Exclusive semileptonic decays and $|V_{ub}|$

Status and challenges at Belle II

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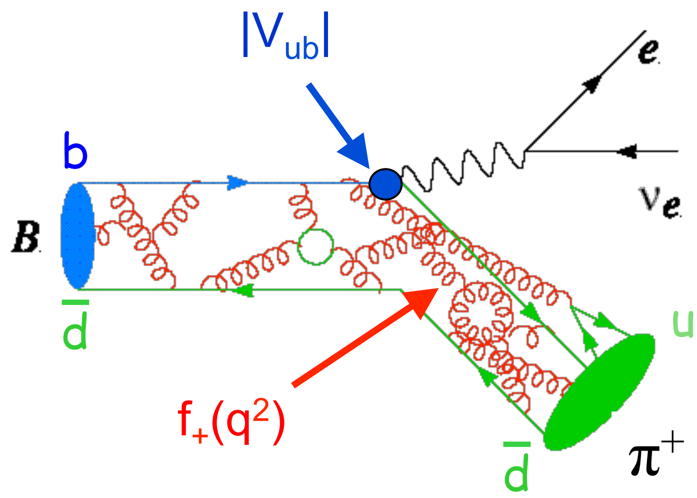
$B \to \pi \ell \nu$: The pseudoscalar case



$$\frac{d\Gamma(B \to \pi \ell \nu)}{dq^2} = \frac{G_F^2}{24\pi^2} |V_{ub}|^2 p_\pi^3 |f_+(q^2)|^2$$

10 measurements:

- 4 untagged (CLEO, 2×BaBar, Belle)
- 2 semilep. tag (BaBar, Belle)
- 2 hadronic tag (BaBar, Belle)

B→π form factor calculations:

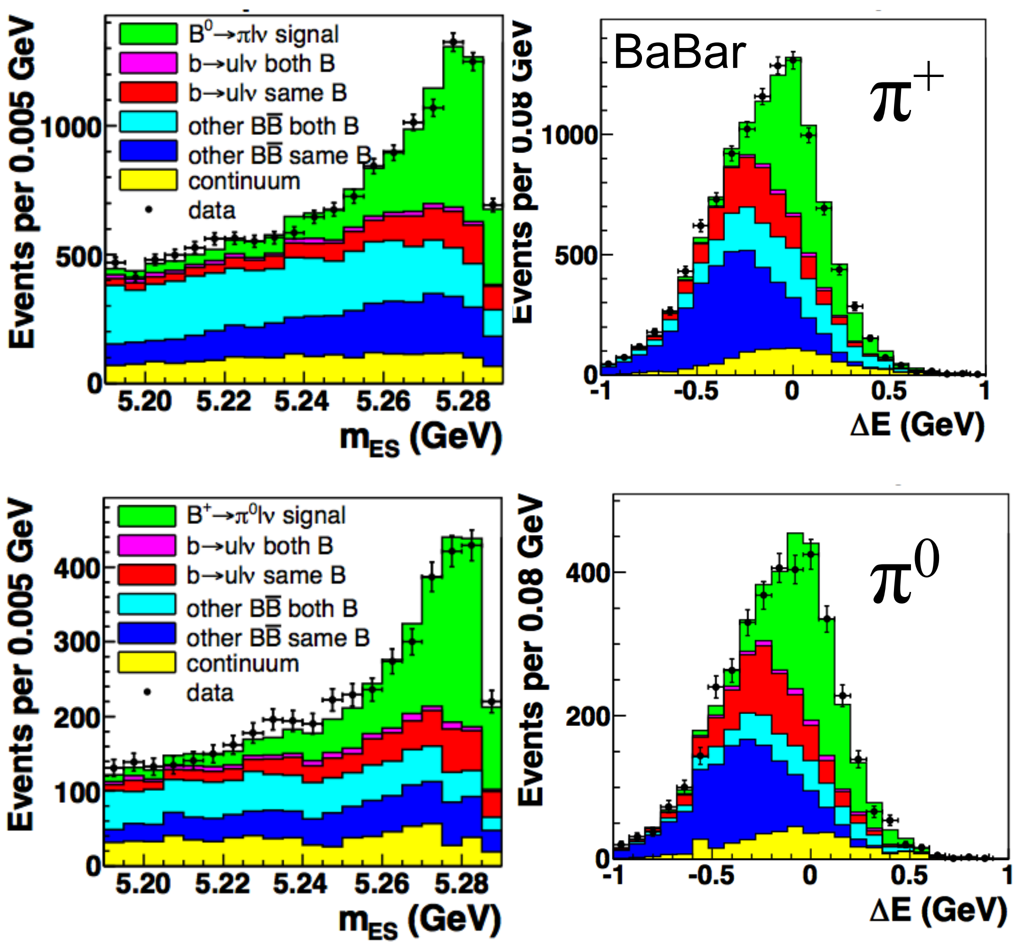
- LQCD: - FNAL/MILC
  - HPQCD
  - RBD/UKQCD
- LCSR: - Ball-Zwicky
  - Khodjamirian et al.
  - Bharucha
- Quark models, e.g. ISGW2

$B \to \pi \ell \nu$ measurements: Two examples

Signal extracted **in bins of q²** using the following discriminating variables:

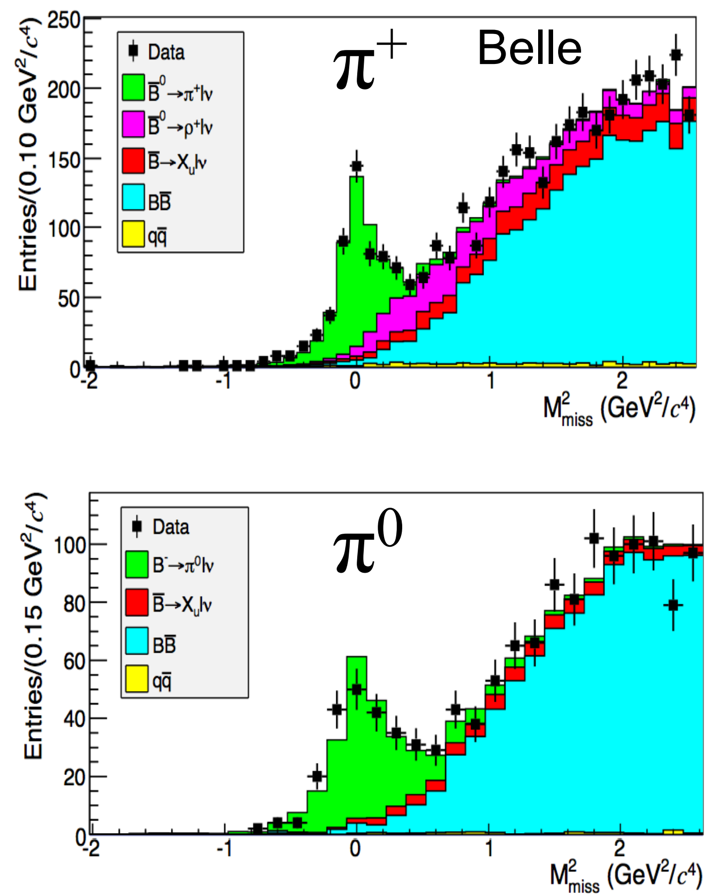
Untagged

$$m_{\rm ES} = \sqrt{E^{*2}_{\rm beam} - p^{*2}_B}\ ,\quad \Delta E = E^*_B - E^*_{\rm beam}$$

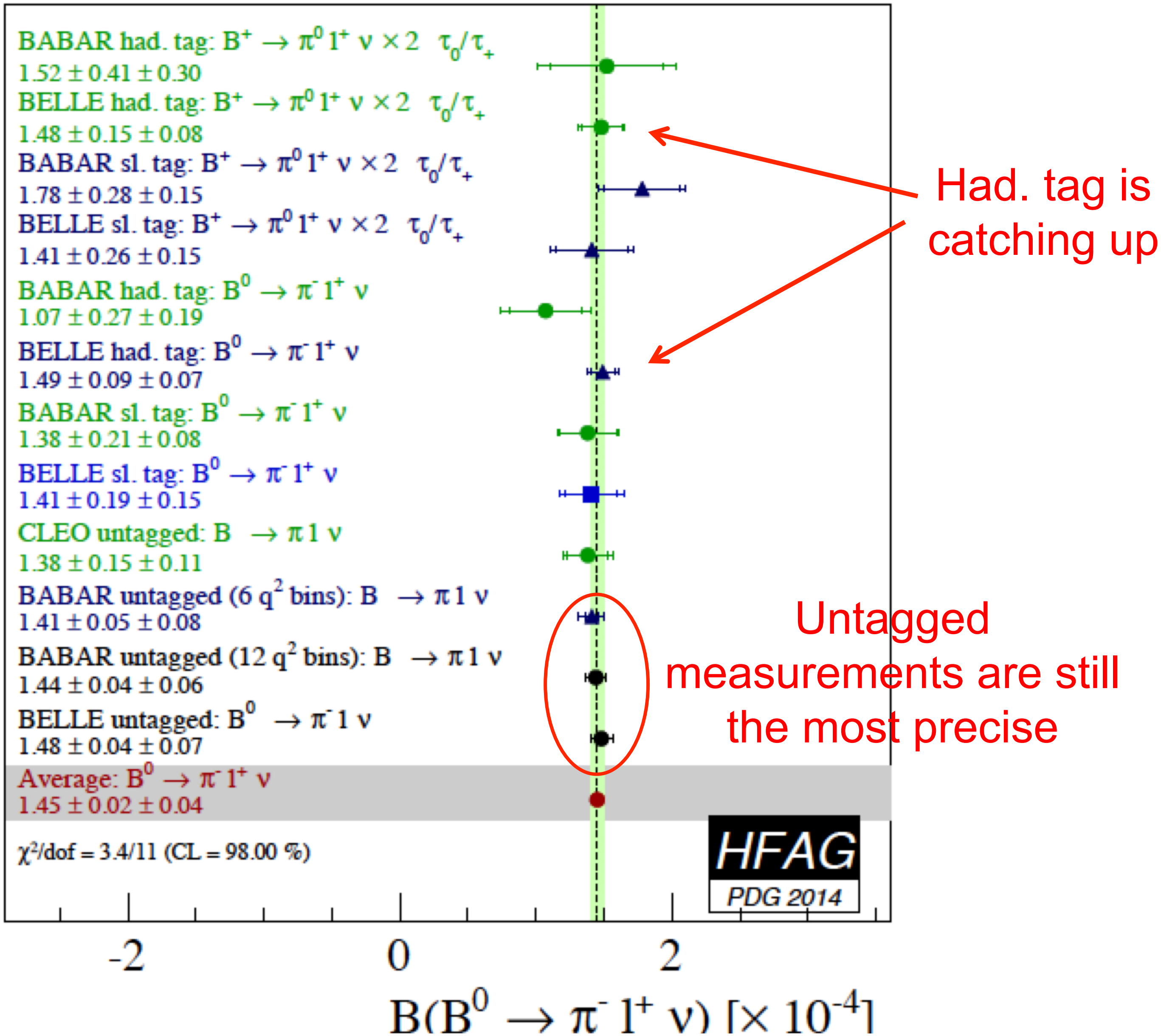


Hadronic tag

$$M^2_{\rm miss} = (P_B - P_\ell - P_X)^2$$

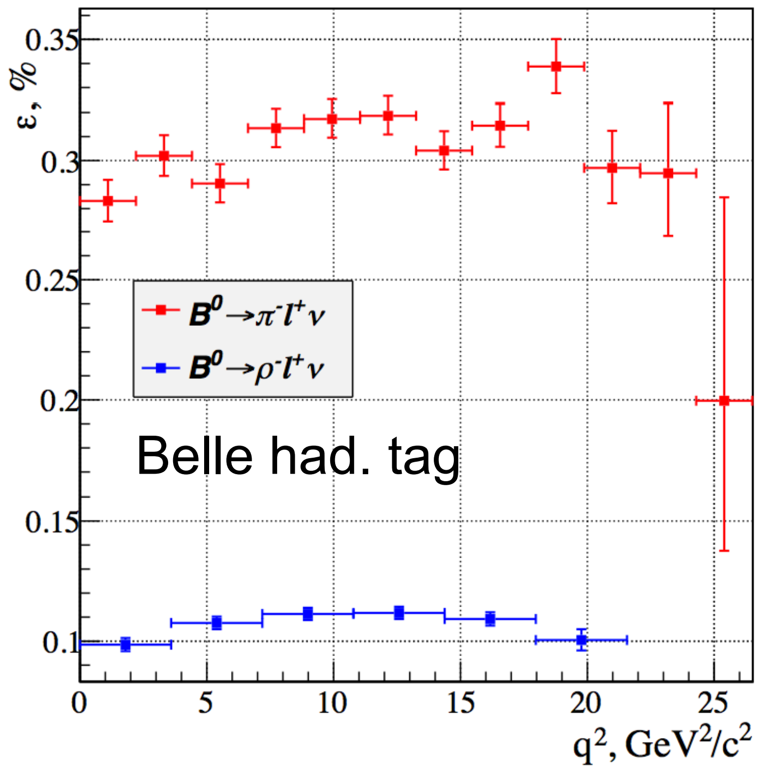


$B \to \pi \ell \nu$ branching fraction

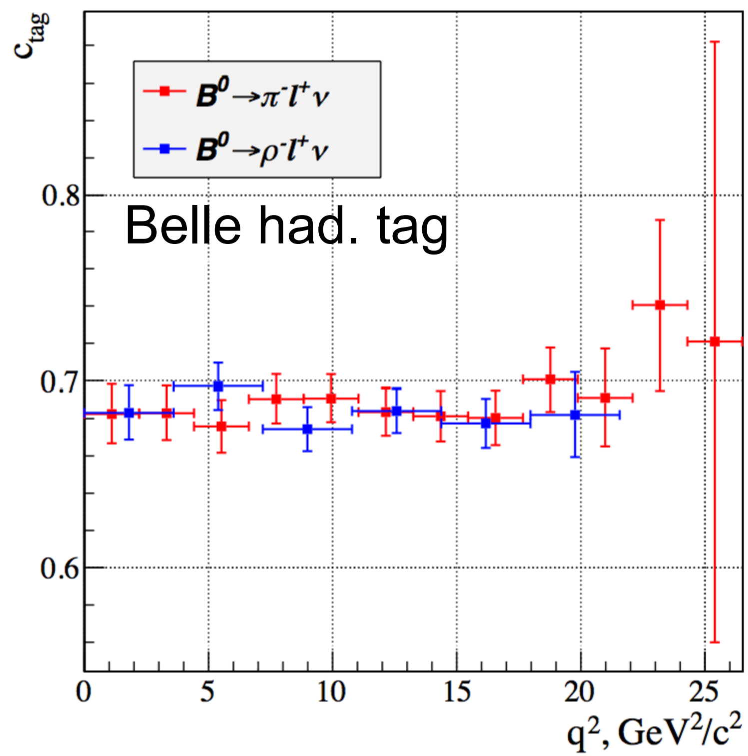


Efficiency and tag correction vs. q^2

Signal efficiency



Tagging correction



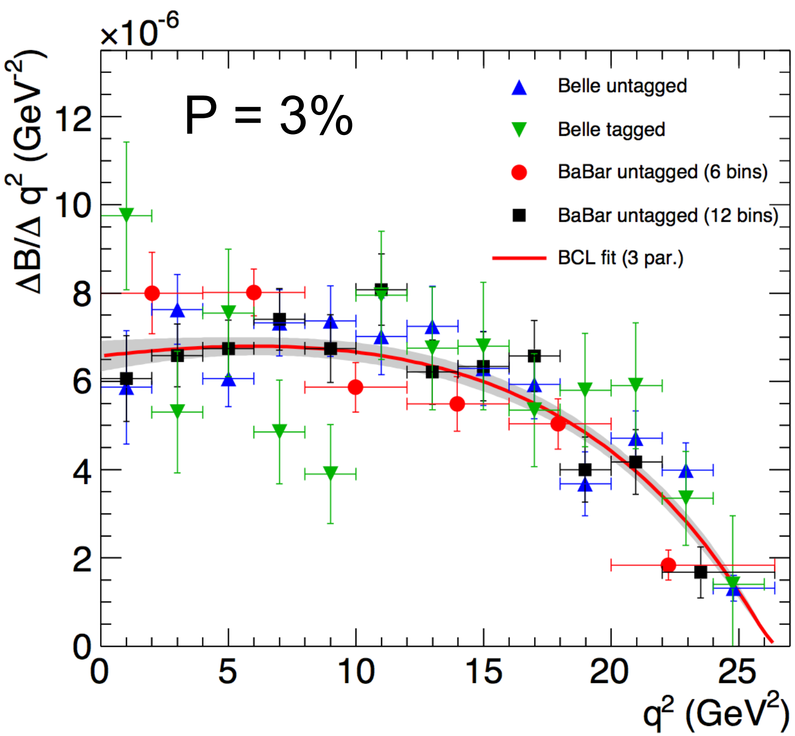
⇒ uniform efficiencies/corrections as a function of q^2

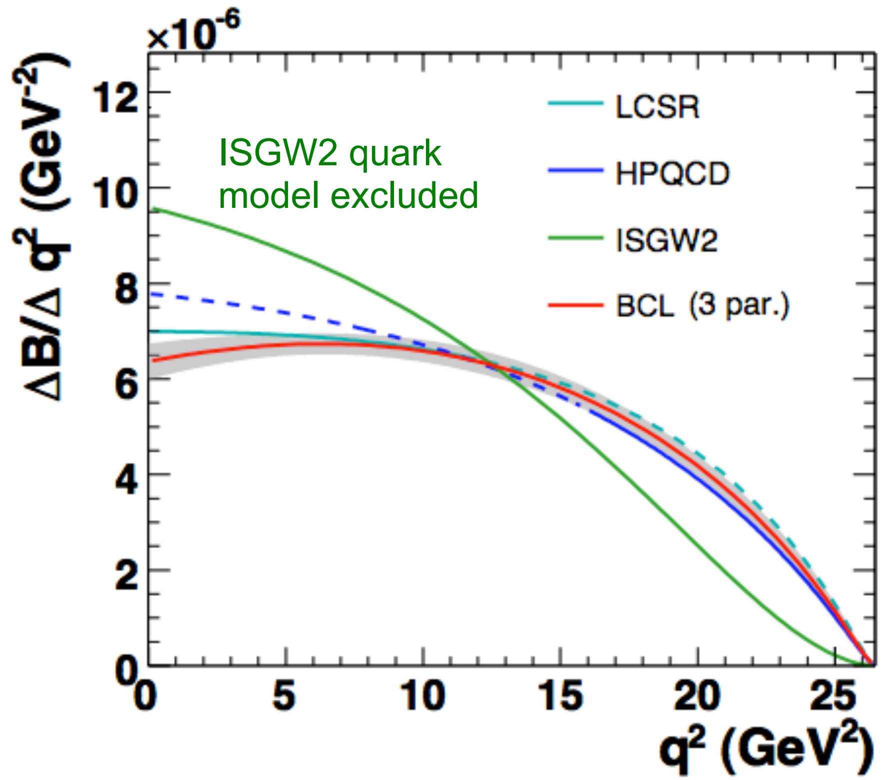
⇒ minimizes model dependence for q^2 spectrum measurement

q^2 spectrum and $|V_{ub}|$

Fit BCL parameterization of $f_+(q^2)$ to data:

$$f_+(q^2, \vec{b}) = \frac{1}{1 - q^2/m_{B^*}^2} \sum_{k=0}^{K} b_k(t_0)\, z(q^2)^k \qquad z(q^2, t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$



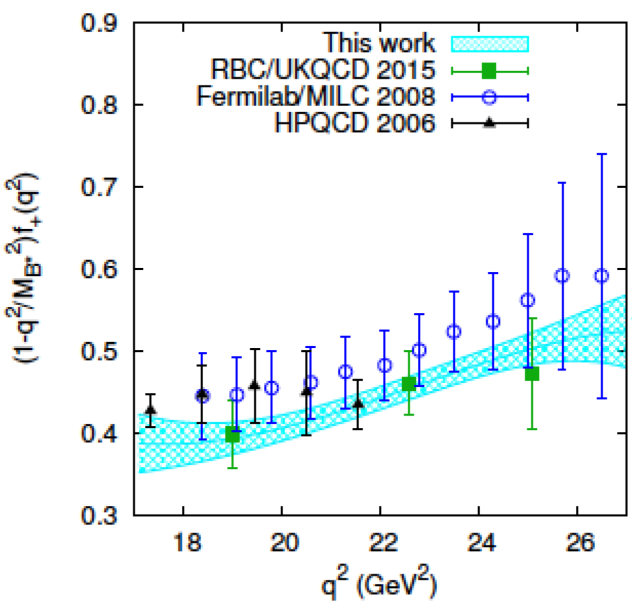


Data in agreement with form factor shapes from LQCD and LCSR

$|V_{ub}|$ from "classic method"

Compute $|V_{ub}|$ using $|V_{ub}| = \sqrt{\frac{C_v \Delta\mathcal{B}}{\tau_B \Delta\zeta}}$ with theory input $\Delta\zeta = \int d\Gamma/|V_{ub}|^2$

	LCSR	HPQCD	FNAL/MILC (2008)	FNAL/MILC (2015)
q^2 range (GeV^2)	$0-12$	$16-26.4$	$16-26.4$	$16-26.4$
$\Delta\zeta_{\rm th}$ (ps^{-1})	$4.59^{+1.00}_{-0.85}$	2.02 ± 0.55	$2.21^{+0.47}_{-0.42}$	1.72 ± 0.14
$\|V_{ub}\|$ (10^{-3})	$3.41\pm0.06^{+0.37}_{-0.32}$	$3.52\pm0.08^{+0.61}_{-0.40}$	$3.36\pm0.08^{+0.37}_{-0.31}$	$3.81\pm0.09^{+0.17}_{-0.15}$
Uncertainty:	11%	17%	11%	**5%**



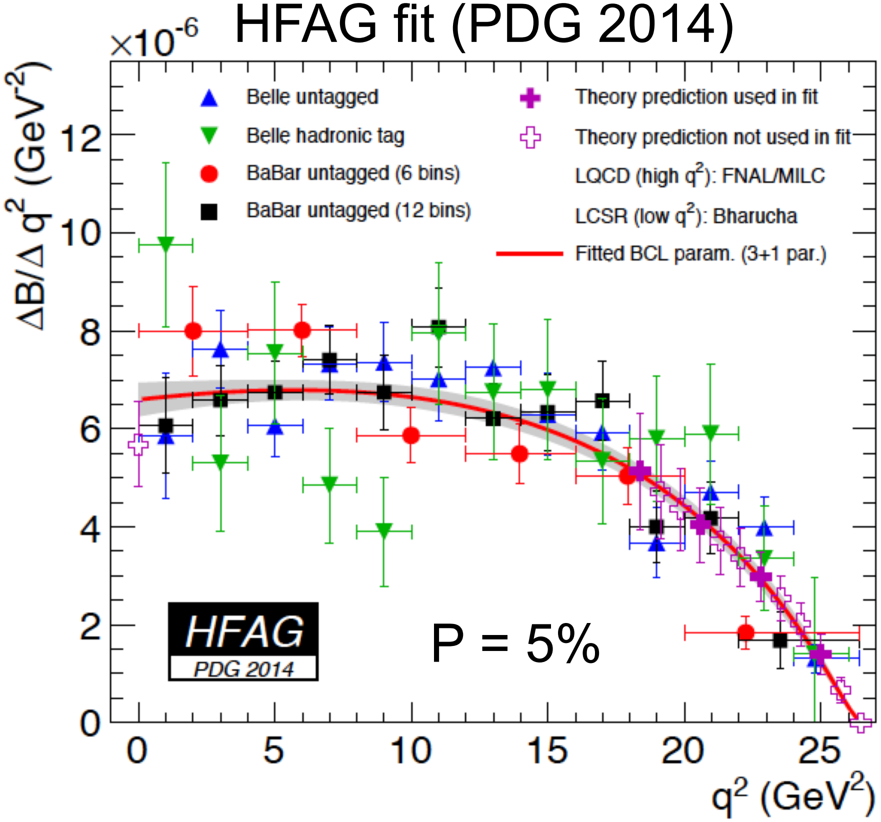
New FNAL/MILC value
~ 1.1σ higher
than 2008 result

Look at this $|V_{ub}|$ precision!

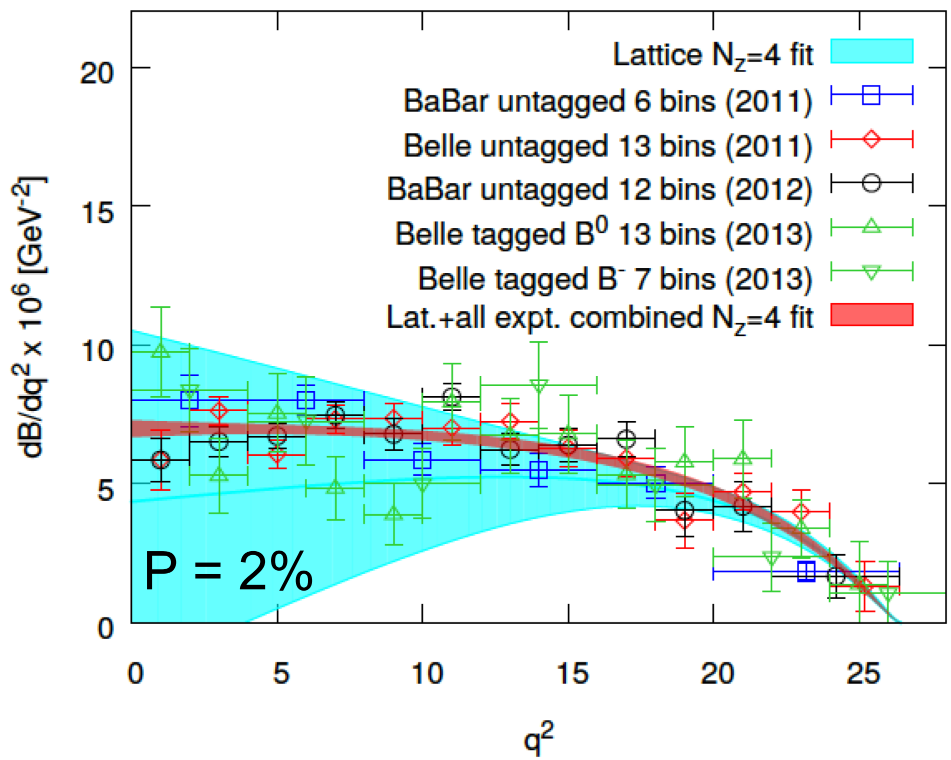
$|V_{ub}|$ from combined fit to data and LQCD

- Fit of BCL parameterization to (most recent) experimental $B \to \pi \ell \nu$ data and FNAL/MILC results
- Makes use of form factor shape measurement over **full q^2 range**

HFAG fit (PDG 2014)



FNAL/MILC fit



$|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$

Uncertainty: 9%

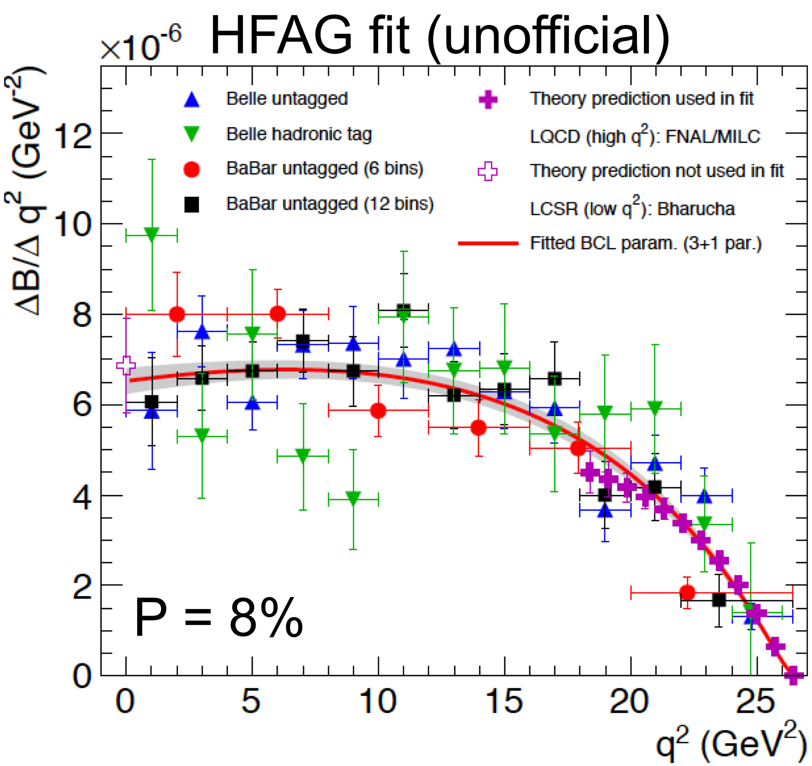
~1.5σ higher →

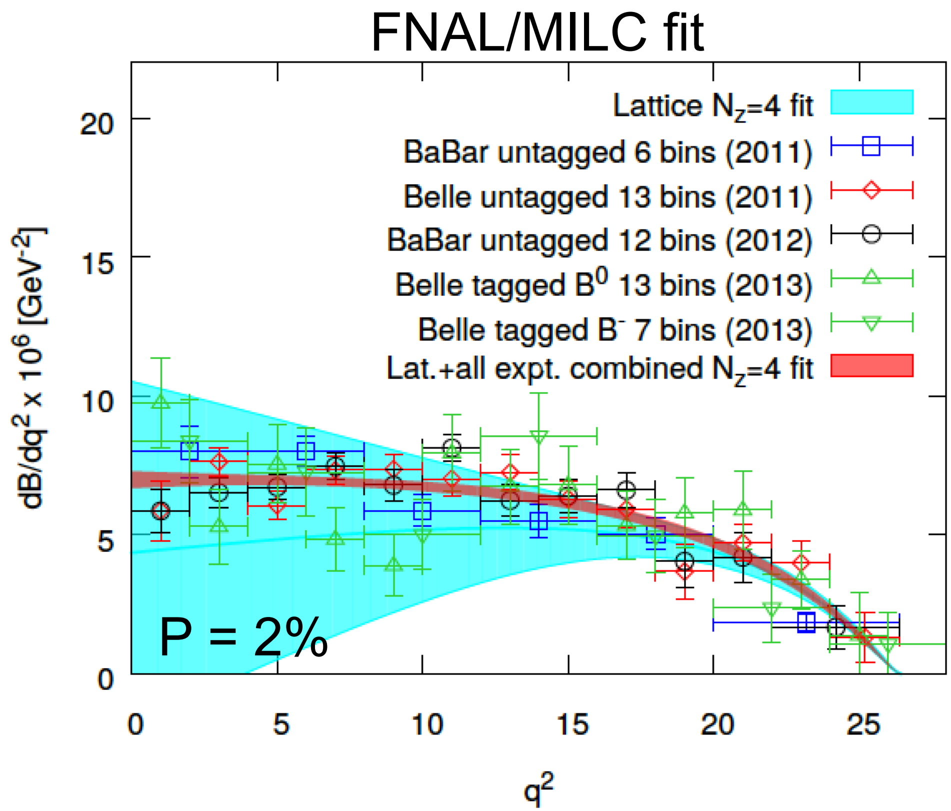
$|V_{ub}| = (3.72 \pm 0.16) \times 10^{-3}$

Uncertainty: 4%

$|V_{ub}|$ from combined fit to data and LQCD

- Tried to include new FNAL/MILC results in HFAG fit, using **12 discrete lattice points** (thanks to Daping Du for providing them!)





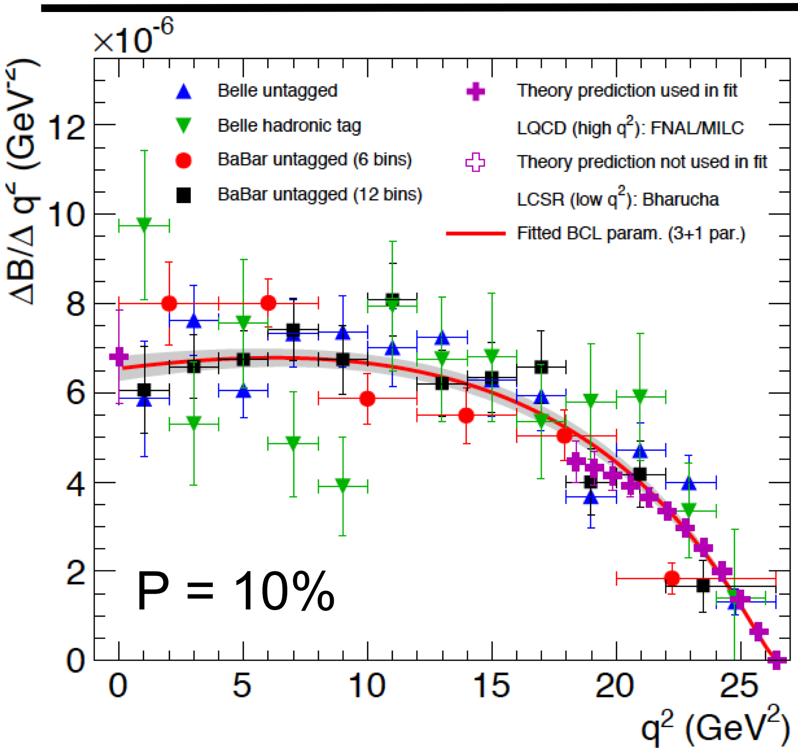
3 par: $|V_{ub}| = (3.61 \pm 0.13\,) \times 10^{-3}$

3 par: $|V_{ub}| = (3.63 \pm 0.11\,) \times 10^{-3}$

4 par: $|V_{ub}| = (3.72 \pm 0.16\,) \times 10^{-3}$

- First attempt gives ~ consistent results. Update HFAG fit to use 4 parameters.

Combined fit with LCSR point at $q^2=0$



FNAL only: $|V_{ub}| = (3.61 \pm 0.13) \times 10^{-3}$

FNAL+LCSR: $|V_{ub}| = (3.59 \pm 0.12) \times 10^{-3}$

LCSR only: $|V_{ub}| = (3.53 \pm 0.29) \times 10^{-3}$

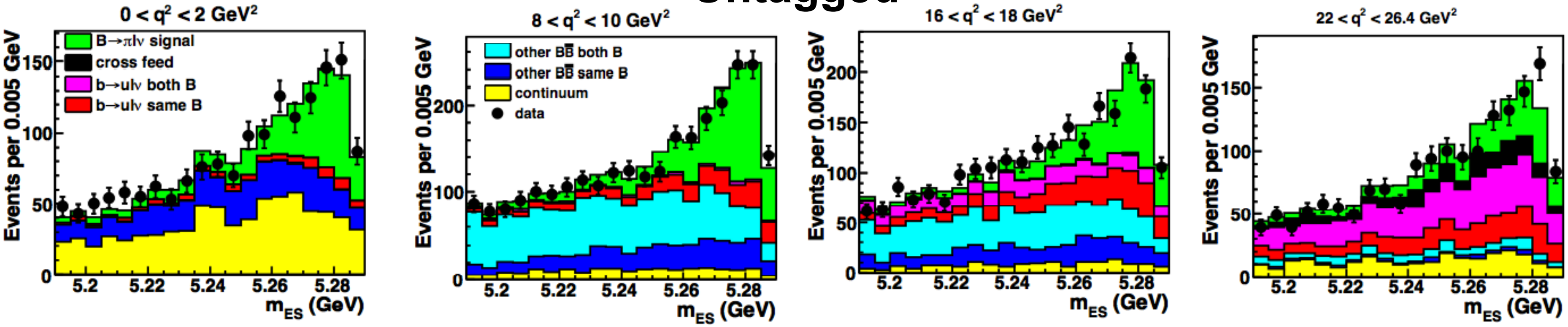
Inclusion of **LCSR point at q^2=0** further slightly improves the precision.

Some questions:

- Should we include LCSR in the fit?
- Should we include both FNAL/MILC and RBC/UKQCD in the fit?
- Can we expect LQCD results at lower q^2 in the near future?
- Should we include LCSR results at $q^2>0$ in the fit (correlation matrix?)?
- Shouldn't we treat stat. and syst. part of LQCD errors separately (Gaussian distributed vs. flat)? ⇒ breakdown of theory uncertainties

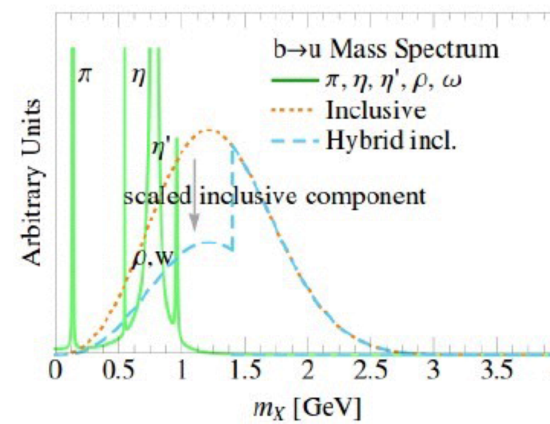
Systematic uncertainties / challenges for Belle II

Untagged



Decay mode		$\pi^- \ell^+ \nu$		
q^2 range (GeV^2)	q^2<12	q^2<16	q^2>16	$0 < q^2 < 26.4$
Unfolded yield	5604.1	6982.4	2314.2	9296.5
$\Delta\mathcal{B}(q^2)$ (10^{-4})	0.83	1.07	0.40	1.47
Statistical error	4.3	3.8	6.7	3.5
Detector effects	3.4	3.5	3.2	2.8
Continuum bkg	0.4	0.4	1.4	0.4
$b \to u\ell\nu$ bkg	1.6	1.4	2.1	1.3
$b \to c\ell\nu$ bkg	0.6	0.5	0.6	0.5
Total uncertainty	6.2	5.8	8.1	5.1

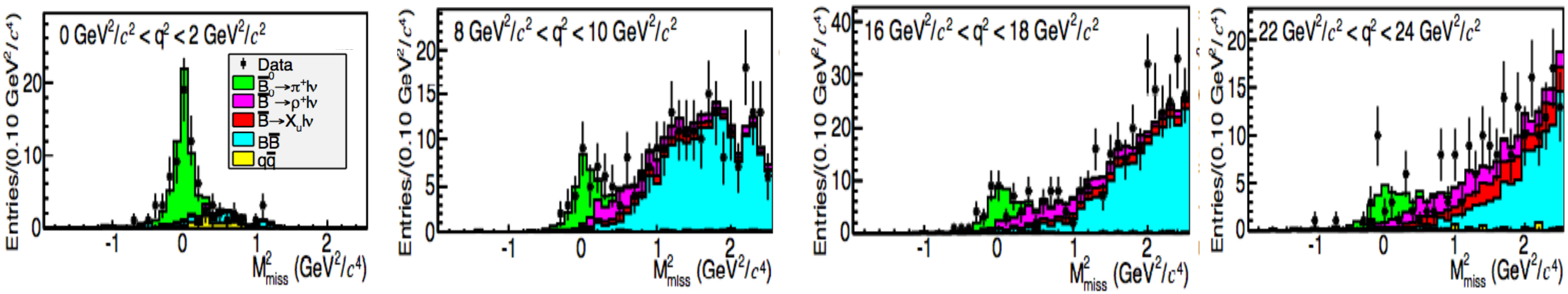
- Detector effects impact neutrino reconstruction from whole event (needed to reduce background!)
- Continuum background relevant at low and high q^2 ⇒ offres. data and continuum MC tuning



- $X_u \ell\nu$ bkg has a sizeable uncertainty (BFs, FFs, incl.-excl. mix), important at high q^2

Systematic uncertainties / challenges for Belle II

Hadronic tag



X_u	π^+	π^0
Detector Simulation:		
Track reconstruction	0.35	-
π^0 reconstruction	-	2.0
Lepton identification	1.0	1.0
Kaon veto	0.9	-
Continuum description	1.0	0.5
X_u cross-feed	0.9	-
Tag calibration	4.5	4.2
Combined	4.9	4.8
Form Factor Shapes:	1.1	1.9
Total systematic error	5.0	5.1

→ see next slide

→ mostly from B → ρℓν cross-feed

Tagging bias and calibration

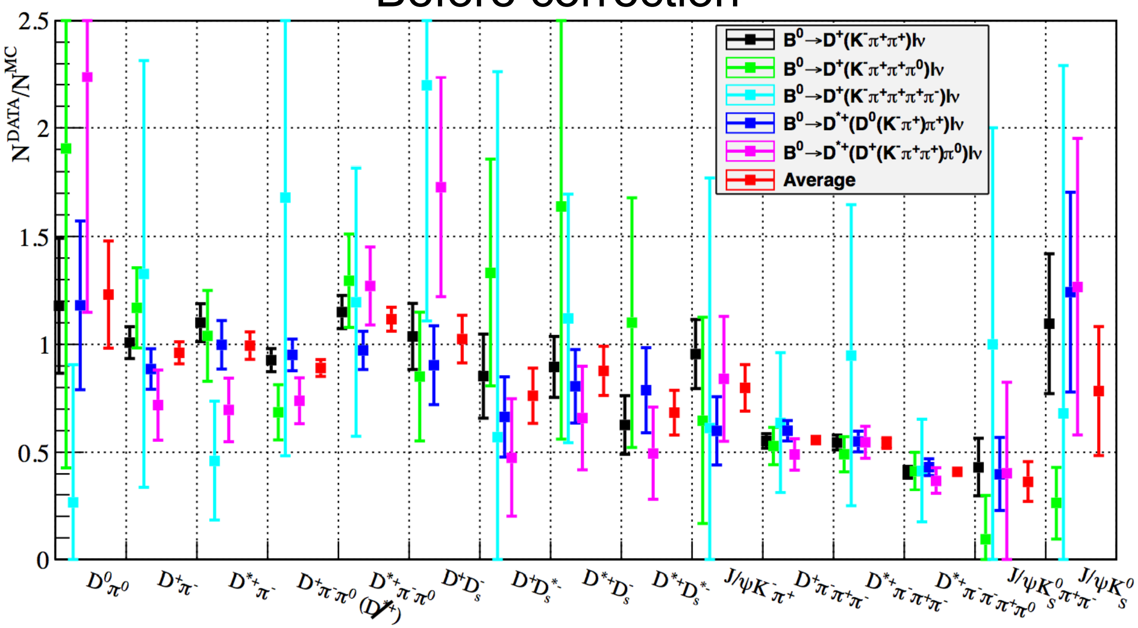
- BF's and dynamics of many hadronic decay modes not well known
  ⇒ Cannot rely on tagging efficiency from MC
- Use well-known $B \to X_c \ell\nu$ decays in data to derive tagging eff. correction

$$N(B \to \text{had},\, B \to X_c\ell\nu) = N_{B\overline{B}} \times \mathcal{B}(B \to \text{had}) \times \mathcal{B}(B \to X_c\ell\nu) \times \varepsilon^{\text{rec}}(B \to \text{had},\, B \to X_c\ell\nu)$$

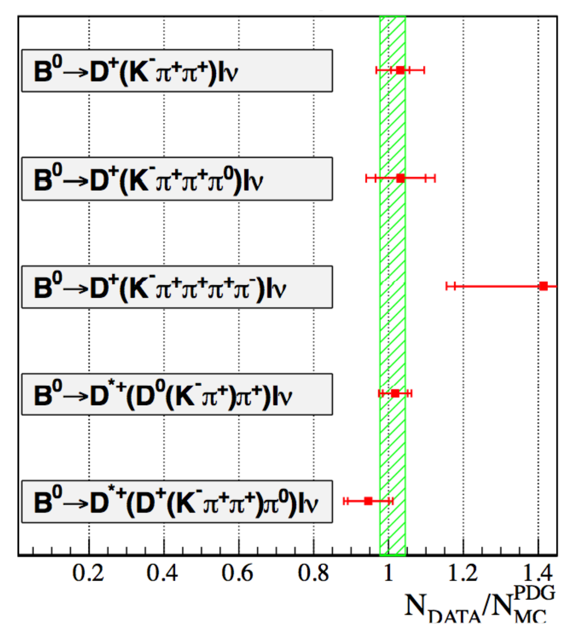
$$\varepsilon^{\text{rec}}(B \to \text{had}, B \to X_c\ell\nu) = \varepsilon^{\text{rec}}(B \to \text{had}) \times \varepsilon^{\text{rec}}(B \to X_c\ell\nu) \times C$$

- For each tag mode, determine average correction factor over all $B \to X_c \ell\nu$ modes and reweight MC

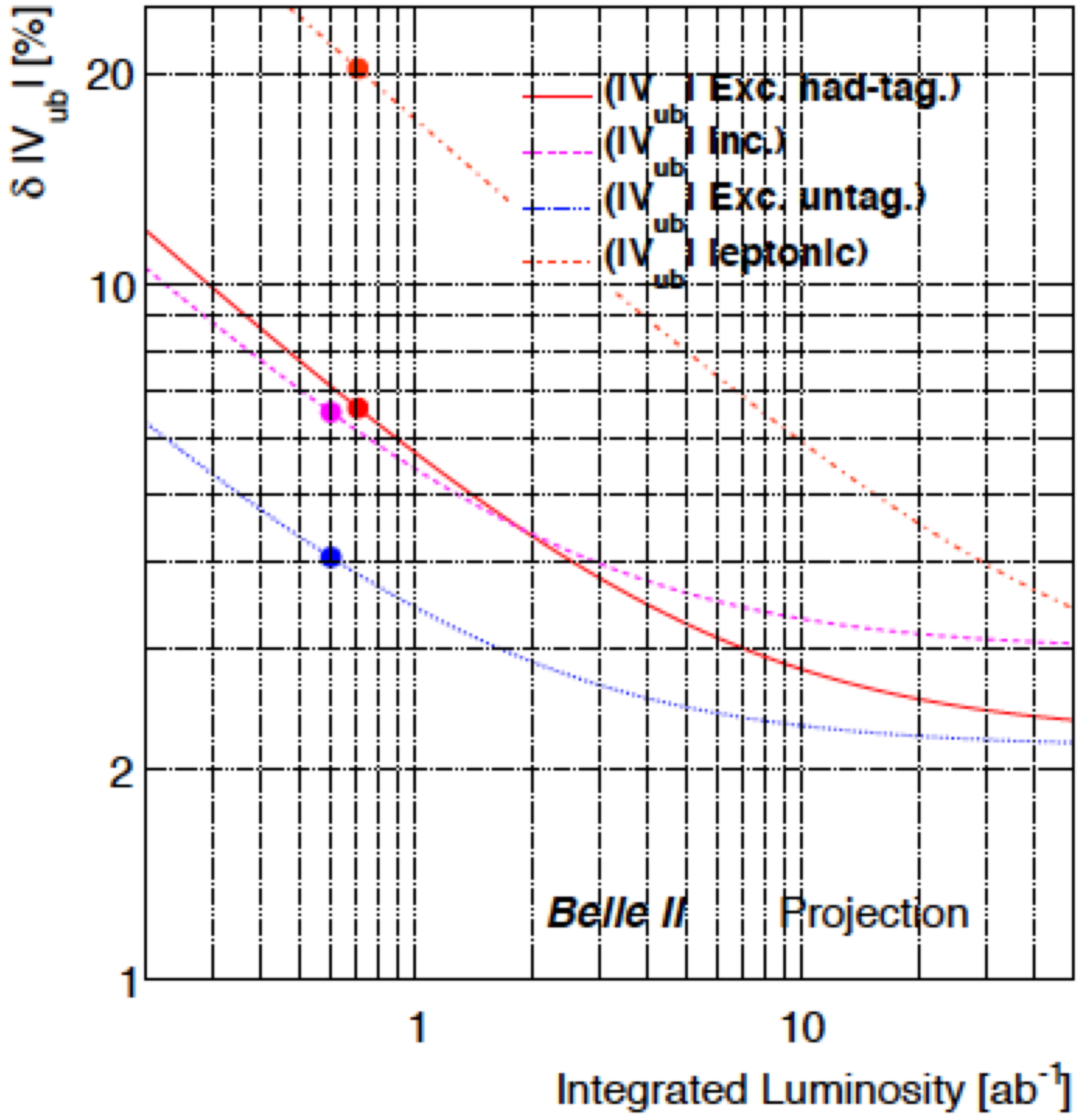
Before correction



After correction



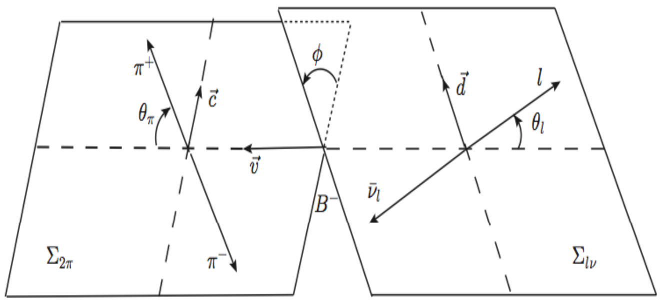
$|V_{ub}|$ extrapolation for Belle II



2% precision for both tagged and untagged

B → ρℓν: The vector meson case

$$\frac{d\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi\, dm_V} = \frac{3}{8(4\pi)^4} G_F^2 |V_{ub}|^2 \frac{|\vec{p}_V| q^2}{m_B^2} \mathcal{B}(V \to P_1 P_2) BW(m_V)$$
$$\times \Big[(1 - \eta\cos\theta_\ell)^2 \sin^2\theta_V |H_+(q^2, m_V)|^2$$
$$+ (1 + \eta\cos\theta_\ell)^2 \sin^2\theta_V |H_-(q^2, m_V)|^2$$
$$+ 4\sin^2\theta_\ell \cos^2\theta_V |H_0(q^2, m_V)|^2$$
$$- 4\eta \sin\theta_\ell (1 - \eta\cos\theta_\ell) \sin\theta_V \cos\theta_V \cos\chi H_+(q^2, m_V) H_0(q^2, m_V)$$
$$+ 4\eta \sin\theta_\ell (1 + \eta\cos\theta_\ell) \sin\theta_V \cos\theta_V \cos\chi H_-(q^2, m_V) H_0(q^2, m_V)$$
$$- 2\sin^2\theta_\ell \sin^2\theta_V \cos 2\chi H_+(q^2, m_V) H_-(q^2, m_V) \Big]$$



$$H_\pm(q^2) = (m_B + m_V) A_1^V(q^2) \mp \frac{2 m_B |\vec{p}_V|}{m_B + m_V} V^V(q^2),$$

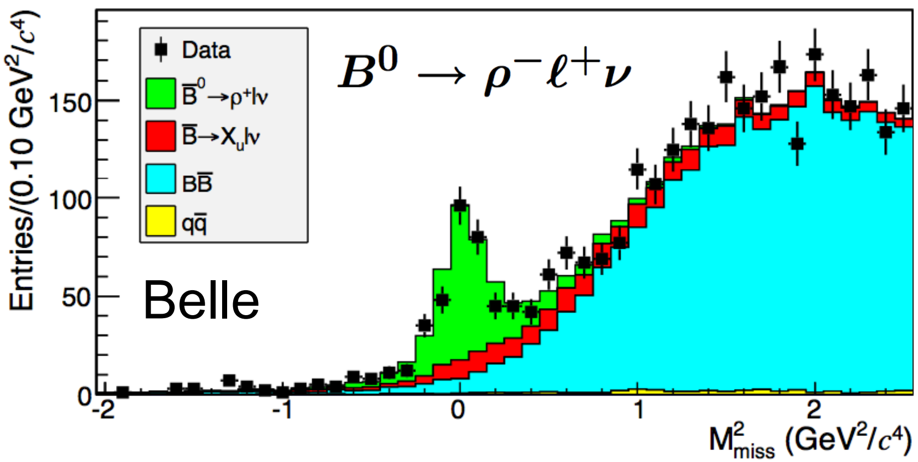
$$H_0(q^2) = \frac{1}{2 m_V \sqrt{q^2}} \left[(m_B^2 - m_V^2 - q^2)(m_B + m_V) A_1^V(q^2) - 4 \frac{m_B^2 |\vec{p}_V|^2}{m_B + m_V} A_2^V(q^2) \right].$$

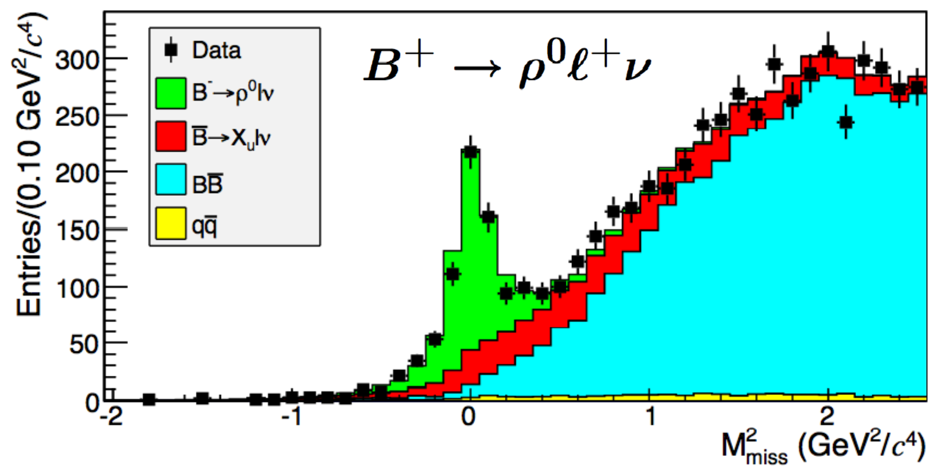
q^2-dependent form factors

- Ideally, measure fully differential decay rate by extracting B → ρℓν (V = ρ) signal in **bins of q^2, cosΘ$_\ell$, cosΘ$_V$, χ** ⇒ reduce model dependence
- However, not yet feasible with current data statistics
- Perform measurement in **bins of q^2 only**

$B \to \rho \ell \nu$

- Hadronic-tag measurement already the most precise
- Extraction of signal in fit to $\mathbf{M^2_{miss}}$ in **bins of $\mathbf{q^2}$**





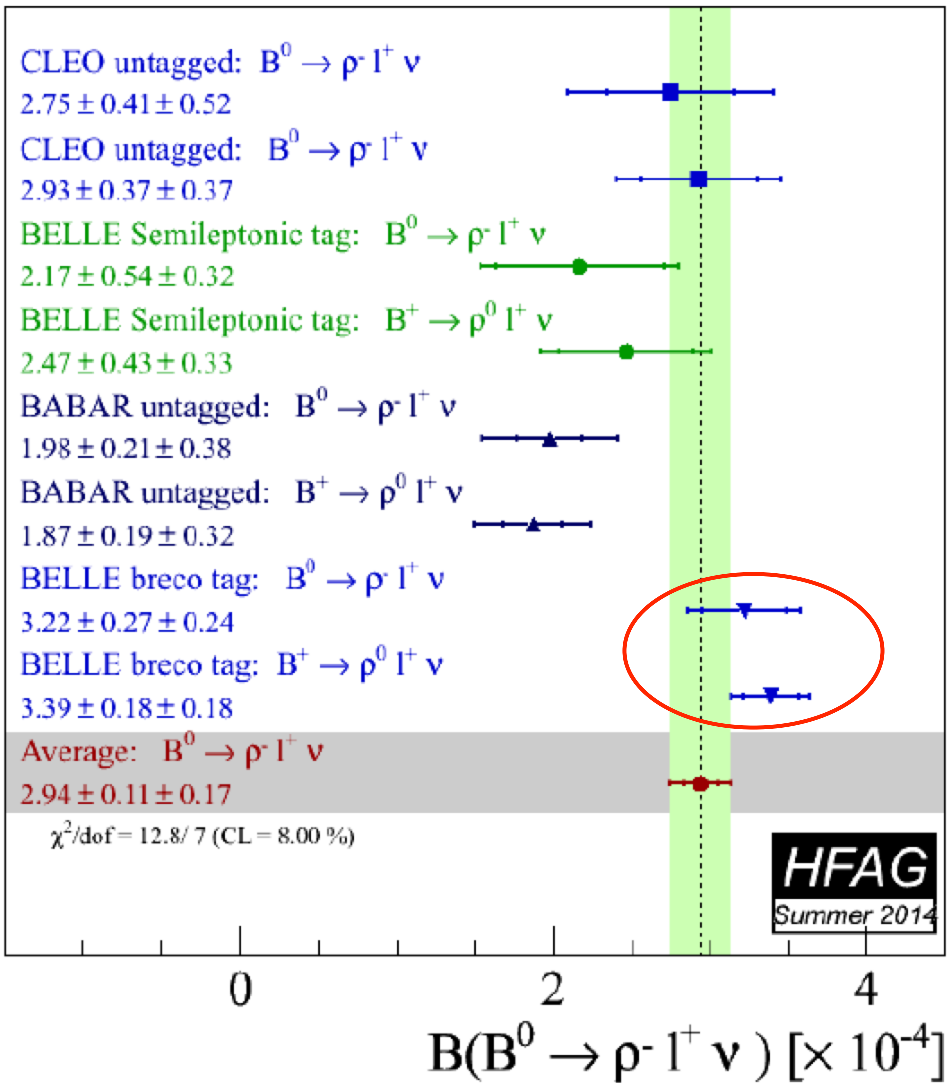
Component	Yield
$\bar{B}^0 \to \rho^+ \ell^- \bar{\nu}_\ell$	343.3 ± 28.3
$\bar{B} \to X_u \ell^- \bar{\nu}_\ell$	243.4 ± 91.6
$B\bar{B}$	4039.7 ± 105.1
$q\bar{q}$	59.2(fixed)
$\bar{B}^0 \to \pi^+ \ell^- \bar{\nu}_\ell$	10.5(fixed)
$\bar{B}^0 \to D^{(*)+}(\pi^+\pi^0)\ell^- \bar{\nu}_\ell$	1.3(fixed)
χ^2/ndf	84.4/65

free

fixed

Component	Yield
$B^- \to \rho^0 \ell^- \bar{\nu}_\ell$	621.7 ± 35.0
$\bar{B} \to X_u \ell^- \bar{\nu}_\ell$	757.3 ± 109.0
$B\bar{B}$	6901.6 ± 128.9
$B^- \to f_2 \ell^- \bar{\nu}_\ell$	13.3(fixed)
$B^- \to D^{(*)0}(K^-\pi^+)\ell^- \bar{\nu}_\ell$	25.1(fixed)
$B^- \to D^{(*)0}(\pi^+\pi^-)\ell^- \bar{\nu}_\ell$	1.2(fixed)
$B^- \to \omega(\pi\pi)\ell^- \bar{\nu}_\ell$	6.1(fixed)
$B^- \to f_0 \ell^- \bar{\nu}_\ell$	9.5(fixed)
$q\bar{q}$	169.9(fixed)
χ^2/ndf	59.5/52

$B \to \rho \ell \nu$ branching fraction



Hadronic-tag measurement already now the most precise!
⇒ promising for Belle II

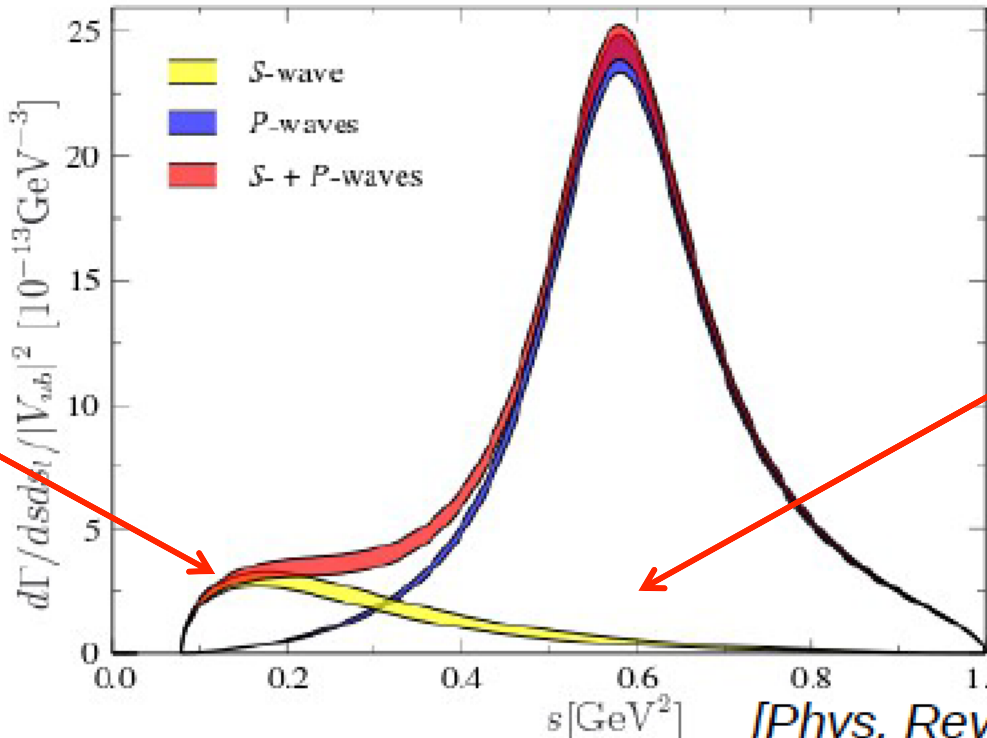
Systematic uncertainties

Source of uncertainty [%]		
X_u	ρ^+	ρ^0
Detector Simulation:		
Track reconstruction	0.35	0.7
π^0 reconstruction	2.0	-
Lepton identification	1.0	1.0
Kaon veto	1.0	2.0
Continuum description	0.5	0.7
X_u cross-feed	5.0	2.4
Tag calibration	4.5	4.2
Combined	7.2	5.4
Form Factor Shapes:	1.7	1.3
Total systematic error	7.4	5.6

Systematic uncertainty dominated by **tagging calibration** and **X_u cross-feed**

Understanding the ππ mass peak

What we call a ρ may not be a ρ !



S-wave

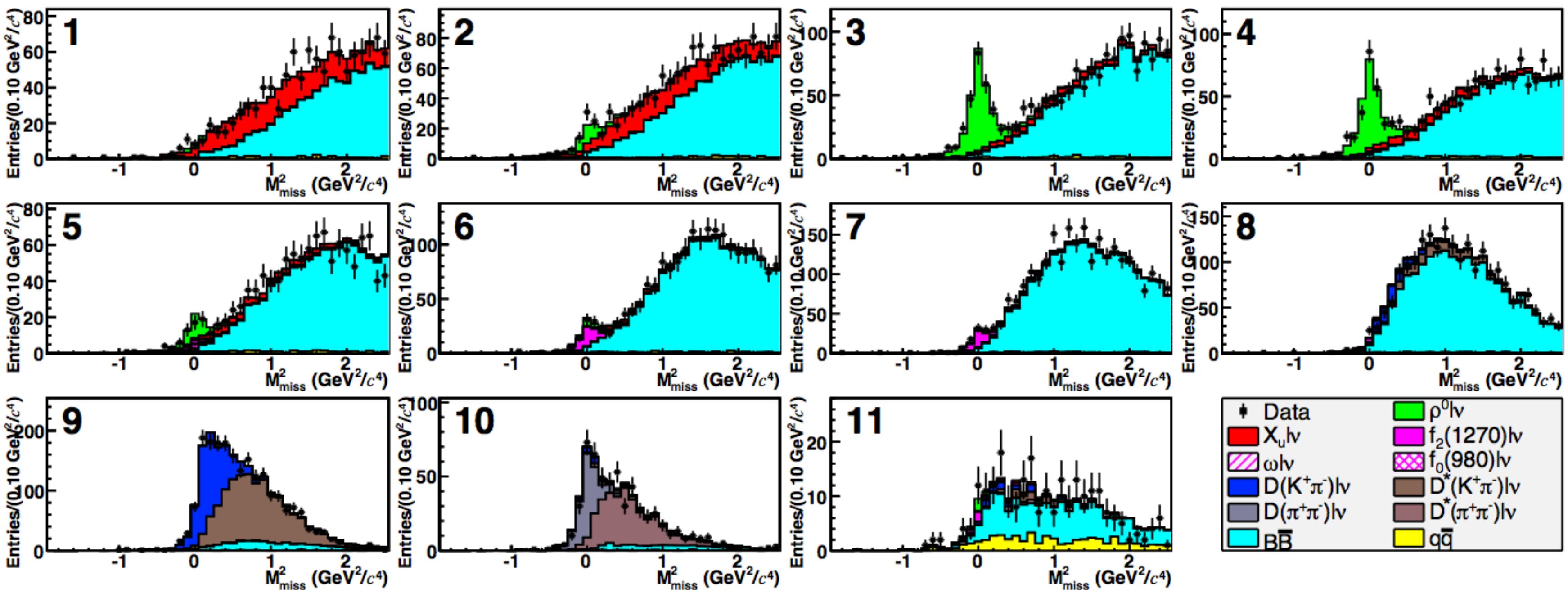
Non-resonant P-wave?

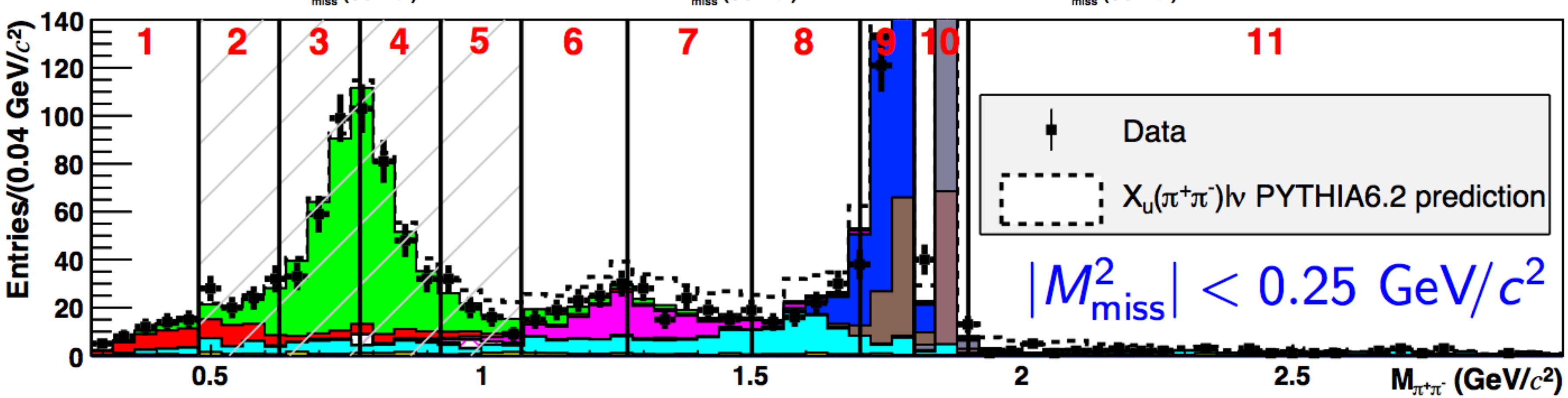
[Phys. Rev. D 89, 053015(2014)]

- Currently not possible to disentagle these contributions experimentally
- With higher statistics at Belle II, can separate S- and P-wave through angular analysis
- Non-resonant P-Wave contribution ⇒ need guidance from theory

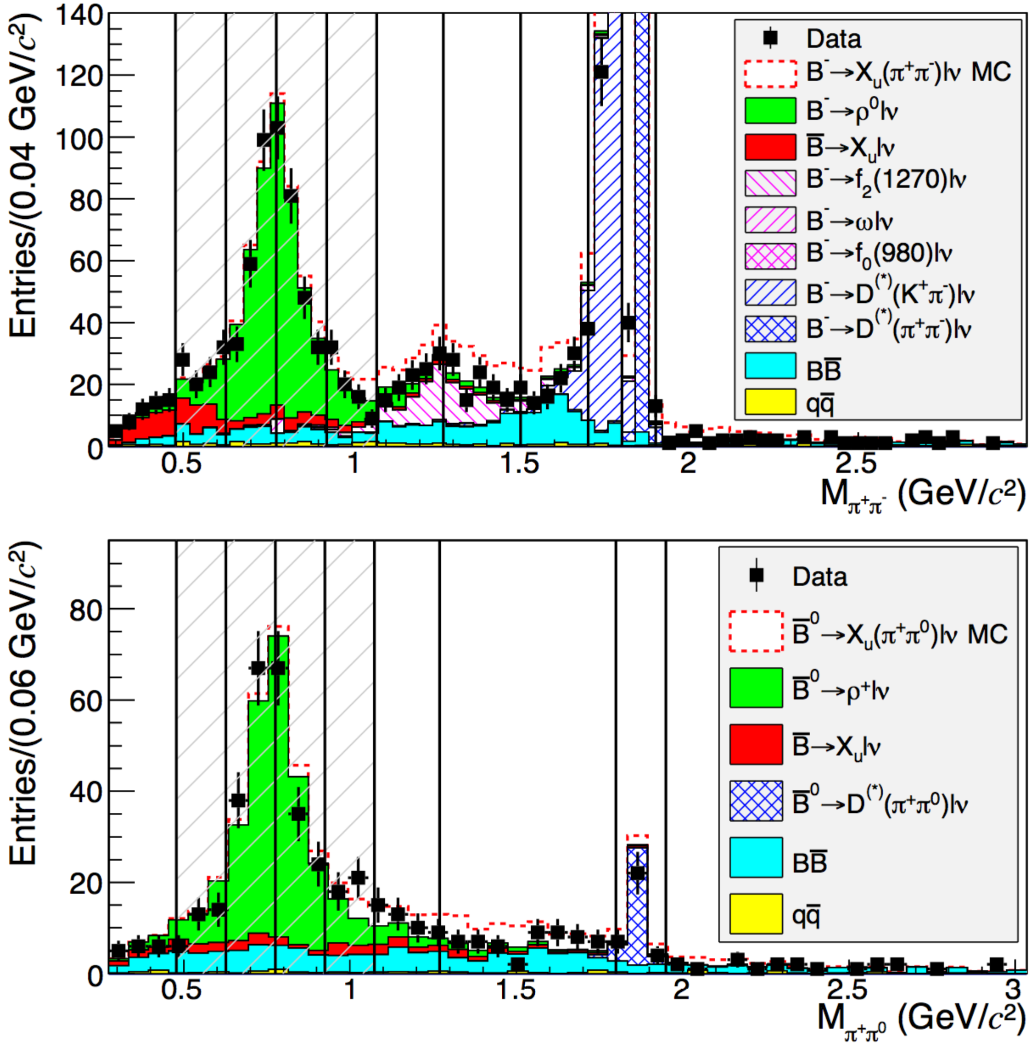
$B \to \pi\pi\ell\nu$: Fit in bins of $M_{\pi\pi}$

To constrain $B \to X_u\ell\nu$ cross-feed components, perform fit in bins of $M_{\pi\pi}$





$B \to \pi\pi\ell\nu$: Fit in bins of $M_{\pi\pi}$

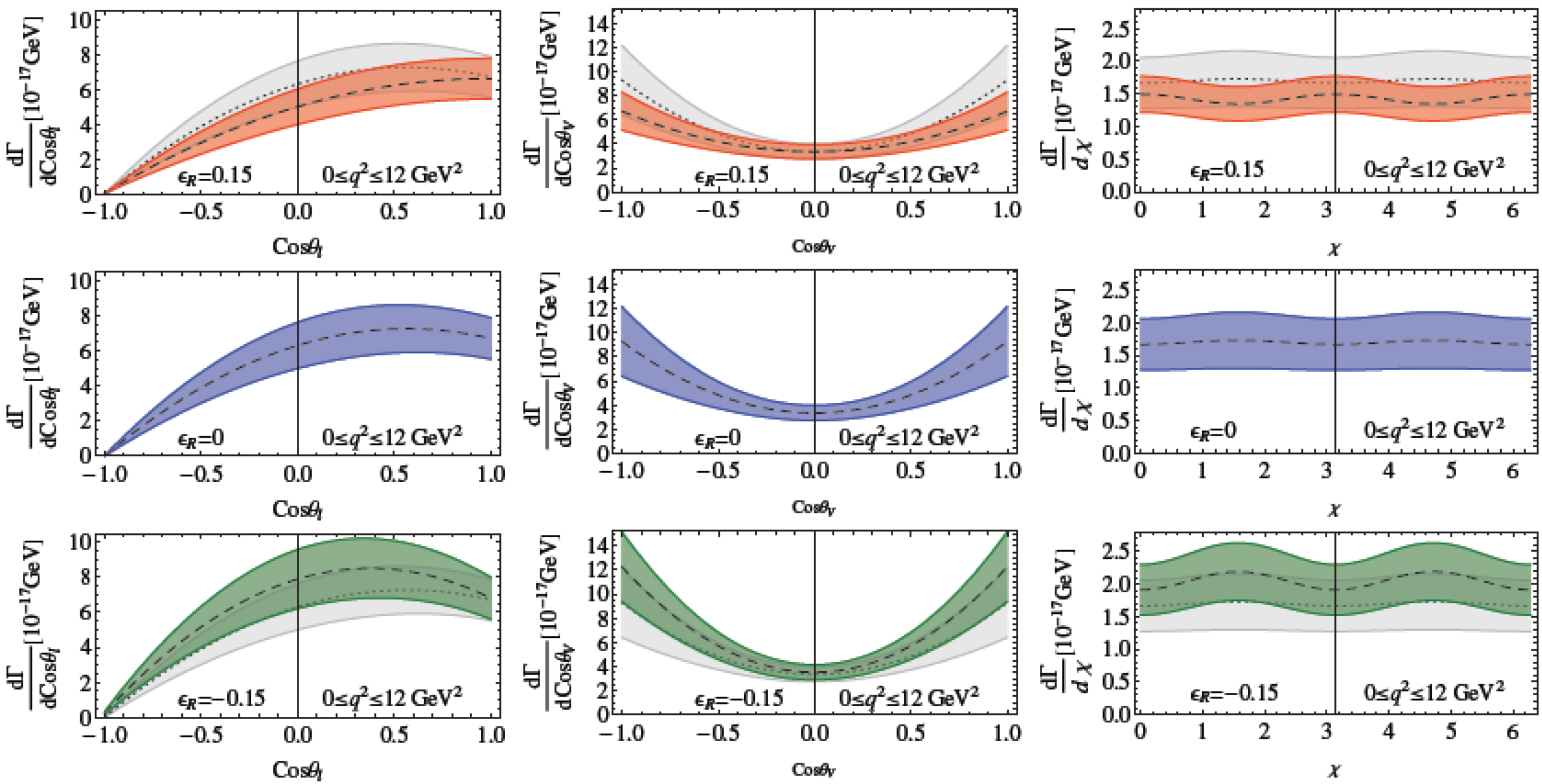


- Signal yield for $B \to \rho\ell\nu$ in good agreement with $M^2_{miss} - q^2$ fits.
- No significant evidence for non-resonant $B \to \pi\pi\ell\nu$ (as modeled by PYTHIA6.2) seen in data.
- $B \to f_2\ell\nu$ yield 2-3× higher than ISGW2 prediction

Angular analysis for $B \to \rho \ell \nu$

E.g. in the context of a search for right-handed currents

Bernlochner, Ligeti, Turczyk hep-ph/1408.2516



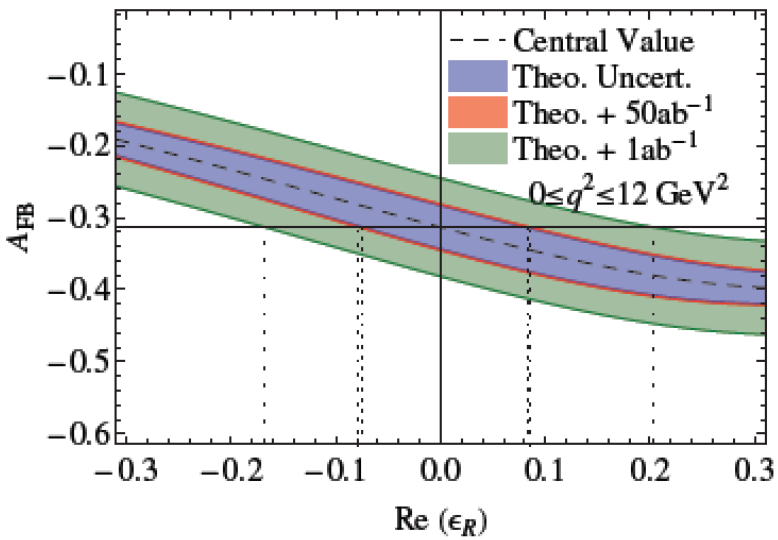
For full angular analysis, need ~10,000 $B \to \rho \ell \nu$ decays

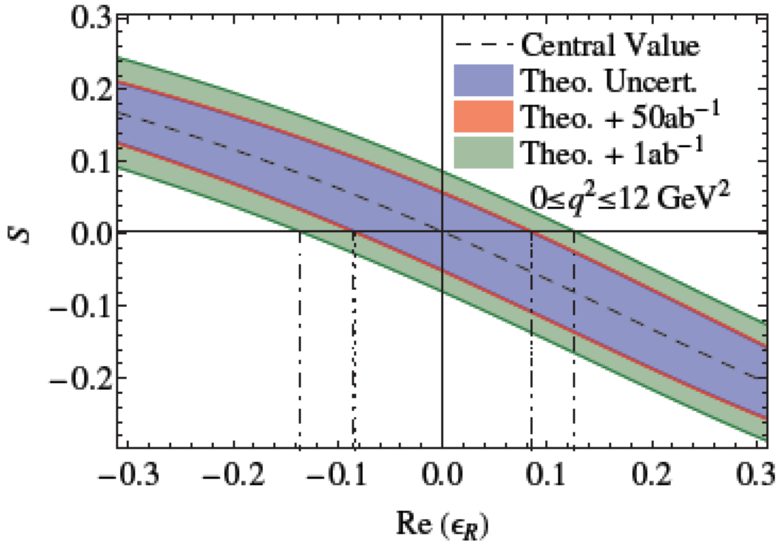
⇒ Belle II with > 10 ab^{-1}

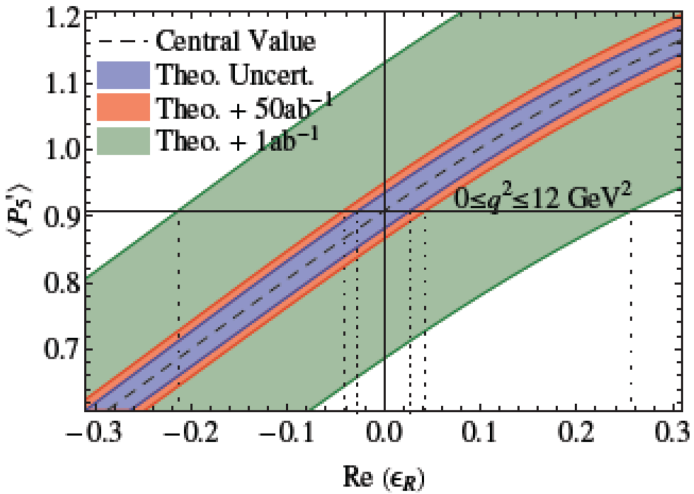
Angular analysis: Constraints on NP observables

Interesting at Belle II: Constrain NP-sensitive observables (in analogy to B→K*ℓℓ)

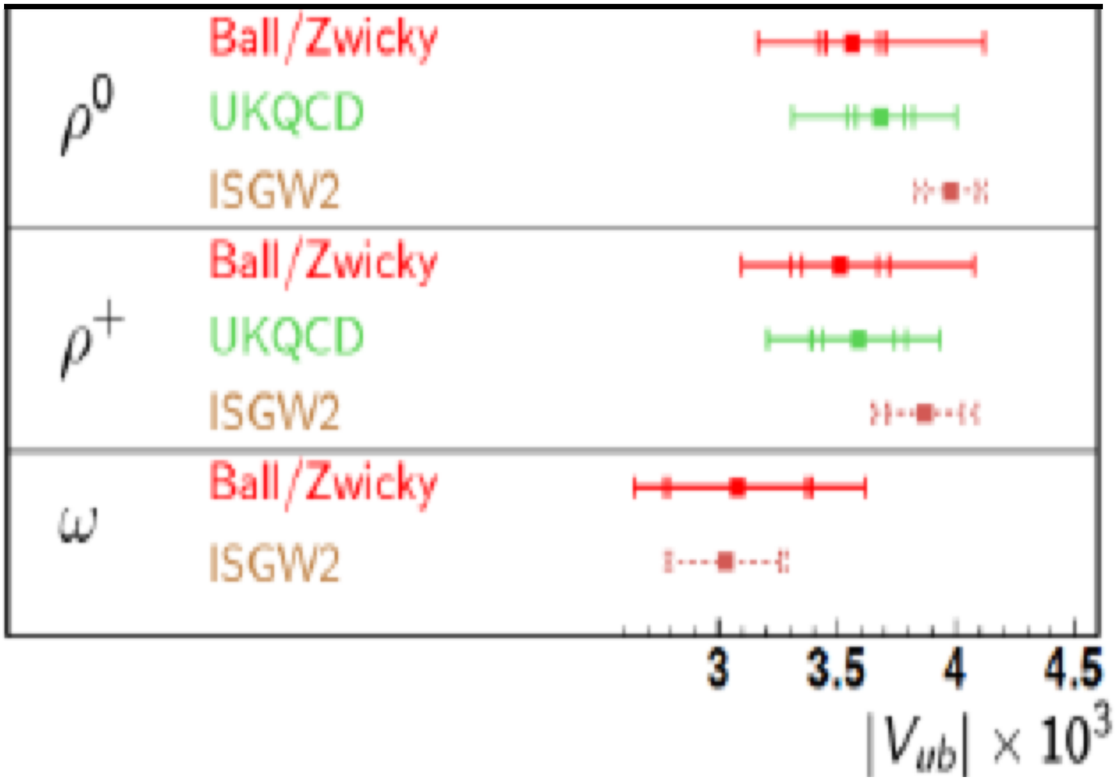
Bernlochner, Ligeti, Turczyk hep-ph/1408.2516







$|V_{ub}|$ from $B \to \rho\ell\nu$



Ball/Zwicky
PRD **71**, 014015 (2005)
PRD **71**, 014029 (2005)

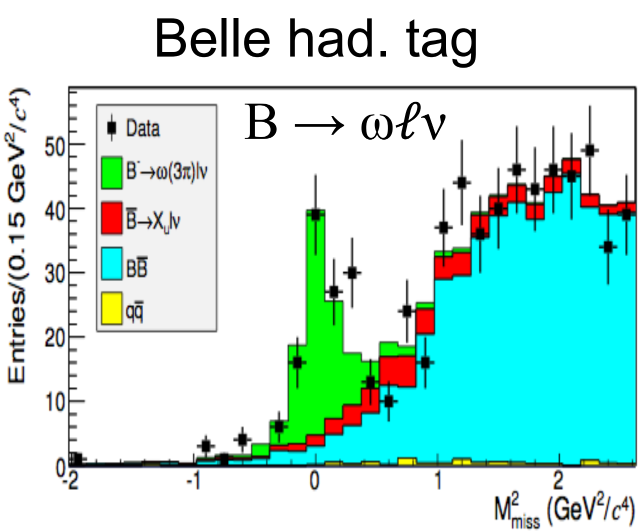
UKQCD
PLB **416**, 392 (1998)

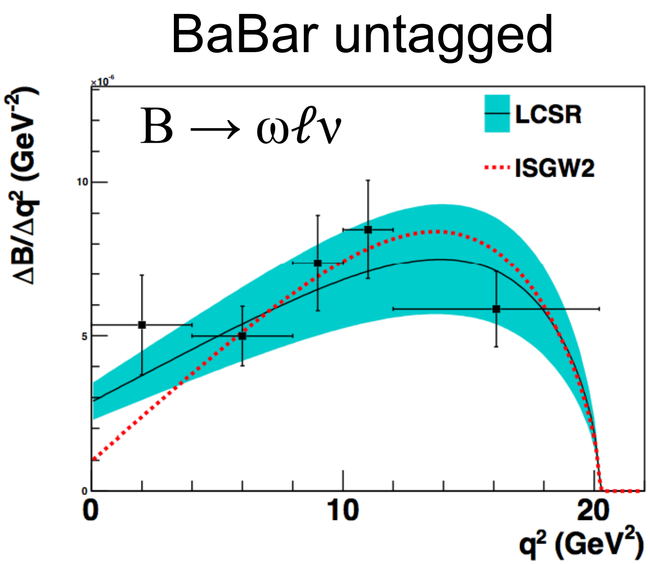
ISGW2
PRD **52**, 2783 (1995)
Theory error is not available.

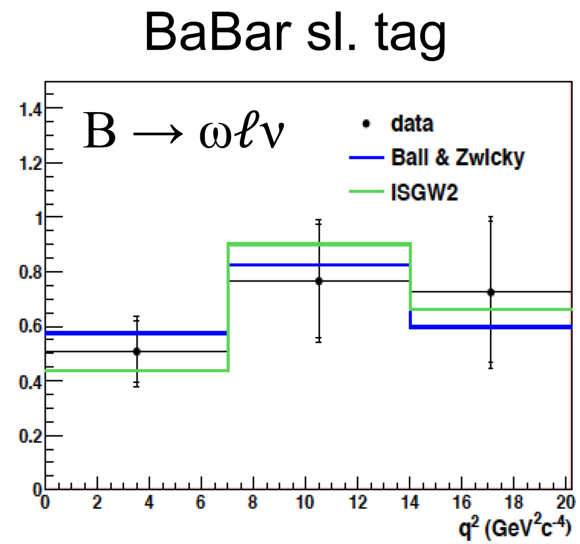
BaBar untagged measurement:

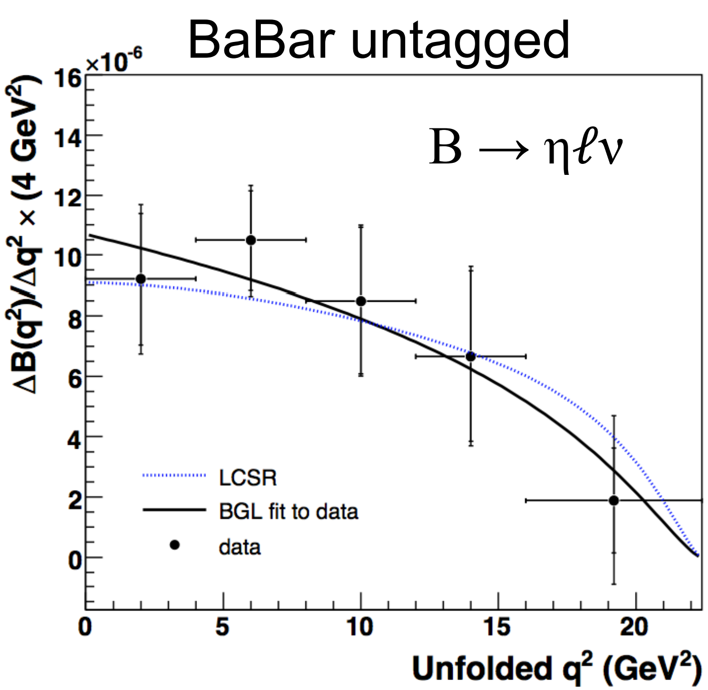
	q^2 Range (GeV^2)	$\Delta\mathcal{B}$ (10^{-4})	$\Delta\zeta$ (ps^{-1})	$\lvert V_{ub}\rvert$ (10^{-3})
$B \to \rho\ell\nu$				
LCSR [17]	$0-16.0$	1.48 ± 0.28	13.79	2.75 ± 0.24
ISGW2 [14]	$0-20.3$	1.75 ± 0.31	14.20	2.83 ± 0.24

Other charmless modes: $B \to \omega \ell \nu$, $B \to \eta/\eta' \ell \nu$







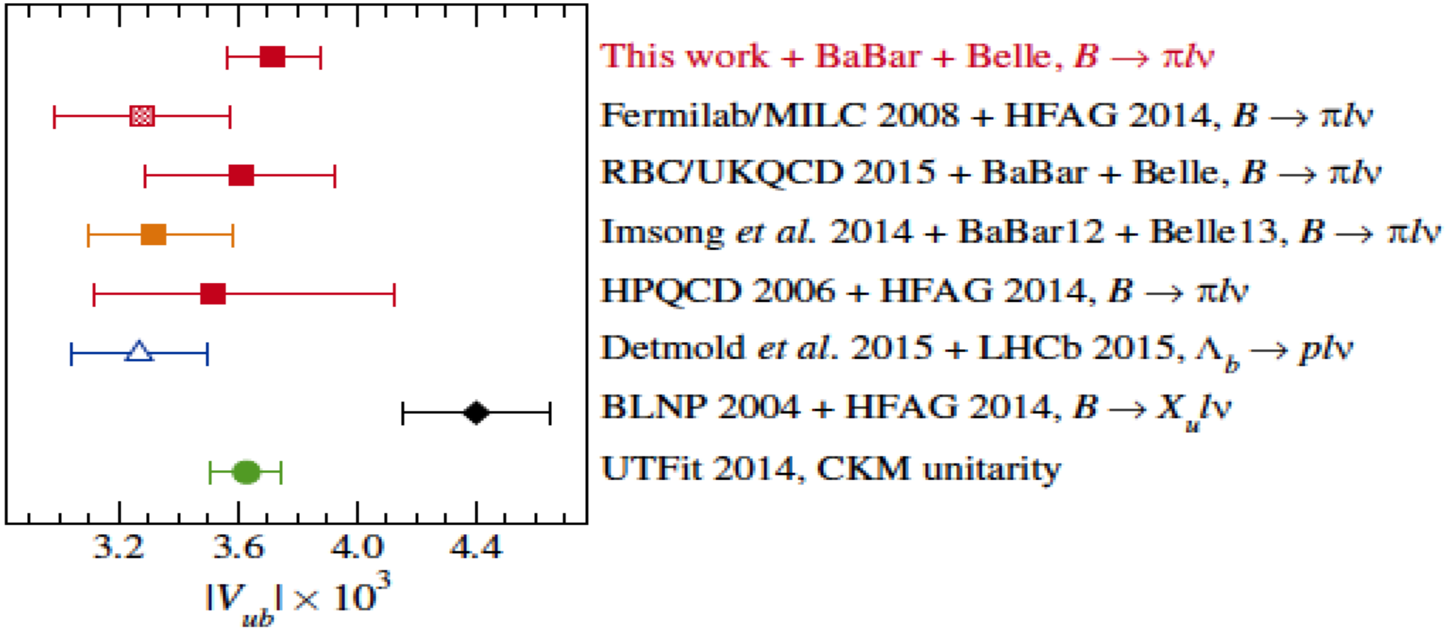


- $|V_{ub}|$ from these decays based on LCSR
  $\Rightarrow$ agree with $|V_{ub}|$ from $B \to \pi \ell \nu$, but more statistics needed!

- Would be nice to get LQCD calculations

Conclusions

- Large step forward in $|V_{ub}|$ from $B \to \pi\ell\nu$, precision of 4% reached!
- $B \to \rho\ell\nu$ at Belle II very interesting as cross-check of $|V_{ub}|$, to study angular distributions (NP sensitivity) and to shed light on $B \to \pi\pi\ell\nu$.
- Other charmless modes can be studied precisely at Belle II, but we need LQCD caluculations to derive $|V_{ub}|$



$|V_{ub}|$ remains extremely interesting!