Flavour Physics
@
future lepton colliders

Michele Tammaro

@LNF, 23/01/2025

Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE

Some Flavour Physics @ future lepton colliders

circular e^+e^- (And maybe muons)

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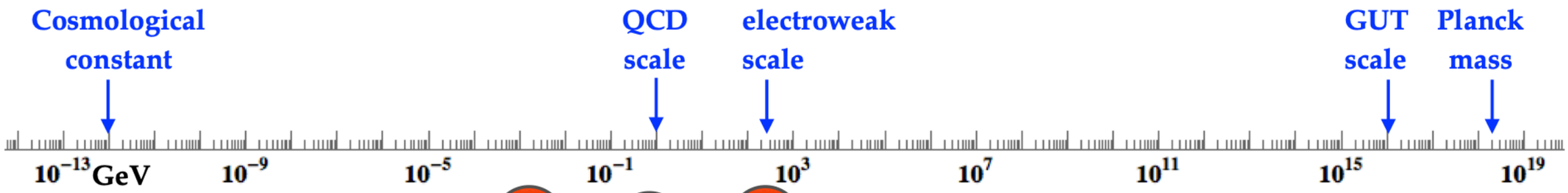
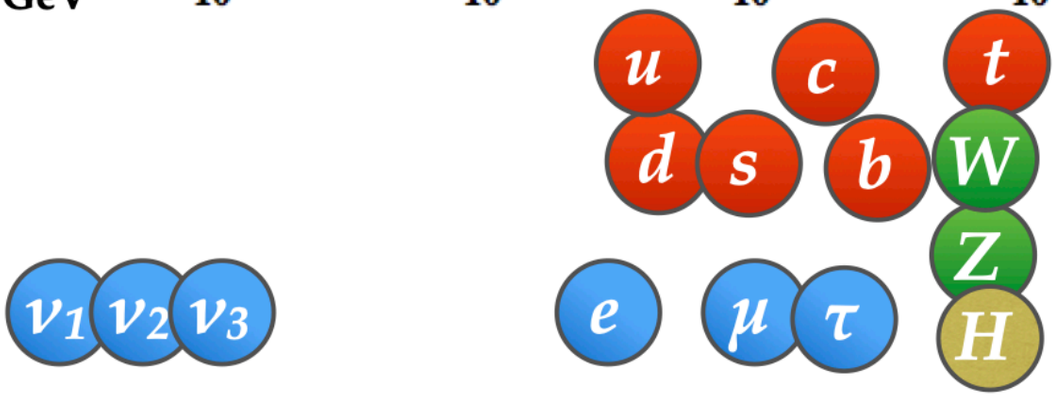
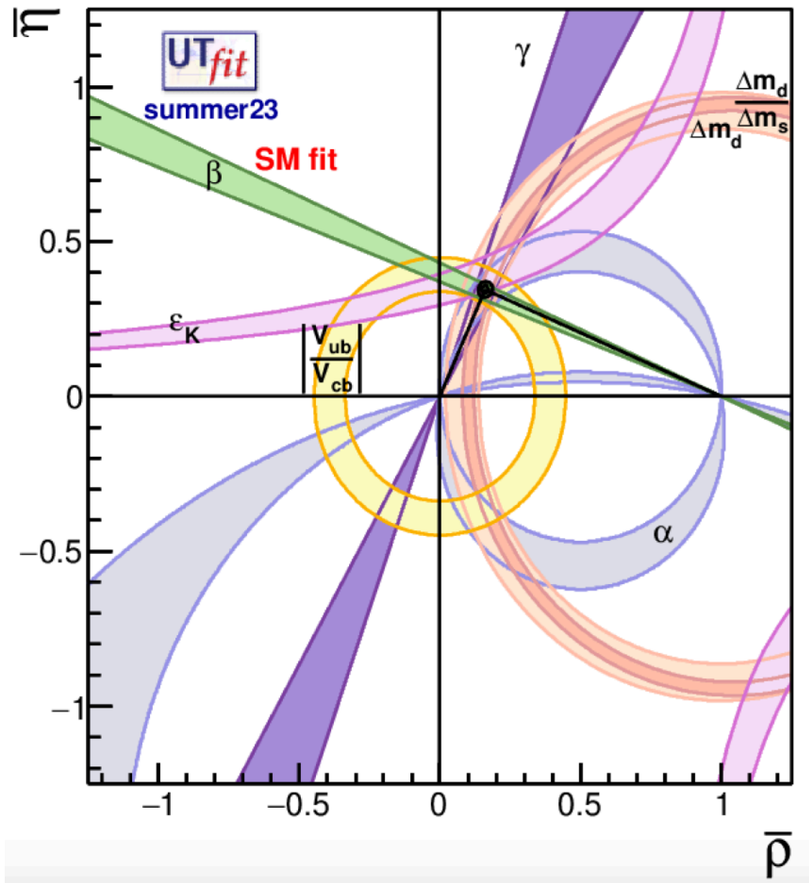
The flavor puzzle



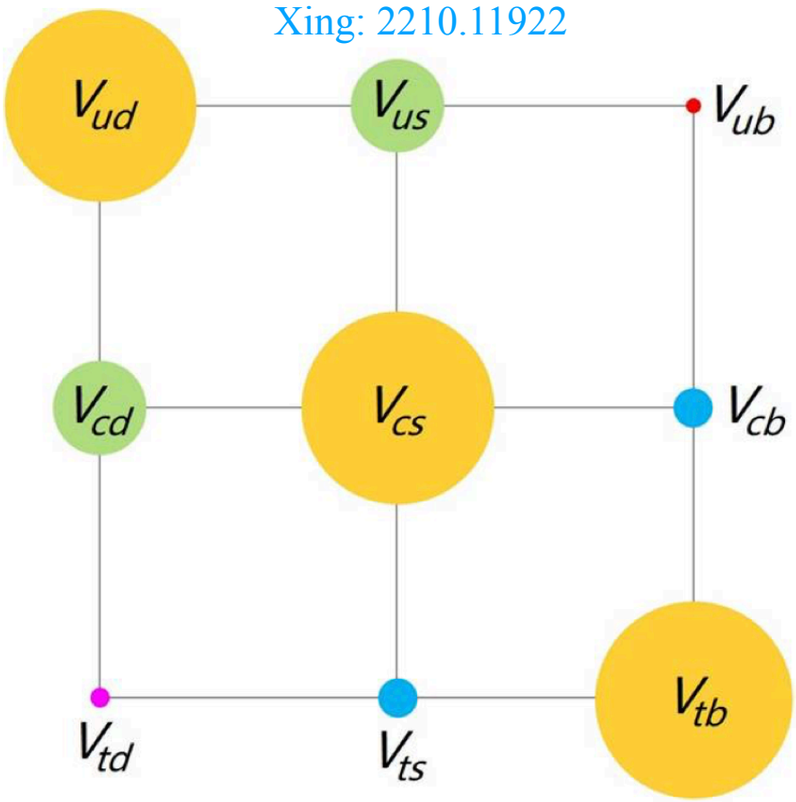
Zupan: 1903.05062



UTfit Coll.: 2212.03894



Xing: 2210.11922



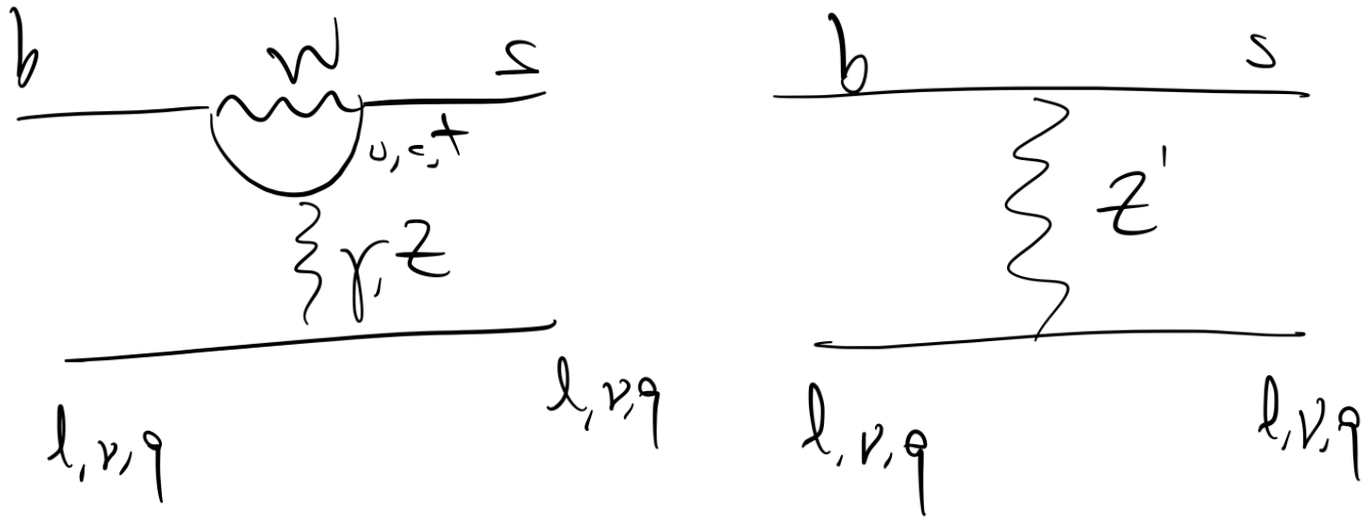
Masses and mixings of quarks and leptons have a peculiar structure

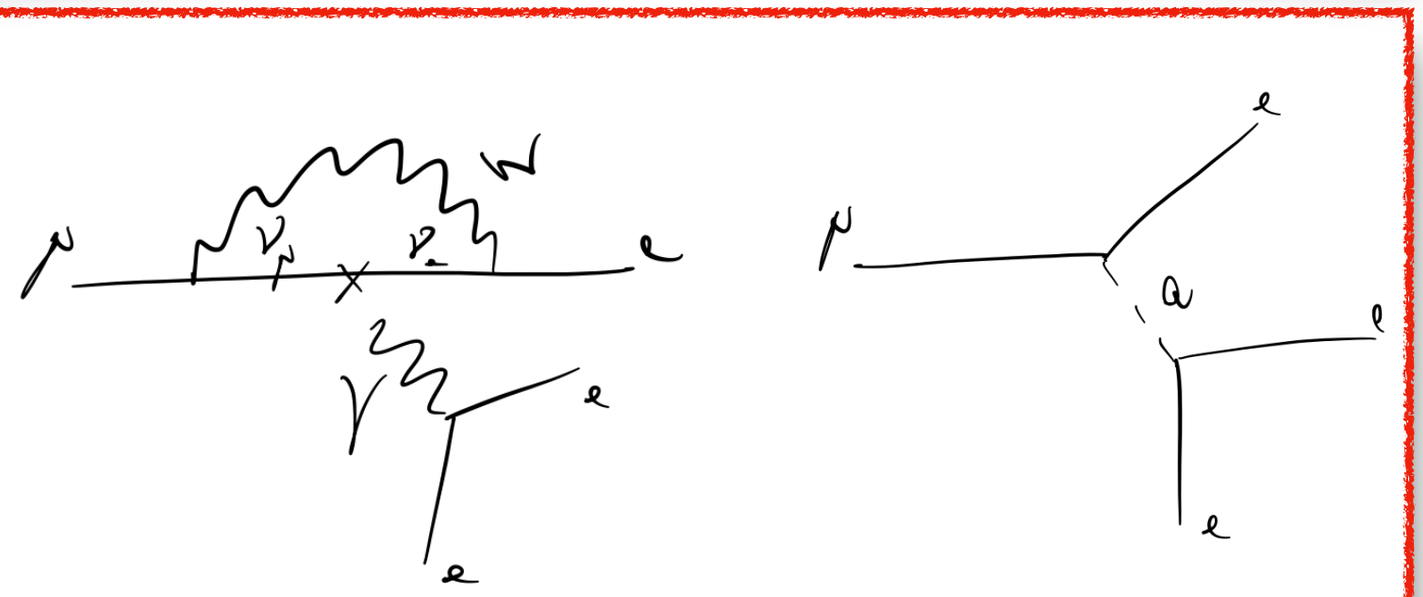
Probe heavy mediators with rare processes: SM as Effective Theory

$$\mathcal{L}_{\rm SMEFT} = \sum_{d,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_i^{(d)}$$

(which NP? Models of Flavor Review)

Altmannshofer, Greljo: 2412.04549





BSM does not need to respect accidental features of the SM (e.g.: FCNCs at tree-level, baryon/lepton number changing)

Many channels cannot be probed yet at LHC and flavor-factories

Probes of more general BSM from flavor structure

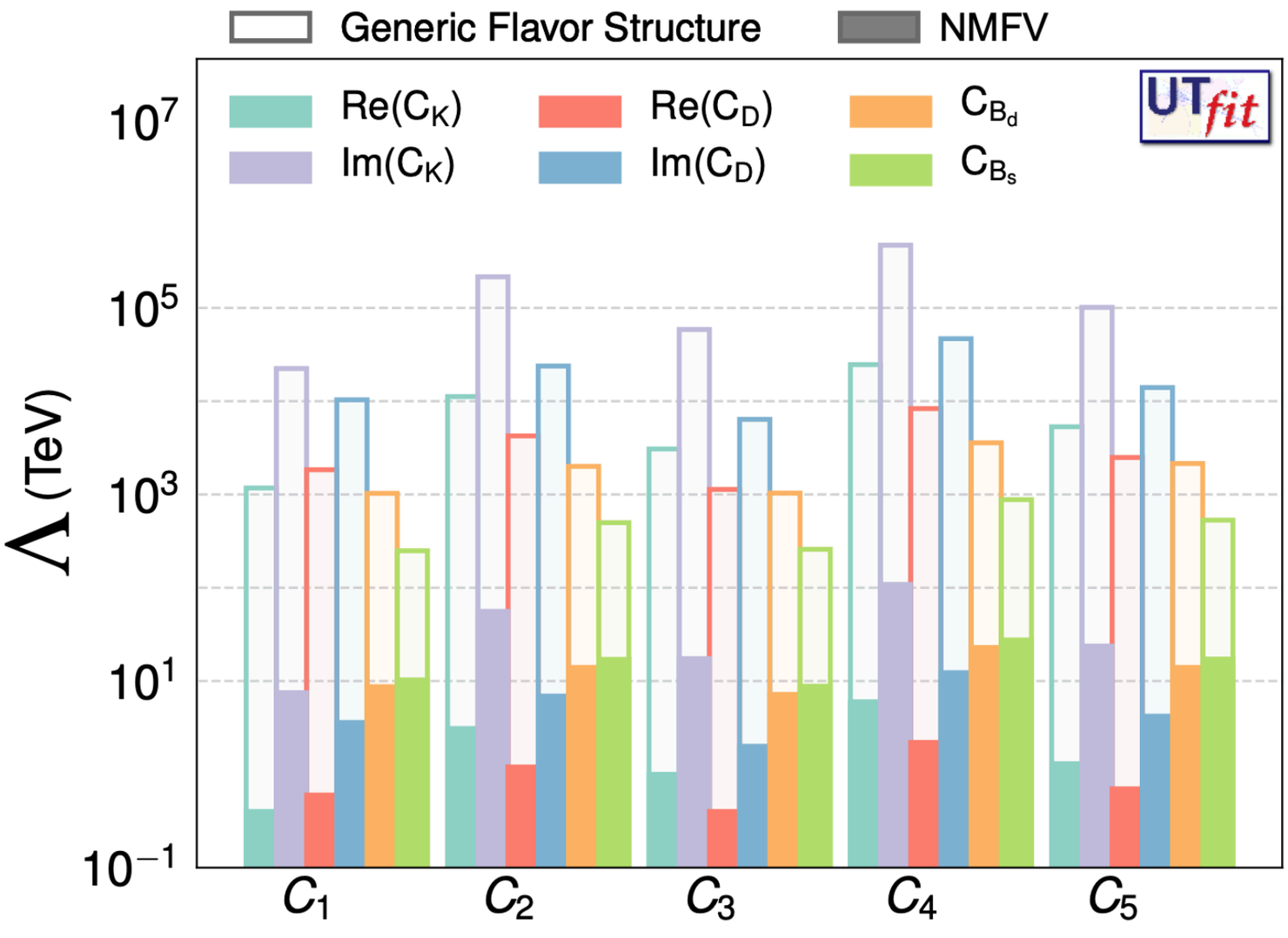
Probe heavy mediators with rare processes: SM as Effective Theory

$$\mathcal{L}_{\rm SMEFT} = \sum_{d,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_i^{(d)}$$

(which NP? Models of Flavor Review)

Altmannshofer, Greljo: 2412.04549

Minimal Flavor Violation (MFV): NP has the same flavor structure as the SM



UTfit Coll.: 0707.0636, 2212.03894

Heavy NP at ~10 TeV scale

Probe heavier scales = more precision

More precision = circular collider

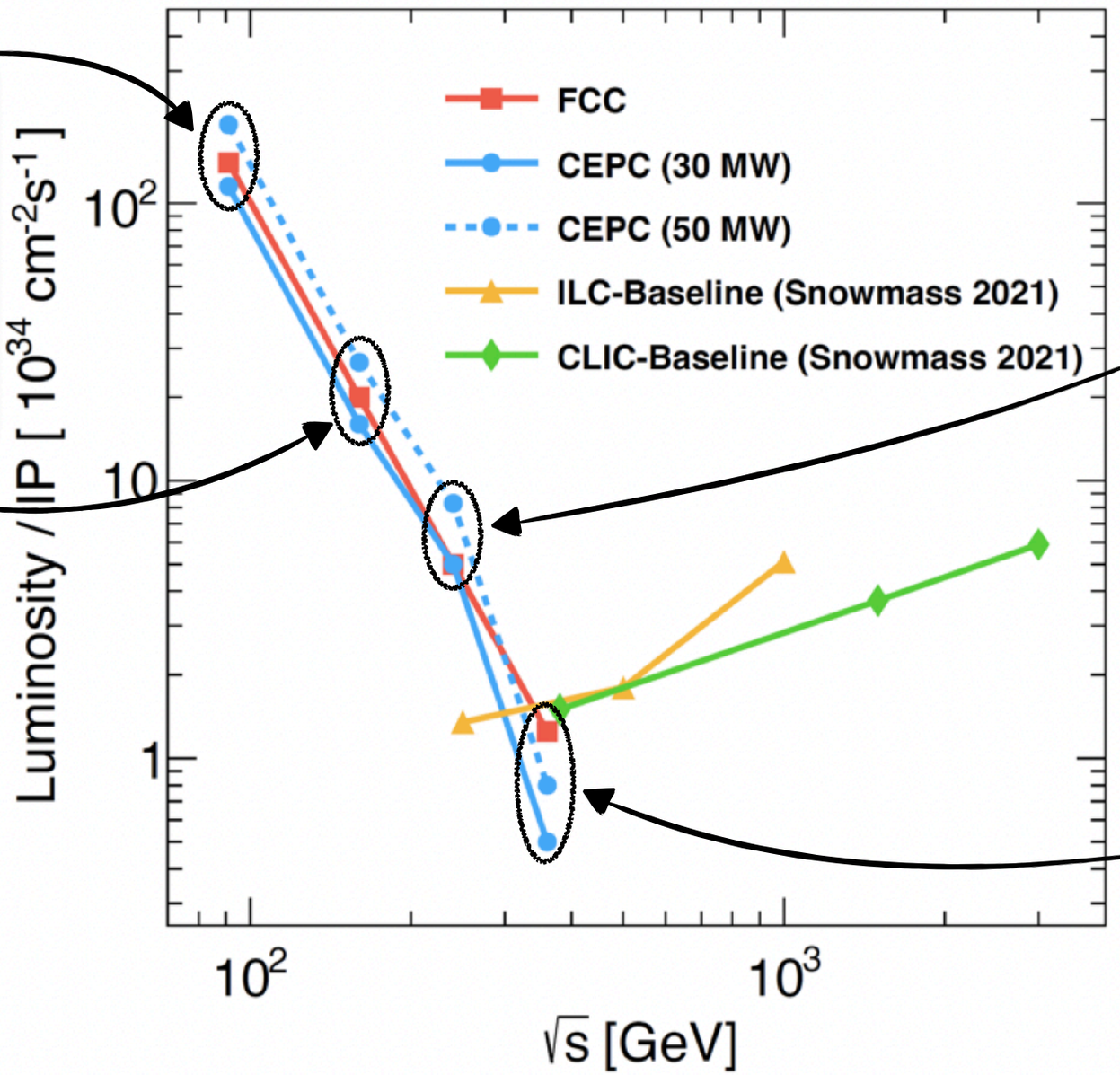
CEPC TDR: 2312.14363

$N_Z \sim 6 \times 10^{12}$

$N_H \sim 10^6$

$N_W \sim 6 \times 10^8$

$N_{t\bar{t}} \sim 10^6$



$N_i(\times 10^{10})$	$B^\pm$	$B^0/\bar{B}^0$	$B_s^0/\bar{B}_s^0$	$B_c^\pm$	$\Lambda_b/\bar{\Lambda}_b$	$c/\bar{c}$	$\tau^\pm$
Belle II	5.5	5.5	0.06	/	/	13	9
FCC-ee	77	77	17	0.7	15	140	40

More precision = circular collider

CEPC TDR: 2312.14363

$N_Z \simeq 6 \times 10^{12}$

Monteil, Wilkinson: 2106.01259

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

★ ...but large luminosity

★ c and b momenta distributions well understood, known exactly for leptons

$N_i(\times 10^{10})$	$B^\pm$	$B^0/\bar{B}^0$	$B_s^0/\bar{B}_s^0$	$B_c^\pm$	$\Lambda_b/\bar{\Lambda}_b$	$c/\bar{c}$	$\tau^\pm$
Belle II	5.5	5.5	0.06	/	/	13	9
FCC-ee	77	77	17	0.7	15	140	40

Some Searches

At Z-pole

- $b \to s\tau\tau$
- $b \to s\nu\nu$
- $bq \to \ell\nu$ in the backup slides
- τ physics in the backup slides
-
-
-

Off Z-pole ~ valid also for linear colliders

- Higgs FCNCs
- Direct CKM measurment
-
-
-

More done in

CEPC Flavor White Paper: 2412.19743

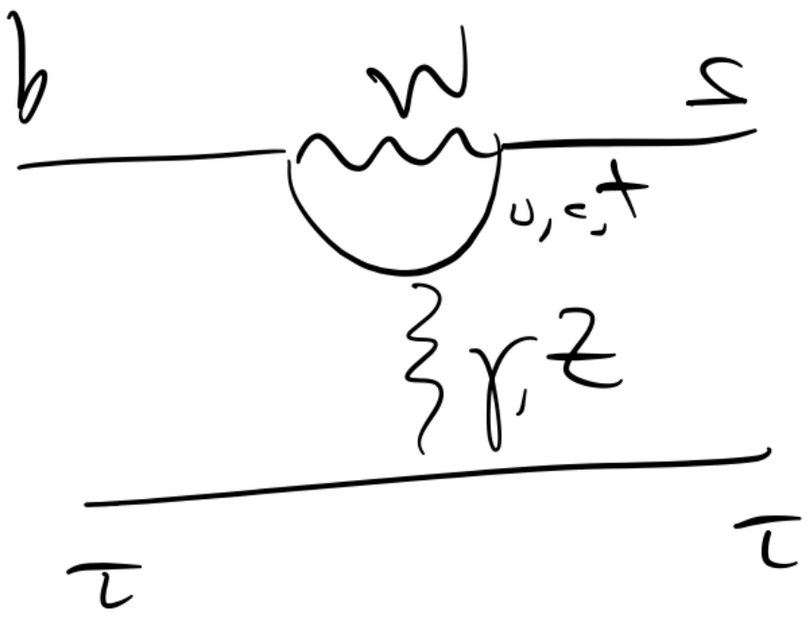
ECFA Report (to appear soon)

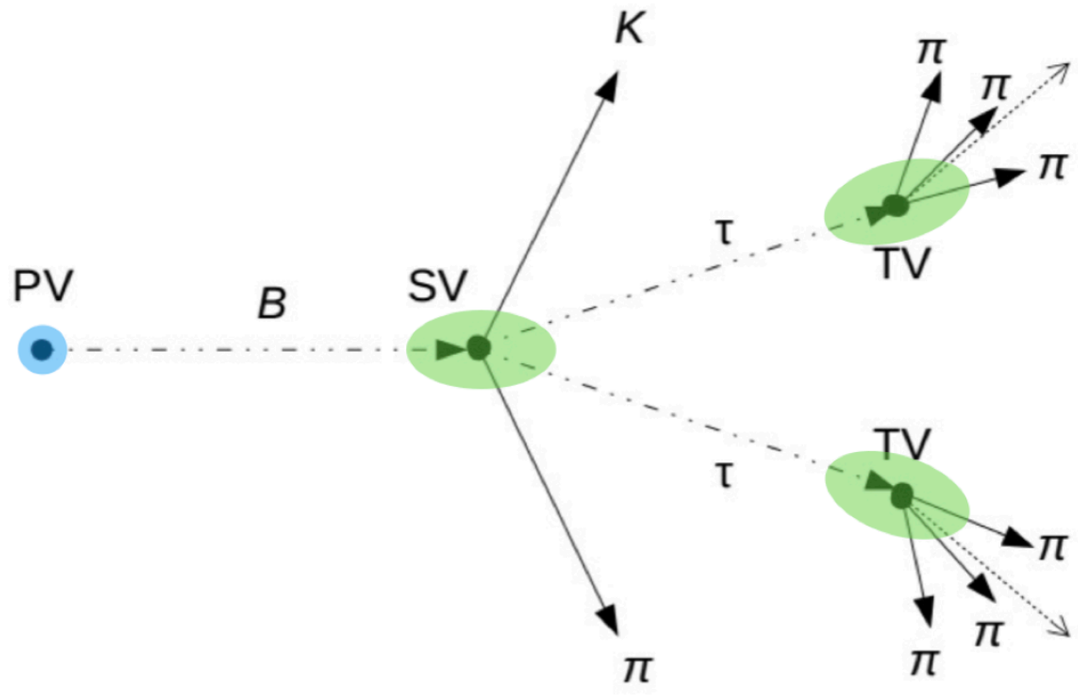
INFN Input (to appear soon)

Many workshops

(and way more to be done)

$b \to s\tau\tau$





$$\mathcal{B}_{\rm exp}(B \to K^*\tau\tau) \lesssim 3 \times 10^{-3}$$ BaBar: 1605.09637

$$\mathcal{B}_{\rm SM}(B \to K^*\tau\tau) \sim 10^{-7}$$ Kamenik, Monteil, Semkiv, Vale Silva: 1705.11106

Ample space for NP!

FCC-ee > LHC

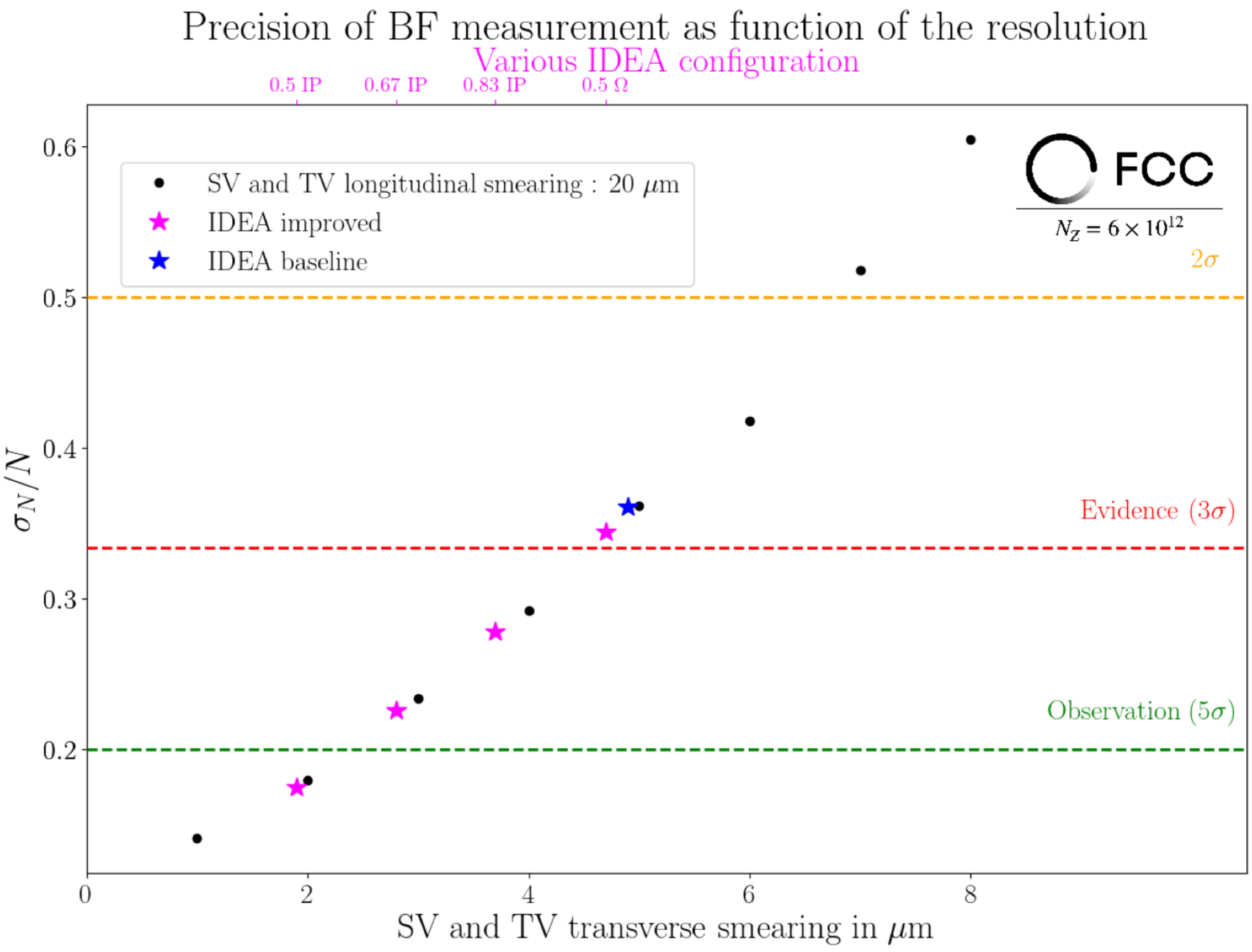
Better reconstruction

FCC-ee > BelleII

More statistics

$b \to s\tau\tau$

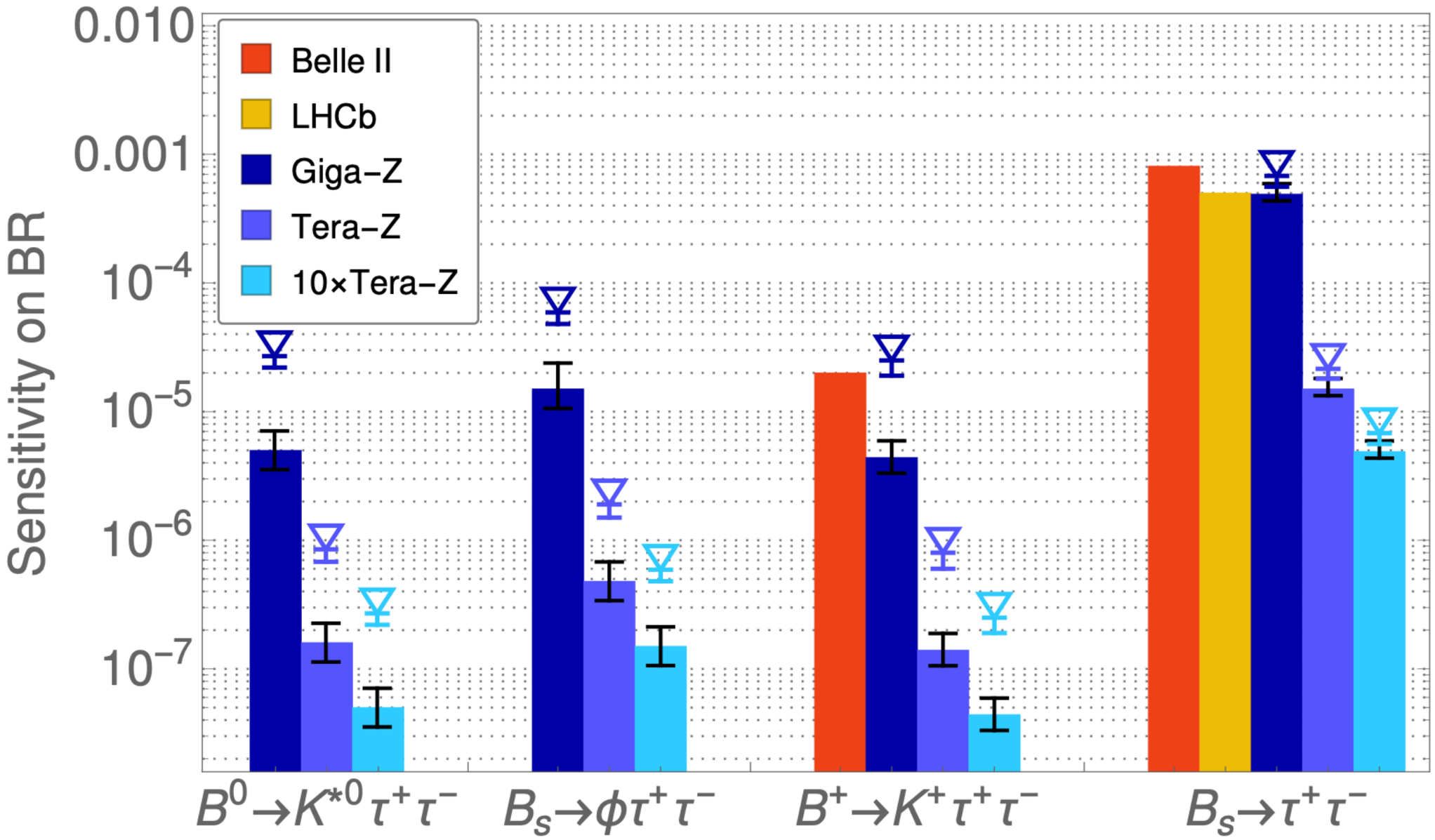
Talk by T. Miralles at 7th FCC week
https://indico.cern.ch/event/1307378



Vertex resolution is crucial!

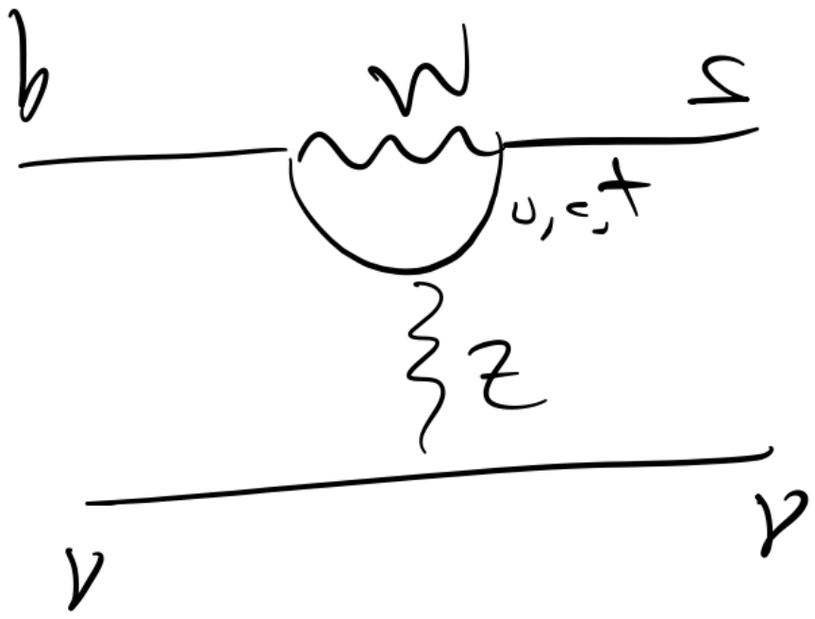
$b \to s\tau\tau$

Li, Liu: 2012.00665



Extend to other modes also possible

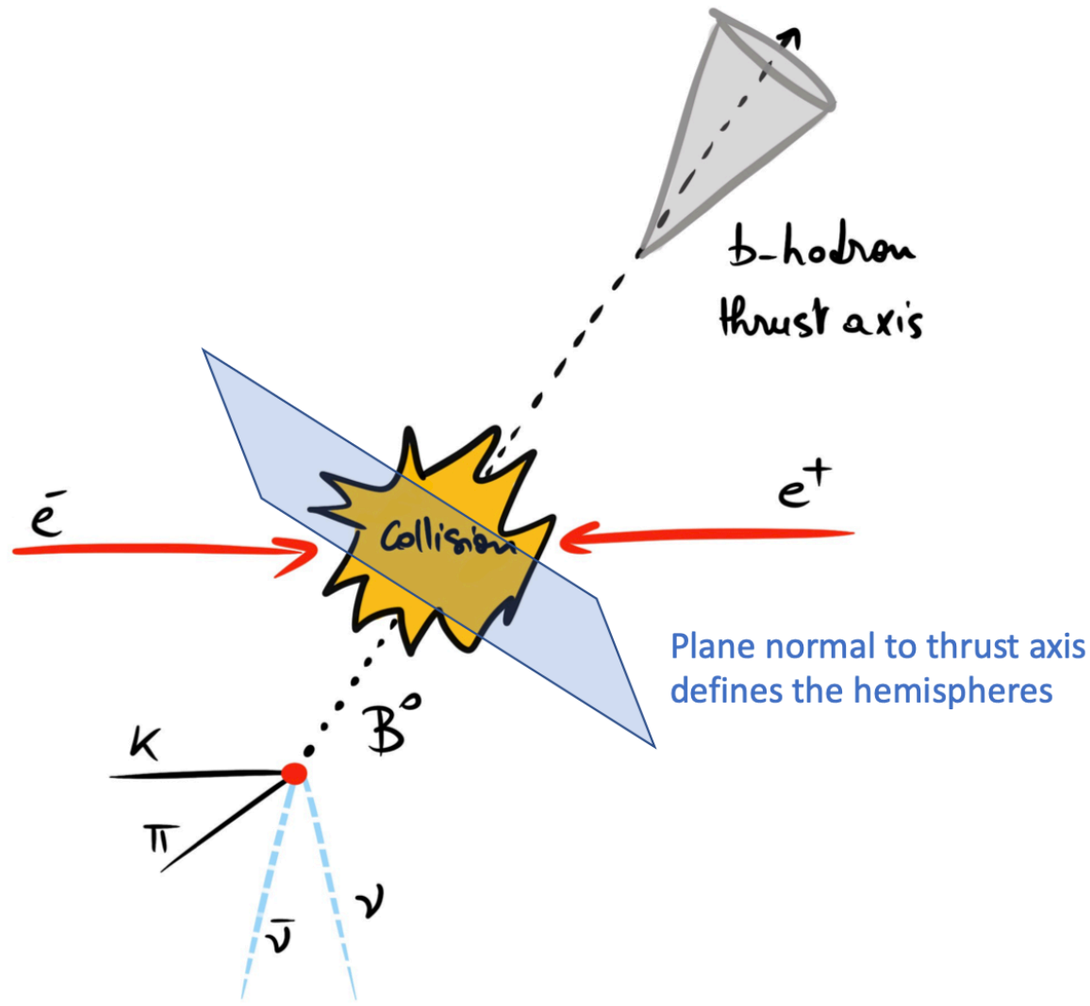
$b \to s\nu\nu$



$$\frac{\mathrm{d}\mathcal{B}_{\mathrm{SM}}}{\mathrm{d}q^2} \propto |\lambda_t|^2 |C_L^{\mathrm{SM}}|^2$$

$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2} \propto |\lambda_t|^2 |C_L \pm C_R|^2$$

$$\lambda_t = V_{tb} V_{ts}^*$$



Amhis, Kenzie, Reboud, Wiederhold: 2309.11353

Decay	Candidate	Candidate Children
$B^0 \to K^{*0}\nu\bar{\nu}$	K^{*0}	$K^{\pm}\pi^{\mp}$
$B_s^0 \to \phi\nu\bar{\nu}$	ϕ	K^+K^-

FCC-ee > LHC

Better reconstruction

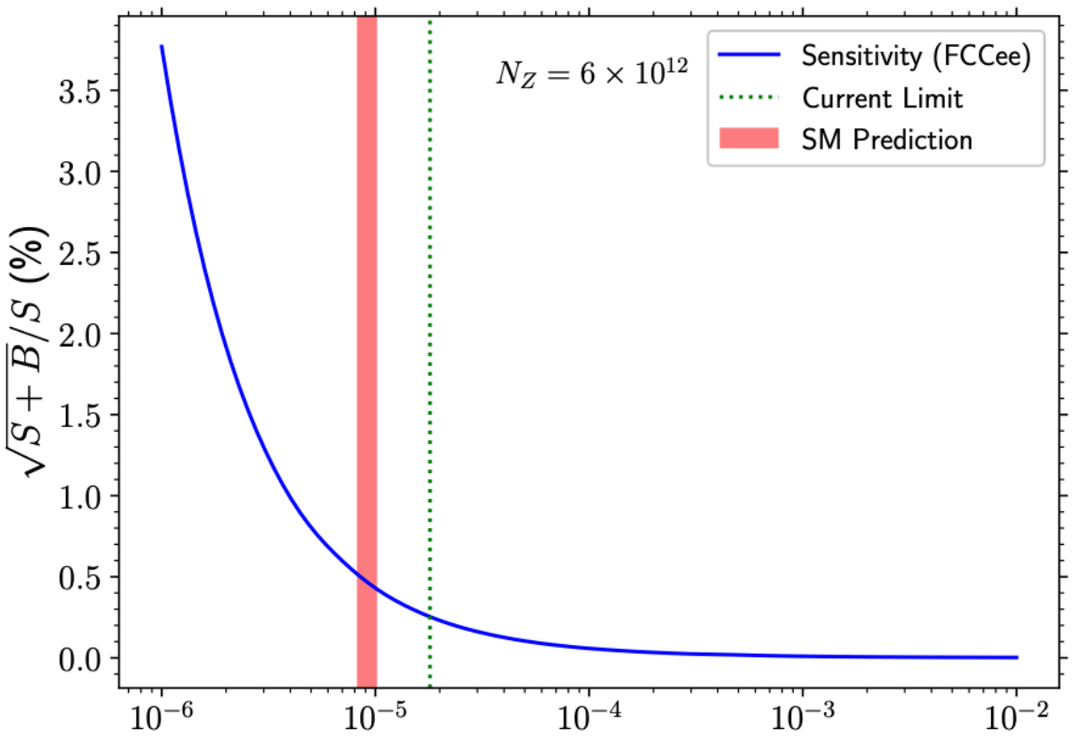
FCC-ee ~> BelleII

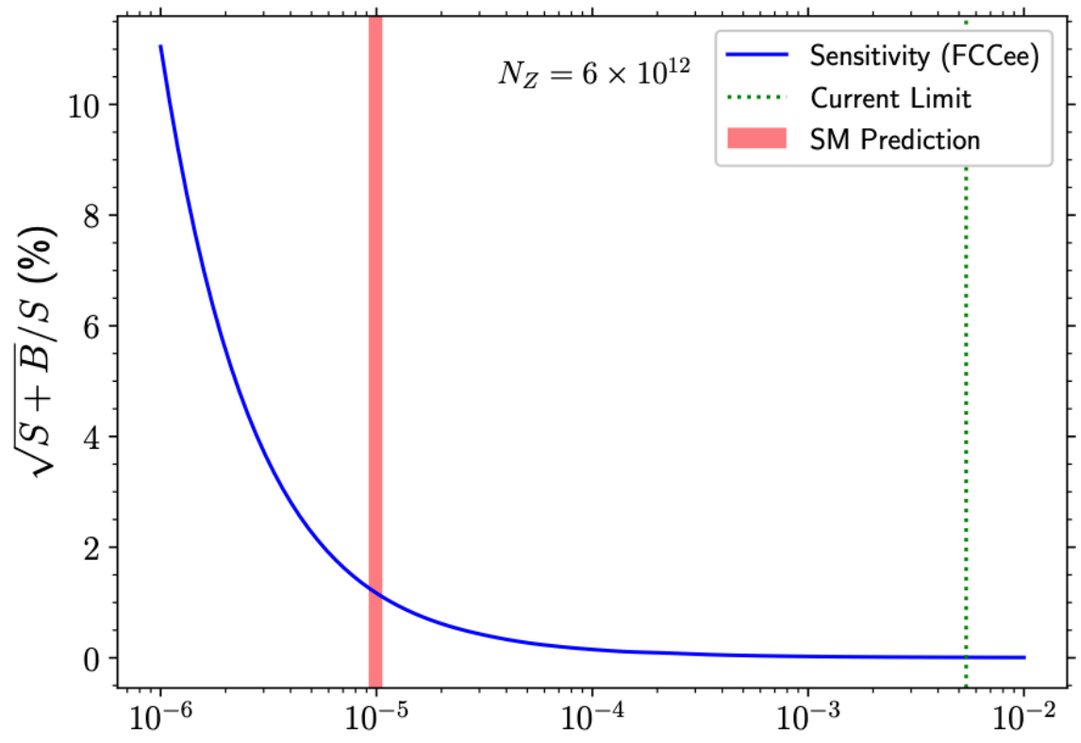
B2 can reach O(10%)
with full luminosity

$b \to s\nu\nu$

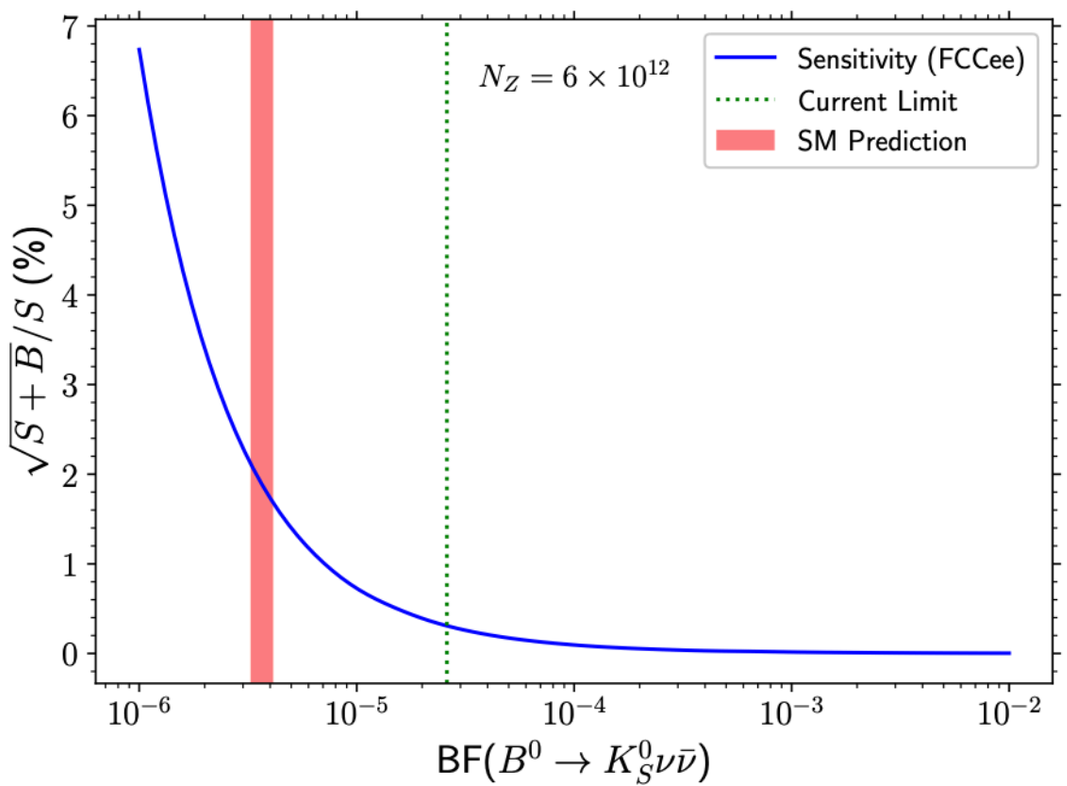
Amhis, Kenzie, Reboud, Wiederhold: 2309.11353

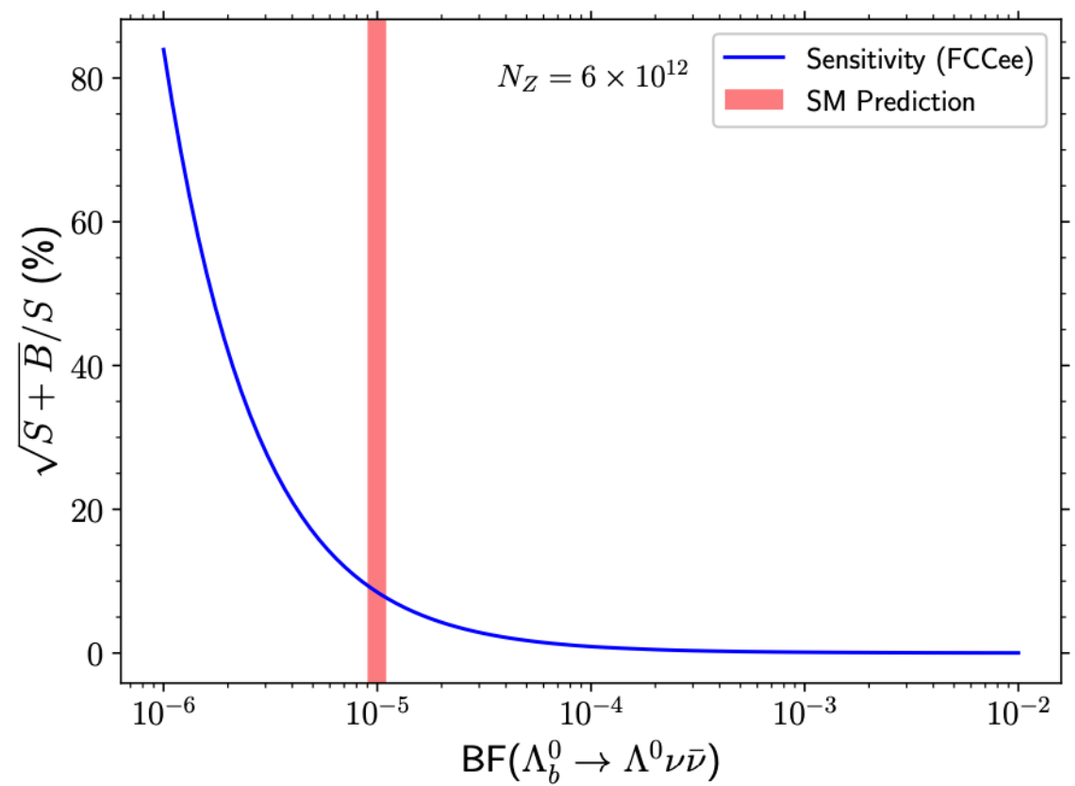
O(1%) precision at SM level!





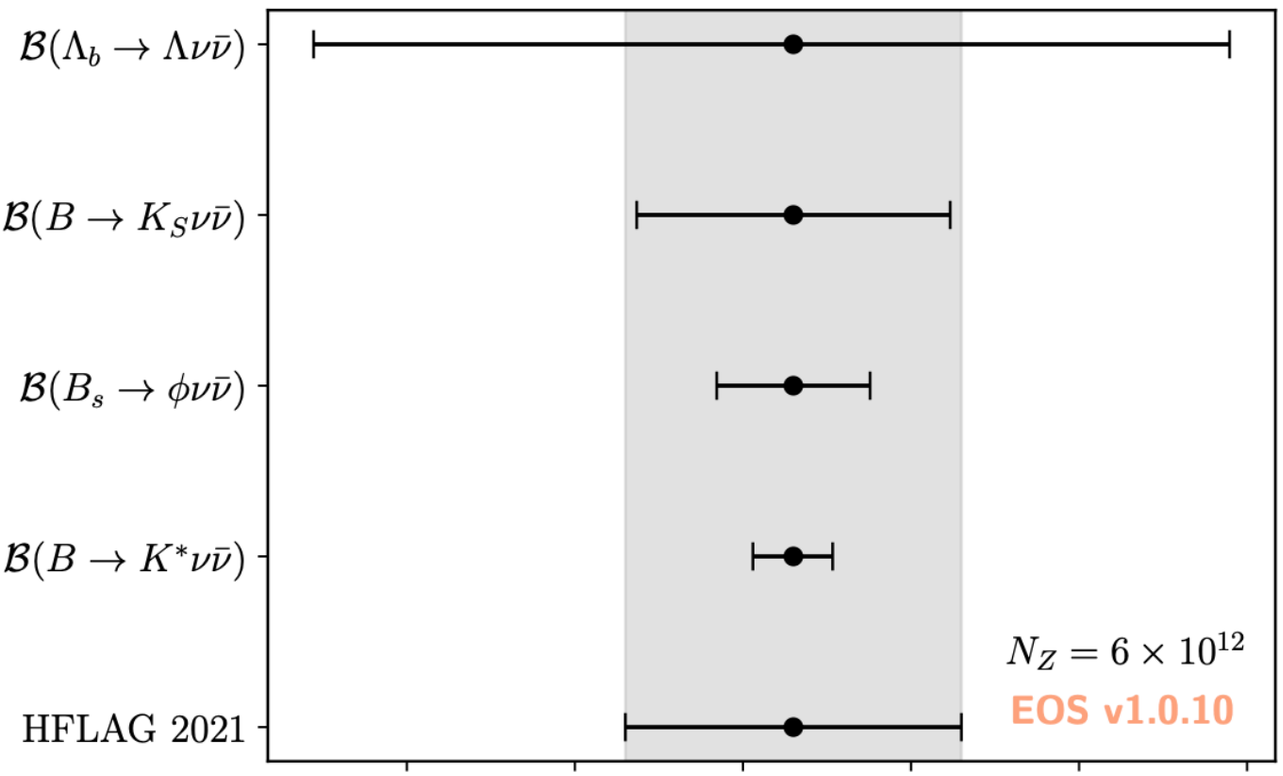
Extrapolate to neutral modes (with O(10%) precision)



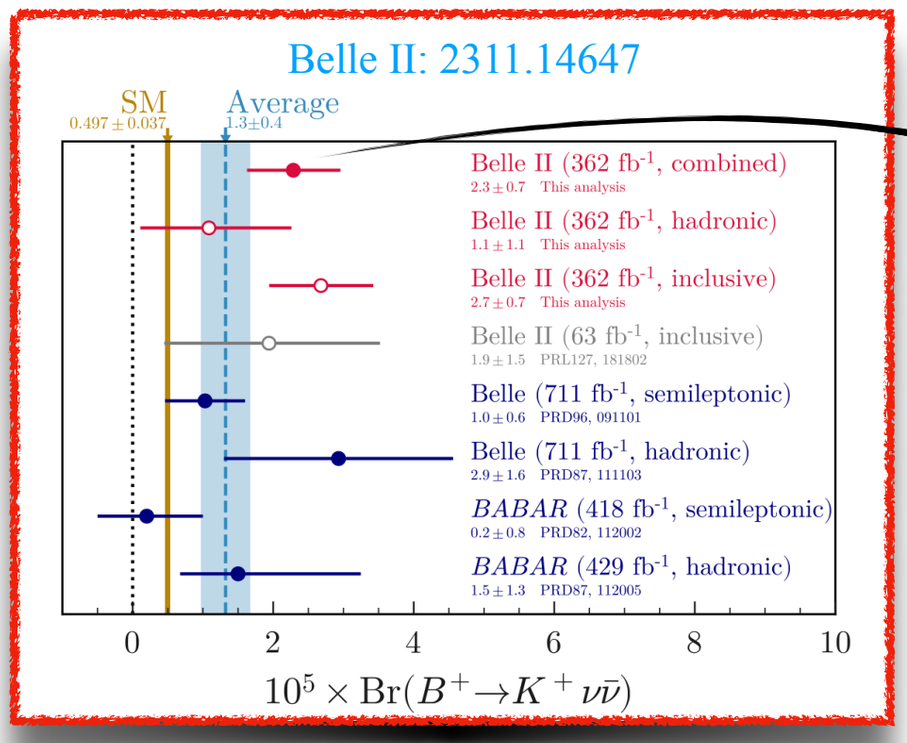


$b \to s\nu\nu$

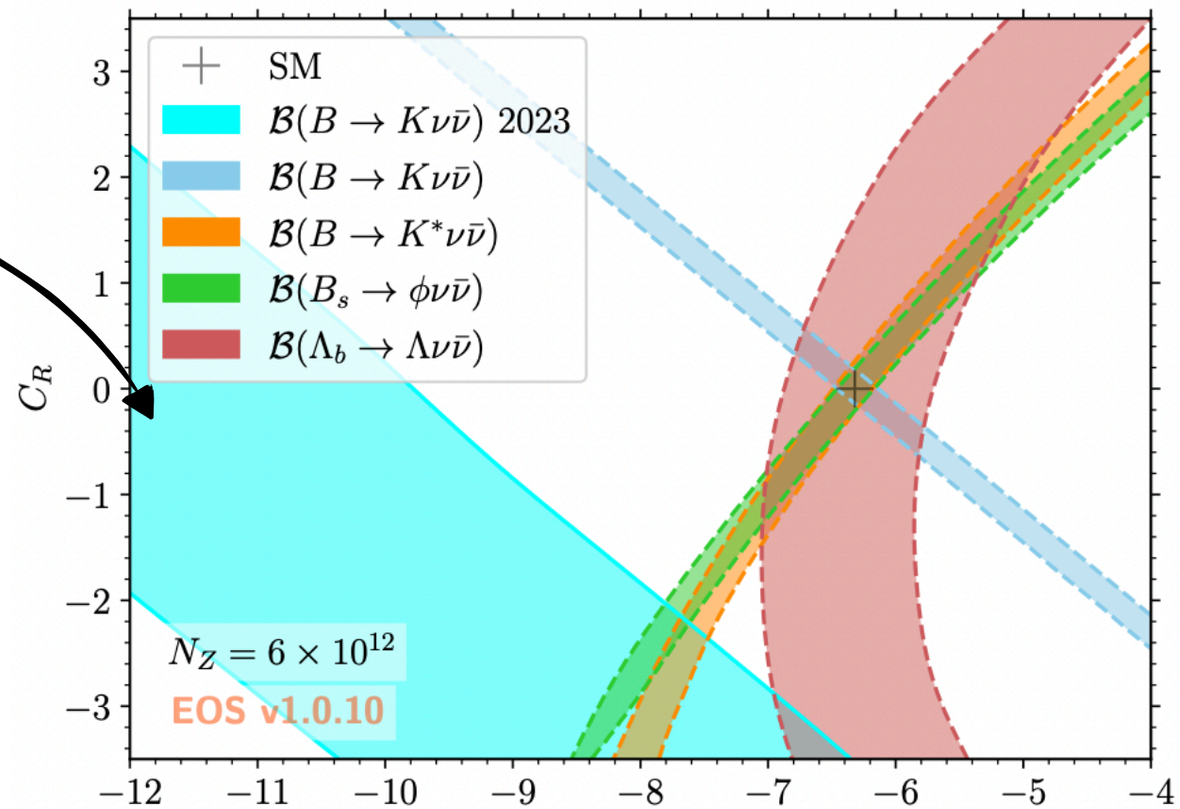
Amhis, Kenzie, Reboud, Wiederhold: 2309.11353



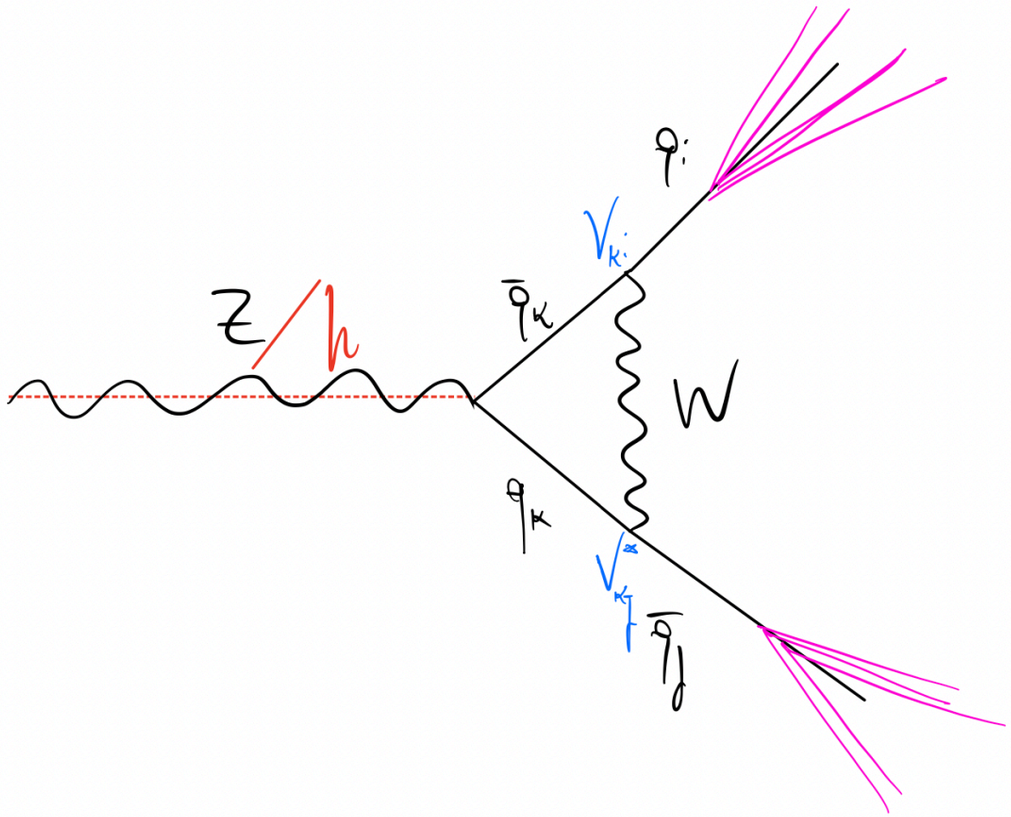
Extracted by assuming CKM unitarity



Measure SM level and constraint NP



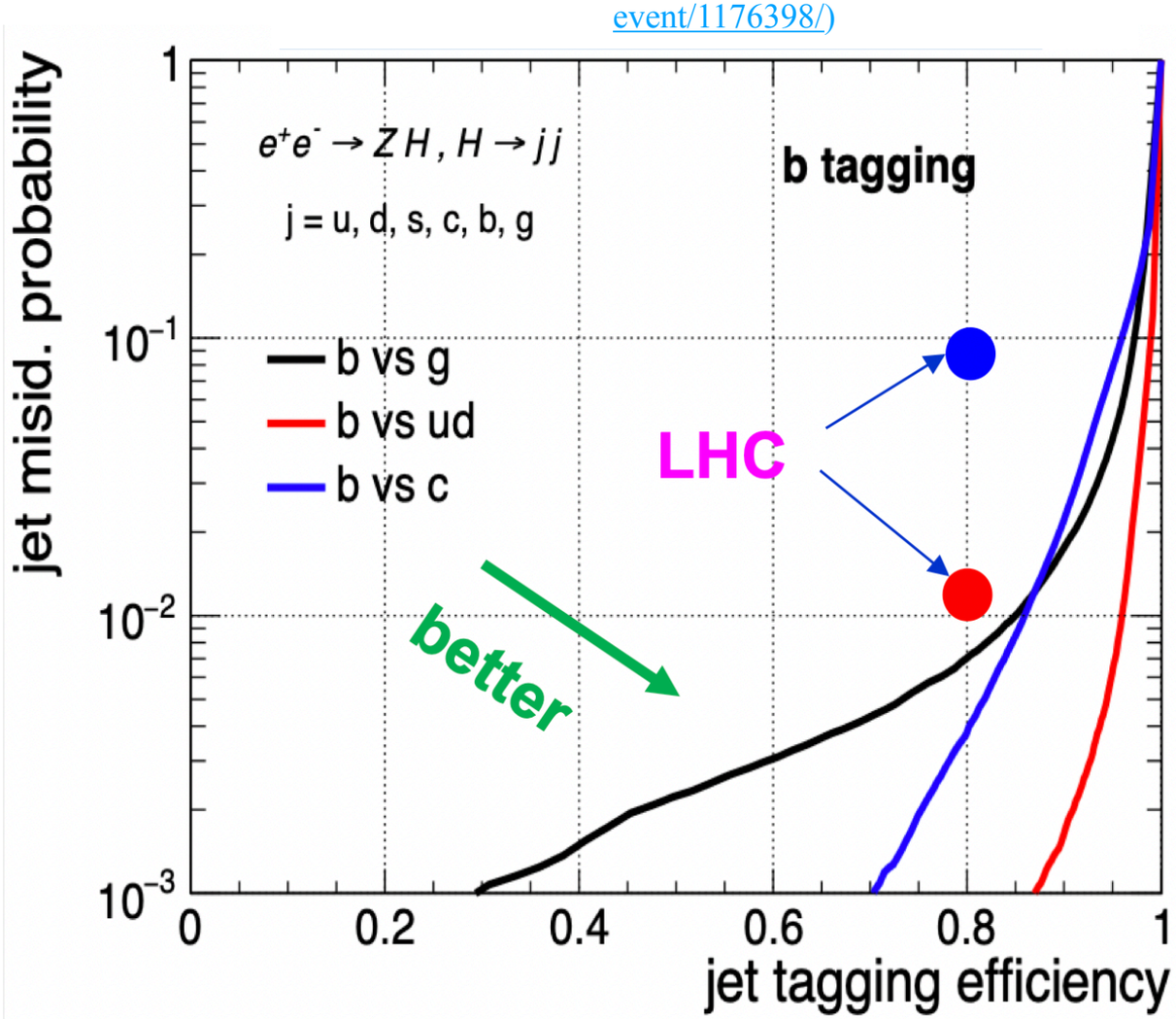
$H \to qq'$



Direct measurement with jet tagger/PID

~ 0.1 - 1% systematics expected on tagger parameters

Bedeschi, Gouskos, Selvaggi: 2202.03285
Gouskos' talk at "FCC Physics Workshop" (indico.cern.ch/event/1176398/)

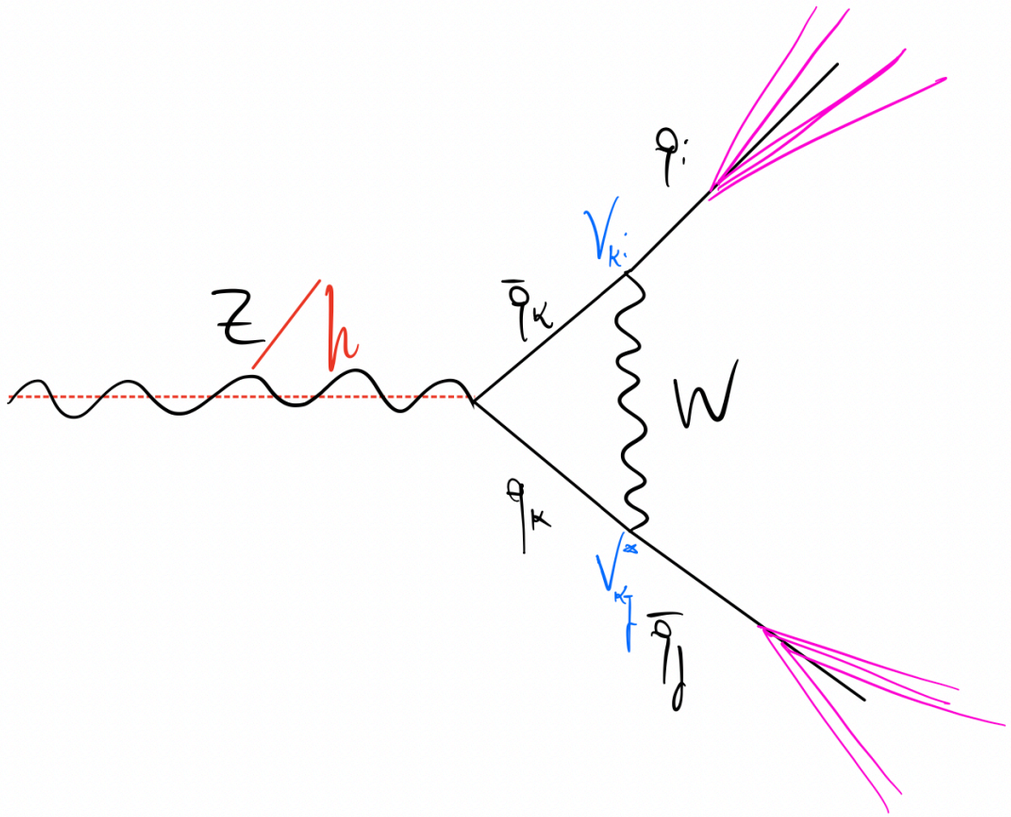


Decay	SM prediction	exp. bound	indir. constr.
$\mathcal{B}(h \to bs)$	$(8.9 \pm 1.5) \cdot 10^{-8}$	0.16	2×10^{-3}
$\mathcal{B}(h \to bd)$	$(3.8 \pm 0.6) \cdot 10^{-9}$	0.16	10^{-3}
$\mathcal{B}(h \to cu)$	$(2.7 \pm 0.5) \cdot 10^{-20}$	0.16	2×10^{-2}

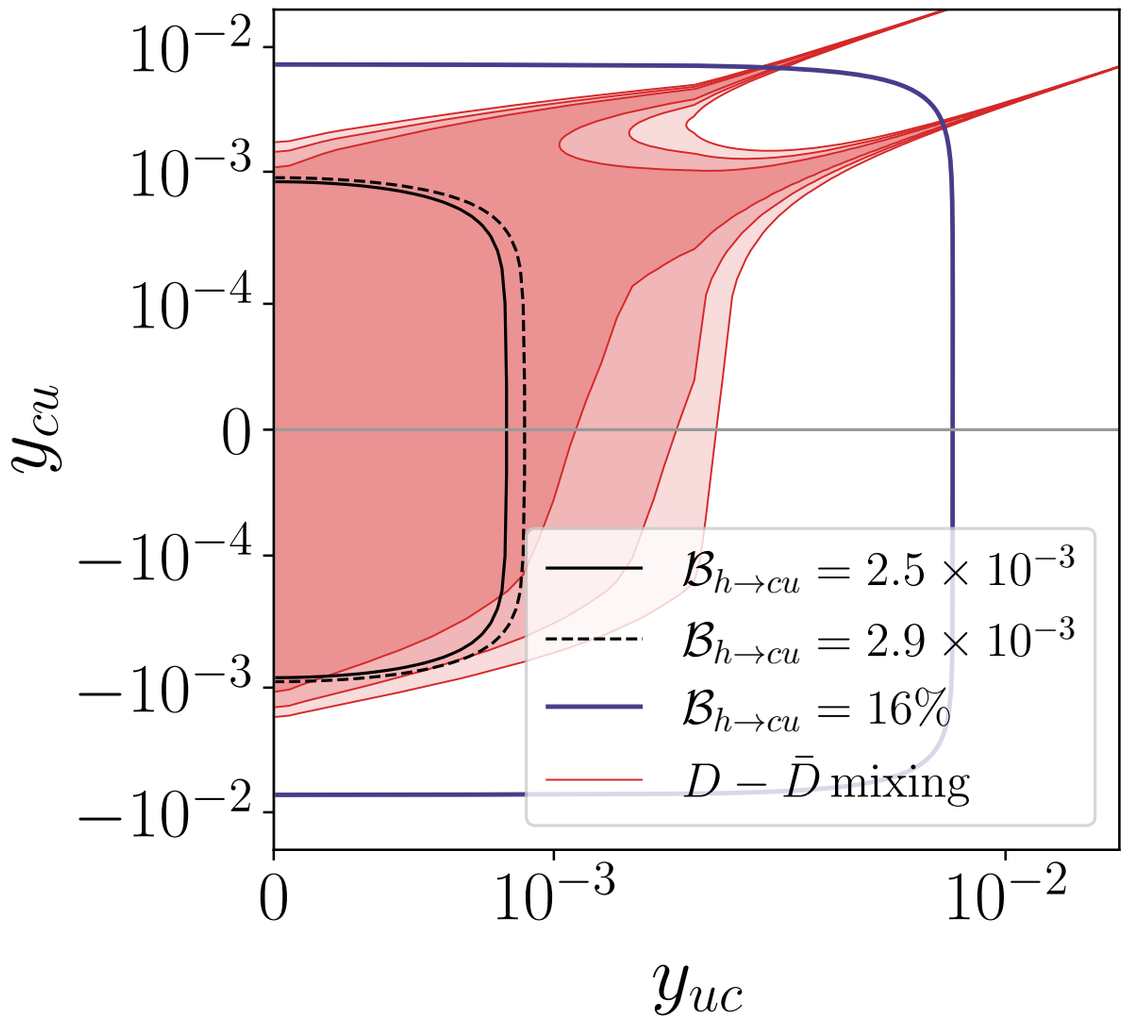
$h \to$ BSM (CMS+ATLAS, 2207.00043)

Meson mixings

$H \to qq'$



Kamenik, Korajac, Szewc, MT, Zupan: 2306.17520



Improve bounds on all channels

$$\mathcal{B}(h \to cu) \lesssim 6.6 \times 10^{-4}$$

$$\mathcal{B}(h \to cu) \lesssim 4 \times 10^{-4}$$ Liang et al.: 2310.03440

Decay	SM prediction	exp. bound	indir. constr.
$\mathcal{B}(h \to bs)$	$(8.9 \pm 1.5) \cdot 10^{-8}$	0.16	2×10^{-3}
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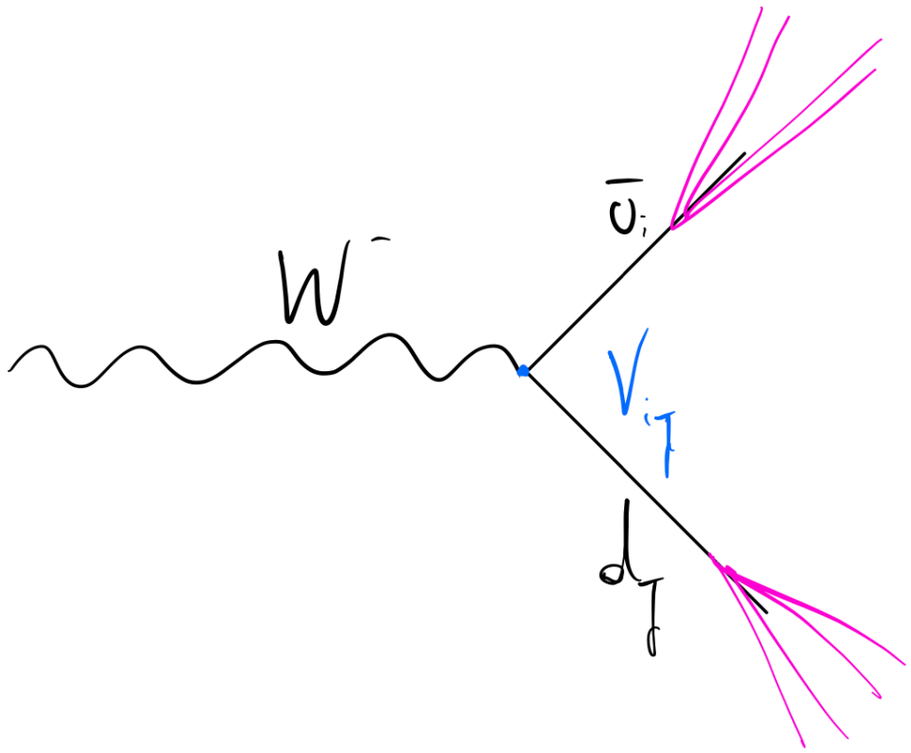
$h \to$ BSM (CMS+ATLAS, 2207.00043)

Meson mixings

CKM



Direct measurement with jet tagger/PID

~ 0.1 - 1% systematics expected on tagger parameters

Bedeschi, Gouskos, Selvaggi: 2202.03285
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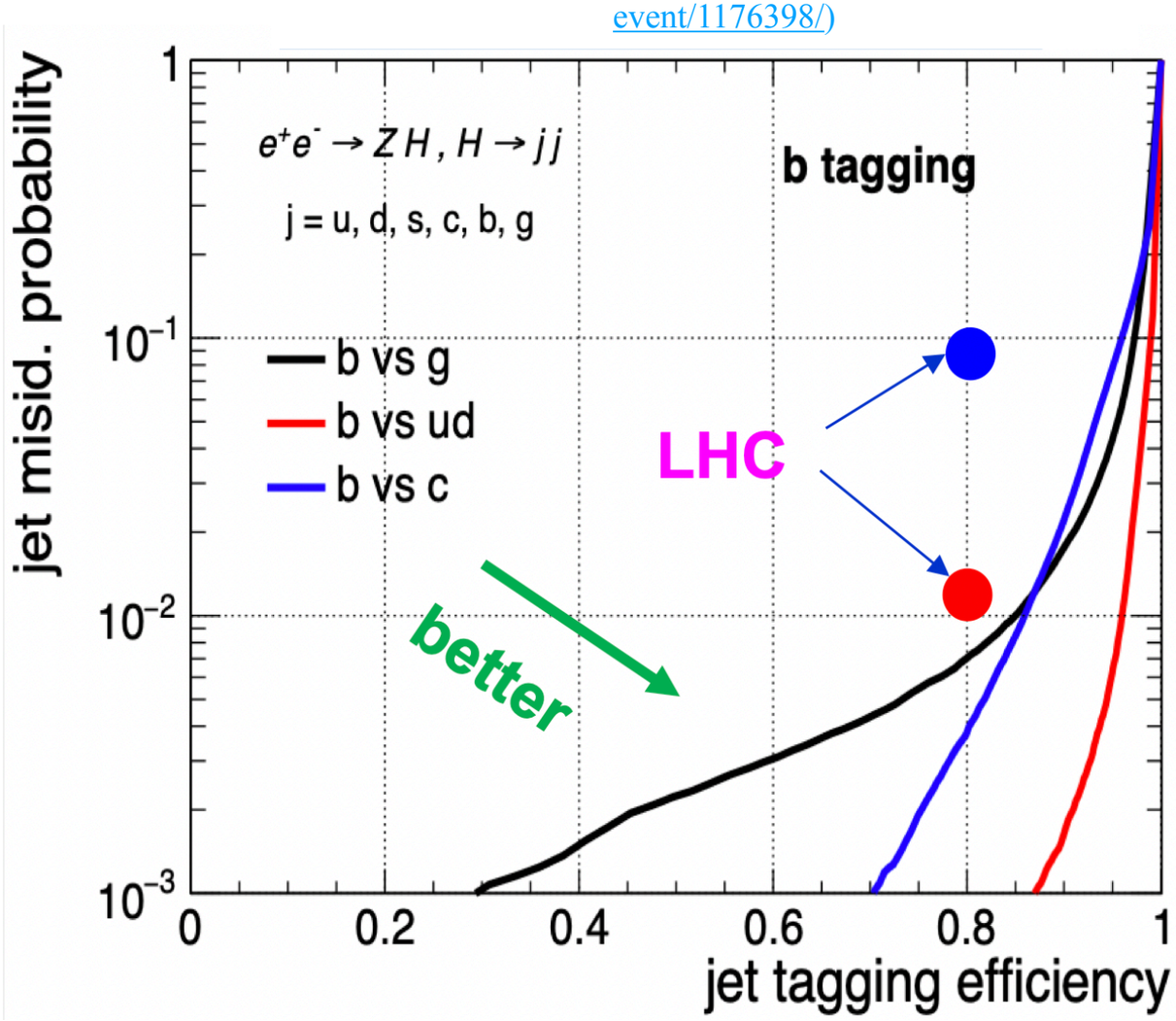
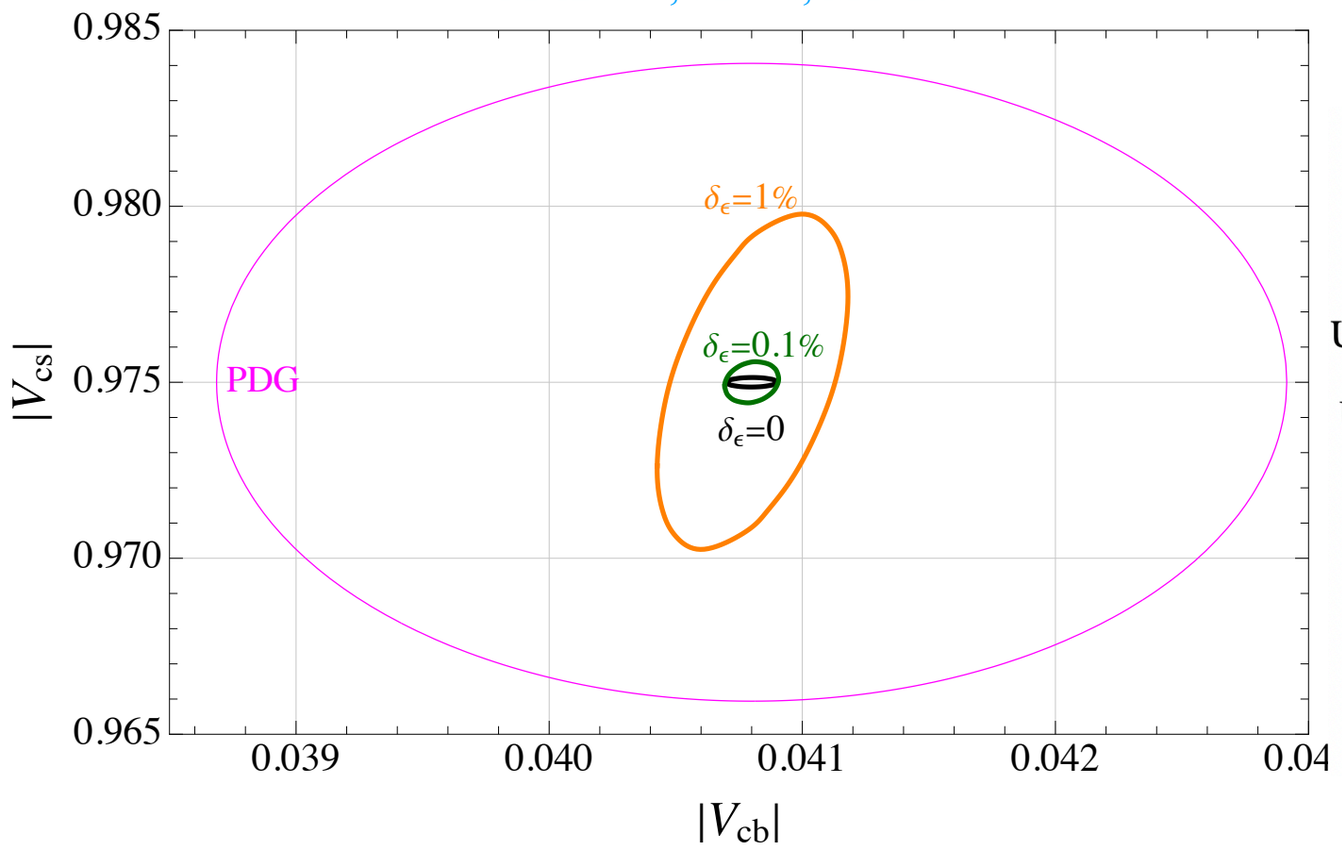


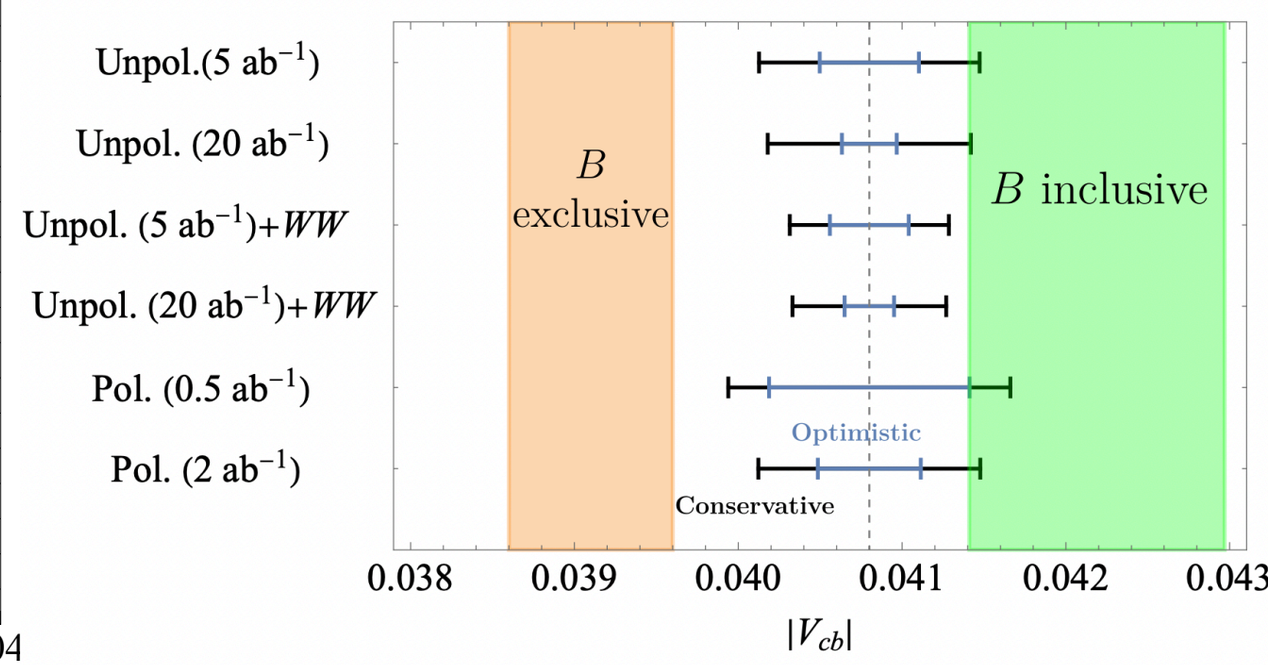
$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix}$$

$\lvert V_{ij}\rvert$	Current	
$\lvert V_{cs}\rvert$	0.975 ± 0.006	(0.6%)
$\lvert V_{cb}\rvert$	$(40.8 \pm 1.4) \times 10^{-3}$	(3.4%)

Marzocca, Szewc, MT: 2405.08880



Liang, Li, Zhu, Shen, Ruan: 2406.01675



Direct measurement with jet tagger/PID

~ 0.1 - 1% systematics expected on tagger parameters

"Lattice-free" determination, can resolve inclusive vs exclusive tension

$\lvert V_{ij}\rvert$	Current (PDG)		FCC-ee ($\delta_\epsilon = 1\%$)	FCC-ee ($\delta_\epsilon = 0.1\%$)	FCC-ee (Stat. only)
$\lvert V_{cs}\rvert$	0.975 ± 0.006	(0.6%)	0.36%	0.05%	0.008%
$\lvert V_{cb}\rvert$	$(40.8 \pm 1.4) \times 10^{-3}$	(3.4%)	0.52%	0.16%	0.14%

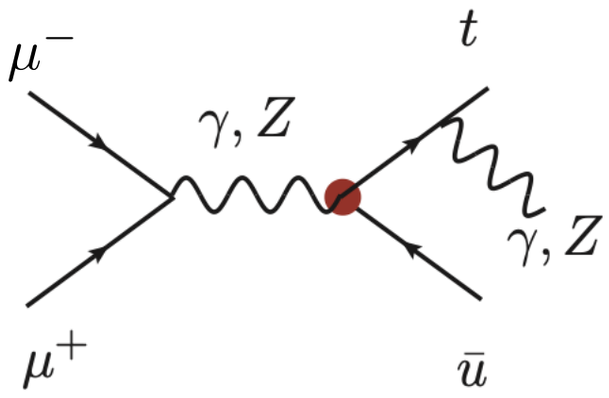
Technically challenging...

...but has advantages of both lepton and hadron colliders

Muon Smasher's Guide: 2103.14043

$\sqrt{s}$ [TeV]	1	3	6	10	14	30	50	100
$\mathcal{L}_{\rm int}^{\rm opt}$ [ab^{-1}]	0.2	1	4	10	20	90	250	1000
$\mathcal{L}_{\rm int}^{\rm con}$ [ab^{-1}]	0.2	1	4	10	10	10	10	10

Ake', Bouzas, Larios: 2103.14043

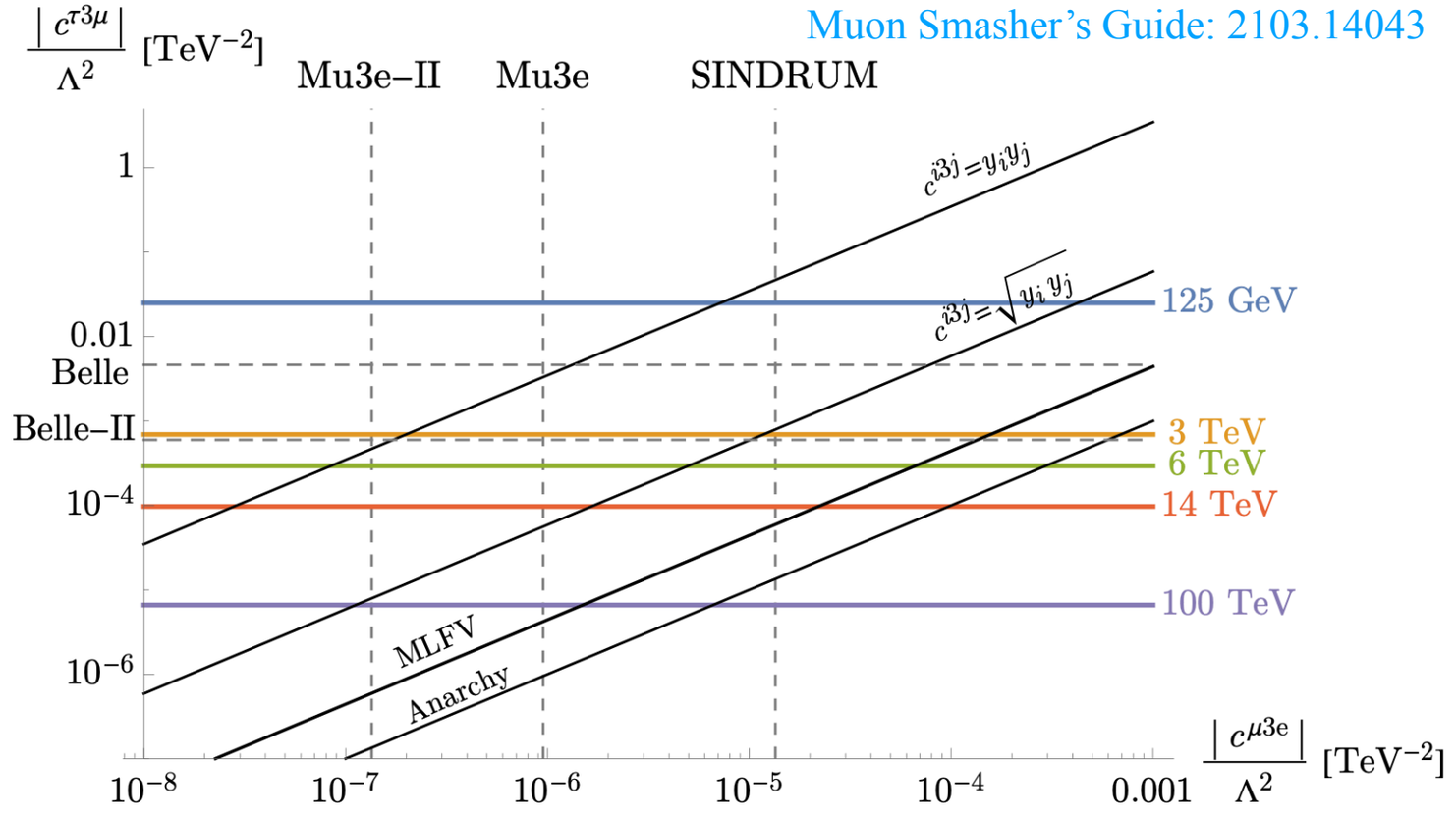


Top FC couplings from single top production

$\tau \to 3\mu$ from $(\bar{\tau}\Gamma\mu)(\mu\Gamma\mu)$

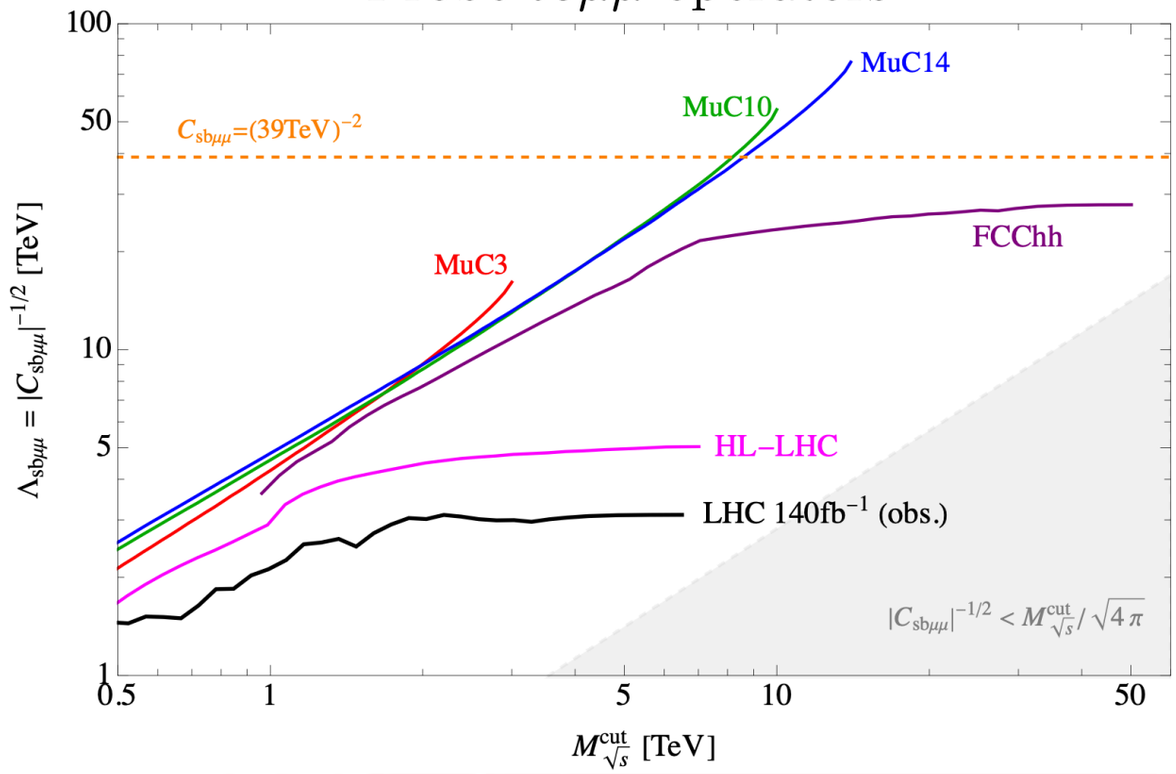
but also other combinations

Muon Smasher's Guide: 2103.14043



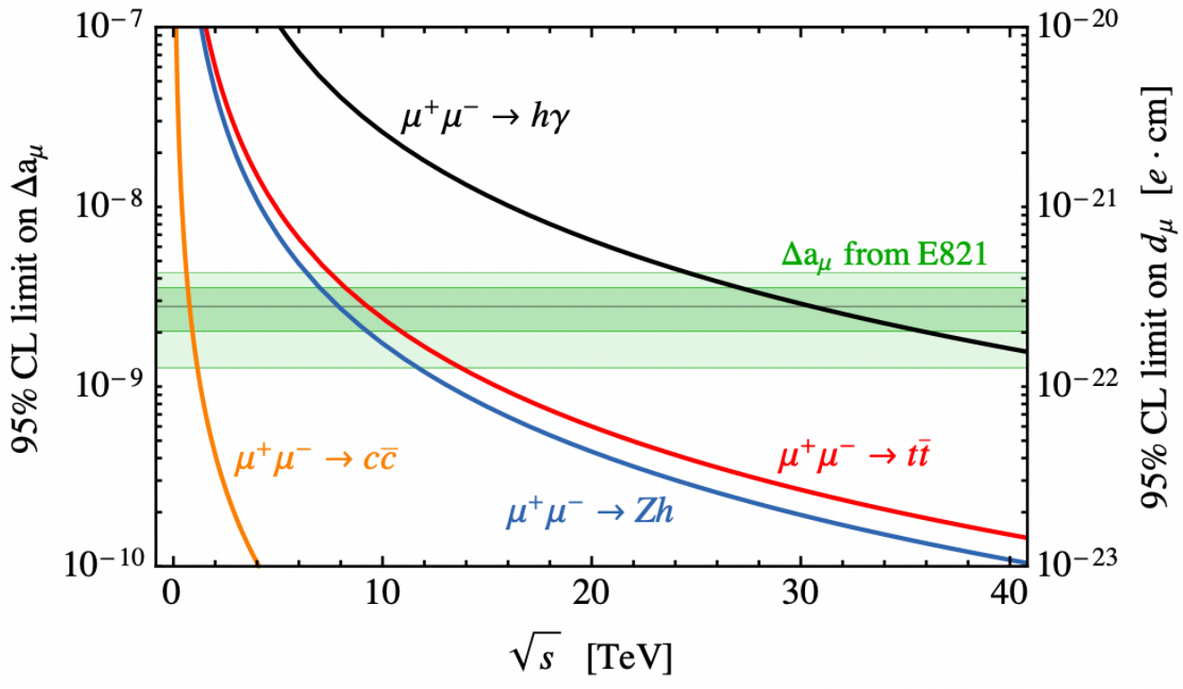
Azatov, Garosi, Greljo, Marzocca, Salko, Trifinopoulos: 2205.13552

Probe $bs\mu\mu$ operators



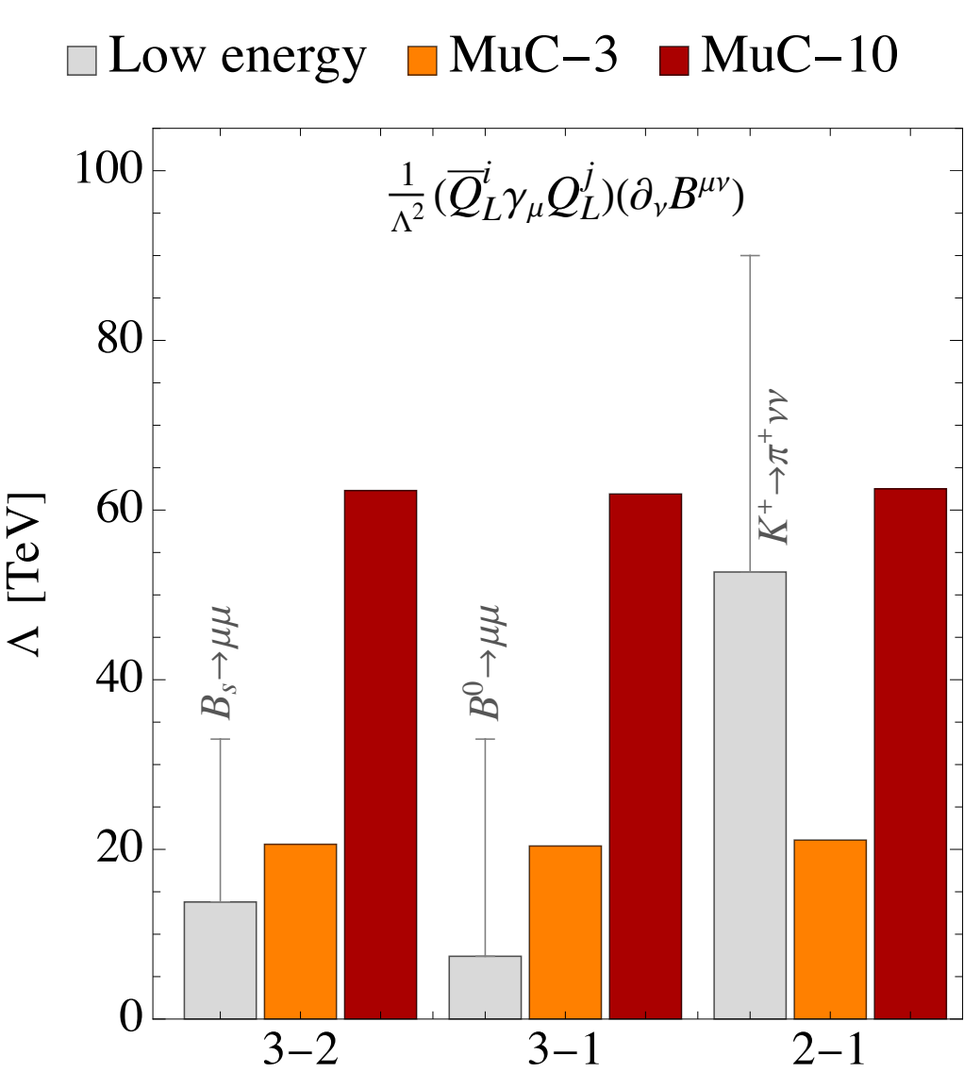
Buttazzo, Paradisi: 2012.02769

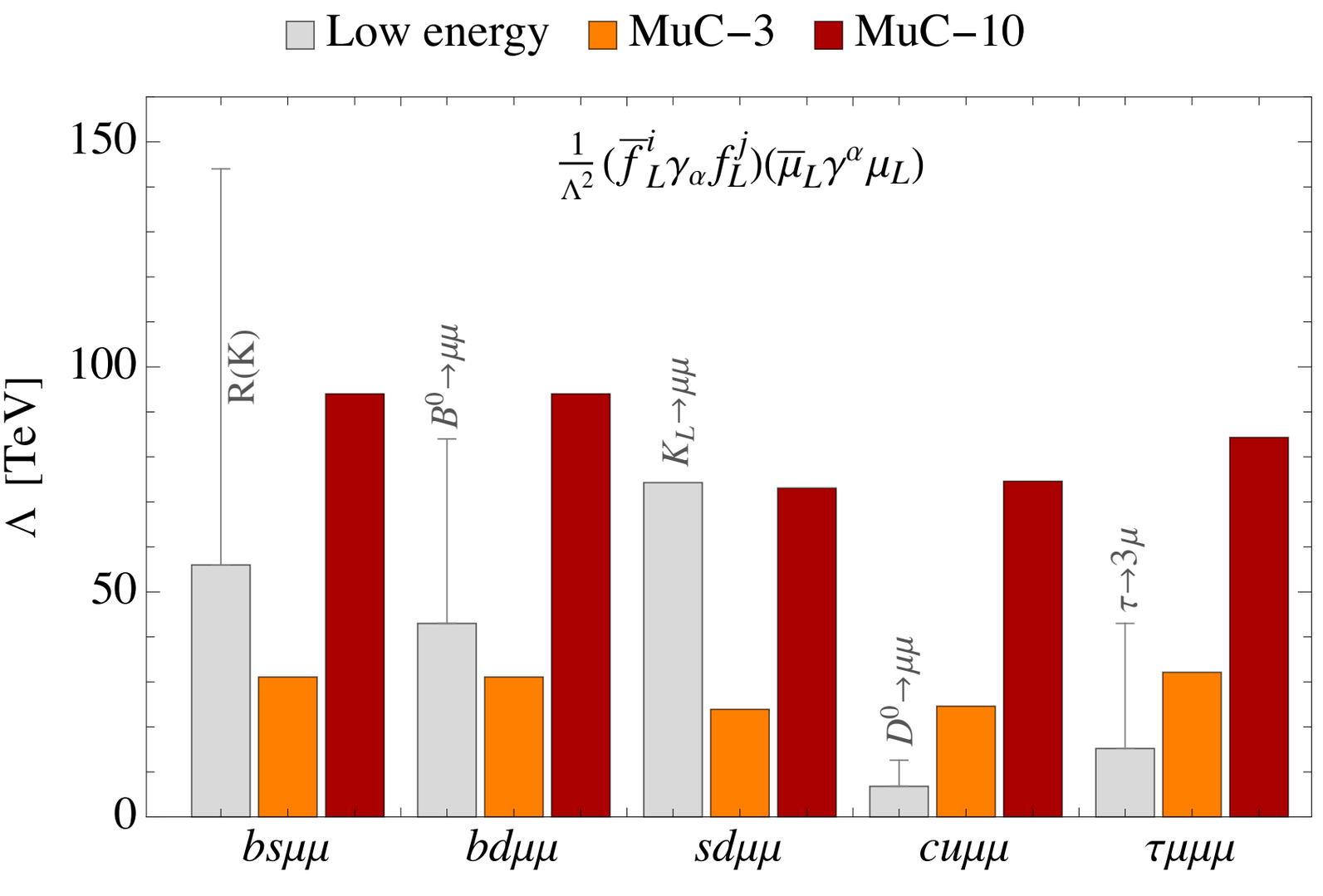
Probe dipoles $(\mu\mu HX)$



More (preliminary) results

See Lucchesi's talk from yesterday





MuC-10 can significantly improve sensitivity for bottom/charm/tau

Take-home messages

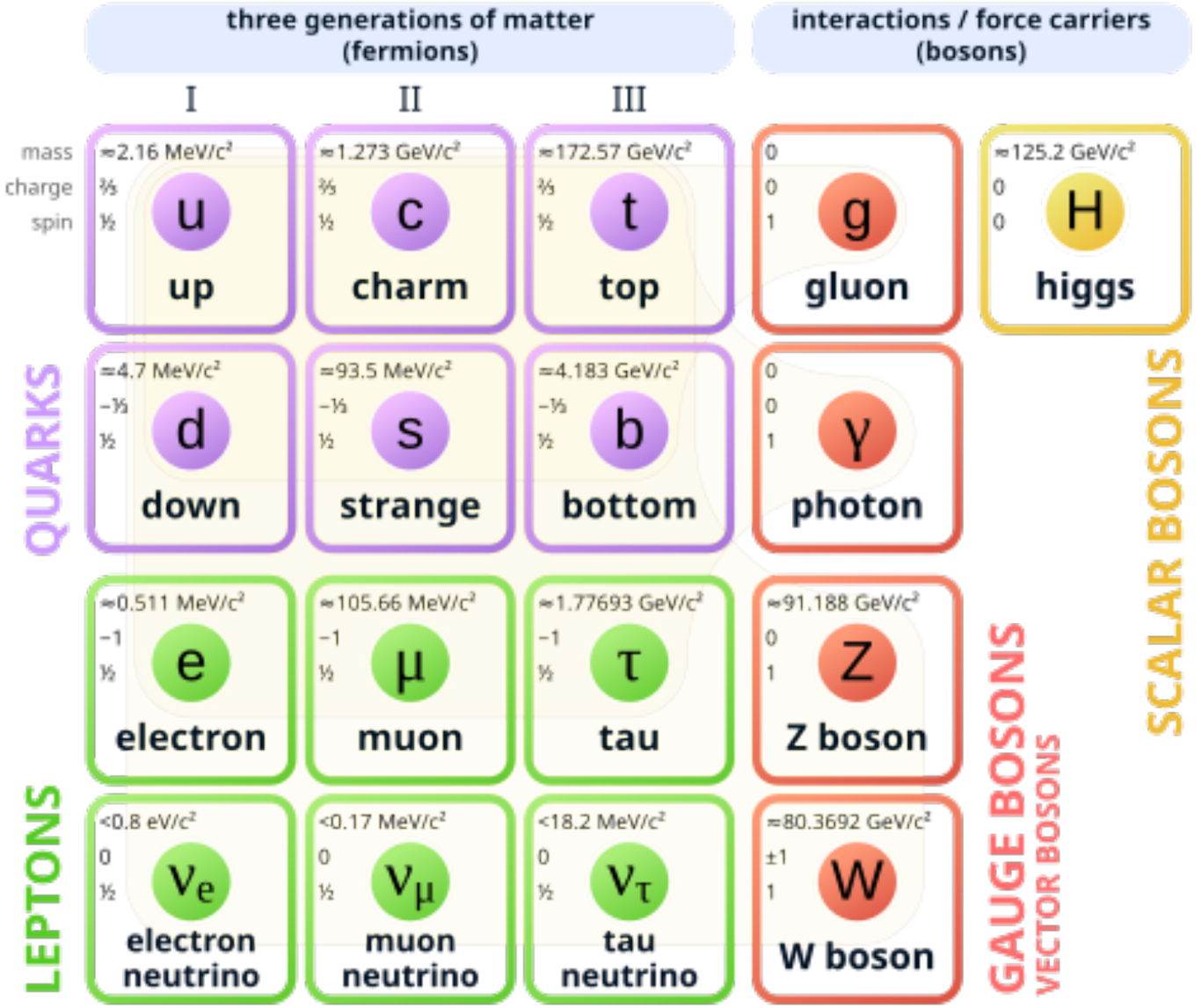
Long-standing flavor puzzle, but SM works very well

Better BSM sensitivity requires more precision

Circular lepton colliders (FCC/CepC/MuC) are an ideal ground for flavor physics

Backup slides

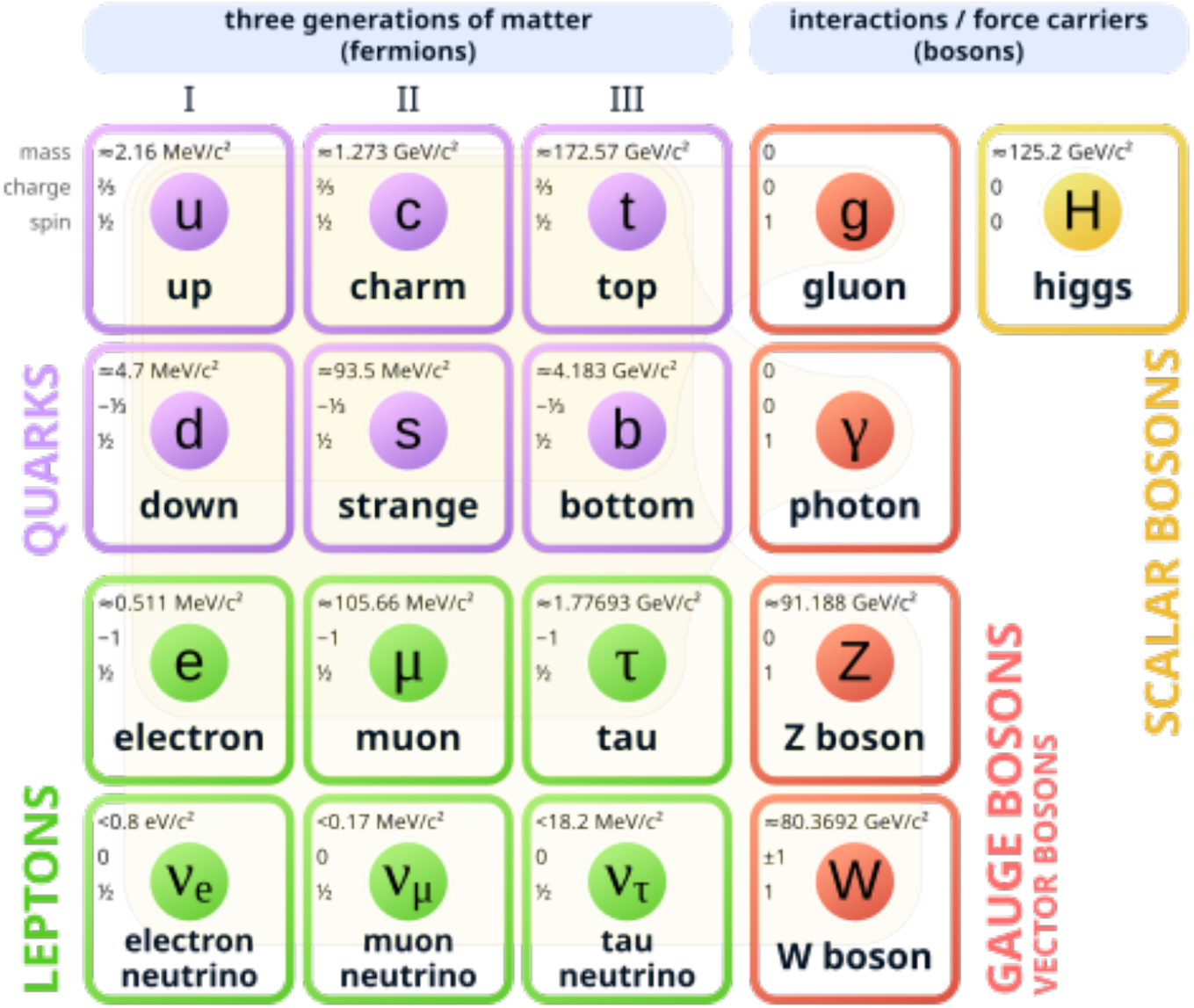
Standard Model of Elementary Particles



$$G_F \equiv U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$$

Flavor symmetry for $m_f = 0$

Standard Model of Elementary Particles



$$\cancel{G_F} \equiv U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$$

Explicitly broken by Yukawa terms

$$U(1)^4 = U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

Accidental symmetries!

$b \to q\ell\nu$

Zuo, Fedele, Helsens, Hill, Iguro, Klute: 2305.02998

$$\mathcal{B}(B_q^+ \to \tau^+\nu_\tau) \propto |V_{bq}|^2 m_\tau^2$$

$$\mathcal{B}(B_c^+ \to \tau^+\nu_\tau)^{\rm SM} = 2.29(9) \times 10^{-2}$$

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau)^{\rm SM} = 0.87(5) \times 10^{-4}$$

Helicity suppressed, but
predicted to be relatively large

FCC-ee > LHC

Better reconstruction

Lower backgrounds

FCC-ee > BelleII

B2 cannot produce B_c

O(20%) precision for B^+

$bq \to \ell\nu$

Zuo, Fedele, Helsens, Hill, Iguro, Klute: 2305.02998

$$\mathcal{B}(B_q^+ \to \tau^+\nu_\tau) \propto |V_{bq}|^2 m_\tau^2$$

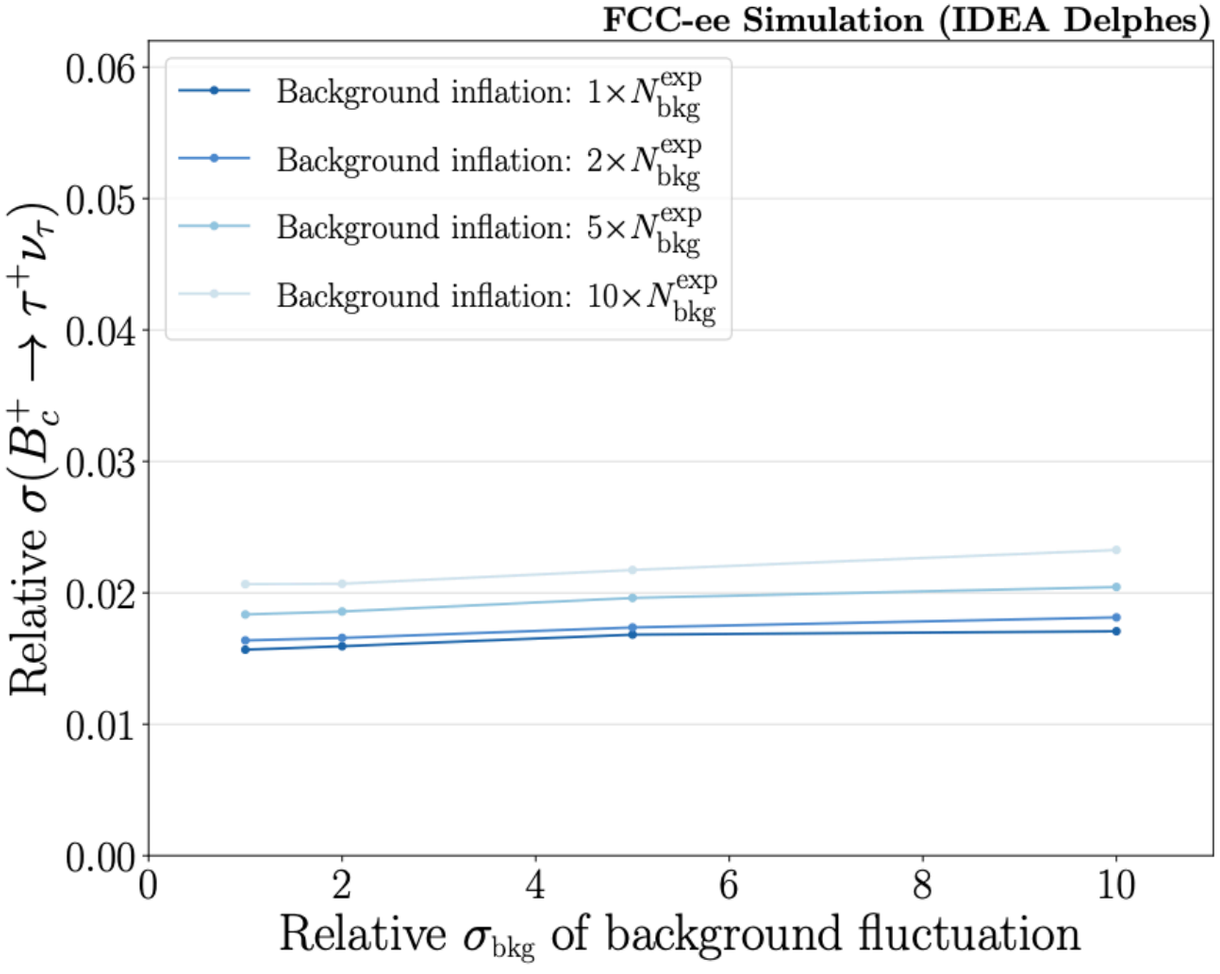
$$\mathcal{B}(B_c^+ \to \tau^+\nu_\tau)^{\rm SM} = 2.29(9) \times 10^{-2}$$

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau)^{\rm SM} = 0.87(5) \times 10^{-4}$$

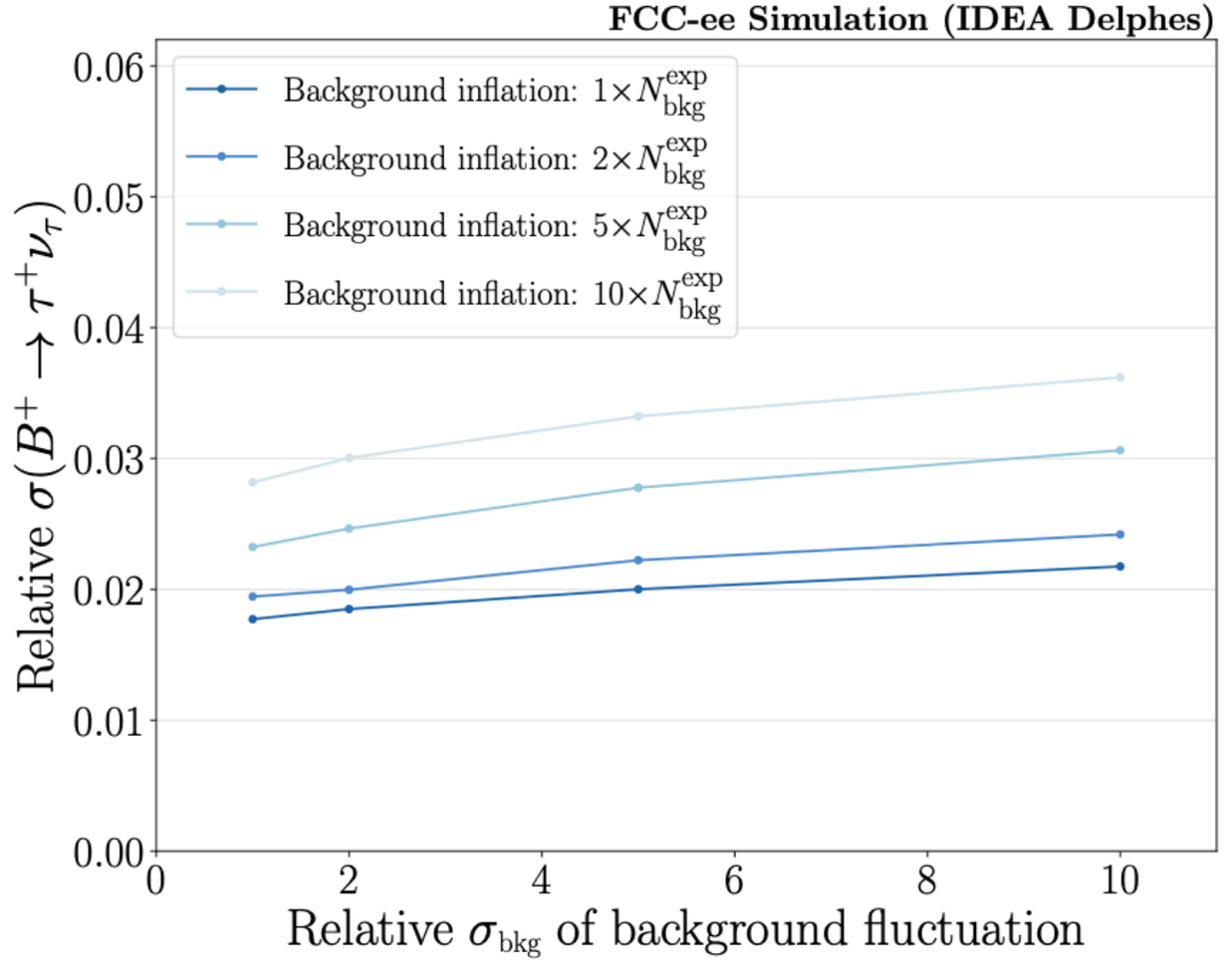
Helicity suppressed, but predicted to be relatively large

High S/B ratio, 1-3% precision projected

$B_c^+ \to \tau^+\nu_\tau$



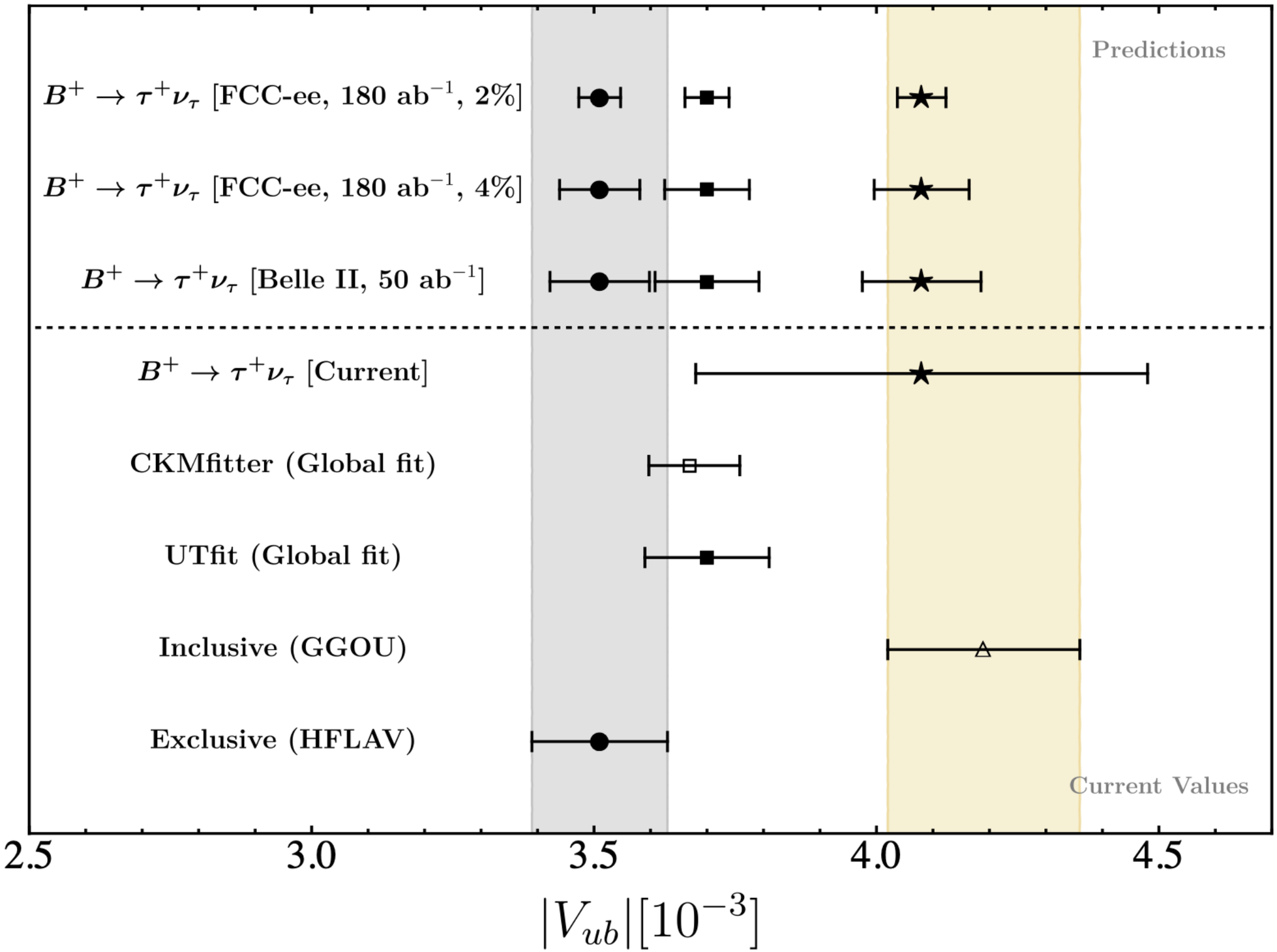
$B^+ \to \tau^+\nu_\tau$



$bq \to \ell\nu$

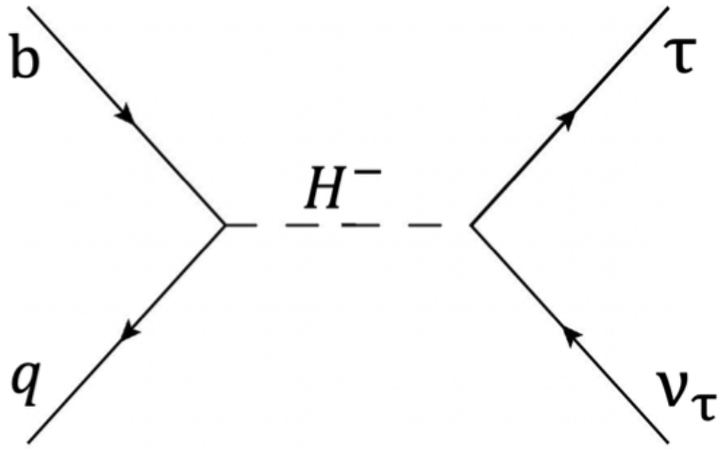
Zuo, Fedele, Helsens, Hill, Iguro, Klute: 2305.02998

Extract CKM (depends on lattice results)



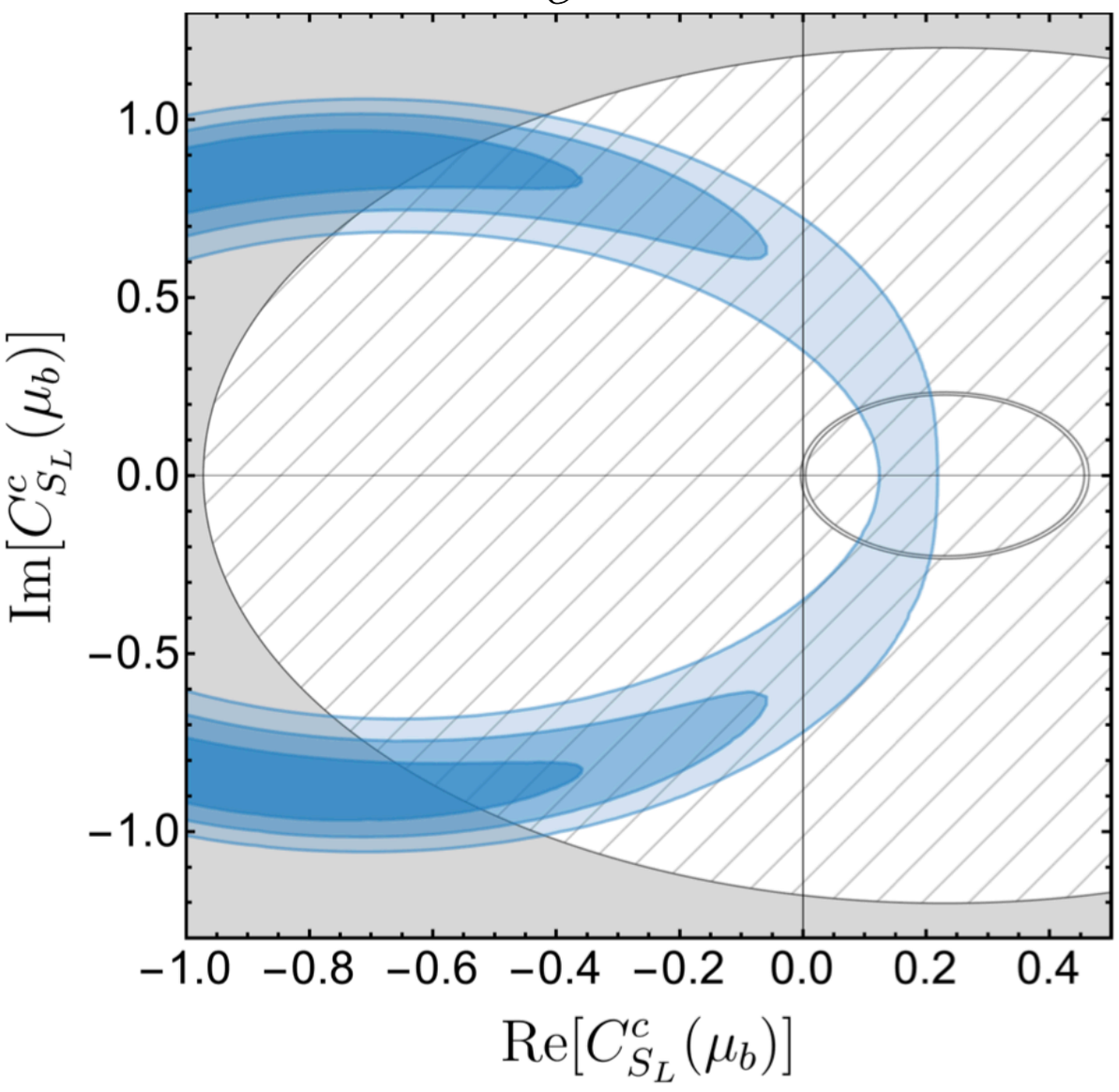
$bq \to \ell\nu$

Zuo, Fedele, Helsens, Hill, Iguro, Klute: 2305.02998

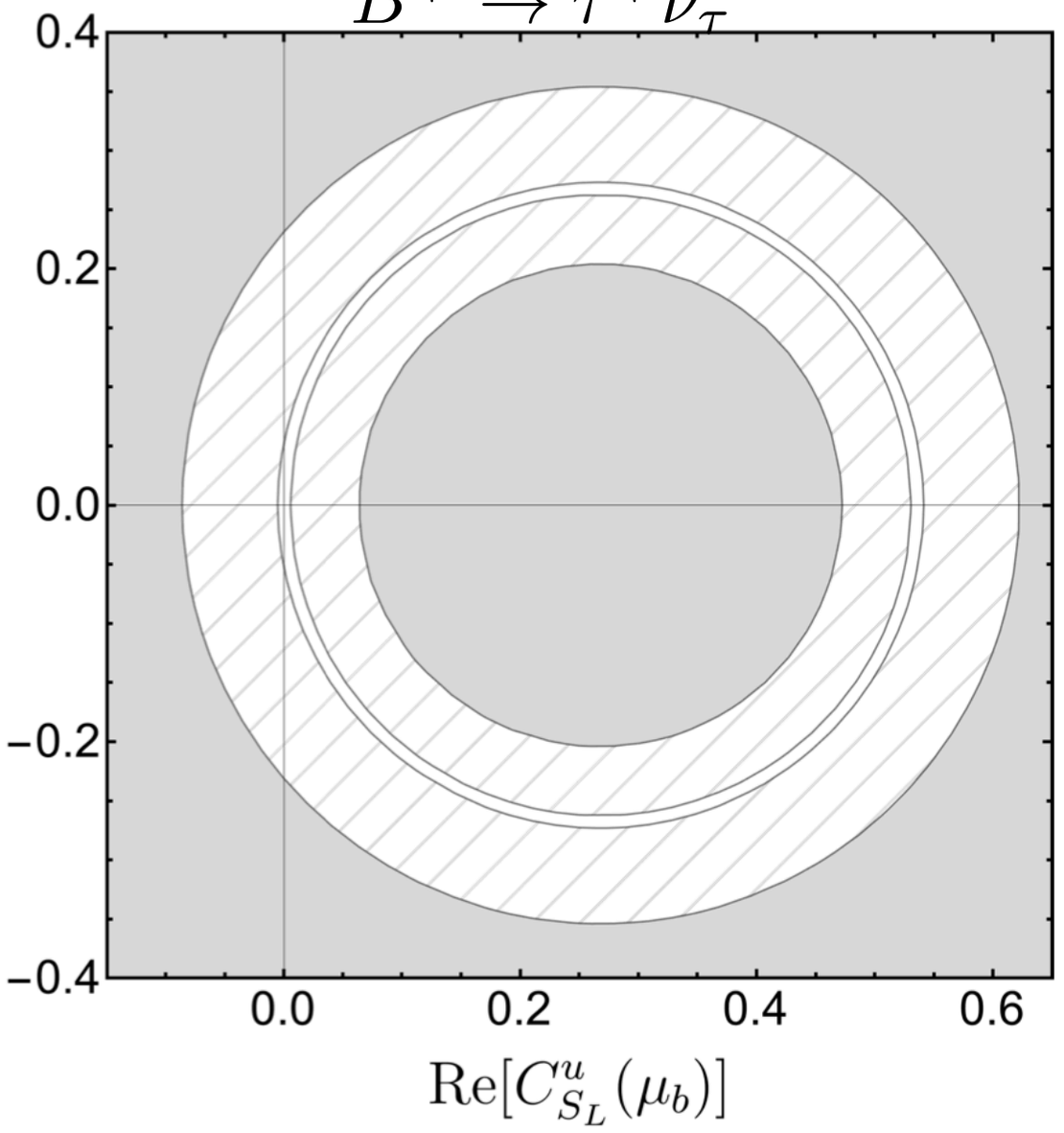


NP reach: Generic 2HDM

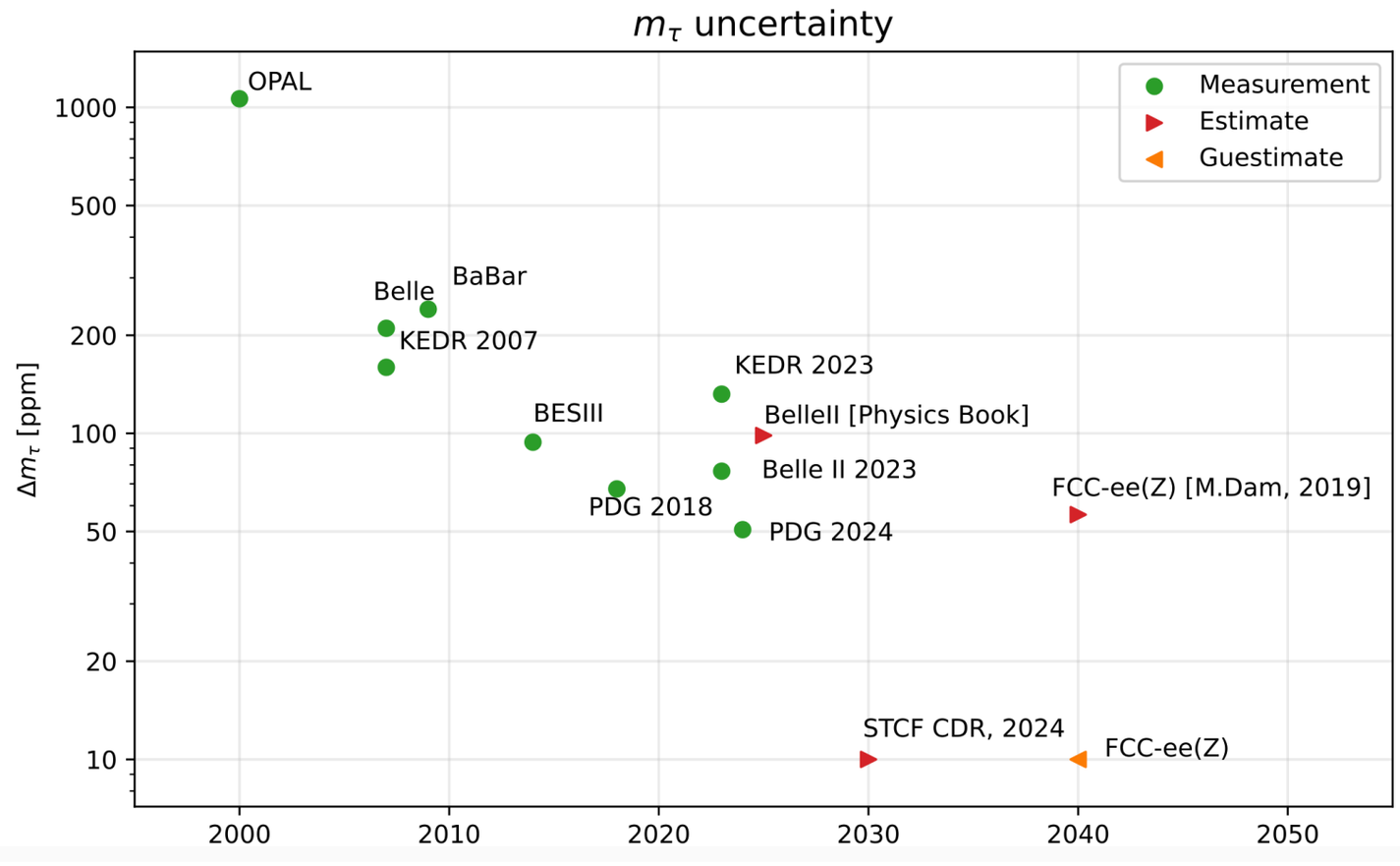
$B_c^+ \to \tau^+\nu_\tau$



$B^+ \to \tau^+\nu_\tau$



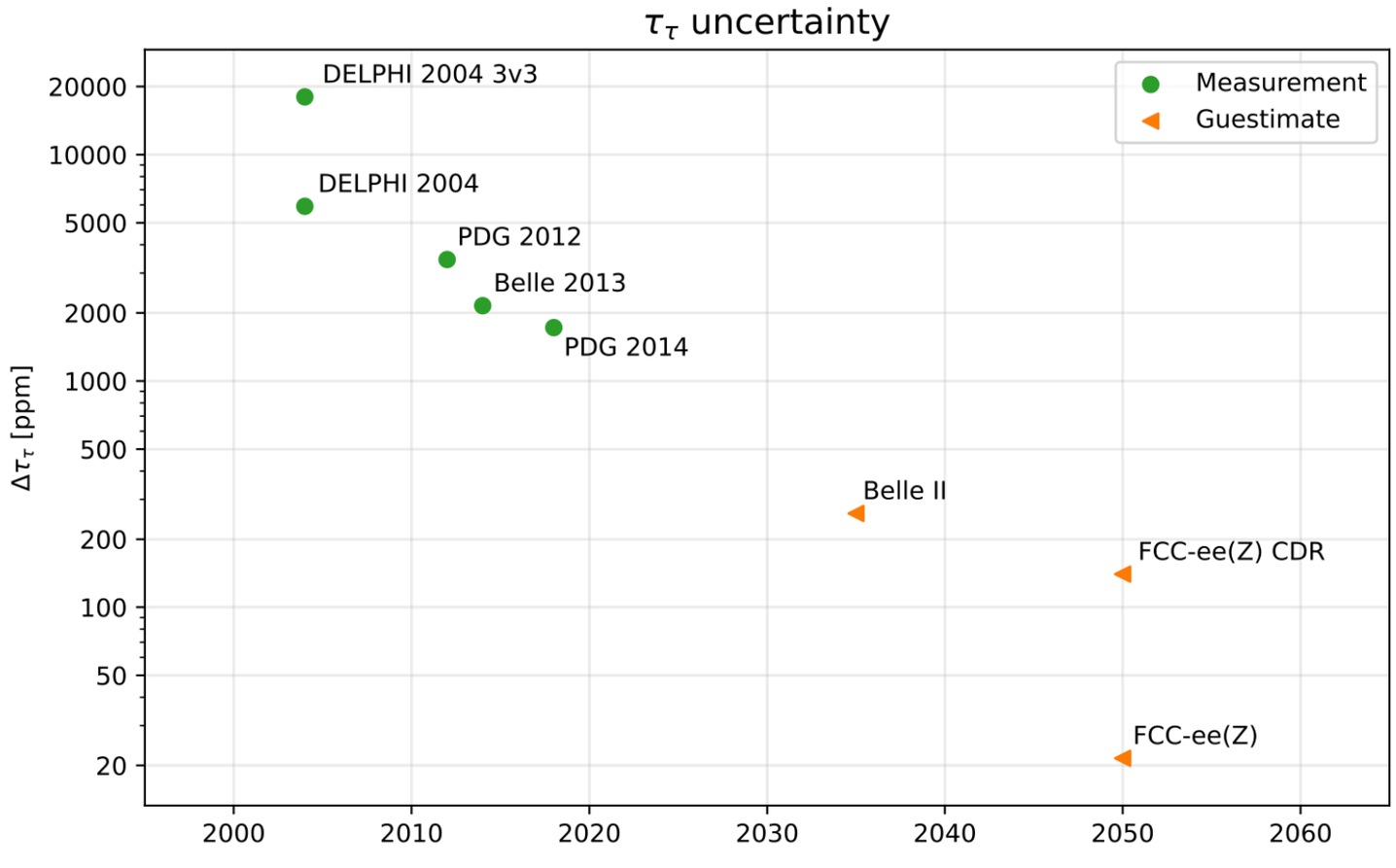
Tau lepton



Super Tau-Charm Factory (STCF) will also enter the game

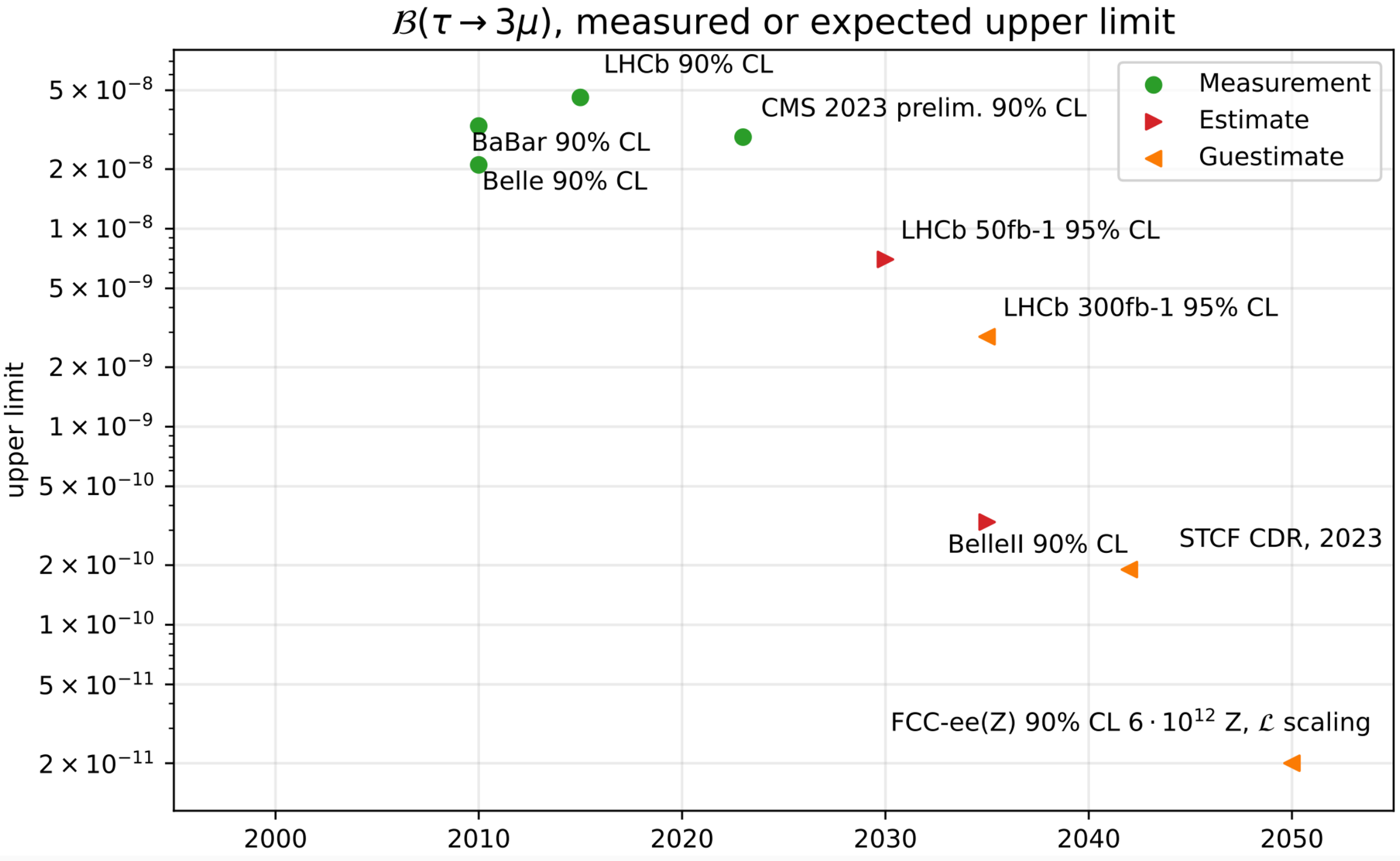
Lusiani's talk at "2nd FCC Italy&France Workshop (https://indico.cern.ch/event/1457081/)

General improvement by orders of magnitude



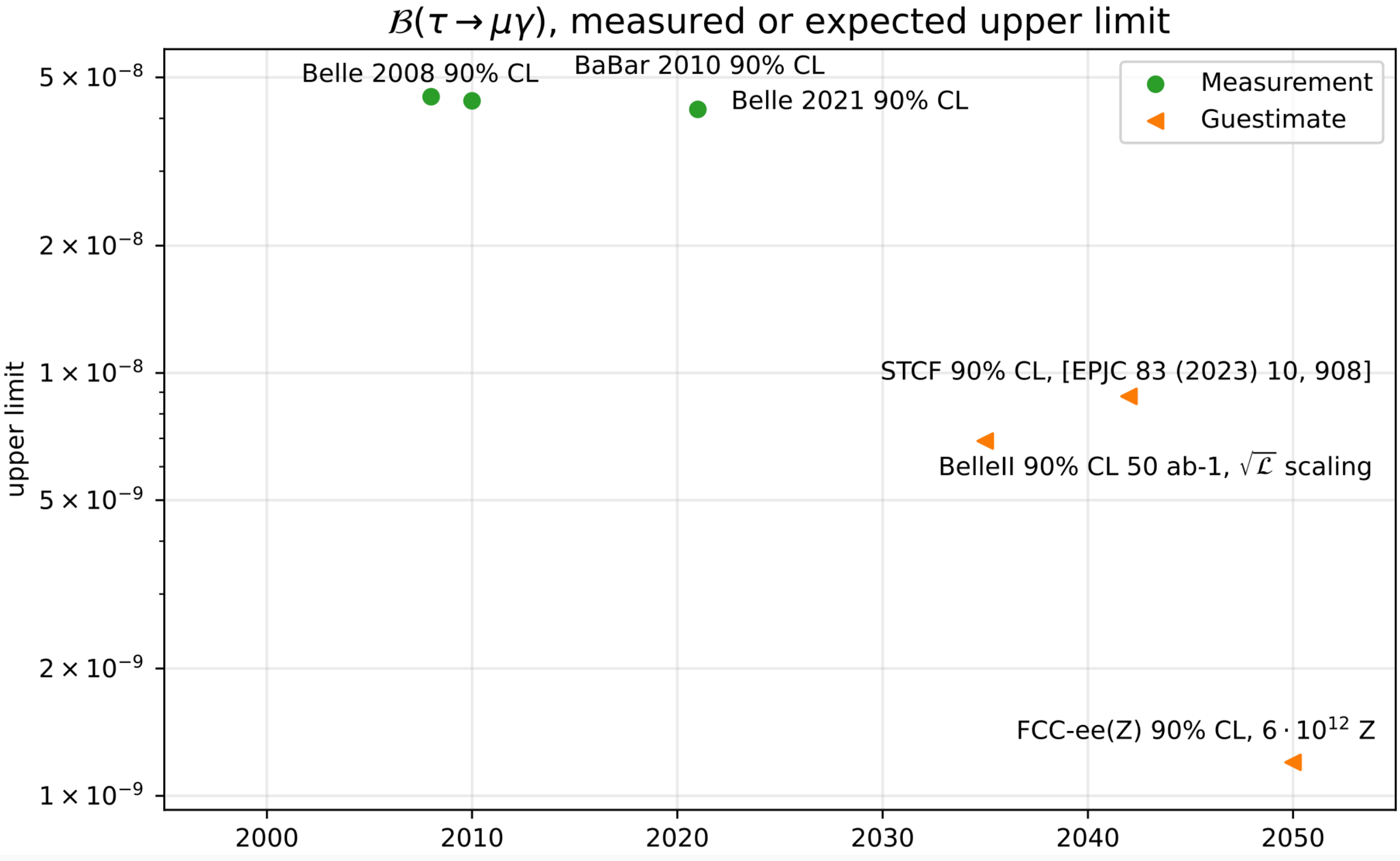
Tau lepton

Lusiani's talk at "2nd FCC Italy&France Workshop (https://indico.cern.ch/event/1457081/)

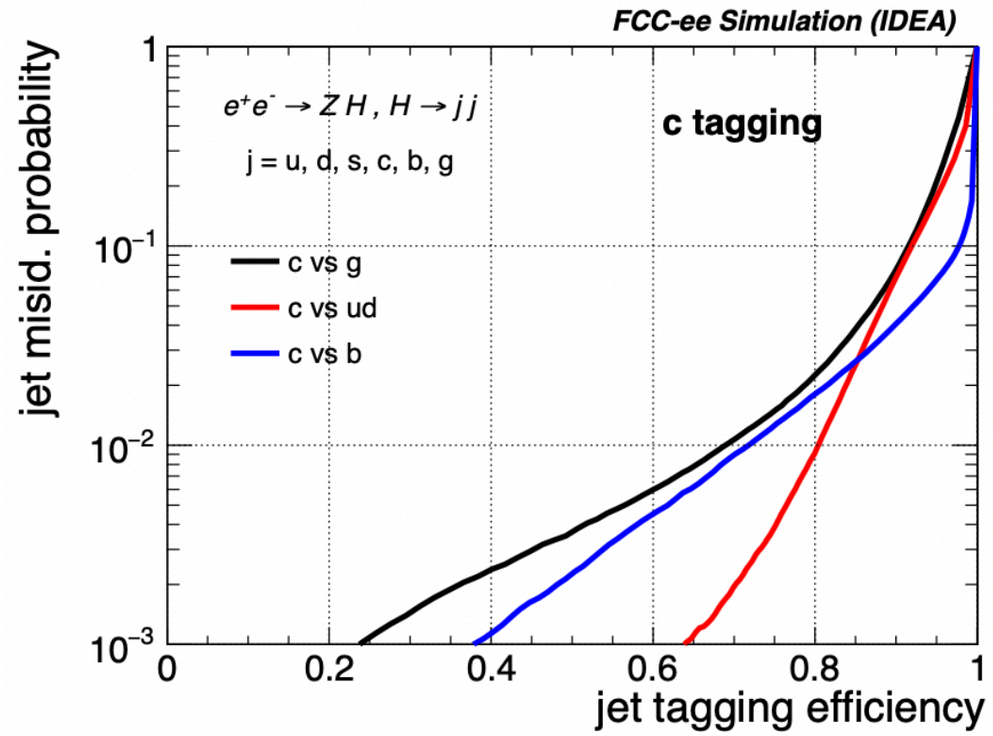


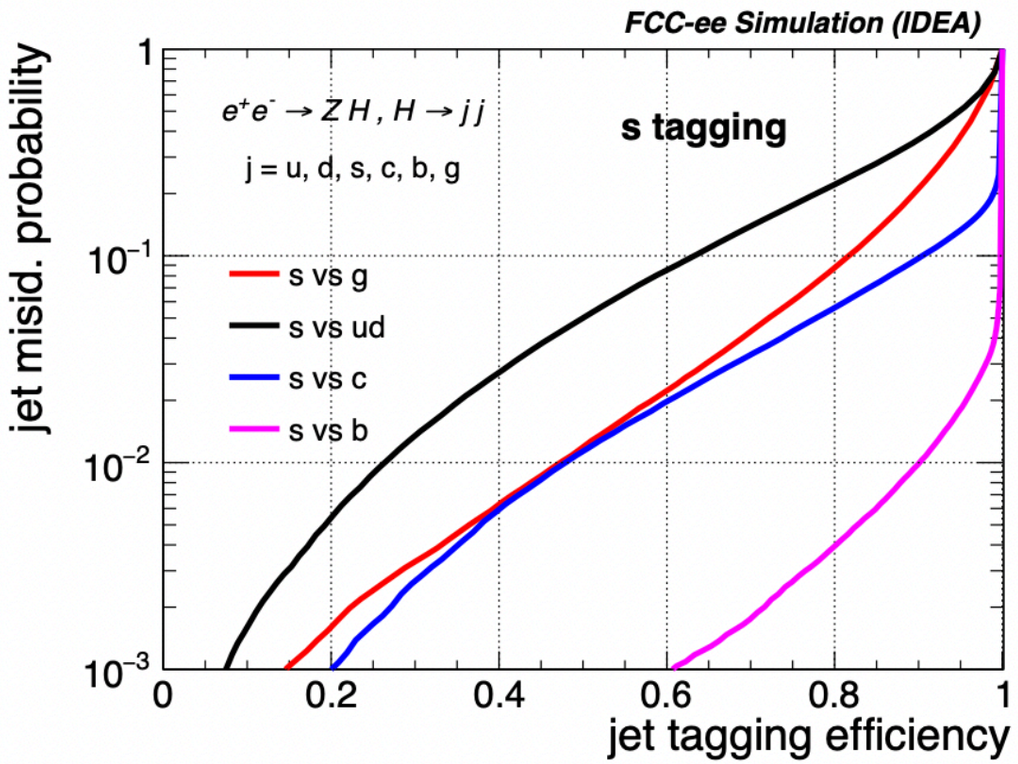
Tau lepton

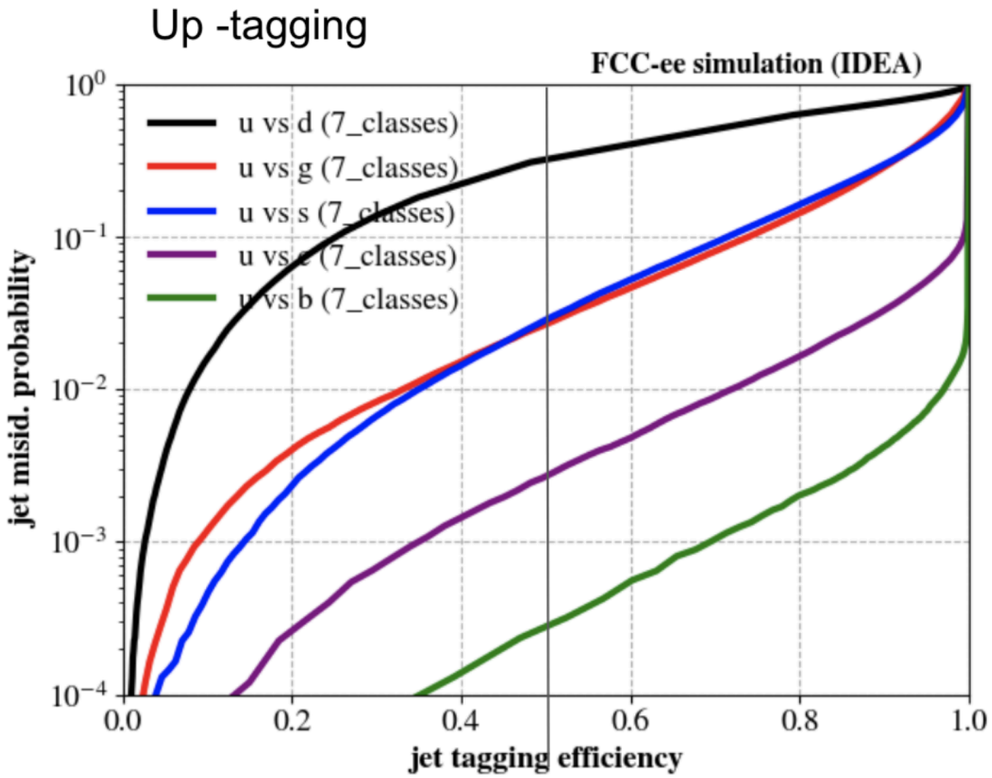
Lusiani's talk at "2nd FCC Italy&France Workshop (https://indico.cern.ch/event/1457081/)

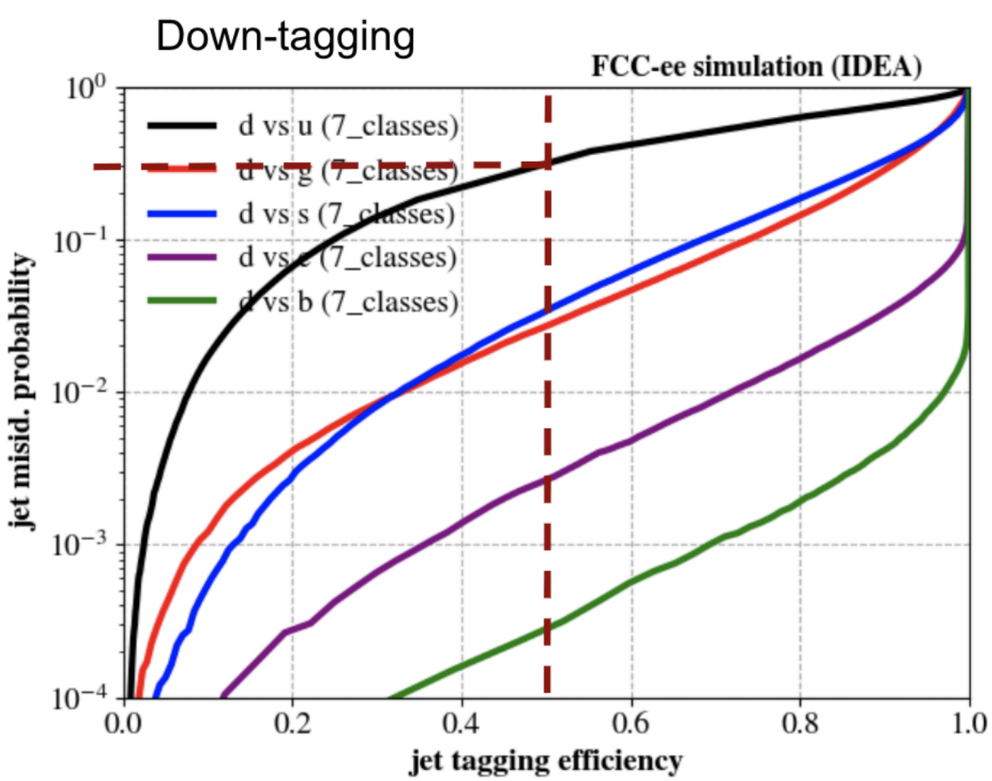


Jet flavor taggers

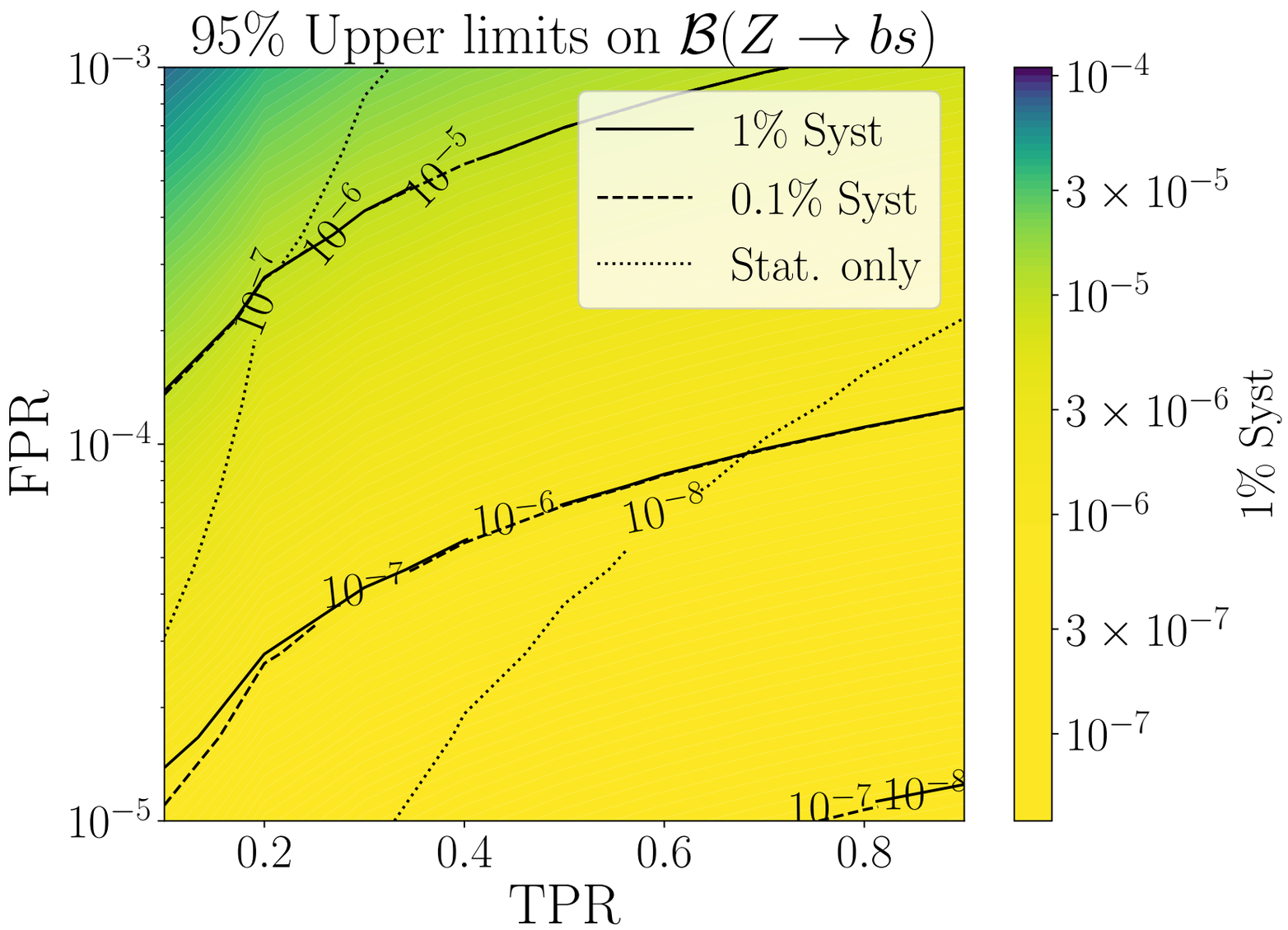








Selvaggi's talk at "FCC Phenomenology Workshop" (https://indico.cern.ch/event/1278845/)



TPR

$\epsilon_b^b = \epsilon_s^s$

FPR

$\epsilon_{udsc}^b = \epsilon_{udcb}^s$

$\epsilon_b^s \lesssim 10^{-4}$ limited by vertexing

3-5μm estimated

Barchetta, Collins, Riedler: 2112.13019

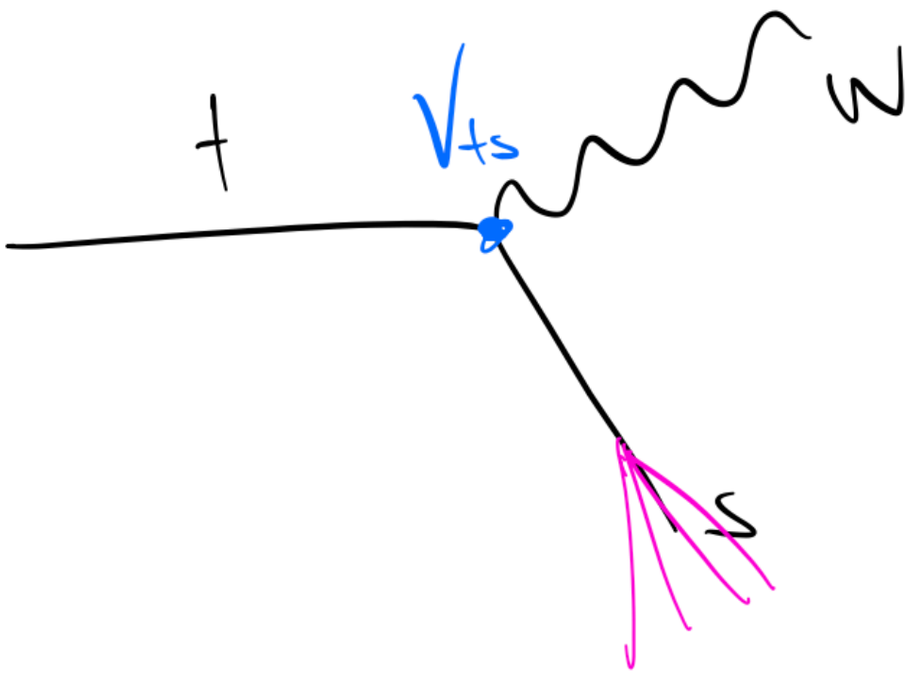
$(\text{TPR}, \text{FPR}, \Delta\epsilon_\beta^\alpha/\epsilon_\beta^\alpha)$	$\mathcal{B}(Z \to bs)$ (95% CL)
$(0.4,\ 10^{-4},\ \ 1\%)$	1.8×10^{-6}
$(0.4,\ 10^{-4},\ 0.1\%)$	1.8×10^{-7}
$(0.2,\ 10^{-5},\ \ 1\%)$	4.2×10^{-7}
$(0.2,\ 10^{-5},\ 0.1\%)$	4.2×10^{-8}

Is 0.1% feasible?

See M. Selvaggi's plenary talk at "7th FCC Physics Workshop" (https://indico.cern.ch/event/1307378)

SM level

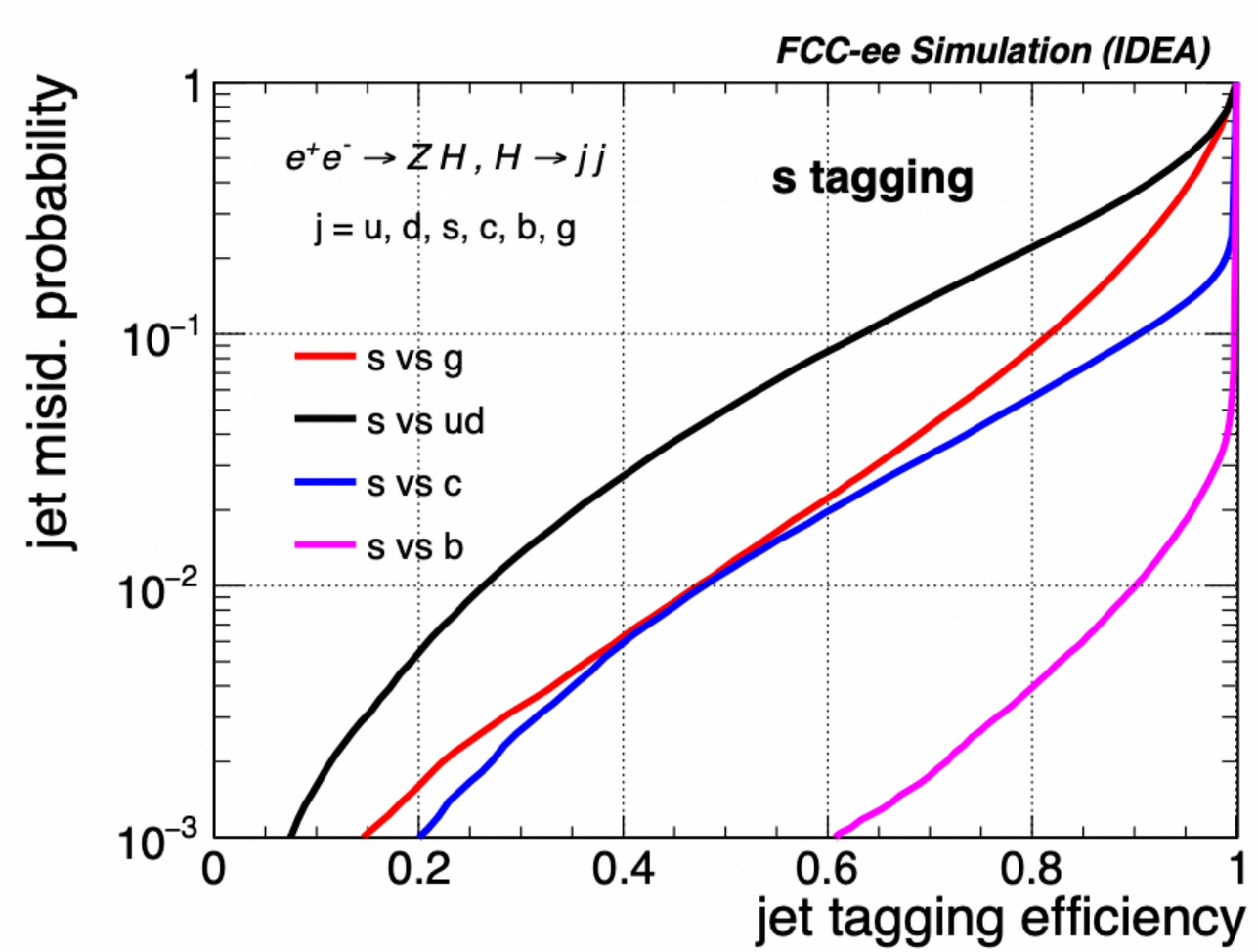
CKM



Strange tagger is the key

Zuo's talk at "3rd ECFA Workshop" (https://indico.in2p3.fr/event/32629)

Bedeschi, Gouskos, Selvaggi: 2202.03285
Gouskos' talk at "FCC Physics Workshop" (indico.cern.ch/event/1176398/)



Tagger at tt run could improve with retraining

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

Current

$$(41.5 \pm 0.9) \times 10^{-3} \qquad (2.2\%)$$

Future (FCC-ee)

$$\sigma(|V_{ts}|) \sim 10\%$$