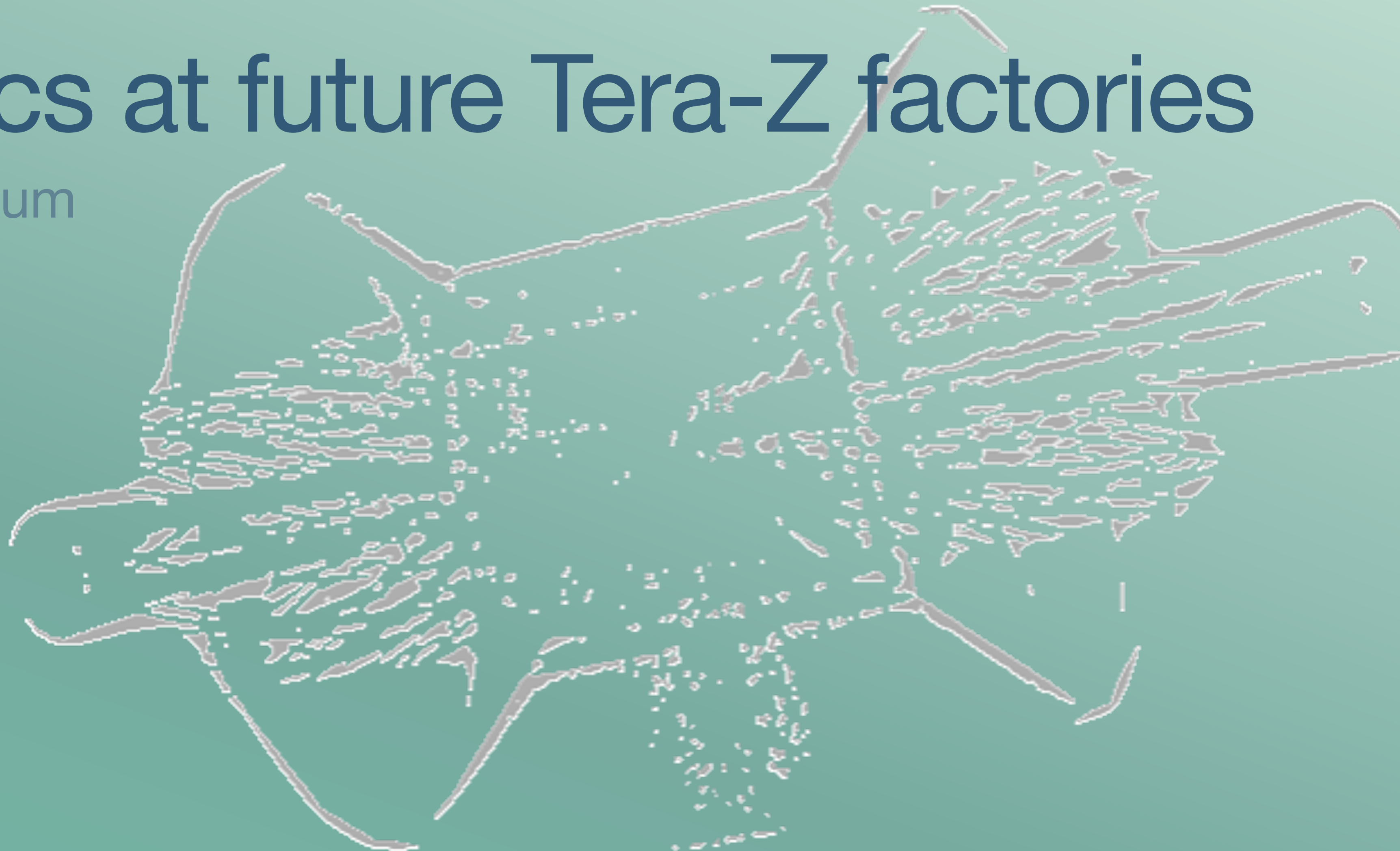


Flavor physics at future Tera-Z factories

online flavor physics forum
25.12.2025

Xunwu Zuo (EPFL)



FCC-ee project

- General design
- European Strategy & feasibility study
- Run plan

Tera-Z flavor overview

Tera-Z flavor topics

- Rare b-hadron decays
- CKM measurements
- CP violation
- Charm
- Tau
- Strange

The FCC-ee project

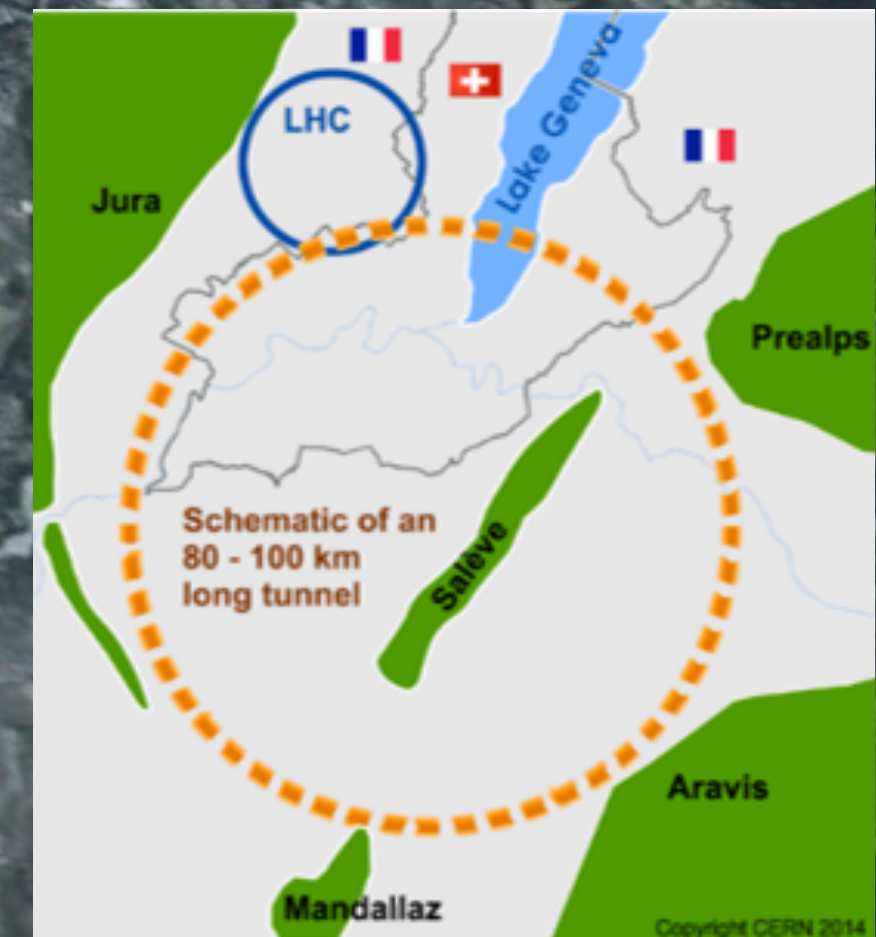
FCC project

New infrastructure

- 90.7 km tunnel
- 8 surface points
- 4 experimental sites
- Deepest shaft 400 m, average 240 m

Two stages

- FCC-ee (~15 years)
- FCC-hh (>20 years)



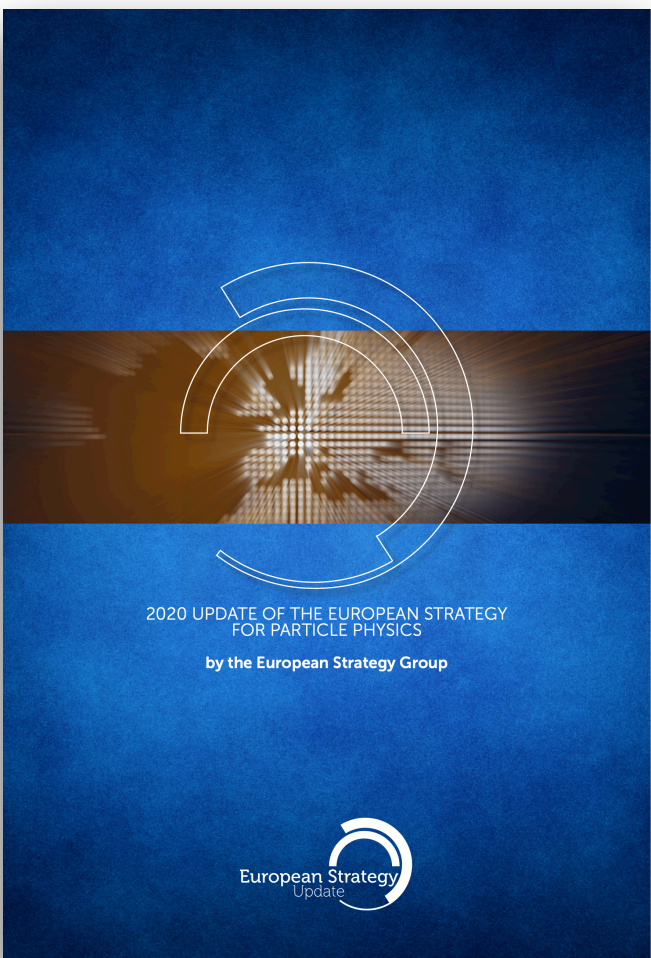
Historic timeline

1st European strategy



“Europe needs to be in a position to **propose** an ambitious **post-LHC accelerator project** at CERN by the time of the next Strategy update”

2nd European strategy



Europe, together with its international partners, should investigate the **technical and financial feasibility** of a **future hadron collider** at CERN with a center-of-mass energy of at least 100 TeV and with an **electron-positron Higgs and electroweak factory** as a possible first stage.

3rd European strategy

March 31, 2025: Contribution submission complete

October 02, 2025: Physics briefing book

January 2026: ESPP draft to CERN council

May 29 2026: council decision

Higgs discovery
2012

2013

2019

2026

❖ 2012-2013

❖ 2014-2018

❖ 2021-2025

❖ 2025-2027

Early concepts

FCC conceptual design study

FCC feasibility study

pre-TDR

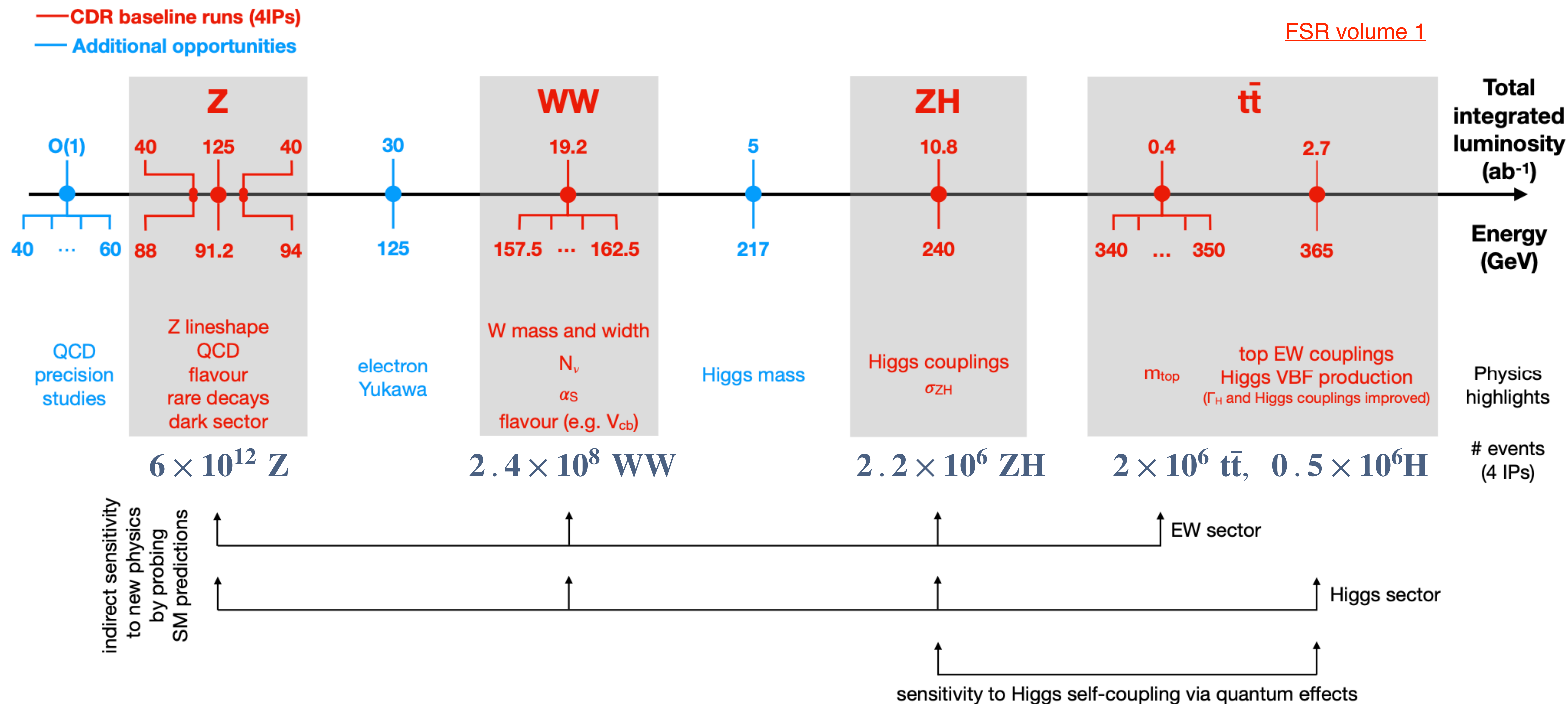
- TLEP concept

- FCC CDRs

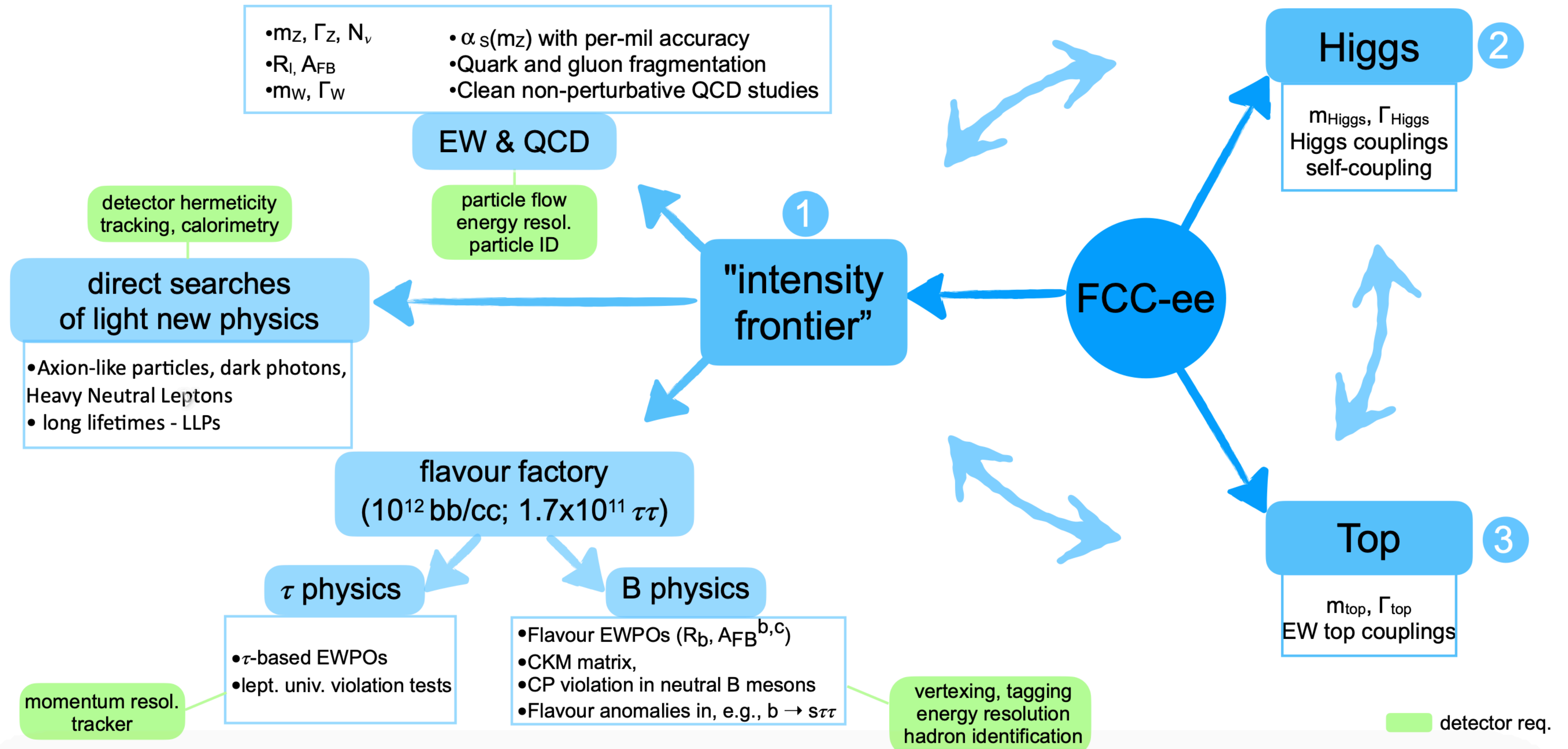
- Feasibility study reports

Decision around 2028

FCC-ee physics runs



Physics program



Flavor physics at FCC-ee/CEPC

Tera-Z factory as a flavor machine

Best option for next-generation flavor machine

Advantage over Belle II

- About 14x more B^0/B^+ than Belle II (50 ab^{-1})
- All species of b-hadrons are produced

Advantage over LHCb

- Clean collision environment, much better photon, electron reconstruction
- Precisely known initial energy $\rightarrow$ missing energy information

particle count ($\times 10^9$)	$B^0 (\bar{B}^0)$	$B^\pm$	$B_s (\bar{B}_s)$	$B_c^\pm$	$\Lambda_b (\bar{\Lambda}_b)$	$c (\bar{c})$	$\tau^\pm$
Belle II	55	55	0.6	N.A.	N.A.	130	90
FCC-ee	770	770	170	0.7	150	1400	400

Beyond Z factory

$O(10^8)$ WW pairs

- Direct CKM measurement
- $\mathcal{B}(W \rightarrow \ell \nu)$ for LFU

$O(10^6)$ Higgs bosons

- Flavor violating $H \rightarrow qq', \ell \ell'$ decays

$O(10^6)$ top pairs

- Direct CKM measurement
- FCNC top production

Main refs for this talk

- FCC flavor summary

<https://indico.cern.ch/event/1439855/contributions/6461584/>

- FCC flavor workshop series

<https://indico.cern.ch/event/1588013/>

- CEPC flavor white paper

[Chinese Phys. C 49 103003](#)

Flavours at FCC Workshop

Nov 19 – 21, 2025
CERN
Europe/Zurich timezone

Enter your search term



Overview

Scientific Program
Timetable
Contribution List
Registration
Participant List
Privacy Information
CERN Hostel

Physics at the Flavoured Circular Collider: preparing for heavy quark and lepton studies in the post HL-LHC/Belle II era

Next in-person event: 16-19 June at CERN. Details to be announced early in New Year.

Experimentalists and theorists from the world-wide particle physics community are invited to participate in an extended workshop, beginning autumn 2025 and scheduled to continue until summer 2027 to deepen our understanding of the potential of the FCC-ee for heavy-flavour physics in the quark and lepton sector. This will build on the studies performed for the Conceptual Design Report and Feasibility Study Report and seek to set the agenda, and prepare the tools, for physics in the post HL-LHC and Belle II era.

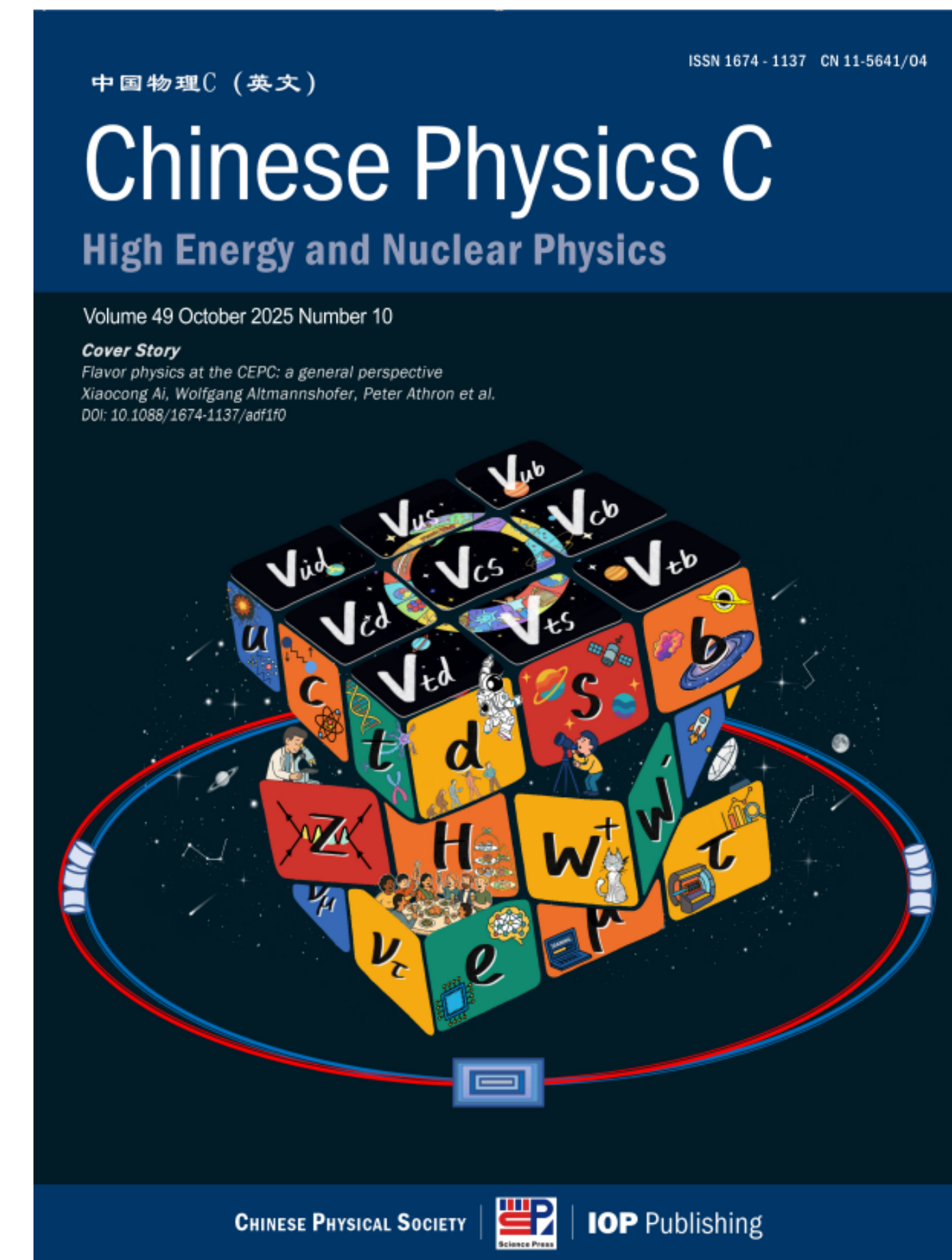


Table of content

- Rare b-hadron decays
- CKM measurements
- CP violation
- Charm
- Tau
- Strange

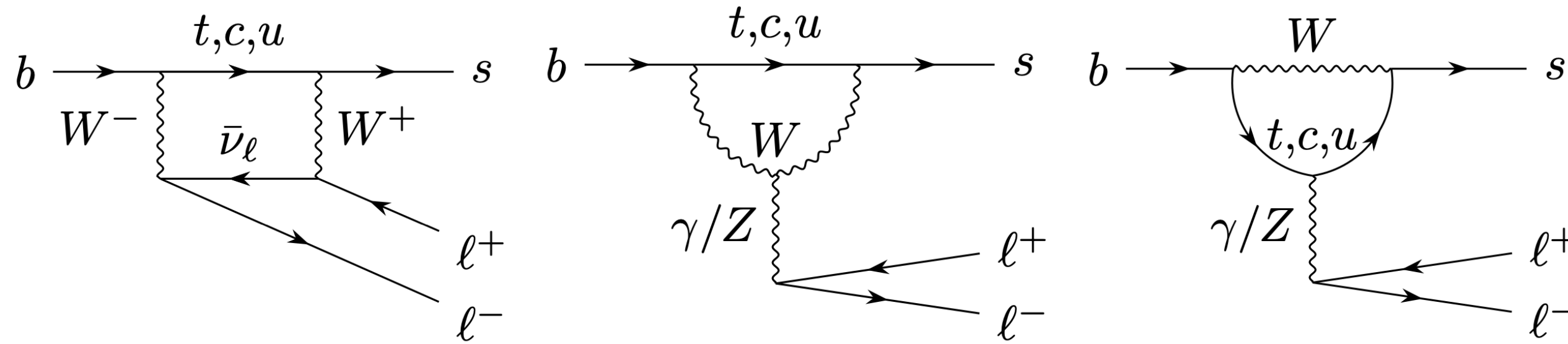
Opportunity to completely examine flavor landscape, only a fraction studied so far.

Rare b-hadron decays

Cases:

- $b \rightarrow s\ell\ell: B_s \rightarrow \tau^+\tau^-, B^0 \rightarrow K^{*0}\tau^+\tau^-$ [FCC note: B->Ktautau](#)
- $b \rightarrow s\nu\nu: B \rightarrow K\nu\bar{\nu}, B_s \rightarrow \nu\nu$ [2309.11353](#) [2508.04471](#)

$$b \rightarrow s \ell \ell$$

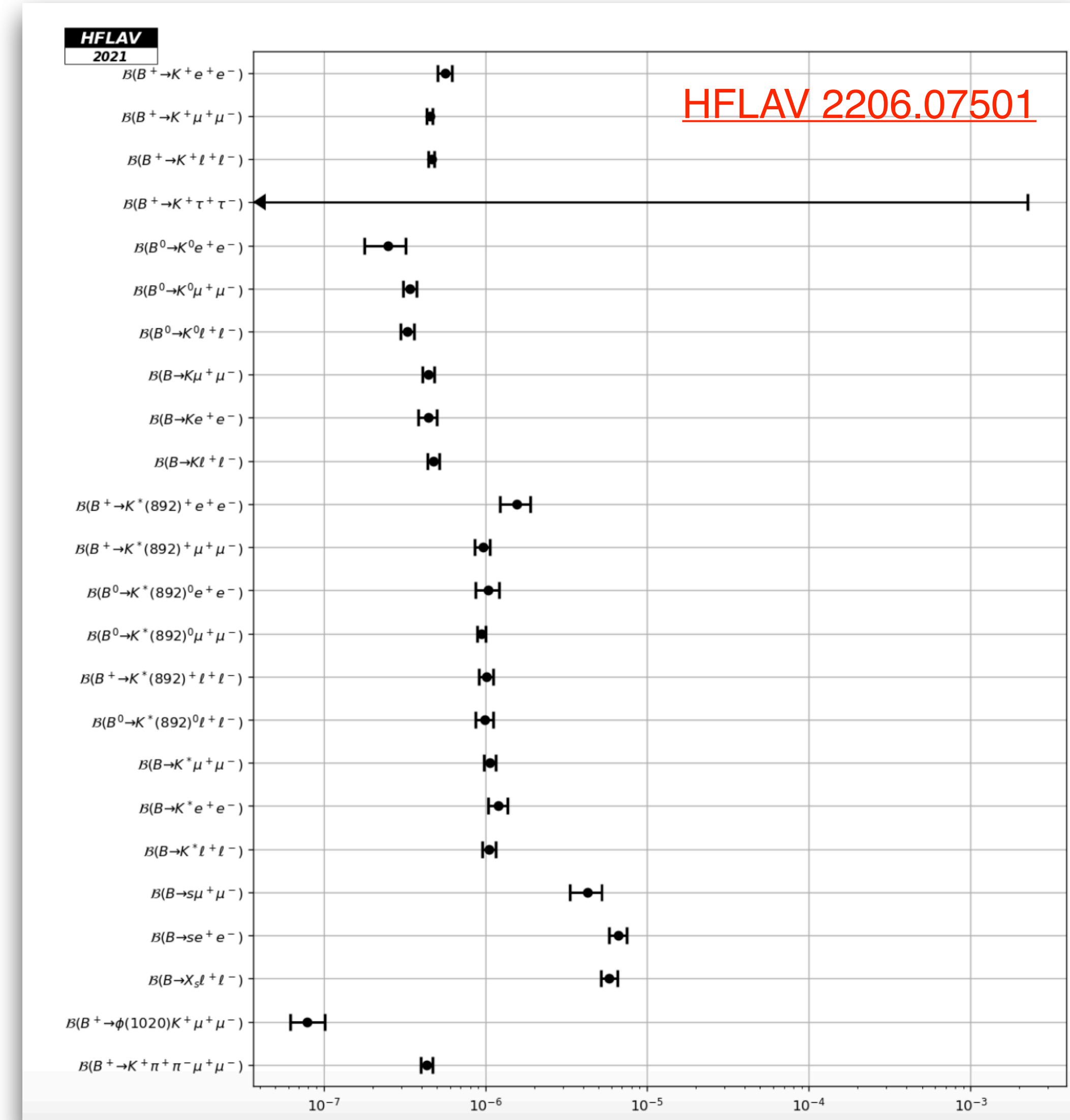


Case study - $B^0 \rightarrow K^{*0} \tau^+ \tau^-$

- Expected $BR_{SM}(B \rightarrow K \tau \tau) \sim O(10^{-7})$
- Belle II (365 fb^{-1}): $< 1.8 \times 10^{-3}$ [2504.10042](#)
- Belle II (50 ab^{-1}): $< 5.3 \times 10^{-4}$ [2207.06307](#)

requires an excellent detector

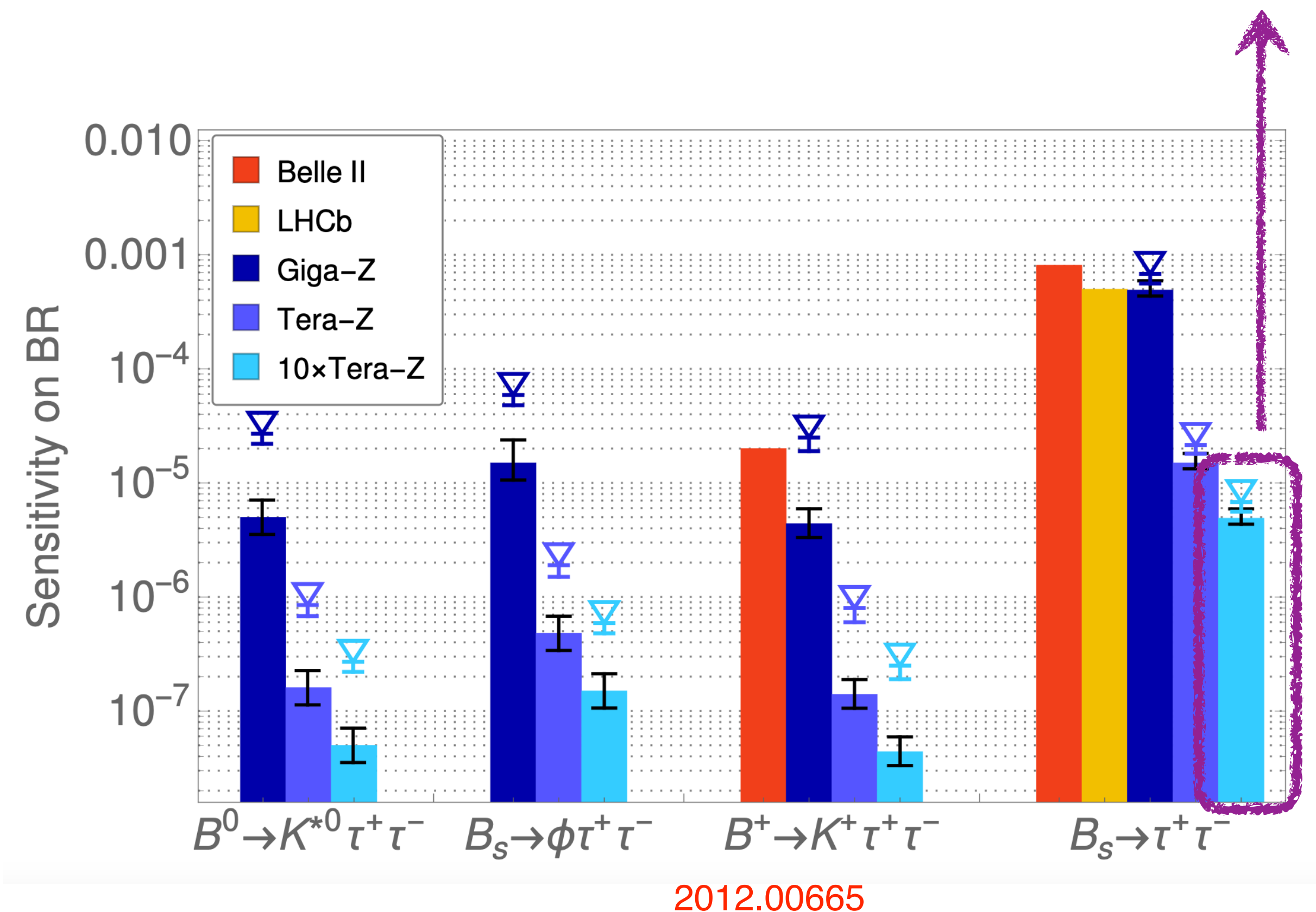
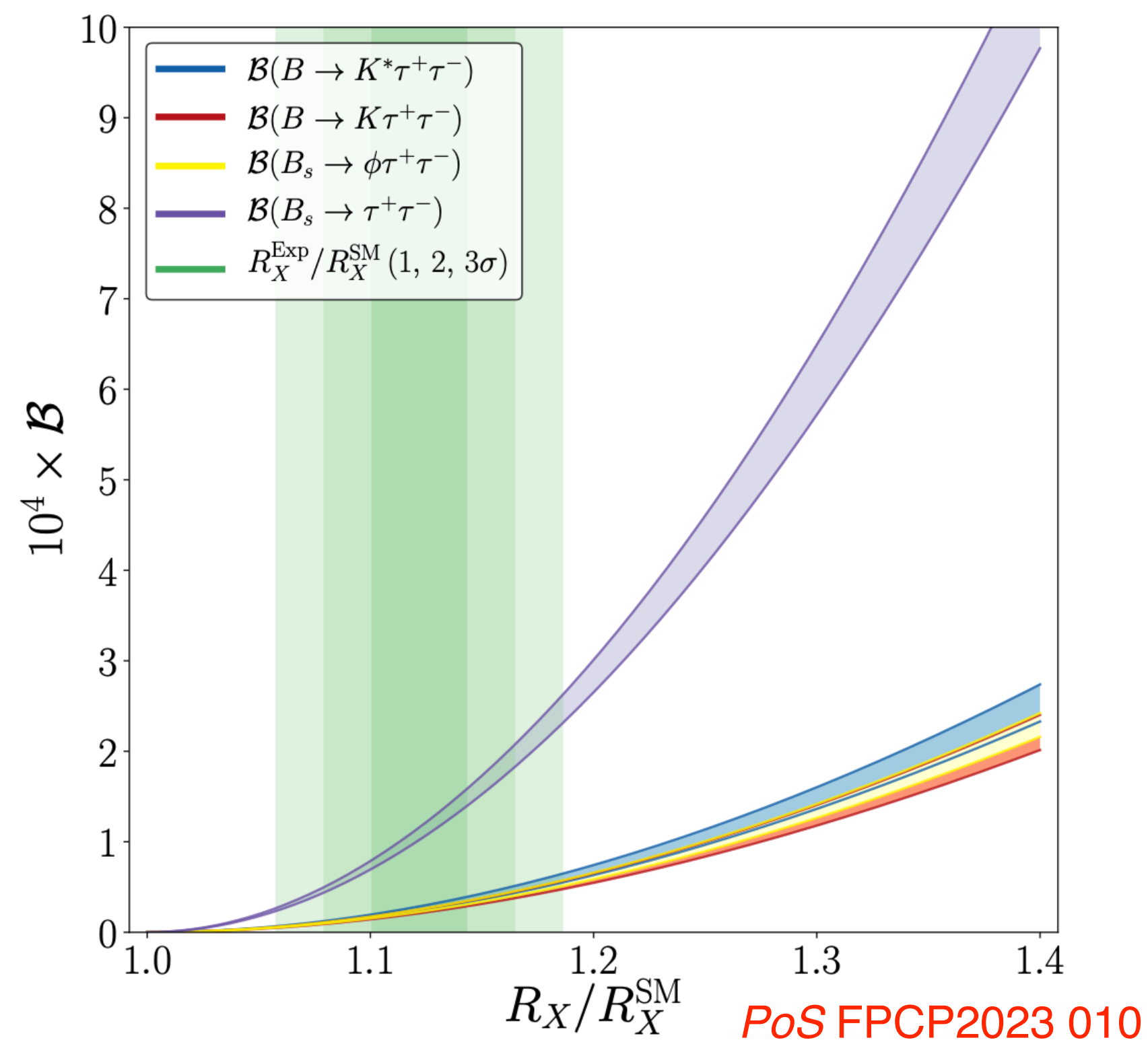
- PID efficiency
- Energy resolution
- Vertex resolution
- Missing energy info



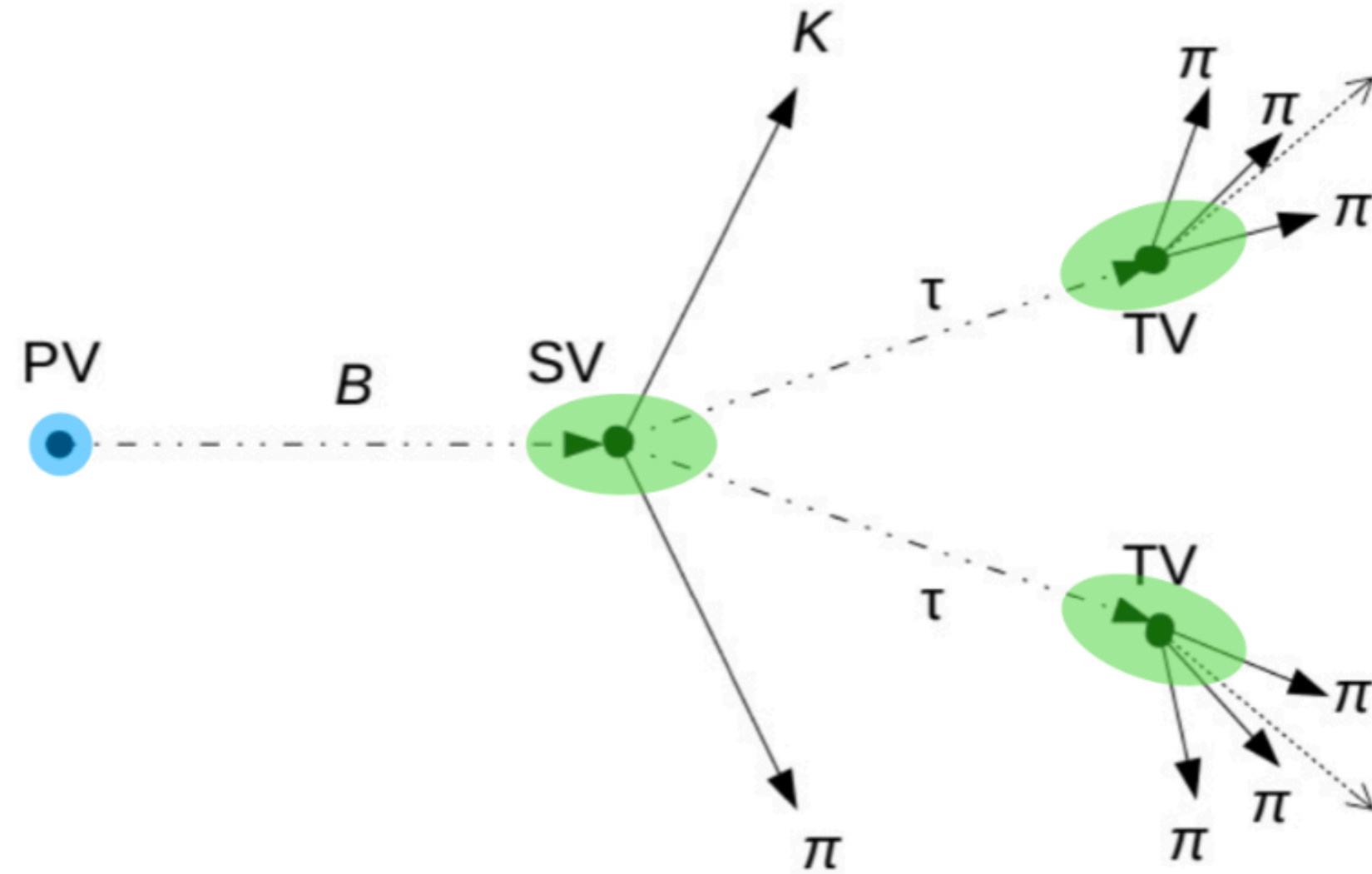
Case study - $B_s \rightarrow \tau^+ \tau^-$

- Theory motivation: $O(10^4)$ enhancement allowed for $B_s \rightarrow \tau^+ \tau^-$
- Challenge at Belle II: limited amount of B_s
- Challenge at LHCb: difficult to reduce backgrounds
- Expect strong constraint at Tera-Z

$$\delta \approx 5 \times 10^{-6}, \sim 10X \text{ SM}$$

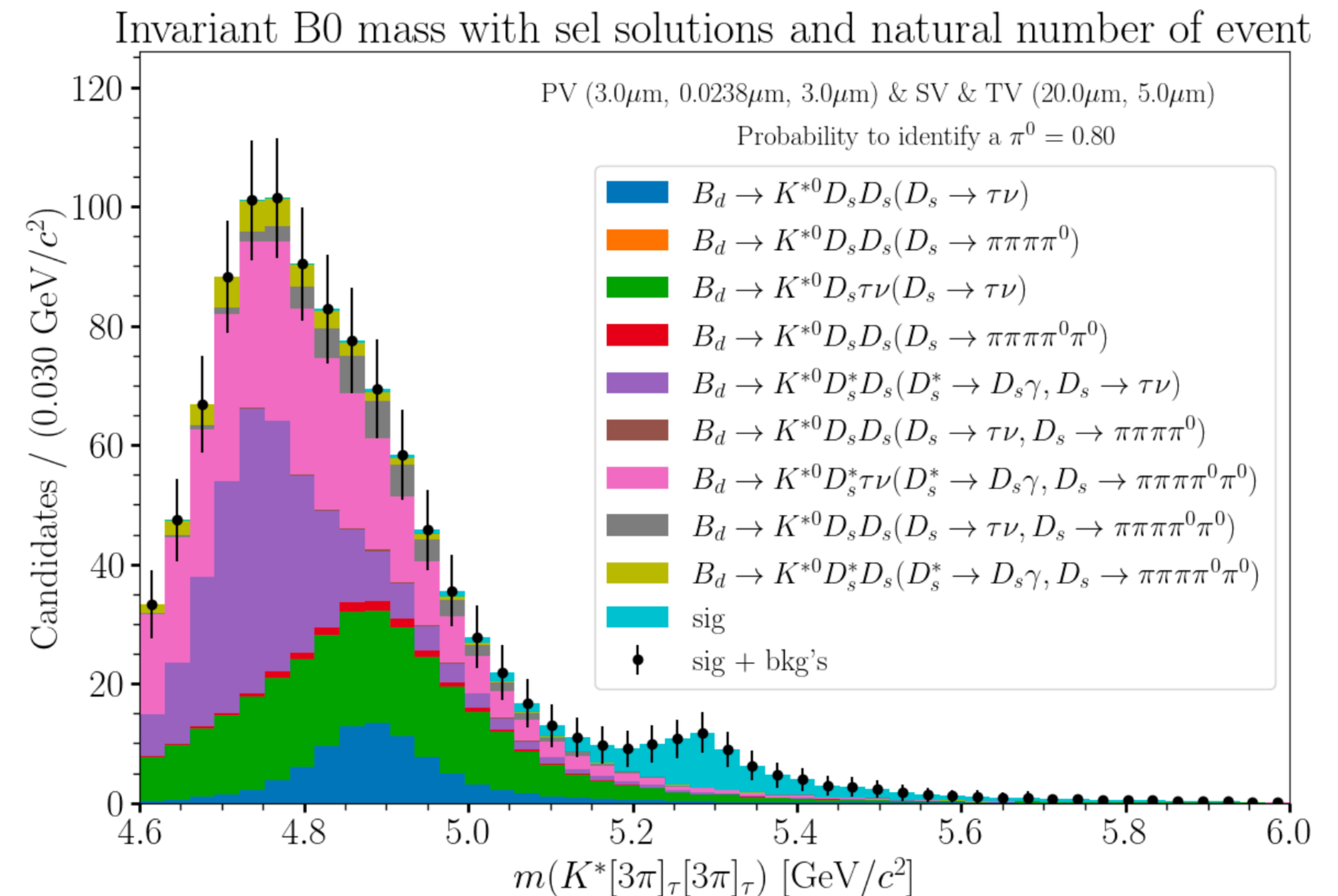


Case study - $B^0 \rightarrow K^{*0} \tau^+ \tau^-$

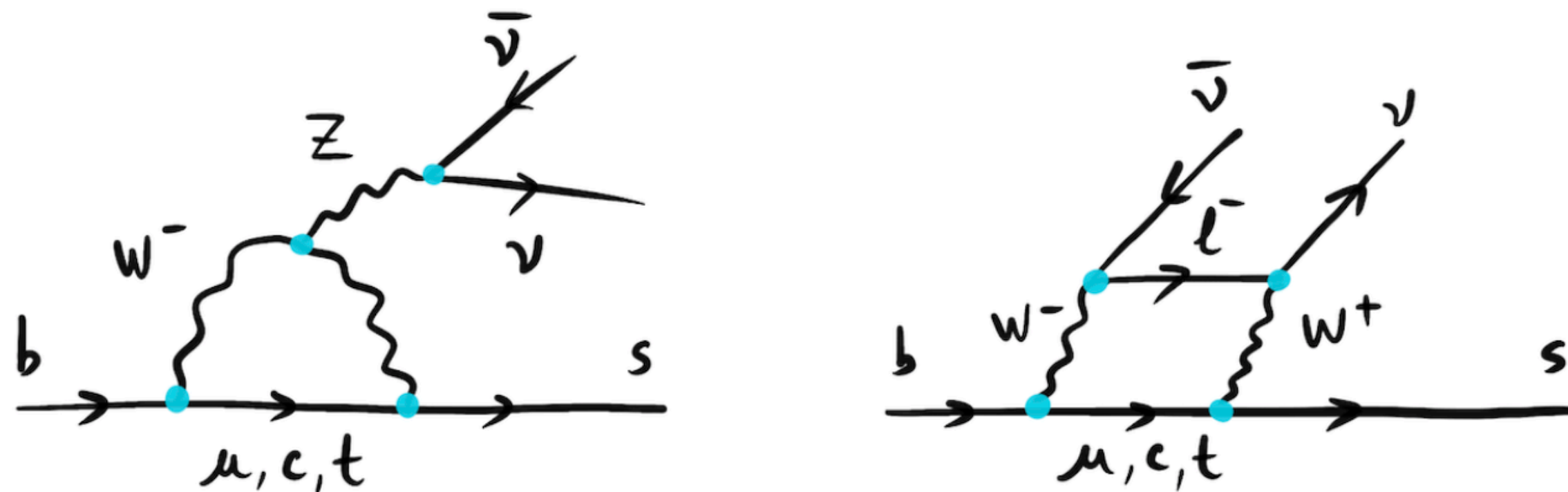


[Tristan Miralles et al.](#)

- Event kinematics fully reconstructable (with 4-fold ambiguity)
- Expect 3σ significance with nominal IDEA detector
- Extensive detector study: strong dependence on vertex resolution and material budget



$b \rightarrow s\nu\nu$ transition



Decay mode	SM prediction $\times 10^6$	Experimental value $\times 10^6$	Source
$B^+ \rightarrow K^+ \nu \bar{\nu}$	5.22 ± 0.32	13 ± 4	arXiv:2311.14647
$B^0 \rightarrow K_S^0 \nu \bar{\nu}$	2.12 ± 0.15	< 13 (90% C.L.)	arXiv:1702.03224
$B^+ \rightarrow K^{*+} \nu \bar{\nu}$	11.27 ± 1.51	< 40 (90% C.L.)	arXiv:1303.3719
$B^0 \rightarrow K^{*0} \nu \bar{\nu}$	9.47 ± 0.32	< 18 (90% C.L.)	arXiv:1702.03224

[talk by C. Santos](#)

- **Belle II:** $B^+ \rightarrow K^+ \nu \nu$ established
 - Expect 10% precision with 50 ab^{-1}
- **LHCb:** measurement not possible

- **Tera-Z:** high precision expected
 - Unique probes of $B_s \rightarrow \phi \nu \nu$, $\Lambda_b \rightarrow \Lambda \nu \nu$

Modes	$\mathcal{B}_{SM} (\times 10^{-6})$	Signature
$B^0 \rightarrow K^{*0} \nu \bar{\nu}$	7.9	$K^{*0} \rightarrow K^\pm \pi^\mp$
$B_s^0 \rightarrow \phi \nu \bar{\nu}$	9.7	$\phi \rightarrow K^+ K^-$
$B^0 \rightarrow K_S^0 \nu \bar{\nu}$	2.0	$K_S^0 \rightarrow \pi^+ \pi^-$
$\Lambda_b^0 \rightarrow \Lambda \nu \bar{\nu}$	8.6	$\Lambda \rightarrow p \pi^-$

Prompt decays

- Requirements on Kaon/pion ID

Long-lived

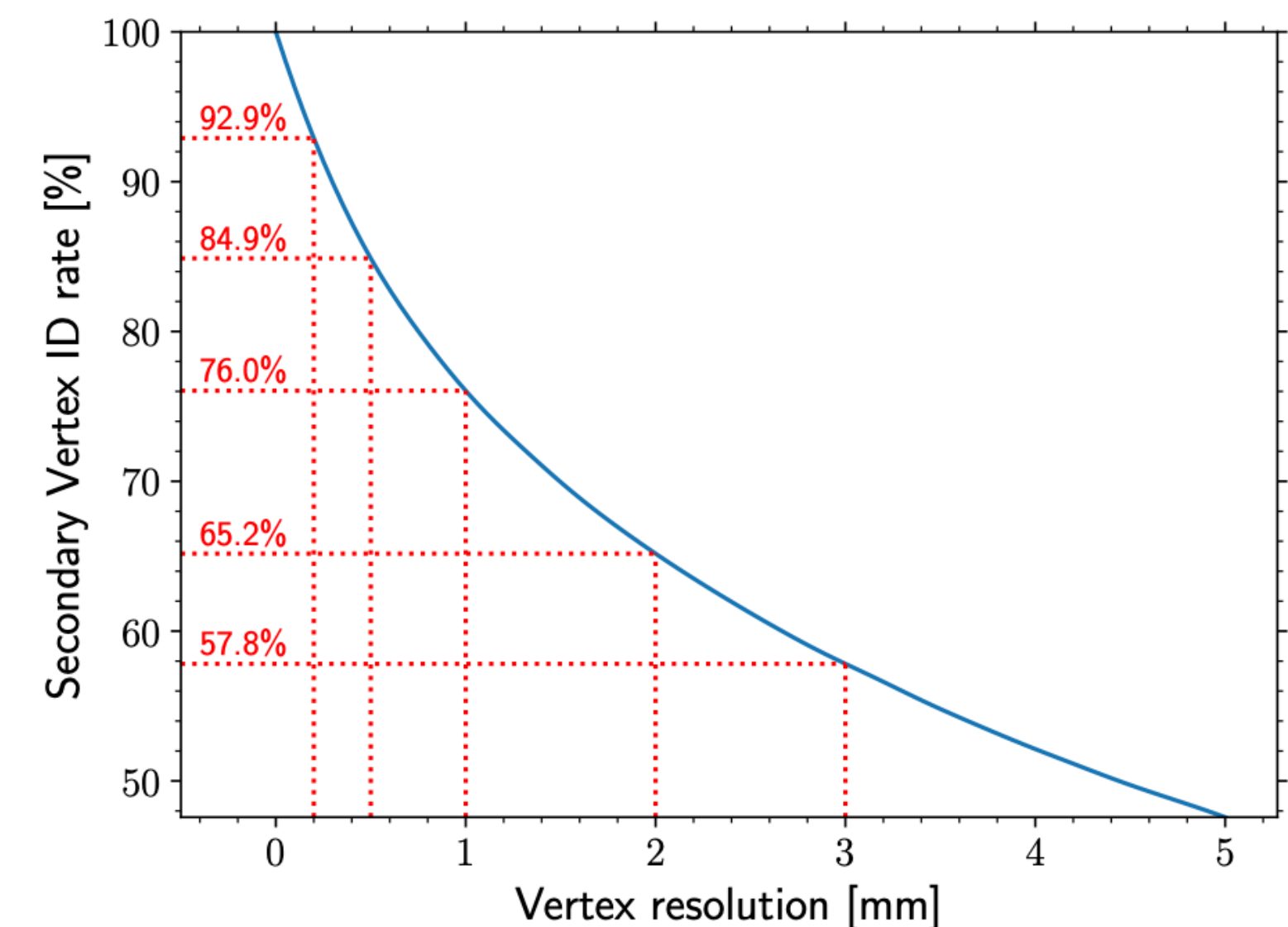
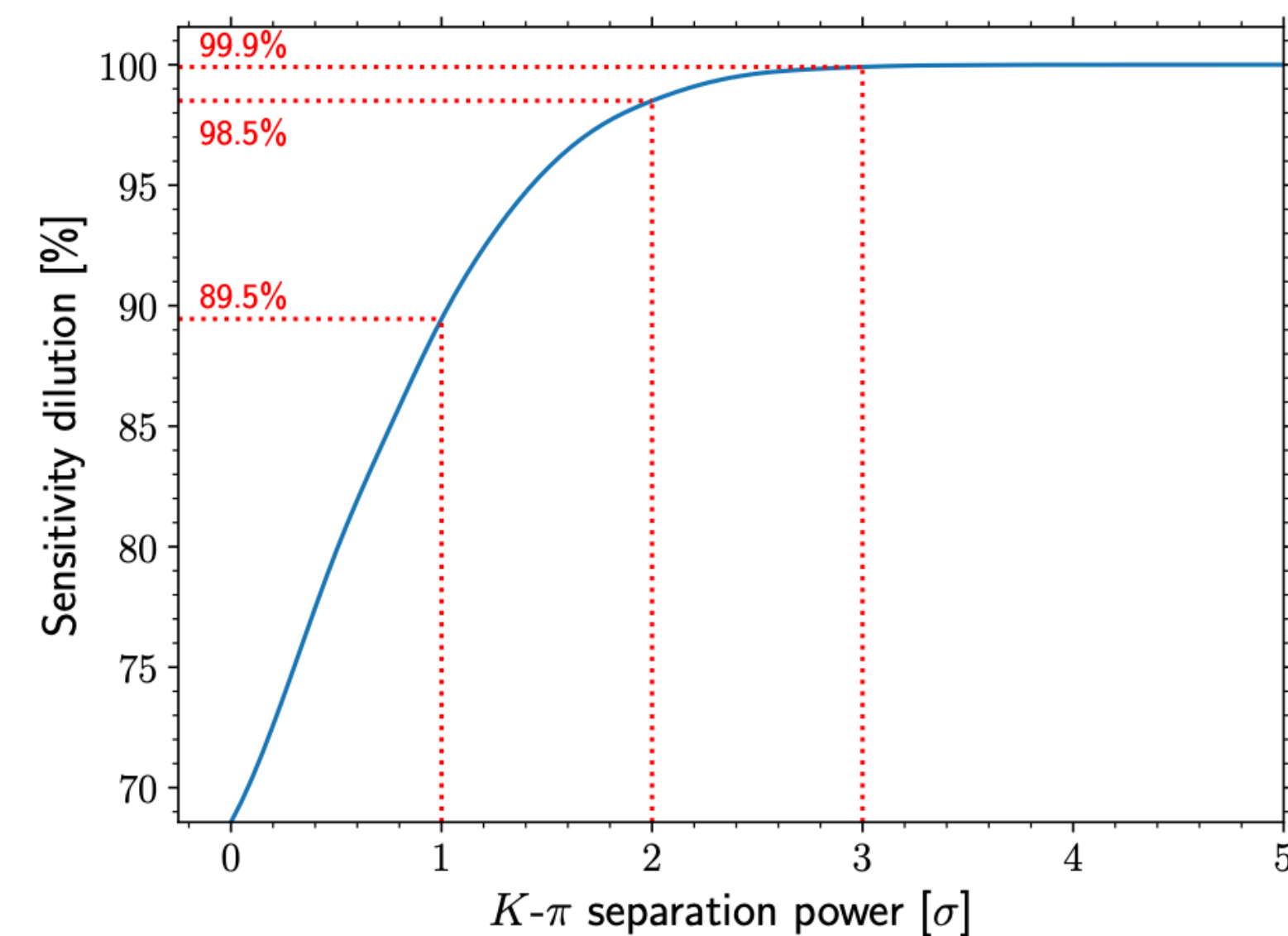
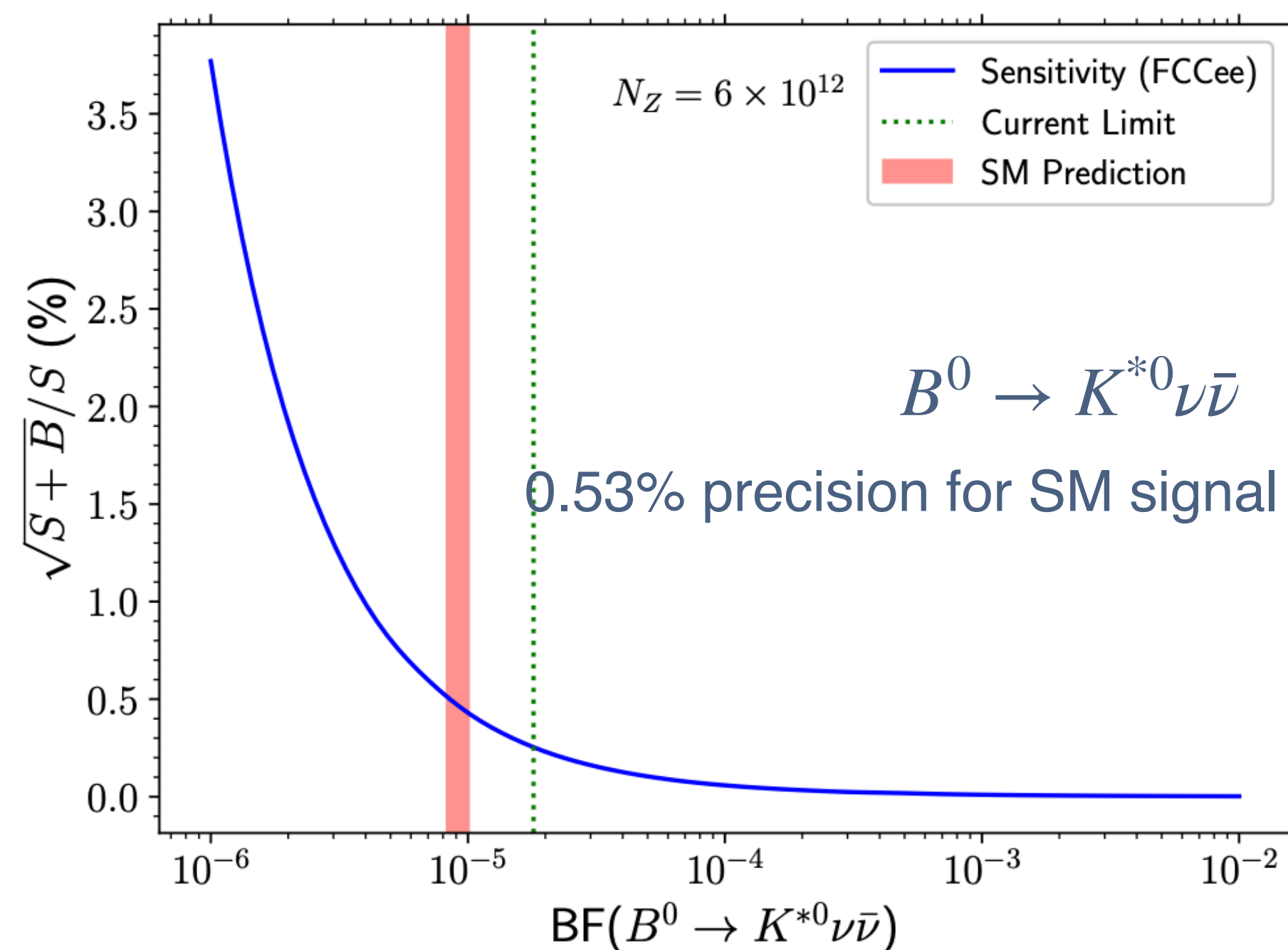
- Requirements on displaced vertexing and proton ID

[arxiv:2309.11353](#)

Case study - $b \rightarrow s\nu\nu$

Precision most dependent on PID, vertexing, and total stats

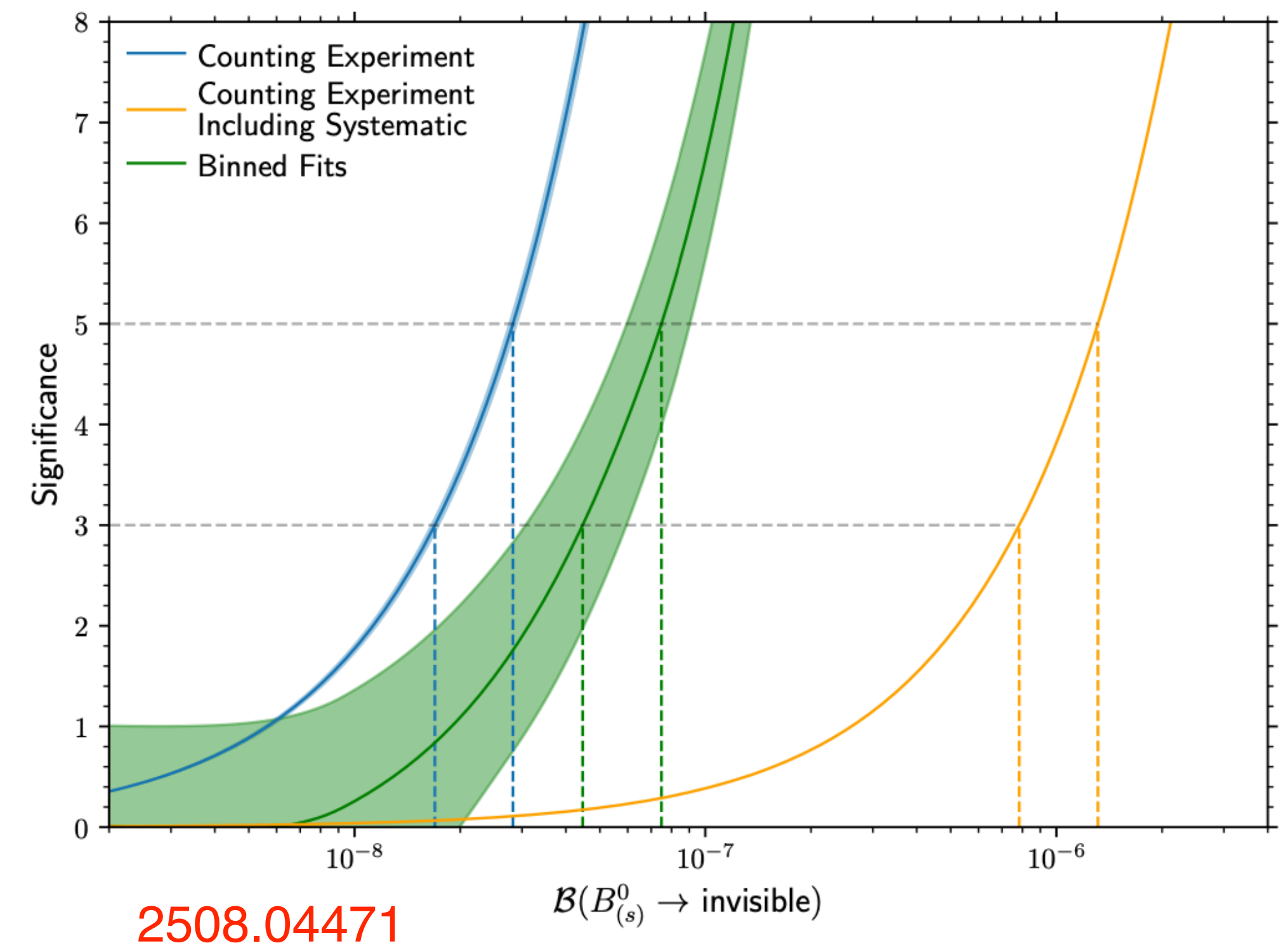
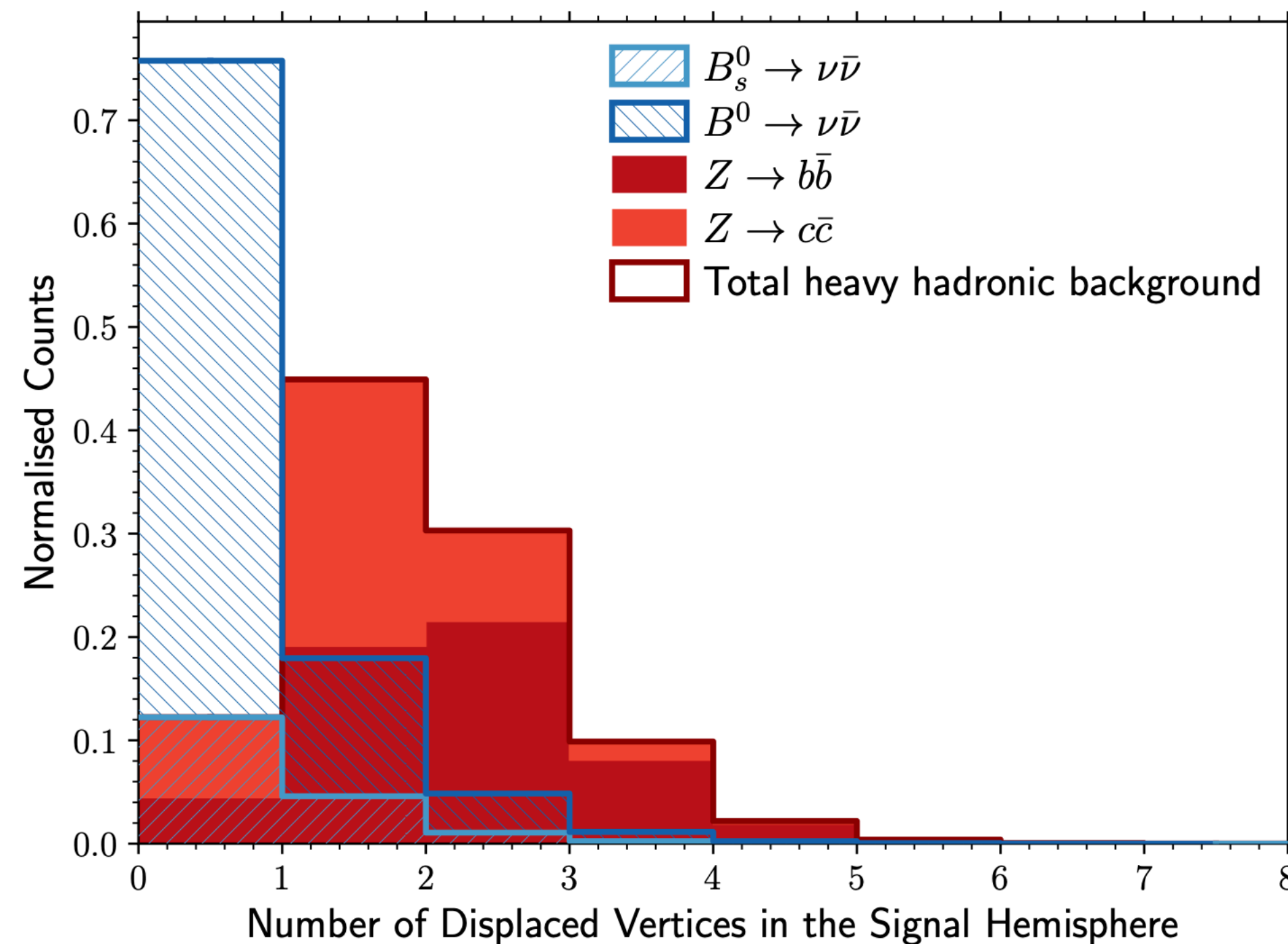
- With perfect PID, **O(1%) precision** for $B^0 \rightarrow K^{*0}\nu\bar{\nu}$ and $B_s^0 \rightarrow \phi\nu\bar{\nu}$
- With 80% K_S^0 , Λ reco eff, expect better than **10% precision** for $B^0 \rightarrow K_S^0\nu\bar{\nu}$, $\Lambda_b^0 \rightarrow \Lambda\nu\bar{\nu}$



2309.11353

Case study - $B_{(s)} \rightarrow \nu\nu$

- Heavily suppressed in SM, null test
- $\mathcal{B}(B_{(s)} \rightarrow \nu\nu) \approx 10^{-25}$, $\mathcal{B}(B_{(s)} \rightarrow 4\nu) \approx 10^{-15}$, can be enhanced by $\mathcal{B}(B_{(s)} \rightarrow \gamma\nu\nu)$
- No visible decay product, rely on missing energy and absence of objects



More to cover

- Study of Λ_b rare decays
- Radiative decays $B_s \rightarrow \gamma\gamma$, $B_s \rightarrow \mu\mu(ee)\gamma$, ...
- LFV decays $B_{(s)} \rightarrow \tau\mu, \tau e$

CKM matrix measurements

- V_{ub}, V_{cb} from $B^+/B_c^+ \rightarrow \tau^+ \nu_\tau$ [2007.08234](#) [2105.13330](#) [2305.02998](#)
- V_{cs}, V_{cb} from on-shell W decays [2405.08880](#) [2406.01675](#)
- V_{ts}, V_{tb} from on-shell top decays [FCC note: Vts](#)

Current CKM measurements

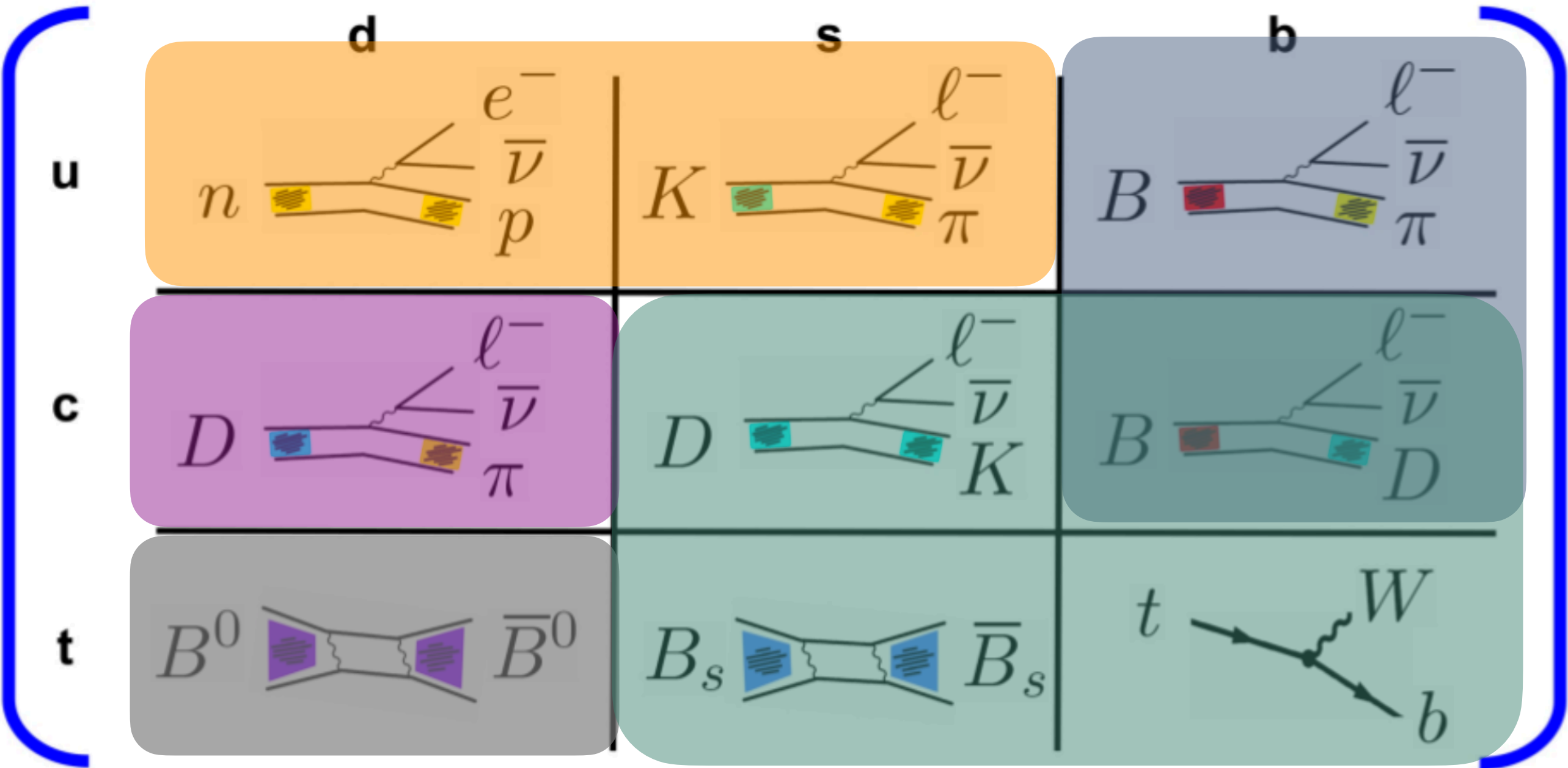
$$V = \begin{bmatrix} \begin{array}{c} \text{d} \\ \text{u} \end{array} \begin{array}{c} n \text{ } e^- \bar{\nu} \\ p \end{array} & \begin{array}{c} \text{s} \\ K \text{ } \ell^- \bar{\nu} \\ \pi \end{array} & \begin{array}{c} \text{b} \\ B \text{ } \ell^- \bar{\nu} \\ \pi \end{array} \\ \hline \begin{array}{c} \text{c} \\ D \text{ } \ell^- \bar{\nu} \\ \pi \end{array} & \begin{array}{c} D \text{ } \ell^- \bar{\nu} \\ K \end{array} & \begin{array}{c} B \text{ } \ell^- \bar{\nu} \\ D \end{array} \\ \hline \begin{array}{c} \text{t} \\ B^0 \text{ } \bar{B}^0 \\ B_s \text{ } \bar{B}_s \end{array} & \begin{array}{c} B_s \text{ } \bar{B}_s \end{array} & \begin{array}{c} t \text{ } W^- \\ b \end{array} \end{bmatrix}$$

- Relying on precise theory inputs
- Inclusive vs exclusive puzzle
- Measurements through loops not sensitive to BSM

New methodology to explore at FCC-ee

Likely no advantage at FCC-ee

$V =$
Possibility with
W decay,
precision to be
studied



From $B^+(B_c^+)$ meson decay

Direct W or top decay

Can FCC-ee do something?

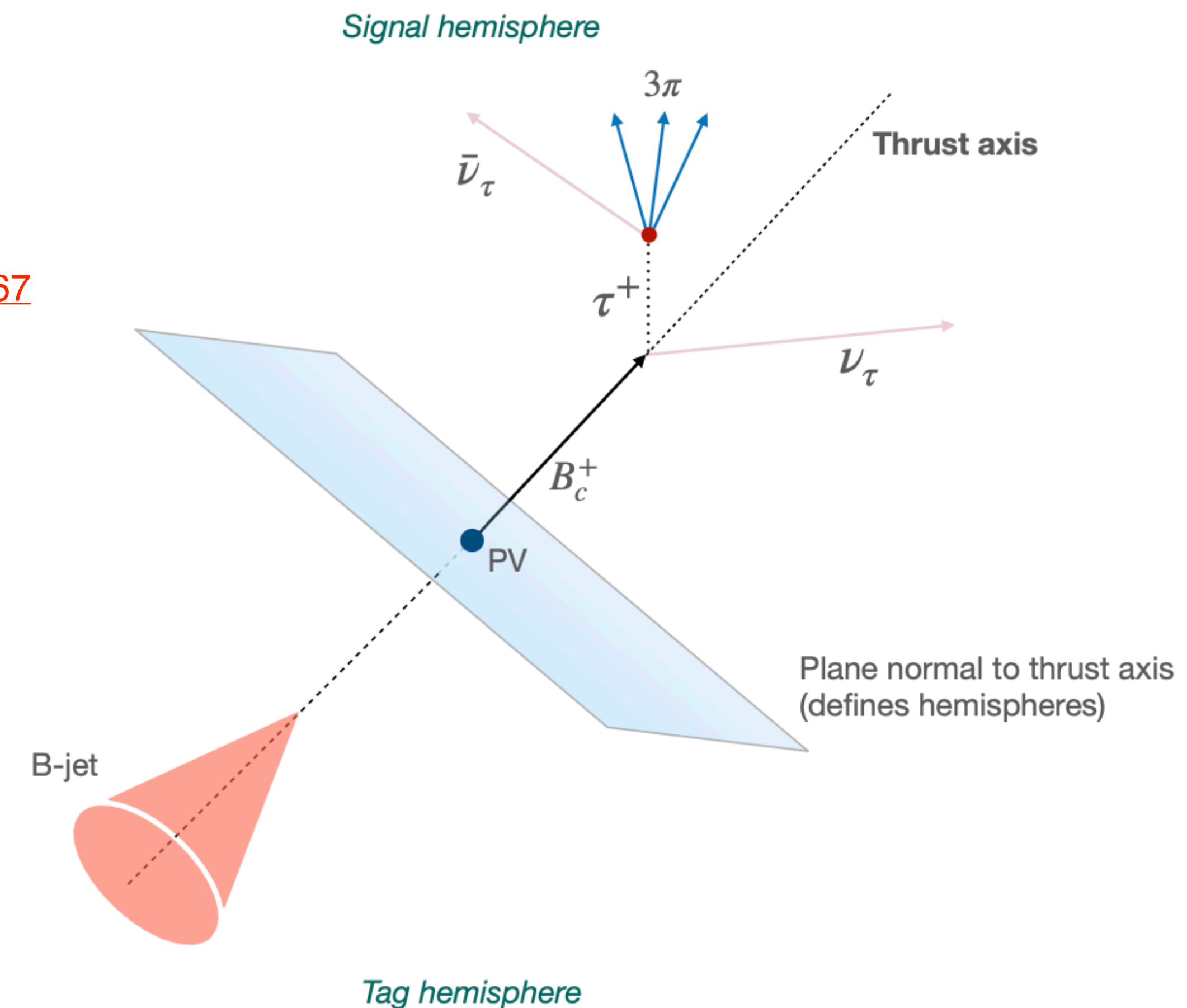
$$b \rightarrow q \ell \nu$$

Case study - $B^+/B_c^+ \rightarrow \tau^+ \nu_\tau$

- Difficult to identify at LHCb
- No B_c^+ at Belle II, $B^+ \rightarrow \tau^+ \nu_\tau$ measurable to 5% [1808.10567](#)

At Tera-Z factory

- 1~2% precision for $\tau \rightarrow 3\pi^\pm$ mode [2105.13330](#) [2305.02998](#)
- O(1%) precision for $\tau \rightarrow e/\mu$ mode [2007.08234](#)
- Few kinematic handles, some backgrounds irreducible
- Ultimate precision relies on τ -ID in all modes

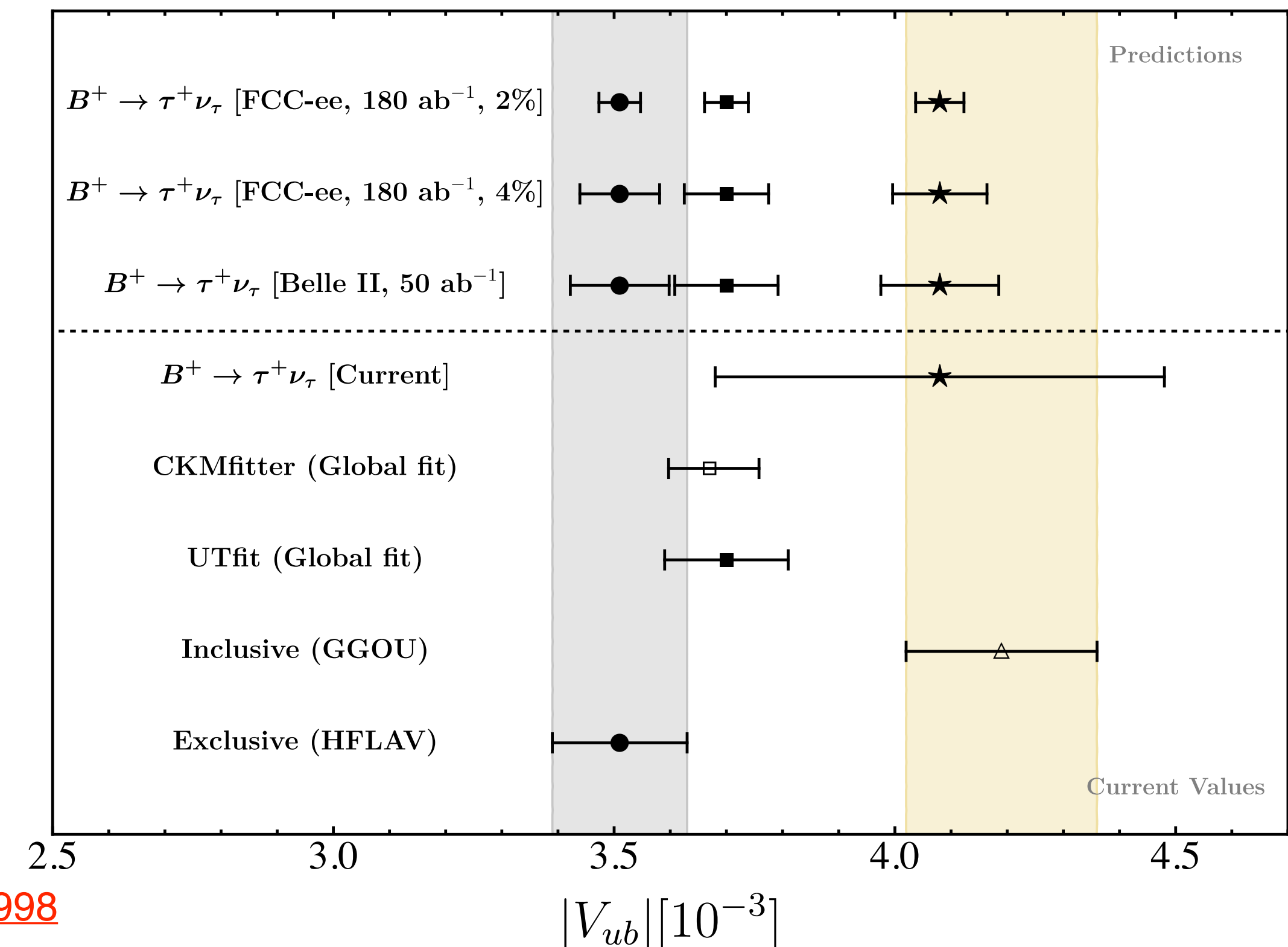
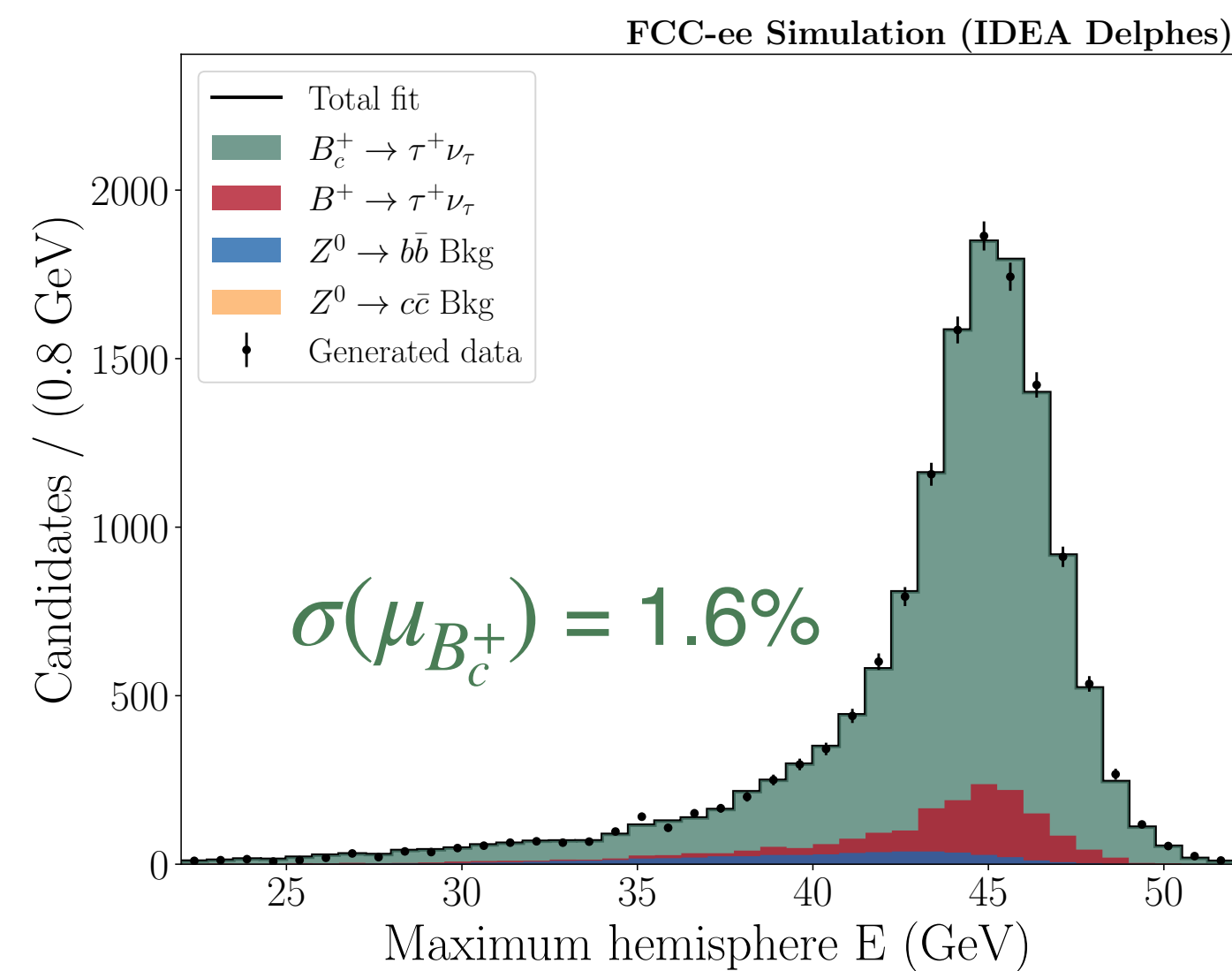
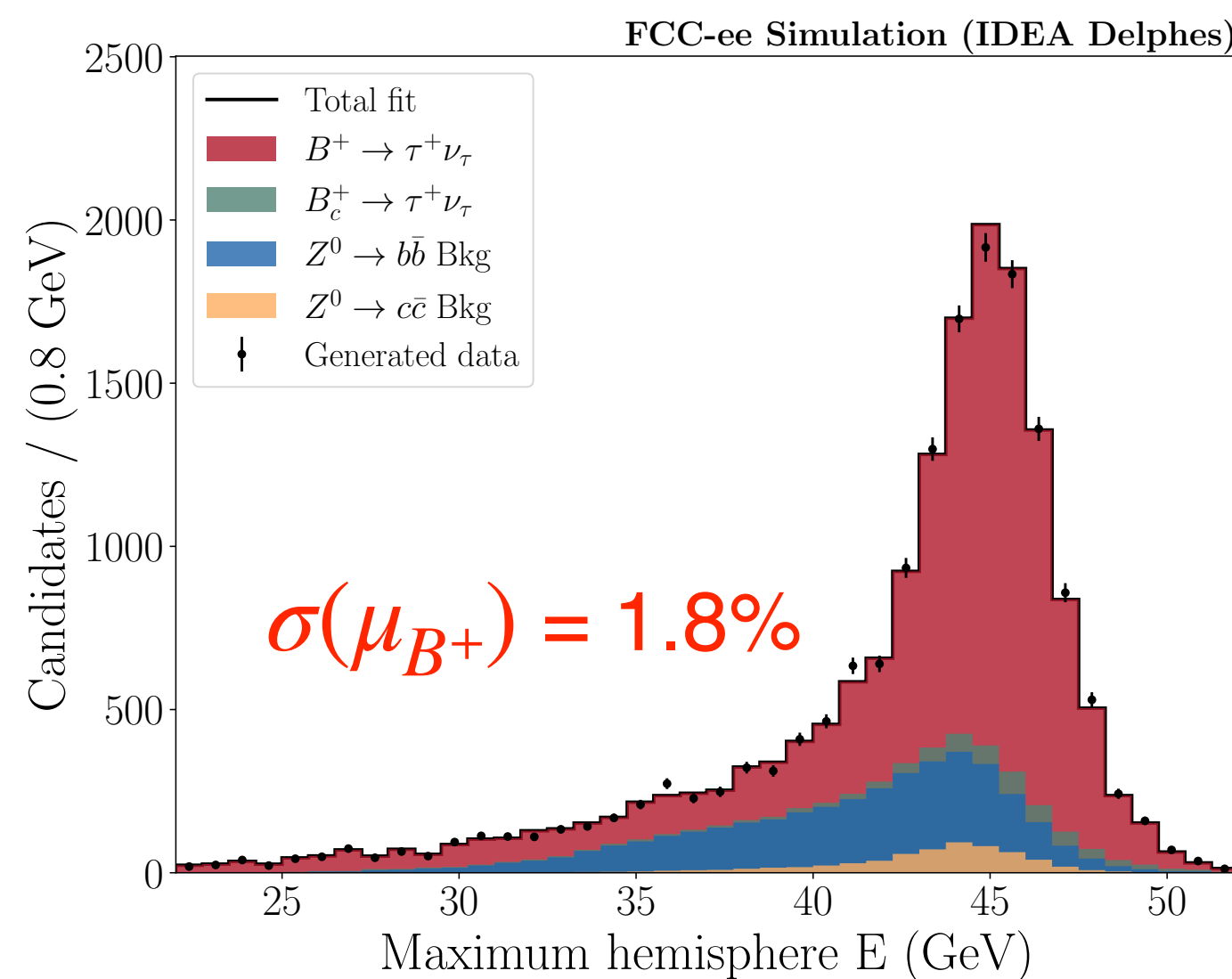


Case study - $B^+/B_c^+ \rightarrow \tau^+ \nu_\tau$

- Super clean SM prediction, only unknown is $|V_{qb}|$ (in addition to fragmentation function $f(B_c^+)$)

$$\mathcal{B}(B_q^+ \rightarrow \tau^+ \nu_\tau)^{\text{SM}} = \tau_{B_q^+} \frac{G_F^2 |V_{qb}|^2 f_{B_q^+}^2 m_{B_q^+} m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_{B_q^+}^2}\right)^2, \quad q = u, c$$

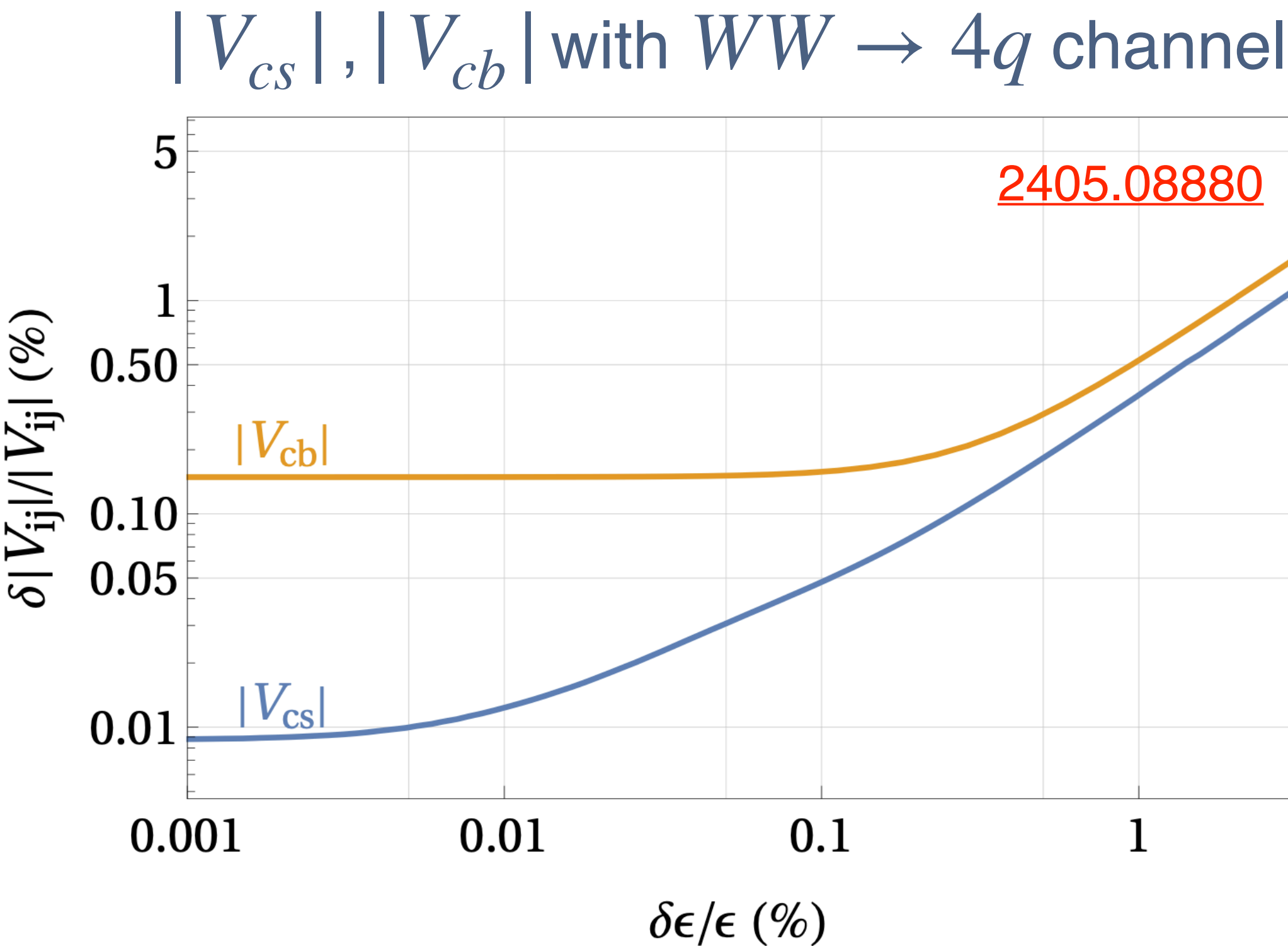
- Determine $|V_{ub}|$ at 1% precision
- Similarly, determine with knowledge of $f(B_c^+)$, or vice versa



2305.02998

Direct CKM measurements — $|V_{cs}|, |V_{cb}|$

- At LEP, O(10%) precision on $|V_{cs}|$ [DELPHI](#) [ALEPH](#) [OPAL](#)
- At Tera-Z, O(0.01%) precision on $|V_{cs}|$, O(0.1%) on $|V_{cb}|$



$|V_{cb}|$ with $WW \rightarrow \ell\nu qq$ channel

Exp uncert most from mis-tag and bkg rate:

Scena 1. unc. from Herwig vs Pythia

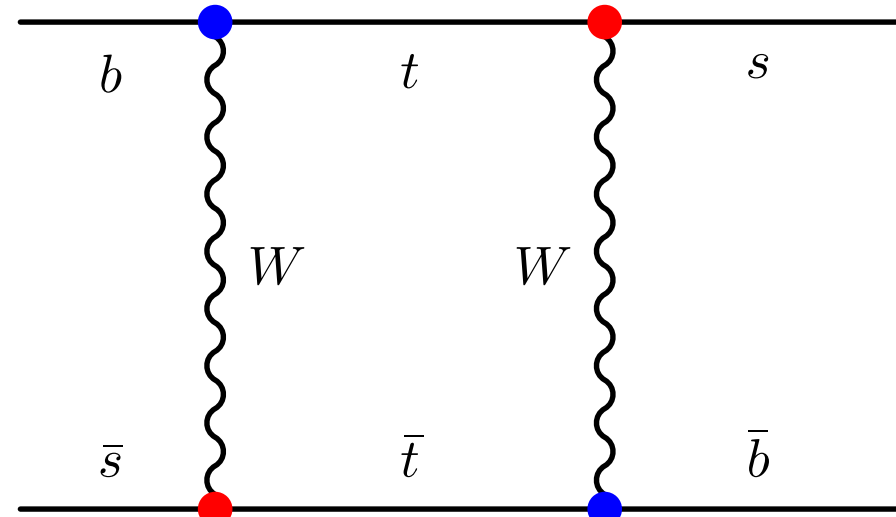
Scena 2. 8x better

2406.01675

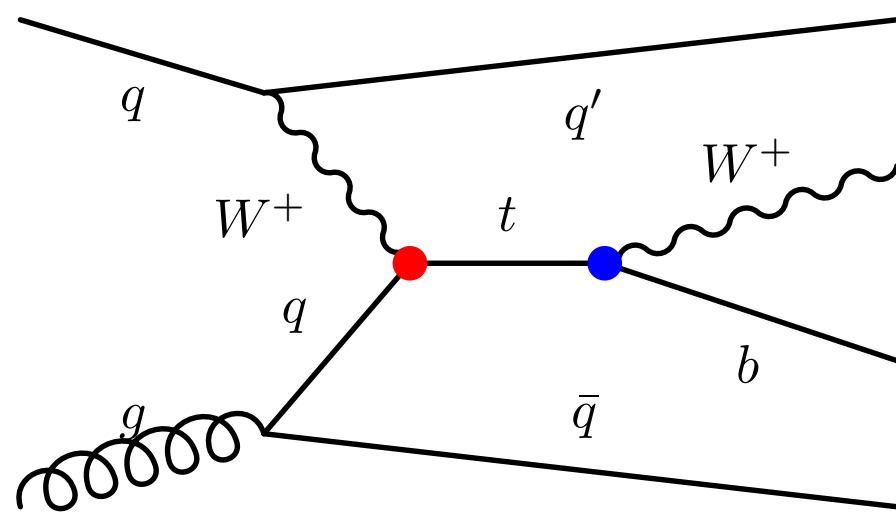
Uncertainty	Stat.	Syst., Secnario 1	Syst., Secnario 2
Unpolarized, Baseline (5 ab^{-1})	0.72%	1.5%	0.20%
Unpolarized, Extended (20 ab^{-1})	0.36%	1.5%	0.20%
WW Threshold ($5 \times 10^7 \text{ WW}$)	0.95%	1.5%	0.20%
Unpolarized, Baseline + WW	0.57%	1.1%	0.15%
Unpolarized, Extended + WW	0.33%	1.1%	0.18%
Polarized, Baseline (0.5 ab^{-1})	1.5%	1.5%	0.20%
Polarized, Extended (2 ab^{-1})	0.75%	1.5%	0.20%

More in talk by [Zhaoling Zhang](#)

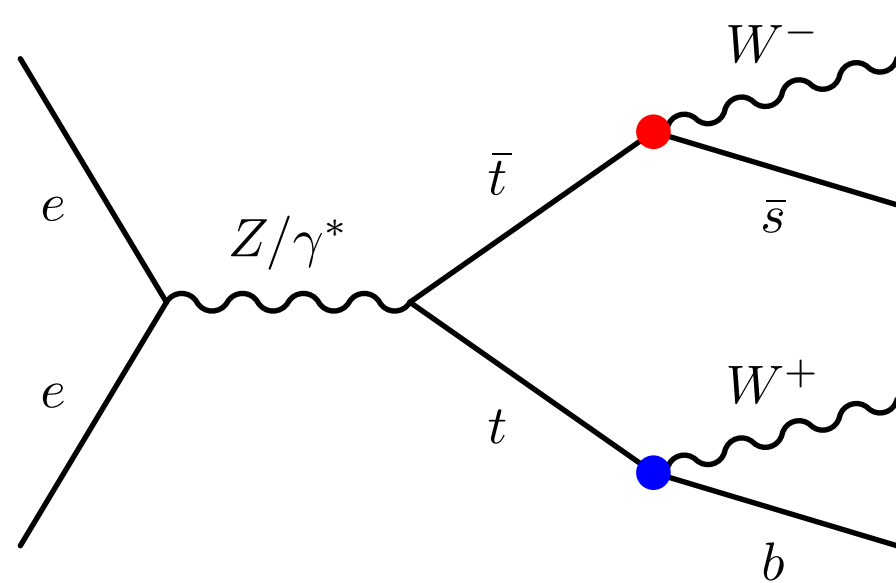
Direct CKM measurements — $|V_{ts}|$



- Current (PDG): from $B_s^0 - \bar{B}_s^0$ mixing at LHCb
 - $|V_{ts}| = (41.5 \pm 0.9) \times 10^{-3}$ (**2.2%** precision)
 - Assume no NP in the loop, dominated by LQCD uncertainty



- Direct measurement at LHC: single top production
 - $|V_{ts}|^2 + |V_{td}|^2 = 0.06 \pm 0.06$, far from SM precision



- Potential at e^+e^- colliders
 - Model-independent direct measurement
 - FCC-ee expects $2 \times 10^6 \times 2 \times |V_{ts}|^2 \sim 6600$ cases of $t \rightarrow Ws$
 - Expect precision on $|V_{ts}|$ at **3.1% or better** [FCC note: Vts](#)
 - Similar measurement for $|V_{tb}|$, expect O(0.1%) precision

• $|V_{tb}|$ • $|V_{ts}|$

More to cover

- Inclusive V_{xb} determination
- $R(Xc)$ for all c-hadrons + theory discussion
- Double inclusive decay (measure quark level transition, agnostic of initial and final hadrons)

CP violation

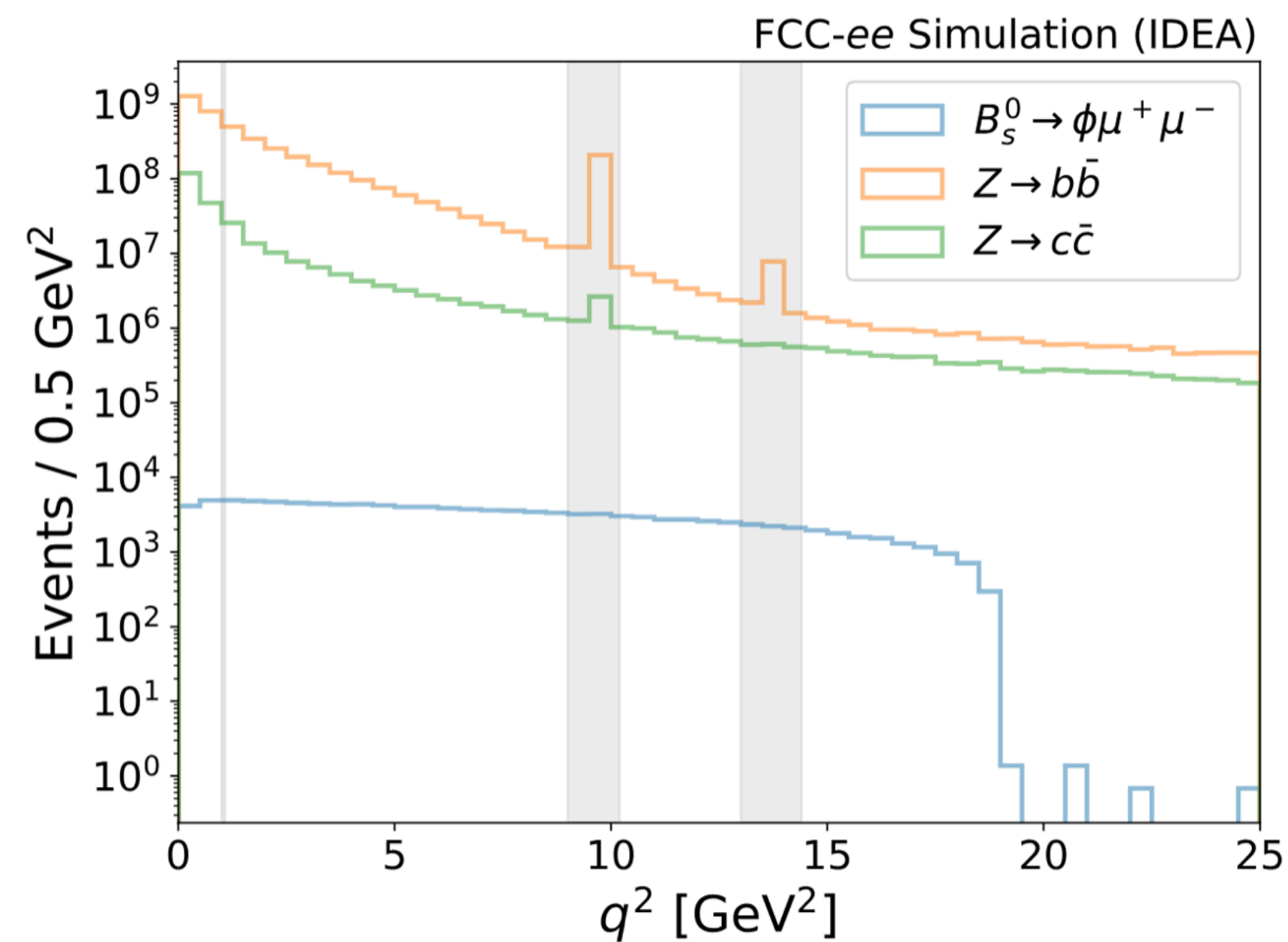
Case:

- $B_s \rightarrow \phi\mu\mu$ time-dependent analysis [2506.08089](#)

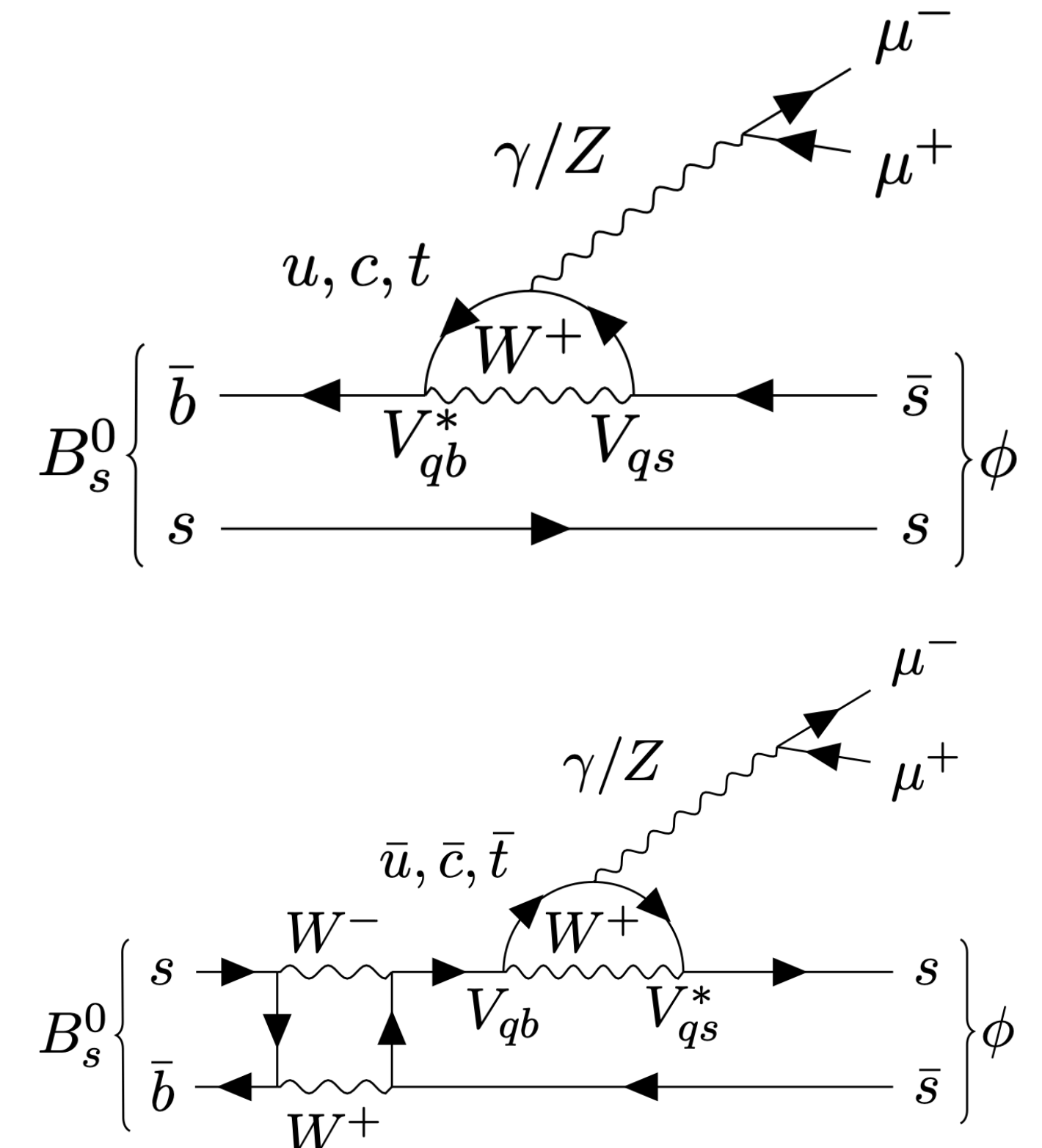
$B_s \rightarrow \phi \mu \mu$

- SM $\mathcal{B}(B_s \rightarrow \phi \mu \mu)$ at $\mathcal{O}(10^{-6})$
- Time-dependent CP asymmetry through mixing
- After selections, 40K signals with S/B = 25 (bkg free)

$$A_{CP}(t) = \frac{\text{Direct CPV } C_f \cos(\Delta m_s t) - \text{CPV in Interference } S_f \sin(\Delta m_s t)}{\cosh(\Delta \Gamma_s t/2) + D_f \sinh(\Delta \Gamma_s t/2)}$$



q^2 vetoes for ϕ , J/ψ , $\psi(2S)$ resonances



[2506.08089](#)

Decay time resolution

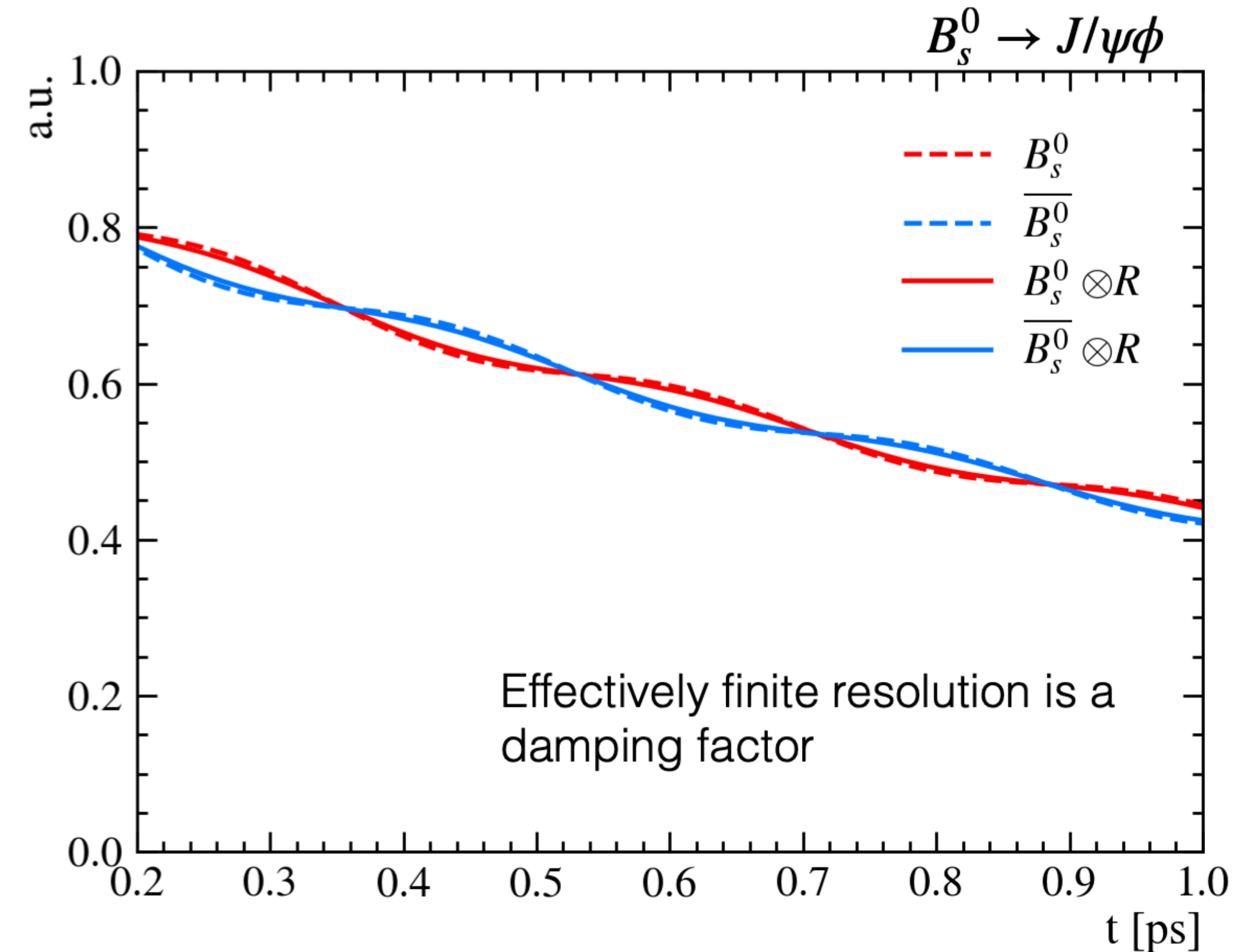
Slide from Valeriia Lukashenko@FCC flavor WS

- B_s^0 oscillations are extremely fast with a frequency
 $\Delta m_s^{WA} = 17.765 \pm 0.005 \text{ ps}^{-1}$
- We need resolution that can capture it
- Effectively finite resolution introduces a damping factor D

$$\sigma_{LHCb} = 47 \text{ fs} \quad D_{LHCb} = 0.7$$

$$\sigma_{CMS} = 67 \text{ fs} \quad D_{CMS} = 0.5$$

$$\sigma_{IDEA} \sim 5.5 \text{ fs} \quad D_{IDEA} \sim 0.995^*$$



Practically we can forget about resolution!

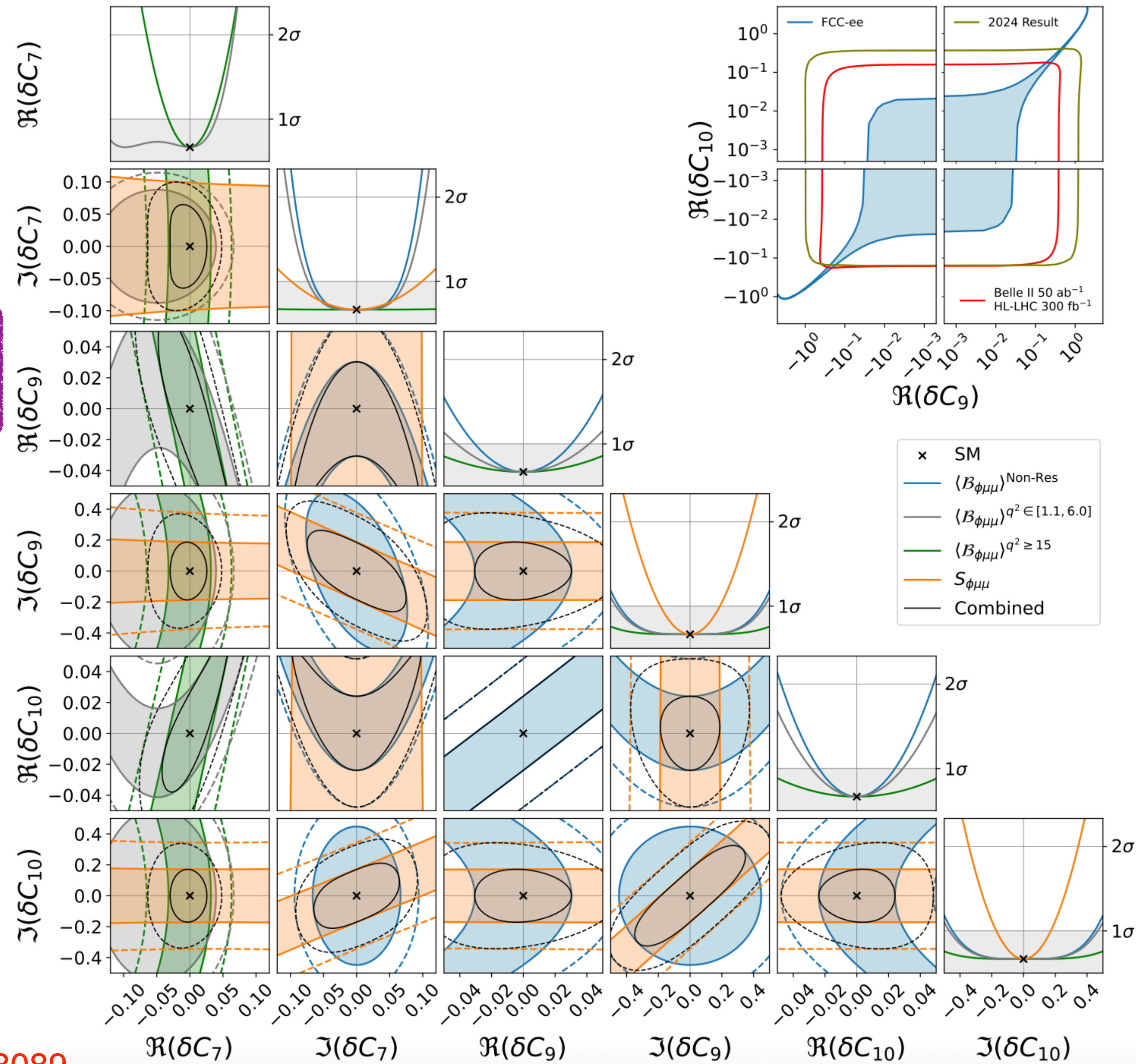
*For average decay length of $B_s^0 \sim 2.8\text{mm}$ (ignore momentum resolution)

$B_s \rightarrow \phi \mu \mu$

- High precision on many observables

$\frac{\sigma(\text{Br})}{\text{Br}}$	$\frac{\sigma(\text{Br}^{q^2 \in [1.1, 6]})}{\text{Br}^{q^2 \in [1.1, 6]}}$	$\frac{\sigma(\text{Br}^{q^2 \geq 15})}{\text{Br}^{q^2 \geq 15}}$	$\sigma(D_f)$	$\sigma(\langle A_{CP} \rangle)$	$\sigma(C_f)$	$\sigma(S_f)$
0.515%	0.810%	1.577%	0.103	9.21×10^{-3}	0.0210	0.0214

Expressed in WCs



2506.08089

More to cover

- Key B decay modes
 - $B \rightarrow J/\psi K_s$
 - $B^0 \rightarrow \pi^0 K_s, B_s \rightarrow D_s K, B \rightarrow \pi\pi, B \rightarrow \rho\rho$
 - $B_s \rightarrow \ell\ell, B \rightarrow K\ell\ell, B_s \rightarrow \phi\ell\ell$

Charm physics

Particle species	D^0	D^+	D_s^+	Λ_c	D^{*+}
FCC-ee yield ($\times 10^{11}$)	7.94	3.38	1.31	0.84	3.36

$$N(c\bar{c}) @ LHCb, 300 \text{ fb}^{-1} \gg N(c\bar{c}) @ FCC-ee > N(c\bar{c}) @ Belle II, 50 \text{ fb}^{-1}$$

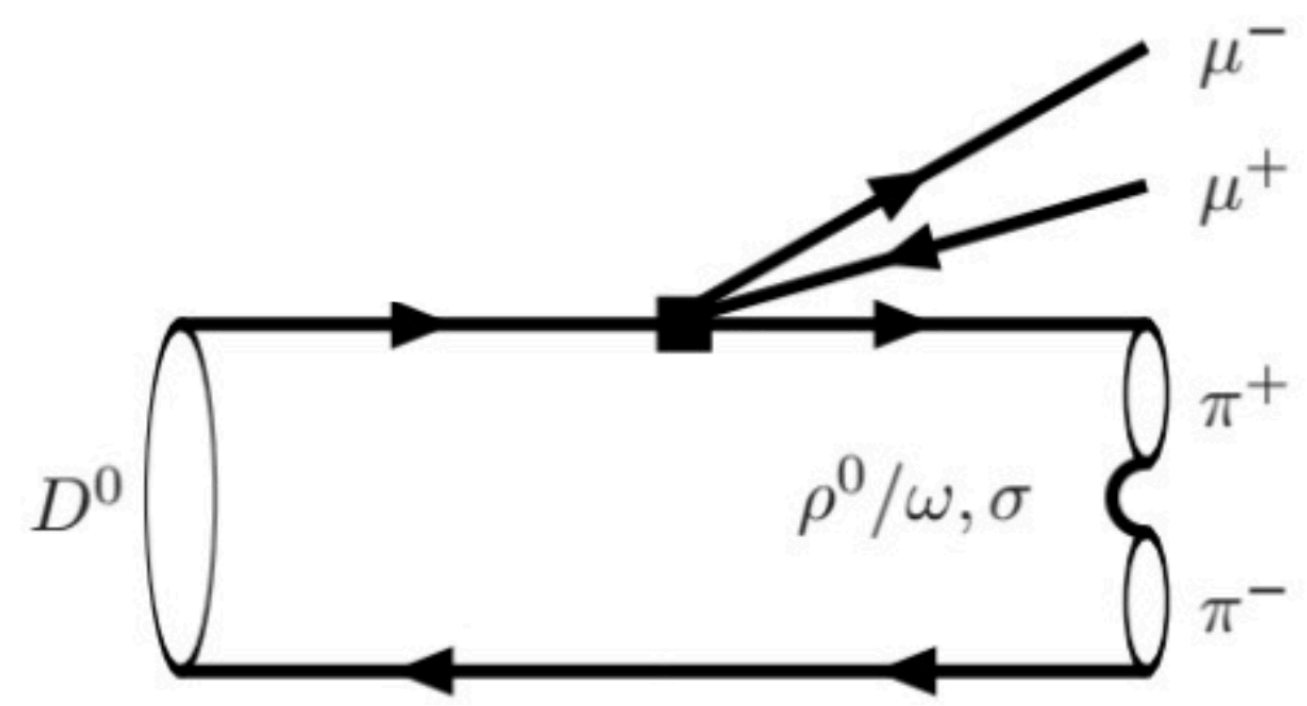
$\sim 1000x$
 $\sim 10x$

Cases:

- $D^0 \rightarrow \pi^+ \pi^- \nu \nu$ [2509.10447](#)
- $D^0 \rightarrow \pi^0 \pi^0$ [Willy Weber@FCC flavor WS](#)

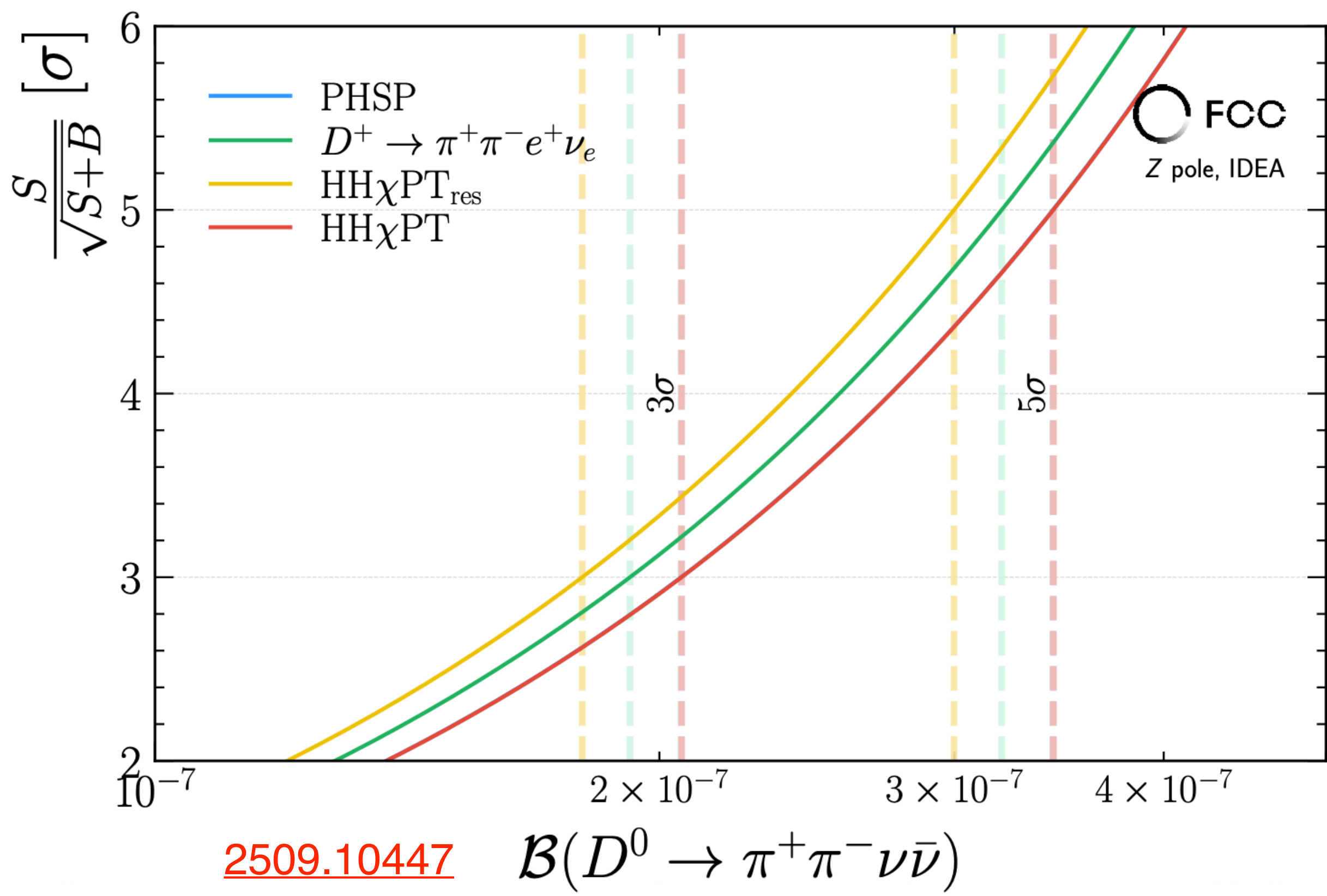
Charm: $c \rightarrow u\nu\nu$

- $c \rightarrow u\nu\nu$ highly suppressed in SM $\rightarrow$ clean null test



- FCC-ee example: probe $D^0 \rightarrow \pi^+\pi^-\nu\nu$ at $O(10^{-7})$ level

Decay	$\mathcal{B}$ @ 90 C.L.	References
$D^0 \rightarrow invisible$	$< 9.4 \cdot 10^{-5}$	[Belle, 1611.09455]
$D^0 \rightarrow \pi^0 \nu \bar{\nu}$	$< 2.1 \cdot 10^{-4}$	[BESIII, 2112.14236]
$\Lambda_c \rightarrow p \gamma'$	$< 8.0 \cdot 10^{-5}$	[BESIII, 2208.04496]
$D^0 \rightarrow \omega \gamma'$	$< 1.1 \cdot 10^{-5}$	[BESIII, 2409.02578]
$D^0 \rightarrow \gamma \gamma'$	$< 2.0 \cdot 10^{-6}$	[BESIII, 2409.02578]



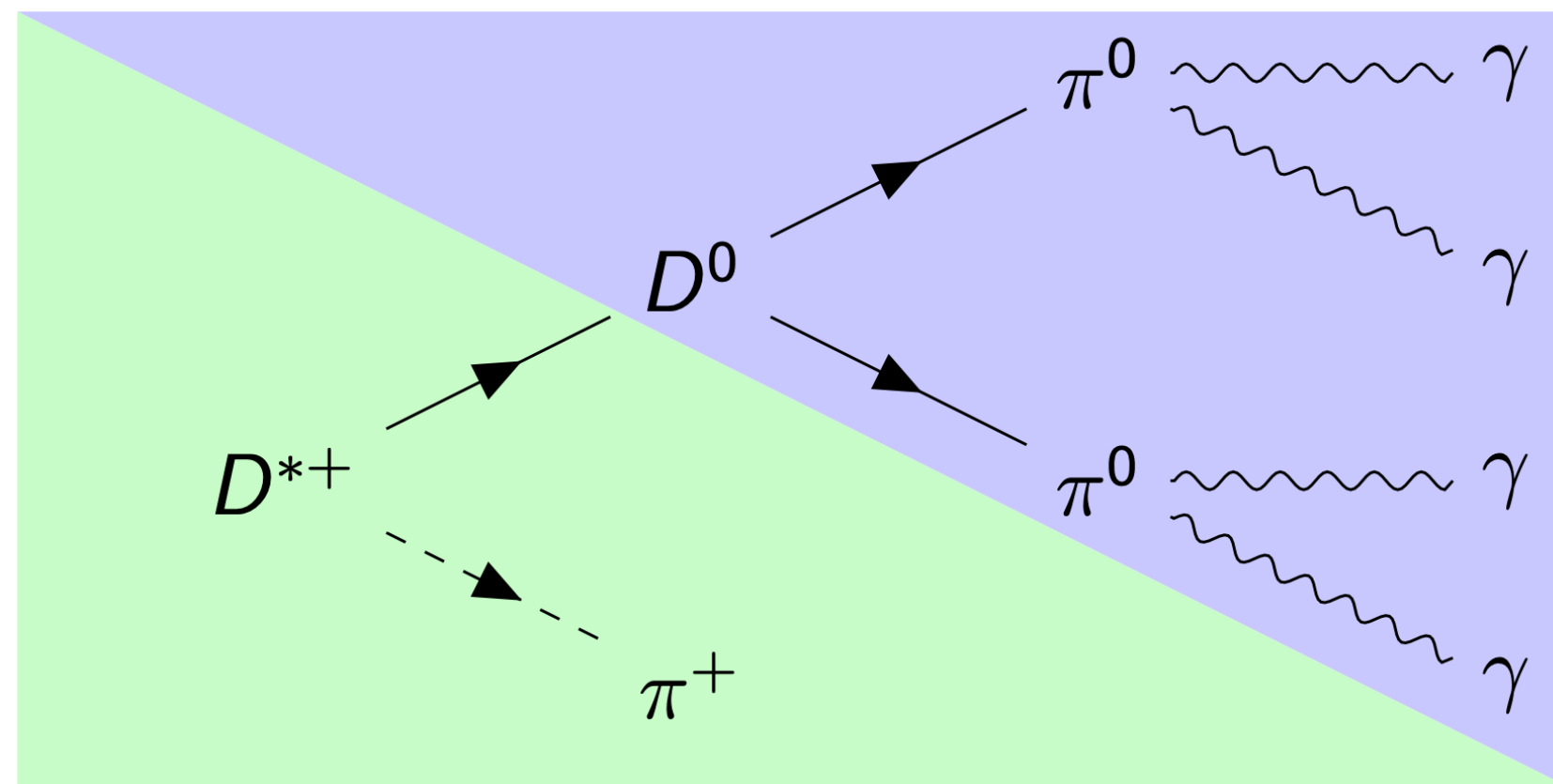
Charm: CP in $D^0 \rightarrow \pi^0 \pi^0$

Decay rate asymmetry by LHCb [2209.03179](#)

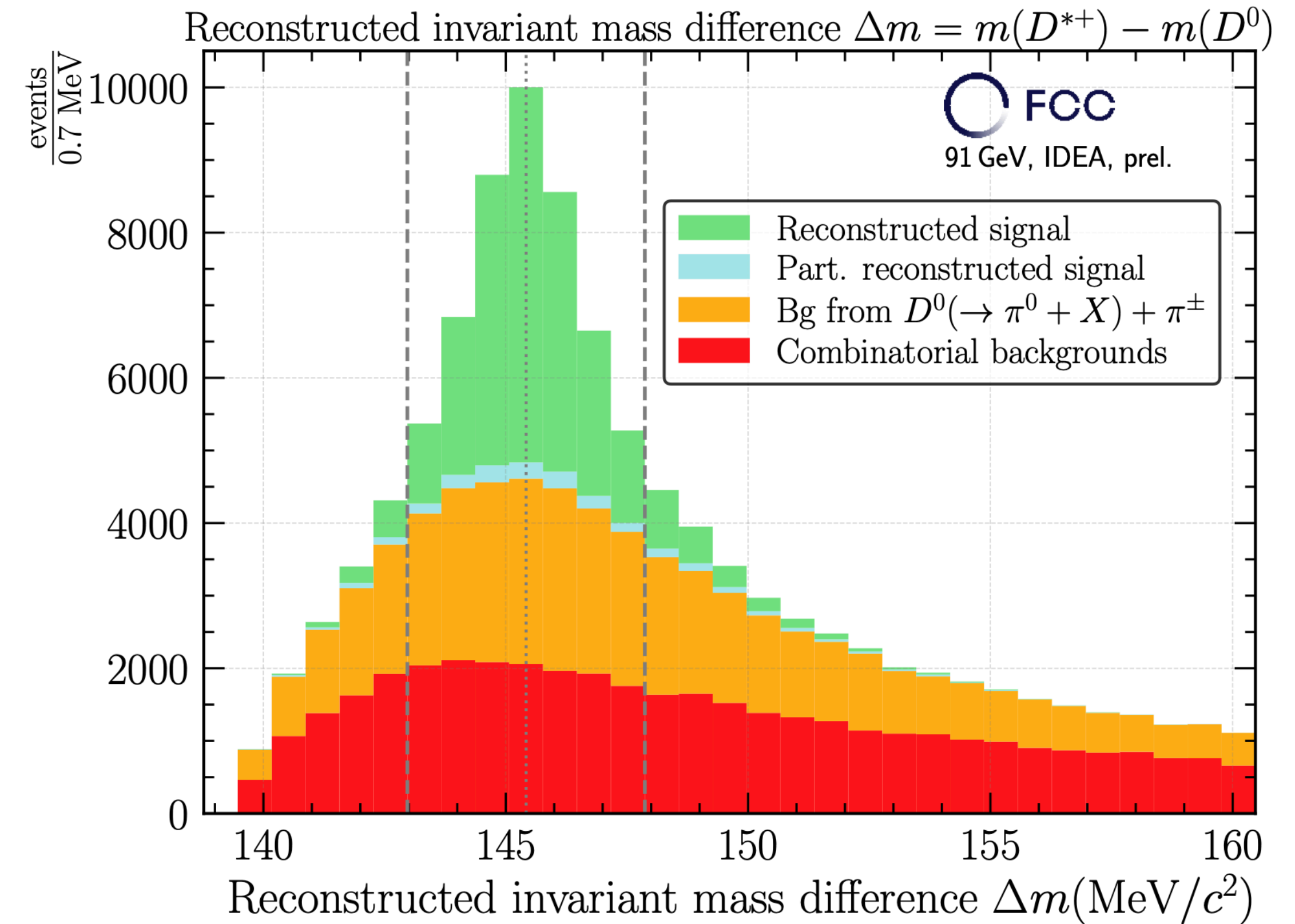
- $A_{CP}(D^0 \rightarrow K^+ K^-) = (7.7 \pm 5.7) \times 10^{-4}$
- $A_{CP}(D^0 \rightarrow \pi^+ \pi^-) = (23.1 \pm 6.1) \times 10^{-4}$

Neutral mode at Belle [1404.1266](#)

- $A_{CP}(D^0 \rightarrow \pi^0 \pi^0) = (0.000 \pm 0.006)$
- Full Belle II $\sigma_{A_{CP}(D^0 \rightarrow \pi^0 \pi^0)} = \pm 7 \times 10^{-4}$ [2503.24346](#)



[Willy Weber@FCC flavor WS](#)



$$\Delta m = m(D^{*+}) - m(D^0)$$

- Use $\pi^\pm$ to tag D^0 vs $\bar{D}^0$
- Estimated uncertainty $\sigma_{A_{CP}(D^0 \rightarrow \pi^0 \pi^0)} = \pm 2.2 \times 10^{-4}$

More to cover

Aim for next workshop

Guy.Wilkinson@FCC.flavor.WS

- Elaborate also on **multi-pronged charged modes** and estimate the **sensitivity for CPV in $D \rightarrow h^+ h^-$** . Go ahead with the initial studies presented.
- Explore **radiative decays**, including $D \rightarrow \gamma\gamma$, $D \rightarrow \phi\gamma$, $D \rightarrow \rho\gamma$, ...
Time-integrated and time-dependent analysis of radiative decays?
- Find **benchmarks to define detector requirements**. Calorimetry resolution for decays with neutrals? Move towards improved simulation models

Also

- $c \rightarrow u\ell\ell$
- $D_{(s)} \rightarrow \tau\nu$
- Progress in lattice would be appreciated

Tau physics

Case:

- LFU test
- CLFV probes

[FCC note: tau physics](#)

τ : LFU test

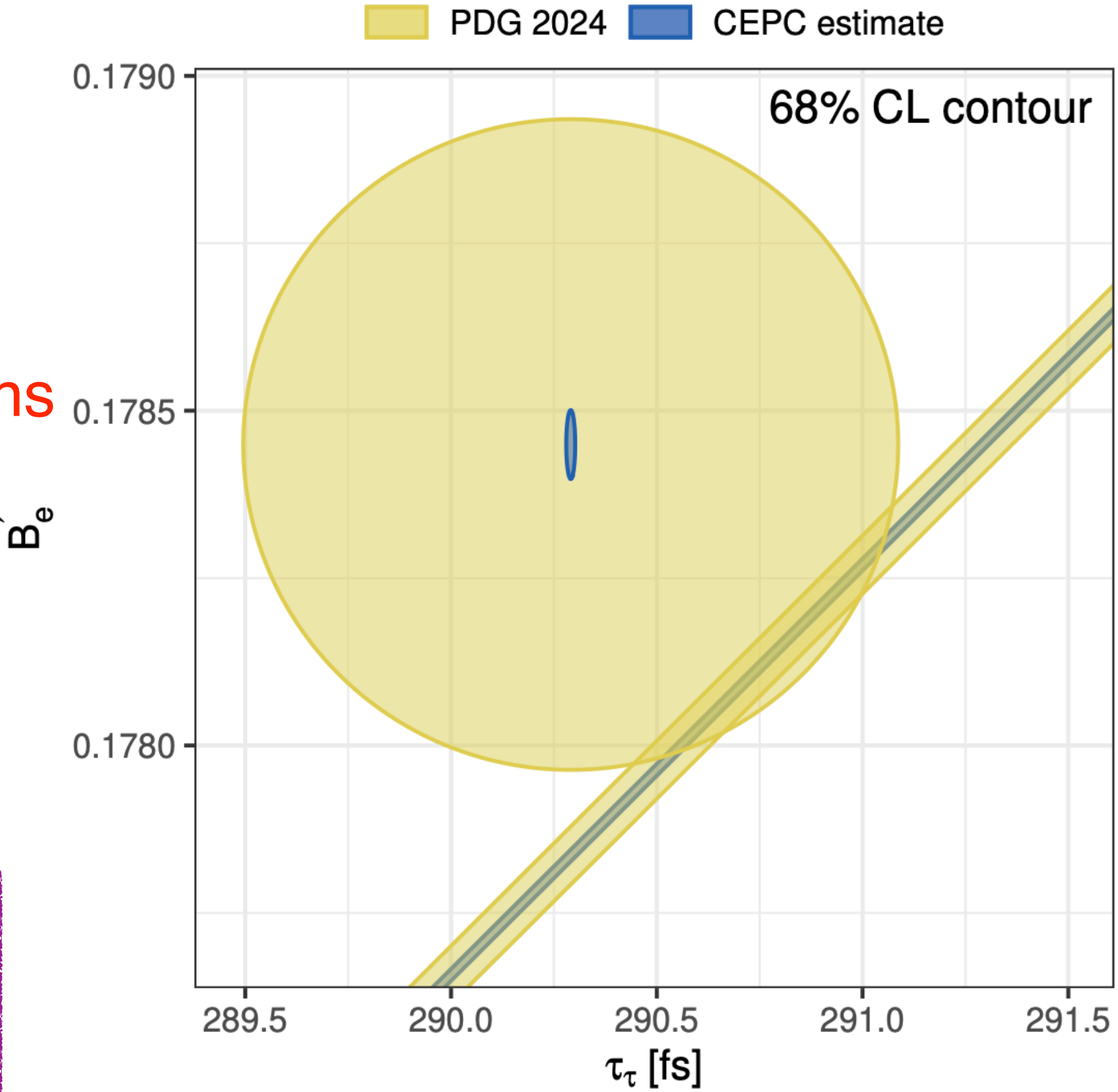
- LFU: $g_e = g_\mu = g_\tau = g$
- Tera-Z tests tau LFU at 10^{-4} level, probing NP up to 20 TeV

$$\left(\frac{g_\mu}{g_e}\right)^2 = \frac{\text{BR}(\tau \rightarrow \mu \nu \bar{\nu})}{\text{BR}(\tau \rightarrow e \nu \bar{\nu})} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)} \frac{R_W^{\tau e}}{R_W^{\tau \mu}},$$
$$\left(\frac{g_\tau}{g_{e/\mu}}\right)^2 = \frac{\tau_\mu}{\tau_\tau} \left(\frac{m_\mu}{m_\tau}\right)^5 \frac{\text{BR}(\tau \rightarrow \mu/e \nu \bar{\nu})}{\text{BR}(\mu \rightarrow e \nu \bar{\nu})} \frac{f(m_e^2/m_\mu^2)}{f(m_{\mu/e}^2/m_\tau^2)} \frac{R_W^{\mu e} R_\gamma^\mu}{R_W^{\tau \mu/e} R_\gamma^\tau},$$

phase-space factors

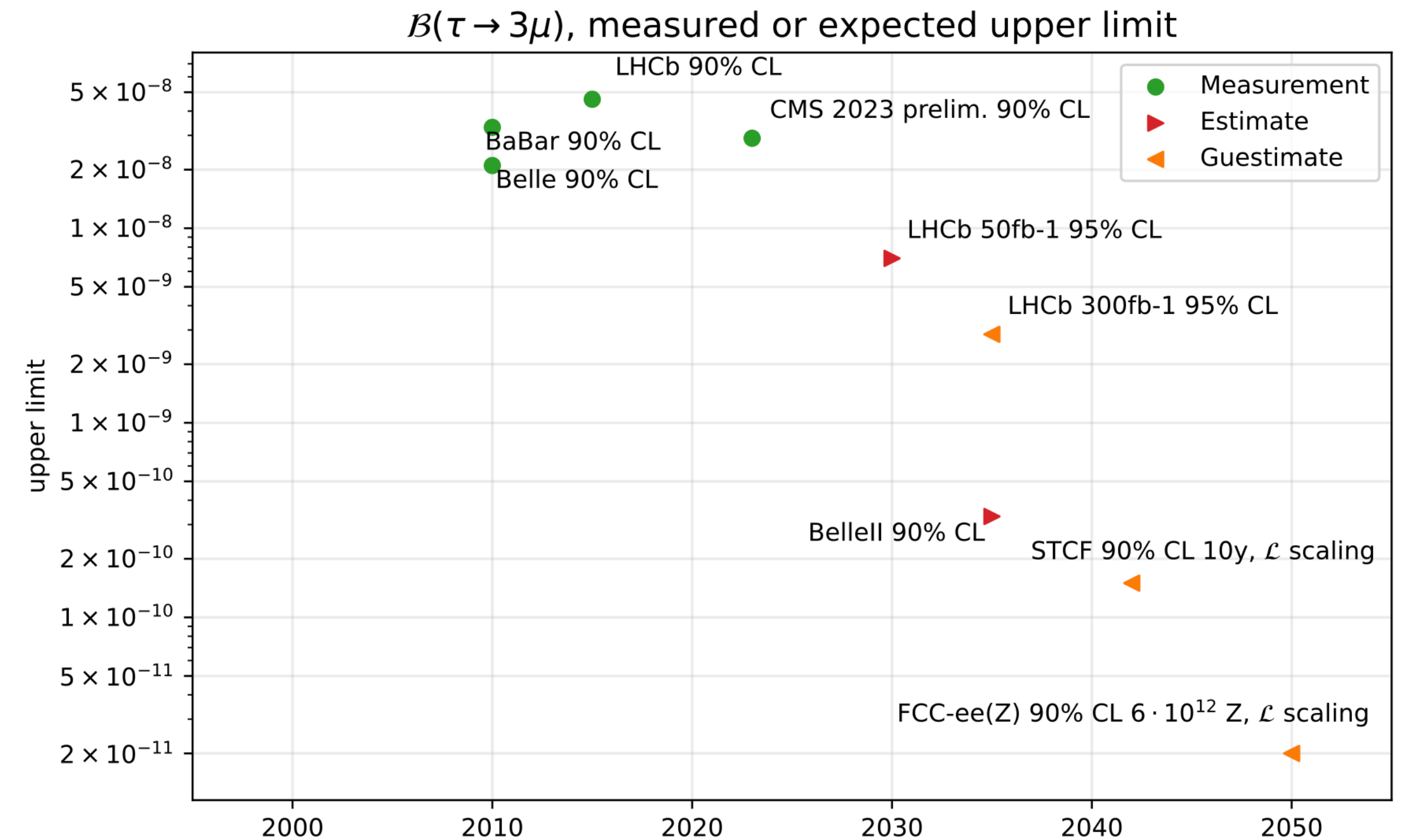
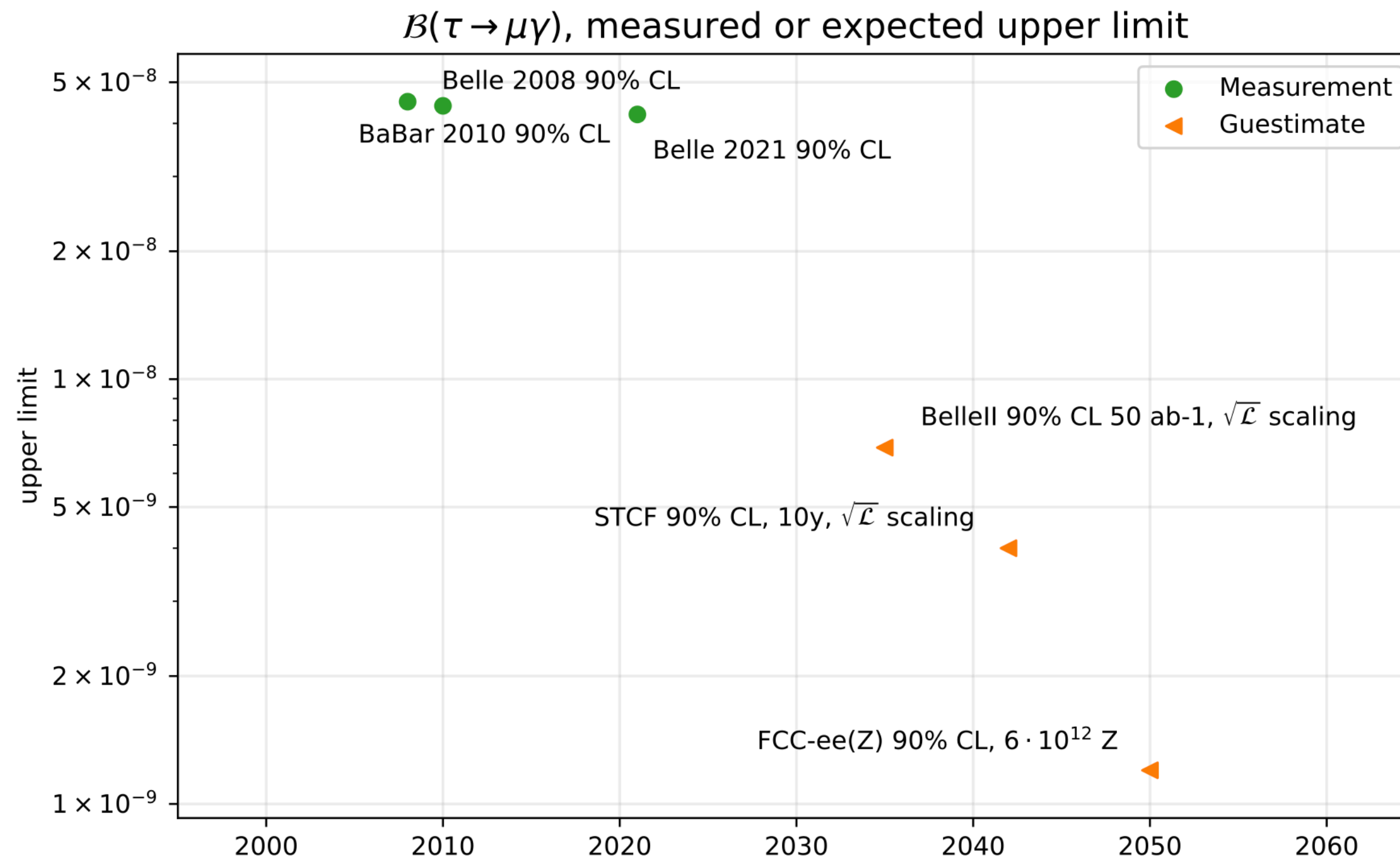
radiative corrections

Measurement	Current	Belle II	FCC	CEPC prelim.
Lifetime [sec]	$(2903 \pm 5) \times 10^{-16}$		$\pm 6 \times 10^{-18}$	$\pm 7 \times 10^{-18}$
$\text{BR}(\tau \rightarrow e \nu \bar{\nu})$	$(17.82 \pm 0.04)\%$		$\pm 0.003\%$	$\pm 0.003\%$
$\text{BR}(\tau \rightarrow \mu \nu \bar{\nu})$	$(17.39 \pm 0.04)\%$		$\pm 0.003\%$	$\pm 0.003\%$
m_τ [MeV]	1776.93 ± 0.09		± 0.0016 (stat.) ± 0.018 (syst.)	



CEPC flavor paper

- Lepton number is an accidental symmetry in SM, linked to small neutrino masses
- FCC-ee expect to probe $\tau \rightarrow \mu\gamma$ at $O(10^{-9})$ and $\tau \rightarrow 3\mu$ at $O(10^{-11})$



[FCC note: tau physics](#)

More to cover

- Rare hadronic decays: tau $\rightarrow$ 7 prongs, $\tau \rightarrow \eta\pi$
- Decays involving kaons
- Valuable tool to understand non-perturbative QCD and determine CKM (e.g. V_{us})

Strange physics

Detector not very long, $c\tau_{K^+(K_L)} = 3.7(15)$ m

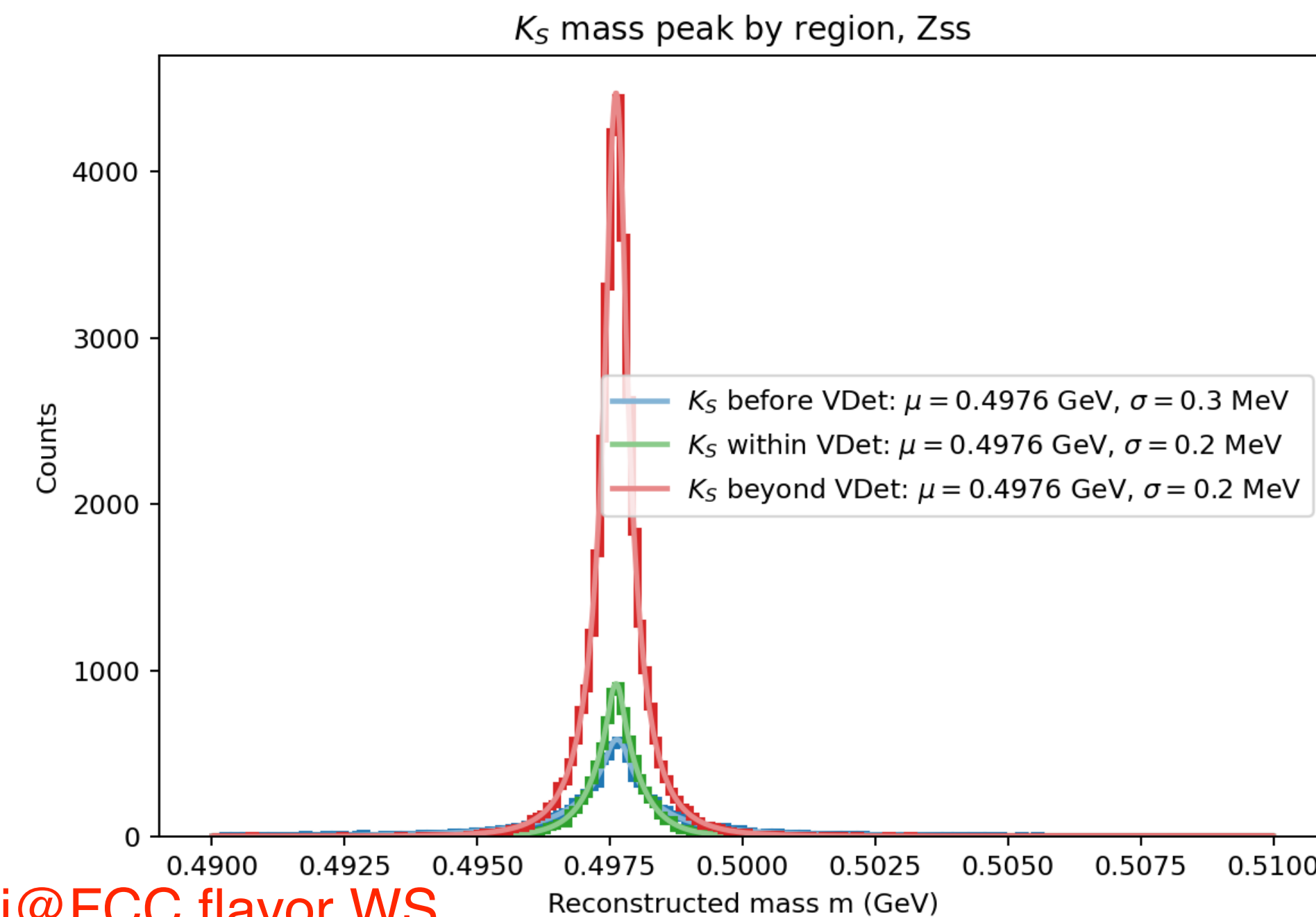
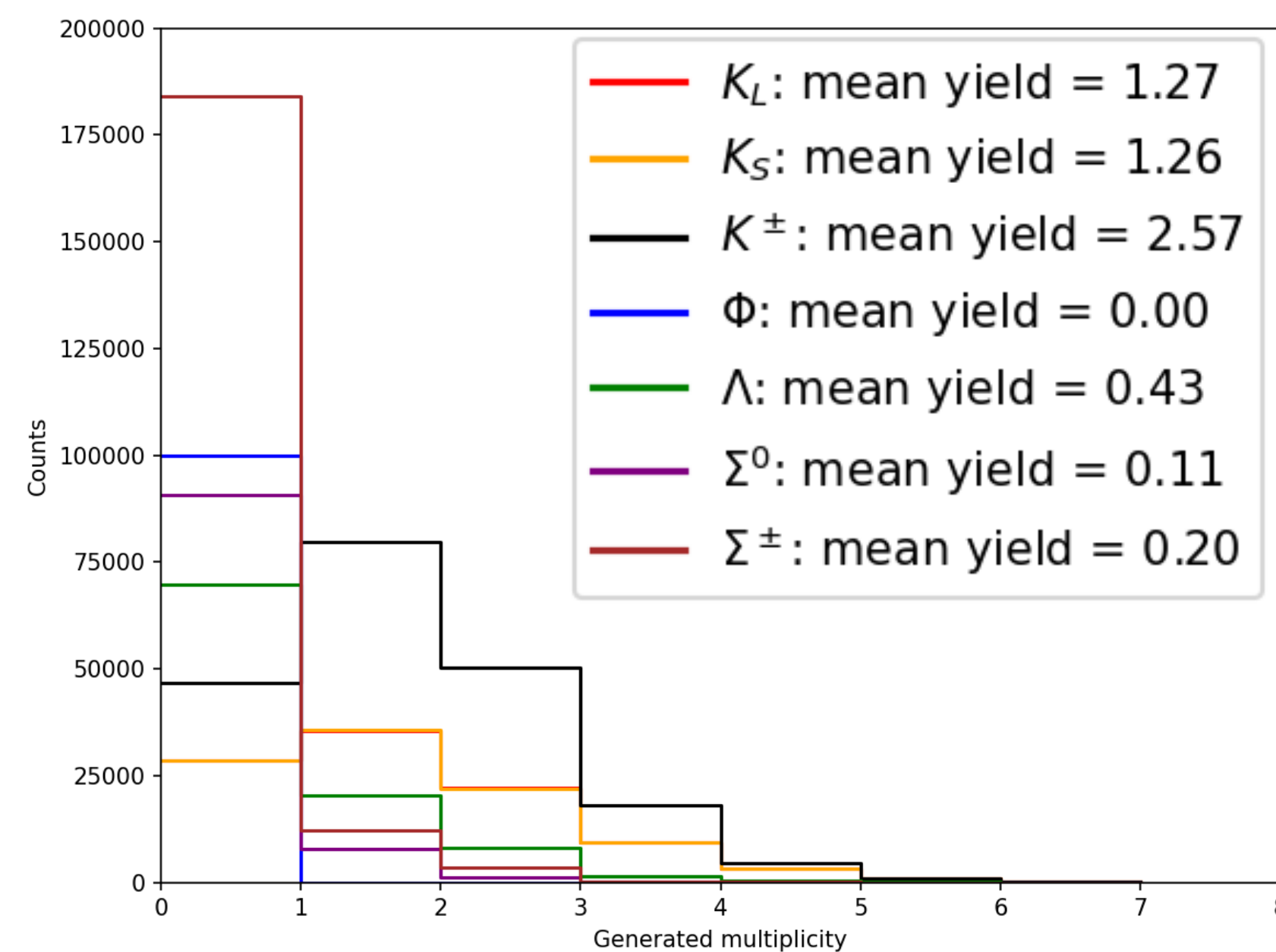
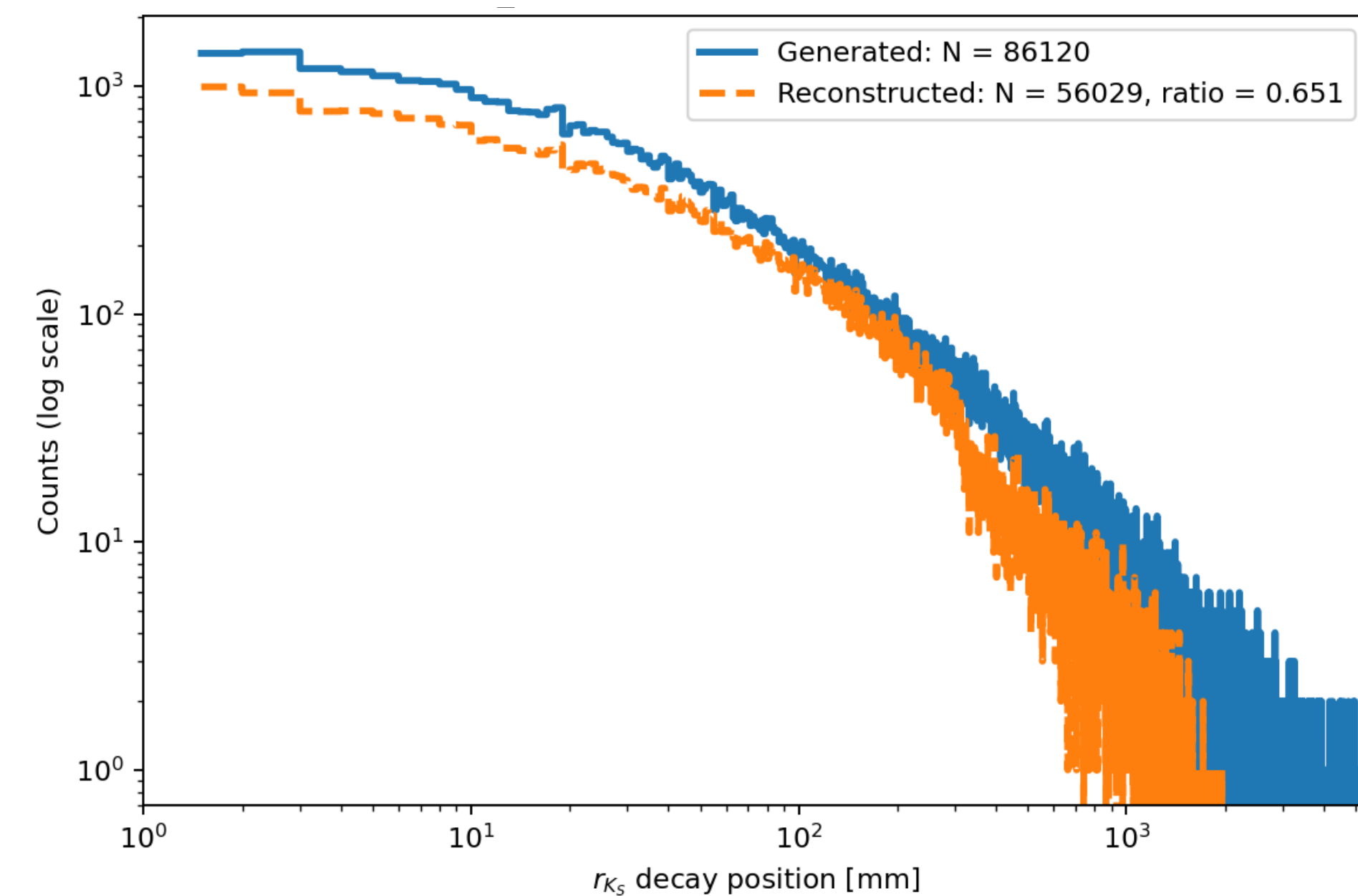
Great for K_s and hyperons

- Large acceptance
- Clean environment
- Excellent mass resolution

[Rado Marchevski@FCC](mailto:Rado.Marchevski@FCC) flavor WS

Teaser for Kaon decays

- Expect $O(10^{13})$ kaons at FCC-ee
- Acceptance X efficiency = 65%
- Sub-MeV mass resolution for very displaced $K_S \rightarrow \pi^+ \pi^-$



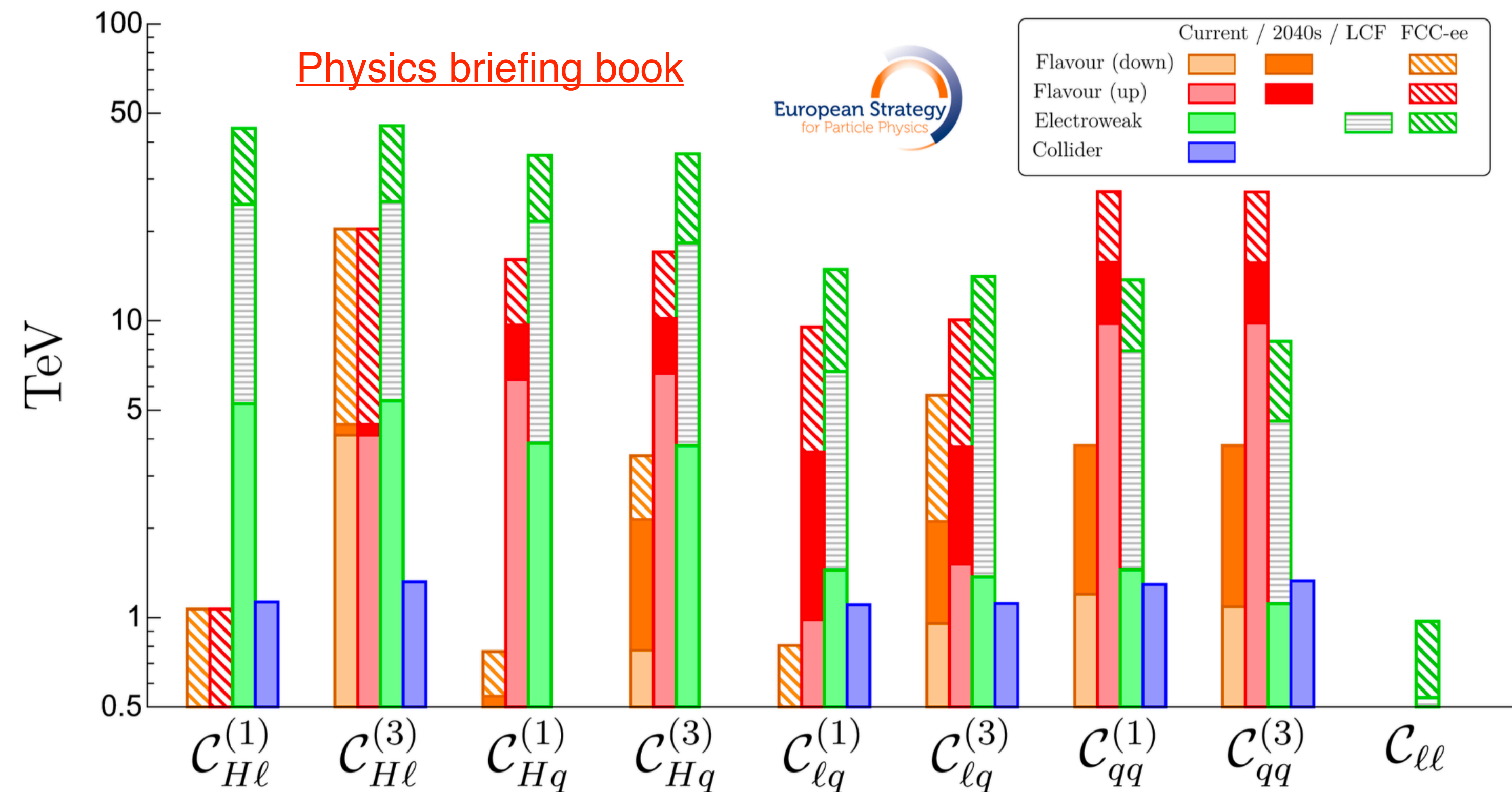
[Rado Marchevski@FCC flavor WS](mailto:Rado.Marchevski@FCC.flavor.WS)

More to cover

- $K_s \rightarrow \mu\mu$ benchmark
- $K_s \rightarrow \pi^0 \ell \ell$
- Hyperon channels

Summary

- An ideal machine to fully explore flavor landscape
- Broad program, great precision
- Test NP generally at O(10) TeV

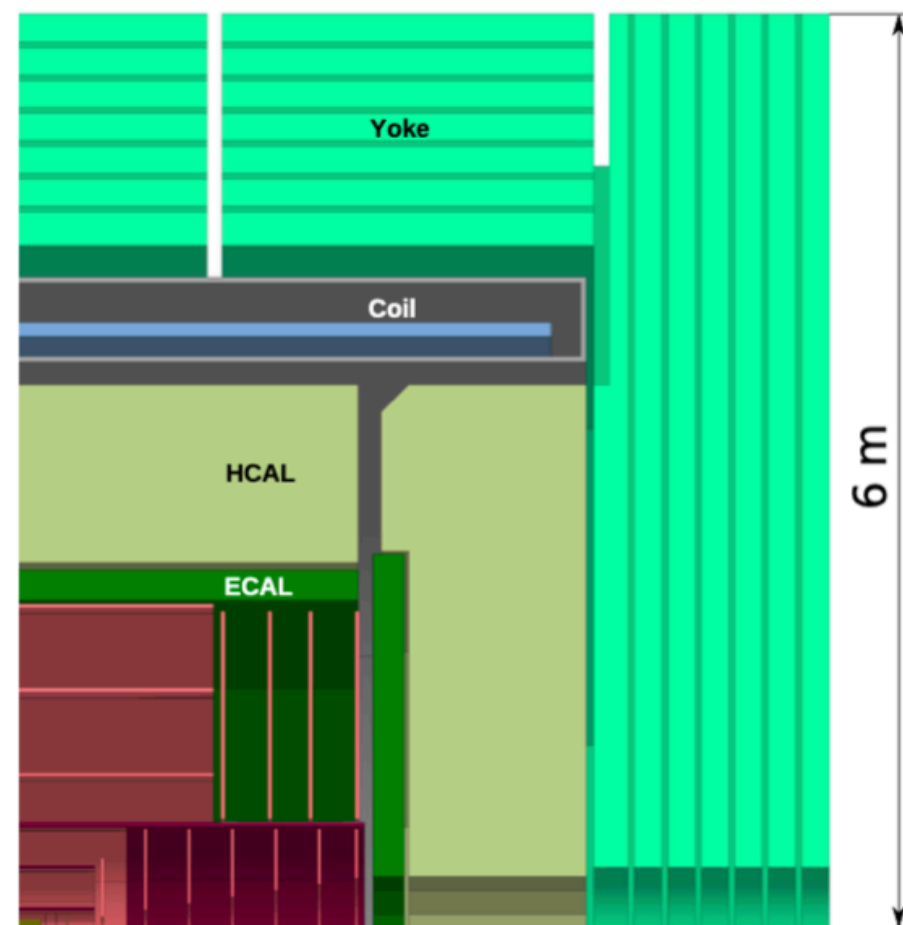


Backups

Detector concepts

taken from Mogens Dam

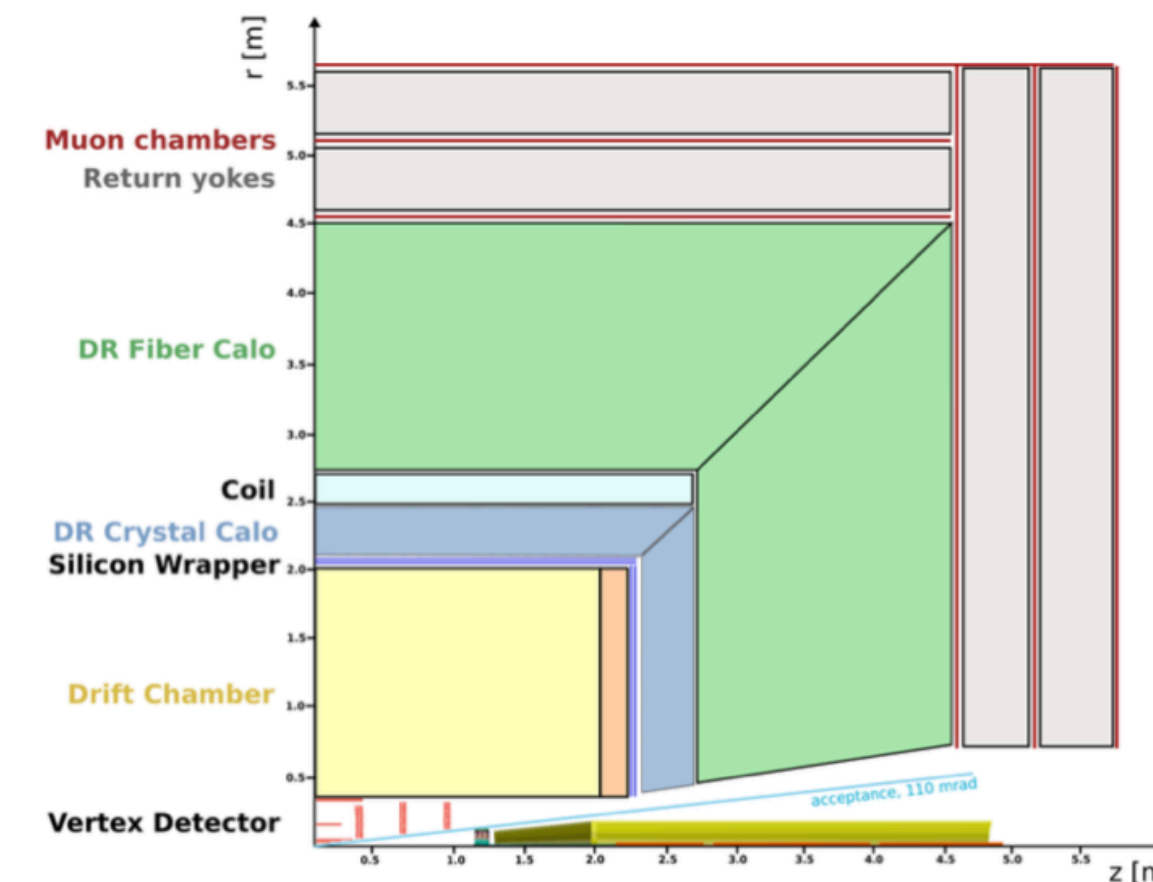
CLD



- Well established design
 - ILC → CLIC detector → CLD
- Full Si VXD + tracker
- CALICE-like calorimetry – very high granularity
- Coil outside calorimetry, muon system
- Possible detector optimizations
 - Improved σ_p/p , σ_E/E
 - PID: precise timing and RICH

[arXiv:1911.12230](https://arxiv.org/abs/1911.12230)

IDEA



- Design developed specifically for FCC-ee and CEPC
- Si VXD; ultra-light drift chamber with powerful PID
- Crystal ECAL w. dual readout
- Compact, light coil;
- Dual readout fibre calorimeter
- Muon system

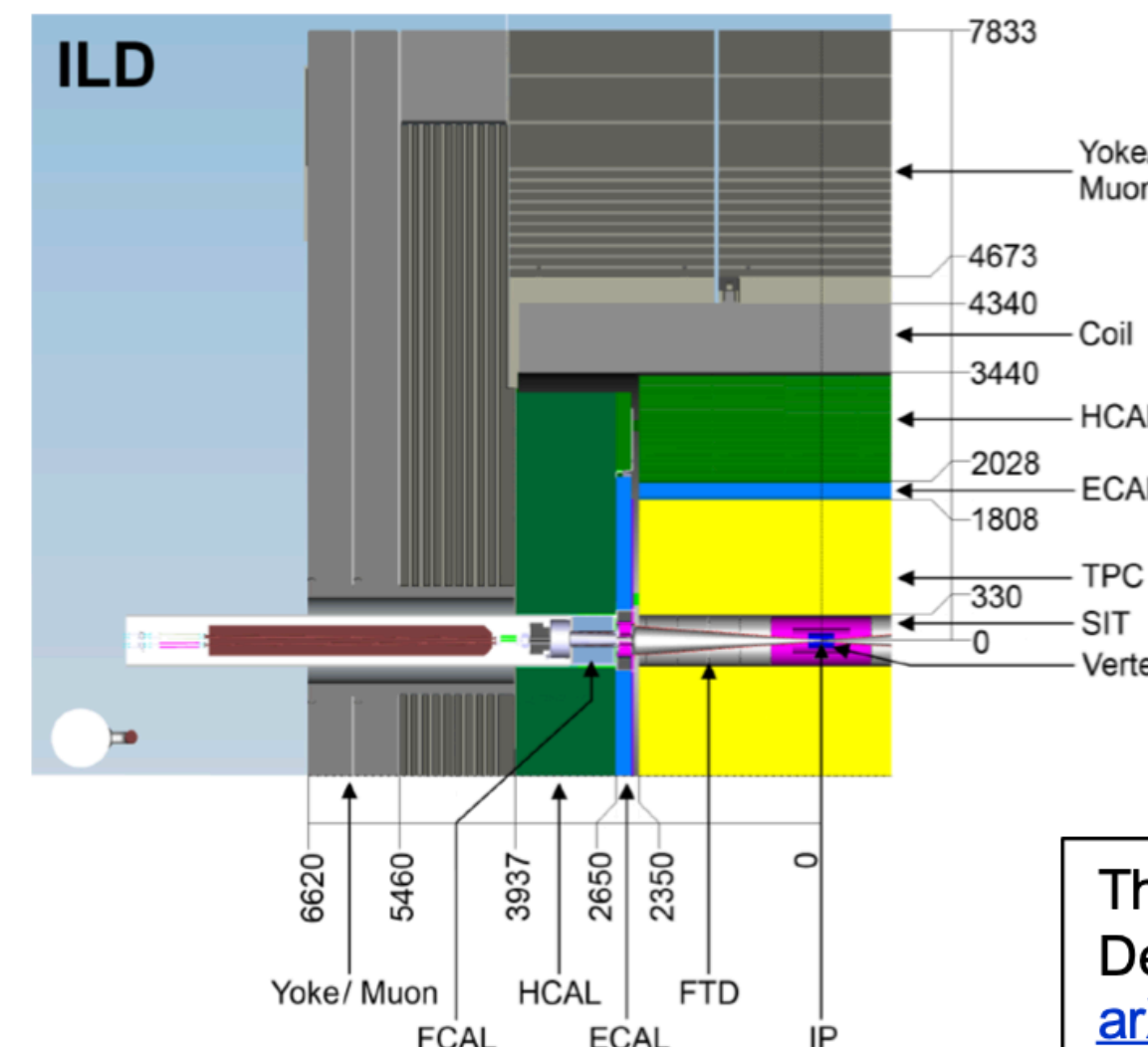
<https://doi.org/10.48550/arXiv.2502.21223>

Allegro



- Still in early design phase
- Design centred around High granularity **Noble Liquid ECAL**
 - Pb+LAr (or denser W+LKr)
- Si VXD
- Tracker: Drift chamber, straws, or Si
- Steel-scintillator HCAL
- Coil outside ECAL in same cryostat
- Muon system

[Eur.Phys.J.Plus 136 \(2021\) 10, 1066, arXiv:2109.00391](https://arxiv.org/abs/2109.00391)



- Designed originally for operation at the ILC
- Together with SiD, ancestor of CLD.
- Main difference and signature element:
 - Large-volume time projection chamber (TPC)

The International Linear Collider Technical Design Report - Volume 4: Detectors
[arXiv:1306.6329](https://arxiv.org/abs/1306.6329)

IDEA detector

Superconducting solenoid

- 2 T, $R = 2.0 - 2.4$ m
- $0.74 X_0$, 0.16λ @ 90°

Wire drift chamber

- 112 layers, $R = 35 - 200$ cm
- $0.016 X_0$ @ 90°

Silicon vertex detector

- 5 layers, $R = 1.7 - 34$ cm
- Pixel $20 \times 20 \mu\text{m}^2$

Beam pipe

- $R \sim 1.5$ cm

Preshower

- 2 layers, gas detector
- Spatial reso $< 100 \mu\text{m}$

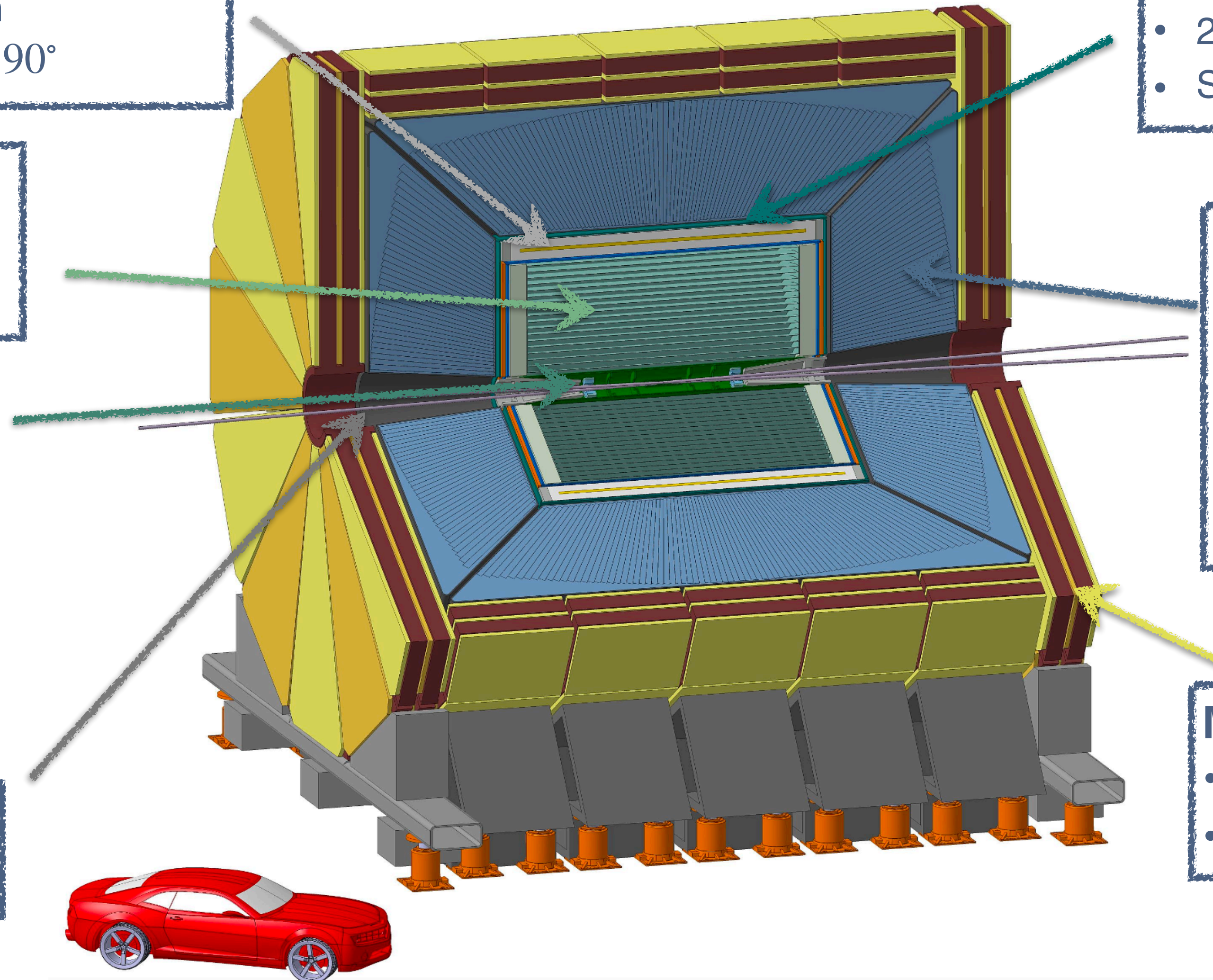
Dual-readout calorimeter

- 2 m capillaries
- Alternate Cherenkov and scintillation fibers

$$\sigma_{EM} \approx \frac{10\%}{\sqrt{E}}, \quad \sigma_{had} \approx \frac{30\%}{\sqrt{E}}$$

Muon chambers

- 3 layers, gas detector
- Spatial reso $< 400 \mu\text{m}$



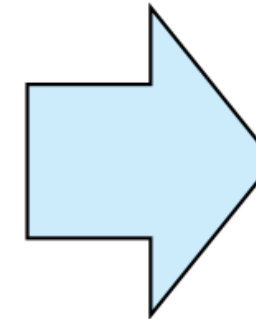
Detector requirements

taken from [Mogens Dam](#)



Higgs Factory Programme

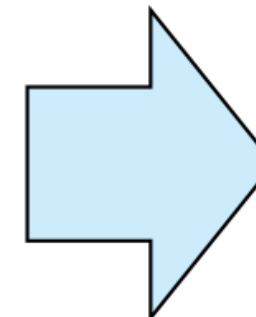
- At $\sqrt{s}=240$ and $\sqrt{s}=365$ GeV collect 2.6M HZ and 150k WW $\rightarrow$ H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling ($\sim 4 \sigma$) via loop diagrams
- Unique possibility: s-channel $e^+e^- \rightarrow H$ at 125 GeV



- **Momentum resolution $\sigma(p_T)/p_T \simeq 10^{-3}$ @ $p_T \sim 50$ GeV**
 - $\sigma(p)/p$ limited by multiple scattering $\rightarrow$ minimise material
- **Jet $\sigma(E)/E \simeq 3\text{-}4\%$ in multijet events for Z/W/H separation**
- **Superior impact parameter resolution for b, c tagging**
- **Hadron PID for s tagging**

Precision EW and QCD Programme

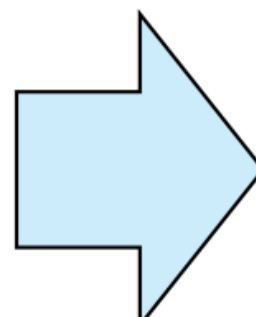
- 6×10^{12} Z and 2×10^8 WW events
- $\times 500$ improvement of statistical precision on EWPO:
 $m_Z, \Gamma_Z, \Gamma_{inv}, \sin^2\theta_W, R_b, m_W, \Gamma_W, \dots$
- 2×10^8 tt events: $m_{top}, \Gamma_{top}, \text{EW couplings}$
- Indirect sensitivity to new physics up to tens of TeV



- **Absolute normalisation of luminosity to $10^{-5} - 10^{-4}$ level**
- **Relative normalisation to $\mathcal{O}(10^{-6})$ [e.g. Γ_{had}/Γ_ℓ]**
 - Acceptance definition to $\mathcal{O}(10 \mu\text{m})$
- **Track angular resolution < 0.1 mrad**
- **Stability of B field to 10^{-6}**

Heavy Flavour Programme

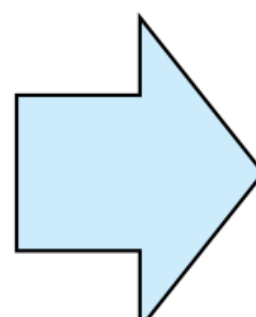
- 10^{12} bb, cc, 2×10^{12} $\tau\tau$ (clean, boosted): $10 \times$ BelleII stats.
- CKM matrix, CP measurements
- rare decays, CLFV searches, lepton universality



- **Superior impact parameter resolution**
- **Precise identification and measurement of secondary vertices**
- **ECAL resolution at few %/VE**
- **Excellent π^0/γ separation for τ decay-mode identification**
- **PID: K/ π separation over wide p range $\rightarrow$ dN/dx, RICH, timing**

Feebly coupled particles Beyond SM

- Opportunity to directly observe new feebly interacting particles with masses below m_Z
- Axion-like particles, dark photons, Heavy Neutral Leptons
- Long-lifetime LLPs



- **Sensitivity to (significantly) detached vertices (mm $\rightarrow$ m)**
 - tracking: more layers, "continuous" tracking
 - calorimetry: granularity, tracking capabilities
- **Precise timing**
- **Hermeticity**

Analysis framework

Abundant centrally-produced simulation

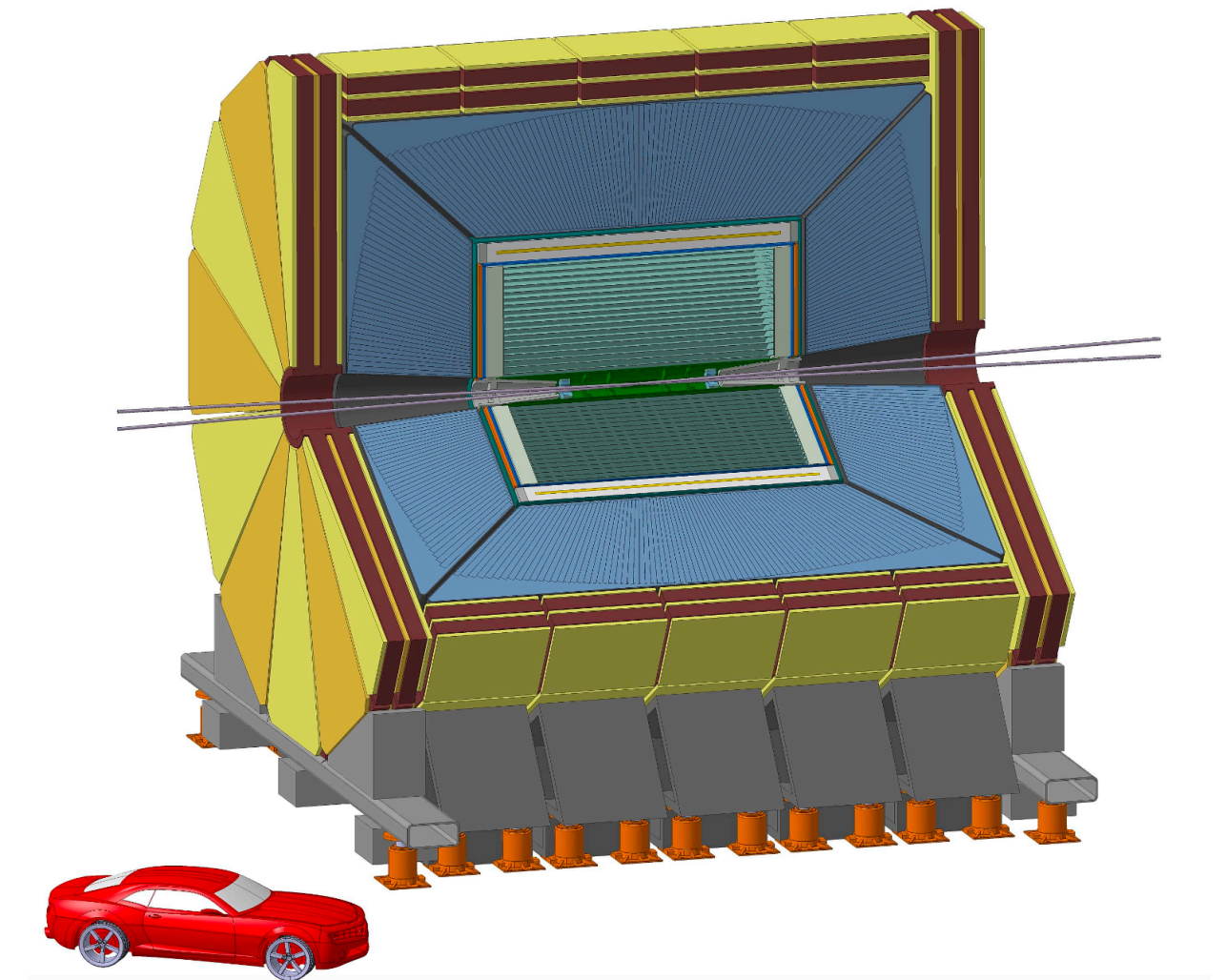
- Generators: Pythia 8, Whizard + Pythia 6
- Simulation: Delphes fastsim based on IDEA concept
- 600+ MC samples, tens of billion events

Common analysis tools

- RDataFrame-based common workflow
- Jet reconstruction: FastJet, exclusive Durham k_T algorithm for most cases
- Flavor tagging: Particle Net, considering properties of all constituents (full track info, dN/dx , $mTOF$)
- Statistical analysis: CMS combine tool

Dedicated analyses to cover all Higgs properties

- ~ 20 dedicated analysis notes
- Centrally coordinated and reviewed



Simulated samples

Generators: pythia8 + EvtGen

Simulation: Delphes with IDEA concept

[FCC tutorial: generation workflow](#)

Official samples

- Central storage @CERN EOS

Decay process	num. of evt.	sample size
Inclusive $Z \rightarrow b\bar{b}, c\bar{c}, s\bar{s}, q\bar{q}$	5×10^8 /sample	5 TB/sample
~70 excl. decays of $Z \rightarrow b\bar{b}$ ~10 excl. decays of $Z \rightarrow c\bar{c}$	1×10^8 /sample	O(100) GB/sample

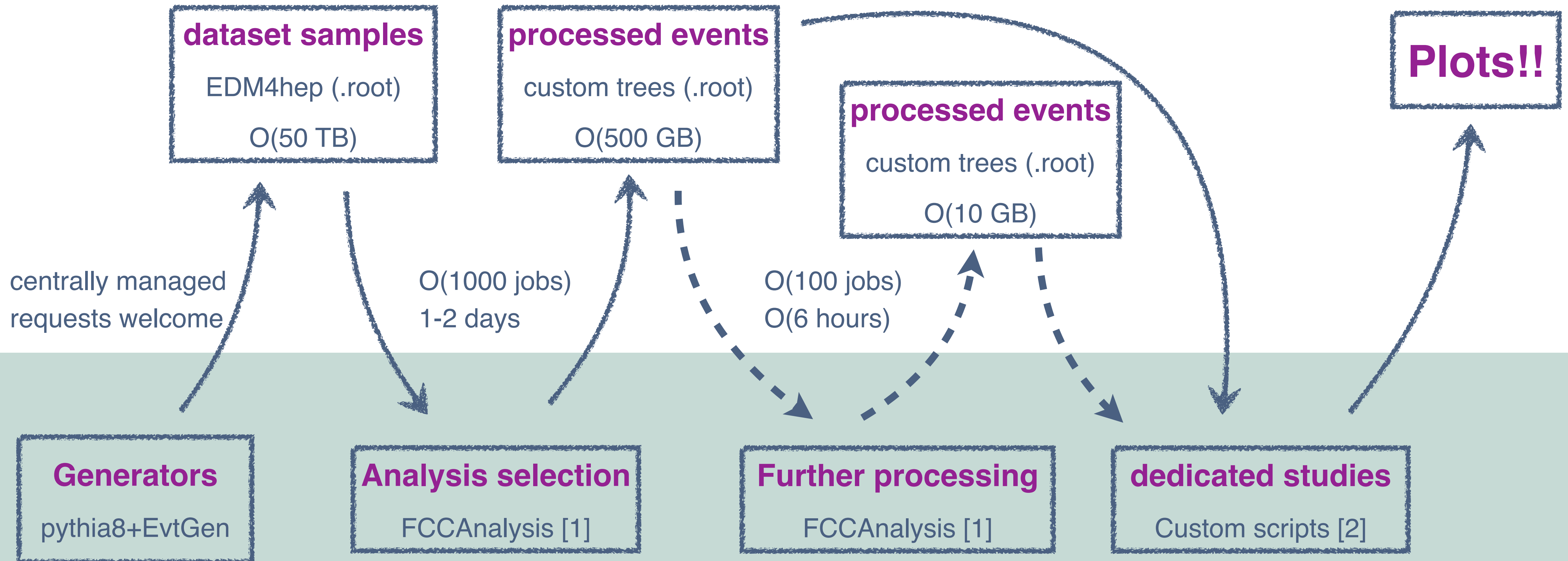
[Official sample listing](#)

Example: excl. samples considered for $B_c^+ / B^+ \rightarrow \tau^+ \nu_\tau$ study

- $Z \rightarrow b\bar{b}, B \rightarrow D\tau^+\nu_\tau$
- $Z \rightarrow b\bar{b}, B \rightarrow D^*\tau^+\nu_\tau$
- $Z \rightarrow b\bar{b}, B \rightarrow De^+\nu_e$
- $Z \rightarrow b\bar{b}, B \rightarrow D^*e^+\nu_e$
- $Z \rightarrow b\bar{b}, B \rightarrow D\mu^+\nu_\mu$
- $Z \rightarrow b\bar{b}, B \rightarrow D^*\mu^+\nu_\mu$
- $Z \rightarrow b\bar{b}, B \rightarrow D\pi^+\pi^+\pi^-$
- $Z \rightarrow b\bar{b}, B \rightarrow D^*\pi^+\pi^+\pi^-$
- $Z \rightarrow b\bar{b}, B \rightarrow DD_s^+$
- $Z \rightarrow b\bar{b}, B \rightarrow D^*D_s^+$
- $Z \rightarrow b\bar{b}, B \rightarrow D^*D_s^{*+}$

- $D^+ \rightarrow \tau^+\nu_\tau$
- $D^+ \rightarrow K^0\pi^+\pi^+\pi^-$
- $D_s^+ \rightarrow \tau^+\nu_\tau$
- $D_s^+ \rightarrow \rho^+\eta'$
- $\Lambda_c^+ \rightarrow \Lambda^0 e^+ \nu_e$
- $\Lambda_c^+ \rightarrow \Lambda^0 \mu^+ \nu_\mu$
- $\Lambda_c^+ \rightarrow \Lambda^0 \pi^+ \pi^+ \pi^-$
- $\Lambda_c^+ \rightarrow \Sigma^+ \pi^+ \pi^-$

Example workflow



[1]. <https://github.com/HEP-FCC/FCCAnalyses/tree/master/examples/FCCee/flavour/BuBc2TauNu>

[2]. <https://github.com/HEP-FCC/FCCeePhysicsPerformance/tree/master/case-studies/flavour/BuBc2TauNu>

Feasibility study and ESPPU submission



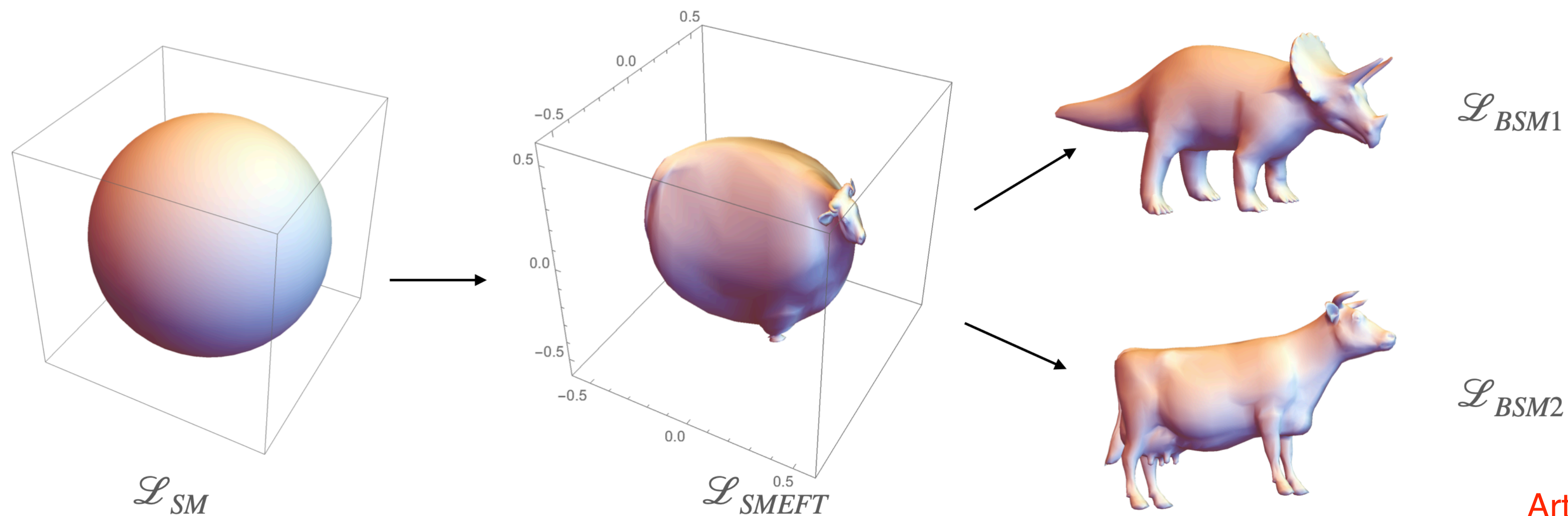
FCC feasibility study reports

- Vol. 1: Physics, Experiment, Detectors (~260 pages)
- Vol. 2: Accelerators, technical infrastructure and safety (~600 pages)
- Vol. 3: Civil Engineering, Implementation and Sustainability (~330 pages)

Submissions to ESPPU (10 pages each)

- FCC Integrated Programme Stage 1: The FCC-ee
- FCC Integrated Programme Stage 2: The FCC-hh
- The FCC Integrated Programme: A physics manifesto
- Prospects in Electroweak, Higgs and Top physics at FCC
- Prospects in BSM physics at FCC
- FCC: QCD physics
- Prospects for flavour physics at FCC
- Prospects for physics at FCC-hh
- Expressions of Interest for the development of Detector Concepts and Sub-detector Systems for the FCC

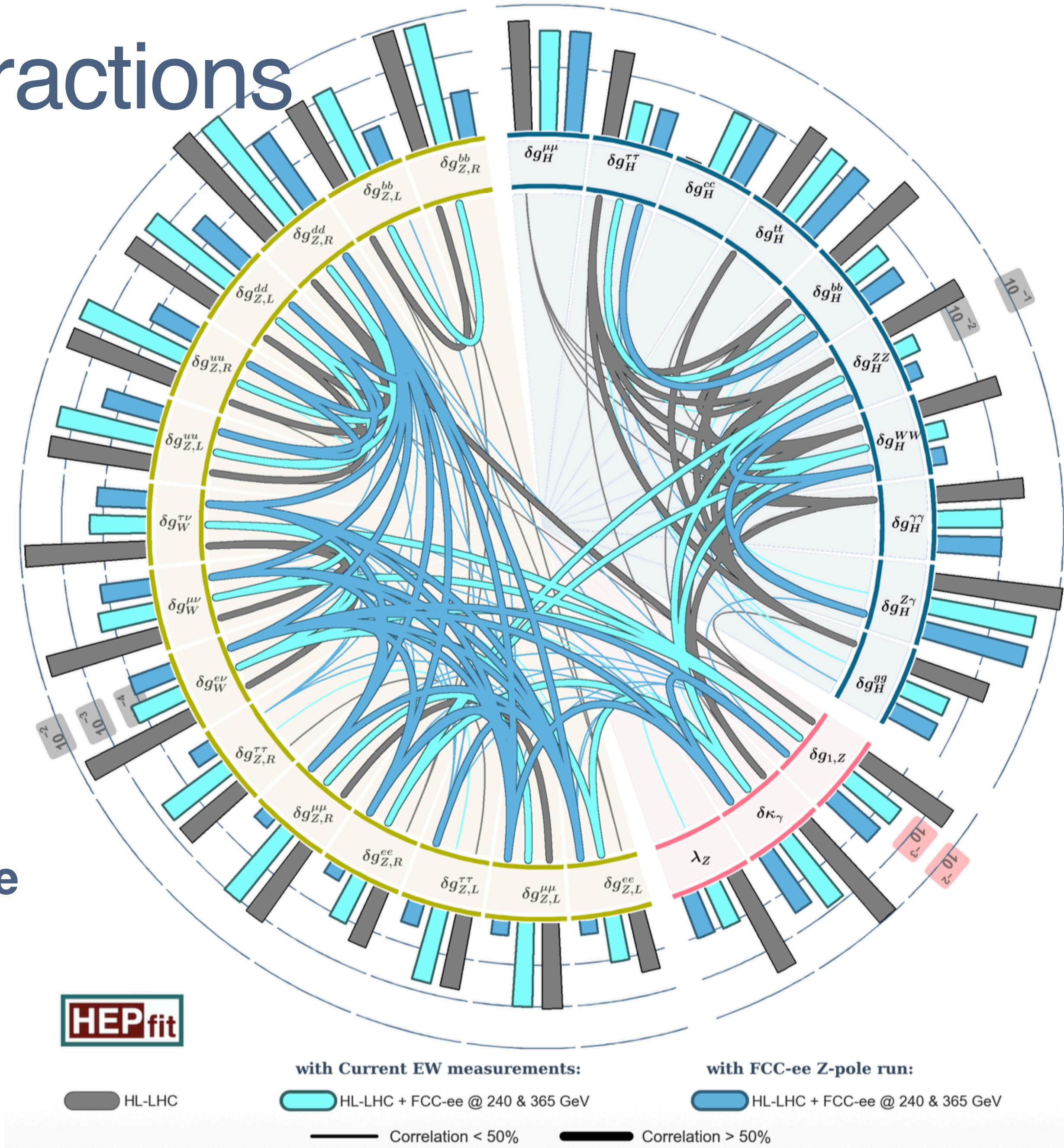
EFT landscape



Art from [Fabio Maltoni](#)

EW/Higgs interactions

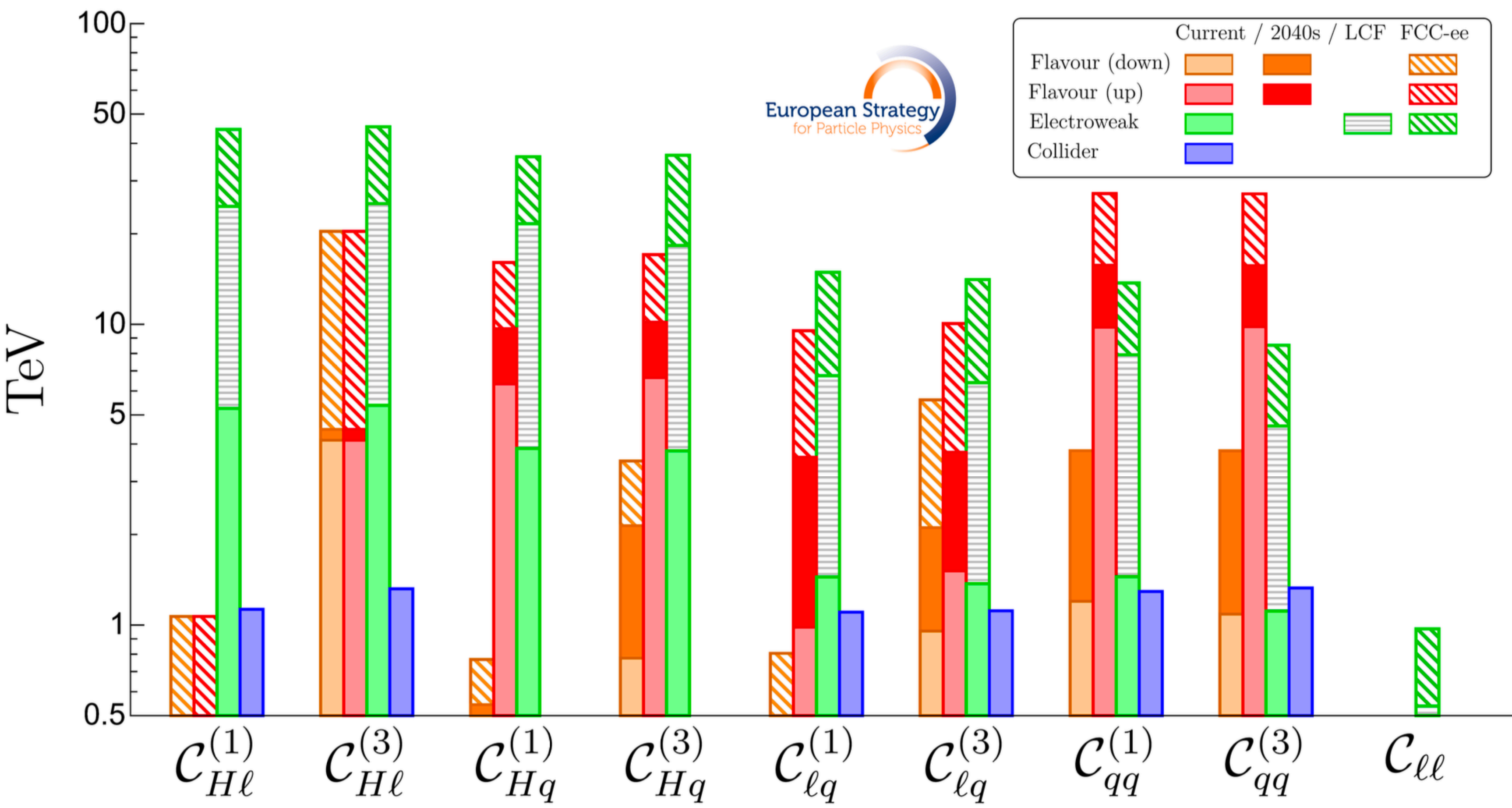
At least 1 order of magnitude advancement everywhere



[FSR volume 1](#)

Dim-6 flavor operators

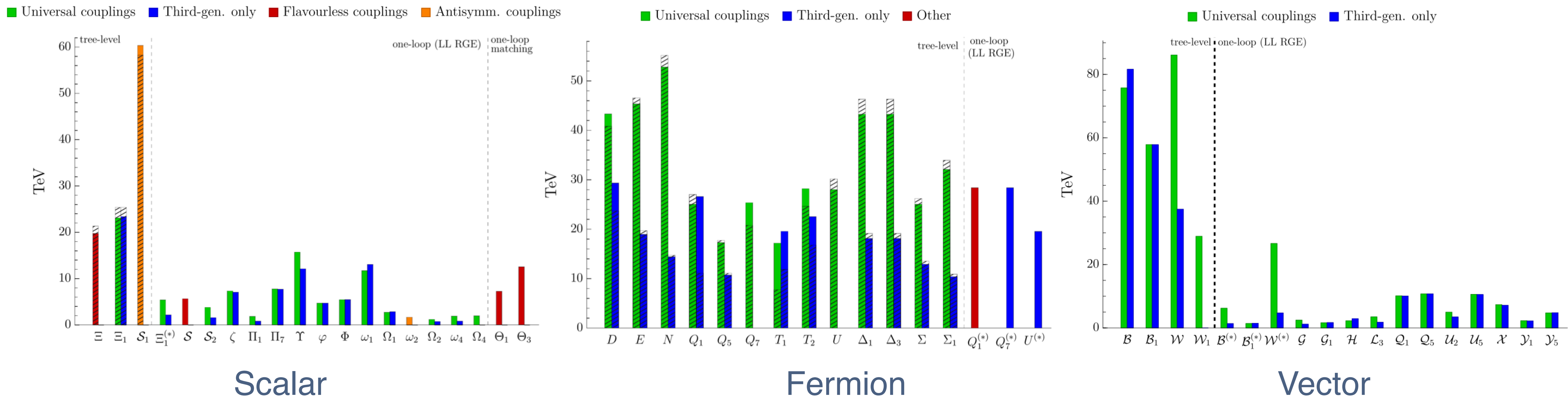
- Large advancement wrt. HL-LHC + Belle II for all operators
- Probe scale of O(10) TeV globally

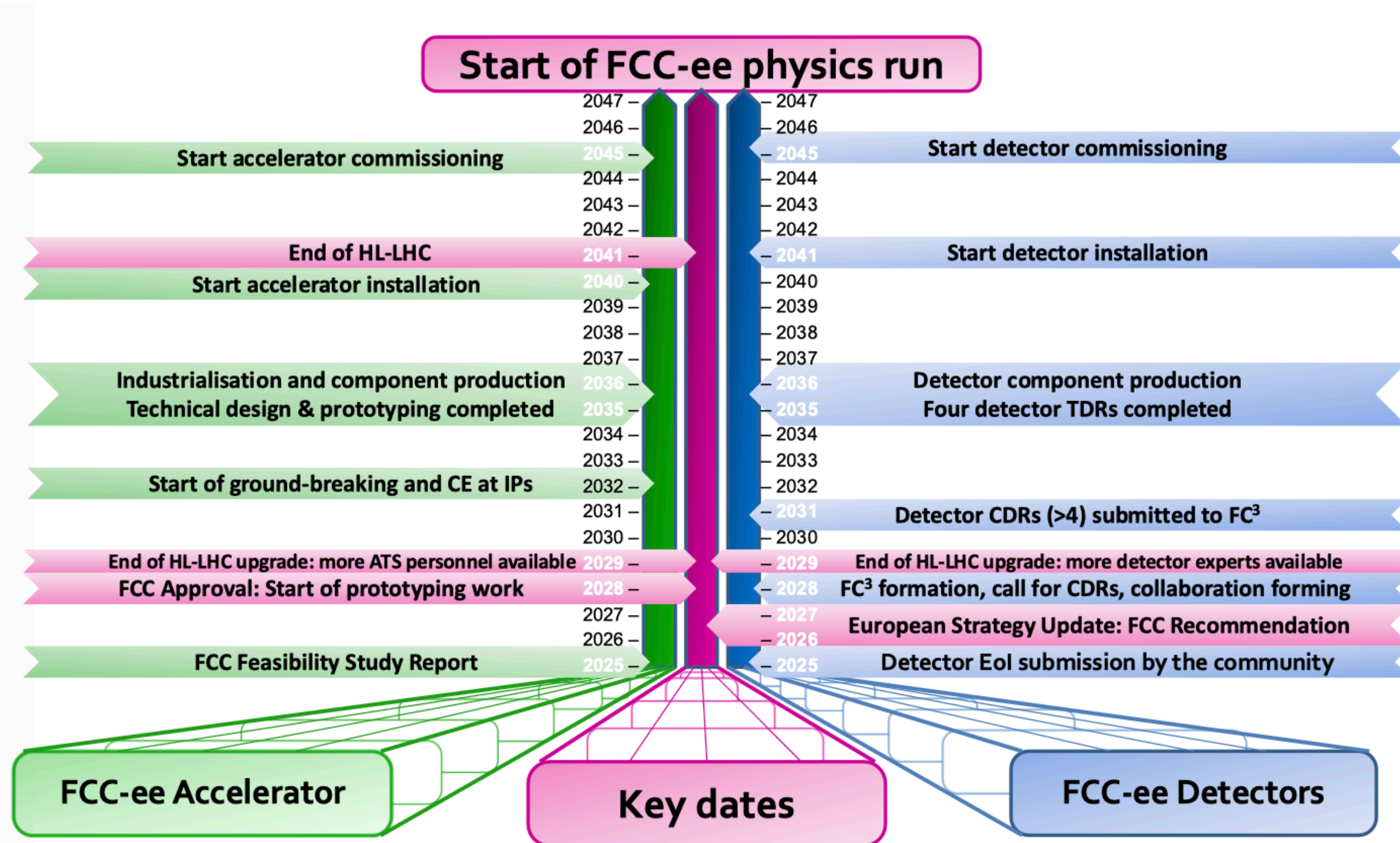


Probing new particles

- 48 possible types of particles that can have tree-level linear interaction to SM, matched to Dim-6 SMEFT operators.
- All, but a few, can be probed by W- and Z-pole observables

[arXiv: 2408.03992](https://arxiv.org/abs/2408.03992)





Updated project cost for FCC-ee up to and including operation at ZH and 4 experiments
t-tbar upgrade requires additional 1.3 BCHF

Domain	Cost [MCHF]
Civil engineering	6160
Technical infrastructures	2840
Injectors and transfer lines	590
Booster and collider	4140
CERN contribution to four experiments	290
FCC-ee total	14 020
+ Four experiments (non-CERN part)	1300
FCC-ee total, including four experiments	15 320

Funding of FCC (and any other major future collider project) will come from two main sources:

- ❑ **CERN Budget** (i.e. revenues from Member and Associate Member States): **would cover more than 50% of FCC investment cost**
- ❑ **External contributions:**
 - additional voluntary contributions (in-cash or in-kind) from **Member and Associate Member States**
 - contributions from **non-Member States**
 - exploring possible contributions from the **European Union in the next Multiannual Financial Framework** (MFF 2028-2034)
 - exploring possible contributions of **private donors** (→ in Dec 2024, Council approved “*Policy for fundraising from private donors for scientific activities at CERN*”)

Several funding models developed, based on different assumptions (e.g. constant or slightly increased CERN Budget)
→ final report will be submitted to Council and its subordinate bodies in August

Comparison of proposals

Project	Construction start	First beams	Peak L at HZ per IP ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	Years of operation	Project cost (BCHF)	Next stage collider
FCC-ee	2033	2046	7.5	16	15.3	FCC-hh
LEP3	2037	2047	1.8	15	4.1	FCC-hh
LHeC	2037	2044	2.3	7	2.1	FCC-hh
LCF 250 → 550 GeV	2035	2045	1.3 – 3.8	21	9.4+5.4 14.8	1-10 TeV collider?
CLIC 380→1500 GeV	2035	2045	2.2 - 3.7	22	7.5 + 7.1 14.6	3 TeV collider?

Gianotti at 117th plenary ECFA

All first-stage facilities start ~ 2045 (driven by HL-LHC running until 2041)

Higher peak luminosity for FCC-ee and 4 IPs → operation is few years shorter than for linear colliders

Project cost (only CERN part shown here) similar for FCC-ee and linear colliders, lower for colliders re-using the LHC tunnel

Options for next stage collider:

- For FCC-ee: FCC-hh
- For LEP3 and LHeC: FCC-hh; maybe a muon collider if technology demonstrated, not built in the US, and machine available on ~ 2070 timeframe?
- For linear colliders: 1-10 TeV upgrade (technology? power consumption)? Muon collider if not built in the US, machine available on ~ 2070 timeframe and can mostly be built within current CERN land?

FCC-ee cost estimate (FSR 2025)

Capital cost (2024 CHF) for construction of the FCC-ee is summarised below. This cost includes construction of the entire new infrastructure and all equipment for operation at the Z, WW and ZH working points.

FCC-ee

Domain	Cost [MCHF]
Civil engineering	6,160
Technical infrastructures	2,840
Injectors and transfer lines	590
Booster and collider	4,140
CERN contribution to four experiments	290
FCC-ee total	14,020
+ four experiments (non-CERN part)	1,300
FCC-ee total incl. four experiments	15,320

LCF

CLIC

Unit: MCHF	LCF 250 (LP)	Δ LCF 550 (FP)	CLIC 380	Δ CLIC 1500
Collider	3864	4204	2471	4684
Main Beam inj./transfer	1181	86	1046	23
Drivebeam inj./transfer	-	-	1060	302
Civil Engineering	2338	0	1403	703
Technical Infrastructure	1109	1174	1361	1404
Sum	8492	5464	7341	7116

LEP3

Cost Element	2 new Xpts	2 Exist Xpts
Accelerator	2705	2705
Injectors and Transfer Lines	295	295
Technical Infrastructures	435	435
Experiments	130	60
Civil Engineering	165	165
LHC Removal/LEP3 Installation	140	140
Total CERN (MCHF)	3870	3800
Experiments non-CERN part	900	270

Note: Upgrade of SRF (800 MHz) & cryogenics for ttbar operation corresponds to additional cost of 1,260 MCHF

Cost summary table in 2024 MCHF for the construction of FCC-hh.

FCC-hh
(after FCC-ee)

Domain	FCC-hh Cost [MCHF]
FCC-ee dismantling	200
Collider*	13400
Injectors and transfer linear	1000
Civil Engineering	520
Technical infrastructures	3960
Experiments	N/A
Total	19080

*target price of 2.0 MCHF per 14.3 m long magnet with 1.0 MCHF of conductor, 0.5 MCHF for assembly, and 0.5 MCHF for components

Muon Collider



LHeC (cost estimate 2018, 60 GeV e-)

Budget Item	Cost
SRF System	805MCHF
SRF R&D and Proto Typing	31MCHF
Injector	40MCHF
Magnet and Vacuum System	215MCHF
SC IR magnets	105MCHF
Dump System and Source	5MCHF
Cryogenic Infrastructure	100MCHF
General Infrastructure and installation	69MCHF
Civil Engineering	386MCHF
Total	1756MCHF

→ ~2 BCHF (2025)

