Flavour Physics opportunities at FCC-ee

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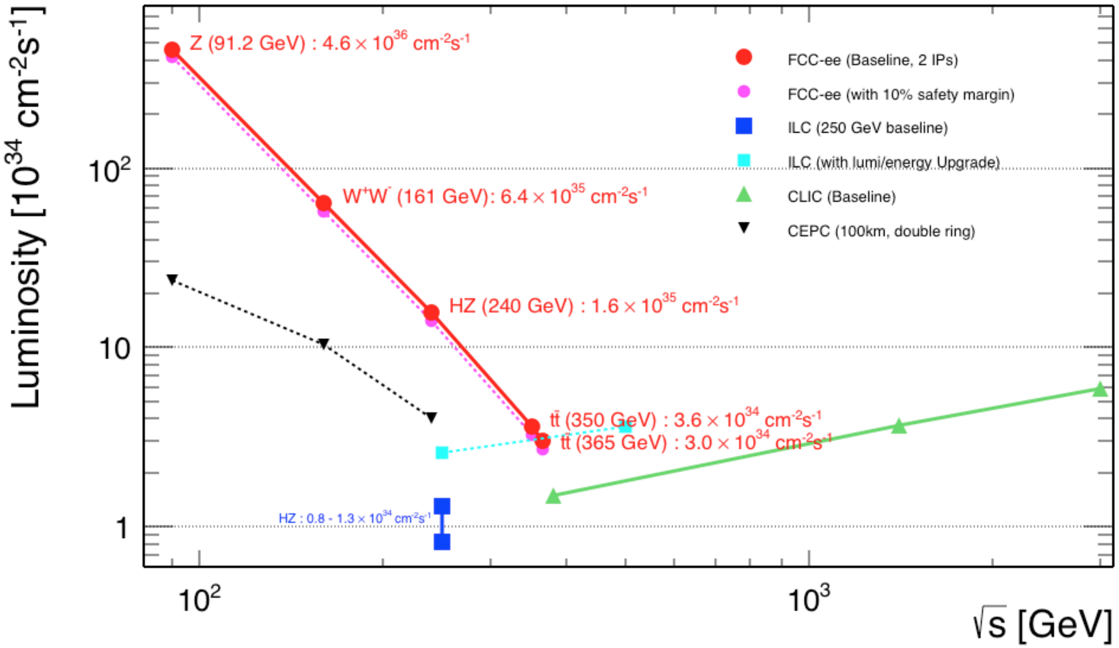
Outline

- Future Circular Collider FCC-ee in a glance.
- Flavours@FCC-ee: setting the scene.
- Overview of selected studies performed so far
  - Rare decays.
  - CKM profile.
  - Tau Physics.
- Outlook.

1) FCC-ee main features



- Be it only for the Higgs properties, a future leptonic collider is required. FCC-*ee* crosses the four (five?) relevant electroweak thresholds with the largest luminosities in its whole energy range.

- We‘re speaking of 10^5 *Z*/s , 10^4 *W*/h, 1.5 10^3 *H* and top /d, in a very clean environment: no pile-up, controlled beam backgrounds, *E* and *p* constraints, w/o trigger loss.

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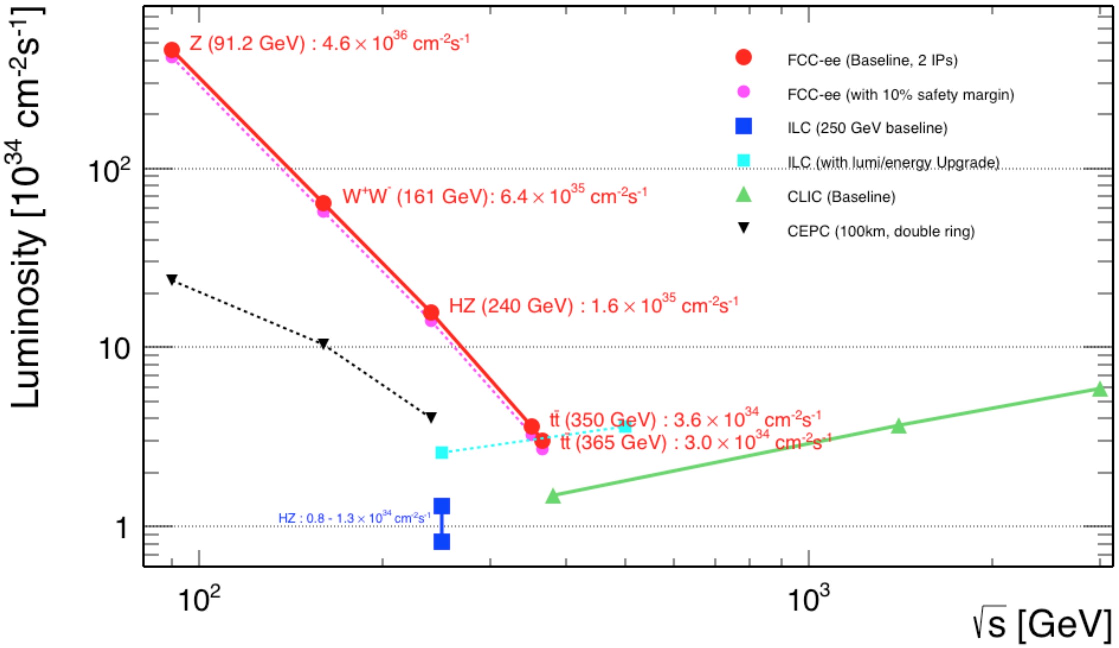

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- In particular, you do the LEP in a minute!

1) FCC-ee specifics for Flavour Physics.

A- Particle production at the Z pole:

- About 15 times the Belle II anticipated statistics for B^0 and B^+.
- All species of b-hadrons are produced.
- Expect ~4.10⁹ 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 / $\overline{\Lambda}_b$	$c\bar{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150

1) FCC-ee specifics for Flavour Physics.

B- The Boost at the Z:

$$\langle E_{X_b} \rangle = 75\% \times E_{\mathrm{beam}}; \langle \beta\gamma \rangle \sim 6.$$

- Fragmentation of the b-quark:
- Makes possible a topological rec. of the decays w/ miss. energy.

C- Comparison w/ LHCb and Belle II. Advantageous attributes:

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

D- Versatility : the Z pole does not saturate all Flavour possibilities. Beyond the obvious flavour-violating Higgs and top decays, the WW operation will enable to collect several 10^8 W decays on-shell AND boosted.

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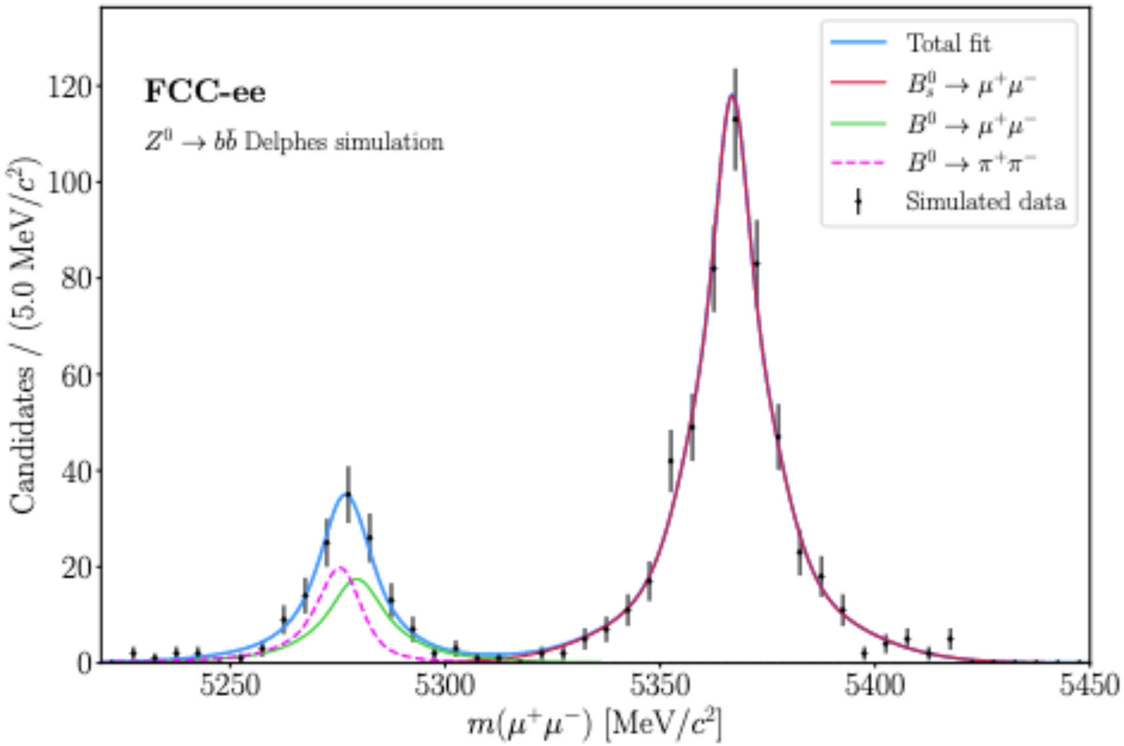
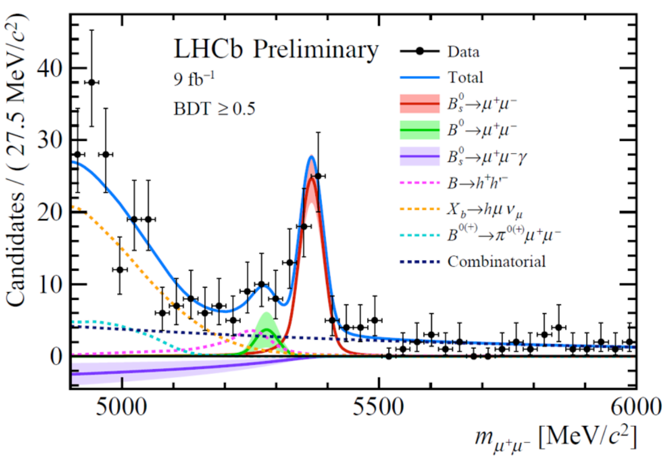
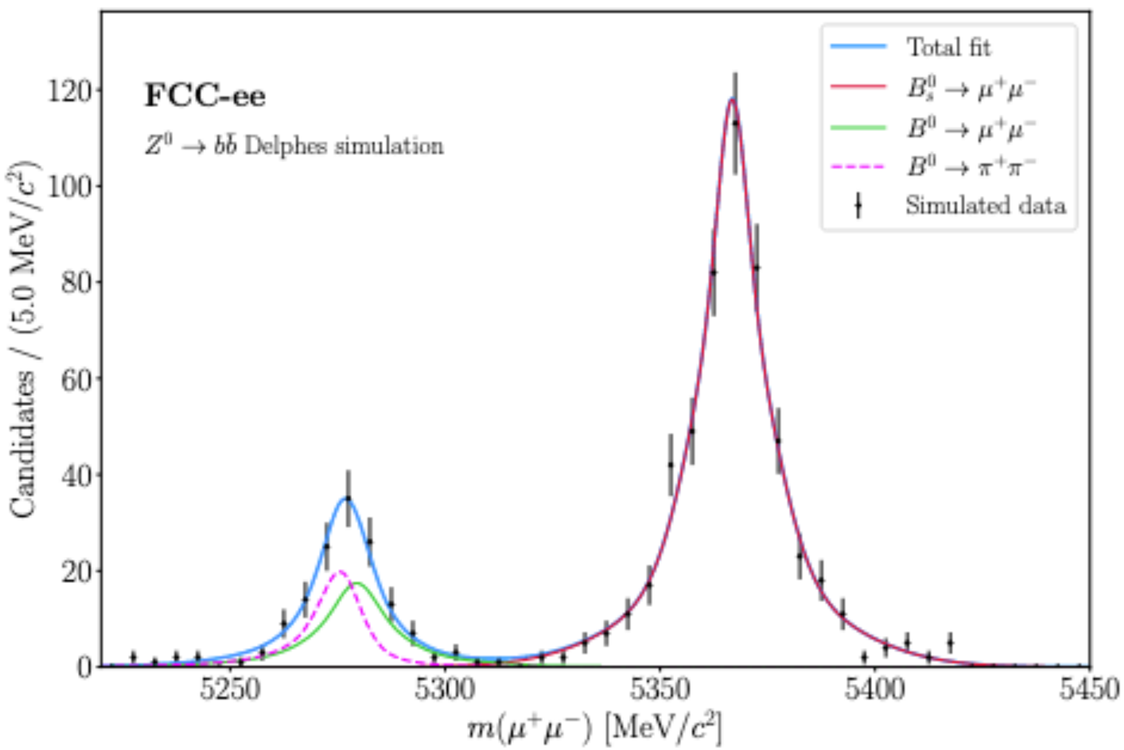
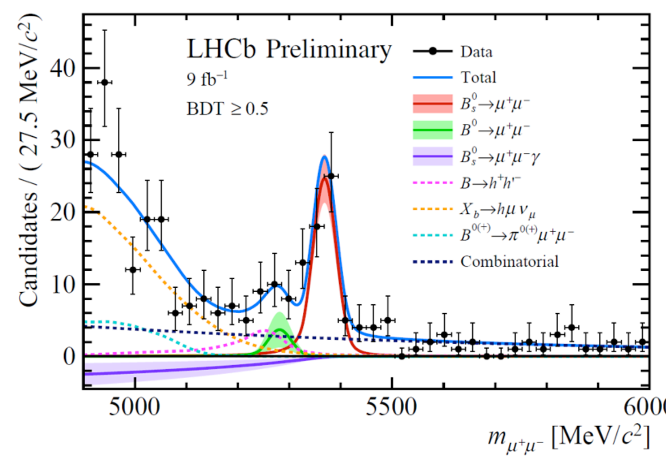




1) FCC-ee specifics for Flavour Physics.

E- Detector performance: exquisite tracking is necessary and at reach.
Invariant-mass resolution as it is in the current state of IDEA fast simulation:





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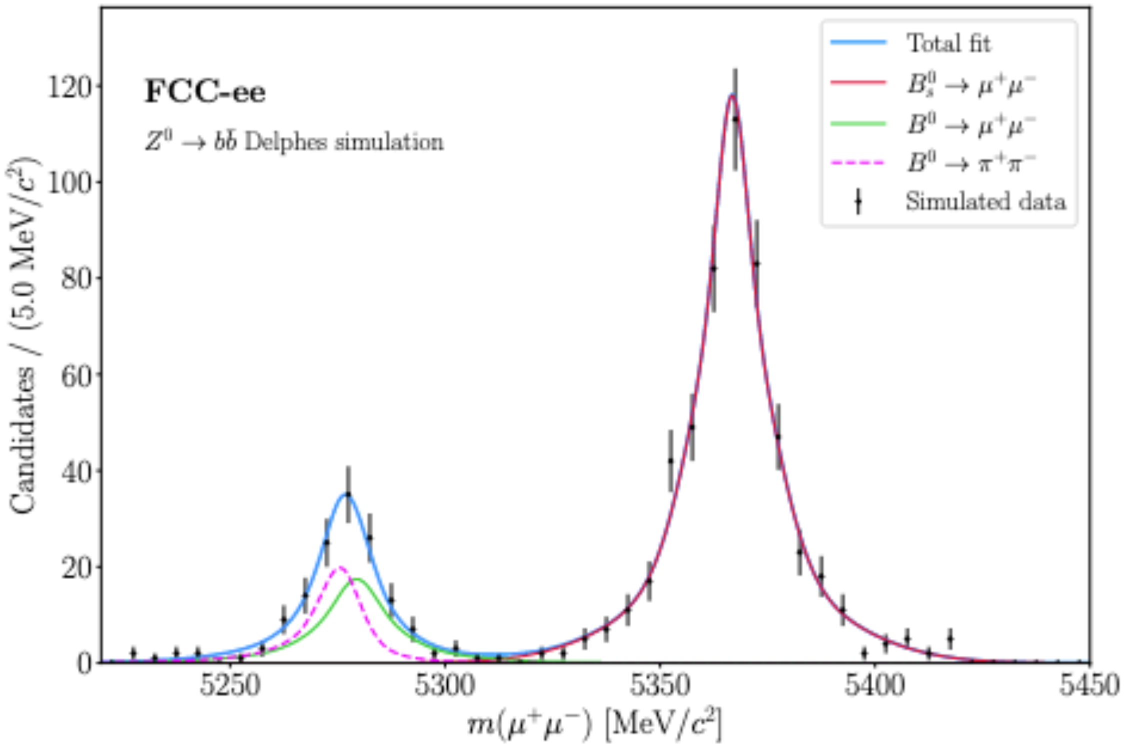

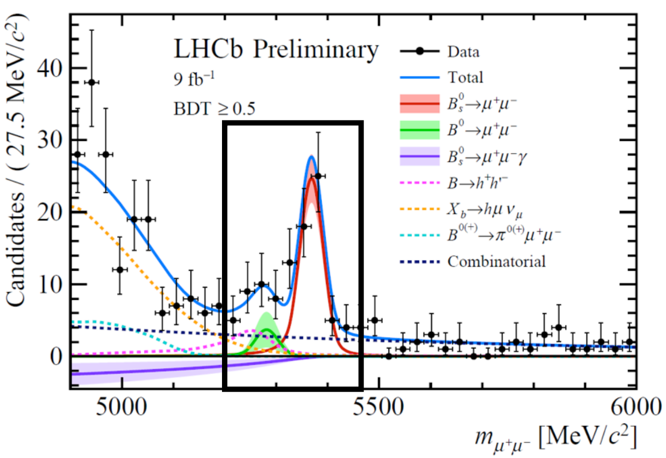

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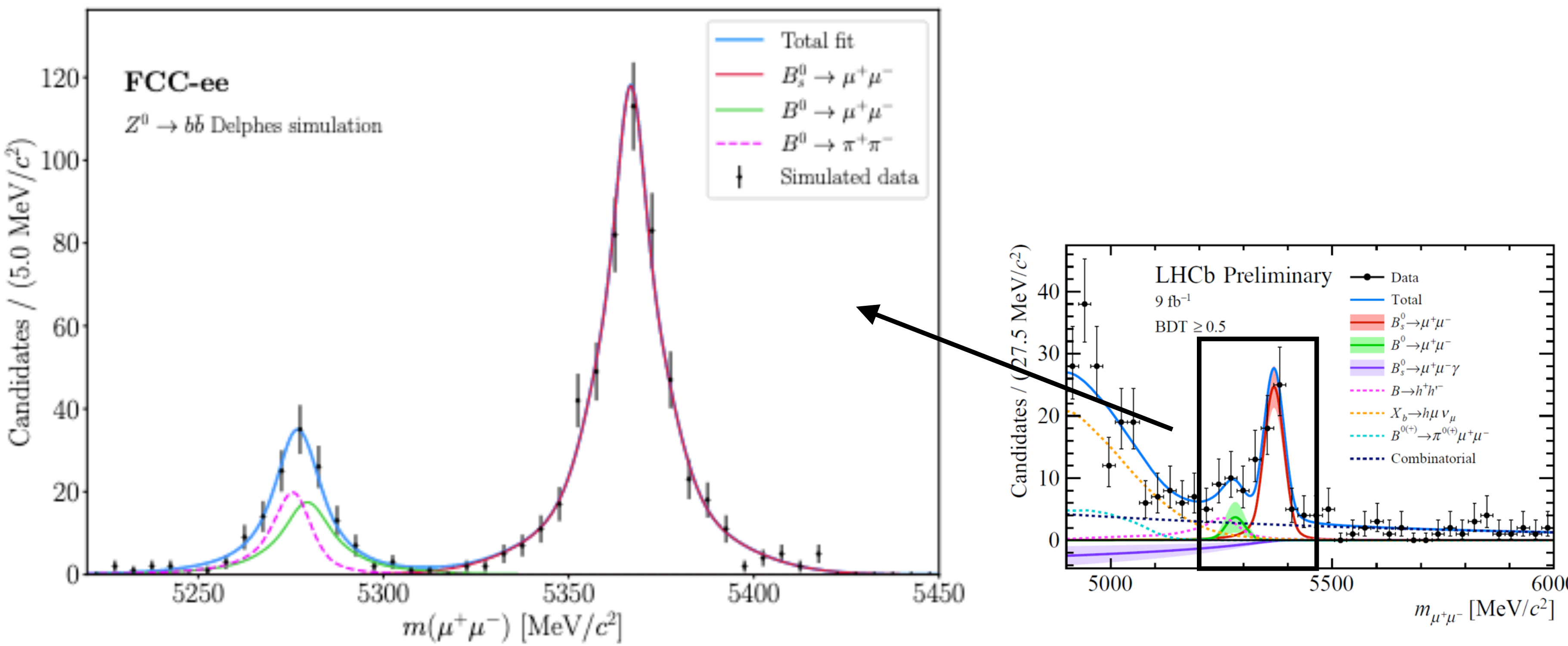

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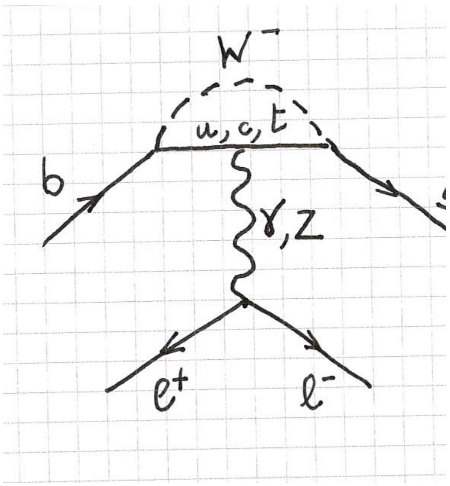
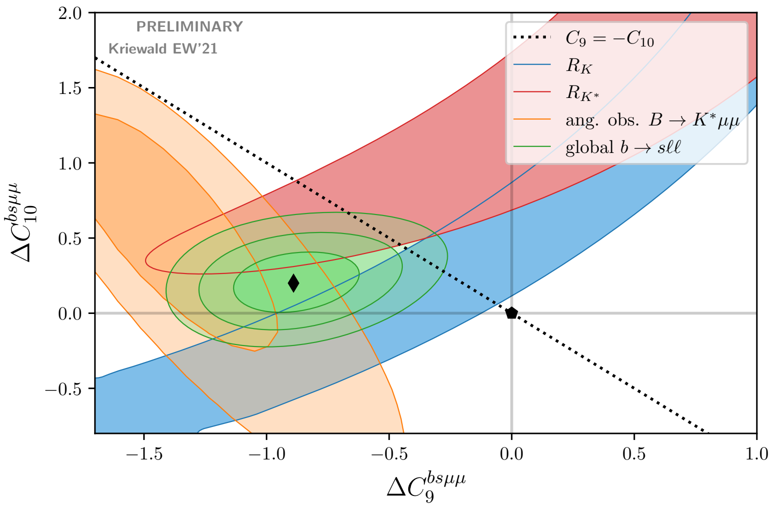
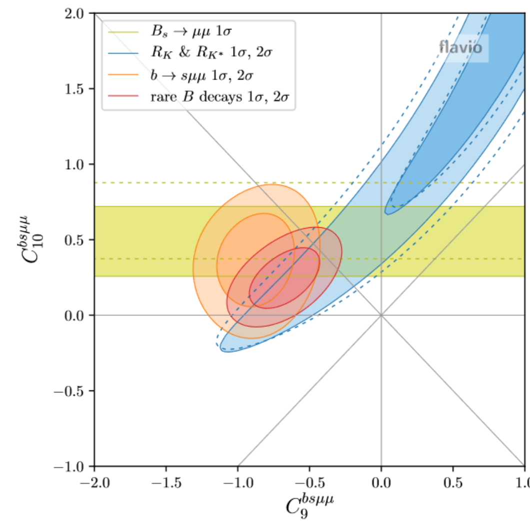
2) Overview of the studies: Rare decays & Friends







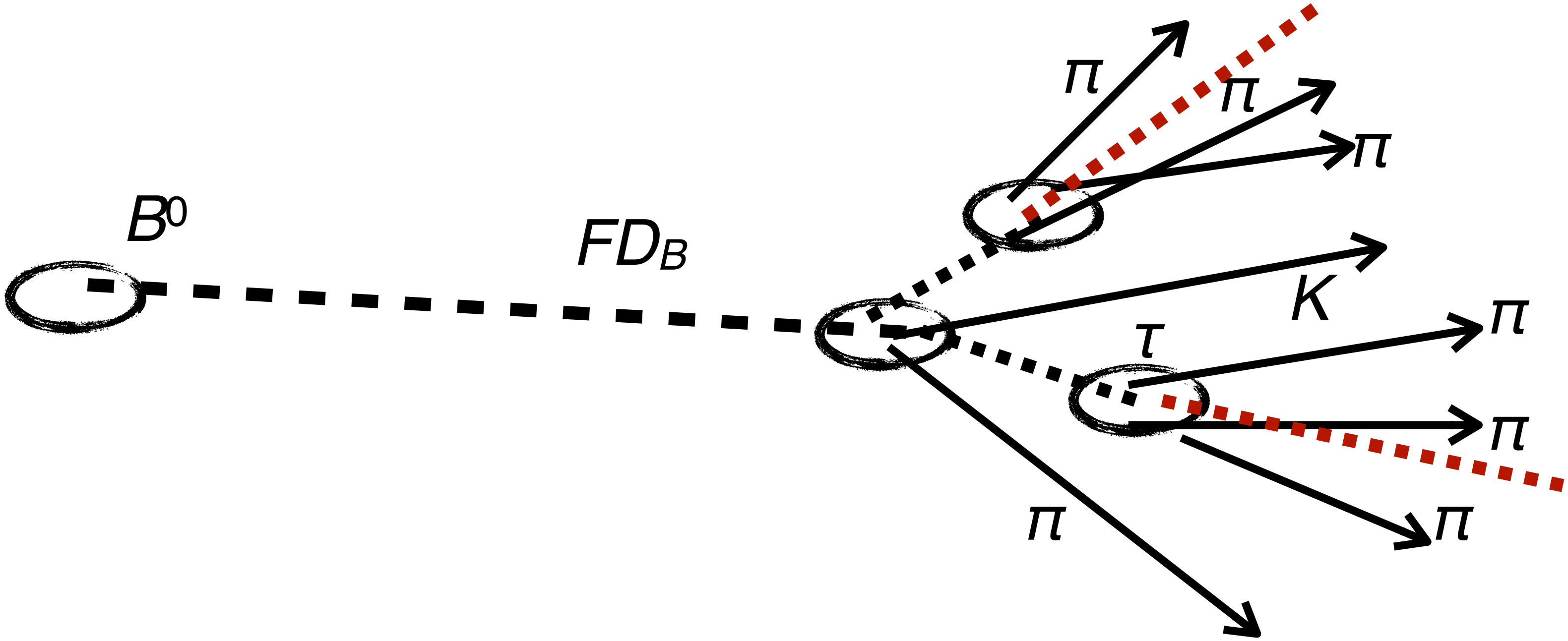
- Multiple global fits in the literature (I picked here 2012.13241 and arXiv:2103.13370, many others around). Intriguing consistent pattern pointing towards a C_9 modification.

- How to go further with indirect measurements ? Final states with tau lepton is a promising way forward. FCC-ee likely unique to address these searches. Two flashed here $B^0 \to K^{*0}\ \tau^+\tau^-$ and $B_c \to \tau^+\nu$. Other modes (relevant as well) are under study, e.g. $b \to s\nu\nu$.

- Even w/o anomalies, these third generation studies are a must.

2) Overview of the studies: Rare decays & Friends

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



- 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.

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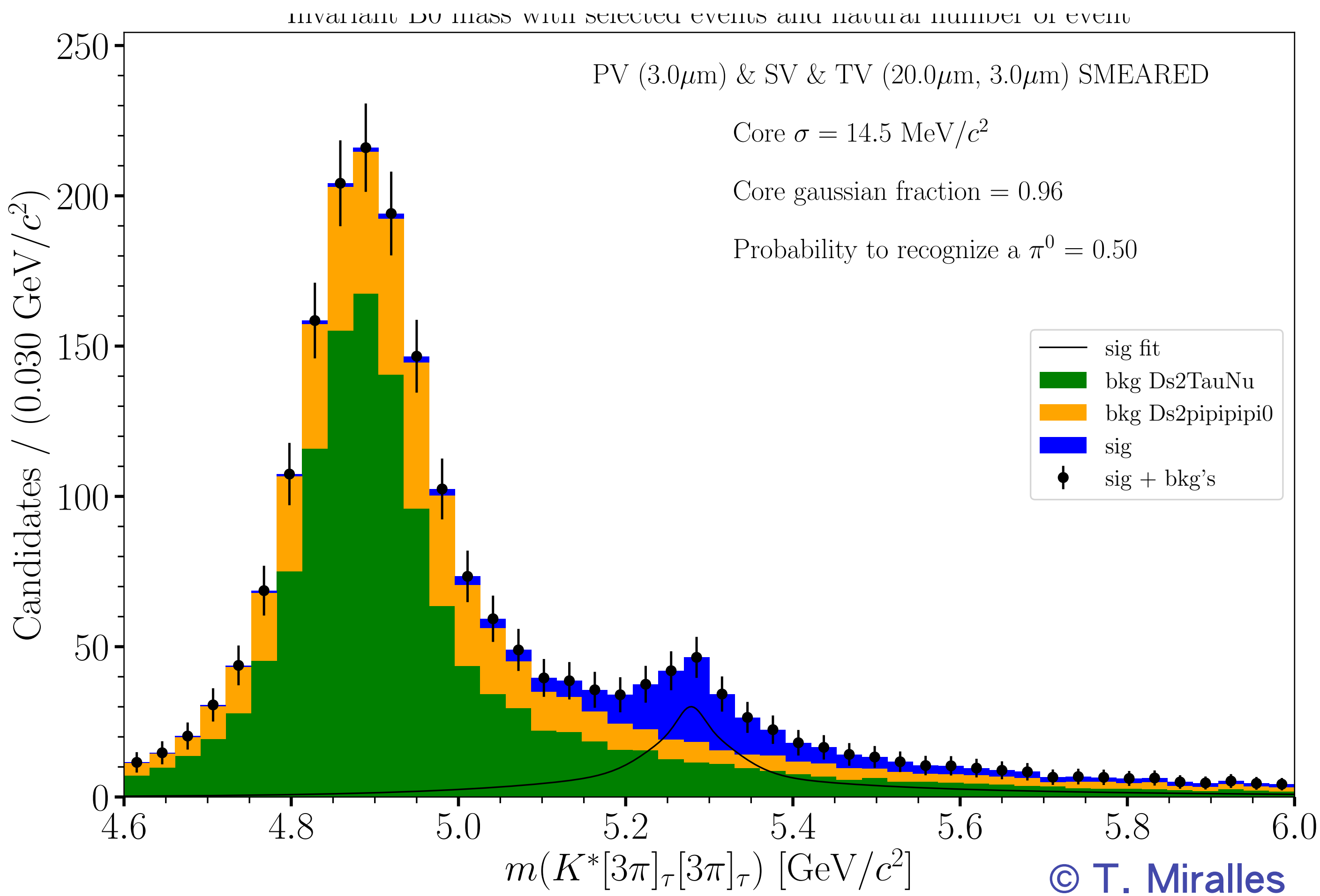

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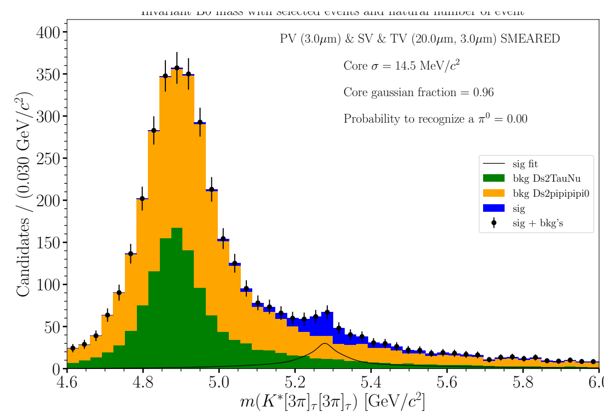
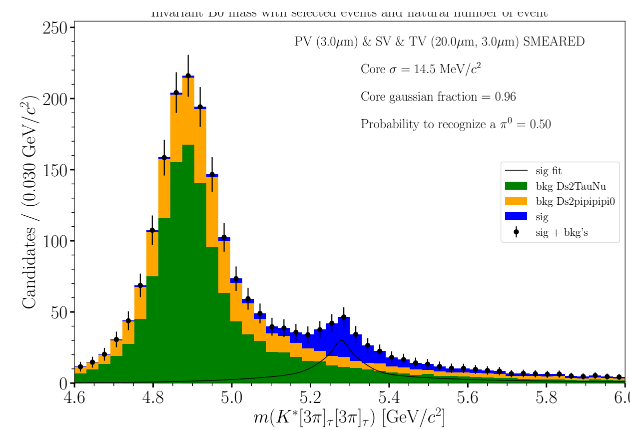
2) Overview of the studies: Rare decays & Friends

- $B^0 \rightarrow K^{*0}\ \tau^+\tau^-$: executive summary

- IDEA Delphes card for *p* resolution Vertexing performance from smearing: allows to assess the required performance.



- Study w/ background has started. No selection cut yet beyond the topological reconstruction efficiency (note ALEPH pi0 reconstruction eff. for the time being). Not all of bkgs that one can thought of are considered.

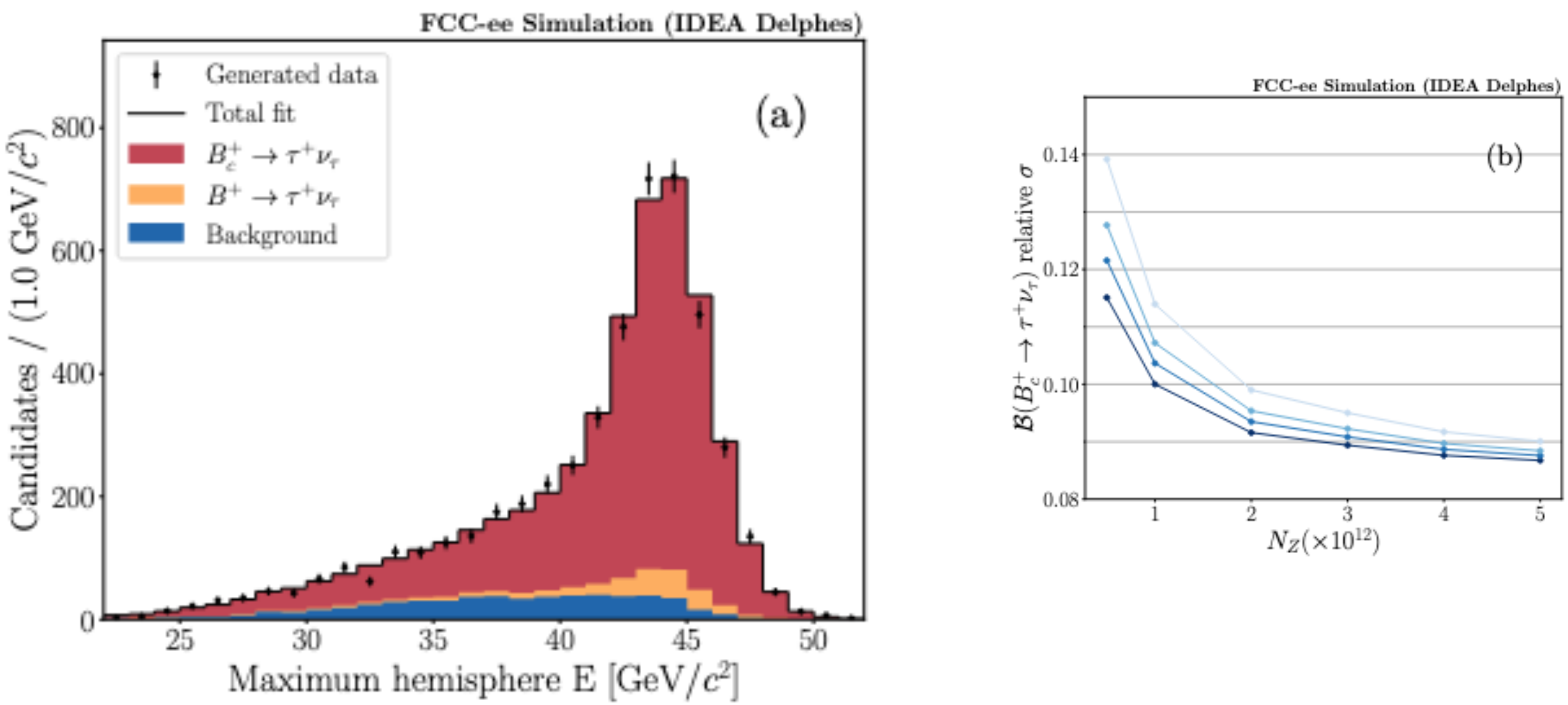


- O(200) events at SM value.

- Outlook: attempt at a “comprehensive" bkg estimate (we’re far from it). Actual vertex detector geometries to be assessed as a function of the precision.

2) Overview of the studies: Rare decays & Friends

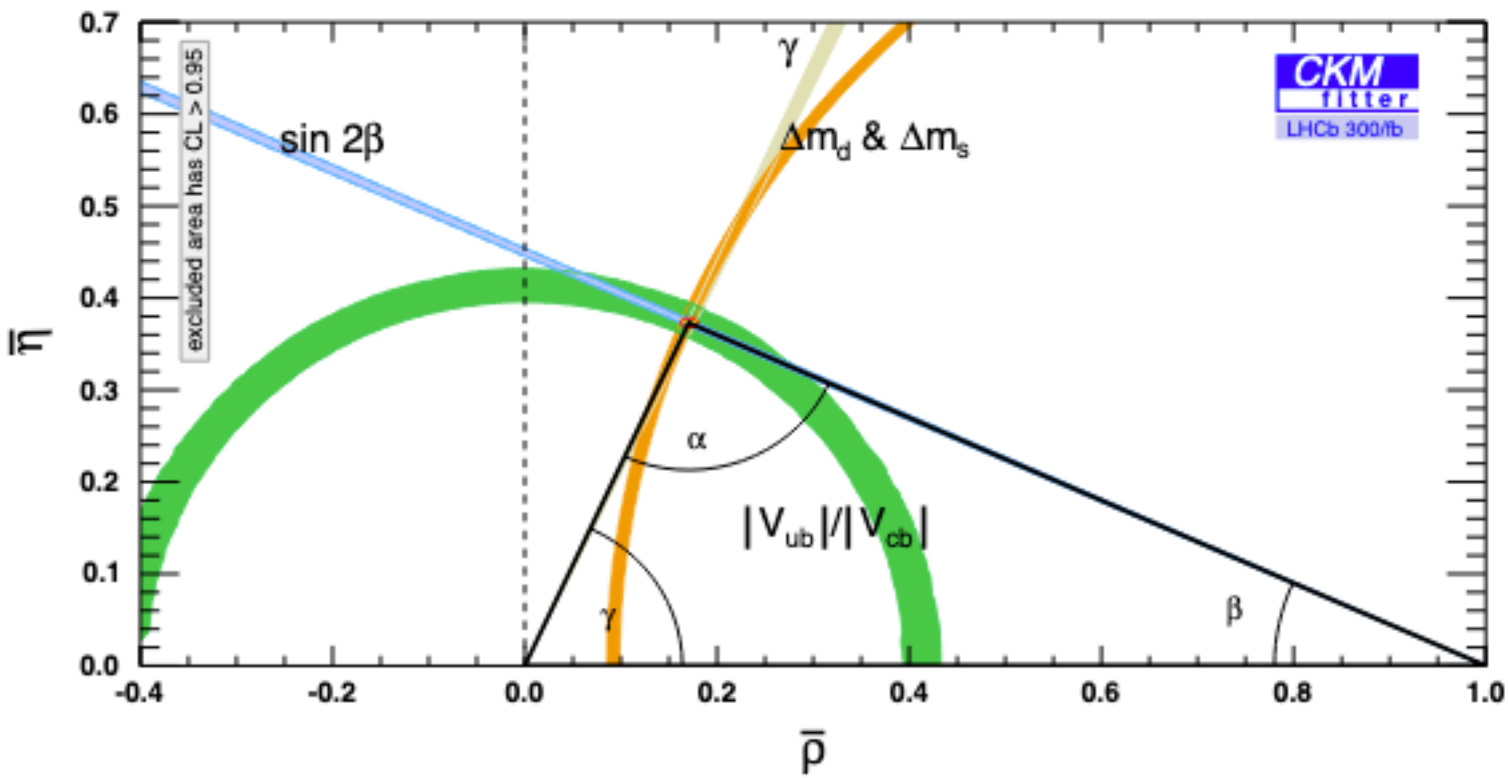
- $B_c \rightarrow \tau^+\nu$: another fundamental test of lepton universality. Counterpart of R_{D,D^*}. A promising study lies here [2105.13330, see also 2007.08234]



Bottomline: few percent precision mostly limited by the knowledge of the normalisation BF (J/$\psi\mu\nu$)

2) Overview of the studies: CKM profile & Friends

- The possible status of the CKM profile in the late 2030s (LQCD expected improvements in; LHCb-biased view)



- Belle II will add up to this.

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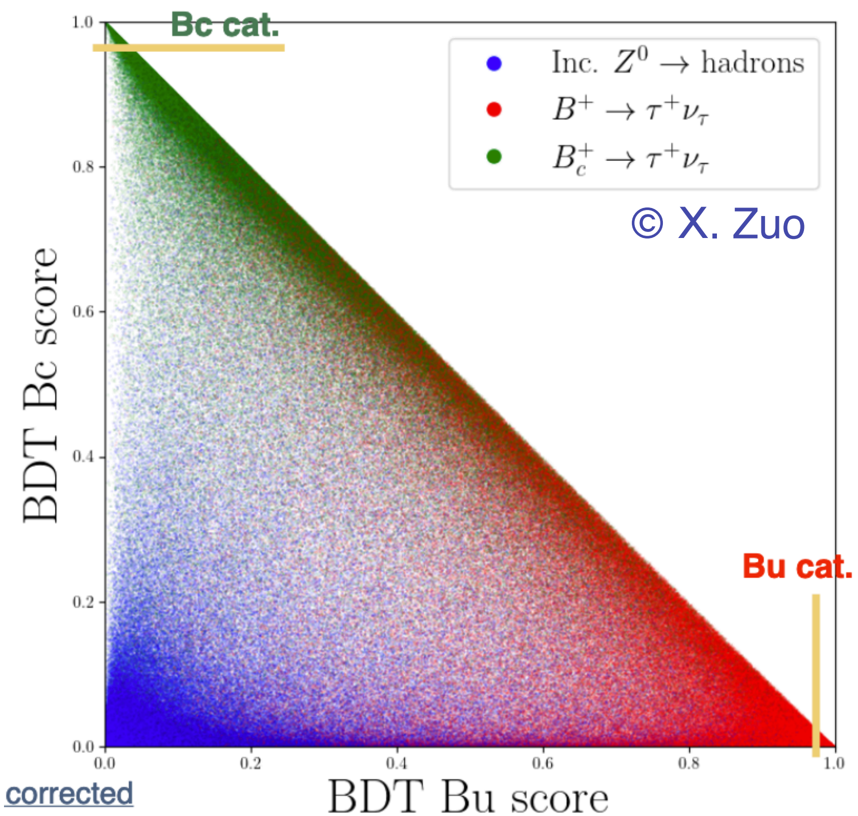
- *$B^+ \rightarrow \tau^+\nu$:* access Vub with the only knowledge of the decay constant. Work in progress building on [hep-ex:2105.13330]



Bottomline: similar yields with purities as for $B_c \rightarrow \tau^+\nu$.

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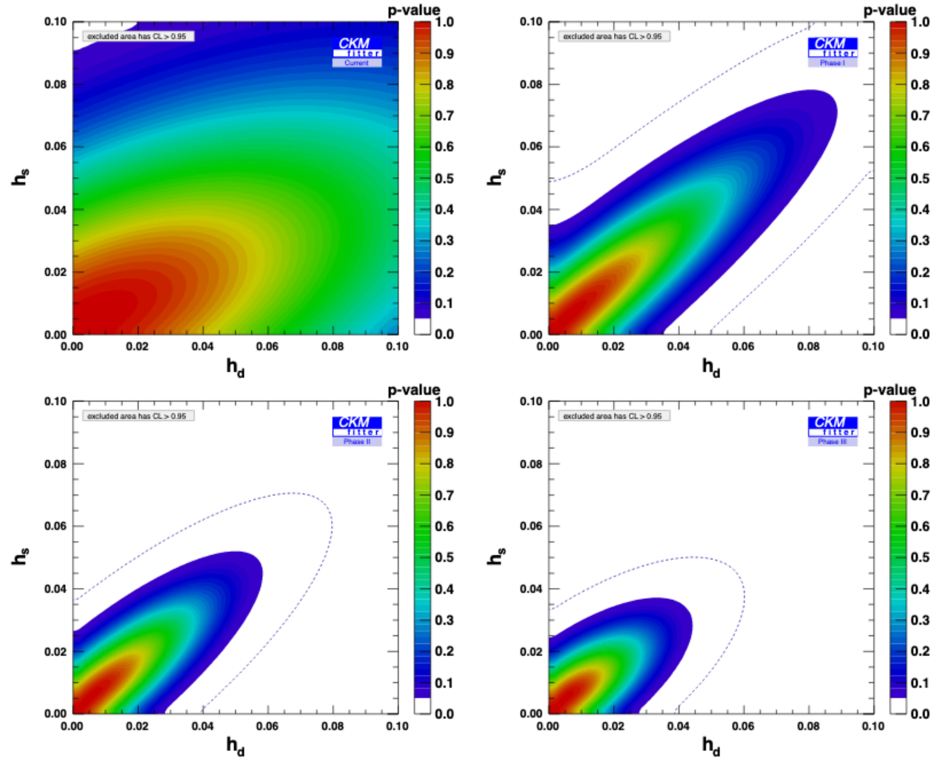

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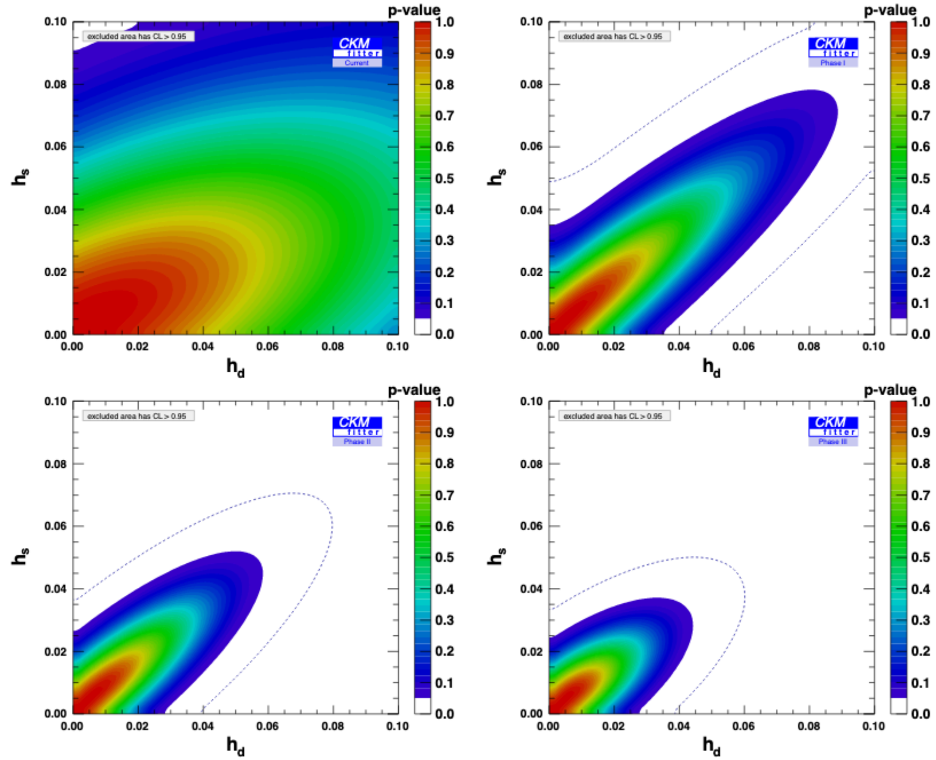

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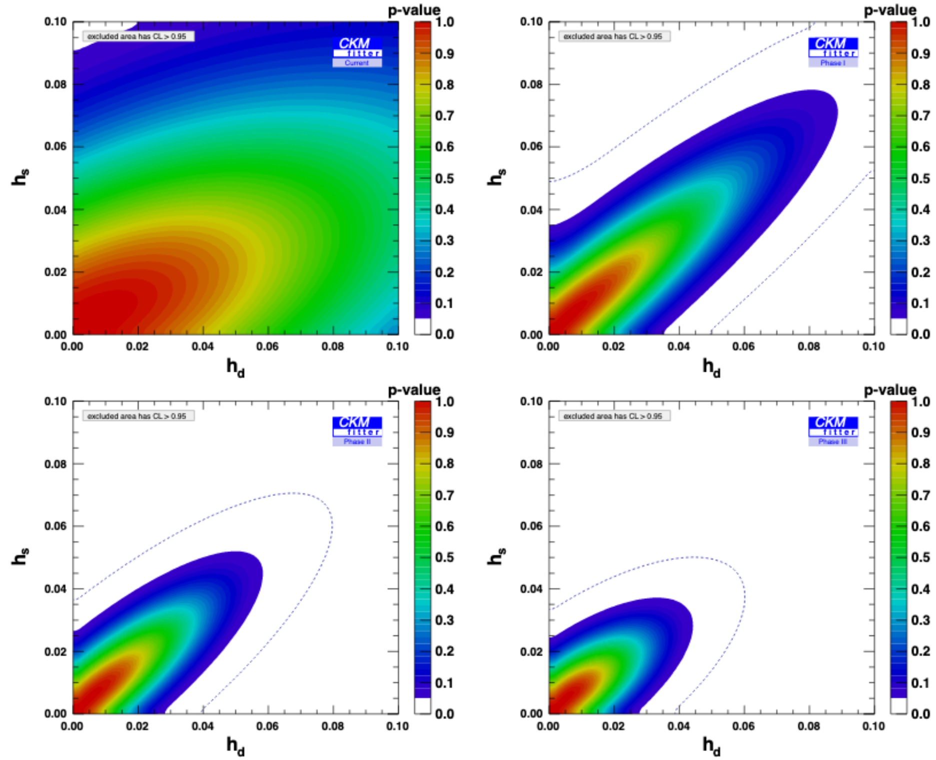
Now, rescaled to SM



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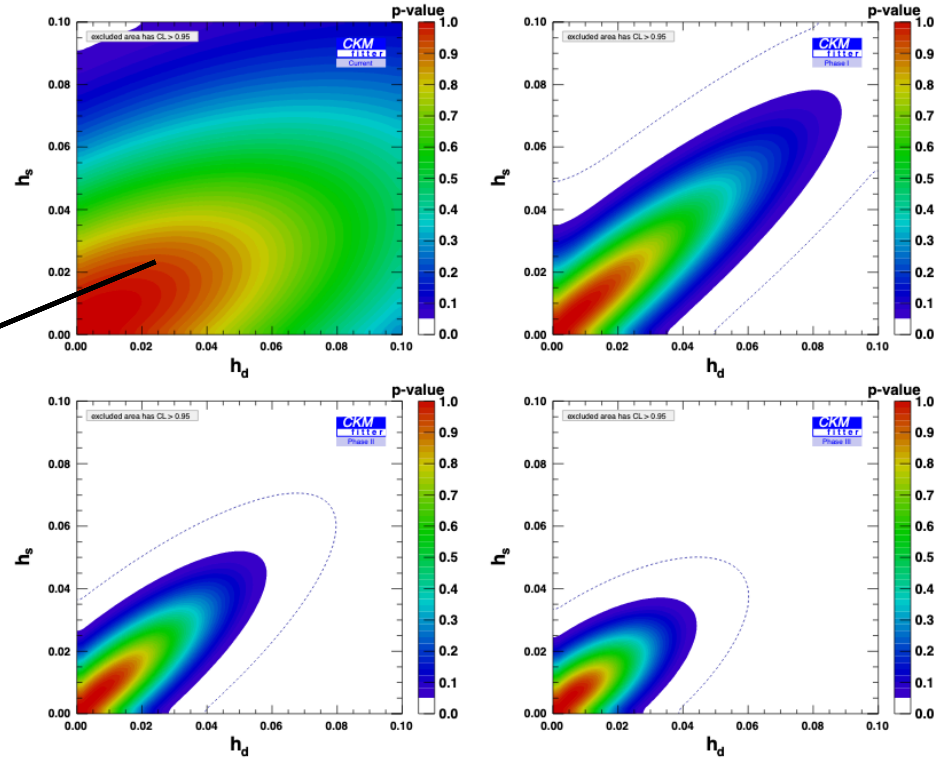

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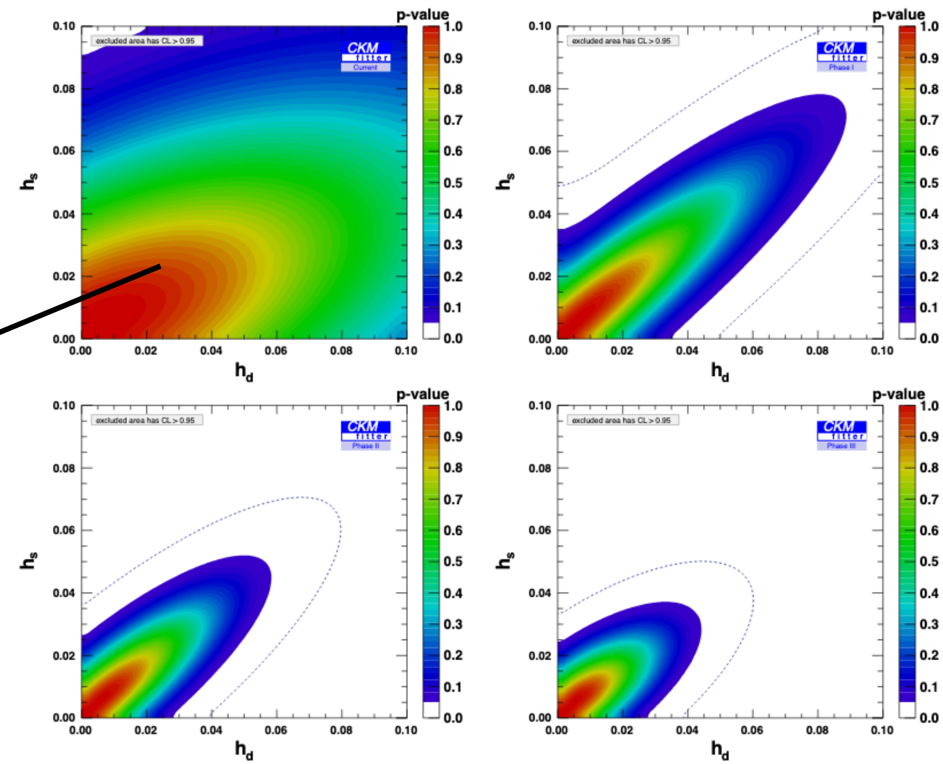

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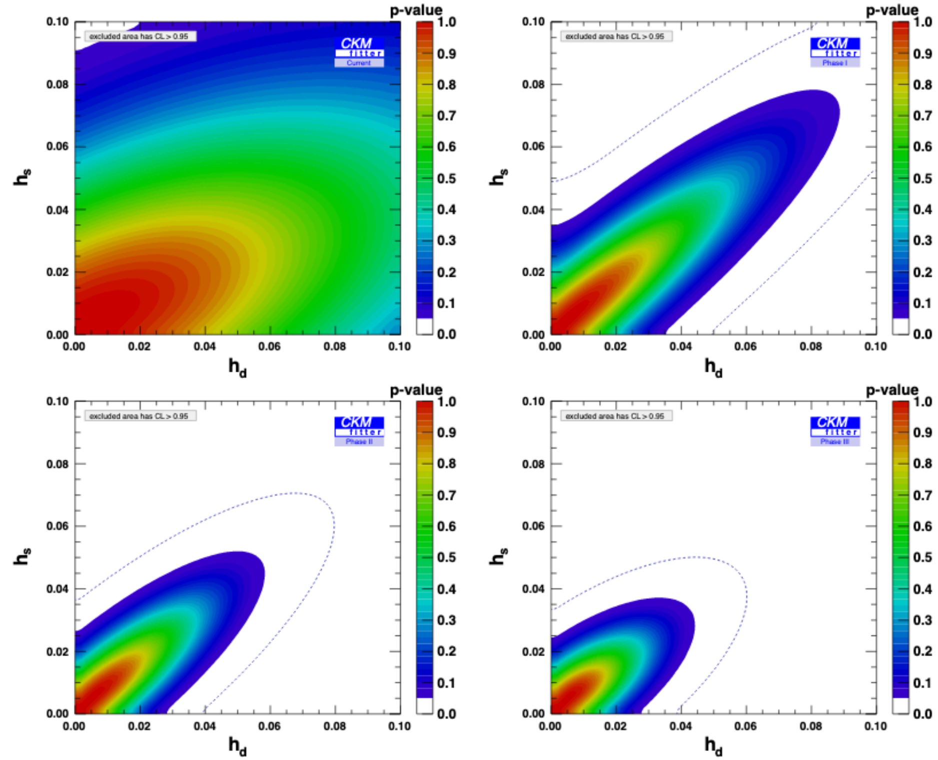

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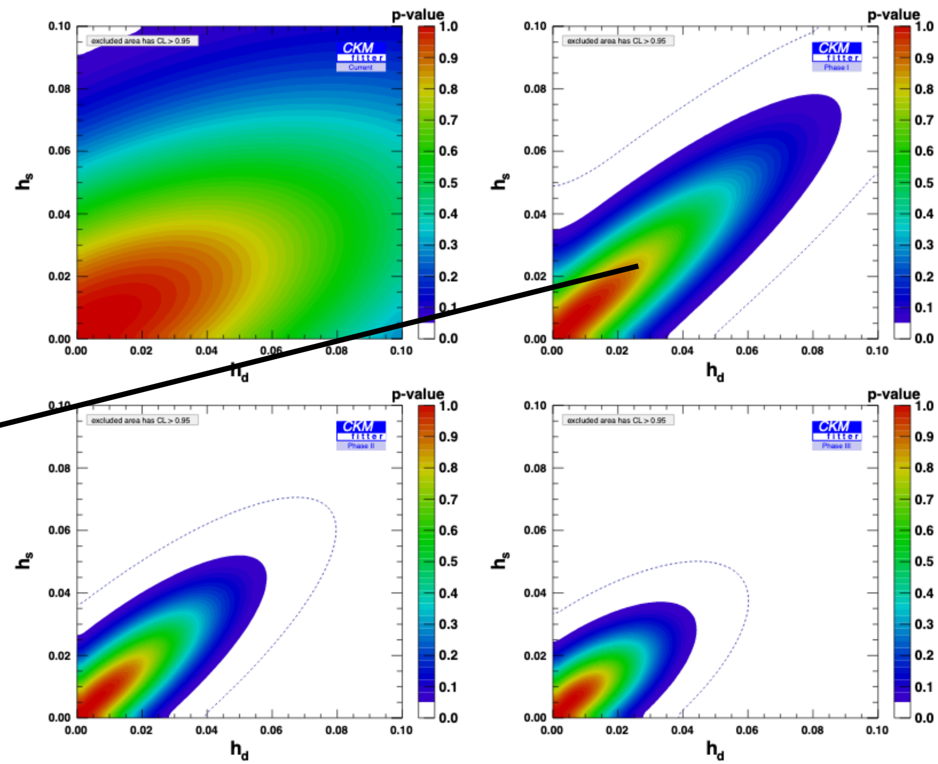

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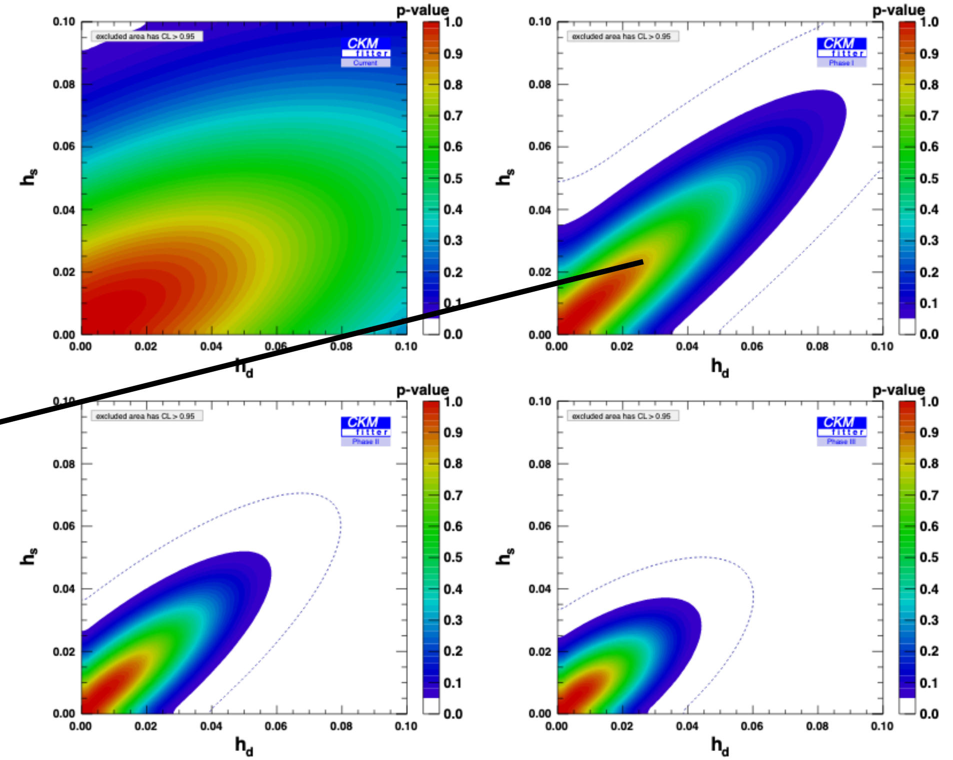
after LHCb U1 and Belle II — 2030



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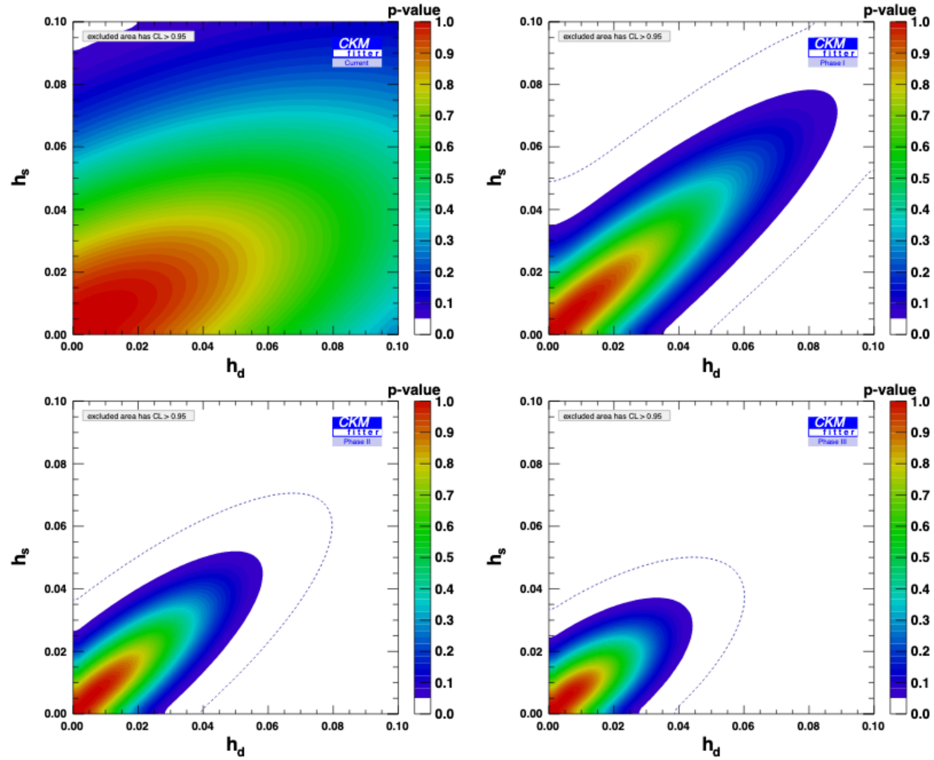

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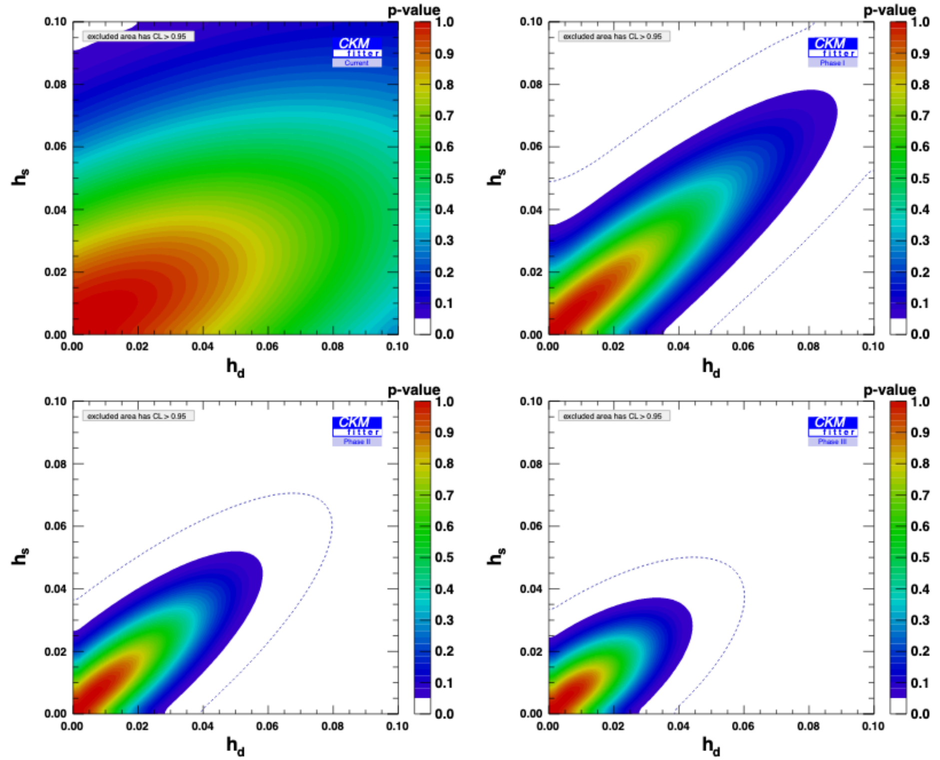

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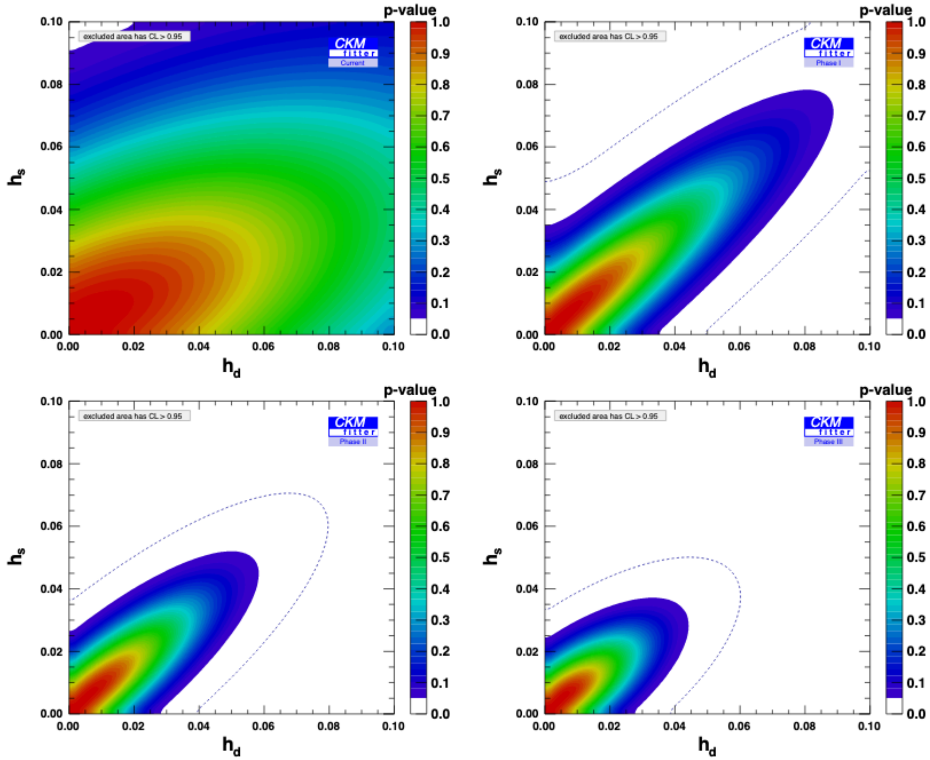

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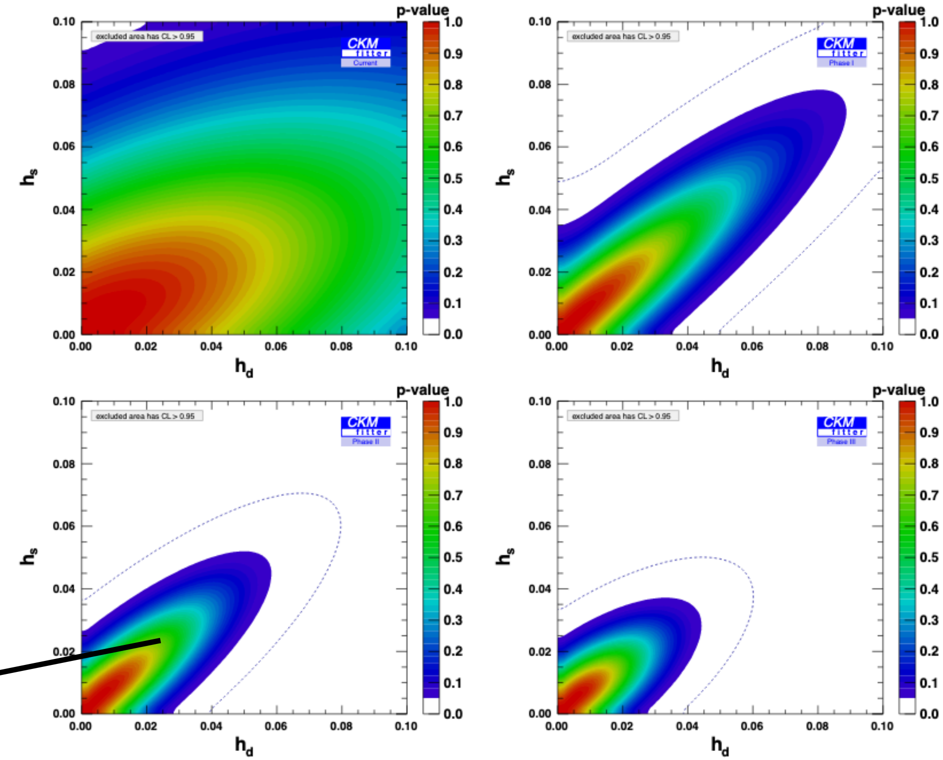

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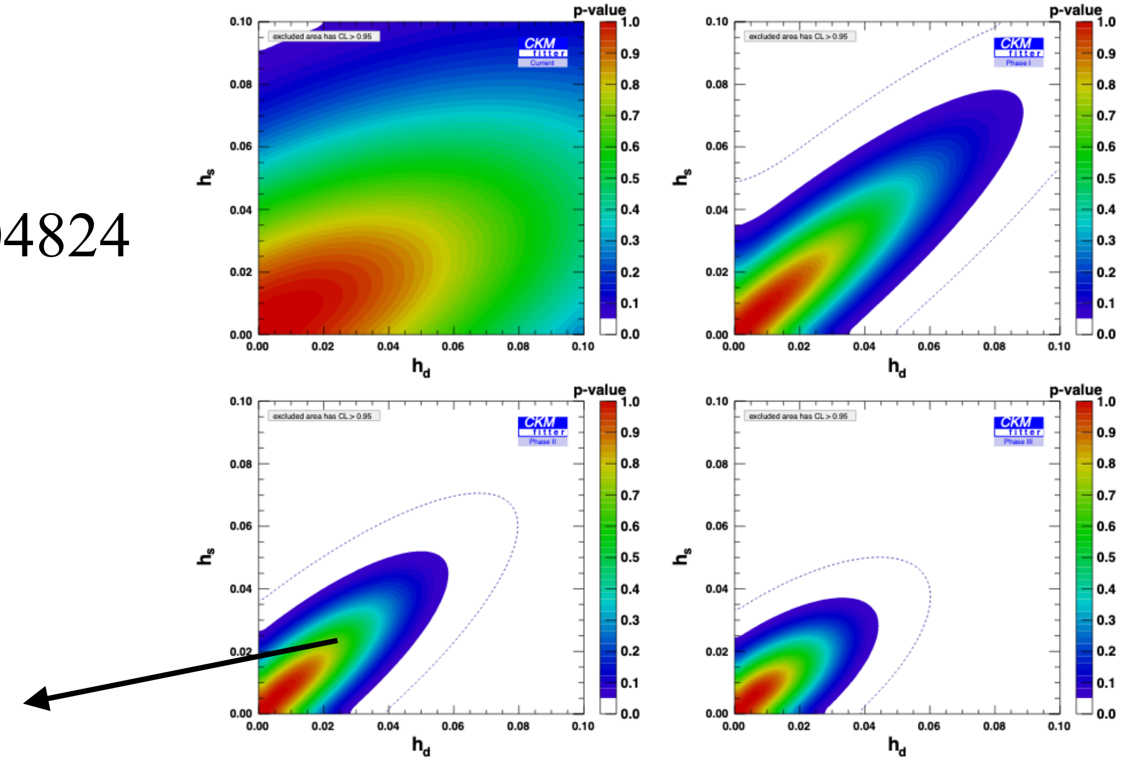

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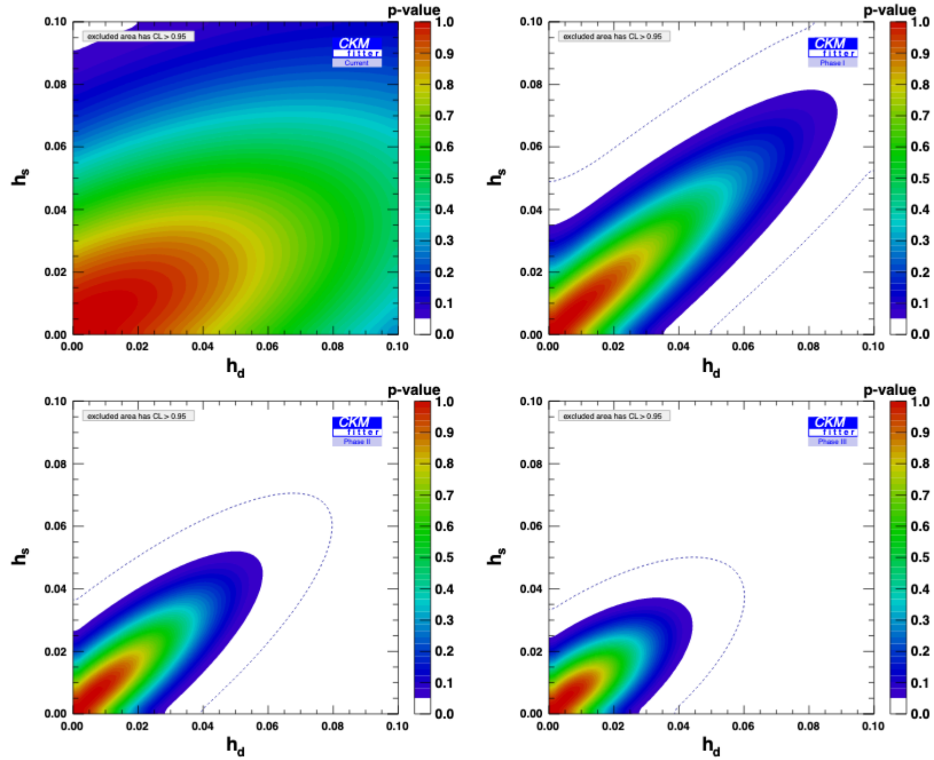

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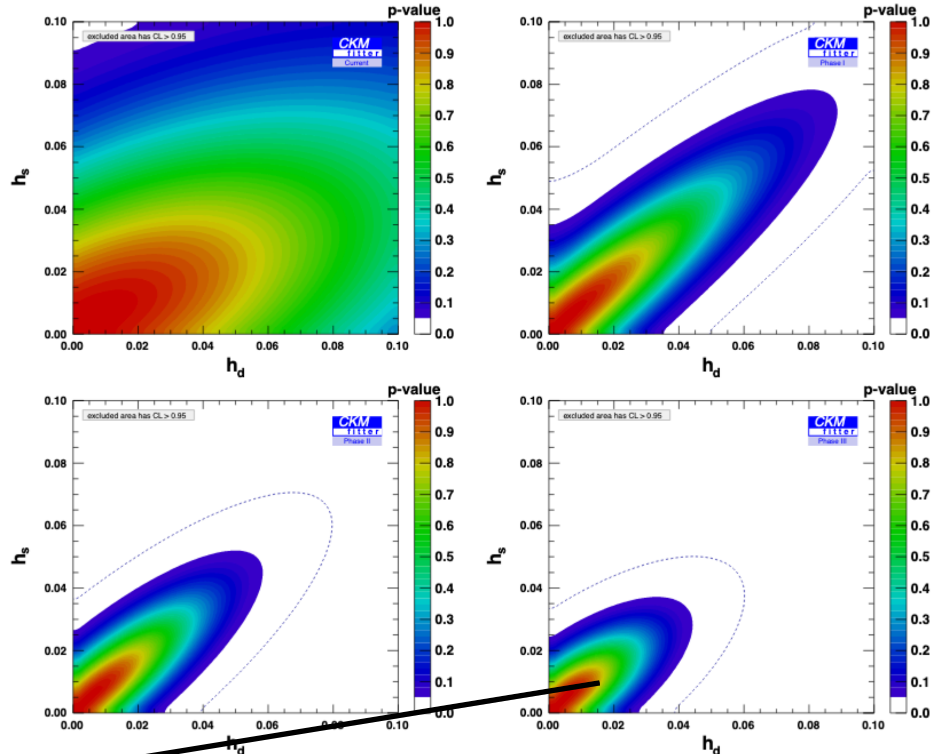

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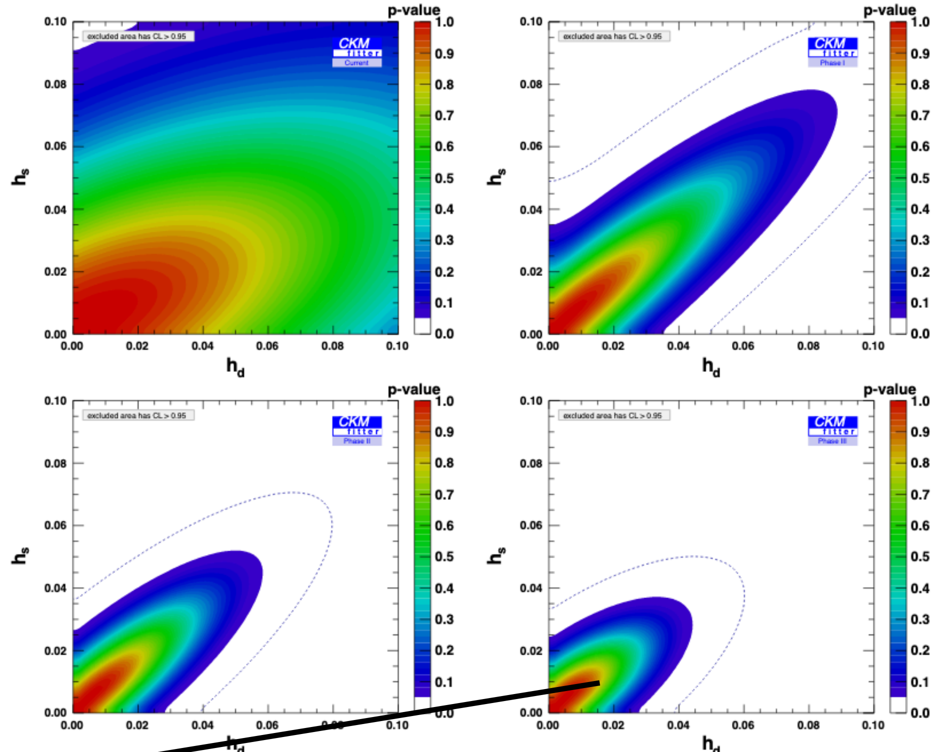

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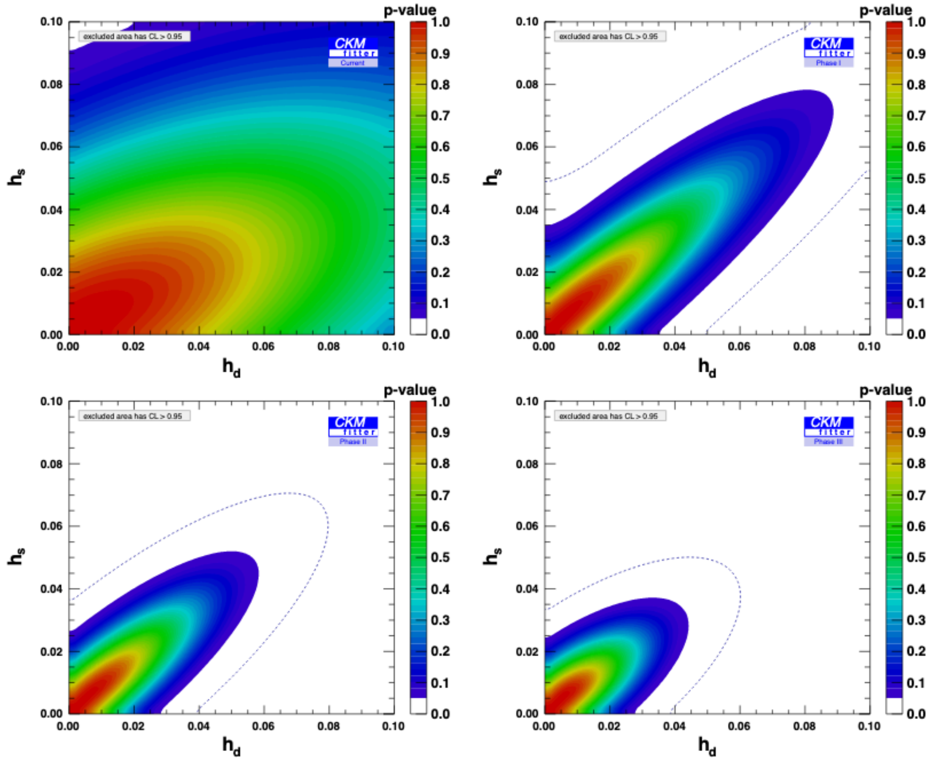

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Vcb in. LQCD not

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2) Overview of the studies: CKM profile & Friends

- Another projection is the model-independent search for BSM CPV phases in mixing processes

hep-ph 2006.04824

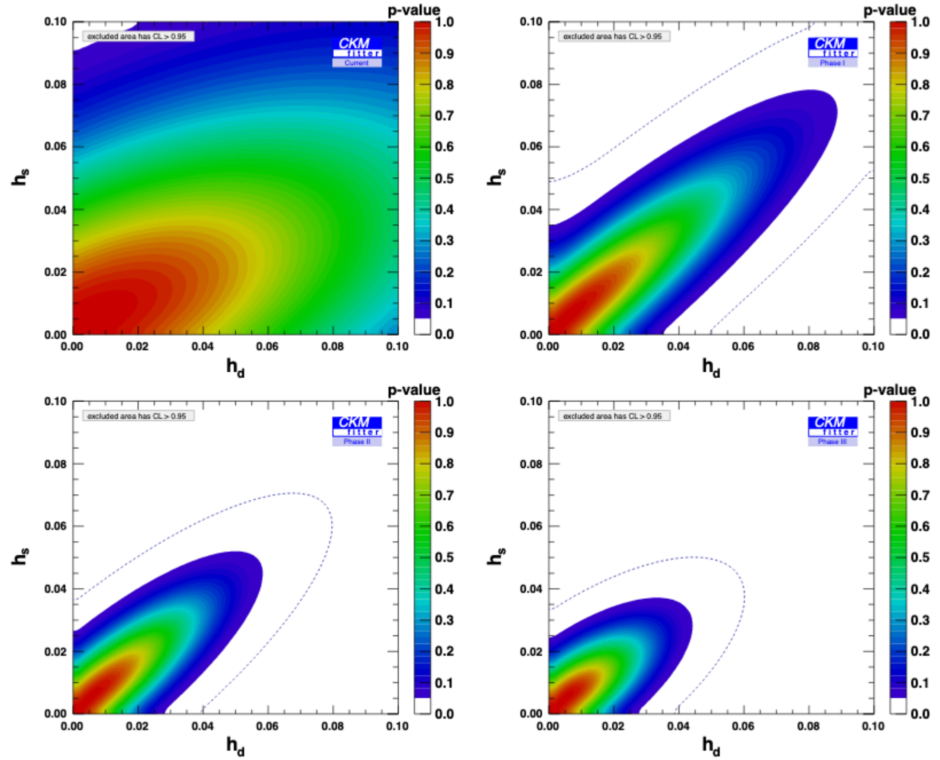


FIG. 2. Current (top left), Phase I (top right), Phase II (bottom left), and Phase III (bottom right) sensitivities to $h_d - h_s$ in B_d and B_s mixings, resulting from the data shown in Table I (where central values for the different inputs have been adjusted). The dotted curves show the 99.7% CL (3σ) contours.

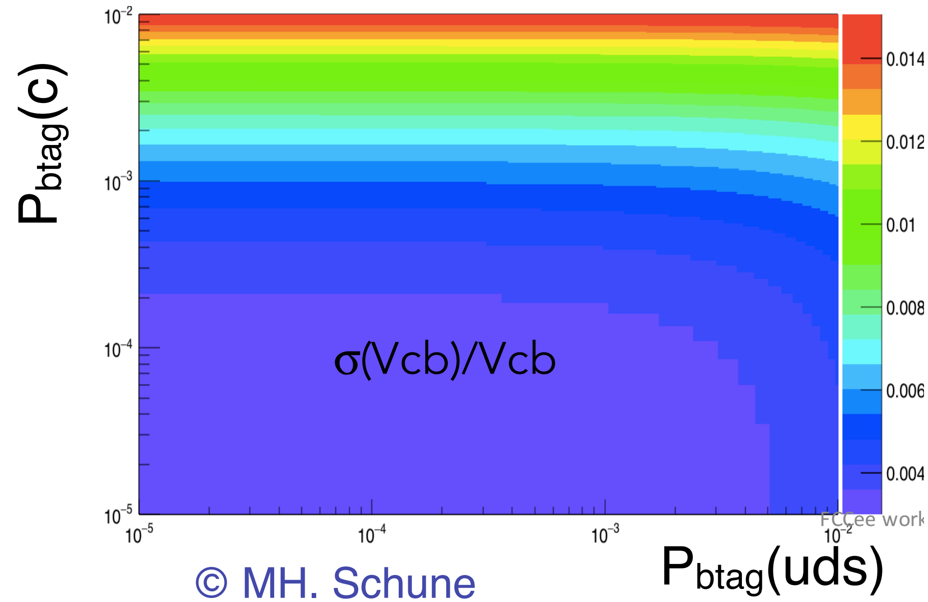
- Bottleneck in precision: Vcb and LQCD mixing parameters

2) Overview of the studies: CKM profile & Friends

- $|V_{cb}|$ measurement: the WW threshold. First look 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



© MH. Schune

- 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.

2) Overview of the studies: CKM profile & Friends

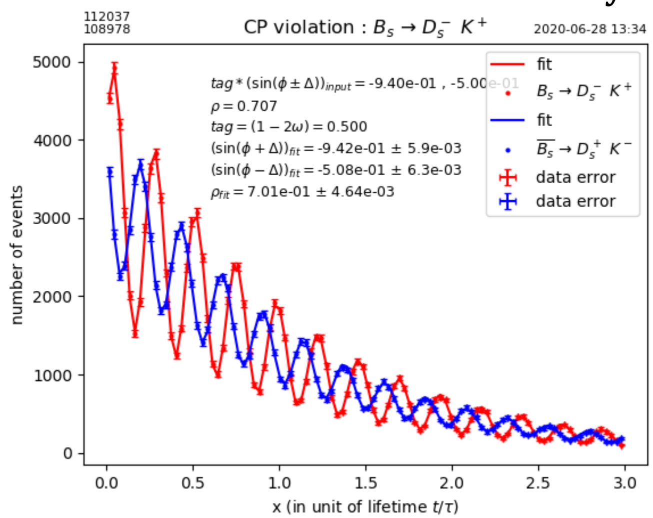
- Sub-degree gamma angle measurement at reach :

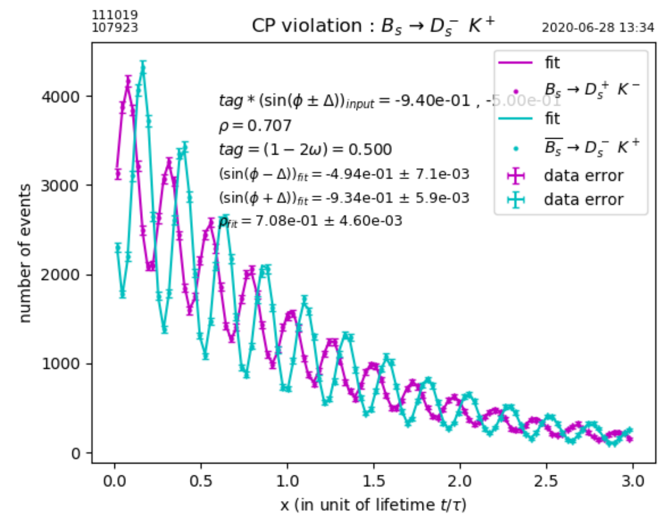
Measurement of CP violation with $B_s \to D_s K$

© R. Aleksan

$\int Ldt = 150\ ab^{-1}$

PDG: $\gamma = (71.1^{+4.6}_{-5.3})°$





Result 3 :

$\delta(\rho) \approx 3.2 \times 10^{-3}(stat.)$

$\delta(sin^2\phi_{CKM}) \approx \delta(sin^2\gamma) \approx 5 \times 10^{-3}(stat.) \cong \delta(\gamma) \approx 0.4°\,(stat.)$

Potential statistical gain of factor 4-5 with $D_S^{\pm} \to K^{*0}K^{\pm}, \phi\rho^{\pm}$, … but background needs to be studied (see later)+
Additionnal potential gain (another factor ~2) with $B_s \to D_s^{*\pm}K^{\mp}, D_s^{\pm}K^{*\mp}, D_s^{*\pm}K^{*\mp}$, most modes including γ(s)

- More to do with neutrals. Several null tests of the SM accessible w/ unprecedented precision, *e.g.* semileptonic asymmetries.

2) Overview of the studies: CKM profile & Friends

- Degree alpha measurement : a study to get started.

- The alpha angle can be measured through an isospin analysis from $B^0 \to (\pi\pi)^{+-/00}$. The knowledge of parameter S^{00} , that can be accessed from time-dependent studies, allows to lift degeneracies among solutions.

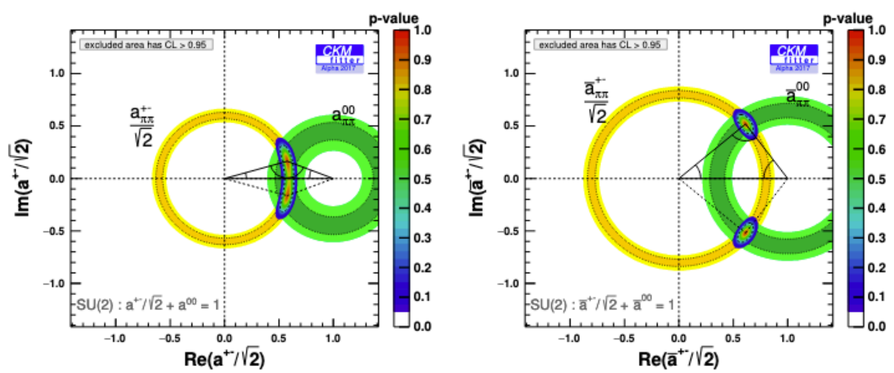


Figure 4: *Constraint on the reduced amplitude $a^{+-} = A^{+-}/A^{+0}$ in the complex plane for the $B \to \pi\pi$ (left) and $\bar{B} \to \pi\pi$ systems (right). The individual constraint from the $B^0(\bar{B}^0) \to \pi^+\pi^-$ observables and from the $B^0(\bar{B}^0) \to \pi^0\pi^0$ observables are indicated by the yellow and green circular areas, respectively. The corresponding isospin triangular relations $a^{00} + a^{+-}/\sqrt{2} = 1$ (and CP conjugate) are represented by the black triangles.*

- Accessible through Dalitz decays of the π^0 in $B^0 \to (\pi^0\pi^0)$. Vertex is there. Statistics too [O(10k)]. A possible golden channel for EM calo. design.

2) Overview of the studies: others

- Many other categories to explore. To cite two of them that will be addressed in the feasibility study.

  —) Mass and lifetime properties, spectroscopy, exotics.

  —) Charm physics.

  Both categories are not touched yet to my knowledge on the experimental side but are a must-do.

    - The invariant-mass resolutions, charged and hopefully neutrals as well, at FCC-ee for narrow states shall make marvels in spectroscopy.
    - For charm, significant phenomenological works do exist for FCC-ee. One of the last in line : https://arxiv.org/pdf/2010.02225.pdf. The exploration shall be launched.

2) Overview of the studies: Tau lepton physics

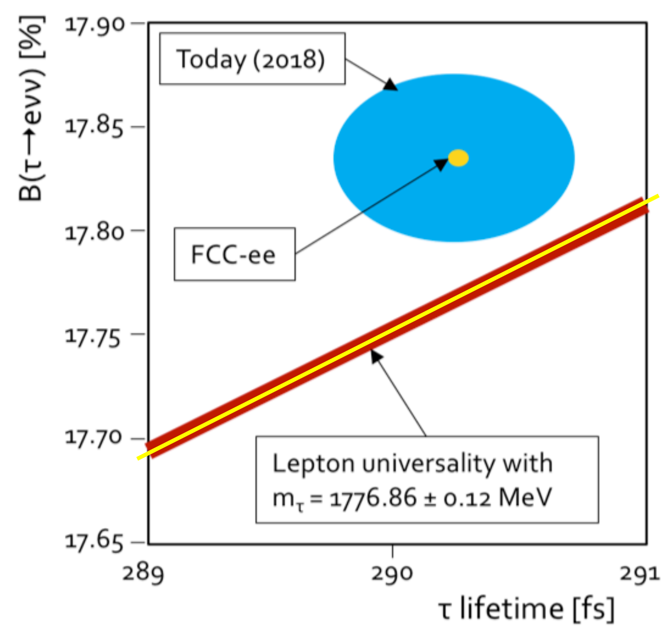
- Touched so far through the lepton universality studies and Lepton Flavour violating decays (LFV Z and tau directly).

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_τ [MeV]	Threshold / inv. mass endpoint	1776.86 ± 0.12	0.004	0.04 (?)	Mass scale
τ_τ [fs]	Flight distance	290.3 ± 0.5 fs	0.001	0.04	Vertex detector alignment
$B(\tau\to e\nu\nu)$ [%]	Selection of $\tau^+\tau^-$, identification of final state	17.82 ± 0.05	0.0001	0.003	Efficiency, bkg, Particle ID
$B(\tau\to\mu\nu\nu)$ [%]		17.39 ± 0.05			

© M. Dam

Necessary ingredients:

- Mass
- Lifetime
- Leptonic branching fractions



2) Overview of the studies: Tau lepton physics

- A non-exhaustive Tau Physics advantages and prospects :
  - About 200 billions of tau pairs at the *Z* pole.
  - About 3 times the Belle II anticipated statistics but with a 25 boost !
  - Beyond EWPO (polarisation), stringent lepton universality tests. Global improvement can be two orders of magnitude w.r.t. state of the art.
  - Three orders of magnitude w.r.t. state of the art in sensitivity for LFV Z decays. One order of magnitude for actual LFV tau decays.
  - Hadronic branching fractions, spectral functions, strong coupling constant: the QCD program with tau is rich.

3) Outlook

- The FCC feasibility study has started. CDR+ for the next ESPP update 2026. Detector concepts to be addressed.

- Flavour Physics defines shared (vertexing, tracking, calorimetry) and specific (hadronic PID) detector requirements. The feasibility study entangles the Physics performance and detector concepts. Flavour physics places most demanding requirements for vertexing and calorimetry.

- All studies at the Z pole shown above are made for 5.10^{12} Z decays. Most of flavour observables will remain statistically limited. More would be desirable ! The machine study from two IPs to four IPs is positive. It has (all, imo) virtues. Four experiments is a good model and allows for different experiment designs. One could envisage a flavour-oriented concept. Incidentally, about a factor 2 in integrated luminosity.

3) Outlook

- A high potential and a lot to be done to go beyond exploratory studies and systematically address the physics case / detector design.

- A flavour physics working group has been set up and will get up and running before this Summer. Here to subscribe:

  - https://e-groups.cern.ch/e-groups/EgroupsSubscription.do?egroupName=FCC-PED-PhysicsGroup-Flavours

- If you want to get to the other FCC mailing lists, please issue

  - https://e-groups.cern.ch/e-groups/EgroupsSearchForm.do.

  - then issue FCC-PED in the search form.