Heavy to light exclusive at Belle (II)

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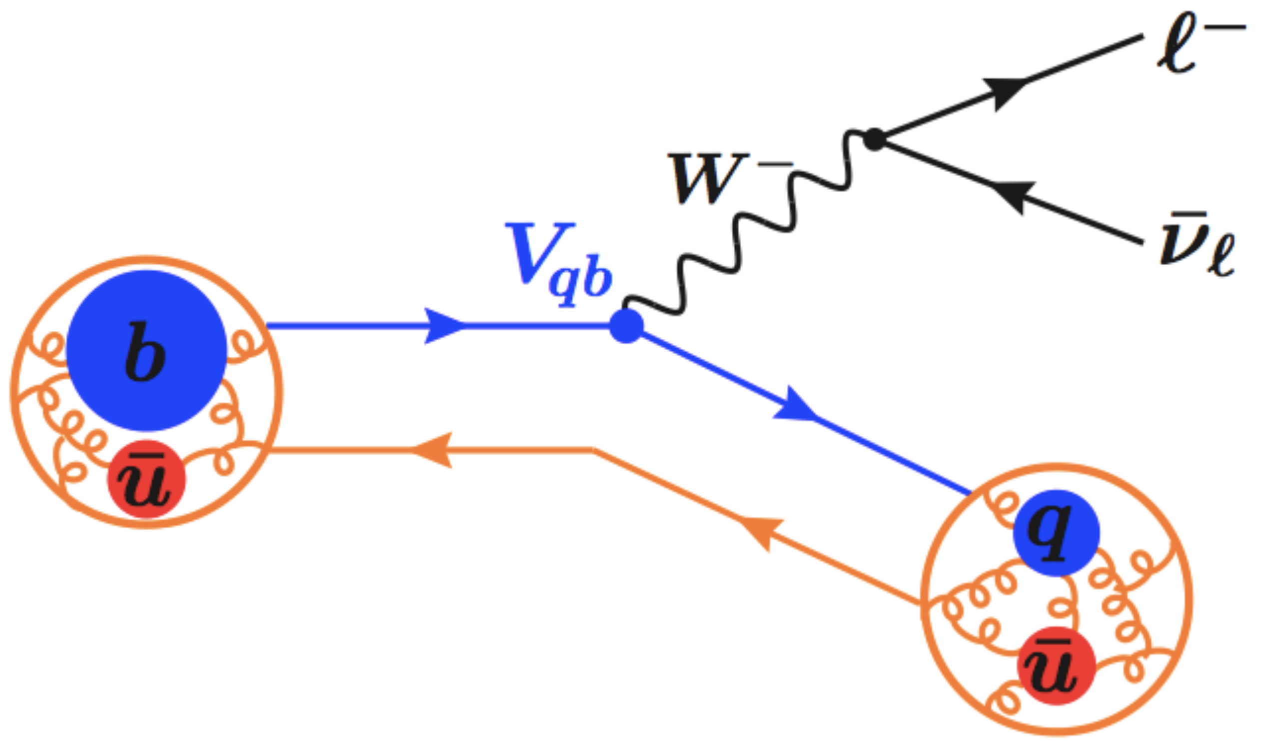
for the Belle/Belle II collaborations

Challenges in Semileptonic B Decays, April 19-23, 2022, Barolo (IT)

$B \to \pi \ell \nu$

The golden mode



- Differential rate in terms of $q^2 = (p_\ell + p_\nu)^2$

$$\frac{d\Gamma(B^0 \to \pi^- \ell^+ \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 |p_\pi|^3 |f_+(q^2)|^2$$

- BCL extraction of $|V_{ub}|$ [Phys.Rev.D79:013008,2009; Erratum-ibid.D82:099902,2010]
  - Experiments determine the differential rate in bins of q^2
  - Theory calculates $f_+(q^2)$ at values of q^2
  - Combined fit to the BCL expansion to determine $|V_{ub}|$ and b_k (z is a map of q^2)

$$f_+(q^2) = \frac{1}{1 - q^2/m_{B*}^2} \sum_{k=0}^{K-1} b_k \left[z^k - (-1)^{k-K} \frac{k}{K} z^K \right]$$

$B \to \pi \ell \nu$
Theory input

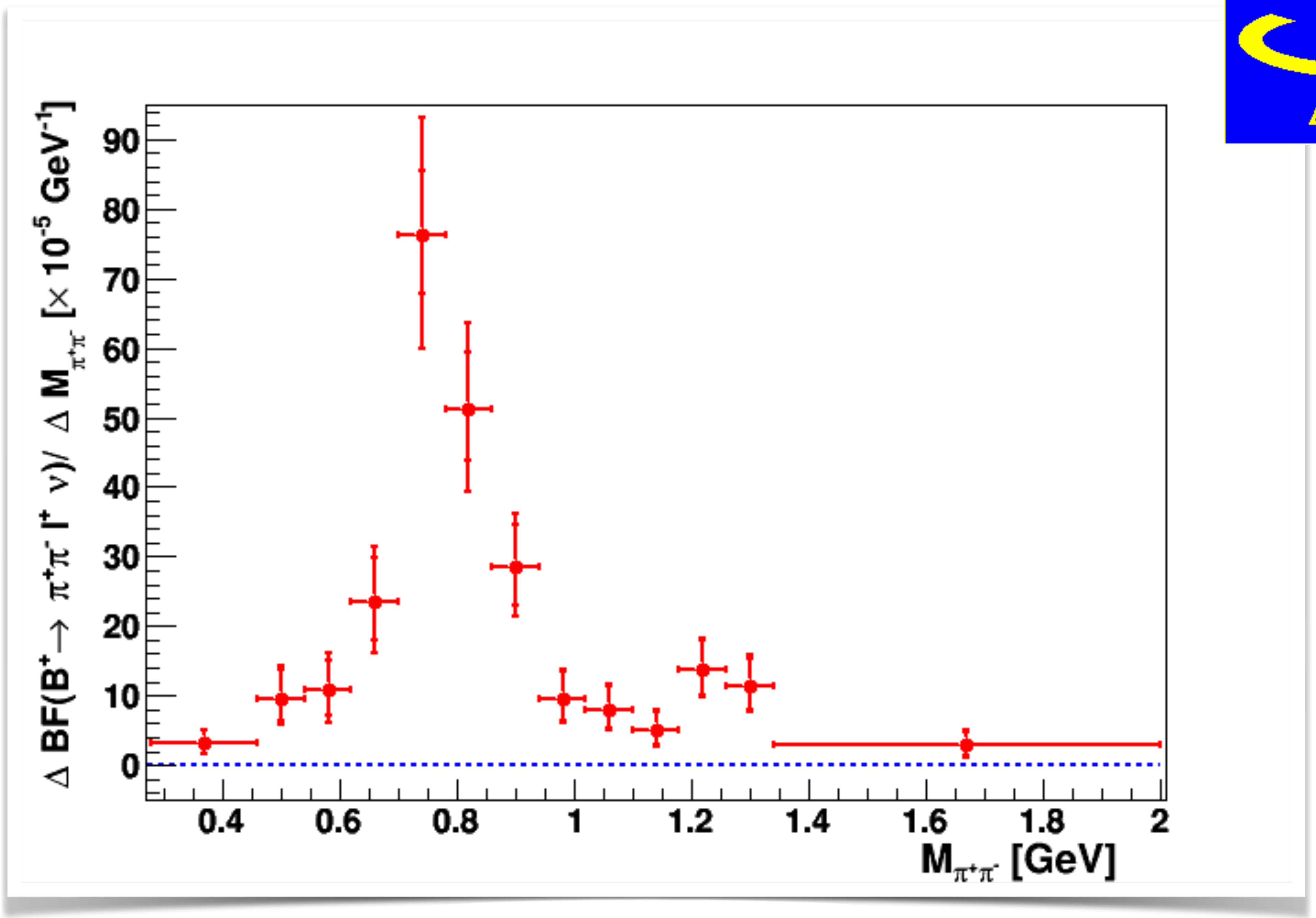
- Lattice QCD
  - Fermilab-MILC [Phys. Rev. D 92, 014024 (2015)]
    form factor calculation presented as BCL expansion
  - RBC-UKQCD [Phys. Rev. D 91, 074510 (2015)]
    form factor at $q^2 = 19.0,\ 22.6,\ 25.1$ GeV^2
- Light-cone sum rules
  - A. Bharucha [*JHEP* 05 (2012) 092]
    form factor at $q^2 = 0$

$B \to \rho, \omega, \eta^{(\prime)} \ell \nu$

- Although these modes have been measured precisely at B factories, we haven't seen competitive determinations of $|V_{ub}|$
- Theoretical issues
    - LCSR FF available for rho and omega [J. High Energ. Phys. (2016) 2016: 98]
    - Lack of precise lattice predictions for the vector modes
- Experimental issues
    - $B \to \rho \ell \nu$: Spin of the rho not identified in experimental analyses, scalar pi pi background?

$B^+ \to \pi^+\pi^-\ell^+\nu$

[Phys. Rev. D 103, 112001 (2021)]



BELLE

$$\mathcal{B}(B^+ \to \pi^+\pi^-\ell^+\nu_\ell) = (22.7^{+1.9}_{-1.6}(\text{stat}) \pm 3.5(\text{syst})) \times 10^{-5}$$

vs.

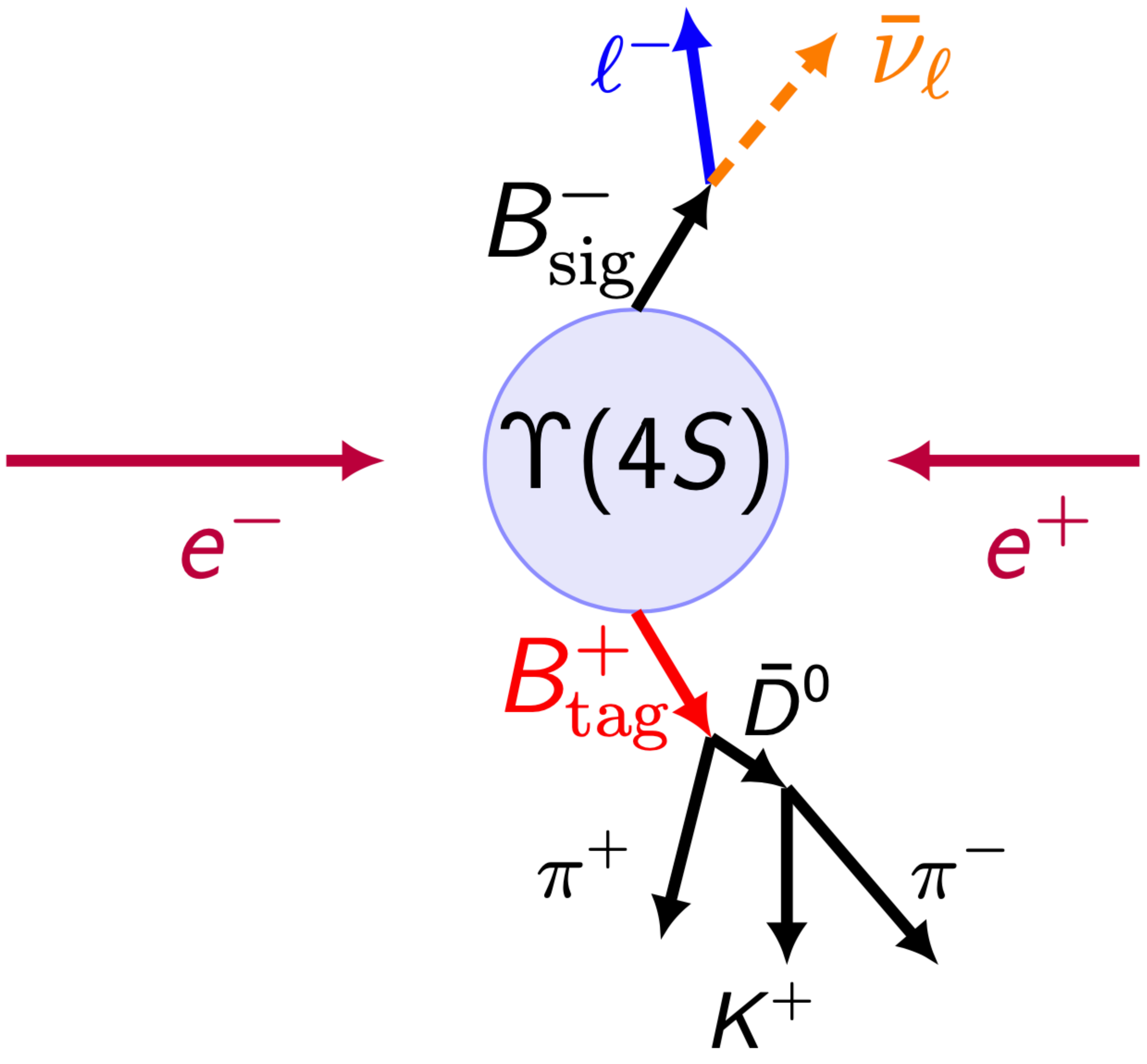
$$\mathcal{B}(B^+ \to \rho^0\ell^+\nu_\ell) = [18.3 \pm 1.0(\text{stat}) \pm 1.0(\text{syst})] \times 10^{-5}$$

on the same data set [Phys. Rev. D 88, 032005 (2013)]

Untagged vs. Tagged

Untagged:
only B_{sig} is reconstructed

high signal yield (+)
high backgrounds (-)
poor q^2 resolution (-)



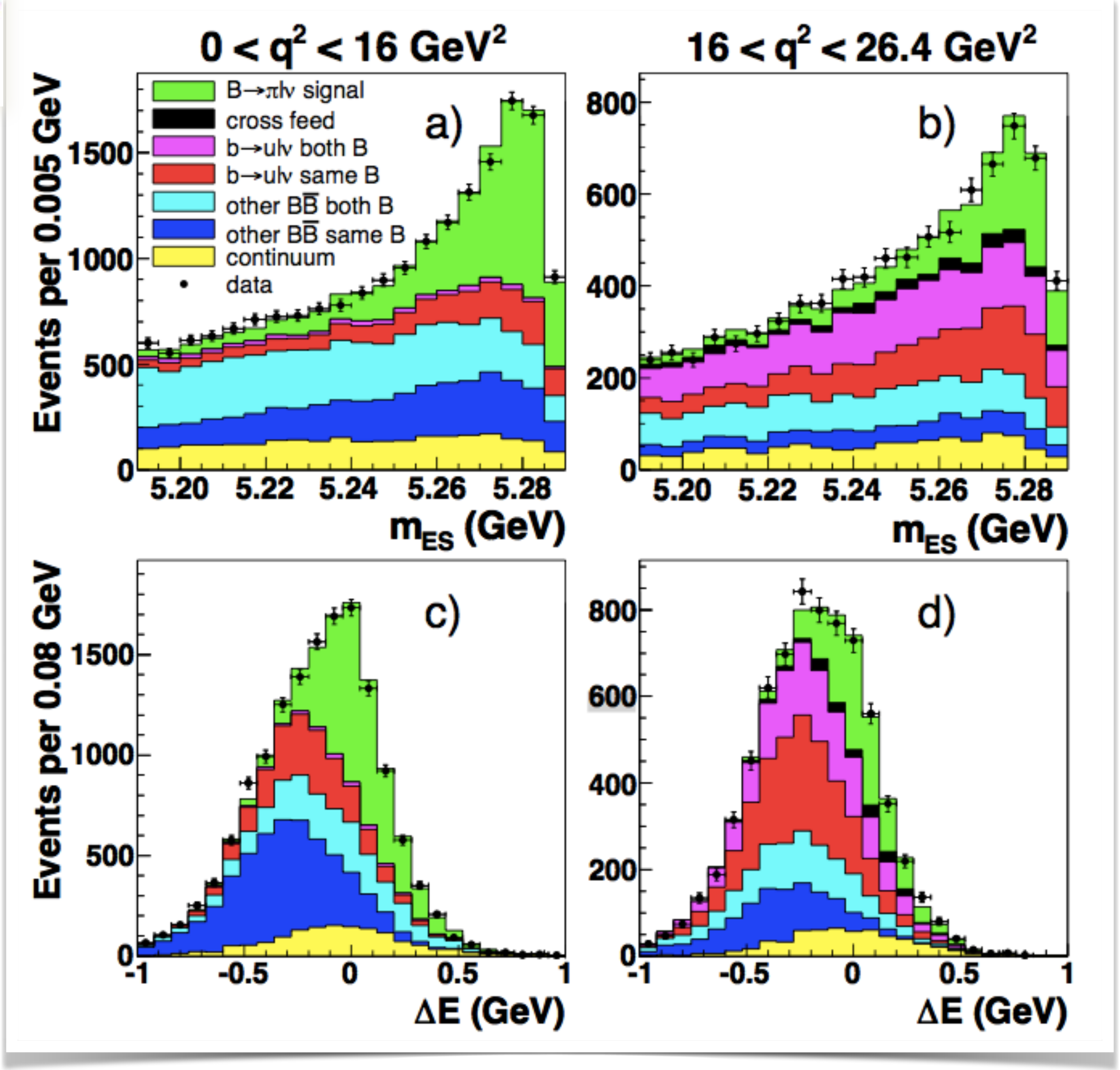
Tagged:
B_{sig} and B_{tag} are reconstructed

signal yield $O(10^3)$ lower (-)
low backgrounds (+)
good q^2 resolution (+)
tag calibration (-)

$B \to \pi \ell \nu$ untagged

[PRD 86, 092004 (2012)]

- 416/fb of BaBar $\Upsilon(4S)$ data
- Reconstruct only $\pi e, \pi\mu$, infer neutrino momentum from $p_{\rm miss}$ (loose neutrino reconstruction technique)
- About 12,000 signal events, S/N ~0.1
- Partial branching fractions obtained in 12 q^2 bins
- Systematics: detector effects, $b \to u$ background

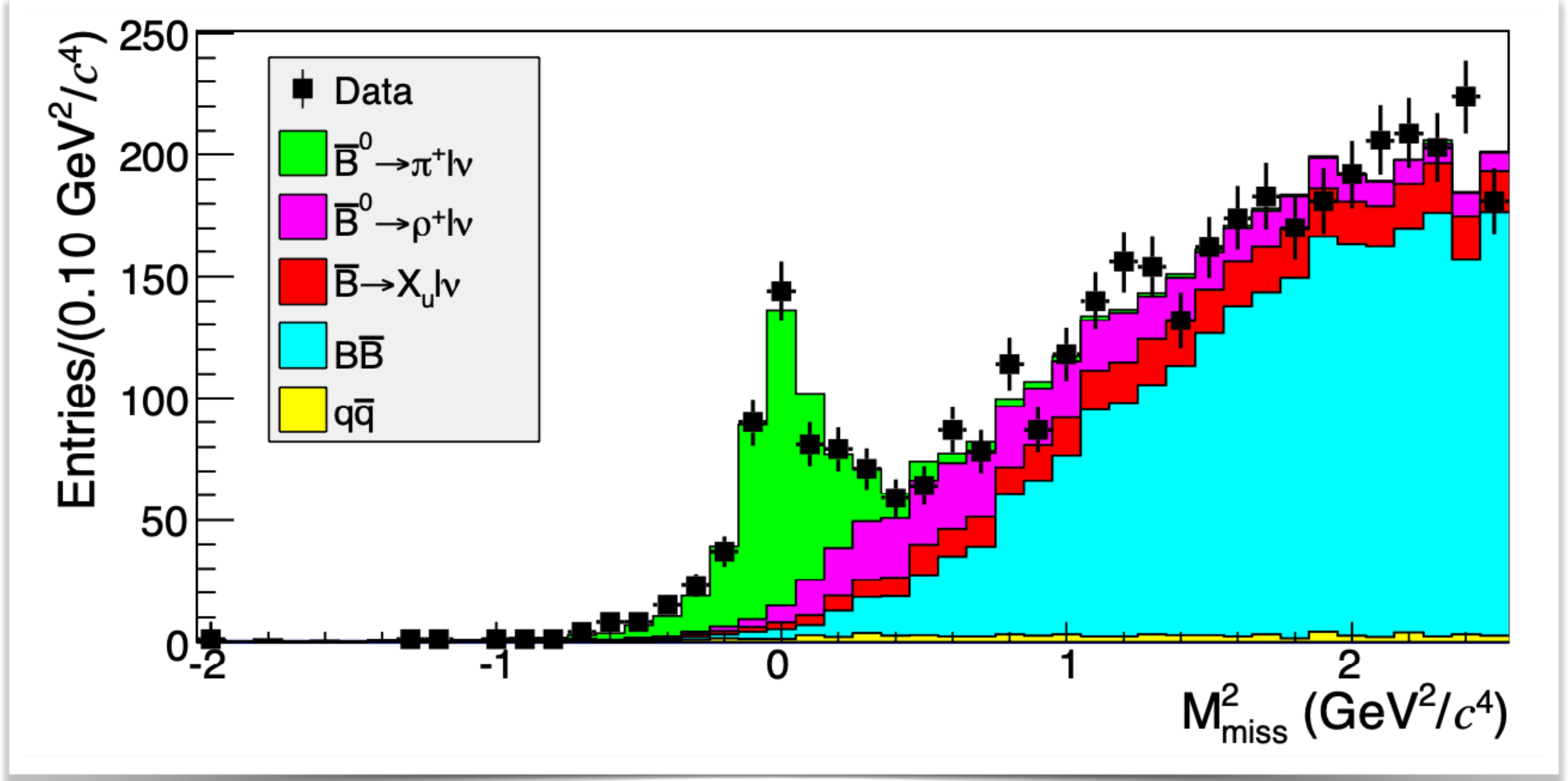


$$m_{ES} = \sqrt{E^{*2}_{beam} - \mathbf{p}^{*2}_{\pi\ell\nu}}$$
$$\Delta E = E^{*}_{\pi\ell\nu} - E^{*}_{beam}$$

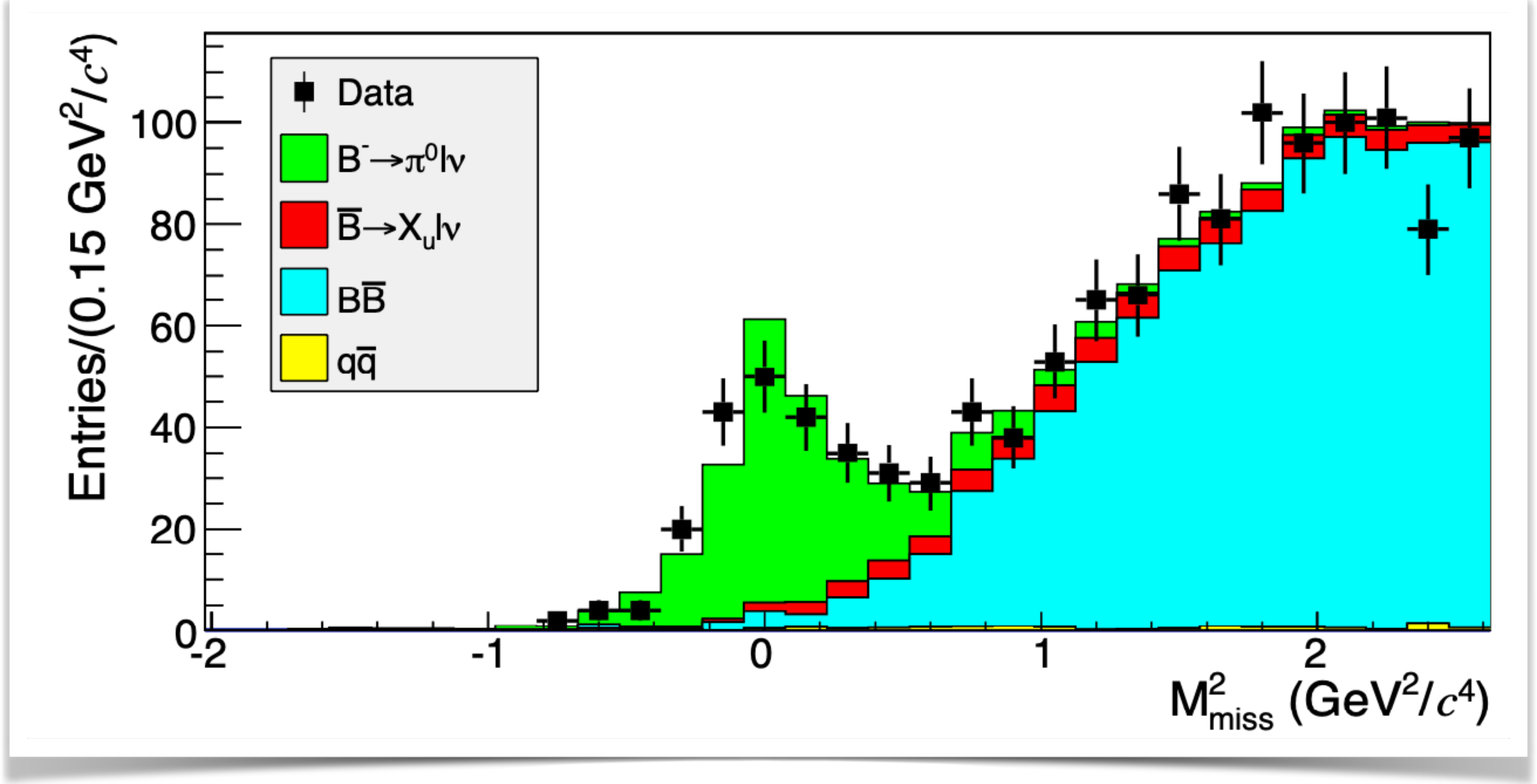
$B \to \pi \ell \nu$ with hadronic tag

[PRD 88, 032005 (2013)]

$B^0 \to \pi^- \ell^+ \nu$



$B^+ \to \pi^0 \ell^+ \nu$



- 711/fb of Belle $\Upsilon(4S)$ data
- Belle hadronic tag
- Yield extracted from M^2_{miss} in 13 (7) bins of q^2 for $B^0 \to \pi^- \ell^+ \nu$ ($B^+ \to \pi^0 \ell^+ \nu$)
- Main systematics: tag calibration

$B^0 \to \pi^- \ell^+ \nu$

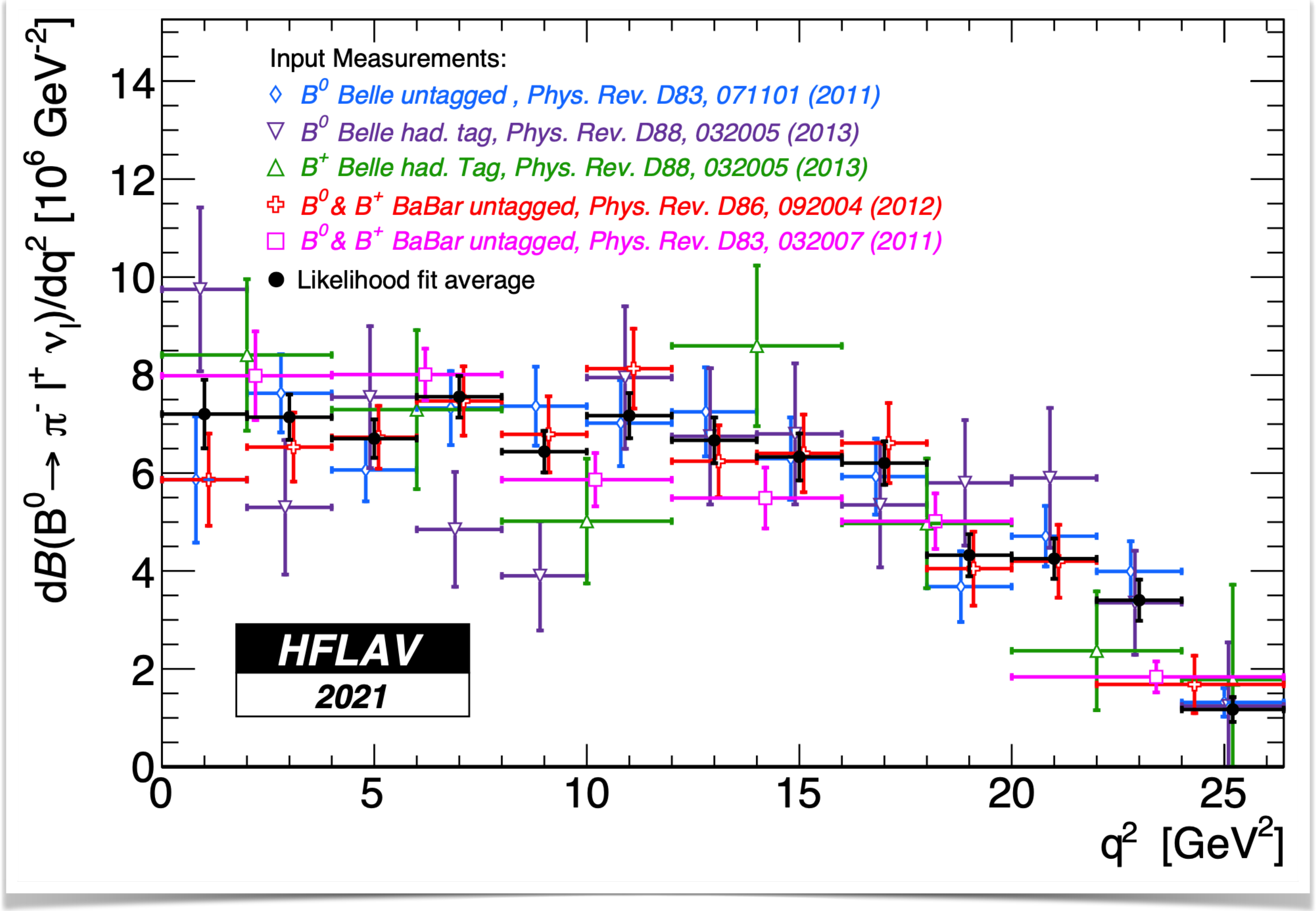
Component	Yield
$\bar{B}^0 \to \pi^+ \ell^- \bar{\nu}_\ell$	462.6 ± 27.7
$\bar{B}^0 \to \rho^+ \ell^- \bar{\nu}_\ell$	514.5(fixed)
$\bar{B} \to X_u \ell^- \bar{\nu}_\ell$	599.5 ± 198.4
$B\bar{B}$	5511.6 ± 200.7
$q\bar{q}$	111.8(fixed)
χ^2/ndf	76.0/76

$B^+ \to \pi^0 \ell^+ \nu$

Component	Yield
$B^- \to \pi^0 \ell^- \bar{\nu}_\ell$	232.2 ± 22.6
$\bar{B} \to X_u \ell^- \bar{\nu}_\ell$	100.0 ± 86.7
$B\bar{B}$	1993.4 ± 90.7
$q\bar{q}$	18.5(fixed)
χ^2/ndf	56.3/50

$B \to \pi \ell \nu$ average

HFLAV 2021

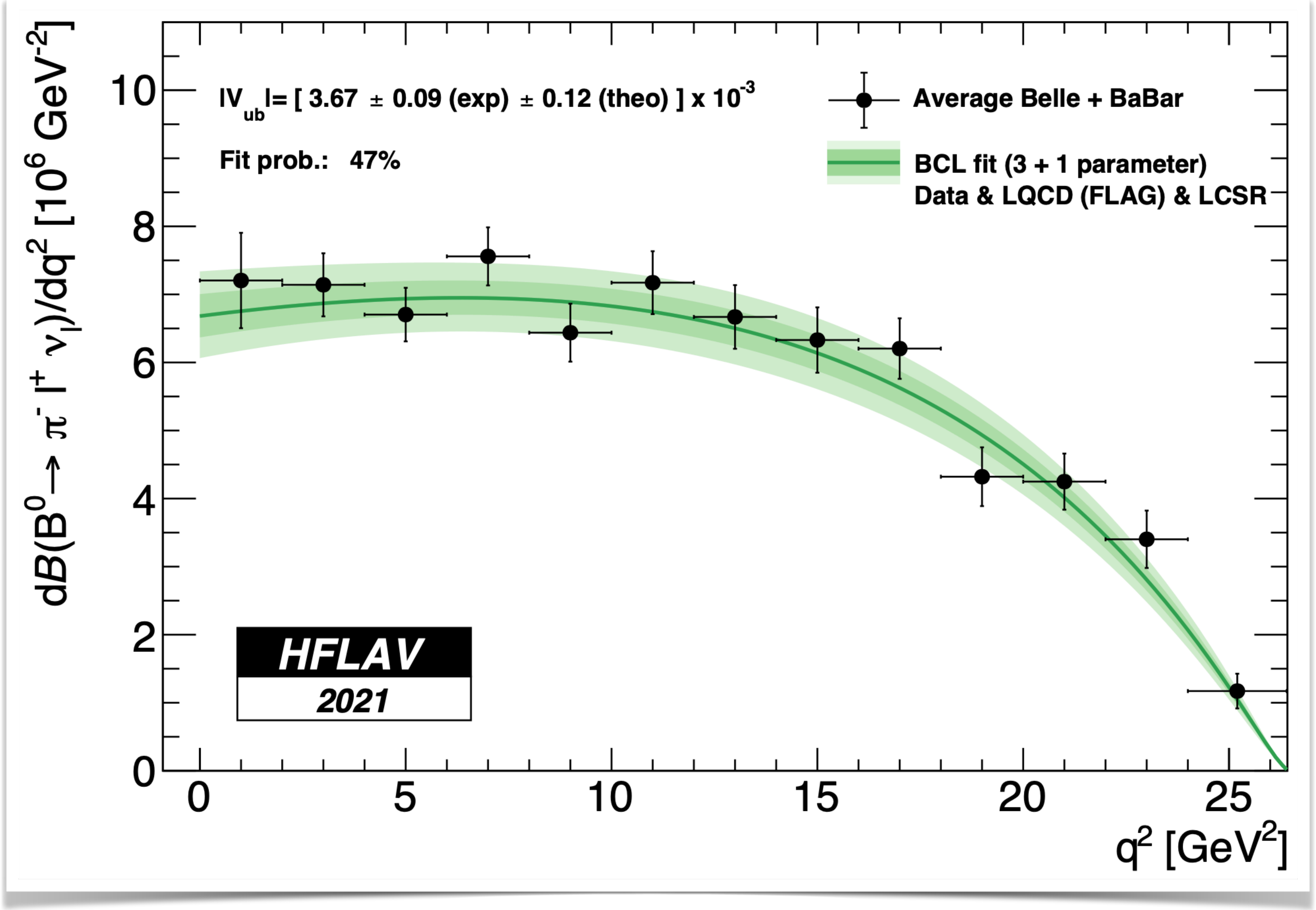


- Average in each bin of q^2
- Taking into account correlated systematic uncertainties
- $P(\chi^2) = 6\,\%$
- Total $\mathscr{B}$ is obtained from summing up partial branching ratios (accuracy 6%)

$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.50 \pm 0.02_{\text{stat}} \pm 0.06_{\text{syst}}) \times 10^{-4}$$

BCL fit

HFLAV 2021



Parameter	Value
$\lvert V_{ub}\rvert$	$(3.67 \pm 0.15) \times 10^{-3}$
b_0	0.418 ± 0.012
b_1	-0.399 ± 0.033
b_2	-0.578 ± 0.130

Parameter	$\lvert V_{ub}\rvert$	b_0	b_1	b_2
$\lvert V_{ub}\rvert$	1.000	-0.780	-0.404	0.401
b_0	-0.780	1.000	2.110	-0.587
b_1	-0.404	2.110	1.000	-0.686
b_2	0.401	-0.587	-0.686	1.000

$$|V_{ub}| = (3.67 \pm 0.09_{\,\text{exp}} \pm 0.12_{\,\text{theo}}) \times 10^{-3} \ \ (\text{data} + \text{LQCD} + \text{LCSR})$$

$$|V_{ub}| = (3.70 \pm 0.10_{\,\text{exp}} \pm 0.12_{\,\text{theo}}) \times 10^{-3} \ \ (\text{data} + \text{LQCD})$$

$B \to \rho, \omega \ell \nu$ average

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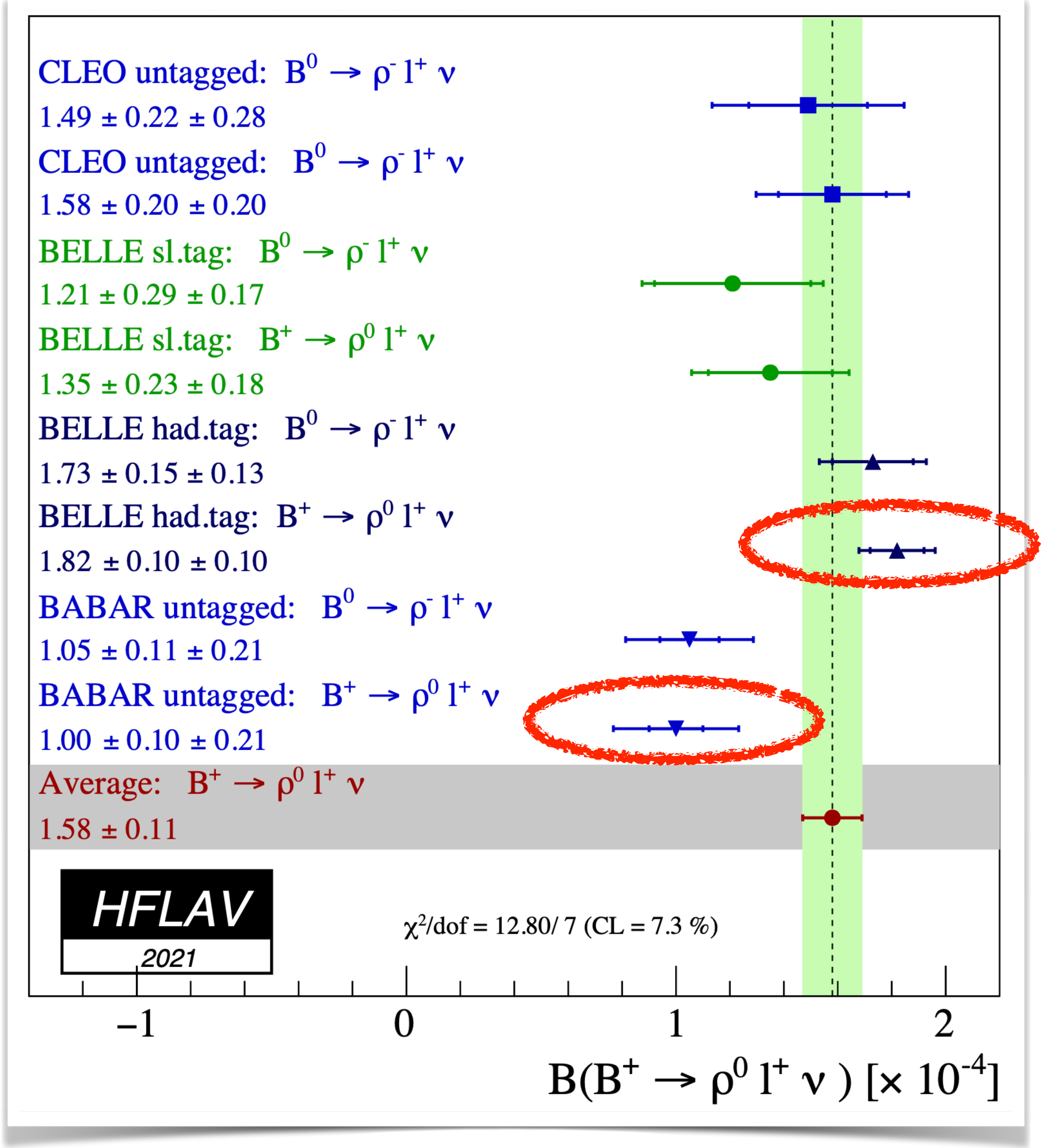
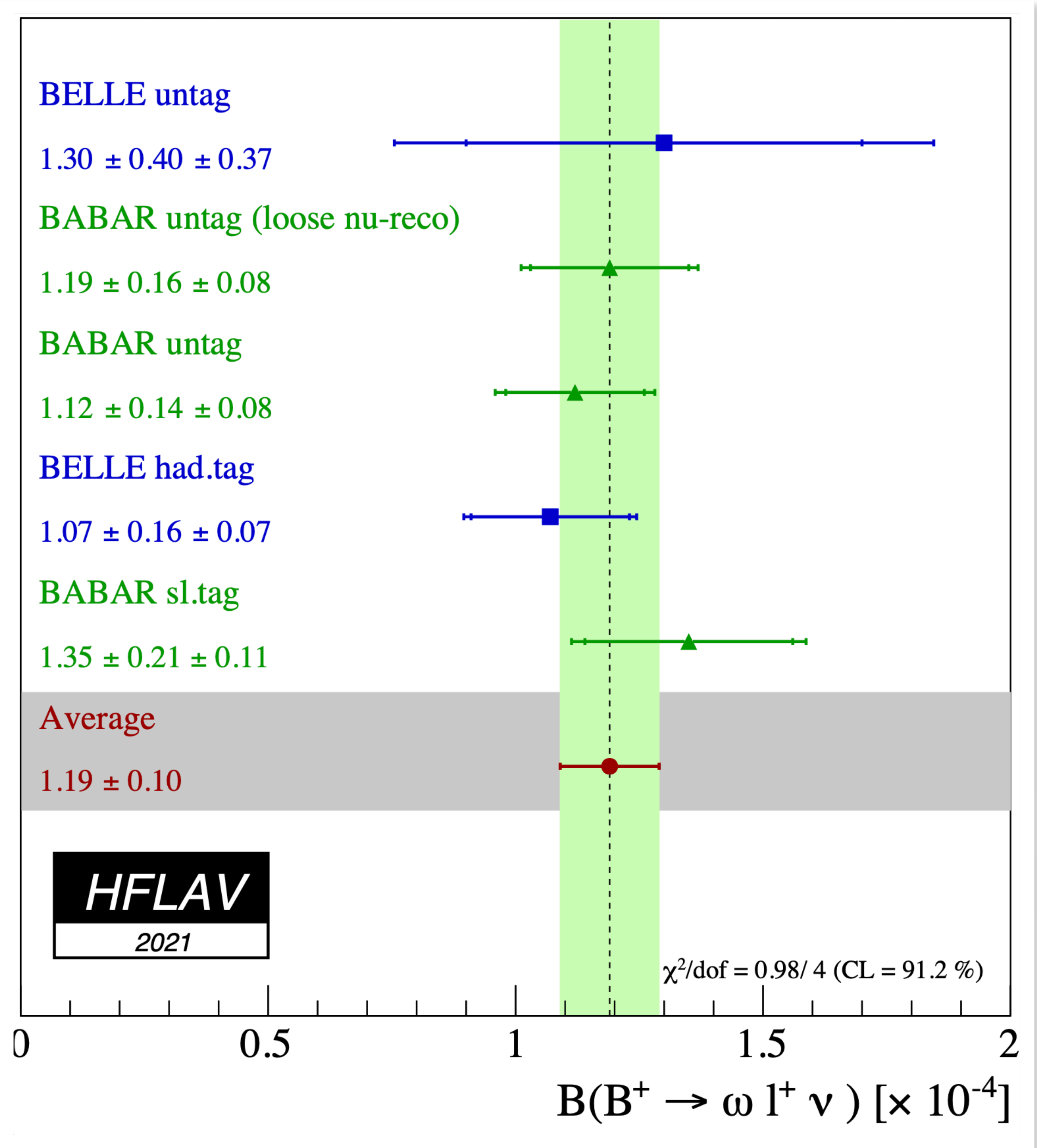


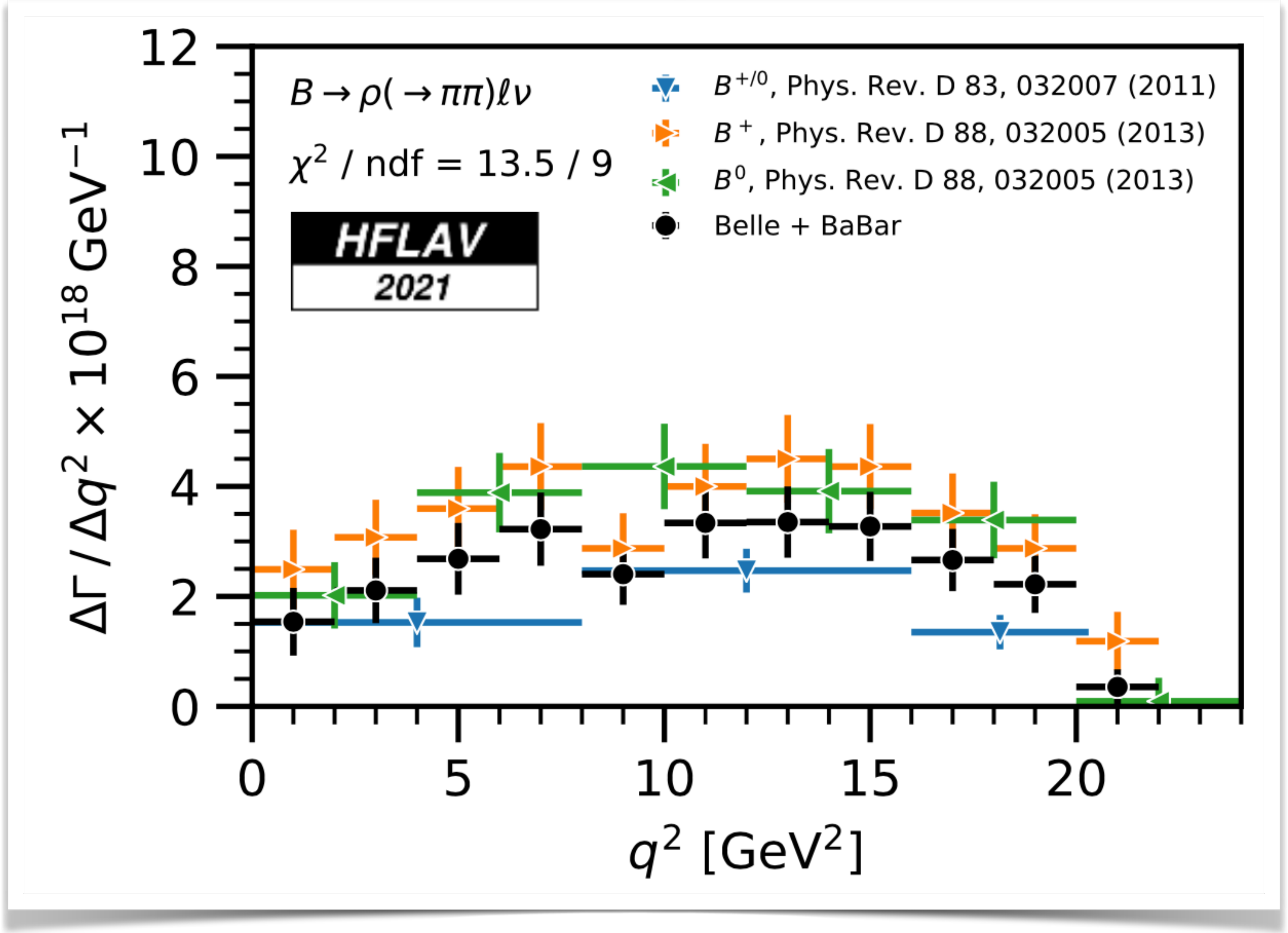


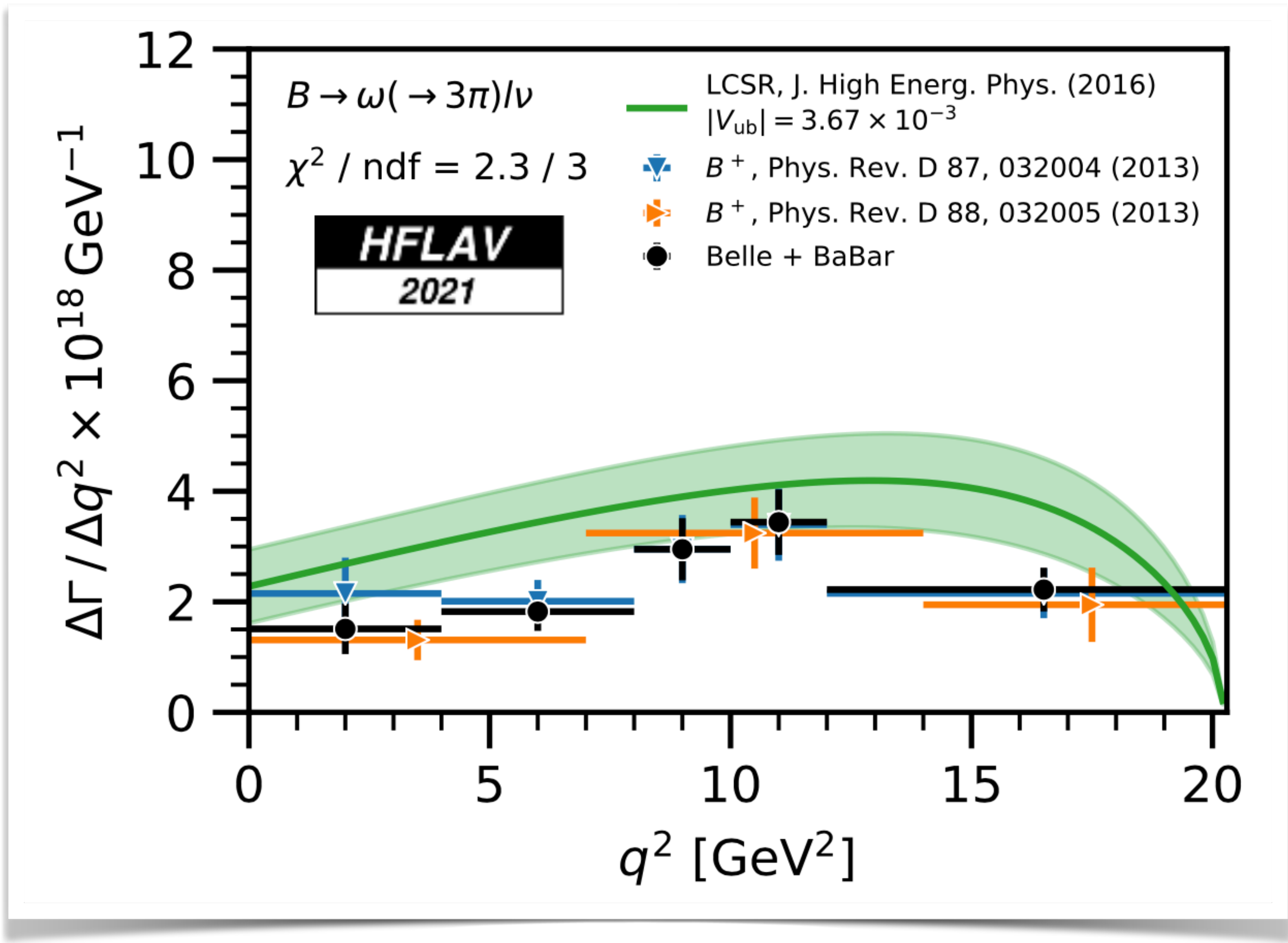
- $B \to \rho \ell \nu$
  - $B^+ \to \rho^0 \ell^+ \nu$ average includes $B^0 \to \rho^- \ell^+ \nu$ results rescaled by $0.5 \tau_{B^+}/\tau_{B^0}$ (isospin symmetry)
  - 7% overall precision
  - 3 sigma discrepancy between BaBar untagged and Belle tagged for $B^+ \to \rho^0 \ell^+ \nu$
- $B \to \omega \ell \nu$
  - 8% overall precision

$B \to \rho, \omega \ell \nu \; q^2$ spectrum

HFLAV 2021

- $B \to \rho \ell \nu$
    - Rate times bin width of the most precise measurements (BaBar untagged, Belle tagged) are averaged
- $B \to \omega \ell \nu$
    - BaBar untagged and Belle tagged are averaged
    - 2nd and 5th bin of the Belle spectrum is split using the LCSR spectrum [J. High Energ. Phys. (2016) 2016: 98]





$B \to \eta^{(\prime)}\ell\nu$ average

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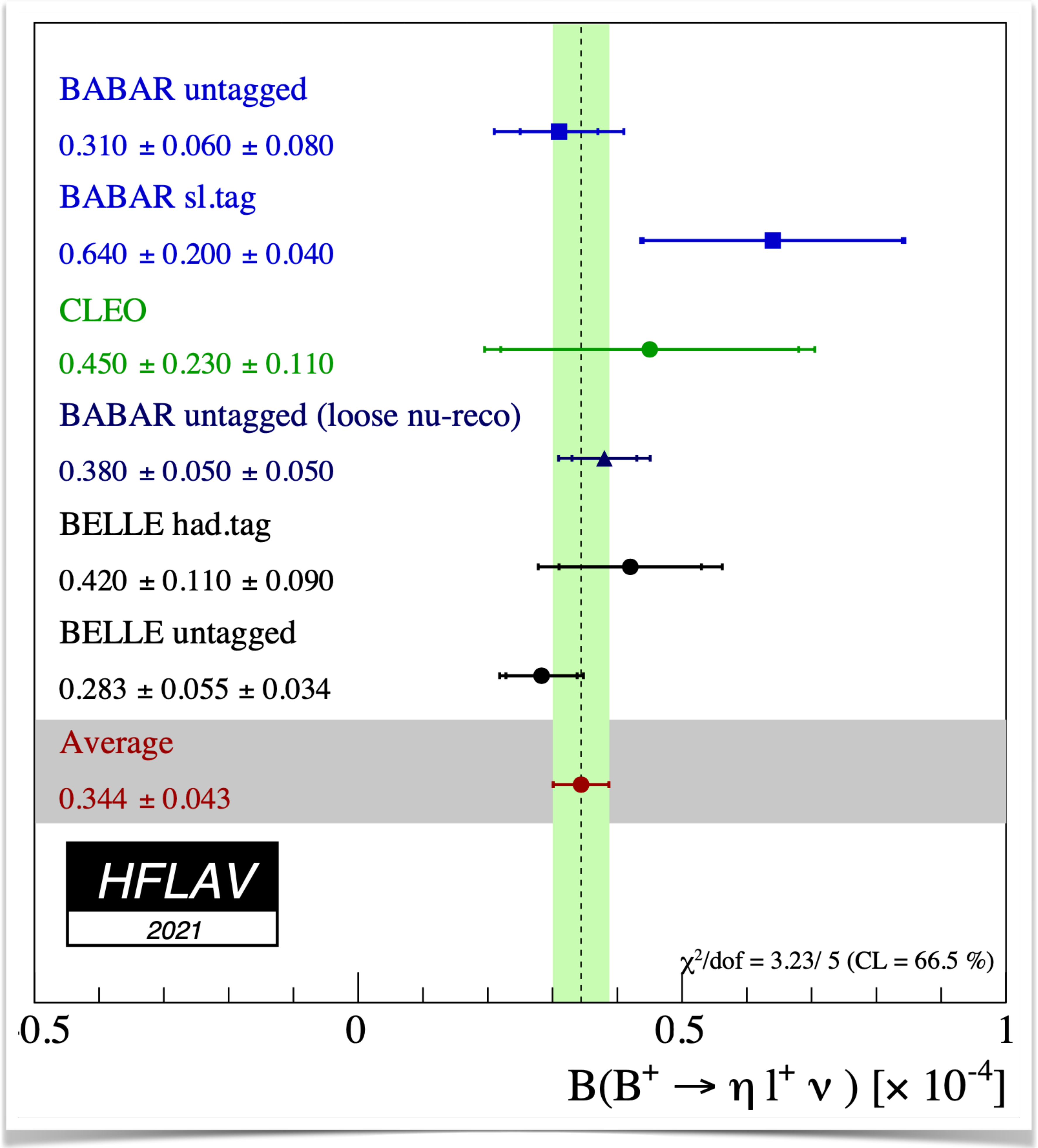
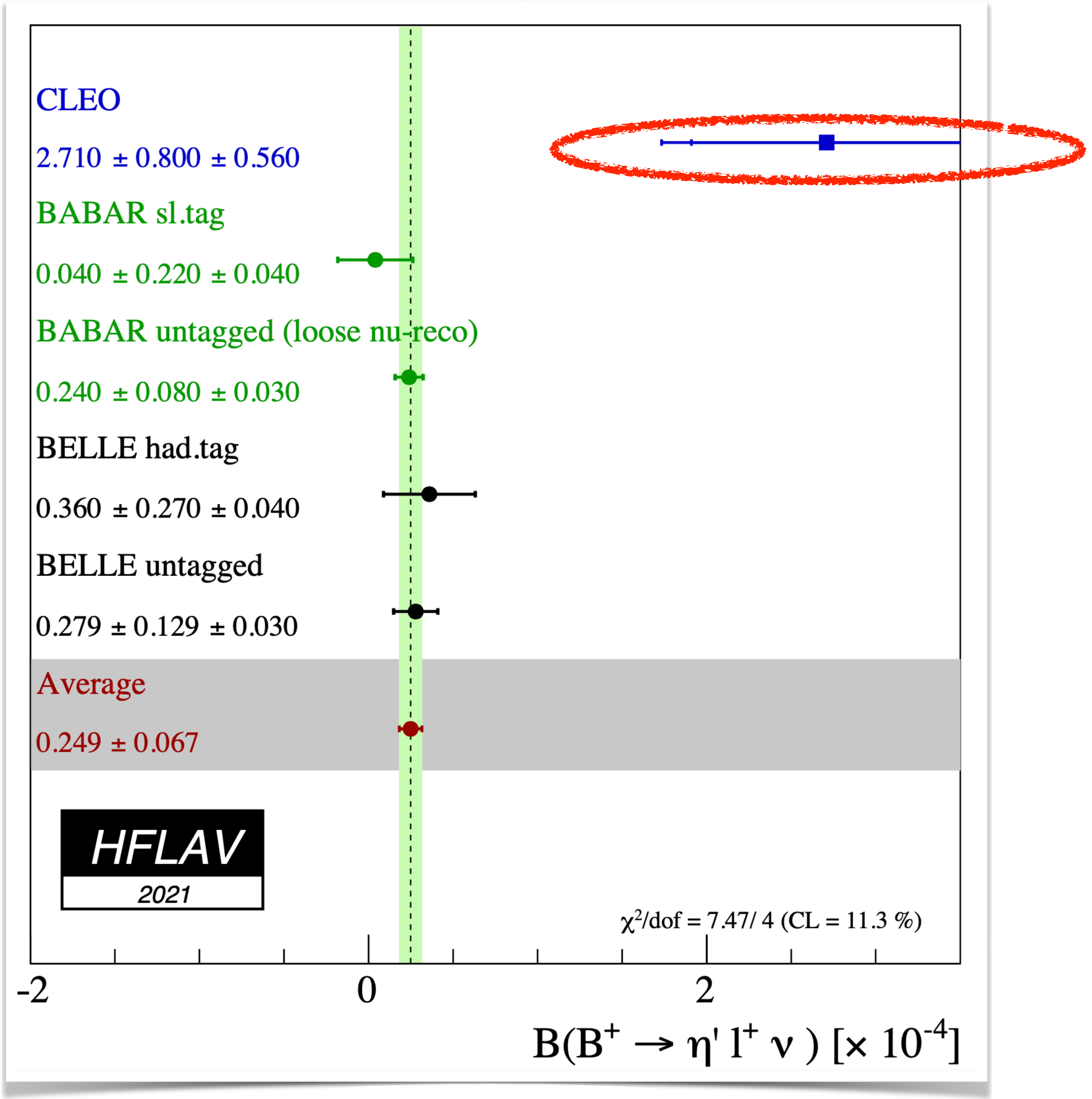
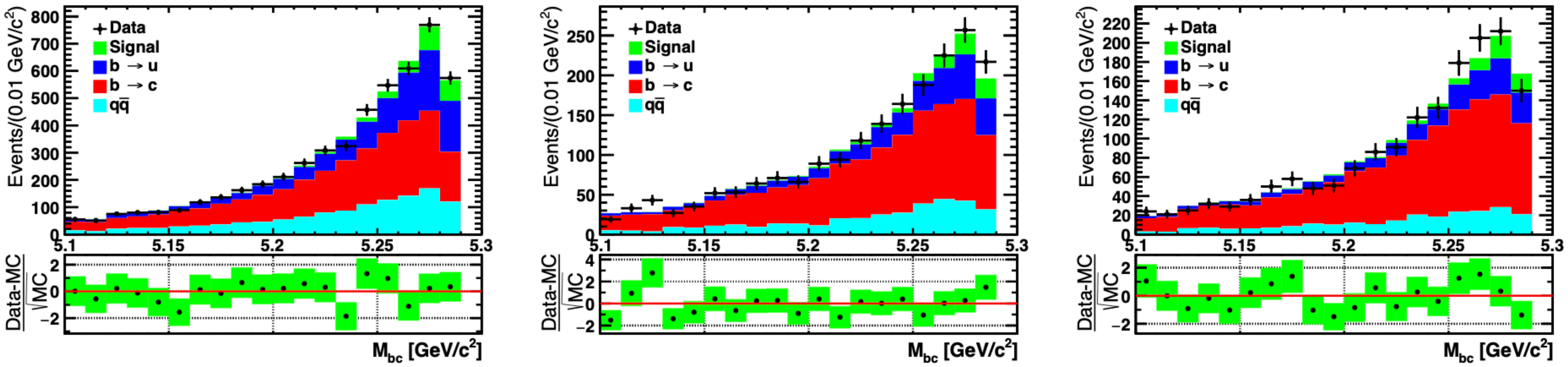




$B^+ \to \eta^{(\prime)}\ell^+\nu$

Submitted to PRD [arXiv:2104.13354]



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

$$\mathcal{B}(B^+ \to \eta\ell^+\nu_\ell) = (2.83 \pm 0.55 \pm 0.34) \times 10^{-5}$$

$$\mathcal{B}(B^+ \to \eta'\ell^+\nu_\ell) = (2.79 \pm 1.29_{(\rm stat.)} \pm 0.30_{(\rm syst.)}) \times 10^{-5}$$

Hadronic tagging at Belle II

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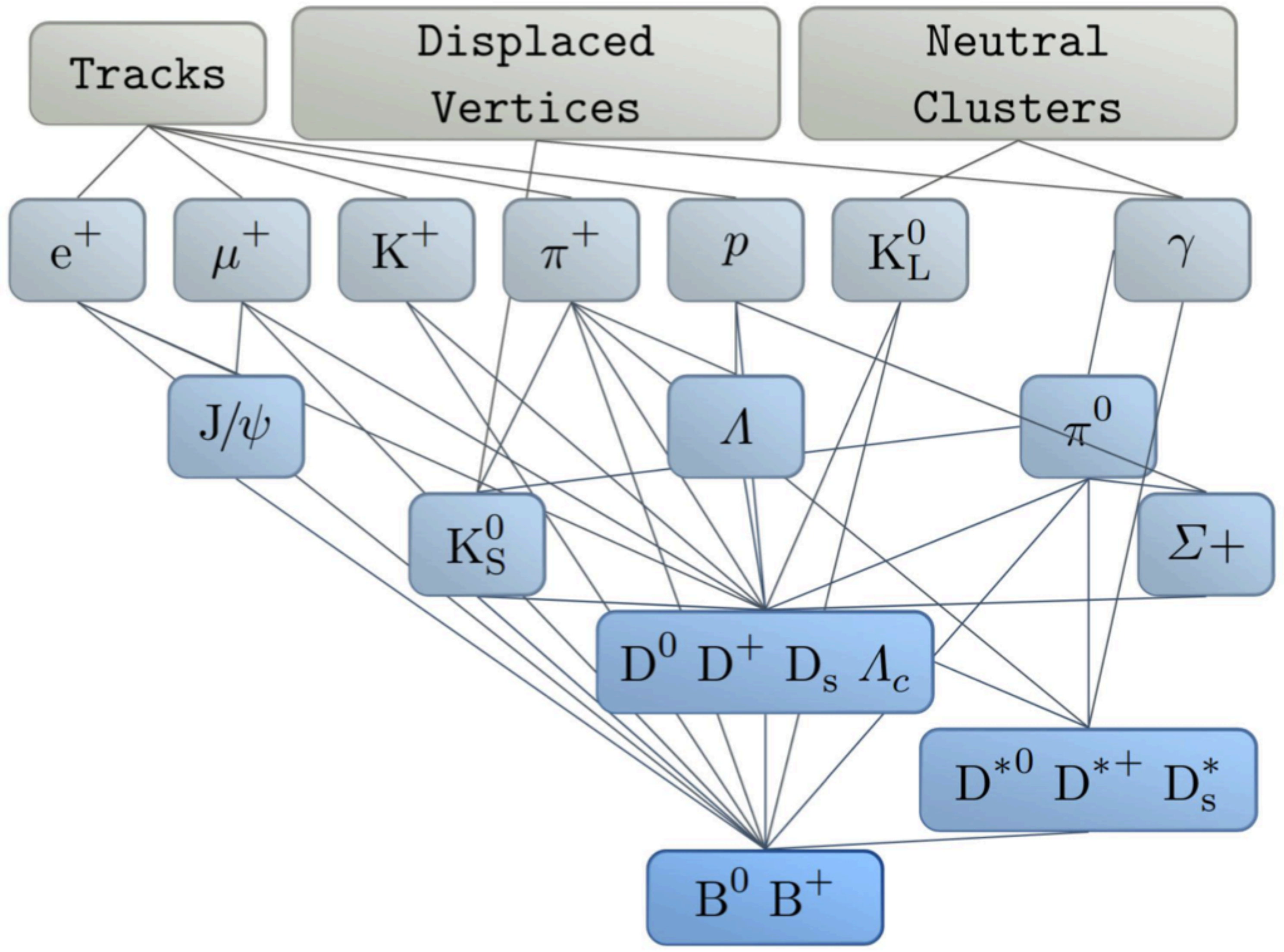
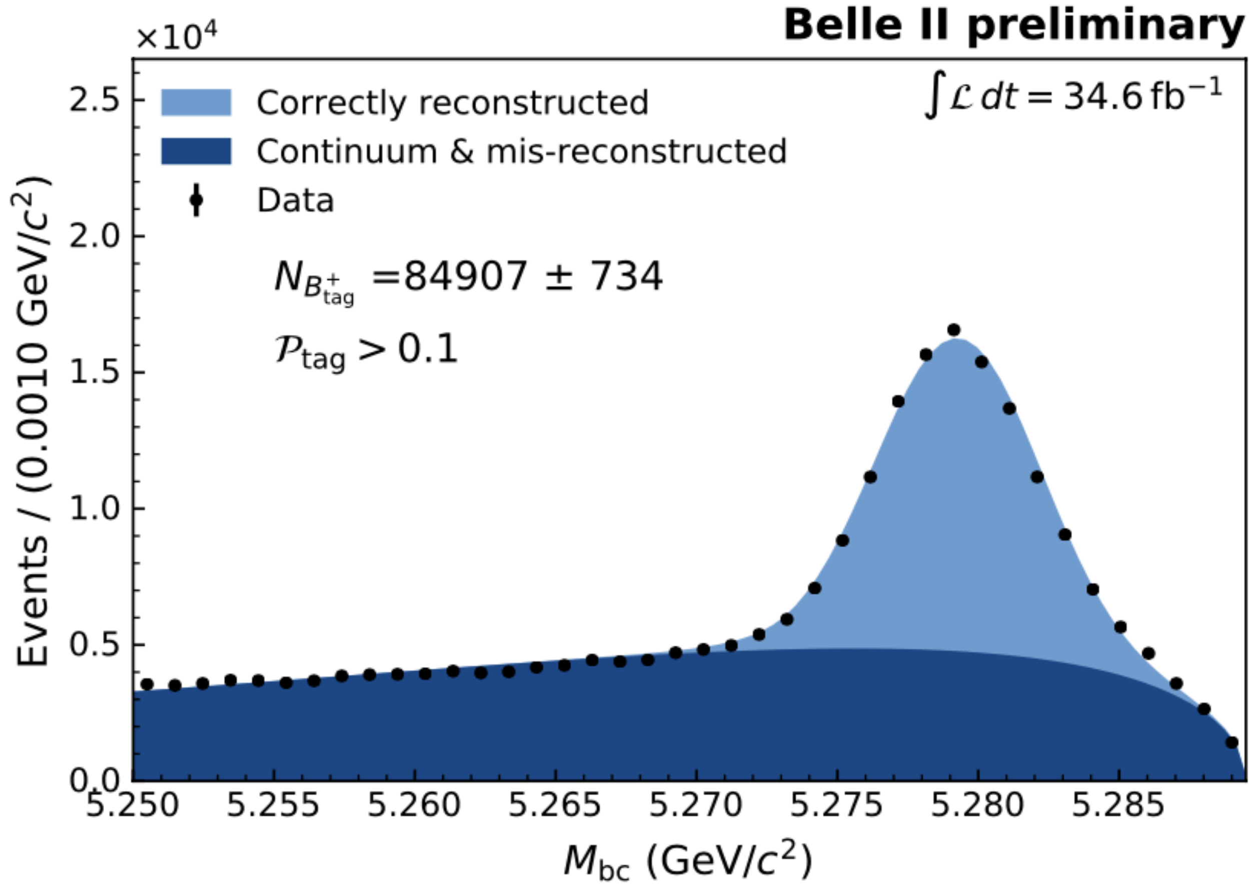
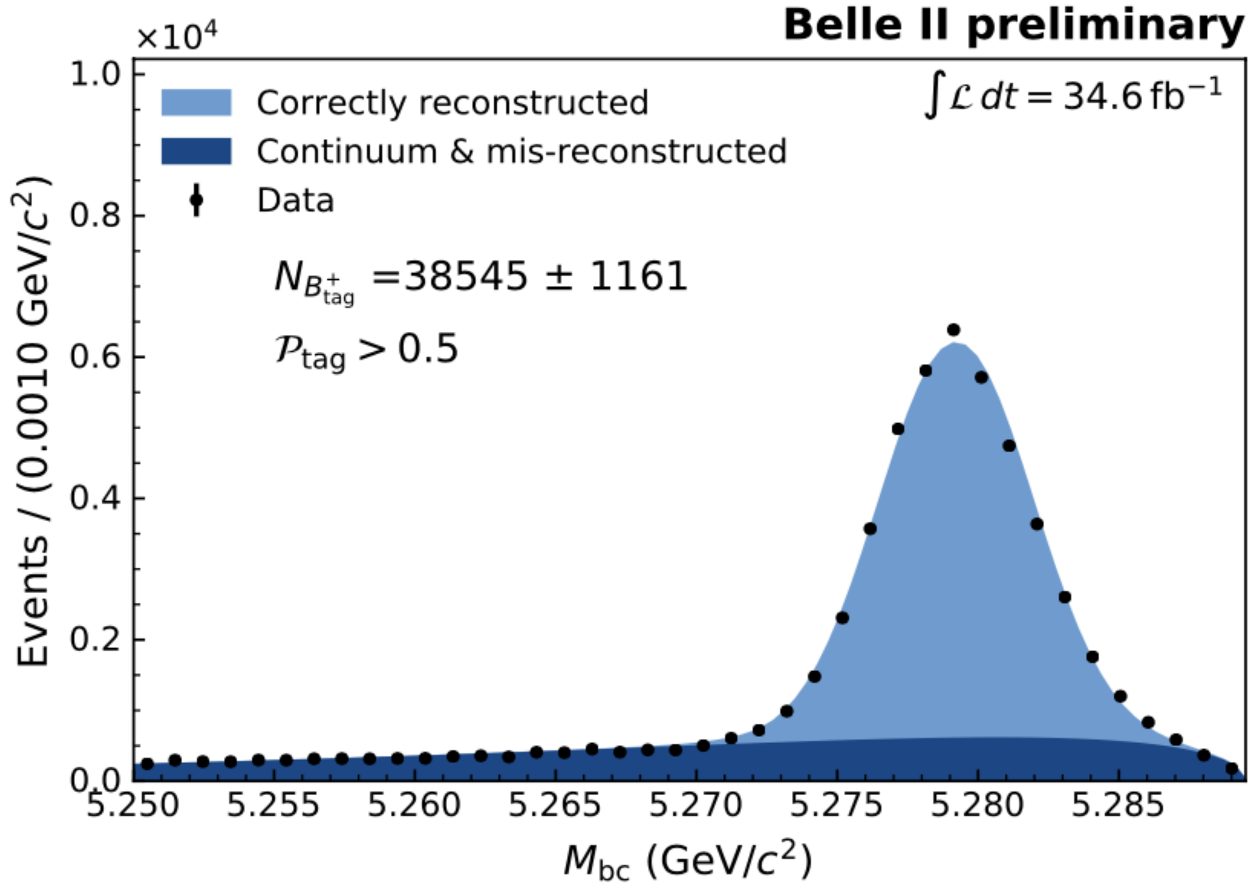




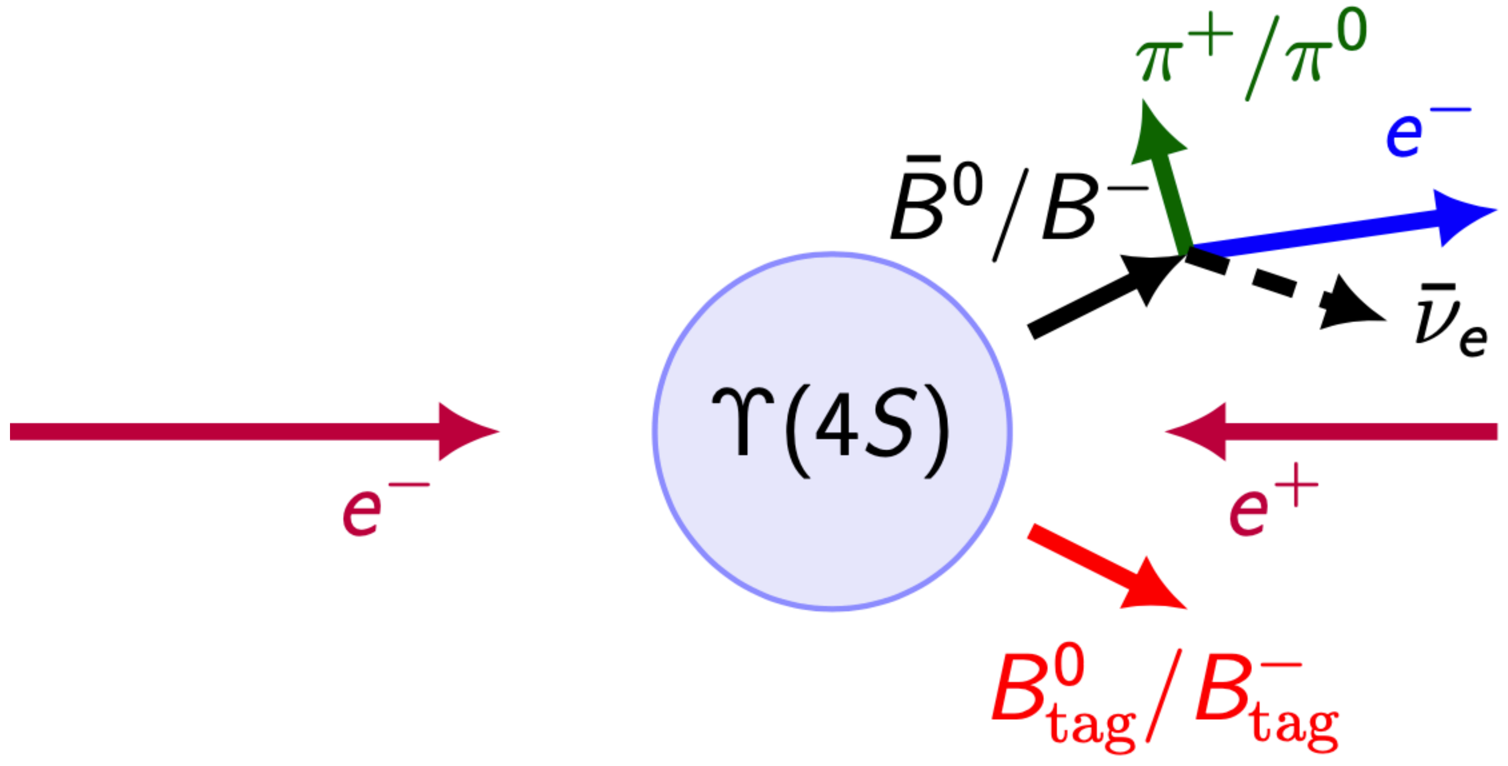


$$M_{bc} = \sqrt{E_{beam}^2/4 - (p_{B_{tag}}^{cm})^2} > 5.27\ \mathrm{GeV}/c^2$$

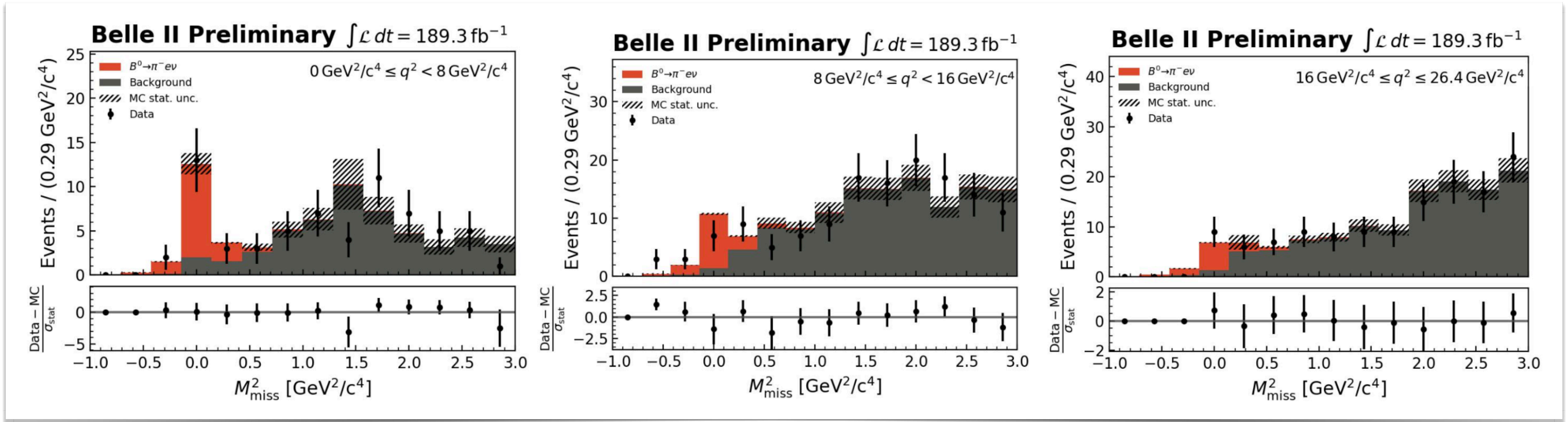
- The hadronic FEI employs over 200 boosted decision trees to reconstruct 10000 B decay chains
  - $\epsilon_{B^+} \approx 0.5\,\%$, $\epsilon_{B^0} \approx 0.3\,\%$ at low purity

$B \to \pi e \nu$ tagged at Belle II

Winter 2021 — paper in preparation



- 189.3/fb of Belle II, tag side is reconstructed by hadronic FEI
- $\pi^- e^+$ and $\pi^0 e^+$ are reconstructed on the signal side
- Signal yield is extracted from the missing mass distribution in three bins of q^2
  - $M^2_{\rm miss} = (p_{\Upsilon(4S)} - p_{B_{\rm tag}} - p_\pi - p_e)^2$



$B \to \pi e \nu$ tagged at Belle II

Winter 2021 — paper in preparation

q^2 bin	Signal efficiency	Unfolded signal yield	$\Delta\mathcal{B}$
		$B^0 \to \pi^- e^+ \nu_e$	
$0\ \mathrm{GeV}^2 \leq q^2 < 8\ \mathrm{GeV}^2$	$(0.189 \pm 0.002)\%$	15.5 ± 4.6	$(0.61 \pm 0.18(\mathrm{stat}) \pm 0.03(\mathrm{syst}))\ \times 10^{-4}$
$8\ \mathrm{GeV}^2 \leq q^2 < 16\ \mathrm{GeV}^2$	$(0.239 \pm 0.003)\%$	15.3 ± 4.8	$(0.48 \pm 0.15(\mathrm{stat}) \pm 0.02(\mathrm{syst}))\ \times 10^{-4}$
$16\ \mathrm{GeV}^2 \leq q^2 \leq 26.4\ \mathrm{GeV}^2$	$(0.229 \pm 0.003)\%$	10.3 ± 4.2	$(0.34 \pm 0.14(\mathrm{stat}) \pm 0.02(\mathrm{syst}))\ \times 10^{-4}$
Sum	–	41.1 ± 7.8	$(1.43 \pm 0.27(\mathrm{stat}) \pm 0.07(\mathrm{syst}))\ \times 10^{-4}$
Fit over full q^2 range	$(0.217 \pm 0.002)\%$	42.0 ± 7.9	$(1.45 \pm 0.27(\mathrm{stat}) \pm 0.07(\mathrm{syst}))\ \times 10^{-4}$

q^2 bin	Signal efficiency	Unfolded signal yield	$\Delta\mathcal{B}$
		$B^+ \to \pi^0 e^+ \nu_e$	
$0\ \mathrm{GeV}^2 \leq q^2 < 8\ \mathrm{GeV}^2$	$(0.329 \pm 0.004)\%$	12.9 ± 4.7	$(2.90 \pm 1.12(\mathrm{stat}) \pm 0.19(\mathrm{syst}))\ \times 10^{-5}$
$8\ \mathrm{GeV}^2 \leq q^2 < 16\ \mathrm{GeV}^2$	$(0.439 \pm 0.005)\%$	18.1 ± 5.1	$(3.05 \pm 0.91(\mathrm{stat}) \pm 0.20(\mathrm{syst}))\ \times 10^{-5}$
$16\ \mathrm{GeV}^2 \leq q^2 \leq 26.4\ \mathrm{GeV}^2$	$(0.451 \pm 0.006)\%$	14.5 ± 4.9	$(2.38 \pm 0.85(\mathrm{stat}) \pm 0.16(\mathrm{syst}))\ \times 10^{-5}$
Sum	–	45.5 ± 8.5	$(8.33 \pm 1.67(\mathrm{stat}) \pm 0.55(\mathrm{syst}))\ \times 10^{-5}$
Fit over full q^2 range	$(0.402 \pm 0.003)\%$	43.9 ± 8.3	$(8.06 \pm 1.62(\mathrm{stat}) \pm 0.53(\mathrm{syst}))\ \times 10^{-5}$

- Yields in q^2 bins are corrected by bin-by-bin unfolding

$B \to \pi e \nu$ tagged at Belle II

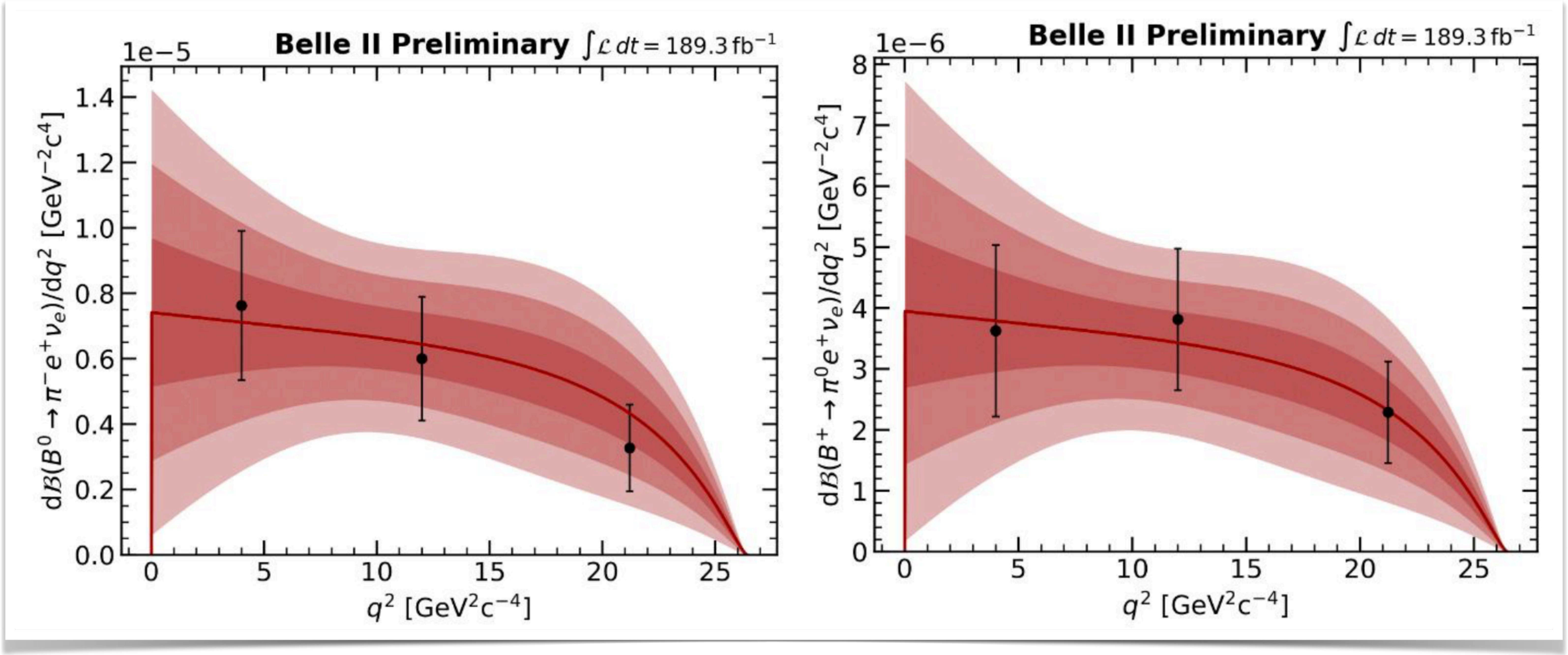
Winter 2021 — paper in preparation

Source	% of $\mathcal{B}(B^0 \to \pi^- e^+ \nu_e)$			% of $\mathcal{B}(B^+ \to \pi^0 e^+ \nu_e)$		
q^2 bin index	1	2	3	1	2	3
$N_{B\bar{B}}$			2.9			
f_{+0}			1.2			
FEI calibration		3.2			3.1	
Tracking		0.6			0.3	
π^0 efficiency		–			4.8	
Signal efficiency ϵ	1.3	1.2	1.4	1.3	1.2	1.3
Electron ID	1.0	0.4	0.4	1.0	0.5	0.5
Pion ID	0.4	0.4	0.4		–	
Total	4.8	4.7	4.8	6.7	6.7	6.7

First Belle II determination of $|V_{ub}|$

Winter 2021 — paper in preparation

- BCL fit with the FNAL-MILC form factor [Phys. Rev. D 92, 014024 (2015)]



Decay mode	Fitted $|V_{ub}|$
$B^0 \to \pi^- e^+ \nu_e$	$(3.71 \pm 0.55)\ \times 10^{-3}$
$B^+ \to \pi^0 e^+ \nu_e$	$(4.21 \pm 0.63)\ \times 10^{-3}$
Combined fit	$(3.88 \pm 0.45)\ \times 10^{-3}$

Summary

- $B \to \pi \ell \nu$
  - The golden mode for $|V_{ub}|$ exclusive from $\Upsilon(4S)$ data
  - $\mathscr{B}(B^0 \to \pi^- \ell^+ \nu) = (1.50 \pm 0.02_{\text{stat}} \pm 0.06_{\text{syst}}) \times 10^{-4}$ (HFLAV 2021)
  - $|V_{ub}| = (3.67 \pm 0.09_{\text{exp}} \pm 0.12_{\text{th}}) \times 10^{-3}$ (HFLAV 2021, LQCD, LCSR)
- $B \to \rho, \omega \ell \nu$
  - $\mathscr{B}$s known to 7-8% precision (HFLAV 2021)
  - Lack of precise FF calculations limits their usefulness in terms of $|V_{ub}|$

Summary

- New Belle II results
  - First determination of $|V_{ub}|$ from $B \to \pi e \nu$ tagged using 189.3/fb of Belle II data
  - $|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}$ (Belle II, LQCD)
- More results are in preparation
  - We expect in particular the untagged measurements for ICHEP 2022 which will significantly increase the precision in $|V_{ub}|$