Determination of the CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$ at Belle II

T. Lück
on behalf of the Belle II collaboration

ICHECP 2018, Seoul (South Korea)

5th July 2018

Istituto Nazionale Fisica Nucleare Sezione di Pisa

Belle II

SCUOLA NORMALE SUPERIORE

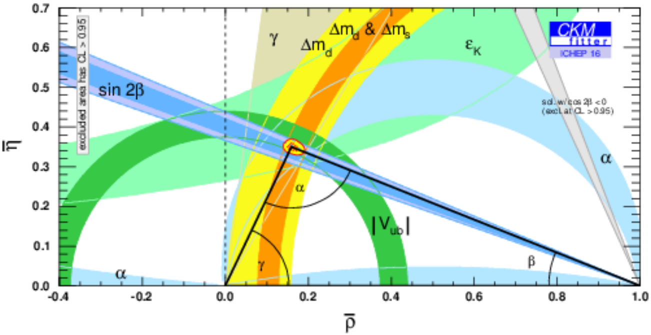
Outline

- Introduction and motivation
- The Belle II detector
- Prospects of $|V_{ub}|$ and $|V_{cb}|$ at Belle II
- First glance at Belle II data
- Summary

Introduction: Why measure $|V_{ub}|$ and $|V_{cb}|$?

- the unitarity of CKM matrix is strong constrain for new physics contributions: $VV^\dagger = 1$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \Rightarrow V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$



- $|V_{ub}|$ and $|V_{cb}|$ only tree-level process constraints $\Rightarrow$ insensitive to new physics (contributing through loops)

How to measure $|V_{ub}|$ and $|V_{cb}|$

Exclusive $|V_{qb}|$ measurement

- reconstruct specific final state e.g.: $B \to D\ell\nu$, $B \to \pi\ell\nu$
- $B \propto |V_{qb}|^2\mathcal{F}^2$ with $\mathcal{F}$ form factor (FF)

Inclusive $|V_{qb}|$ measurement

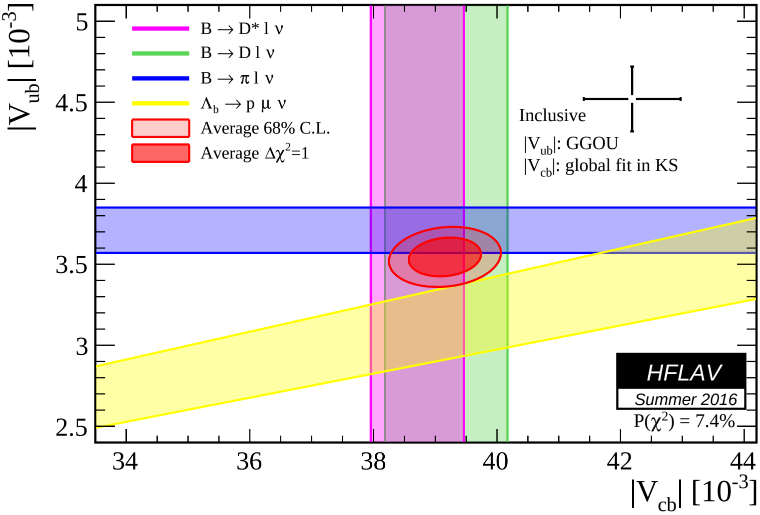
- don't reconstruct specific final state but all: $B \to X_q\ell\nu$
- $B \propto |V_{qb}|^2 \left[\Gamma(b \to q\ell\nu) + \frac{1}{m_b} + \alpha_s + ...\right]$

tagged vs. untagged analysis

- tagged analysis:
  - fully reconstruct other B-meson in $e^+e^- \to B\bar{B}$
  - high purity but low statistics
- untagged analysis:
  - infer kinematics by rest of the event $\Rightarrow$ less precise
  - high statistics but also higher background

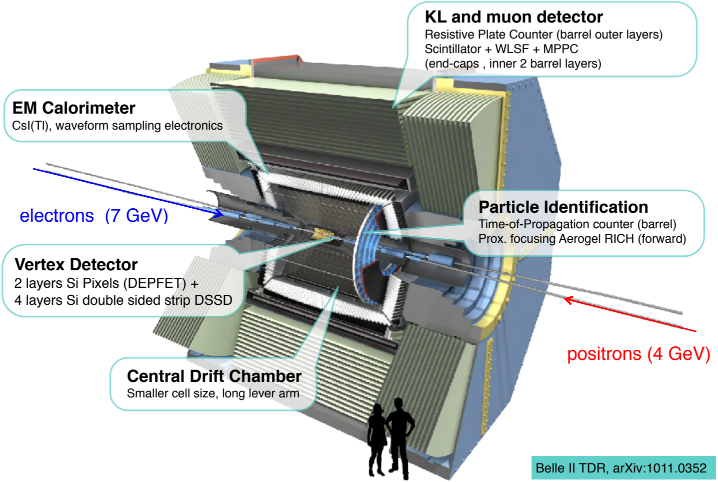
Current status

- discrepancy between inclusive and exclusive $|V_{ub}|$ and $|V_{cb}|$ ($\approx 3\sigma$)
- New physics? Biased measurements? Not well understood theory?



The Belle II detector

- instantaneous luminosity: $\mathcal{L} = 8 \times 10^{35} \; cm^{-2}s^{-1}$ provided by SuperKEKB accelerator at Tsukuba (Japan)
- goal integrated luminosity 50 ab^{-1} by 2025

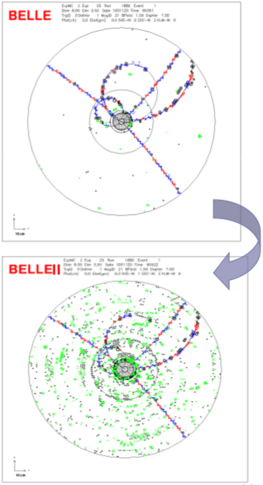


Belle II TDR, arXiv:1011.0352

How to reduce systematic uncertainties and deal with higher background at Belle II (part I)

higher luminosity also higher backgrounds ($\approx 40\times$ wrt. Belle)

- fast readout electronics to reduce pile up effects in the ECL
- smaller boost w.r.t. Belle $\Rightarrow$ better z-resolution needed
  - 2 layer Pixel + 4 layer of strip detectors (Belle: 4 layer strip det.)
- new and improved PID in Barrel region: imaging Time-of-Propagation detector
- added PID in the forward region (ARICH)
- new drift chamber: longer lever arm, smaller cells for inner layers, fast readout



- better detector performance $\Rightarrow$ reduction of some of the systematics

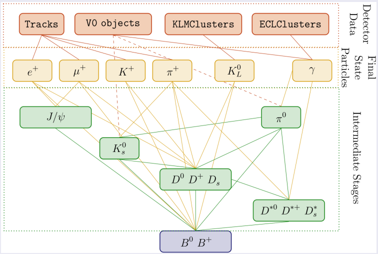
How to reduce systematic uncertainties and deal with higher background at Belle II (part II)

New algorithms to reduce systematic uncertainties

- for tagged analysis the tag calibration is one of the main sources of systematic uncertainties
- Belle II has an improved tagging algorithm (FEI)
- $\approx 2\times$ efficiency, same purity $\Rightarrow$ tighter selection

Full Event Interpretation (FEI)

- hierarchic reconstruction of events using multivariate methods

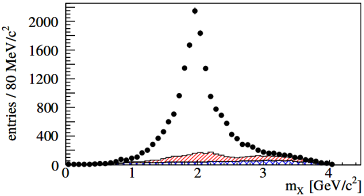


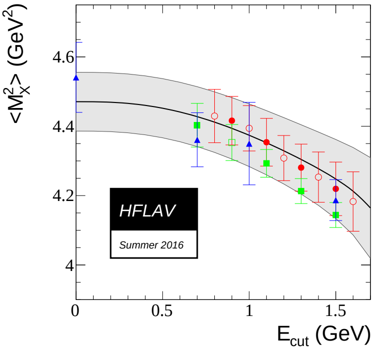
Tag	FR[4] @ Belle	FEI @ Belle MC	FEI @ Belle II MC
Hadronic B^+	0.28 %	0.49 %	0.61 %
Semileptonic B^+	0.67 %	1.42 %	1.45 %
Hadronic B^0	0.18 %	0.33%	0.34 %
Semileptonic B^0	0.63 %	1.33%	1.25 %

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

- most precise determination from measurement of moments $< E_l^n >_{E_{cut}}$; $< M_X^{2n} >_{Ecut}$ as function of lower lepton momentum
- most recent: *BABAR* Phys. Rev. D.81 032003 (2010)
  - subset of total dataset (210 fb^{-1})
  - uncertainty on moments systematically limited
- only minor improvement by adding more statistics
- improved reconstruction can reduce systematics
- detailed study of possible biases w.r.t. incl. vs. excl. discrepancy

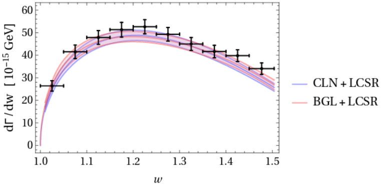
- Phys. Rev. D.81 032003 (2010)

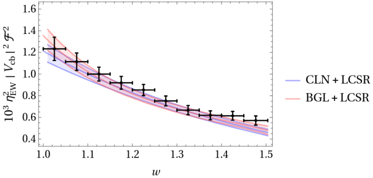




Exclusive $|V_{cb}|$ from $B \to D^* \ell \nu$

- first **unfolded** differential decay rates for $B \to D^* \ell \nu$ by Belle arXiv:1702.01521
- Bigi et al. arXiv:1703.06124: fit to (data + lattice) two different form factor parametrizations (BGL, CLN):
  - $|V_{cb}|_{BGL} = 0.0417(^{+20}_{-21})$
  - $|V_{cb}|_{CLN} = 0.0382(15)$

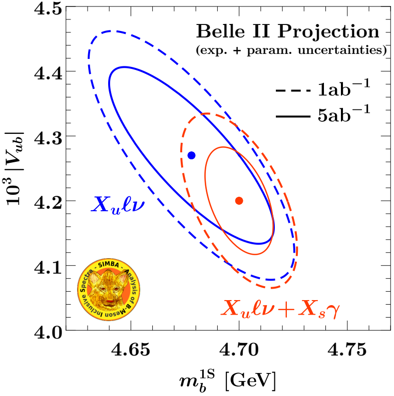




- use of BGL seems to release incl. vs. excl. $|V_{cb}|$ tension ⇒ Real effect? Coincidence?
- more data needed ⇒ Belle II can provide those with its large dataset
- currently measured 4 1D differential decay rates ⇒ at Belle II one 4D differential decay rate measurement may be possible ⇒ very valuable input to theory

Global fit approach for inclusive $|V_{ub}|$

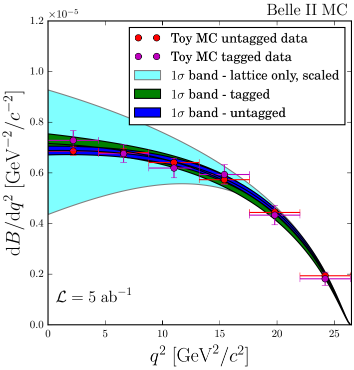
- biggest uncertainty from unknown shape function (motion of b-quark inside of B-meson)
- fit simultaneously $B \to X_c l\nu + B \to X_u l\nu + B \to X_s\gamma$
- allows extraction of $|V_{ub}|$ and shape function parameters at same time
- Belle II can provide required precise measurements of differential distributions

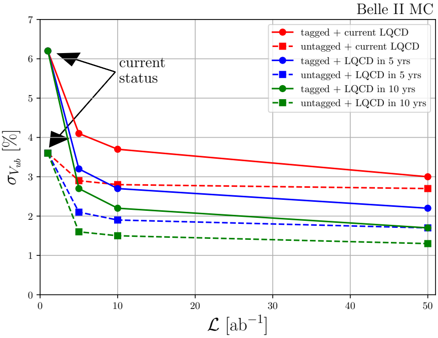


- reference: B2TIP report (submitted in the next two weeks)

Prospects of exclusive $|V_{ub}|$ at Belle II

- most precise estimation from exclusive $B \to \pi^{\pm}\ell\nu$
- simultaneous fit to q^2 spectrum for FF parameters and $|V_{ub}|$





Prospects of $|V_{ub}|$ at Belle II

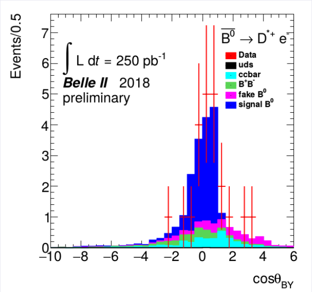
- comparison between most recent Belle (711 fb^{-1} and 605 fb^{-1}) and projected Belle II (at 5 ab^{-1} and 50 ab^{-1}) uncertainties

	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\|V_{ub}\|$ 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
$\|V_{ub}\|$ 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
$\|V_{ub}\|$ 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
$\|V_{ub}\|$ $B \to \tau\nu$ (had. tagged)					
711 fb^{-1}	18.0	(7.1, 2.2)	19.5	2.5	19.6
5 ab^{-1}	6.5	(2.7, 2.2)	7.3	1.5	7.5
50 ab^{-1}	2.1	(0.8, 2.2)	3.1	1.0	3.2
$\|V_{ub}\|$ $B \to \tau\nu$ (SL tagged)					
711 fb^{-1}	11.3	(10.4, 1.9)	15.4	2.5	15.6
5 ab^{-1}	4.2	(4.4, 1.9)	6.1	1.5	6.3
50 ab^{-1}	1.3	(2.3, 1.9)	2.6	1.0	2.8

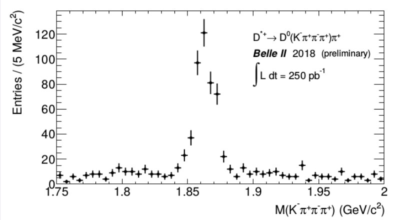
First data from Belle II

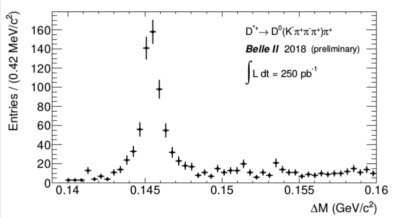
- currently data taking for phase2:
  - full detector except only section of silicon tracker
  - main purpose: machine tuning and bkg. studies
  - though still in calibration phase data already usable for physics analysis

Reconstructed semileptonic B decay candidates



Rediscovery of the standard model: D^0 and D^{*+} candidates





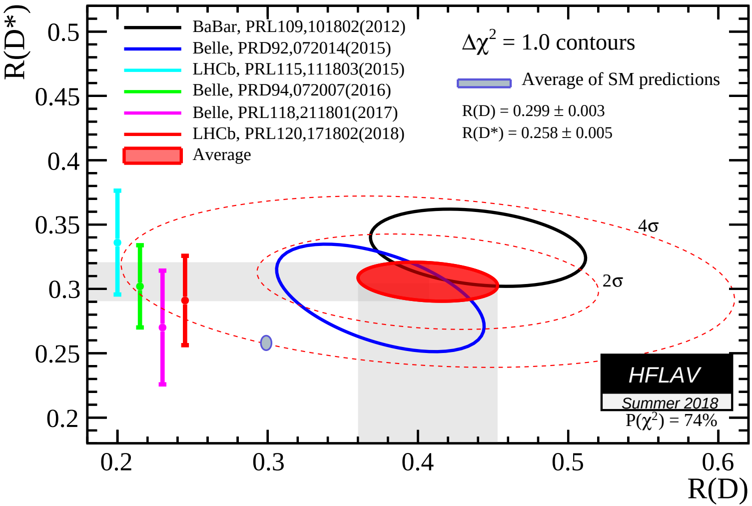
Summary

- prospects $|V_{cb}|$:
  - current measurements already very precise
  - opportunity for Belle II to measure differential rates $\Rightarrow$ valuable input for theory; help to resolve inclusive vs exclusive puzzle
- good prospects to improve on $|V_{ub}|$
- Belle II started taking data with partial detector
- install Layer 1 (pixel) and Layers 3-6 (strips) this fall (Layer 2 will be installed 2020 due to technical difficulties)
- start taking physics runs early 2019

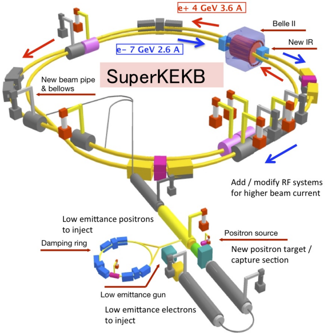
Backup

Machine Parameters

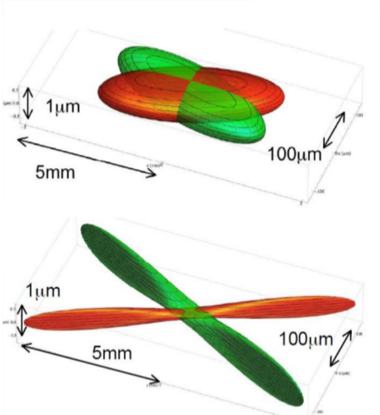
2013/July/29	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28	%	includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	$3.18\text{x}10^{-4}$	$4.53\text{x}10^{-4}$		
σ_δ	$8.10(7.73)\text{x}10^{-4}$	$6.37(6.30)\text{x}10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6.0(5.0)	5(4.9)	mm	():zero current
ν_s	-0.0244	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.86	2.43	MeV	
$\tau_{x,y}/\tau_s$	43.2/21.6	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	$8\text{x}10^{35}$		$cm^{-2}s^{-1}$	


BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, PRL120,171802(2018)
Average
$\Delta\chi^2 = 1.0$ contours
Average of SM predictions
R(D) = 0.299 ± 0.003
R(D*) = 0.258 ± 0.005
4σ
2σ
HFLAV
Summer 2018
$P(\chi^2) = 74\%$
R(D*)
R(D)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.2
0.3
0.4
0.5
0.6

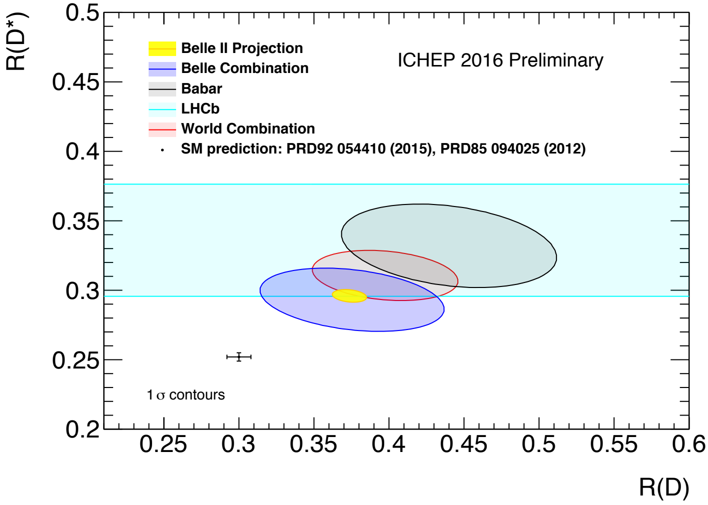
SuperKEKB: a next generation B-factory



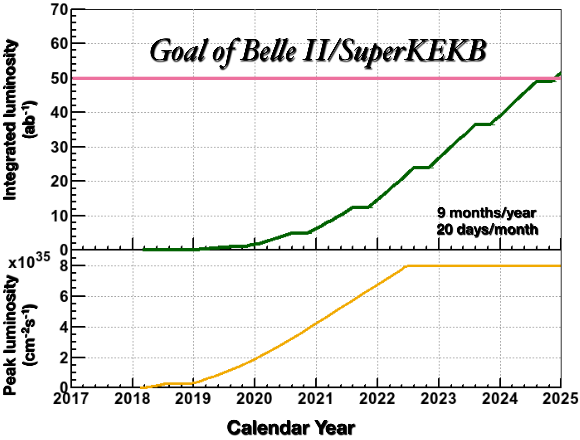
- instantaneous luminosity: $L = 8 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- goal int. luminosity $50\mathrm{ab}^{-1}$ by 2025
- new technologies: nano beam scheme



Extrapolation of Belle results



SuperKEKB luminosity projection



- 50ab^{-1} by the end of 2025
- $\approx 50\times$ the Belle data sample, $\approx 100\times$ the BaBar data sample

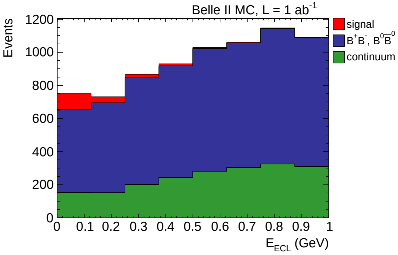
Excerpt of results from Phys. Rev. D.81 032003 (2010)

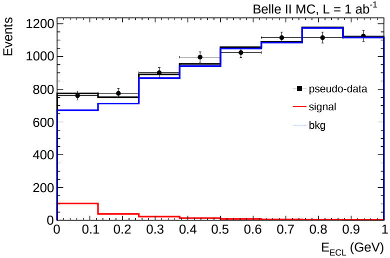
- 4th and 5th column give stat. and syst. uncertainty, respectively
- last five columns give syst. uncertainties divided by source of uncertainty

k	$p^*_{\ell,\min}$ [GeV/c]	$\langle m_X^k \rangle$	σ_{stat}	σ_{sys}	MC statistics	simulation related	extraction method	back-groud	signal model
1	0.8	2.0906	±0.0063	±0.0166	0.0058	0.0099	0.0096	0.0047	0.0031
	0.9	2.0890	±0.0062	±0.0158	0.0048	0.0088	0.0103	0.0045	0.0028
	1.0	2.0843	±0.0061	±0.0153	0.0044	0.0076	0.0109	0.0044	0.0027
	1.1	2.0765	±0.0063	±0.0165	0.0044	0.0072	0.0127	0.0047	0.0026
	1.2	2.0671	±0.0064	±0.0160	0.0046	0.0073	0.0120	0.0045	0.0025
	1.3	2.0622	±0.0068	±0.0168	0.0048	0.0073	0.0131	0.0050	0.0023
	1.4	2.0566	±0.0073	±0.0183	0.0047	0.0069	0.0150	0.0054	0.0021
	1.5	2.0494	±0.0081	±0.0198	0.0036	0.0074	0.0168	0.0061	0.0019
	1.6	2.0430	±0.0092	±0.0221	0.0038	0.0082	0.0187	0.0070	0.0018
	1.7	2.0387	±0.0109	±0.0265	0.0047	0.0081	0.0232	0.0083	0.0015
	1.8	2.0370	±0.0143	±0.0337	0.0069	0.0097	0.0299	0.0098	0.0013
	1.9	2.0388	±0.0198	±0.0413	0.0082	0.0123	0.0355	0.0150	0.0008

Exclusive $|V_{ub}|$ from $B^- \to \tau^- \nu$

- fully reconstruct tag side and lepton on signal side
- extract signal in E_{ECL}: sum over all neutral cluster not used for reconstruction
- $\mathcal{B} \propto |V_{ub}|^2 f_B^2 m_l^2$





Definition $cos\theta_{BY}$

- for a decay $B \to X\ell\nu$
- the Y system defined as $Y = X + \ell$
- $cos\theta_{BY} = \frac{2E_B^* E_Y^* - M_B^2 - m_Y^2}{2p_B^* p_Y^*}$