Semileptonic and leptonic B decay results from early Belle II data

A.Passeri (INFN Roma Tre)
on behalf of the Belle II collaboration

INFN Sezione di Roma Tre

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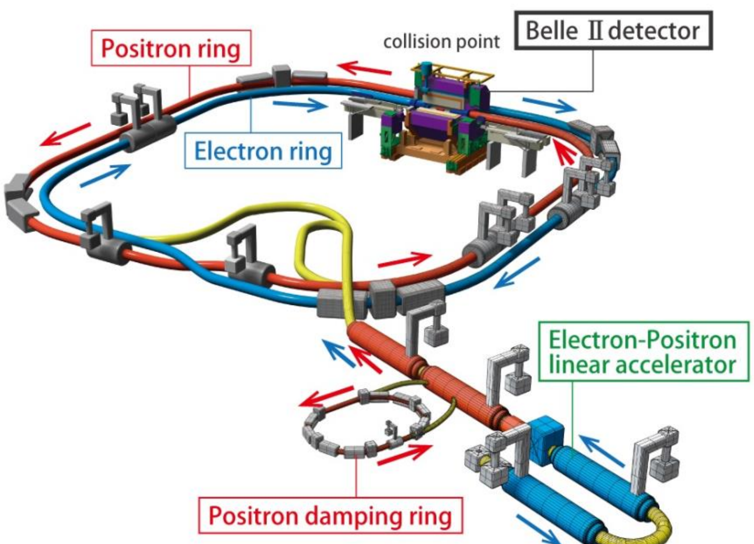
SuperKEKB project

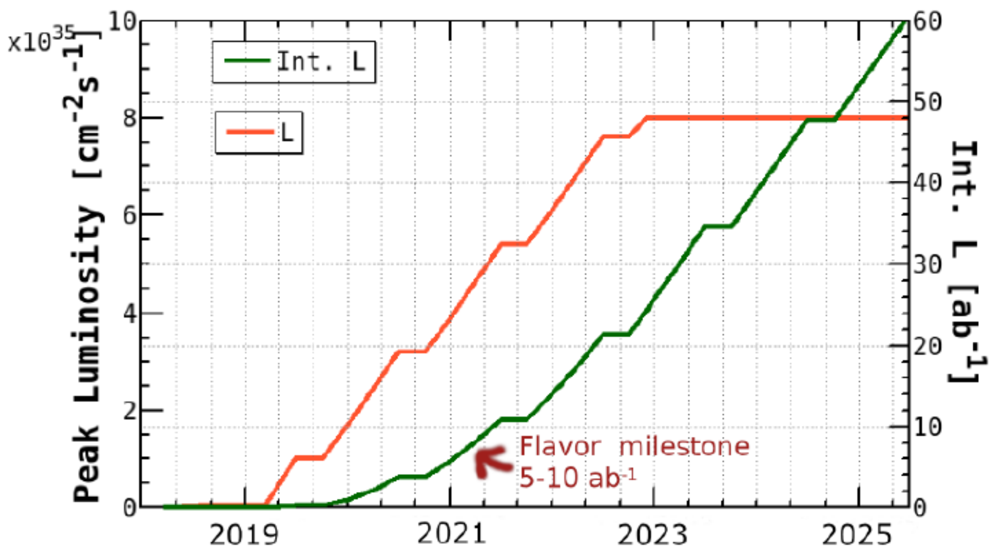
parameter	LER (e^+)	HER (e^-)	units
Energy	4.000	7.007	GeV
Half crossing angle	41.5		mrad
Horizontal emittance	3.2	4.6	nm
Emittance ratio	0.27	0.25	%
Beta functions at IP (x/y)	32 / 0.27	25 / 0.30	mm
Beam currents	3.6	2.6	A
Beam-beam parameter	0.0881	0.0807	
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$

KEKB machine heavily upgraded:

- New positron damping ring
- New 3 km positron ring vacuum chamber
- New superconducting final focus

Aim to deliver 50 ab^{-1} in 6 years !

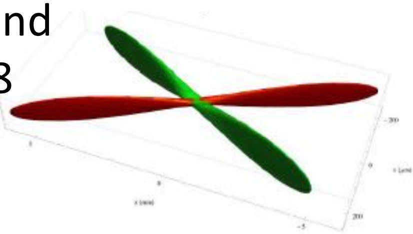


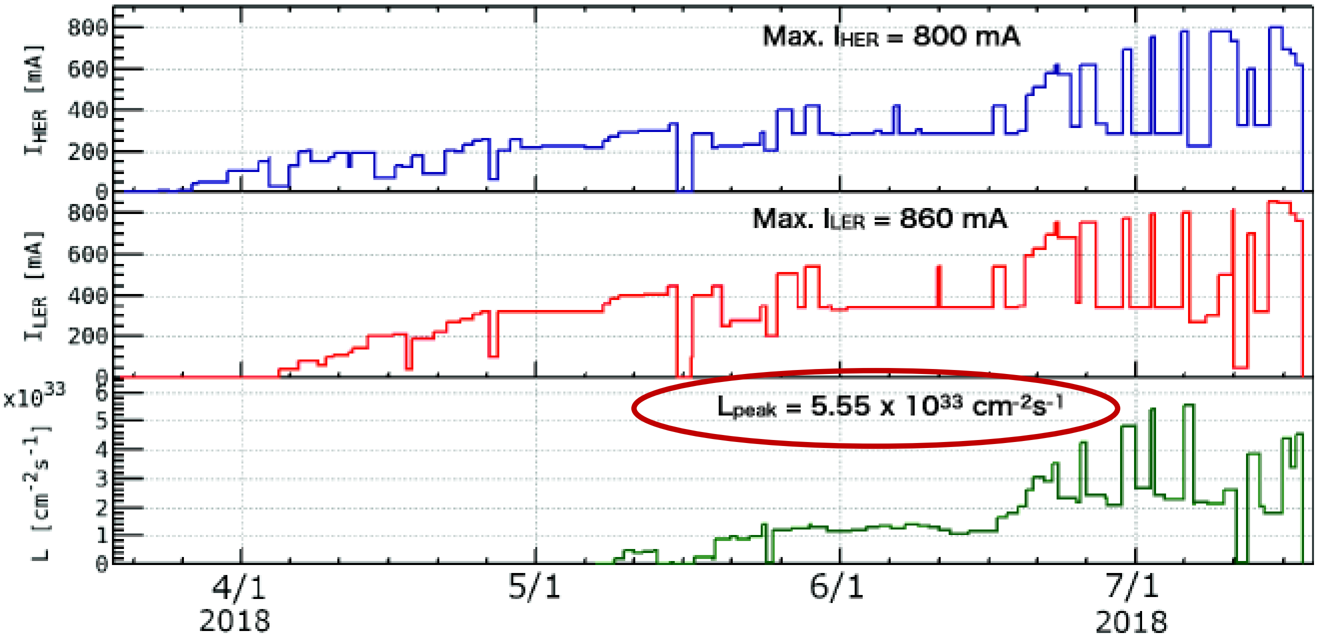


SuperKEKB operations

Phase 1: Single beam commissioning, without final focus, performed in 2016

Phase 2: Collision commissioning , with final focus, nanobeam scheme, and Belle II detector in place (without vertex detector), from April to July 2018





bunch length 0.5 mm
Vertical size to be optimized (aim to 50 nm).

β_y^* = 3 mm

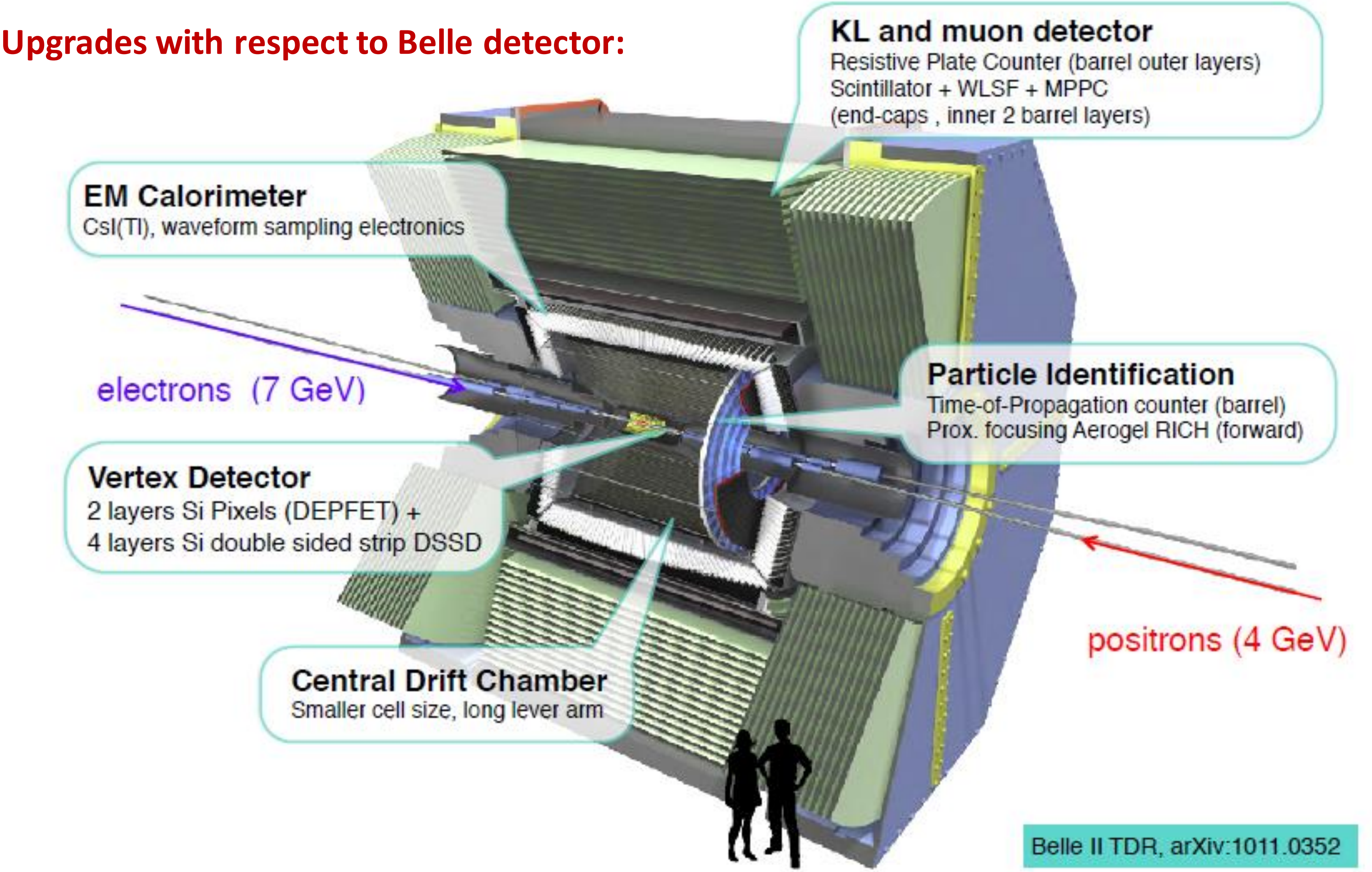
Belle II managed to collect 0.5 fb^{-1} in the time left from machine tuning, very useful sample for commissioning and first physics !!!

Phase 3: stable data taking with full Belle II detector in place started in March 2019.

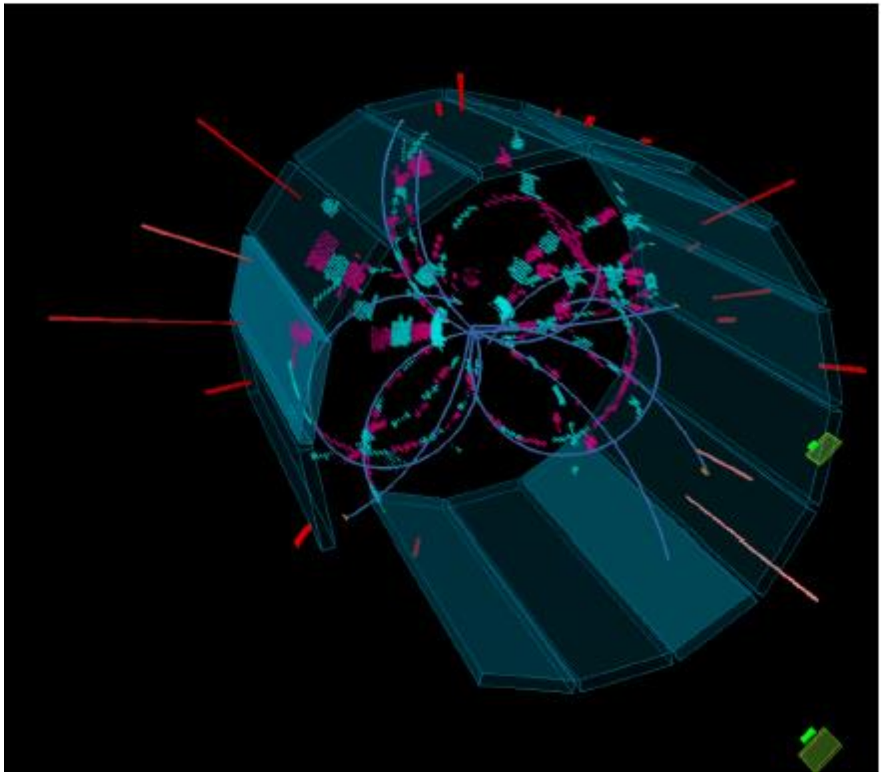
See talk by Manfred Berger

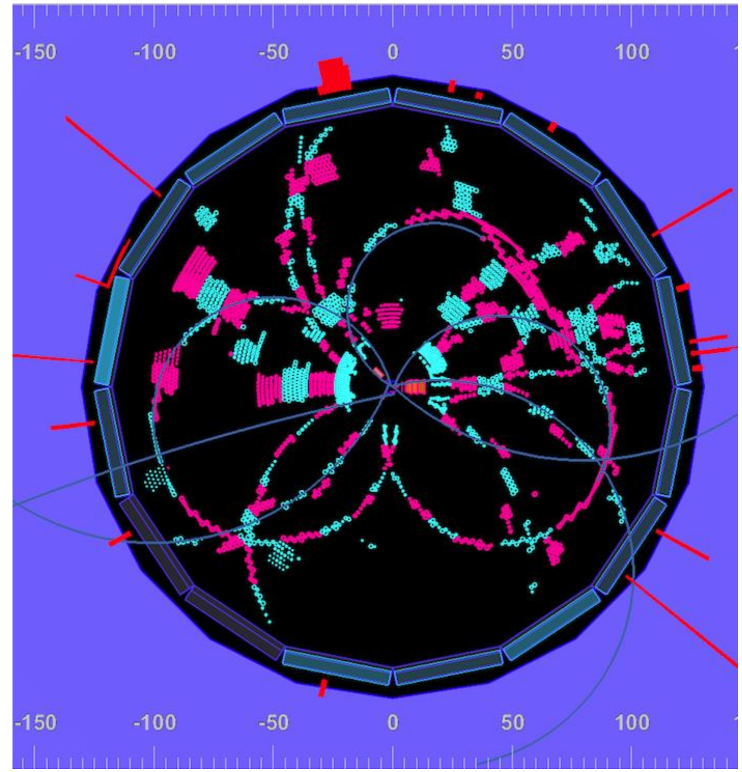
The Belle II detector

Upgrades with respect to Belle detector:



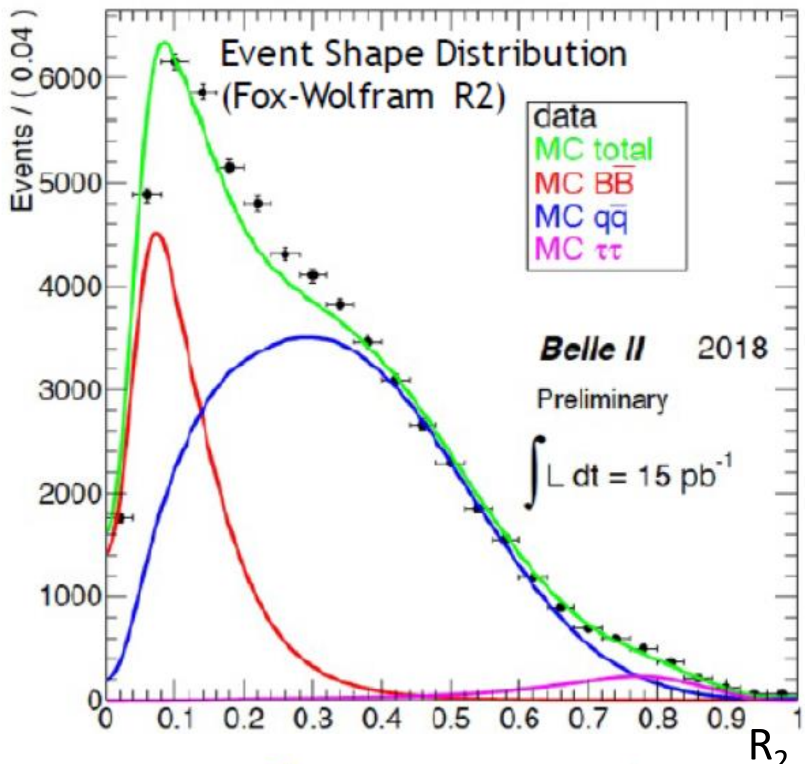
Belle II event displays in Phase2 run

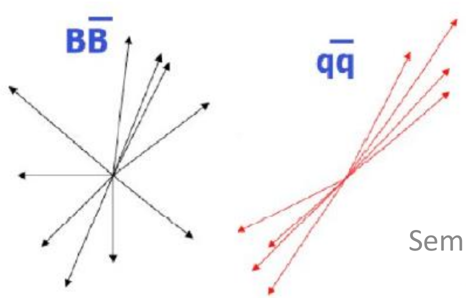


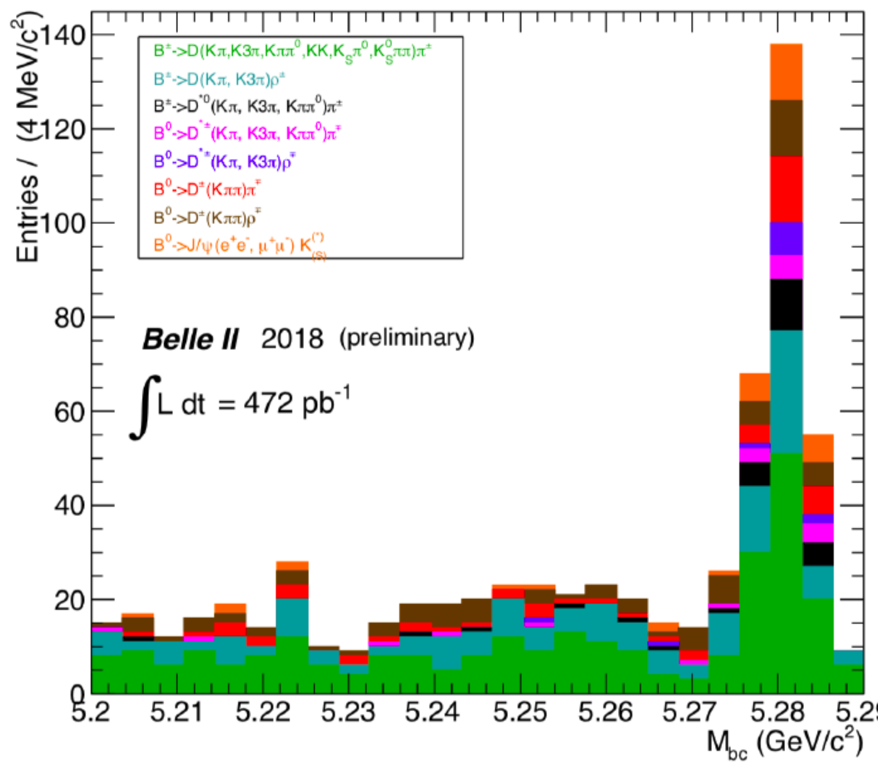


All subdetectors operational. Collisions mostly used for commissioning

Belle II detector shows already good performance in phase 2 data: all anticipated particles have been re-discovered. B mesons mass peak is well reconstructed.

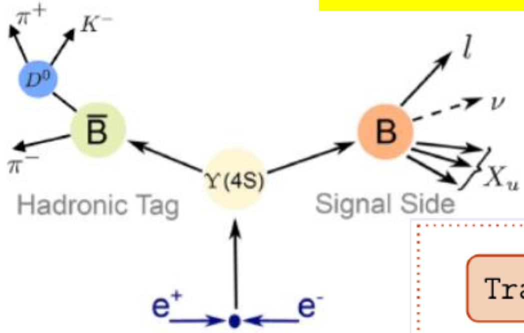




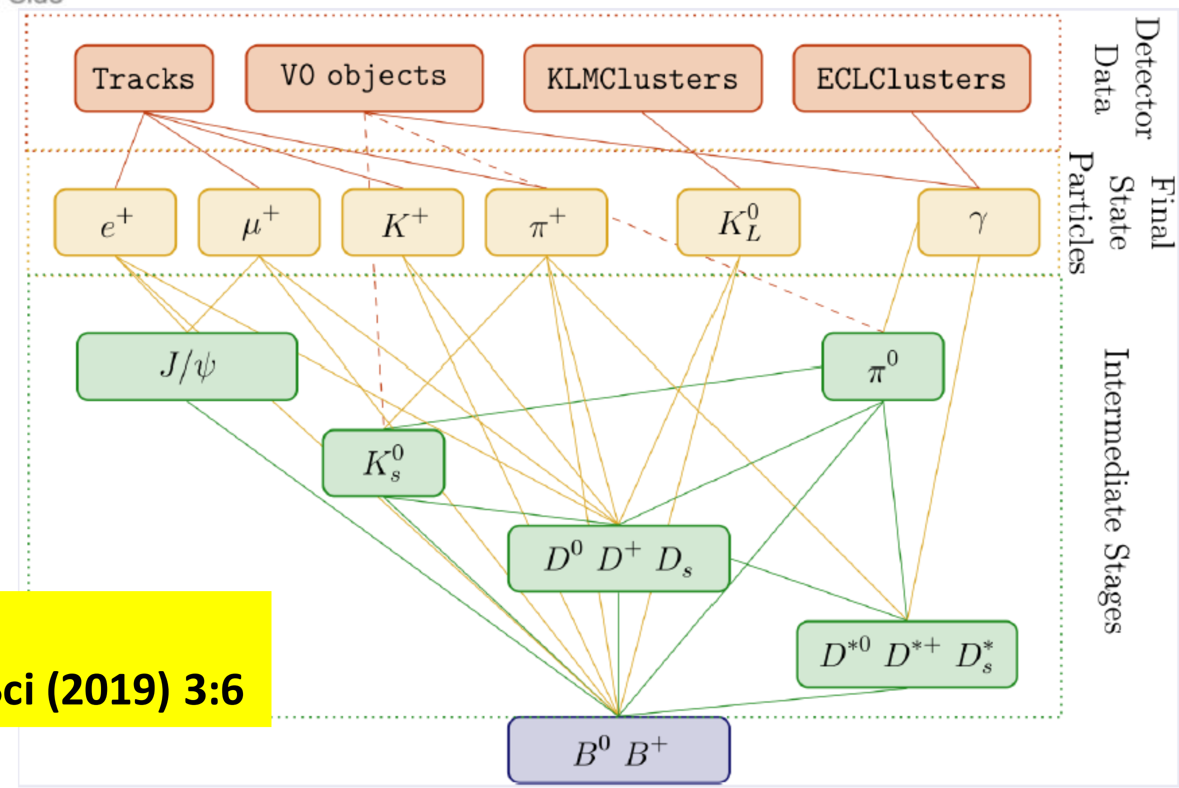


Good test bench for physics analysis tools !

FEI: Full event interpretation, enhances by a factor of 2 the event tagging efficiency



A dedicated boosted decision tree for each step
More than 1000 B decay modes are reconstructed



T. Keck et al.,
Comput Softw Big Sci (2019) 3:6

Very powerful tool for all tagged analyses: high purity but usually low statistics
Untagged analyses by converse have high statistics, high background, and less kinematical constraints (Rest of the Event)

FEI performances on phase 2 data

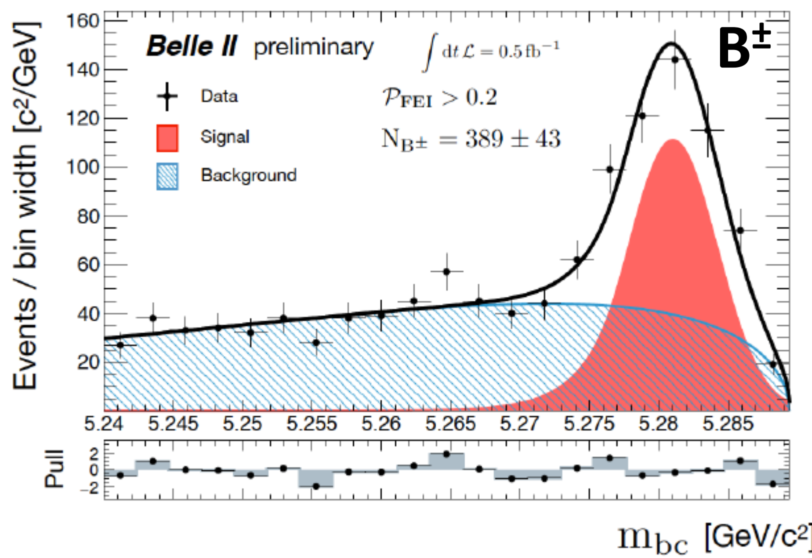
- Only hadronic tags
- Continuum suppressed by cut on R_2
- **Fit** $m_{bc} = \sqrt{\frac{s}{4} + \vec{p}^{\,2}_{Btag}}$

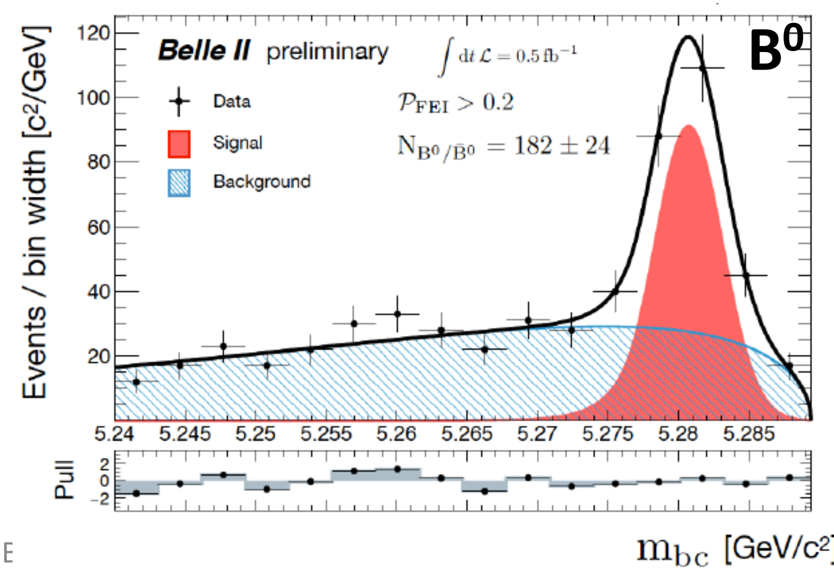
Efficiency = $N_B^{correct} / N_{Y(4s)}^{total}$

Purity = $N_B^{correct} / N_B^{all}$

	Candidates	Efficiency	Purity
	FEI Signal Probability $\mathcal{P} > 0.01$		
Charged Candidates	937 ± 126	0.17%	24%
Neutral Candidates	394 ± 59	0.09%	25%
	FEI Signal Probability $\mathcal{P} > 0.2$		
Charged Candidates	389 ± 43	0.07%	63%
Neutral Candidates	182 ± 24	0.03%	73%

FEI Signal Probability $\mathcal{P} > 0.2$.





Inclusive analysis of $B \rightarrow Xe\nu$ in phase 2 data

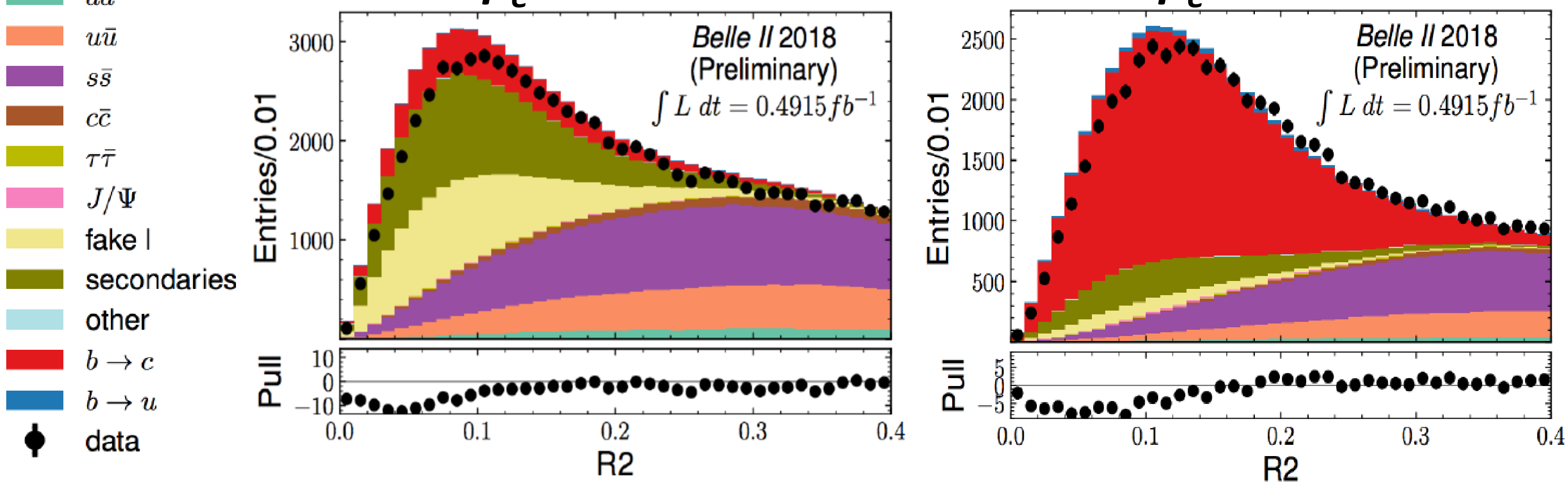
Data sample of 0.4915 fb^{-1}

electrons identified by cutting on E_{ECL}/P_{track}

J/ψ candidates rejected

Fox -Wolfram moments ratio R2<0.4 to suppress continuum background

p_e < 1 GeV **p_e > 1 GeV**

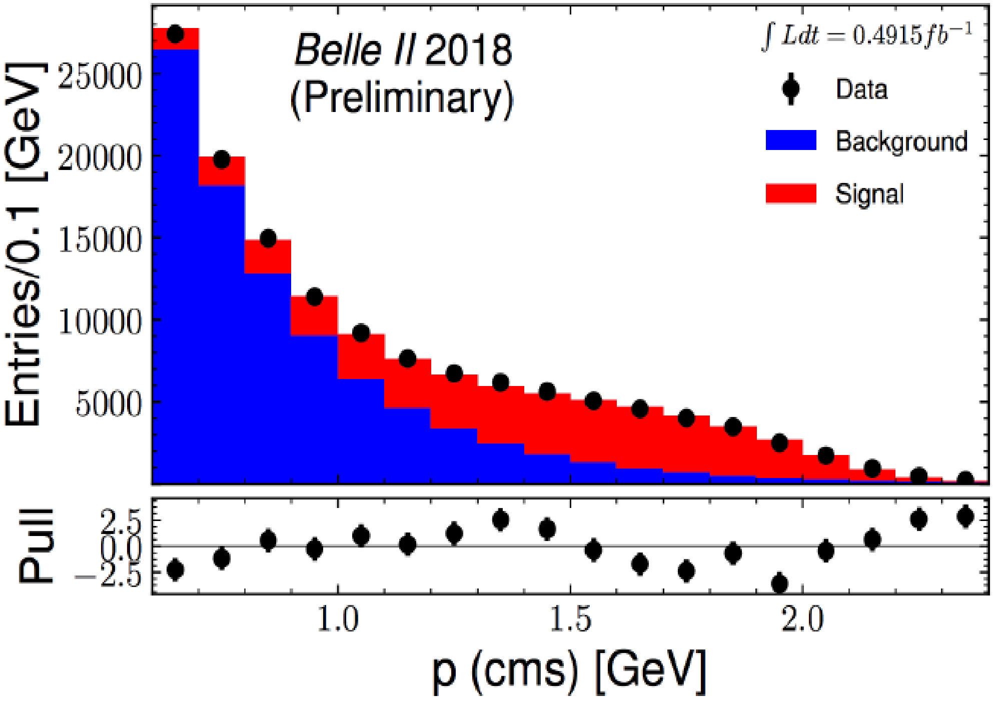


Inclusive analysis of $B \to Xe\nu$ in phase 2 data

Good data – Monte Carlo agreement for electron momentum > 1 GeV

Fitting momentum distribution in the range 0.6 < p_e(cms) < 2.4 GeV yields:

42191 ± 304 **signal events**
(40209 ± 200 expected from MC)



Still a lot of work to do to measure $|V_{cb}|$ and $|V_{ub}|$….

…..but very good starting point given the small available sample, the new detector and the changing conditions in which it was collected !

Exclusive reconstruction of $\overline{B}^0 \rightarrow D^{*+}e^-\overline{\nu}_e$ in phase 2 data

A data sample of 366 pb^{-1} is used

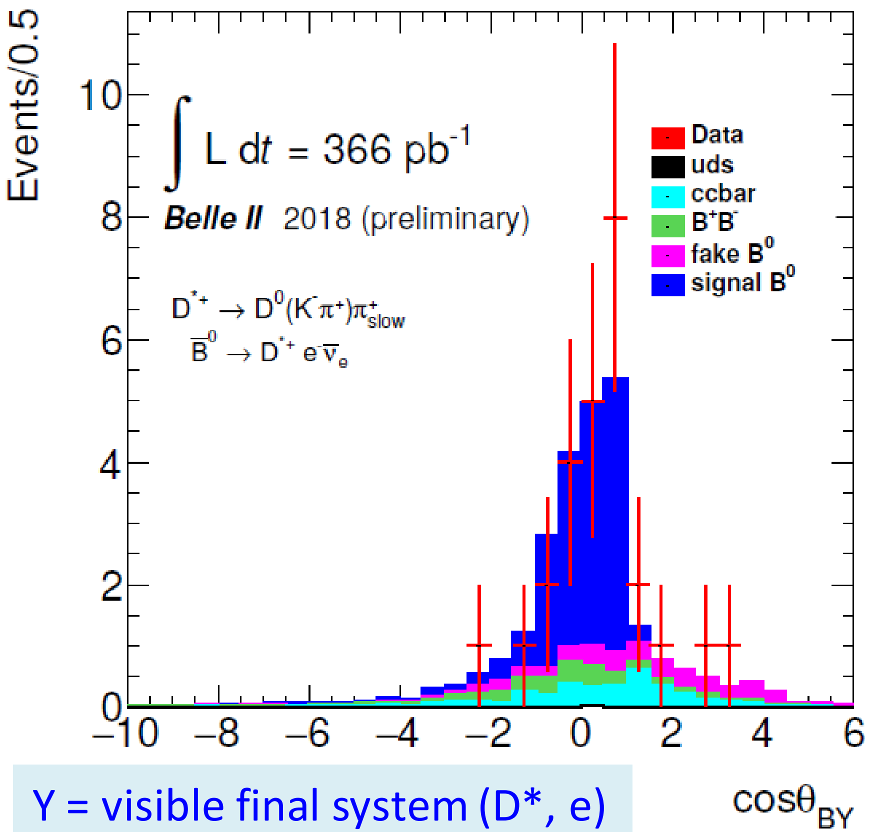
$\overline{B}^0 \rightarrow D^{*+}e^-\overline{\nu}_e$ **is reconstructed in the channel where $D^* \rightarrow D^0 (\rightarrow K\,\pi)\,\pi_{slow}$**

Events Selections:

- **electrons identified by cutting on E_{ECL}/P_{track}**
- **R2 < 0.25 to suppress continuum**
- **Slow π cms momentum < 0.4 GeV/c**
- **Selection around M_D and (M_{D*} - M_D) expected values**

Exclusive reconstruction of $\overline{B}^0 \to D^{*+}e^-\overline{\nu}_e$ in phase 2 data

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



Y = visible final system (D*, e)

22 signal events observed

15 events in the range (-1, 1)

13 predicted by MC

Belle II perspectives with semileptonic B decays

Exclusive measurements:

reconstruct final states: $B \to D \ell \nu$, $B \to \pi \ell \nu$

BR $\propto |V_{qb}|^2$ *F (w)*   (*F* form factor)

need input from lattice QCD

Inclusive measurements:

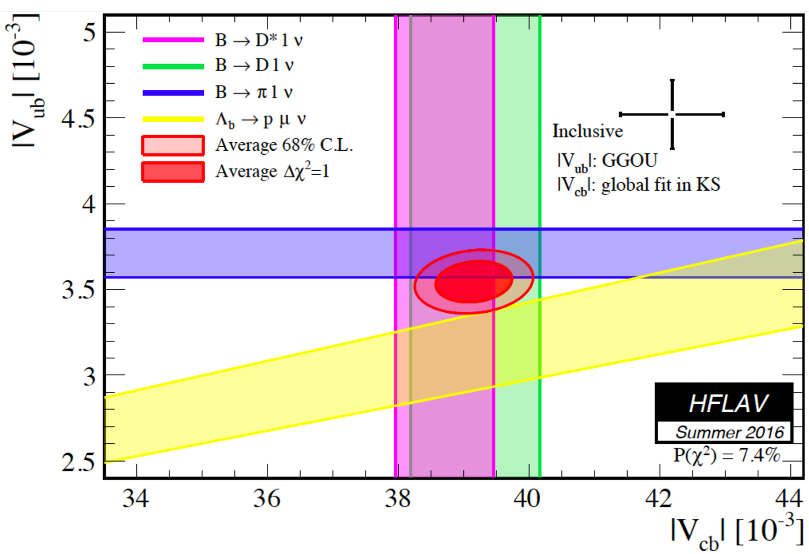
Include all $B \to X_q \ell \nu$.

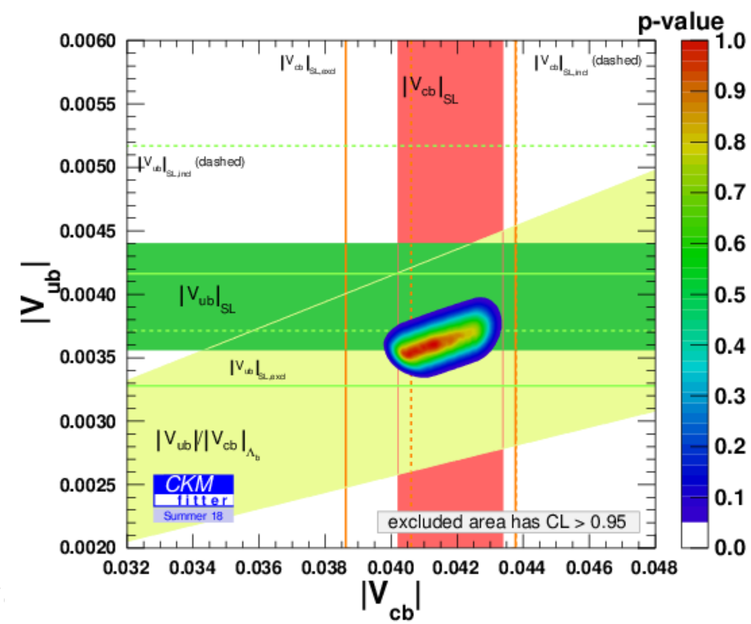
via optical theorem:

BR $\propto |V_{qb}|^2$ $(\Gamma(b \to q \ell \nu) + \ldots\ldots)$

HQE needed to determine total rate

Inclusive vs exclusive measurements used to show some discrepancies, but recent averages and model independent FF parametrization recovered agreement:





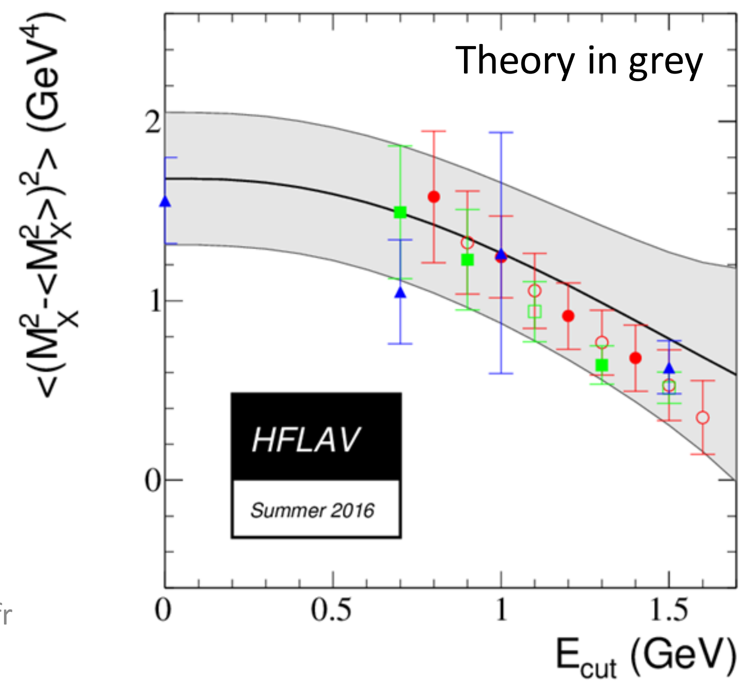
V_{cb} @Belle II

Belle II will improve both statistical and systematical uncertainties and in most cases it will allow to fit the FF shape thus reducing theory error:

- **$|V_{cb}|$exclusive: from $B \to D^* \ell \nu$ and $B \to D \ell \nu$**
  compatible results, but V_{cb} value depends on FF parametrization:
  CLN vs BGL i.e. discrepancy or not with inclusive determination.
  Currently systematics dominated mainly coming from hadronic tag calibration.
  Powerful FEI technique and high statistcal sample will allow FF fit from differential $B \to D \ell \nu$ decay rates and help reducing theory error on parametrization.

- **$|V_{cb}|$ inclusive:** simultaneous fit to the semileptonic inclusive width, the moments of the lepton energy spectrum and the moments of the hadronic mass spectrum squared.

  currently theory error dominated. High statistical sample will allow accurate measurement of the E_l spectrum and of other momenta, and to test the validity of the OPE description at low energy, thus reducing theory errors.



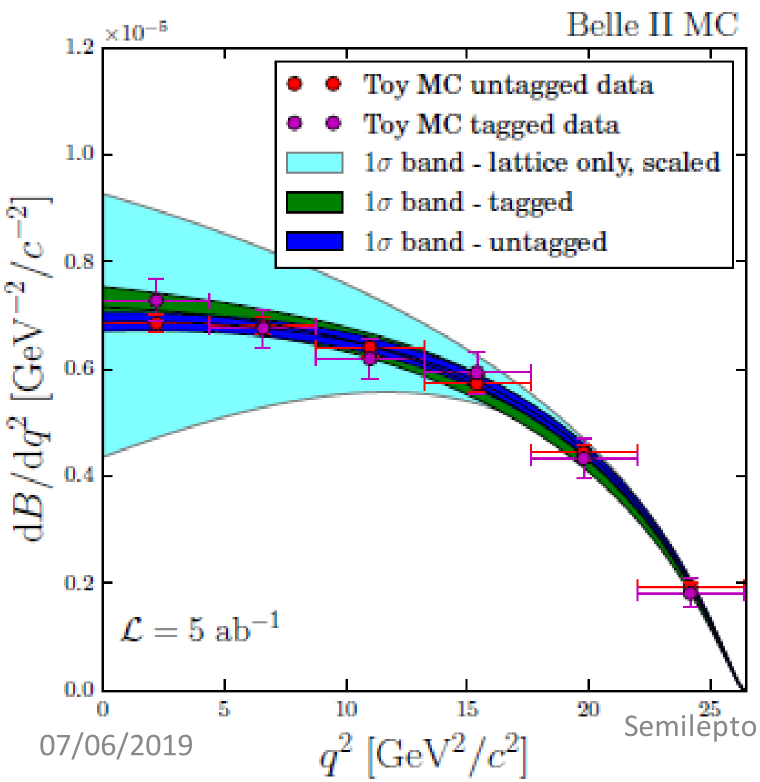
Exclusive V_{ub}

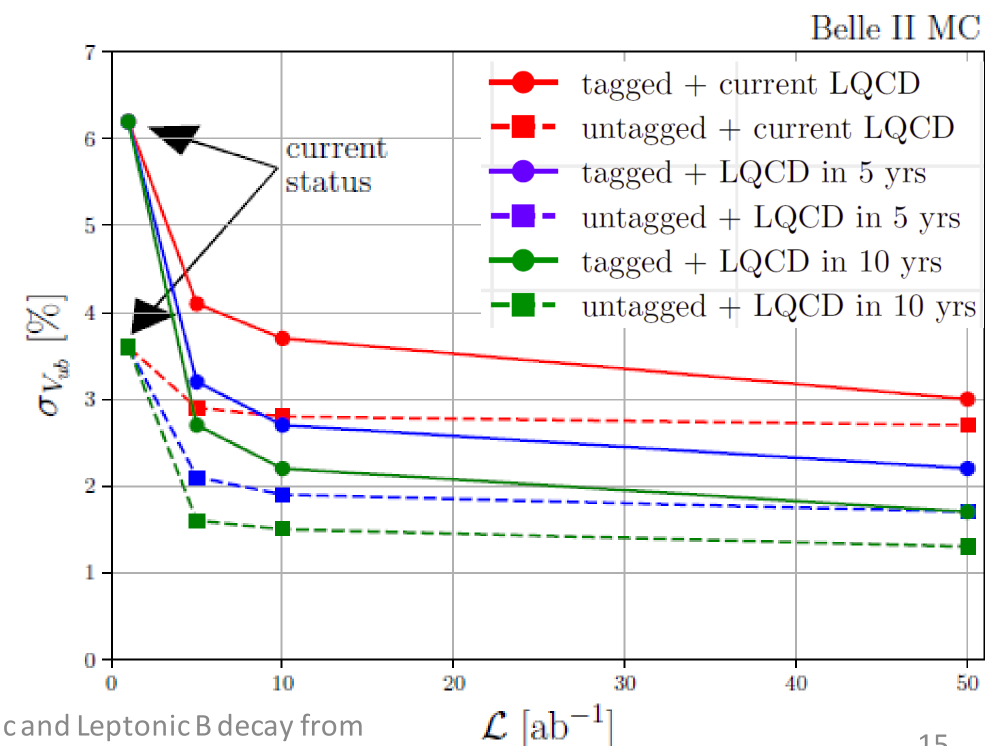
$B \to \pi \ell \nu$ both tagged and untagged.

$B_s \to K \ell \nu$ untagged only, at Y(5s), less precise.

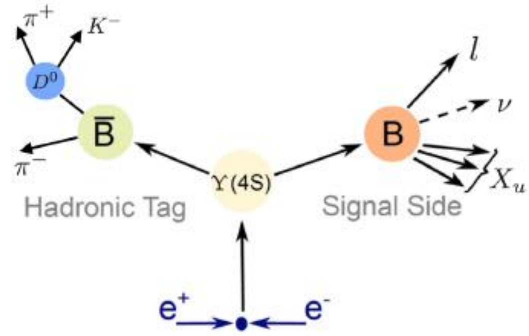
Extract V_{ub} from a combined fit to the measured q^2 spectrum and Lattice QCD predictions. Higher Belle II selection efficiencies and improved resolutions will allow to pin down the V_{ub} error by a ~2 already with 5 ab^{-1}.

Lattice QCD improvements may gain another factor of 2.





Inclusive V_{ub}



Can be obtained both from untagged and hadronic tagged analyses, where neutrino momentum is reconstructed or constrained.

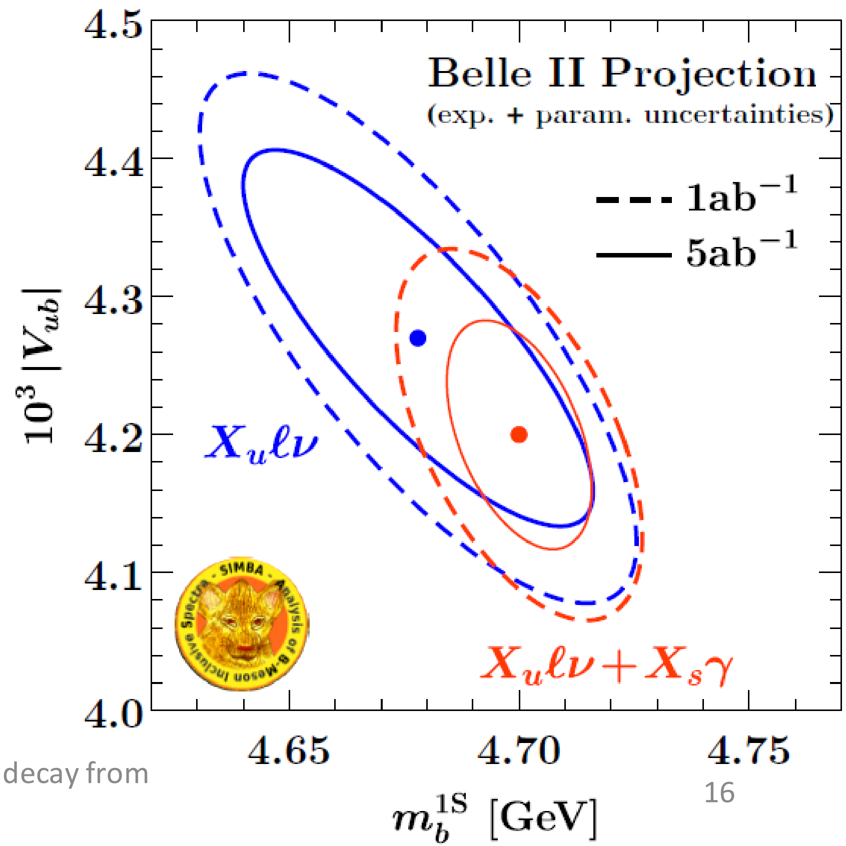
Soft pions used to identify D* and reduce $B \rightarrow X_c \, l \, \nu$ background.

V_{ub} is extracted from a model independent combined fit to:

$B \rightarrow X_u \, l \, \nu$, $B \rightarrow X_c \, l \, \nu$, $B \rightarrow X_s \, \gamma$

together with the parameters of the same shape function F(k) taking into account b quark momentum distribution inside B meson (SIMBA technique).

Belle II precise measurements of differential distributions will further constrain the fit.



Belle II expectations for V_{ub} from semileptonic decays

The Belle II Physics Book, arXiv:1808.10567

% uncertainties	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory Lattice projections	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
$\lvert V_{ub}\rvert$ 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

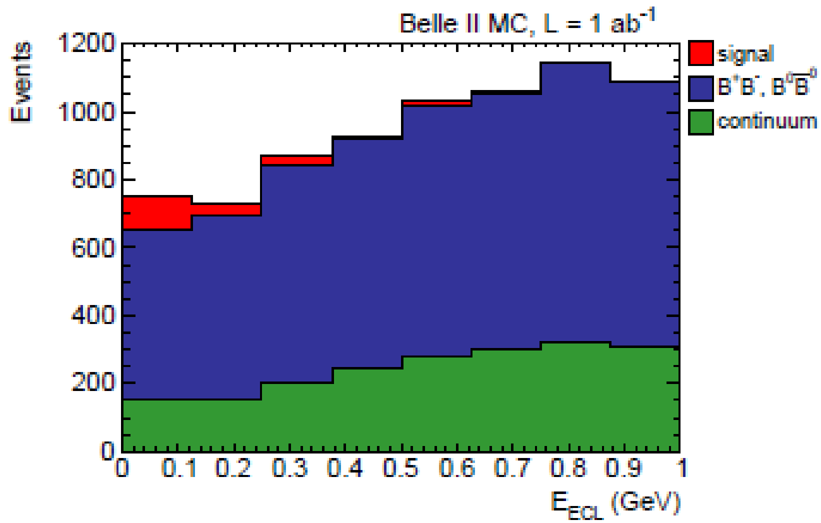
Large statistical sample and improved Belle II particle reconstruction will allow to reach ~ 1% experimental error on V_{ub}, both in the tagged and untagged exclusive channels, systematics dominated, and comparable with expected theory errors.

Inclusive channel has slightly higher systematics and larger theory error.

Belle II expectations for V_{ub} from $B \to \tau\nu$

$BR \propto |V_{ub}|^2 F_B^2 m_\tau^2$

- Both leptonic and hadronic tag
- Fully reconstruct tag side and lepton on signal side. > 1 ν in final state.
- E_{ECL} = energy sum of all neutral clusters not used for reconstruction
- Signal shows up as a low energy excess in E_{ECL} spectrum



	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\|V_{ub}\|$ $B \to \tau\nu$ (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	$\boxed{3.2}$
$\|V_{ub}\|$ $B \to \tau\nu$ (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	$\boxed{2.8}$

The Belle II Physics Book, arXiv:1808.10567

Conclusions

- **SuperKEKB machine has been commissioned and is starting stable run**
- **Belle II detector is fully installed and commissioned.**
- **0.5 fb^{-1} collected in 2018 during commissioning allow some first physics**
- **FEI techniques tested on data and very powerful**
- **First semileptonic B decays reconstructed with inclusive and exclusive analysis.**
- **Stay tuned for future results!**

SPARES

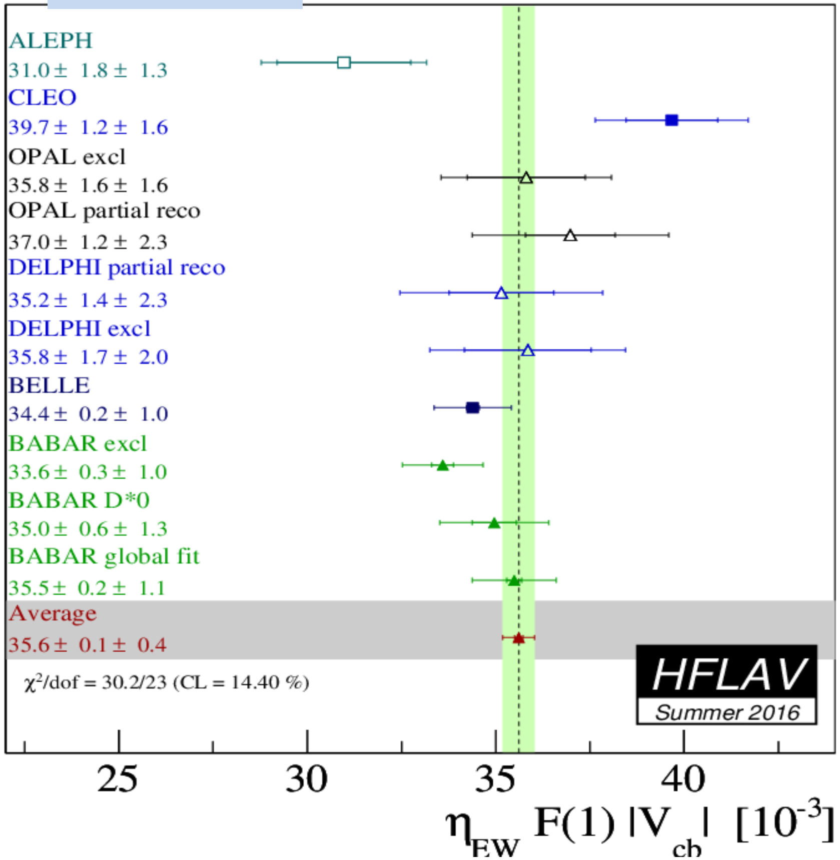
… x40 luminosity means also much higher background…!

…but Belle II is equipped with upgraded detectors capable to rescue rare signals and reject garbage !

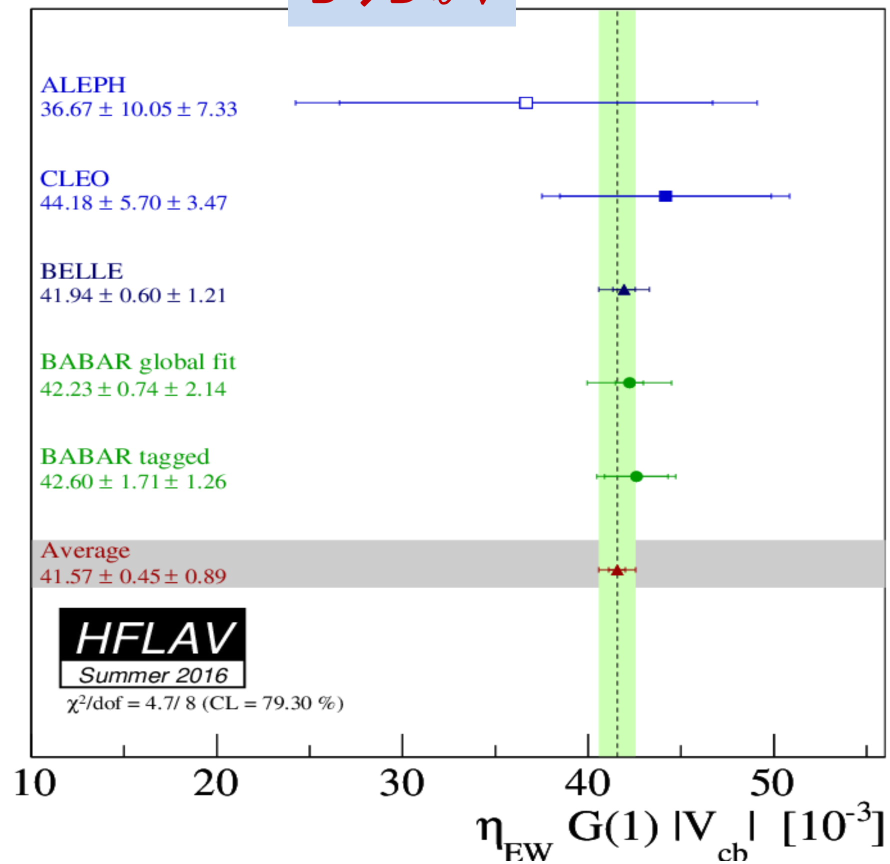
- A new and larger drift chamber: longer lever arm, smaller cells in the inner region, fast readout.
- An imaging Time of Propagation detector to perform PID in the barrel region
- A PID detector in the forward region (ARICH)
- An improved z resolution in the interaction region, thanks to Pixel (2 layers) + strip (4 layers) vertex detector.
- Fast ECL readout to reduce pile-up
- KLM 2 inner layers replaced with scintillators

Exclusive V_{cb}

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



$B \to D \ell \nu$



Both measurements are systematics limited !

V_{cb} determination from the 2 channels gives compatible results, but depends on FF parametrization: CLN vs BGL i.e. discrepancy or not with inclusive determination.

Belle II will reduce systematic uncertainty, mainly coming from hadronic tag calibration. Its large dataset can afford FF fit from differential $B \to D \ell \nu$ decay rates and help reducing theory error on parametrization.

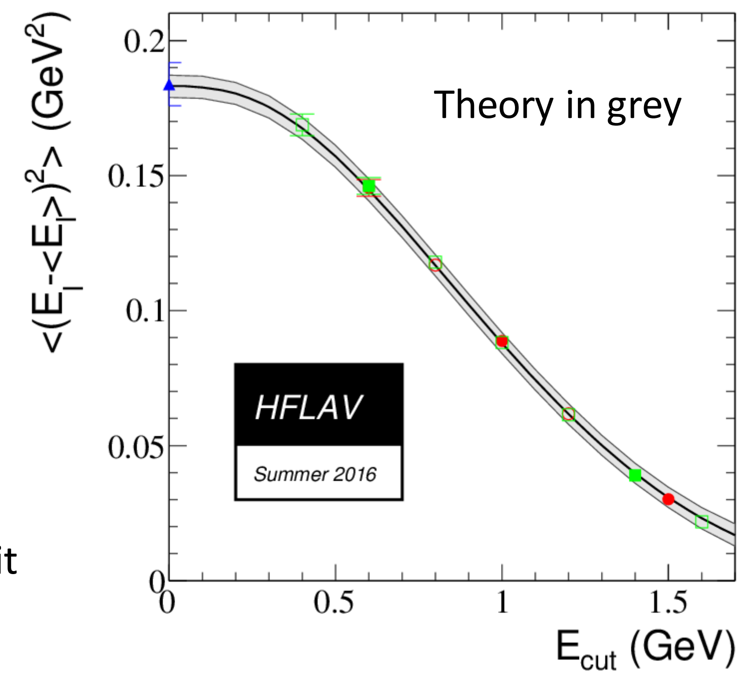
Inclusive V_{cb}

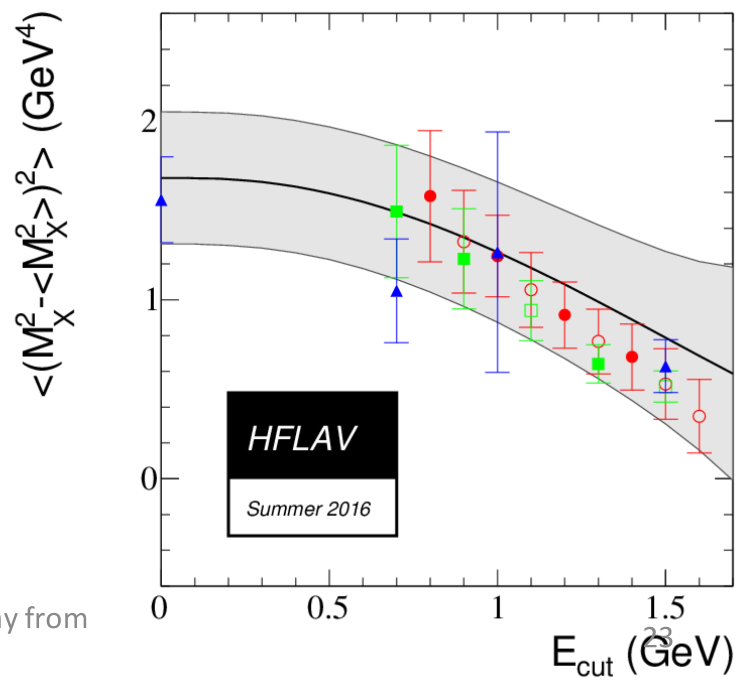
Perform a simultaneous fit of V_{cb}, the b and c quark masses and other OPE parameters, to the semileptonic inclusive width, the moments of the lepton energy spectrum and the moments of the hadronic mass spectrum squared.

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

HFLAV 2016 fit

actually dominated by theoretical uncertainties





Belle II large data set will allow accurate measurement of the E_l spectrum and of other momenta, and to test the validity of the OPE description at low energy, thus helping theorists to reduce errors.

Flavour tag at Belle II

$$\overline{B}^0 \to D^{*+}\ \overline{\nu}_\ell\ \ell^-$$
$$\hookrightarrow D^0\ \pi^+$$
$$\hookrightarrow X\ K^-$$

$$\overline{B}^0 \to D^+\ \pi^-\ (K^-)$$
$$\hookrightarrow K^0\ \nu_\ell\ \ell^+$$

$$\overline{B}^0 \to \Lambda_c^+\ X^-$$
$$\hookrightarrow \Lambda\ \pi^+$$
$$\hookrightarrow p\ \pi^-$$

Charged leptons, kaons, pions and Λ's allow to tag the B flavour without reconstructing it, thanks to quantum correlation of the two B mesons.

Multivariate discriminating algorithm provides optimized tagging, already tested on Belle data:

$$\varepsilon_{eff} = \Sigma_i\ \varepsilon_i(1\text{-}2w_i)^2 \quad , \quad w_i \text{ mistag probability}$$

Tagging efficiency improved by 10% already on Belle data.
Belle II will profit of its improved PID.

Old FT Belle data:	ε_{eff} =(30.1±0.4)%
New FT Belle data:	ε_{eff} =(33.6±0.5)%
New FT Belle MC:	ε_{eff} =(34.18±0.03)%
New FT Belle II MC:	ε_{eff} =(37.16±0.03)%

Long Term prospects for R(D*)

$$R_{D^{(*)}} = \frac{\mathrm{Br}\left(B \to D^{(*)}\tau\nu_\tau\right)}{\mathrm{Br}\left(B \to D^{(*)}\ell\nu_\ell\right)} \quad (\ell = e, \mu)$$