$|V_{cb}|$ and $|V_{ub}|$ at the B-factories

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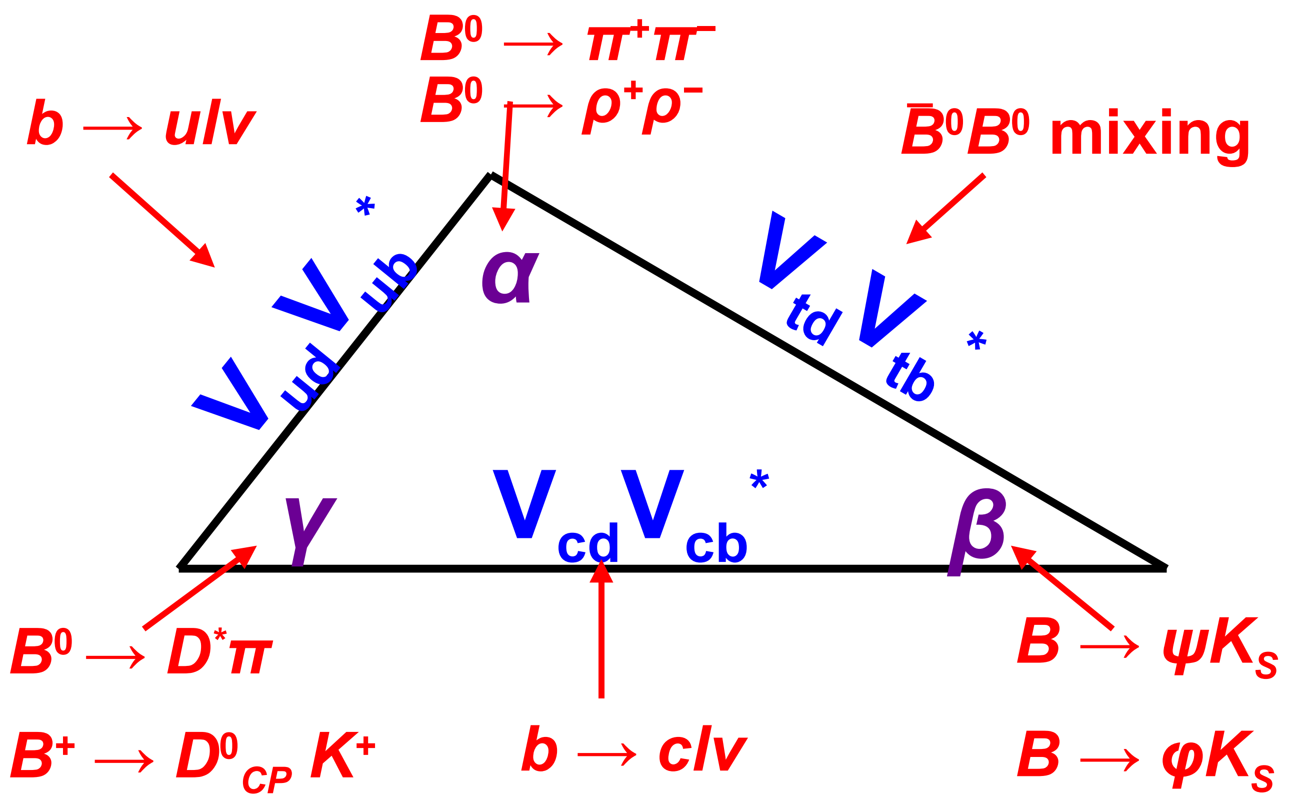
DESY

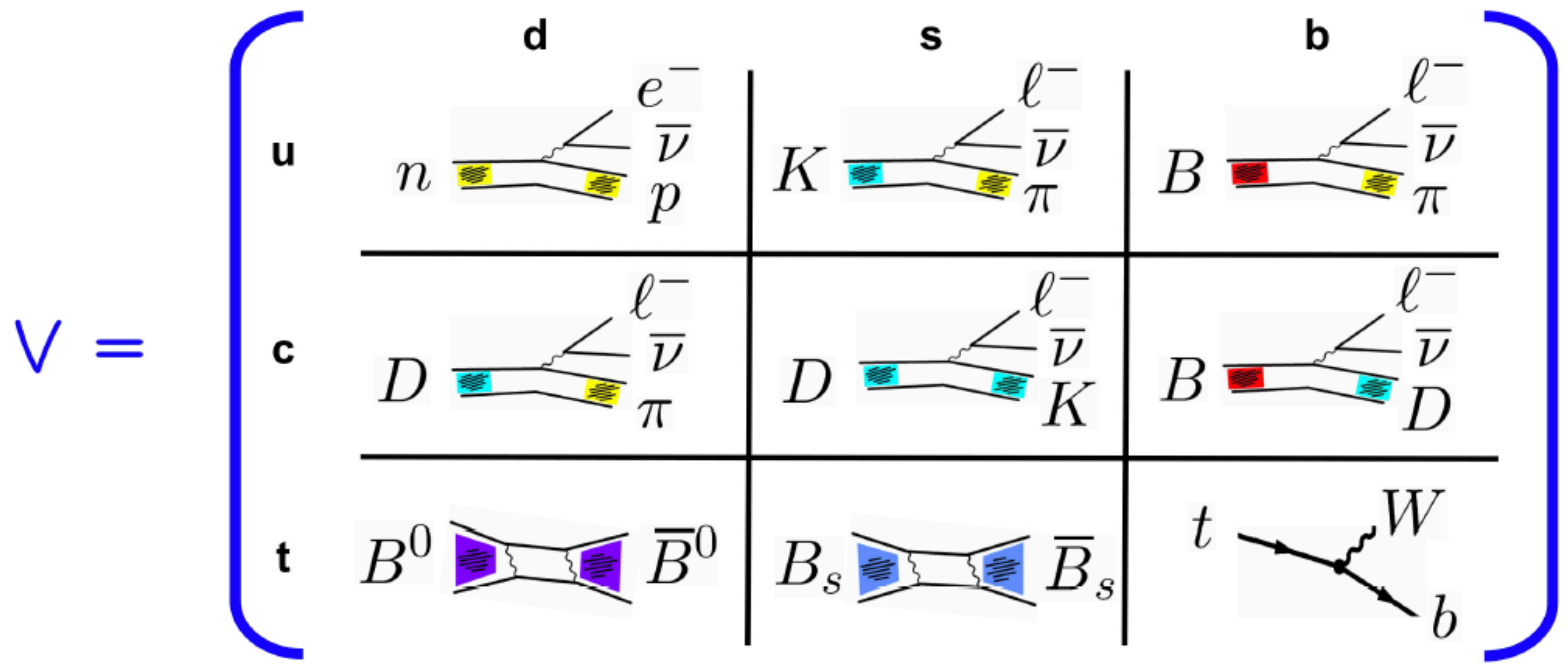
Theory meets Experiment on $|V_{ub}|$ and $|V_{cb}|$ workshop
Jan. 11, 2021

On behalf of the B-Factories

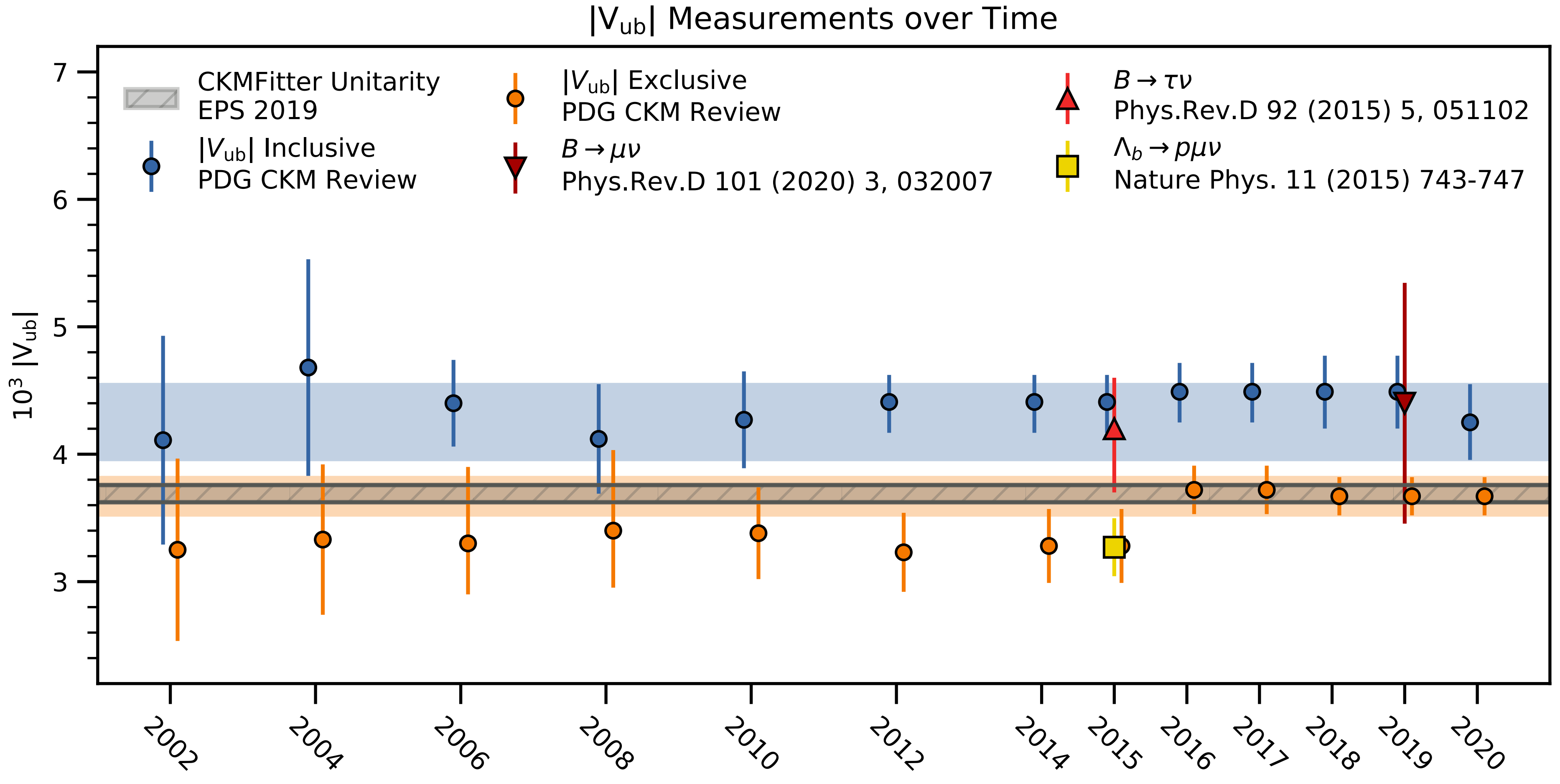
$|V_{cb}|$ and $|V_{ub}|$

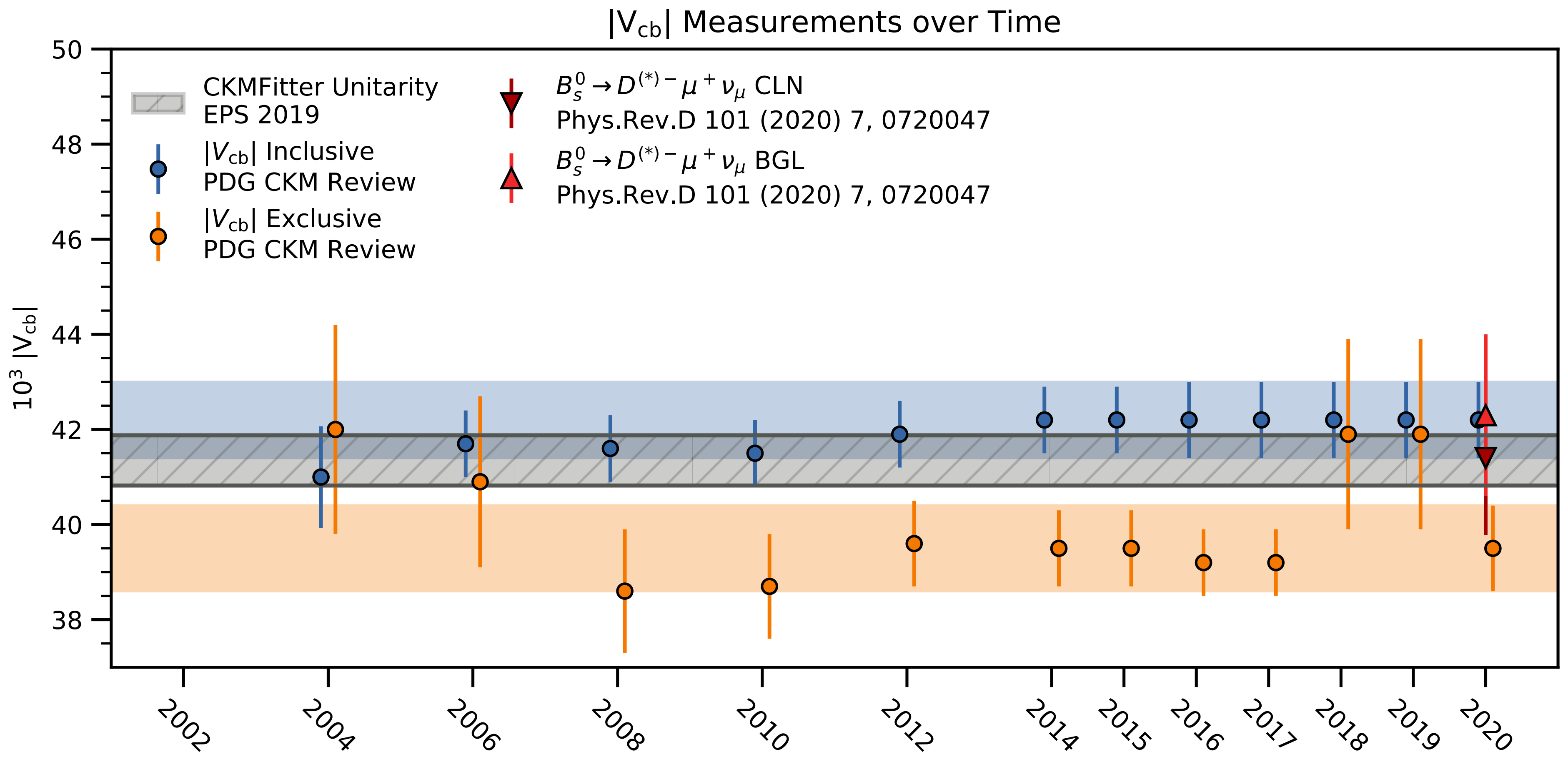
Precision measurements of CKM matrix at the core of the physics program at *B*- factories

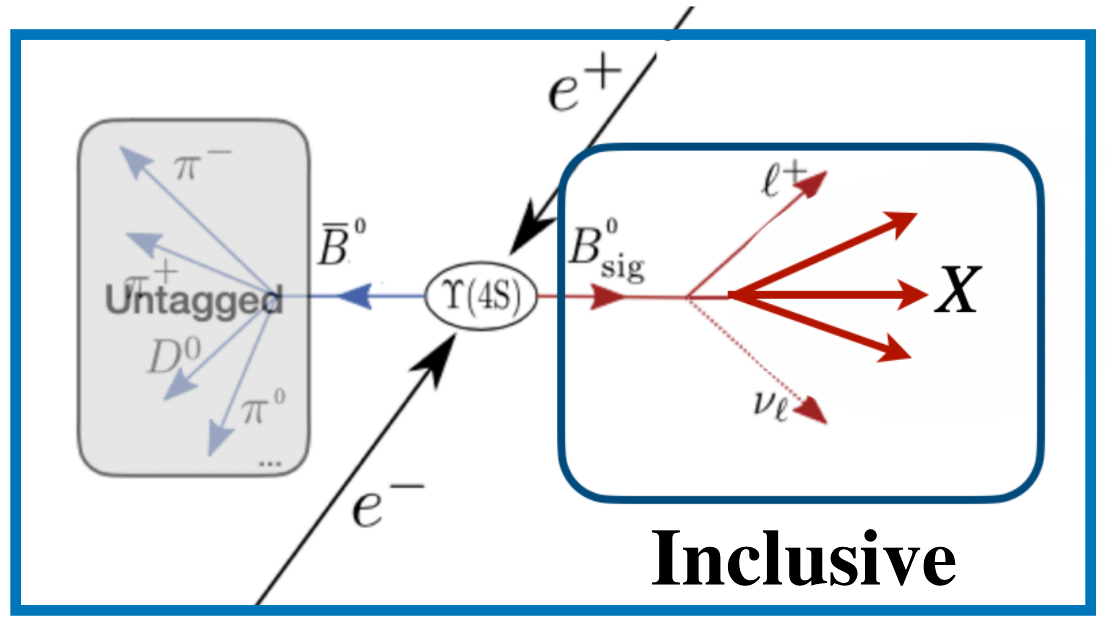


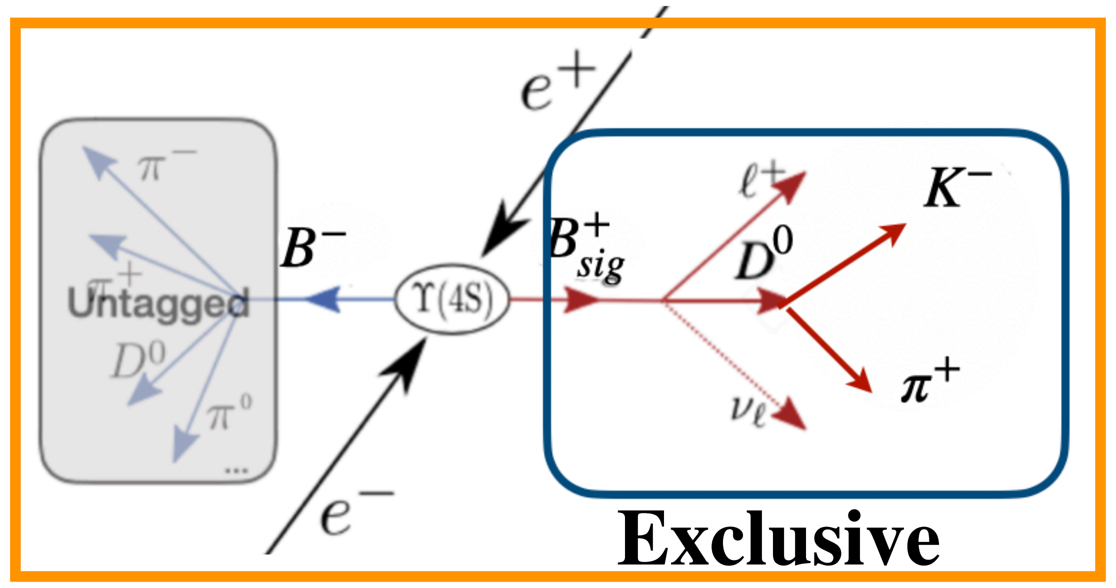


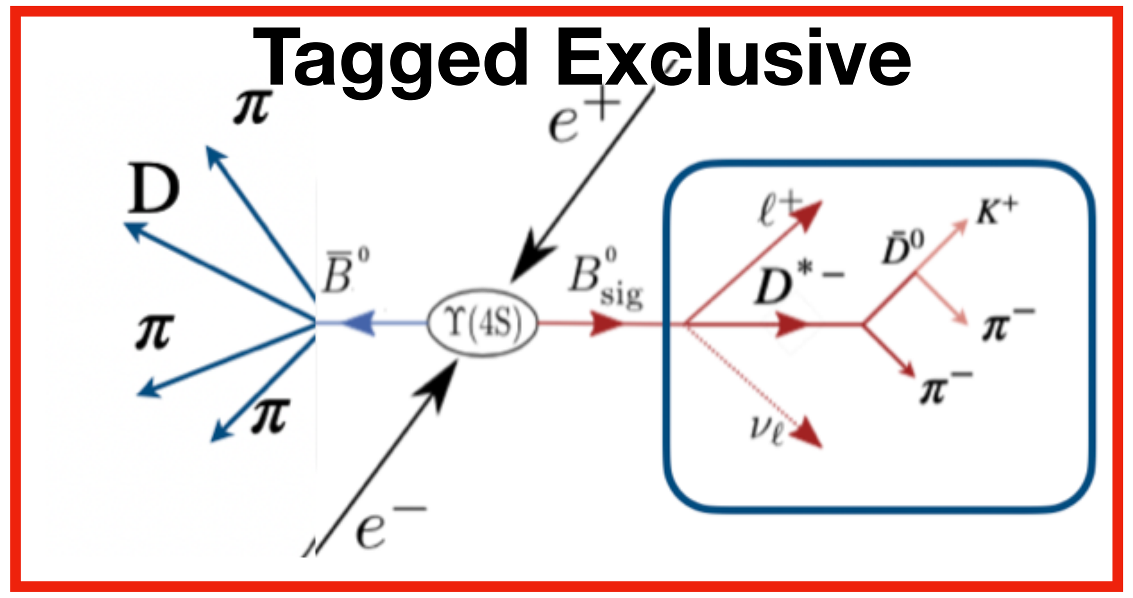
$|V_{ub}|$ **and** $|V_{cb}|$ **mainly from semileptonic decays of *B* mesons**











Tension between exclusive and inclusive $|V_{ub}|$ and $|V_{cb}|$ measurements along with other related *B*-anomalies .

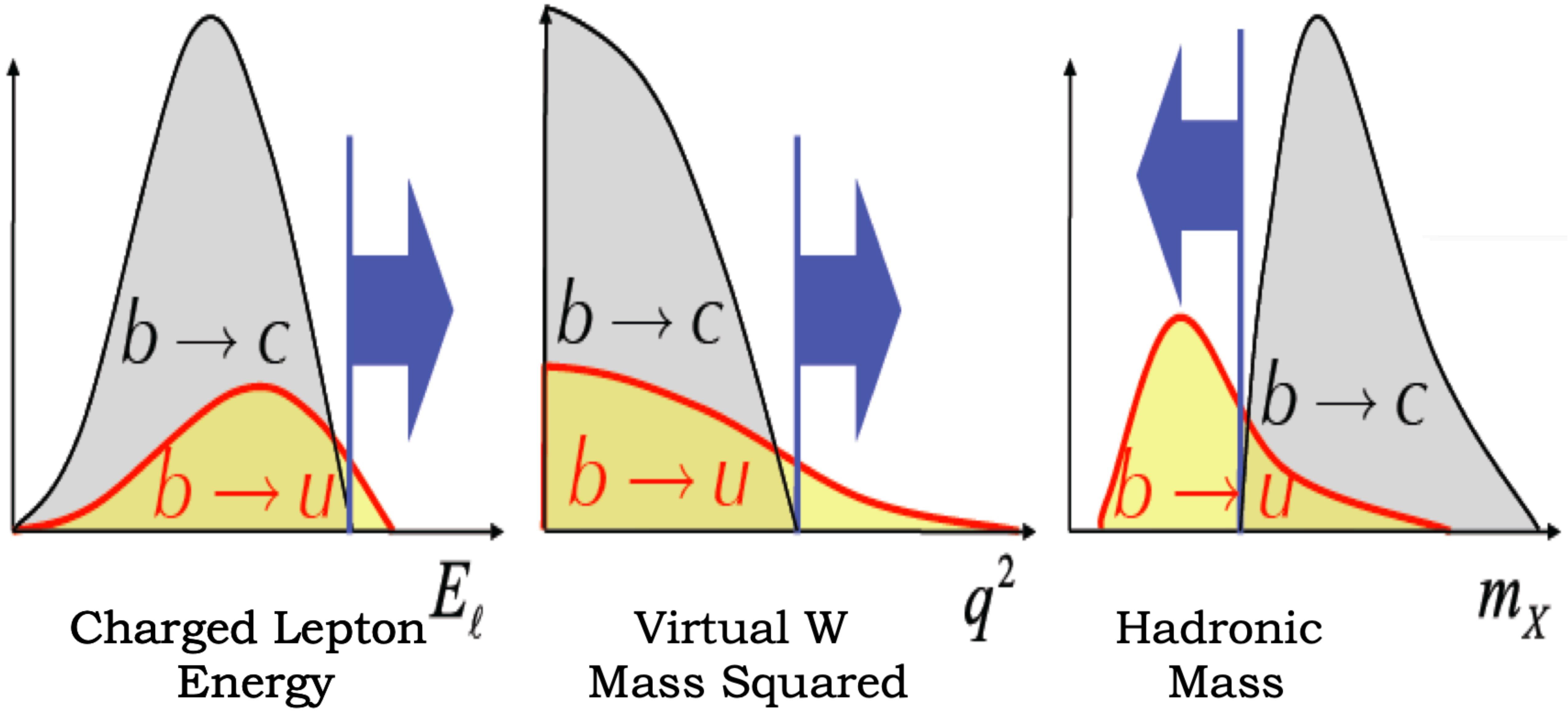
$|V_{ub}|$

- Experimentally challenging due to dominant $B \to X_c \ell \nu$ background.
- Only certain kinematic regions allow for clean separation: lepton momentum endpoint spectrum or low m_X.
- Inclusive via $B \to X_u \ell \nu$:
  - Precision of (~7%)
  - Operator Product Expansion (OPE) = Heavy Quark Expansion.
  - HQE breaks down and a non-perturbative shape function is required.

$$d\Gamma = d\Gamma_0 + d\Gamma_2 \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^2 + d\Gamma_3 \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^3 + d\Gamma_4 \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^4$$

- Exclusive via $B \to \pi \ell \nu$
  - Most precise determination of $|V_{ub}|$ (~4%)
  - Form factor determined non-perturbative from lattice QCD (high q^2) or LCSR (q^2~0) .

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



$$|V_{ub}| = (4.25 \pm 0.12^{+0.15}_{-0.14} \pm 0.23) \times 10^{-3}$$ **PDG inclusive**

$$|V_{ub}| = (3.70 \pm 0.10 \pm 0.12) \times 10^{-3}$$ **PDG exclusive**

Current ~3σ tension between inclusive and exclusive determinations

Inclusive $|V_{ub}|$

Phys. Rev. Lett. 88, 231803 (2002)
Phys. Lett. B621, 28 (2005)
Phys. Rev. D95, 7, 072001 (2017)
Phys. Rev. D73, 012006 (2006)
Phys. Rev. Lett. 95, 111801 (2005)

Based on HQE of $B \to X_u \ell \nu$ with 5% theoretical uncertainty and requires parametrization of the shape function (SF) using various theoretical approaches:

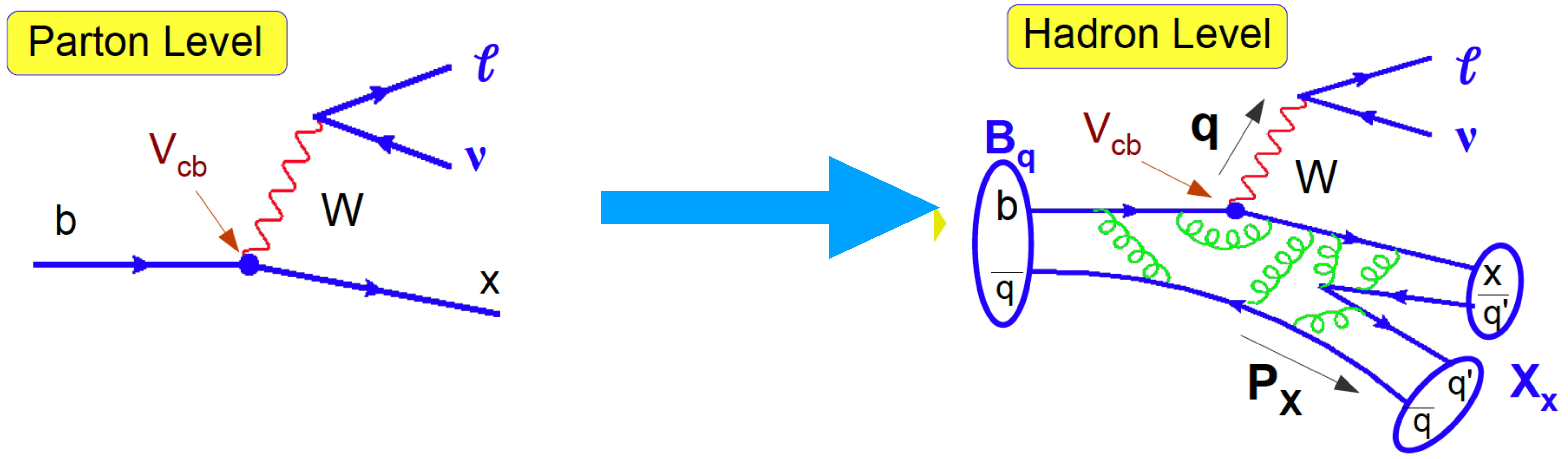
- **BLNP**: B. O. Lange, M. Neubert and G. Paz, Phys. Rev. D 72, 073006 (2005)
- **DGE**: J. R. Andersen and E. Gardi JHEP 0601 097 (2006)
- **GGOU**: P. Gambino et al., JHEP 0710 058 (2007)

Ref.	cut (GeV)	BLNP	GGOU	DGE
CLEO	$E_e > 2.1$	$422 \pm 49 \,{}^{+29}_{-34}$	$423 \pm 49 \,{}^{+22}_{-31}$	$386 \pm 45 \,{}^{+25}_{-27}$
BABAR	$E_e - q^2$	$471 \pm 32 \,{}^{+33}_{-38}$	not available	$435 \pm 29 \,{}^{+28}_{-30}$
BABAR	$E_e > 2.0$	$452 \pm 26 \,{}^{+26}_{-30}$	$452 \pm 26 \,{}^{+17}_{-24}$	$430 \pm 24 \,{}^{+23}_{-25}$
Belle	$E_e > 1.9$	$493 \pm 46 \,{}^{+26}_{-29}$	$495 \pm 46 \,{}^{+16}_{-21}$	$482 \pm 45 \,{}^{+23}_{-23}$
BABAR	$E_e > 0.8$	$441 \pm 12 \,{}^{+27}_{-27}$	$396 \pm 10 \,{}^{+17}_{-17}$	$385 \pm 11 \,{}^{+8}_{-7}$
BABAR	$q^2>8$ $m_X<1.7$	$432 \pm 23 \,{}^{+26}_{-28}$	$433 \pm 23 \,{}^{+24}_{-27}$	$424 \pm 22 \,{}^{+18}_{-21}$
BABAR	$P_+ < 0.66$	$409 \pm 25 \,{}^{+25}_{-25}$	$425 \pm 26 \,{}^{+26}_{-27}$	$417 \pm 25 \,{}^{+28}_{-37}$
BABAR	$m_X < 1.7$	$403 \pm 22 \,{}^{+22}_{-22}$	$410 \pm 23 \,{}^{+16}_{-17}$	$422 \pm 23 \,{}^{+21}_{-27}$
BABAR	$E_\ell > 1$	$433 \pm 24 \,{}^{+19}_{-21}$	$444 \pm 24 \,{}^{+9}_{-10}$	$445 \pm 24 \,{}^{+12}_{-13}$
Belle	$E_\ell > 1$	$450 \pm 27 \,{}^{+20}_{-22}$	$462 \pm 28 \,{}^{+9}_{-10}$	$462 \pm 28 \,{}^{+13}_{-13}$
HFLAV	Combination	444^{+13+21}_{-14-22}	$432 \pm 12 \,{}^{+12}_{-13}$	$399 \pm 10 \,{}^{+9}_{-10}$

Shape function accounts for the motion of the b quark inside the B meson and should be universal for all b transitions to light quarks.

3 main approaches to measuring inclusive $|V_{ub}|$:

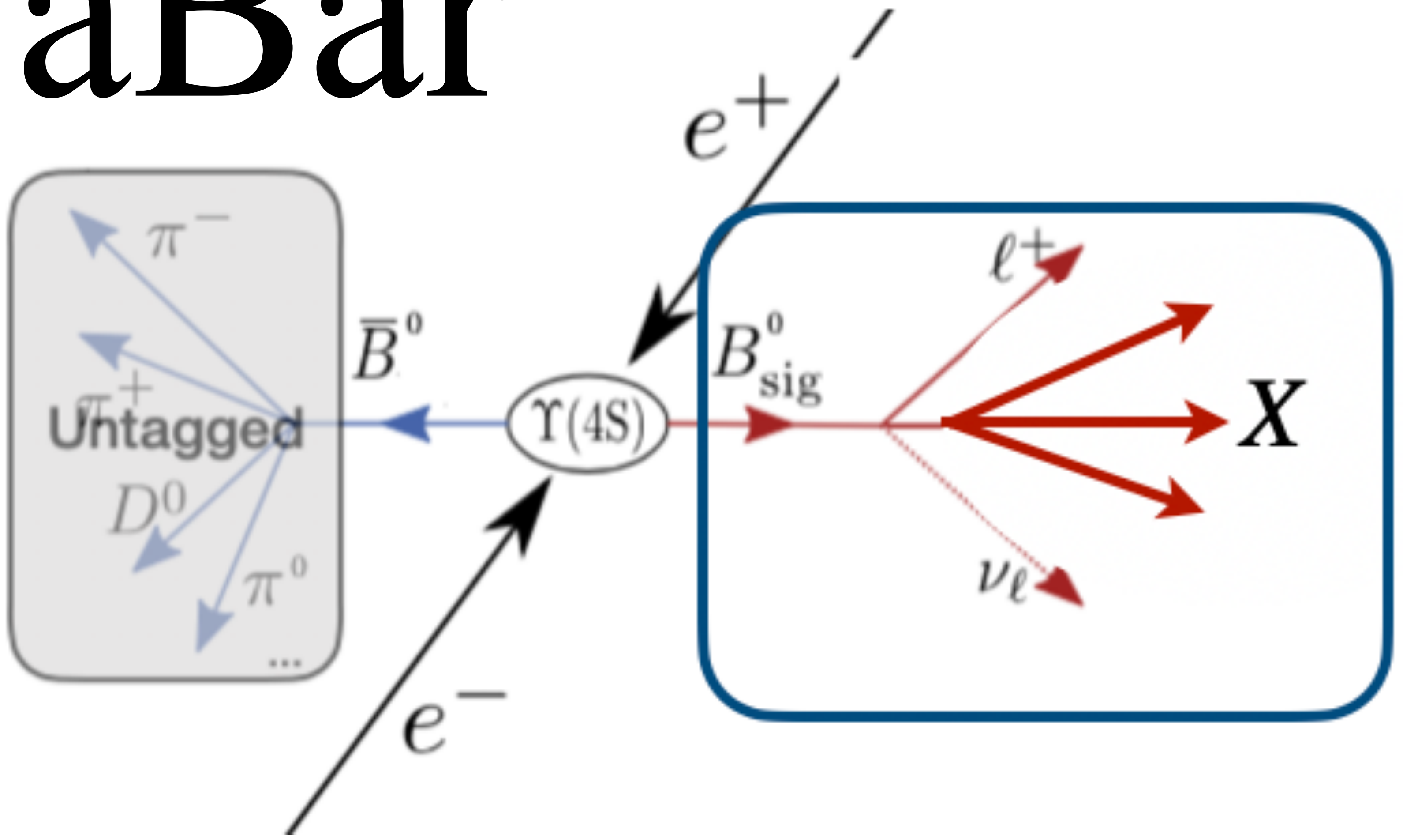
1. Lepton endpoint spectrum:
   Reconstruct a single charged electron and measure the partial rate near the kinematic endpoint
2. Untagged "neutrino reconstruction"
   Reconstruct lepton + missing momentum vector
3. Tagged reconstruction, where one B is fully constrained using hadronic modes.

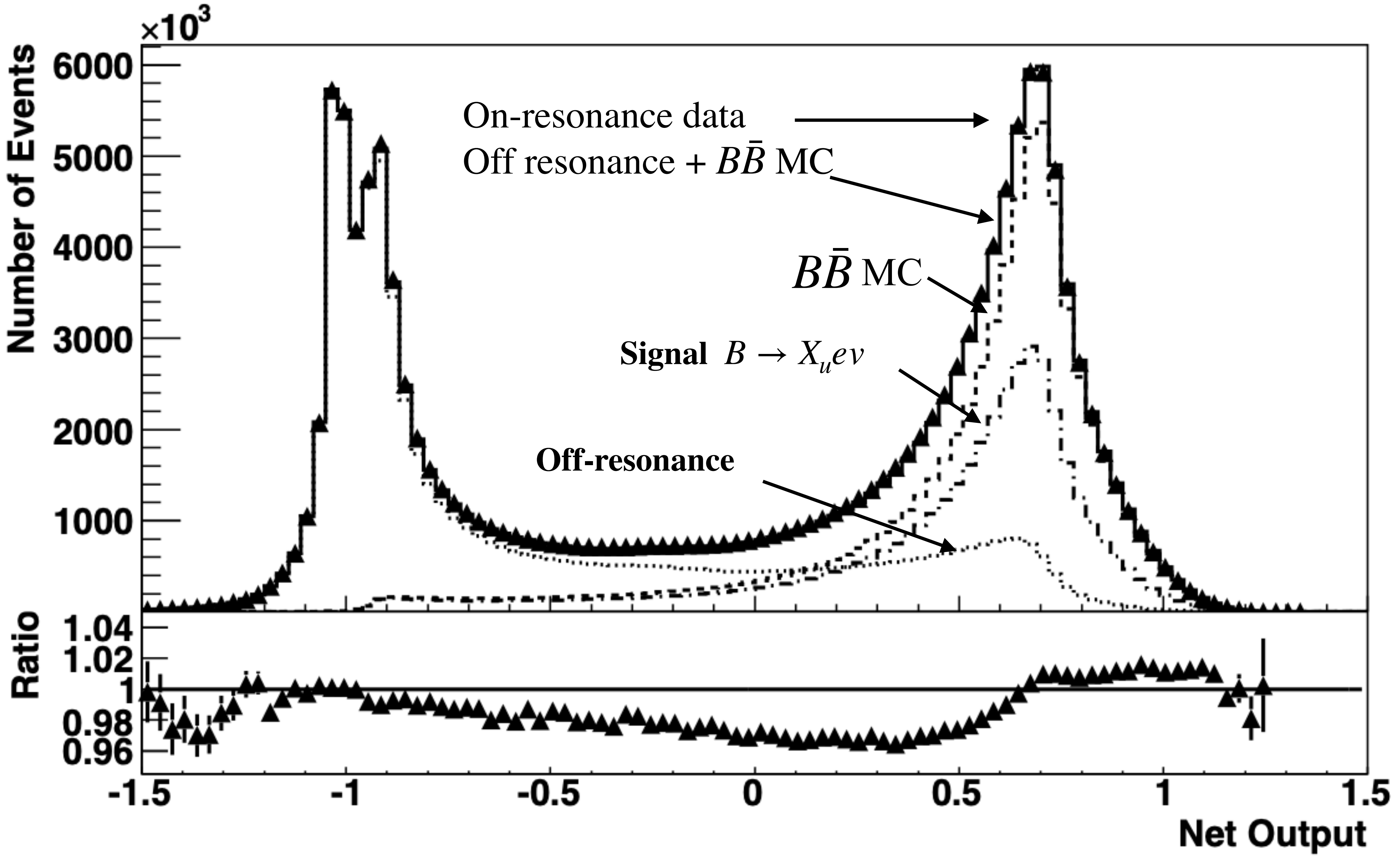


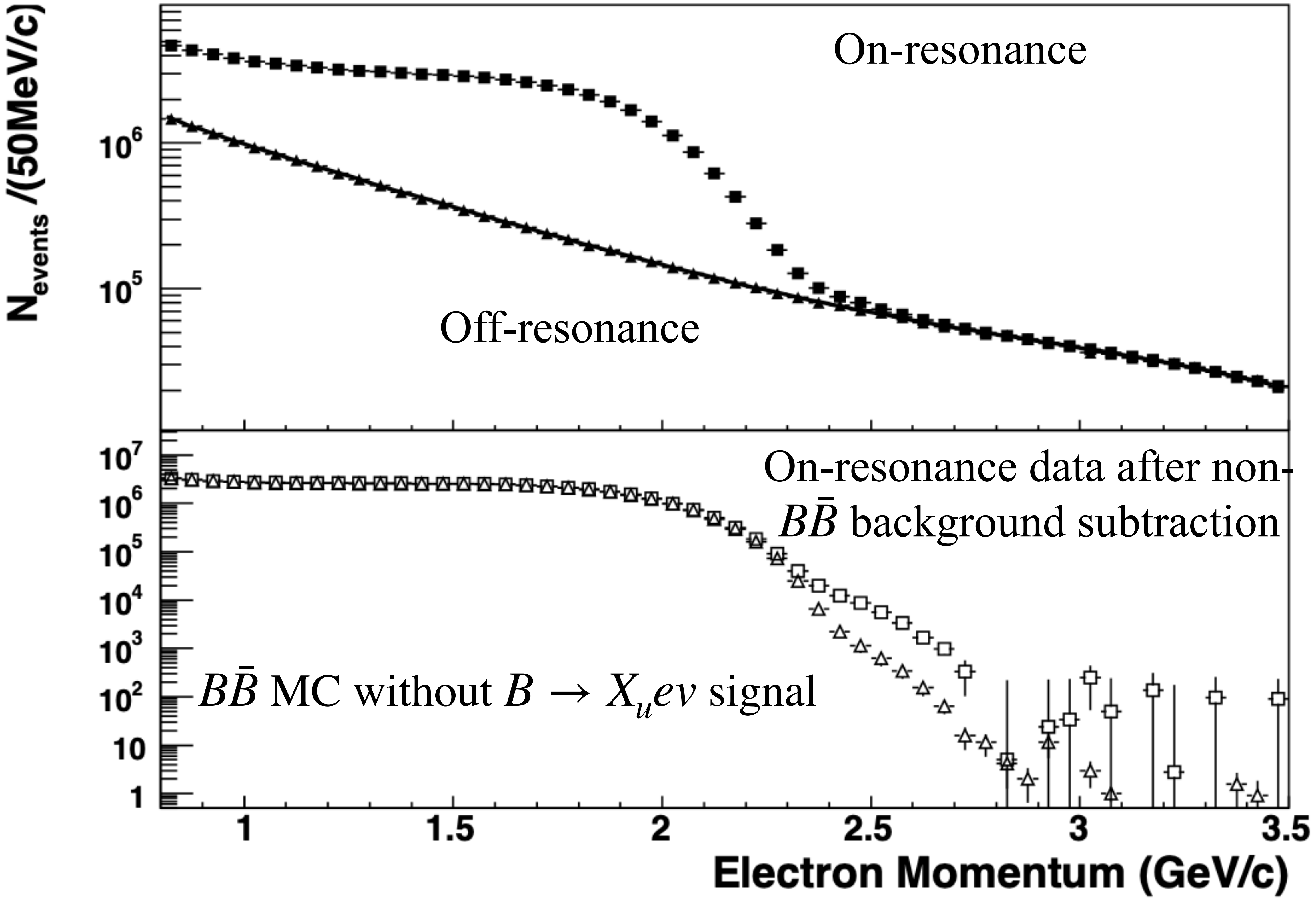
Phys. Rev. D 95, 072001 (2017)

Inclusive $|V_{ub}|$ at BaBar

- Using 470 fb^{-1}extract $|V_{ub}|$ and measure $B \to X_u e\nu$
- Identify electron with $0.8 < p_{CMS} < 5.0$ GeV/c
- Suppress non-$B\bar{B}$ background using Neural Network.







- Subtract continuum background using χ^2 fit to off-resonance data
- Subtract BB background using simultaneous χ^2 fit to off and on resonance data, relying on MC simulation for the inclusive Xc spectra.

Phys. Rev. D 95, 072001 (2017)

Inclusive $|V_{ub}|$ at BaBar

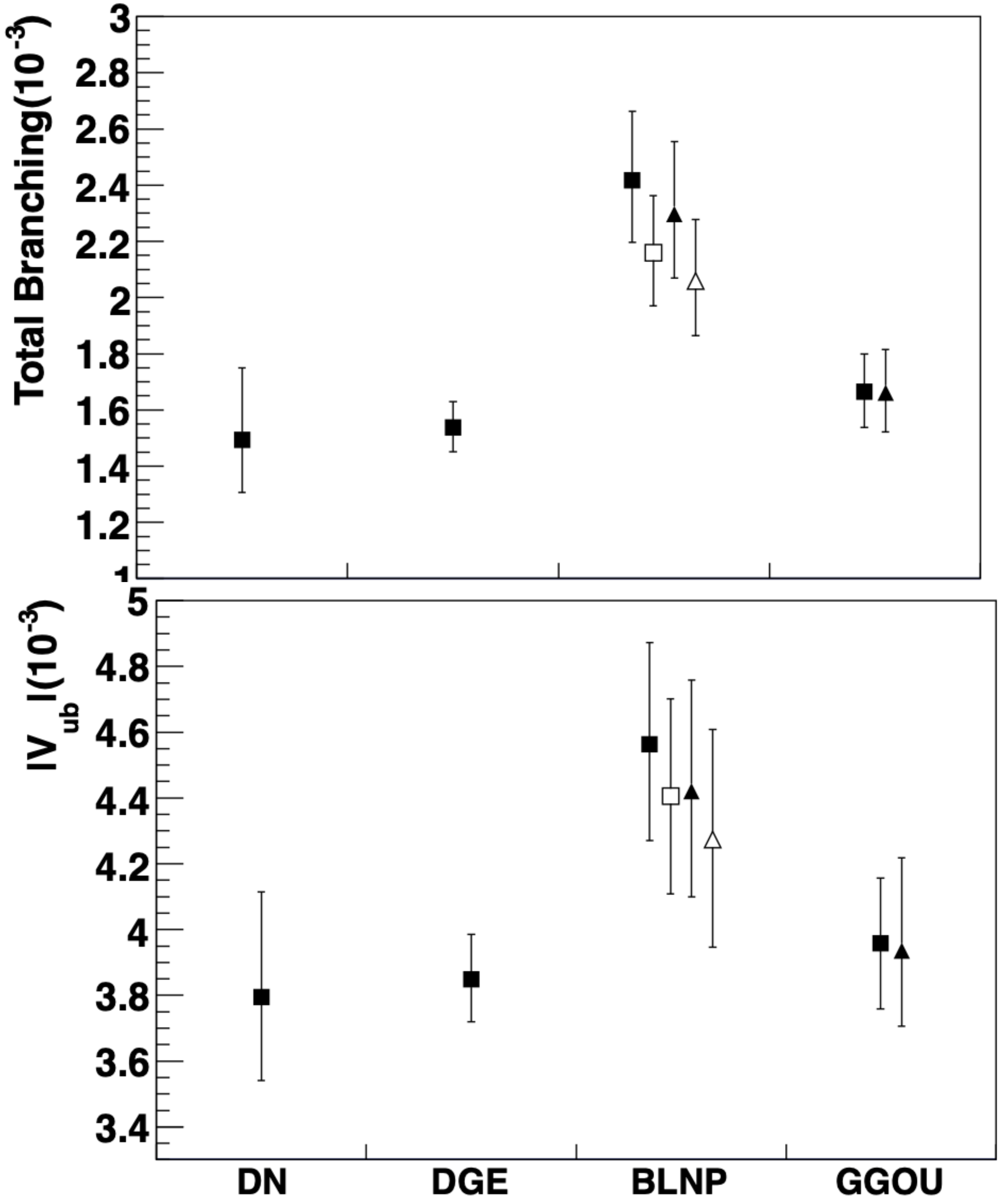
- Extract |Vub| using:

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(\Delta p)}{\tau_b\,\Delta\zeta(\Delta p)}}.$$

PDG value of *B* lifetime

Input from 4 theoretical models

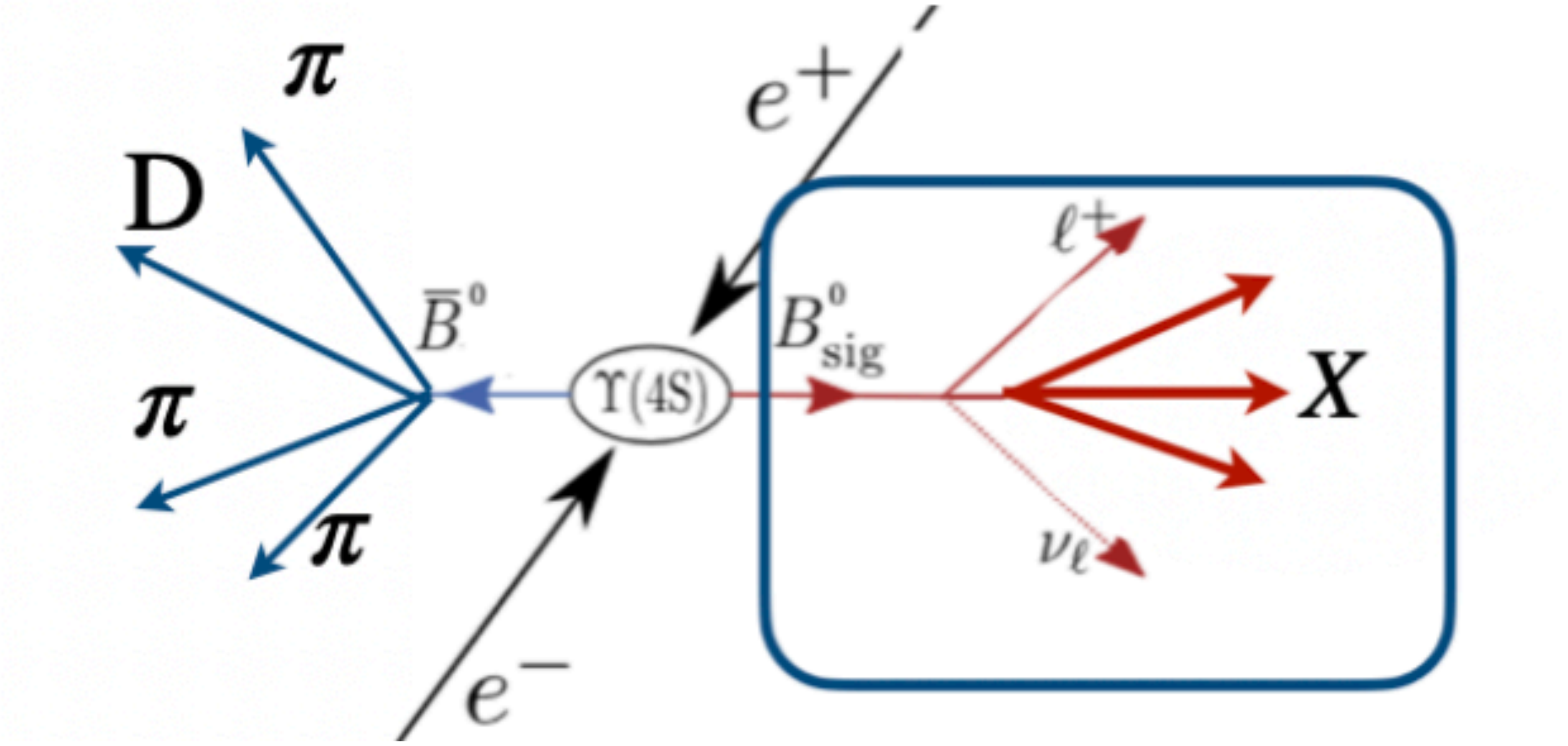
- Main uncertainties due to:
  - Simulation of the electron signal spectrum
  - Background subtraction: shape of the signal and background spectra
  - uncertainty on the SF parameters and theoretical predictions of the rate (both perturbative and non-perturbative)

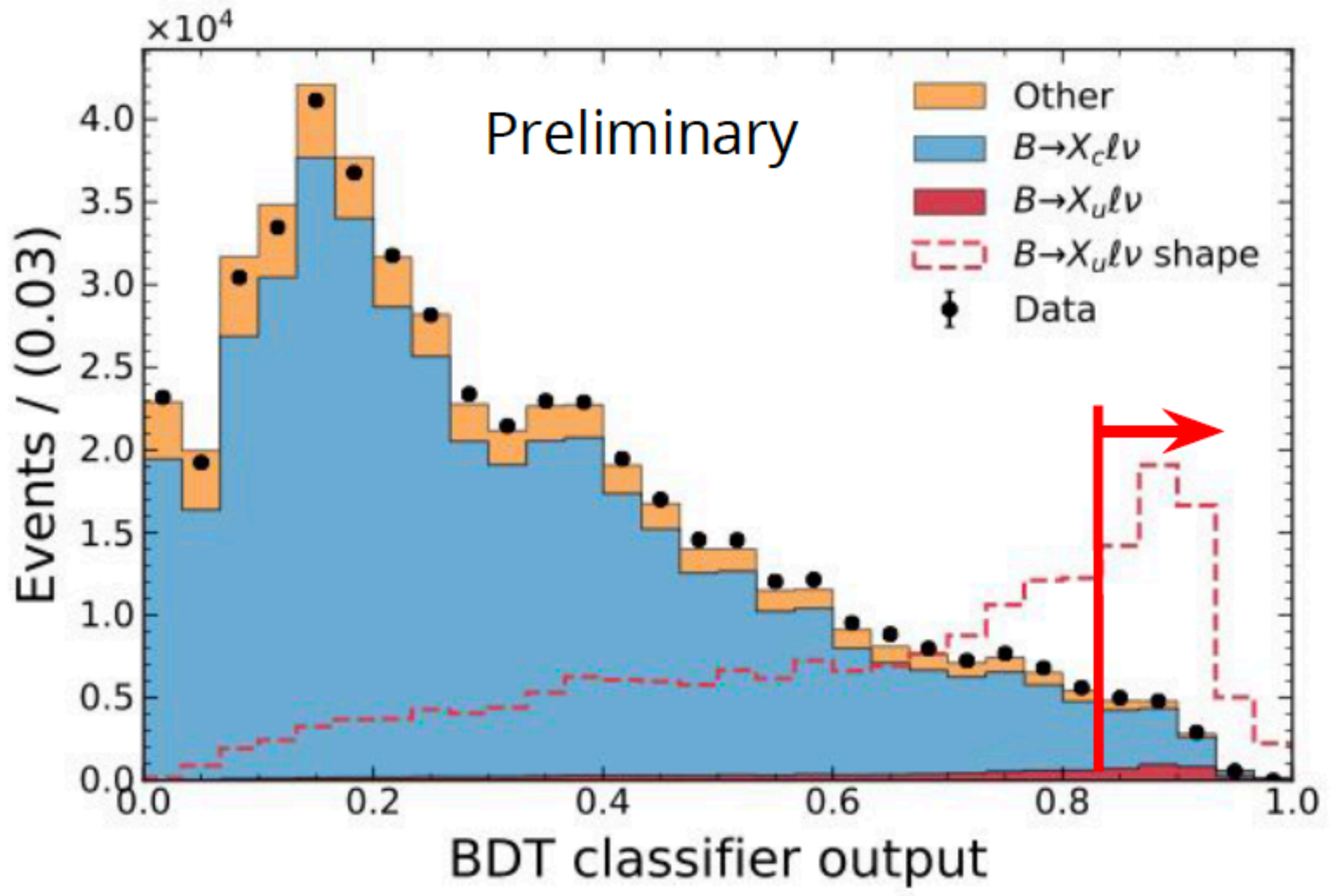


Inclusive $|V_{ub}|$ at Belle

Preliminary

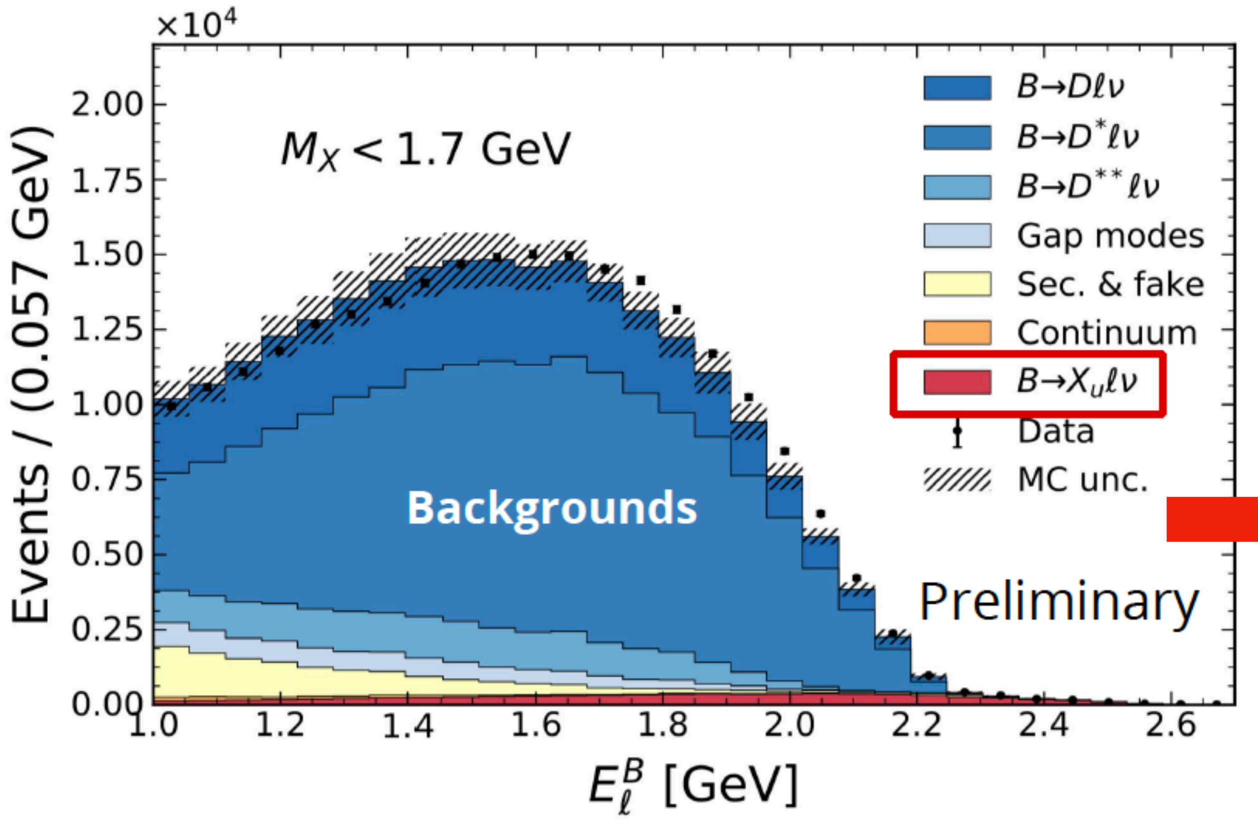
Using 711 fb^{-1} of Belle data
Hadronic Tagging with Neural Network (0.2-0.3% efficiency)
Reconstruct X system using remaining tracks and clusters in the event
Suppress backgrounds using Boosted Decision Tree

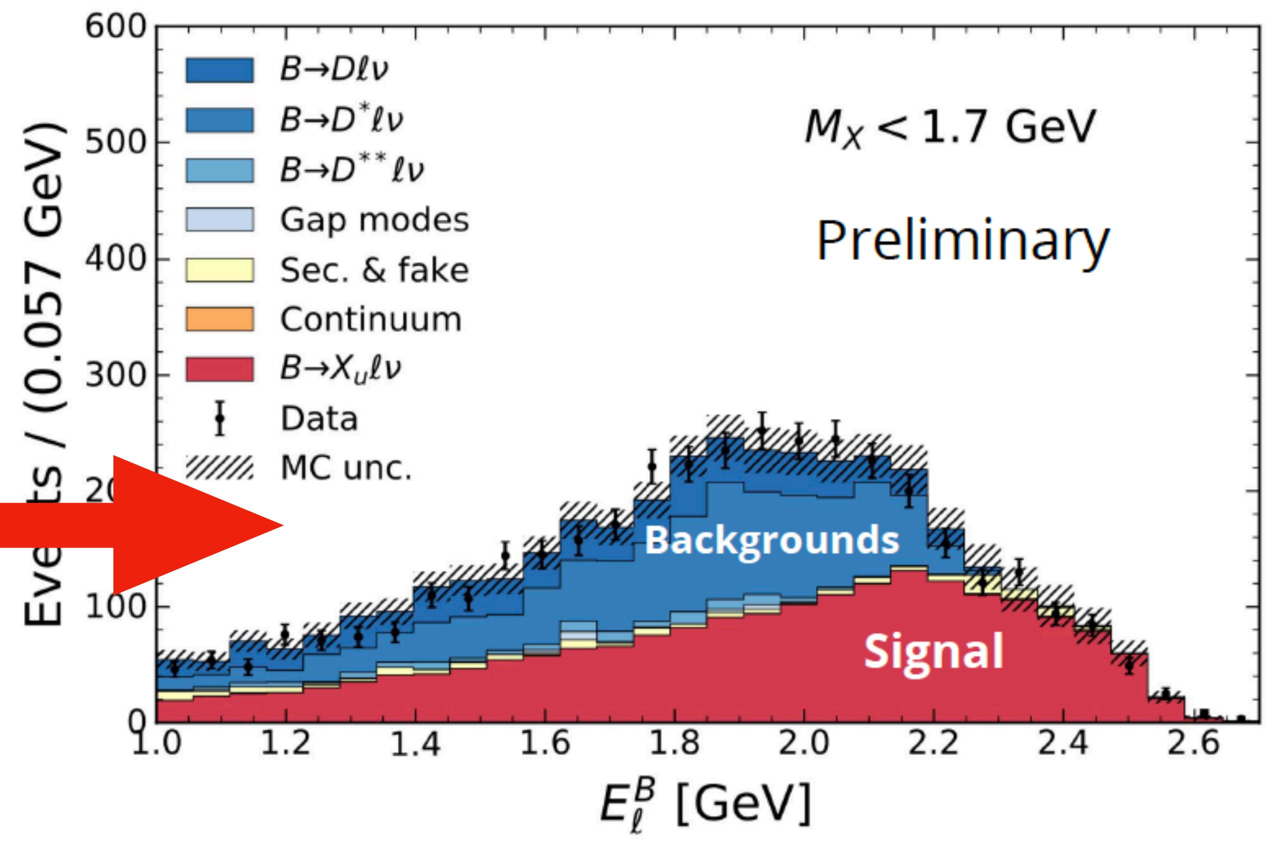




Extract signal using binned likelihood to 3 variables in 3 phase space regions :

	Fit var	Phase space	Additional cut
	M_X	$E_\ell^B > 1$ GeV, $M_X < 1.7$ GeV	
	q^2	$E_\ell^B > 1$ GeV, $M_X < 1.7$ GeV, $q^2 > 8$ GeV^2	$M_X^{\text{reco}} < 1.7$ GeV
	E_ℓ^B	$E_\ell^B > 1$ GeV, $M_X < 1.7$ GeV	$M_X^{\text{reco}} < 1.7$ GeV
	E_ℓ^B	$E_\ell^B > 1$ GeV	$M_X^{\text{reco}} < 1.7$ GeV
2D-fit	$M_X - q^2$	$E_\ell^B > 1$ GeV	



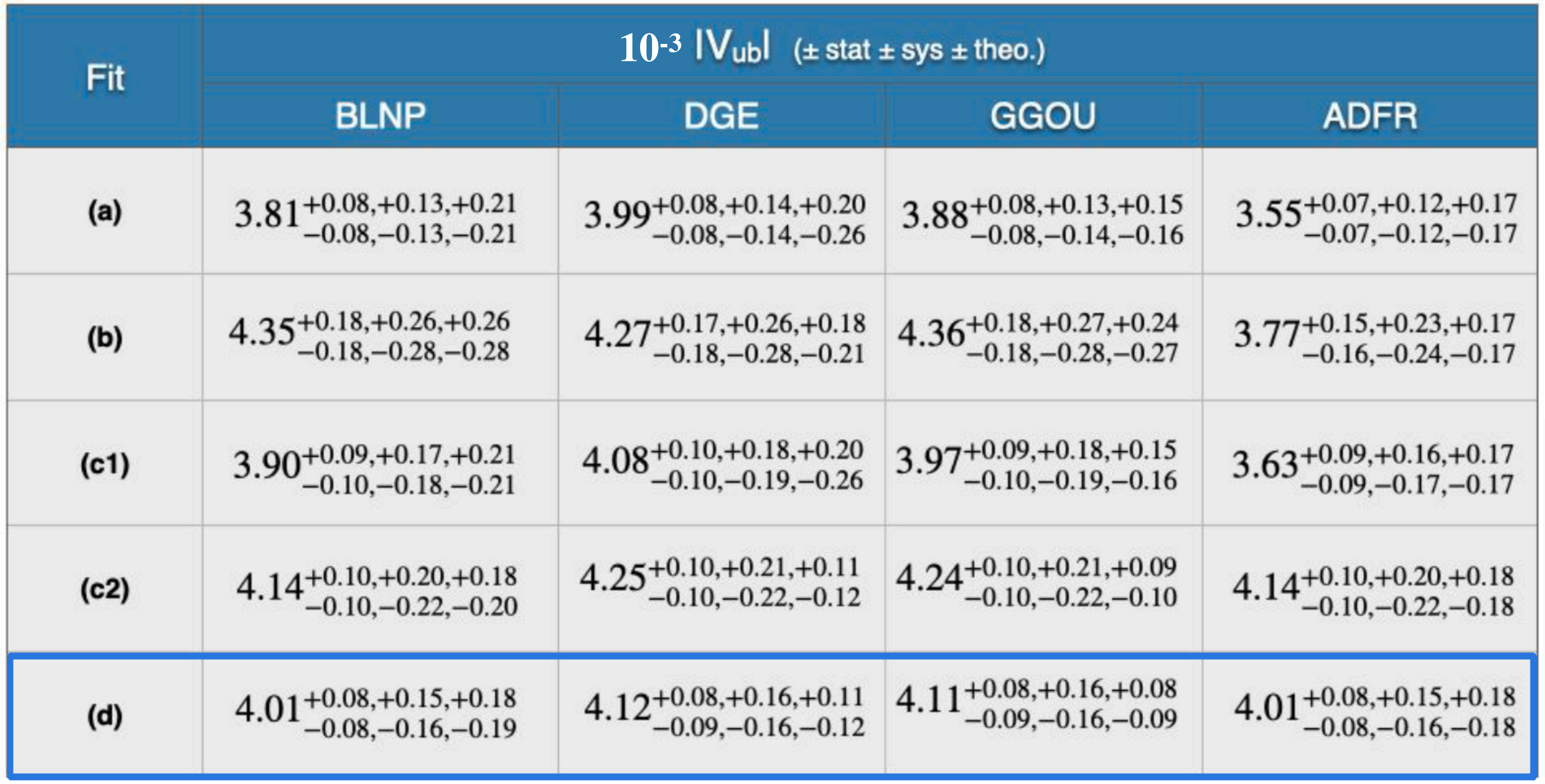


Additional kinematic cuts to reduce impact of $B \to X_c \ell \nu$ modelling

Inclusive $|V_{ub}|$ at Belle

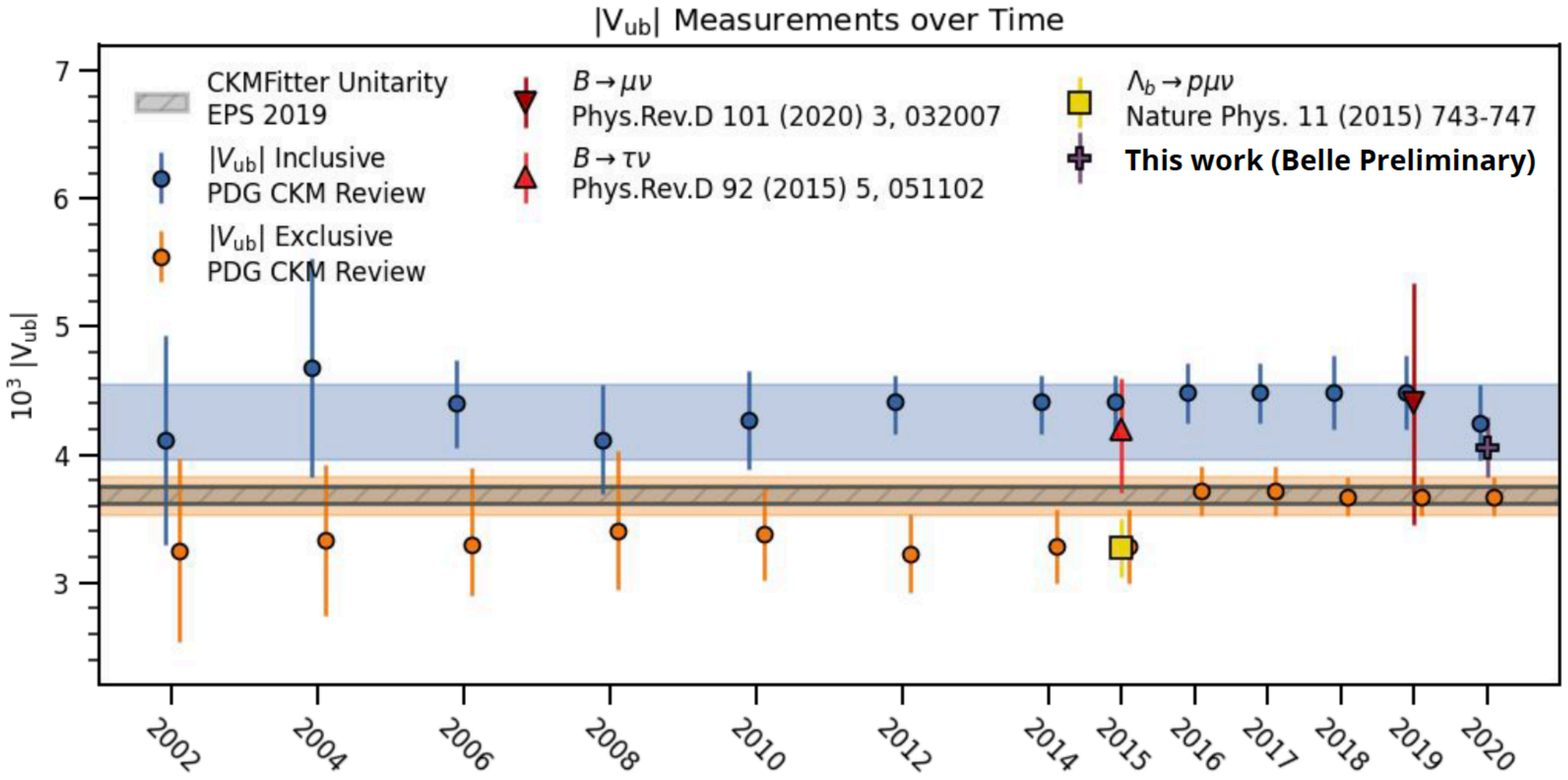
$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u\, \ell^+\, \nu_\ell)}{\tau_B \cdot \Delta\Gamma(B \to X_u\, \ell^+\, \nu_\ell)}}$$

Preliminary



Fit	10^{-3} $|V_{ub}|$ (± stat ± sys ± theo.)			
	BLNP	DGE	GGOU	ADFR
(a)	$3.81^{+0.08,+0.13,+0.21}_{-0.08,-0.13,-0.21}$	$3.99^{+0.08,+0.14,+0.20}_{-0.08,-0.14,-0.26}$	$3.88^{+0.08,+0.13,+0.15}_{-0.08,-0.14,-0.16}$	$3.55^{+0.07,+0.12,+0.17}_{-0.07,-0.12,-0.17}$
(b)	$4.35^{+0.18,+0.26,+0.26}_{-0.18,-0.28,-0.28}$	$4.27^{+0.17,+0.26,+0.18}_{-0.18,-0.28,-0.21}$	$4.36^{+0.18,+0.27,+0.24}_{-0.18,-0.28,-0.27}$	$3.77^{+0.15,+0.23,+0.17}_{-0.16,-0.24,-0.17}$
(c1)	$3.90^{+0.09,+0.17,+0.21}_{-0.10,-0.18,-0.21}$	$4.08^{+0.10,+0.18,+0.20}_{-0.10,-0.19,-0.26}$	$3.97^{+0.09,+0.18,+0.15}_{-0.10,-0.19,-0.16}$	$3.63^{+0.09,+0.16,+0.17}_{-0.09,-0.17,-0.17}$
(c2)	$4.14^{+0.10,+0.20,+0.18}_{-0.10,-0.22,-0.20}$	$4.25^{+0.10,+0.21,+0.11}_{-0.10,-0.22,-0.12}$	$4.24^{+0.10,+0.21,+0.09}_{-0.10,-0.22,-0.10}$	$4.14^{+0.10,+0.20,+0.18}_{-0.10,-0.22,-0.18}$
(d)	$4.01^{+0.08,+0.15,+0.18}_{-0.08,-0.16,-0.19}$	$4.12^{+0.08,+0.16,+0.11}_{-0.09,-0.16,-0.12}$	$4.11^{+0.08,+0.16,+0.08}_{-0.09,-0.16,-0.09}$	$4.01^{+0.08,+0.15,+0.18}_{-0.08,-0.16,-0.18}$

Highest precision achieved with 2D fit!



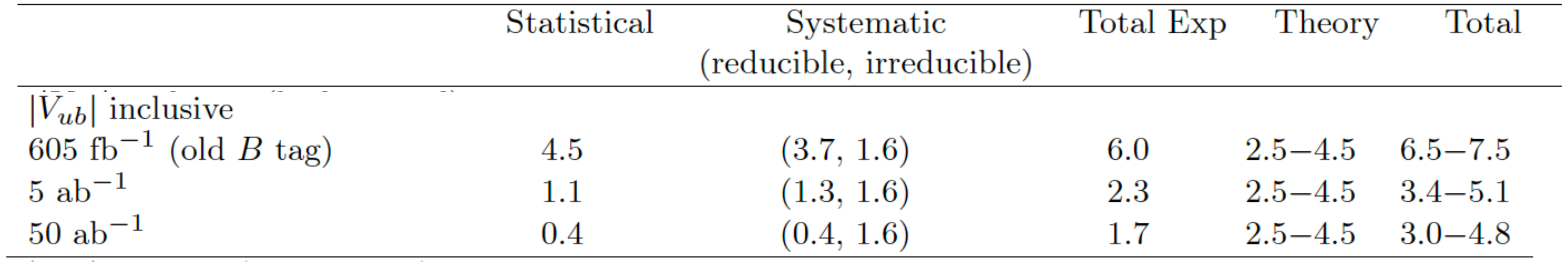
Result compatible within 1.4 σ with exclusive determinations.

$|V_{ub}|$ (avg) = **($4.06 \pm 0.09_{\text{stat}} \pm 0.16_{\text{sys}} \pm 0.15_{\text{theo}}$) x 10^{-3}**

Arithmetic average over 4 determinations!

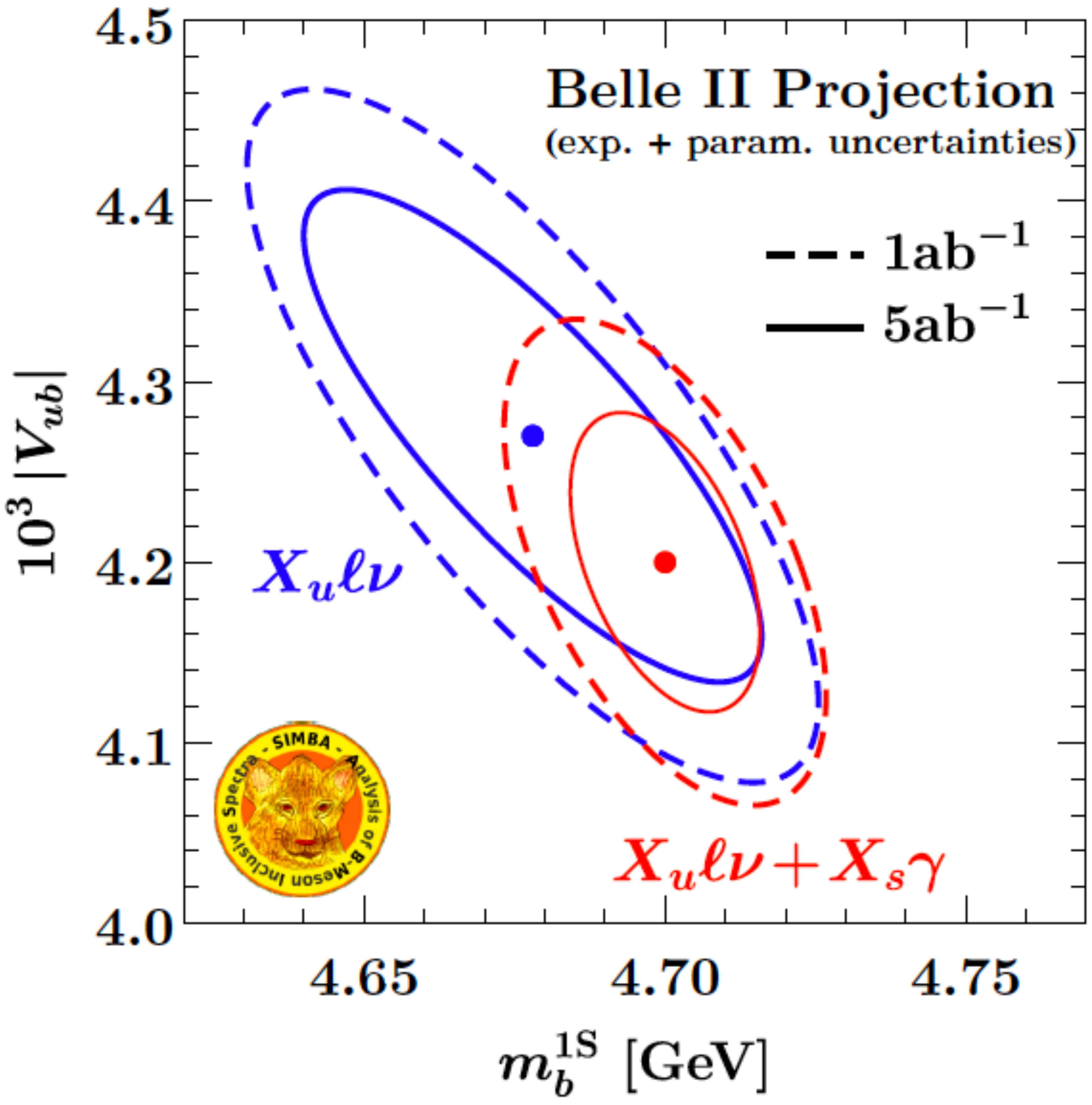
Inclusive $|V_{ub}|$ at Belle II

- Maximize shape function information by measuring a large number of differential spectra
- Global fit to the full spectrum, combining $B \to X_u \ell \nu$ and $B \to X_s \gamma$ with constraints on HQE parameters from $B \to X_c \ell \nu$ simultaneously
- This has been demonstrated by SIMBA, **A**nalysis of ***B***-Meson, **I**nclusive **S**pectra, group.



	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\|V_{ub}\|$ inclusive					
605 fb^{-1} (old B tag)	4.5	(3.7, 1.6)	6.0	2.5–4.5	6.5–7.5
5 ab^{-1}	1.1	(1.3, 1.6)	2.3	2.5–4.5	3.4–5.1
50 ab^{-1}	0.4	(0.4, 1.6)	1.7	2.5–4.5	3.0–4.8

- Systematic uncertainties related to tracking and PID will be improved by Belle II upgrades:
  - New and improved PID in the barrel region (time of propagation counter)
  - Smaller drift chamber cell size .
  - Improved detector performance

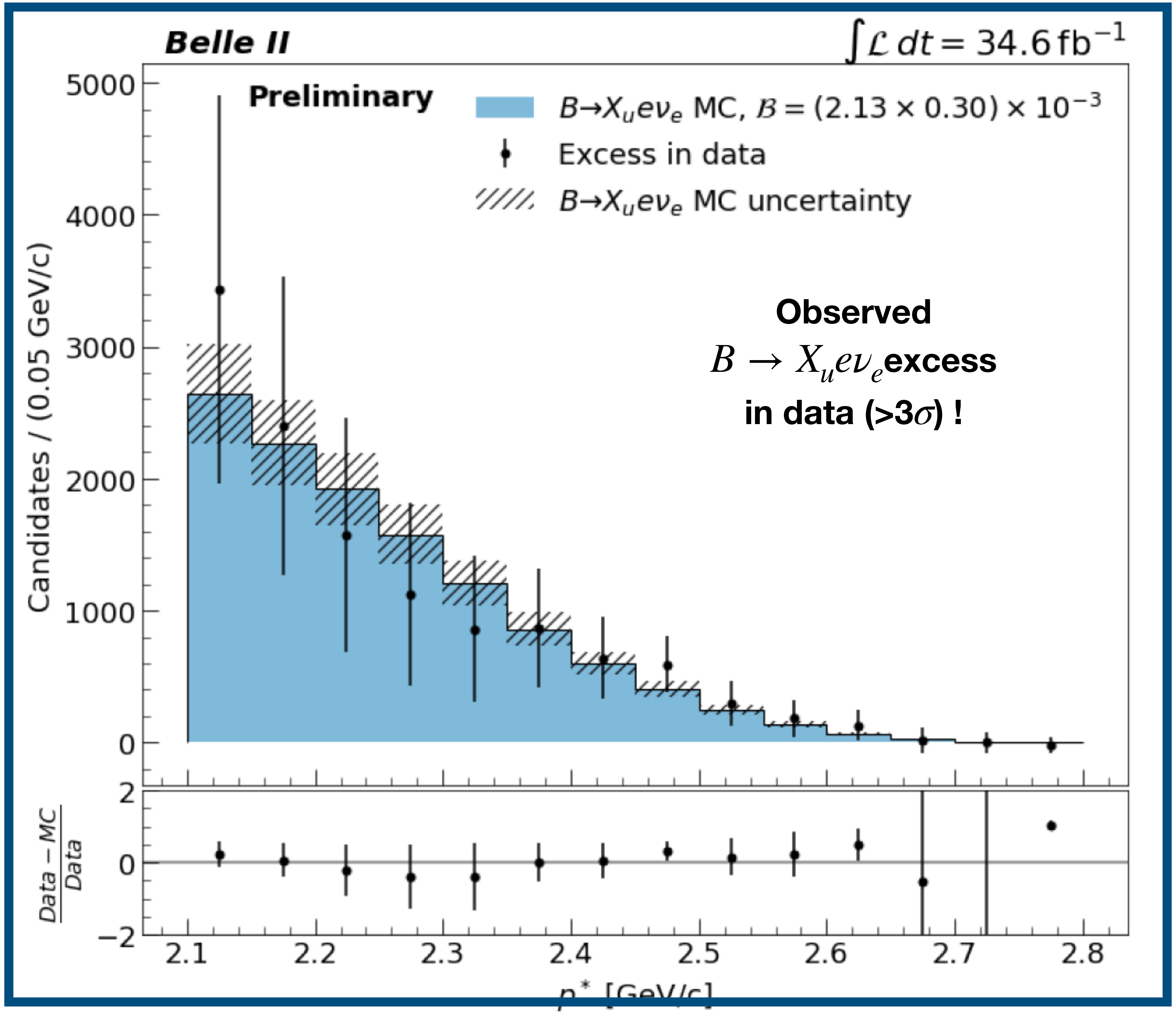


Inclusive $|V_{ub}|$ at Belle II

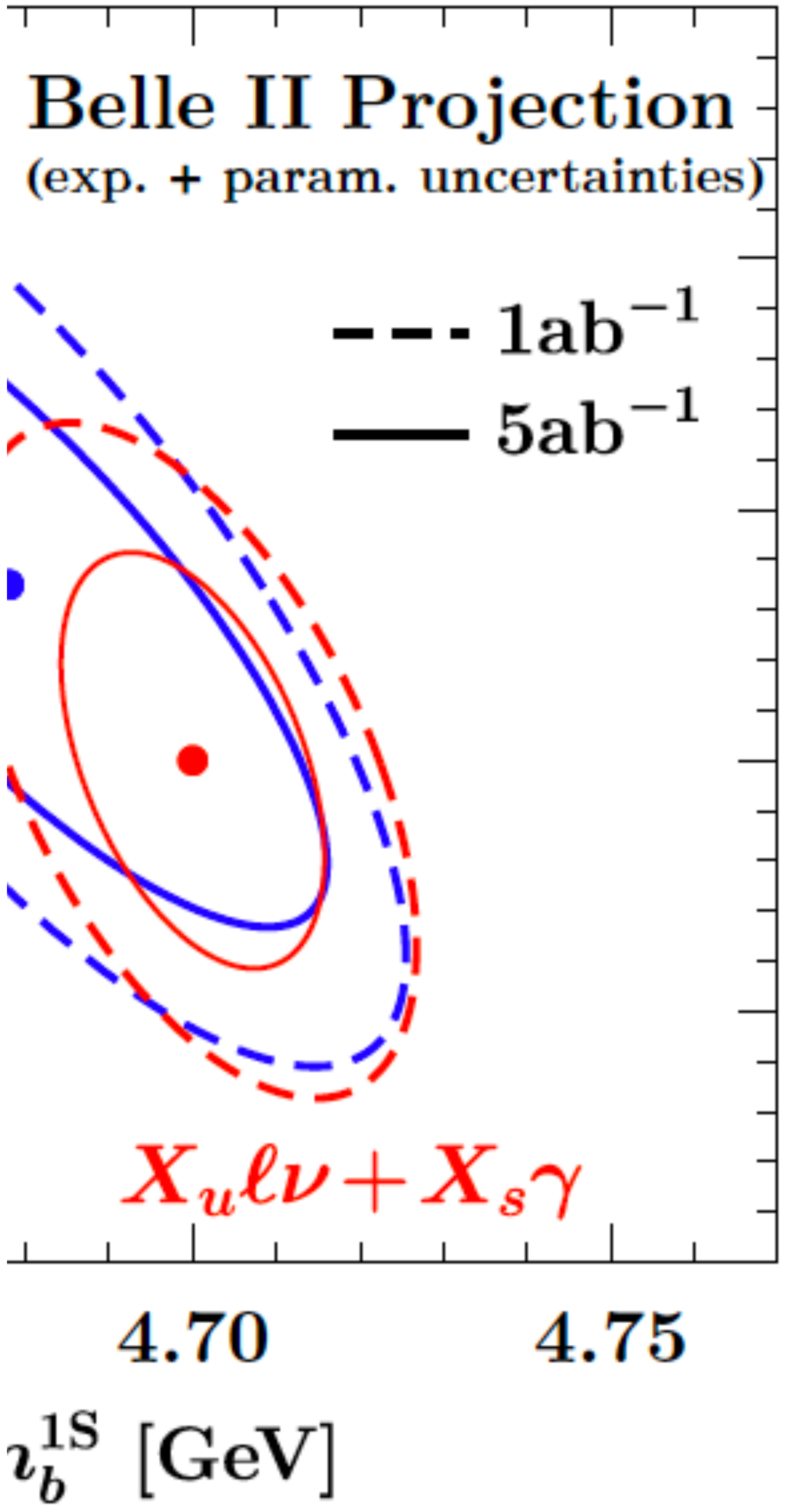
- Maximize shape funct of differential spectra
- Global fit to the full sp with constraints on HC simultaneously
- This has been demons

	Statis
$\lvert V_{ub}\rvert$ inclusive	
605 fb^{-1} (old B tag)	4.5
5 ab^{-1}	1.1
50 ab^{-1}	0.4

- Systematic uncertainti improved by Belle II u
  - New and improvec counter)
  - Smaller drift chaml
  - Improved detector



Observed
$B \to X_u e \nu_e$**excess**
in data (>3σ) !



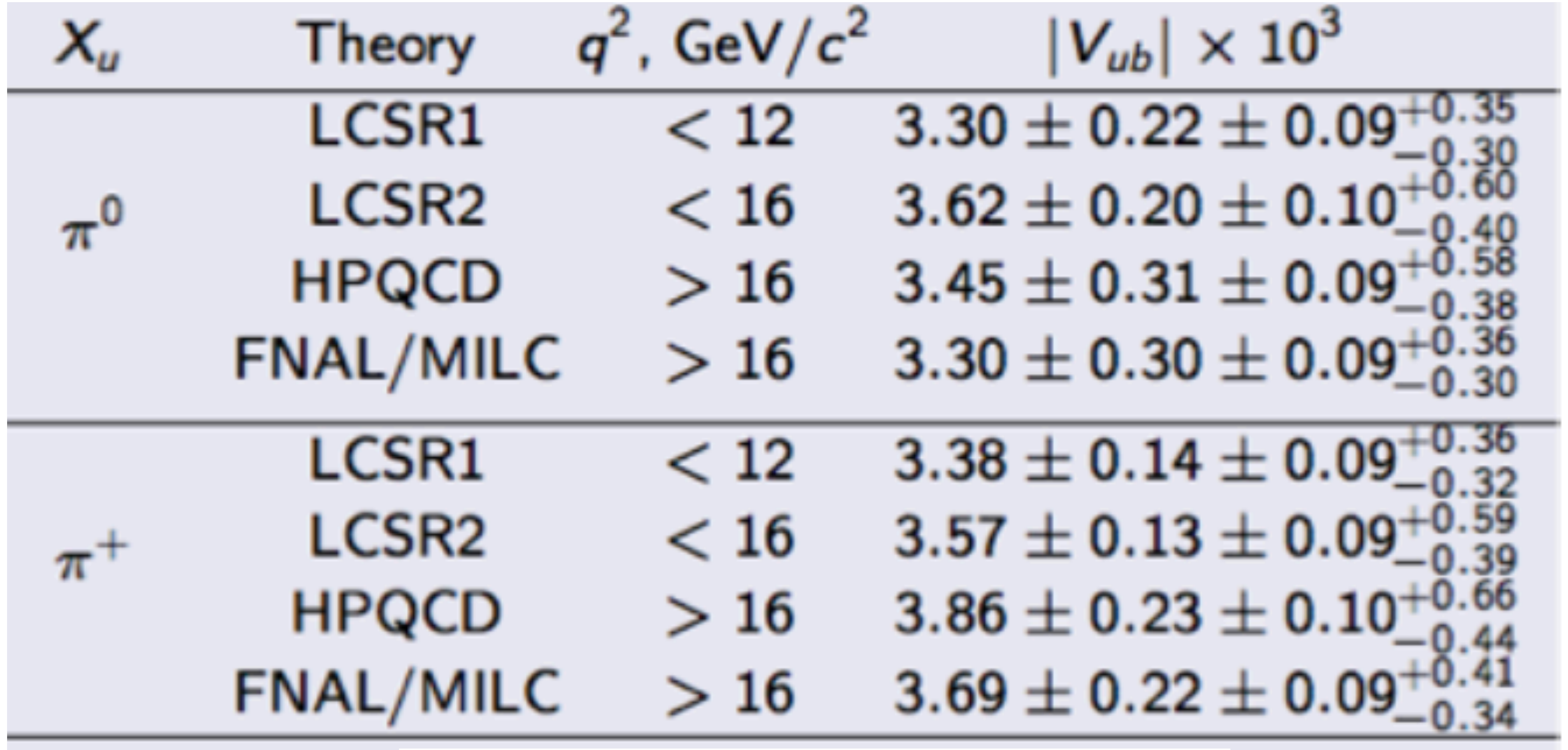
Phys Rev D 88, 032005 (2013)

Exclusive |V$_{ub}$|

- Using tagged and untagged $B \to \pi \ell \nu$
  - Tagged analyses: high q² resolution, lower statistics. Main systematic: calibration of tagging efficiency.
  - Untagged analyses: higher background, more restrictive kinematic cuts. Main systematic: determination of the missing neutrino momentum

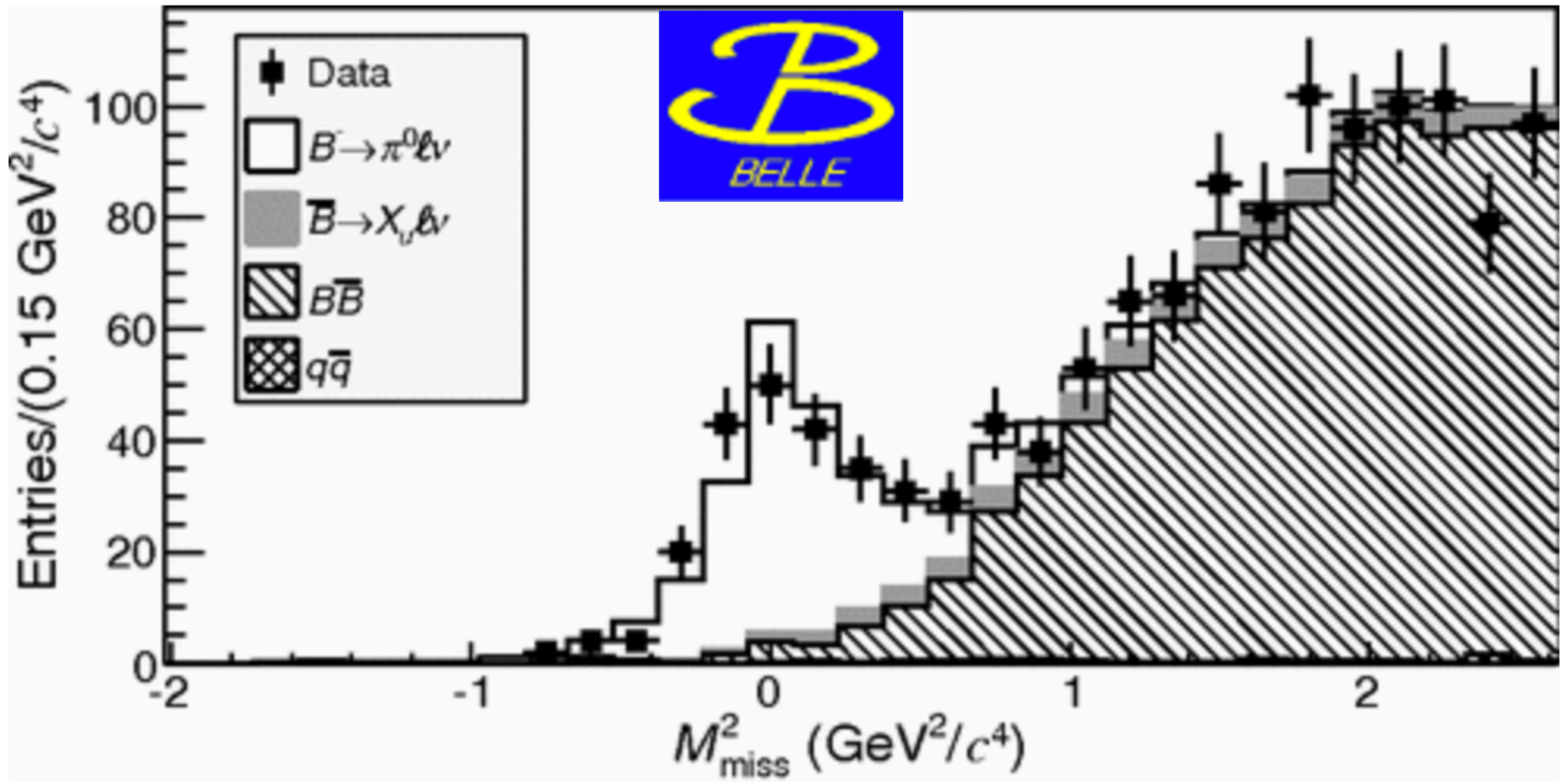
- Hadronic reconstruction with 711 fb^{-1} of Belle data.
- Determine M^2_{miss} by subtracting $B_{tag}, \pi_{sig}, \ell_{sig}$ from $\Upsilon(4S)$
- Extract yields from fit to M^2_{miss}.
- Extract |Vub| using different theoretical parametrization of the form factor f_{+0}

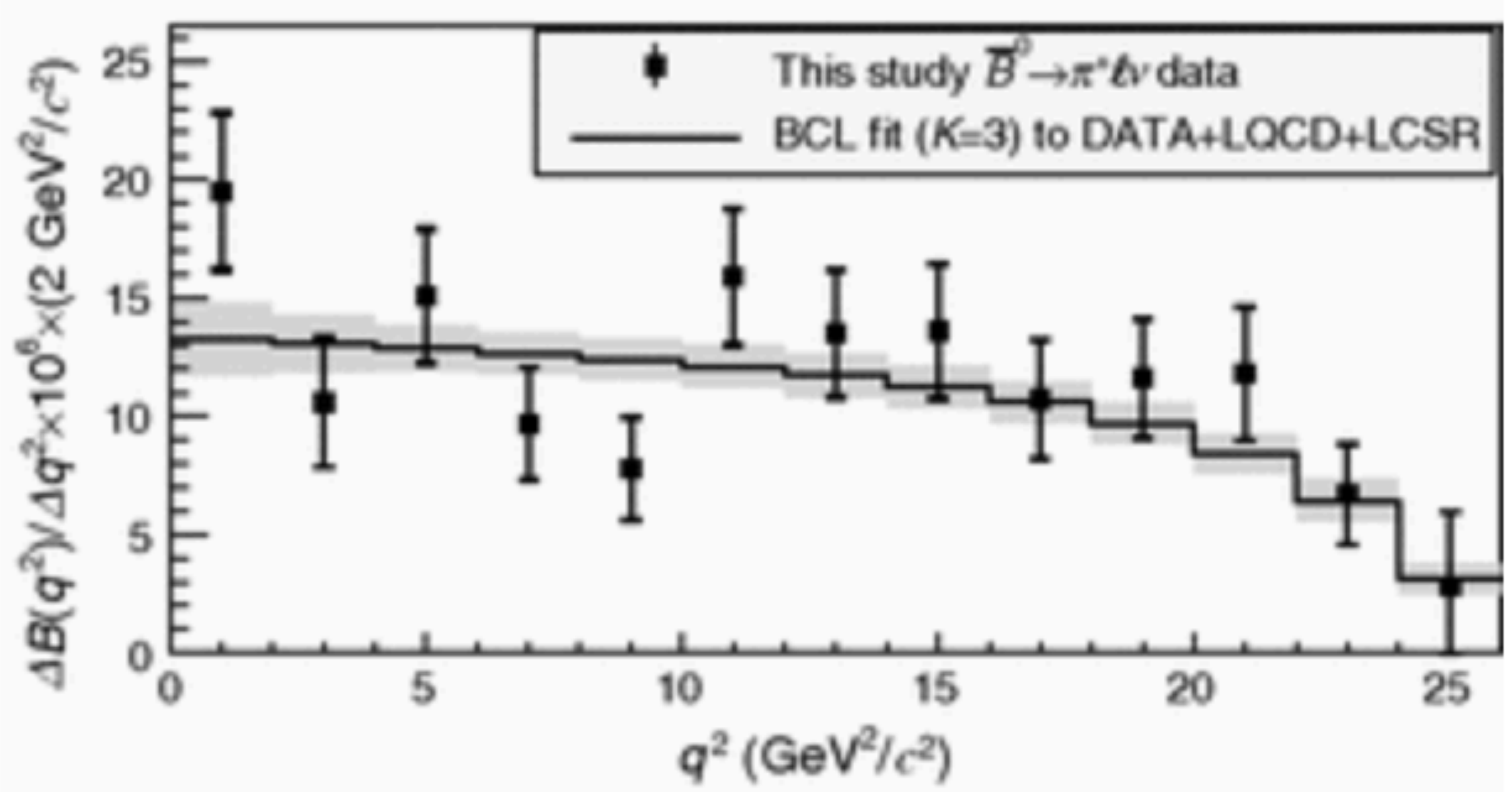
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |p_\pi|^3 |f_+(q^2)|^2$$



X_u	Theory	q^2, GeV/c^2	$\lvert V_{ub}\rvert \times 10^3$
π^0	LCSR1	< 12	$3.30 \pm 0.22 \pm 0.09^{+0.35}_{-0.30}$
	LCSR2	< 16	$3.62 \pm 0.20 \pm 0.10^{+0.60}_{-0.40}$
	HPQCD	> 16	$3.45 \pm 0.31 \pm 0.09^{+0.58}_{-0.38}$
	FNAL/MILC	> 16	$3.30 \pm 0.30 \pm 0.09^{+0.36}_{-0.30}$
π^+	LCSR1	< 12	$3.38 \pm 0.14 \pm 0.09^{+0.36}_{-0.32}$
	LCSR2	< 16	$3.57 \pm 0.13 \pm 0.09^{+0.59}_{-0.39}$
	HPQCD	> 16	$3.86 \pm 0.23 \pm 0.10^{+0.66}_{-0.44}$
	FNAL/MILC	> 16	$3.69 \pm 0.22 \pm 0.09^{+0.41}_{-0.34}$

$$|V_{ub}| = (3.52 \pm 0.29) \times 10^{-3}$$

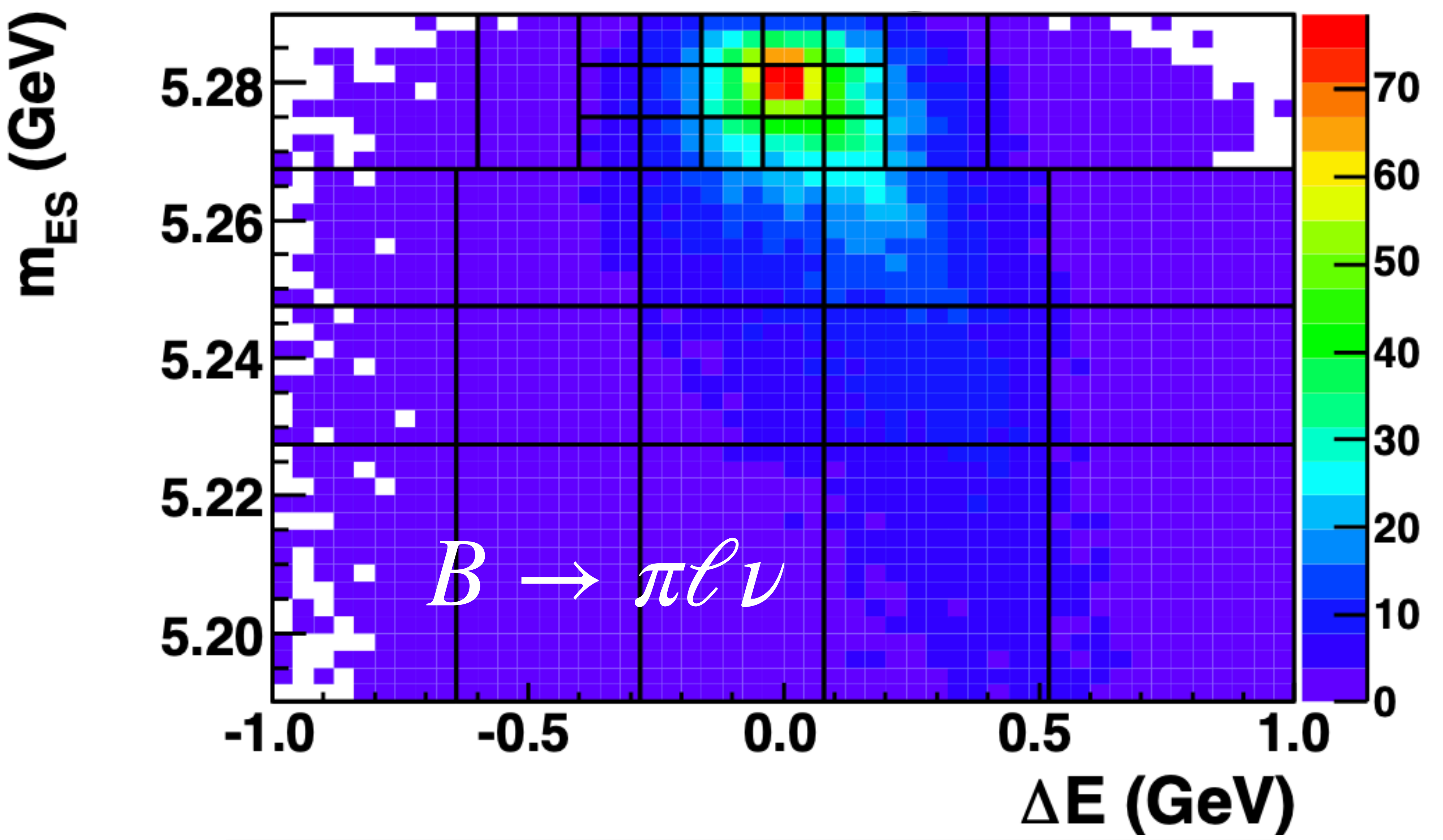




Phys. Rev. D 86 092004, 2012

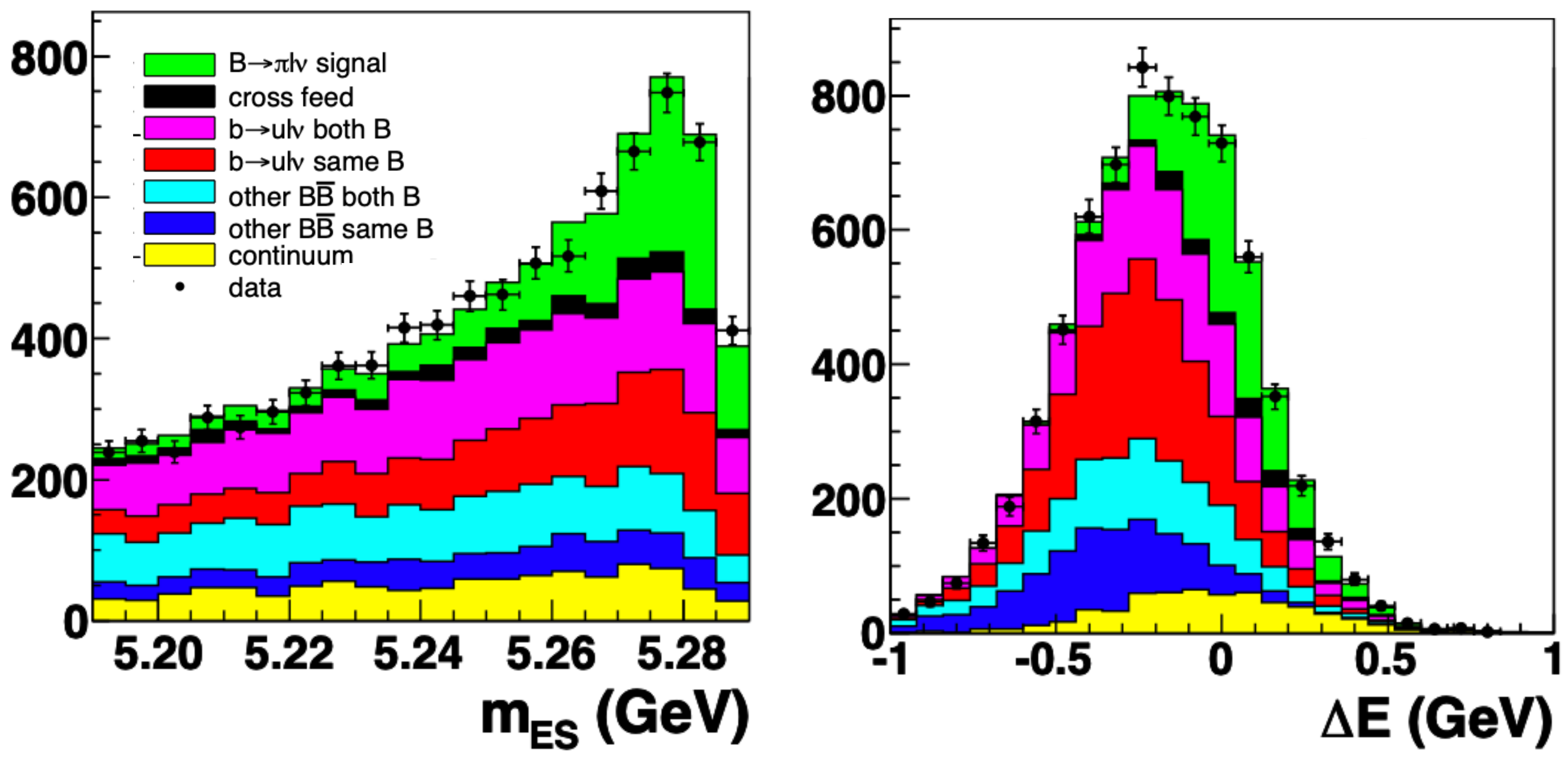
Untagged $B \to \pi\ell\nu$

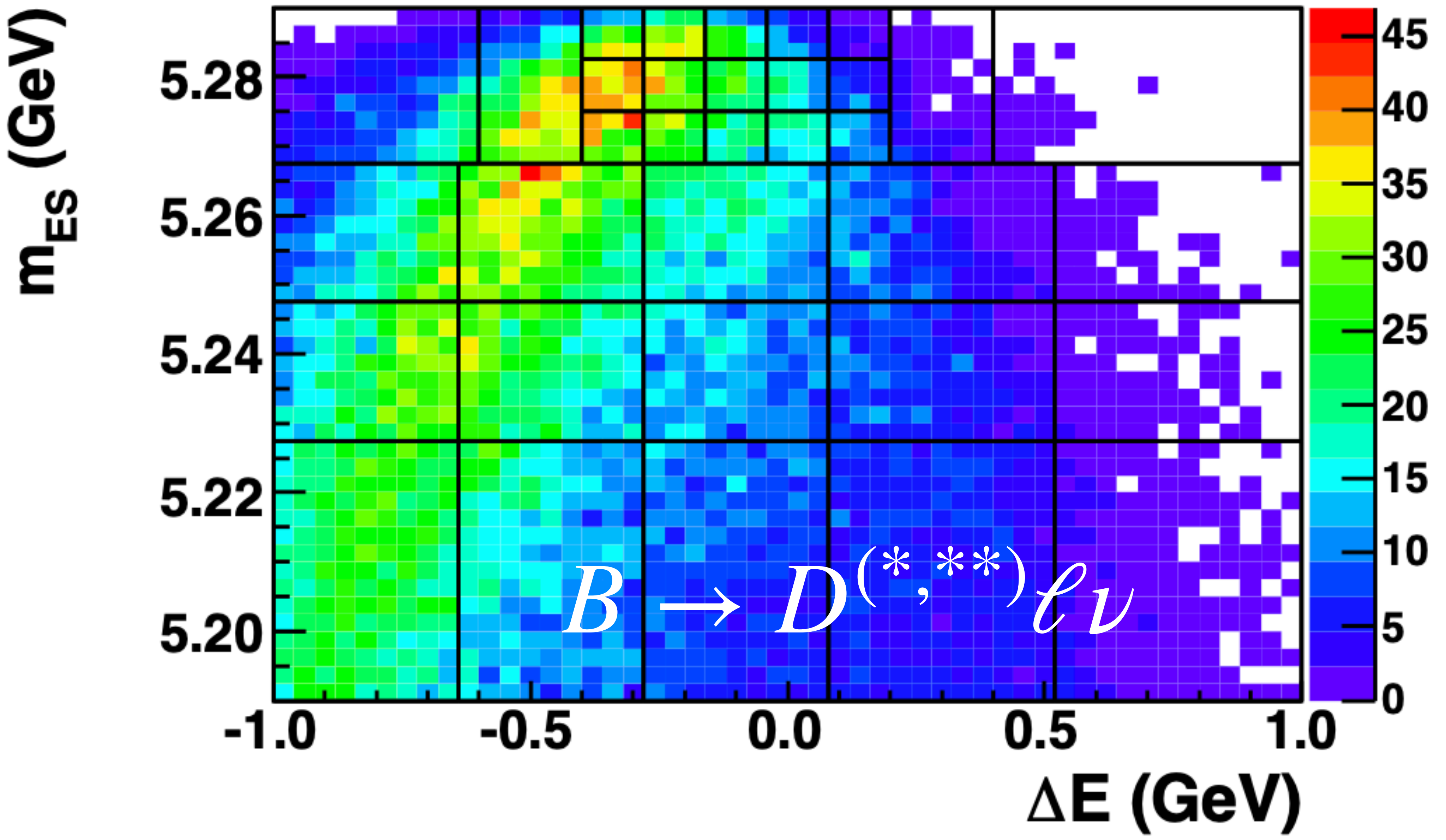
- Measure partials BFs of $B^0 \to \pi^-\ell\nu, B^+ \to \pi^0\ell\nu$, $B^+ \to \omega\ell\nu, B^+ \to \eta^{(')}\ell\nu$ in bins of q^2.
- Reconstruct Y= lepton+ charmless meson system.
- Infer neutrino 4-momentum from $\overrightarrow{p^*}_{miss} = \overrightarrow{p^*}_{beams} - \overrightarrow{p^*}_{tot}$ where the latter is determined from the sum of all detected particles in the $\Upsilon(4S)$ frame
- $q^2 = (P_B - P_{meson})^2$ calculated as an average over 4 angles B momentum known up to an angle ψ about the momentum.
- Apply q^2 dependent selections to suppress backgrounds
- Extract signal and background yields in a 2D fit to the $\Delta E - m_{ES}$



$$\Delta E = (P_B \cdot P_{beams} - s/2)/\sqrt{s} \quad m_{ES} = \sqrt{(s/2 + \vec{p}_B \cdot \vec{p}_{beams})^2/E^2_{beams} - \vec{p}_B^{\,2}}$$

q^2>16





Phys. Rev. D 86 092004, 2012

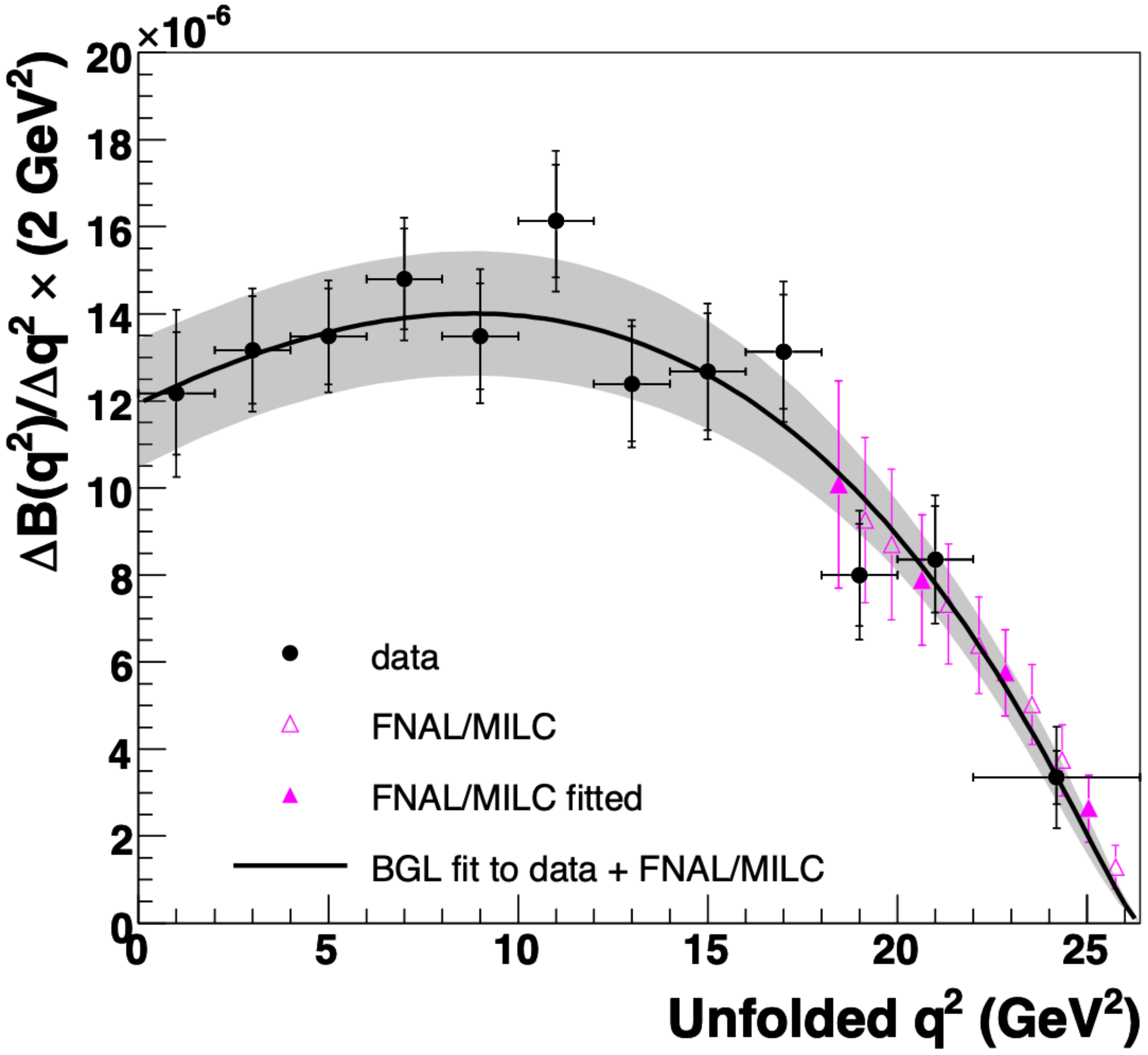
Untagged $B \to \pi \ell \nu$

- Extract $|V_{ub}|$ from the combined $B \to \pi \ell \nu \Delta \mathcal{B}(q^2)$ using 3 different theoretical parametrization of the form factors.

$$|V_{ub}| = \sqrt{\Delta \mathcal{B}/(\tau_{B^0} \Delta\zeta)}$$

	q^2 (GeV^2)	$\Delta\mathcal{B}$ (10^{-4})	$\Delta\zeta$ (ps^{-1})	$\lvert V_{ub}\rvert$ (10^{-3})	χ^2/ndf	$Prob(\chi^2)$
$B \to \pi \ell^+ \nu$						
HPQCD [5]	$16 - 26.4$	$0.37 \pm 0.02 \pm 0.02$	2.02 ± 0.55	$3.47 \pm 0.10 \pm 0.08^{+0.60}_{-0.39}$	2.7/4	60.1%
FNAL [6]	$16 - 26.4$	$0.37 \pm 0.02 \pm 0.02$	$2.21^{+0.47}_{-0.42}$	$3.31 \pm 0.09 \pm 0.07^{+0.37}_{-0.30}$	3.9/4	41.5%
LCSR [3]	$0 - 12$	$0.83 \pm 0.03 \pm 0.04$	$4.59^{+1.00}_{-0.85}$	$3.46 \pm 0.06 \pm 0.08^{+0.37}_{-0.32}$	8.0/6	24.0%
LCSR2 [34]	0			$3.34 \pm 0.10 \pm 0.05^{+0.29}_{-0.26}$		
$B^+ \to \omega \ell^+ \nu$						
LCSR3 [18]	$0 - 20.2$	$1.19 \pm 0.16 \pm 0.09$	14.2 ± 3.3	$3.20 \pm 0.21 \pm 0.12^{+0.45}_{-0.32}$	2.24/5	81.5%

- Simultaneous fit of the BGL parametrization and 4 points in the FNAL/MILC lattice data yield $|V_{ub}| = (3.25 \pm 0.31) \times 10^{-3}$
- Result compatible with alternative determinations using LCSR and compatible with previous Belle tagged results



$$|V_{ub}| = (3.25 \pm 0.31) \times 10^{-3}$$

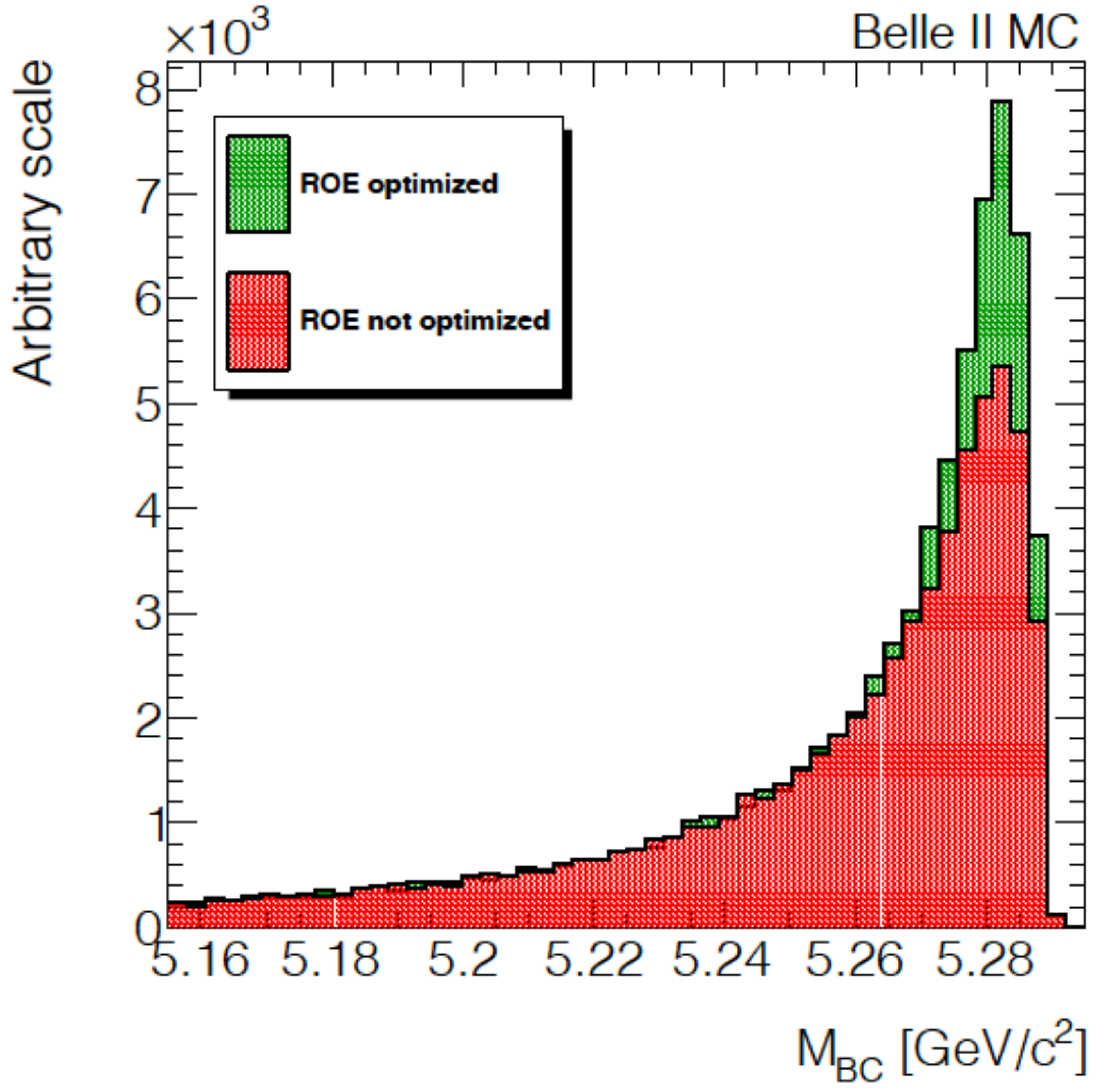
Still in tension with inclusive determination!

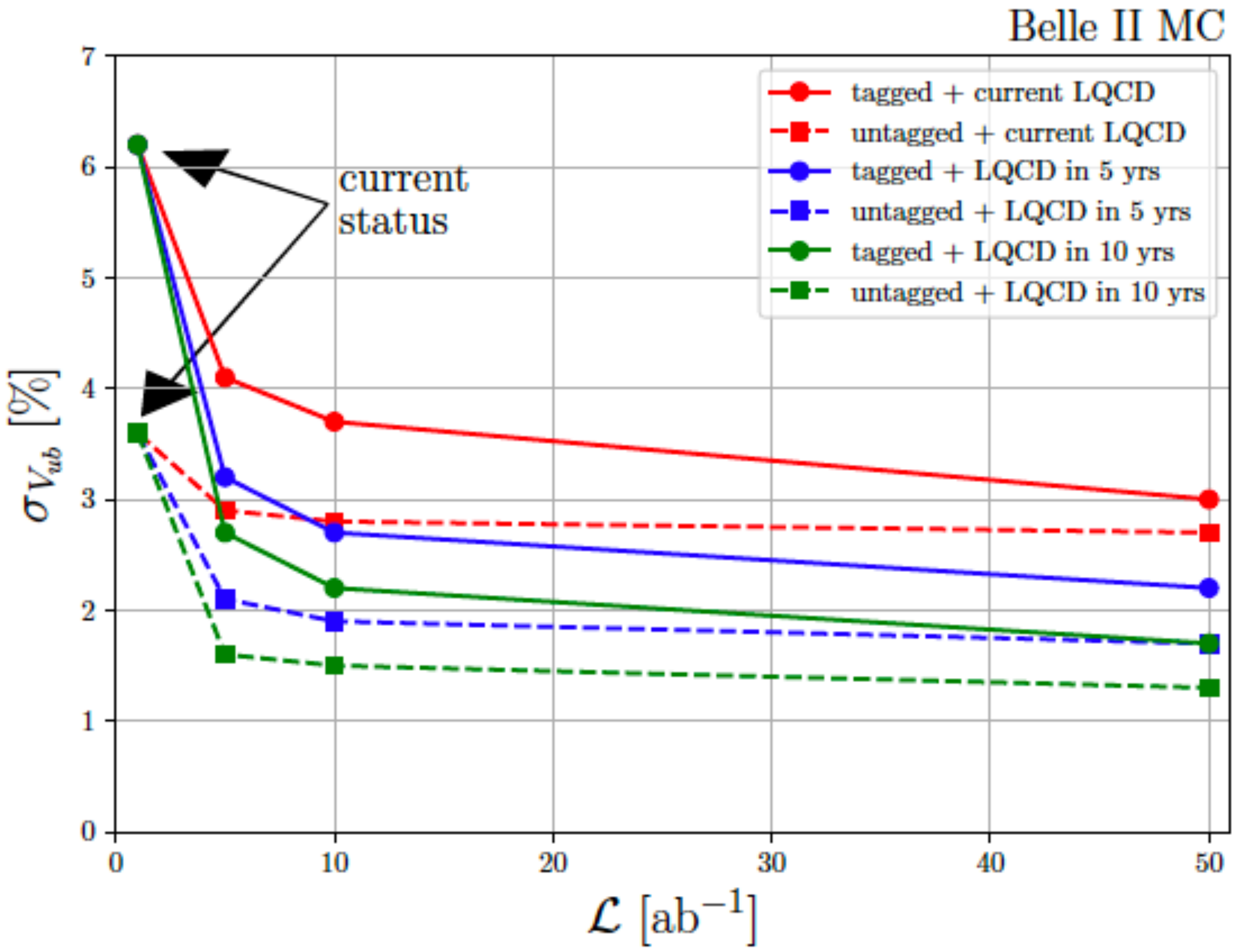
LCSR: Phys. Rev. D83, 094031 (2011).
HPQCD: Phys. Rev. D73,074502 (2006); Erratum ibid. D75, 119906 (2007).
FNAL J. A. FNAL: Phys. Rev. D79, 054507 (2009)
LCSR2:A. Bharucha, 10.1007/JHEP05(2012)092.
LCSR3: Phys. Rev. D71, 014029 (2005)

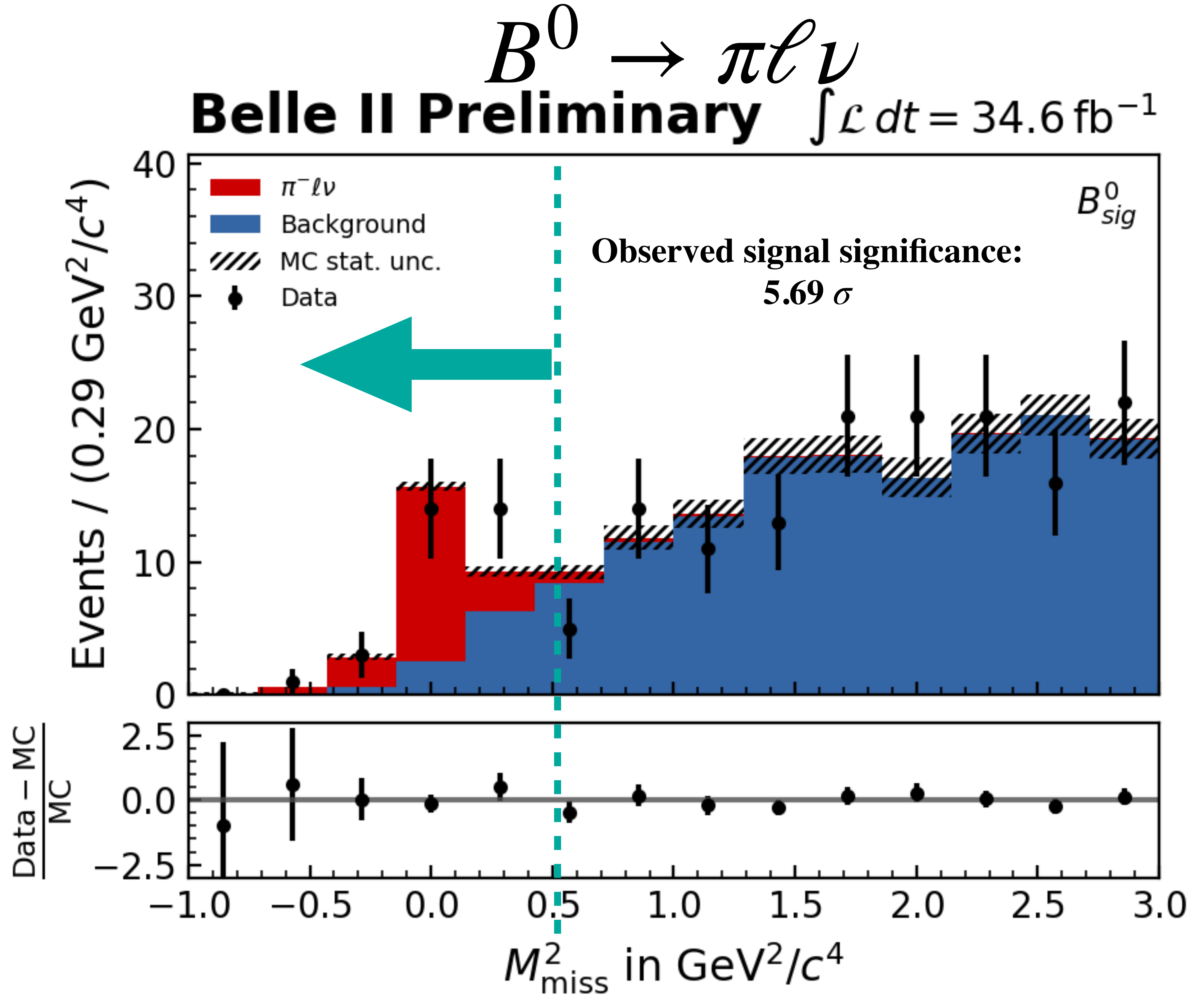
Exclusive $|V_{ub}|$ at Belle II

- Larger data sample will improve statistical power.
- Combined with lattice QCD determinations in the full kinematic range.
- Expect reduced systematics on $N_{B\bar{B}}$ and f_{00}/f_{+0} for untagged analyses.
- Improved tagging techniques Full Event Interpretation(see backup) is expected to increase efficiency by ~2%
- Implement multivariate rest-of-event optimization to improve ΔE and m_{ES} resolution in untagged analyses.

	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\lvert V_{ub}\rvert$ exclusive (had. tagged)					
711 fb^{-1}	3.0	(2.3, 1.0)	3.8	7.0	8.0
5 ab^{-1}	1.1	(0.9, 1.0)	1.8	1.7	3.2
50 ab^{-1}	0.4	(0.3, 1.0)	1.2	0.9	1.7
$\lvert V_{ub}\rvert$ exclusive (untagged)					
605 fb^{-1}	1.4	(2.1, 0.8)	2.7	7.0	7.5
5 ab^{-1}	1.0	(0.8, 0.8)	1.2	1.7	2.1
50 ab^{-1}	0.3	(0.3, 0.8)	0.9	0.9	1.3







|V$_{cb}$|

- Inclusive via $B \to X_c \ell \nu$:

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2(1 + \frac{c_5(\mu)\langle O_5\rangle(\mu)}{m_b^2} + \frac{c_6(\mu)\langle O_6\rangle(\mu)}{m_b^3} + \mathcal{O}(\frac{1}{m_b^4}))$$

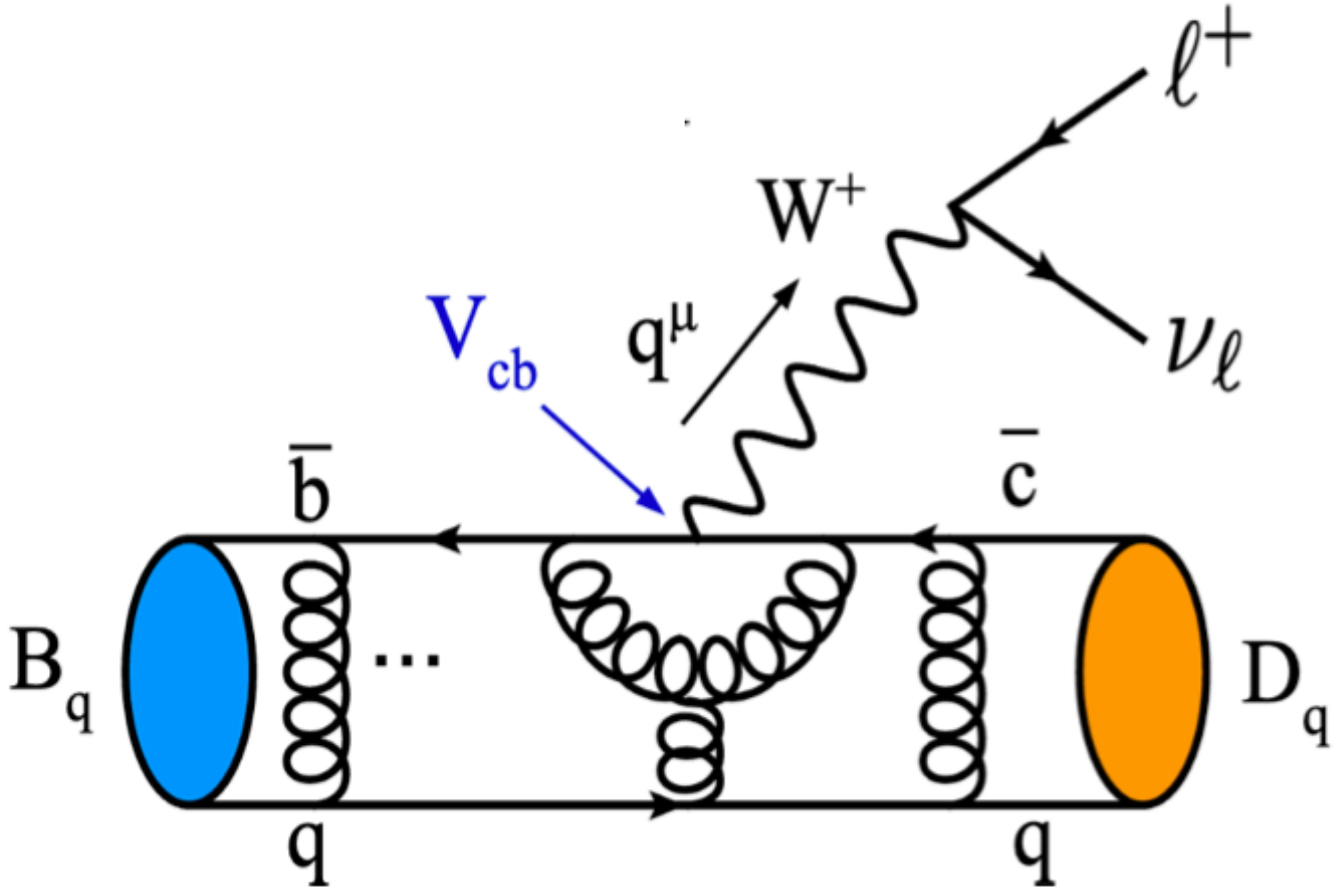
  - Heavy Quark expansion of decay rate with non-perturbative matrix elements and perturbative coefficients.
  - Non-perturbative parameters determined using the lepton energy or hadronic mass moments of $B \to X_c \ell \nu$

- Exclusive via $B \to D^{(*)} \ell \nu$:
  - Clean experimental modes with low background.
  - Decay rate requires input on the form factor parametrization.

$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3}$ (inclusive) **PDG value**

$|V_{cb}| = (39.5 \pm 0.9) \times 10^{-3}$ (exclusive) **PDG value**

Tension between exclusive and inclusive determinations.



$B \to D^* \ell \nu$

$$\frac{d\Gamma}{dw}(\bar{B} \to D^* \ell \bar{\nu}_\ell) = \frac{G_F^2 m_B^5}{48\pi^3} |V_{cb}|^2 (w^2-1)^{1/2} P(w) (\eta_{\mathrm{ew}} \mathcal{F}(w))^2 \qquad w = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$$

- Requires input on form factor parametrization:

$$f_i(z) = \frac{1}{P_i(z)\phi_i(z)} \sum_{n=0}^{N} \boxed{a_{i,n}} z^n, \qquad z(w) = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

Boyd, Grinstein, Lebed parametrization

Phys. Rev. Lett. 74, 4603 (1995)

$$\begin{aligned} h_{A_1}(w) &= h_{A_1}(1)\left[1 - 8\rho^2 z + (53\rho^2 - 15) z^2 \right. \\ &\qquad \left. - (231\boxed{\rho^2} - 91) z^3\right] , \\ R_1(w) &= \boxed{R_1(1)} - 0.12(w-1) + 0.05(w-1)^2 , \\ R_2(w) &= \boxed{R_2(1)} + 0.11(w-1) - 0.06(w-1)^2 , \end{aligned}$$

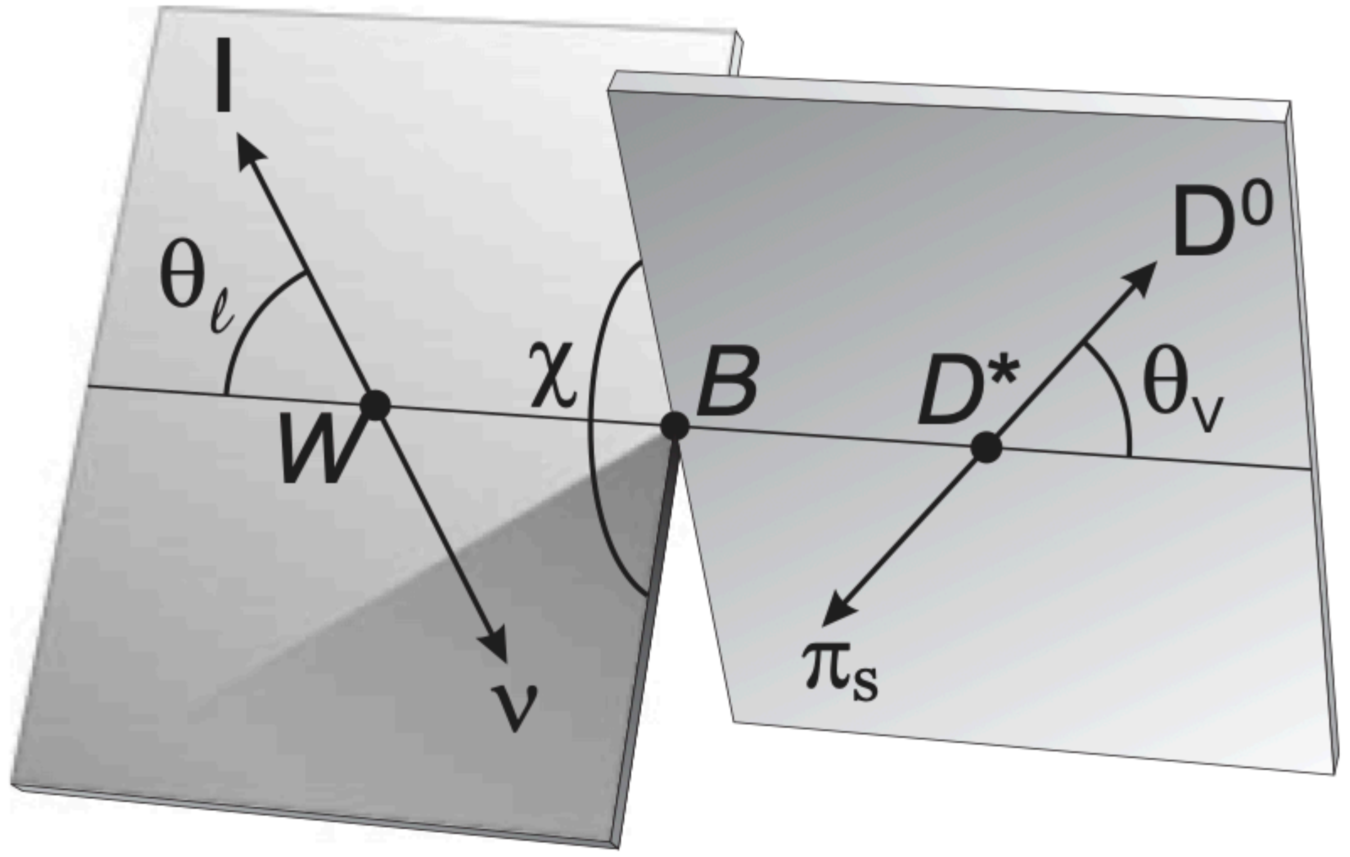
Caprini, Lellouch, Neubert parametrization

Nucl. Phys. B530, 153(1998)

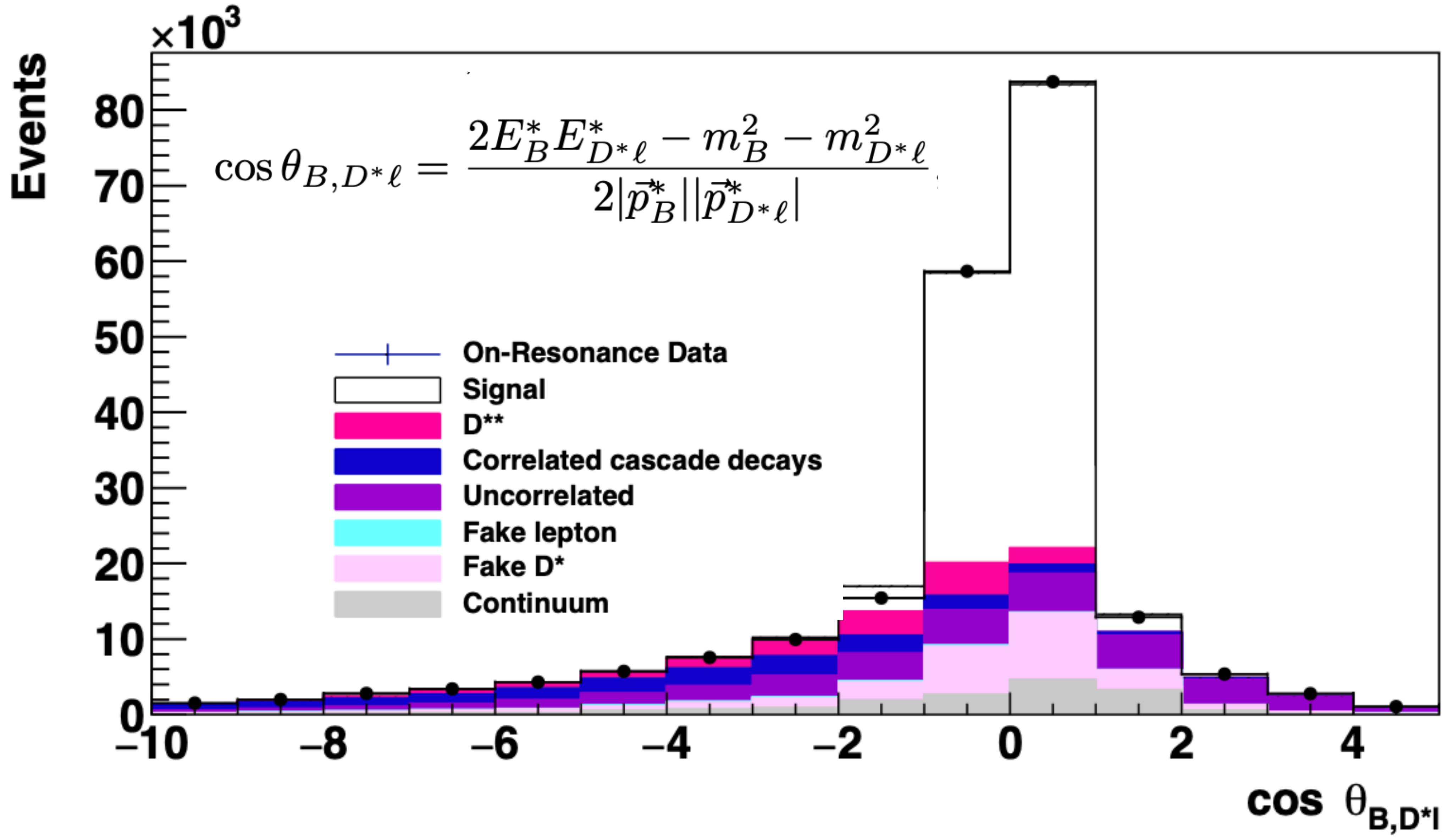
- Extract $|V_{cb}|$ at zero recoil, $w = 1$ by measuring the differential rate.
- Use measured differential rate as input to a fit for the form factors and $\eta_{EW}\mathcal{F}(1)|V_{cb}|$.
- Lattice calculations available only at zero-recoil $\mathcal{F}(1) = 0.895 \pm 0.026$ (Phys. Rev. D 97, 054502 (2018)) or $\mathcal{F}(1) = 0.906 \pm 0.013$ (Phys.Rev.D89, 115404 (2014)) .Work in progress towards calculations at larger recoil.

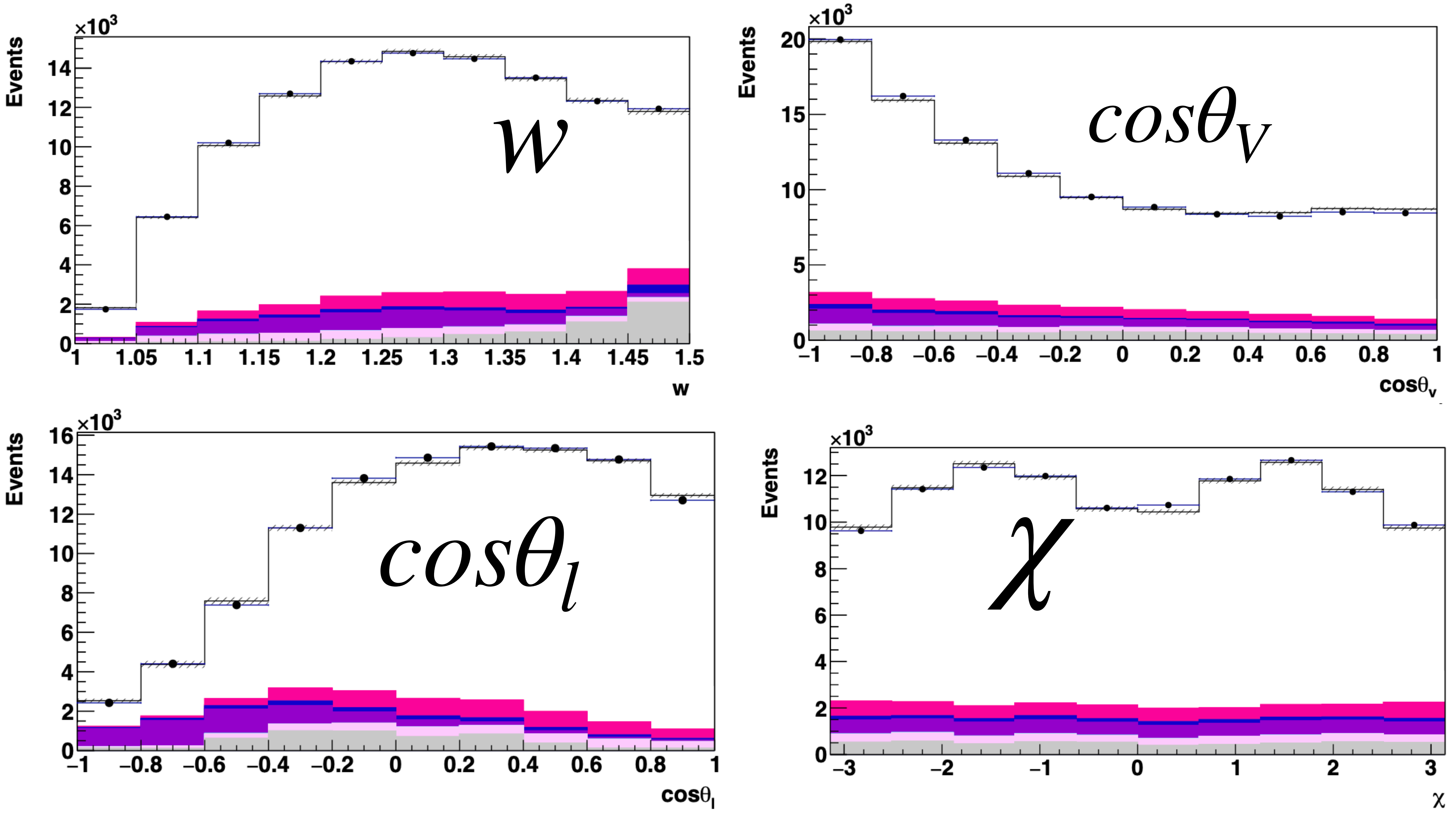
Phys. Rev. D 100, 052007 (2019)

$B^0 \to D^{*-}\ell\nu$



- Untagged analysis using Full Belle dataset: 711 fb^{-1}
- Reconstruct D* and identify lepton candidate
- Estimate backgrounds using fits $cos\theta_{B,D^*l}, \Delta M, p_\ell$.
- Determine direction of non-signal B using residual tracks and clusters not used in the reconstruction.





- Perform binned χ^2 fit using 1-D projections of $w, cos\theta_\ell, cos\theta_V, \chi$ to extract form factor parameters and |V$_{cb}$|

Phys. Rev. D 100, 052007 (2019)

$B^0 \to D^{*-}\ell\nu$

CLN parametrization

$$\begin{aligned}
\rho^2 &= 1.106 \pm 0.031 \pm 0.007,\\
R_1(1) &= 1.229 \pm 0.028 \pm 0.009,\\
R_2(1) &= 0.852 \pm 0.021 \pm 0.006,\\
\boxed{\mathcal{F}(1)|V_{cb}|\eta_{\mathrm{EW}} \times 10^3 = 35.06 \pm 0.15 \pm 0.56}\\
\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell) &= (4.90 \pm 0.02 \pm 0.16)\%,
\end{aligned}$$

BGL parametrization

$$\begin{aligned}
\tilde{a}_0^f \times 10^3 &= -0.506 \pm 0.004 \pm 0.008,\\
\tilde{a}_1^f \times 10^3 &= -0.65 \pm 0.17 \pm 0.09,\\
\tilde{a}_1^{F_1} \times 10^3 &= -0.270 \pm 0.064 \pm 0.023,\\
\tilde{a}_2^{F_1} \times 10^3 &= +3.27 \pm 1.25 \pm 0.45,\\
\tilde{a}_0^g \times 10^3 &= -0.929 \pm 0.018 \pm 0.013,\\
\boxed{\mathcal{F}(1)|V_{cb}|\eta_{\mathrm{EW}} \times 10^3 = 34.93 \pm 0.23 \pm 0.59},\\
\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell) &= (4.90 \pm 0.02 \pm 0.16)\%.
\end{aligned}$$

BF is consistent with different parametrization

$$\frac{\mathcal{B}(B^0 \to D^{*-}e^+\nu)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu)} = 1.01 \pm 0.01 \pm 0.03$$

Model independent measurement of exclusive $\mathscr{F}(1)|V_{cb}|$

$|V_{cb}| = (42.5 \pm 0.3 \pm 0.7 \pm 0.6) \times 10^{-3}$ **Exclusive $|V_{cb}|$ (BGL)**

$|V_{cb}| = (38.4 \pm 0.2 \pm 0.6 \pm 0.6) \times 10^{-3}$ **Exclusive $|V_{cb}|$ (CLN)**

Lattice QCD uncertainty

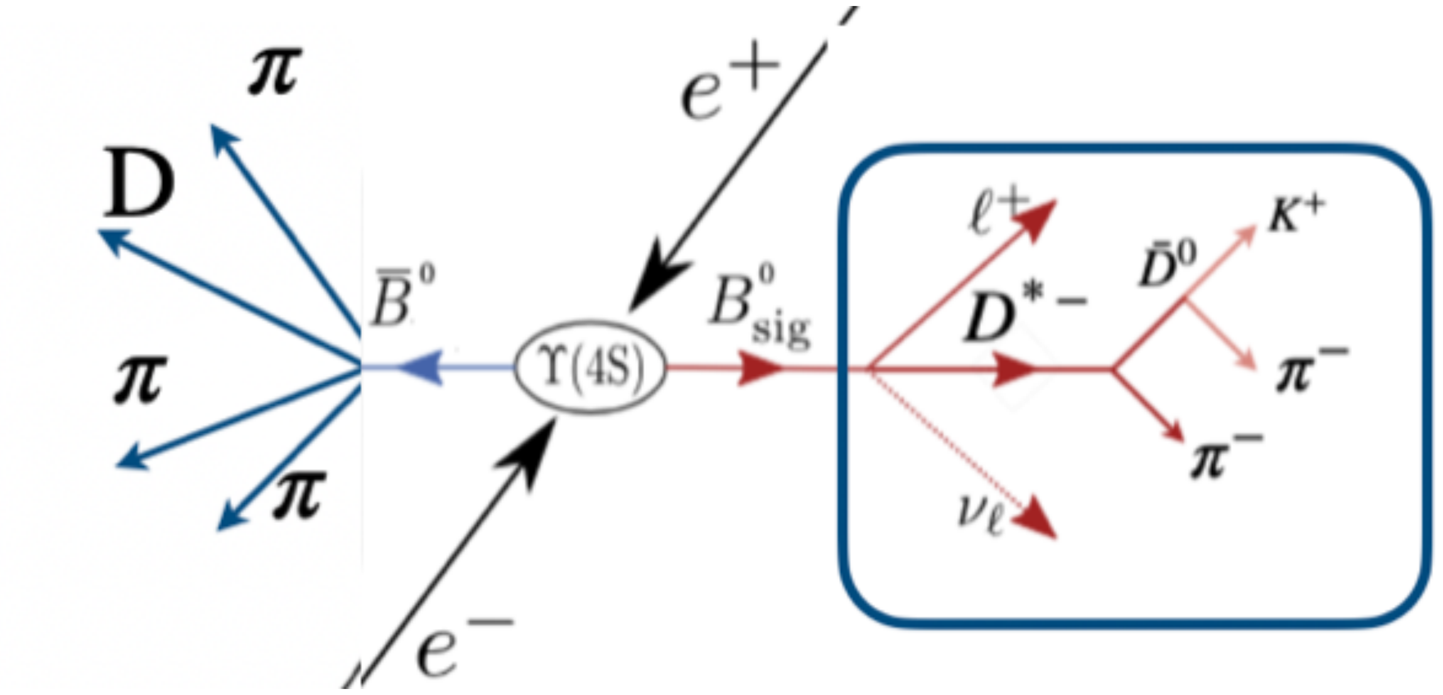
Consistent $|V_{cb}|$ result between BGL and CLN

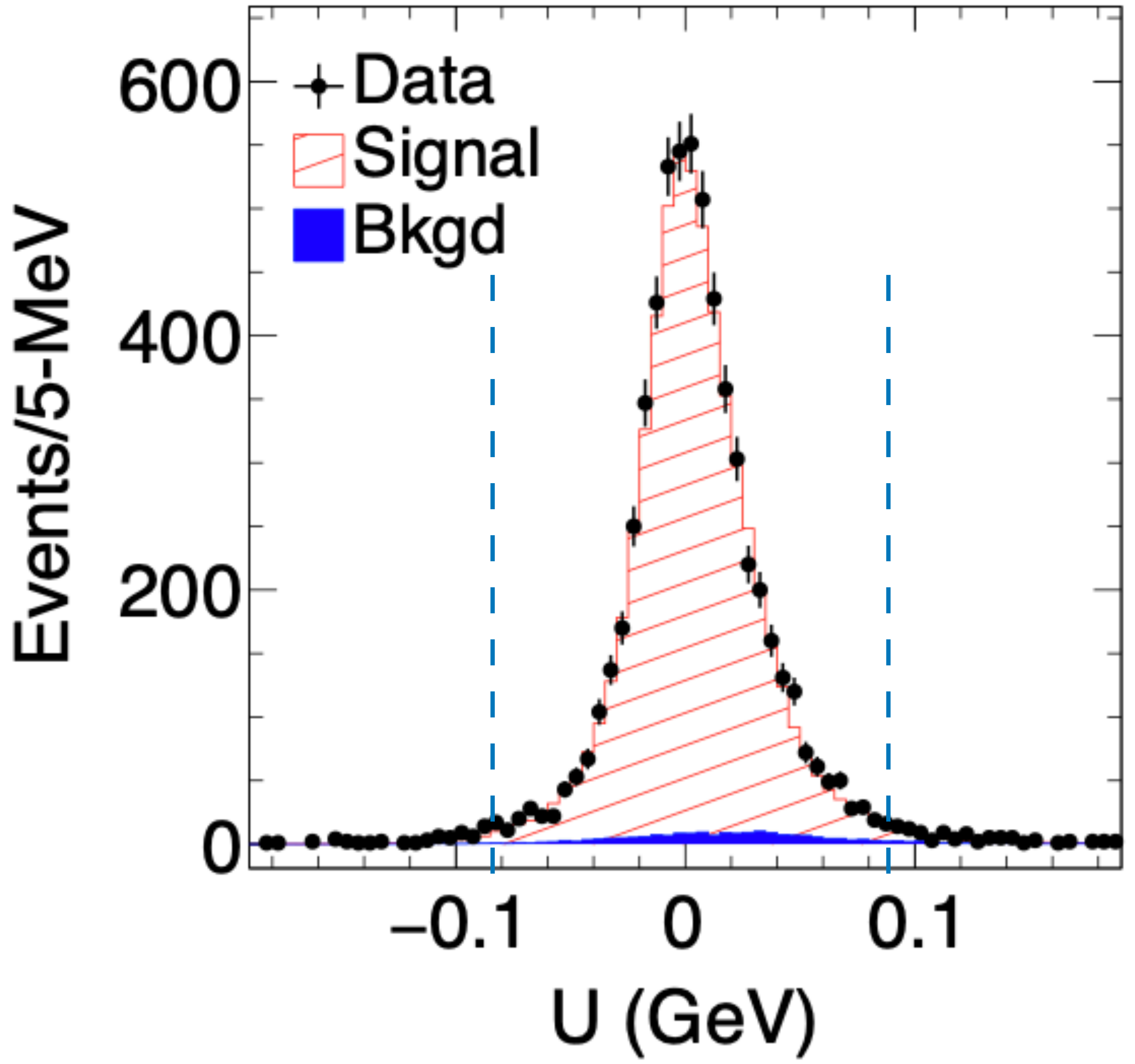
Dominant systematic uncertainties track reconstruction & lepton ID

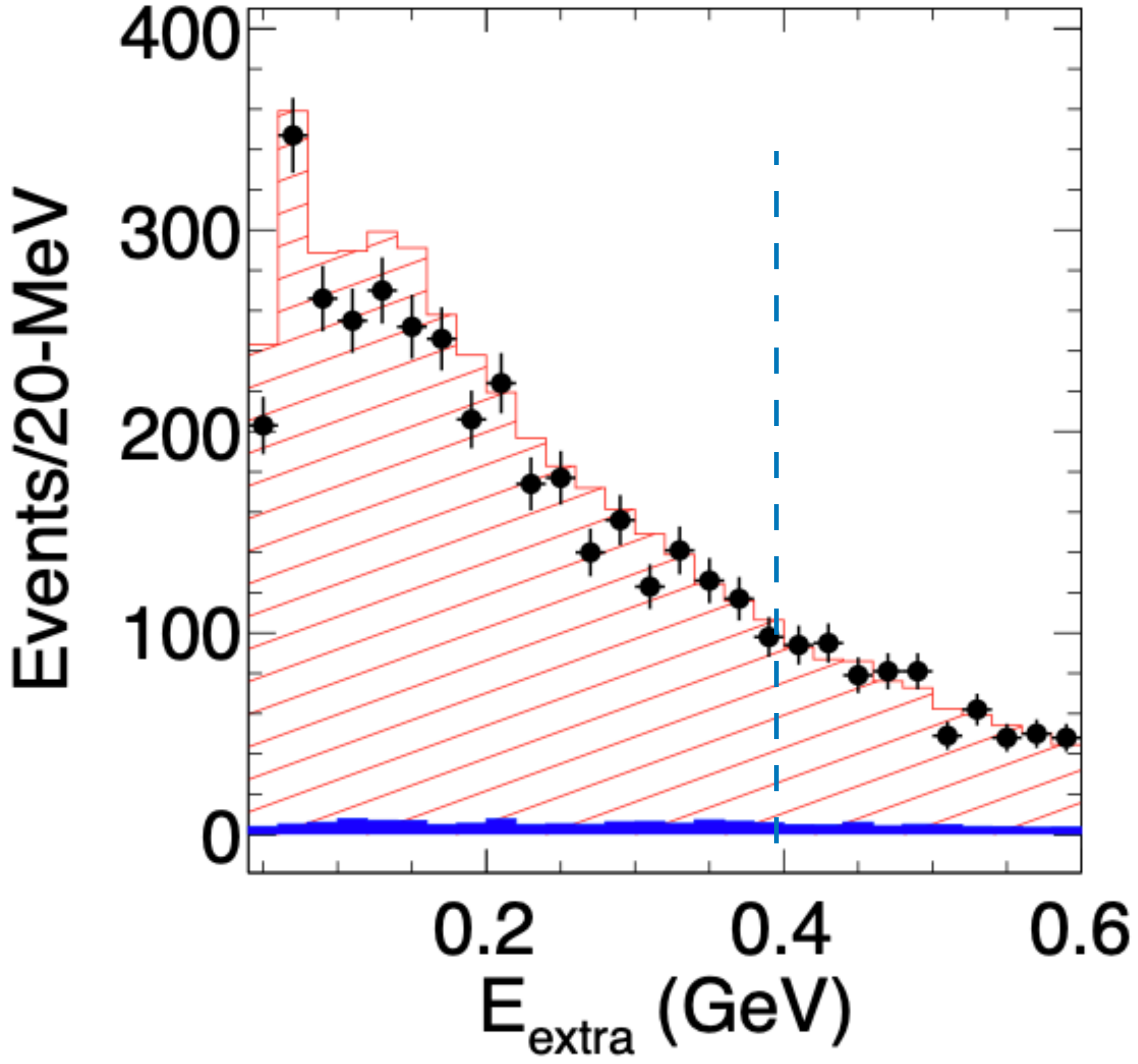
Phys. Rev. Lett. 123, 091801 (2019)

$B \to D^*\ell\nu$

- Exploit hadronic reconstruction using BaBar dataset.
- Reconstruct $D^0 \to K^-\pi^+, K^-\pi^-\pi^0, K^-\pi^+\pi^-\pi^+$ and form a D^{*0}, D^{*+}
- Suppress background using cuts on E_{extra} and $U = E_{miss} - p_{miss}$







Unbinned maximum likelihood fit to the four-dimensional decay rate using all selected events:

- Not-extended fit: extract form factors only
- Extended fit: Extract by constraining the integrated decay rate to world average values of the $\mathscr{B}$ and τ

$$\int \frac{d\Gamma}{dq^2\,d\Omega}\,dq^2\,d\Omega = \frac{\mathrm{Br}\left(B\to D^* l\,\nu_l\right)}{\tau(B)}$$

Background < 3%

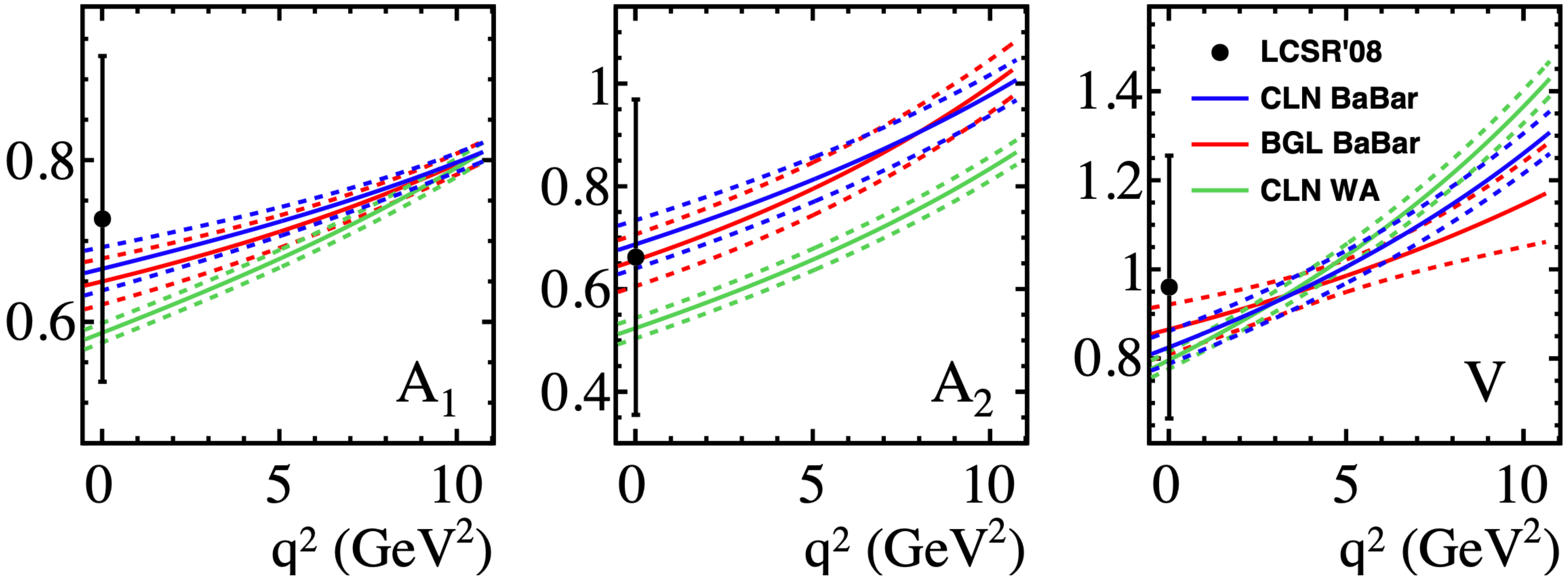
Phys. Rev. Lett. 123, 091801 (2019)

$B \to D^*\ell\nu$

- $|V_{cb}|$ results lower than recent Belle BGL result.
- Discrepancy between CLN BaBar result and CLN world average.
- Does not solve current $|V_{cb}|$ puzzle.

$\rho^2_{D^*}$	$R_1(1)$	$R_2(1)$	$\lvert V_{cb}\rvert \times 10^3$
0.96 ± 0.08	1.29 ± 0.04	0.99 ± 0.04	38.40 ± 0.84

$a_0^f \times 10^2$	$a_1^f \times 10^2$	$a_1^{F_1} \times 10^2$	$a_0^g \times 10^2$	$a_1^g \times 10^2$	$\lvert V_{cb}\rvert \times 10^3$
1.29 $\pm$0.03	1.63 $\pm$1.00	0.03 $\pm$0.11	2.74 $\pm$0.11	8.33 $\pm$6.67	38.36 $\pm$0.90



Similar $B \to D\ell\nu$ BaBar analysis currently in progress!
Plan is to perform a combined HQE fit to D and D*.

Phys. Rev. Lett. 104 011802 ,2010

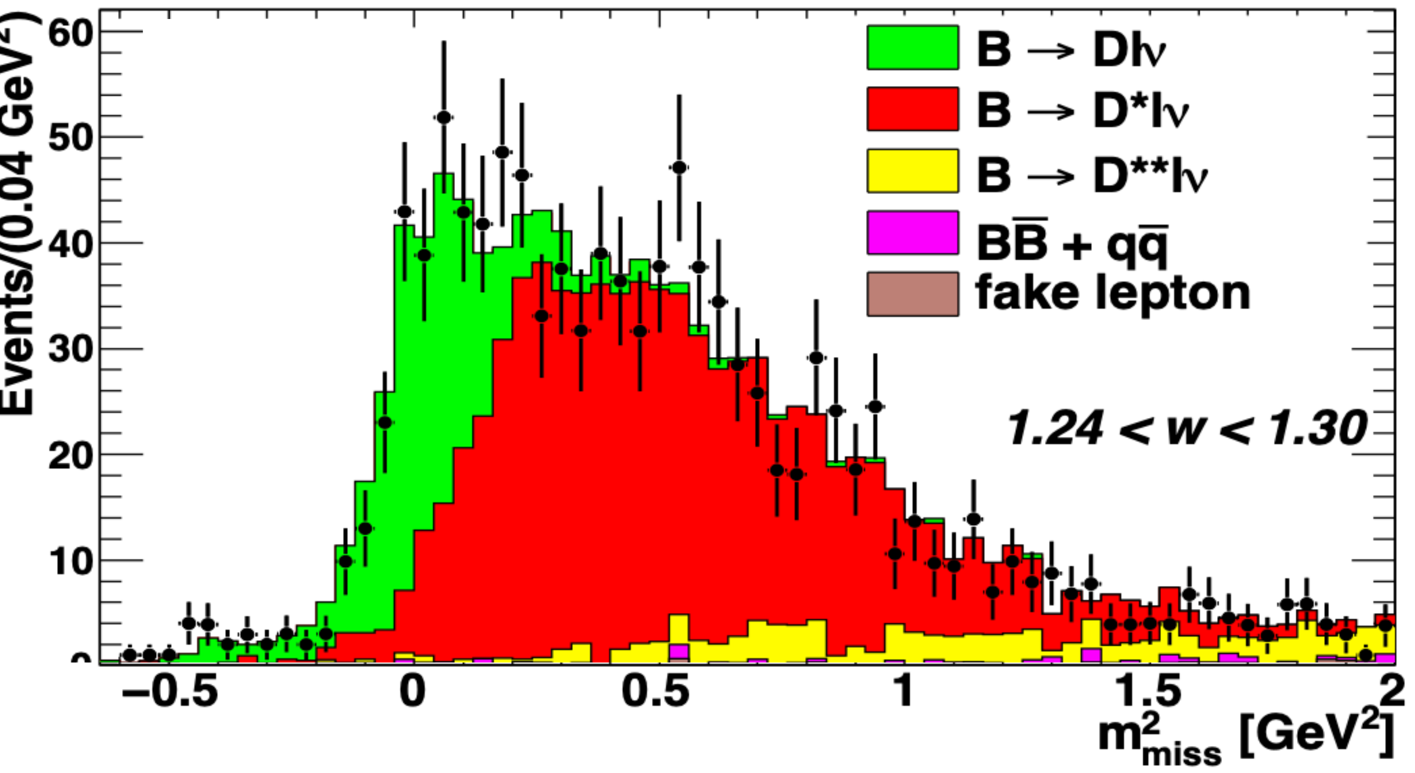
$\bar{B} \to D\ell\nu$

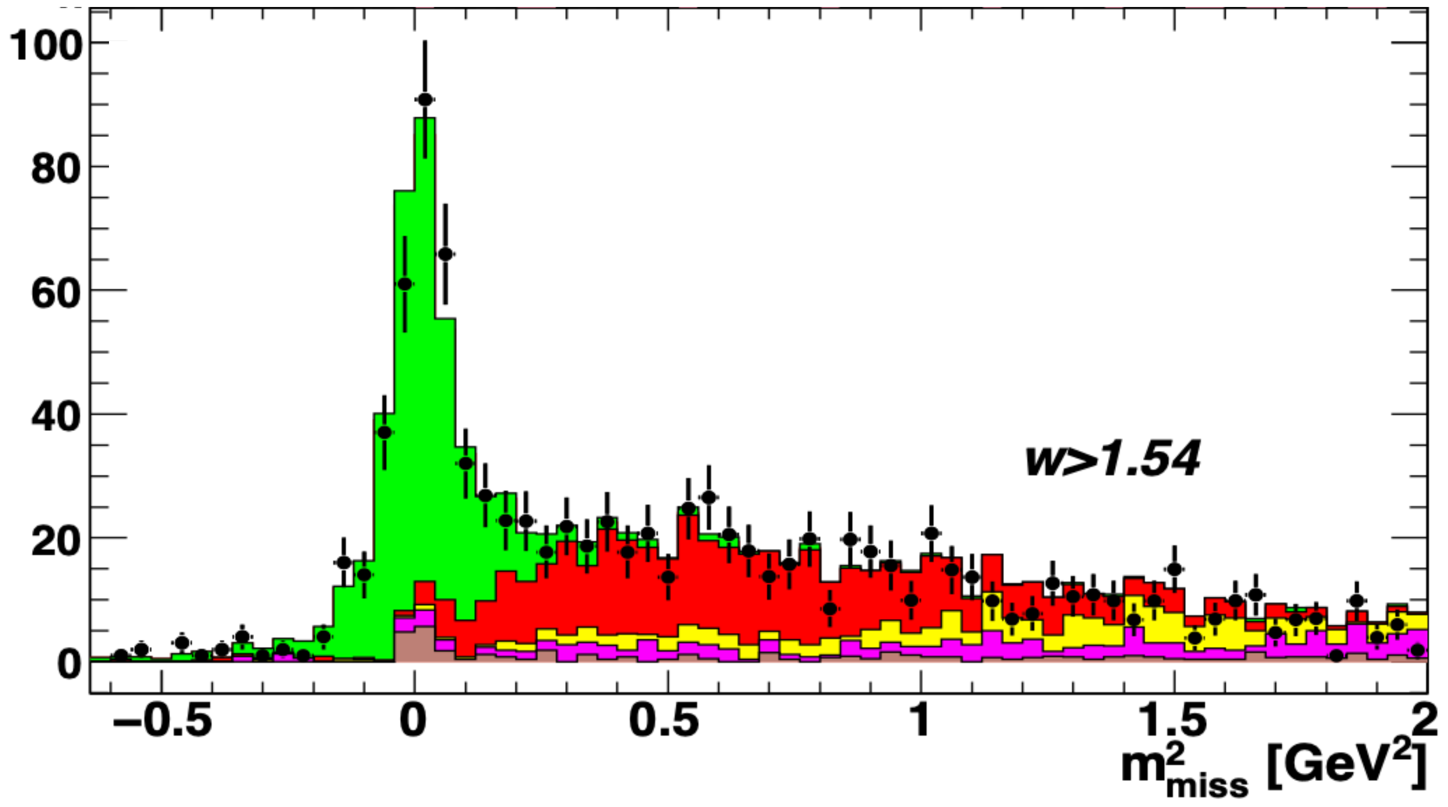
$$\frac{d\Gamma(\bar{B} \to D\ell\nu)}{dw} = \frac{G_F^2}{48\pi^3\hbar} M_D^3 (M_B + M_D)^2 (w^2-1)^{3/2} \mid V_{cb} \mid^2 \; \mathcal{G}^2(w)$$

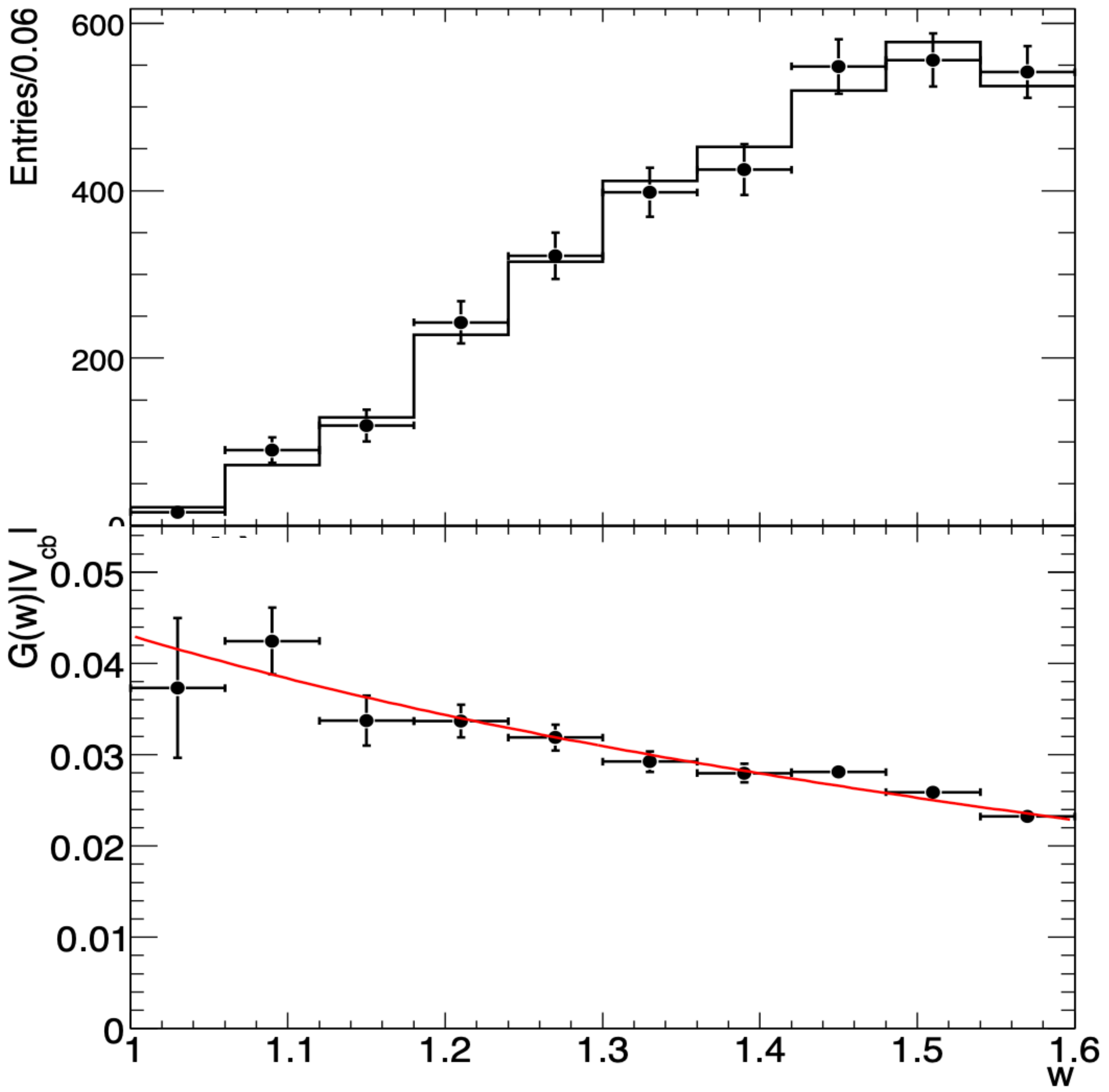
CLN Parametrization

$$\mathcal{G}(z) = \mathcal{G}(1)(1 - 8\rho^2 z + (51\rho^2 - 10)z^2 - (252\rho^2 - 84)z^3)$$

- Hadronic reconstruction with full BaBar dataset.
- Reconstruct signal D meson and identify lepton
- Extract signal yield using an un-binned maximum likelihood fit to the M^2_{miss} distribution
- Main systematic uncertainty: tagging efficiency







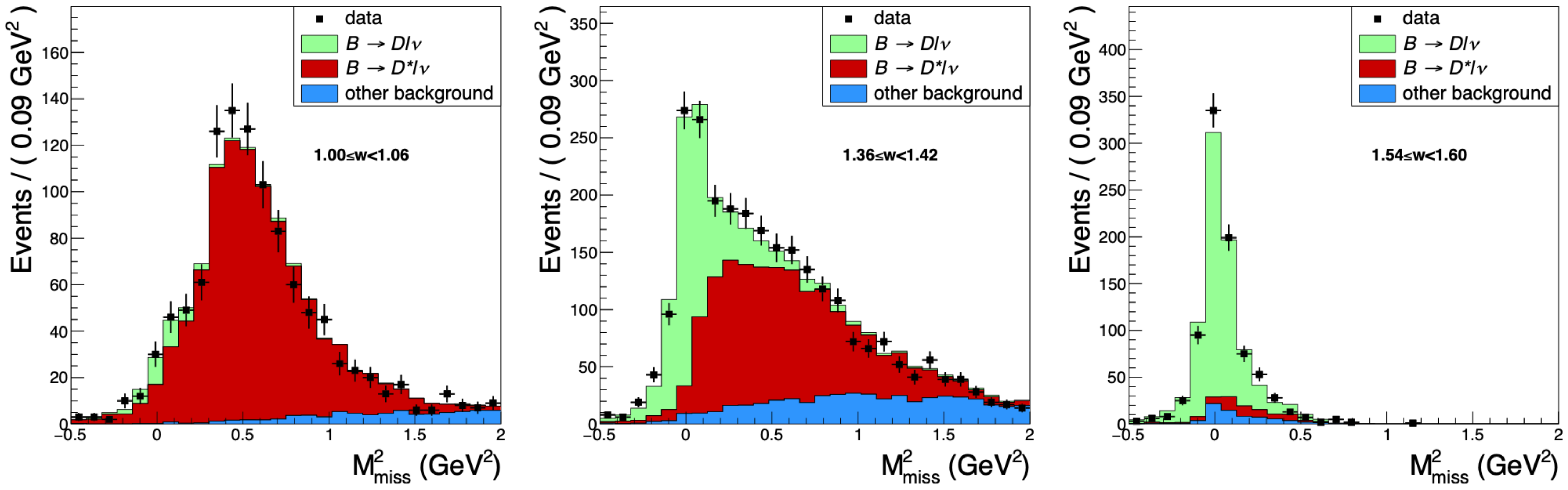
- Measure |Vcb| and ρ^2 using a least square fit in ten bins of w.

$$|\,Vcb\,| = (41.6 \pm 1.8 \pm 1.4 \pm 0.7_{FF}) \times 10^{-3}$$

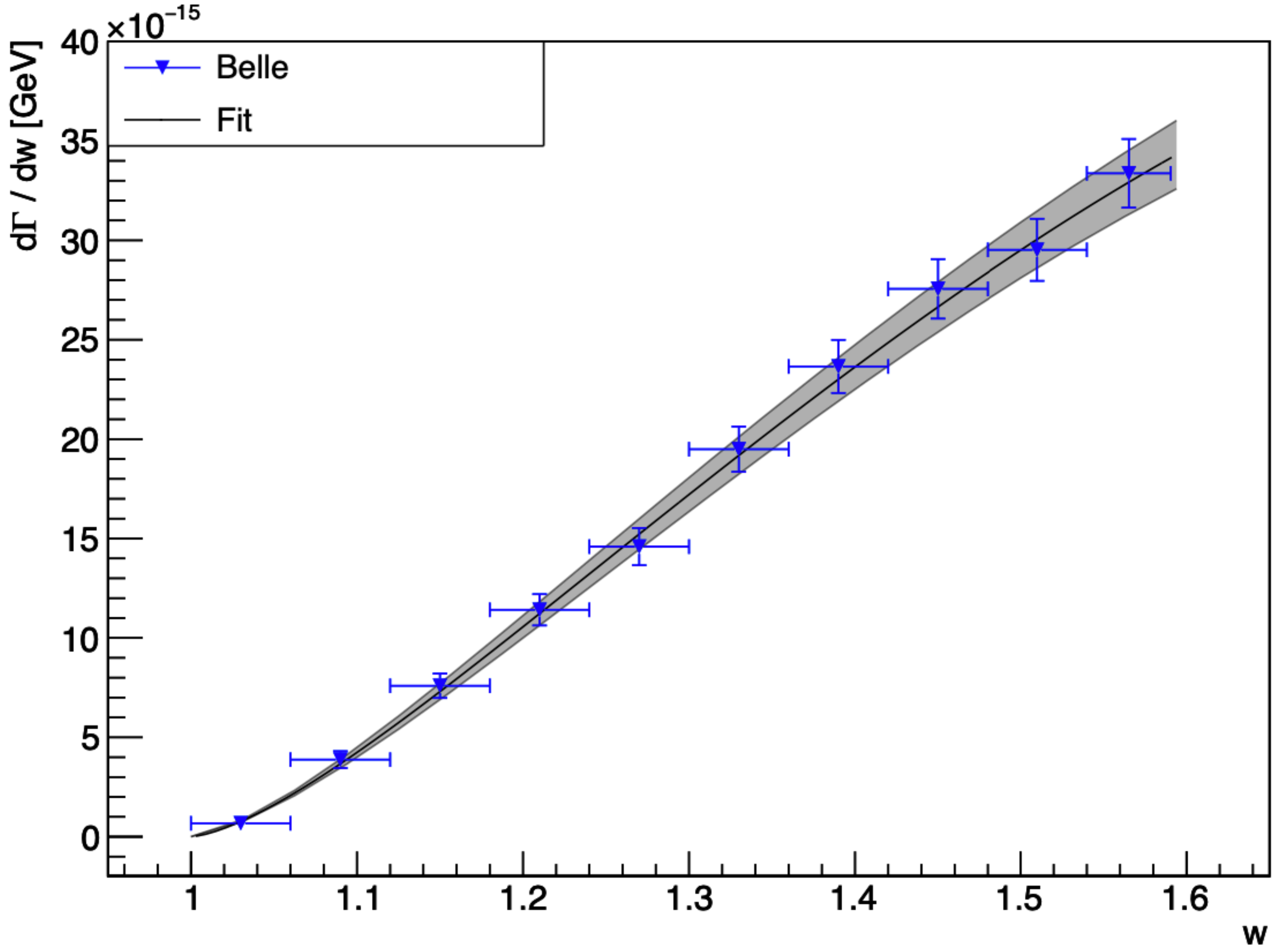
$\bar{B} \to D\ell\nu$

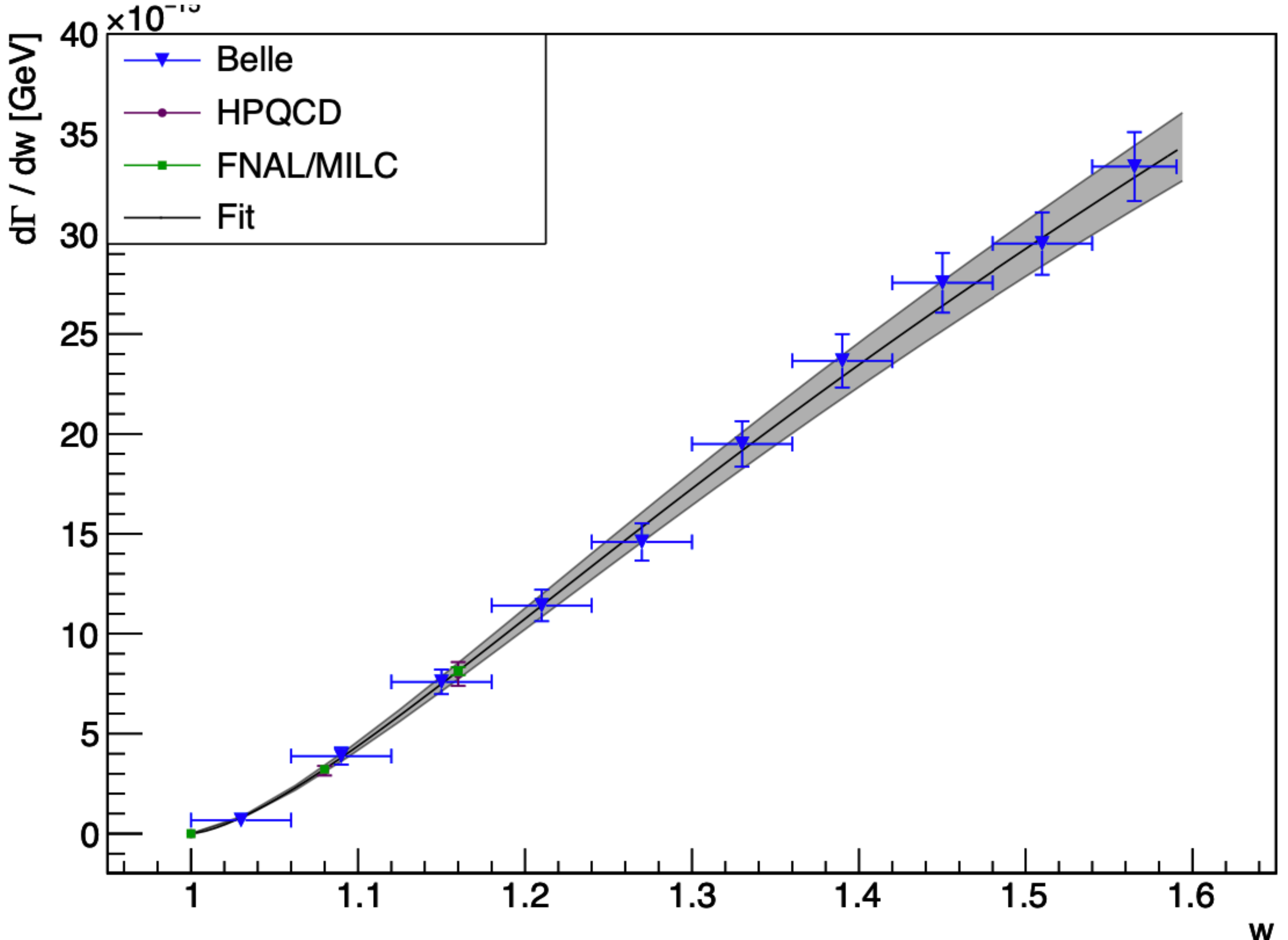
Phys. Rev. D93, 032006 (2016)

- Updated analysis with hadronic tagging at Belle.
- 10 D^+ and 13 D^0 modes, 5 times the width reconstructed by BaBar
- Signal yield extracted from a fit to M^2_{miss}.



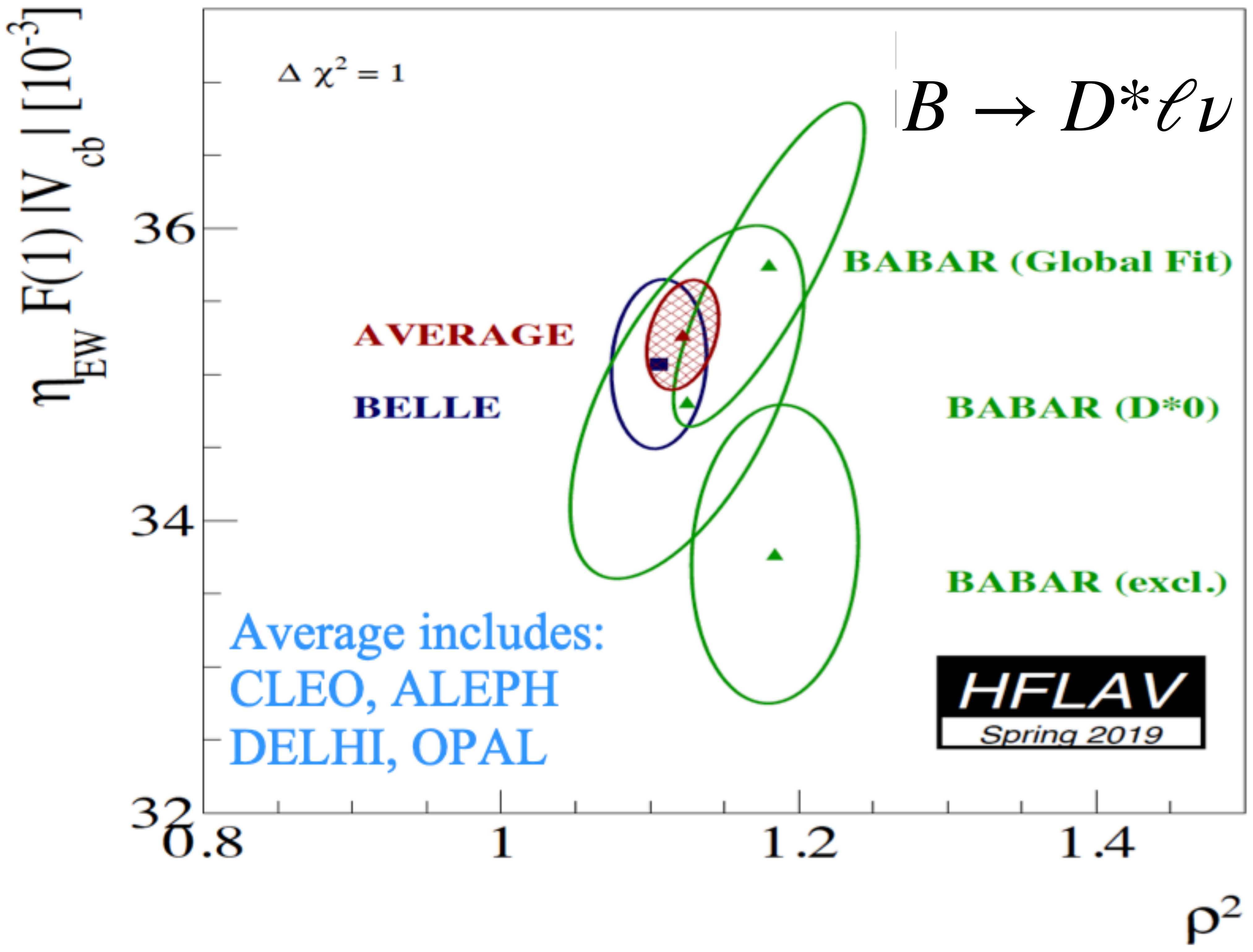
- Perform fit to CLN parametrization and use $\mathscr{G}(1) = 1.0541 \pm 0.0083$, determine $\boxed{V_{cb}| = (39.86 \pm 1.33) \times 10^{-3}}$
- Repeat with BGL parametrization and lattice calculations to find $\boxed{|V_{cb}| = (40.83 \pm 1.13) \times 10^{-3}}$
- Consistent with $B \to D^*\ell\nu$, smaller deviation from inclusive $|V_{cb}|$

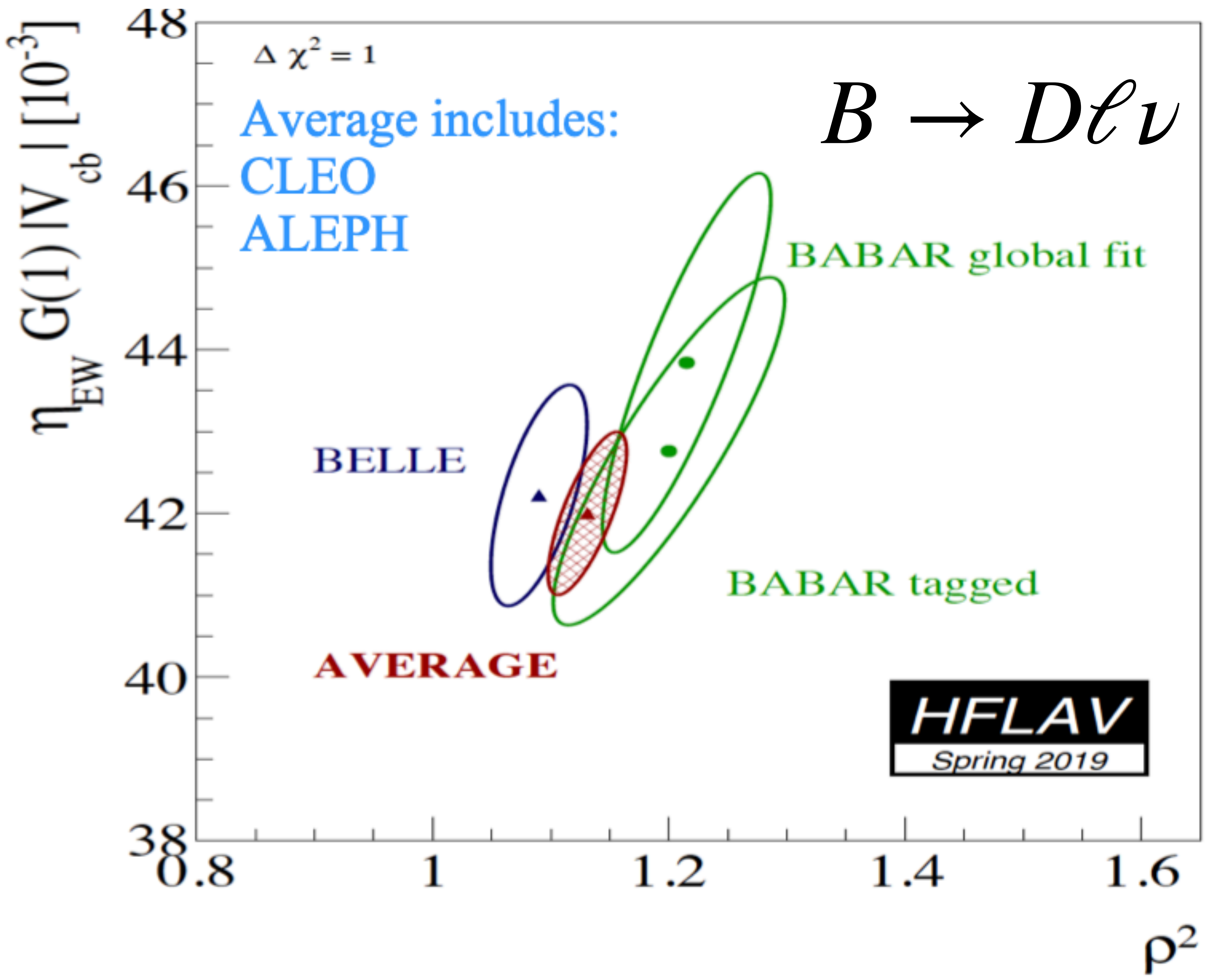




Exclusive $|V_{cb}|$

CLN parametrization only





$$|V_{cb}| = (38.76 \pm 0.42_{exp} \pm 0.55_{th}) \cdot 10^{-3}$$

$$|V_{cb}| = (39.58 \pm 0.94_{exp} \pm 0.37_{th}) \cdot 10^{-3}$$

Inclusive $|V_{cb}|$

- HQE in powers of $1/m_b$
- Determine parameters of HQE using moments of the differential rate.

$$\langle E^n\rangle_{\rm cut} = \frac{\int_{E_\ell > E_{\rm cut}} dE_\ell\, E_\ell^n \,\frac{d\Gamma}{dE_\ell}}{\int_{E_\ell > E_{\rm cut}} dE_\ell \,\frac{d\Gamma}{dE_\ell}} \qquad \langle (M_X^2)^n\rangle_{\rm cut} = \frac{\int_{E_\ell > E_{\rm cut}} dM_X^2\, (M_X^2)^n \,\frac{d\Gamma}{dM_X^2}}{\int_{E_\ell > E_{\rm cut}} dM_X^2 \,\frac{d\Gamma}{dM_X^2}} \qquad R^*(E_{\rm cut}) = \frac{\int_{E_\ell > E_{\rm cut}} dE_\ell \,\frac{d\Gamma}{dE_\ell}}{\int_0 dE_\ell \,\frac{d\Gamma}{dE_\ell}}$$

$$\mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3, m_b, (m_c)$$

- Using the branching fraction, determine $|V_{cb}|$

$$\mathrm{Br}(\bar{B} \to X_c \ell \bar{\nu}) \propto \frac{|V_{cb}|^2}{\tau_B} \left[\Gamma_0 + \Gamma_{\mu_\pi} \frac{\mu_\pi^2}{m_b^2} + \Gamma_{\mu_G} \frac{\mu_G^2}{m_b^2} + \Gamma_{\rho_D} \frac{\rho_D^3}{m_b^3}\right]$$

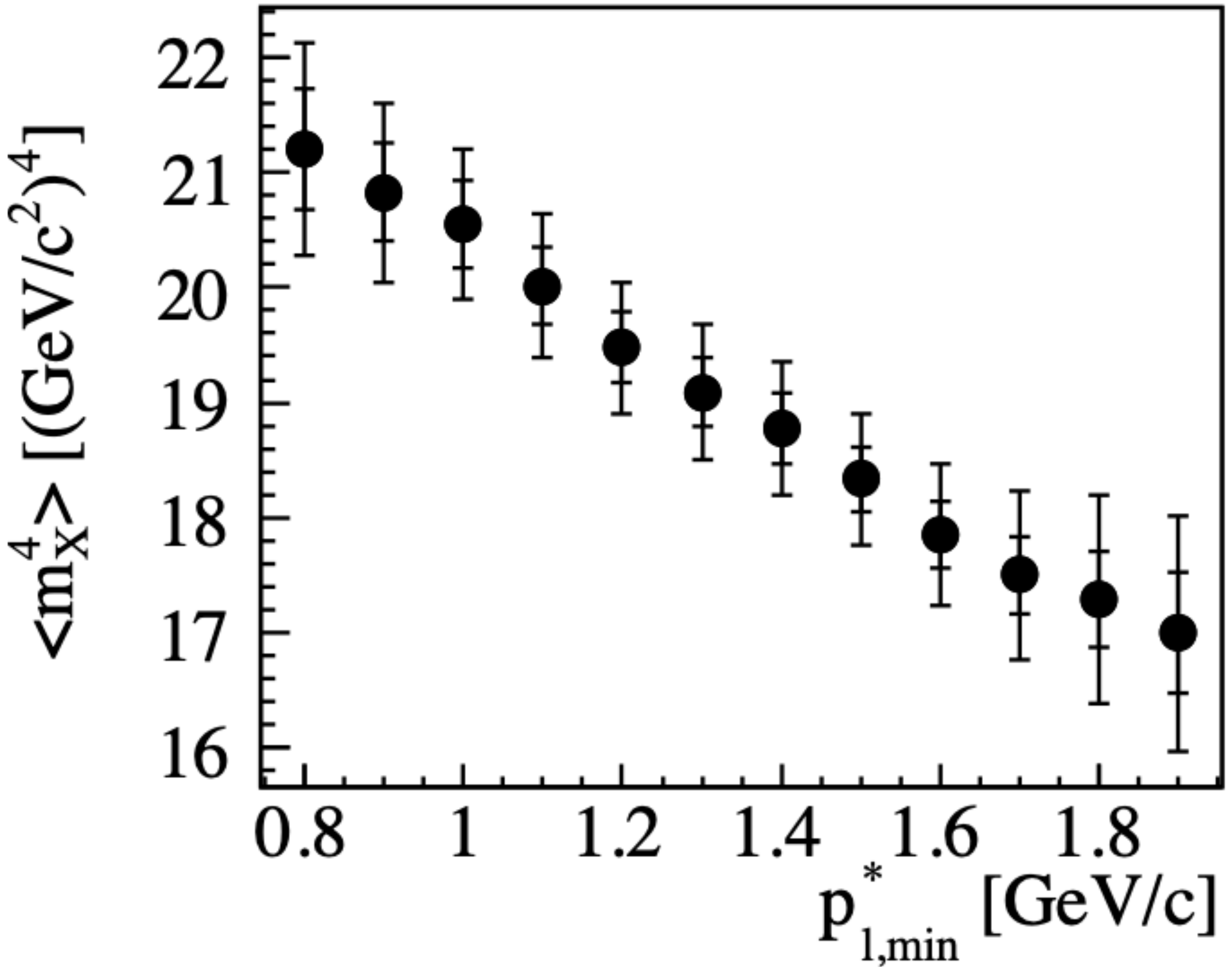
	Kinetic scheme	1S scheme
$O(1)$	m_b, m_c	m_b
$O(1/m_b^2)$	μ_π^2, μ_G^2	λ_1, λ_2
$O(1/m_b^3)$	ρ_D^3, ρ_{LS}^3	ρ_1, τ_{1-3}

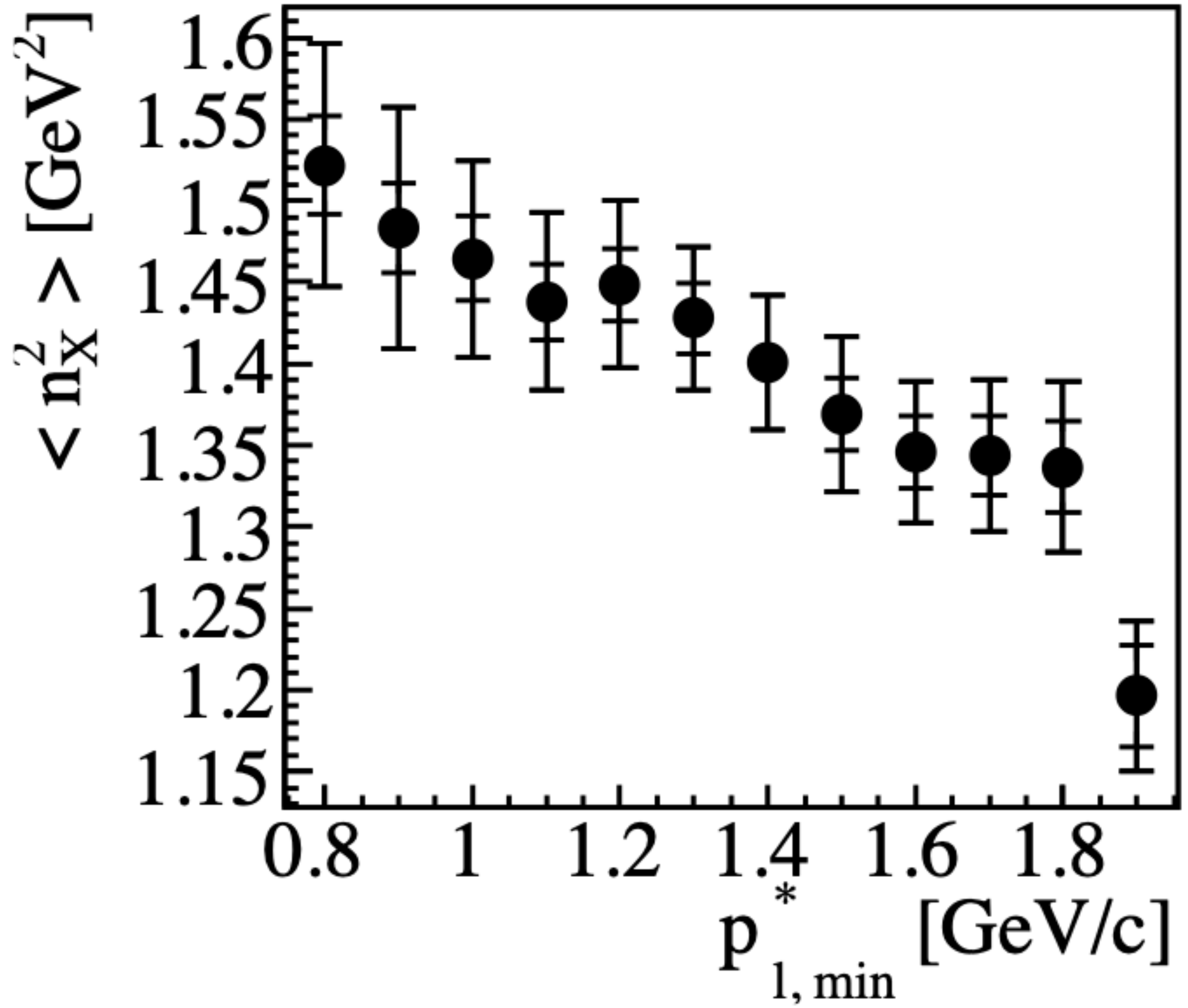
JHEP 1109 055 2011)
Phys Rev D 70, 094017 (2004)

Phys. Rev. D 81 032003, 2010

BaBar Inclusive $|V_{cb}|$

- Using 210 fb^{-1} of BaBar data, measure the m_X and lepton energy moments and the combined moments $n_X^2 = m_X^2c^4 - 2\Lambda E_X + \Lambda$
- Use hadronic tagging and reconstruct X system from remaining tracks and clusters in the event.
- Use kinematic fitting to improve M_X resolution and derive calibration functions to correct for mis-reconstruction and detector effects





Calibration Bias

$$\langle m_X^k\rangle = \frac{\sum_{i=1}^{N_{ev}} w_i(m_X)\, m^k_{X,calib,i}}{\sum_{i}^{N_{ev}} w_i} \times \mathcal{C}_{cal}(p^*_\ell,k)\times \mathcal{C}_{true}(p^*_\ell,k)$$

Reconstruction bias

- Main systematics: background subtraction, calibration functions, etc..

Phys. Rev. D 81 032003, 2010

BaBar Inclusive $|V_{cb}|$

- Determine $|V_{cb}|, \mathscr{B}, m_b, m_c, \mu_\pi^2, \mu_g^2, \rho_D^3,$ and ρ_{LS}^3 using simultaneous χ^2 fit to the measured moments and partial branching fractions as functions of the minimum lepton momentum and minimum photon energy E.
- Consistent results between fits to m_X and n_X.

$$\frac{|V_{cb}|}{0.0417} = \sqrt{\frac{\mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu})}{0.1032} \frac{1.55}{\tau_B}} \times [1 + 0.30(\alpha_s(m_b) - 0.22)] \times [1 - 0.66(m_b - 4.60) + 0.39(m_c - 1.15) + 0.013(\mu_\pi^2 - 0.40) + 0.09(\rho_D^3 - 0.20) + 0.05(\mu_G^2 - 0.35) - 0.01(\rho_{LS}^3 + 0.15)].$$

	$\lvert V_{cb}\rvert \times 10^3$	$m_b\,[\mathrm{GeV}/c^2]$	$m_c\,[\mathrm{GeV}/c^2]$	$\mathcal{B}\,[\%]$	$\mu_\pi^2\,[\mathrm{GeV}^2]$	$\mu_G^2\,[\mathrm{GeV}^2]$	$\rho_D^3\,[\mathrm{GeV}^3]$	$\rho_{LS}^3\,[\mathrm{GeV}^3]$
Results	42.05	4.549	1.077	10.642	0.476	0.300	0.203	-0.144
Δ_{exp}	0.45	0.031	0.041	0.165	0.021	0.044	0.017	0.075
Δ_{theo}	0.37	0.038	0.062	0.063	0.059	0.038	0.027	0.056
$\Delta_{\Gamma_{SL}}$	0.59							
Δ_{tot}	0.83	0.049	0.074	0.176	0.063	0.058	0.032	0.094

$$|V_{cb}| = (42.05 \pm 0.45 \pm 0.70) \times 10^{-3}$$

Latest global fits in the kinetic scheme

$$|V_{cb}| = (42.19 \pm 0.78) \cdot 10^{-3}$$

$$\mathcal{B}(B \to X_c \ell \nu) = 10.65 \pm 0.16\ \%$$

$$m_b^{kin} = 4.544 \pm 0.018\ GeV$$

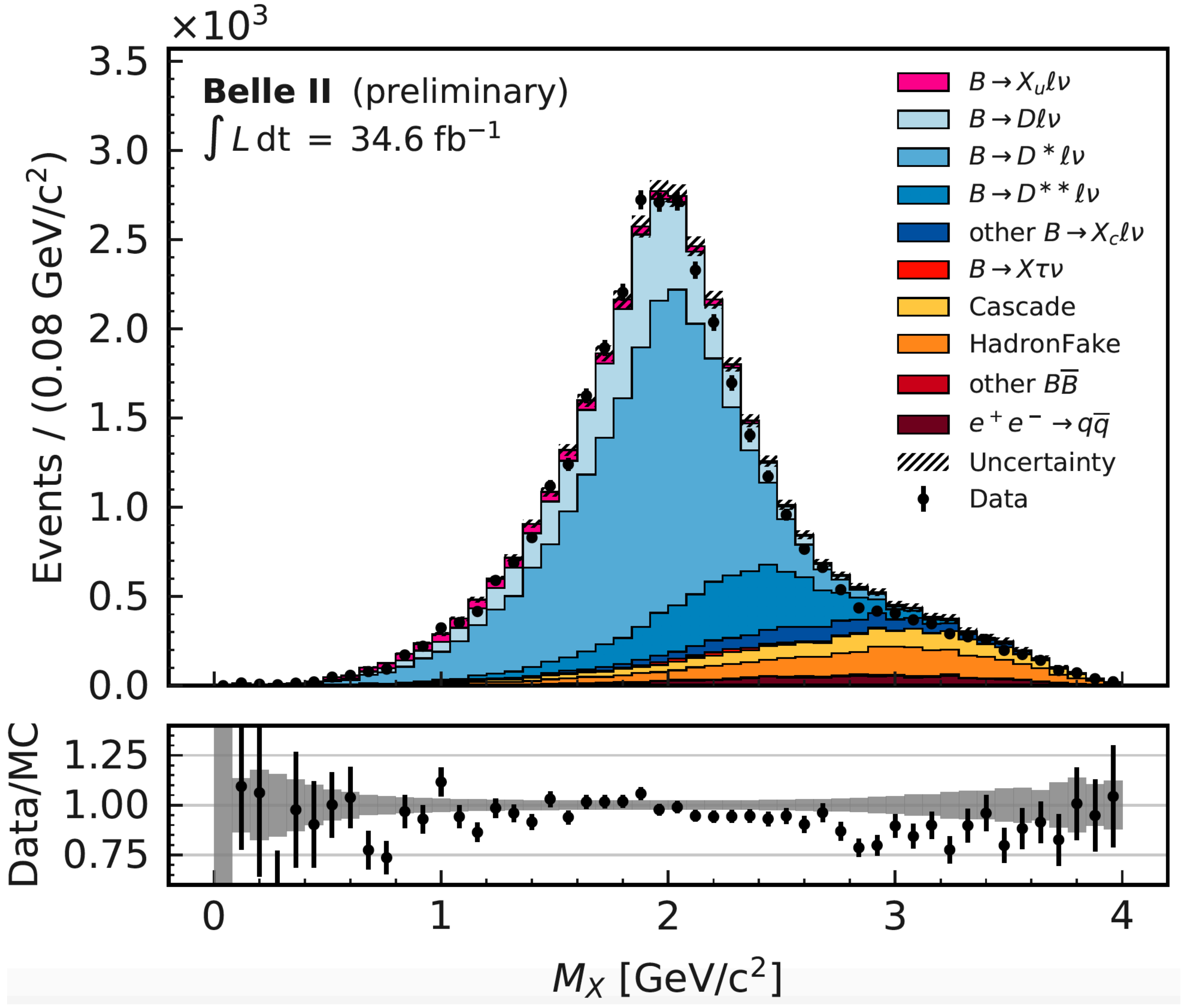
$$\mu_\pi^2 = 0.464 \pm 0.076\ GeV^2$$

Gambino, Schwanda, Phys Rev D 89, 014022 (2014)
Alberti, Gambino, Healey, Nandi Phys. Rev. Lett 114,061802 (2015)

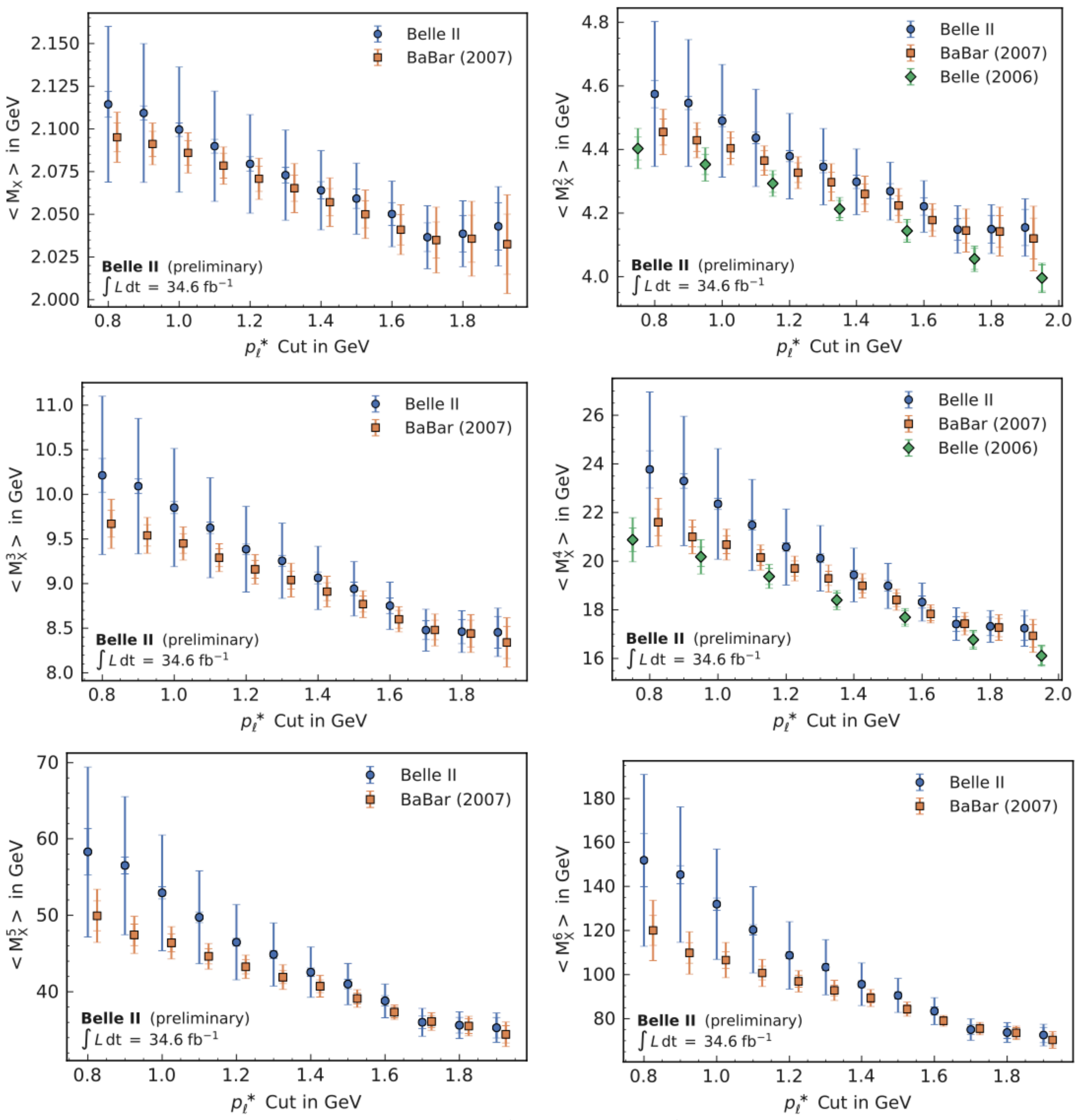
No new experimental results since 2010!

Hadronic Mass Moments of $B \to X_c \ell \nu_\ell$

- Use hadronic FEI tagging and identify one lepton with $p*_l > 0.8$ GeV/c and PID likelihood >0.9.
- 6 signal channels $B^0 \ell^\pm, B^+ \ell^-$ and two control $B^+ \ell^+$ to estimate N^i_{bkg}
- Identify X_c system using remaining tracks and clusters in the $\Upsilon(4S)$ rest of event.
- Suppress continuum and require E_{miss} and p_{miss}>0.5 GeV.



Phys. Rev. D 75, 032005, 2007



In agreement with previous measurements!

Alternative Inclusive |V_{cb}|

- Achieve more precision by including higher order:

$$\Gamma \propto |V_{cb}|^2 m_b^5 \Bigg[\Gamma_0 + \Gamma_0^{(1)} \frac{\alpha_s}{\pi} + \Gamma_0^{(2)} \left(\frac{\alpha_s}{\pi}\right)^2 + \frac{\mu_\pi^2}{m_b^2}\left(\Gamma^{(\pi,0)} + \frac{\alpha_s}{\pi}\Gamma^{(\pi,1)}\right)$$
$$+ \frac{\mu_G^2}{m_b^2}\left(\Gamma^{(G,0)} + \frac{\alpha_s}{\pi}\Gamma^{(G,1)}\right) + \frac{\rho_D^3}{m_b^3}\Gamma^{(D,0)} + \mathcal{O}\left(\frac{1}{m_b^4}\right) \cdots \Bigg)$$

NOVEL APPROACH!!!

- Number of parameters: 4 up to$1/m_b^3$, 13 up to $1/m_b^4$ and 31 up to $1/m_b^5$
- Use reparametrization invariance to link different orders of 1/mb and reduce the number of total parameters
- Requires RPI observables such as q^2

- $2M_B r_G^4 \equiv \frac{1}{2}\langle B|\bar{b}_v\,[iD_\mu, iD_\nu]\,[iD^\mu, iD^\nu]\,b_v|B\rangle \propto \langle \vec{E}^2 - \vec{B}^2\rangle$
- $2M_B r_E^4 \equiv \frac{1}{2}\langle B|\bar{b}_v\,[ivD, iD_\mu]\,[ivD, iD^\mu]\,b_v|B\rangle \propto \langle \vec{E}^2\rangle$
- $2M_B s_B^4 \equiv \frac{1}{2}\langle B|\bar{b}_v\,[iD_\mu, iD_\alpha]\,[iD^\mu, iD_\beta]\;(-i\sigma^{\alpha\beta})b_v|B\rangle \propto \langle \vec{\sigma}\cdot\vec{B}\times\vec{B}\rangle$
- $2M_B s_E^4 \equiv \frac{1}{2}\langle B|\bar{b}_v\,[ivD, iD_\alpha]\,[ivD, iD_\beta]\;(-i\sigma^{\alpha\beta})b_v|B\rangle \propto \langle \vec{\sigma}\cdot\vec{E}\times\vec{E}\rangle$
- $2M_B s_{qB}^4 \equiv \frac{1}{2}\langle B|\bar{b}_v\,[iD_\mu, [iD^\mu, [iD_\alpha, iD_\beta]]]\;(-i\sigma^{\alpha\beta})b_v|B\rangle \propto \langle \Box\,\vec{\sigma}\cdot\vec{B}\rangle\ .$

8 parameters instead of 13 !

$$\langle (q^2)^n \rangle_{\mathrm{cut}} = \int_{q^2>q^2_{\mathrm{cut}}} dq^2\,(q^2)^n \frac{d\Gamma}{dq^2} \Bigg/ \int_{q^2>q^2_{\mathrm{cut}}} dq^2 \frac{d\Gamma}{dq^2}$$

$$R^*(q^2_{\mathrm{cut}}) = \int_{q^2>q^2_{\mathrm{cut}}} dq^2 \frac{d\Gamma}{dq^2} \Bigg/ \int_0 dq^2 \frac{d\Gamma}{dq^2}$$

Fael, Mannel, Vos , JHEP 02 (2019) 177

Alternative Inclusive $|V_{cb}|$

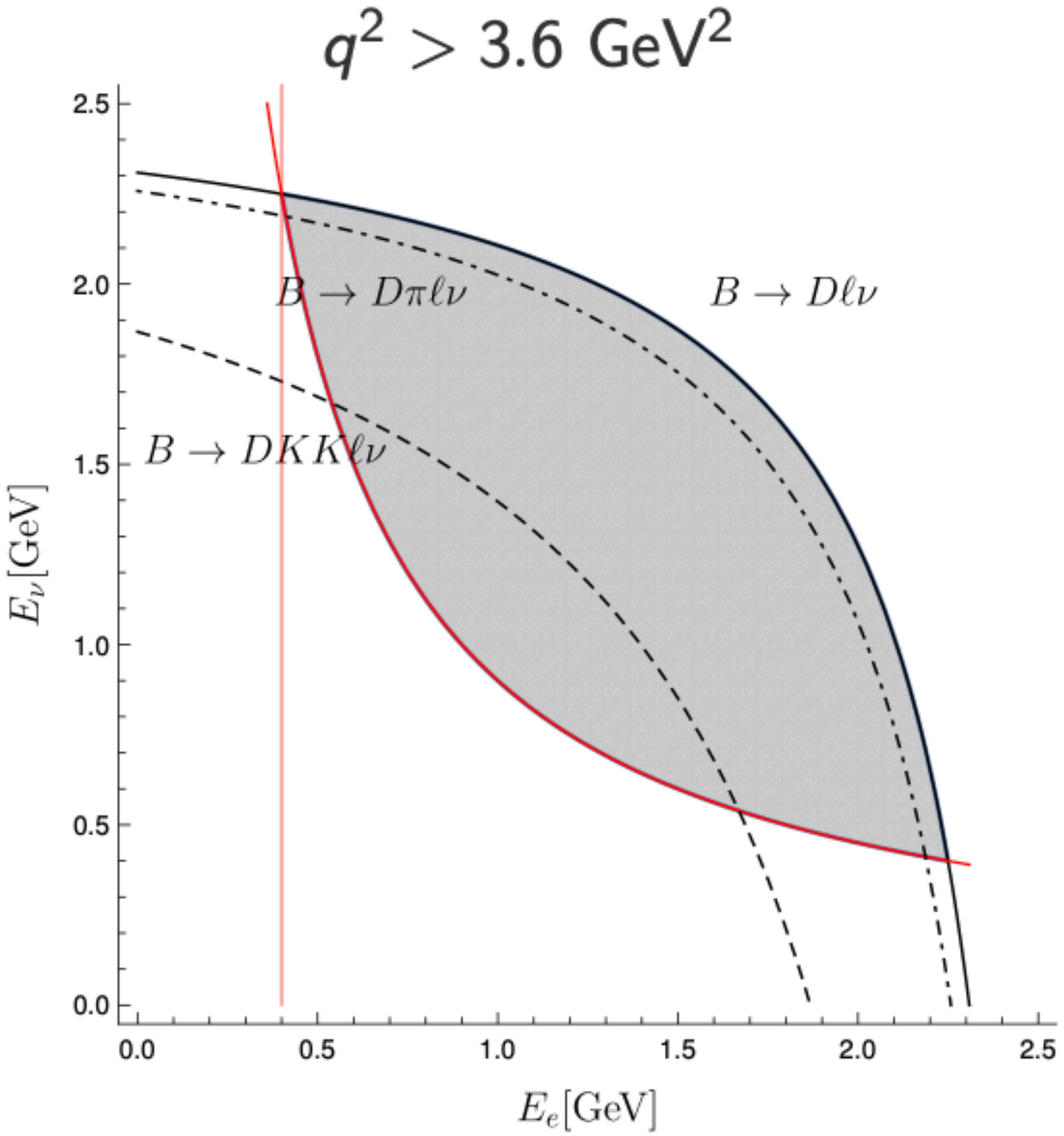
NOVEL APPROACH!!!

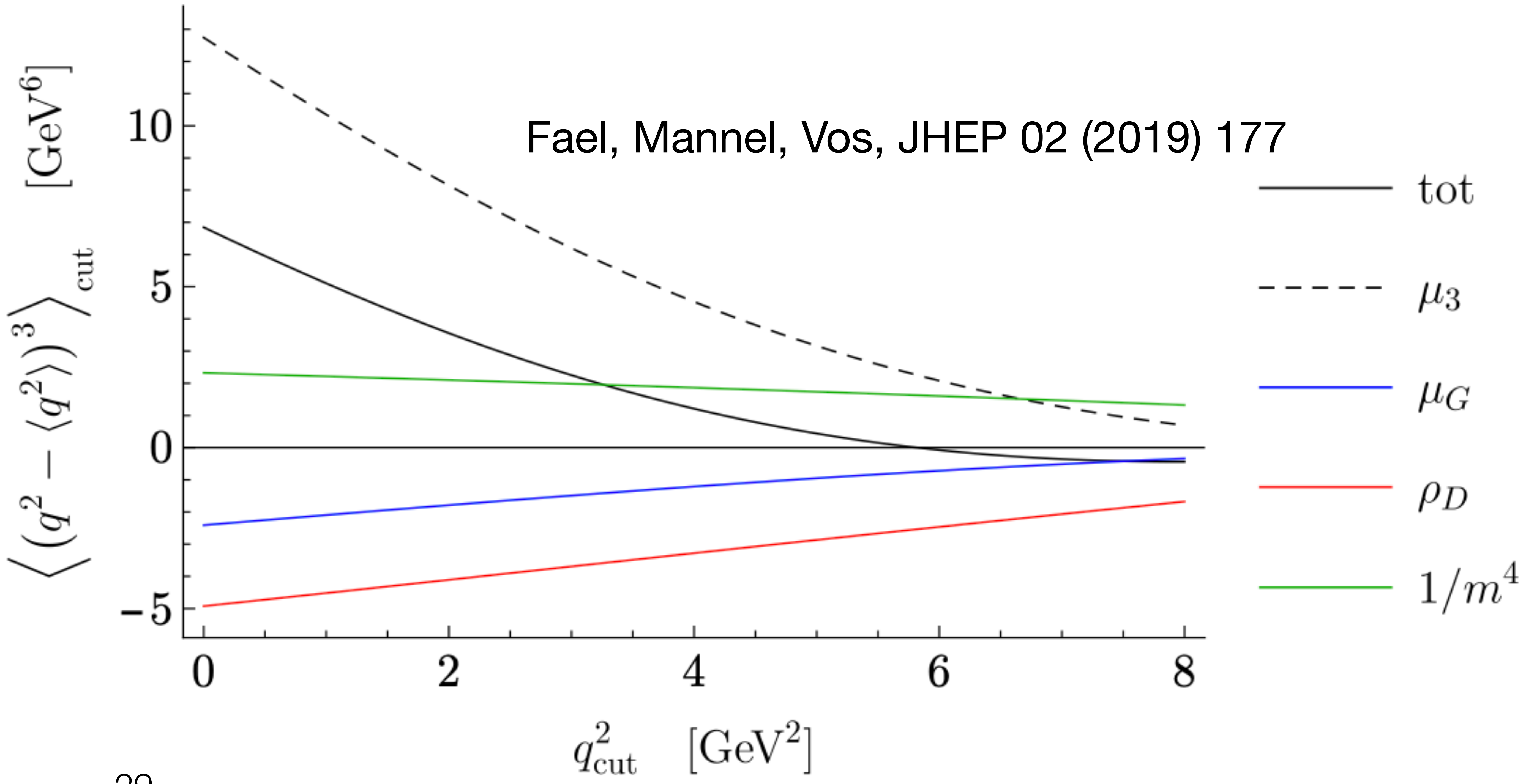
- HQE expressed in higher order terms

$$\mathrm{Br}(\bar{B} \to X_c \ell \bar{\nu}) \propto \frac{|V_{cb}|^2}{\tau_B} \Big[\Gamma_{\mu_3} \mu_3 + \Gamma_{\mu_G} \frac{\mu_G^2}{m_b^2} + \Gamma_{\tilde{\rho}_D} \frac{\tilde{\rho}_D^3}{m_b^3} + \Gamma_{r_E} \frac{r_E^4}{m_b^4} + \Gamma_{r_G} \frac{r_G^4}{m_b^4} + \Gamma_{s_B} \frac{s_B^4}{m_b^4} + \Gamma_{s_E} \frac{s_E^4}{m_b^4} + \Gamma_{s_{qB}} \frac{s_{qB}^4}{m_b^4} \Big]$$

$\mu_3, \mu_G, \tilde{\rho}_D, r_E, r_G, s_E, s_B, s_{qB}, m_b, m_c$

Determine moments and use it determine $|V_{cb}|$



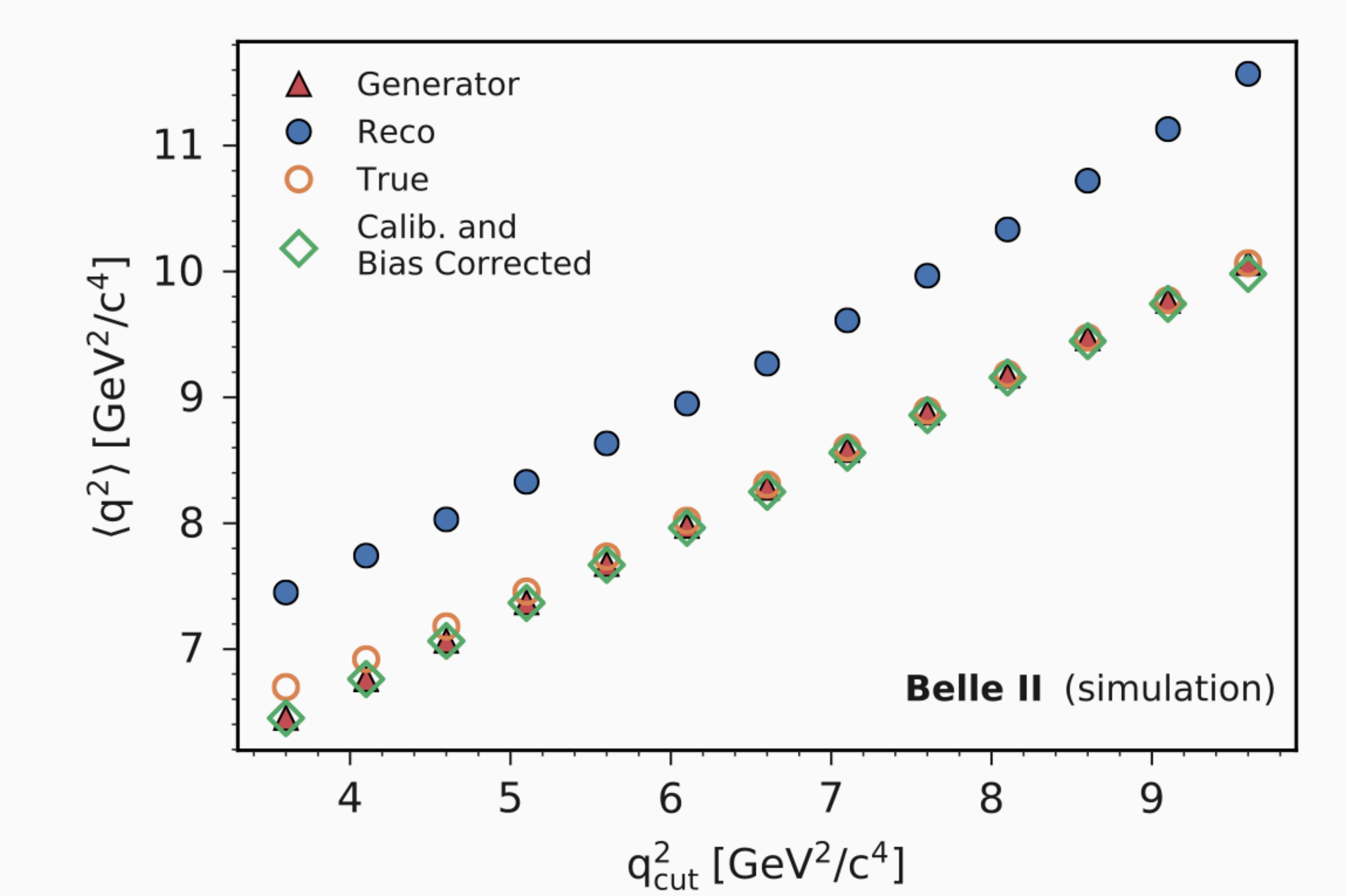


Fael, Mannel, Vos, JHEP 02 (2019) 177

q^2 moments at Belle and Belle II

Tagged approach:

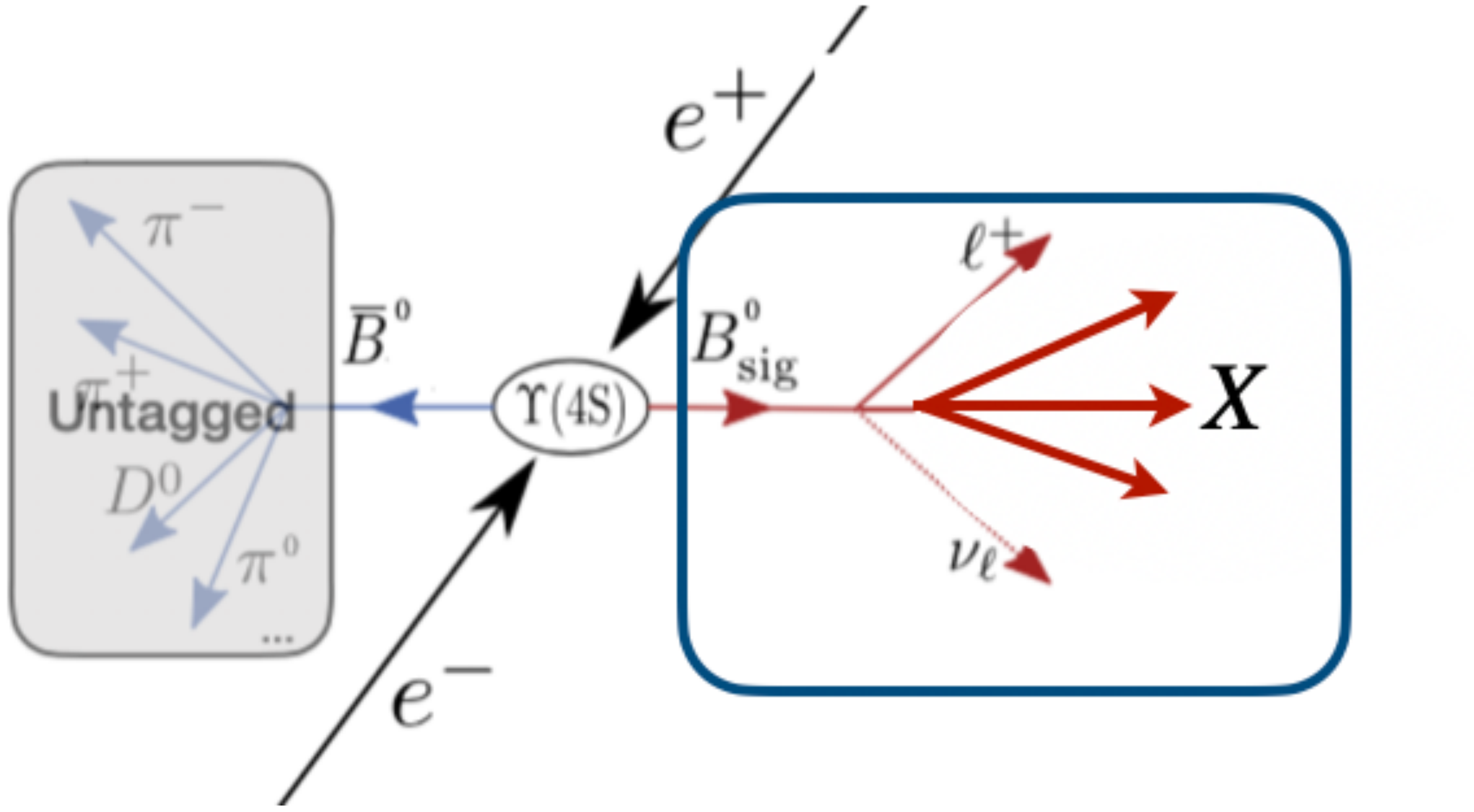
- Use similar strategy as m_X moments analysis.
- Apply q^2>3.6 GeV2/c4 cut instead of lepton momentum cut.
- Determine background normalization using a fit to M_X spectrum
- Derive calibrations in bins of q^2



First results expected by Moriond 2021!

Untagged approach:

- Identify lepton and suppress continuum events using fox Wolfram R2 cut.
- use missing momentum in the events as an estimate of the neutrino momentum.
- Require M^2_{miss} 0
- Determine $q^2 = P_\ell + P_\nu$



Summer 2021 target: combine untagged and tagged measurements!

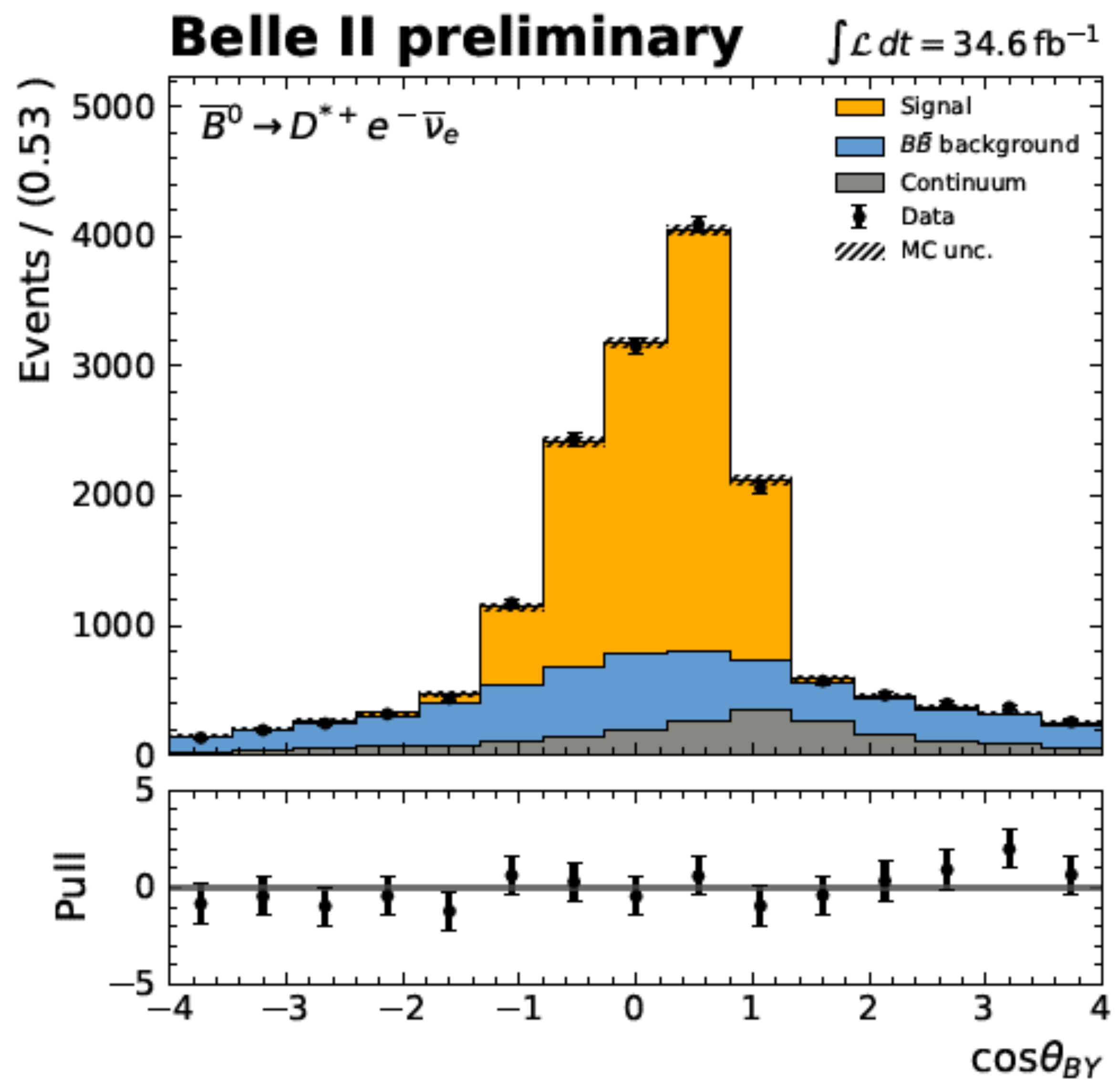
$|V_{cb}|$ Prospects at Belle II

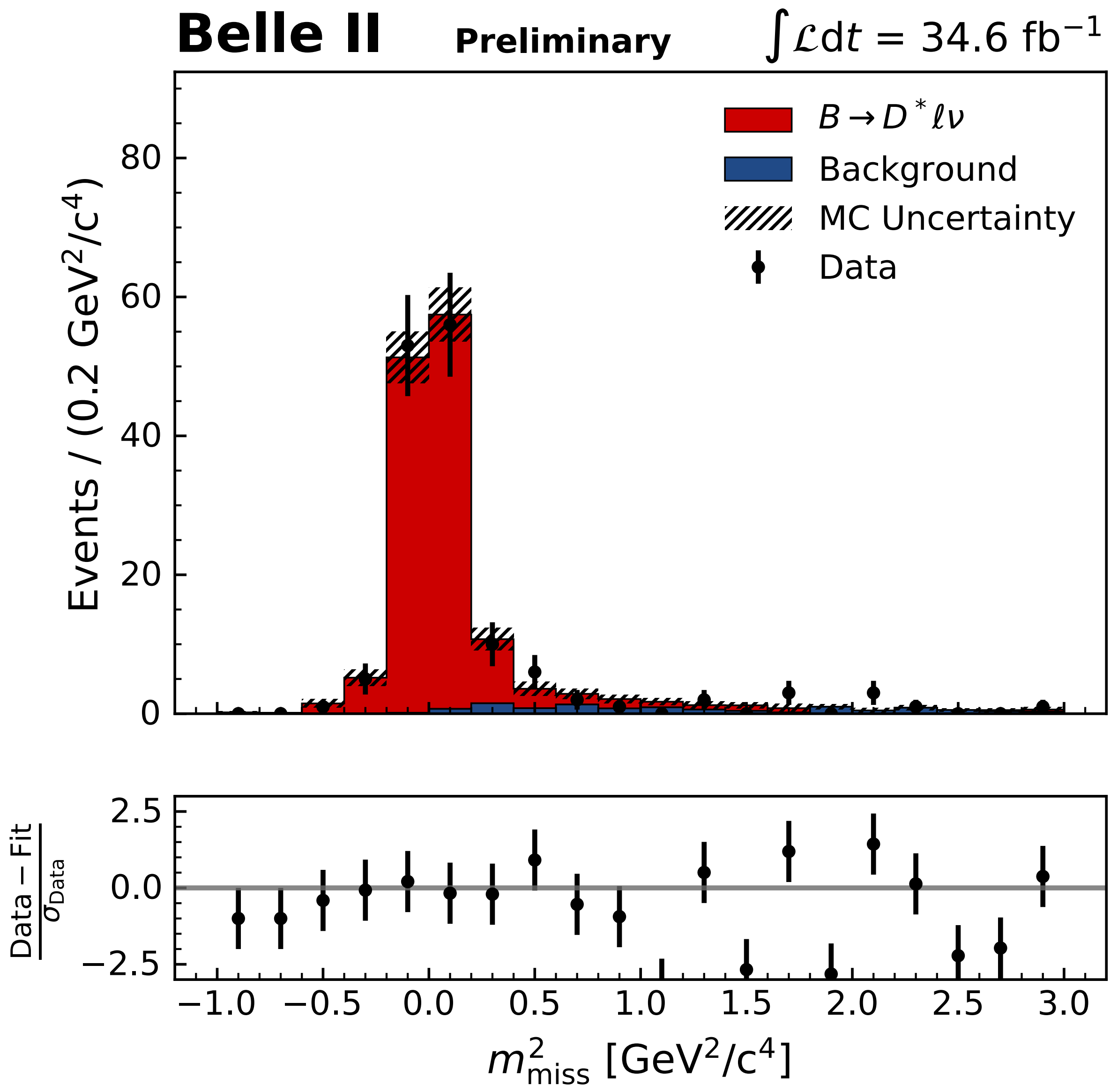
- With 1 ab^{-1} size dataset, the limitation will mainly be systematic.
  - Improved tracking, PID and vertexing tools.

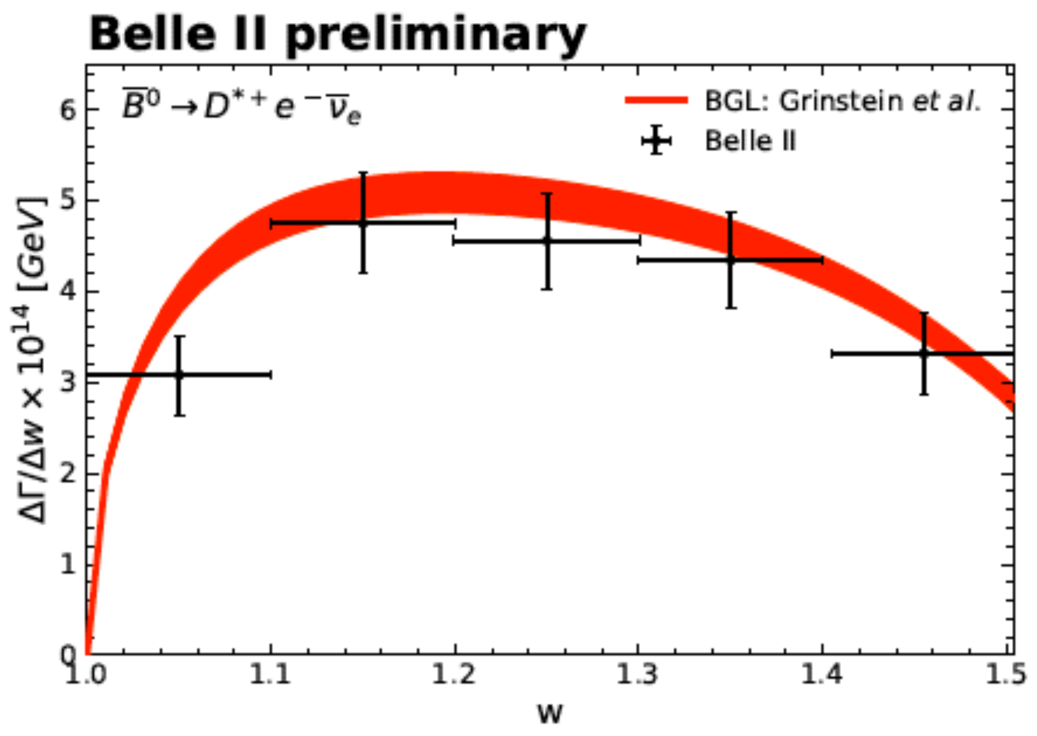
- Reduce systematic uncertainties related to tagging efficiency.
  - Clean up low purity modes.

- Improved measurements for $N_{B\bar{B}}$ and f^{+0}
- Achieve higher precision in the measurements of the moments for inclusive $|V_{cb}|$.
  - Valuable input for theory!

- Provide complementary kinetic information by measuring other single differential spectra, such as the hadronic energy or q2.
  - Work already in progress.
- Improved measurements of $B \to D^{**}\ell\nu$ with 1 ab^{-1}



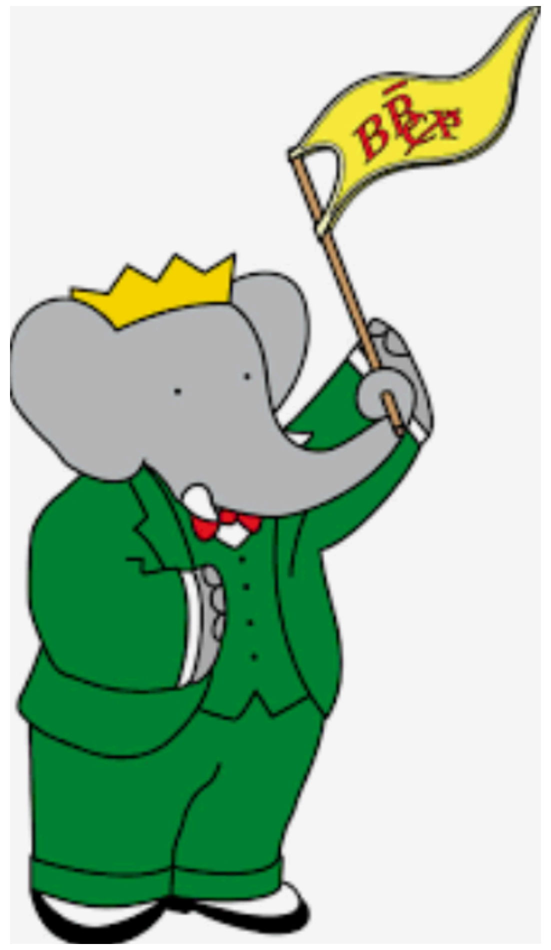


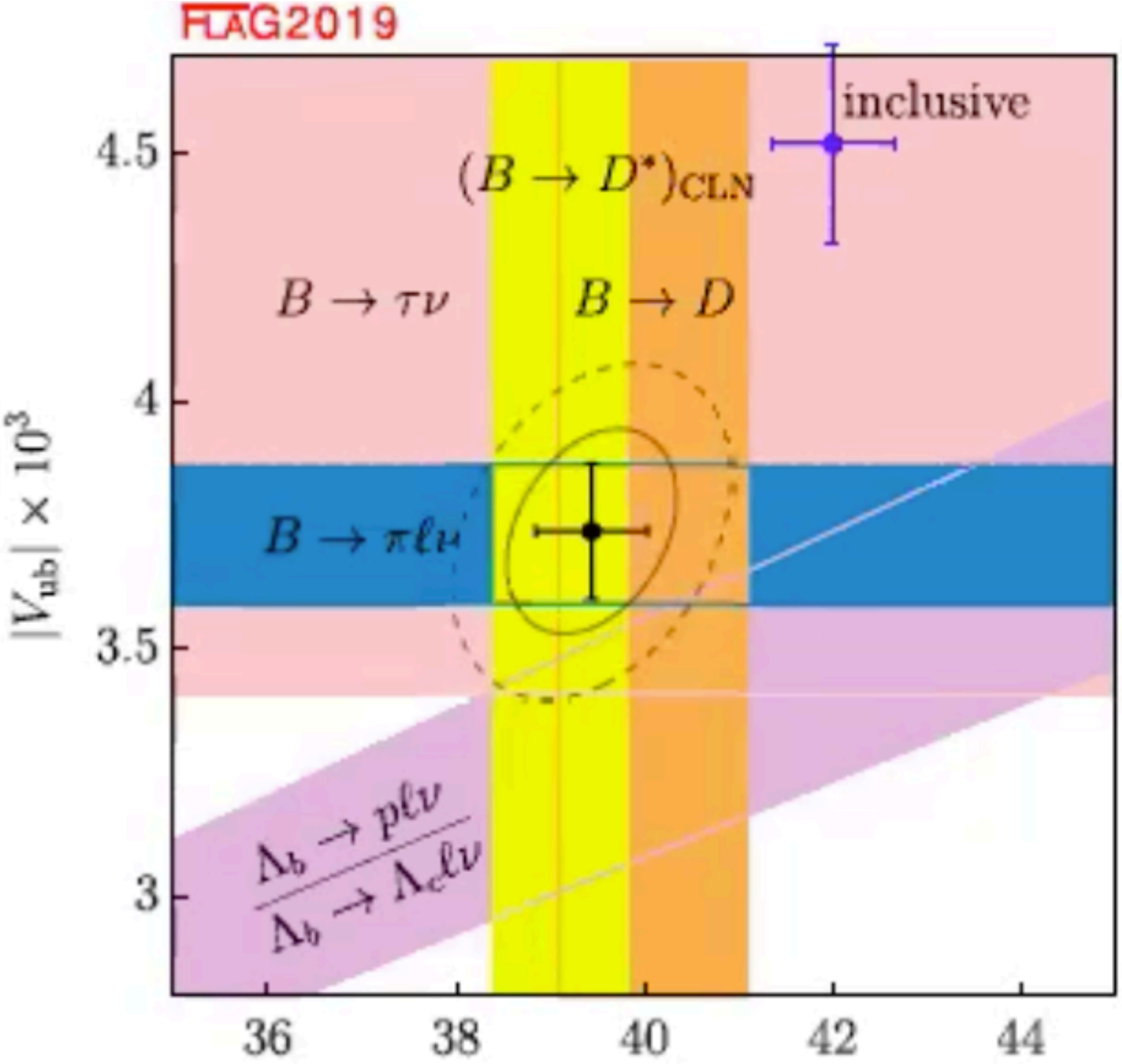


Measured branching fraction is compatible with current world average!

Conclusion

- Lots of work in progress in attempt to resolve $|V_{ub}|$ and $|V_{cb}|$ puzzle.
- Exclusive $|V_{cb}|$:
  - Upcoming model independent $B \to D\ell\nu$ result at BaBar and a combined D and D* HQET fit
  - Work in progress at Belle II for improved precision in $B \to D\ell\nu$ and $B \to D^*\ell\nu$ results.
- Inclusive $|V_{cb}|$:
  - Novel q^2 moments to be measured at Belle II using tagged and untagged approaches.
  - Updated m_X moments study at Belle II .
- Exclusive $|V_{ub}|$:
  - Upcoming analysis on $B \to \eta^{'}\ell\nu$ for Winter 2021
  - Work in progress at Belle II for improved precision in $B \to \pi\ell\nu$ and $B \to \rho\ell\nu$ results.
- Inclusive $|V_{ub}|$:
  - Updated Belle analysis with reduced tension with exclusive modes, to be published soon.
  - Work in progress at Belle II for first result using lepton endpoint spectrum analysis.




FLAG2019
inclusive
$(B \to D^*)_{\mathrm{CLN}}$
$B \to \tau\nu$
$B \to D$
$B \to \pi\ell\nu$
$\frac{\Lambda_b \to p\ell\nu}{\Lambda_b \to \Lambda_c\ell\nu}$
$|V_{\mathrm{ub}}| \times 10^3$
4.5
4
3.5
3
36
38
40
42
44

Back up

Leading uncertainties

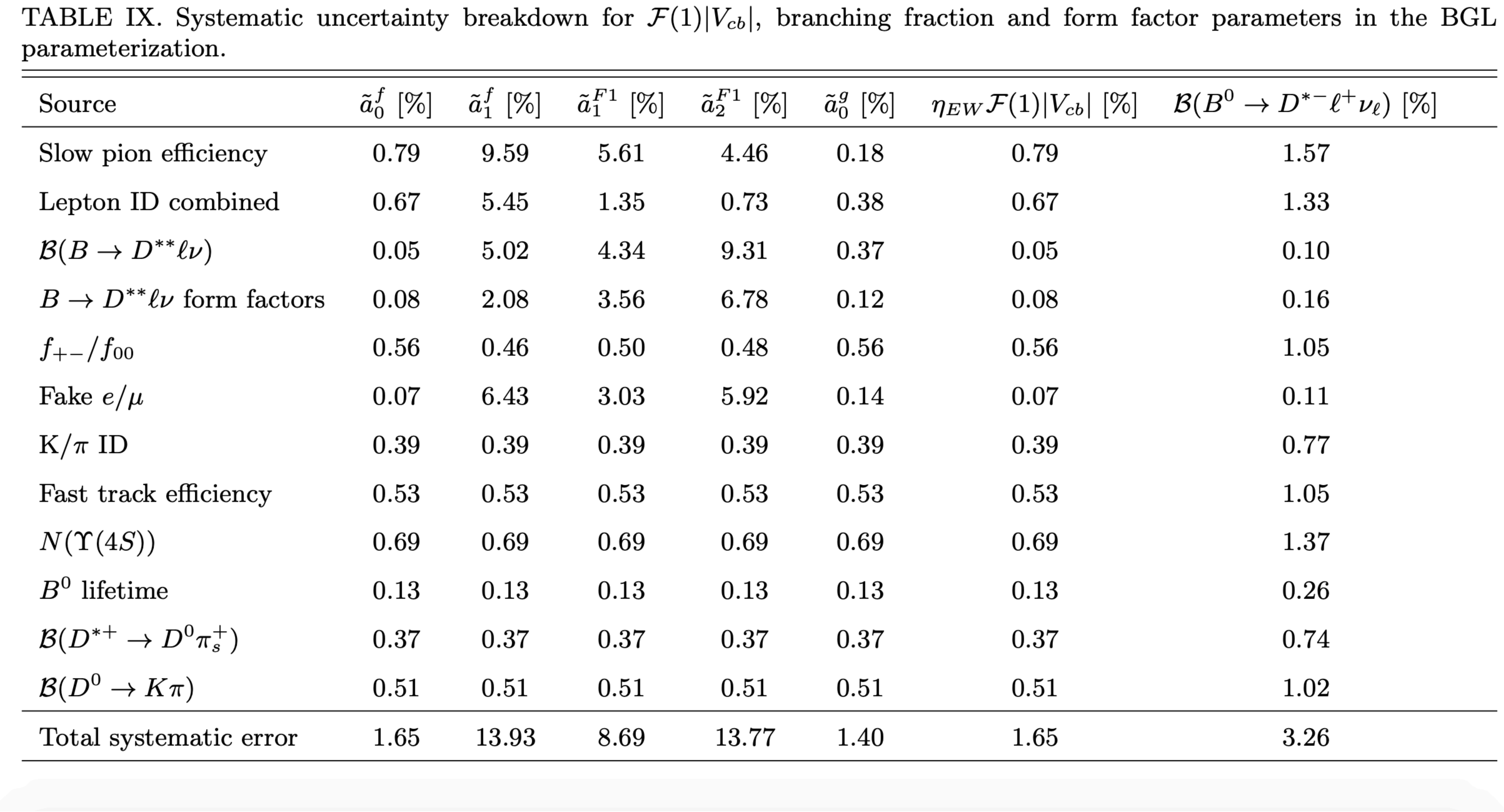


TABLE IX. Systematic uncertainty breakdown for $\mathcal{F}(1)|V_{cb}|$, branching fraction and form factor parameters in the BGL parameterization.

Source	$\tilde{a}_0^f$ [%]	$\tilde{a}_1^f$ [%]	$\tilde{a}_1^{F1}$ [%]	$\tilde{a}_2^{F1}$ [%]	$\tilde{a}_0^g$ [%]	$\eta_{EW}\mathcal{F}(1)\|V_{cb}\|$ [%]	$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell)$ [%]
Slow pion efficiency	0.79	9.59	5.61	4.46	0.18	0.79	1.57
Lepton ID combined	0.67	5.45	1.35	0.73	0.38	0.67	1.33
$\mathcal{B}(B \to D^{**}\ell\nu)$	0.05	5.02	4.34	9.31	0.37	0.05	0.10
$B \to D^{**}\ell\nu$ form factors	0.08	2.08	3.56	6.78	0.12	0.08	0.16
f_{+-}/f_{00}	0.56	0.46	0.50	0.48	0.56	0.56	1.05
Fake e/μ	0.07	6.43	3.03	5.92	0.14	0.07	0.11
K/π ID	0.39	0.39	0.39	0.39	0.39	0.39	0.77
Fast track efficiency	0.53	0.53	0.53	0.53	0.53	0.53	1.05
$N(\Upsilon(4S))$	0.69	0.69	0.69	0.69	0.69	0.69	1.37
B^0 lifetime	0.13	0.13	0.13	0.13	0.13	0.13	0.26
$\mathcal{B}(D^{*+} \to D^0\pi_s^+)$	0.37	0.37	0.37	0.37	0.37	0.37	0.74
$\mathcal{B}(D^0 \to K\pi)$	0.51	0.51	0.51	0.51	0.51	0.51	1.02
Total systematic error	1.65	13.93	8.69	13.77	1.40	1.65	3.26

Phys. Rev. D 95, 072001 (2017)

Inclusive $|V_{ub}|$ at BaBar

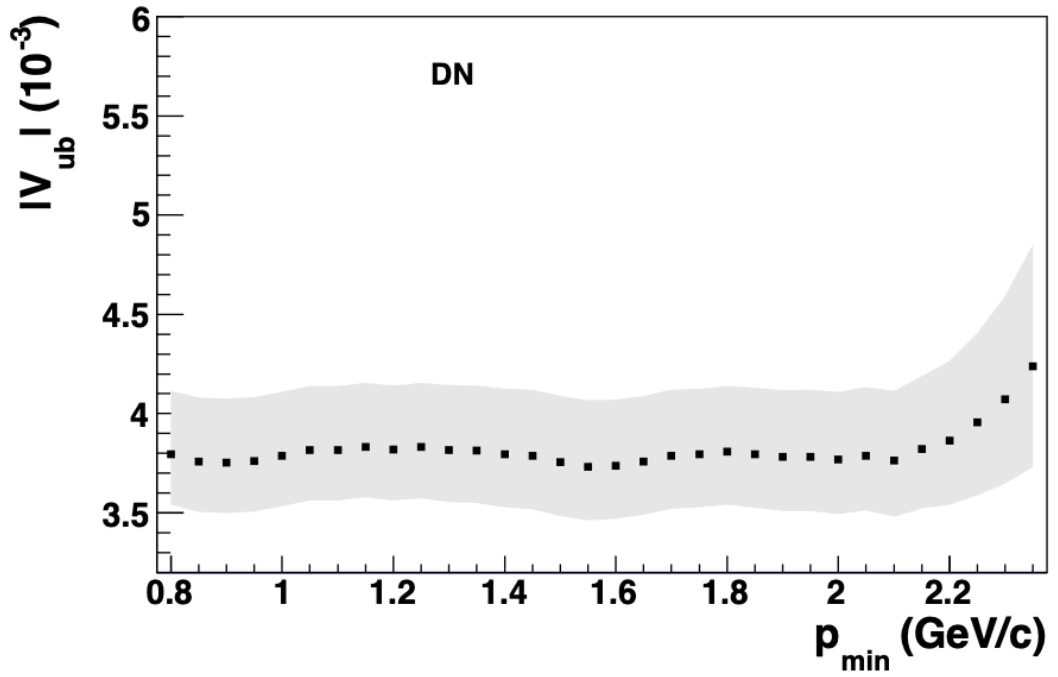
- Extract |Vub| using:

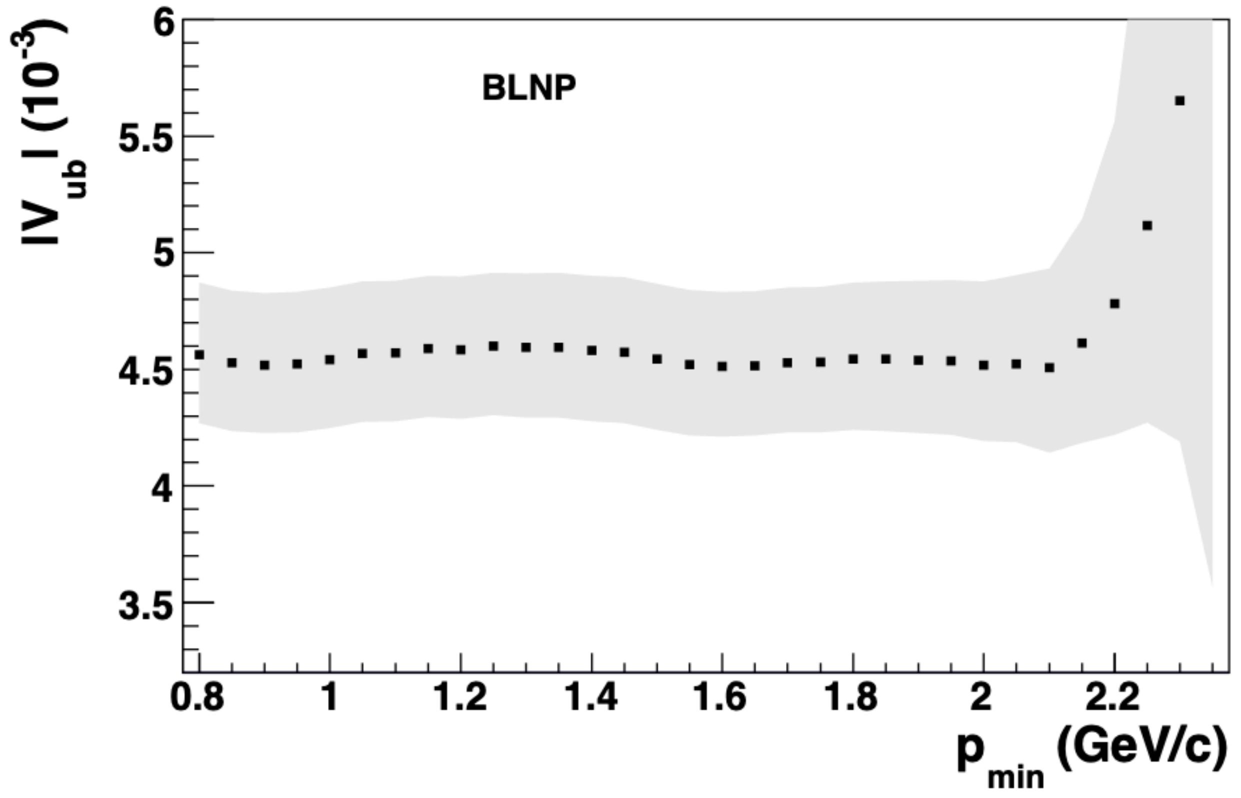
$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(\Delta p)}{\tau_b\,\Delta\zeta(\Delta p)}}.$$

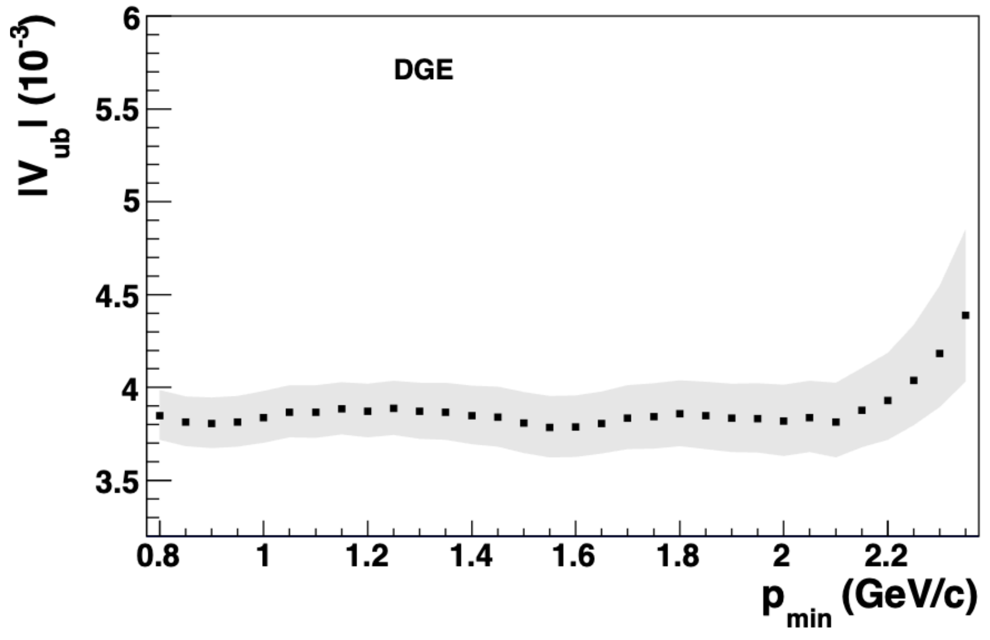
PDG value of B-lifetime

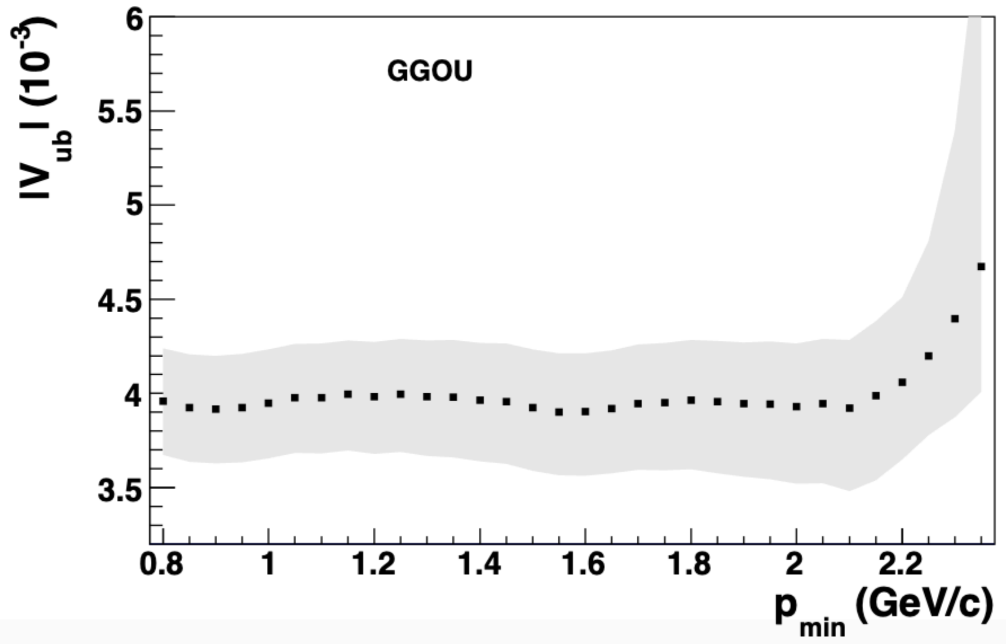
Input from 4 theoretical models

- Main uncertainties due to:
  - Simulation of the electron signal spectrum
  - Background subtraction
  - uncertainty on the SF parameters

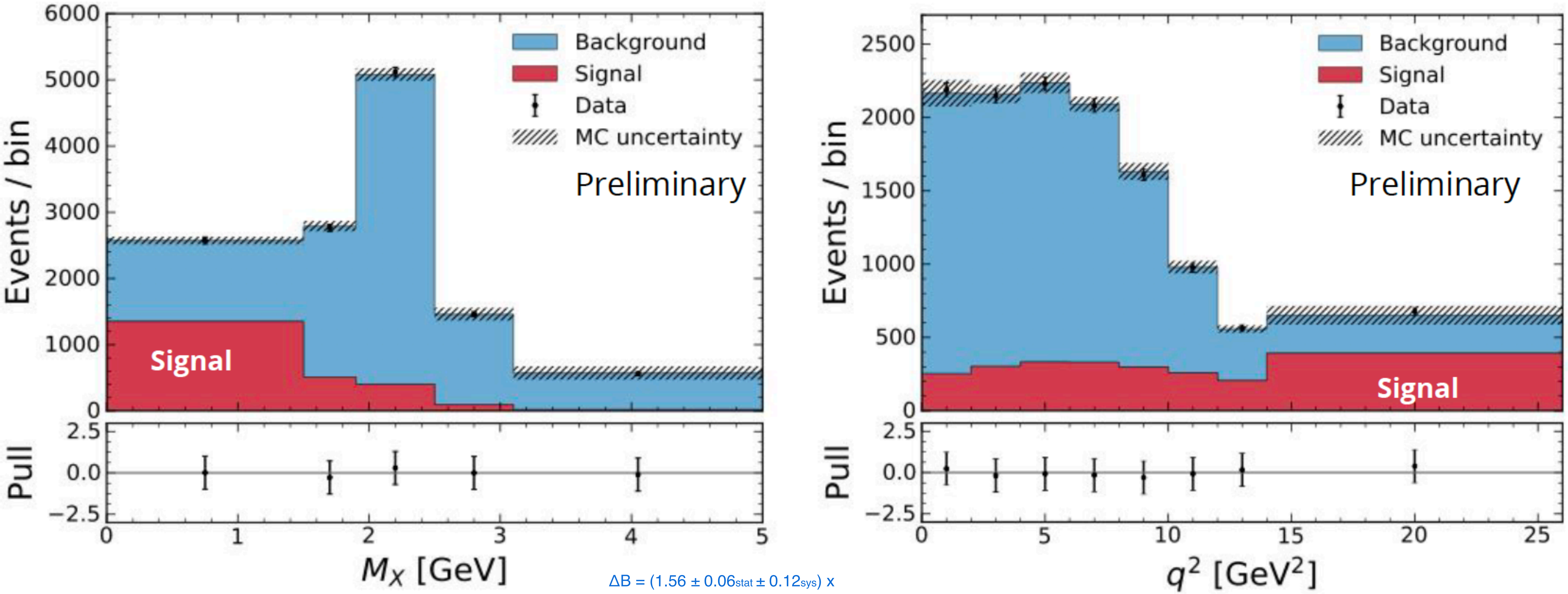








Inclusive $|V_{ub}|$ at Belle



$\Delta B = (1.56 \pm 0.06_{stat} \pm 0.12_{sys})$ x 10_{-3}

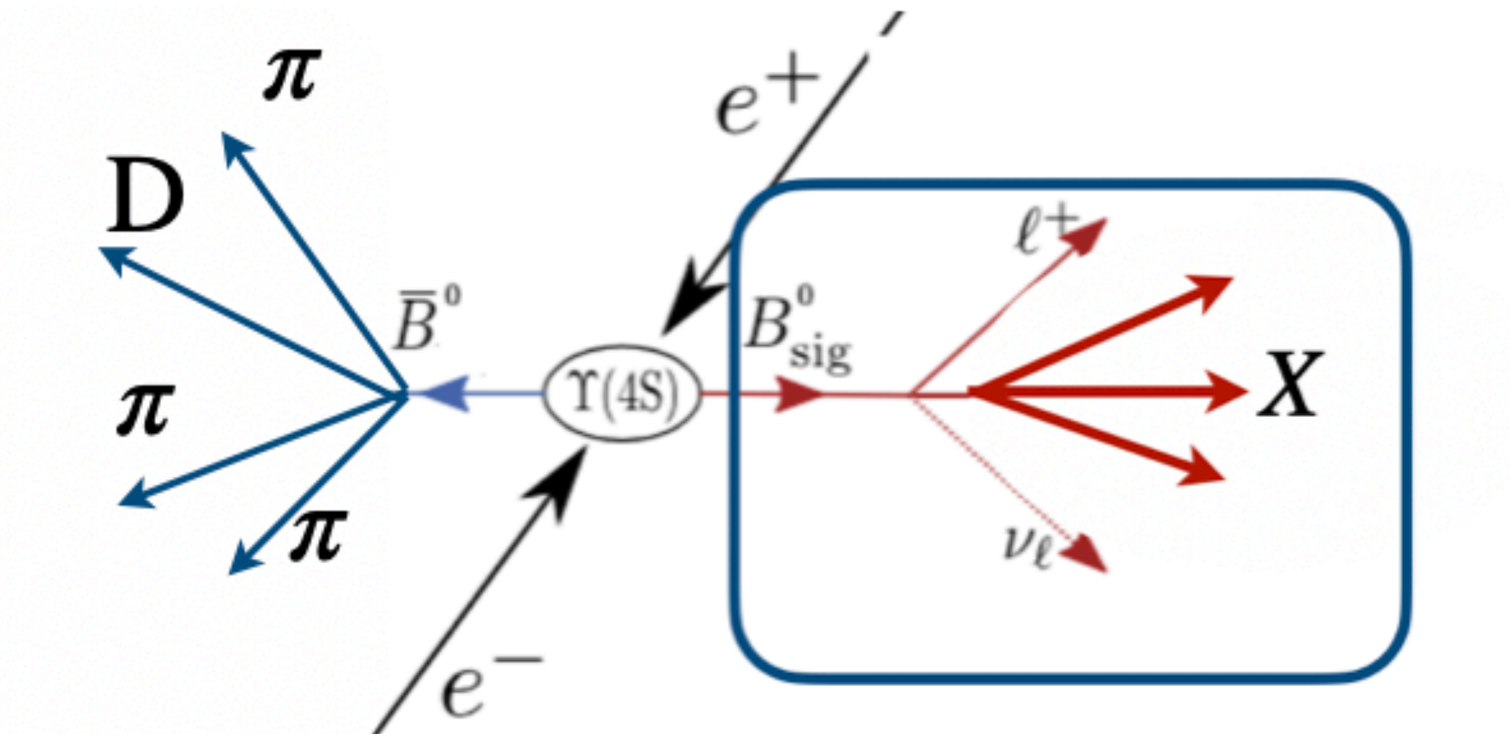
BaBar (2017): ΔB = **(1.55 ± 0.12) x 10^{-3}**

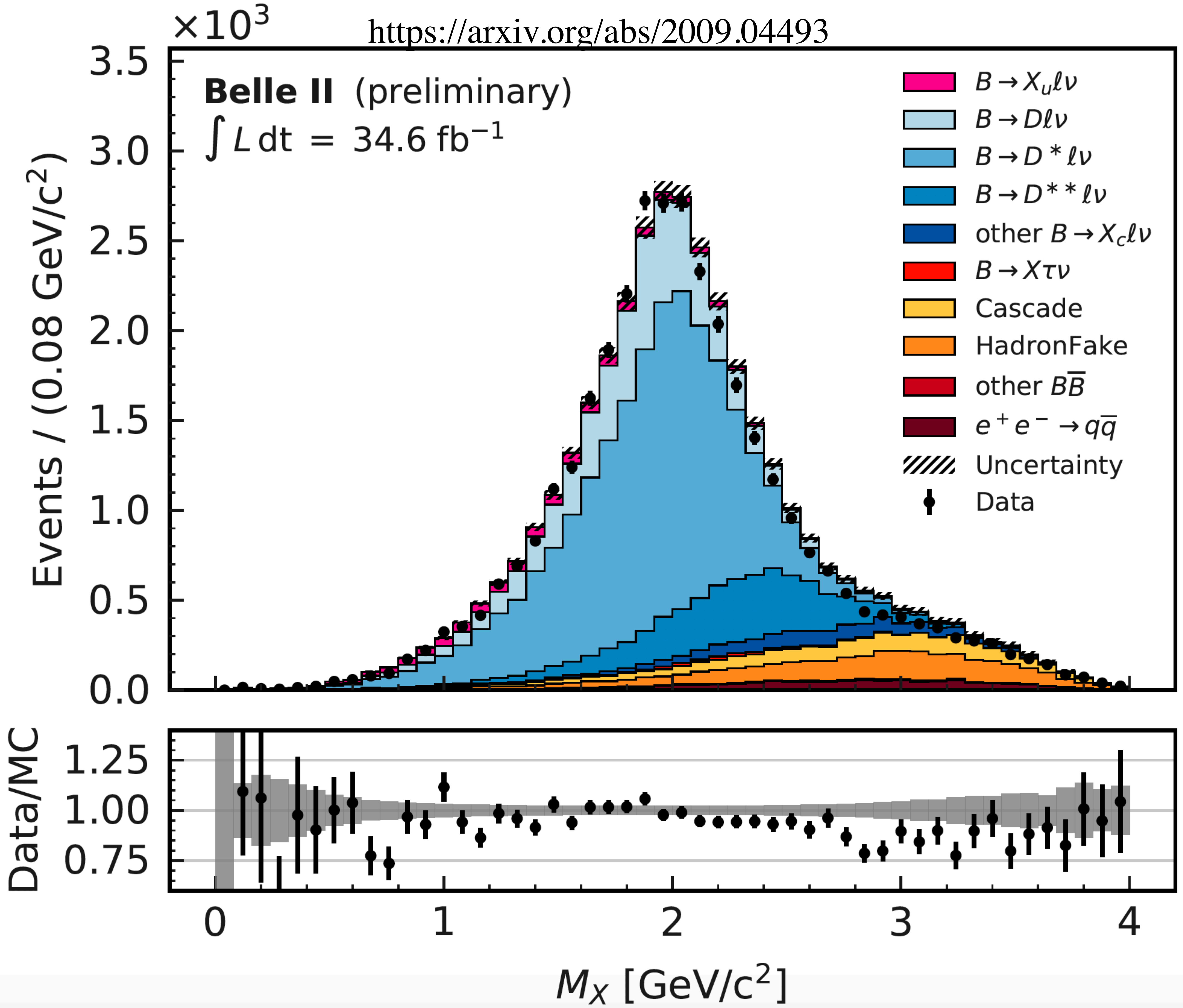
BaBar (2012): ΔB = **(1.82 ± 0.19) x 10^{-3}**

Belle (2010):ΔB = **(1.96 ± 0.23) x 10^{-3}**

Hadronic Mass Moments of $B \to X_c \ell \nu_\ell$

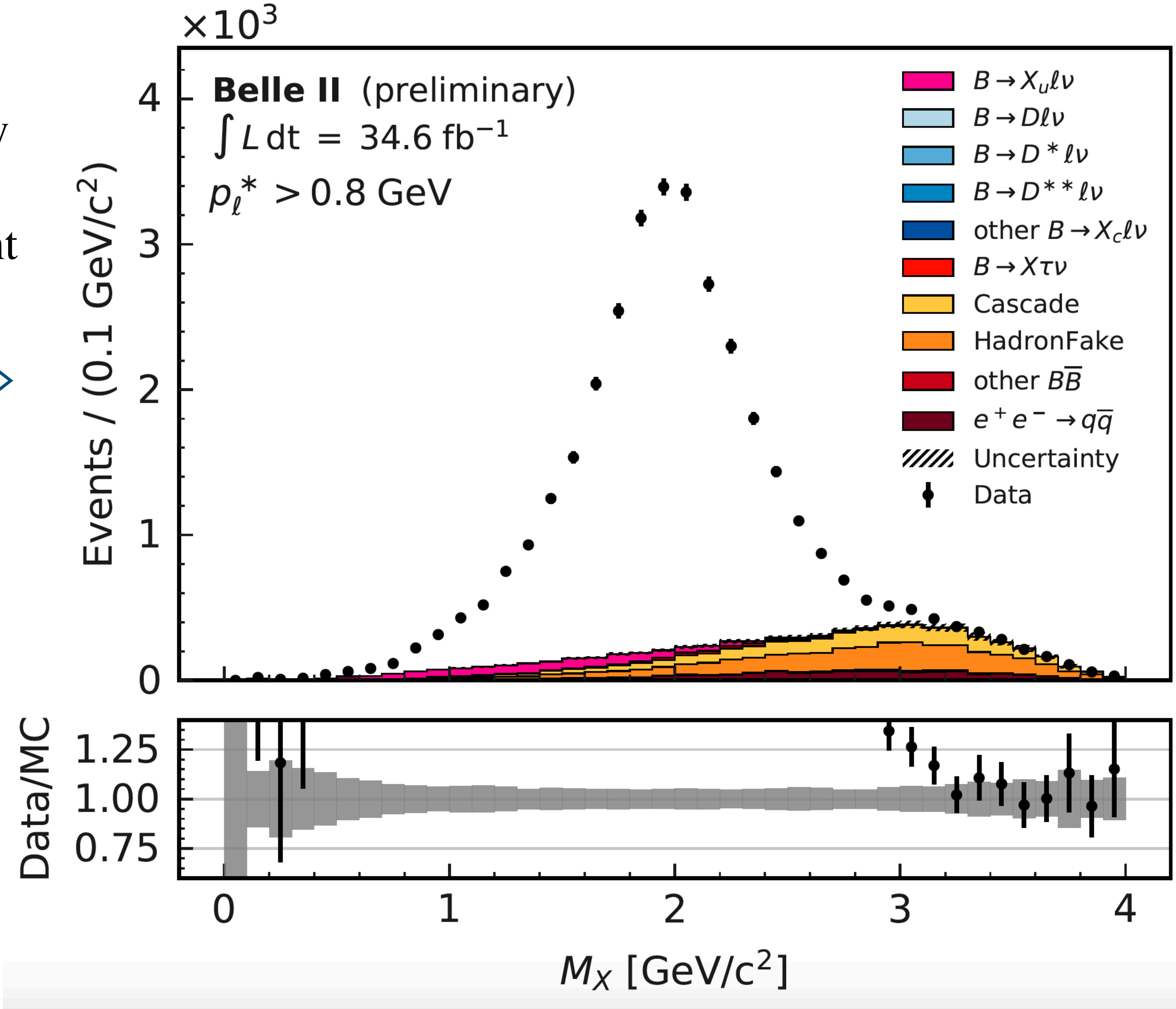
- Use hadronic FEI tagging and identify one lepton with $p*_l > 0.8$ GeV/c and PID likelihood >0.9.
- 6 signal channels $B^0\ell^\pm, B^+\ell^-$ and two control $B^+\ell^+$ to estimate N^i_{bkg}
- Identify X$_c$ system using remaining tracks and clusters in the $\Upsilon(4S)$ rest of event.
- Suppress continuum and require E$_{miss}$ and p$_{miss}$>0.5 GeV.



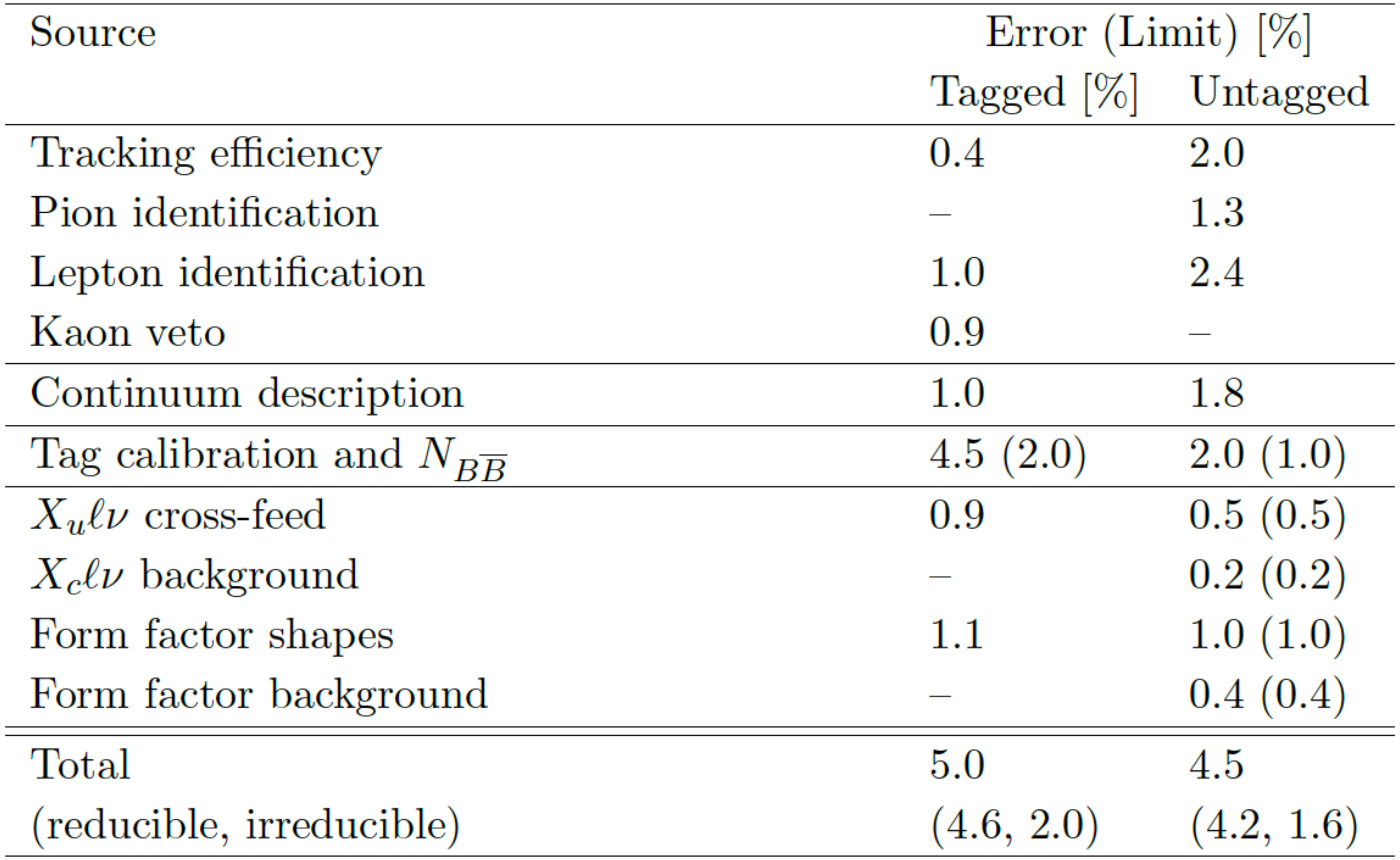


https://arxiv.org/abs/2009.04493

Subtract background by assigning a signal probability to each event



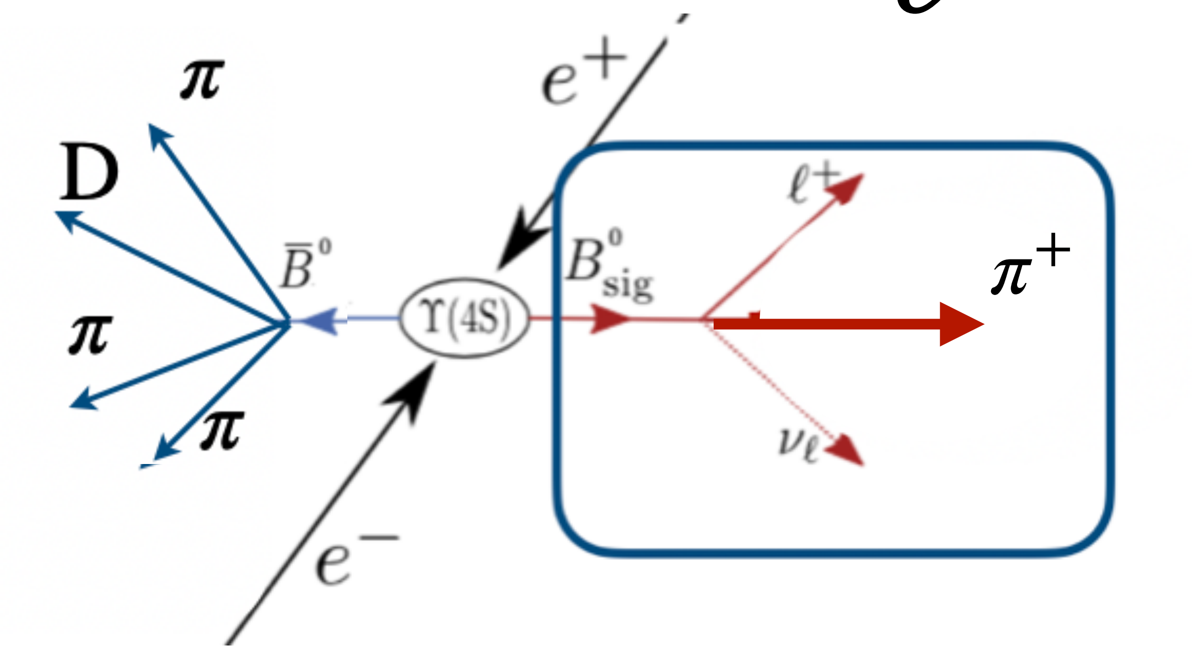
Main sources of systematics in exclusive |Vub|



Source	Error (Limit) [%]	
	Tagged [%]	Untagged
Tracking efficiency	0.4	2.0
Pion identification	–	1.3
Lepton identification	1.0	2.4
Kaon veto	0.9	–
Continuum description	1.0	1.8
Tag calibration and $N_{B\overline{B}}$	4.5 (2.0)	2.0 (1.0)
$X_u \ell \nu$ cross-feed	0.9	0.5 (0.5)
$X_c \ell \nu$ background	–	0.2 (0.2)
Form factor shapes	1.1	1.0 (1.0)
Form factor background	–	0.4 (0.4)
Total	5.0	4.5
(reducible, irreducible)	(4.6, 2.0)	(4.2, 1.6)

Belle II Tagged Exclusive $B^0 \to \pi^-\ell\nu_\ell$

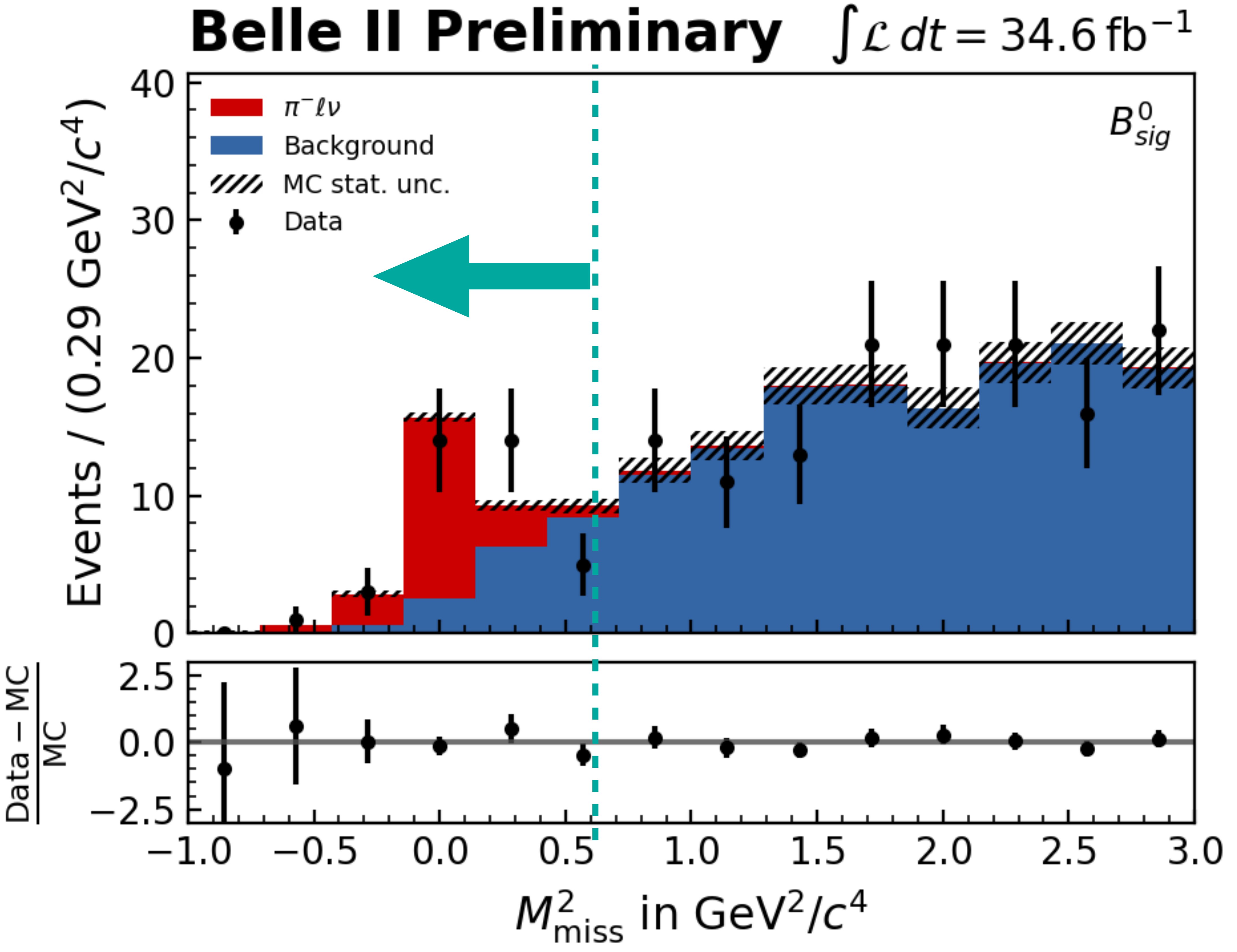
- FEI hadronic tagging to measure $\mathscr{B}(B^0 \to \pi^-\ell\nu)$ with
- Identify oppositely charged lepton, $p_e > 0.3$and $p_\mu > 0.6$ GeV/c, and pion using PID algorithms.
- Suppress continuum using FoxWolfram moment R2.
- Apply E_{miss}>0.3 and $E_{residual}$<1.0 GeV.



$$p_{miss} \equiv (E_{miss}, \vec{p}_{miss}) = p_{Bsig} - p_{Y}$$

- Analysis performed blinded in the signal region $M^2_{miss} \leq 1$ GeV^2/c^4.

$N^{\text{data}}_{\text{sig}}$	20.79 ± 5.68
f_{+0}	1.058 ± 0.024
CF_{FEI}	0.8301 ± 0.0286
$N_{B\bar{B}}$	$(37.711 \pm 0.602)\ \times 10^6$
ϵ	$(0.216 \pm 0.001)\%$
$\mathcal{B}(B^0 \to \pi^-\ell\nu)$	$(1.58 \pm 0.43_{\text{stat}} \pm 0.07_{\text{sys}})\ \times 10^{-4}$



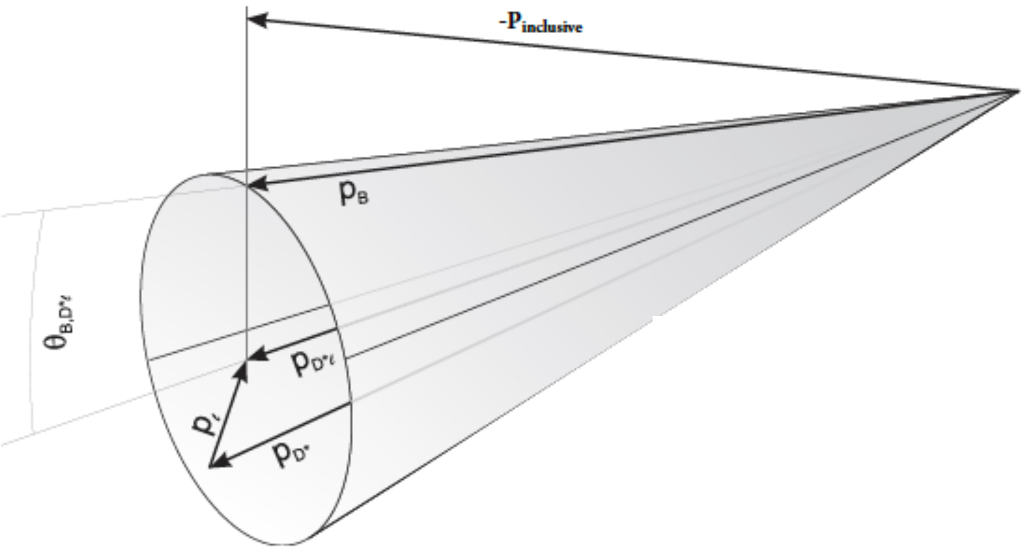
In agreement with world average!

Observed signal significance: 5.69 σ

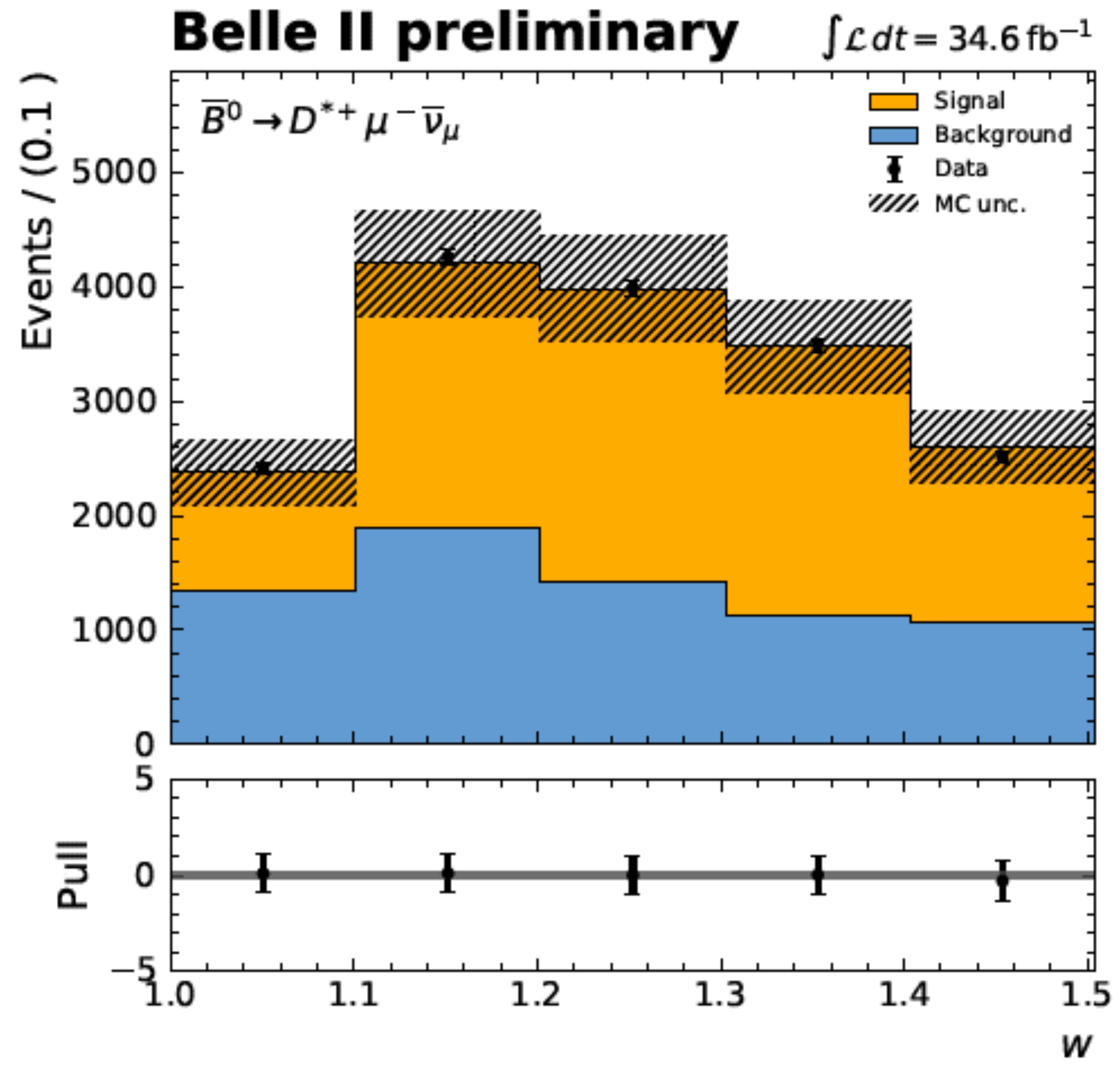
$\bar{B}^0 \to D^{*+}\ell\nu_\ell$

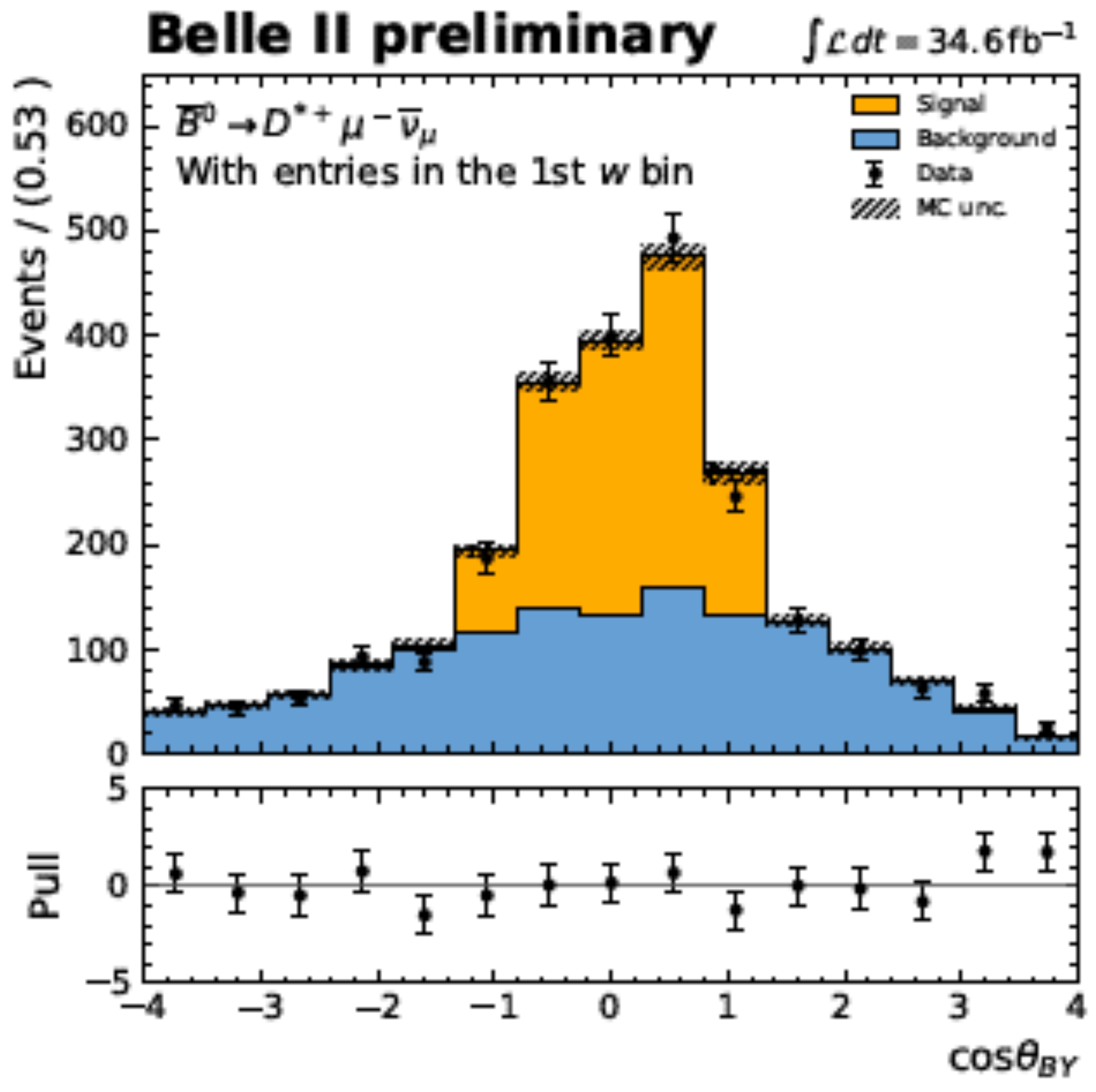
Examine hadronic recoil parameter spectrum

$$w = \frac{m_B^2 - m_{D*}^2 - q^2}{2m_B m_{D*}}$$



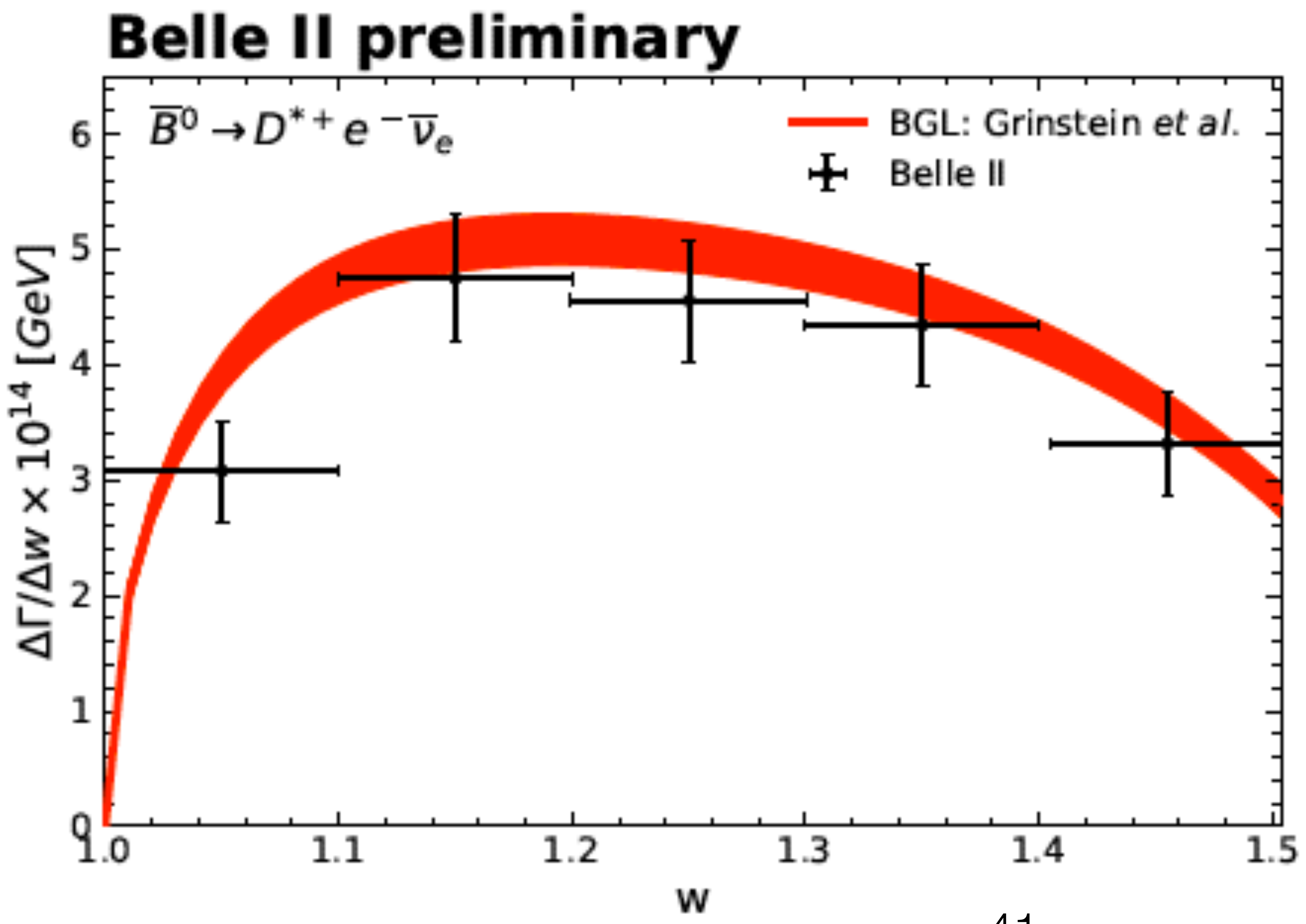
Divide spectrum into 5 equal bins of 0.1008 between w=1 and w_{max}=1.504.

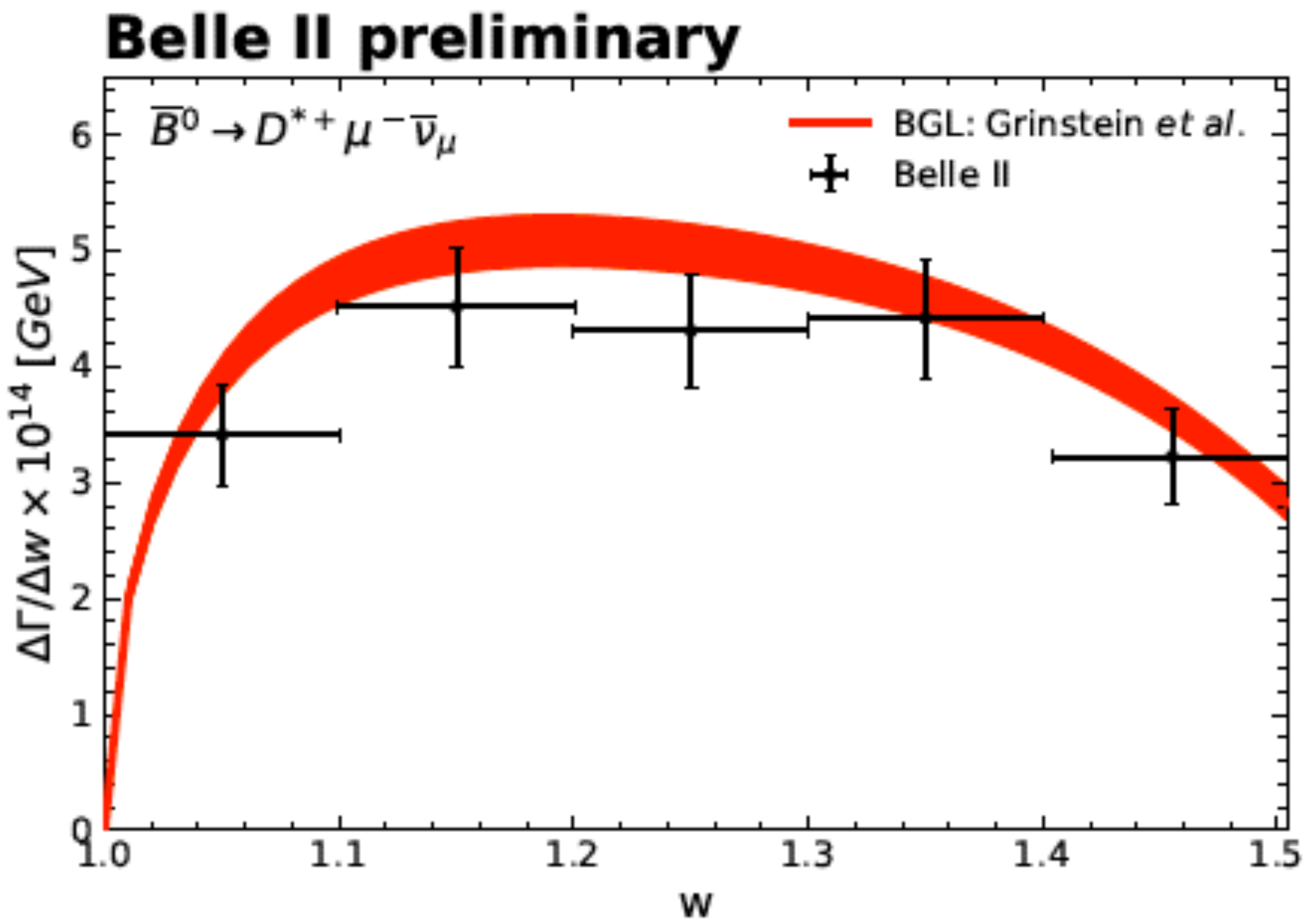




Unfold the *w* spectrum to compare with BGL.

Partial branching fractions in bins of ***w*** are a key step to determine V_{cb}.





Phys. Lett. B 771, 359 (2017)

Inclusive $|V_{ub}|$ at Belle

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

Preliminary

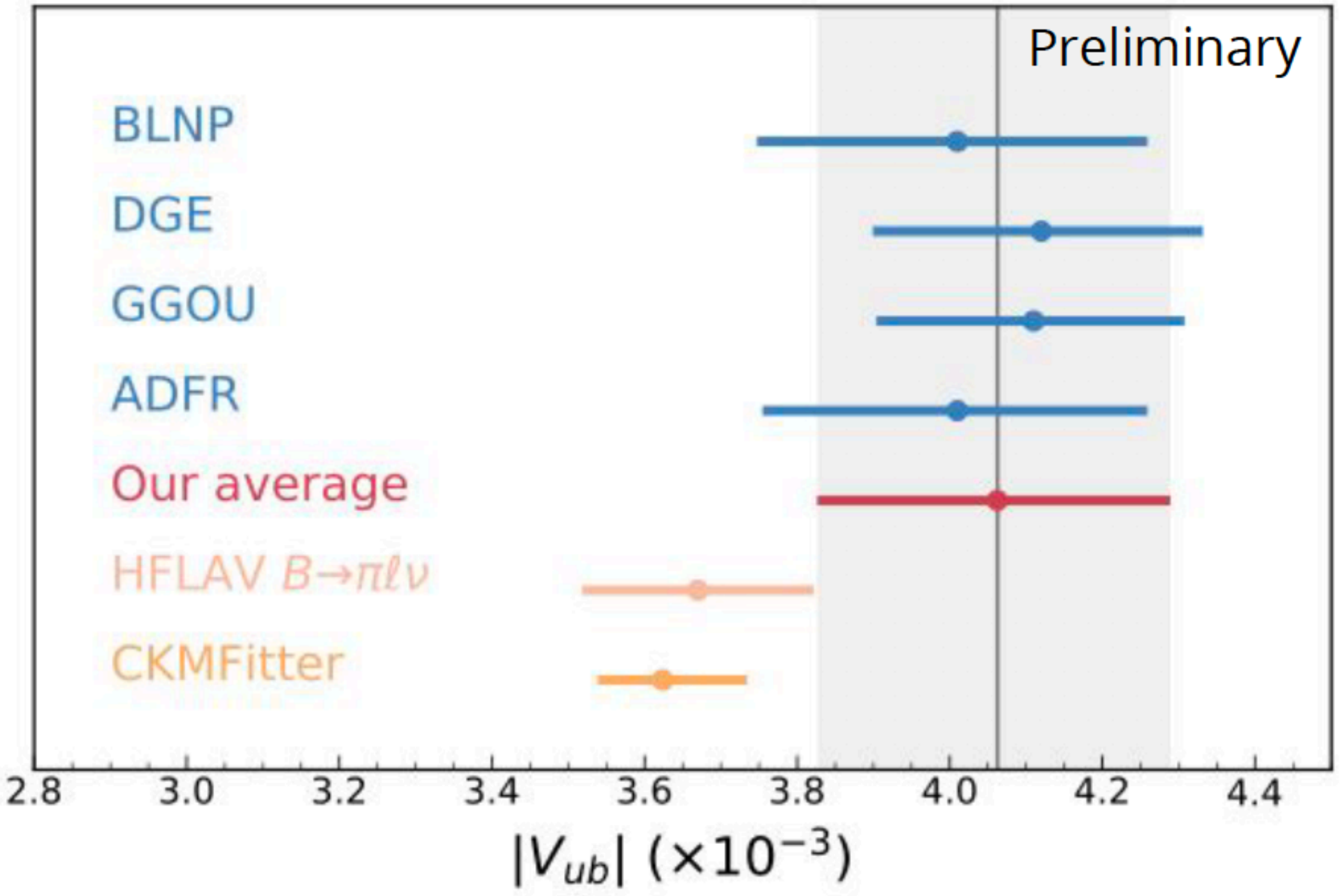
Fit	$\|V_{ub}\|$ (± stat ± sys ± theo.)			
	BLNP	DGE	GGOU	ADFR
(a)	$3.81^{+0.08,+0.13,+0.21}_{-0.08,-0.13,-0.21}$	$3.99^{+0.08,+0.14,+0.20}_{-0.08,-0.14,-0.26}$	$3.88^{+0.08,+0.13,+0.15}_{-0.08,-0.14,-0.16}$	$3.55^{+0.07,+0.12,+0.17}_{-0.07,-0.12,-0.17}$
(b)	$4.35^{+0.18,+0.26,+0.26}_{-0.18,-0.28,-0.28}$	$4.27^{+0.17,+0.26,+0.18}_{-0.18,-0.28,-0.21}$	$4.36^{+0.18,+0.27,+0.24}_{-0.18,-0.28,-0.27}$	$3.77^{+0.15,+0.23,+0.17}_{-0.16,-0.24,-0.17}$
(c1)	$3.90^{+0.09,+0.17,+0.21}_{-0.10,-0.18,-0.21}$	$4.08^{+0.10,+0.18,+0.20}_{-0.10,-0.19,-0.26}$	$3.97^{+0.09,+0.18,+0.15}_{-0.10,-0.19,-0.16}$	$3.63^{+0.09,+0.16,+0.17}_{-0.09,-0.17,-0.17}$
(c2)	$4.14^{+0.10,+0.20,+0.18}_{-0.10,-0.22,-0.20}$	$4.25^{+0.10,+0.21,+0.11}_{-0.10,-0.22,-0.12}$	$4.24^{+0.10,+0.21,+0.09}_{-0.10,-0.22,-0.10}$	$4.14^{+0.10,+0.20,+0.18}_{-0.10,-0.22,-0.18}$
(d)	$4.01^{+0.08,+0.15,+0.18}_{-0.08,-0.16,-0.19}$	$4.12^{+0.08,+0.16,+0.11}_{-0.09,-0.16,-0.12}$	$4.11^{+0.08,+0.16,+0.08}_{-0.09,-0.16,-0.09}$	$4.01^{+0.08,+0.15,+0.18}_{-0.08,-0.16,-0.18}$

Most precise result from 2D fit

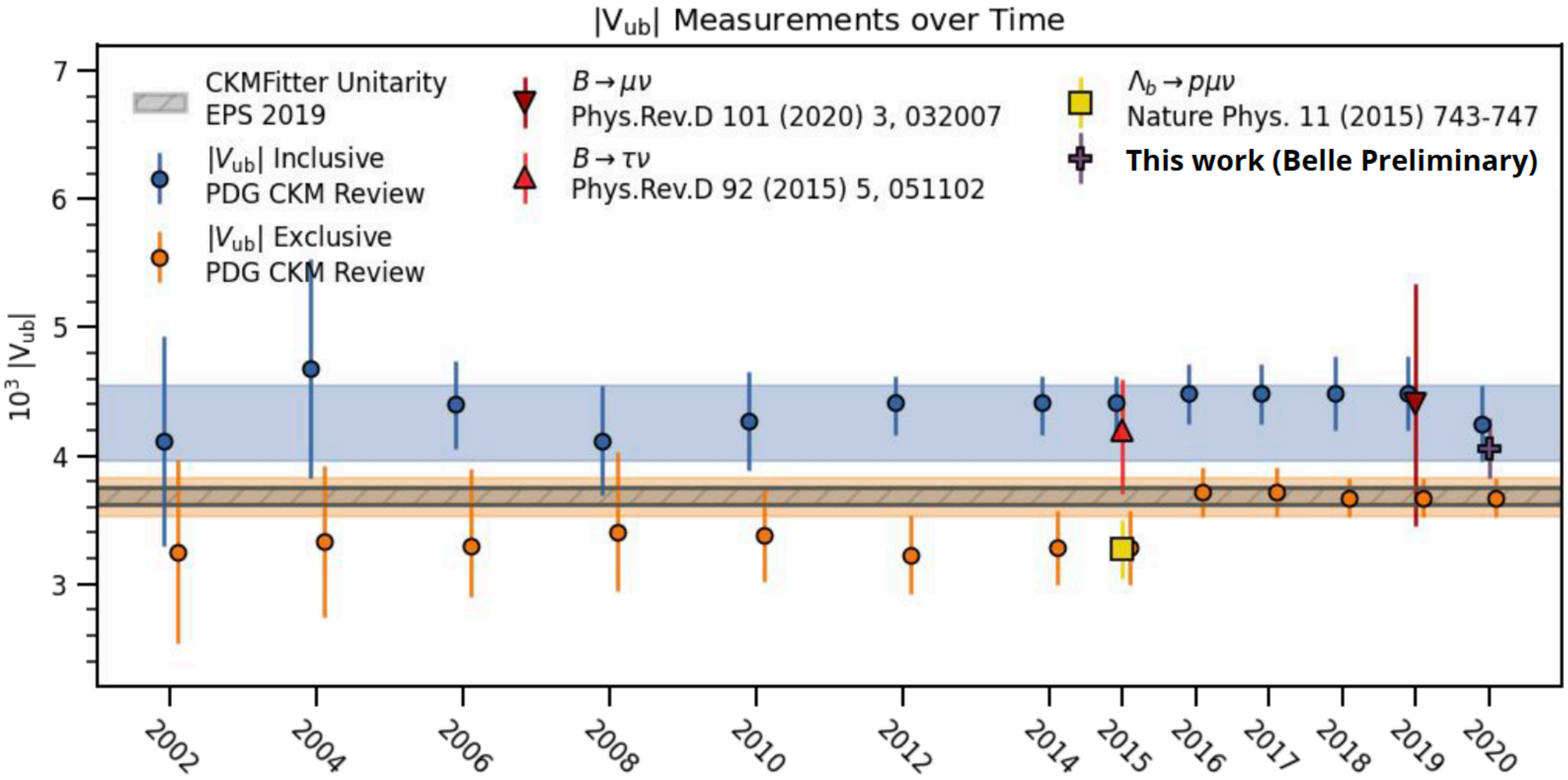
$|V_{ub}|$ (avg) = $\mathbf{(4.06 \pm 0.09_{stat} \pm 0.16_{sys} \pm 0.15_{theo}) \times 10^{-3}}$

Phase-space region	**BLNP**	**DGE**	**GGOU**	**ADFR**
$M_X < 1.7$ GeV	$45.2^{+5.4}_{-4.6}$	$42.3^{+5.8}_{-3.8}$	$43.7^{+3.9}_{-3.2}$	$52.3^{+5.4}_{-4.7}$
$M_X < 1.7$ GeV, $q^2 > 8$ GeV^2	$23.4^{+3.4}_{-2.6}$	$24.3^{+2.6}_{-1.9}$	$23.3^{+3.2}_{-2.4}$	$31.1^{+3.0}_{-2.6}$
$E_\ell^B > 1$ GeV	$61.5^{+6.4}_{-5.1}$	$58.2^{+3.6}_{-3.0}$	$58.5^{+2.7}_{-2.3}$	$61.5^{+5.8}_{-5.1}$

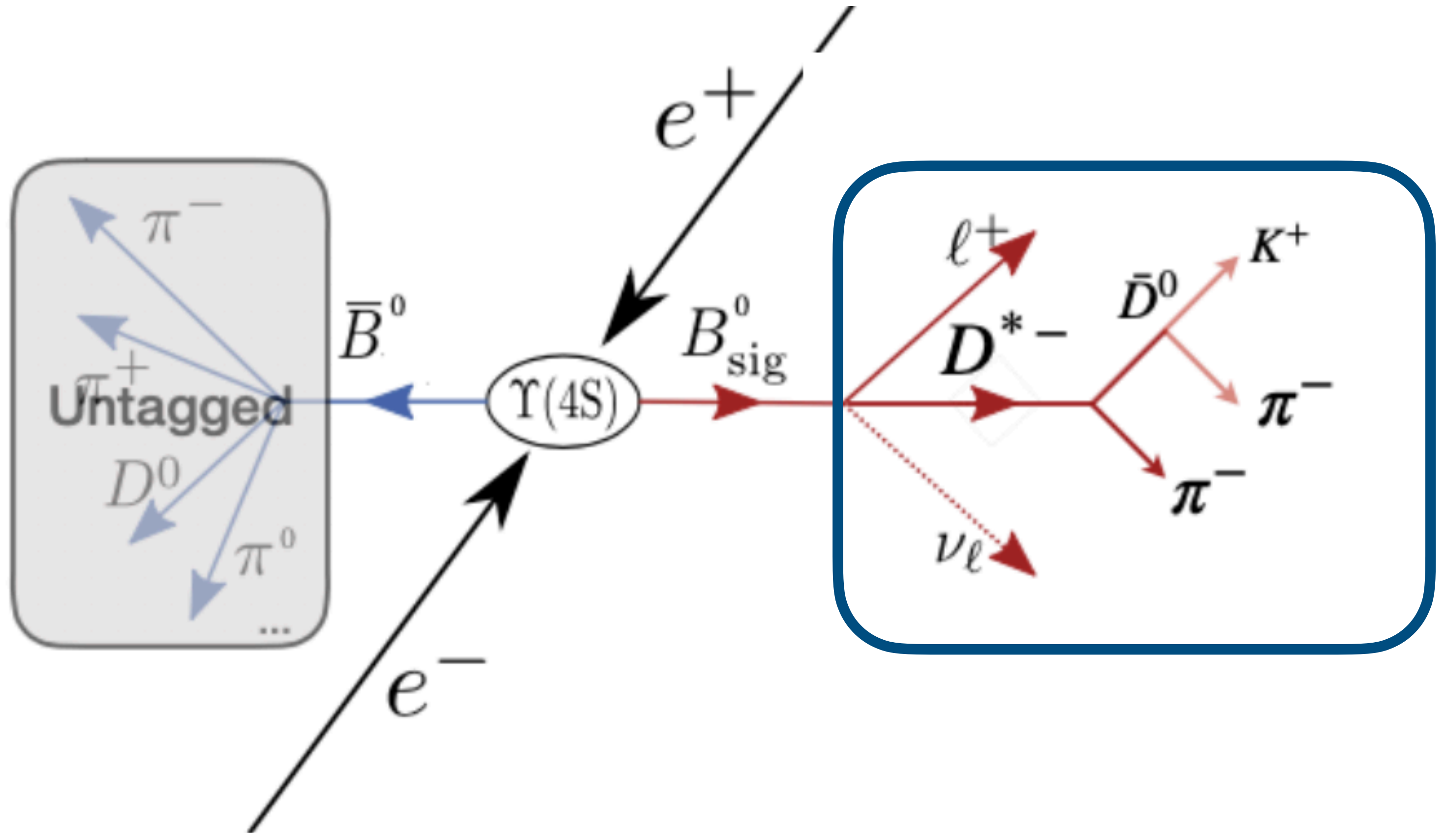
[in unit of ps^{-1}]



Inclusive $|V_{ub}|$ at Belle



Exclusive $\bar{B}^0 \to D^{*+}\ell\nu_\ell$



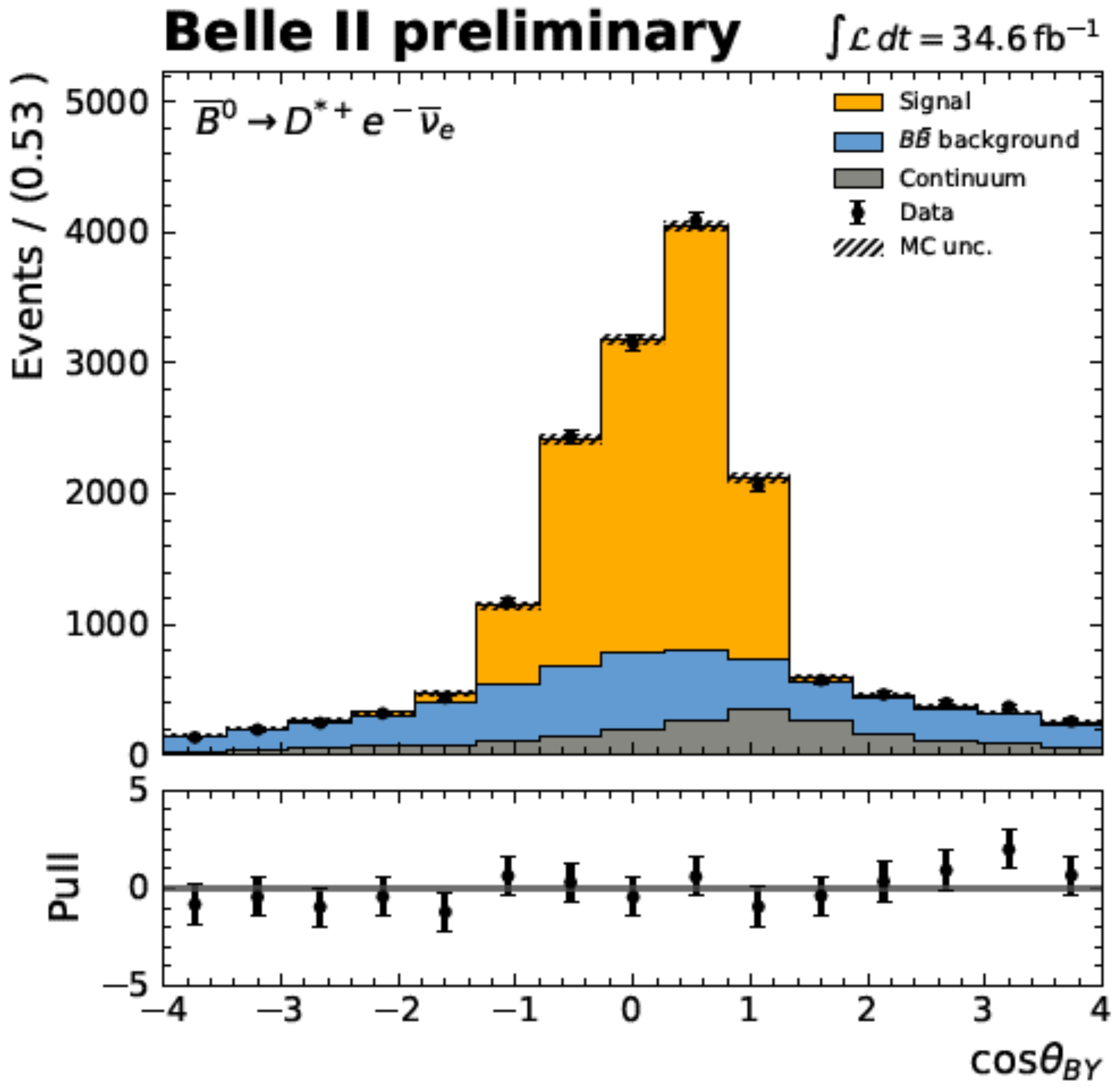
Reconstruct $D^0 \to K^-\pi^+$ and $D^{*+} \to D^0\pi_s$.
Identify lepton using PID algorithms.
Suppress $e^+e^- \to q\bar{q}$ events using p_{D^*}<2.4 GeV/c and R_2 <0.3.

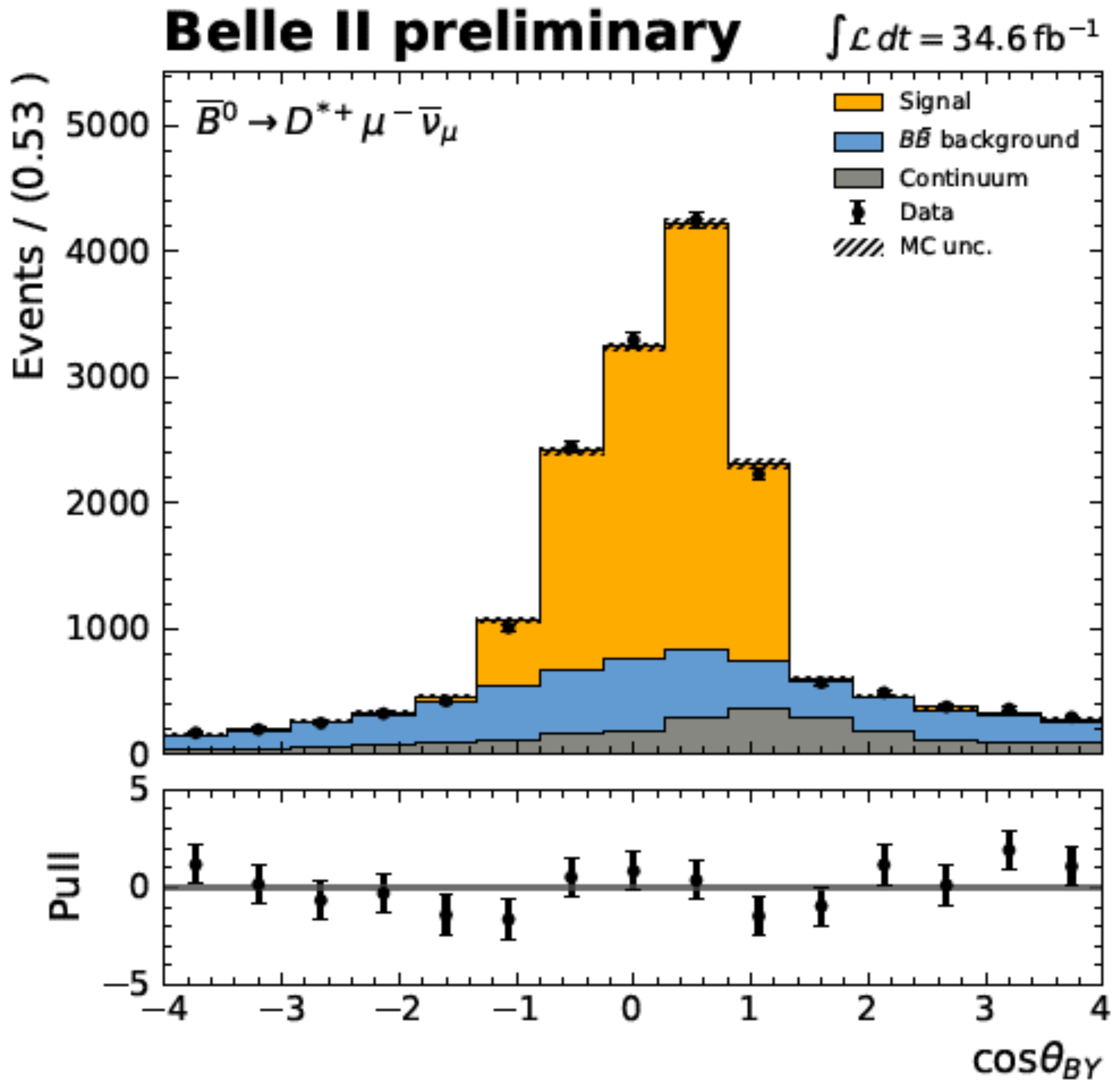
Extract signal yield with a fit to $cos\theta_{BY}$.

$$\mathscr{B}(\bar{B}^0 \to D^{*+}\ell\bar{\nu}) = (4.60 \pm 0.05(stat) \pm 0.18(sys) \pm 0.45_{\pi_s})\,\%$$

Compatible with current world average!

$$R_{e\mu} = \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}e^-\overline{\nu}_e)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)} = 0.99 \pm 0.03\,,$$

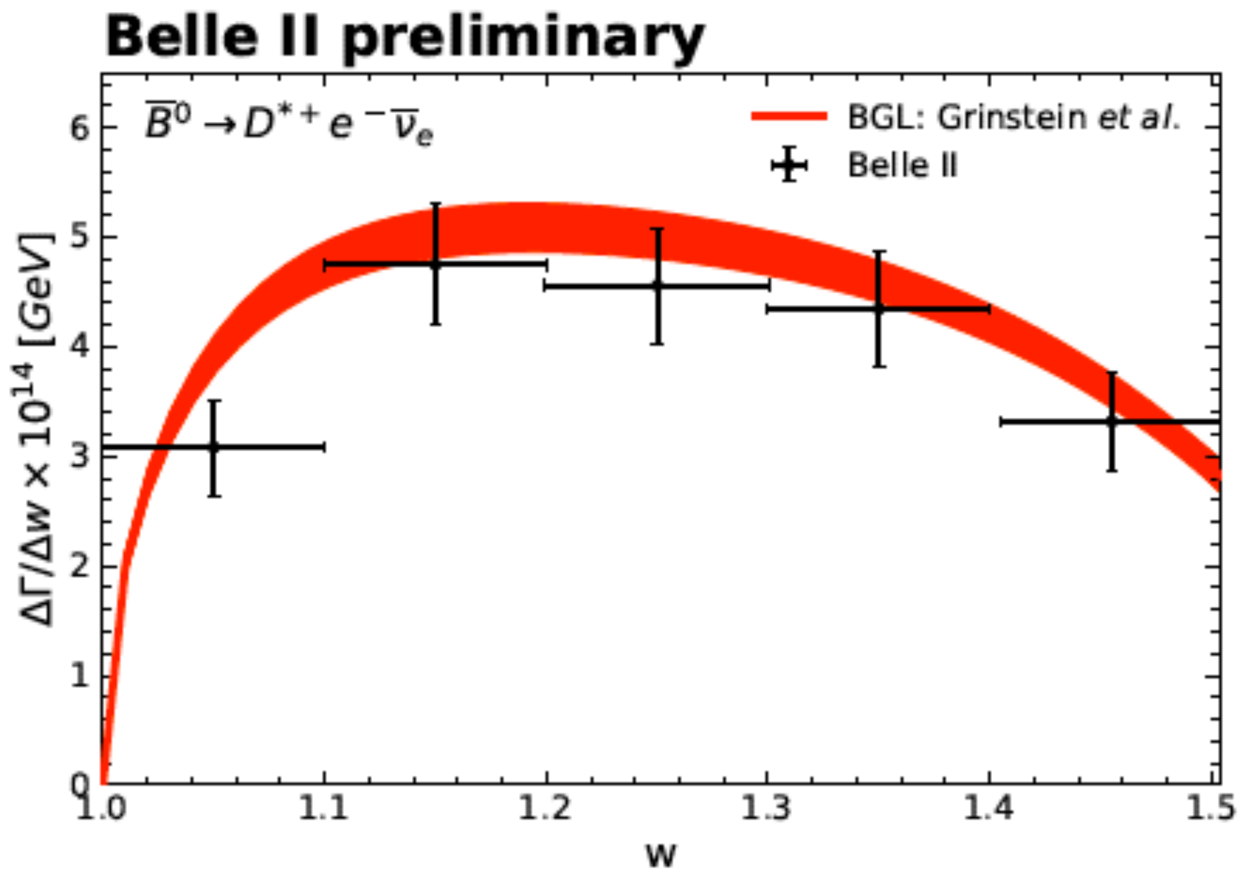


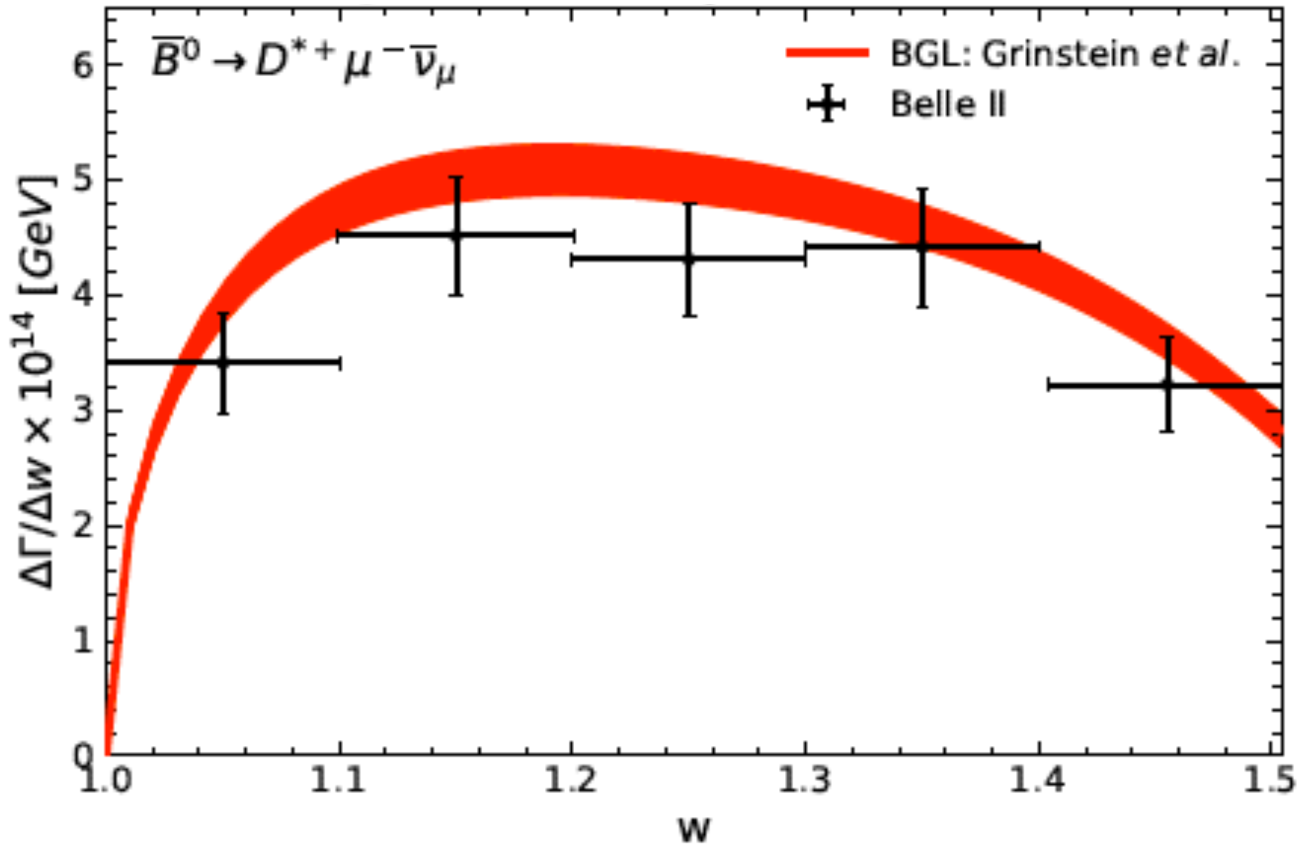


$$cos\theta_{BY} = \frac{2E_B^*E_Y^* - m_B^2 - m_Y^2}{2|p_B^*||p_Y^*|}$$

Unfold the *w* spectrum to compare with BGL.

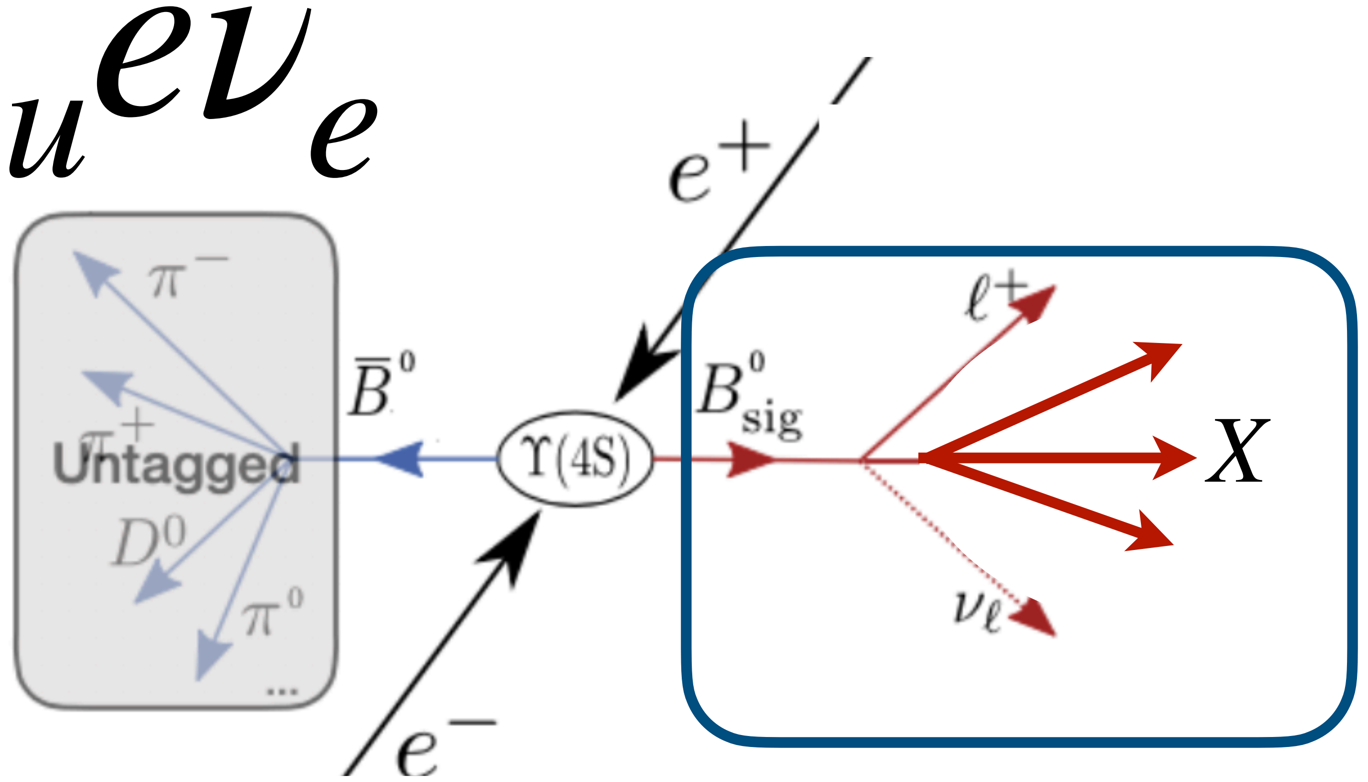
Partial branching fractions in bins of ***w*** are a key step to determine V_{cb}.

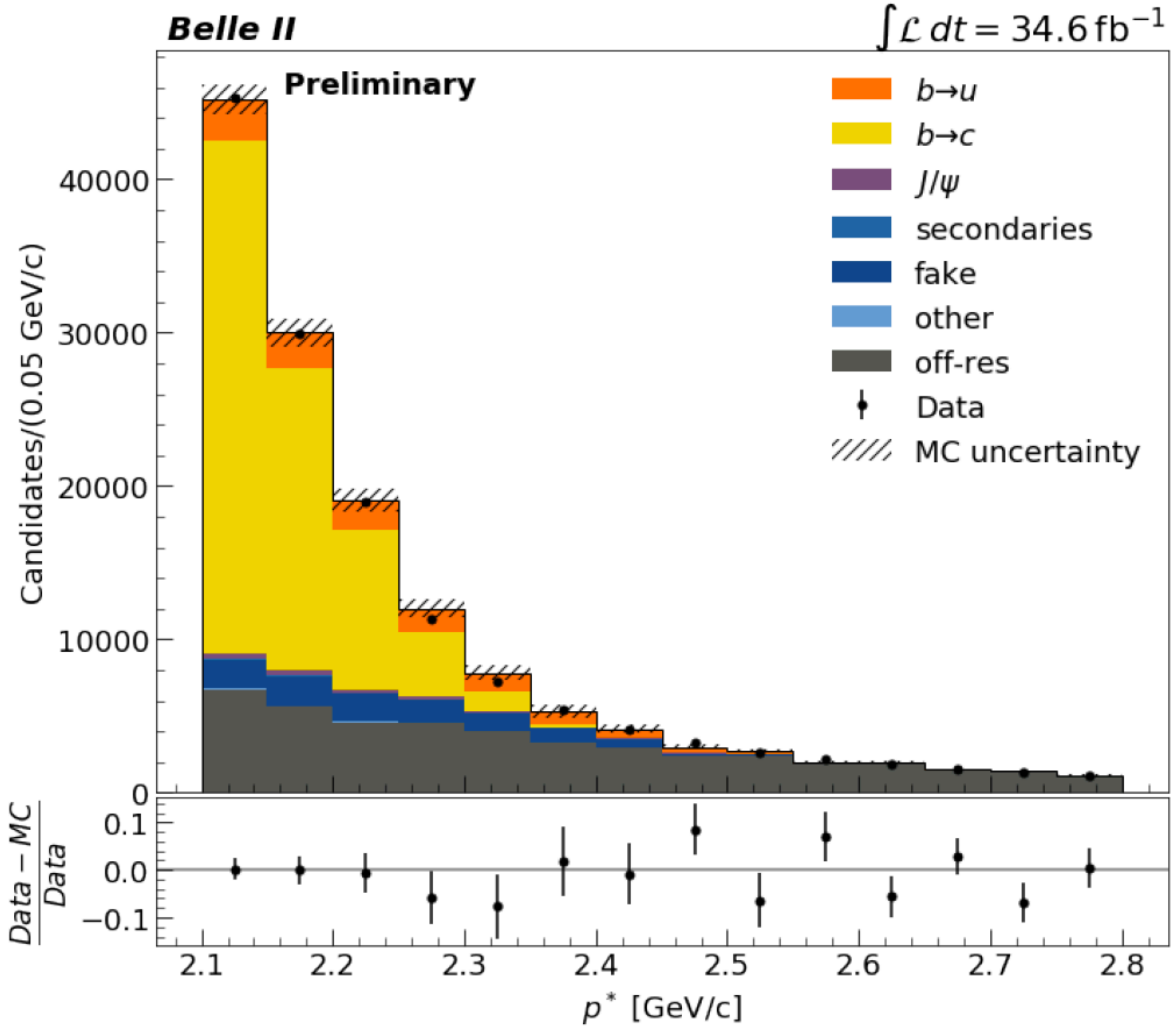


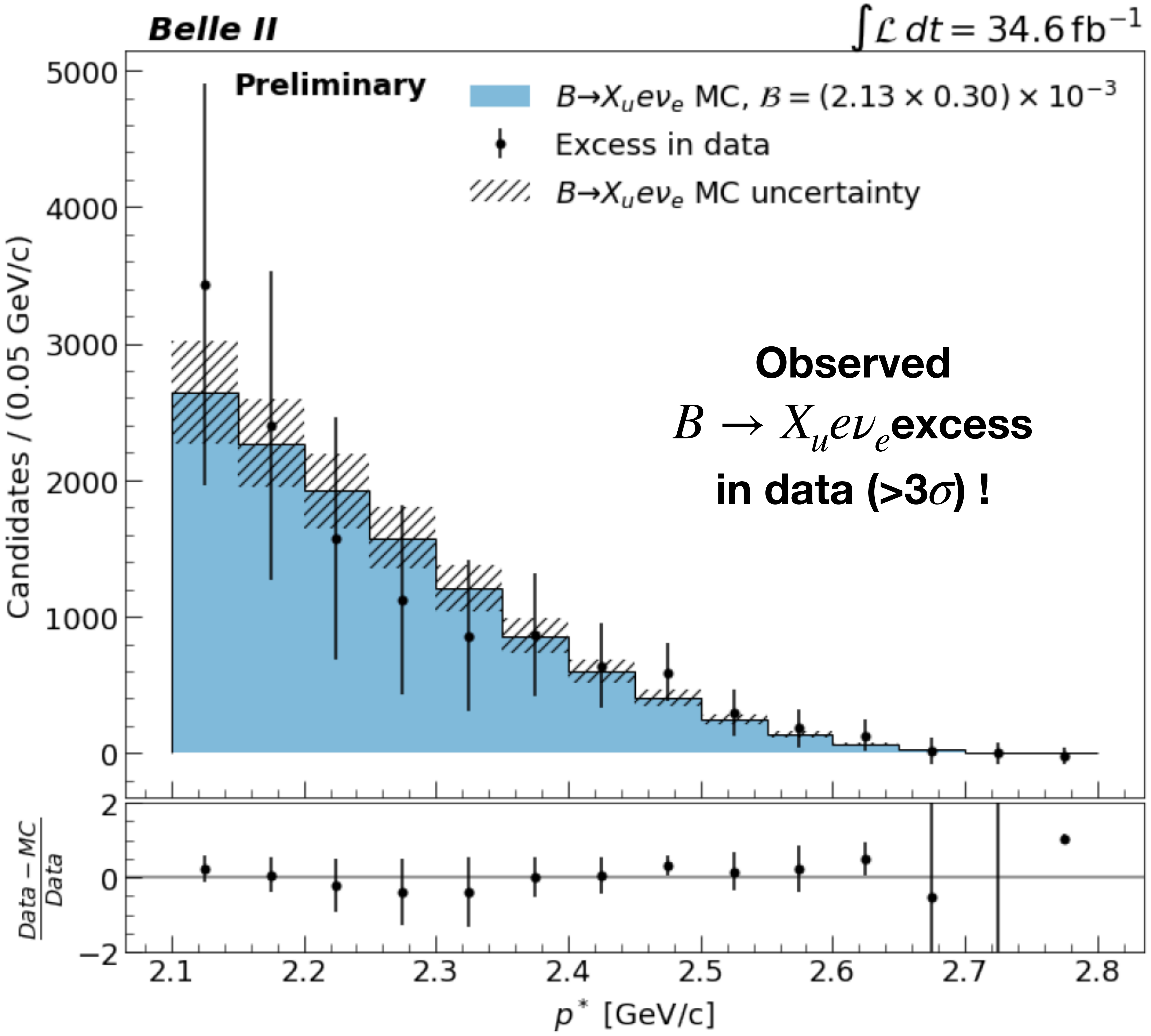


Belle II Inclusive $B \to X_u e \bar{\nu}_e$

- Measurement of $|V_{ub}|$ in the lepton endpoint momentum spectrum.
  - Identify one lepton in the event using PID algorithms.
  - Suppress continuum using MVA trained with event shape variables.
  - Subtract continuum and other $B\bar{B}$ contributions.



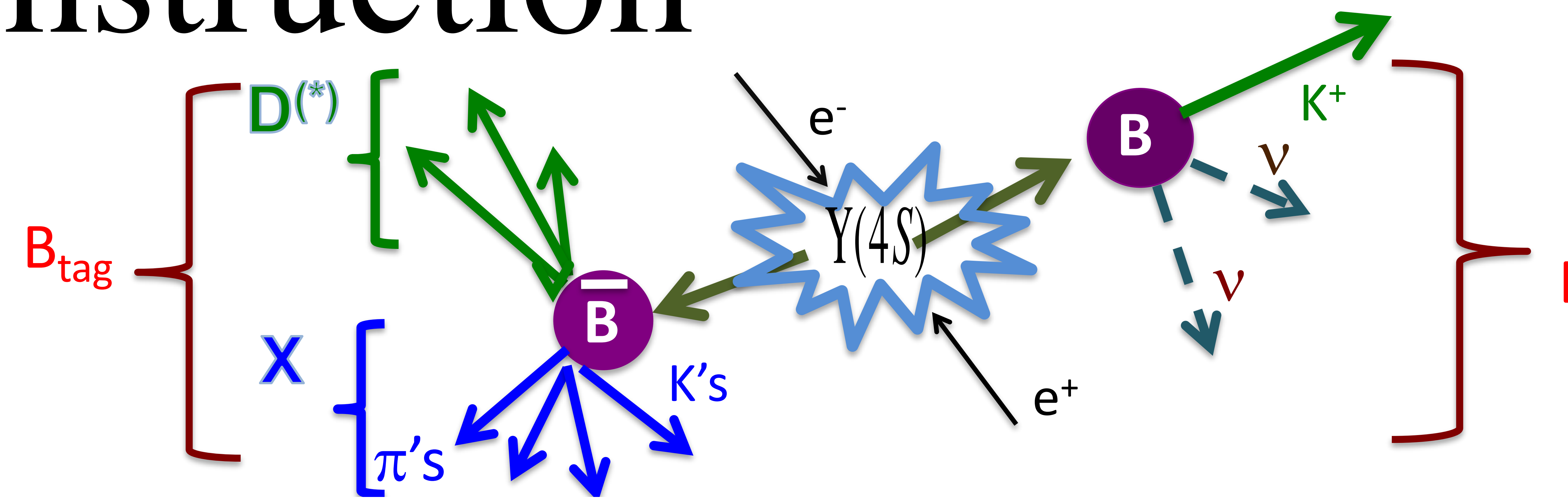


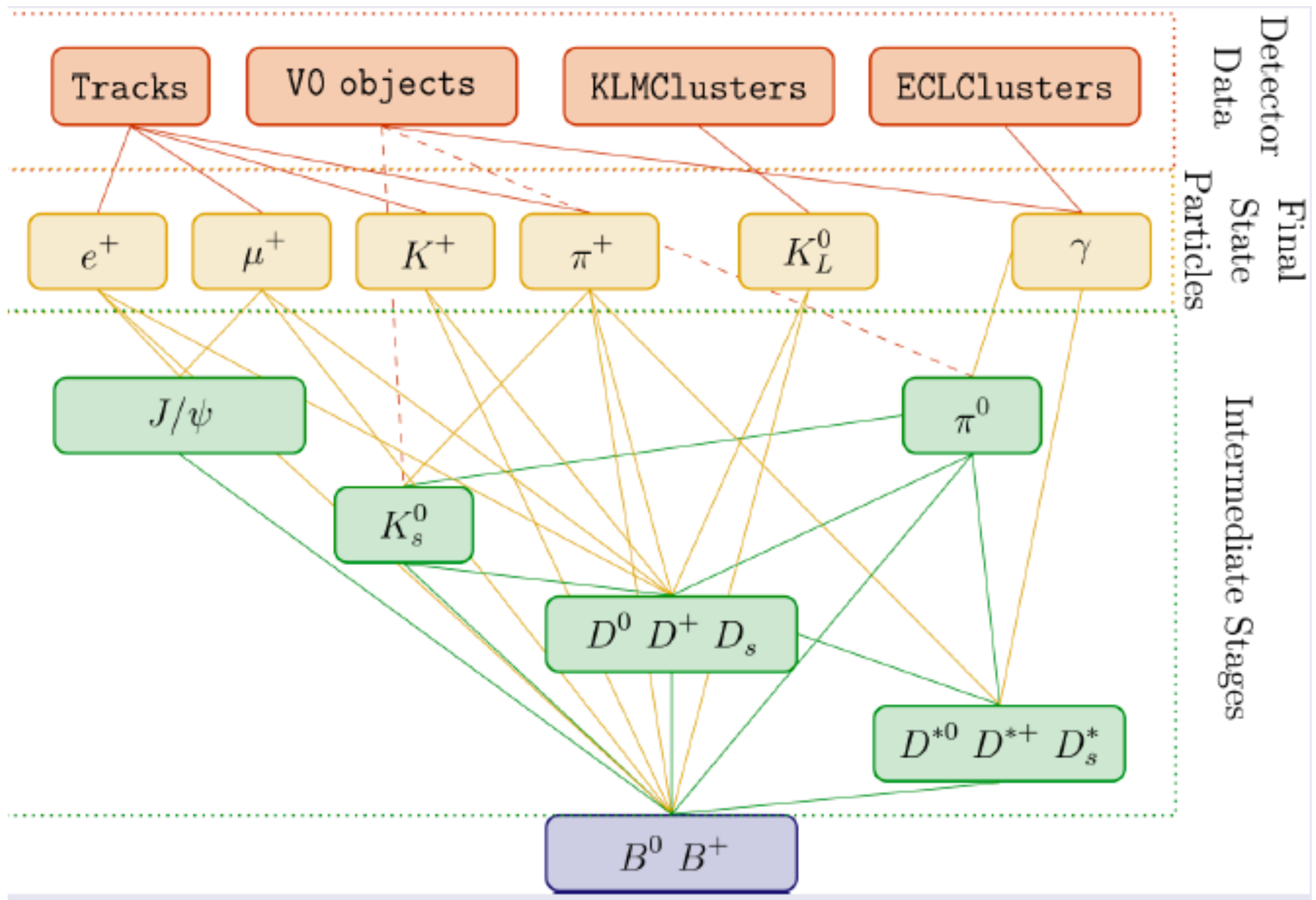


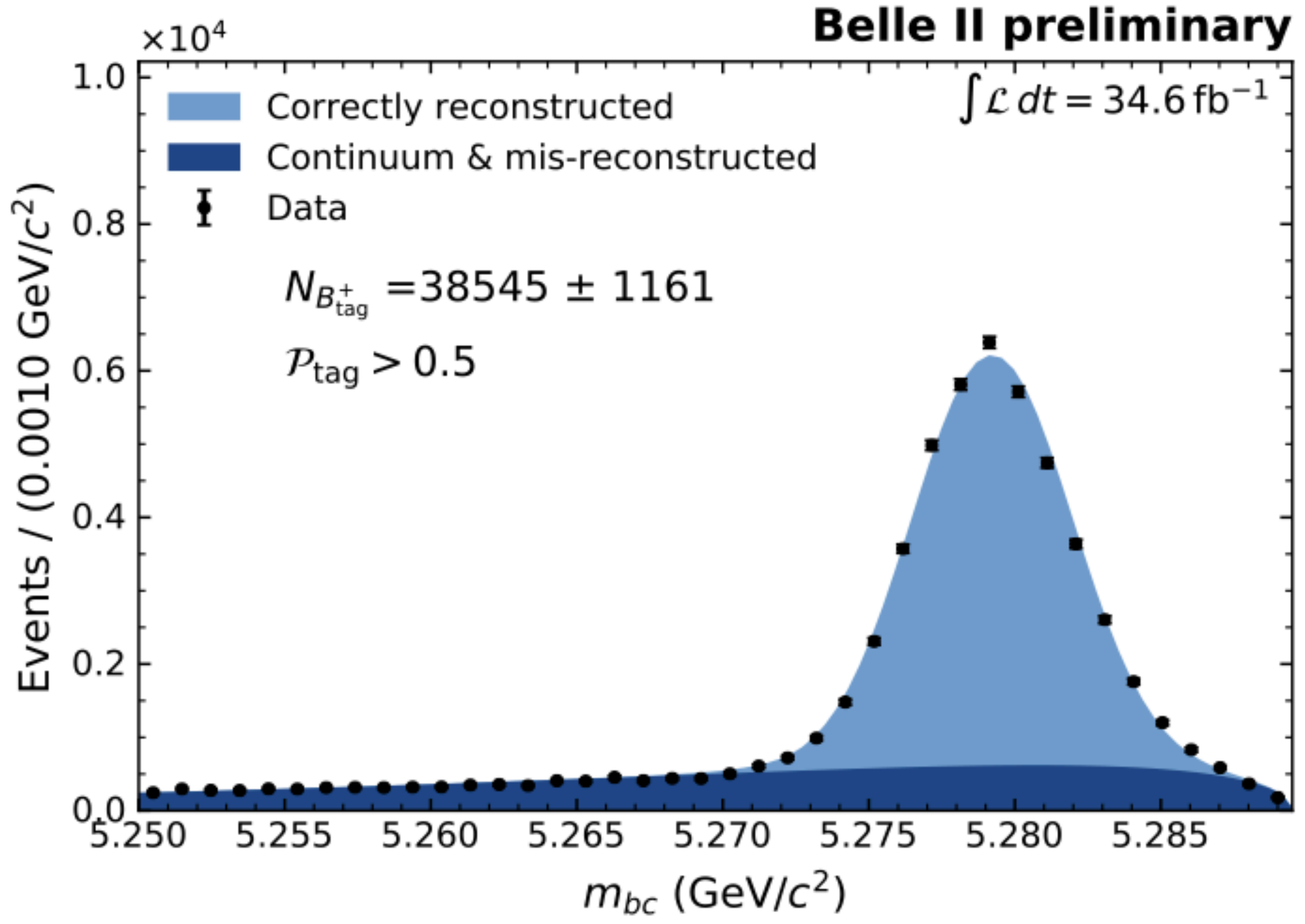
Observed
$B \to X_u e \nu_e$ excess
in data (>3σ) !

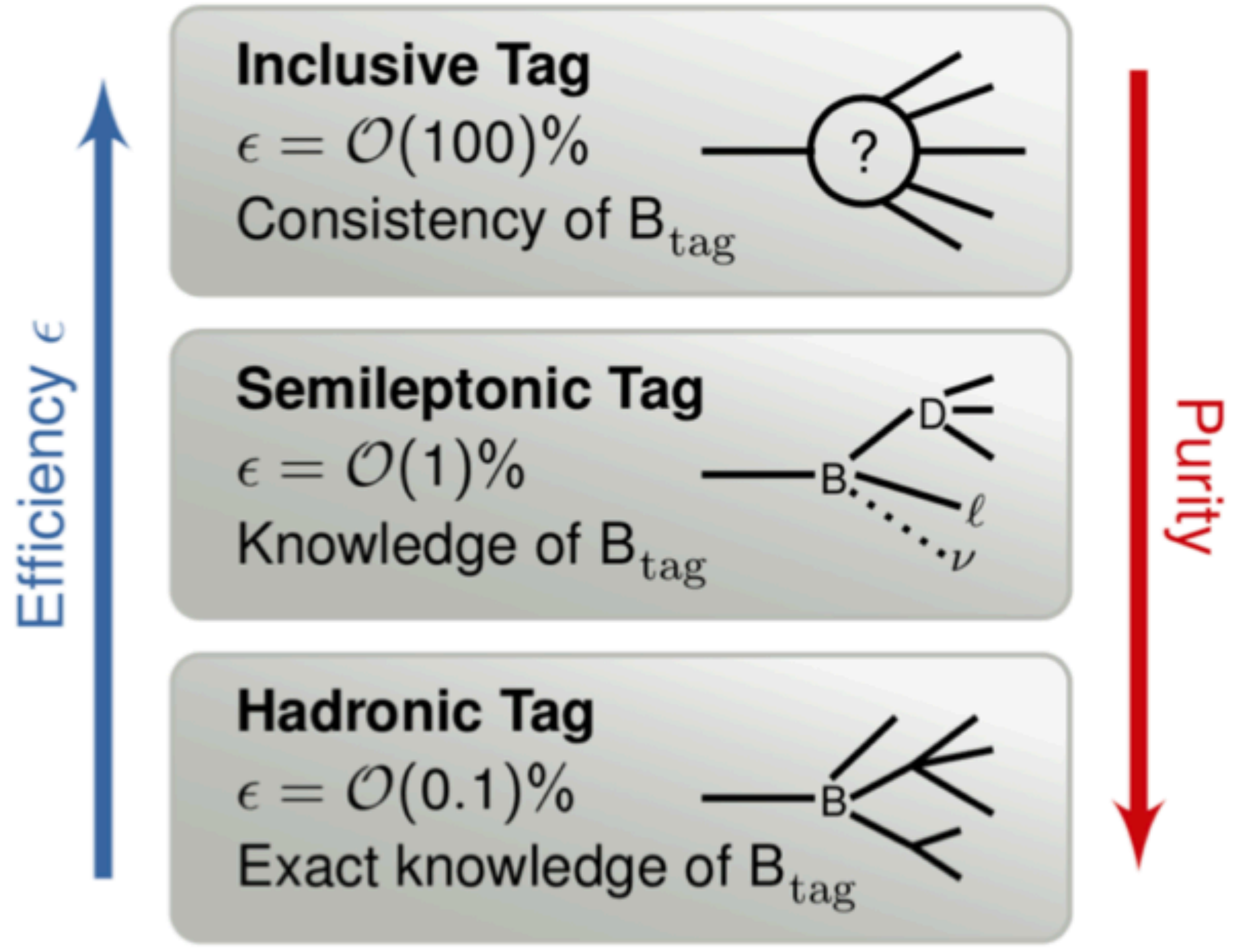
FEI reconstruction

- Exclusive reconstruction of hadronic B modes.
- Multivariate algorithm with hierarchal approach









Inclusive Tag
$\epsilon = \mathcal{O}(100)\%$
Consistency of B_{tag}

Semileptonic Tag
$\epsilon = \mathcal{O}(1)\%$
Knowledge of B_{tag}

Hadronic Tag
$\epsilon = \mathcal{O}(0.1)\%$
Exact knowledge of B_{tag}

Infer momentum and direction of signal B candidate:

$$p_{Bsig} \equiv (E_{Bsig}, \vec{p}_{Bsig}) = \left(\frac{m_{\Upsilon(4S)}}{2}, -\vec{p}_{B\mathrm{tag}}\right)$$

Ideal for decays with neutrinos, missing energy signatures!

Tagging Algorithm	Had B+/B0	SL B+/B0
Full Reconstruction Belle	0.28/0.18	0.67/0.63
FEI Belle	0.78/0.46	1.80/2.04

MC Tagging efficiency at 10% purity!