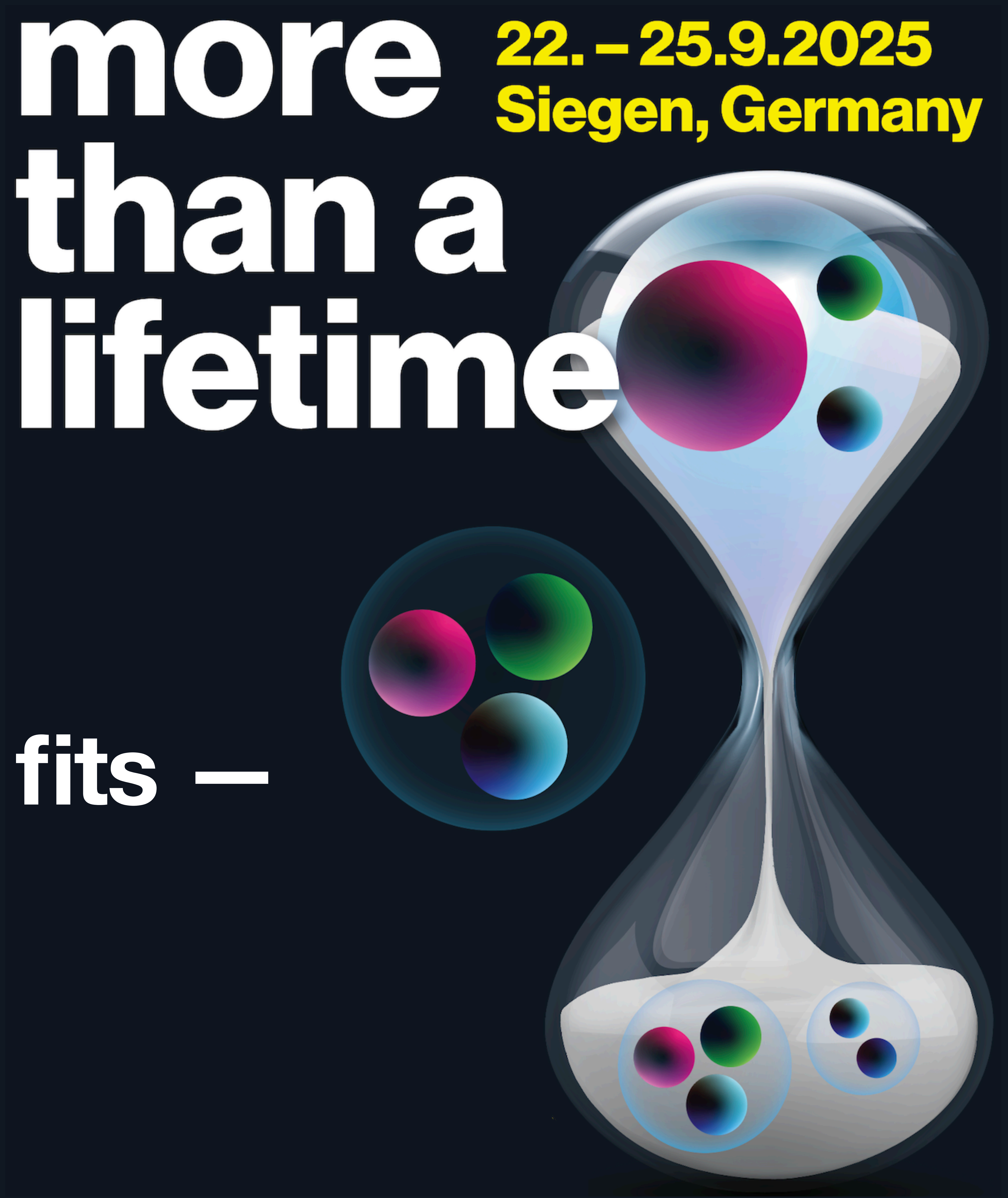


Inclusive semi-leptonic fits — experimental aspects

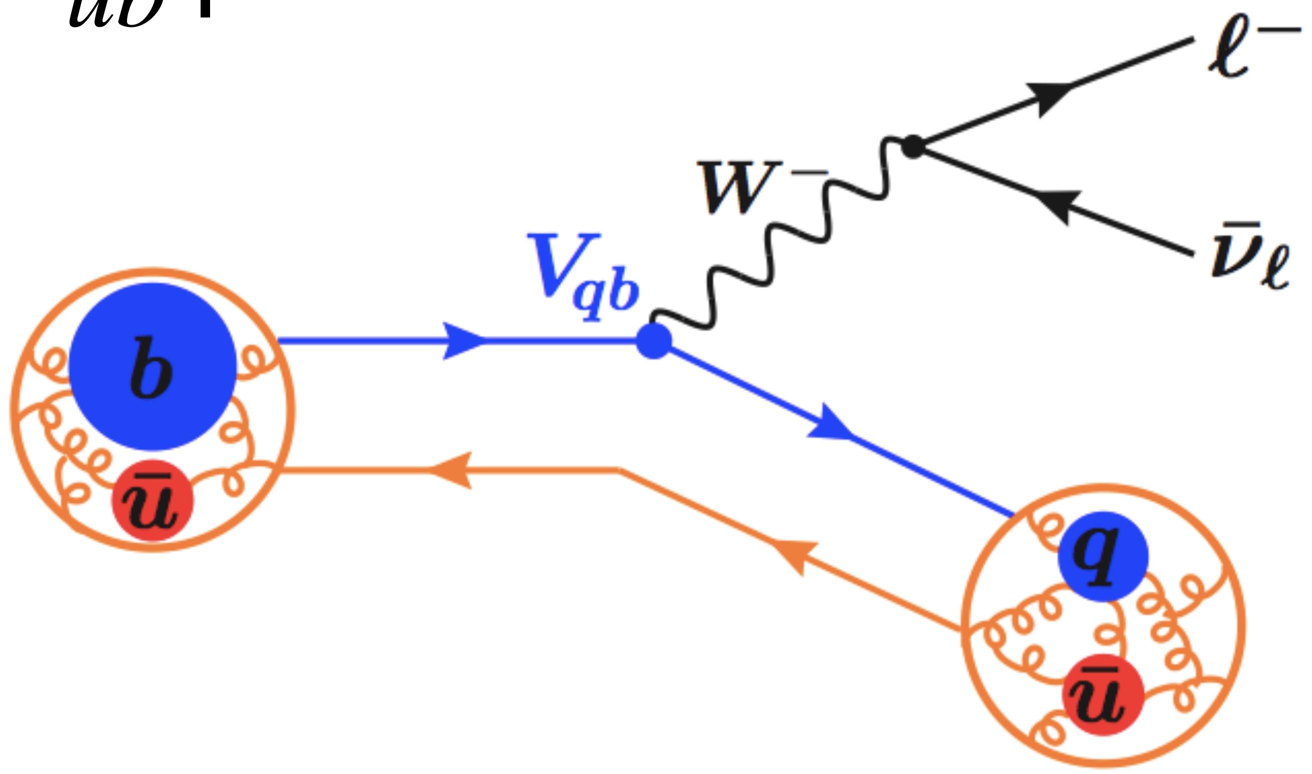
Christoph Schwanda
MBI Vienna

A short introduction

Semileptonic B decays

Determination of the CKM elements $|V_{cb}|$ and $|V_{ub}|$

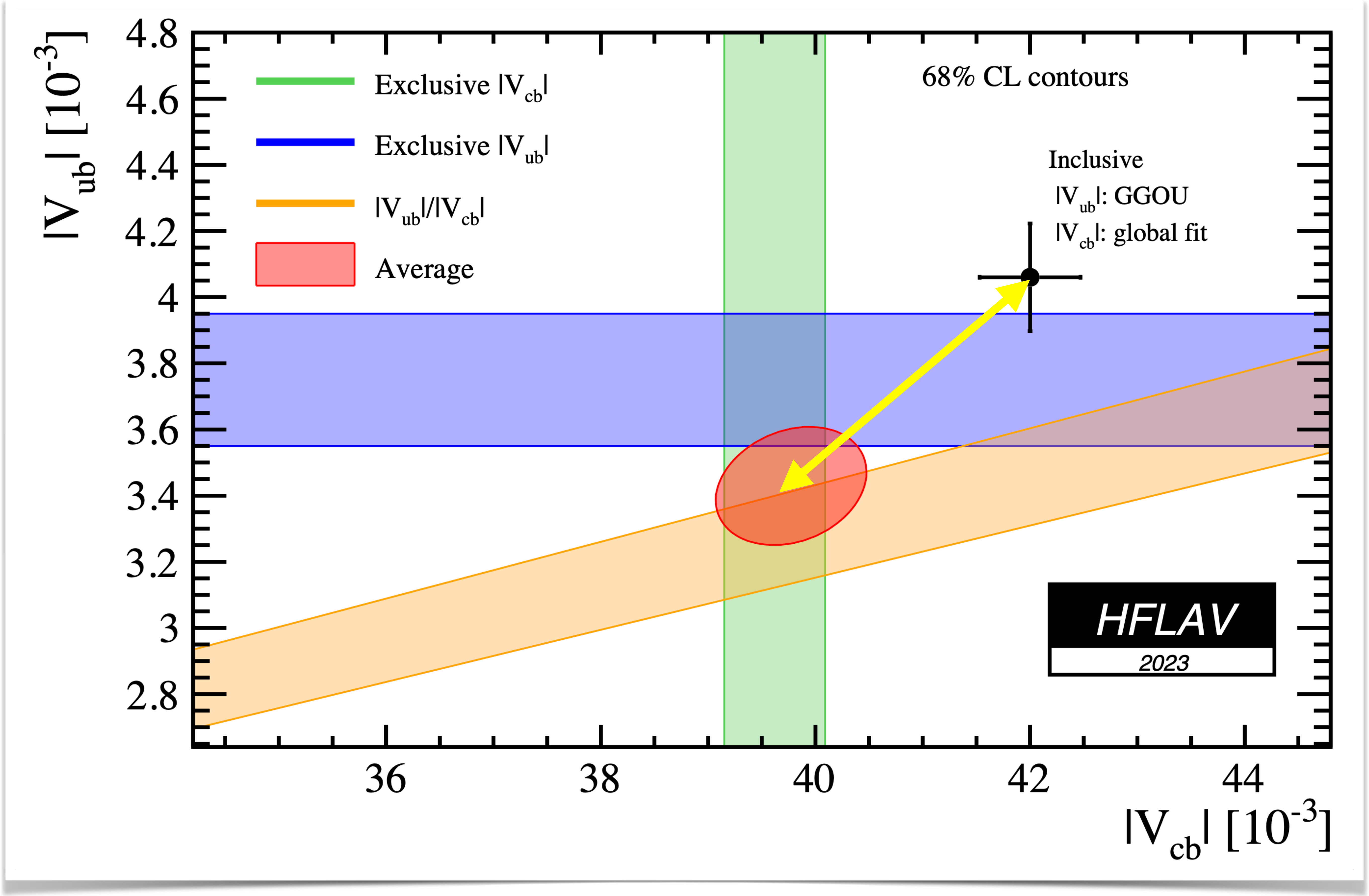
- SL B decays are studied to determine the CKM elements $|V_{cb}|$ and $|V_{ub}|$
  - $|V_{xb}|$ are limiting the global constraining power of UT fits
  - Important inputs in predictions of SM rates for ultrarare decays such as $B_s \to \mu\nu$ and $K \to \pi\nu\nu$
- The determinations can be
  - *Exclusive* — from a single final state
  - *Inclusive* — sensitive to all SL final states



$$d\Gamma \propto G_F^2 |V_{qb}|^2 \left| L_\mu \langle X | \bar{q}\gamma_\mu P_L b | B \rangle \right|^2$$

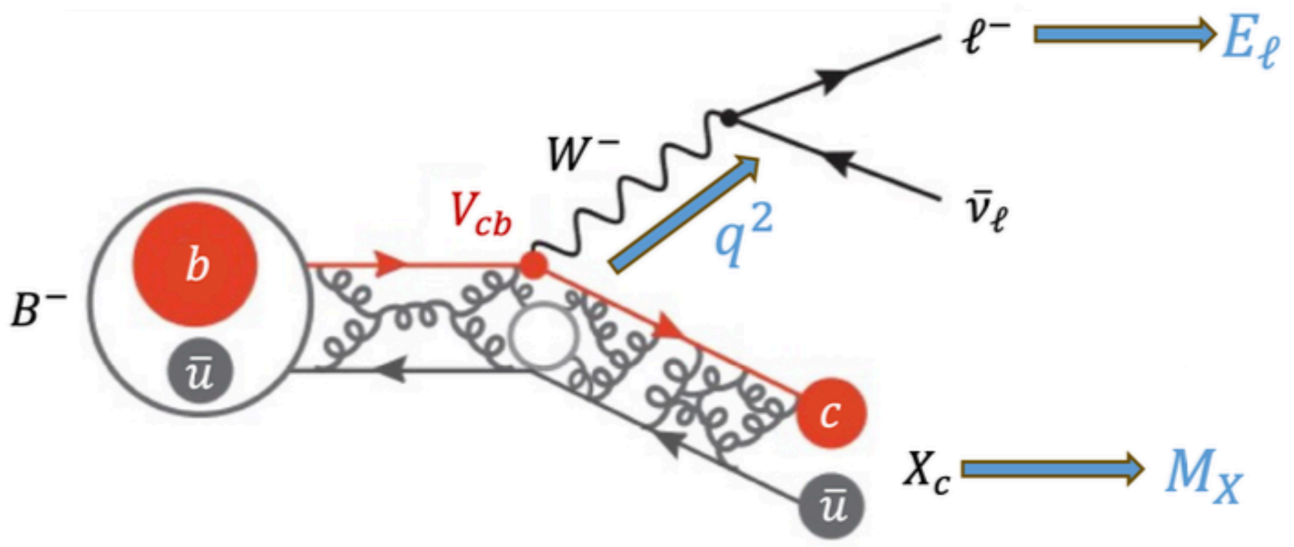
	Experiment	Theory
Exclusive $\|V_{cb}\|$	B → Dlν, D*lν (low backgrounds)	Lattice QCD, light cone sum rules
Inclusive $\|V_{cb}\|$	B → Xlν (higher background)	Operator product expansion

Inclusive/exclusive anomaly



~3σ difference between *inclusive* and *exclusive* $|V_{xb}|$

$|V_{cb}|$ from $B \to X_c \ell \nu$



$$\langle O^n \rangle_{\text{cut}} = \int_{\text{cut}} (O)^n \frac{d\Gamma}{d\Phi} d\Phi \Big/ \int_{\text{cut}} \frac{d\Gamma}{d\Phi} d\Phi$$

Cut = moments are measured with progressive cuts in E_l or q^2

$\langle E_l \rangle, \langle M_X^2 \rangle, \langle q^2 \rangle$

$\mu_\pi, \mu_G, \rho_D, \rho_{LS}, \ldots$

$$\Gamma = \Gamma_3 + \Gamma_{\mu_\pi} \frac{\mu_\pi^2}{m_b^2} + \Gamma_{\mu_G} \frac{\mu_G^2}{m_b^2} + \ldots$$

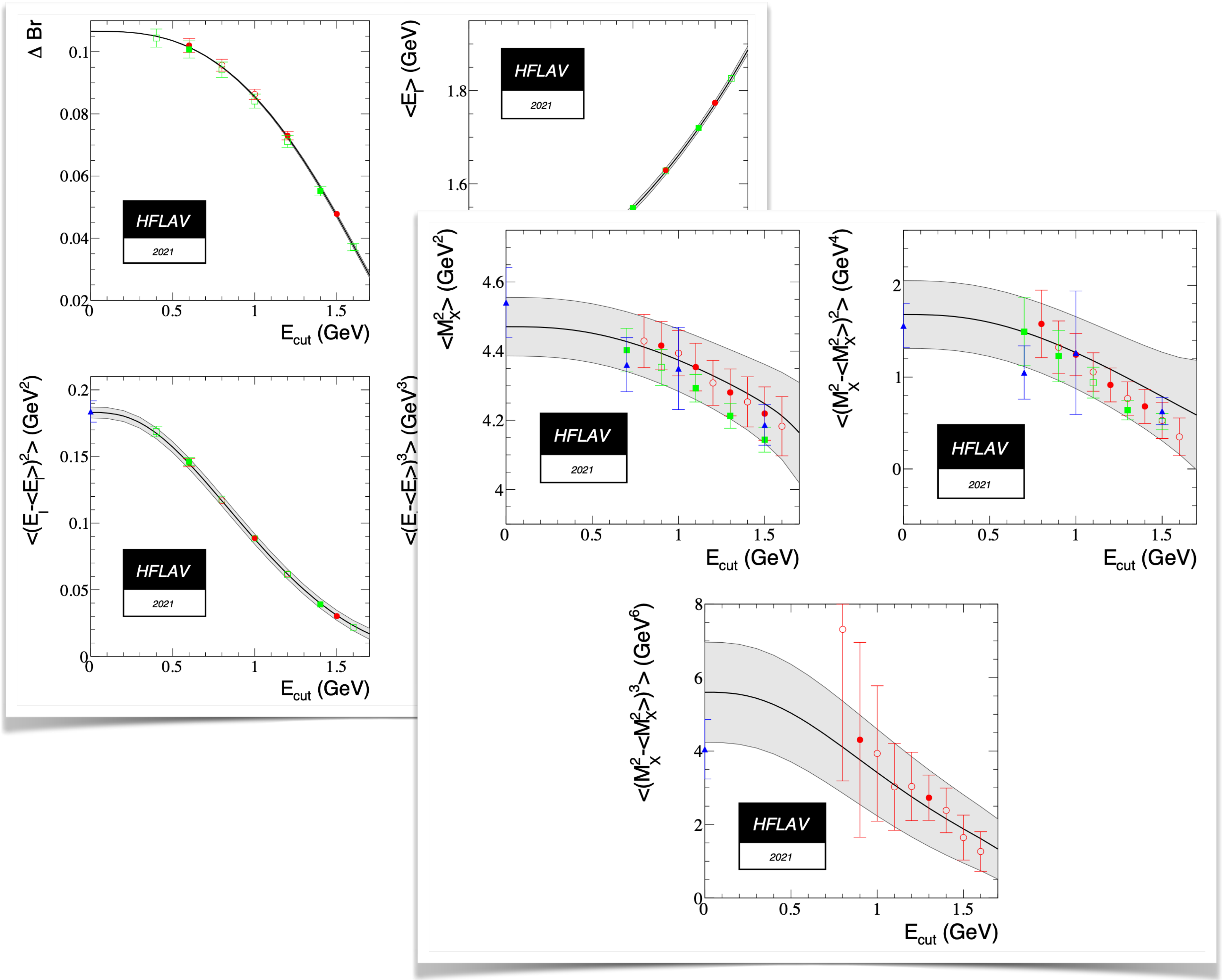
$|V_{cb}|$

$O = (p_l + p_\nu)^2 = q^2$	leptonic invariant mass
$O = (p_B - q)^2 = M_X^2$	hadronic invariant mass
$O = v_B \cdot p_l = E_l$	lepton energy

Moments — experimental status

Circa 2004-2010: the legacy

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



From 2021: a renaissance of interest

- Belle, Phys. Rev. D 104, 112011 (2021)
- Belle II, Phys. Rev. D 107, 072002 (2023)

Triggered by:
"V_{cb} determination from inclusive $b \to c$ decays: an alternative method" [JHEP 02 (2019) 177]

Reparametrization invariance

[JHEP 02 (2019) 177]

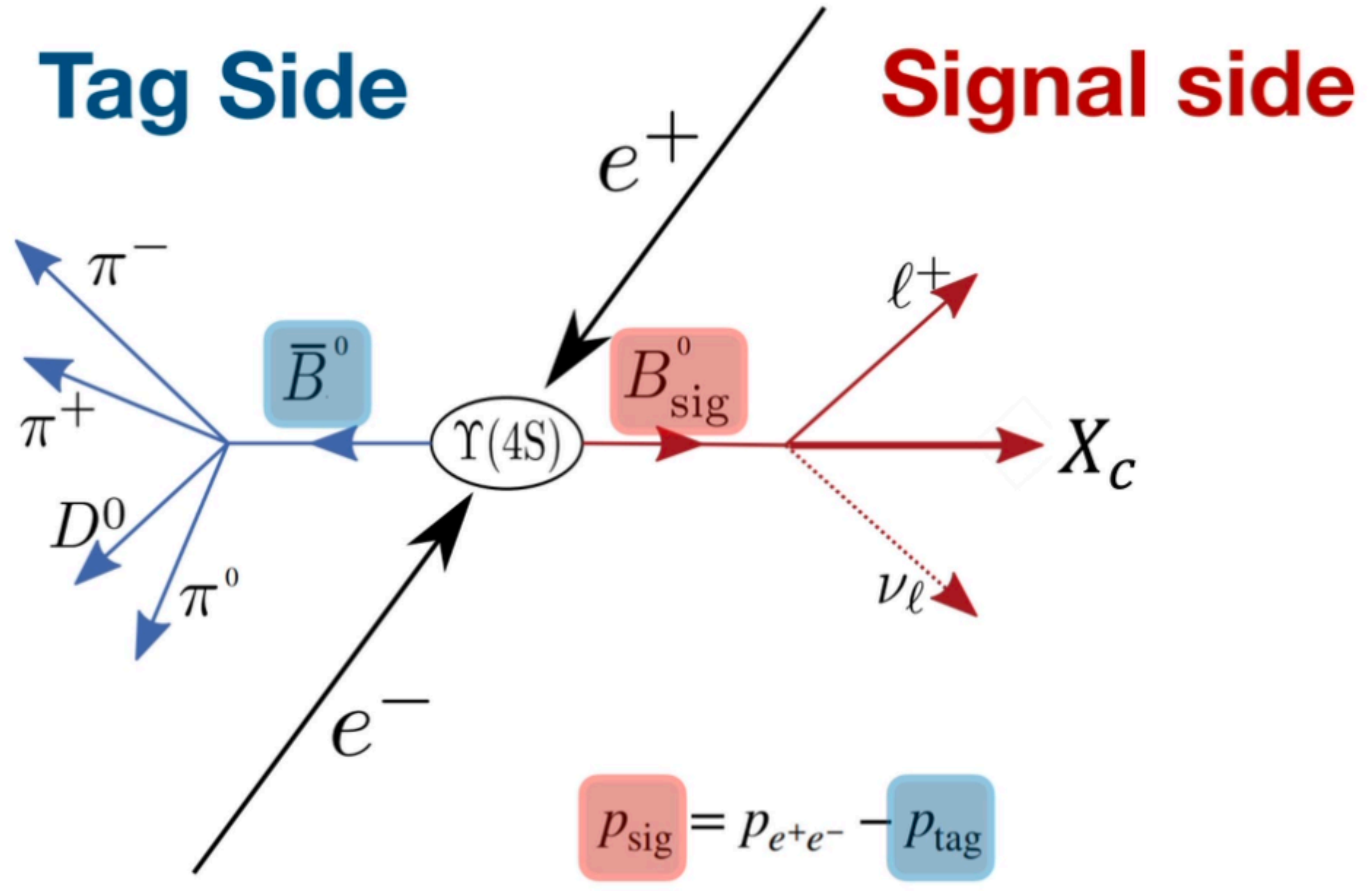
- While there are only two operators at $1/m_b^2$ and two at $1/m_b^3$, going to $1/m_b^4$ would introduce 13 new matrix elements
- Reparametrization invariance links different operators in the Heavy-Quark expansion and reduces the number of independent operators at $1/m_b^4$ to eight
- This is valid in particular for moments of $q^2 = (p_\ell + p_\nu)^2$ while the energy and hadronic mass moments (measured thus far) depend on the full set of matrix elements

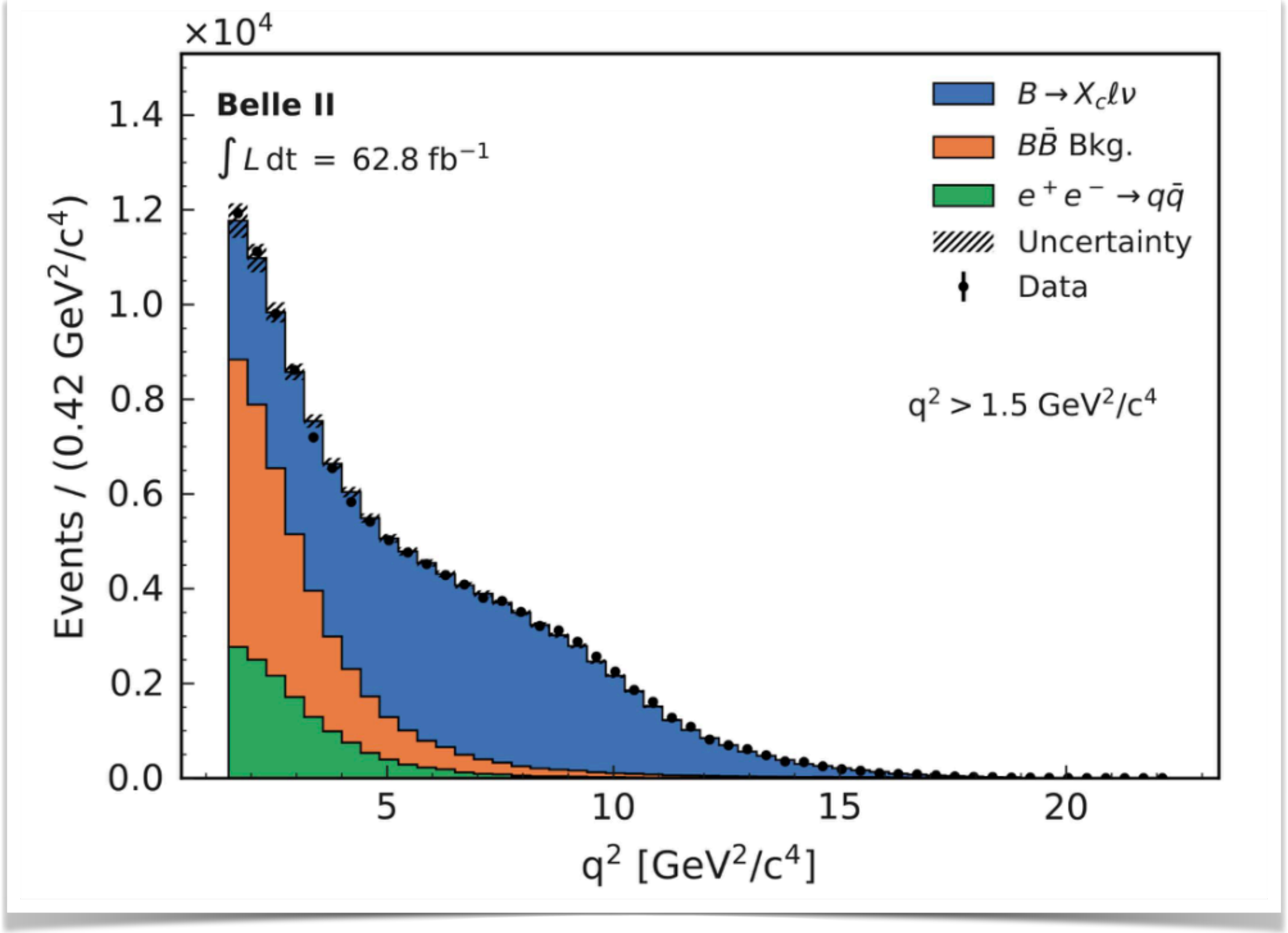
Belle II measurement of q^2 moments in $B \to X_c \ell \nu$

[Phys.Rev.D 107 (2023) 7, 072002]

Reconstruction

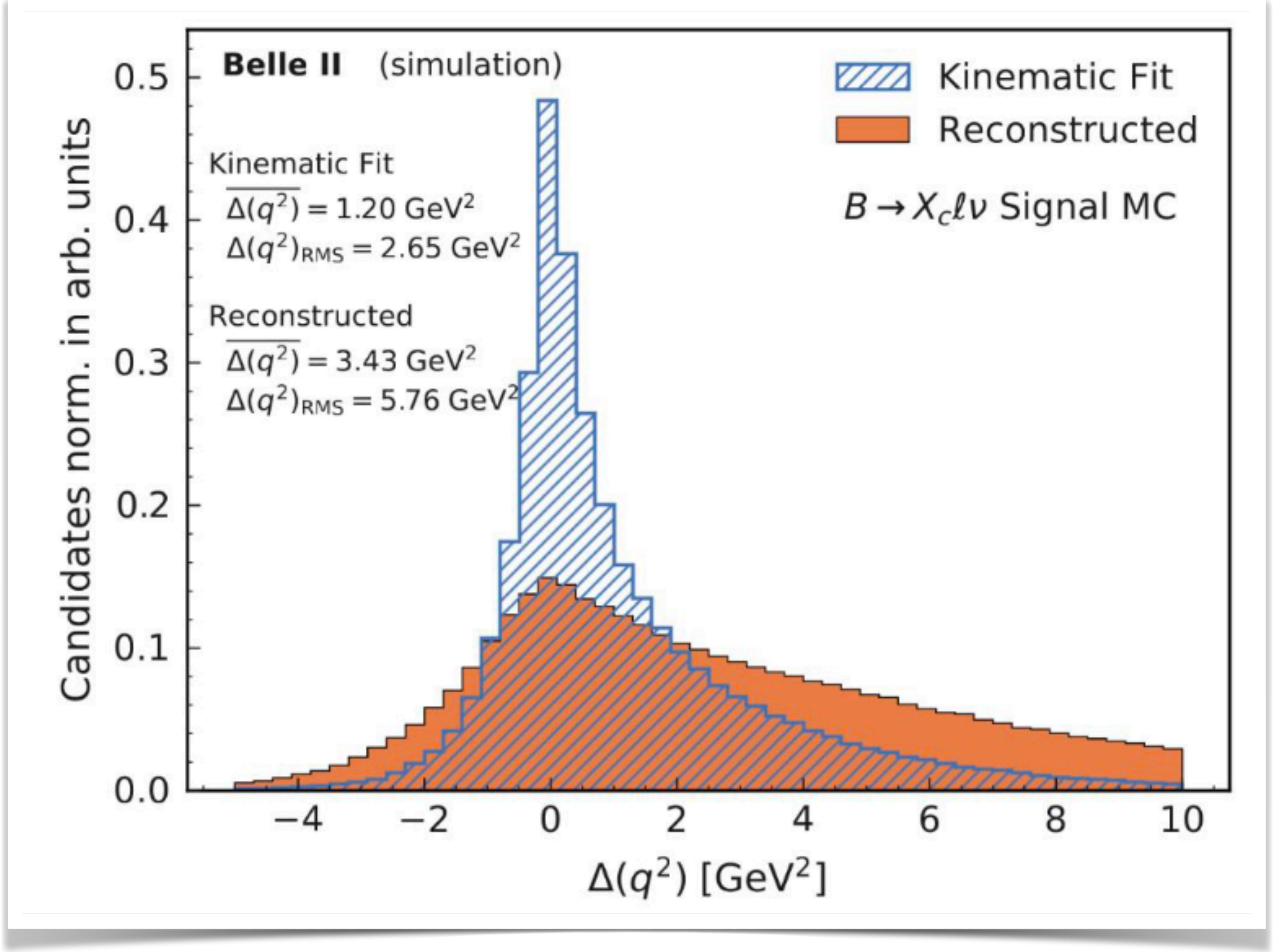
- Based on 62/fb of Belle II $\Upsilon(4S)$ data
- One B meson is reconstructed in a hadronic decay mode (hadronic tag)
- Only the charged lepton on the signal side is reconstructed, the hadronic system X_c is inferred from the remaining particles in the event

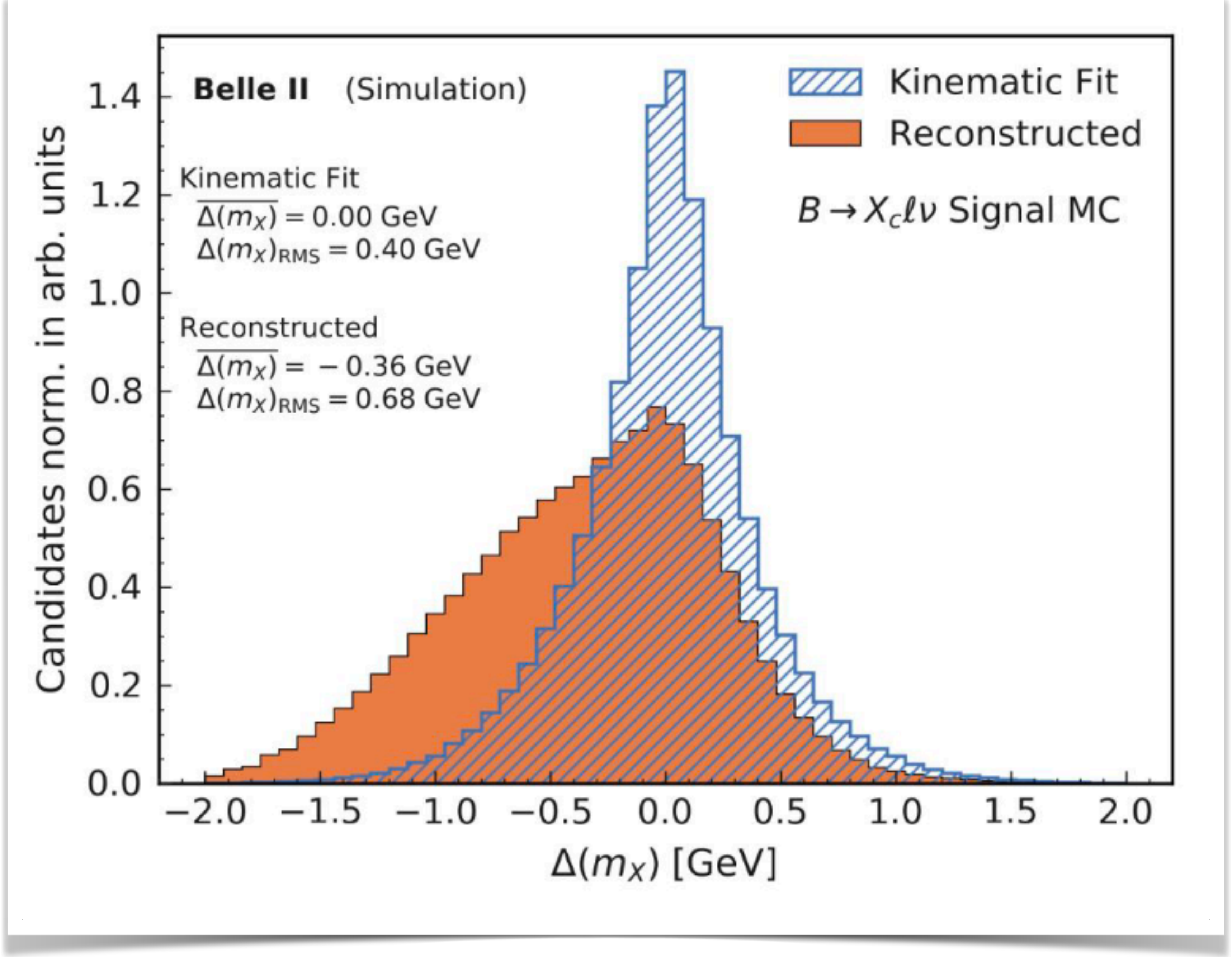




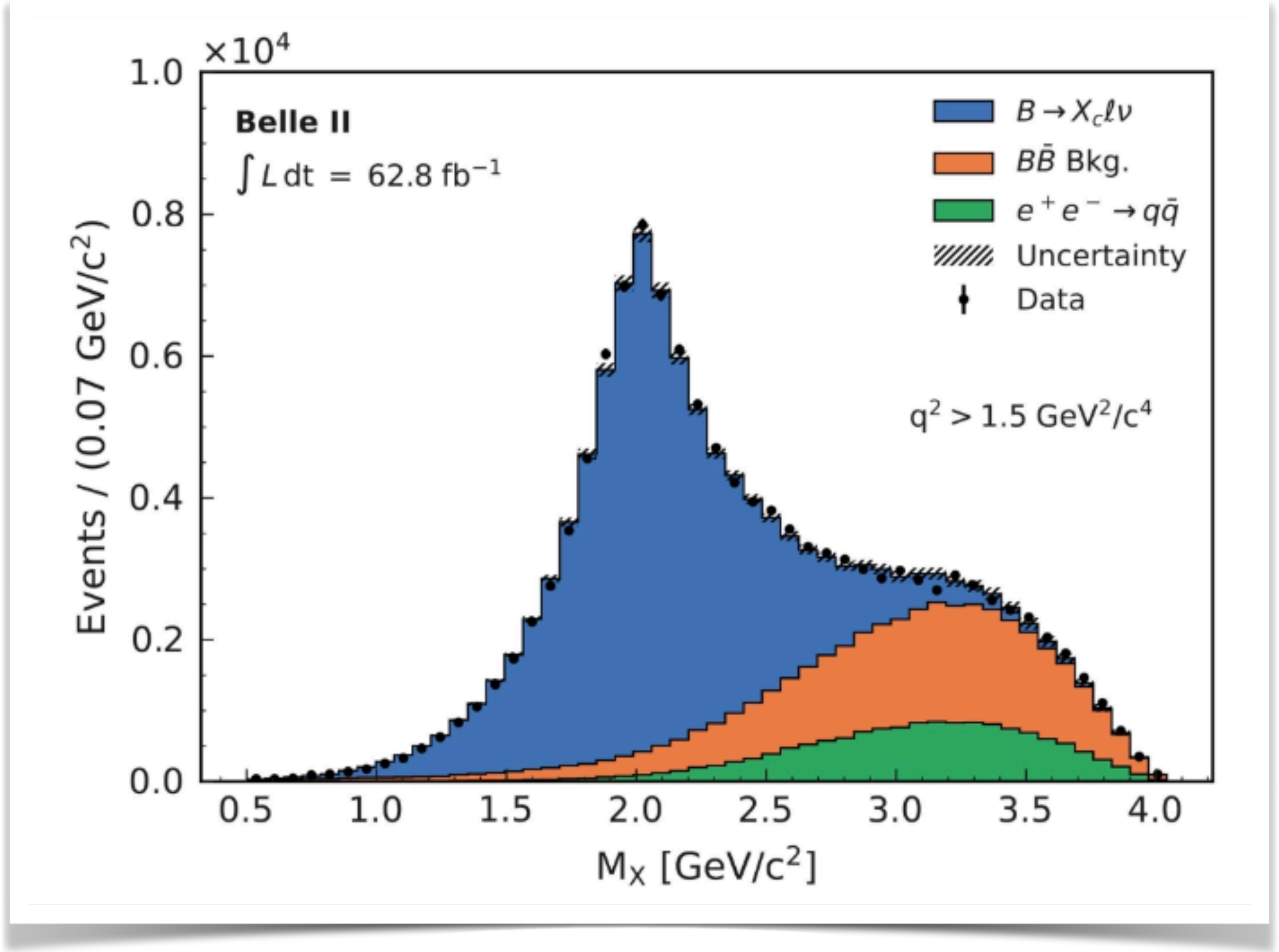
Kinematic fit

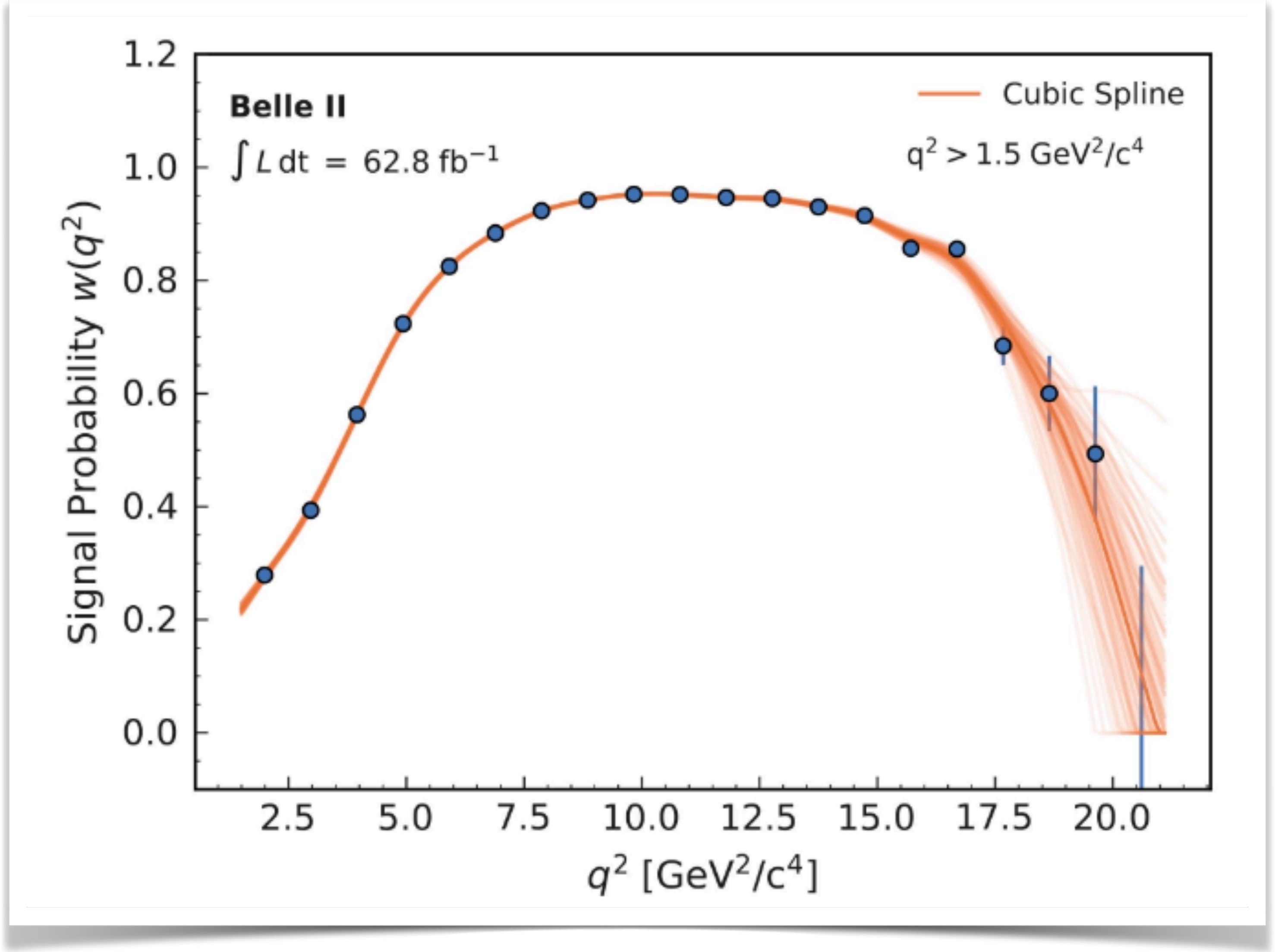
- The reconstruction of M_X and q^2 is improved by a fit constraining
  - The B meson mass to 5.279 GeV
  - No missing mass
  - Positive value of M_x^2





Background subtraction

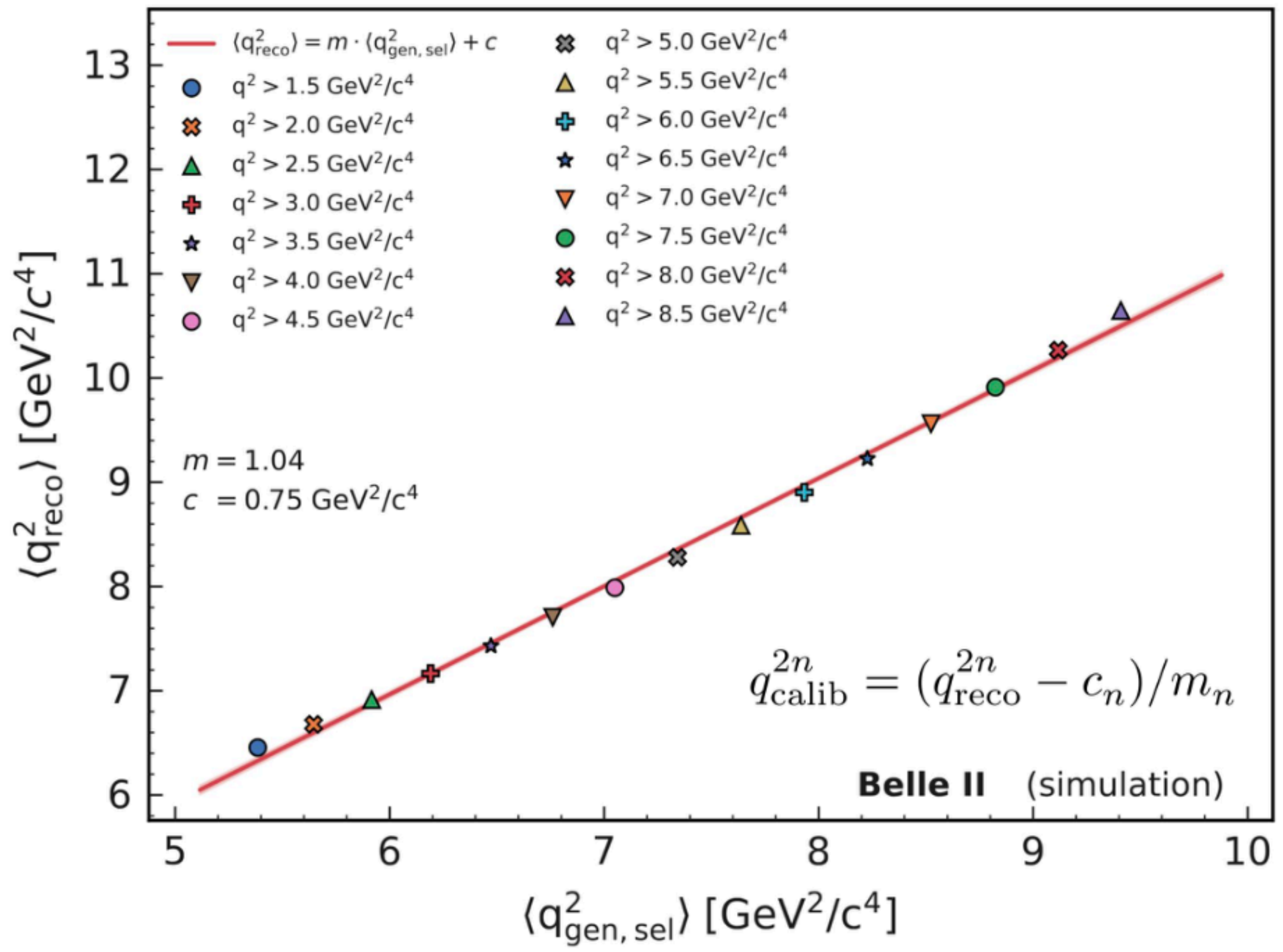




- Fit to M_X to extract signal and background normalization
  - Free floating signal-yield
  - Bin-wise nuisance parameters
  - One fit for each lower threshold cut in q^2
- Determine bin-wise signal probability
  - Fitted with a cubic spline interpolation to obtain continuous signal probability function

Calibration procedure

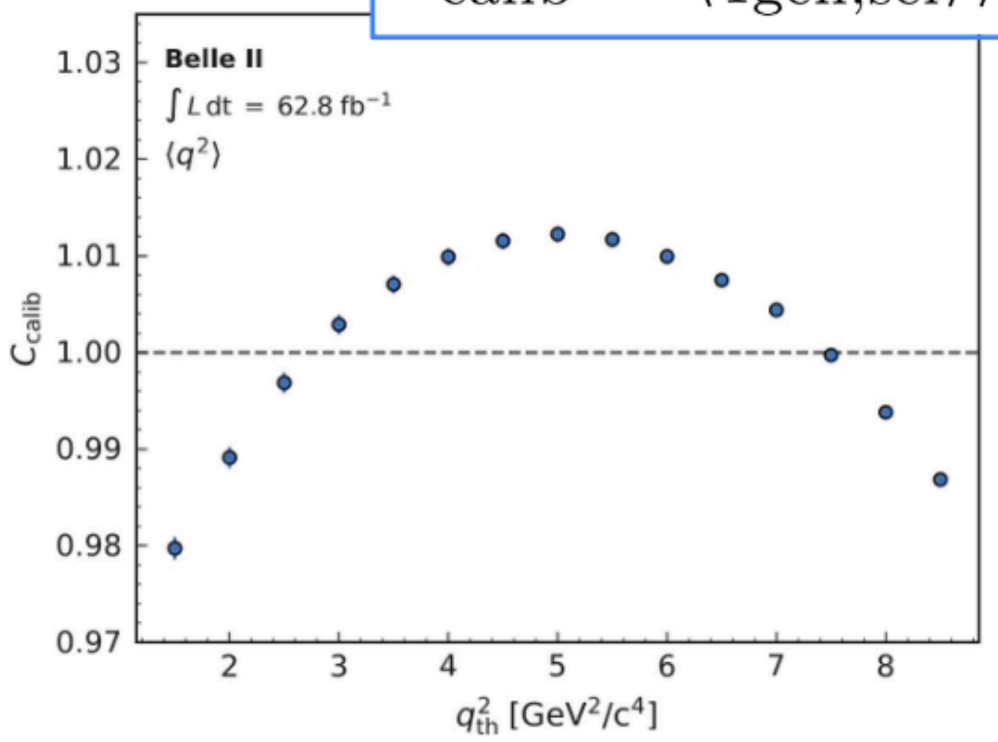
- Linear fit on MC to reconstructed moments vs generator-level moments
- For each moment & threshold cut, constant factors $\mathscr{C}_{\text{calib}}$ and $\mathscr{C}_{\text{gen}}$ to correct further bias



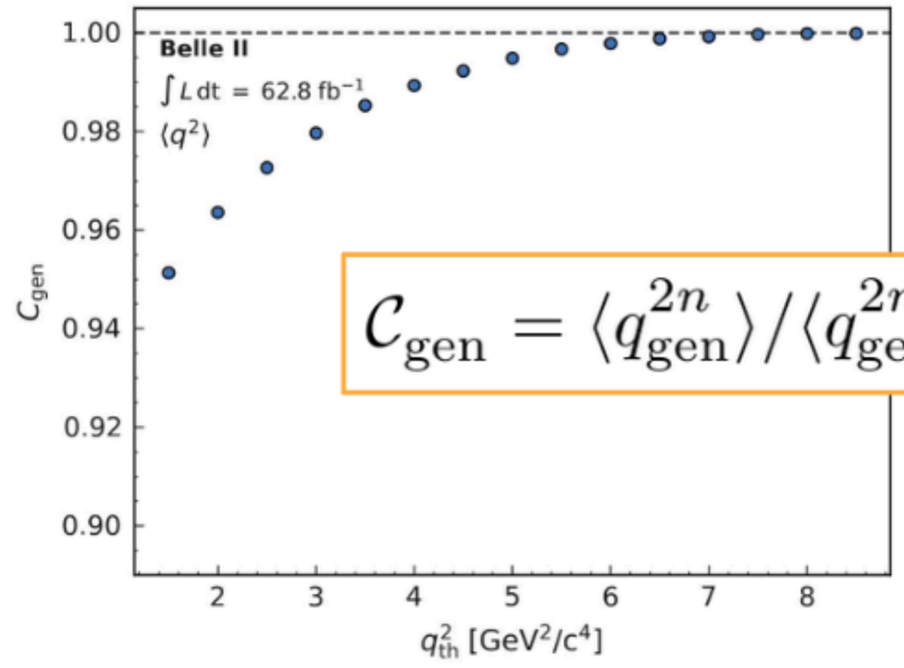
Event-wise master formula

$$\langle q^{2n} \rangle = \frac{\Sigma_{i=0}^{N_{data}} w(q_i^2) \times q_{calib,i}^{2n}}{\Sigma_{j=0}^{N_{data}} w(q_j^2)} \times \mathcal{C}_{calib} \times \mathcal{C}_{gen}$$

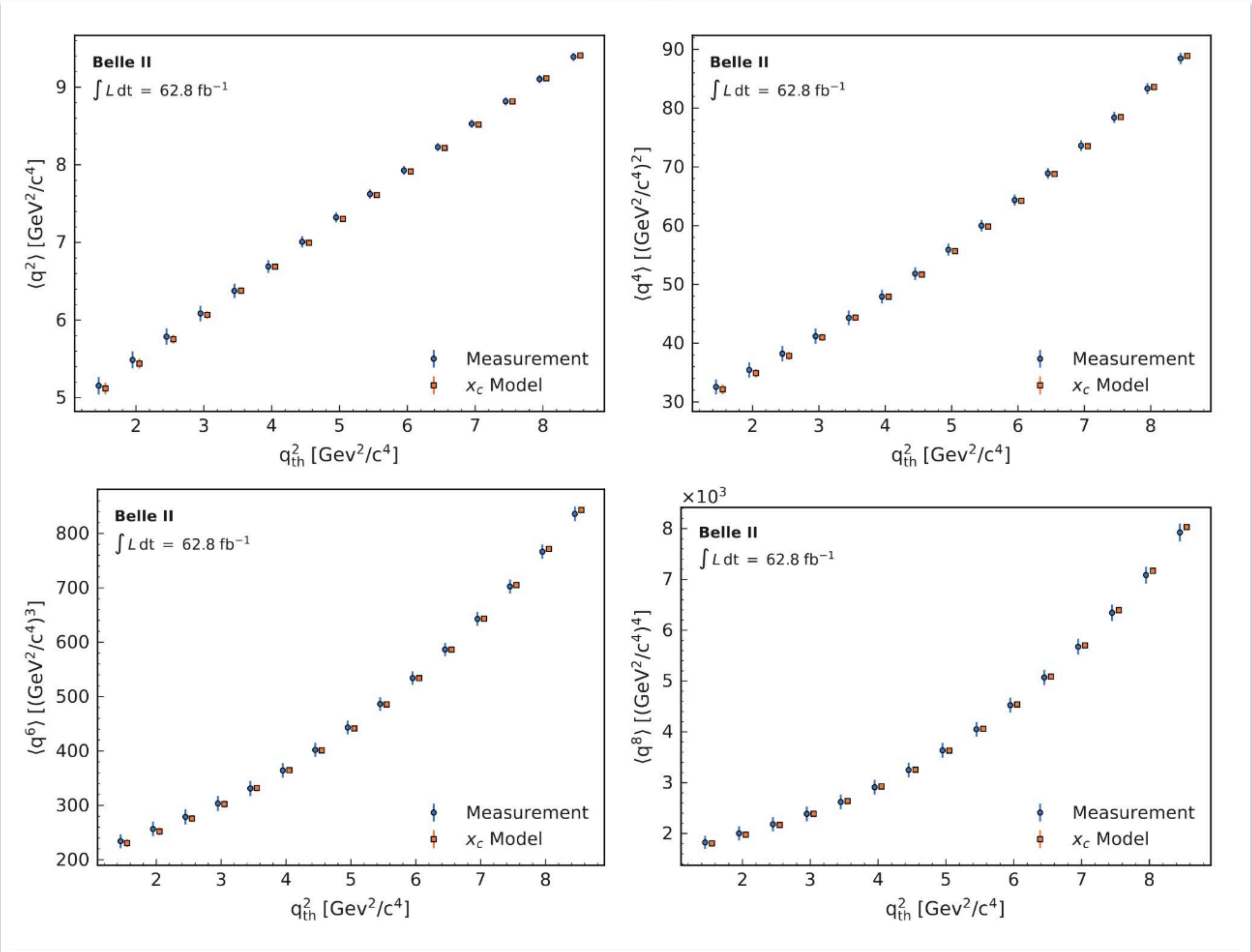
$$\mathcal{C}_{\text{calib}} = \langle q^{2n}_{\text{gen,sel}} \rangle / \langle q^{2n}_{\text{calib}} \rangle$$



$$\mathcal{C}_{\text{gen}} = \langle q^{2n}_{\text{gen}} \rangle / \langle q^{2n}_{\text{gen,sel}} \rangle$$



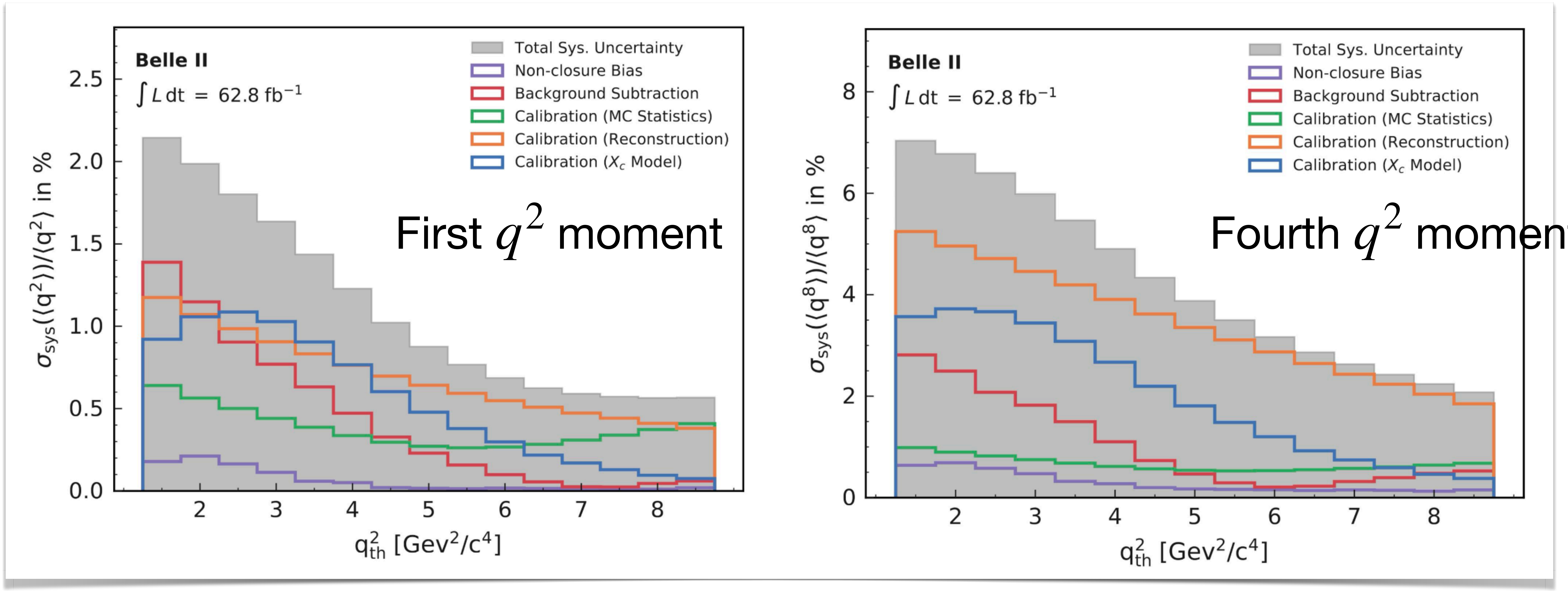
Results



- First, second, third and fourth moment of q^2
  - q^2 thresholds between 1.5 and 8.5 GeV^2
  - Raw and central moments

Systematic uncertainties

- Depends on the moment and on the q^2 threshold



About the fit

Recent results for $|V_{cb}|$ inclusive

OPE-based analyses

- E_ℓ and M_X^2 moments
  [M. Bordone, B. Capdevila, and P. Gambino, Phys. Lett. B 822 (2021) 136679]

$$\boxed{|V_{cb}| = (42.16 \pm 0.30(th) \pm 0.32(exp) \pm 0.25(\Gamma)) \times 10^{-3} \qquad \mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu}_\ell) = (10.66 \pm 0.15)\%}$$

- q^2 moments ($\mathscr{B}_{\mathrm{SL}}$ is input)
  [F. Bernlochner et al., JHEP 10 (2022) 068]

$$\boxed{|V_{cb}| = (41.69 \pm 0.63) \times 10^{-3} \qquad \mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu}_\ell) = (10.48 \pm 0.13)\%}$$

- E_ℓ, M_X^2 and q^2 moments
  [M. Bordone, B. Capdevila, and P. Gambino, Phys. Lett. B 822 (2021) 136679]

$$\boxed{|V_{cb}| = (41.97 \pm 0.27(\mathrm{exp}) \pm 0.31(\mathrm{th}) \pm 0.25(\Gamma)) \times 10^{-3} \qquad \mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu}_\ell) = (10.63 \pm 0.15)\%}$$

Rescaling JHEP 10 (2022) 068 to the same $\mathscr{B}_{\mathrm{SL}}$

- q^2 moments ($\mathscr{B}_{\mathrm{SL}}$ is input)
  [F. Bernlochner et al., JHEP 10 (2022) 068]

$$\boxed{|V_{cb}| = (41.69 \pm 0.63) \times 10^{-3}}$$

$$\mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu}_\ell) = (10.48 \pm 0.13)\%$$

$$\boxed{(41.99 \pm 0.65) \times 10^{-3}}$$

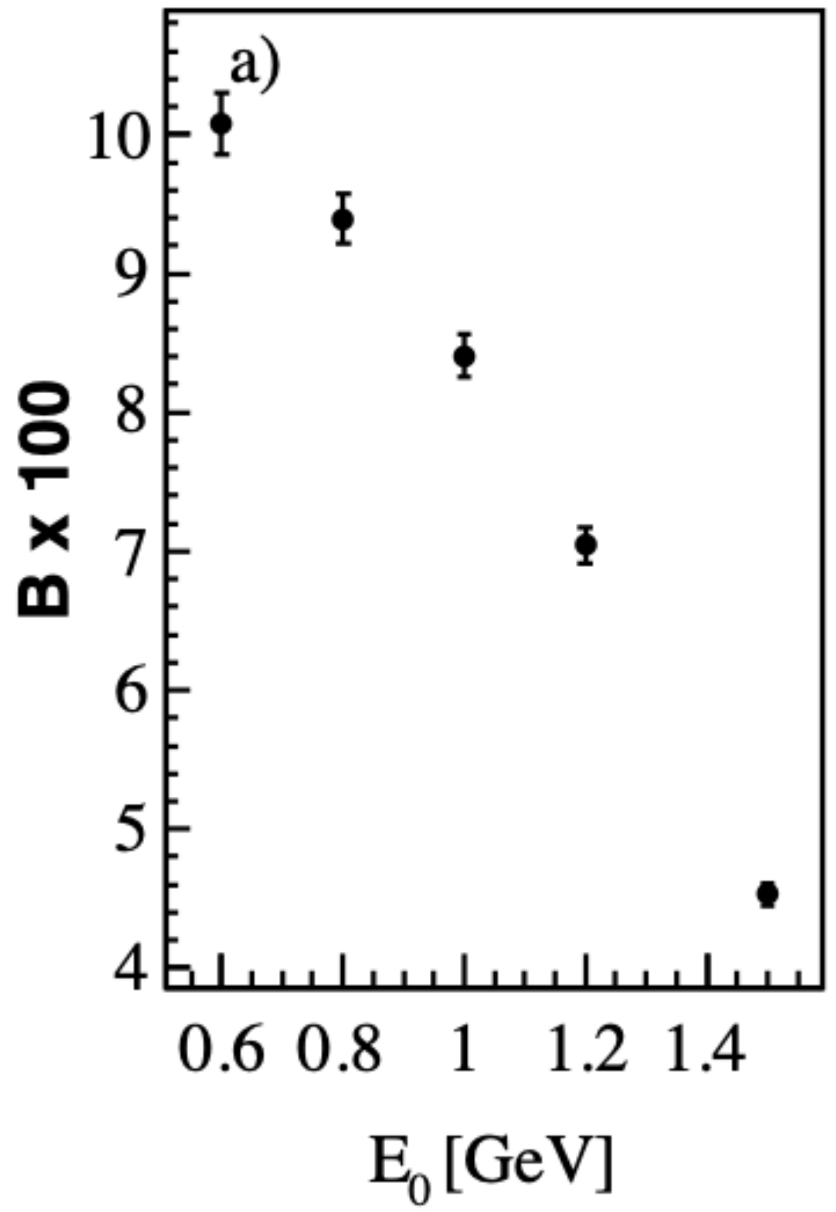
$$\mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu}_\ell) = (10.63 \pm 0.19)\%$$

Significant tension in $\mathscr{B}_{\mathrm{SL}}$ measurements…

	$\mathcal{B}(B \to X\ell\bar{\nu}_\ell)$ (%)	$\mathcal{B}(B \to X_c\ell\bar{\nu}_\ell)$ (%)	In Average
Belle [63] $E_\ell > 0.6\,\mathrm{GeV}$	-	10.54 ± 0.31	✓
Belle [63] $E_\ell > 0.4\,\mathrm{GeV}$	-	10.58 ± 0.32	
CLEO [65] incl.	10.91 ± 0.26	10.72 ± 0.26	
CLEO [65] $E_\ell > 0.6$	10.69 ± 0.25	10.50 ± 0.25	✓
BaBar [62] incl.	10.34 ± 0.26	10.15 ± 0.26	✓
BaBar SL [64] $E_\ell > 0.6\,\mathrm{GeV}$	-	10.68 ± 0.24	✓
Our Average	-	10.48 ± 0.13	
Average Belle [63] & BaBar [64] ($E_\ell > 0.6\,\mathrm{GeV}$)	-	10.63 ± 0.19	

Partial BR measurements

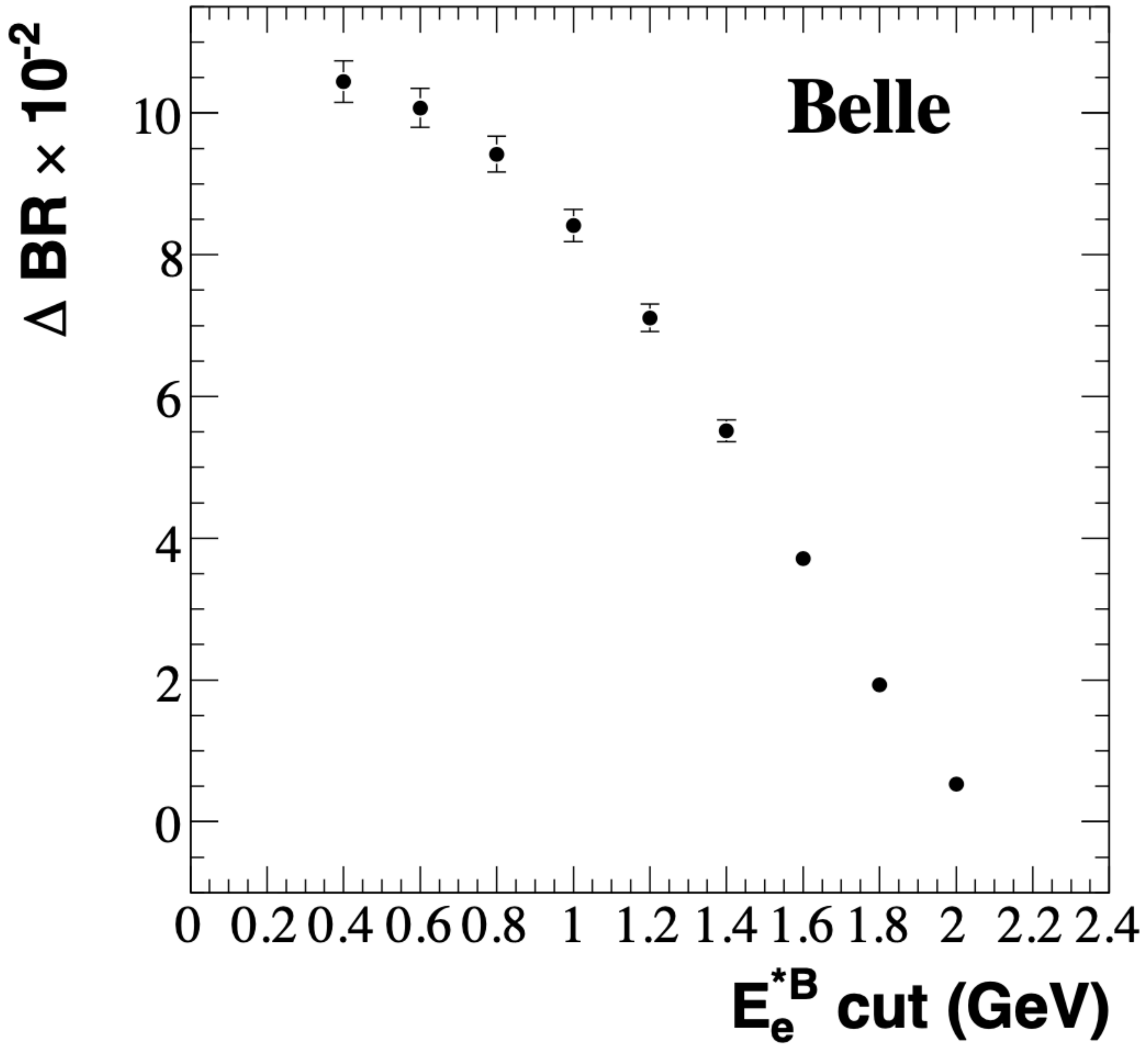
Input to E_ℓ and M_X^2 moment fits



BaBar
Double semileptonic decays
[Phys.Rev. D81 (2010) 032003]

E_0[GeV]	$\mathcal{B}[10^{-2}]$
0.6	10.30 ± 0.06 ± 0.24
0.8	9.61 ± 0.05 ± 0.20
1.0	8.65 ± 0.04 ± 0.17
1.2	7.31 ± 0.04 ± 0.14
1.5	4.79 ± 0.03 ± 0.09

(2004 table)

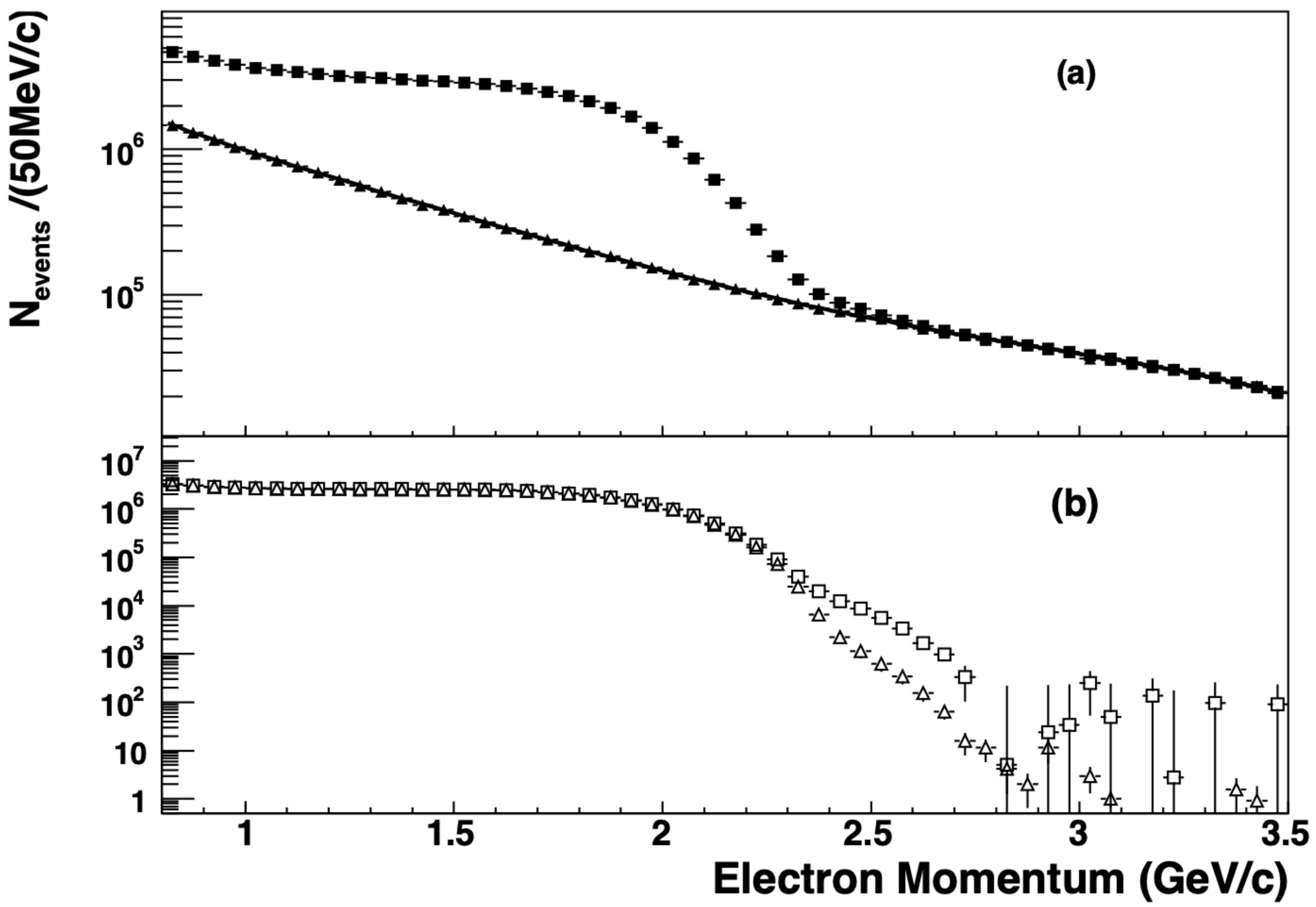


Belle
Hadronic tag
[Phys.Rev. D75 (2007) 032001]

E_{cut}[GeV]	$\Delta\mathcal{B}$ $[10^{-2}]$
0.4	10.44 ± 0.19 ± 0.22
0.6	10.07 ± 0.18 ± 0.21
0.8	9.42 ± 0.16 ± 0.19
1.0	8.41 ± 0.15 ± 0.17
1.2	7.11 ± 0.13 ± 0.14
1.4	5.52 ± 0.11 ± 0.11
1.6	3.71 ± 0.09 ± 0.07
1.8	1.93 ± 0.06 ± 0.04
2.0	0.53 ± 0.02 ± 0.02

Phys.Rev.D 95 (2017) 7, 072001

BaBar publication on $|V_{ub}|$ inclusive



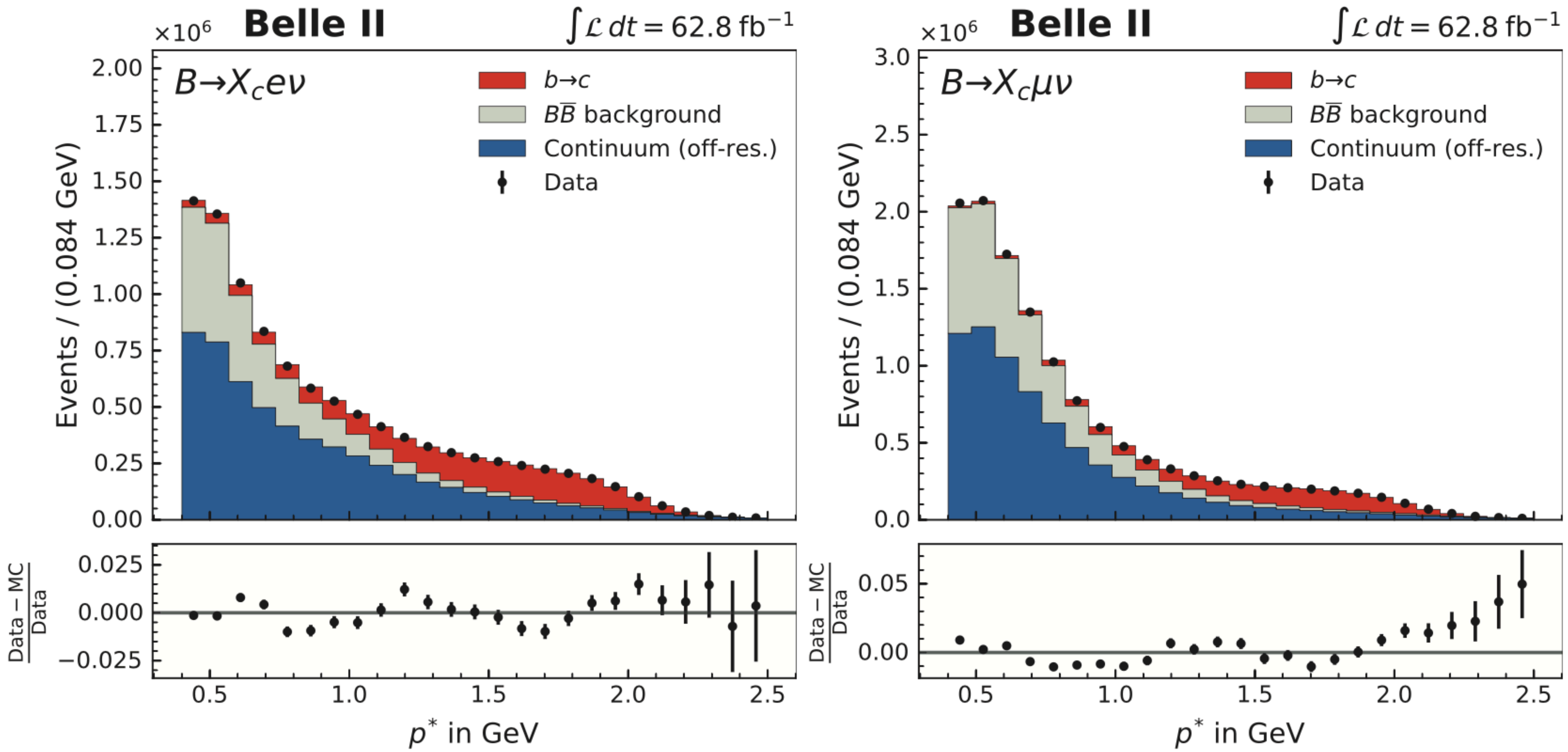
$$\boxed{\mathcal{B}(B \to Xe\nu) = (10.34 \pm 0.04_{\mathrm{stat}} \pm 0.26_{\mathrm{syst}})\%}$$

Revisiting the measurement of $\mathscr{B}_{\mathrm{SL}}$

- There is ample motivation for revisiting the measurement of the inclusive, semileptonic BR measurement
    - Only few recent measurements, issue with consistency?
    - $\mathscr{B}_{\mathrm{SL}}$ has a very significant impact on the value of $|V_{cb}|$ inclusive
- A new measurement should be inclusive to avoid issues with tagging
    - Requires excellent understanding of backgrounds and detector systematics

Belle II $B \to X\ell\nu$ inclusive [arXiv:2111.09405]

Preliminary conference result



- Pure inclusive measurement seems hard due to significant backgrounds, double-tag measurement a la BaBar?

B^0 and B^+ lifetimes

B^0

Experiment	Method	Data set	$\tau(B^0)$ (ps)	Ref.
ALEPH	$D^{(*)}\ell$	91–95	$1.518 \pm 0.053 \pm 0.034$	[58]
ALEPH	Exclusive	91–94	$1.25^{+0.15}_{-0.13} \pm 0.05$	[59]
ALEPH	Partial rec. $\pi^+\pi^-$	91–94	$1.49^{+0.17+0.08}_{-0.15-0.06}$	[59]
DELPHI	$D^{(*)}\ell$	91–93	$1.61^{+0.14}_{-0.13} \pm 0.08$	[60]
DELPHI	Charge sec. vtx	91–93	$1.63 \pm 0.14 \pm 0.13$	[61]
DELPHI	Inclusive $D^*\ell$	91–93	$1.532 \pm 0.041 \pm 0.040$	[62]
DELPHI	Charge sec. vtx	94–95	$1.531 \pm 0.021 \pm 0.031$	[57]
L3	Charge sec. vtx	94–95	$1.52 \pm 0.06 \pm 0.04$	[63]
OPAL	$D^{(*)}\ell$	91–93	$1.53 \pm 0.12 \pm 0.08$	[64]
OPAL	Charge sec. vtx	93–95	$1.523 \pm 0.057 \pm 0.053$	[65]
OPAL	Inclusive $D^*\ell$	91–00	$1.541 \pm 0.028 \pm 0.023$	[66]
SLD	Charge sec. vtx ℓ	93–95	$1.56^{+0.14}_{-0.13} \pm 0.10$	[67] [a]
SLD	Charge sec. vtx	93–95	$1.66 \pm 0.08 \pm 0.08$	[67] [a]
CDF1	$D^{(*)}\ell$	92–95	$1.474 \pm 0.039^{+0.052}_{-0.051}$	[68]
CDF1	Excl. $J/\psi K^{*0}$	92–95	$1.497 \pm 0.073 \pm 0.032$	[69]
CDF2	Excl. $J/\psi K^0_S$, $J/\psi K^{*0}$	02–09	$1.507 \pm 0.010 \pm 0.008$	[70]
D0	Excl. $J/\psi K^{*0}$	03–07	$1.414 \pm 0.018 \pm 0.034$	[71]
D0	Excl. $J/\psi K^0_S$	02–11	$1.508 \pm 0.025 \pm 0.043$	[72]
D0	Inclusive $D^-\mu^+$	02–11	$1.534 \pm 0.019 \pm 0.021$	[73]
BABAR	Exclusive	99–00	$1.546 \pm 0.032 \pm 0.022$	[74]
BABAR	Inclusive $D^*\ell$	99–01	$1.529 \pm 0.012 \pm 0.029$	[75]
BABAR	Exclusive $D^*\ell$	99–02	$1.523^{+0.024}_{-0.023} \pm 0.022$	[76]
BABAR	Incl. $D^*\pi$, $D^*\rho$	99–01	$1.533 \pm 0.034 \pm 0.038$	[77]
BABAR	Inclusive $D^*\ell$	99–04	$1.504 \pm 0.013^{+0.018}_{-0.013}$	[78]
Belle	Exclusive	00–03	$1.534 \pm 0.008 \pm 0.010$	[79]
ATLAS	Excl. $J/\psi K^0_S$	2011	$1.509 \pm 0.012 \pm 0.018$	[80]
CMS	Excl. $J/\psi K^{*0}$	2012	$1.511 \pm 0.005 \pm 0.006$	[81] [b]
CMS	Excl. $J/\psi K^0_S$	2012	$1.527 \pm 0.009 \pm 0.009$	[81] [b]
LHCb	Excl. $J/\psi K^{*0}$	2011	$1.524 \pm 0.006 \pm 0.004$	[82]
LHCb	Excl. $J/\psi K^0_S$	2011	$1.499 \pm 0.013 \pm 0.005$	[82]
LHCb	$K^+\pi^-$	2011	$1.524 \pm 0.011 \pm 0.004$	[83]
Average			1.519 ± 0.004	

[a] The combined SLD result quoted in Ref. [67] is $1.64 \pm 0.08 \pm 0.08$ ps.
[b] The combined CMS result quoted in Ref. [81] is $1.515 \pm 0.005 \pm 0.006$ ps.

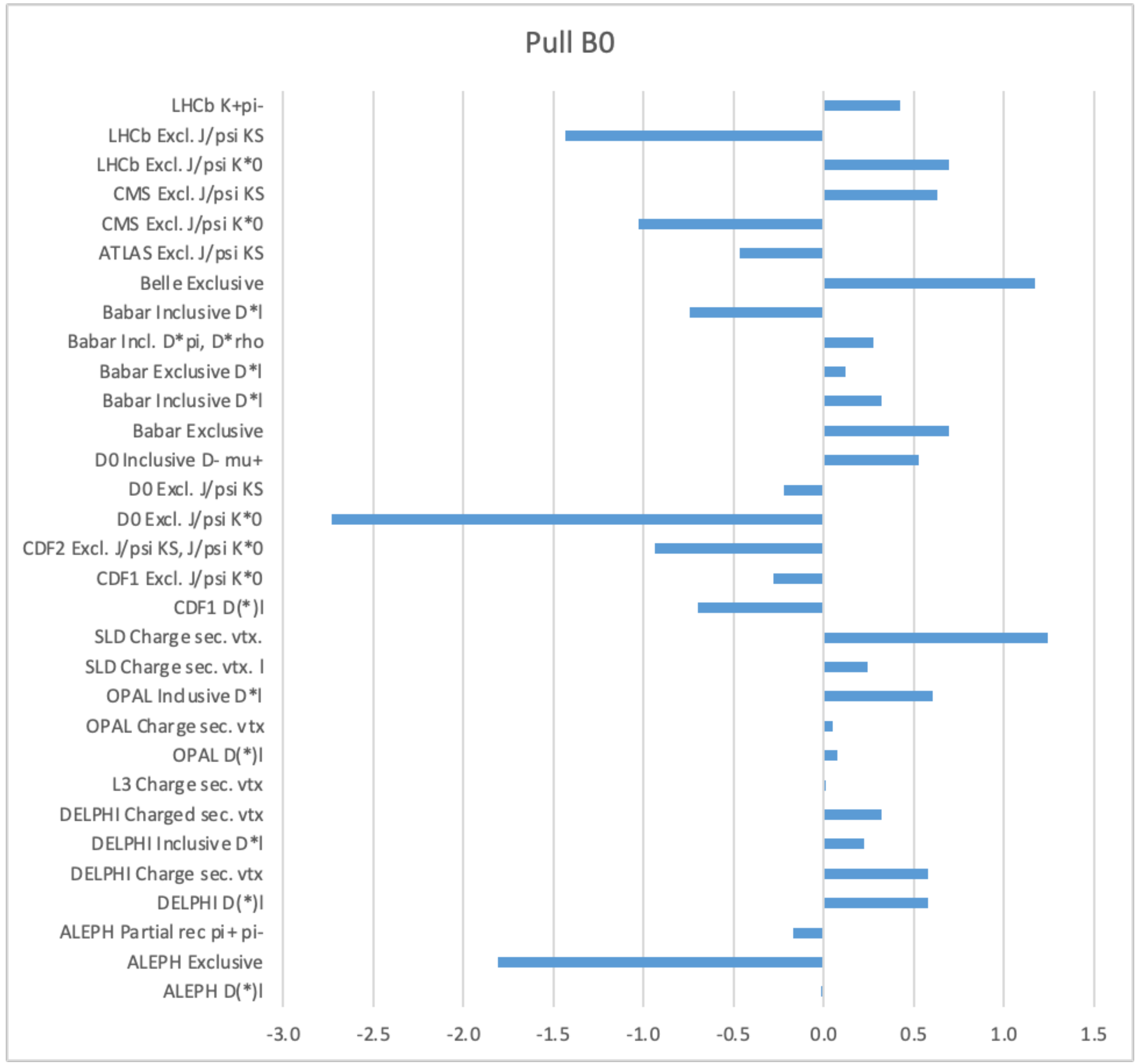
B^+

Experiment	Method	Data set	$\tau(B^+)$ (ps)	Ref.
ALEPH	$D^{(*)}\ell$	91–95	$1.648 \pm 0.049 \pm 0.035$	[58]
ALEPH	Exclusive	91–94	$1.58^{+0.21+0.04}_{-0.18-0.03}$	[59]
DELPHI	$D^{(*)}\ell$	91–93	$1.61 \pm 0.16 \pm 0.12$	[60] [a]
DELPHI	Charge sec. vtx	91–93	$1.72 \pm 0.08 \pm 0.06$	[61] [a]
DELPHI	Charge sec. vtx	94–95	$1.624 \pm 0.014 \pm 0.018$	[57]
L3	Charge sec. vtx	94–95	$1.66 \pm 0.06 \pm 0.03$	[63]
OPAL	$D^{(*)}\ell$	91–93	$1.52 \pm 0.14 \pm 0.09$	[64]
OPAL	Charge sec. vtx	93–95	$1.643 \pm 0.037 \pm 0.025$	[65]
SLD	Charge sec. vtx ℓ	93–95	$1.61^{+0.13}_{-0.12} \pm 0.07$	[67] [b]
SLD	Charge sec. vtx	93–95	$1.67 \pm 0.07 \pm 0.06$	[67] [b]
CDF1	$D^{(*)}\ell$	92–95	$1.637 \pm 0.058^{+0.045}_{-0.043}$	[68]
CDF1	Excl. $J/\psi K$	92–95	$1.636 \pm 0.058 \pm 0.025$	[69]
CDF2	Excl. $J/\psi K$	02–09	$1.639 \pm 0.009 \pm 0.009$	[70]
CDF2	Excl. $D^0\pi$	02–06	$1.663 \pm 0.023 \pm 0.015$	[84]
BABAR	Exclusive	99–00	$1.673 \pm 0.032 \pm 0.023$	[74]
Belle	Exclusive	00–03	$1.635 \pm 0.011 \pm 0.011$	[79]
LHCb	Excl. $J/\psi K$	2011	$1.637 \pm 0.004 \pm 0.003$	[82]
Average			1.638 ± 0.004	

[a] The combined DELPHI result quoted in [61] is 1.70 ± 0.09 ps.
[b] The combined SLD result quoted in [67] is $1.66 \pm 0.06 \pm 0.05$ ps.

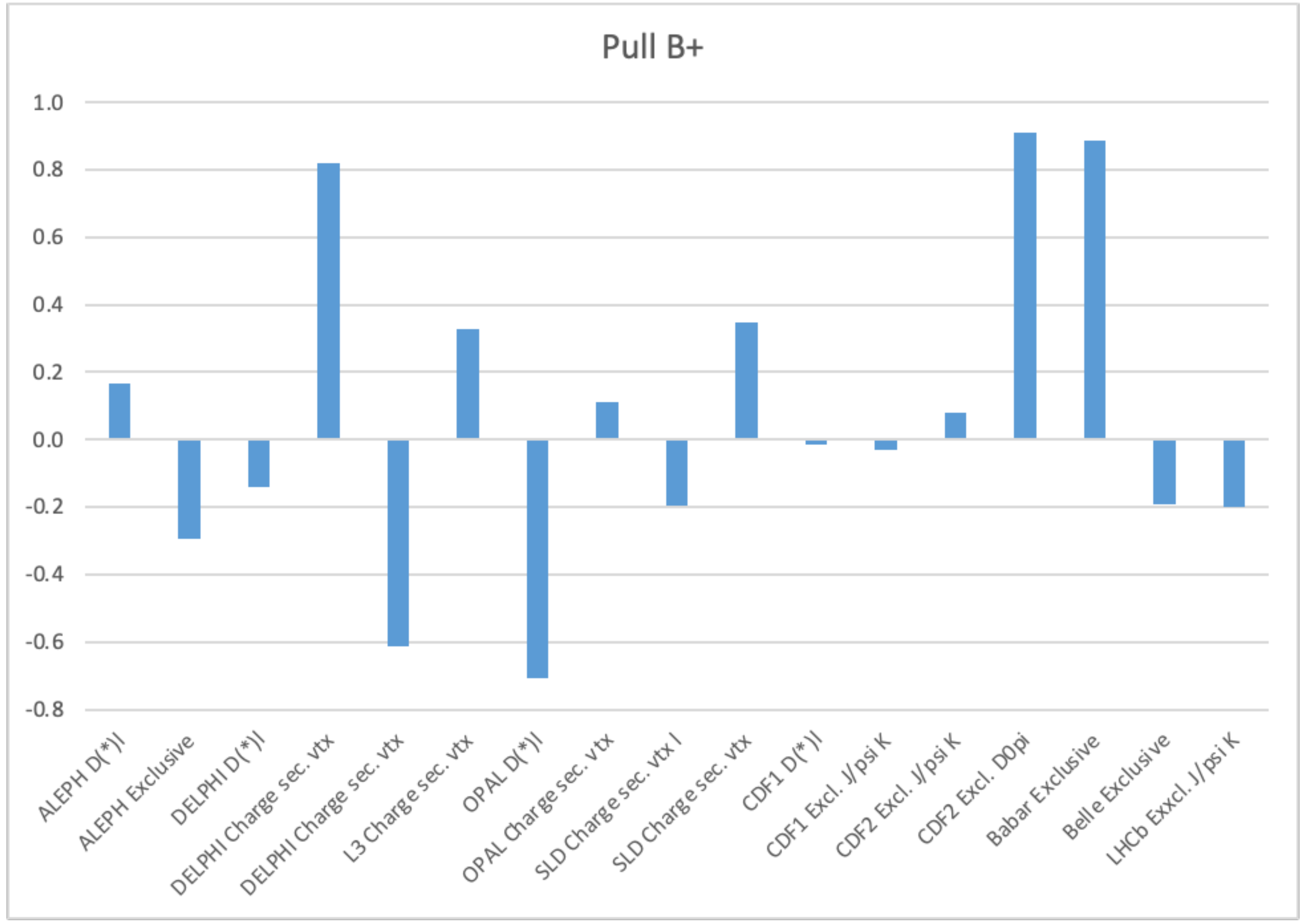
B^0 and B^+ lifetimes / pulls

B^0



χ^2/ndf = 0.72

B^+



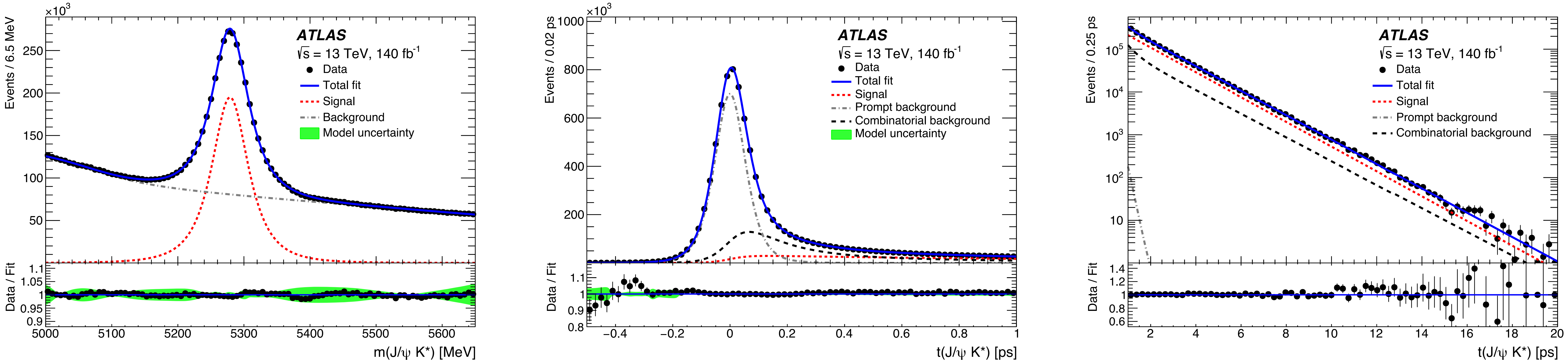
χ^2/ndf = 0.22

Talk by M. Smizanska yesterday

Results: The B^0 effective lifetime and the mass and time projections of the likelihood fit

The B^0 effective lifetime value measured with a total of $2\,450\,500 \pm 2400$ $B^0 \to J/\psi K^{*0}$ signal events The measured effective lifetime is

$$\tau = 1.5053 \pm 0.0012\ (\text{stat.}) \pm 0.0035\ (\text{syst.})\ \text{ps}.$$



- Mass fit projection (left). Proper decay time fit projections in two different ranges: $(-0.5; 1.0)$ ps (Middle) and $(1; 20)$ ps (Right).
- Solid blue line - total fit, dashed red line - signal.
- The lower panels: ratio of data point to the fit value. The green band - the envelope of model variations included in the systematic uncertainty, the bars on the data points indicate statistical uncertainties. Plot -right - the model variation band too small to be visible.

Lowers $\tau(B^0)$ WA to ~(1.512 +/- 0.003) ps

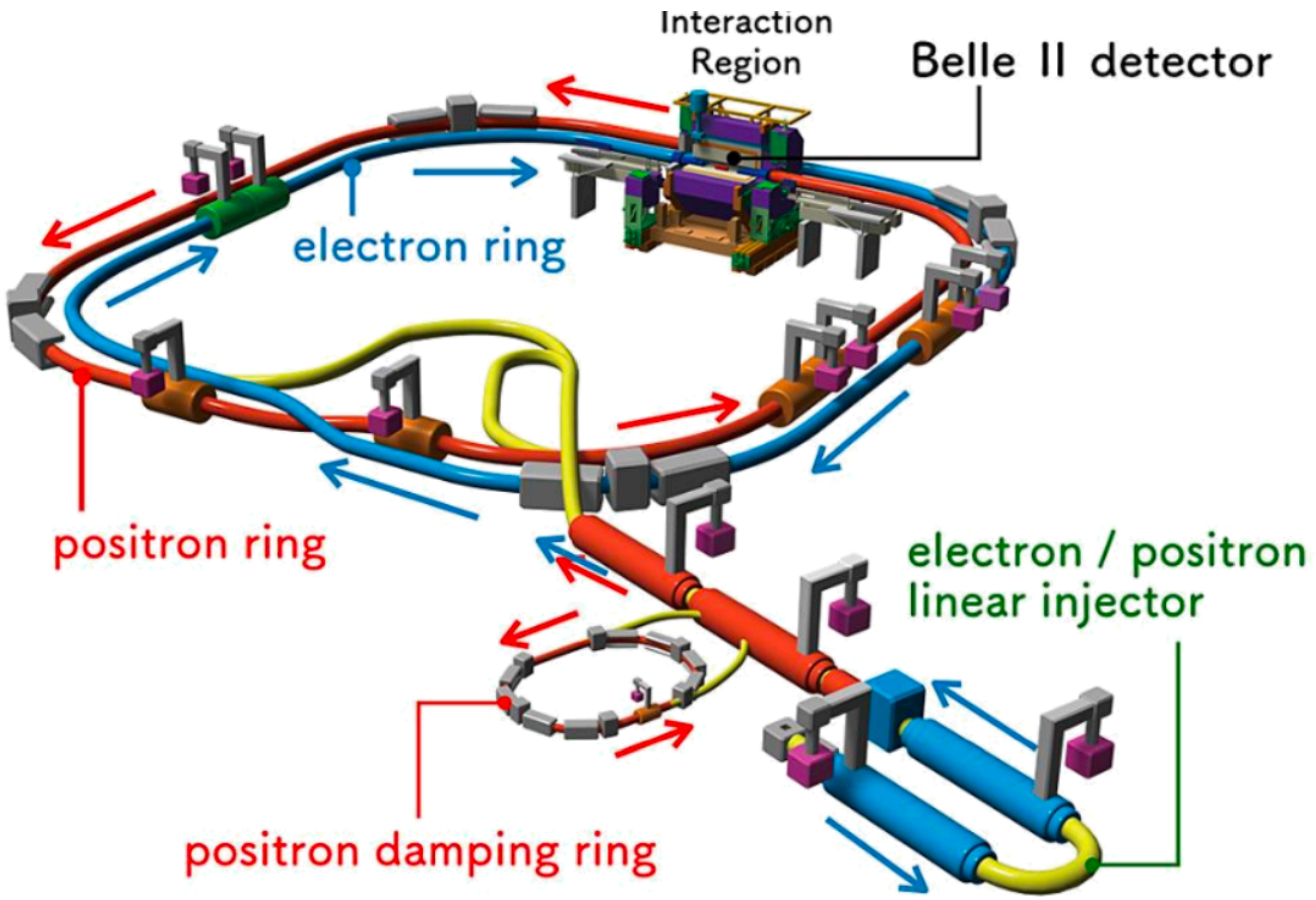
Summary

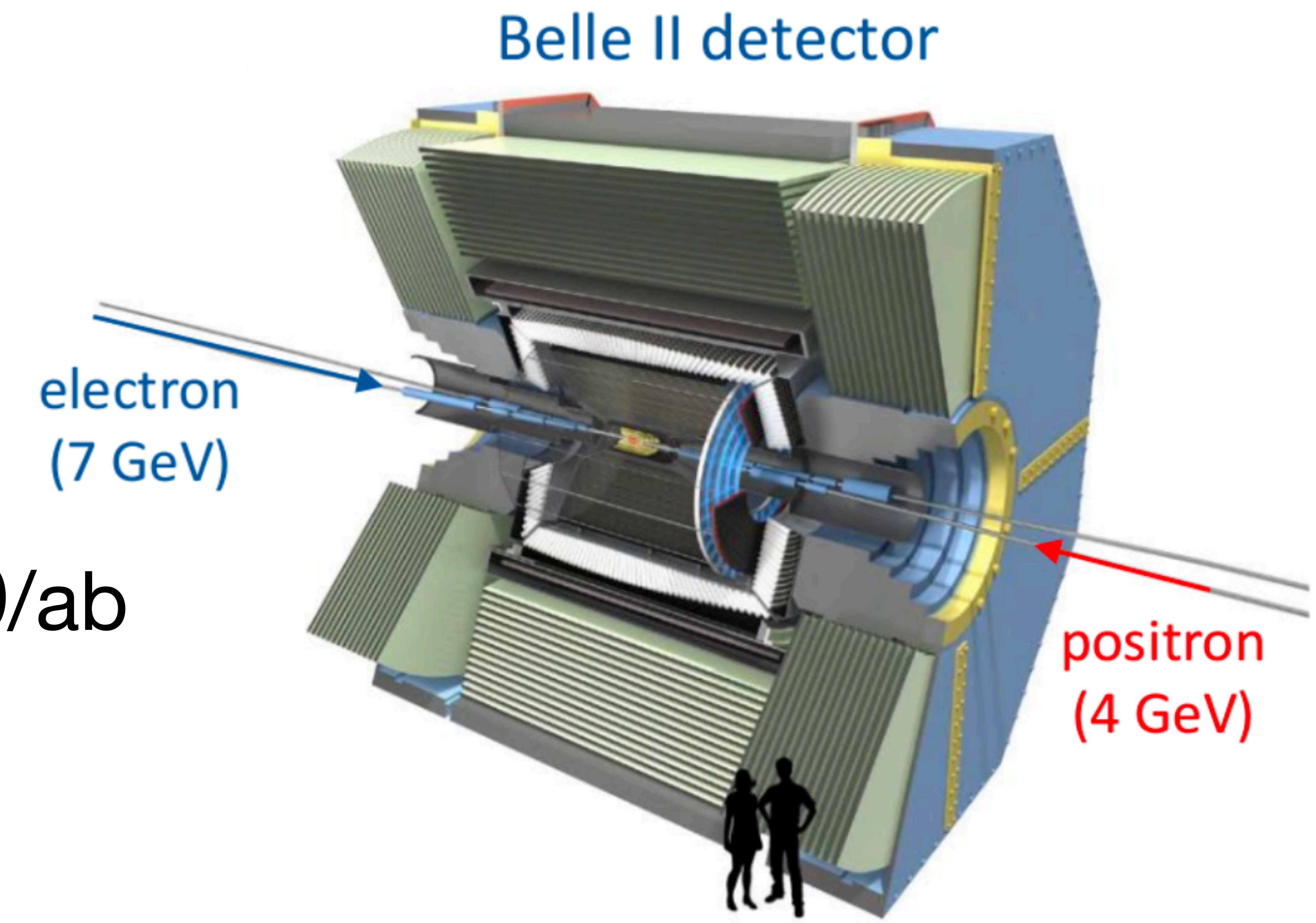
- The OPE is a robust tool to determine $|V_{cb}|$ from inclusive decays $B \to X_c \ell \nu$
- q^2 moments/calculations exploiting reparametrization invariance have allowed to add the order $1/m_b^4$ to the analysis
  - Belle, Phys. Rev. D 104, 112011 (2021)
  - Belle II, Phys. Rev. D 107, 072002 (2023)
- However, numerically these new analyses have confirmed the results of the $1/m_b^3$ analyses and the $|V_{cb}|$ anomaly is still with us
- Imho the problem lies with the semileptonic branching fraction and an updated analysis is on the way

Backup

Belle II @ SuperKEKB

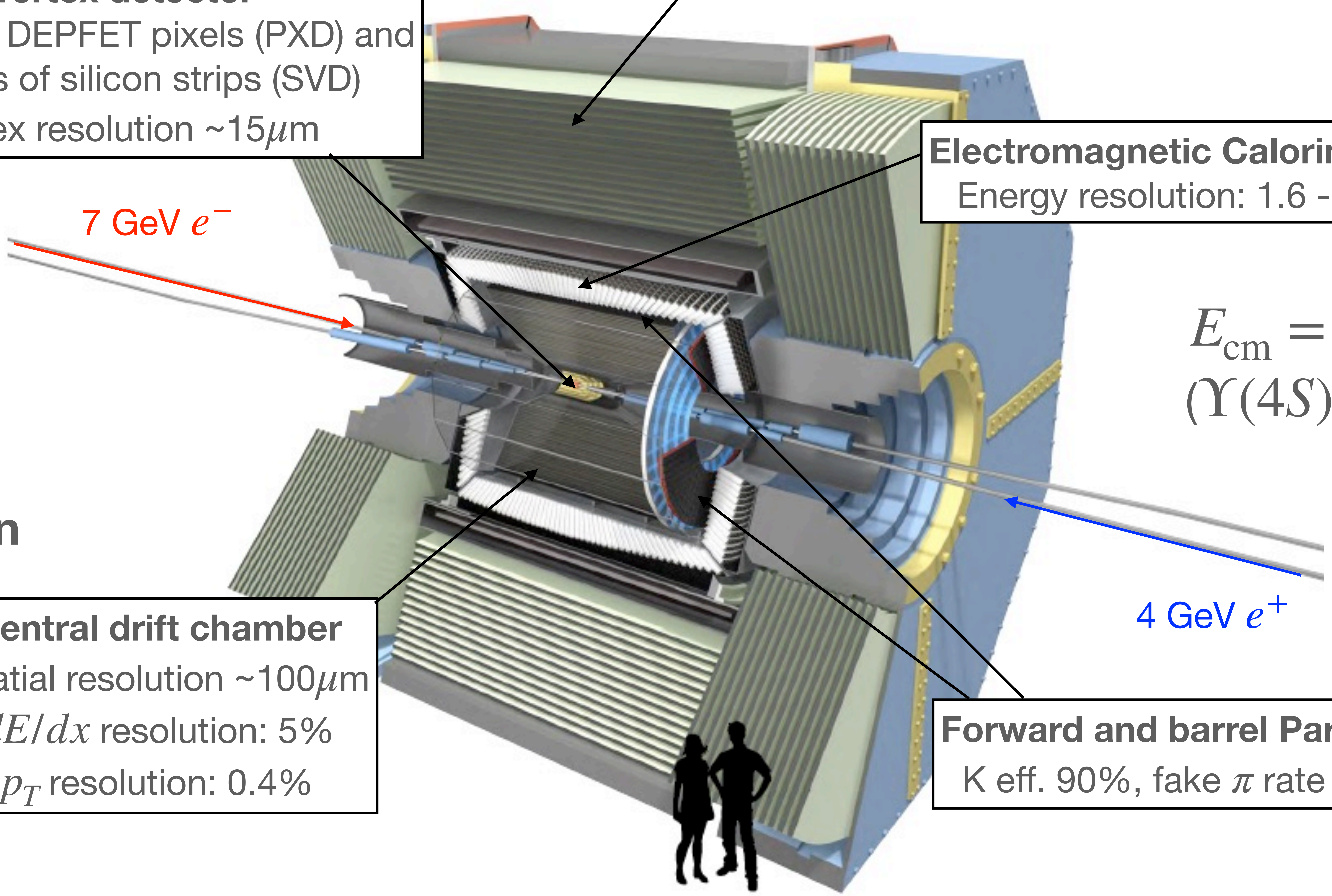
- Luminosity frontier experiment to search for Physics beyond the Standard Model
  - e^+e^- asymmetric collision at the $\Upsilon(4S)$
  - High current / nano-beams, challenging background conditions
- Luminosity targets to achieve physics goals:
  - $\mathscr{L} = 6 \times 10^{35}$ cm^{-2} s^{-1}, $\int \mathscr{L} dt = 50$/ab





The Belle II detector

KEK
Tsukuba, Japan



KLM
Instrumented flux return

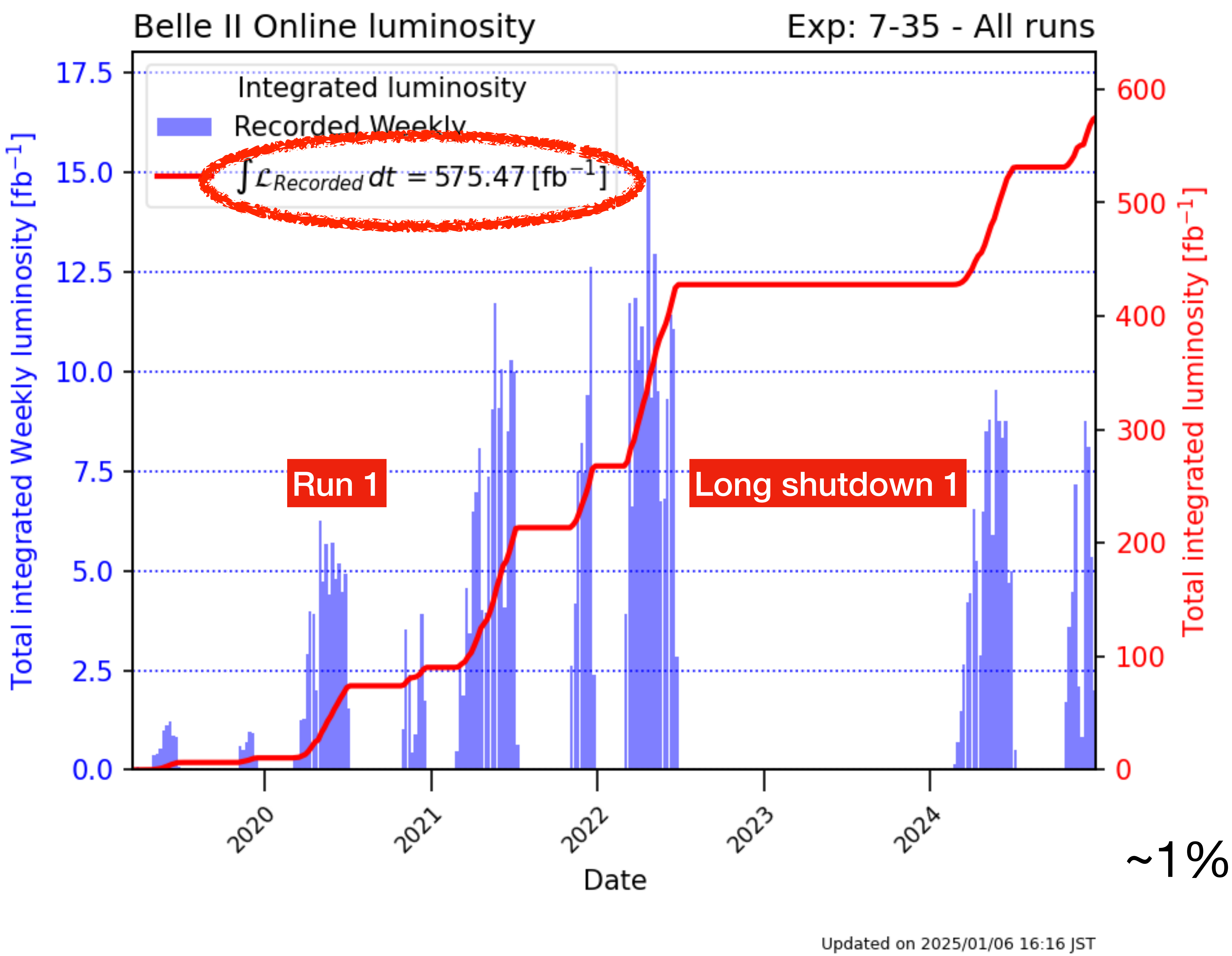
Vertex detector
2 layers of DEPFET pixels (PXD) and
4 layers of silicon strips (SVD)
Vertex resolution ~15μm

Electromagnetic Calorimeter
Energy resolution: 1.6 - 4%

Central drift chamber
Spatial resolution ~100μm
dE/dx resolution: 5%
p_T resolution: 0.4%

Forward and barrel Part. Id.
K eff. 90%, fake π rate 5%

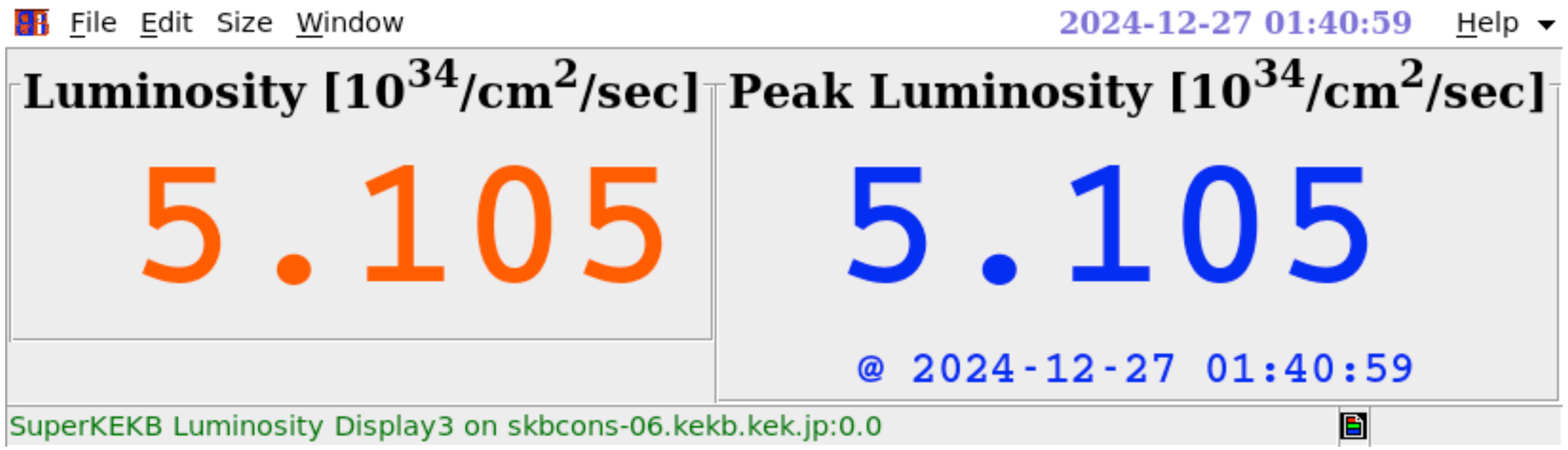
$E_{\text{cm}} = 10.58$ GeV
($\Upsilon(4S)$ resonance)



~1% of 50/ab target

New luminosity record

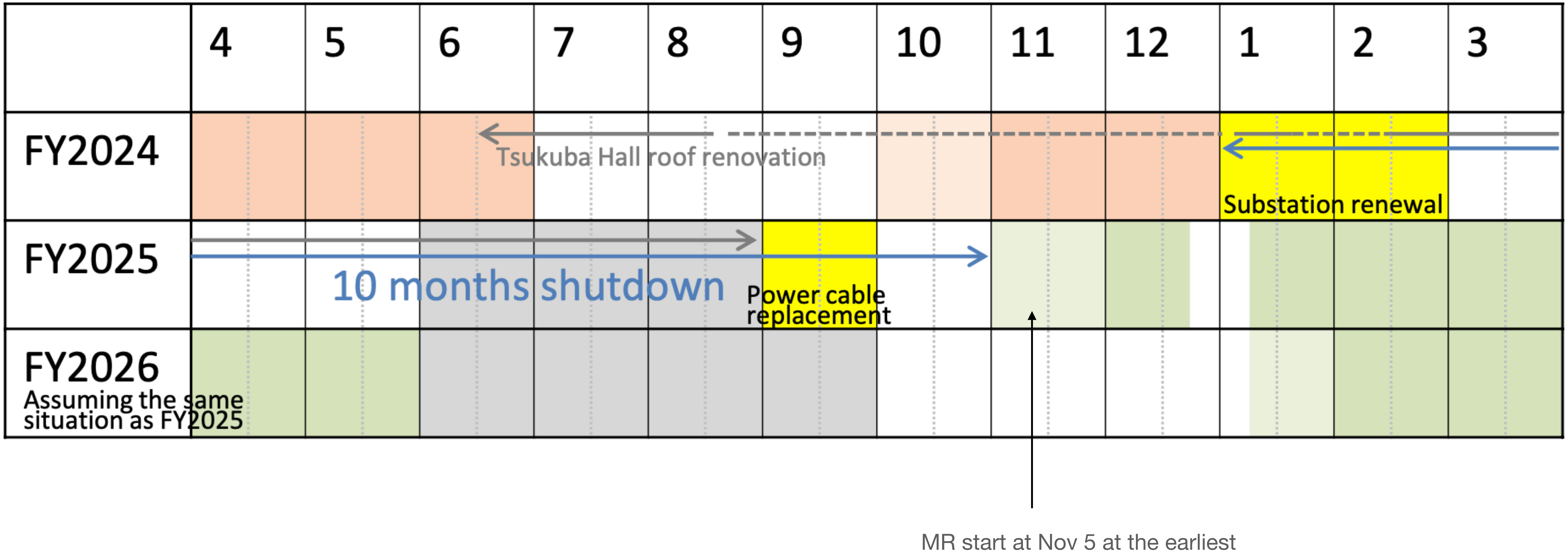
Dec 27, 2024



2025c operation schedule

[Baseline]

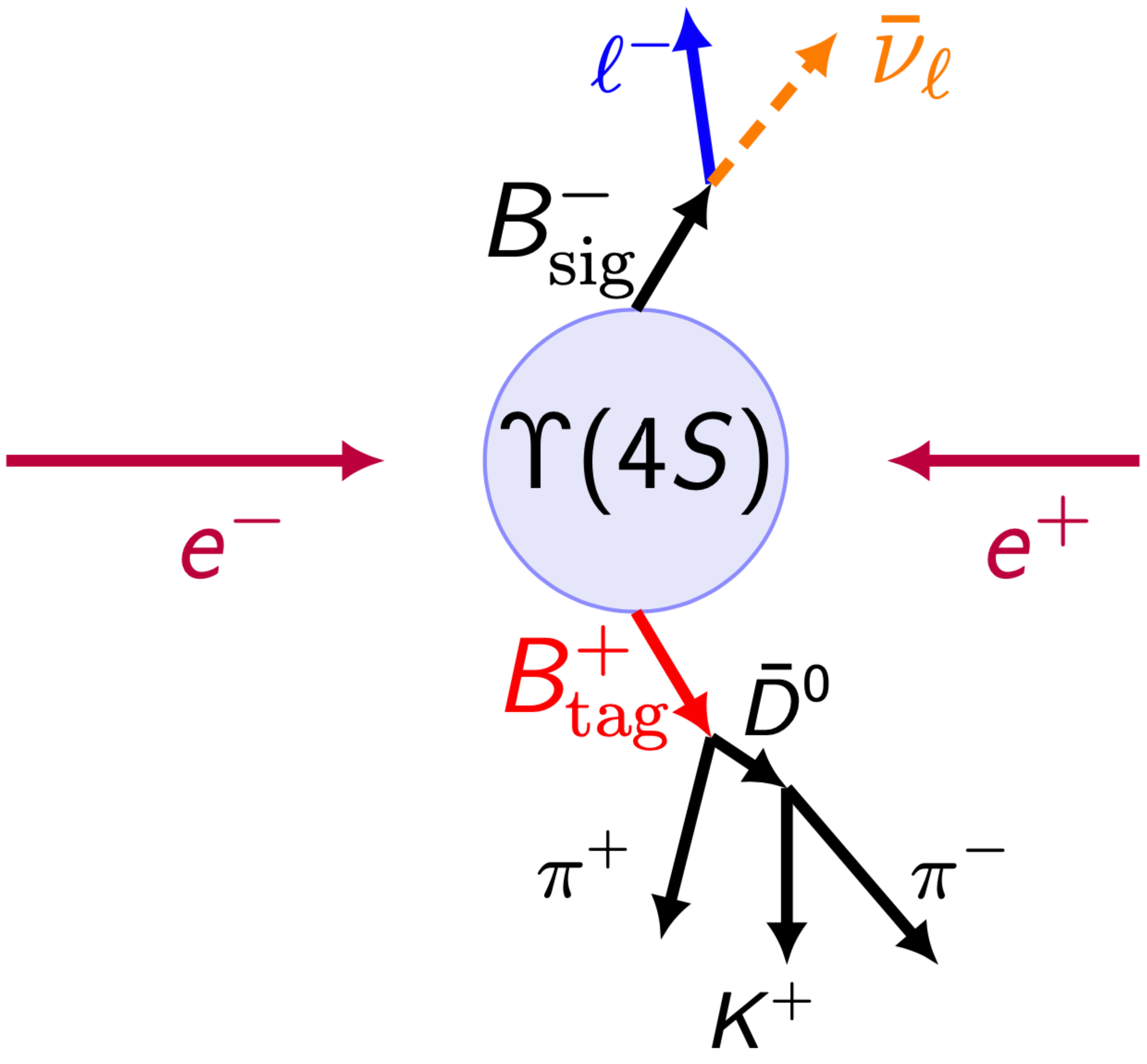
Faint colors for the machine start-up time



Tagging in $\Upsilon(4S)$ events

Untagged:
only B_{sig} is reconstructed

high signal yield (+)
high backgrounds (-)
poor neutrino reconstruction (-)

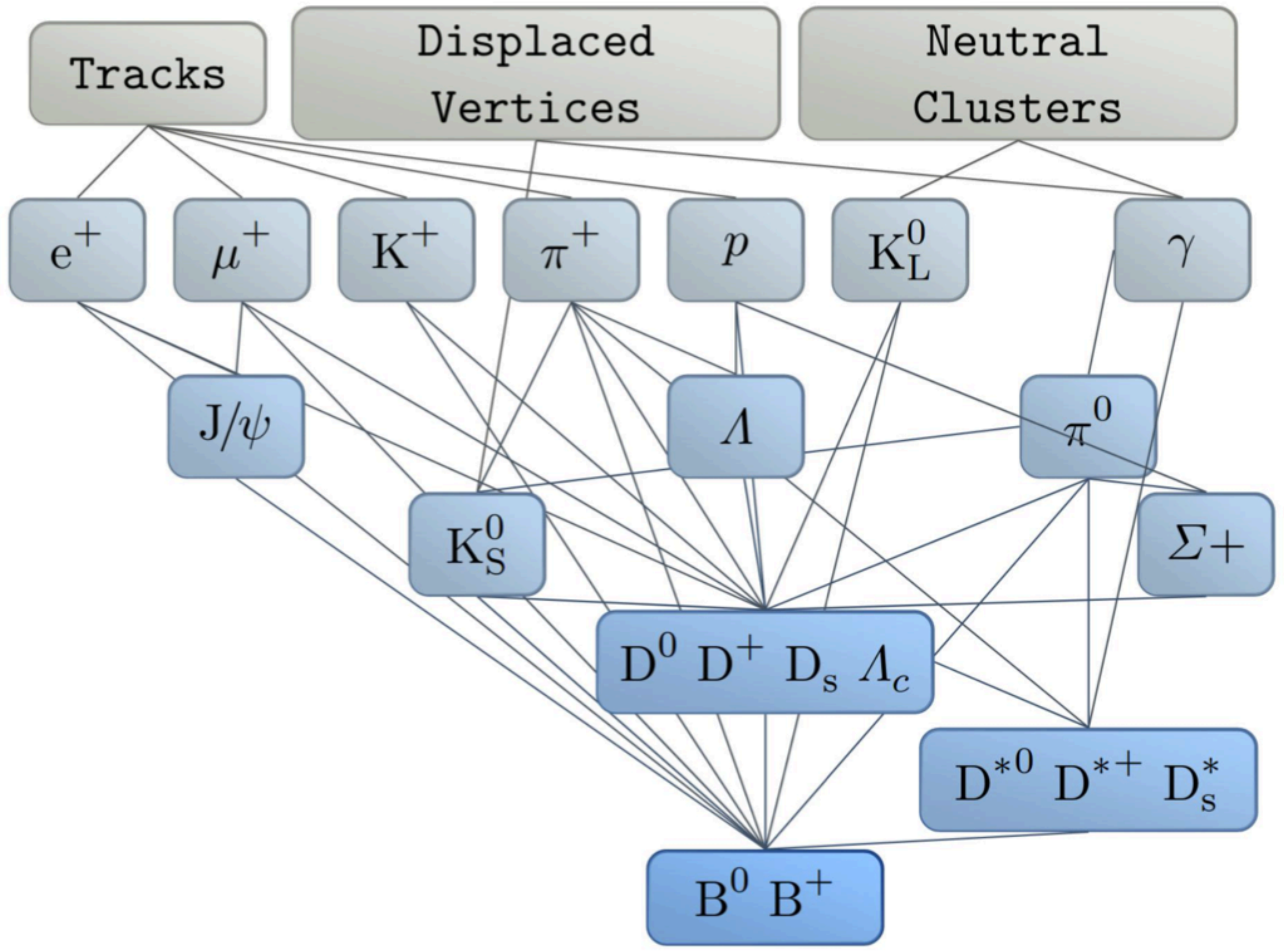


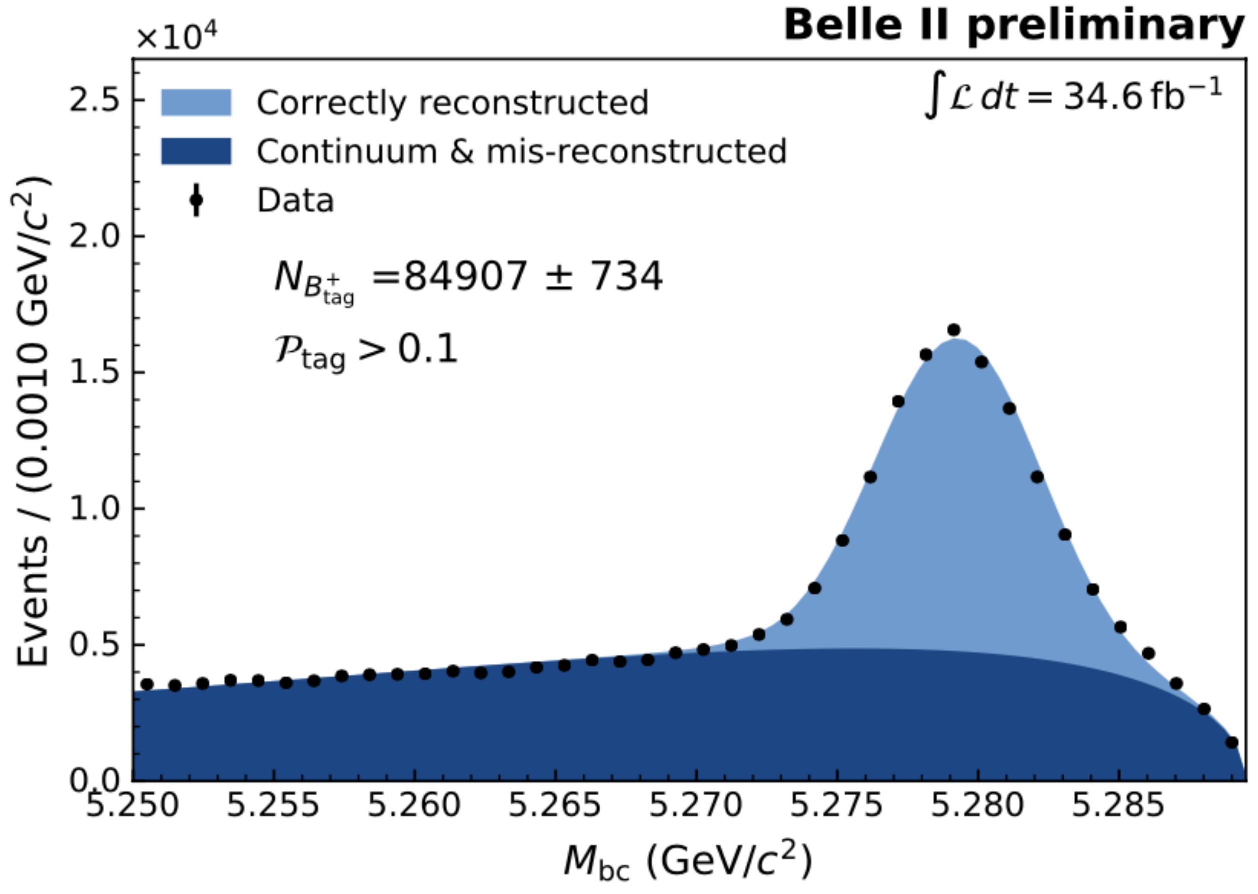
Tagged:
B_{sig} and B_{tag} are reconstructed

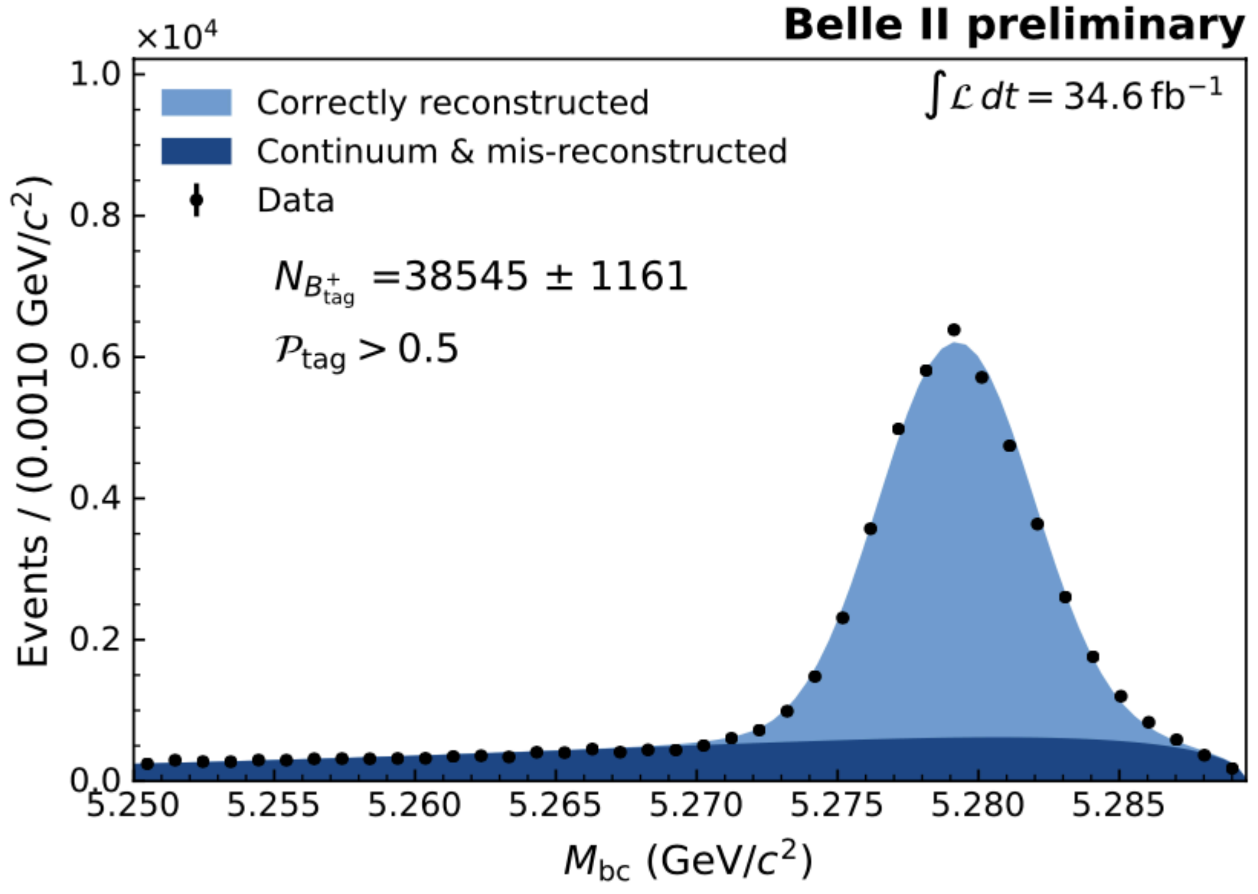
signal yield $O(10^3)$ lower (-)
low backgrounds (+)
good neutrino reconstruction (+)
tag calibration (-)

Hadronic tagging at Belle II

Comput Softw Big Sci (2019) 3: 6.







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

- 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 (about 50% increase with respect to the Belle tag)