Flavour studies at FCC-*ee*.

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Outline

1) A kind of summary
2) FCC-*ee* machine specifics for Flavour Physics
3) Flavour anomalies and FCC-*ee.*
4) New results on *CP* violation studies.

0) Method / lessons for the FCC-*ee* Flavour Physics working group.

- Given the available manpower to conduct the Flavour studies at FCC-*ee*, instead of trying to cover the whole Physics case, we focused on some outstanding subjects of the field by selecting a few places where the FCC-*ee* experiments will (most likely) be unique.

- We succeeded at getting:
    - The EWP dileptonic decays covered through their most difficult final state one can imagine ($B^0 \to K^{*0}\ \tau^+\tau^-$). On both phenomenology end experimental sides. It sets the scale. *Qui peut le plus peut le moins*.
    - The LFV Z decays studied both phenomenologically and experimentally.
    - An exploration of the possible observation of the *CP* violation in *B*-meson mixings.
    - Flavour Physics requirements (vertexing, tracking and hadron PID).

- We failed in this sequence of the Design Study at
    - having explored the infamous / important $B_s \to \tau^+\tau^-$
    - getting a significant experimental community on board (yet).

1) FCC-ee machine specifics for Flavour Physics.

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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*	1000	1000	250	250	1000	500

- The baseline parameters and the operation model yields the following production rates of *b*-hadrons and tau leptons assumed for the CDR.

- A direct comparison with LHCb yields requires a more involved approach (mode by mode) to take into account trigger and reconstruction efficiencies. LHCb (50 /fb) will dominate the time-integrated beauty and charm physics in fully charged modes.

1) FCC-ee machine specifics for Flavour Physics.

Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-*ee*
EW/H penguins				
$B^0 \to K^*(892)e^+e^-$	$\mathcal{O}(2000)$	150	$\mathcal{O}(5000)$	$\mathcal{O}(200000)$
$B^0 \to K^*(892)\tau^+\tau^-$ ($\mathcal{B}$)	$\mathcal{O}(10)$	–	–	$\mathcal{O}(1000)$
$B_s \to \mu^+\mu^-$	n/a	20	$\mathcal{O}(500)$	$\mathcal{O}(800)$
$B^0 \to \mu^+\mu^-$	$\mathcal{O}(5)$	–	$\mathcal{O}(50)$	$\mathcal{O}(100)$
CP-violating phases				
$B^0 \to J/\Psi K_S$	$\mathcal{O}(2.10^6)$	41500	$\mathcal{O}(10^6)$	$\mathcal{O}(35.10^6)$
$\sigma_{\sin(2\phi_d)}$	0.008	0.04	0.01	0.006
$B_s(B^0) \to J/\Psi\phi$	n/a	96000	$\mathcal{O}(2.10^6)$	$\mathcal{O}(15.10^6)$
σ_{ϕ_s} (rad)	n/a	0.049	0.008	0.003
$B_s \to D_s^\pm K^\mp$	n/a	6000	$\mathcal{O}(200000)$	$\mathcal{O}(30.10^6)$

- The Belle II and LHCb experiments are complementary in their Physics reach. Belle II will mostly dominate the *CP* eigenstates measurements w *B*-mesons, LHCb's realm will be on fully charged final states for all *b*-hadron species. The FCC-ee experiments will compete favourably everywhere.

1) FCC-ee machine specifics for Flavour Physics.

- The energy spread of the beams (~ 50 MeV) to determine event-by-event the actual initial conditions energy-wise.

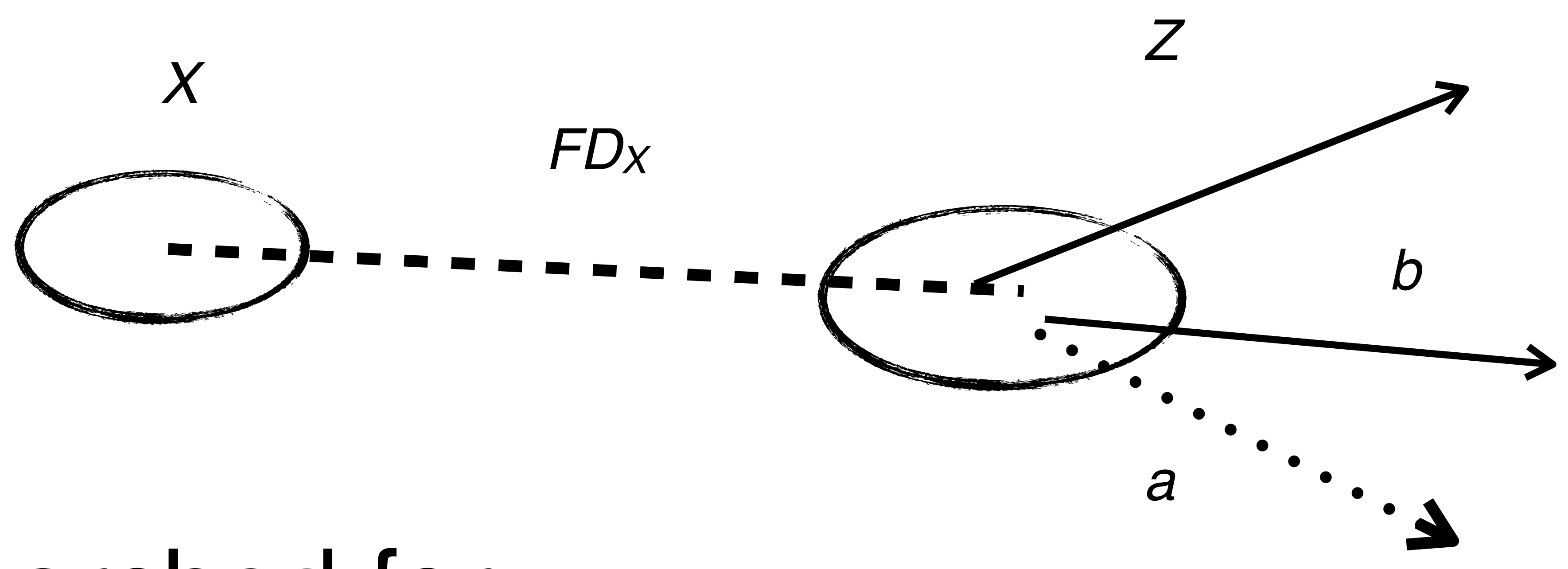
- Amongst the main characteristics for Flavour Physics is the boost experienced at the *Z* pole (fragmentation of the b-quark provides is ~75% of the beam energy to the *b*-hadron).

- Conversely, the excellent capacity of reconstructing detached vertices is a decisive feature for the Flavour Physics studies (beyond those presented here).

1) FCC-ee machine specifics for Flavour Physics.

- The expected vertexing performance at FCC-*ee* (detector at < 2 cm from the interaction point) allows to reconstruct precisely the missing momentum in decays inferred from the decay flight distances.

- 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.

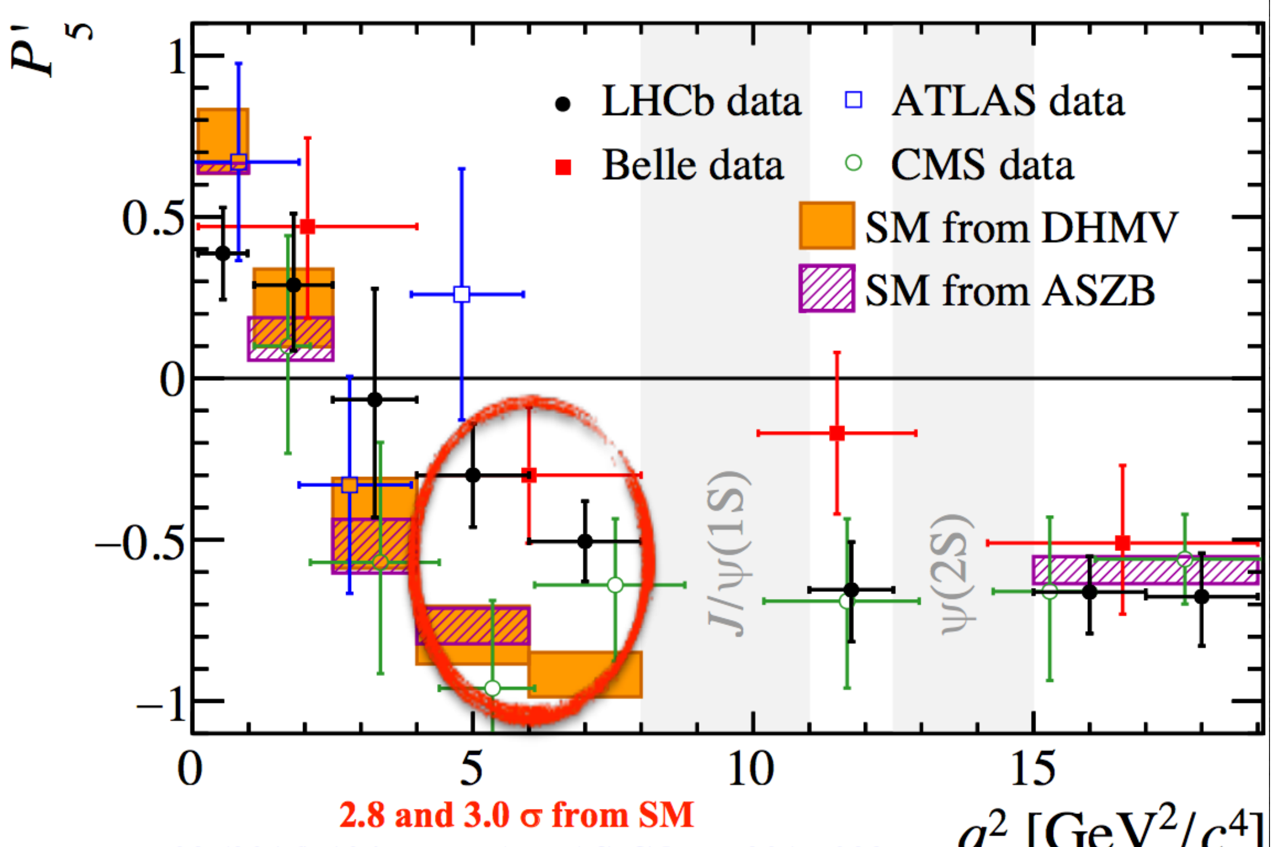
2) Flavour anomalies and FCC-*ee*

2) Flavour anomalies

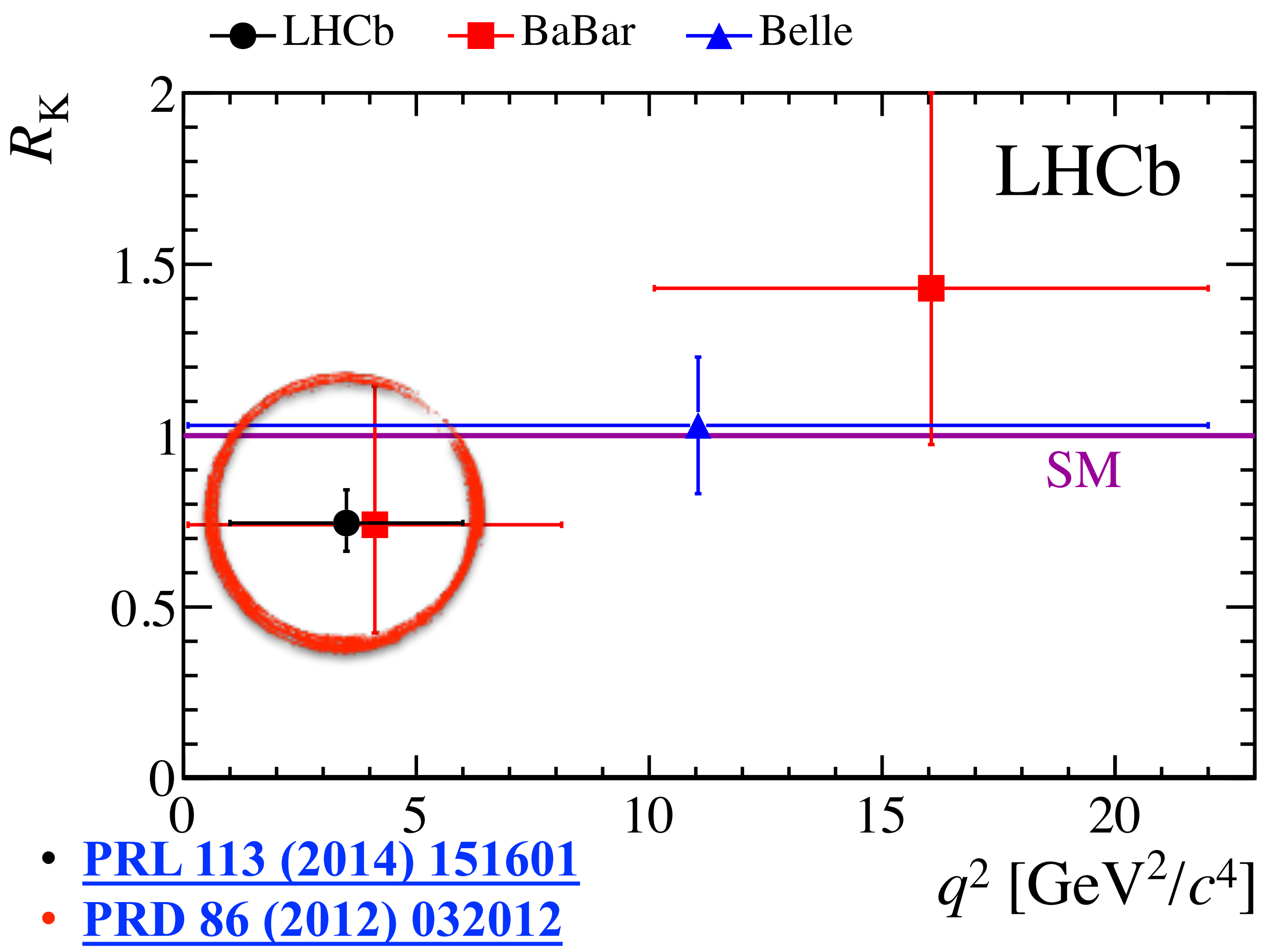
- There are persistent departures of the measurements of the FCNC decays $b \to s\ \ell^+\ell^-$ w.r.t. the SM / QCD predictions. They are consistent among experiments (Belle, LHCb and others) as far as the angular distributions of the mode $B^0 \to K^{*0}\ \mu^+\mu^-$ are concerned.

- LHCb sees consistent departures to lepton universality (LU) in the ratios. Comments on theoretical and experimental challenges: the angular analyses do have theoretical uncertainties (long distance QCD). The LU studies have experimental challenges (q^2 dependence / double ratio).

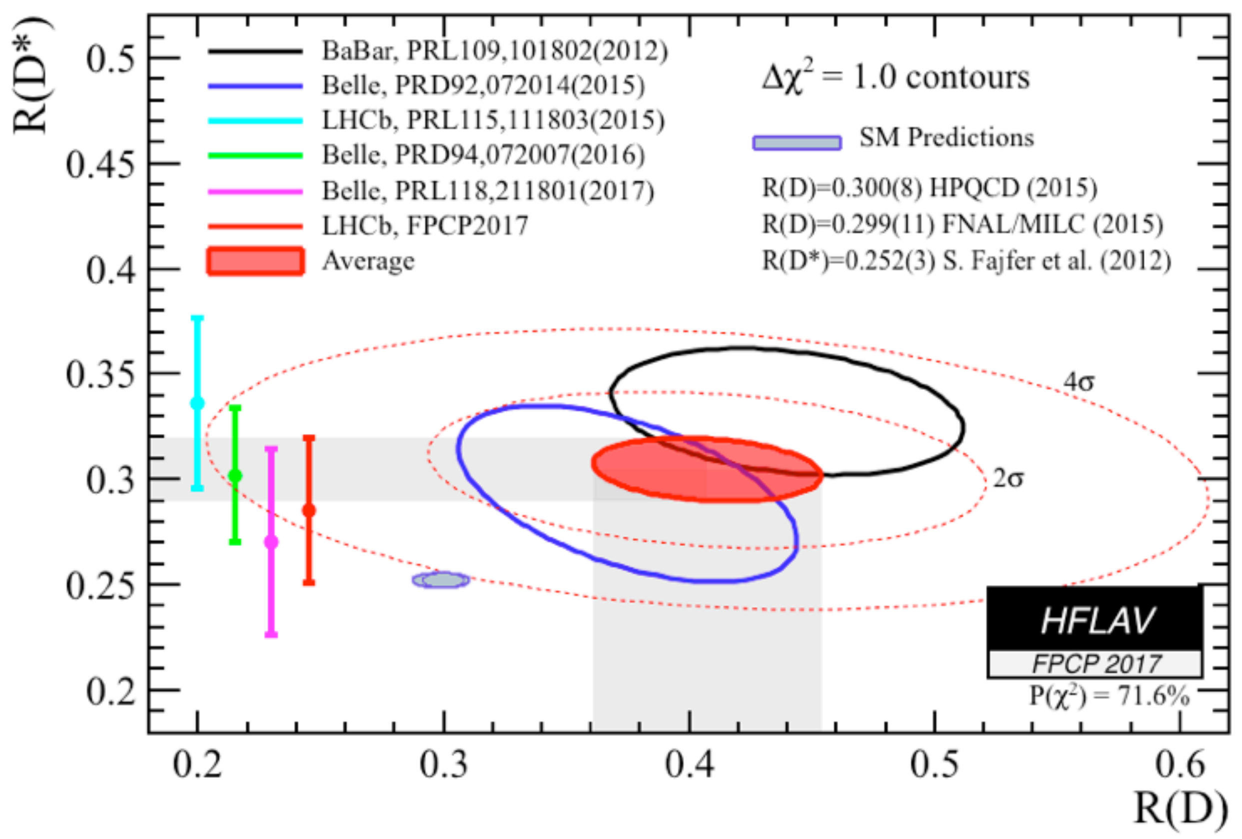
- These add up to the R(D*) and R(D) departures w.r.t. SM predictions.

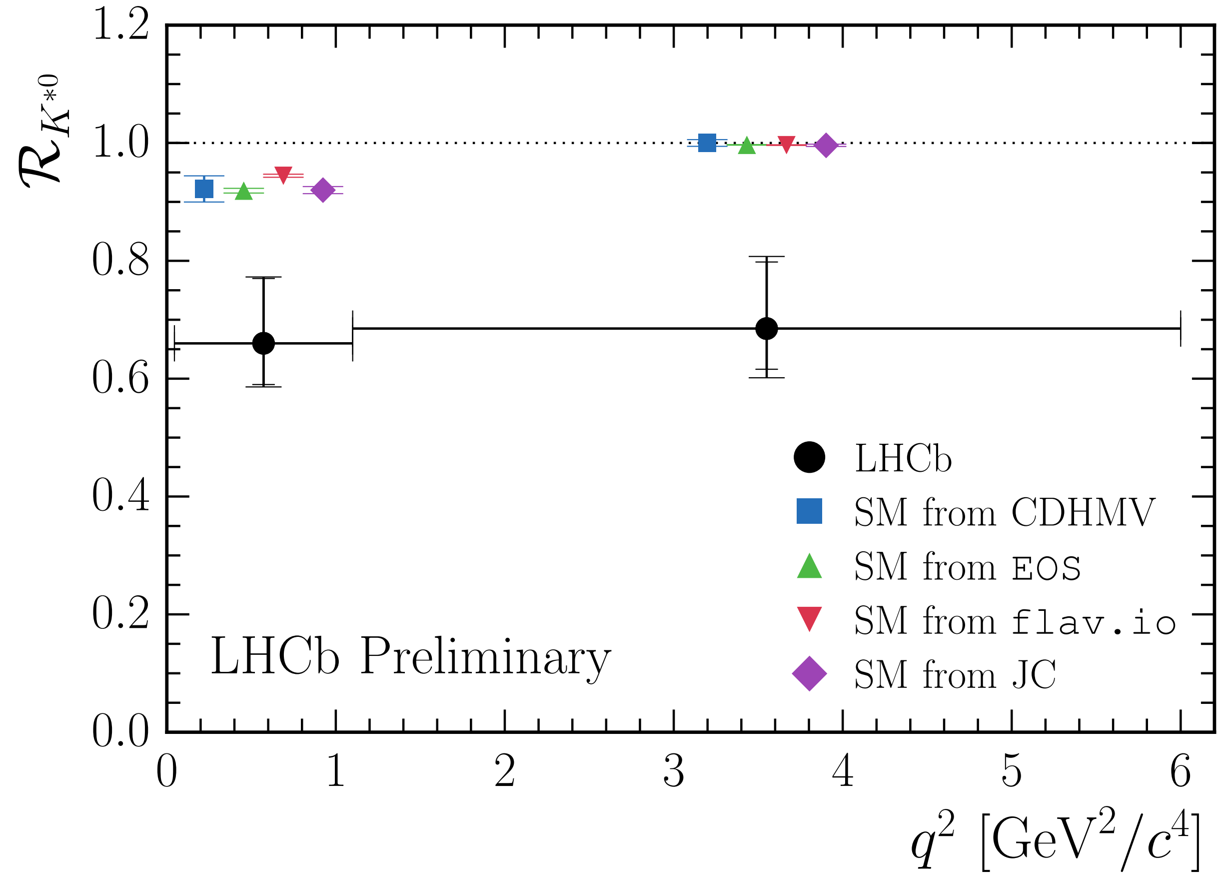


- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008



- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801





2) Flavour anomalies and FCC-ee

- The companion decay modes $B^0 \to K^{*0}\ e^+e^-$ (angular analysis) and mostly $B^0 \to K^{*0}\ \tau^+\tau^-$ are important ingredients to interpret the discrepancies, should they be confirmed: likely unique at FCC-*ee*.

- The available statistics for the former at FCC-*ee* is beyond competition.

- The latter requires partial reconstruction, *i.e.* the use of the production and decay vertices to solve the kinematics of the decay. But the SM branching fraction can likely only be attained at FCC-*ee*.

- Data-driven model-independent approaches provide very significant enhancement of arXiv:1712.01919 of $b \to s\tau^+\tau^-$ transitions. More generally, **final states with τ particles are model killers.**

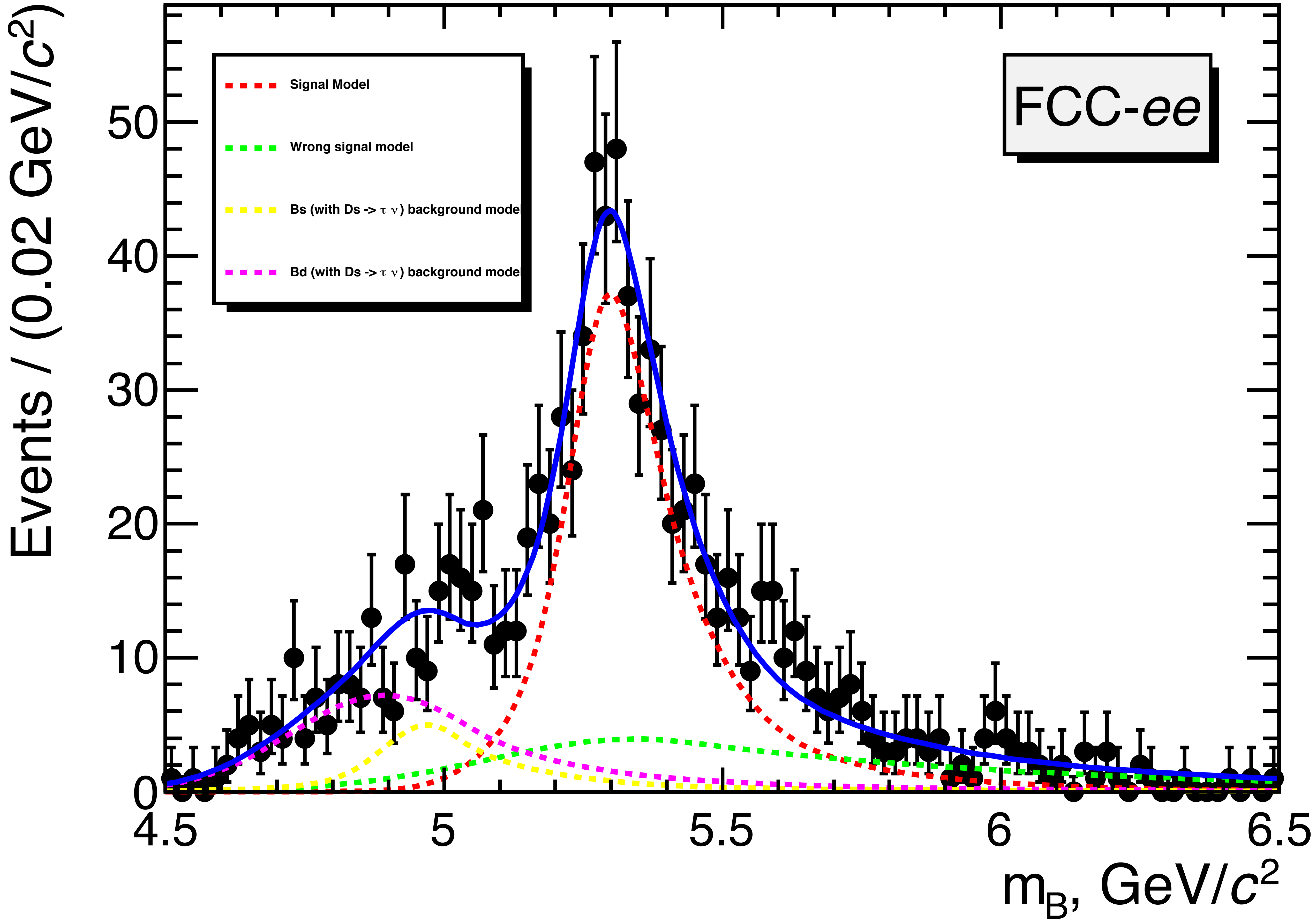
- The mode $B^0 \to K^{*0}\ \tau^+\tau^-$ has received a special attention in the FCC-*ee* context.

2) The search for $B^0 \to K^{*0}\tau^+\tau^-$

- Makes use of partial reconstruction technique to solve the kinematics of the decay. Sensitivity relies on vertexing performance

- 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

- Backgrounds: (pink - DsK*taunu and DsDsK*) [signal in red+green].



Comment in order: at baseline luminosity, under SM hypothesis, more than 10^3 events of reconstructed signal. Angular analysis possible.

2) The search for $B^0 \to K^{*0}\tau^+\tau^-$

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)

2) The search for $B^0 \to K^{*0}\tau^+\tau^-$. Executive summary.

- Should the LFUV anomalies confirmed, the mode $B^0 \to K^{*0}\tau^+\tau^-$ is a model killer. It is likely unique ro FCC-*ee.*

- The study so far is considering the three-prongs decays of taus w/o neutrals. More than doubling the statistics w/ neutral pions, w/o loss of method generality.

- Clean measurement of the branching fraction, even differential in q^2 [O(5%) for a SM-like decay].

- As soon as we go to angular observables, the angular resolution will provide additional constraints on the detector.

- The paper arXiv:1705.11106 suggests several observables, to be considered in the next steps of the design study, with full simulation embodied.

3) Hunting for new *CP*-violating phases

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- The 3x3 CKM mass mixing matrix exhibits a unique complex parameter. It is the *only* source of *CP* violation in the Standard Model. It fails at explaining the observed baryonic asymmetry in the Universe.

- Yet, all *CP* asymmetries observed in the *K* and *B* meson systems are accounted for consistently by this single parameter (see next-to-next slide).

- The hunt for additional *CP*-violating phases can advantageously proceed through model-independent approaches, acknowledging the tremendous success of the CKM paradigm to describe the data (Minimal Flavour Violation hypothesis).

- All what follows is tagged preliminary.

3) Hunting for new *CP*-violating phases. And the good old ones first?

- Given the cleanliness of the experimental environment, all *CP* eigenstates can be advantageously studied. The boost at the *Z* provides the versatility of precise decay-time dependent studies. The flavour tagging (because of the incoherent *b*-quark pair production) is less efficient than at Belle II but mitigated by the statistics increase. Here luminosity scaling of the Physics reach.

Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-*ee*
$B^0 \to J/\Psi K_S$	$\mathcal{O}(2.10^6)$	41500	$\mathcal{O}(10^6)$	$\mathcal{O}(35.10^6)$
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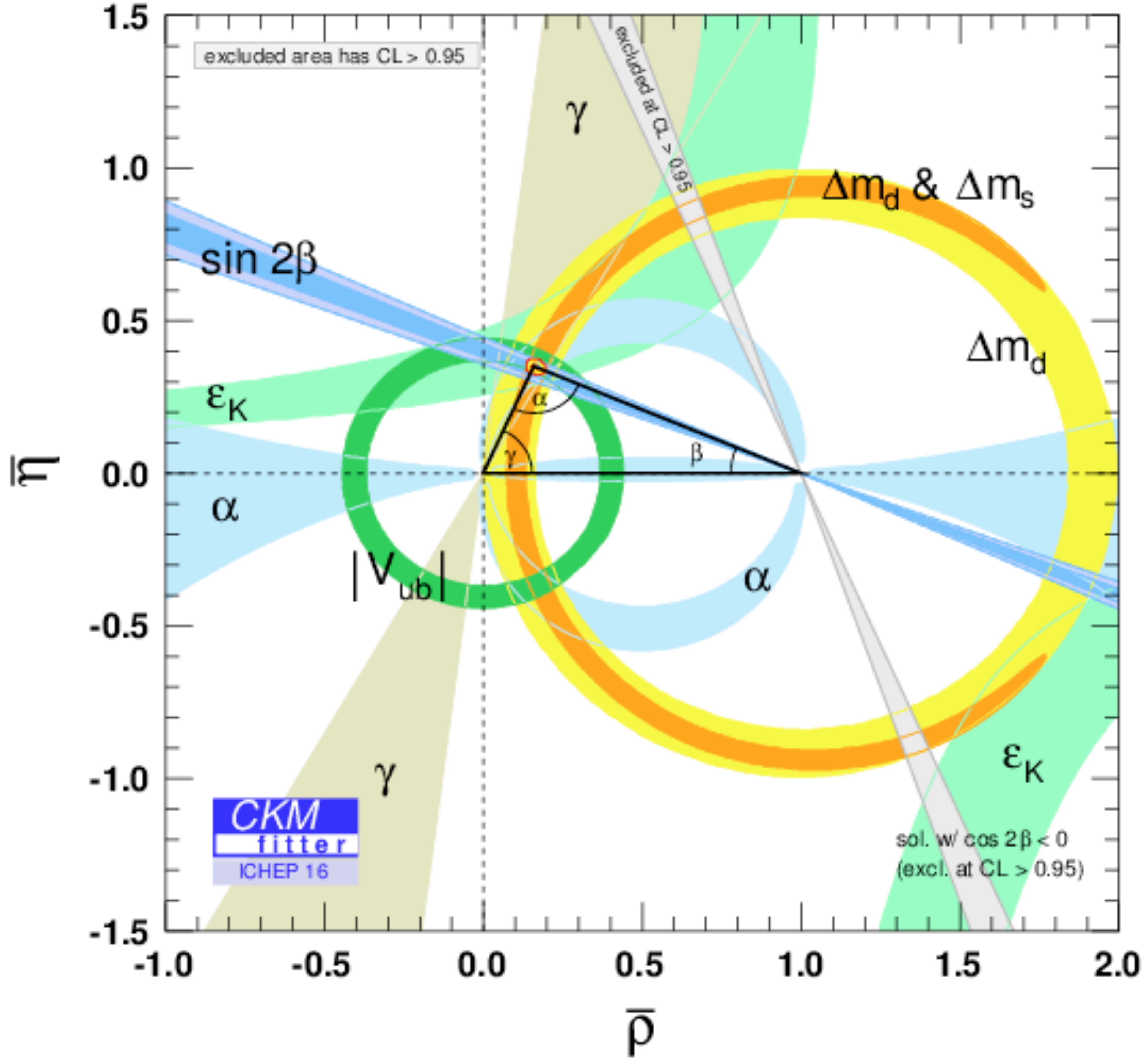
The unitarity triangle



- The focus was not these last years on the UT anymore (though Belle II and LHCb improvements on *CP* observables should revive the subject). Yet, there are firm statements that can be drawn and can't be escaped

- CKM is at work in weak charged current.

- The KM phase IS the dominant source of *CP* violation in *K* and *B* particle systems. Implications for what comes next.

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

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

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

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.

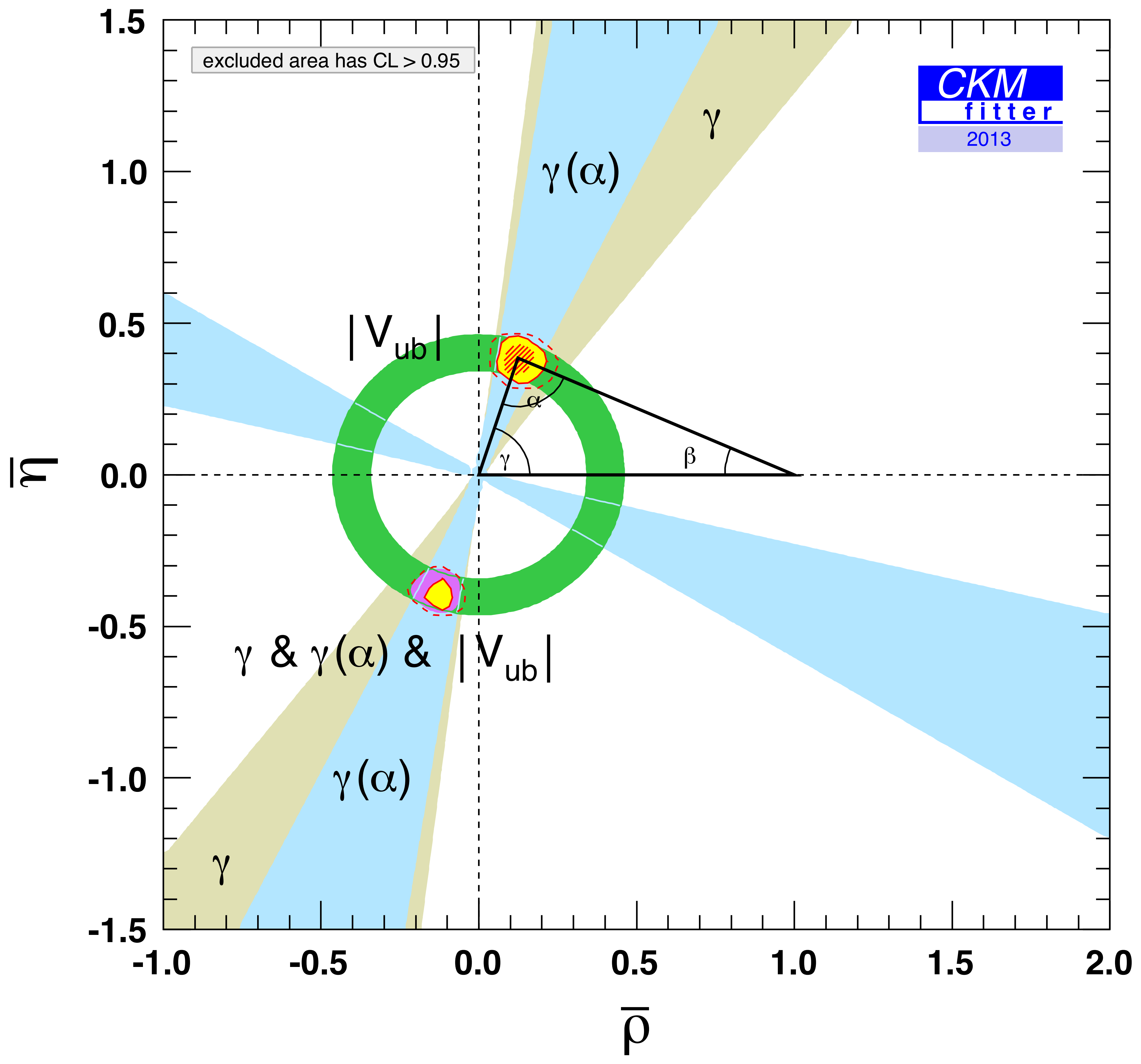
✓Unitary 3x3 CKM matrix (Flavour violation only from the Yukawas-MFV hypothesis).

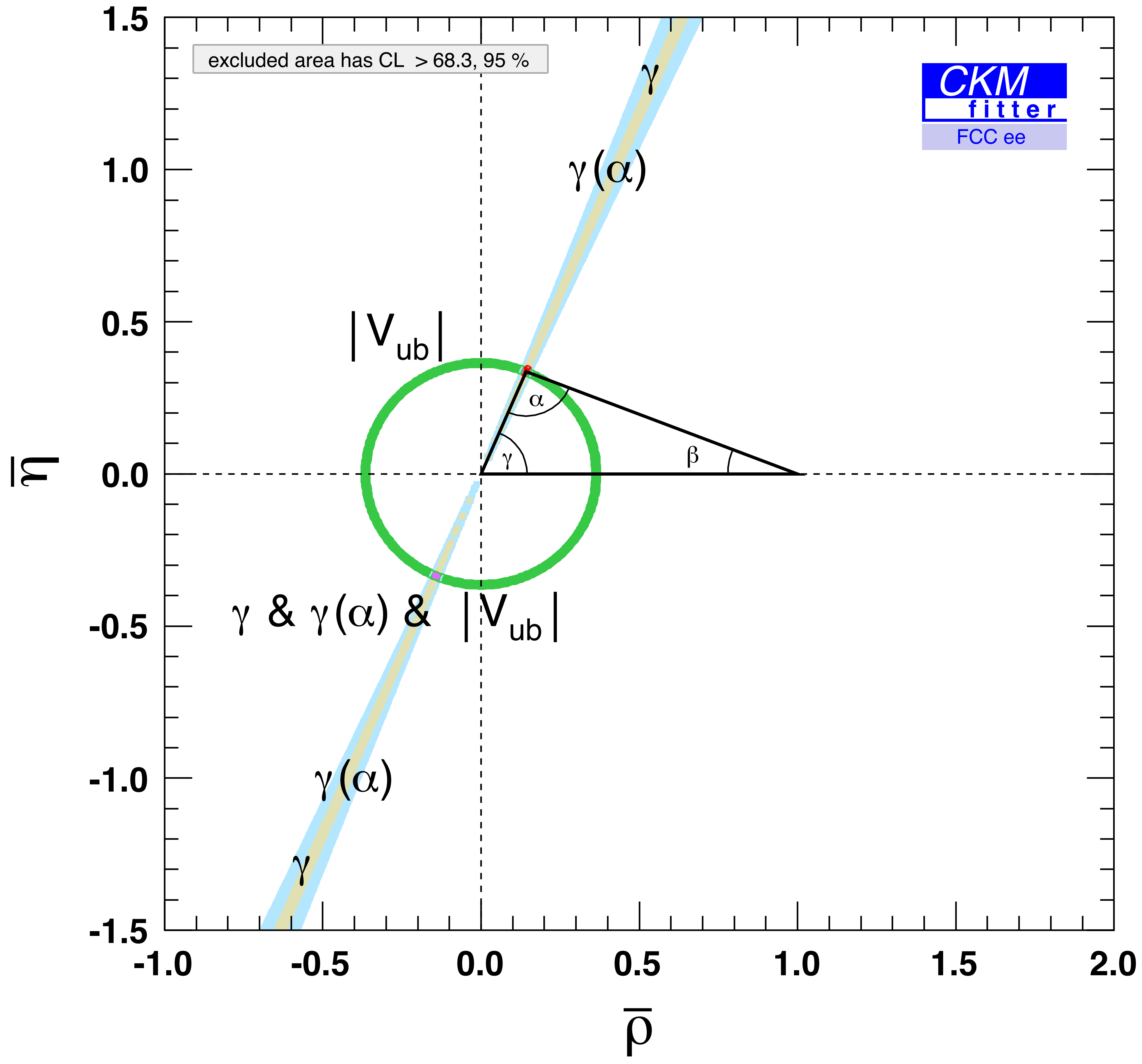
✓ Tree-level processes are not affected by NP (so-called SM4FC: $b \rightarrow q_i q_j q_k$ ($i \neq j \neq k$)). As a consequence, the quantities which do not receive NP contributions in that scenario are:

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

3) Hunting for new CP-violating phases - BSM in $\Delta F = 2$ quark transitions

A - The universal unitarity triangle: fixing CKM parameters. Comparison of the state of the art w/ the FCC-*ee* anticipated landscape (assuming SM).





3) Hunting for new *CP*-violating phases - BSM in $\Delta F = 2$ quark transitions

B - Knowing the CKM parameters, one can introduce the constraints of the *B* mixing obs. 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	$\frac{\Gamma_{12,q}}{M_{12,q}^{\mathrm{SM}}} \times \frac{\sin(\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}})}{\lvert\Delta_q^{\mathrm{NP}}\rvert}$
$\Delta\Gamma_q$	$2\lvert\Gamma_{12,q}\rvert \times \cos(\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}})$

Hyp: SM values of the flavour-specific asymmetries can be measured w/ 20% precision.

Aparté - *CP* violation in the neutral *B*-meson mixing at FCC-*ee*

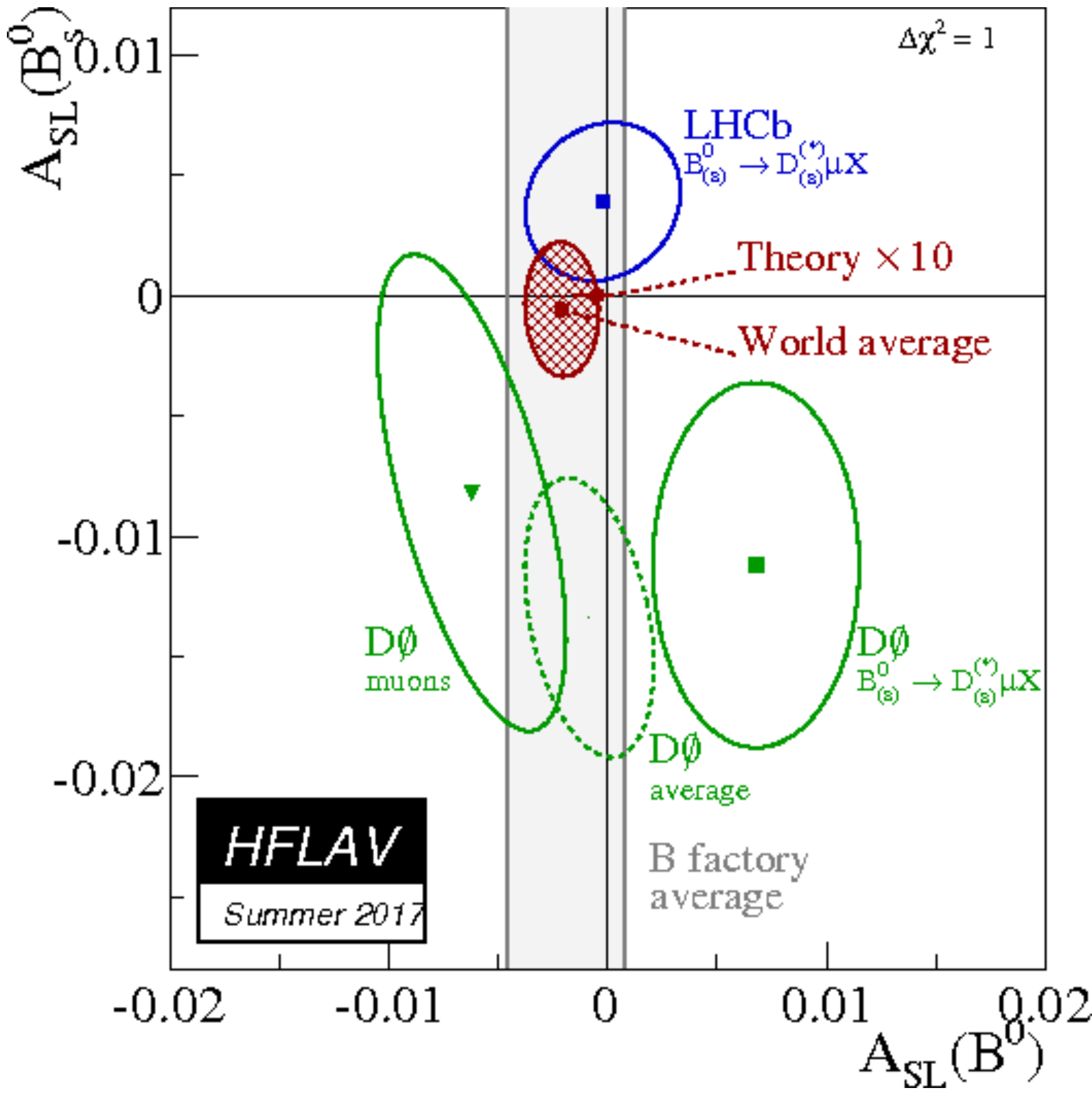
- The *CP* breaking in the interference between the decay and the mixing of the B^0 was firmly established by the BaBar and Belle experiments in 2001. In contrast *CP* violation in *B*-meson mixings is not observed to date. It can be searched for through measurements of asymmetries in the decay rates into flavour-specific states

$$a_{\rm fs} = \frac{\Gamma(\overline{B}^0_q \to B^0_q \to f) - \Gamma(B^0_q \to \overline{B}^0_q \to f)}{\Gamma(\overline{B}^0_q \to B^0_q \to f) + \Gamma(B^0_q \to \overline{B}^0_q \to f)}$$

- SM predictions are small

$$a^d_{\rm fs} = -(4.7 \pm 0.6) \cdot 10^{-4}$$
$$a^s_{\rm fs} = +(2.2 \pm 0.3) \cdot 10^{-5}$$

- Current measurements consistent with the SM predictions but with large uncertainties. Some measurements in tension with the WA.



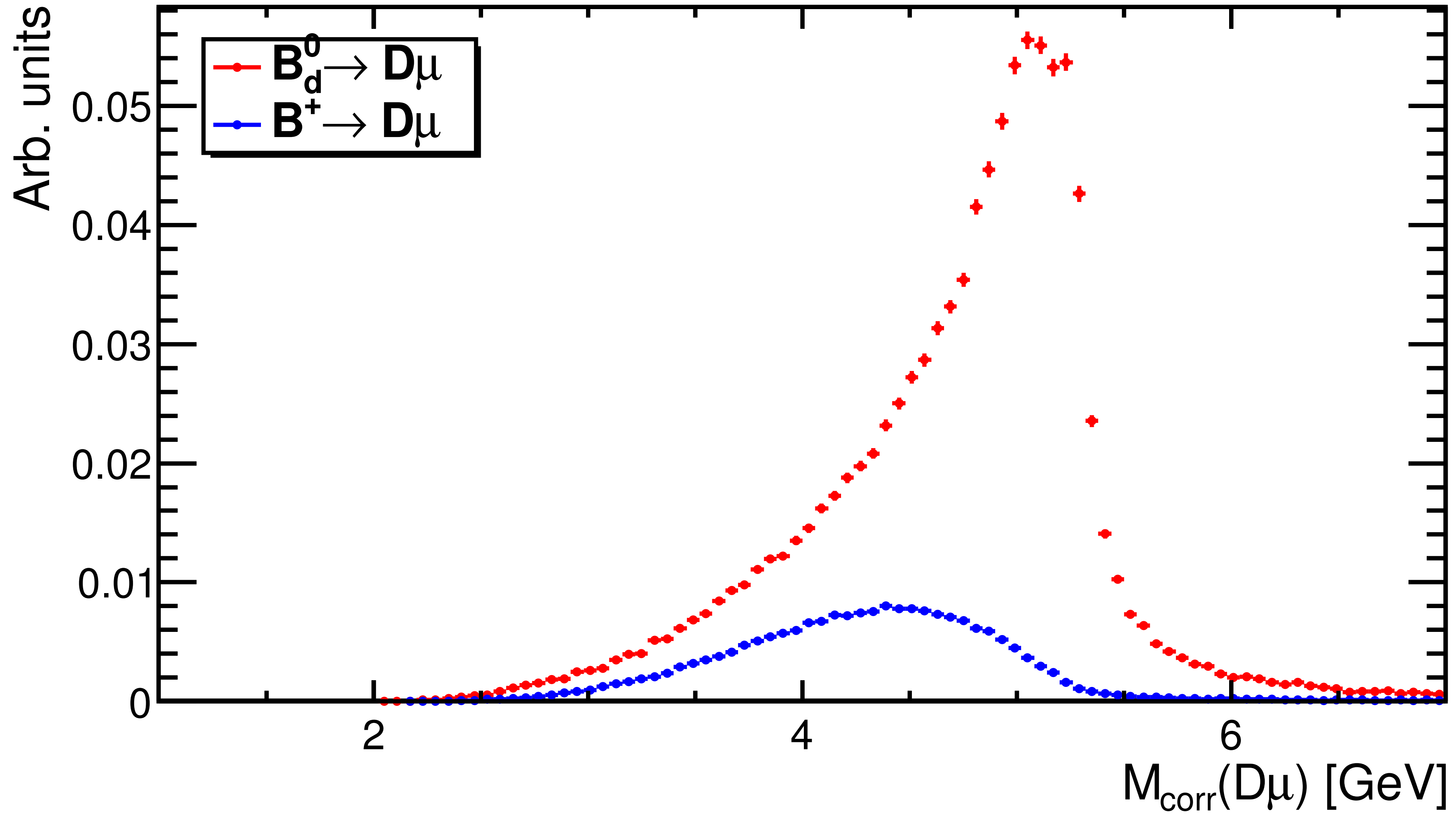
- Generation w/ Pythia8+Evtgen of about 20 decay modes corresponding to

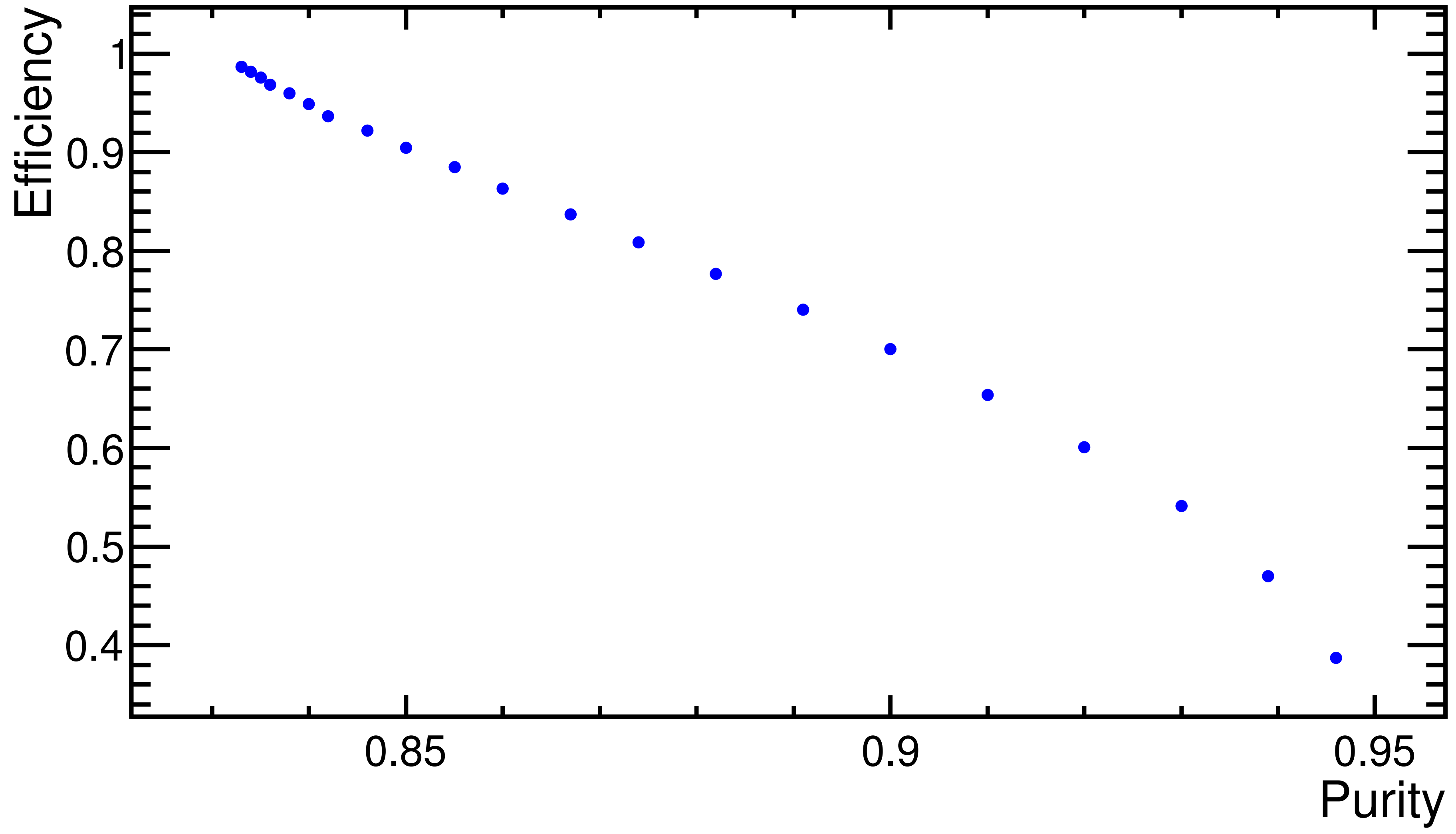
$$\bar{b} \to B^0 \to D^- \mu^+ \nu_\mu X,\ D^- \to K^+ \pi^- \pi^-$$

- Dominant backgound from charged *B*-mesons

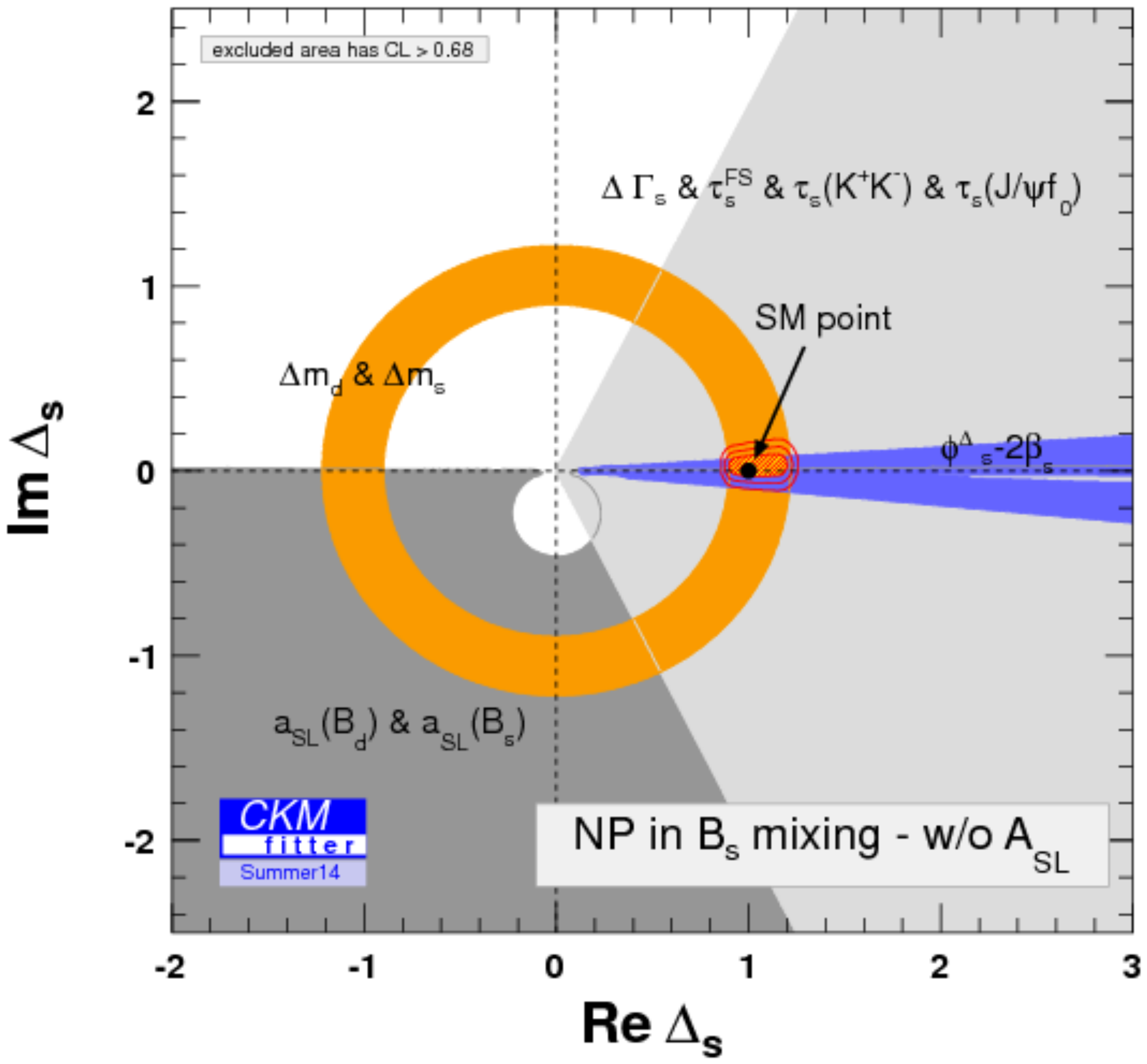
- At baseline luminosity, assuming a flavour tagging efficiency of *O*(10%), a selection efficiency of *O*(80%), the total number of useful tagged events at FCC-*ee* amounts to few 10^8, which must improve the present accuracy by one order of magnitude and allows for first observation.

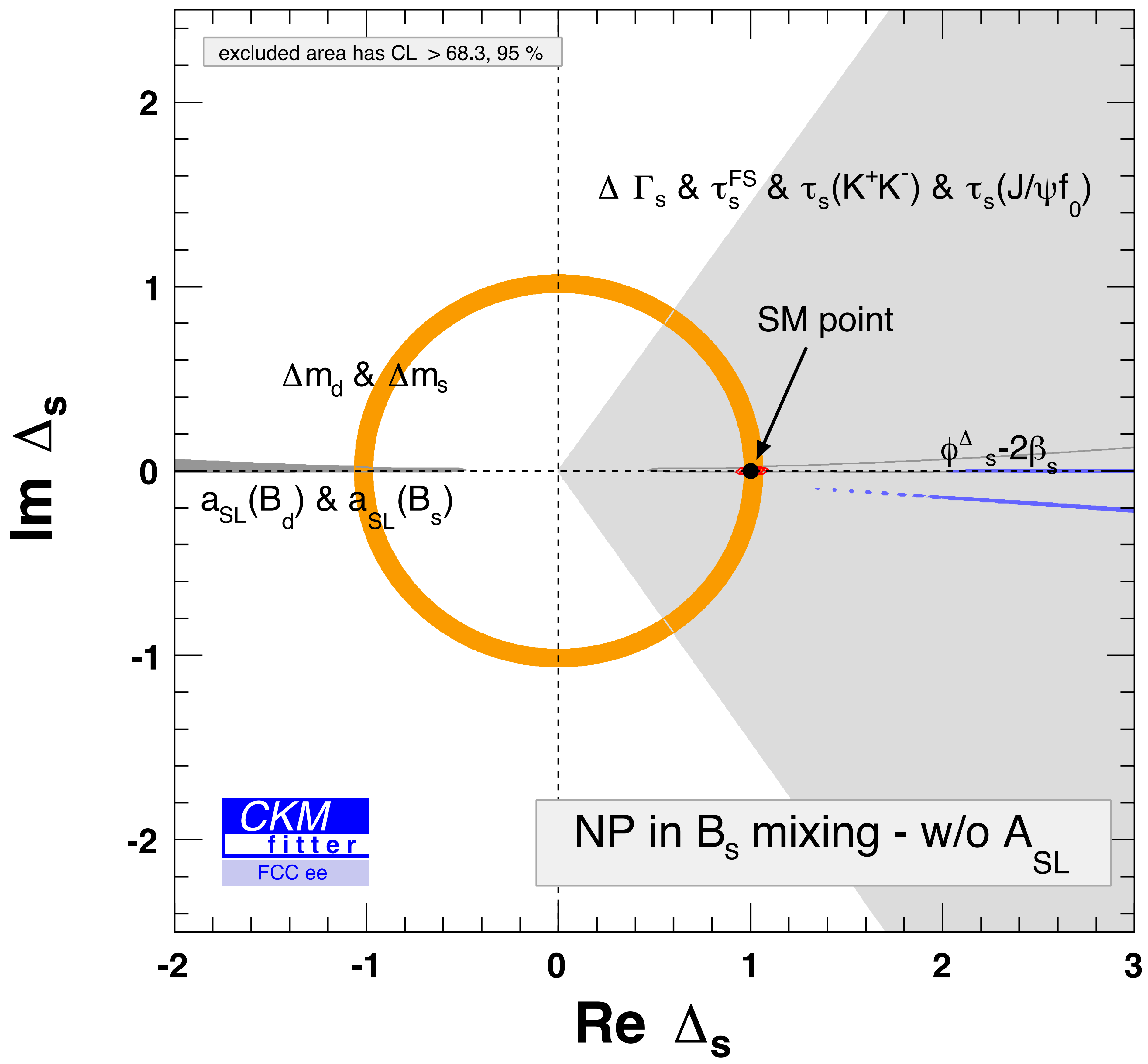
- Similar study to be performed for B_s



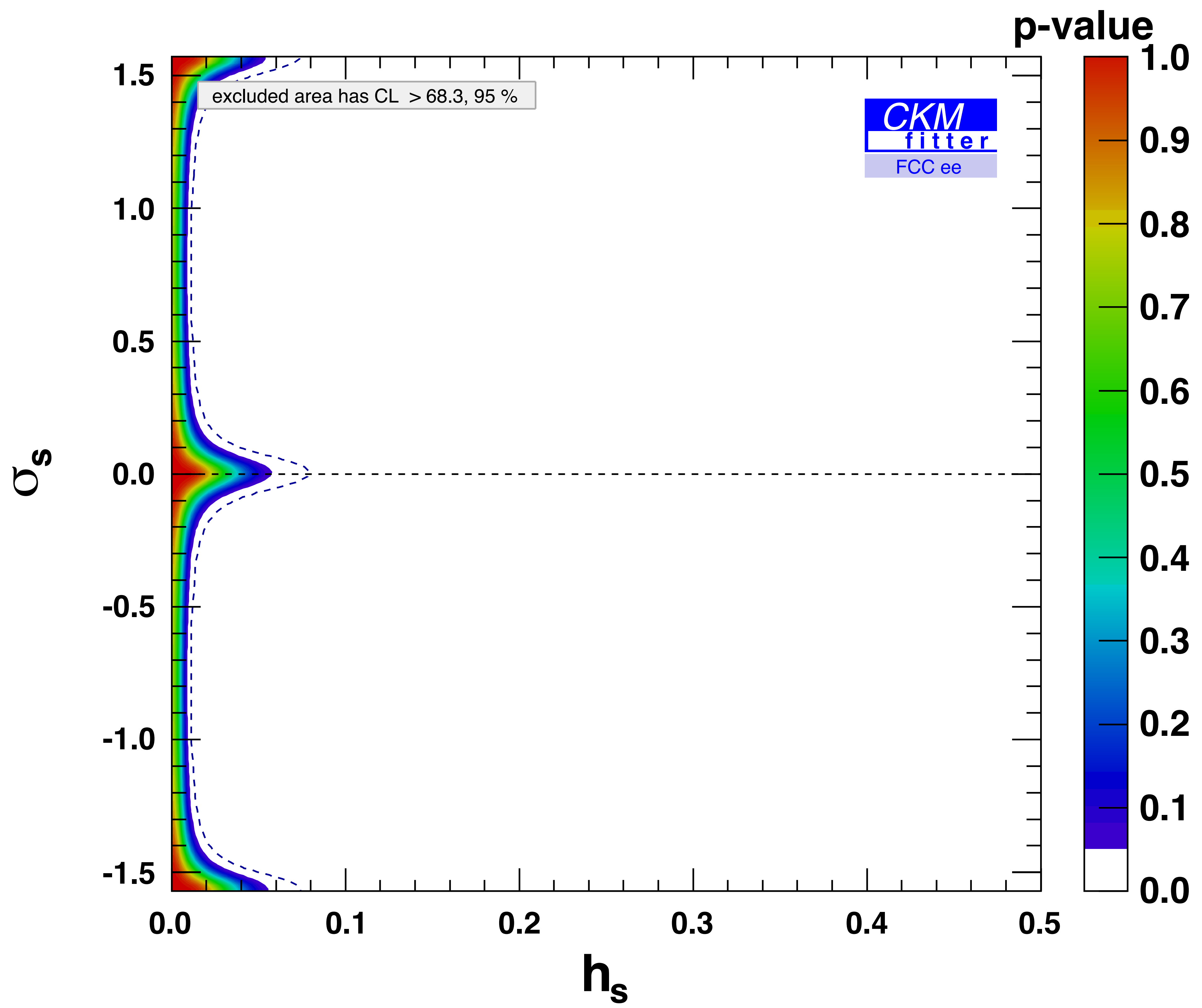


C - Results for the *Bs* assuming that FCC-*ee* can measure *CP* violation in the *Bs* mixing

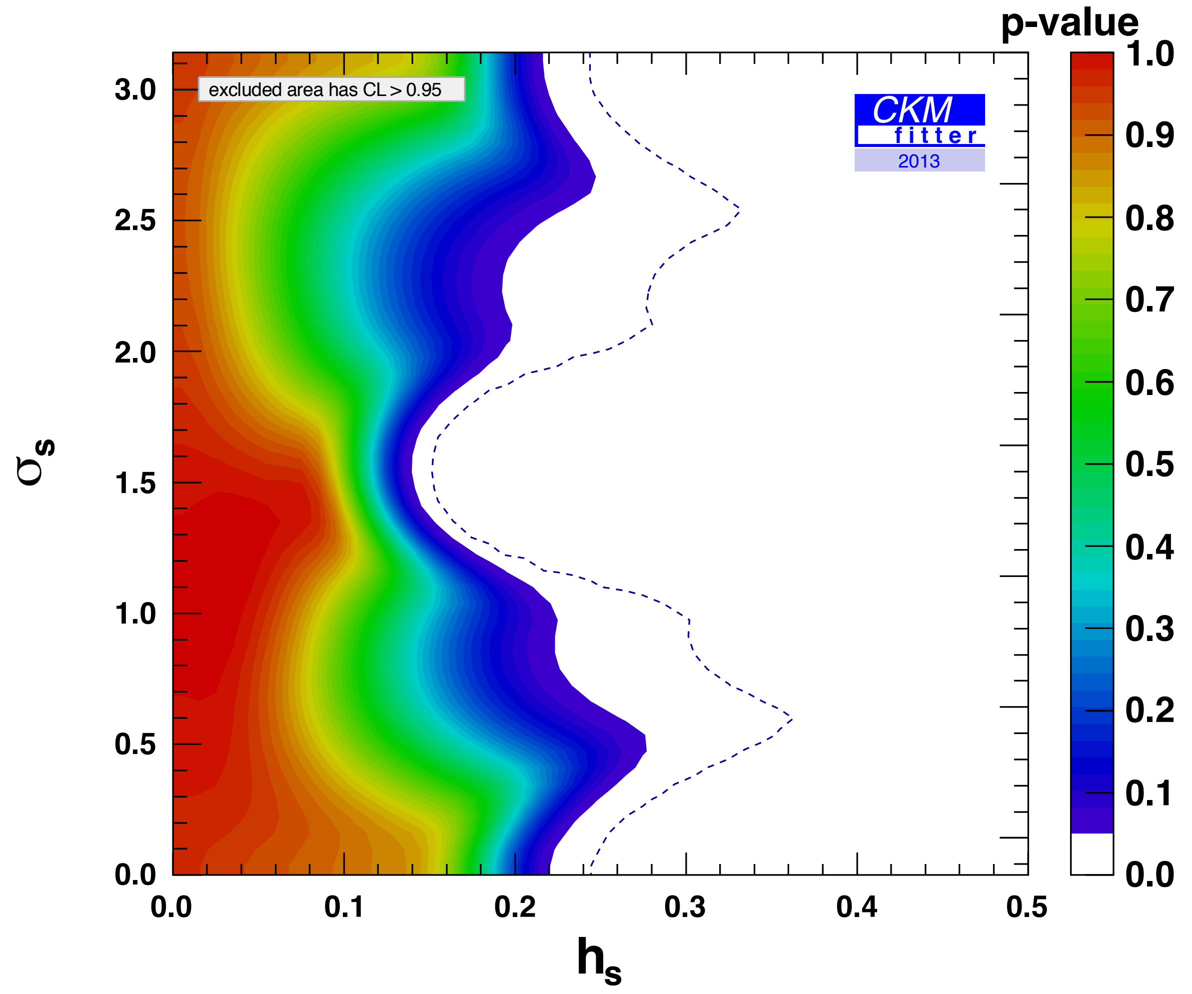




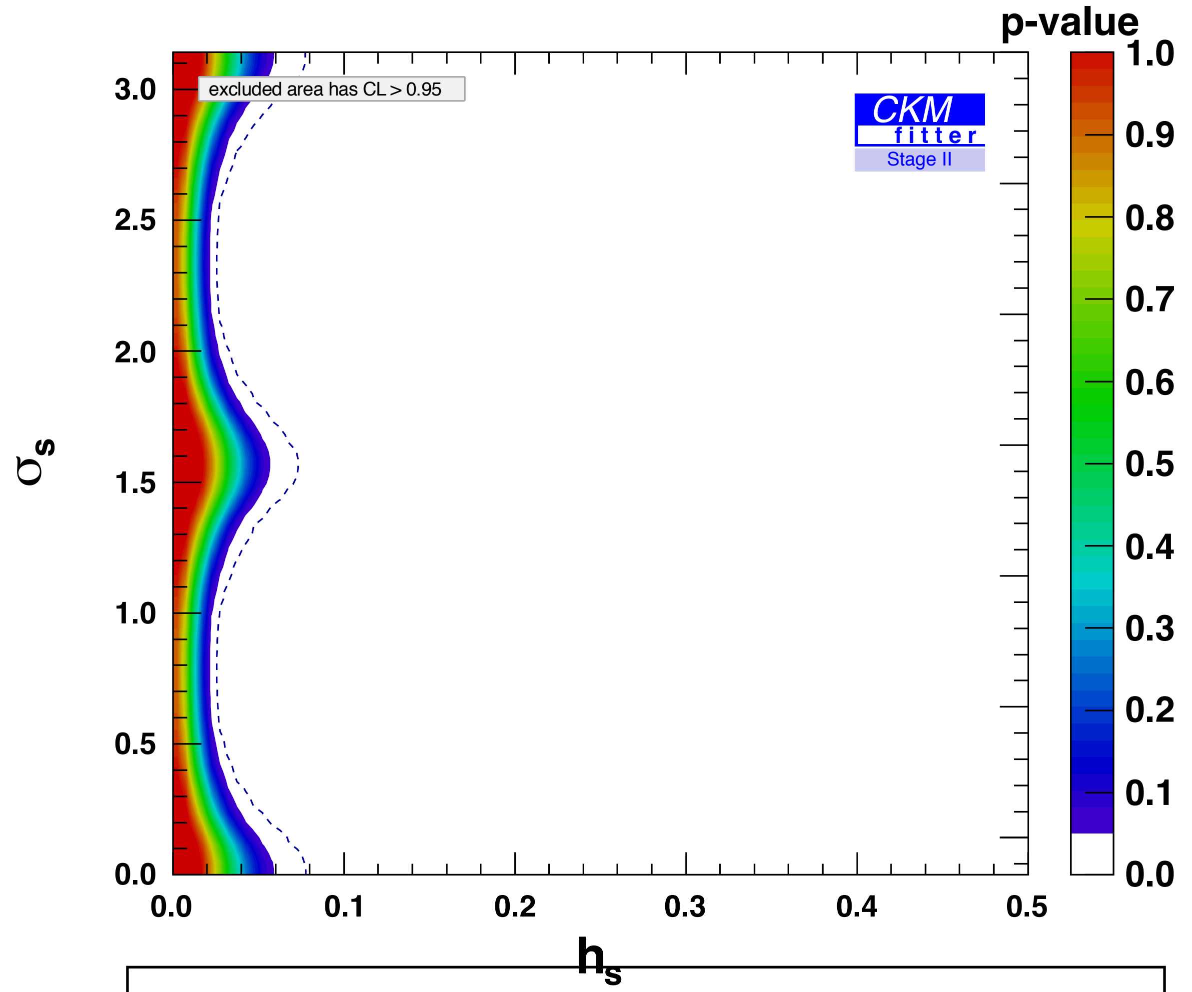
D - In the other BSM parameterisation space



State of the art



After Belle II and LHCb upgrade



[arXiv:1309.2293 [hep-ph]]

A typical factor 2 improvement for B_s.

Improves in turn the NP scale constraint by 40%.

4) Outlook and wrap-up

- The prospective paper arXiv:1309.2293 [hep-ph]] will be shortly updated (before Summer) in the light of the revised Physics reach of the Belle II experiment and the experimental programs envisaged with LHCb upgrades. A section will be dedicated to FCC-*ee* reach.

- The *CP* violation in the *B* mixings (SM ballpark), interesting per se, is at reach at FCC-*ee* and would improve the BSM constraints.

- Anomalies about Lepton Flavour Universality: should they be confirmed, the most complicated final state experimentally $B^0 \to K^{*0}\tau^+\tau^-$ (which can help as well to sort out models) can be studied in details at FCC-*ee*, up to angular distributions. There must be synergies with the direct searches.

- This Physics scope covers the developed Flavours @ FCC-ee CDR chapter.

1 **Installation of a Flavour Physics case at FCC-*ee***

2 **The anticipated landscape after LHCb upgrade and Belle II experiments**

3 **Rare decays and lepton universality violation**

3.1 $b \to s\ell^+\ell^-$ **phenomenology**

3.2 **Experimental sensitivity for** $B^0 \to K^*(892)\tau^+\tau^-$

3.3 **Search for** $B^0 \to \tau^+\tau^-$

4 **Lepton Flavour violation in** Z **decays**

5 CP **violation in the quark sector**

5.1 **The** γ **angle measurement with** $B_s \to D_s^\pm K^\mp$

5.2 **Search for** CP **violation in neutral** B **meson mixings**

5.3 **Perspectives for the CKM global fit**

5.4 **Perspectives for the search for BSM Physics in** $\Delta F = 2$ **transitions CKM global fit**

6 **Additional studies: LFV in** τ **decays ,** c**-and** b**-hadron spectroscopy, exclusive decays of the** Z **boson**

7 **Requirements for the detector design and performance**