Measurement of $B^0 \to \pi^- \ell^+ \nu_\ell$ in untagged events and determination of $|V_{ub}|$ at Belle

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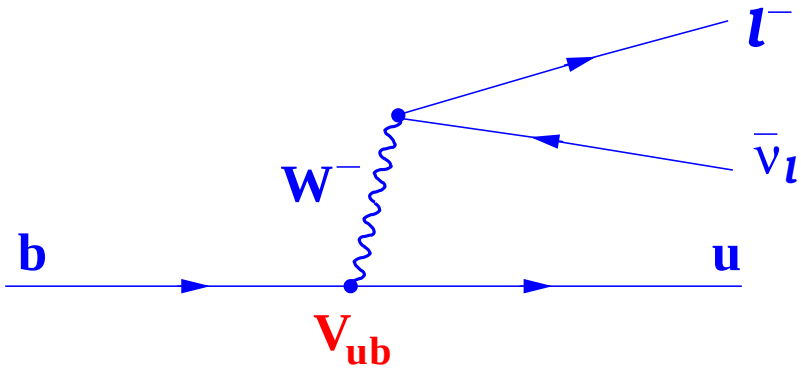
The transition $b \to u\ell\nu$ gives information on $|V_{ub}|$

Tree level and simple



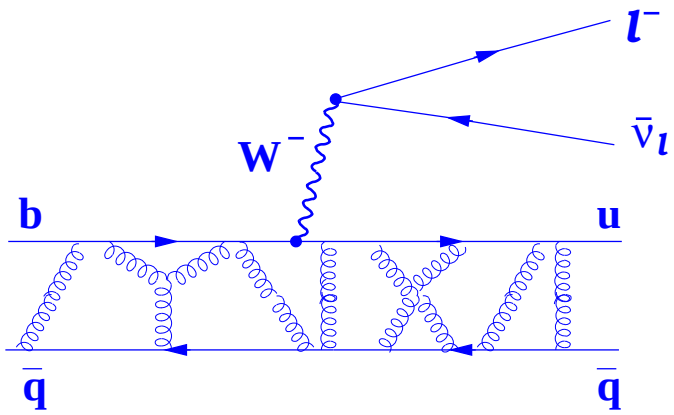
The B-factories are an abundant source of B mesons

$$e^+ + e^- \to \Upsilon(4S) \to B + \overline{B}$$

An example decay involving this transition is

$$\overline{B^0} \to \pi^+ \ell^- \overline{\nu}_\ell \qquad \ell = e, \mu$$

Strong interaction effects introduce complications and a form factor



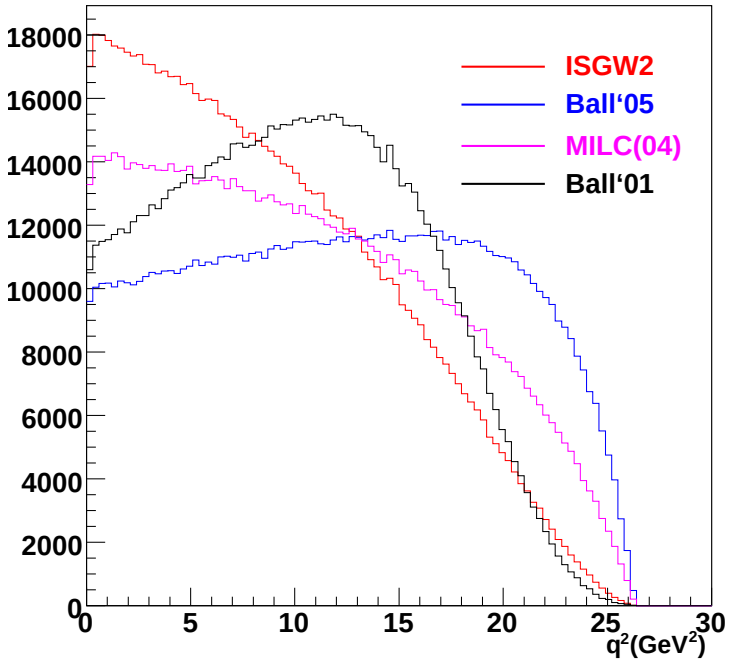
- Differential Branching Fraction:

$$\frac{d\Gamma(B \to \pi l \nu)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{192\pi^3 m_B^3} \lambda(q^2)^{3/2} |f_+^\pi(q^2)|^2$$

$$\lambda(q^2) = (q^2 + m_B^2 - m_\pi^2)^2 - 4 m_B^2 m_\pi^2$$

$$q^2 = (p_l + p_\nu)^2 = (p_B - p_\pi)^2$$

There are various $f_+^\pi(q^2)$ predictions



Lattice predicts at high $q^2 >\sim 16\ \mathrm{GeV}^2$

A loose (untagged) neutrino reconstruction is used

- Single charged pion and lepton (opposite charge) coming from Interaction Point
- Find missing 3-momentum

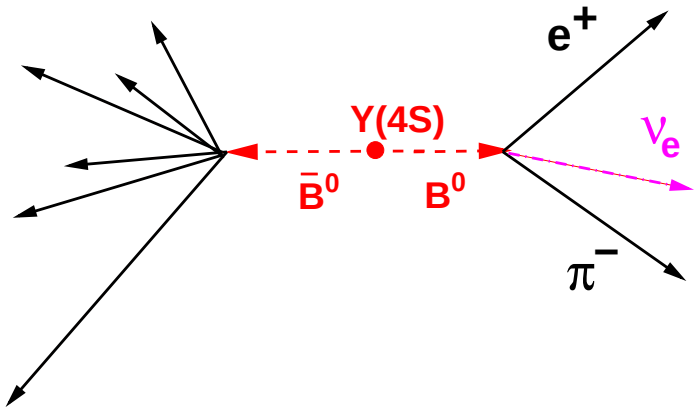
$$\vec{p}_{miss} \equiv -\sum_i \vec{p}_i$$

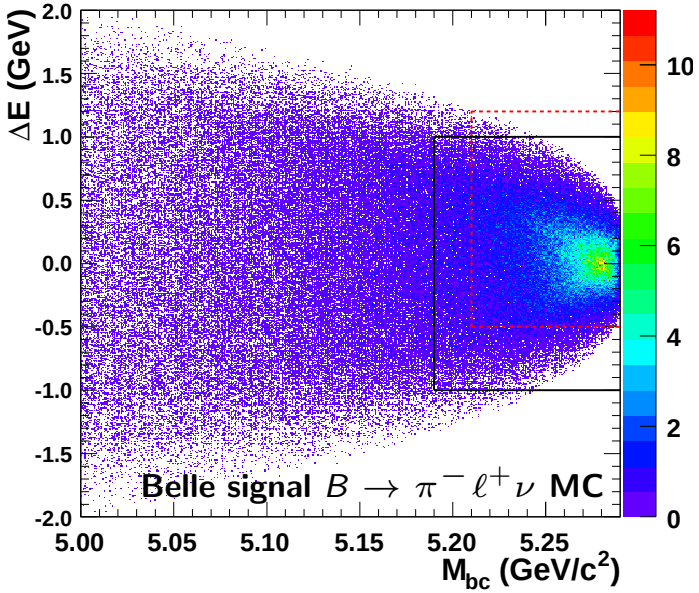
- Set neutrino 4-vector to be

$$p_\nu = (\,|\vec{p}_{miss}|,\ \vec{p}_{miss}\,)$$

- Select B candidates based on

$$M_{\rm bc} = \sqrt{E^2_{beam} - |\vec{p}_\pi + \vec{p}_l + \vec{p}_\nu|^2}$$
$$\Delta E = E_{beam} - (E_\pi + E_l + E_\nu)$$





Black line $M_{\rm bc} > 5.19\ {\rm GeV}/c^2$

$|\Delta E| < 1\ {\rm GeV}$

Loose criteria lead to high efficiency / backgrounds

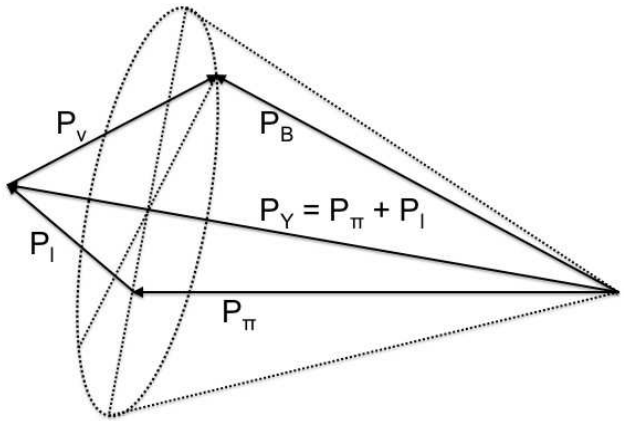
- Principal background sources are
  - $B \to X_u \ell \nu$ feed-down (mostly high q^2)
  - $B \to X_c \ell \nu$ (mostly lower q^2)
  - $e^+e^- \to q\bar{q}$ continuum
- Estimated using Monte Carlo samples
  - Continuum shape estimated from off-resonance data (60 MeV below $\Upsilon(4S)$). Used to reweight MC

Data statistics and q^2 resolution determine binning

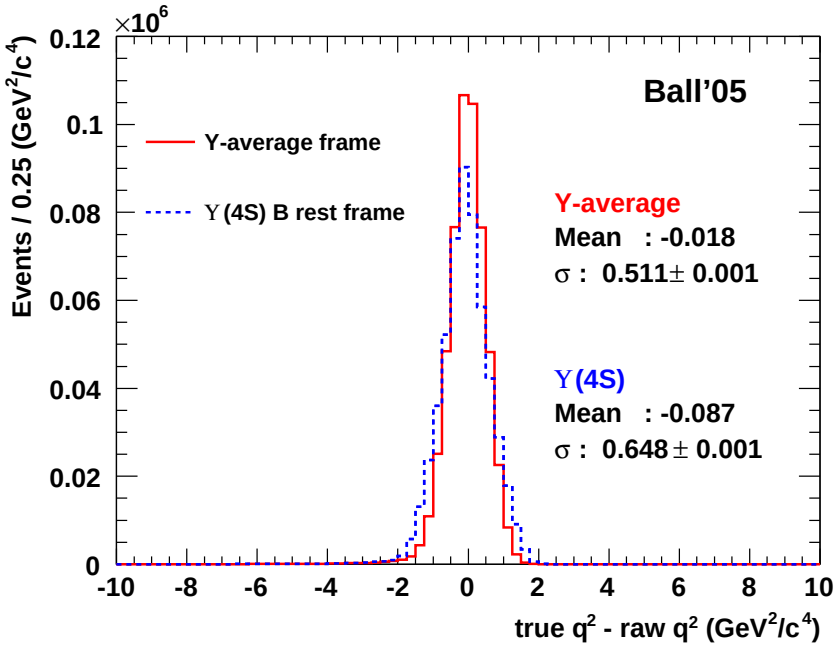
- q^2 is obtained from 4-vectors of pion and reconstructed B

$$q^2 = (p_B - p_\pi)^2$$

- Ambiguity in B direction accounted for using weighted average over cone



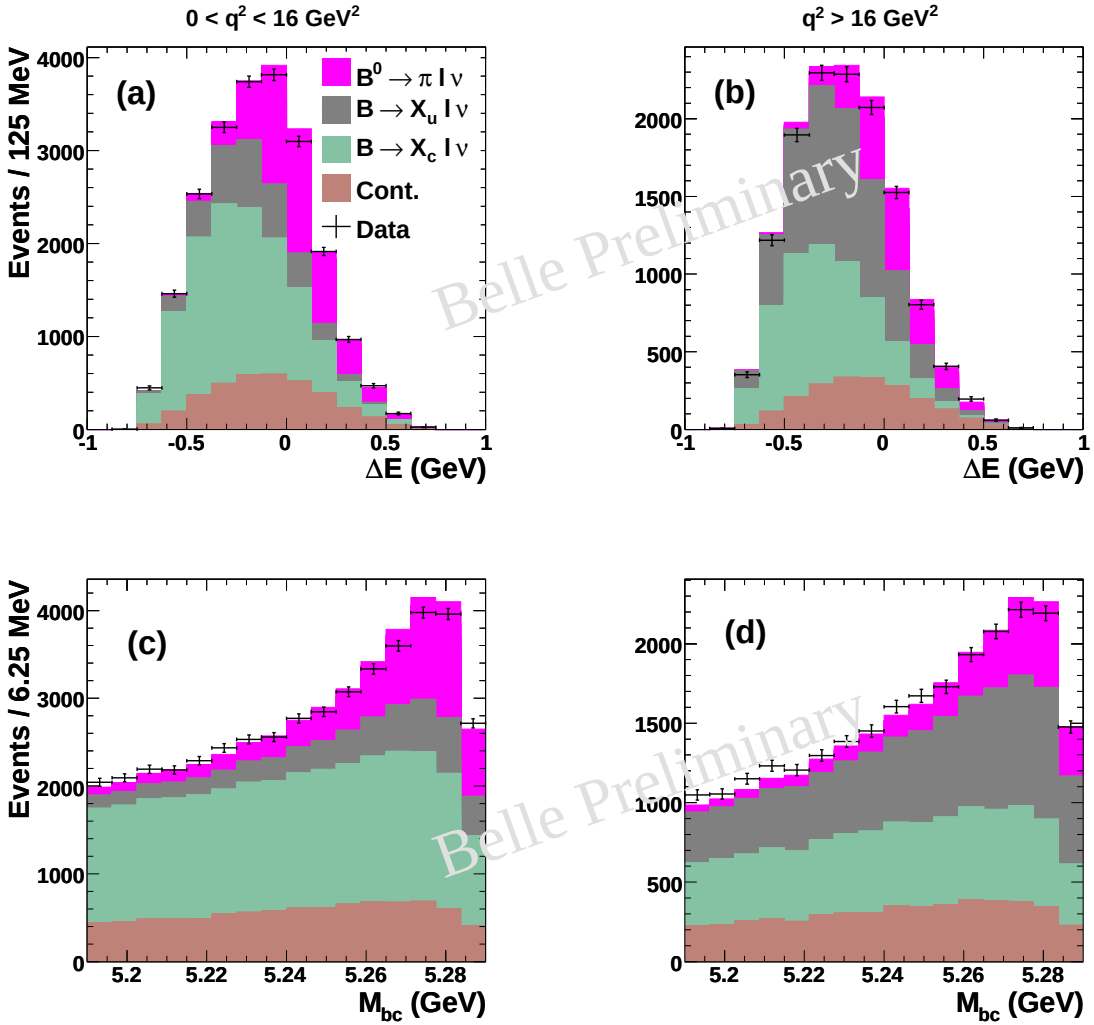
Belle signal $B \to \pi^- \ell^+ \nu$ MC



$$\sigma_{q^2} \sim 0.5 \text{ GeV}^2/c^2$$

A simultaneous fit to $(M_{\rm bc}, \Delta E)$ in q^2 bins is made

- Belle data sample is 605 fb^{-1}
- q^2 bins for fit:
  - 13 for $\pi\ell\nu$
  - 3 for $X_u\ell\nu$
  - 4 for $X_c\ell\nu$
  - Continuum fixed
- Fit projections:
  $M_{\rm bc} > 5.27$ GeV for ΔE
  $|\Delta E| < 0.125$ GeV for $M_{\rm bc}$



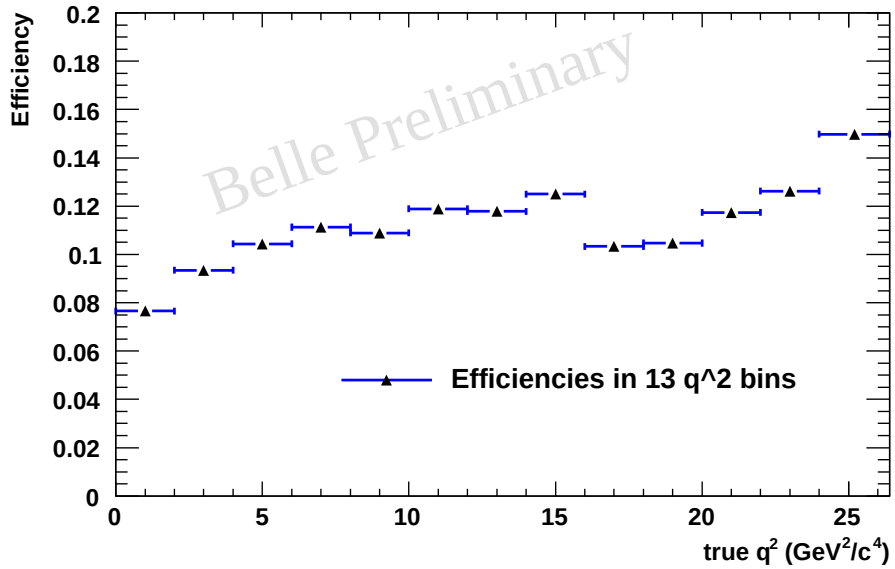
From the fitted yields the partial branching fractions can be obtained

In 13 bins i of q^2

$$\Delta\mathcal{B}_i = \frac{\sum_j (D^{-1})_{ij} Y_j}{0.5 \times 2 \times 2 \times n_{B\bar{B}} \times \epsilon_i}$$

Here

- D is detector response matrix
- Y_i is yield in given bin
- ϵ_i is efficiency in given bin
- $n_{B\bar{B}}$ is number of $B\bar{B}$ pairs



The Total BF is the sum over partial BFs

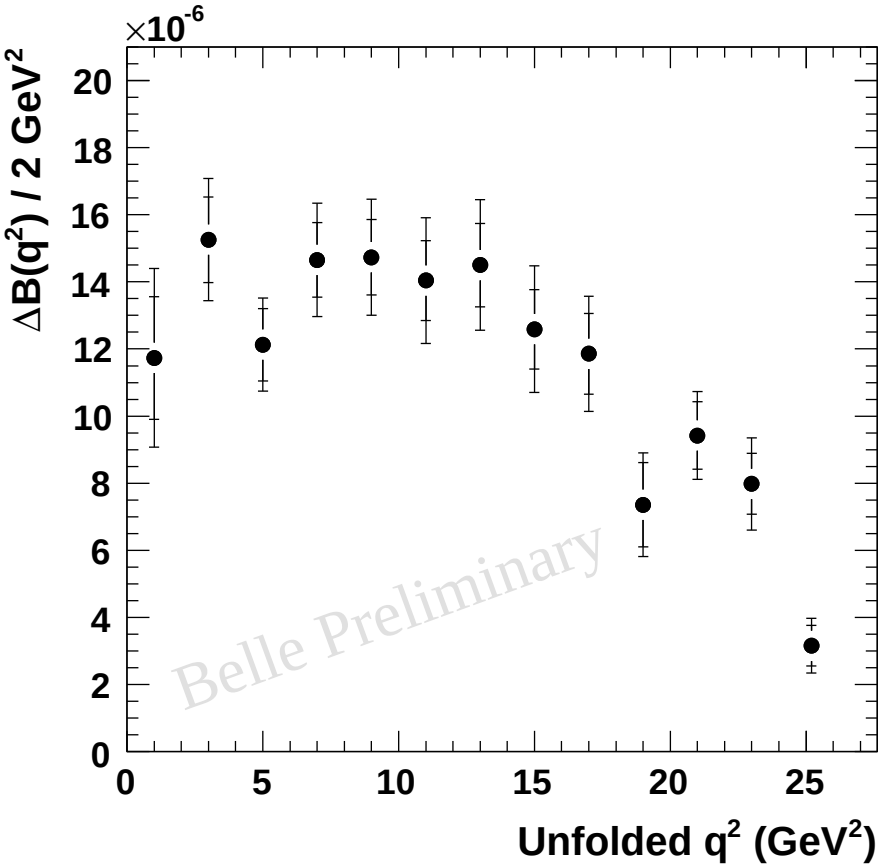
605 fb^{-1}

- Sum is over the 13 q^2 bins

$$\mathcal{B} = \sum_{i=1}^{13} \Delta\mathcal{B}_i$$

- The uncertainty is obtained using the covariance matrix V from the unfolding procedure

$$\sigma^2_{\mathcal{B}} = \sum_{i,j=1}^{13} \sigma_{\Delta\mathcal{B}_i} V_{ij} \; \sigma_{\Delta\mathcal{B}_j}$$



$$\mathcal{B} = (1.49 \pm 0.04_{\rm stat} \pm 0.07_{\rm syst}) \times 10^{-4}$$

The Systematics are summarised in two q^2 regions

$q^2(\mathrm{GeV}^2/c^4)$	0 - 16	16 - 26.4	Total
$\Delta\mathcal{B}$ ($\times 10^7$)	1096	398	1494
Lepton ID	2.40	2.49	2.44
Pion ID	1.37	1.08	1.26
Tracking efficiency	2.00	2.09	2.04
γ efficiency	0.37	0.51	0.42
Detector effects	3.43	3.46	3.44
Continuum Correction	2.14	2.62	1.80
$\Upsilon(4S) \to B^0\bar{B}^0$ BF	1.56	1.72	1.40
Signal MC stat. error	0.12	0.39	0.15
FSR	0.45	0.60	0.37
B counting	1.36	1.36	1.36
Other sources	2.12	2.30	1.99

All uncertainties expressed as (%)

$q^2(\mathrm{GeV}^2/c^4)$	0 - 16	16 - 26.4	Total
$\Delta\mathcal{B}$ ($\times 10^7$)	1096	398	1494
$B \to \rho\ell\nu$ BF	0.44	0.42	0.43
$B \to \omega\ell\nu$ BF	0.11	0.31	0.16
$B \to b_1\ell\nu$ BF	0.14	0.14	0.14
V_{ub} + other $X_u\ell\nu$ BF	0.19	0.15	0.15
$B \to D^*\ell\nu$ BF	0.18	0.13	0.16
$B \to D\ell\nu$ BF	0.07	0.14	0.08
$B \to D^{**}\ell\nu$ BF	0.11	0.22	0.13
Other $X_c\ell\nu$ BF	0.06	0.13	0.06
Physics parameters (BF)	0.56	0.64	0.55
$B^0 \to \pi^-\ell^+\nu$ FF	0.63	0.86	0.53
$B^0 \to \rho^-\ell^+\nu$ FF	0.72	0.95	0.60
SF parameter	0.71	1.17	0.63
$B^0 \to D^{*-}\ell^+\nu$ FF	0.48	0.34	0.36
$B^0 \to D^-\ell^+\nu$ FF	0.10	0.08	0.08
Physics parameters (FF)	1.28	1.77	1.07
Total systematic error	4.78	5.26	4.53
Total statistical error	3.03	5.31	2.63
Total Error	5.66	7.47	5.23

The systematic uncertainties make the larger overall contribution

Partial BFs give product of $|V_{ub}|$ and form factor

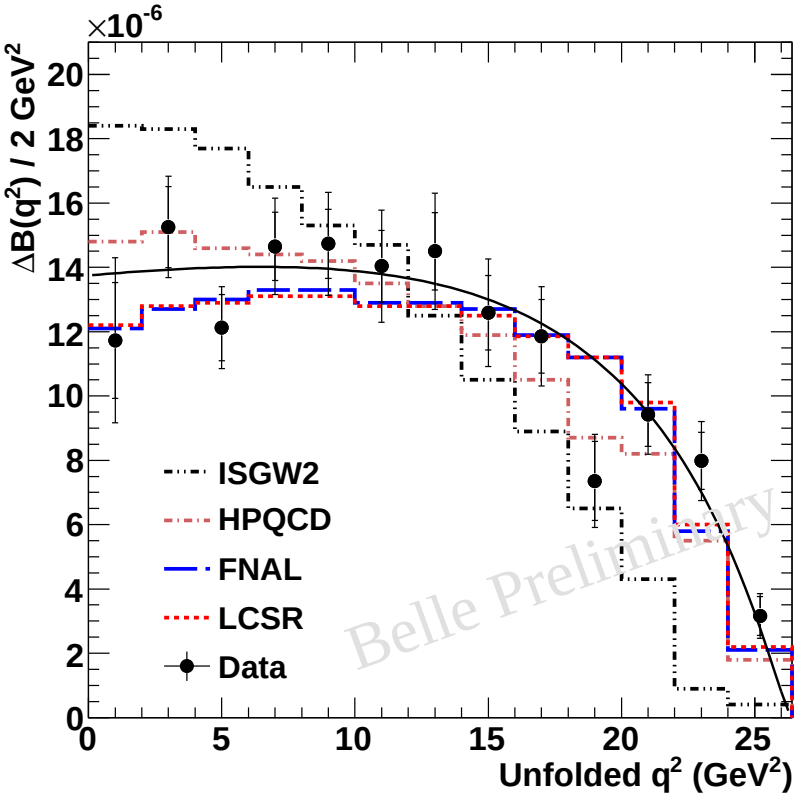
BK parameterization is performed for comparison with other results

$\|V_{ub}f_+(0)\|$	$(9.24 \pm 0.18(stat) \pm 0.20(syst) \pm 0.07(\tau_{B^0})) \times 10^{-4}$
α	$0.60 \pm 0.03(stat) \pm 0.02(syst) \pm 0.01(\tau_{B^0})$
Prob.	62 %

Fits to q^2 distribution of BF

Model	χ^2 probability
HPQCD	42%
FNAL	43%
LCSR	49%
ISGW2	0%

ISGW2 disfavoured



By assuming a model $|V_{ub}|$ can be extracted

- Assuming a form factor model, $|V_{ub}|$ can be extracted from the partial BF

$$|V_{ub}| = \sqrt{\Delta\mathcal{B}(q^2)/(\tau_{B^0}\Delta\zeta)}$$

$\Delta\zeta$: integral of form factor prediction over relevant q^2 range
$\tau_{B^0} = 1.530 \pm 0.009$ ps

- Results for different models

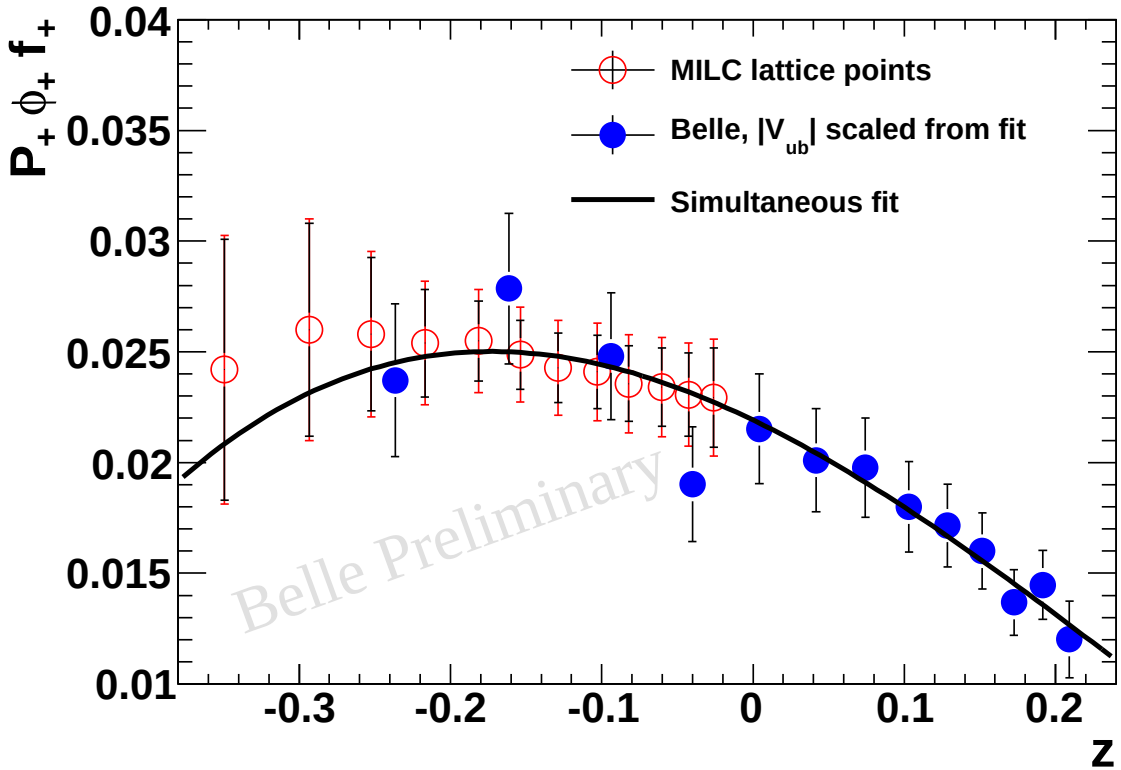
	q^2 (GeV^2)	$\Delta\zeta$ (ps^{-1})	$\lvert V_{ub}\rvert(10^{-3})$
HPQCD	> 16	2.07 ± 0.57	$3.55 \pm 0.09 \pm 0.09\ ^{+0.62}_{-0.41}$
FNAL	> 16	1.83 ± 0.50	$3.78 \pm 0.10 \pm 0.10\ ^{+0.65}_{-0.43}$
LCSR	< 16	5.44 ± 1.43	$3.64 \pm 0.06 \pm 0.09\ ^{+0.60}_{-0.40}$
ISGW2	all	9.6 ± 4.8	$3.19 \pm 0.04 \pm 0.07\ ^{+1.32}_{-0.59}$

- Form factor uncertainties dominate

$|V_{ub}|$ can also be obtained from a fit to Belle data and lattice prediction - model independent

Recent method employed in PRD **79** 054507 (2009) (MILC)

- $z = z(q^2)$
- Lattice points:
  $f_+(q^2)$
- Experiment:
  $|V_{ub}| \times f_+(q^2)$
- Simultaneous fit $\Rightarrow |V_{ub}|$



Result:

$$|V_{ub}| = (3.43 \pm 0.33) \times 10^{-3} \quad (\textit{Error stat. and syst. combined})$$

Summary

- Belle has a new preliminary branching fraction for $B^0 \to \pi^- \ell^+ \overline{\nu}_\ell$

$$\mathcal{B} = (1.49 \pm 0.04_{\rm stat} \pm 0.07_{\rm syst}) \times 10^{-4}$$

- Partial BFs are extracted in 13 bins of q^2

- $|V_{ub}|$ is extracted by two methods

  - In a model dependent way e.g. using LCSR

$$|V_{ub}| = \left(3.64 \pm 0.06_{stat} \pm 0.09_{syst} {}^{+0.60}_{-0.40\,FF}\right) \times 10^{-3}$$

  - In a model independent way combining Belle and MILC data

$$|V_{ub}| = (3.43 \pm 0.33_{stat+syst}) \times 10^{-3}$$

c.f. BaBar+MILC $|V_{ub}| = (2.95 \pm 0.31) \times 10^{-3}$ arXiv:1005.3288v1 [hep-ex]

Backup slides

Analysis selections in slightly more detail

- Signal track selection:
  - lepton ℓ is e or μ
  - pion has K veto applied
  - tracks originate from near IP
    $|dr| < 2.0$ cm, $|dz| < 4.0$ cm
  - π, ℓ vertex fit prob. > 0.01
- Event selections:
  - Event charge $|Q_{tot}| \leq 3$
  - $|\cos\theta_{BY}| < 1$ $(Y = \pi + \ell)$
  - Suppress continuum, $R_2 < 0.35$
  - Tighten lept. mom. selection
    $p_e^{lab} > 0.8$ GeV, $p_\mu^{lab} > 1.1$ GeV.
  - Veto $J/\psi \to \mu\mu$
    $3.075 < m_Y < 3.125$ GeV/c^2
  - Treat final state radiation
    (for $\ell = e$)
- q^2 dependent cuts on:
  - $\cos\theta_{thrust}$
  - $\cos\theta_\ell$
  - θ_{miss}
  - M^2_{miss}
- For multiple B candidates:
  - take one with smallest
    $|\cos\theta_\ell|$

Yields, Efficiencies and $\Delta\mathcal{B}$

$q^2(\mathrm{GeV}^2/c^4)$	Raw	Err(%)	Unfolded	Err(%)	$\Delta\mathcal{B}(\times 10^7)$	Err (%)
0-2	1225.8	12.4	1179.9	15.3	117.3	15.3
2-4	1788.5	6.0	1873.6	8.3	152.6	8.3
4-6	1756.5	5.5	1662.6	8.5	121.3	8.5
6-8	2074.8	5.2	2141.6	7.2	146.5	7.2
8-10	2100.6	5.2	2107.3	7.3	147.3	7.3
10-12	2136.4	6.1	2192.3	7.9	140.4	7.9
12-14	2139.0	6.5	2244.0	8.3	145.0	8.3
14-16	1951.7	7.4	2066.7	9.2	125.9	9.2
16-18	1538.0	8.0	1609.1	9.7	118.6	9.7
18-20	1070.3	12.3	1011.9	16.7	73.6	16.7
20-22	1422.8	8.5	1452.8	10.5	94.2	10.5
22-24	1369.8	8.7	1323.4	11.1	79.8	11.1
24-	912.3	11.3	621.3	19.0	31.6	19.0
Total	21486.5	2.6	21486.5	2.6	1494.1	2.6

Systematic Uncertainties: individual q^2 bins

All uncertainties in %

$q^2(\mathrm{GeV}^2/c^4)$	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10	10 - 12	12 - 14	14 - 16	16 - 18	18 - 20	20 - 22	22 - 24	24 - 26.4
$\Delta\mathcal{B}$ $(\times 10^7)$	117.33	152.58	121.28	146.54	147.32	140.39	145.00	125.90	118.57	73.59	94.21	79.80	31.59
Lepton ID	2.35	2.41	2.39	2.41	2.38	2.38	2.43	2.47	2.47	2.49	2.45	2.44	2.56
Pion ID	1.32	1.37	1.43	1.49	1.41	1.36	1.32	1.24	1.11	0.97	0.85	1.12	1.38
Tracking efficiency	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.01	2.45
γ efficiency	0.21	0.41	0.14	0.25	0.32	0.45	0.94	0.24	0.81	0.80	0.23	0.26	0.49
$B \to \rho\ell\nu$ BF	0.58	0.60	0.59	0.46	0.74	0.60	0.41	0.57	0.48	0.47	0.41	0.41	0.33
$B \to \omega\ell\nu$ BF	0.28	0.16	0.14	0.12	0.13	0.11	0.16	0.08	0.09	0.12	0.30	0.52	1.19
$B \to b_1\ell\nu$ BF	0.30	0.16	0.14	0.12	0.13	0.12	0.13	0.09	0.11	0.12	0.11	0.14	0.59
V_{ub} + other $X_u\ell\nu$ BF	4.43	1.55	0.96	0.87	0.45	0.35	0.45	0.61	0.13	0.13	0.12	0.17	0.77
$B \to D^*\ell\nu$ BF	0.42	0.40	0.15	0.67	0.09	0.12	0.20	0.09	0.16	0.12	0.12	0.14	0.27
$B \to D\ell\nu$ BF	0.27	0.14	0.14	0.12	0.12	0.09	0.07	0.12	0.09	0.14	0.14	0.18	0.61
$B \to D^{**}\ell\nu$ BF	0.20	0.16	0.16	0.14	0.14	0.12	0.11	0.11	0.42	0.15	0.14	0.20	0.11
Other $X_c\ell\nu$ BF	0.13	0.09	0.13	0.09	0.18	0.12	0.13	0.09	0.14	0.14	0.14	0.20	0.12
$B^0 \to \pi^-\ell^+\nu$ FF	3.58	1.64	1.26	1.27	1.44	1.57	1.67	1.70	1.78	1.97	1.61	1.92	4.03
$B^0 \to \rho^-\ell^+\nu$ FF	3.59	1.73	1.51	1.47	1.64	1.82	2.04	1.89	2.01	2.30	1.99	2.50	4.98
SF parameter	1.44	0.63	1.59	1.07	2.10	2.80	2.52	2.42	2.24	4.02	2.12	3.15	4.66
$B^0 \to D^* - \ell^+\nu$ FF	0.51	0.64	0.60	0.89	1.54	1.77	2.51	0.81	1.18	0.56	0.51	0.42	0.98
$B^0 \to D - \ell^+\nu$ FF	0.33	0.09	0.20	0.30	0.24	0.12	0.26	0.20	0.20	0.09	0.16	0.11	0.11
$\Upsilon(4S) \to B^0\bar{B}^0$ BF	2.11	1.39	2.41	3.28	3.68	3.90	3.67	2.76	2.83	4.58	3.62	5.21	2.28
Signal MC stat. error	0.48	0.15	0.23	0.27	0.30	0.24	0.28	0.28	0.38	0.52	0.58	0.74	1.97
FSR	0.31	0.58	1.03	0.88	0.93	1.24	1.18	1.43	1.01	1.23	1.15	0.78	0.66
B counting	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36
continuum q^2	13.33	3.64	3.01	4.35	4.91	6.62	6.04	7.42	6.22	6.60	4.67	7.13	5.90
Total systematic error	15.63	6.22	6.14	7.19	8.04	9.56	9.27	9.60	8.71	10.30	7.80	10.63	11.23
Total statistic error	15.35	8.27	8.50	7.24	7.27	7.91	8.32	9.19	9.67	16.68	10.54	11.12	18.98
Total Error	21.90	10.35	10.48	10.20	10.84	12.41	12.46	13.29	13.01	19.60	13.12	15.39	22.08

Correlation Matrix $\Delta\mathcal{B}\left(B^0 \to \pi^- \ell^+ \nu\right)$ Statistical Uncertainties

q^2 (GeV/c^2)	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-
0-2	1.000	-0.335	0.149	0.052	0.030	0.032	0.048	-0.008	-0.002	-0.003	-0.004	-0.007	-0.014
2-4	-0.225	1.000	-0.326	0.200	-0.009	0.033	0.037	-0.006	-0.001	-0.003	-0.005	-0.004	-0.006
4-6	0.080	-0.261	1.000	-0.244	0.163	0.056	0.114	-0.017	-0.003	-0.005	-0.005	-0.005	-0.004
6-8	0.025	0.141	-0.215	1.000	-0.250	0.131	0.068	-0.010	-0.003	-0.004	-0.003	-0.003	-0.004
8-10	0.015	-0.006	0.149	-0.261	1.000	-0.170	0.243	-0.037	-0.001	-0.004	-0.004	-0.005	-0.008
10-12	0.013	0.020	0.043	0.115	-0.143	1.000	-0.053	0.024	-0.006	-0.002	-0.006	-0.007	-0.011
12-14	0.020	0.023	0.090	0.061	0.208	-0.054	1.000	-0.254	0.006	-0.025	-0.007	-0.011	-0.016
14-16	-0.003	-0.003	-0.012	-0.008	-0.028	0.021	-0.226	1.000	-0.011	0.120	-0.028	-0.006	-0.011
16-18	-0.001	-0.001	-0.003	-0.003	-0.001	-0.007	0.008	-0.016	1.000	0.102	-0.032	-0.003	-0.006
18-20	-0.001	-0.002	-0.005	-0.004	-0.005	-0.002	-0.031	0.171	0.099	1.000	-0.188	-0.030	-0.057
20-22	-0.002	-0.003	-0.004	-0.002	-0.003	-0.007	-0.007	-0.032	-0.025	-0.149	1.000	-0.038	0.007
22-24	-0.002	-0.002	-0.003	-0.002	-0.003	-0.006	-0.010	-0.006	-0.002	-0.021	-0.033	1.000	-0.132
24-	-0.004	-0.002	-0.002	-0.002	-0.004	-0.007	-0.010	-0.008	-0.003	-0.028	0.004	-0.094	1.000

Correlation Matrix $\Delta\mathcal{B}\left(B^0 \to \pi^-\ell^+\nu\right)$ Systematic Uncertainties

q^2 (GeV/c^2)	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-
0-2	1.000	-0.256	0.187	-0.162	0.297	0.181	0.224	0.114	0.104	0.112	0.084	0.020	0.069
2-4	-0.256	1.000	0.142	0.570	0.075	0.163	0.162	0.193	0.202	0.210	0.244	0.303	0.282
4-6	0.187	0.142	1.000	0.202	0.459	0.451	0.469	0.212	0.368	0.329	0.332	0.322	0.336
6-8	-0.162	0.570	0.202	1.000	-0.017	0.240	0.202	0.280	0.256	0.284	0.312	0.333	0.272
8-10	0.297	0.075	0.459	-0.017	1.000	0.375	0.633	0.156	0.321	0.290	0.258	0.244	0.231
10-12	0.181	0.163	0.451	0.240	0.375	1.000	0.433	0.214	0.328	0.332	0.252	0.284	0.230
12-14	0.224	0.162	0.469	0.202	0.633	0.433	1.000	-0.013	0.337	0.278	0.291	0.245	0.246
14-16	0.114	0.193	0.212	0.280	0.156	0.214	-0.013	1.000	0.334	0.500	0.287	0.337	0.322
16-18	0.104	0.202	0.368	0.256	0.321	0.328	0.337	0.334	1.000	0.452	0.334	0.356	0.344
18-20	0.112	0.210	0.329	0.284	0.290	0.332	0.278	0.500	0.452	1.000	0.208	0.430	0.333
20-22	0.084	0.244	0.332	0.312	0.258	0.252	0.291	0.287	0.334	0.208	1.000	0.222	0.402
22-24	0.020	0.303	0.322	0.333	0.244	0.284	0.245	0.337	0.356	0.430	0.222	1.000	0.220
24-	0.069	0.282	0.336	0.272	0.231	0.230	0.246	0.322	0.344	0.333	0.402	0.220	1.000