1) Vertexing performance driven by Flavour Physics at FCC-*ee* and 2) $|V_{cb}|$ possible improvements.

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Outline

- I will start by some specifics for Flavour Physics at FCC-ee.
- Two subjects gathered in this talk:

1) Complete decay chain reconstruction by means of the vertex distances measurements.

2) Normalisation matters ! $|V_{cb}|$ as a key observable for future optimal interpretation of *CP*-violating observables.

0) FCC-ee specifics for Flavour Physics.

0) FCC-ee specifics for Flavour Physics.

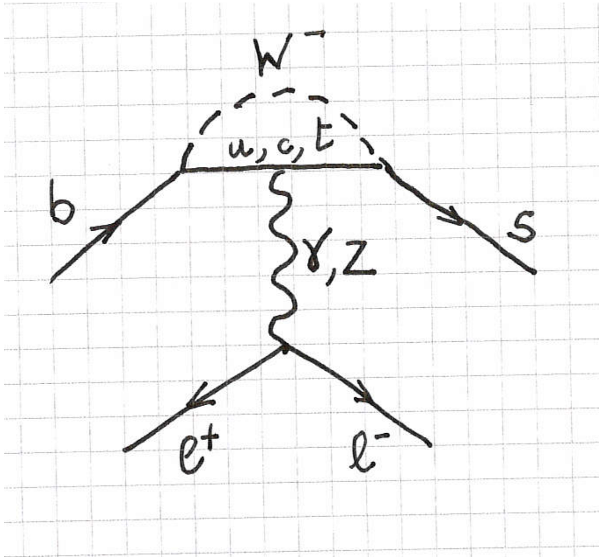
- A- Particle production:
  - About 15 times the Belle II anticipated statistics for B^0 and B^+.
  - All species of *b*-hadrons are produced.
  - Expect ~4.10^9 B_c-mesons assuming $f_{B_c}/(f_{B_u}+f_{B_d}) \sim 3.7 \cdot 10^{-3}$

Working point	Lumi. / IP $[10^{34}\ \mathrm{cm}^{-2}.\mathrm{s}^{-1}]$	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150

- B- The Boost at the *Z*:
  - Fragmentation of the *b*-quark: $\langle E_{X_b}\rangle = 75\% \times E_{\mathrm{beam}}; \langle\beta\gamma\rangle \sim 6.$
  - Makes possible a topological rec. of the decays w/ miss. energy.

1) Vertexing performance and Flavours:



1) Vertexing and Flavours: physics motivation (Damir)

- The LHCb experiment measured a set of observables in electroweak penguin (EWP) transitions of a *b* quark, which are found in persistent and consistent tensions w.r.t. the Standard Model predictions.

- In particular, the Lepton Flavour Universality in quark transitions is challenged. This is observed by comparing the rates of pairs of electrons and muons in the decays $B^0 \to K^{*0}\ \ell^+\ell^-$. FCC-*ee* shows a fantastic sensitivity to low q^2 *ee* final states. cLFV processes would come often naturally aside.

- Should these current tensions be confirmed, the next laboratory to guide the relevant model of the effect comes from transitions as $b \to s\tau^+\tau^-$. Even if they are not confirmed, this is a place to go, third generation couplings.

- The available statistics and the capacity to fully reconstruct the decay even in the absence of the tauonic neutrinos at FCC-*ee* is beyond foreseeable competition. The reconstruction of the mode $B^0 \to K^{*0}\ \tau^+\tau^-$ has received a special attention in the FCC-*ee* context.

1) Vertexing and Flavours: position of the problem

- The $b \rightarrow s\tau^+\tau^-$ transition implies two undetected particles in the decay chain.

- The backgrounds coming from double charm production in *b*-hadron chain are rich. The average charged-track multiplicity in b-hadron decays is large. $Ds \rightarrow \tau\nu$ is large.

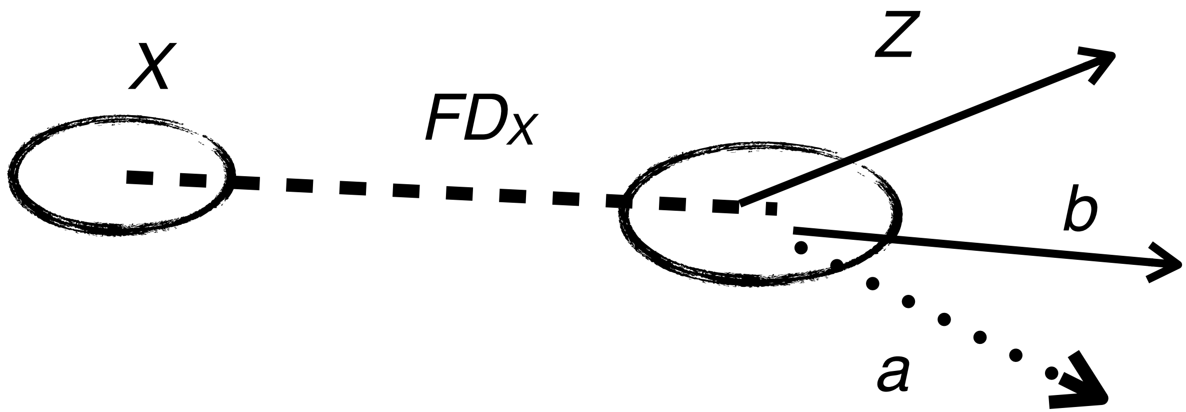
- The kinematic reconstruction of the neutrinos (or constraints on it) is key to beat the backgrounds.

- One would like in addition to use the actual kinematics of the decay to check for additional observables: angular analysis.

1) Vertexing and Flavours: reconstruction principle

- The state-of-the-art vertexing performance applied to FCC-*ee* allows to reconstruct the missing momentum in decays inferred from the decay flight distances. Counting the degree of freedoms.

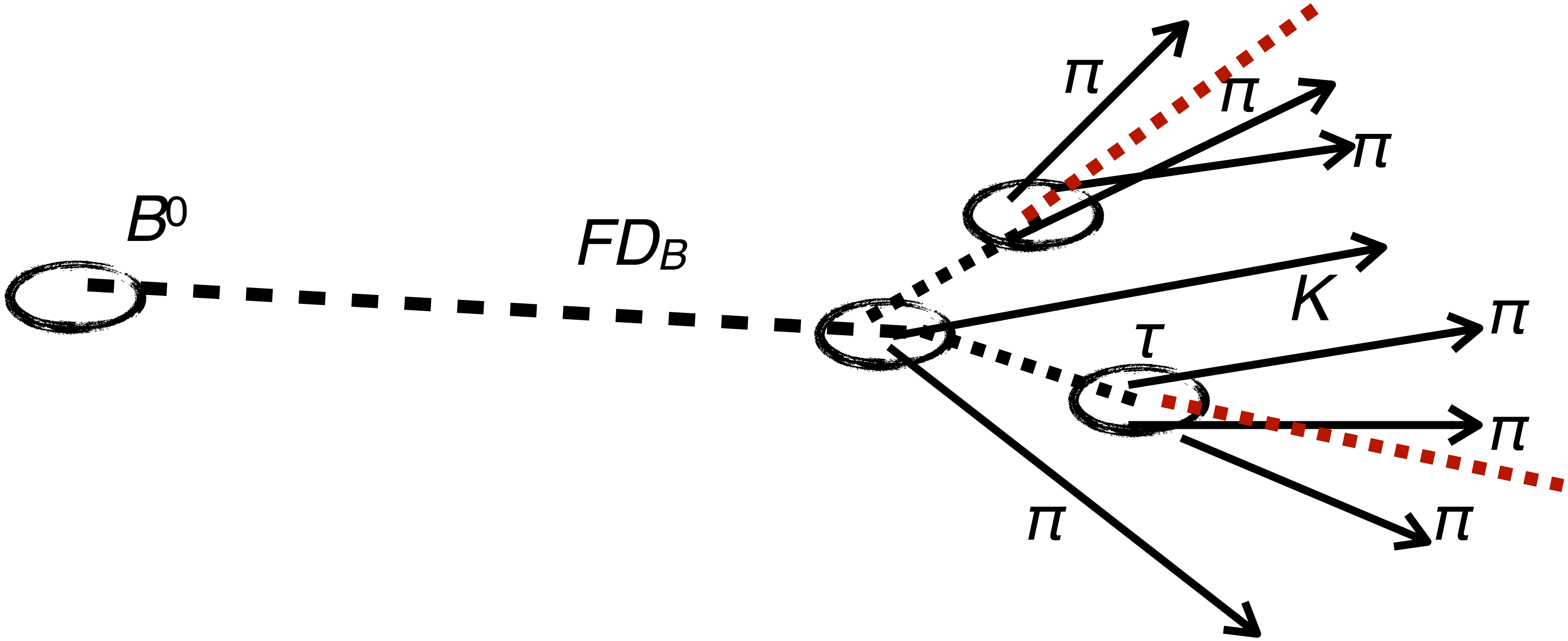
- Example: $X \rightarrow Y\,(\,Y \rightarrow [a]b\,)\,Z$ with *a* not reconstructed.



- Three momentum components to be searched for:
  - The measurement of *X* momentum direction fixes 2 d.o.f.
  - An additional constraint closes the system: m_Y or a tertiary vertex.
  - Usually, quadratic form of the constraints: solution up to an ambiguity.

1) Vertexing and Flavours: application to $B^0 \to K^{*0}\ \tau^+\tau^-$

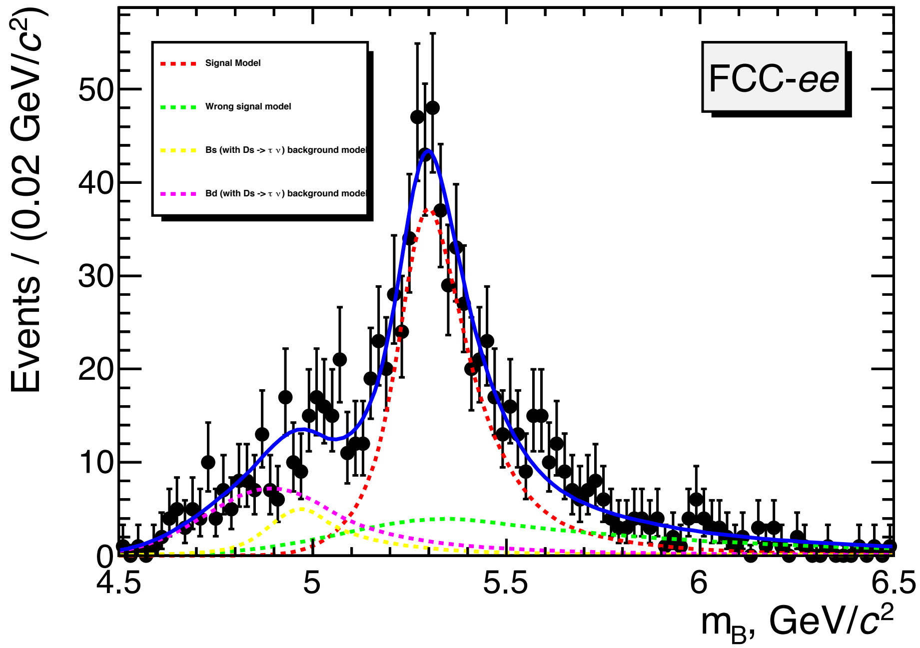
- Example: $B^0 \to K^{*0}\ \tau^+\tau^-$.



- Six momentum components to be searched for:
  - B^0 momentum direction from $K\pi$ fixes 2 d.o.f.
  - τ momenta direction fixes 4 d.o.f.
  - Mass of the τ provides 2 additional constraints
  - The system is in principle over-constrained.

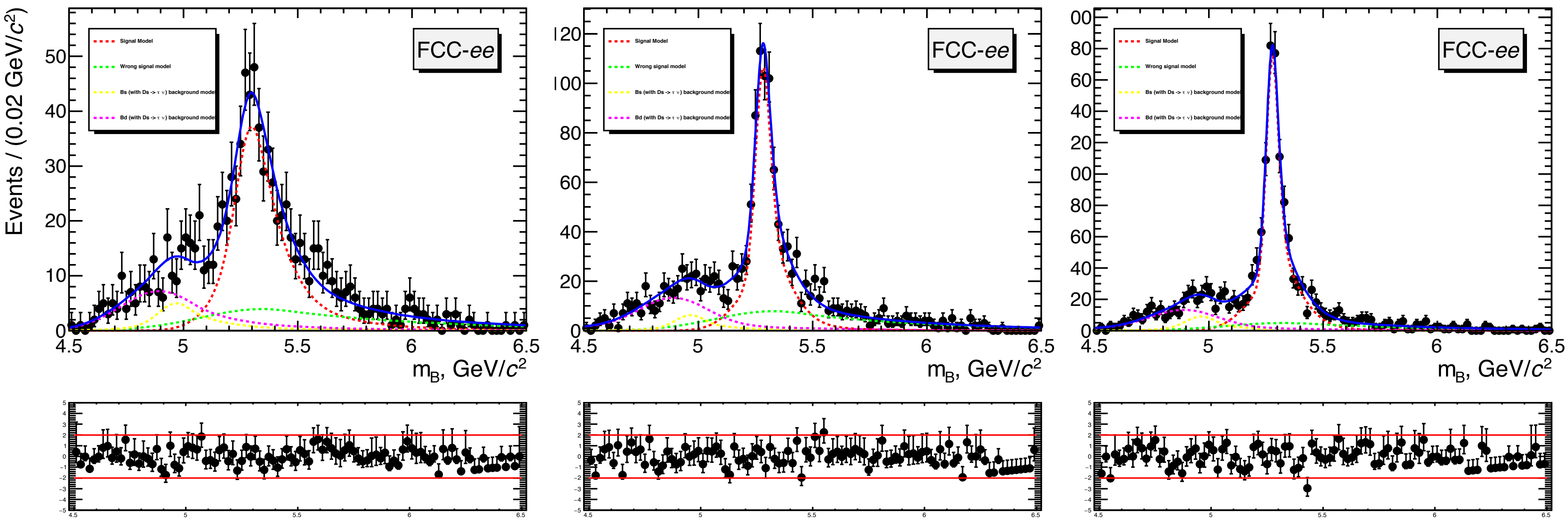
1) Vertexing and Flavours: application to $B^0 \to K^{*0}\ \tau^+\tau^-$

- Makes use of partial reconstruction technique to solve the kinematics of the decay.
- Fast simulation of signal and backgrounds (Pythia + EvtGen + parametric tracker and vertex detector).
- Backgrounds: (pink - DsK*taunu and yellow DsDsK*) [signal in red+green].
- Conditions: baseline luminosity, SM calculations of signal and background BF, vertexing and tracking performance as ILD detector. **Primary vertex** → 3 um, **SV** → 7 um, **TV** → 5 um



- At baseline luminosity, under SM hypothesis, about 10^3 events of reconstructed signal. O(5%) on BF.

1) Vertexing and Flavours: evolution of performance



Performance / Conditions	ILD-like	ILD /2	ILD / 4
Efficiency of the identification of the correct solution (%)	42,3	52,6	62
Invariant mass resolution (core) [MeV/c^2]	42(1)	36(1)	27(1)

Invariant mass resolution is key to beat the backgrounds. Not at the limit yet !

1) Vertexing performance and Flavours.

- With state-of-the-art vertexing performance, O(5%) measurement of the BF at SM value at reach in FCC-ee.
- Initial work completed on fast simulation (experimentally) AND phenomenologically [hep-ph 1705.11106, LVSilva et al.].
- Next step is to evaluate the sensitivity on the measurements of the branching fraction differential in q^2 and the additional observables of angular analysis of the decay.
- Since very demanding requirements, made it a case study for vertex detector (and beam-pipe) design.
- Note: likely not only vertex-detector oriented: check the absence of calorimeter deposit in each of the neutrinos direction. This challenges simultaneously the granularity of the calorimetric apparatus and the angular resolution from partial reconstruction tracking. Also π^0 reconstructed in the tau decay chains would improve dramatically the statistics.

2) $|V_{cb}|$: a key observable

2) $|V_{cb}|$ measurement: physics motivation

- The $|V_{cb}|$ element of the CKM matrix makes the normalisation of the unitarity triangle.
- Though the Unitarity is better displayed in the (ρ, η) plane, any profile of the CKM matrix requires the knowledge of *A*, primarily given by $|V_{cb}|$ measurement.
- $|V_{cb}|$ is usually determined from semileptonic decays of *b*-hadrons. Requires the knowledge of form factors of the decays. Significant hadronic (theoretical uncertainties).
- We are entering a time (already for the LHCb upgrade II) where normalisation matters. It will likely limit the EW interpretation of *CP*-observables. Search for BSM in $\Delta F = 2$ processes is one example of it.
- FCC-ee offers, at WW threshold, a new avenue for its measurement.

2) $|V_{cb}|$ measurement: position of (Flavour) problem

- Quasi-model-independent approach to constrain BSM Physics in neutral meson mixing processes

$$\langle B_q | \mathcal{H}^{\rm SM+NP}_{\Delta B=2} | \bar{B}_q \rangle \equiv \langle B_q | \mathcal{H}^{\rm SM}_{\Delta B=2} | \bar{B}_q \rangle \times (\mathrm{Re}(\Delta_q) + i\,\mathrm{Im}(\Delta_q))$$

$$\mathrm{Re}(\Delta_q) + i\mathrm{Im}(\Delta_q) = r_q^2 e^{i2\theta_q} = 1 + h_q e^{i\sigma_q}$$

Soares & Wolfenstein, PRD 47, 1021 (1993)
Deshpande, Dutta & Oh, PRL77, 4499 (1996)
Silva & Wolfenstein, PRD 55, 5331 (1997)
Cohen et al., PRL78, 2300 (1997)
Grossman, Nir & Worah, PLB 407, 307 (1997)

Assumptions:

✓only the short distance part of the mixing processes might receive NP contributions.

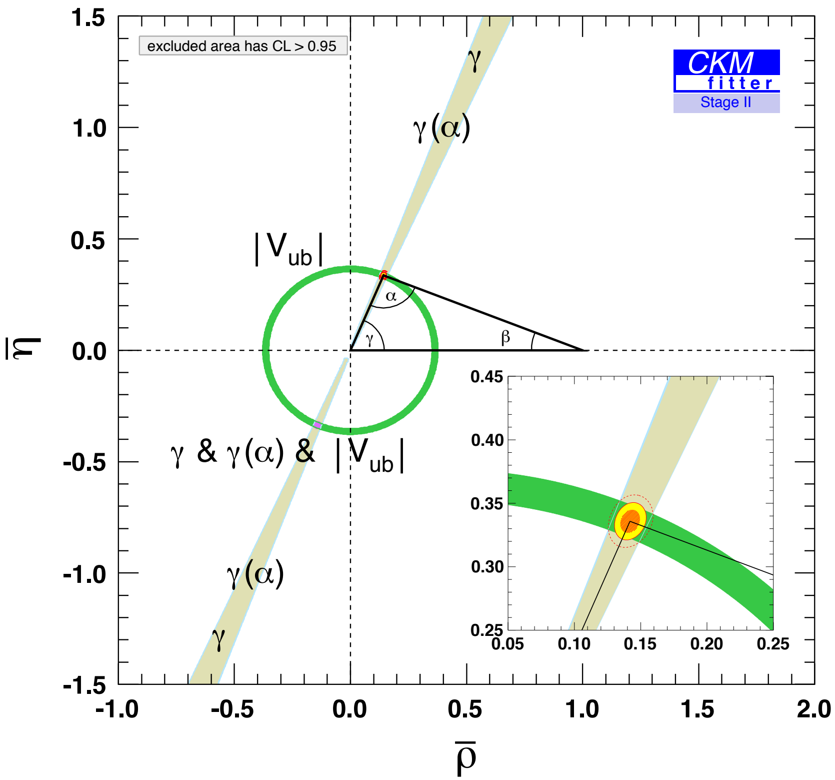
✓Unitary 3x3 CKM matrix.

✓ tree-level processes are not affected by NP (so-called SM4FC: $b \to q_i q_j q_k$ ($i \neq j \neq k$)). As a consequence, the quantities which do not receive NP contributions in that scenario are:

$$|V_{ud}|,\ |V_{us}|,\ |V_{ub}|,\ |V_{cb}|,\ B^+ \to \tau^+ \nu_\tau \text{ and } \gamma$$

2) $|V_{cb}|$ measurement: position of (Flavour) problem

- The unitarity triangle: fixing CKM parameters. This is the anticipated landscape after Belle II and LHCb upgrade.



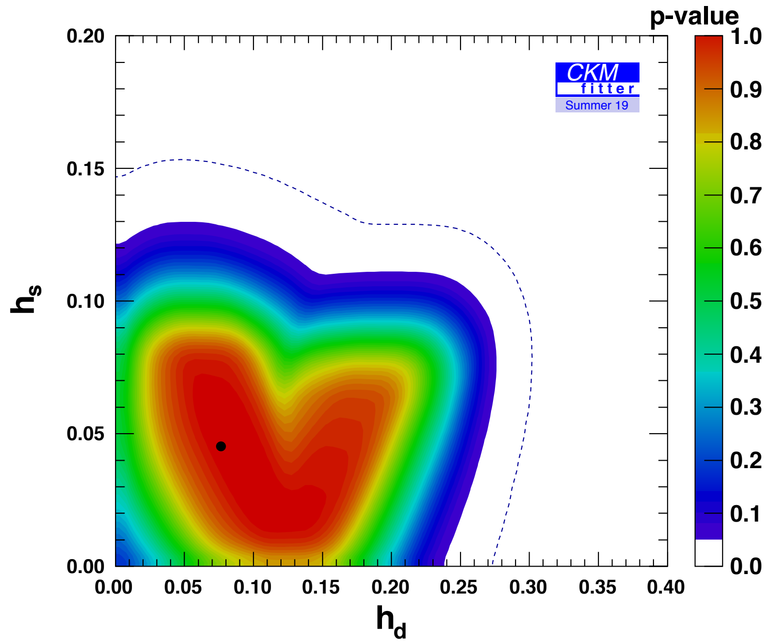
- Knowing the CKM parameters, one can introduce the constraints of the *B* mixing observables depending on the NP complex number (here parameterised as $\Delta_q = |\Delta_q| e^{i2\Phi_q^{\mathrm{NP}}}$).

parameter	prediction in the presence of NP
Δm_q	$\lvert\Delta_q^{\mathrm{NP}}\rvert \times \Delta m_q^{\mathrm{SM}}$
2β	$2\beta^{\mathrm{SM}} + \Phi_d^{\mathrm{NP}}$
$2\beta_s$	$2\beta_s^{\mathrm{SM}} - \Phi_s^{\mathrm{NP}}$
2α	$2(\pi - \beta^{\mathrm{SM}} - \gamma) - \Phi_d^{\mathrm{NP}}$
$\Phi_{12,q} = \mathrm{Arg}[-\frac{M_{12,q}}{\Gamma_{12,q}}]$	$\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}}$
A_{SL}^q	$\frac{\Gamma_{12,q}}{M_{12,q}^{\mathrm{SM}}} \times \frac{\sin(\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}})}{\lvert\Delta_q^{\mathrm{NP}}\rvert}$
$\Delta\Gamma_q$	$2\lvert\Gamma_{12,q}\rvert \times \cos(\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}})$

2) $|V_{cb}|$ measurement: position of (Flavour) problem

- Pheno. work in preparation on the perspectives of this model-independent analysis at future facilities (Phase I is LHCb-upgrade + Belle II, Phase II stands for LHCb upgrade II and Belle upgrade, Phase III is FCC-ee). Main conclusions here.

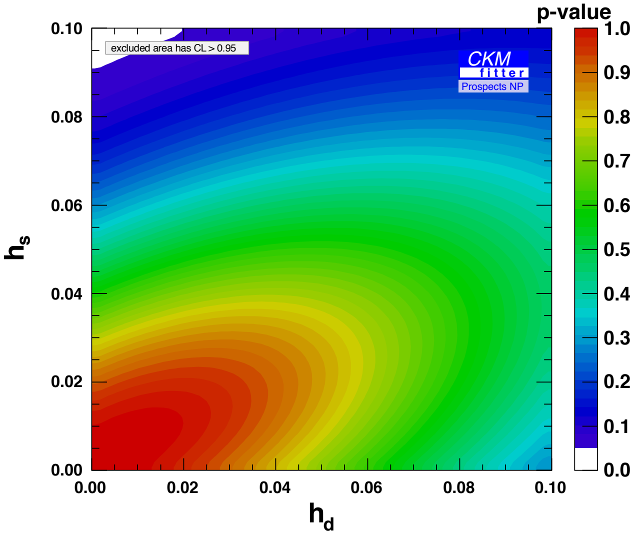
[Constrains as of today.]



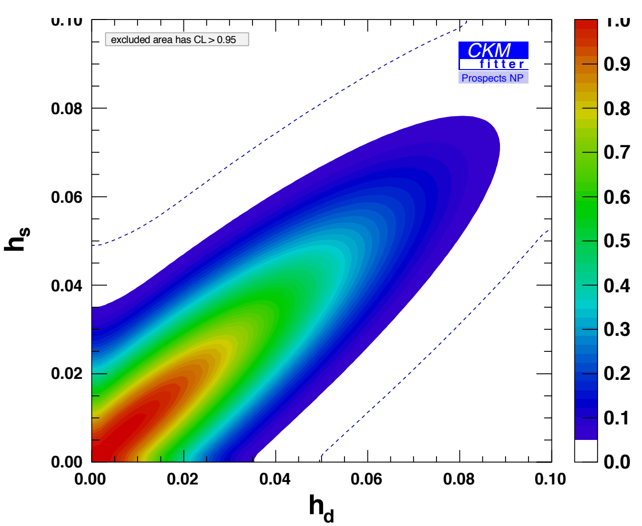
[Z. Ligeti, M. Papucci and CKMfitter, in preparation]

- The constraint is in fair agreement w/ the SM prediction (h=0, σ=0).
- Still significant room O(25%) for BSM contributions.
- When converted to BSM energy scale at natural O(1) couplings, the NP limit is O(PeV).

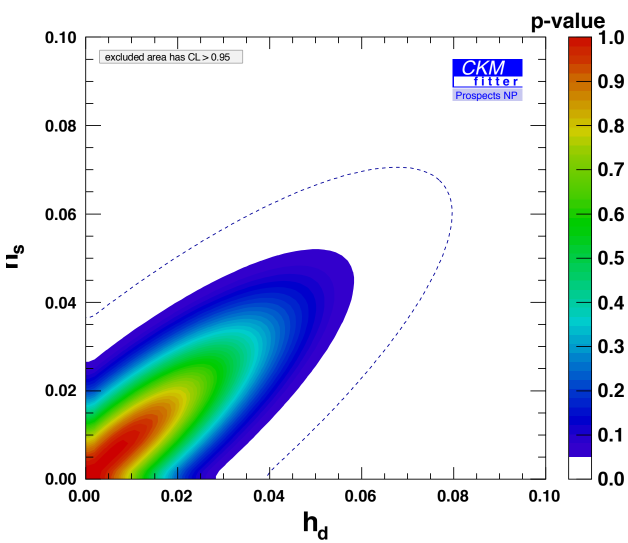
2) $|V_{cb}|$ measurement: position of problem



- The SM is now taken as a reference. What is the NP parameter space that one can constrain? [Z. Ligeti, M. Papucci and CKMfitter, in preparation]
- Large improvement from now to Phase I. Less dramatic progresses afterwards.



~late 202x:
Belle II + LHCb Upgrade I



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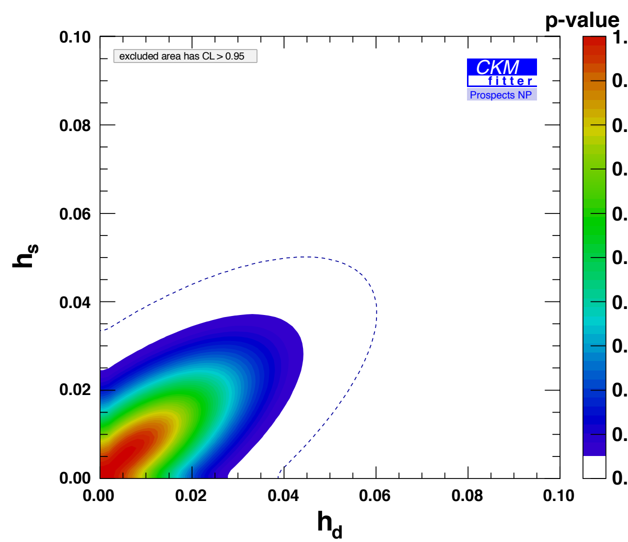
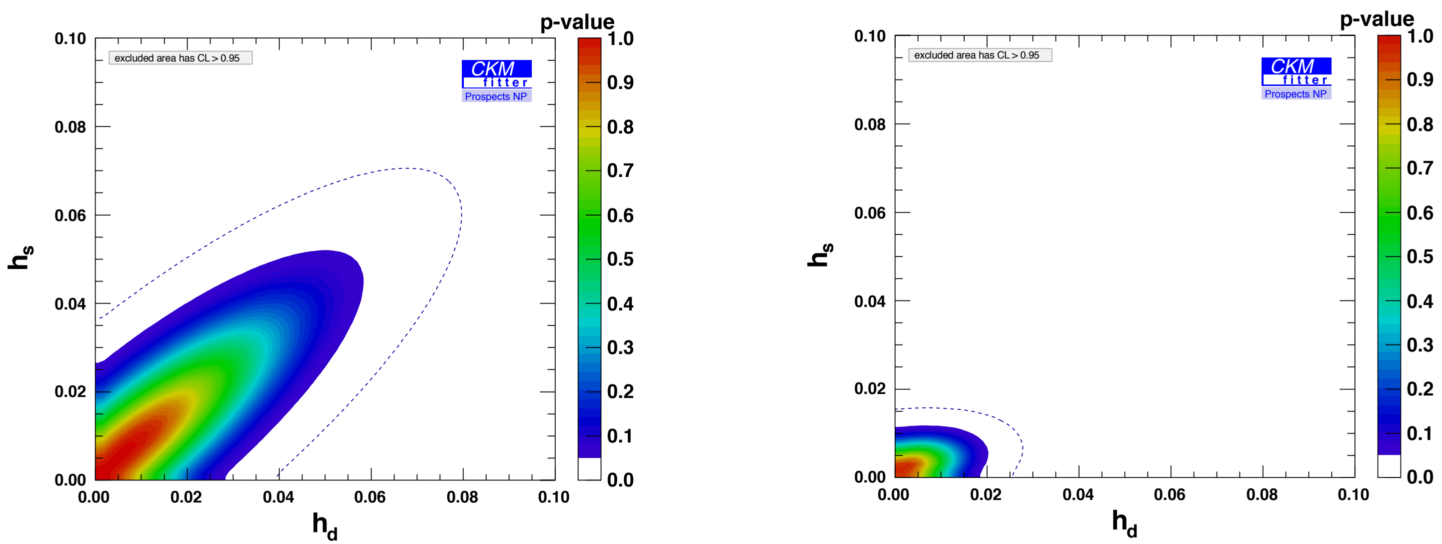
Belle II (250 /ab) + LHCb U. II



204x:
FCC-*ee*

2) $|V_{cb}|$ measurement: position of the problem

- The precision does not improve as it should from Phase I to Phase II and III.
- Two bottlenecks: $|V_{cb}|$ precision and the hadronic parameters of the mixings (LQCD).The phase II precision as an example.



- Remove the uncertainties on $|V_{cb}|$ and hadronic parameters. Keep the other observables as they are expected to be measured.

2) $|V_{cb}|$ measurement: position of the problem

- Lessons (in particular) for FCC-*ee*

- ΔF = 2 processes (K, B^0 and B_s mixing observables) are powerful tools to search for / constrain BSM contributions. They are only on aspect of what can be accessed.

- When reaching the precision attainable at FCC-ee (already true at an earlier Phase), two bottlenecks were identified: $|V_{cb}|$ is a one of them. Interplay of $|V_{cb}|$ precision w/ the uncertainties of the hadronic parameters of the mixings (LQCD).

- At FCC-*ee*, the precision on mixing hadronic parameters considered here corresponds to LQCD anticipations devised at HL-LHC period. It has to be re-investigated for FCC-*ee* times to make the best of the statistical gains.

- Yet, FCC-*ee* can be a game changer for $|V_{cb}|$.

2) $|V_{cb}|$ measurement: the WW threshold

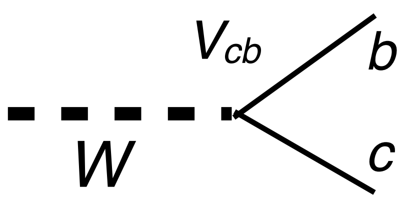
- First look by Marie-Hélène Schune here.

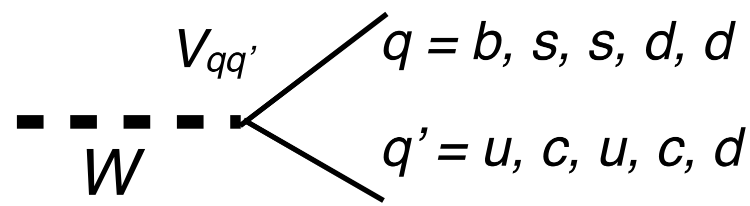
$$V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Make a measurement at high-$p_{\rm T}$.

$$V_{\rm CKM} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

- Use the WW threshold: 10^8 pairs w/ ~67% quarks.





- $N_{\rm sig}$ (10^3) ~ 230 10^3
- $N_{\rm bkg}$ (10^6) ~ 1.7 10^{-3},127, 6.8, 6.8, 127

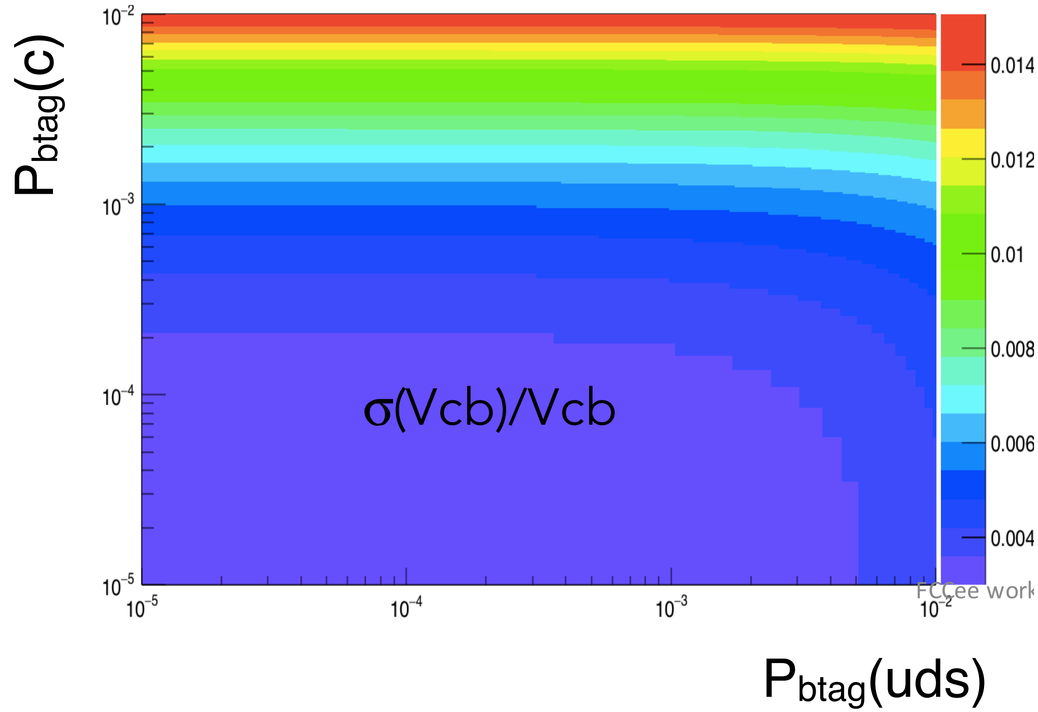
- Name of the game is the *b*- and *c*- jet-tagging purity (efficiency).

2) $|V_{cb}|$ measurement: the WW threshold

- First look by Marie-Hélène Schune here.

Eff. \ *q*-jet	*b*-jet	*c*-jet	*uds*-jet
b-tag	25 %		
c-tag	10 %	50 %	2 %

- Numbers picked from *Tracking and Vertexing at Future Linear Colliders: Applications in Flavour Tagging* — Tomohiko Tanabe. ILD@ILC. IAS Program on High Energy Physics 2017, HKUST



- With these state-of-the-art inputs, precision on $|V_{cb}|$ improves from 1.9% (current) to 0.4%. Ultimate statistical precision is $O(10^{-4})$.

- Actual study in order. A driver for the *b*- and *c*- tagging performance.

3) Conclusions

- Flavour Physics defines shared (vertexing, tracking, calorimetry) and specific (hadronic PID) detector requirements. The next phase of the program will entangle the Physics reach and detector concepts.

- This will happen through the case studies at the immediate next stage of the project.

- Two examples of them were provided in this talk. (We have seen one more in G. Wilkinson's talk, yesterday).

  - At least 5 10^{12} Z decays are wished for the broad case of Flavours (most of the measurements are statistically limited).
  - The WW threshold is important as well for Flavours.
  - Theory progresses, as for the EWK observables , are in order to benefit for the precision.

4) Back-ups

	Central value	Current	Uncertainties Phase I	Phase II	Phase III	Reference
$\lvert V_{ud}\rvert$	0.97437	±0.00021	id	id	id	[17]
$\lvert V_{us}\rvert f_+^{K\to\pi}(0)$	0.2177	±0.0004	id	id	id	[17]
$\lvert\epsilon_K\rvert \times 10^3$	2.240	±0.011	id	id	id	[17]
$\lvert V_{cd}\rvert$	0.225	±0.0043	±0.003	id	id	[18]
$\lvert V_{cs}\rvert$	0.973	±0.0094	id	id	id	[18]
Δm_d [ps^{-1}]	0.5065	±0.0019	id	id	id	[16]
Δm_s [ps^{-1}]	17.757	±0.021	id	id	id	[16]
$\lvert V_{cb}\rvert_{\rm SL} \times 10^3$	42.26	±0.58	±0.60	±0.44	id	[19, 20]
$\lvert V_{cb}\rvert_{W\to cb} \times 10^3$	—	—	—	—	±0.17	[21]
$\lvert V_{ub}\rvert_{\rm SL} \times 10^3$	3.56	±0.22	±0.042	±0.032	id	[19]
$\lvert V_{ub}/V_{cb}\rvert$ (from Λ_b)	0.0842	±0.0050	±0.0025	±0.0008	id	[20]
$\mathcal{B}(B\to\tau\nu)\times 10^4$	0.83	±0.24	±0.04	±0.02	±0.009	[19]
$\mathcal{B}(B\to\mu\nu)\times 10^6$	0.37	—	±0.03	±0.02	id	[19]
$\sin 2\beta$	0.680	±0.017	±0.005	±0.002	±0.0008	[19, 20]
α [°] (mod 180°)	91.9	±4.4	±0.6	id	id	[19]
γ [°] (mod 180°)	66.7	±5.6	±1	±0.25	±0.20	[19–21]
β_s [rad]	−0.035	±0.021	±0.014	±0.004	±0.002	[20, 21]
$A^d_{\rm SL}\times 10^4$	−6	±19	±5	±2	±0.25	[14]
$A^s_{\rm SL}\times 10^5$	3	±300	±70	±30	±2.5	[14]
$\mathcal{B}(B_s\to\mu\mu)\times 10^9$	3.45	±0.66	±0.34	±0.17	id	[20]
$\mathcal{B}(B_d\to\mu\mu)\times 10^{11}$	10.4	—	±3.5	±1.0	id	[20]
$\mathcal{B}(B_d\to\mu\mu)/\mathcal{B}(B_s\to\mu\mu)$	0.030	—	±0.010	±0.003	id	[20]
$\bar m_c$ [GeV]	1.288	±0.012	±0.005	id	id	[20]
$\bar m_t$ [GeV]	165.30	±0.32	id	id	±0.020	[17]
$\alpha_s(m_Z)$	0.1185	±0.0011	id	id	±0.00003	[17]
$f_+^{K\to\pi}(0)$	0.9681	±0.0026	±0.0012	id	id	[20]
f_K [GeV]	0.1552	±0.0006	±0.0005	id	id	[20]
B_K	0.774	±0.012	±0.005	±0.004	id	[20]
f_{B_s} [GeV]	0.2315	±0.0020	±0.0011	id	id	[20]
B_{B_s}	1.219	±0.034	±0.010	±0.007	id	[20]
f_{B_s}/f_{B_d}	1.204	±0.007	±0.005	id	id	[20]
B_{B_s}/B_{B_d}	1.054	±0.019	±0.005	±0.003	id	[20]
$\tilde B_{B_s}/\tilde B_{B_d}$	1.02	±0.05	±0.013	id	id	[22, 23]
$\tilde B_{B_s}$	0.98	±0.12	±0.035	id	id	[22, 23]
η_B	0.5522	±0.0022	id	id	id	[24]

TABLE I. Central values and uncertainties used in our analysis. Central values have been adjusted to eliminate tensions when moving to the smaller uncertainties typical of the future projections. The entries "id" refer to the value in the same row in the previous column. The assumptions entering Phase I, Phase II and Phase III estimates are described in the text.

[Z. Ligeti, M. Papucci and CKMfitter, in preparation]

Couplings	NP loop order	Present Sensitivity [TeV] B_d mixing	Present Sensitivity [TeV] B_s mixing	Phase I Sensitivity [TeV] B_d mixing	Phase I Sensitivity [TeV] B_s mixing	Phase II Sensitivity [TeV] B_d mixing	Phase II Sensitivity [TeV] B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V^*_{tj}\rvert$	tree level	9	13	17	18	20	21
(CKM-like)	one loop	0.7	1.0	1.3	1.4	1.6	1.7
$\lvert C_{ij}\rvert = 1$	tree level	1×10^3	3×10^2	2×10^3	4×10^2	2×10^3	5×10^2
(no hierarchy)	one loop	80	20	2×10^2	30	2×10^2	40