The *Flavours* chapter of the FCC Conceptual Design Report

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Outline

- The anticipated scientific context (Flavours-wise)
- Tau lepton Physics
- Lepton-flavour-violating decays
- *b*-hadron Physics and Flavour anomalies
- *CP* violation studies
- Outlook.

1. Anticipated landscape of Flavours - at start of FCC

- Several large scale experiments are on their way: LHCb upgrade (2021— 2028), Belle II (now — 2025).

- LHCb collaboration explores a second upgrade, denoted LHCbU2 for the High Luminosity phase of the LHC. An upgrade is envisaged at SuperKEKB too.

- Several smaller scale experiments will have delivered their say: (g-2), MEG, COMET, NA62, K0T0 … and bring a break through.

1. Anticipated landscape of Flavours - at start of FCC

- FCC complex has the following characteristics:

  - FCC-*ee* at the *Z* pole: all *b*-hadron species available, large tau production, boost, triggerless, neutrals. Experiments at FCC-*ee* can cover the full programme of LHCb and Belle II. Note: the incoherent production weakens the flavour tagging w.r.t. to Belle II; mitigated by the statistics.

  - FCC-*pp*: the *bb* cross-section gets a (not that spectacular) factor five enhancement at 100 TeV. It was too early to scope the Physics case. Experience from LHCb U2 data acquisition and triggers will be invaluable there to cope with pile-up interactions.

- The CDR Flavours chapter describes both. Focus here on the FCC-*ee*, where actual sensitivity studies were undertaken. A word on FCC-*pp* in the outlook part of this talk.

1. Anticipated landscape of Flavours - at start of FCC

Working point	Lumi. / IP [10^{34} cm^{-2}.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*	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.

- Direct comparison with LHCb yields requires a more involved approach (mode by mode) to take into account trigger and reconstruction efficiencies.

1. Anticipated landscape of Flavours - at start of FCC

Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-*ee*
EW/H penguins				
$B^0 \to K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10	–	–	~ 1000
$B_s \to \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \to \tau^+\tau^-)$				
Leptonic decays				
$B^+ \to \mu^+\nu_{mu}$	5%	–	–	3%
$B^+ \to \tau^+\nu_{tau}$	7%	–	–	2%
$B_c^+ \to \tau^+\nu_{tau}$	n/a	–	–	5%
CP / hadronic decays				
$B^0 \to J/\Psi K_S$ ($\sigma_{\sin(2\phi_d)}$)	$\sim 2. * 10^6$ (0.008)	41500 (0.04)	$\sim 0.8 \cdot 10^6$ (0.01)	$\sim 35 \cdot 10^6$ (0.006)
$B_s \to D_s^\pm K^\mp$	n/a	6000	~ 200000	$\sim 30 \cdot 10^6$
$B_s(B^0) \to J/\Psi\phi$ (σ_{ϕ_s} rad)	n/a	96000 (0.049)	$\sim 2.10^6$ (0.008)	$16 \cdot 10^6$ (0.003)

- 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. Anticipated landscape of Flavours - at start of FCC

Some FCC-*ee* distinctive features and disclaimers :

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

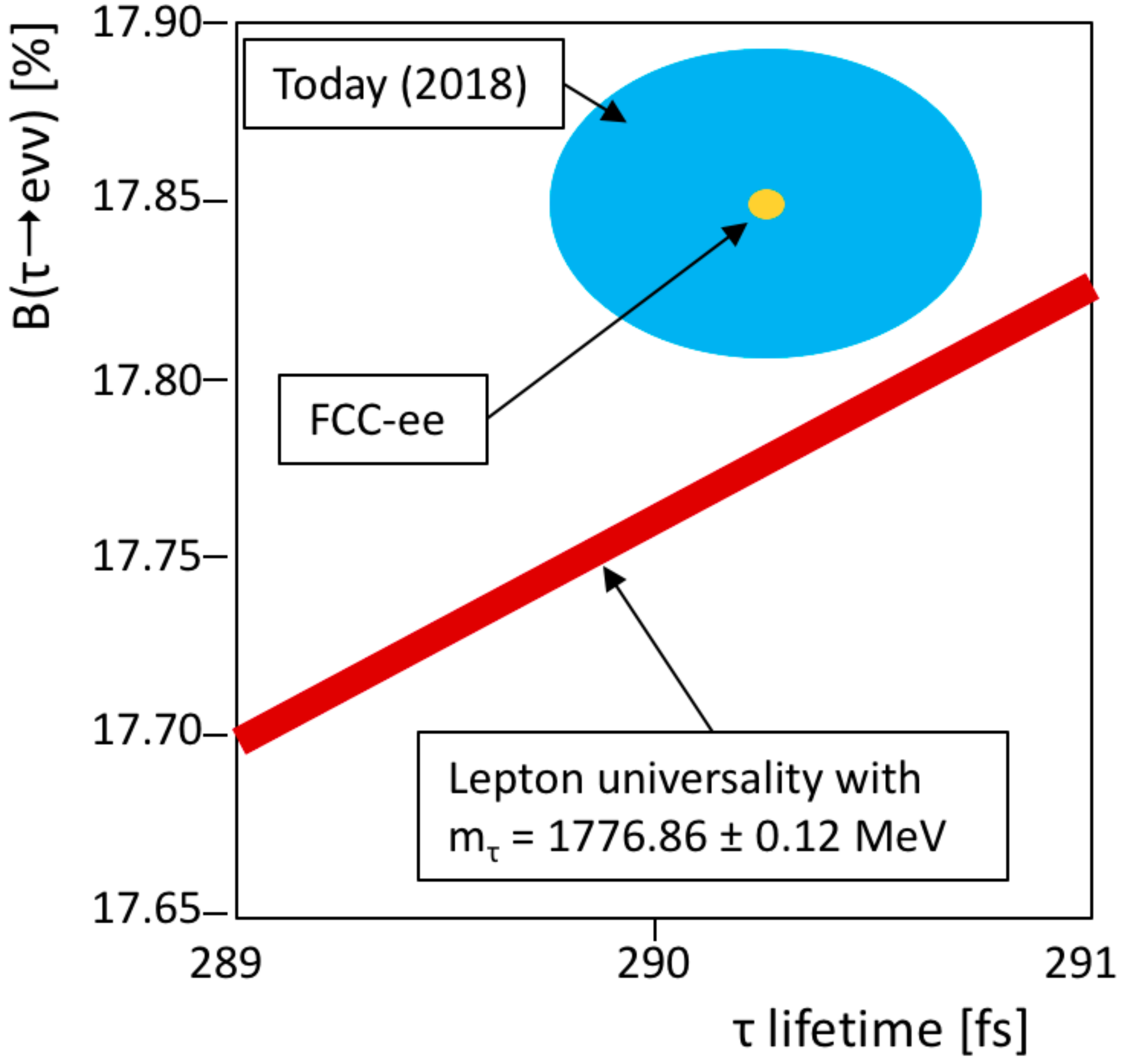
- Amongst the main characteristics for Flavour Physics is the boost experienced at the *Z* pole (fragmentation of the b-quark provides is ~75% of the beam energy to the *b*-hadron). Conversely, the excellent capacity of reconstructing detached vertices is a decisive feature for the studies presented here.

- Remark: it has been chosen to focus the study on Physics cases where FCC-ee has distinctive / unique features, with the idea *In for a pound, in for a penny* (*qui peut le plus peut le moins*).

2. Tau lepton Physics (selection of)

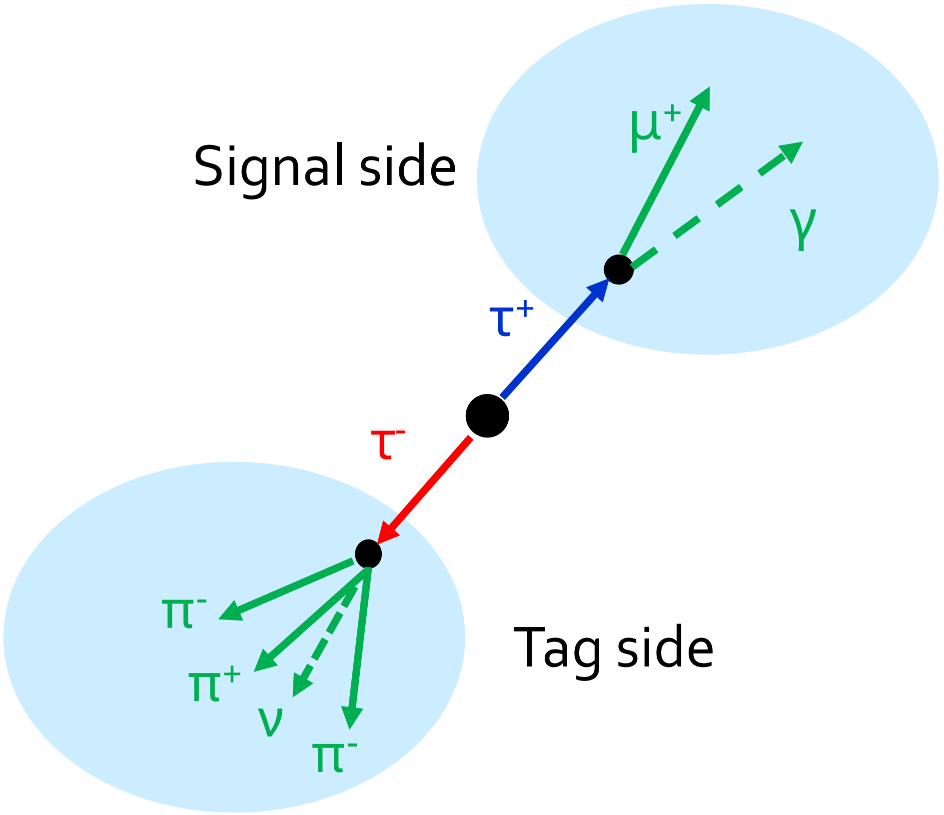
- Unprecedented statistics of boosted tau decay topologies.
- Lifetime measurement in addition to branching fractions.
- Highly competitive Lepton Flavour Universality tests

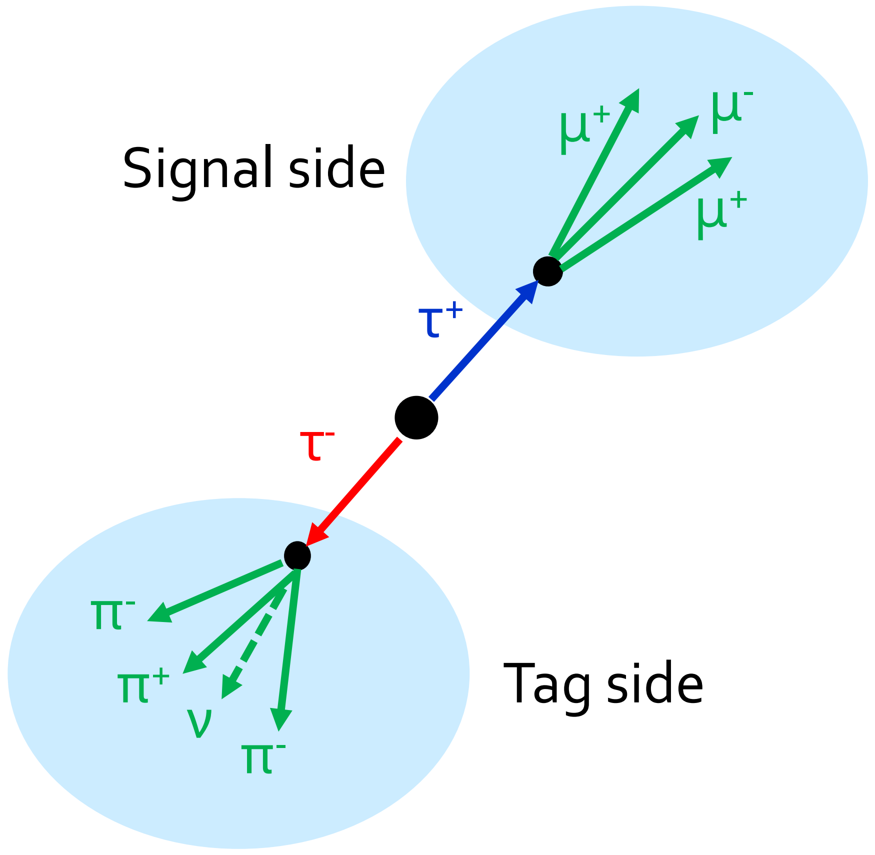
Property	Current WA	FCC-ee stat	FCC-ee syst
Mass [MeV]	1776.86 +/- 0.12	0.004	0.1
Electron BF [%]	17.82 +/- 0.05	0.0001	0.003
Muon BF [%]	17.39 +/- 0.05	0.0001	0.003
Lifetime [fs]	290.3 +/- 0.5	0.005	0.04



Note: systematics are kind of state-of-the-art. Two decades to exercise the experimentalists' cleverness on this.

3. Lepton-flavour-violating decays (tau 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 large tau statistics and boosted topologies.
- Calorimetric performance as ILD.
- Main backgrounds are ISR and FSR
- Brings down the current limits by one to two orders of magnitude.

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}

3. Lepton-flavour-violating decays (*Z* decays)

- Lepton Flavour-Violating *Z* decays in the SM with lepton mixing are typically

$$\mathcal{B}(Z \to e^{\pm}\mu^{\mp}) \sim \mathcal{B}(Z \to e^{\pm}\tau^{\mp}) \sim 10^{-54} \text{ and } \mathcal{B}(Z \to \mu^{\pm}\tau^{\mp}) \sim 4.10^{-60}$$

Any observation of such a decay would be an indisputable evidence for New Physics.

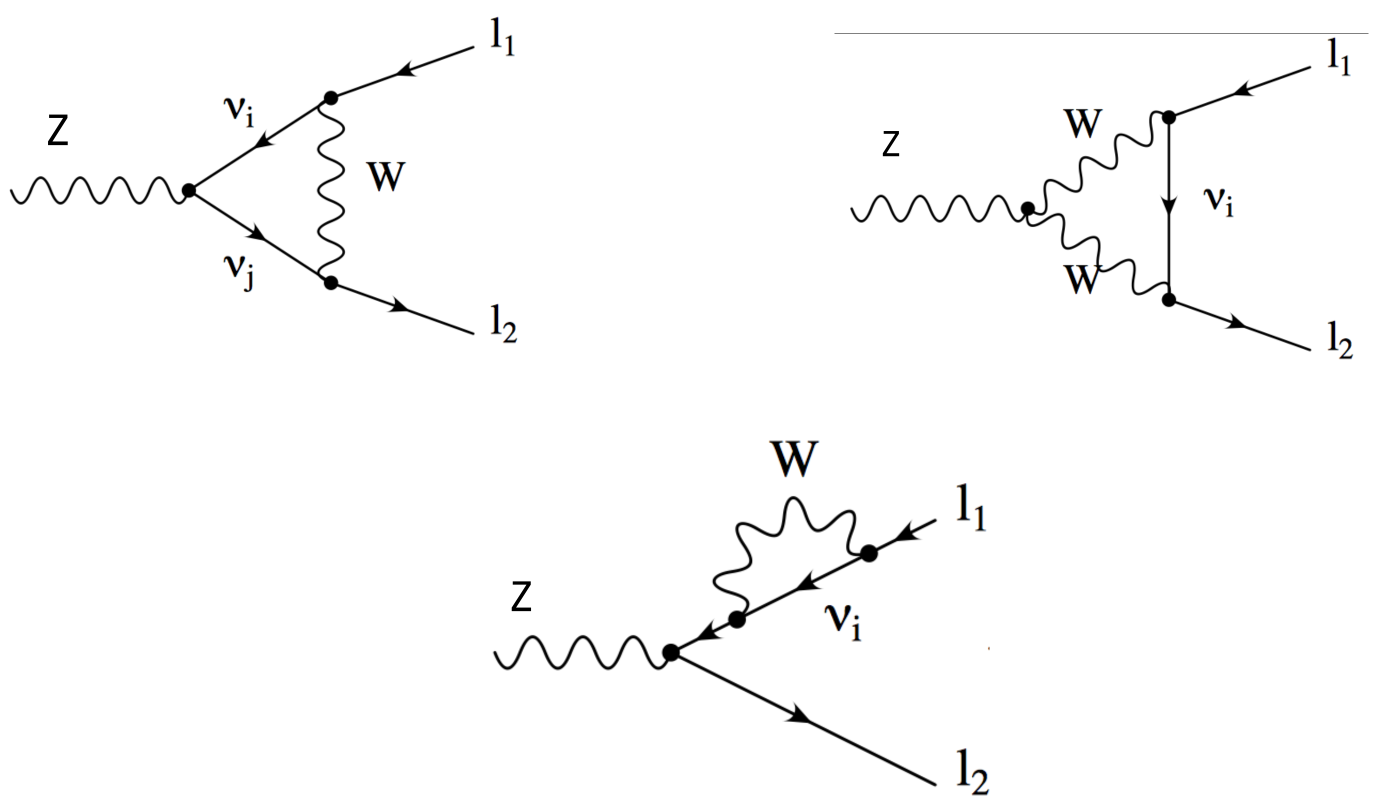
- Current limits at the level of ~10^{-6} (from LEP and more recently Atlas, *e.g.* [DELPHI, Z. Phys. C73 (1997) 243] [ATLAS, CERN-PH-EP-2014-195 (2014)])

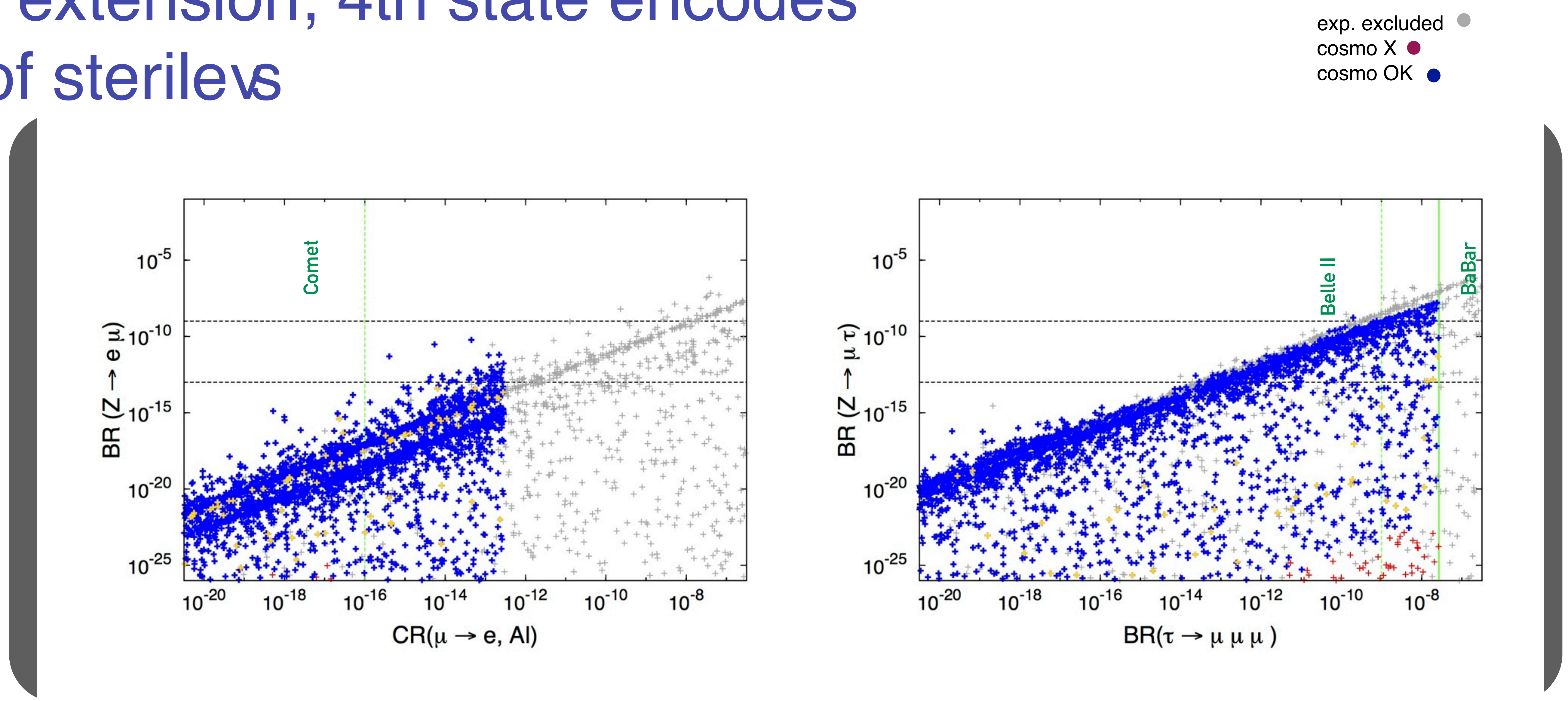
- The FCC-*ee* high luminosity *Z* factory allows in principle to gain several orders of magnitude ... Complementary to the direct search for steriles (see Oliver's talk here).

- Explored with FCC-*ee* in mind for additional neutrinos in [De Romeri et al. JHEP 1504 (2015) 051]. It happens that the final states with taus are the most appealing.

3. Lepton-flavour-violating decays (Z decays)

3+1 model is a convenient ad-hoc extension; 4th state encodes contributions of arbitrary number of sterileνs



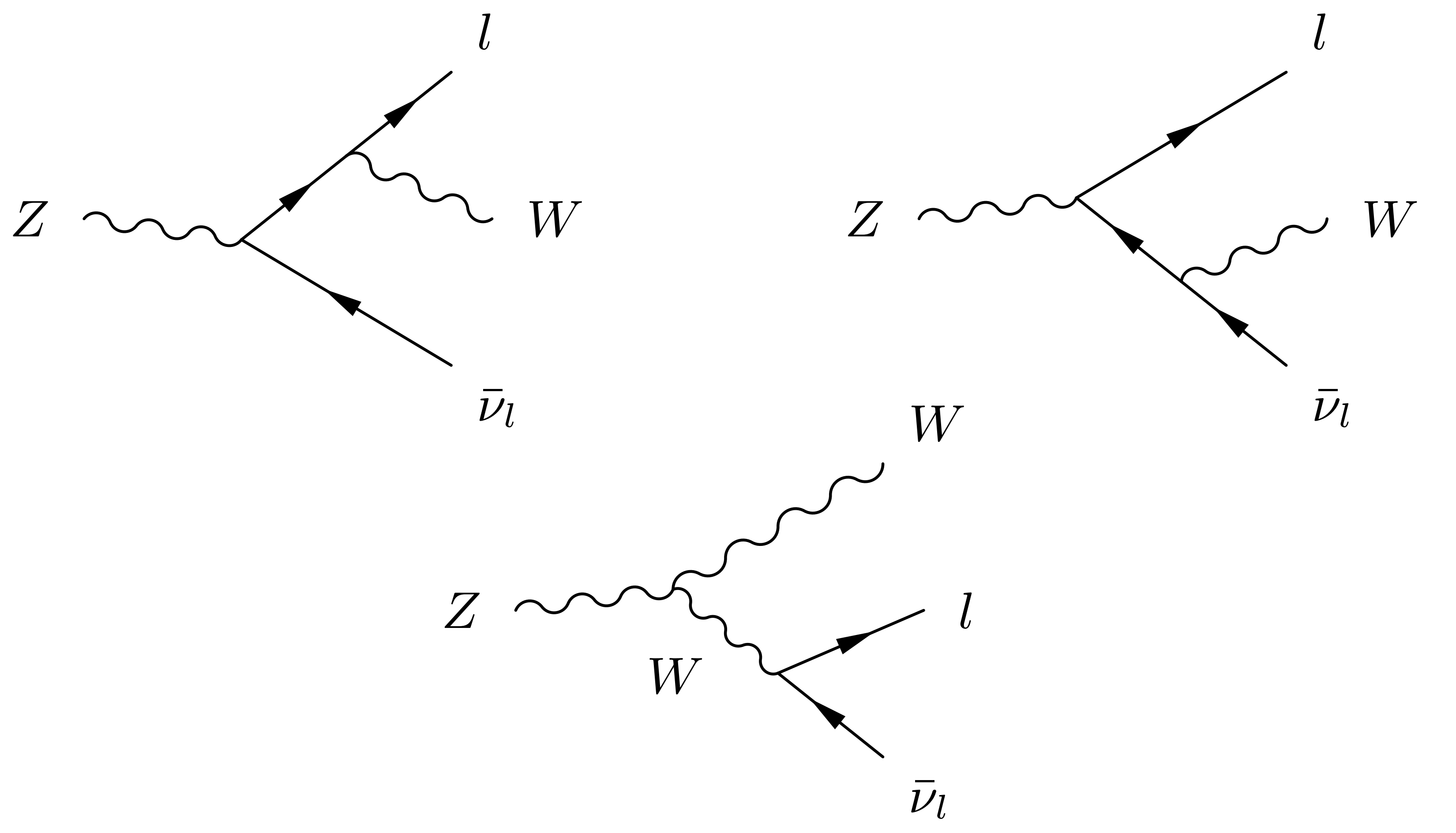


- Steriles with mass > 80 GeV and mixings $O(10^{-5}\text{-}10^{-4})$ within FCC-*ee* reach.

- Low-energy experiments (COMET and friends) at work to probe the electron-muon sector.
- FCC-*ee* would provide the most stringent constraint in tau-(mu/e) sectors.

3. Lepton-flavour-violating decays (Z decays)

- There are actually three processes competing in the ball park FCC-*ee* can address with a final state with a tau and a beam energy light lepton

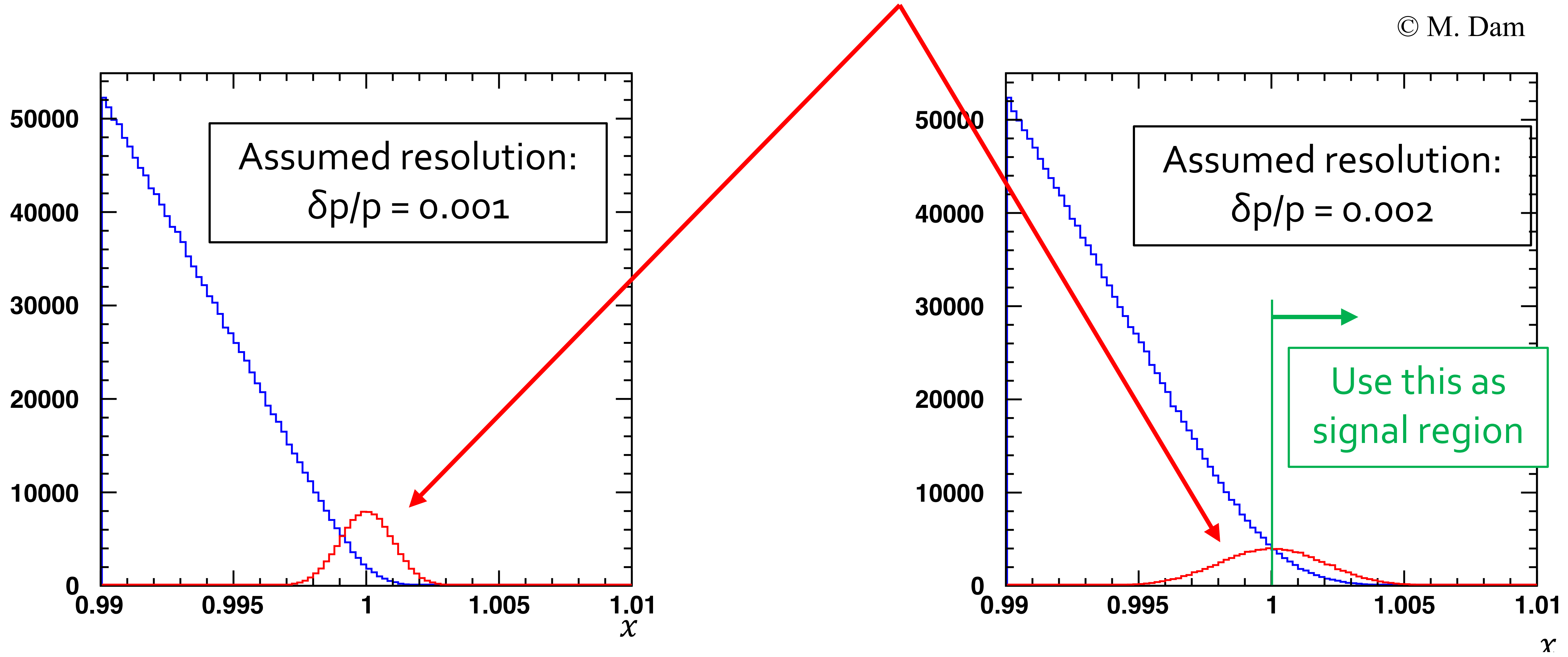


  - The lepton Flavour-Violating *Z* decays
  - The SM $Z \rightarrow \tau^+\tau^-$
  - The SM $Z \rightarrow l^+l^-$ ($l \rightarrow W^*\nu$ and $W^* \rightarrow \tau\,\nu$)

- The latter process in the list [Durieux et al. arXiv:1512.03071] is interesting per se (BSM enhancements). The final state is the same as cLFV (with an additional neutrino) and the authors find a SM branching fraction of 1.4 10^{-8} ! It can be however distinguished from the two others by its kinematical properties.

3. Lepton-flavour-violating decays (Z decays)

- The other SM $Z \rightarrow \tau^+\tau^-(\rightarrow \mu\nu\nu)$ is more annoying. The endpoint of the distribution mimics a beam-energy like lepton.



- Following Mogens Dam's study reported here : $Z \rightarrow \tau^+\tau^-$ provides a limit on cLFV process which goes linearly with the momentum resolution. And which is asymptotically limited in turn by the beam energy spread. This makes the former limit pretty fundamental.

$$\mathcal{B}(Z \to \tau^{\pm}\mu^{\mp}) < 10^{-9} - 10^{-10}$$

4. Flavour anomalies in *b* quark transitions

- 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 in the ratios:

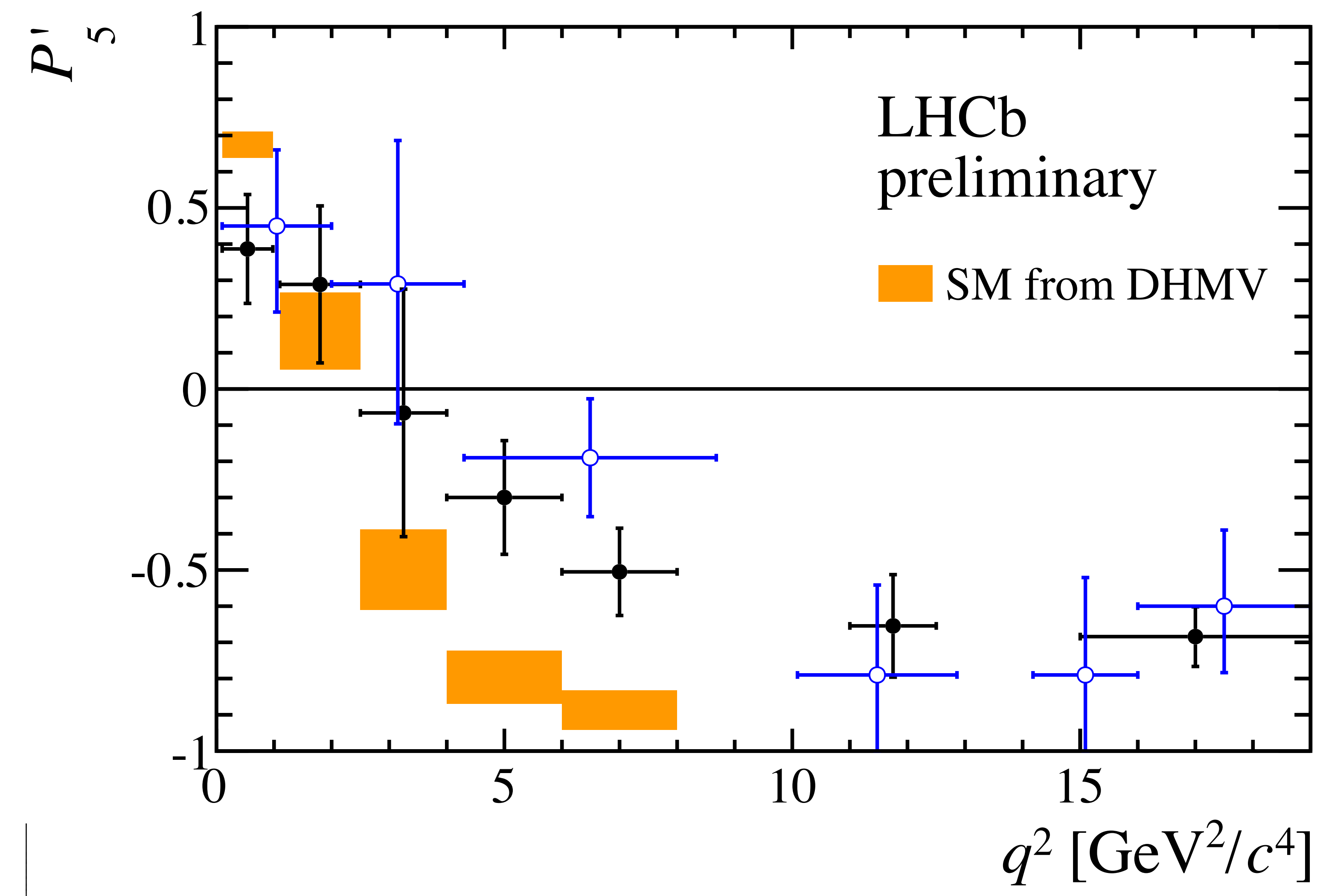
$$R_K = \frac{B^0 \to K e^+ e^-}{B^0 \to K \mu^+ \mu^-} \times \frac{B^0 \to K J/\Psi(\to \mu^+ \mu^-)}{B^0 \to K J/\Psi(\to e^+ e^-)}$$

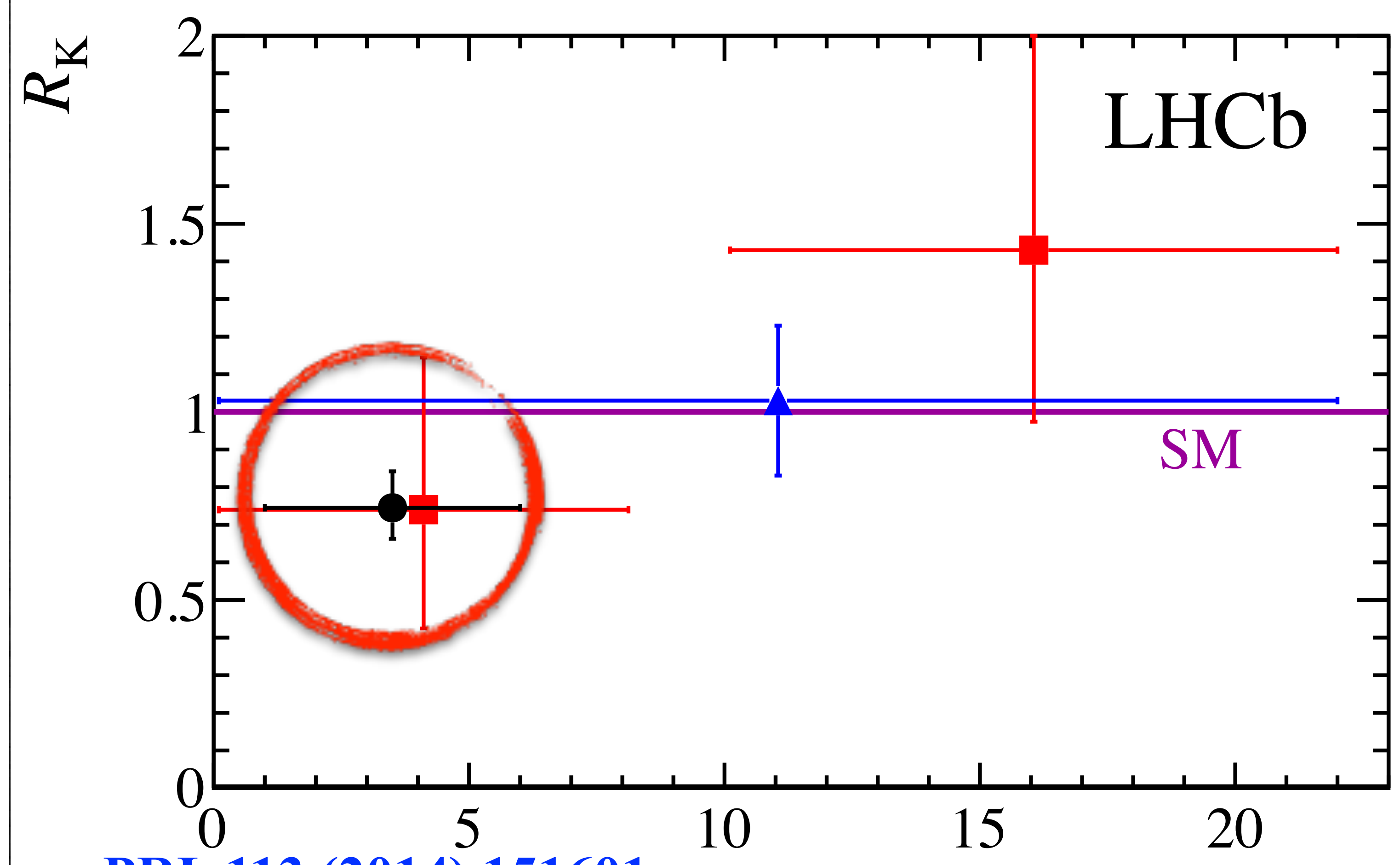
$$R_{K^*} = \frac{B^0 \to K^*(892) e^+ e^-}{B^0 \to K^*(892) \mu^+ \mu^-} \times \frac{B^0 \to K^*(892) J/\Psi(\to \mu^+ \mu^-)}{B^0 \to K^*(892) J/\Psi(\to e^+ e^-)}$$

- Comments on theoretical and experimental challenges: the former analyses do have theoretical uncertainties (long distance QCD). The latter have experimental challenges (q^2 dependence / double ratio /electron rec. at LHCb).

- These add up to $R(D^*)$, $R(D)$ departures from B-factories and LHCb w.r.t. SM predictions.

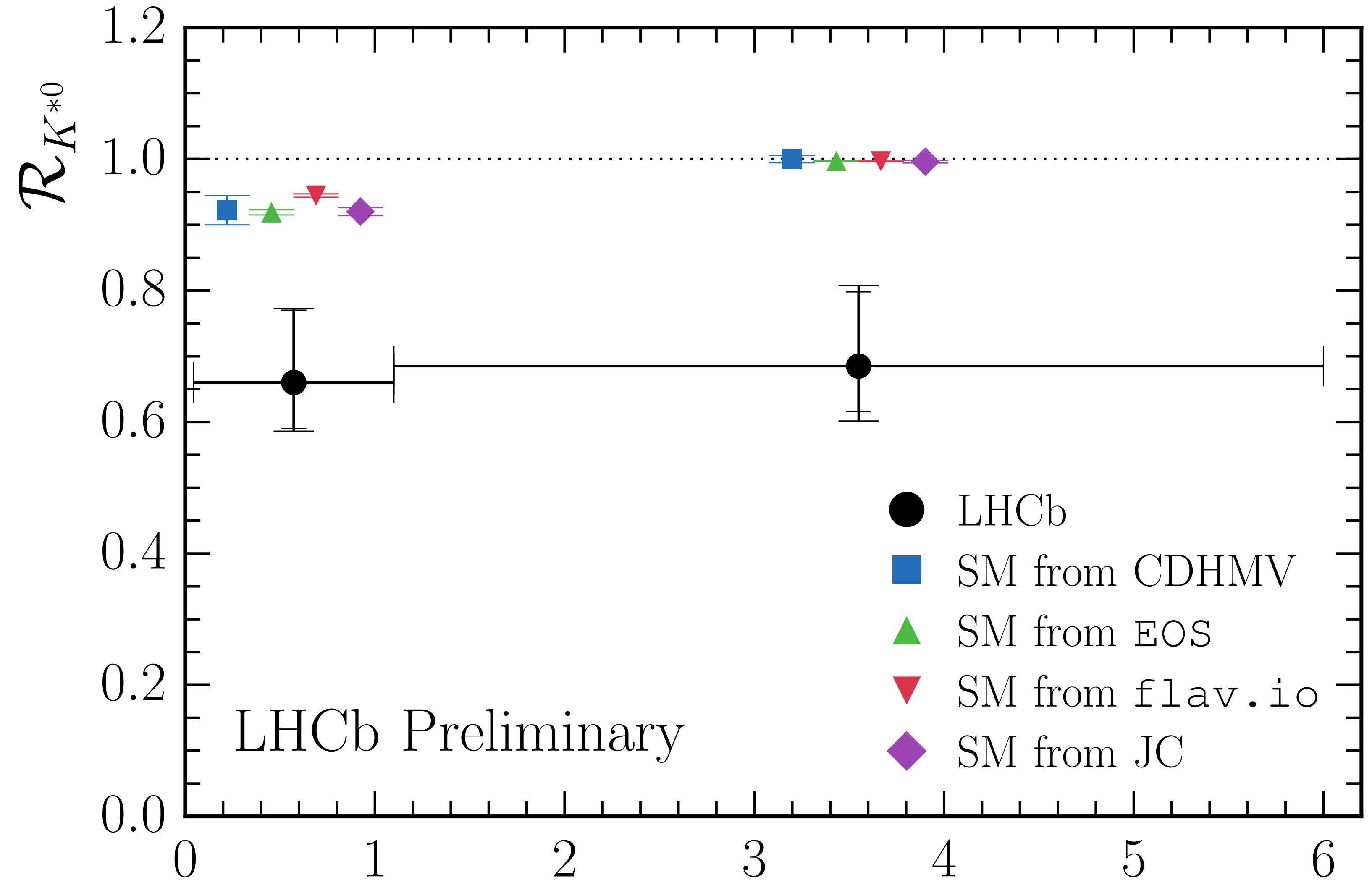
4. Flavour anomalies in *b* quark transitions

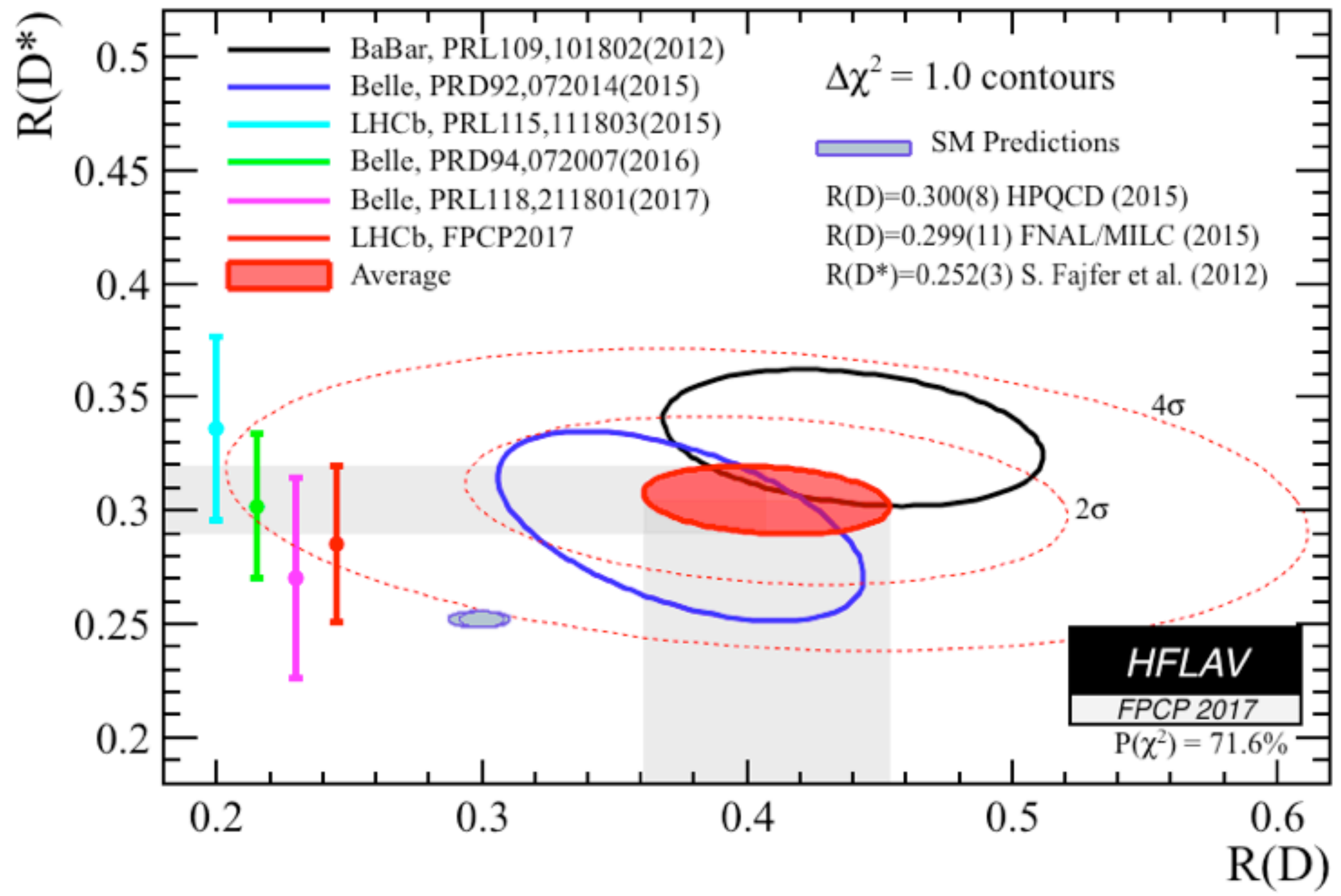




- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

Several important updates to appear in the coming months





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

- 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 $b \to s\tau^+\tau^-$ transitions [arXiv:1712.01919]. Model killer.

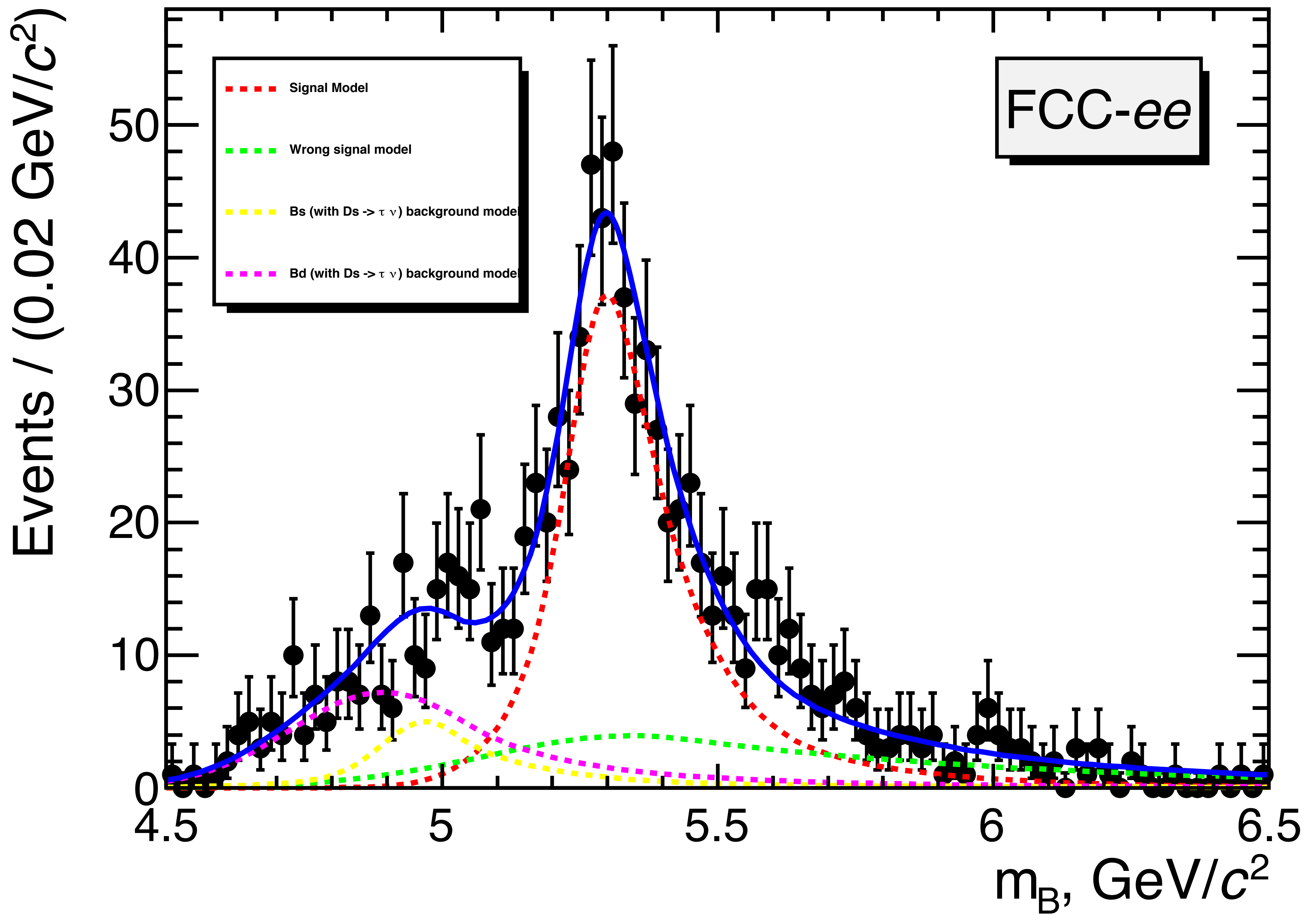
- The mode $B^0 \to K^{*0}\ \tau^+\tau^-$ has received a special attention in the FCC-*ee* context.

4. 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

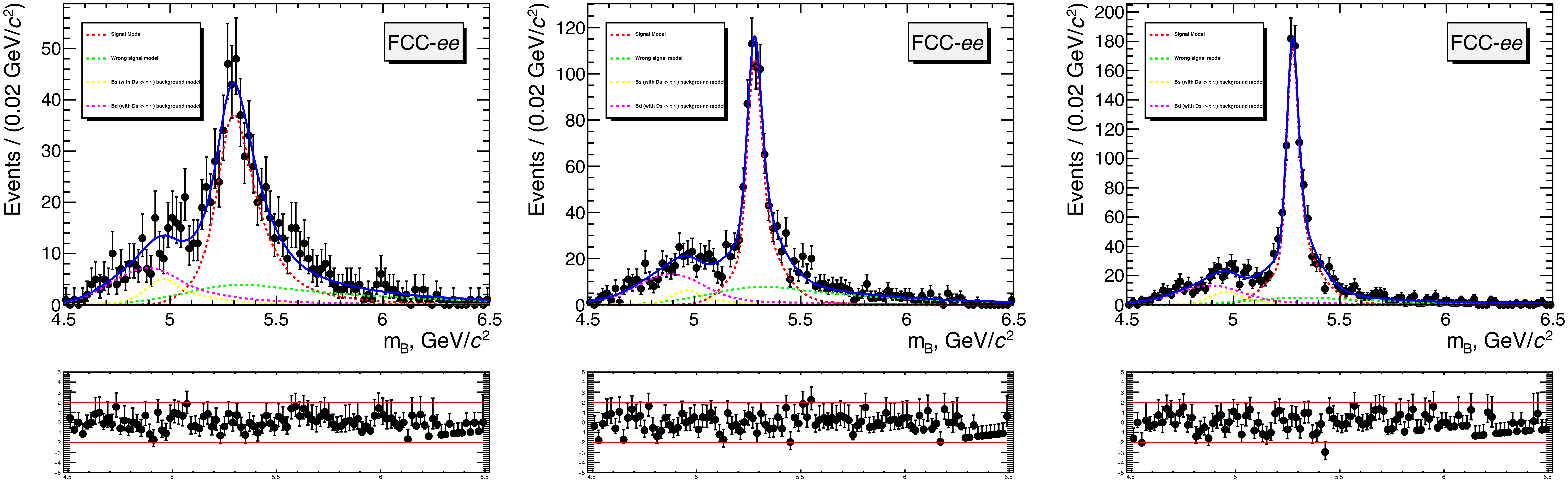
- Conditions: baseline luminosity, SM calculations of signal and background BF, vertexing and tracking performance as ILD detector. **Momentum** → 10 MeV, **Primary vertex** → 3 um, **SV** → 7 um, **TV** → 5 um

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



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

4. The search for $B^0 \rightarrow K^{*0}\tau^+\tau^-$



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

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

- The study is considering the three-prongs decays of taus w/o neutrals. More than doubling the statistics w/ neutral pions.

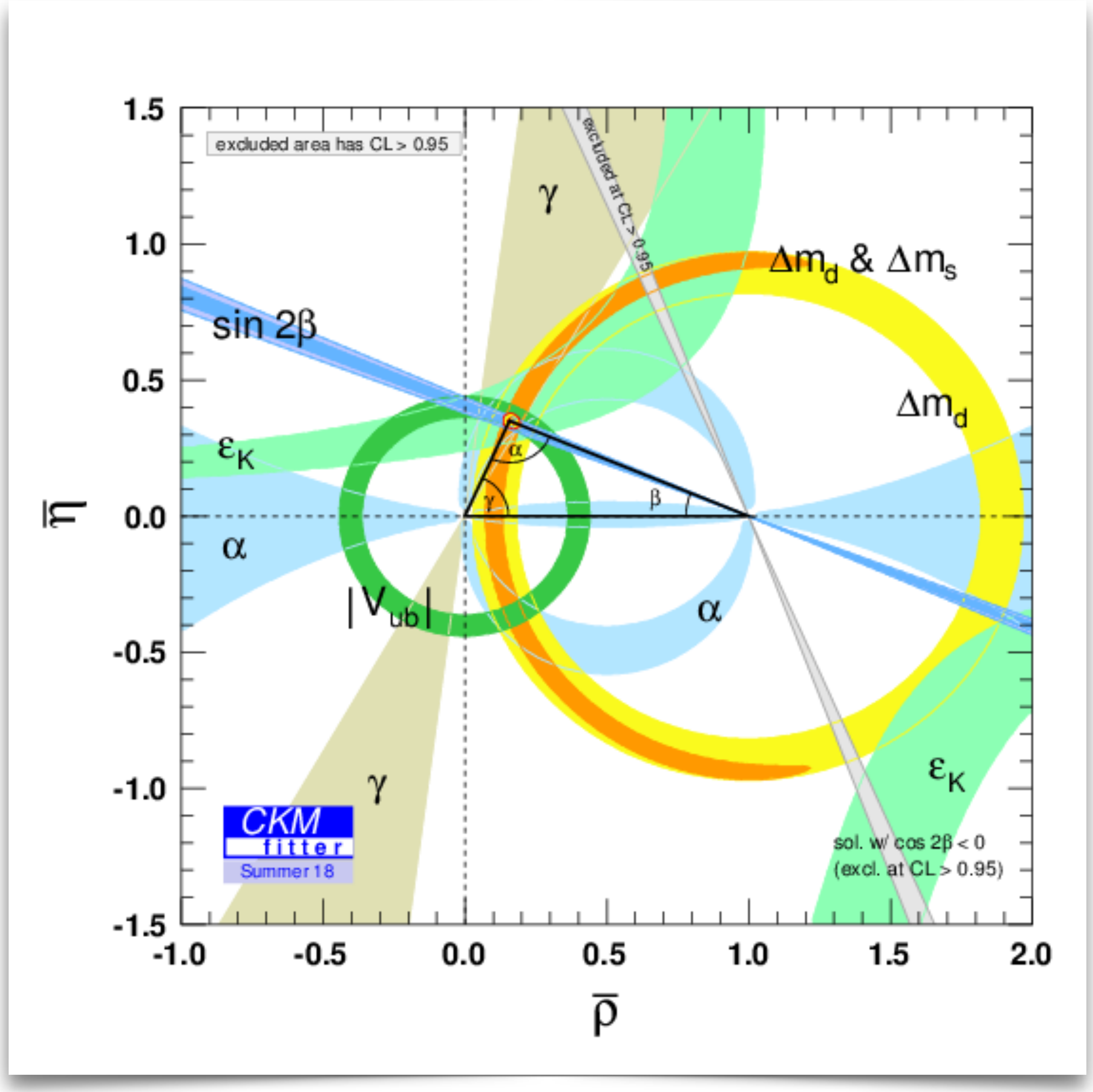
- Clean measurement of the branching fraction, even differential in q^2 [O(5%) for a SM-like decay].

- As soon as we go to angular observables, full simulation of the detector are in order to provide sound estimates of the observables.

- The paper **arXiv:1705.11106** reports the experimental sensitivity results and suggests several new observables.

5. CKM profile(s)

- The unitarity triangle



- The focus is not 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* system. Implications for what comes next.

5. CKM profile(s)

- A powerful Model-independent approach to address BSM Physics in neutral meson mixing processes

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

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)

<u>Assumptions:</u>

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

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

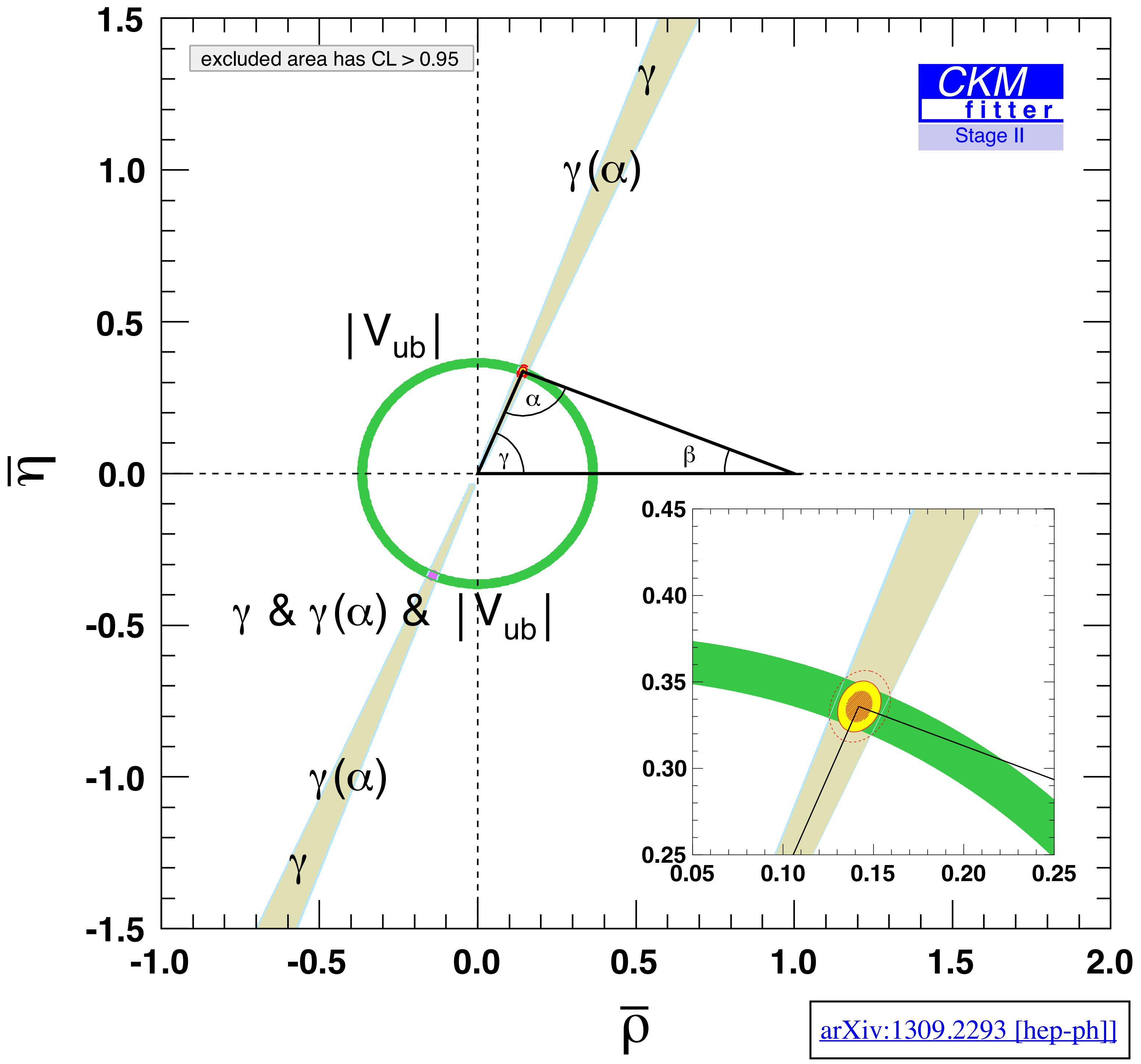
✓Unitary 3x3 CKM matrix (Flavour violation only from the Yukawas — MFV hypothesis).

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

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

5. BSM in $\Delta F = 2$

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



Once fixed, 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	$\frac{\Gamma_{12,q}}{M_{12,q}^{\mathrm{SM}}} \times \frac{\sin(\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}})}{\lvert\Delta_q^{\mathrm{NP}}\rvert}$
$\Delta\Gamma_q$	$2\lvert\Gamma_{12,q}\rvert \times \cos(\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}})$

5. BSM in $\Delta F = 2$

The BSM constraints at the horizon 2025

Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^*\rvert$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$ (no hierarchy)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40

$$h \simeq 1.5\,\frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2}\frac{(4\pi)^2}{G_F\Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2}\left(\frac{4.5\,\text{TeV}}{\Lambda}\right)^2,$$
$$\sigma = \arg(C_{ij}\,\lambda_{ij}^{t*}),$$

Unique additions from FCC-*ee*

- $B_s \to D_s K$ [30 10^6 events; brings $(\gamma+\phi_s)$]
- Semileptonic asymmetries for both flavours of *B* mesons (*CP* violation in the mixing, unobserved to date).

Extrapolated precisions on CKM-related observables in the CDR (mostly stat. limited)

Table 7.3: List of inputs useful to constrain NP in $\Delta F = 2$ quark transitions and comparisons of the projected precisions of the Belle II, LHCb upgrade I and FCC-ee experiments. The central values for the angles are scaled to the same SM-like extrapolation. The estimate of the mixing-induced observables' precision at FCC-ee assumes a flavour tagging efficiency of 7% (10%) for the B_d (B_s meson). The estimate of the $|V_{ub}|$ precision relies on an extrapolation of hadronic inputs calculated on the Lattice [194].

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_{fs}^d (10^{-4}, precision)	23 ± 26	-7 ± 15	-7 ± 15	-7 ± 2
a_{fs}^s (10^{-4}, precision)	-48 ± 48	n/a	0.3 ± 15	0.3 ± 2

5. BSM in $\Delta F = 2$

Notes on this analysis:

- It has to include as well the LHCb Upgrade 2 (300 /fb at HL-LHC) inputs, considered in the recent proposal by the LHCb collaboration: arXiv:1808.08865

- A critical point is the knowledge of hadronic parameters inputs (decay constants and bag factors), which might constitute a bottleneck to push further the energy scale.

- The global analysis including FCC-*ee* inputs is currently being performed (might be in time for Brussels FCC meeting).

6. Outlook - FCC-*ee*

- The next phase of the Study must go through full simulations of actual detector proposals.

- This will allow to have realistic inputs (in particular from calorimetric objects) to evaluate the sensitivity on a series of outstanding observable measurements:

    - Semileptonic b-hadron decays
    - The electrodeak penguins $X_b \to X\nu\nu$
    - The leptonic decay $B_c \to \tau^+\nu_\tau$
    - The dileptonic B^0, $B_s \to \tau^+\tau^-$
    - Tau Physics at large.
    - etc…

- The standard Heavy Flavour program: lifetimes, branching fractions, spectroscopy, etc…

6. Outlook - FCC-*hh*

- The *bb* cross-section receives about a factor 5 enhancement at 100 TeV w.r.t. 14 TeV.

- The distinctive feature of FCC-*hh* is however that high-pt Physics is enhanced by a far larger factor (~100).

- It was still an early stage to devise a Flavour Physics case for the FCC-*hh* in the CDR. It will be part of the next stage of the Study.

- The progresses in data acquisition and triggering systems of the LHCb upgrades (to cope with high pile-up) will be invaluable in that respect.

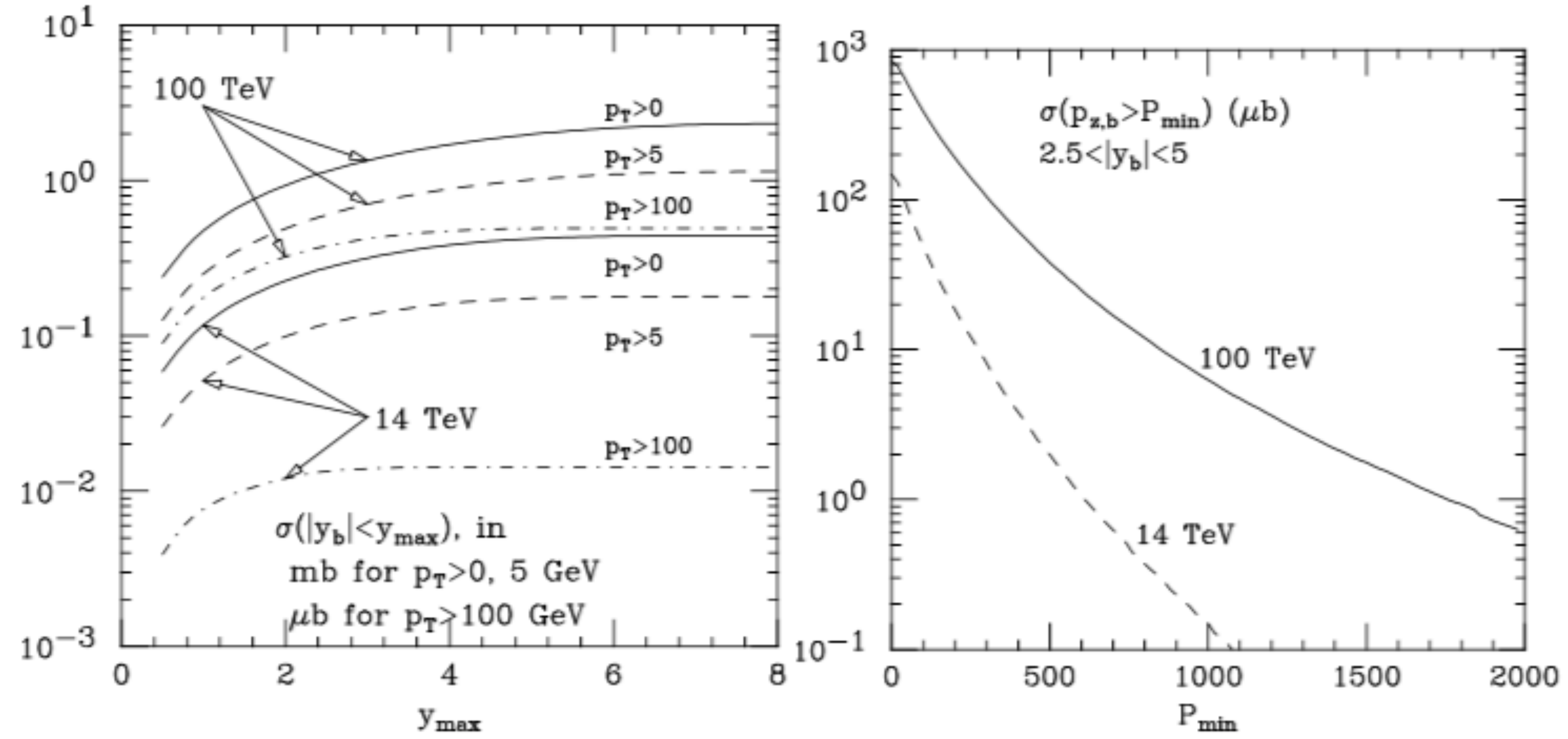


Figure 7.4: Left: production rates for b quarks as a function of detection acceptance in y, for various p_T thresholds (rates in μb for $p_T > 100$ GeV, in mb otherwise). Right: forward b production rates, as a function of the b longitudinal momentum.

6. Summary: Flavours CDR conclusions

- FCC-*ee* competes favourably everywhere in the global Flavour Physics program (at least where we looked at).

- The CDR studies were focussed at (some) places where FCC-*ee* has distinctive features. It indeed appears to make a difference: LFV *Z* and tau decays, lepton universality tests (*b* and tau sectors).

- The next stage of the Study for FCC-*ee* will involve full simulations to address in a more comprehensive way the Flavours Physics case.

- It was still an early stage to devise a Flavours case for the FCC-*hh*. It will be part of the next stage of the Study.