Flavour benchmarks for BSM

ESPPU Symposium, Venice June 2025

European Strategy for Particle Physics

Sophie Renner & Lesya Shchutska

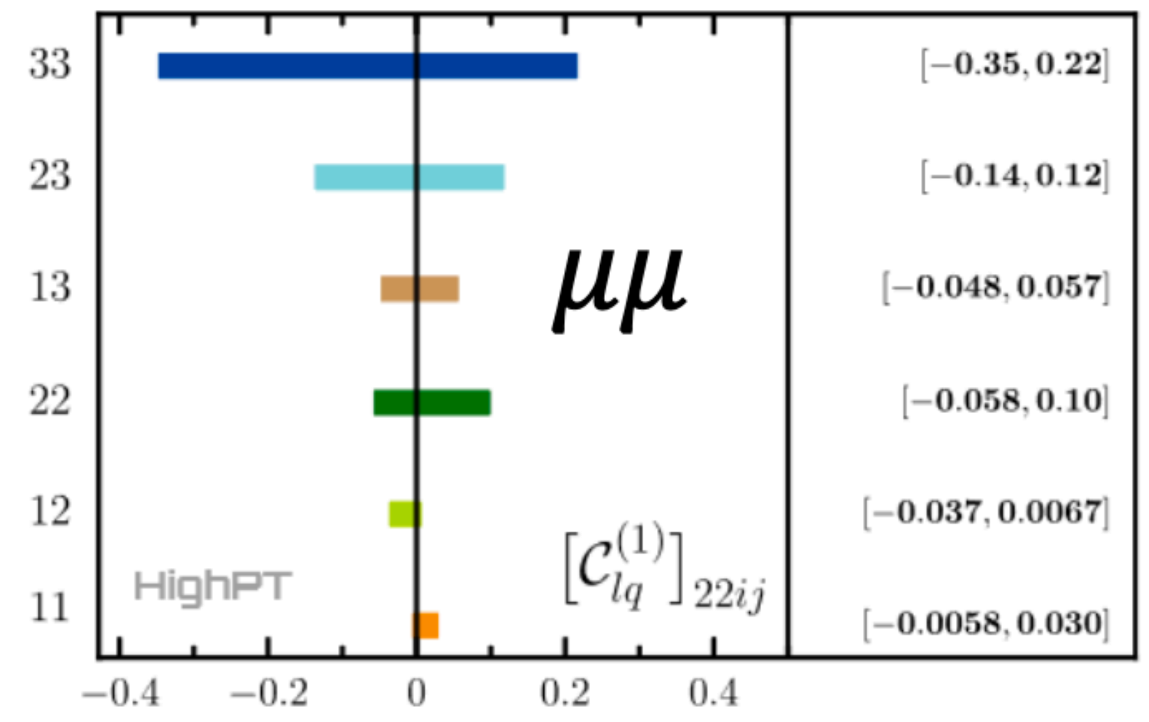
Flavour for BSM

Flavourful models provide a natural target for next generation experiments

Exploring new interactions…

From LHC, strong constraints on flavour-universal new physics

BSM models which couple preferentially to heavier generations are less well-tested



Allwicher et al, 2207.10714

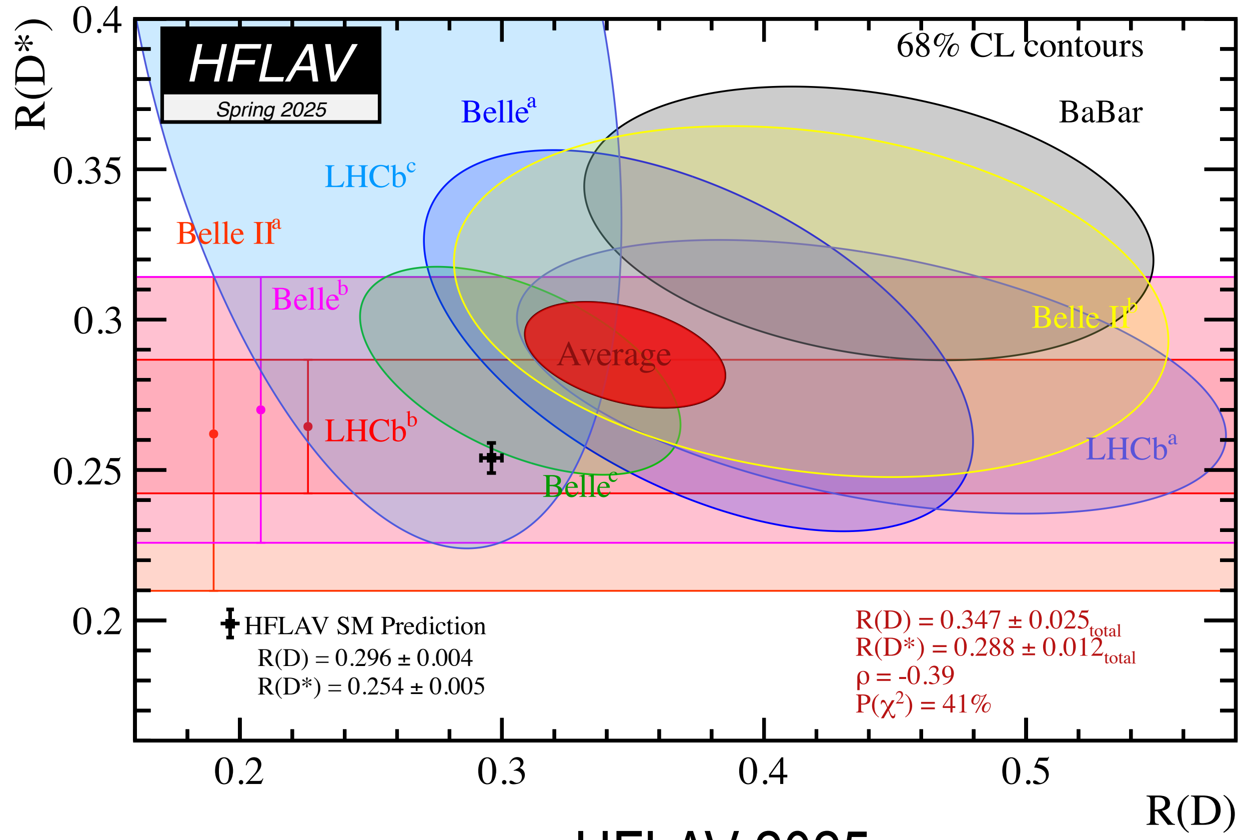
Solving Standard Model puzzles…

Any model that explains origin of SM Yukawas will induce flavour effects (at some scale)

Models for Higgs naturalness often connected to 3rd generation

Investigating experimental anomalies…

e.g. long-standing discrepancy in $R_{D^{(*)}}$ observables



HFLAV 2025

Benchmark models

- **Leptoquarks** **Vector U_1 leptoquark with couplings to left handed 3rd generation quarks and 3rd or 2nd generation leptons**

  Tauonic leptoquark is motivated as a possible origin of the $R_{D^{(*)}}$ anomalies

  Phenomenology: new QCD-charged states with flavour-specific couplings

- **Flavour-deconstructed gauge models** **New gauge bosons arising from a flavoured $G_{12} \times G_{3+\mathrm{Higgs}} \to G$ symmetry breaking**

  Motivated by SM flavour puzzle: final breaking step in larger deconstruction models which generate hierarchical masses and couplings

  Phenomenology: TeV-mass gauge bosons with flavour non-universal couplings

- **Top flavour changing neutral currents (FCNCs)**

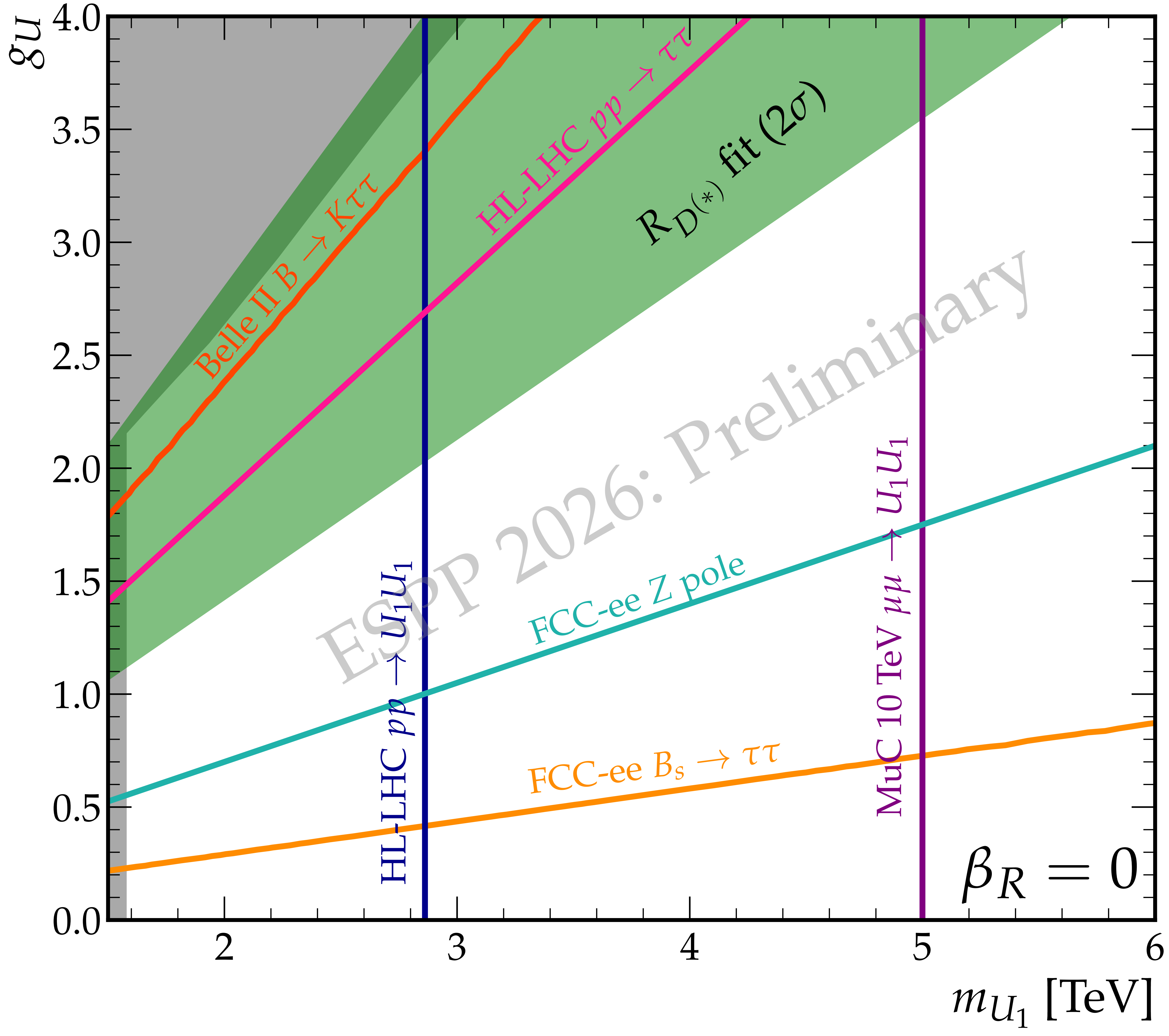
  New opportunities for precision top flavour at future experiments

  Projections for $t \to c$ and $t \to u$ transitions in terms of coefficients of effective operators

Tauonic leptoquark

e.g. Aebischer et al 2210.12422

Vector U_1 leptoquark with couplings to left handed 3rd generation quarks and leptons



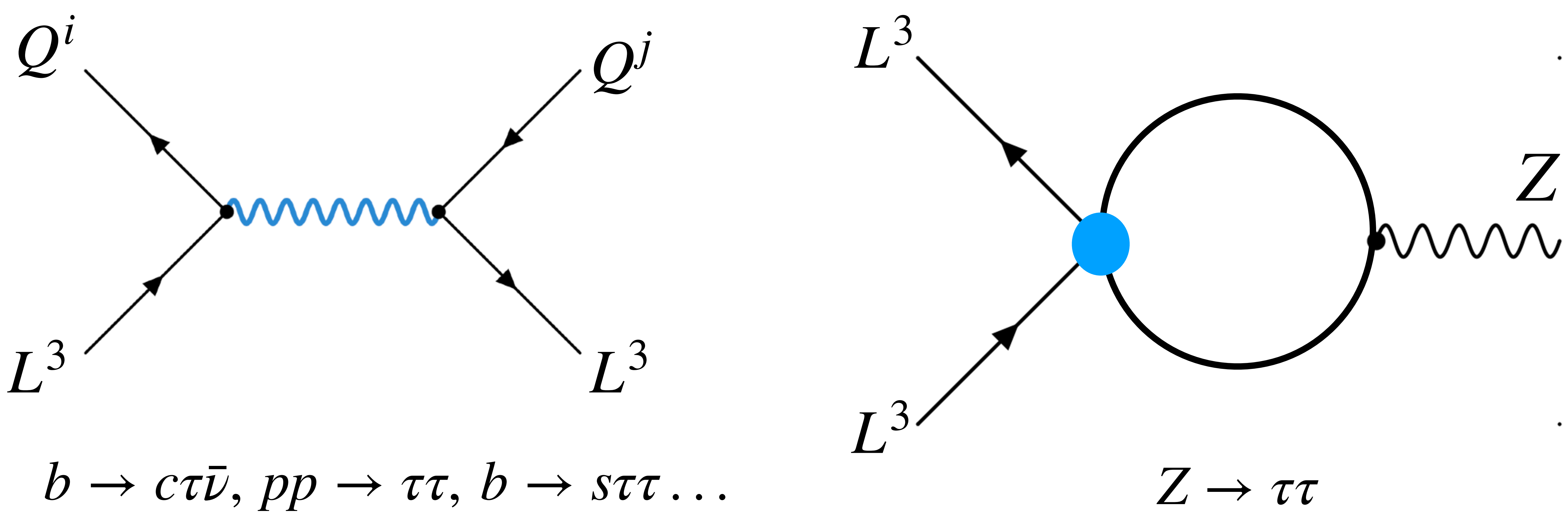
All sensitivities are at 95%

$$\mathcal{L}_{U_1} \supset \frac{g_U}{\sqrt{2}} \beta_{i\tau} \bar{Q}^i_L \gamma_\alpha L^3_L U_1^\alpha + h.c.$$

with $\beta_{b\tau} = 1,\ \beta_{s\tau} = 0.1$

Comments:

- Strong indirect projections from FCC-ee Z pole and flavour programs
- Complementary direct sensitivity from hadron and muon colliders (direct FCC-hh bound is at ~12 TeV)



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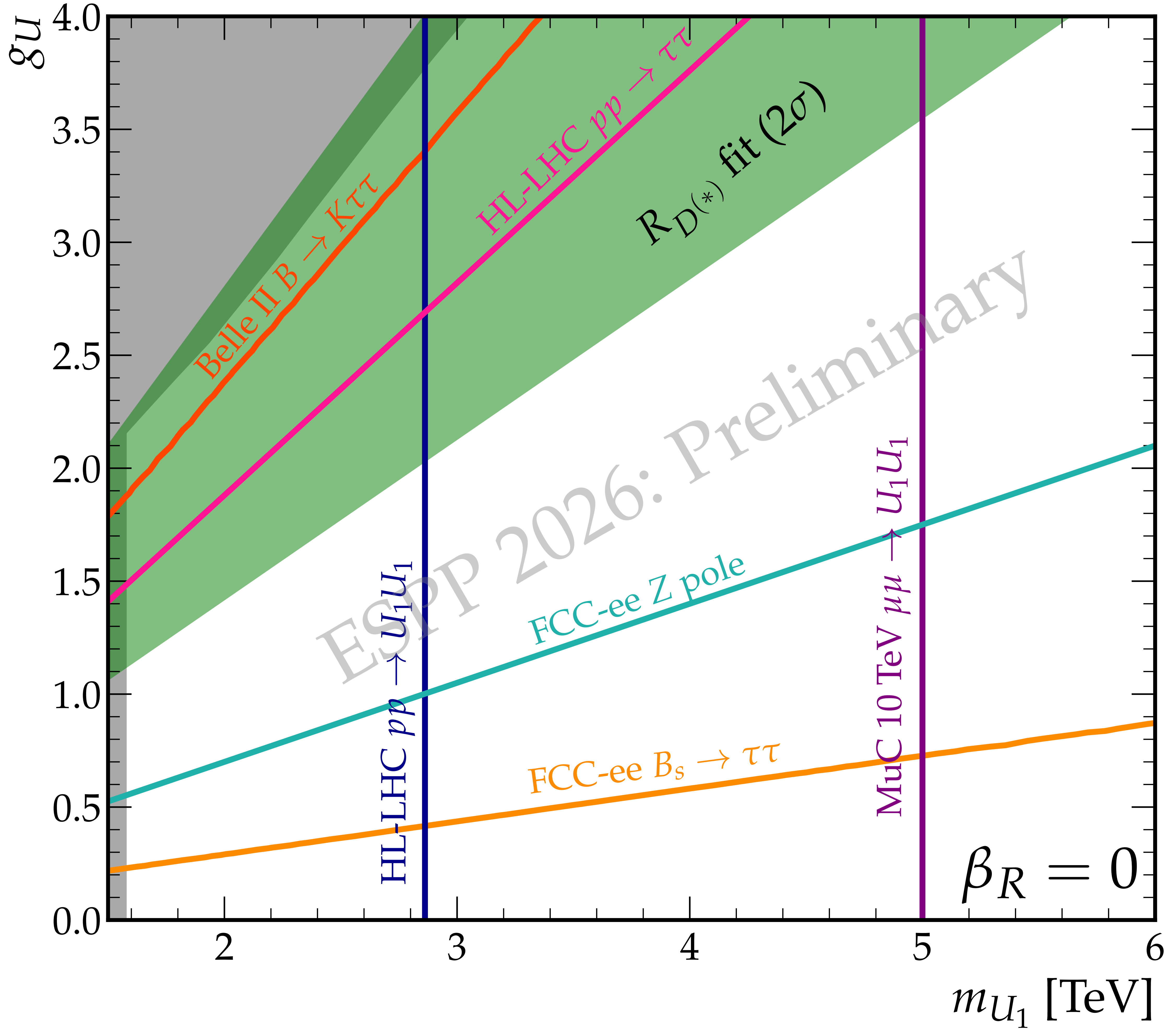

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Inputs and references:

Belle II $B \to K\tau\tau$: "Projections for key measurements in heavy flavour physics" ATLAS, Belle II, CMS, LHCb

HL-LHC $pp \to \tau\tau$: Naive extrapolation to 14 TeV 6ab-1 from current ATLAS, CMS results (shown in grey). Work is underway on an official projection

HL-LHC $pp \to U_1 U_1$: Naive extrapolation to 14 TeV 6ab-1 using Collider Reach tool from current best limit (ATLAS)

FCC-ee Z pole: from "New Physics Through Flavor Tagging at FCC-ee", Greljo, Tiblom, Valenti

$R_{D^{(*)}}$ fit: from "New Physics Through Flavor Tagging at FCC-ee", Greljo, Tiblom, Valenti (using HFLAV combination)

FCC-ee $B_s \to \tau\tau$: from "Flavored Circular Collider: cornering New Physics at FCC-ee via flavor-changing processes", Allwicher, Isidori, Pesut

Muonic leptoquark

Vector U_1 leptoquark with couplings to left handed 3rd generation quarks and 2nd generation leptons

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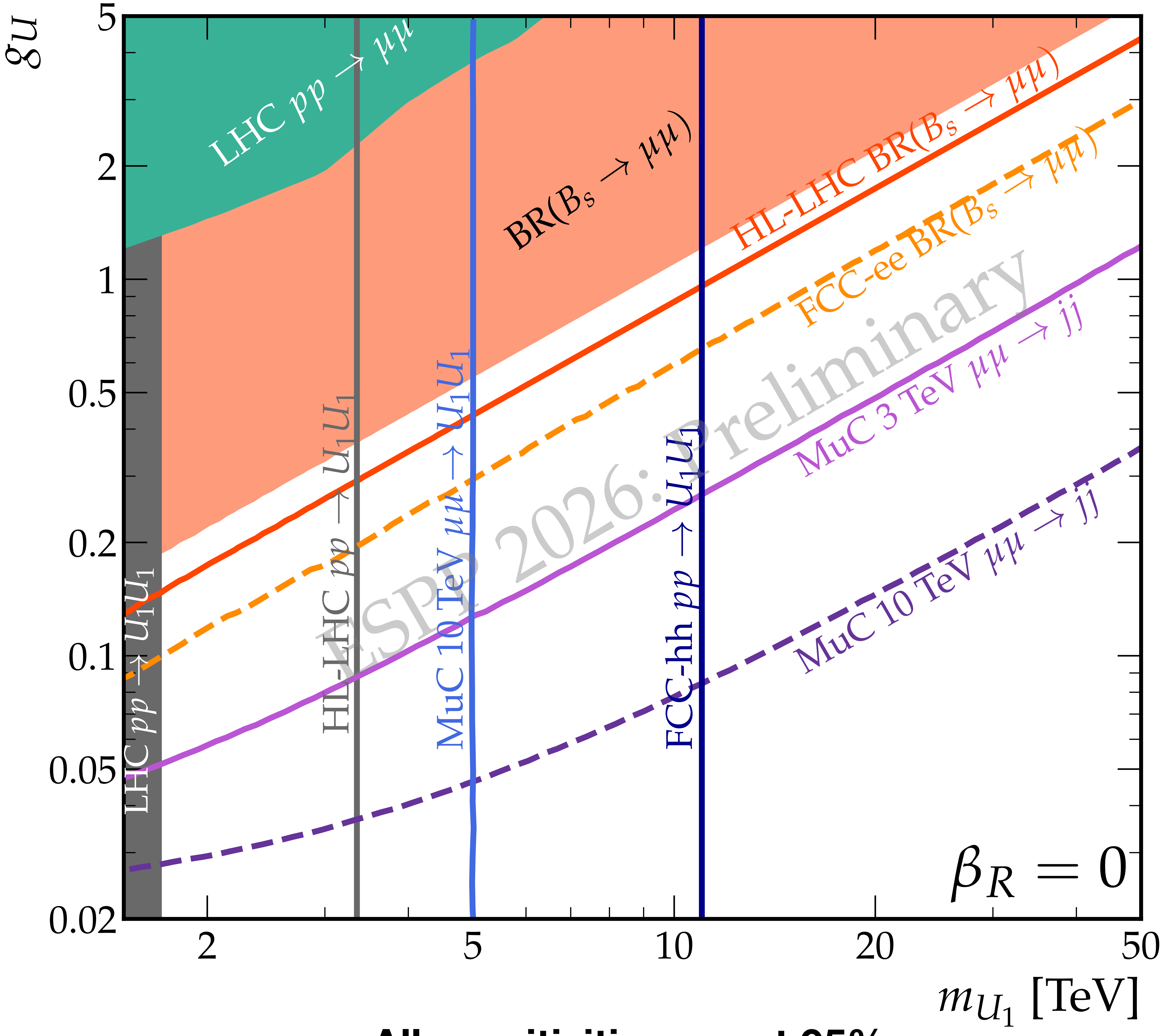

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<u>Comments:</u>

- Not such a large increase in precision at FCC-ee for $B_s \to \mu\mu$ as compared to $B_s \to \tau\tau$ (c.f. previous slide)
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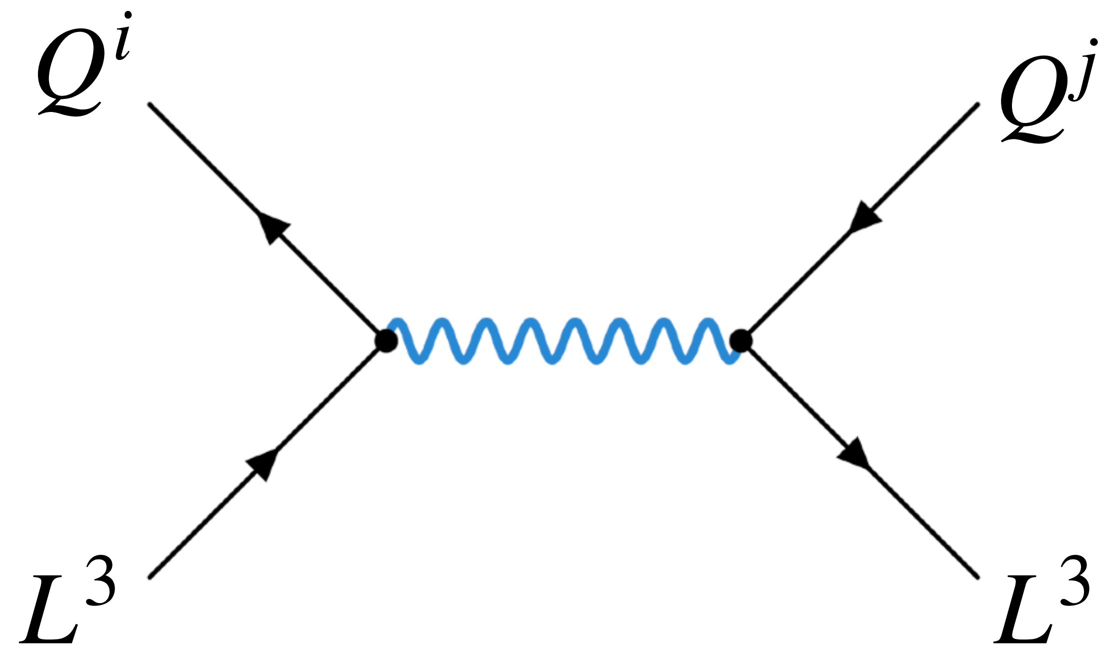
- STILL TO BE DONE: FCC-hh extrapolation of $pp \to \mu\mu$



$b \to s\mu\bar{\mu},\ pp \to \mu\mu,\ \mu\mu \to jj \ldots$

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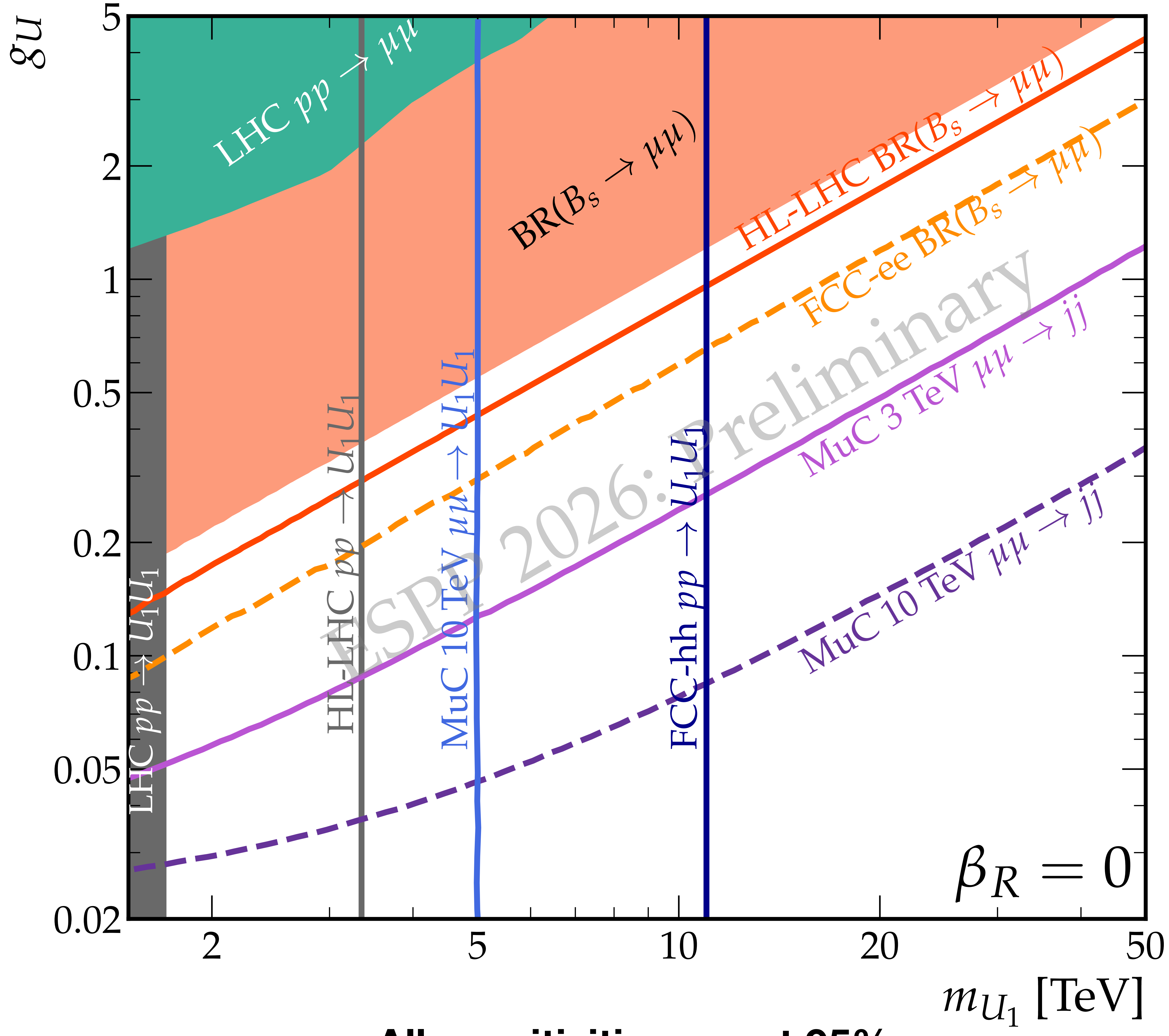

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Inputs and references:

LHC $pp \to \mu\mu$: from the reinterpretation in "New physics in $b \to s\mu\mu$: FCC-hh or a muon collider?" Azatov et al

HL-LHC $B_s \to \mu\mu$: "Projections for key measurements in heavy flavour physics" ATLAS, Belle II, CMS, LHCb

FCC-ee $B_s \to \mu\mu$: "Prospects in flavour physics at the FCC", FCC PED, and "Precision Tests in $b \to sll\,(l = e, \mu)$ at FCC-ee" Bordone, Cornella, Davighi

HL-LHC $pp \to U_1U_1$: Naive extrapolation to 14 TeV 6ab-1 using Collider Reach tool from current best limit (ATLAS)

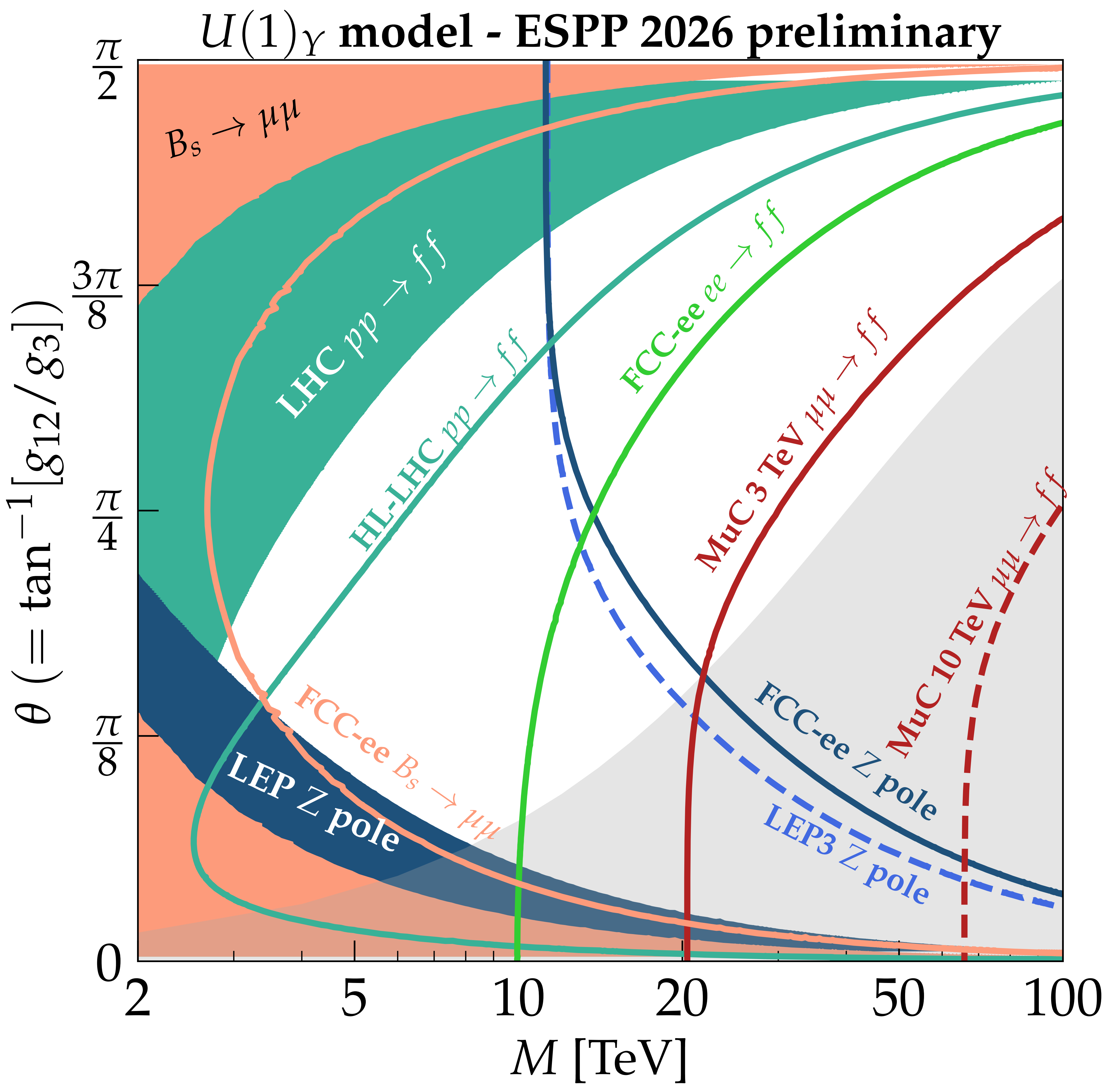
FCC-hh $pp \to U_1U_1$: Naive extrapolation to 85 TeV 30ab-1 using Collider Reach tool from current best limit (ATLAS)

MuC 3 & 10 TeV $\mu\mu \to jj$: likelihood from David Marzocca & IMCC, based on "New physics in $b \to s\mu\mu$: FCC-hh or a muon collider?" Azatov et al, and "Learning from radiation at a very high energy lepton collider" Chen et al

Deconstructed hypercharge model

Fernandez Navarro, King 2305.07690
Davighi, Stefanek 2305.16280

Heavy Z' with flavour-dependent couplings



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$$\mathscr{L} \supset g_{Z'}^{ij} Z'_\mu Y_\psi \bar{\psi}_i \gamma^\mu \psi_j + g_{Z'}^H Y_H Z'_\mu H^\dagger i \overleftrightarrow{D}^\mu H$$

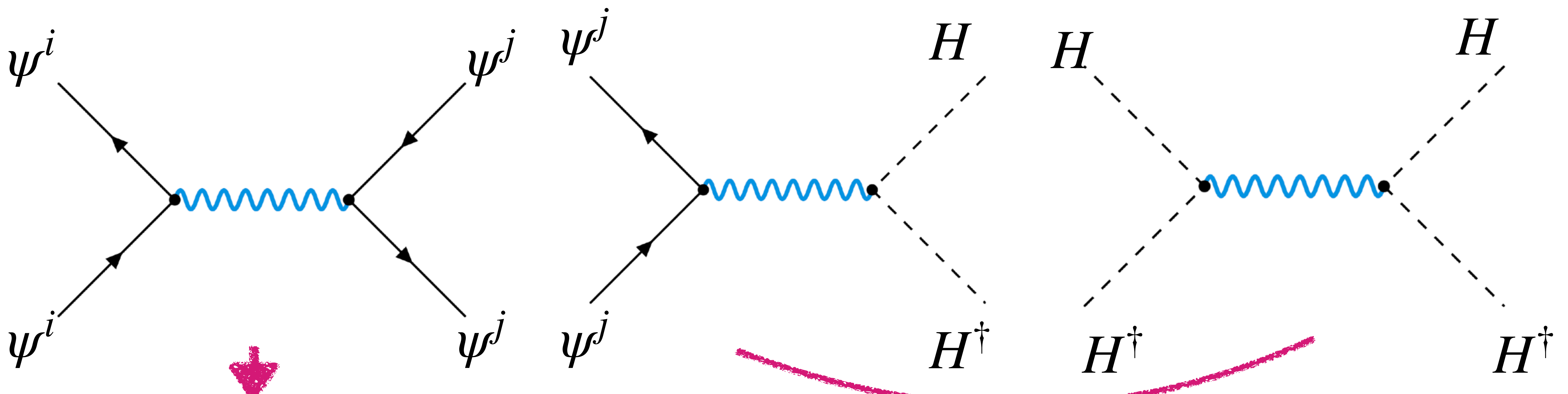
$$g_{Z'}^{ij} = g_Y \,\mathrm{diag}(-\tan\theta, -\tan\theta, \cot\theta) \qquad g_{Z'}^H = g_Y \cot\theta$$

Comments:

- Flavour phenomenology depends on misalignment between gauge and flavour basis: here we assume up-alignment
- Large indirect effects in EWPOs and Drell Yan processes

NB Z pole sensitivities depend strongly on theory error assumptions! This is taking the "aggressive SM" errors from EW PPG, with bkg and MC errors in quadrature

- Light grey shaded region is where $\delta m_h^2 > 1$ TeV (i.e. naturalness-disfavoured)
- STILL TO BE DONE: $ee \to ff$ at LC



$b \to s\mu\mu,\ pp \to ff, \ldots$

Z pole observables

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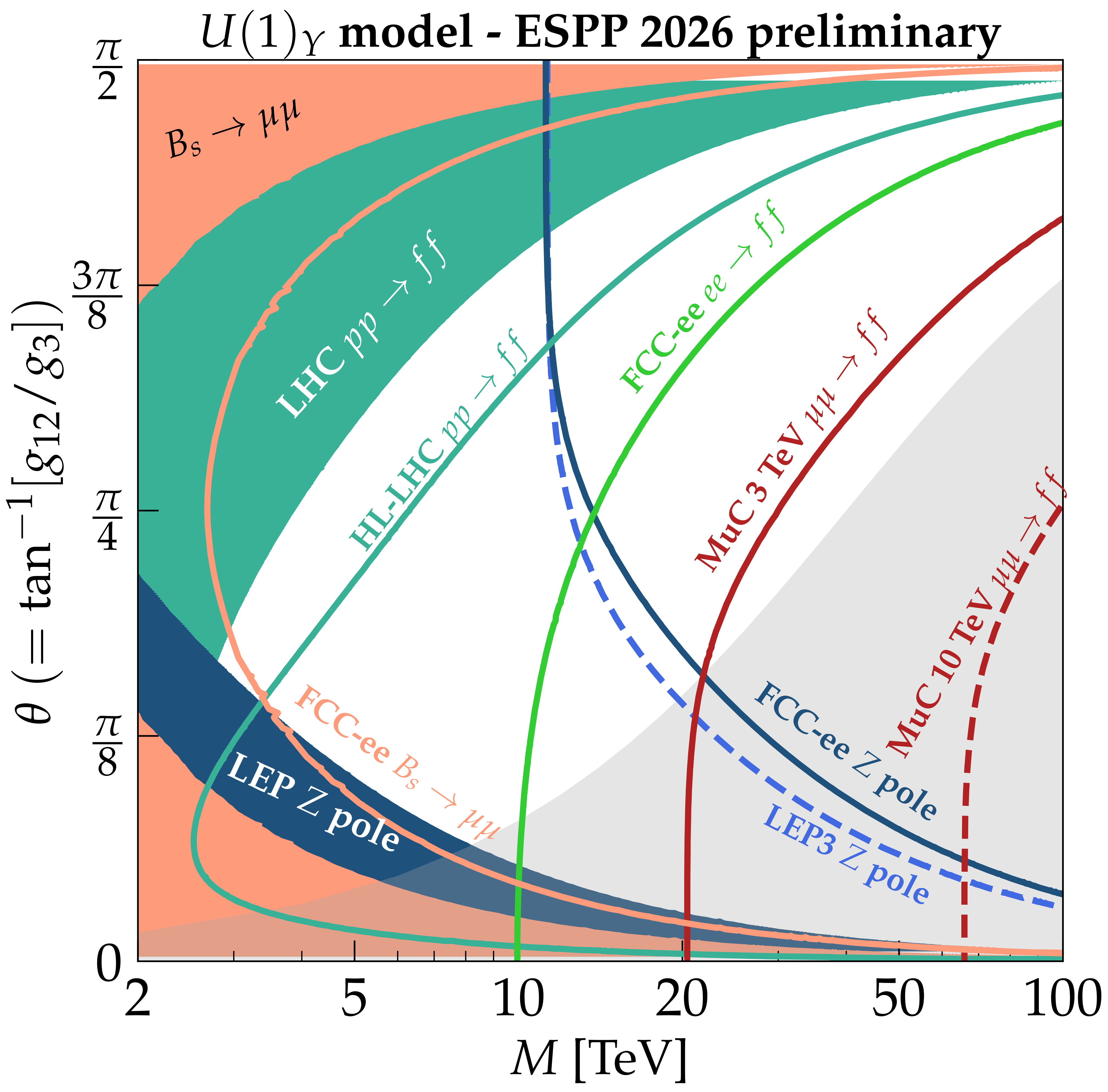

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FCC-ee Z pole "Prospects in electroweak, Higgs and top physics at the FCC", FCC PED & theory errors from EW PPG

LEP3 Z pole "LEP3: A high luminosity electron-positron Higgs boson factory in the LHC tunnel", Anastopoulos et al, & theory errors from EW PPG

HL-LHC $pp \to ff$: from Ben Stefanek, calculated using HighPT package

FCC-ee $e^+e^- \to ff$: likelihood from Ben Stefanek, based on "New Physics Through Flavor Tagging at FCC-ee", Greljo, Tiblom, Valenti

MuC 3 & 10 TeV $\mu\mu \to ff$: likelihood from David Marzocca & IMCC, based on "Learning from radiation at a very high energy lepton collider" Chen et al

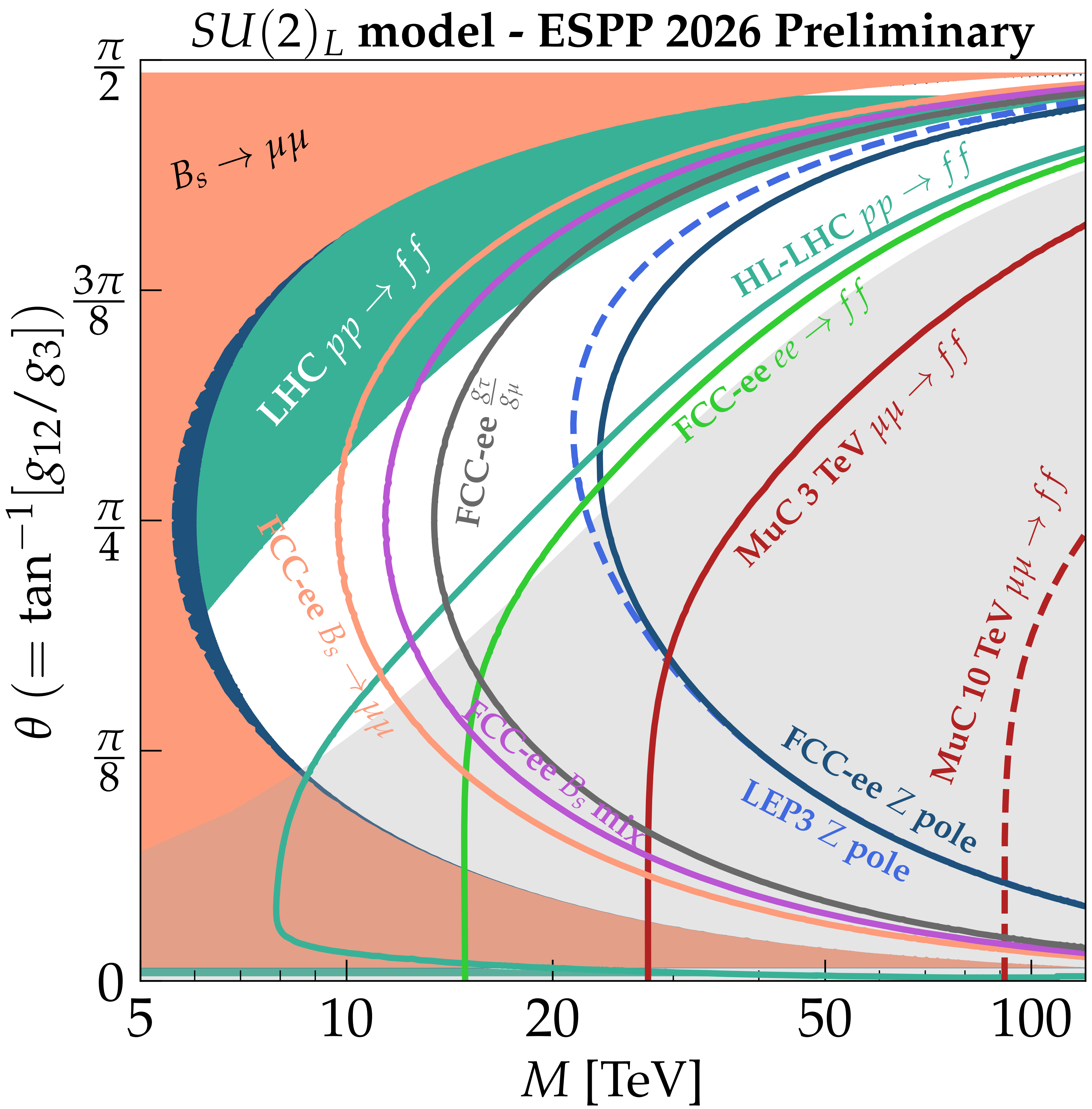
Deconstructed $SU(2)_L$ model

Li, Ma, 1981
Davighi et al 2312.13346
Capdevila et al 2401.00848

Heavy W' with flavour-dependent couplings

$$\mathscr{L} \supset g^{ij}_{W'} W'^I_\mu \bar\psi_{Li}\gamma^\mu\sigma^I\psi_{Lj} + g^H_{W'} Y_H Z'_\mu H^\dagger i\overleftrightarrow{D}^\mu \sigma^I H$$

$$g^{ij}_{W'} = g_L \,\mathrm{diag}(-\tan\theta, -\tan\theta, \cot\theta) \qquad g^H_{W'} = g_L \cot\theta$$



All sensitivities are at 95%

Comments:

All comments from previous slide also apply here

Overall sensitivity greater than hypercharge model since couplings set by g_L rather than g_Y

Combination of indirect searches at FCC-ee have capacity to probe nearly all of natural region at 95%

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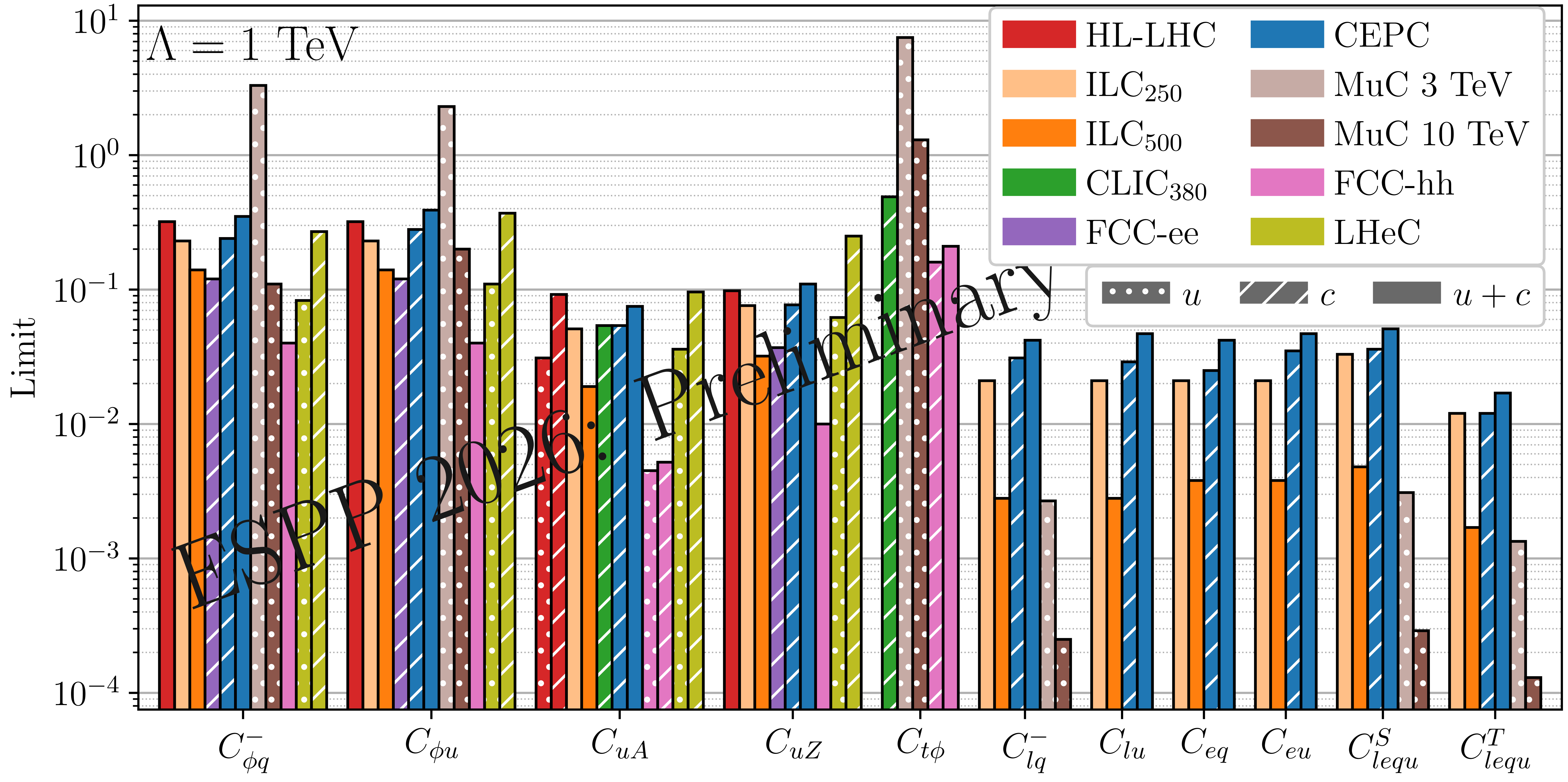
FCC-ee tau LFUV: "Tau physics prospects at FCC-ee"

Top quark flavour changing neutral currents

Sensitivity to $t \to c$ and $t \to u$ transitions in terms of coefficients of SMEFT operators (in LHC TOP WG conventions)



Projected sensitivities all at 95%

Comments

For simplicity, have not separated different lepton flavours $(l, e = e, \mu)$

STILL TO BE DONE: add motivated targets for BSM scenarios, update FCC-hh if possible (this is for 10ab-1 at 100 TeV)

Inputs and references

HL-LHC: "Opportunities in flavour physics at the HL-LHC and HE-LHC"

CLIC: "Top-Quark Physics at the CLIC Electron-Positron Linear Collider"

ILC: "The International Linear Collider: Report to Snowmass 2021"

CEPC: "Flavor Physics at CEPC: a General Perspective" and "Probing the top quark flavor-changing couplings at CEPC", Shi, Zhang

Muon collider: "Top quark flavor changing couplings at a muon collider", Ake et al

FCC-ee: "Top quark FCNC anomalous couplings at the future collider FCC-ee", Khanpour et al

FCC-hh: "FCC CDR 2018"

LHeC: "Fingerprinting the Top quark FCNC via anomalous Ztq couplings at the LHeC", Behera et al & "Probing the Anomalous FCNC tqγ Couplings at Large Hadron electron Collider" Turk Kahir et al

Takeaways and next steps

- Strong complementarity between flavour tests and direct & indirect sensitivity at lepton and hadron colliders for flavour-motivated models
- BSM coupling predominantly to 3rd generation: sensitivity from Z pole and flavour tests involving taus
- BSM also coupling to light generations: strong indirect sensitivity from Drell-Yan processes at hadron and lepton colliders
- Next steps: additional Drell-Yan sensitivities for FCC-hh and linear collider, interpretations of top FCNCs in specific models, …

Thank you!