FLAVOR PHYSICS AND FCC-ee

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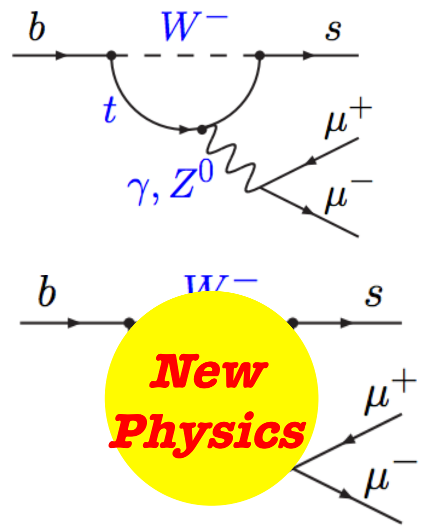
Most of material stolen from:

- https://fcc-cdr.web.cern.ch
- Stephane Monteil: https://cernbox.cern.ch/index.php/s/9ZuIudM8cUATaZD
- Marie Helene Schune: https://indico.cern.ch/event/838435/contributions/3635812/attachments/1971221/3279502/FCCee_17Jan2020_v2.pdf

THE FLAVOR PHYSICS CASE

Main outcome of LHC Run1-2:
1) Discovery of a SM Higgs-like boson
2) No direct observation of new physics particles

$\Rightarrow$ New physics scale is higher than expected



Flavor physics can explore higher scales than the energy of the collisions already now
- Large number of tests of SM consistency performed
- Intriguing anomalies at hands to be further investigated
- Most measurements are currently statistically dominated

➔ **the case for keeping doing flavor physics is stronger than ever!**

$$\boxed{\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_{NP}}{\Lambda^2}}$$

NP coupling

NP scale

It is smart investigating flavor physics capabilities for future accelerator projects, and taking into account flavor physics needs in the design of the detectors.

INGREDIENTS FOR B PHYSICS

- **Large sample of b-hadrons! For this FCC-ee at Z pole is good**

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	B^-	B_s^0	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	800	220

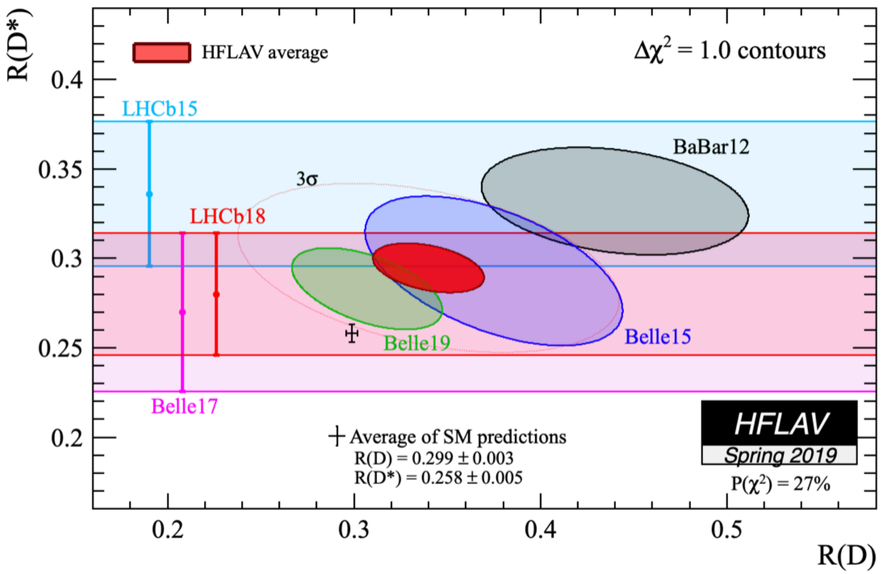
- ~15 times Belle II anticipated statistics.
- All species of *b*-hadrons are produced.
- Boost at the *Z*: topological reconstruction of the decays.
- Effective flavour tagging efficiency can be expected at 10% level.

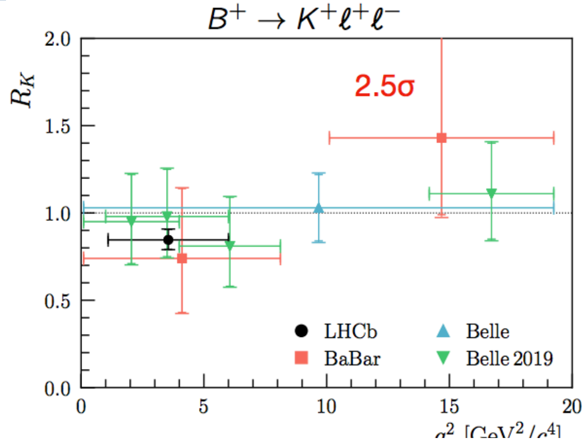
But also need:

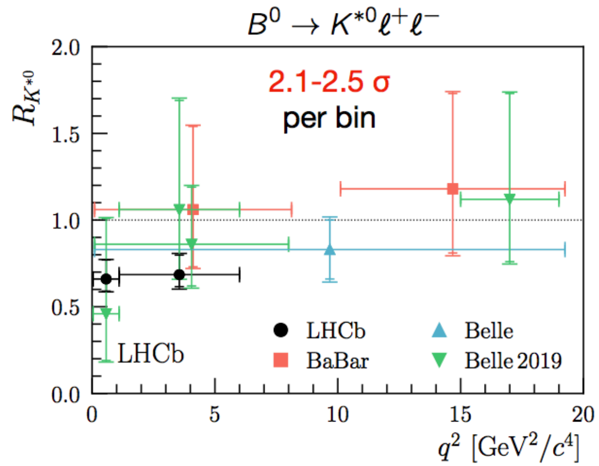
- **Vertexing capabilities** (need to reconstruct primary and secondary vertices). Excellent vertex resolution has a direct impact on the B mass resolution.
- **Particle identification capabilities** for unambiguos exclusive reconstruction of final states
- **Light tracking systems** (low X0) to reduce the bremsstrahlung emissions from electrons

ALL THIS POSSIBLY **PUSHED AT THE HIGHEST POSSIBLE PERFORMANCES**.

B ANOMALIES TODAY



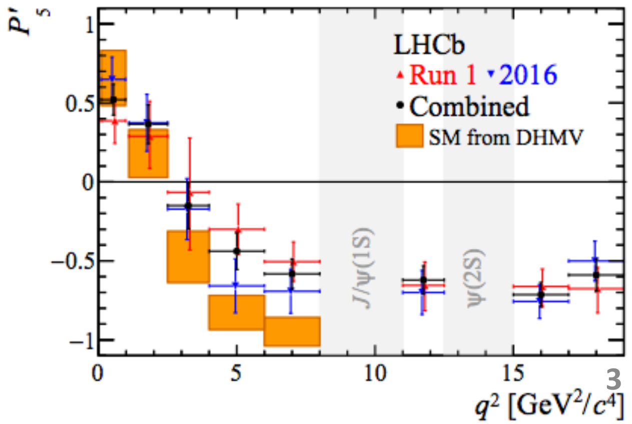




- Anomalies are observed in b->sll and b->clnu transitions.

- The measurements involve multiple decays and multiple observables, some particularly clean (i.e. lepton universality tests in b->sll).

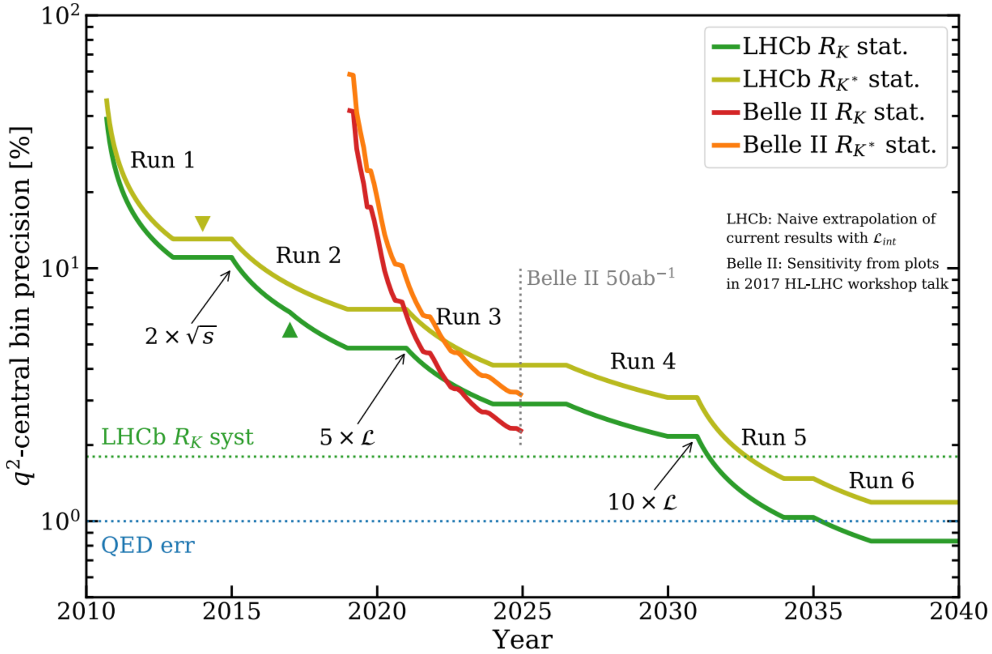
- **Combined interpretations underline a possible new physics sensitive to the lepton flavor and strongly coupled to the third generation.**



B ANOMALIES IN THE FUTURE

- Anomalies will be further investigated at Belle 2 and high-lumi LHC.

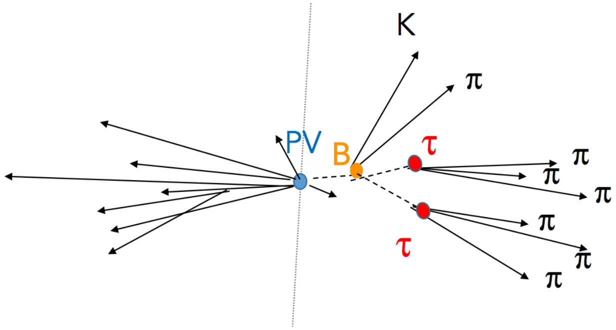
- By the time FCC is built we will know if they are confirmed or not.

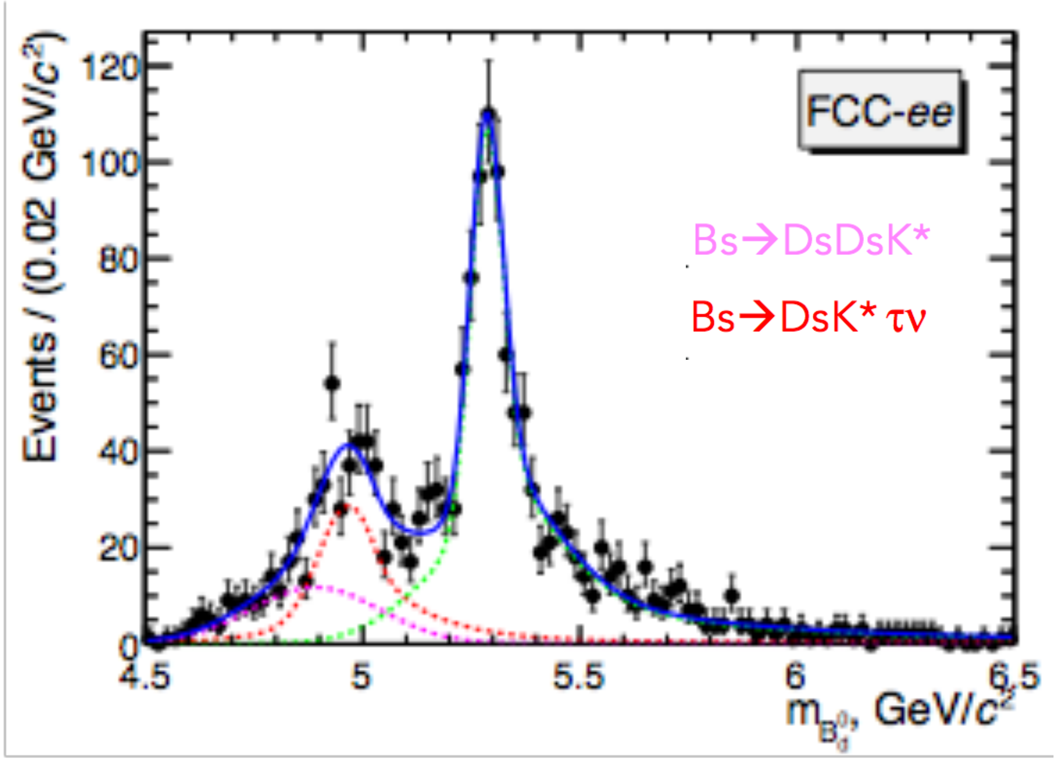


- If not confirmed => only FCC would provide enough data to observe B->K*tau tau as well as other b->dll transitions (suppressed by a factor 20 w.r.t. b->sll), providing new sensitive probes to search for new physics.

- If confirmed => new physics will need to be investigated further in the flavour sector. Observables like angular distributions in B->K*tau tau and similar decays can provide additional information on the nature of the new physics.

B) CDR: Rare decays & anomalies — $B^0 \to K^{*0}\ \tau^+\tau^-$.



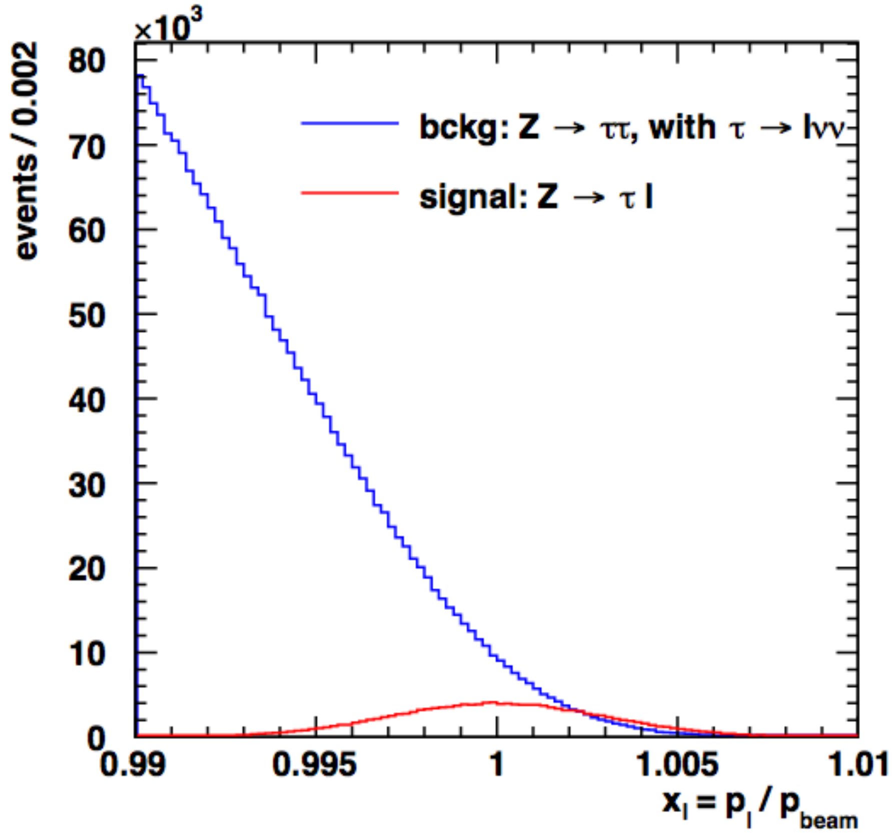


- Topological reconstruction of the missing energy with meas. of the decay vertices.
- Background estimates from generic double-charmed decays at SM values w/proxies (no meas. available).
- Vertex detector can be very close to the beam pipe. Considered ILD-like vertexing performance.
- Focus here on the charged-only three-prongs decays of the taus.

Bottomline: several thousands of decays can be reconstructed, if the branching fraction is at SM value. *O*(5%) precision on BF. Angular analyses can be performed [arXiv:1705.11106].

E) CDR: Lepton Flavour Violating-Z decays

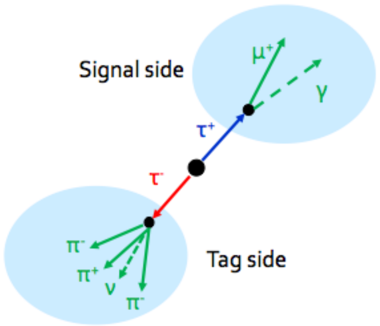
- Lepton Flavour-Violating Z decays in the SM with lepton mixing are typically $< 10^{-50}$.
- Any observation of such a decay would be an indisputable evidence for New Physics. FCC-*ee* exploration [JHEP 1504 (2015) 051].
- The dominant background is ($Z \rightarrow \tau\tau$), where one tau decays into a close to beam energy lepton. The search is limited by the momentum resolution.

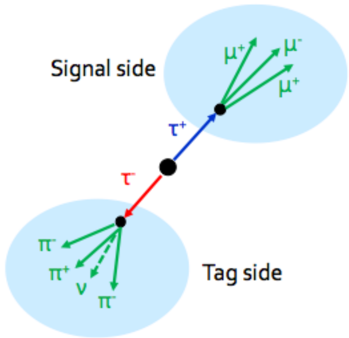


Bottomline: With the expected tracking performance at FCC-*ee*, the current limits are pushed b
three orders of magnitude.

$$\mathcal{B}(Z \to \tau^{\pm}\ell^{\mp}) < 10^{-9} \text{ @ } 95\% \text{ C.L.}$$

F) CDR: Lepton Flavour Violating-τ decays





Visible Z decays	3×10^{12}
$Z \rightarrow \tau^+\tau^-$	1.3×10^{11}
1 vs. 3 prongs	3.2×10^{10}
3 vs. 3 prong	2.8×10^{9}
1 vs. 5 prong	2.1×10^{8}
1 vs. 7 prong	< 67,000
1 vs 9 prong	?

- Benefits from the huge statistics and boosted topologies.
- Calorimetric performance as ILD.
- Main backgrounds are initial and final state radiative events.

Decay	Current bound	FCC-ee sensitivity
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2×10^{-8}	10^{-10}

Bottomline: the current limits can be pushed by one to two orders of magnitude.

CP VIOLATION

(From S. Monteil, Seminaire GT01 Lyon, Mars 2020)

- FCC-*ee* competes favourably with both Belle II and LHCb upgrade, as far as *CP* observables are concerned.

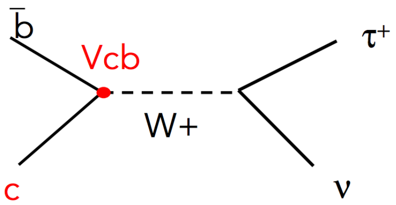
- One of the main limitation of the analysis of NP in mixings is the normalisation of the CKM profile through V_{cb}.. The possibility of determining it at the *WW* threshold is a game changer.

- Flavour Physics and Electroweak precision tests are intertwined. The exclusive reconstruction tags, as pioneered in *B*-factories, can serve the precision of measurements as R_b or $A_{\mathrm{FB}}(bb)$.

- The design study explored territories where FCC-*ee* is unique.

- The comprehensive exploration is yet to perform.

V_{cb} from $B_c \to \tau\nu$



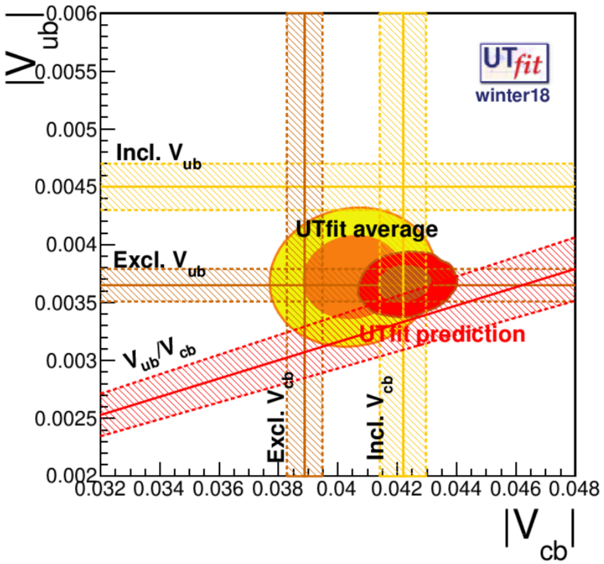
$$\Gamma_{SM}(P^+ \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi}|V_{Qq}|^2 f_P^2 M_P m_\ell^2 (1-\frac{m_\ell^2}{M_P^2})^2$$

with NP : $\Gamma_{H^\pm}(P^+ \to \ell^+\nu_\ell) = \Gamma_{SM}(P^+ \to \ell^+\nu_\ell) \times \left(1 - \frac{\tan^2\beta}{M_H^2} M_P^2\right)^2$

Large missing energy
Use of the other hemisphere

About 20 10^6 $B_c \to \tau\nu$ with $\tau \to e/\mu\,\nu$ produced

1% precision should be achievable



$$\frac{N_{B_c}}{N_{B_u}} = \frac{f(b\to B_c)}{f(b\to B_u)} \left|\frac{V_{cb}}{V_{ub}}\right|^2 \left(\frac{f_{B_c}}{f_{B_u}}\right)^2 \frac{m_{B_c}}{m_{B_u}} \frac{\tau_{B_c}}{\tau_{B_u}} \frac{(1-\frac{m_\tau^2}{m_{B_c}^2})^2}{(1-\frac{m_\tau^2}{m_{B_u}^2})^2} \sim 1$$

	B_u	B_c
Mass	~5280 MeV	~6275 MeV
Lifetime	~1.5 ps	~0.5 ps

$\Rightarrow$ discrimination should be possible

Another way to obtain V_{cb} ?

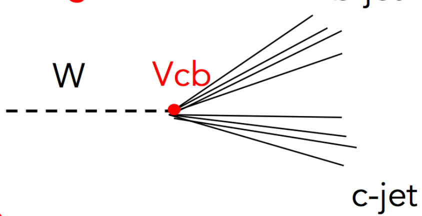
Not on the Z^0 peak

WW production

10^8 WW pairs
BR($W \to q_1 \bar{q}_2$) = 67%

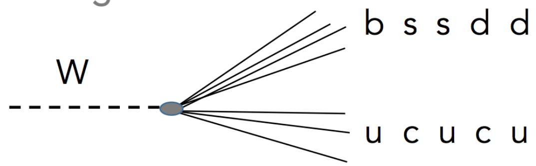
230k

Signal



$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

background



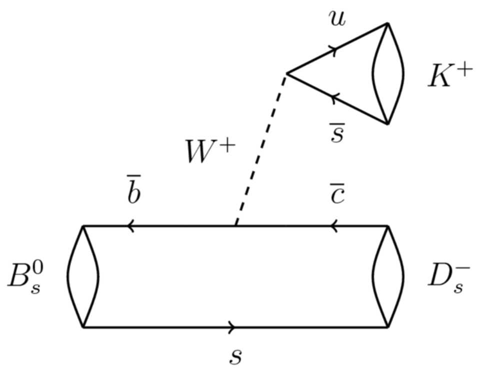
1.7k 127M 6.8M 6.8M 127M

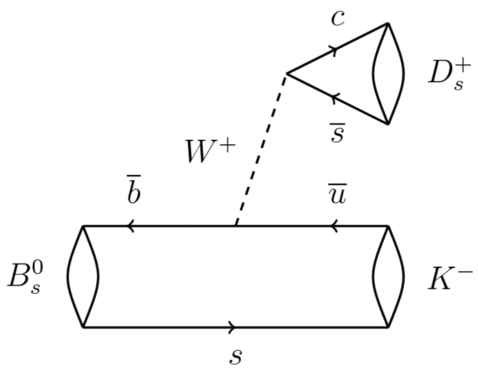
(From M.H. Schune)

3) Hadron PID detector: *p / K / π* separation

Benchmark mode: *CP* violation studies with $B_s \to D_s K$

- for Physics: measure simultaneously the phases γ (decay) and ϕ_s (mixing,B_s). No theoretical uncertainty plaguing the interpretation.



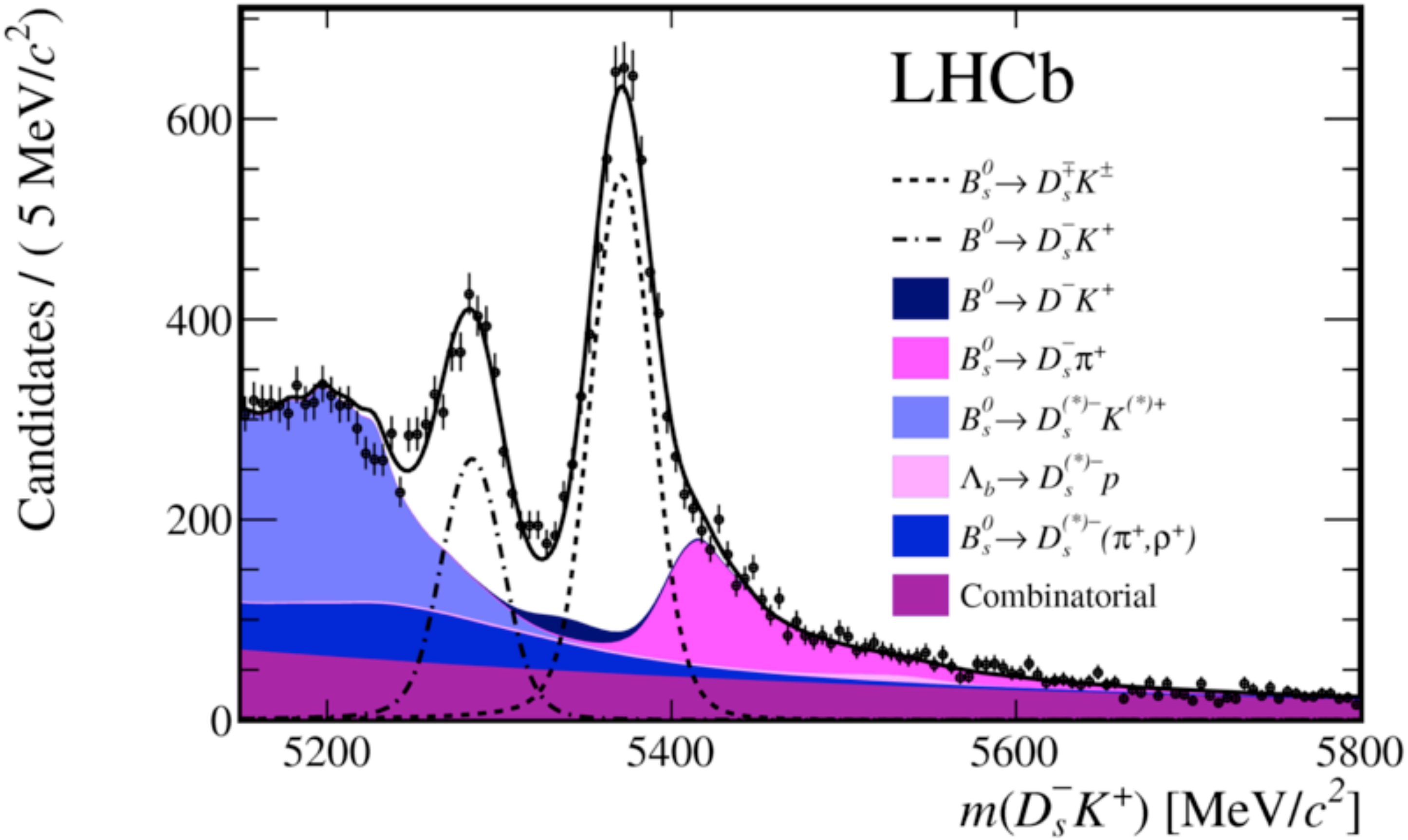


- for detectors: understand the needs of *p / K / π* separation. There is a competition of up-feeding and down-feeding contribution through mis-identification: $B_s \to D_s\pi$ and $\Lambda_b \to D_s p$. Serves also the purpose of quark flavour tagging.

3) Hadron PID detector: p / K / π separation

CP violation studies: $B_s \to D_s K$:

LHCb-PAPER-2014-064
ArXiv:1412.7654

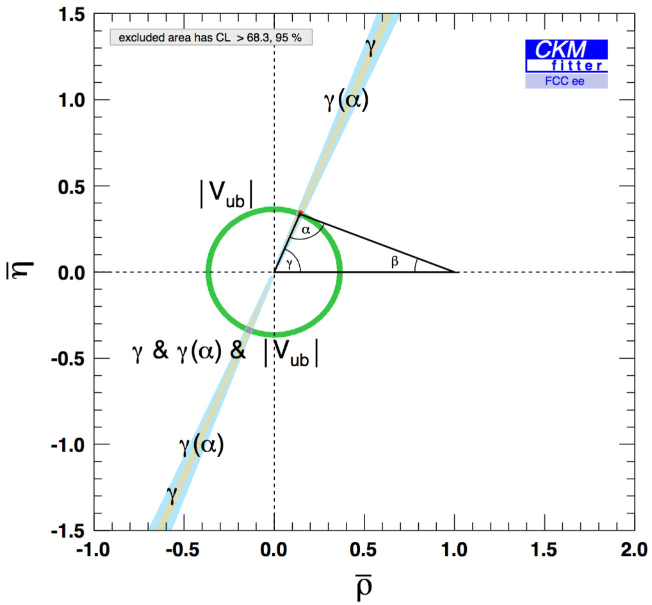


Note: this plot is obtained after PID cuts are applied ...

C) CDR: CKM and *CP* violation in quark mixings

- Expected precisions scaled with statistics and anticipated flavour tagging performance when necessary.
- First observation of *CP* violation in *B* mixing is at reach.
- A global analysis of BSM contributions in box mixing processes, assuming *Minimal Flavour Violation* pushes the BSM energy scale to 20 TeV.

Observable / Experiments	Current W/A	Belle II (50 /ab)	LHCb-U1 (23/fb)	FCC-*ee*
CKM inputs				
γ (uncert., rad)	$1.296^{+0.087}_{-0.101}$	1.136 ± 0.026	1.136 ± 0.025	1.136 ± 0.004
$\lvert V_{ub}\rvert$ (precision)	5.9%	2.5%	6%	1%
Mixing-related inputs				
$\sin(2\beta)$	0.691 ± 0.017	0.691 ± 0.008	0.691 ± 0.009	0.691 ± 0.005
ϕ_s (uncert. rad 10^{-2})	-1.5 ± 3.5	n/a	-3.65 ± 0.05	-3.65 ± 0.01
Δm_d (ps^{-1})	0.5065 ± 0.0020	same	same	same
Δm_s (ps^{-1})	17.757 ± 0.021	same	same	same
$a^d_{\rm fs}$ (10^{-4}, precision)	23 ± 26	-7 ± 15	-7 ± 15	-7 ± 2
$a^s_{\rm fs}$ (10^{-4}, precision)	-48 ± 48	n/a	0.3 ± 15	0.3 ± 2



CONCLUSIONS

- Flavor physics has today a case in particle physics, and is always a good sector to keep exploring, especially when lacking of specific search directions.

- There are interesting opportunities for flavor physics at FCC-ee at the Z pole, both in rare decays and CP violation measurements.

- It makes sense to perform studies of benchmark channels to collect information for the detector design that ensure the flavor capabilities of FCC-ee

- I have the impression that charm physics, as well as spectroscopy of exotic states, are still largely unexplored at the moment (but on the other hand, as of today, they lack of a solid theory for precise tests of the SM).