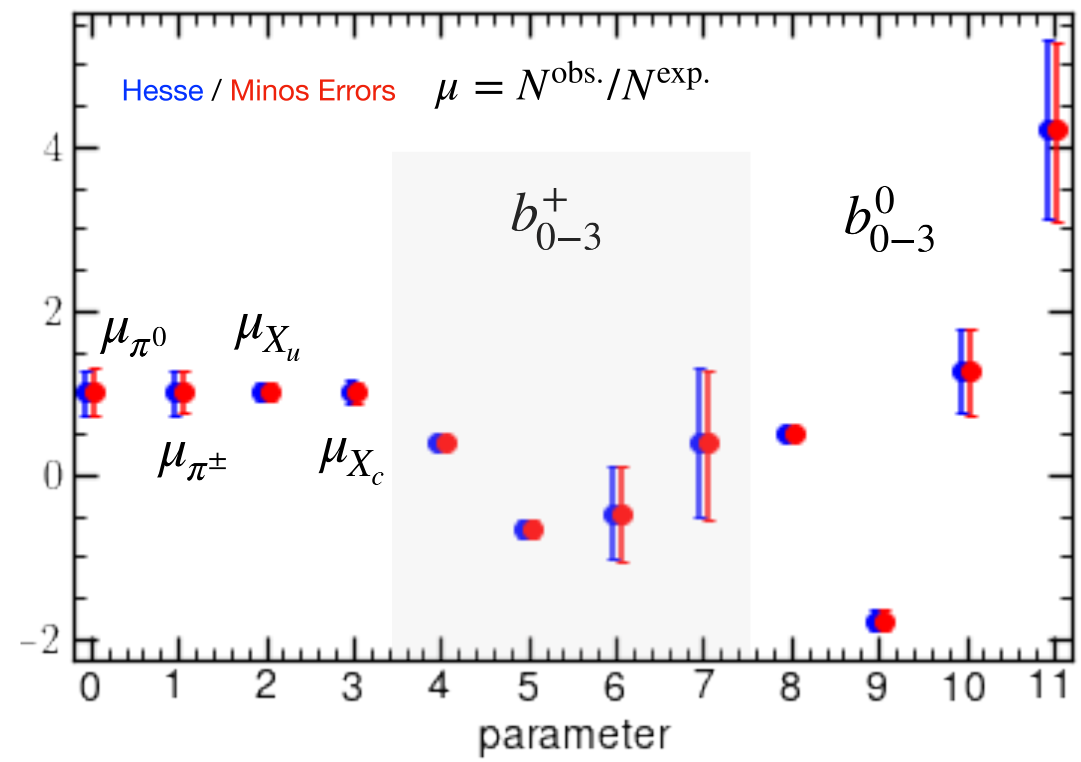
Asimov Fit

$\mu_{\pi^0} = N^{\rm obs}_{\pi^0} / N^{\rm MC}_{\pi^0}$

Fermilab/MILC
Phys. Rev. D 92, 014024 (2015)
arXiv:1503.07839



Fit Setup: $\chi^2 = \chi^2_{\rm exp} + \chi^2_{\rm FNAL}$



μ_{π^0}	$\mu_{\pi^\pm}$	μ_{X_u}	μ_{X_c}	b^+_{0-3}				b^0_{0-3}			
1.00	0.51	0.39	-0.61	0.13	0.55	0.63	0.57	0.23	0.54	0.64	0.43
0.51	1.00	0.10	-0.40	0.17	0.58	0.58	0.51	0.22	0.52	0.62	0.41
0.39	0.10	1.00	-0.89	0.03	0.35	0.53	0.49	0.18	0.40	0.50	0.34
-0.61	-0.40	-0.89	1.00	-0.09	-0.54	-0.70	-0.65	-0.25	-0.57	-0.69	-0.46
0.13	0.17	0.03	-0.09	1.00	0.35	-0.10	-0.16	0.24	0.20	0.10	0.04
0.55	0.58	0.35	-0.54	0.35	1.00	0.44	0.29	0.21	0.60	0.65	0.44
0.63	0.58	0.53	-0.70	-0.10	0.44	1.00	0.97	0.29	0.66	0.87	0.62
0.57	0.51	0.49	-0.65	-0.16	0.29	0.97	1.00	0.30	0.65	0.80	0.47
0.23	0.22	0.18	-0.25	0.24	0.21	0.29	0.30	1.00	0.24	0.07	-0.10
0.54	0.52	0.40	-0.57	0.20	0.60	0.66	0.65	0.24	1.00	0.60	0.08
0.64	0.62	0.50	-0.69	0.10	0.65	0.87	0.80	0.07	0.60	1.00	0.70
0.43	0.41	0.34	-0.46	0.04	0.44	0.62	0.47	-0.10	0.08	0.70	1.00

Individual components
seem to separate well in Asimov with
made-up (but semi-realistic) distributions

Combined Extractions

Interesting if heavy quark symmetry inspired Form Factors are used:

$$\hat{h}(w) = h(w)/\xi(w) \longleftarrow$$ Leading Isgur-Wise function

$B \to D\ell\bar{\nu}_\ell$

$$\hat{h}_+ = 1 + \hat{\alpha}_s\Big[C_{V_1} + \frac{w+1}{2}\,(C_{V_2} + C_{V_3})\Big] + (\varepsilon_c + \varepsilon_b)\,\hat{L}_1\,,$$
$$\hat{h}_- = \hat{\alpha}_s\,\frac{w+1}{2}\,(C_{V_2} - C_{V_3}) + (\varepsilon_c - \varepsilon_b)\,\hat{L}_4\,,$$

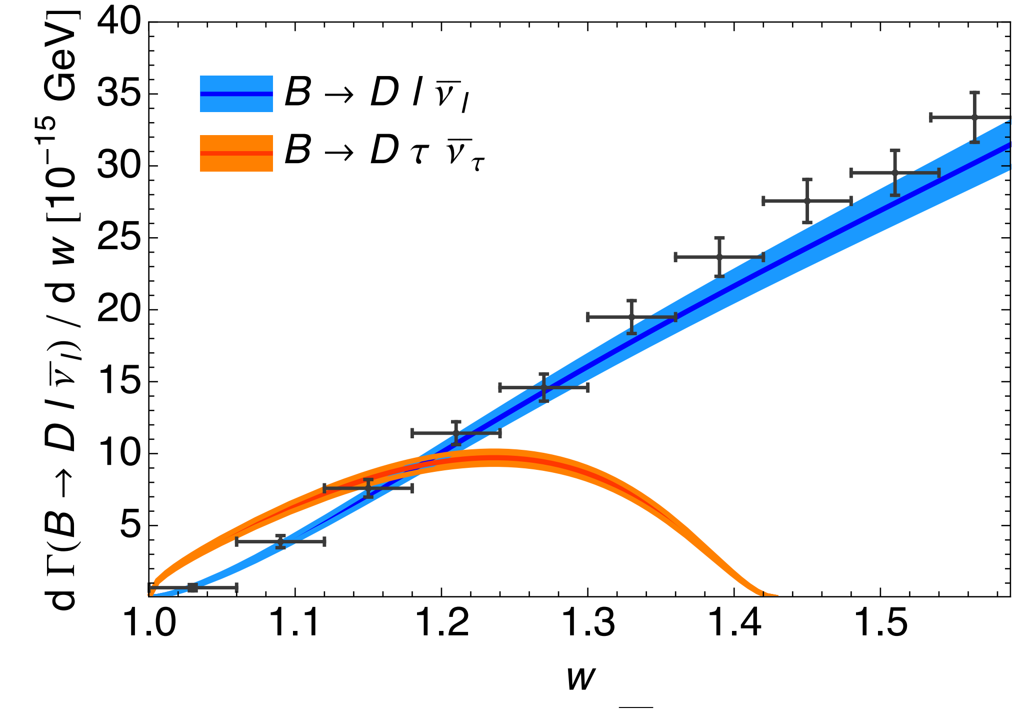
$B \to D^*\ell\bar{\nu}_\ell$

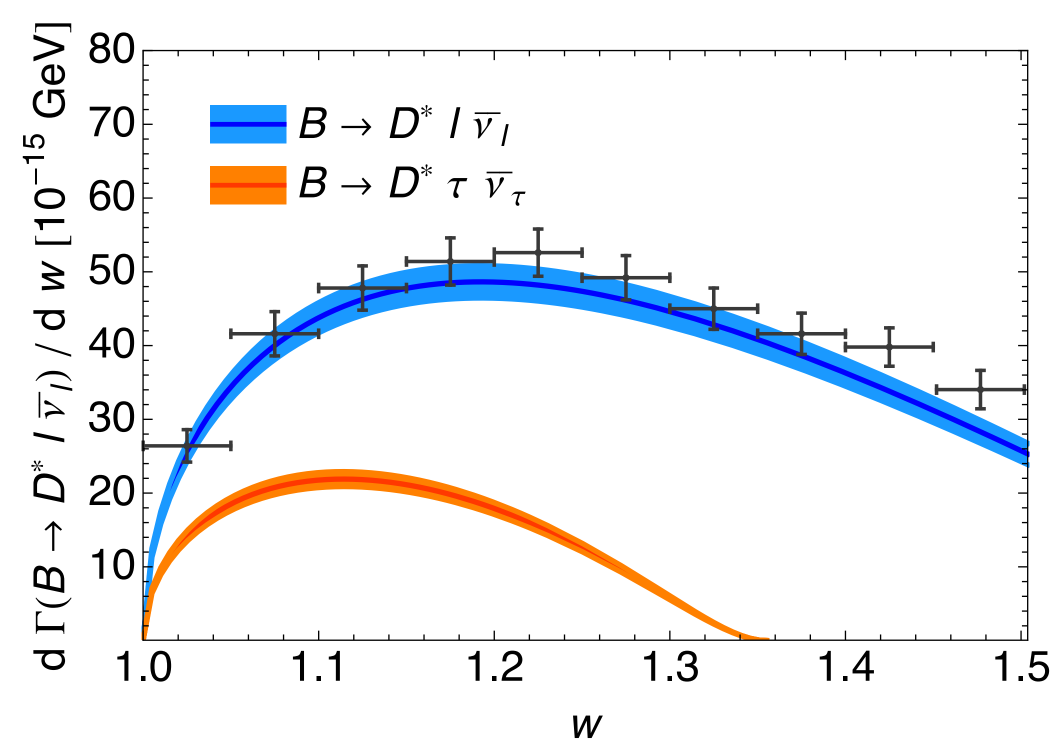
$$\hat{h}_V = 1 + \hat{\alpha}_s\,C_{V_1} + \varepsilon_c\big(\hat{L}_2 - \hat{L}_5\big) + \varepsilon_b\big(\hat{L}_1 - \hat{L}_4\big)\,,$$
$$\hat{h}_{A_1} = 1 + \hat{\alpha}_s\,C_{A_1} + \varepsilon_c\left(\hat{L}_2 - \hat{L}_5\,\frac{w-1}{w+1}\right) + \varepsilon_b\left(\hat{L}_1 - \hat{L}_4\,\frac{w-1}{w+1}\right),$$
$$\hat{h}_{A_2} = \hat{\alpha}_s\,C_{A_2} + \varepsilon_c\big(\hat{L}_3 + \hat{L}_6\big)\,,$$
$$\hat{h}_{A_3} = 1 + \hat{\alpha}_s\big(C_{A_1} + C_{A_3}\big) + \varepsilon_c\big(\hat{L}_2 - \hat{L}_3 + \hat{L}_6 - \hat{L}_5\big) + \varepsilon_b\big(\hat{L}_1 - \hat{L}_4\big)\,,$$

This links dynamics of $B \to D\ell\bar{\nu}_\ell$ & $B \to D^*\ell\bar{\nu}_\ell$

Example fit for leading IW function and sub-leading parameters

$\lvert V_{cb}\rvert \times 10^3$	38.8 ± 1.2
$\mathcal{G}(1)$	1.055 ± 0.008
$\mathcal{F}(1)$	0.904 ± 0.012
$\bar{\rho}_*^2$	1.17 ± 0.12
$\hat{\chi}_2(1)$	-0.26 ± 0.26
$\hat{\chi}_2'(1)$	0.21 ± 0.38
$\hat{\chi}_3'(1)$	0.02 ± 0.07
$\eta(1)$	0.30 ± 0.04
$\eta'(1)$	0 (fixed)
m_b^{1S} [GeV]	4.70 ± 0.05
δm_{bc} [GeV]	3.40 ± 0.02





LHCb Systematics

$B_s \to K\mu\bar{\nu}_\mu$

Uncertainty	All q^2	Low q^2	High q^2
Tracking	2.0	2.0	2.0
Trigger	1.4	1.2	1.6
Particle identification	1.0	1.0	1.0
$\sigma(m_{\mathrm{corr}})$	0.5	0.5	0.5
Isolation	0.2	0.2	0.2
Charged BDT	0.6	0.6	0.6
Neutral BDT	1.1	1.1	1.1
q^2 migration	$\cdots$	2.0	2.0
Efficiency	1.2	1.6	1.6
Fit template	$^{+2.3}_{-2.9}$	$^{+1.8}_{-2.4}$	$^{+3.0}_{-3.4}$
Total	$^{+4.0}_{-4.3}$	$^{+4.3}_{-4.5}$	$^{+5.0}_{-5.3}$

$B_s \to D_s^{(*)}\mu\bar{\nu}_\mu$

Source	Uncertainty															
	CLN parametrization						BGL parametrization									
	$\lvert V_{cb}\rvert$ $[10^{-3}]$	$\rho^2(D_s^-)$ $[10^{-1}]$	$\mathcal{G}(0)$ $[10^{-2}]$	$\rho^2(D_s^{*-})$ $[10^{-1}]$	$R_1(1)$ $[10^{-1}]$	$R_2(1)$ $[10^{-1}]$	$\lvert V_{cb}\rvert$ $[10^{-3}]$	d_1 $[10^{-2}]$	d_2 $[10^{-1}]$	$\mathcal{G}(0)$ $[10^{-2}]$	b_1 $[10^{-1}]$	c_1 $[10^{-3}]$	a_0 $[10^{-2}]$	a_1 $[10^{-1}]$	$\mathcal{R}$ $[10^{-1}]$	$\mathcal{R}^*$ $[10^{-1}]$
$f_s/f_d \times \mathcal{B}(D_s^- \to K^+K^-\pi^-)(\times\tau)$	0.8	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.4
$\mathcal{B}(D^- \to K^-K^+\pi^-)$	0.5	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.3
$\mathcal{B}(D^{*-} \to D^-X)$	0.2	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.1	0.0	0.2	0.0	0.3	–	0.2
$\mathcal{B}(B^0 \to D^-\mu^+\nu_\mu)$	0.4	0.0	0.3	0.1	0.2	0.1	0.5	0.1	0.0	0.1	0.1	0.4	0.1	0.7	–	–
$\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$	0.3	0.0	0.2	0.1	0.1	0.1	0.2	0.0	0.0	0.1	0.1	0.3	0.1	0.4	–	–
$m(B_s^0)$, $m(D^{(*)-})$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	–	–
η_{EW}	0.2	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	–	–
$h_{A_1}(1)$	0.3	0.0	0.2	0.1	0.1	0.1	0.3	0.0	0.0	0.1	0.1	0.3	0.1	0.5	–	–
External inputs (ext)	1.2	0.0	0.4	0.1	0.2	0.1	1.2	0.1	0.0	0.1	0.1	0.6	0.1	0.8	0.5	0.5
$D_{(s)}^- \to K^+K^-\pi^-$ model	0.8	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.4
Background	0.4	0.3	2.2	0.5	0.9	0.7	0.1	0.5	0.2	2.3	0.7	2.0	0.5	2.0	0.4	0.6
Fit bias	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.4	0.2	0.4	0.0	0.0
Corrections to simulation	0.0	0.0	0.5	0.0	0.1	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0
Form-factor parametrization	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.1
Experimental (syst)	0.9	0.3	2.2	0.5	0.9	0.7	0.9	0.5	0.2	2.3	0.7	2.1	0.5	2.0	0.6	0.7
Statistical (stat)	0.6	0.5	3.4	1.7	2.5	1.6	0.8	0.7	0.5	3.4	0.7	2.2	0.9	2.6	0.5	0.5