European Strategy for Particle Physics

Experimental programs to address open issues in flavour physics

Marie-Hélène Schune
(IJCLab IN2P3-CNRS and Université Paris-Saclay)

23-27 JUNE 2025 Lido di Venezia

Preamble : $K_L \to \pi^+ \pi^-$

1958

Long-lived Neutral K Mesons*

M. Bardon, K. Lande, and L. M. Lederman

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and

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Brookhaven National Laboratories, Upton, New York

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CP violation discovery !

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Agreeing at few % with *a-priori* is not enough to conclude.

Is BSM physics just around the corner ?

BSM physics may show-up where we do not expect it

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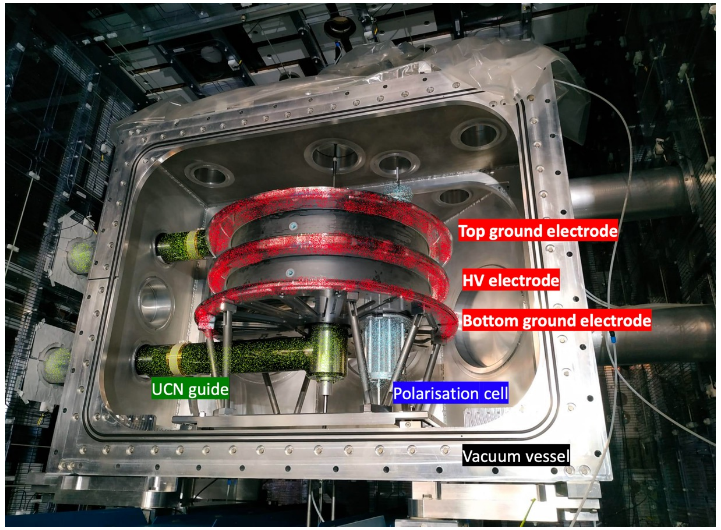
CP violation discovery !

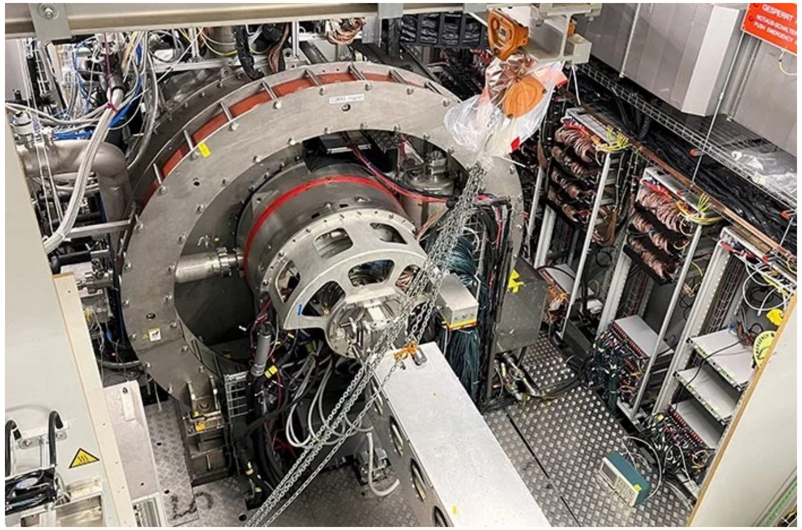
How are we going to find cracks in the SM fortress ?

- Channel(s)-specific experiments: EDM, cLFV, π and K physics
- Use of large scale facilities : τ, D and B physics

Channel(s)- specific experiments



n2EDM



MEG-II

NA62

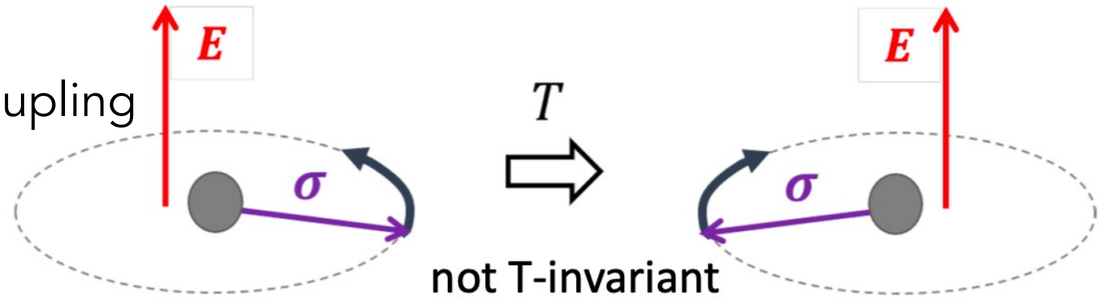
+ Future projects

Electric Dipole Moments and charged Lepton Flavour violation ($\mu \rightarrow e$)

Very high sensitivity to BSM physics

EDM

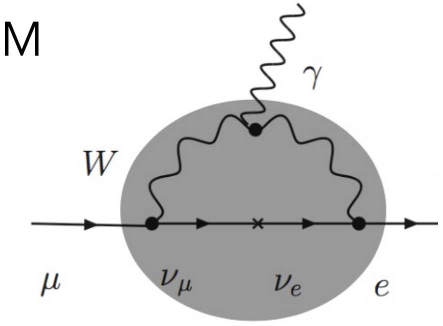
spin coupling to $\vec{E}$



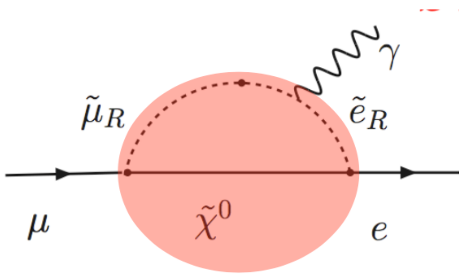
- Test of T violation and (via CPT theorem) of CP
- Hadronic EDMs and in particular nEDM : ‘Strong CP problem’
- e-EDM and p-EDM measurements : extracted from measurements on atoms/molecules.
- The interpretation of a positive measurement is theoretically challenging.

cLFV

SM



BSM



In the SM tiny effect : BR($\mu \rightarrow e\gamma$)~ 10^{-54} due to neutrinos oscillations

Electric Dipole Moments

A multidisciplinary field

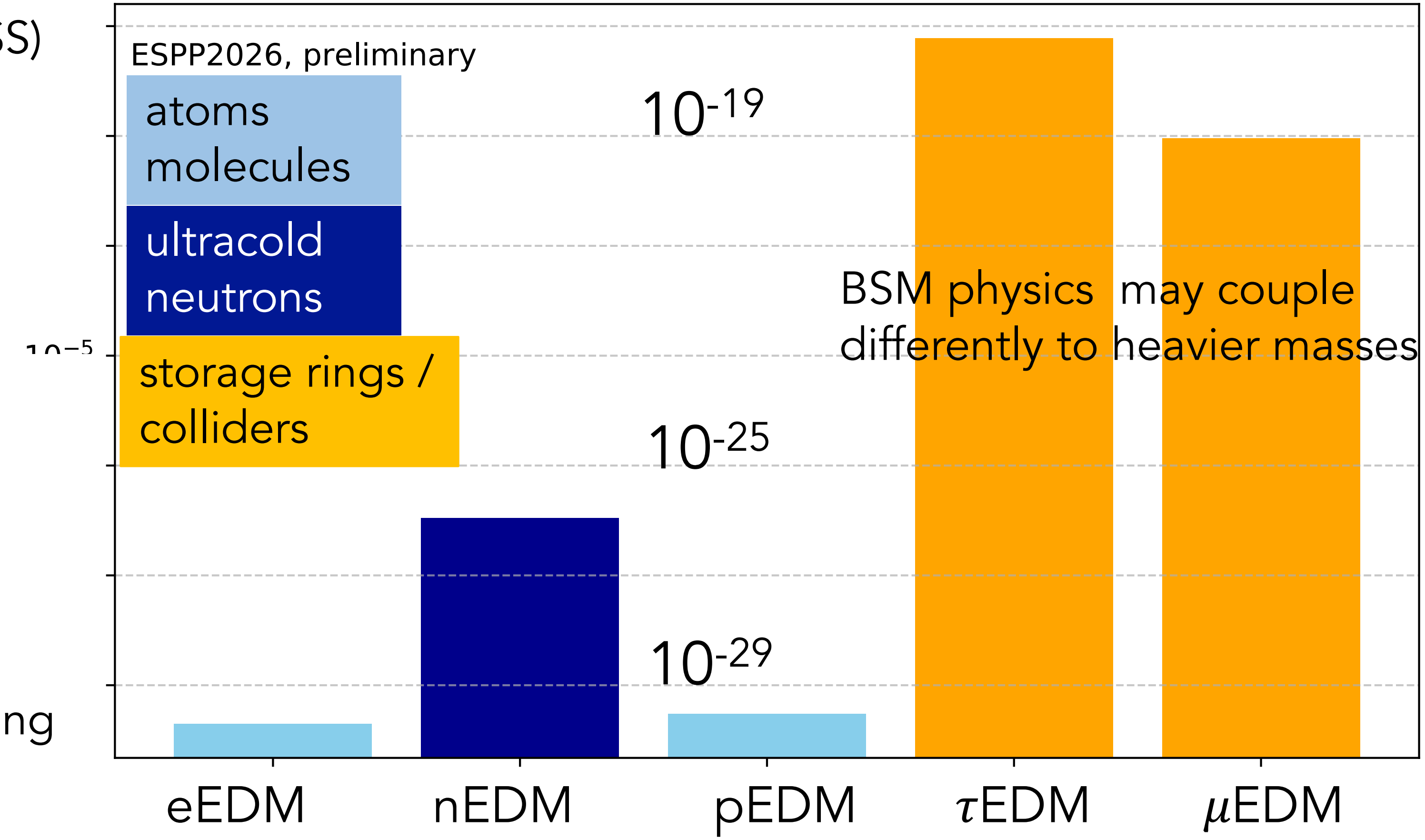
nEDM

- at the heart of European research (ILL, PSI, ESS)
- Longer term : larger scale experiments
- **Access to intense neutron sources**

Charged particles EDM

- A full variety of experimental techniques developing
- pEDM : p storage ring in future
- μEDM : synergies with muon collider in the long term

Current sensitivities



in 10 years : sensitivity will improved by x10

Also at colliders : baryons EDM

Charged Lepton Flavour Violation: $\mu \to e$

Golden channels:

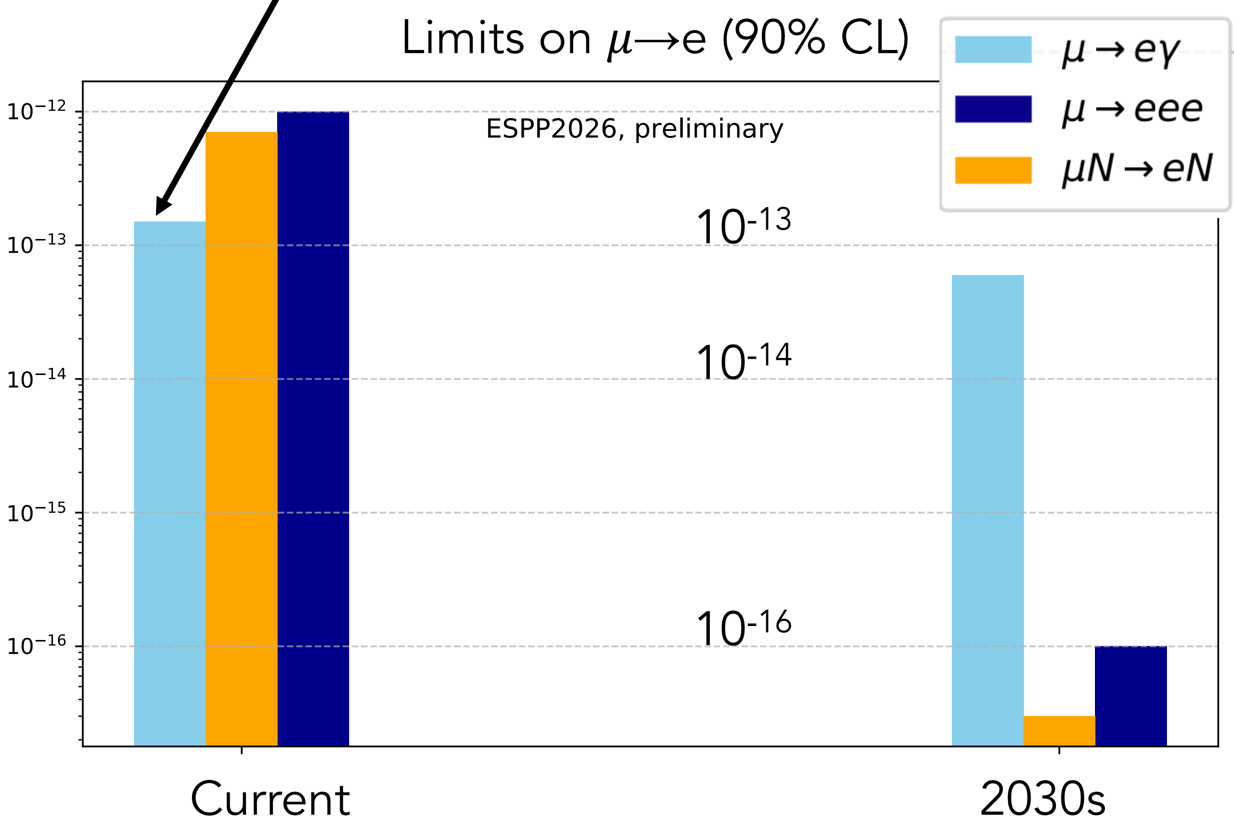
$\mu \to e\gamma$: MEGII @ PSI
$\mu \to eee$: Mu3e @ PSI
$\mu N \to eN$: Mu2e @ FNAL and COMET @ J-PARC

Several orders of magnitude improvements expected in the next coming years

Use of higher intensity μ beam at PSI

Transition from several one-mode experiments to a more general purpose larger one ?

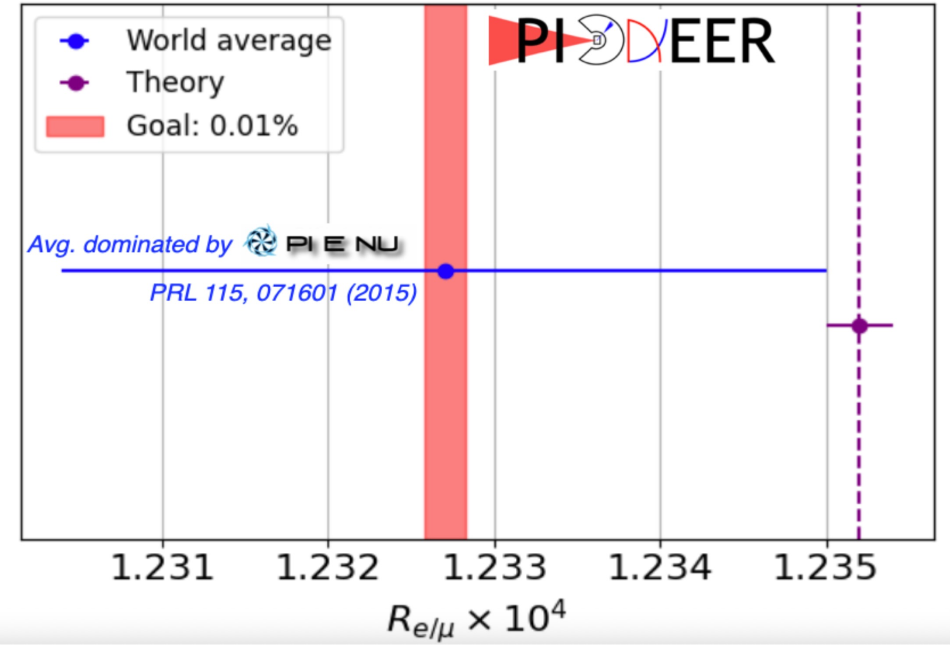
New MEGII result
BR($\mu \to e\gamma$) < 1.5 x 10^{-13} @90% CL



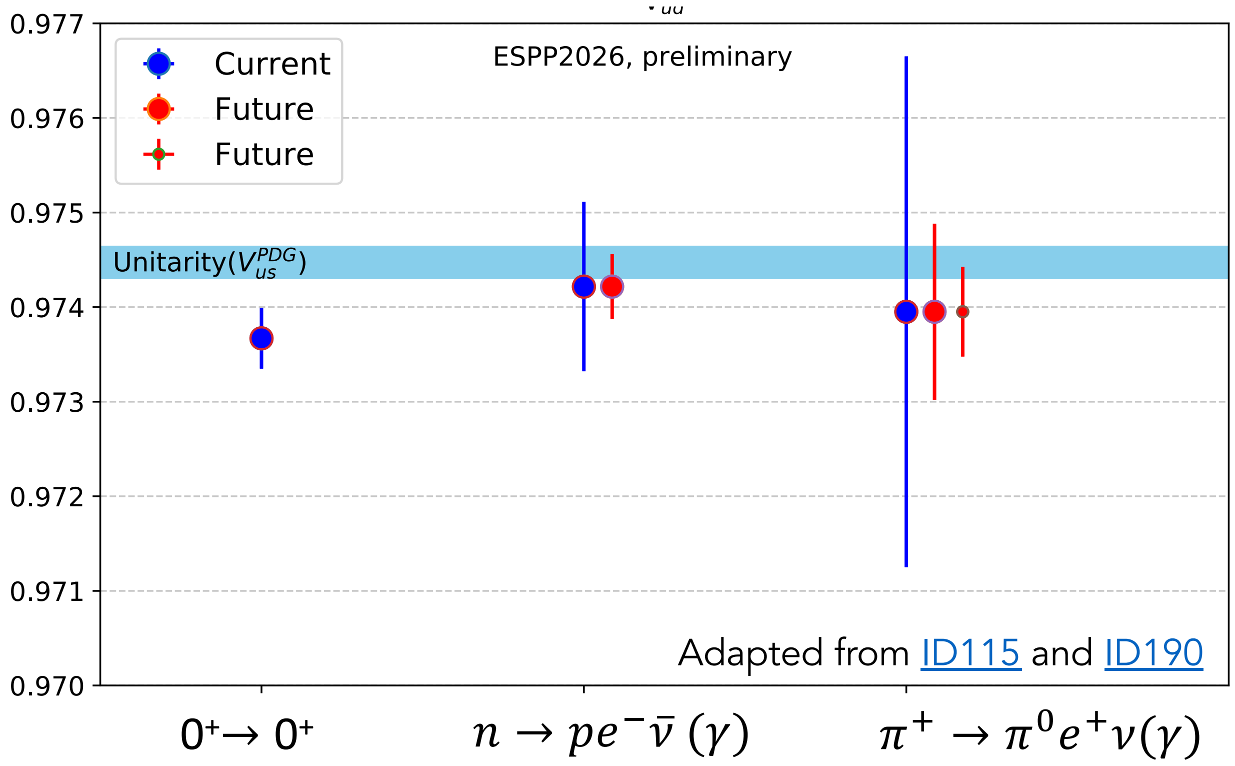
Very rare π decays and measurements of $|V_{ud}|$

High intensity π beam at PSI

$$R_{e/\mu} = \frac{\Gamma(\pi^+ \to e^+\nu(\gamma))}{\Gamma(\pi^+ \to \mu^+\nu(\gamma))}$$



$|V_{ud}|$ element of the CKM matrix



Expected to start in 2030 (~ 1 year run)
Expected precision similar to SM prediction

Different experimental techniques and theory uncertainties
Tension on unitarity : hope for clarification in future

s→d transitions : K physics

$K^+ \rightarrow \pi^+ \nu\nu$: NA62 @ CERN

- unique player for this mode
- current precision (2016-2022) : 25%

$$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (13.0\,^{+3.3}_{-2.9})\times 10^{-11}$$

- will collect data until 2026 ⇒ expected precision 15%
- SM value known to ~ 5%
- **no next-generation K^+ experiment foreseen**

$K_L \rightarrow \pi^0 \nu\nu$: KOTO and KOTO-II @ J-PARC

Very rare decays with specific signatures $K \rightarrow \mu\mu$: LHCb

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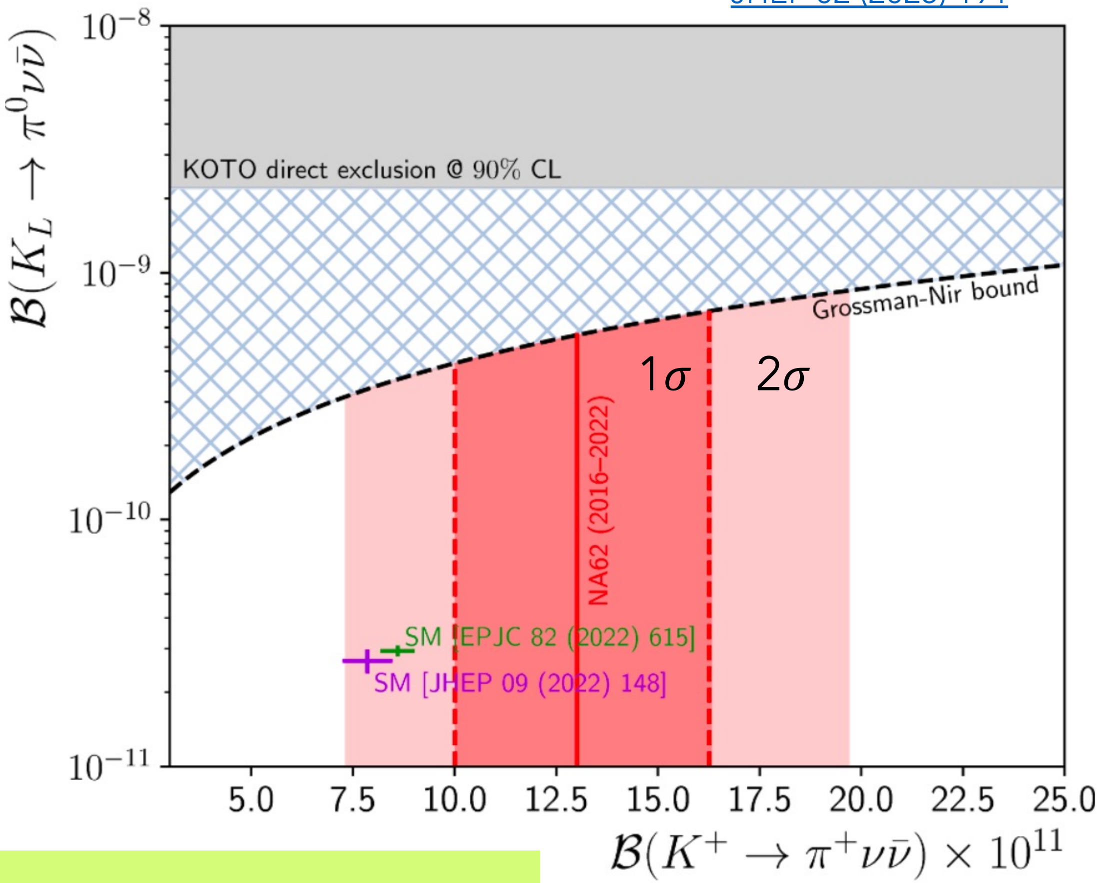
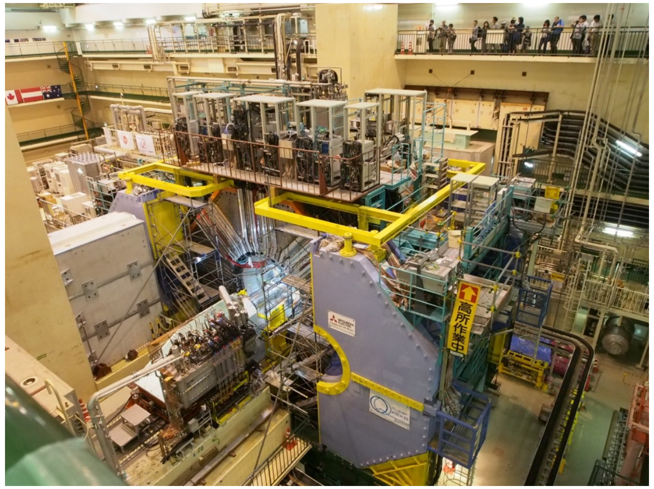


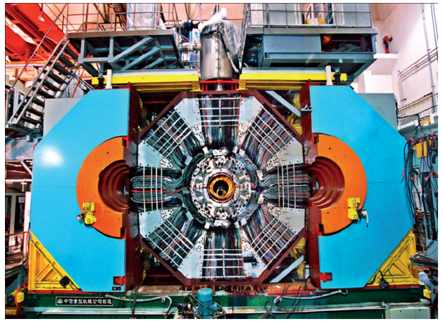
- High complementary with observables in the B sector
- Stringent test of the CKM mechanism, LFU tests and searches for light NP
- Testing ground for precision QCD calculations

Use of large scale facilities : cherry-picked examples of τ, D and B physics



Belle-II

LHC : LHCb but also ATLAS and CMS



+ inputs from BESIII

+ Future projects

Large scale facilities and experiments

Belle-II
e^+e^- @$\Upsilon(4S)$

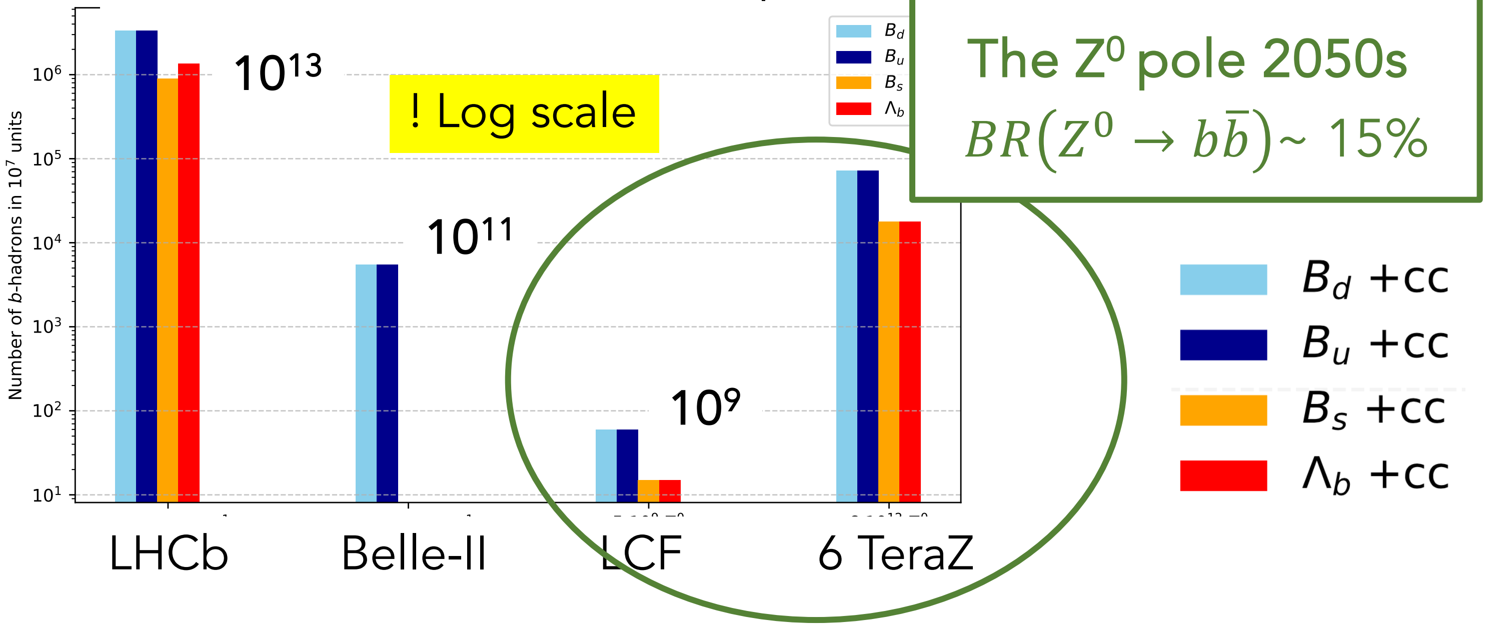
LHCb
(+ ATLAS & CMS)

Running + upgrades

e^+e^- @ Z^0 pole
(+WW)

Proposals

b-hadrons in detector acceptance



The Z^0 pole 2050s
$BR(Z^0 \to b\bar{b}) \sim 15\%$

Some extrapolations are 'wilder' than others due to larger dependence on the detector design which is not known

Once data is recorded, new analysis technics are usually found and foreseen sensitivities are reached … or even surpassed !

Indicative timeline

WE ARE HERE

2030s

Belle-II
e^+e^- @$\Upsilon(4S)$

LHCb
(+ ATLAS & CMS)

LHCb 50 fb^{-1}
Belle-II 10 ab^{-1}

2040s

Belle-II
e^+e^- @$\Upsilon(4S)$

LHCb
(+ ATLAS & CMS)

LHCb-UII 300 fb^{-1}
Belle-II 50 ab^{-1}

2050s

e^+e^- @ Z^0 pole
(+WW)

5 Giga : $5.10^9\ Z^0$
2 TeraZ : $2.10^{12}\ Z^0$
6 TeraZ : $6.10^{12}\ Z^0$

τ and D physics :
BESIII + STCF (1 ab^{-1}/y)

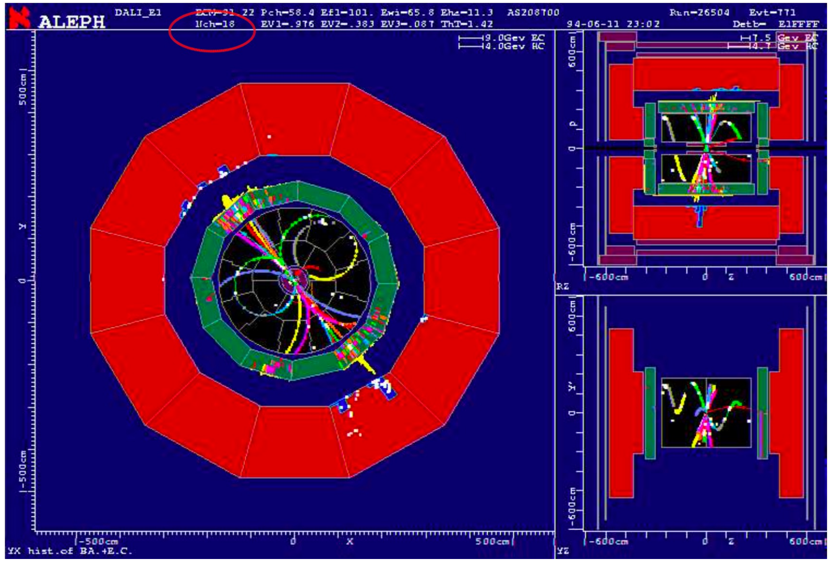
An excellent detector

To cover the full spectrum of Flavour Physics one needs :

- Excellent IP determination (Si vertex detectors) and multiple scattering as low as possible
- Excellent tracking and high hermicity of the detector
- Highly performant charged hadron identification (p/K/π separation) as well as e and μ
- Ability to reconstruct low energy neutrals (γ, π^0)

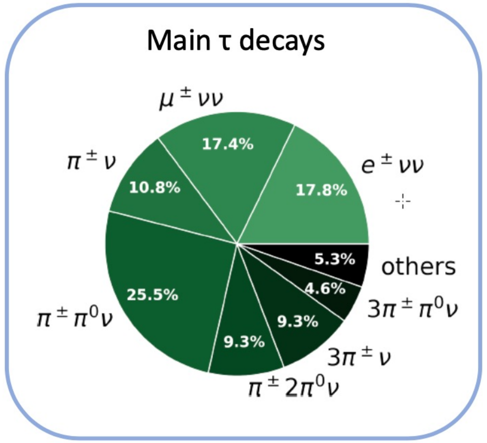
Demonstrated by 'history' at previous facilities with wide program range :

- LEP : full flavour physics program mostly done by ALEPH and DELPHI (Si vertex detectors, charged hadrons ID)
- LHC : having a dedicated detector allows to cover a significantly wider spectrum of Flavour Physics



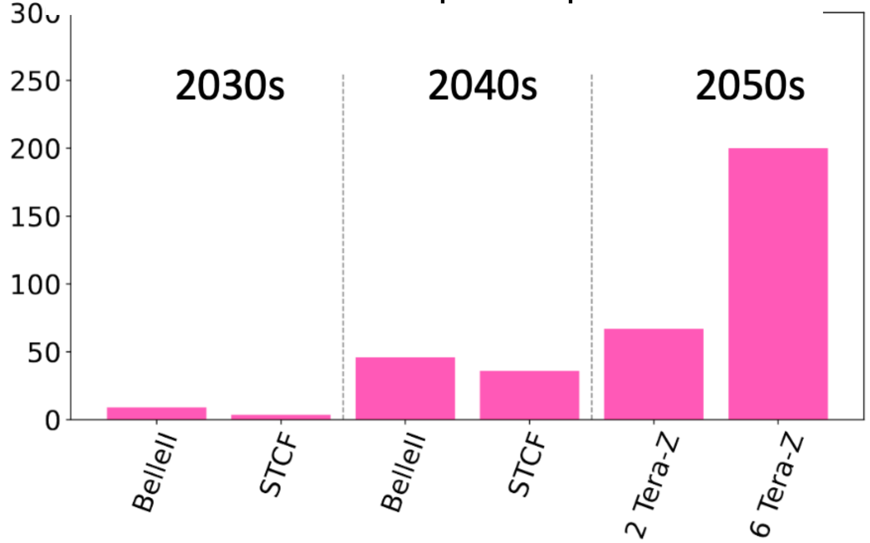
$Z^0 \rightarrow q\bar{q}$ at LEP

The τ lepton



e+ e- colliders

billions of $\tau^+ \tau^-$ pairs produced



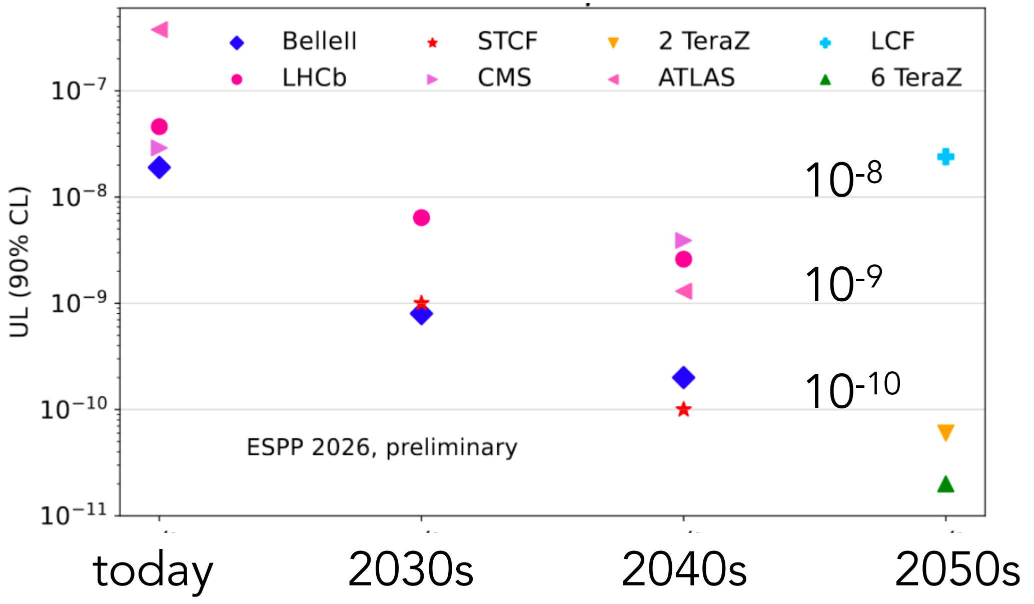
- The heaviest charged lepton and the only one which can decay into hadrons
- In many models NP couples preferentially to the third family
- Search for decays that are forbidden in SM
- Tests of SM through τ precision measurements
- Short lifetime (~2.9 10^{-13} s) and neutrinos : experimentally demanding

⇒ most of the results are coming from e^+e^- colliders but $BR(\tau \to 3\mu)$ where all are contributing

$BR(Z^0 \rightarrow \tau^+ \tau^-) = 3.4\%$

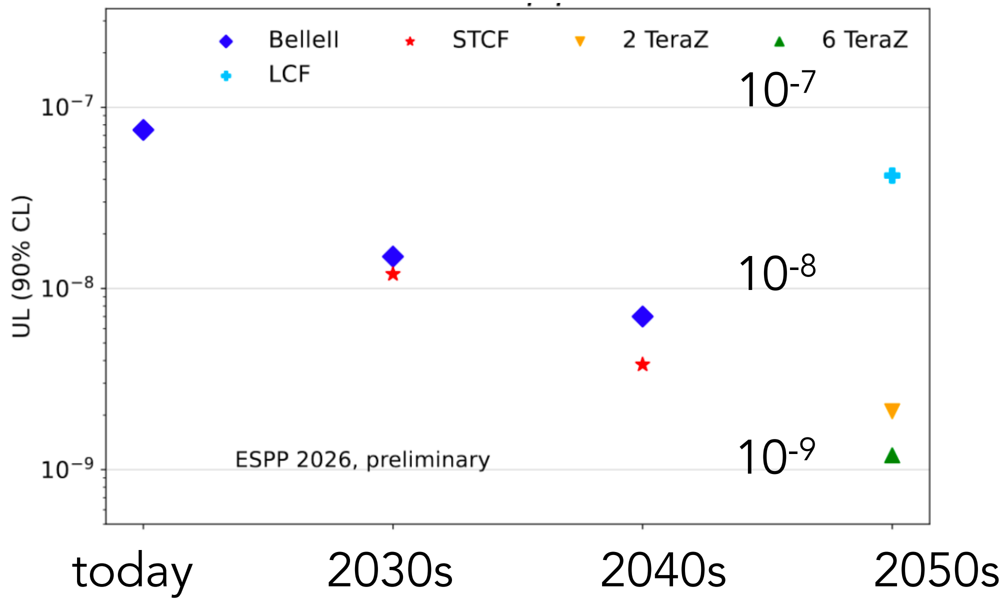
cLFV : $\tau \to \mu$

$BR(\tau \to 3\mu)$ 90 % CL UL



Clean and narrow peak in reconstructed mass ⇒ ~ background free ⇒ doable in pp environment

$BR(\tau \to \mu\gamma)$ 90 % CL UL

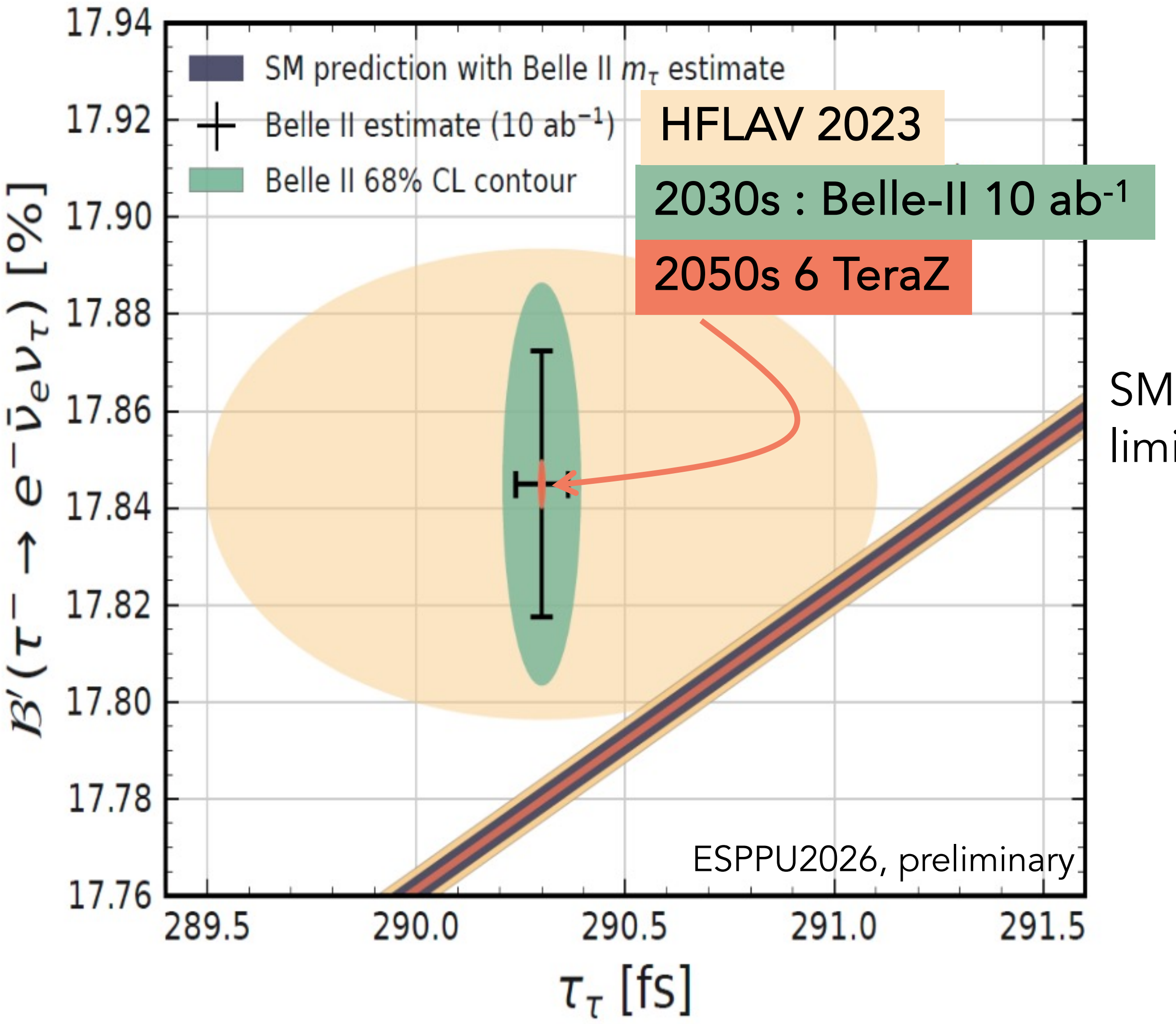


More challenging (mass resolution due to the γ and radiative events pollution)

Belle II and STCF (5 ab^{-1}) : best limits until Tera-Z experiments enters the game.
Steady gain from now to 2050s
TeraZ : improvement of the limits by up to one order of magnitude, down to few 10^{-11} for BR($\tau \to 3\mu$) and few 10^{-9} for BR($\tau \to \mu\gamma$)

Universality test between the 3rd generation and the 2 light ones

Inputs : τ mass, lifetime and BR($\tau \to \ell\nu\nu$) and similar information for μ



SM functional dependence :
limited by the τ mass knowledge

Large improvement possible but measurements will be systematically limited

CP violation in B & D and CKM elements from heavy-quark decays

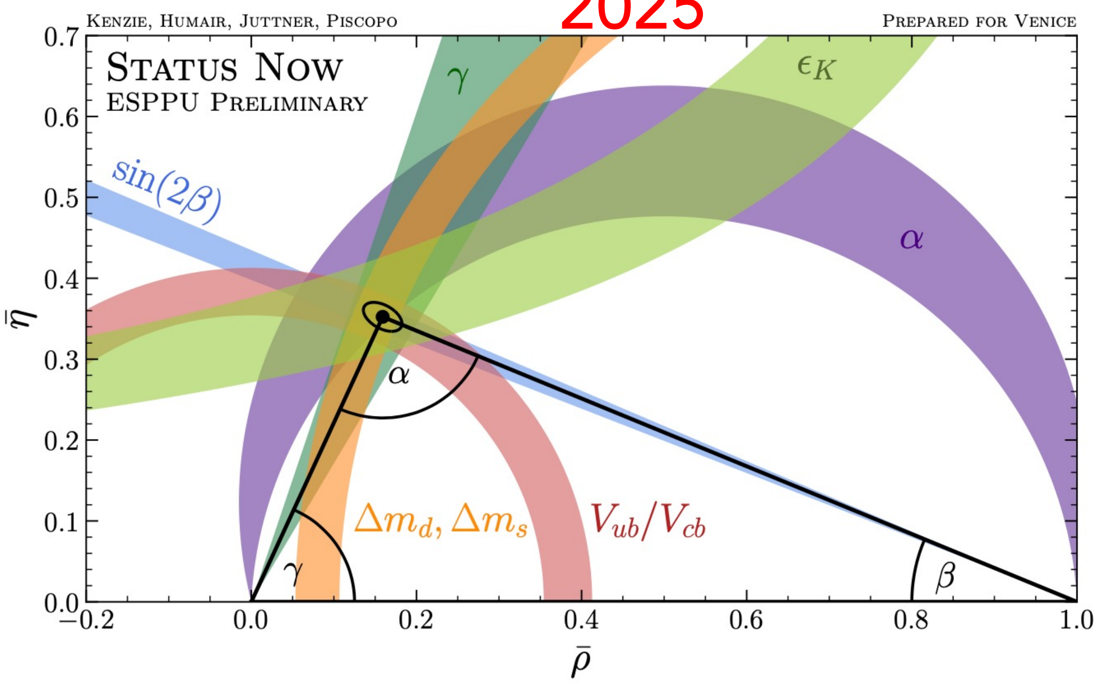
$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

Measurements of moduli and phases

- Study of the CP violation mechanism
- Sensitivity to BSM through comparison of results obtains from tree-dominated and loop-dominated processes

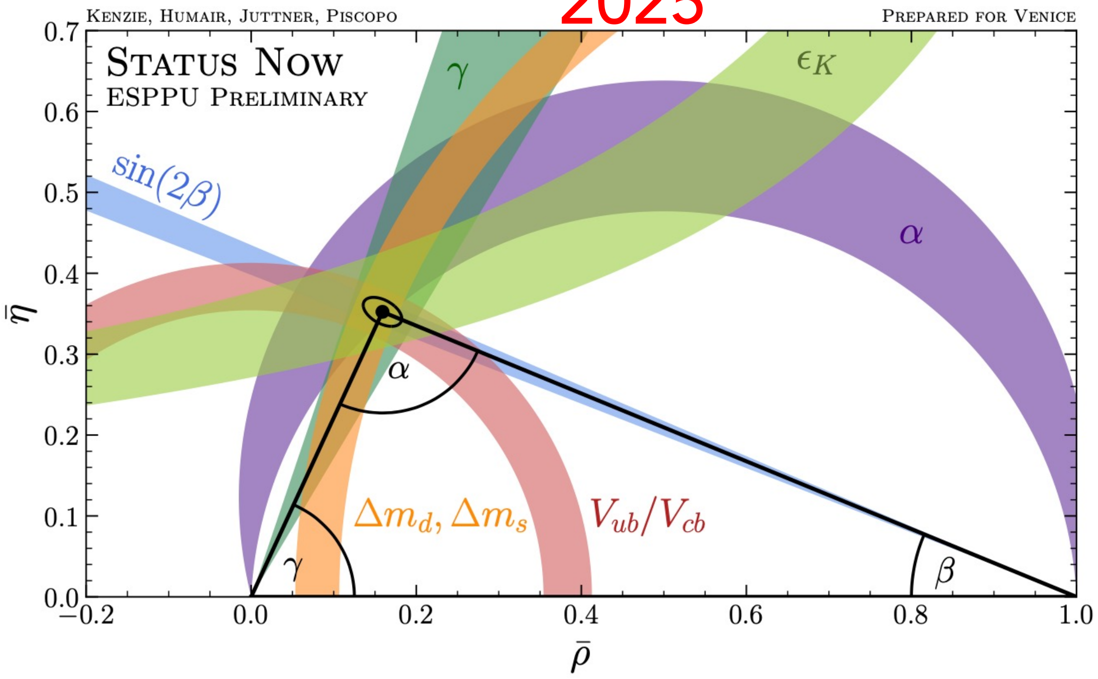
Idea from Yuval Grosmann
Photo from here

2025

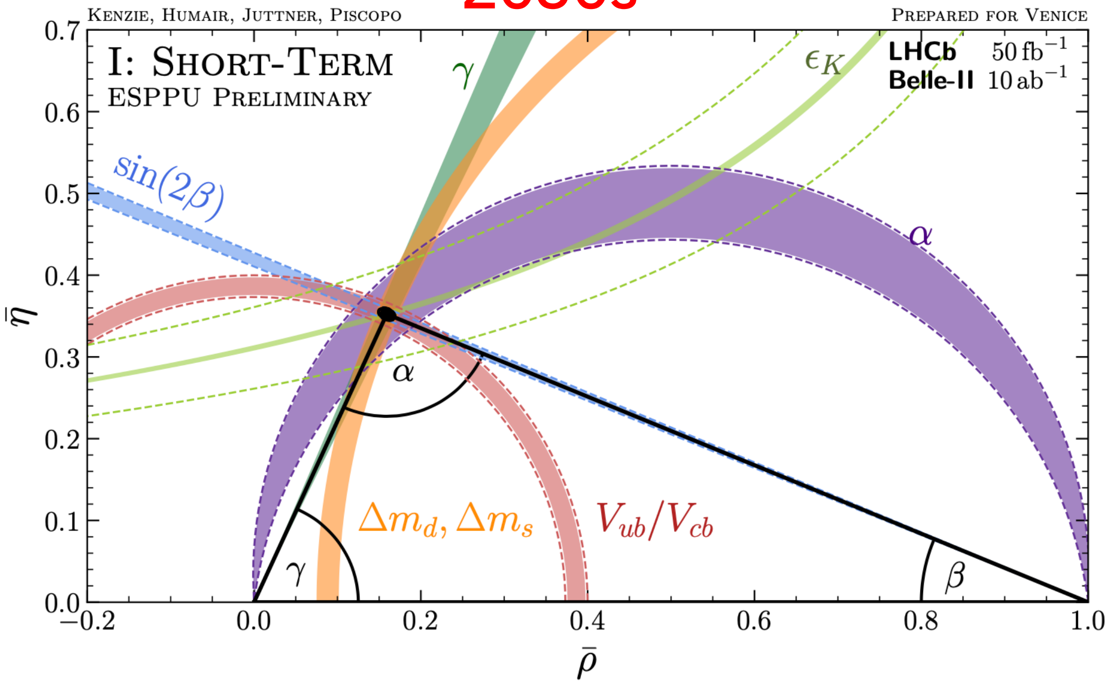


Kenzie, Humair, Juttner, Piscopo
Prepared for Venice
Status Now
ESPPU Preliminary
γ
ϵ_K
$\sin(2\beta)$
α
$\Delta m_d, \Delta m_s$
V_{ub}/V_{cb}
β
$\bar{\eta}$
$\bar{\rho}$

2025

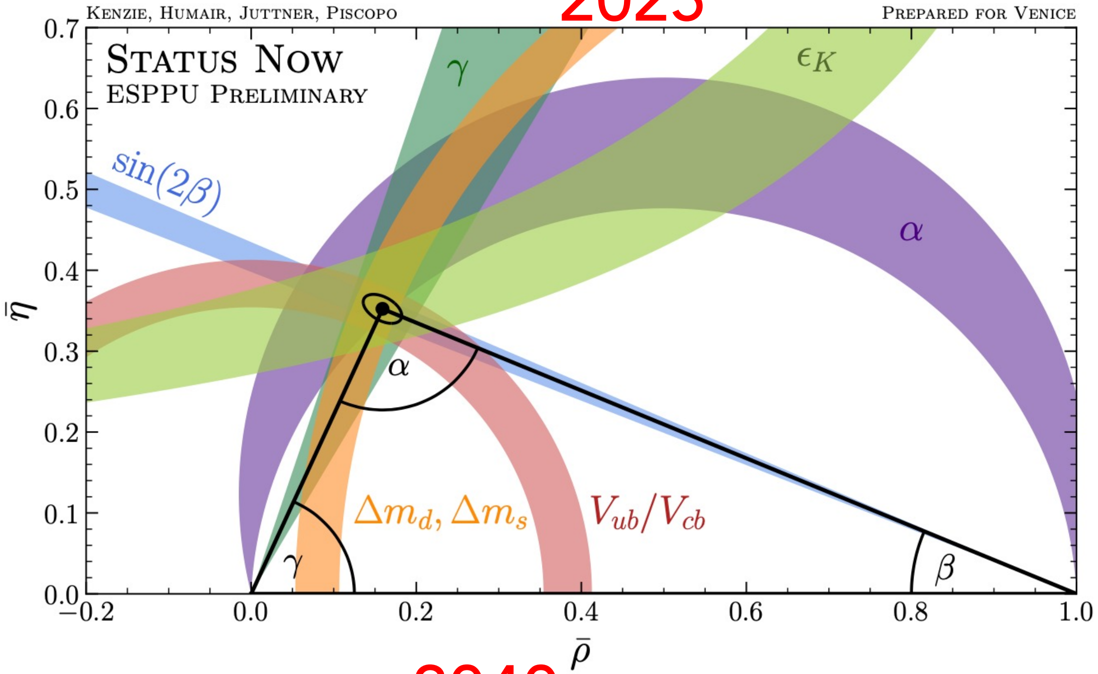


2030s

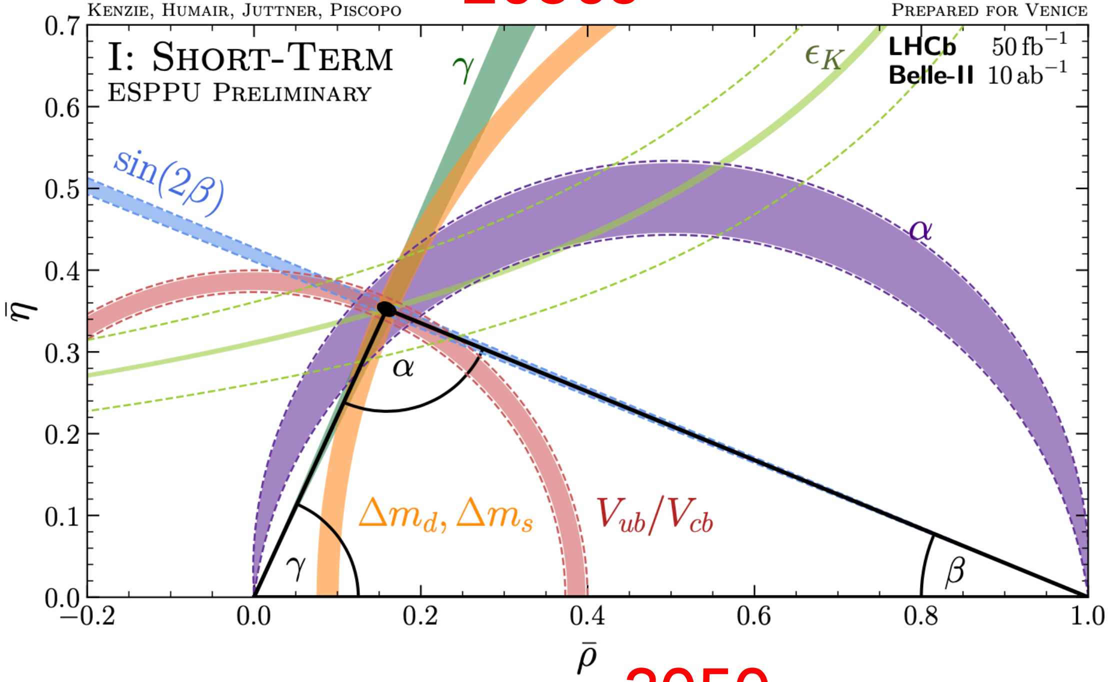


exp+th

2025

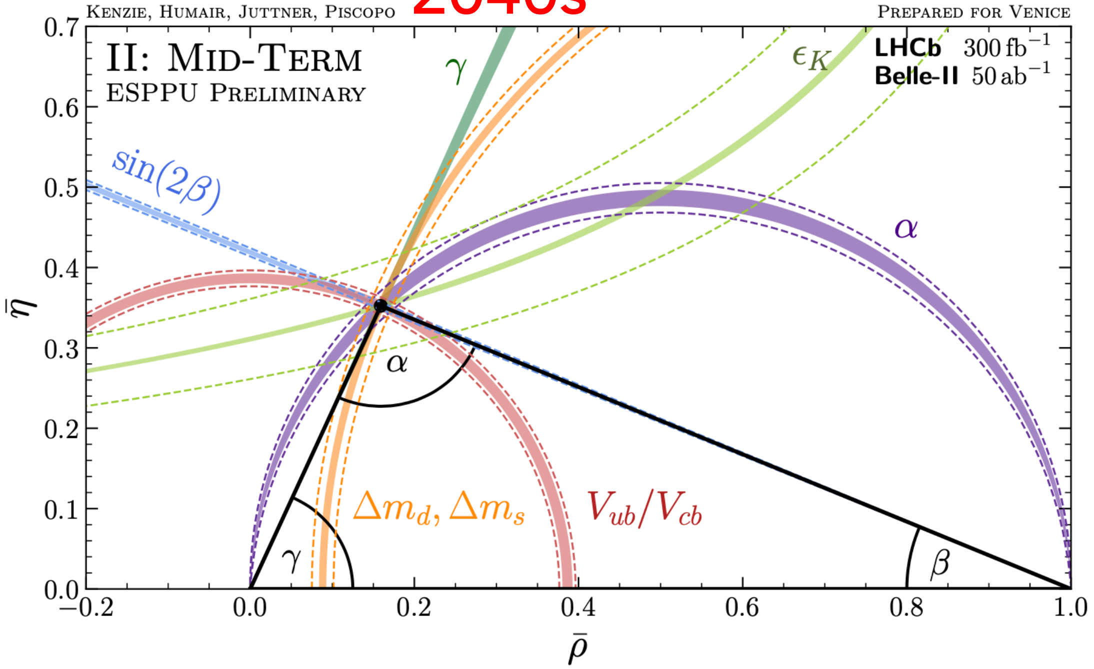


2030s

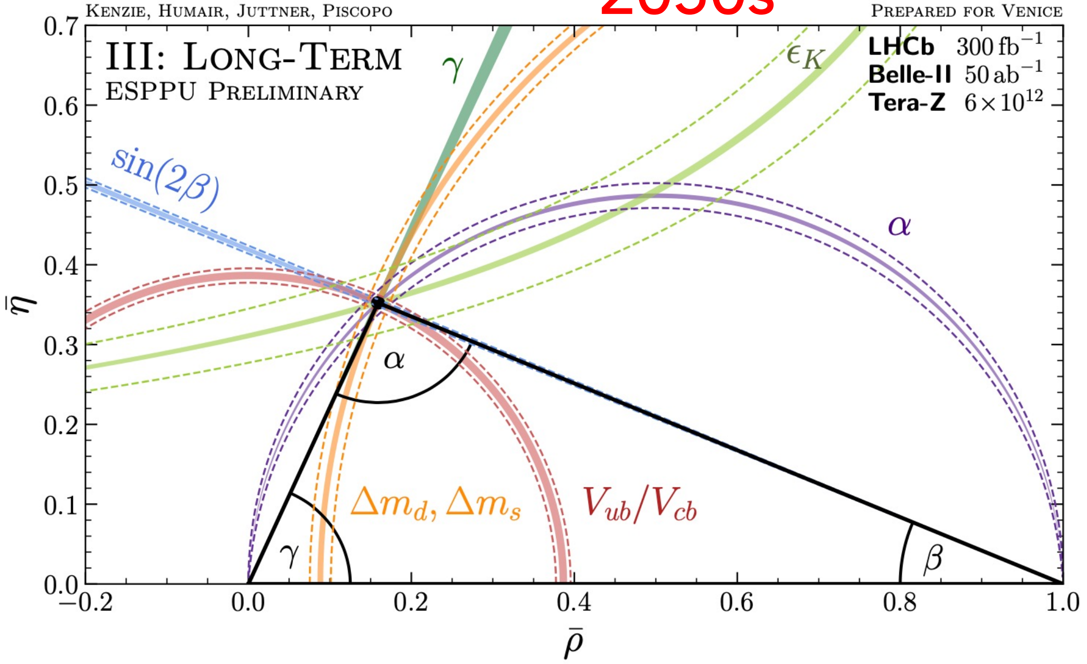


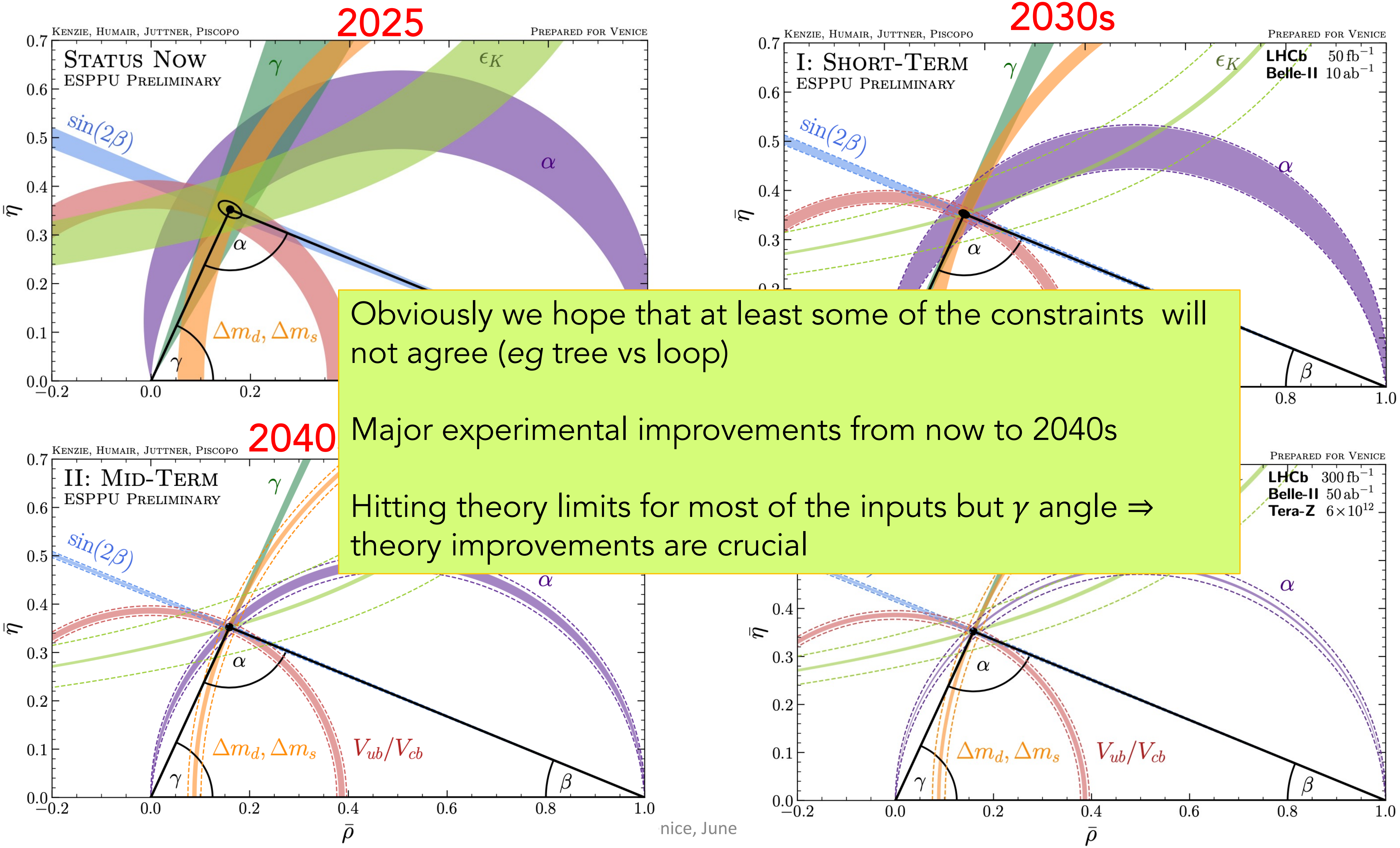
exp+th

2040s



2050s





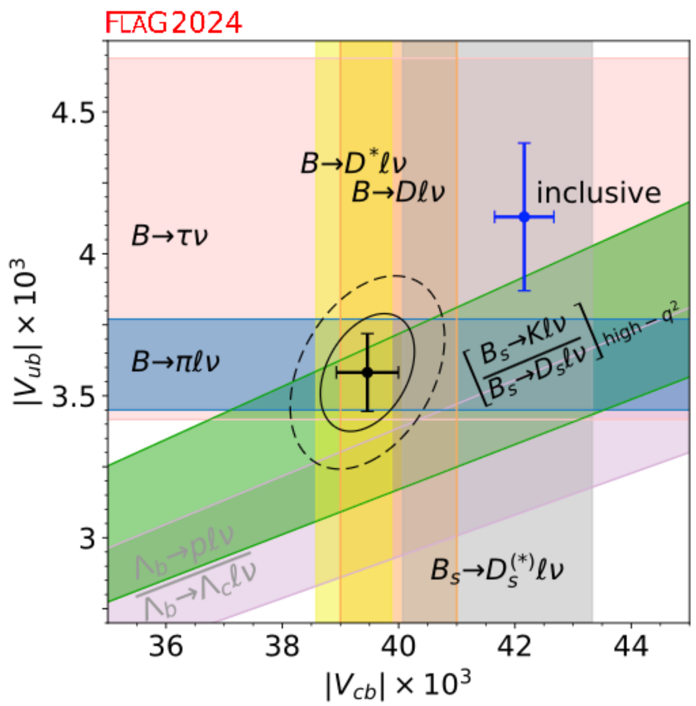
exp+th

Obviously we hope that at least some of the constraints will not agree (*eg* tree vs loop)

Major experimental improvements from now to 2040s

Hitting theory limits for most of the inputs but γ angle ⇒ theory improvements are crucial

About $|V_{cb}|$ (and $|V_{ub}|$)



Longstanding discrepancy between exclusive and inclusive determination of V_{cb}

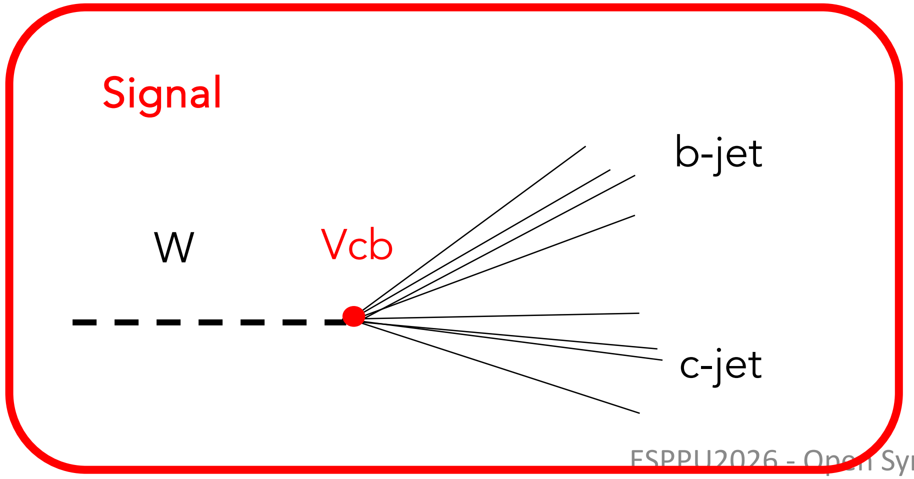
LQCD : B meson decay constant known to ~ %

A game changer

Use of WW pairs at future e^+e^- colliders

Large samples : 2.5 10^7 (LCF250) → 4.8 10^8 (FCCee)

Depends crucially on: b-jet, c-jet, light jet flavour tagging determination



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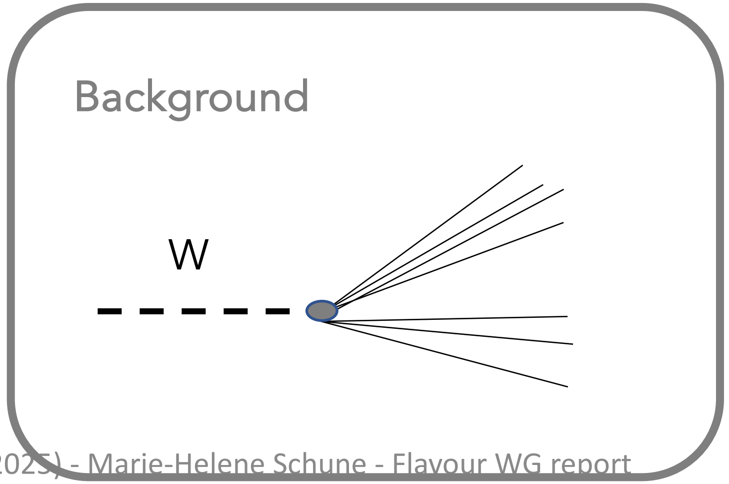
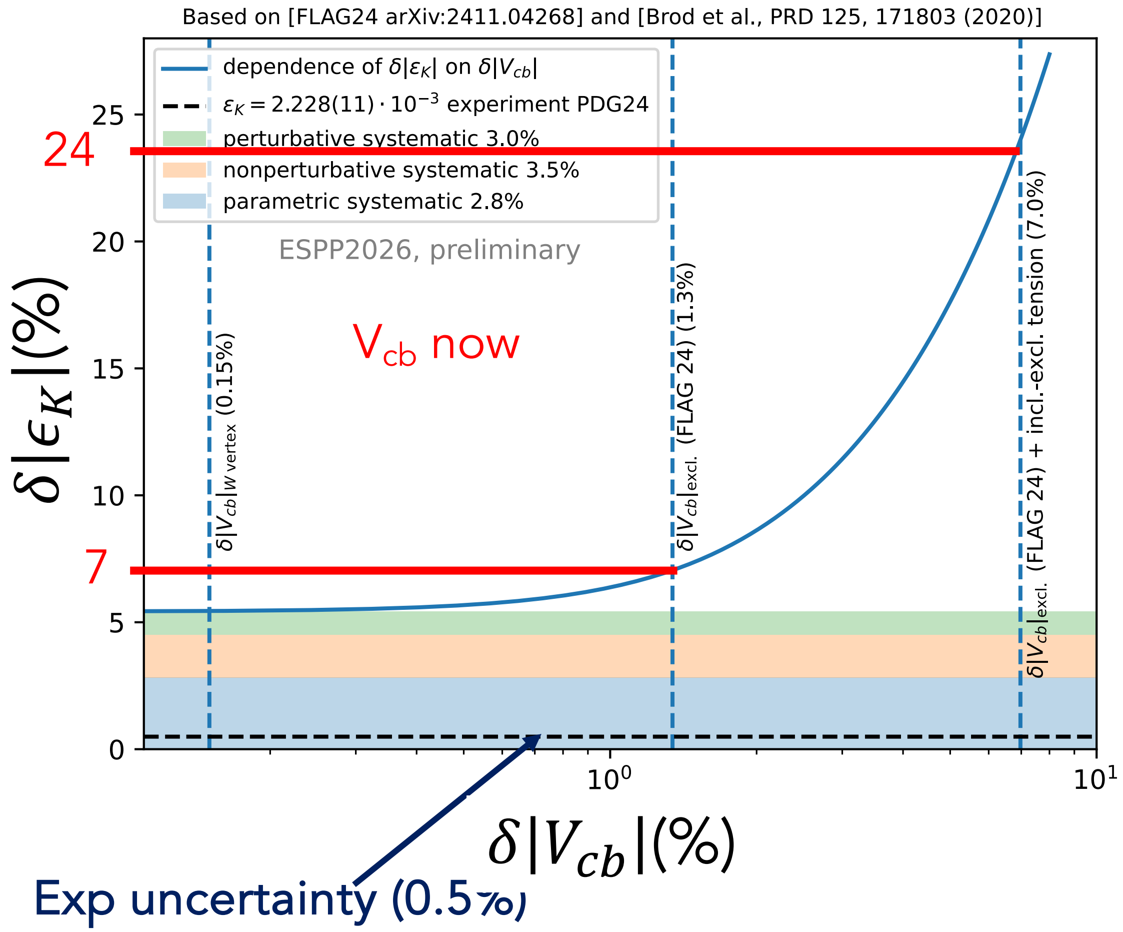


$|V_{cb}|$ enters everywhere in SM predictions (ϵ_K, $BR(B_s^0 \to \mu^+\mu^-), \ldots$)



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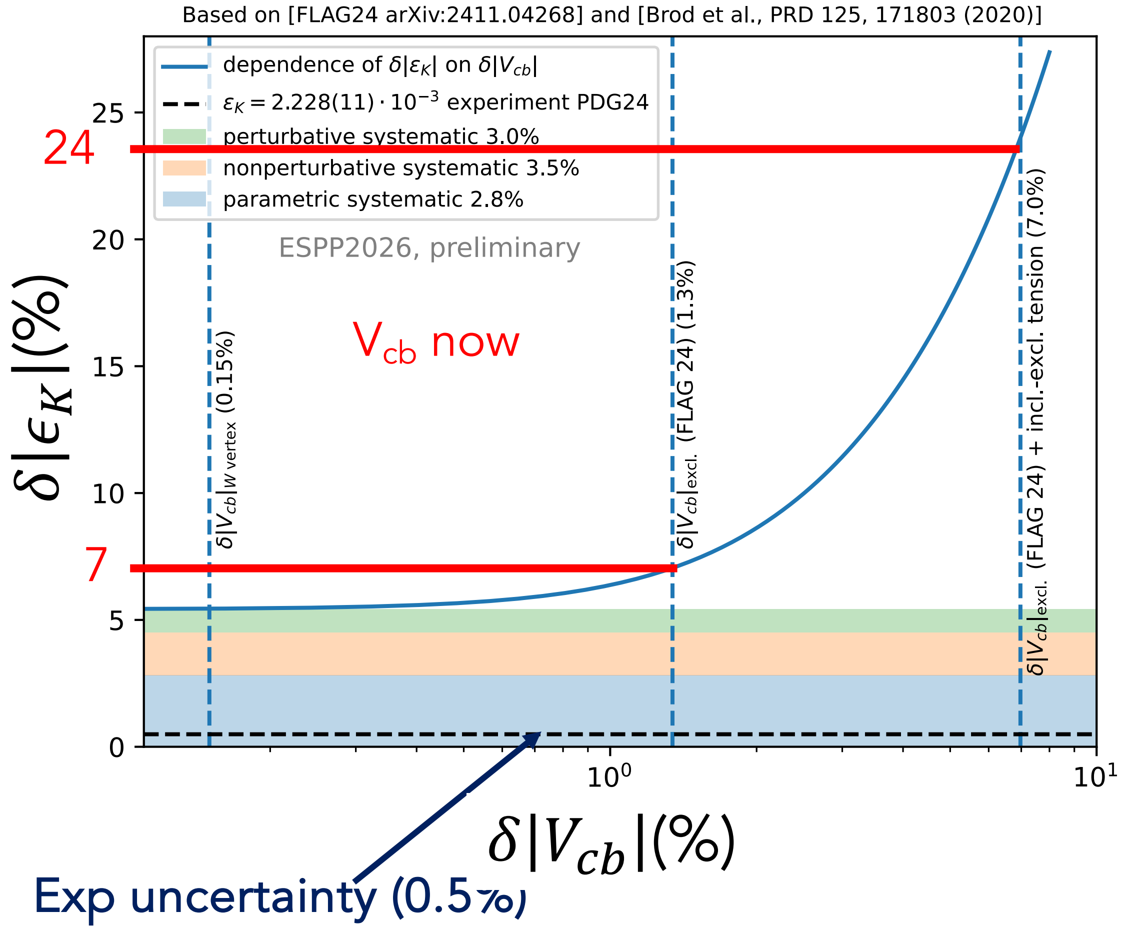
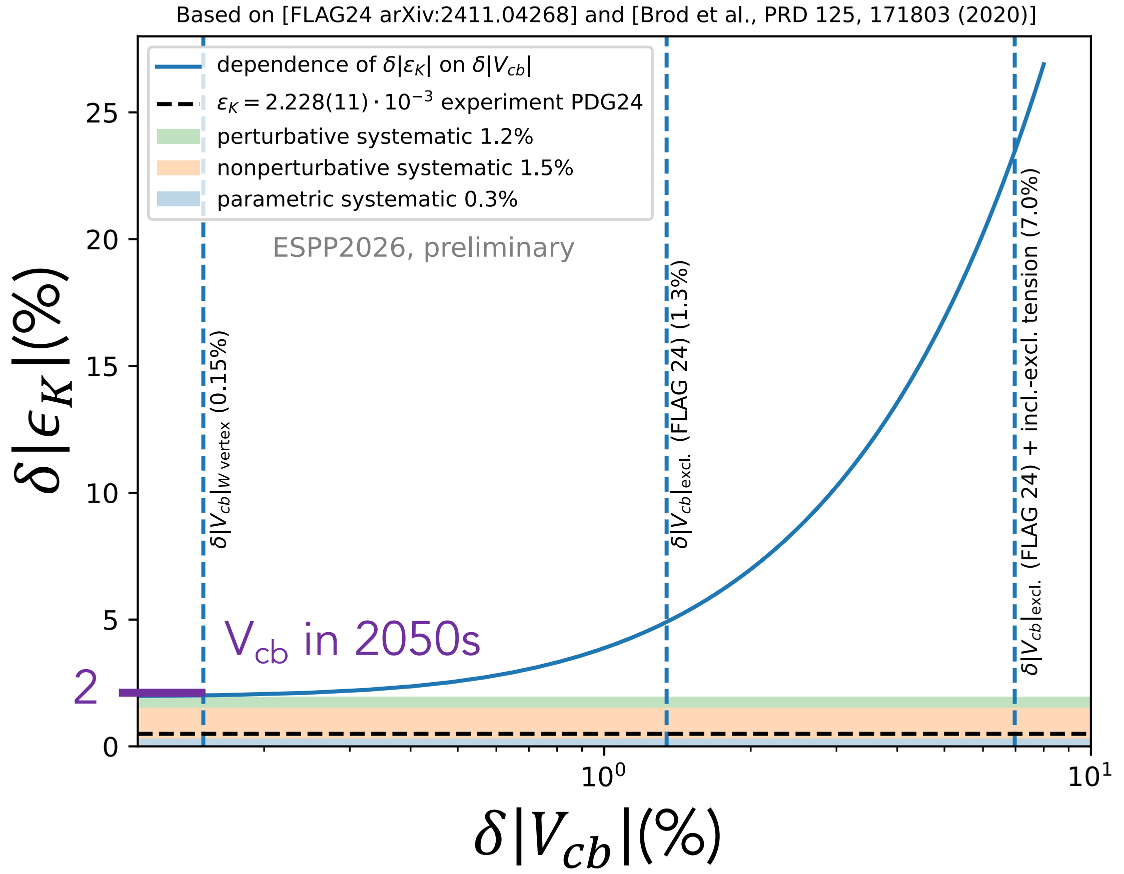


Reduced theory errors (2050s)

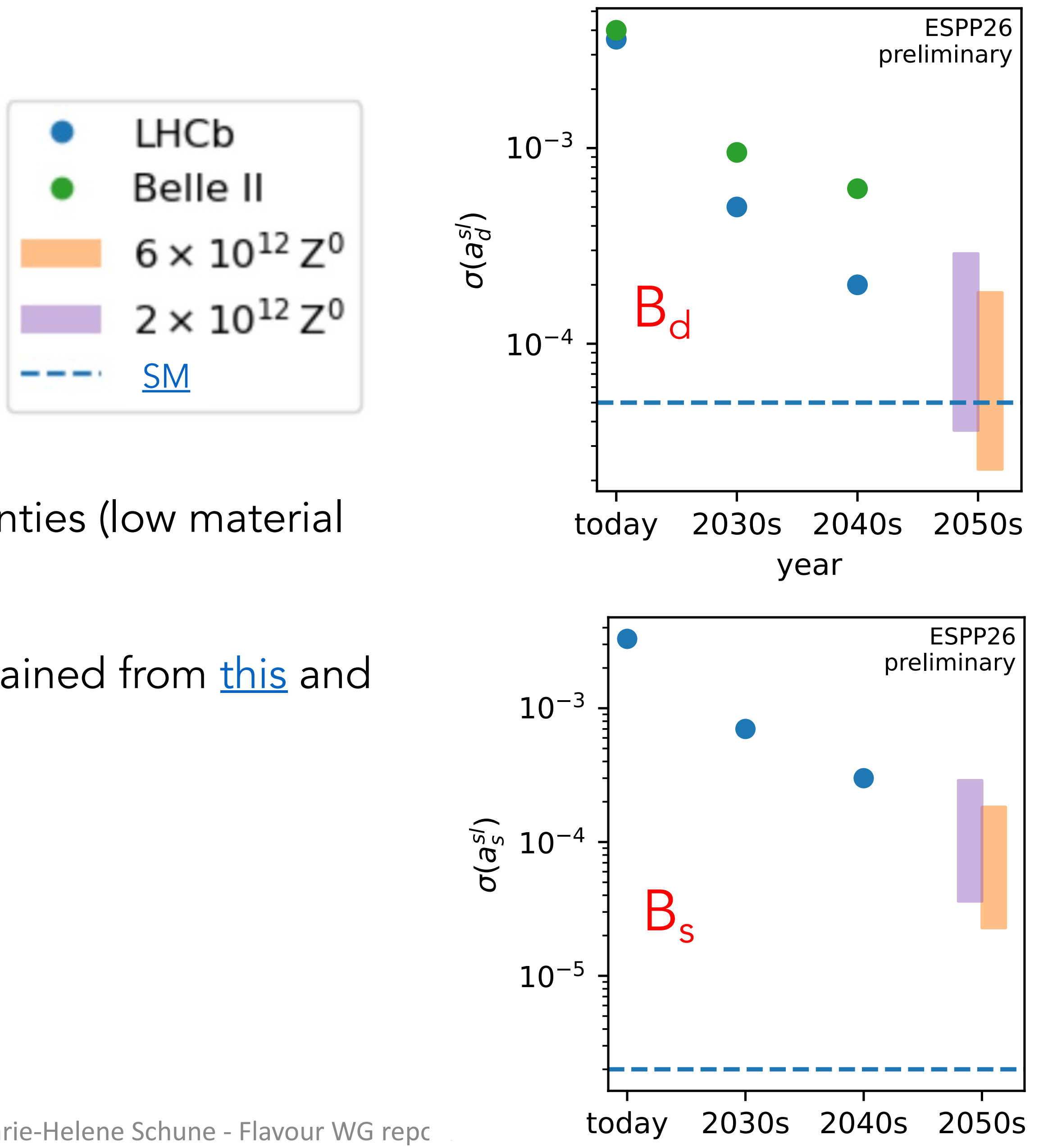


Mandatory for the ultimate tests of SM in the flavour domain : a very precise determination of $|V_{cb}|$

Solving the inclusive/exclusive discrepancy ⇒ better control theory predictions for semileptonic decays

Semileptonic CP asymmetries

$$a_{sl}^{q} = \frac{P(\overline{B_q} \rightarrow B_q) - P(B_q \rightarrow \overline{B_q})}{P(\overline{B_q} \rightarrow B_q) + P(B_q \rightarrow \overline{B_q})}$$



No production asymmetry at e^+e^- colliders

Challenging measurement : control of the systematics uncertainties (low material detector)

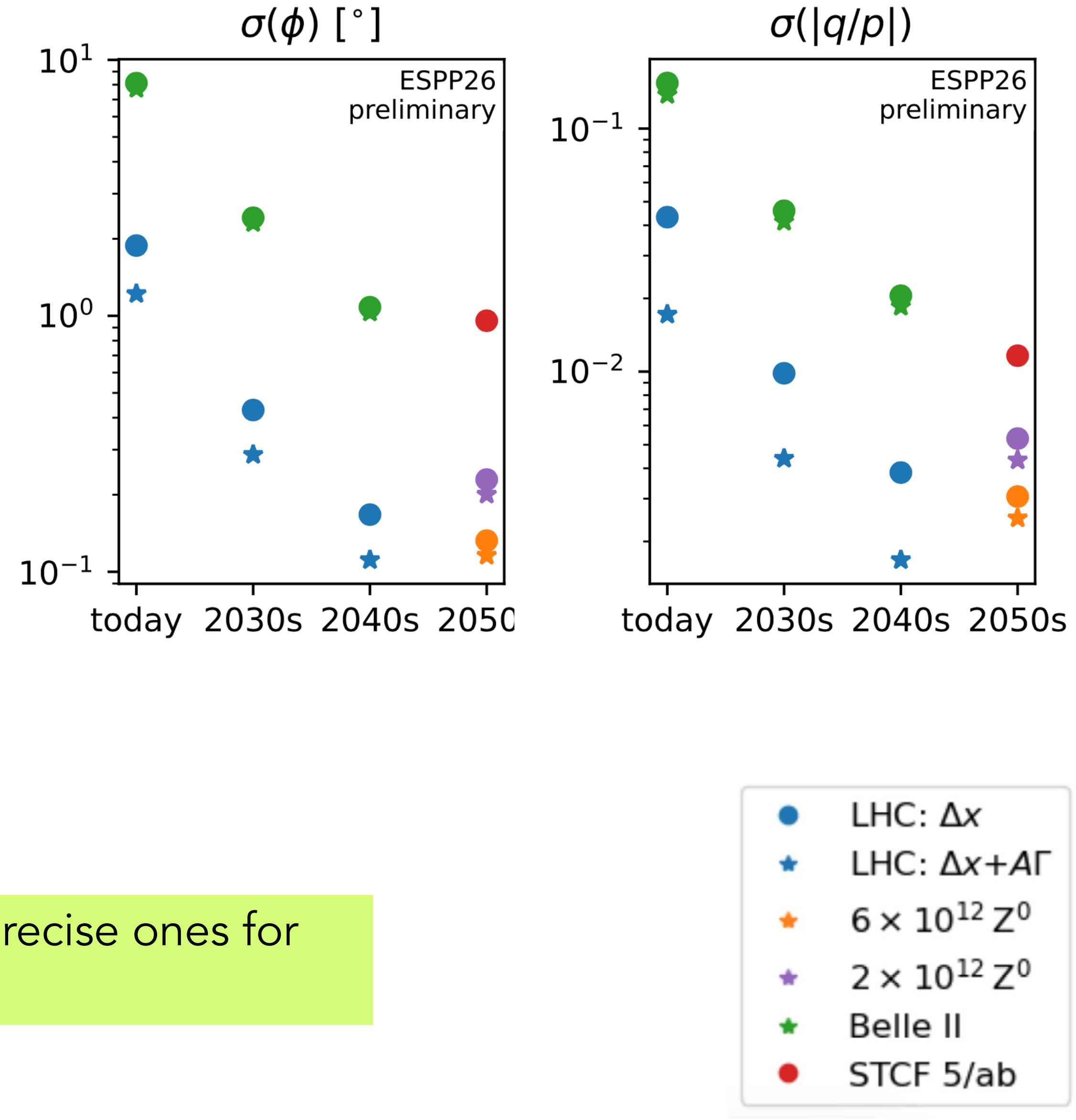
- 10^{-4} assumed for Belle-II and LHCb-UII
- No precise simulation for the 2050s : few 10^{-5} ? (range : obtained from this and that)

Could observe CP violation in mixing for the first time in B_d decays

CP violation in charm decays

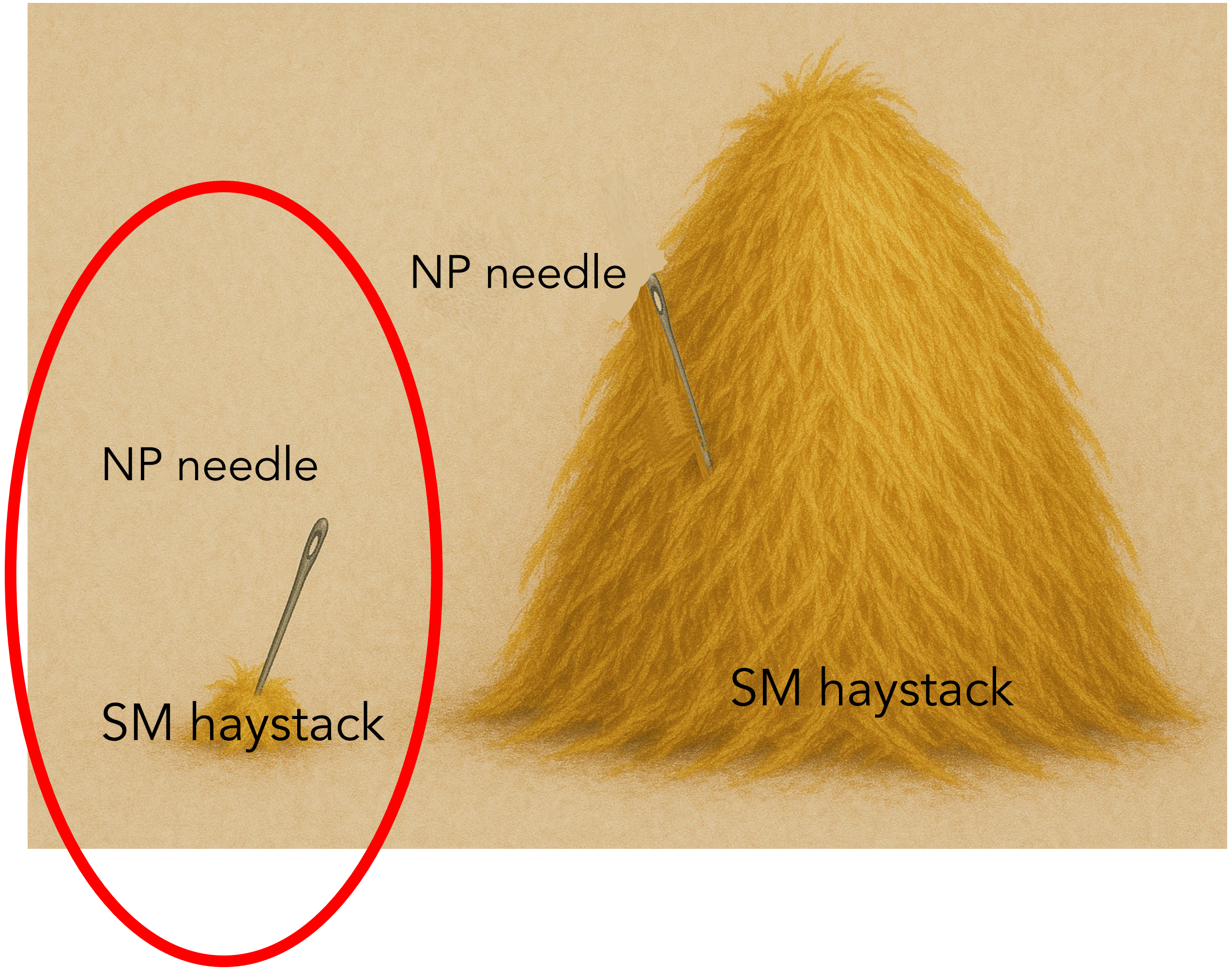
Up-type quark sector : CP violation is small !

- Access to CP violation in the mixing requires the largest samples and excellent detector performances.
- Extremely large samples produced … and reconstructed (billions of events)
- Strong potential for probing the Standard Model contribution
- Access to multiple modes including with neutrals to get insight into the hadronic phases



LHCb-UII results will remained the most precise ones for CP violation in mixing

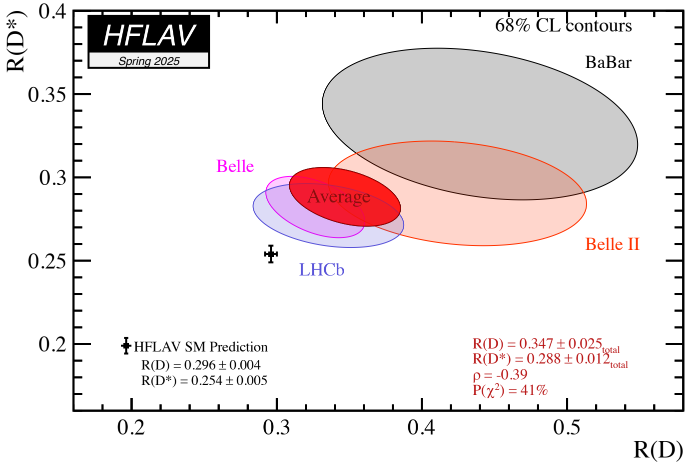
Rare decays and Lepton Flavour Universality tests



Comparing b→c $\tau\nu$ and b→c$\ell\nu$ with $\ell=\mu$ or e

$$R\left(D_{(s)}^{(*)}\right) = \frac{BR\left(B_{(s)} \to D_{(s)}^{(*)}\tau^+\nu_\tau\right)}{BR\left(B_{(s)} \to D_{(s)}^{(*)}\ell^+\nu_\ell\right)} \quad \ell = \mu, e$$

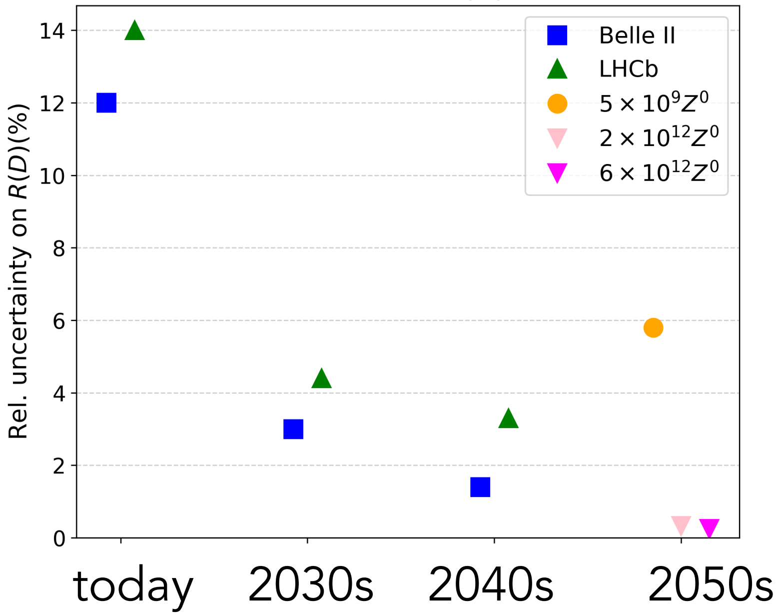
3.8 σ tension with SM

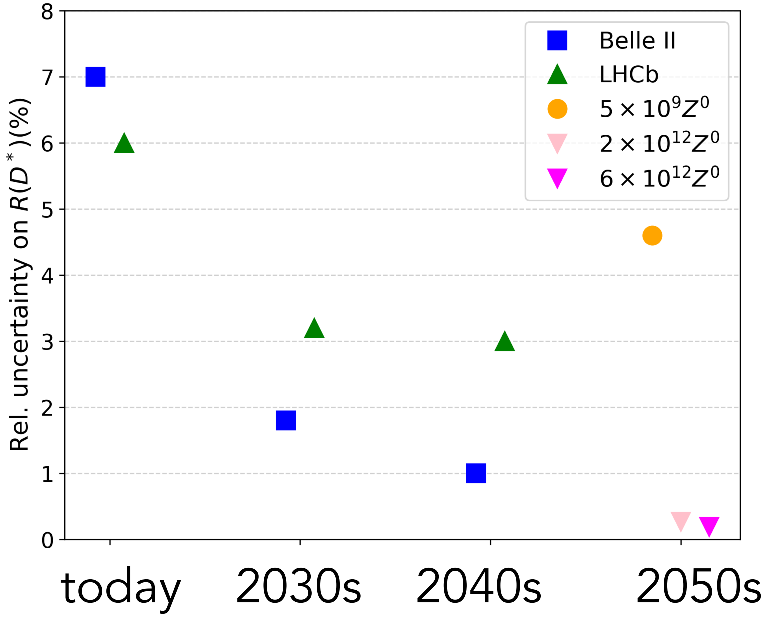


σ(R(D))

ESPPU2026, preliminary

σ(R(D*))





LHCb-UII and Belle-II : improvement of a factor 10 in precision.
With TeraZ sample can reach permil level. Theoretical uncertainties can also improve.

Possibility to measure the whole family (not only R(D) and R(D*))
Interest to connect with universality test of the τ lepton

FCNC decays : $B^0_{d,s} \to \mu^+\mu^-$

SM predictions :

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

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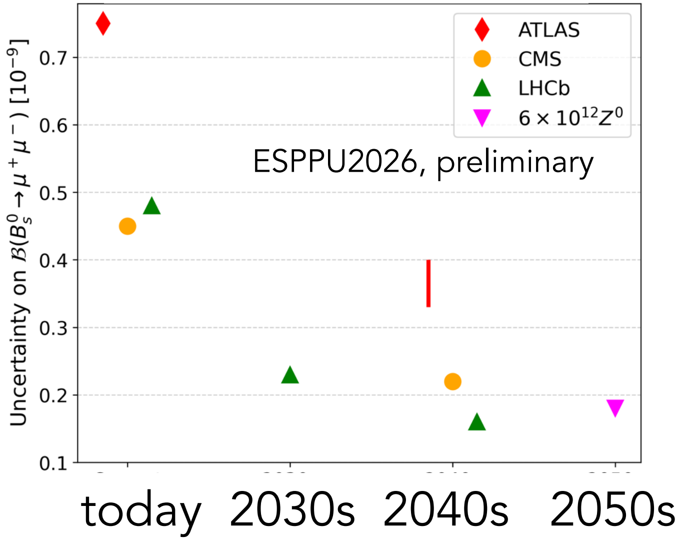
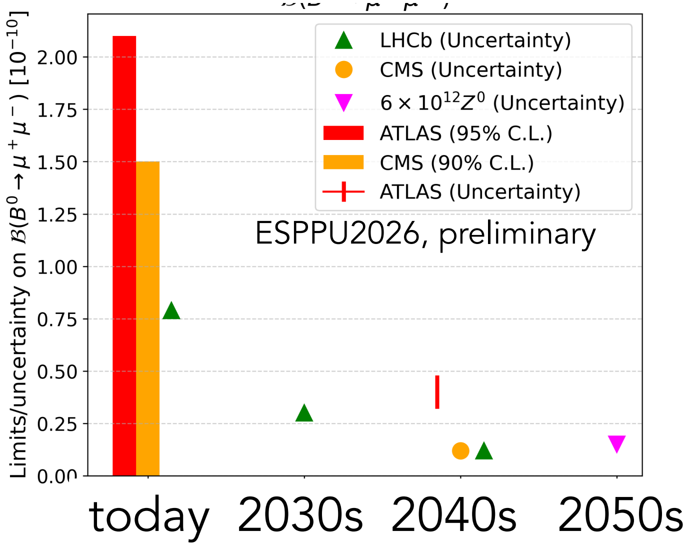
$\sigma(BR(B^0_s \to \mu^+\mu^-))$



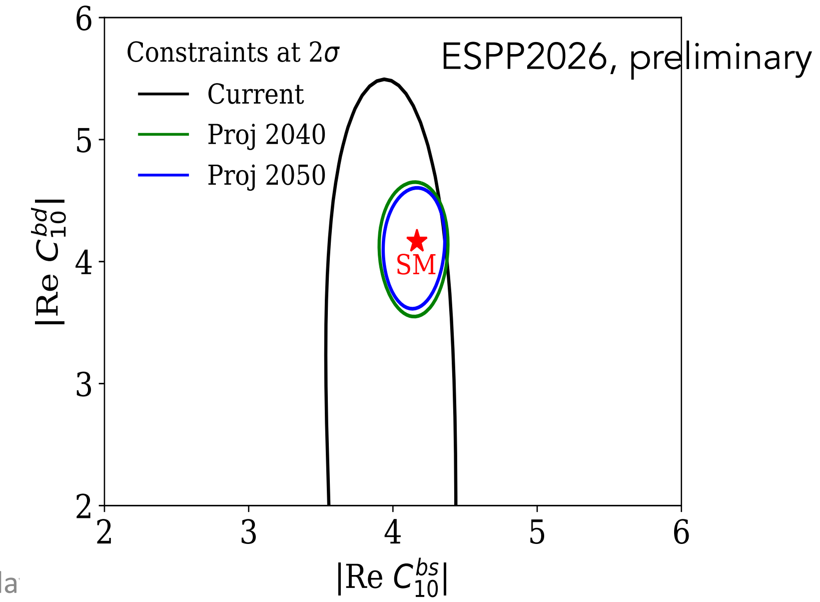
$\sigma(BR(B^0_d \to \mu^+\mu^-))$



HL-LHC (ATLAS, CMS and LHCb) will not be surpassed for BR measurements

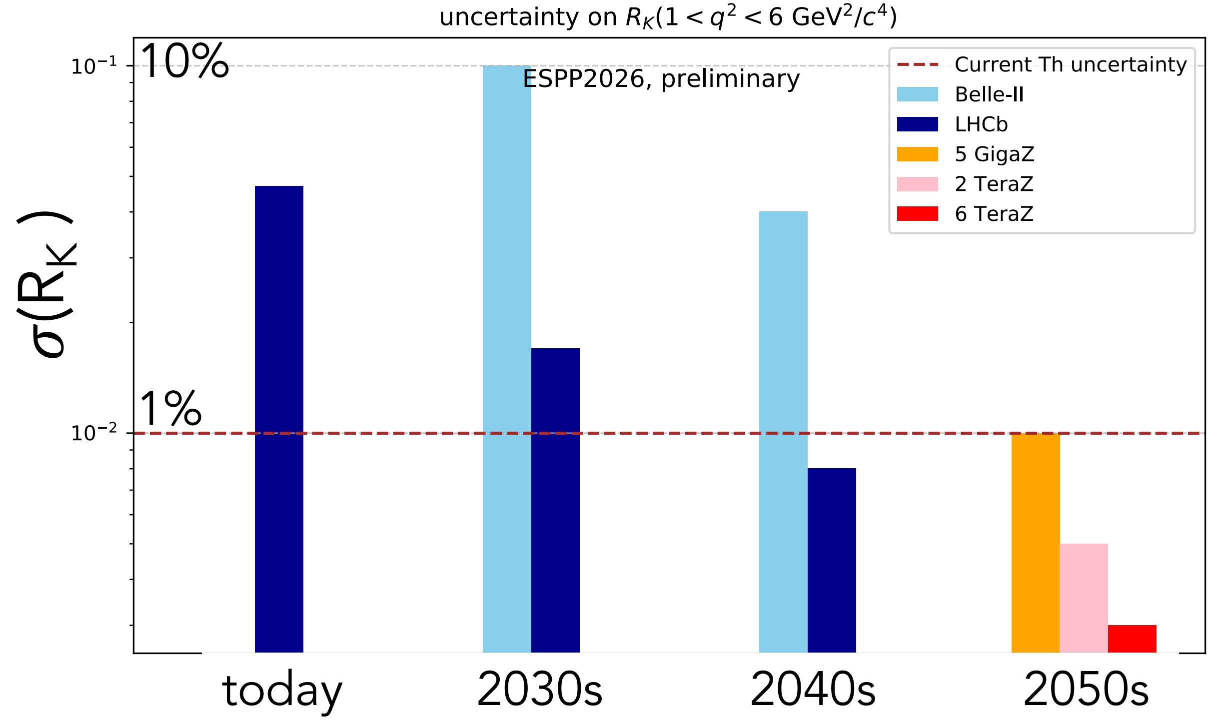
Experimental uncertainty : impact of fragmentation and normalisation BR.

Reaching the theory uncertainty for B_s (decay constant and $|V_{cb}|$)



FCNC : b→s ℓℓ BR and LFU tests

$$R_K = \frac{\int \frac{d\Gamma(B \to K\mu^+\mu^-)}{dq^2}\, dq^2}{\frac{d\Gamma(B \to Ke^+e^-)}{dq^2}\, dq^2} \qquad q^2 = M_{\ell\ell}^2$$



2040s : experimental precision below 1%

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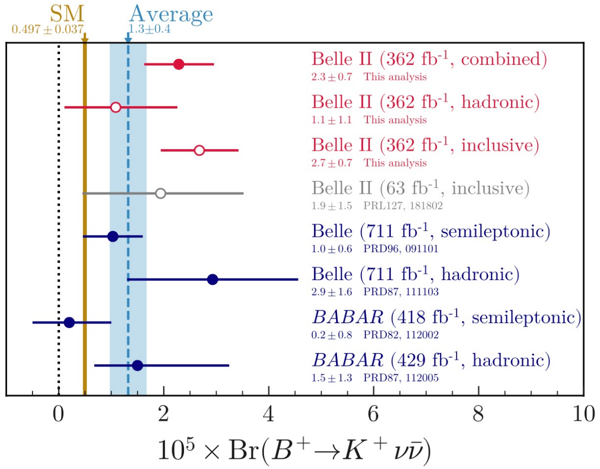
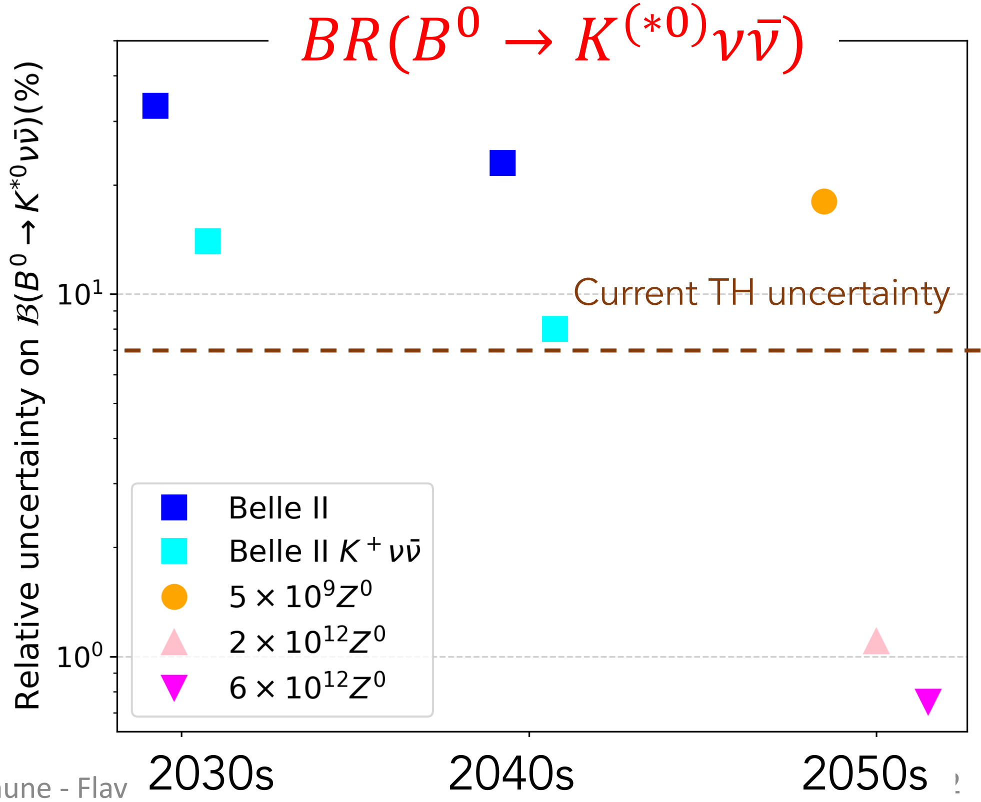
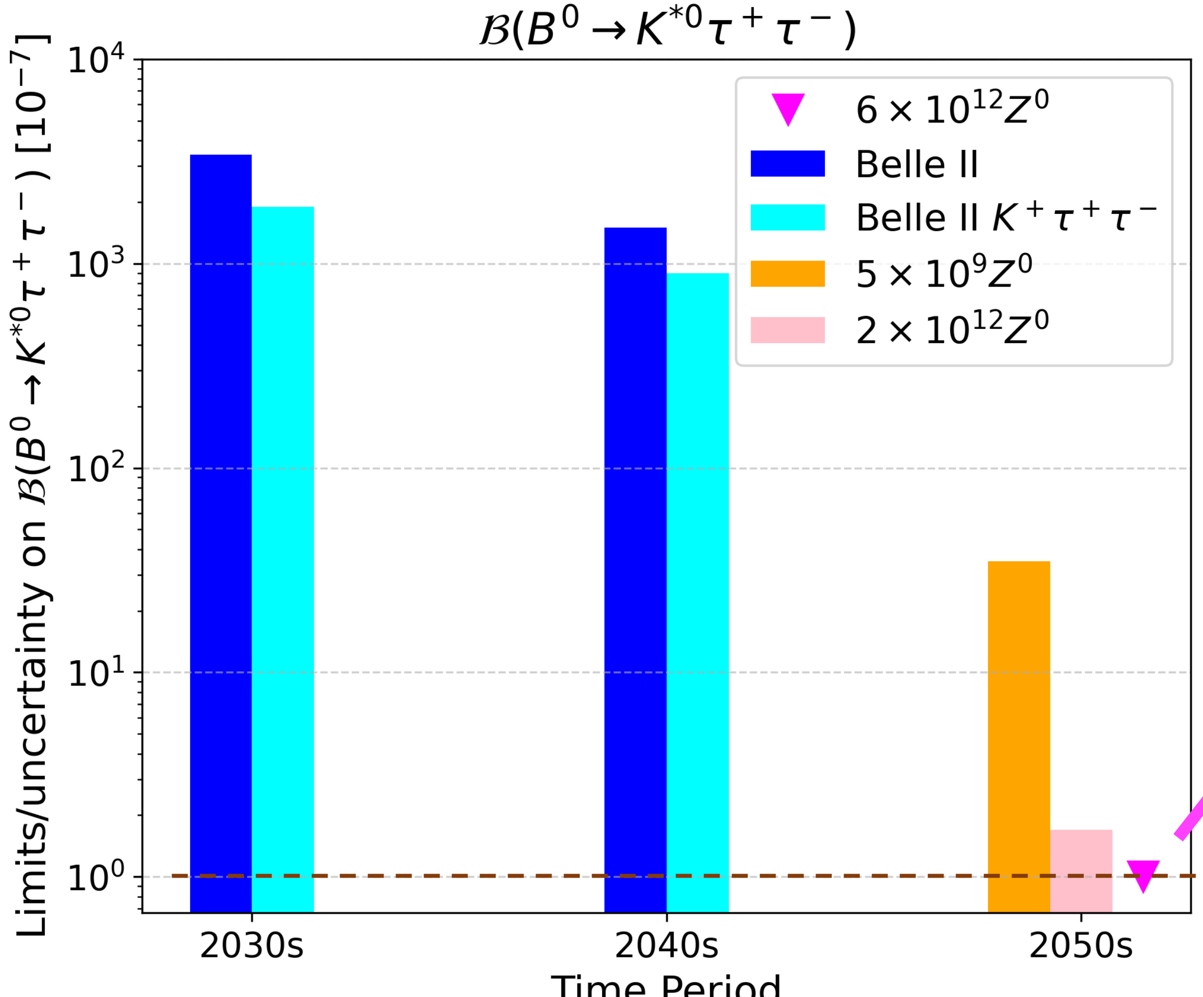


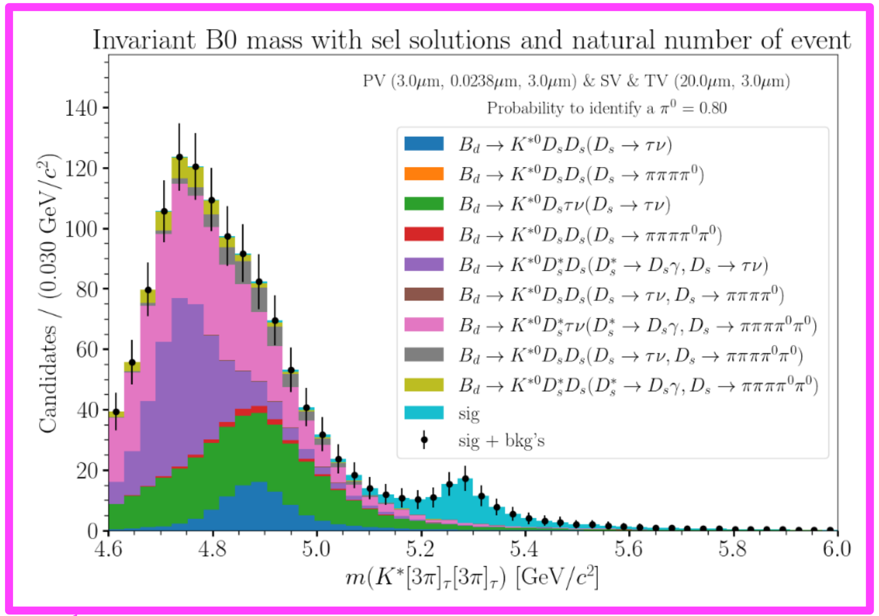


Theory improvements needed by a factor 10

FCNC : b→s $\tau\tau$

$BR(B^+ \to K^+\tau^+\tau^-)$ $BR(B^0 \to K^{*0}\tau^+\tau^-)$





SM prediction

- 6 TeraZ needed to measure the BR
- Highly demanding on detector performances (vertices separation)

Take home messages

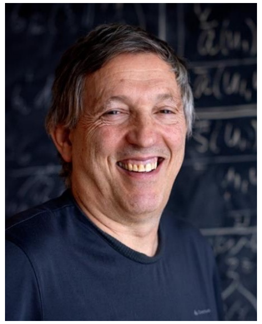
- Flavour physics is a very diversified field with
  - unique & wide-range sensitivity to physics beyond the SM
  - a rich program of small/middle/large size experiments

- For B/D/τ physics:
  - major improvements with the full exploitation of the available facilities up to 2040s: importance of LHCb-UII and Belle-II (nice complementarity between LHCb,ATLAS/CMS and Belle-II)
  - For 2050s perspective what matters is the number of Z^0 and having detector(s) Heavy Flavour compliant
    - 5 10^9 Z^0 is not enough to be competitive
    - FCCee with 6 10^{12} Z^0 (or more!) would have a major impact

- Support needed for theory : precision on SM predictions should also be improved to match the expected experimental precisions

The Flavour Physics Working Group


Marta Calvi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Many thanks to

- Gudrun Hiller, Zoltan Ligeti, Olcyr Sumensari & Jordy De Vries for their inspiring talks of the Open meeting of the Flavour community in view of the ESPPU and all those who attended it !
- Lukas Allwicher & Martino Borsato for helps on numerical analysis

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Practically

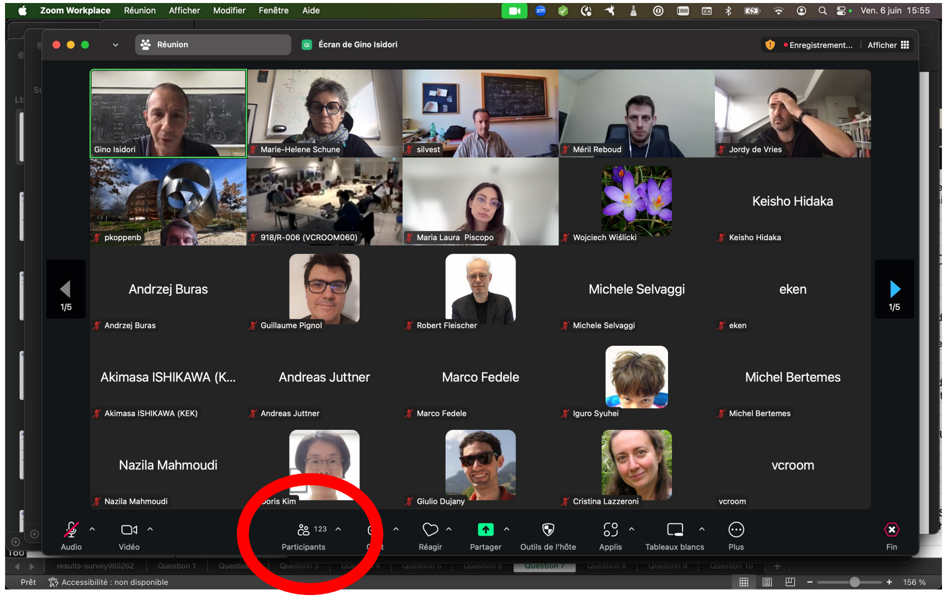
Meetings :

- 3 large working group meetings with physics discussion
- 6 organisational / informal meetings

- one open meeting community meeting :

Friday 6 June

15:30–15:50	**Introduction** Contribution | Speakers: Gino Isidori, Marie-Helene Schune
15:50–15:55	**Questions** Break
15:55–16:15	**EDMs and other low-energy probes** Contribution | Speaker: Jordy de Vries
16:15–16:20	**Questions** Break
16:20–16:40	**Rare decays and CPV in charm** Contribution | Speaker: Gudrun Hiller
16:40–16:45	**Questions** Break
16:45–16:55	**Short break** Break
16:55–17:15	**LFV, LFU and combined fits** Contribution | Speaker: Olcyr Sumensari
17:15–17:20	**Questions** Break
17:20–17:40	**Rare decays and CKM** Contribution | Speaker: Zoltan Ligeti
17:40–17:45	**Questions** Break
17:45–18:15	**Discussion** Contribution



123 participants

Briefing book writing 2-days in person + Zoom writing : 9-10[th] of July

All details in parallel session talks !

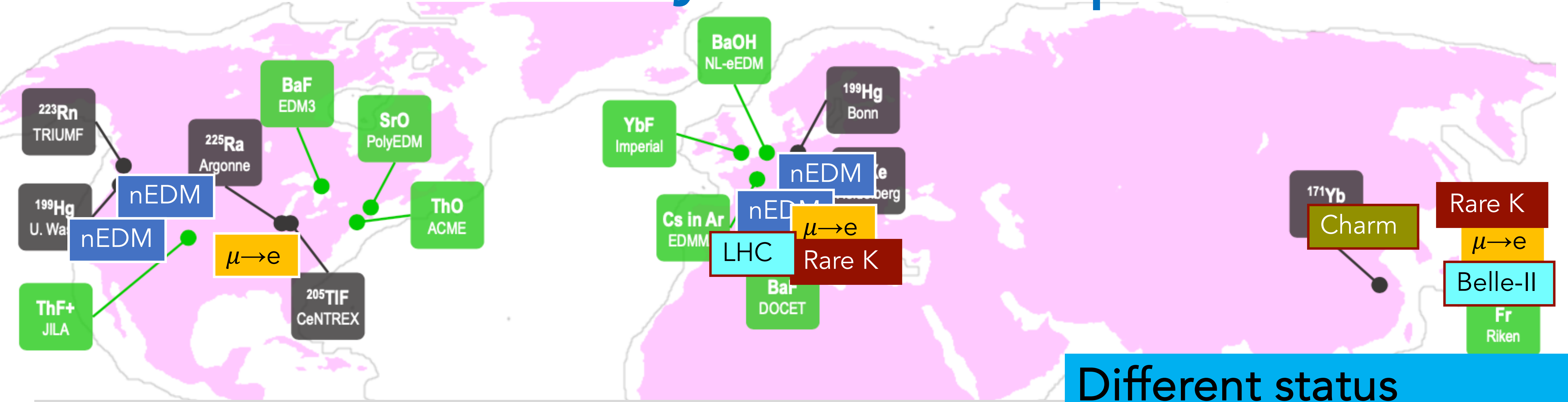
	Rare decays of b and c quarks	*Marta Calvi (INFN-Milano Bicocca)*	*Palazzo del Casinò, Sala Amici*	12:05 - 12:35
	Tau physics	*Justine Serrano (IN2P3)*	*Palazzo del Casinò, Sala Amici*	12:35 - 13:00
13:00				
14:00	**CPV & CKM elements from heavy quark decays**	*Thibaud Humair (DESY)*	*Palazzo del Casinò, Sala Amici*	14:00 - 14:30
	Flavour physics with W & Z	*Patrick Koppenburg (Nikhef)*	*Palazzo del Casinò, Sala Amici*	14:30 - 14:50
	SM tests with Kaons & pions	*Radoslav Marchevski (EPFL)*	*Palazzo del Casinò, Sala Amici*	14:50 - 15:05
15:00	**EMDs and LFV in light families**	*Guillaume Pignol (LPSC - IN2P3)*	*Palazzo del Casinò, Sala Amici*	15:05 - 15:30

Large scale facilities (Rare decays of b and c quarks; Tau physics)

Large scale facilities (CPV & CKM elements from heavy quark decays; Flavour physics with W & Z)

Channel(s)- specific experiments (SM tests with Kaons & pions; EMDs and LFV in light families)

A diverse eco-system of experiments



Different sizes

Small size dedicated experiments (charged LFV, EDMs)

Medium size experiments focussing on a type of particle (K/π physics)

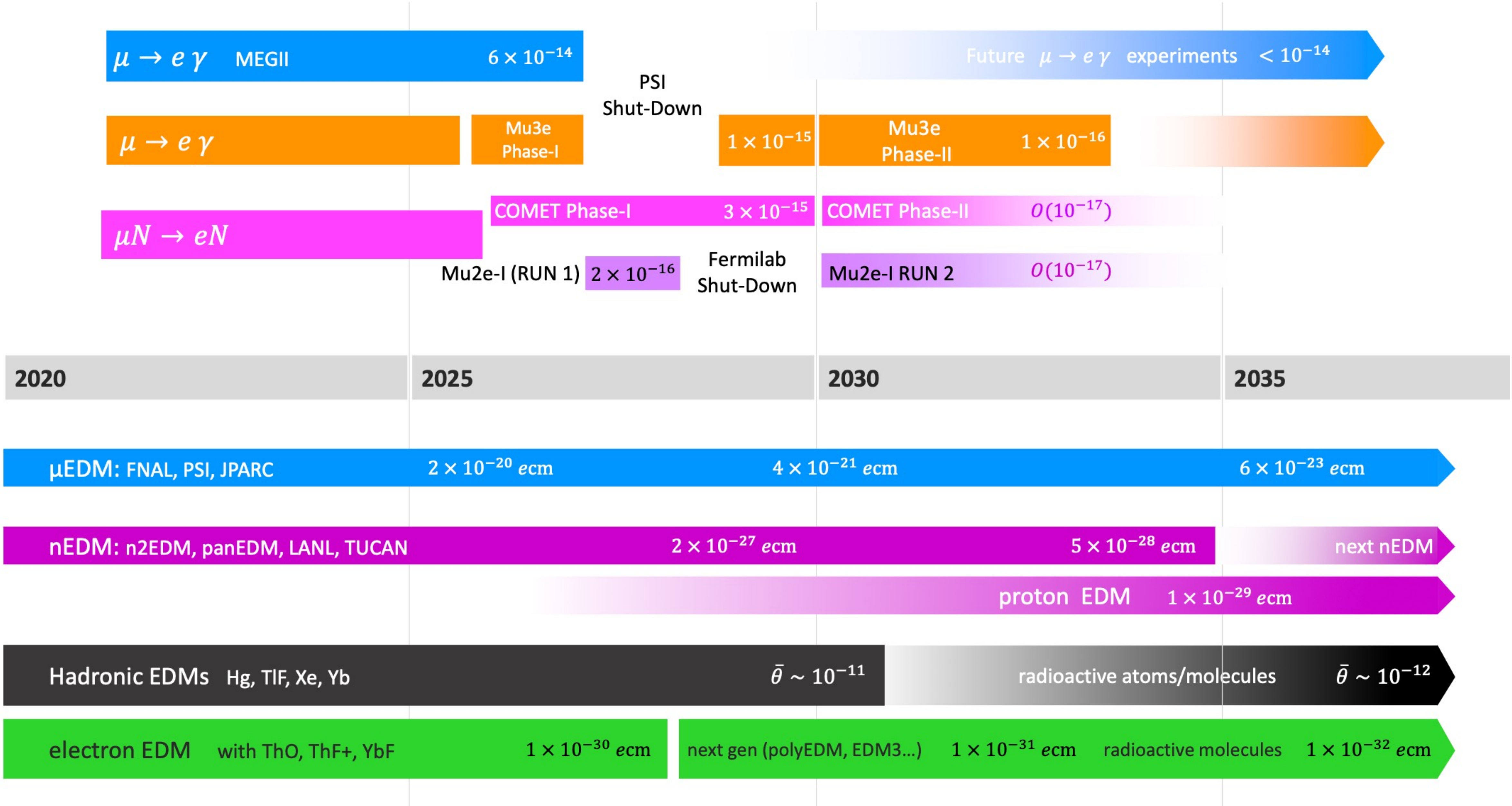
Large experiments 100% focussed (or not!) on Flavour physics

Different status

Running or approved

Proposed (not shown on map)

EDMs & cLFV : a clear roadmap for the next 10 years



EDMs : a clear roadmap for the next 10 years

nEDM
- at the heart of European research : historically, now and future (ILL, PSI, ESS)
- in the next 10 years : sensitivity will improved by x10
- Longer term : larger scale experiments
- Access to intense neutron sources

Charged particles EDM
- eEDM : 'table top ' experiments . A full variety of experimental techniques developing
- pEDM : complement nEDM.
- μEDM : synergies with muon collider in the long term

Also at colliders : τ and baryons EDM

6 TeraZ

~x3 (charged modes)
~x2.2 (neutrals, B decays involving τ and ν)

~x2.5 (charged modes)
~x2.2 (neutrals, B decays involving τ and ν)

~ x10 (B decays involving τ and ν)
~ x 4 (B involving neutrals)
~ x10 (τ decays)
Charged modes: depends…

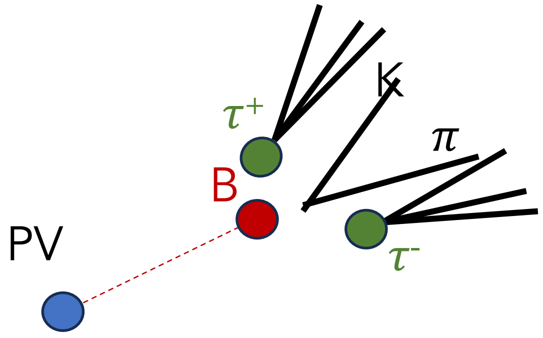
Now → 2030s → 2040s → 2050s

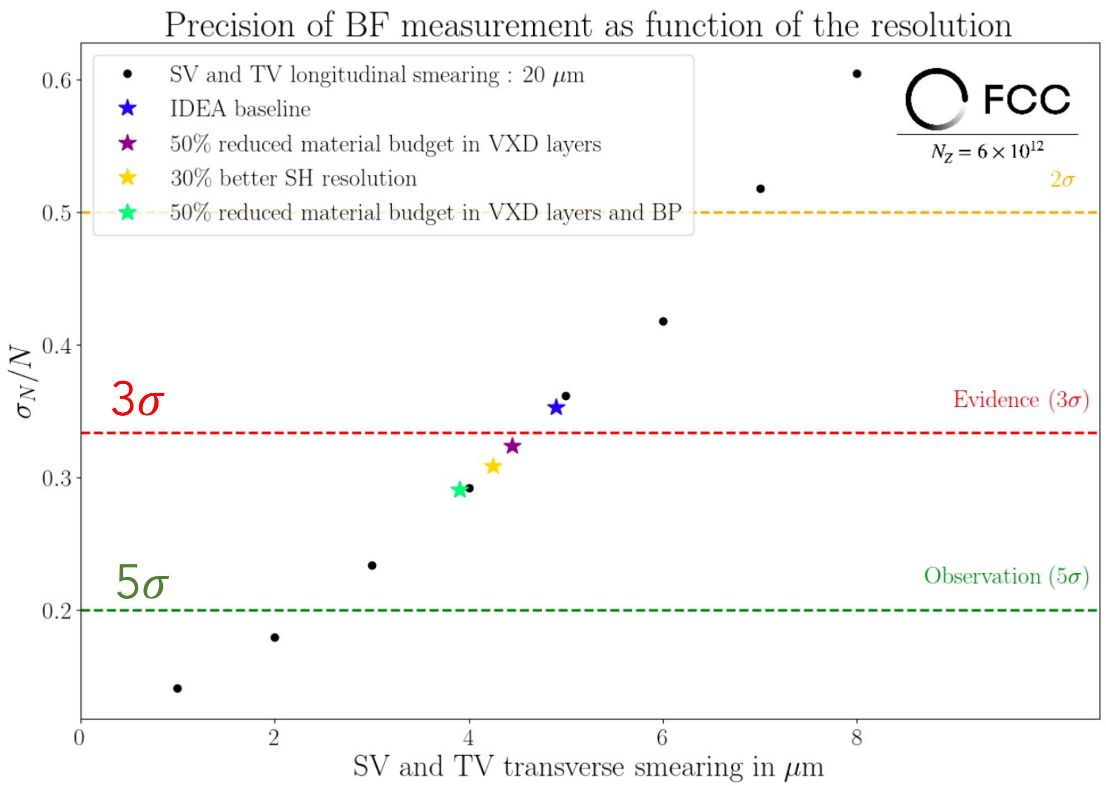
Flavour WG

An excellent detector

Submission ID196

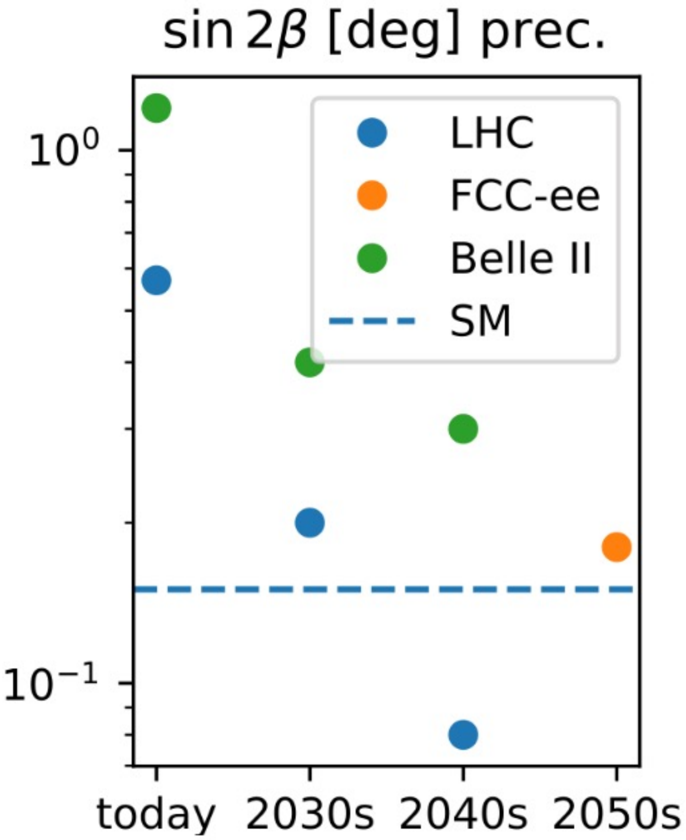
$BR(B^0 \to K^{*0}\tau^+\tau^-)$ sensitivity crucially depend on the separation of the vertices. The lighter detector (and beam pipe) , the better !



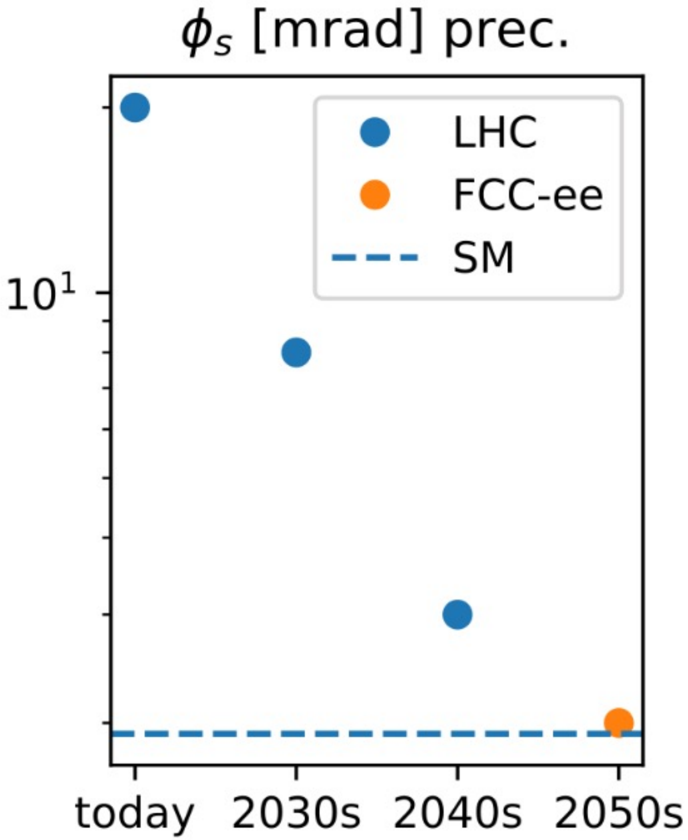


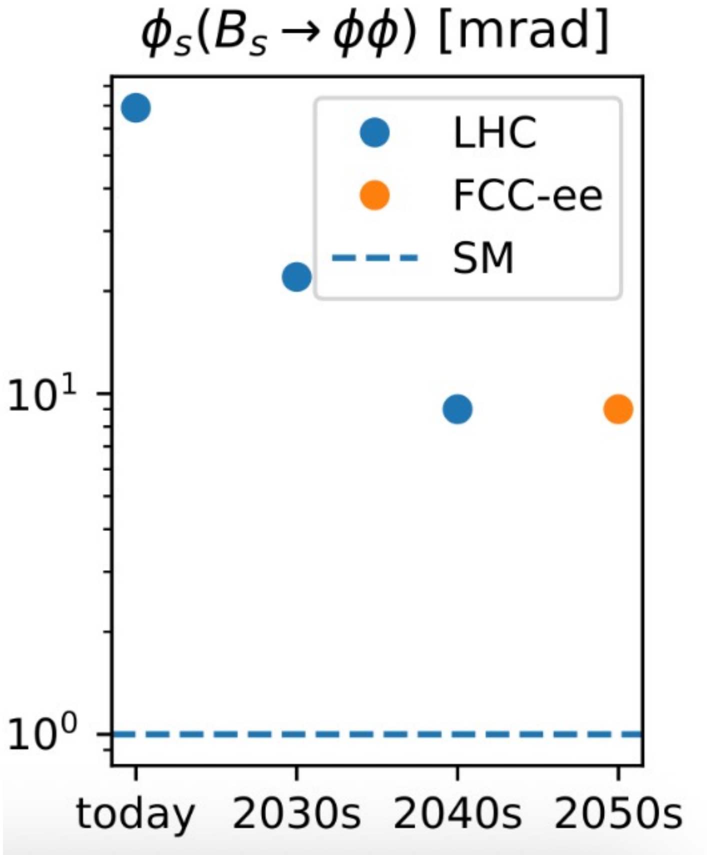
β and ϕ_s

$B_d \rightarrow J/Psi\ Ks$



$B_s \rightarrow J/Psi\ \phi$

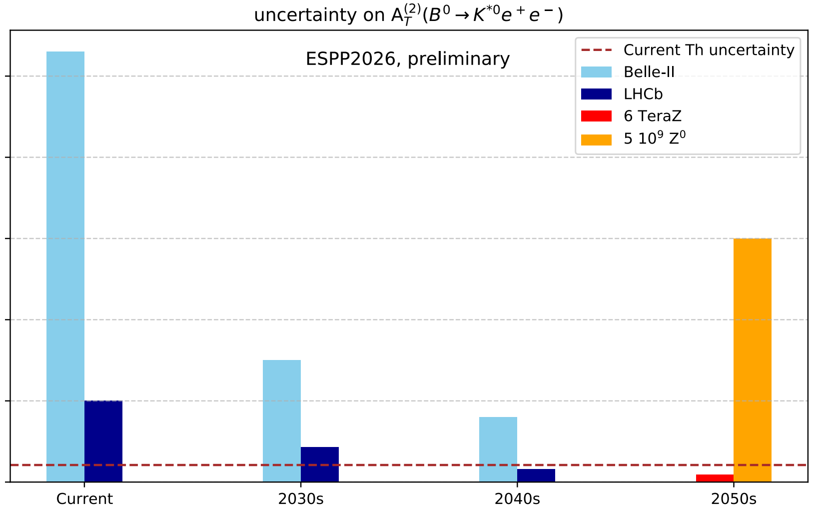




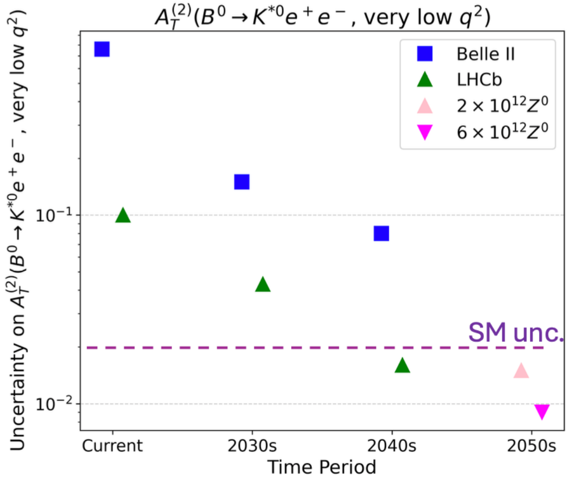
SU(3) limit

Penguins dominated
BSM sensitive

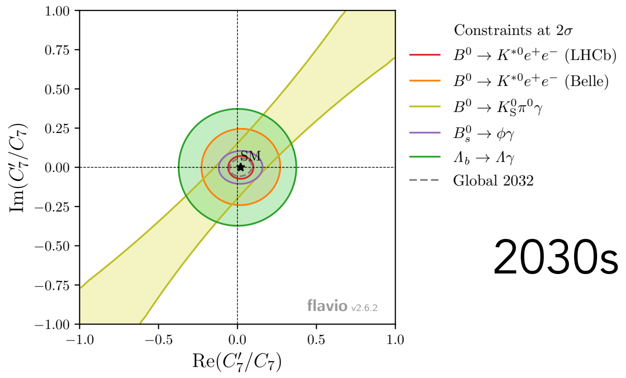
Radiative decays (b→sγ)

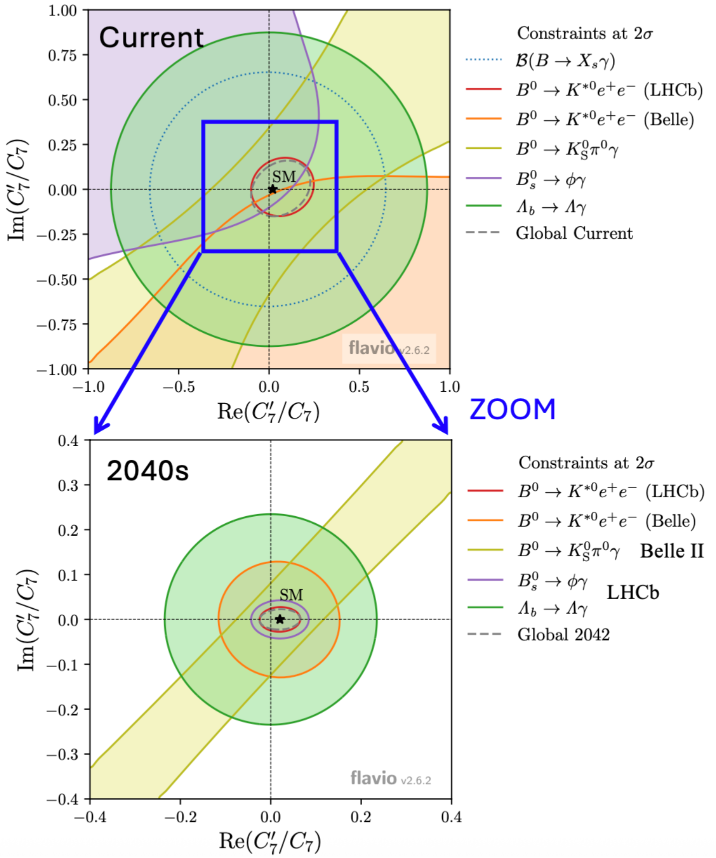


- Precision improvements will come from LHCb and Belle II on complementary observables.



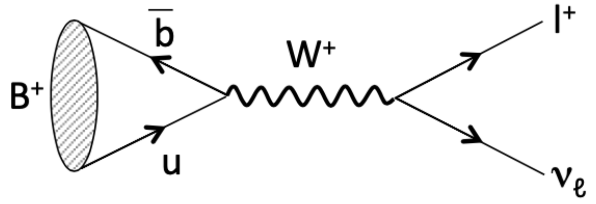
- A further leap will be possible from measurements at future e^+e^- colliders the Z^0 .
- Theoretical uncertainty might become the real limit on some observables.



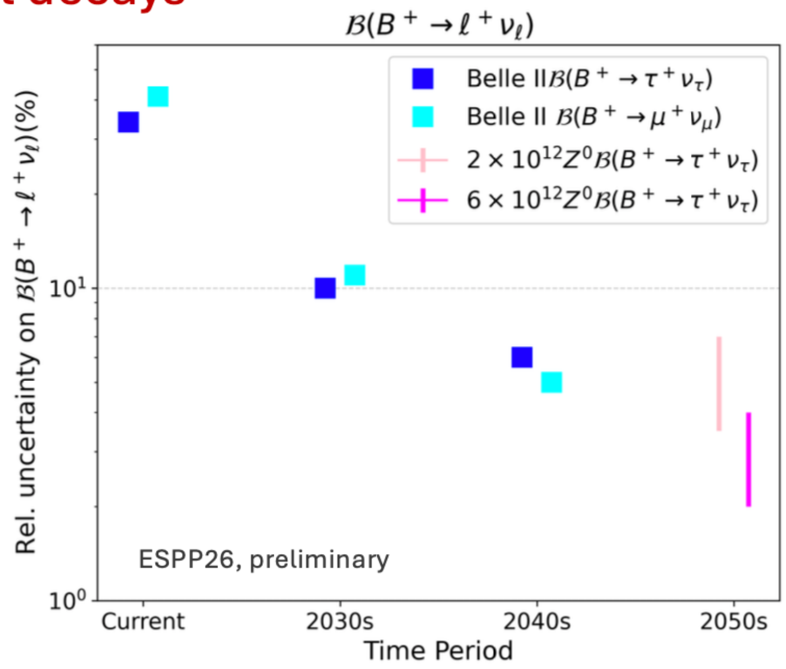


Fully leptonic decays ($B \to \ell\nu$)

- New possibility will be opened for LFU tests also in b→u charged current decays by high statistics samples of leptonic decays to be collected at Belle II.
  - Will complement b→c tests with sensitivity to different coupling.



The ratio $\mathcal{B}(B^+ \to \tau^+\nu)/\mathcal{B}(B^+ \to \mu^+\nu)$ will be determined with a precision below ~10%.



- Future e^+e^- colliders can improve further in tau modes (with hadronic decays), and probably also in muon modes.

- Leptonic decay of charged B_c meson $B_c^+ \to \tau^+\nu_\tau$ can be observed for the first time at e^+e^- colliders .
  - Since $f(b \to B_c)$ is unknown, $\mathcal{B}(B_c^+ \to \tau^+\nu_\tau)$ with ~3% precision can be derived from the ratio to $B_c^+ \to J/\psi\mu^+\nu_\mu$ (that will be known at ~2%, using LQCD).

- $\mathcal{B}(B^+ \to \tau^+\nu_\tau)$ and $\mathcal{B}(B_c^+ \to \tau^+\nu_\tau)$ will play a prominent role in constraining the allowed parameter space in models with Higgs doublets and in specific leptoquark scenarios.