Flavour and τ physics at the FCC-ee

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Prague, Czechia

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Topics

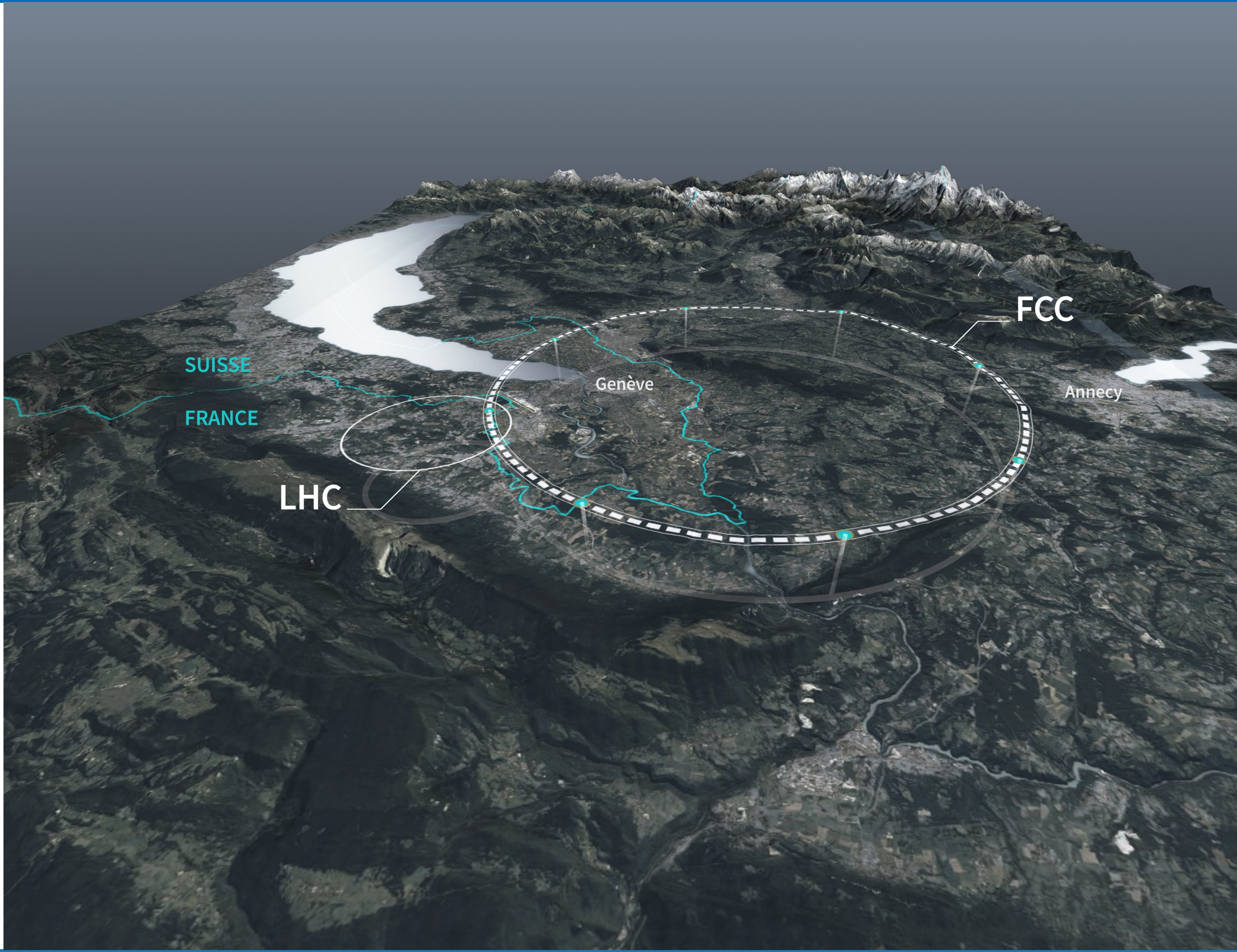
- The FCC-ee and the IDEA detector
- Phenomenology and detector requirements
  - Focusing on:
    - V_{cb} & V_{ub}
    - $b \to s\tau^+\tau^-$
    - $b \to s\nu\bar{\nu}$
    - $\tau^{\pm}$ decays

$$\left.\begin{array}{l} V_{cb} \,\&\, V_{ub} \\ b \to s\tau^+\tau^- \\ b \to s\nu\bar{\nu} \end{array}\right\}$$

European Committee for Future Accelerators (ECFA) focus topics

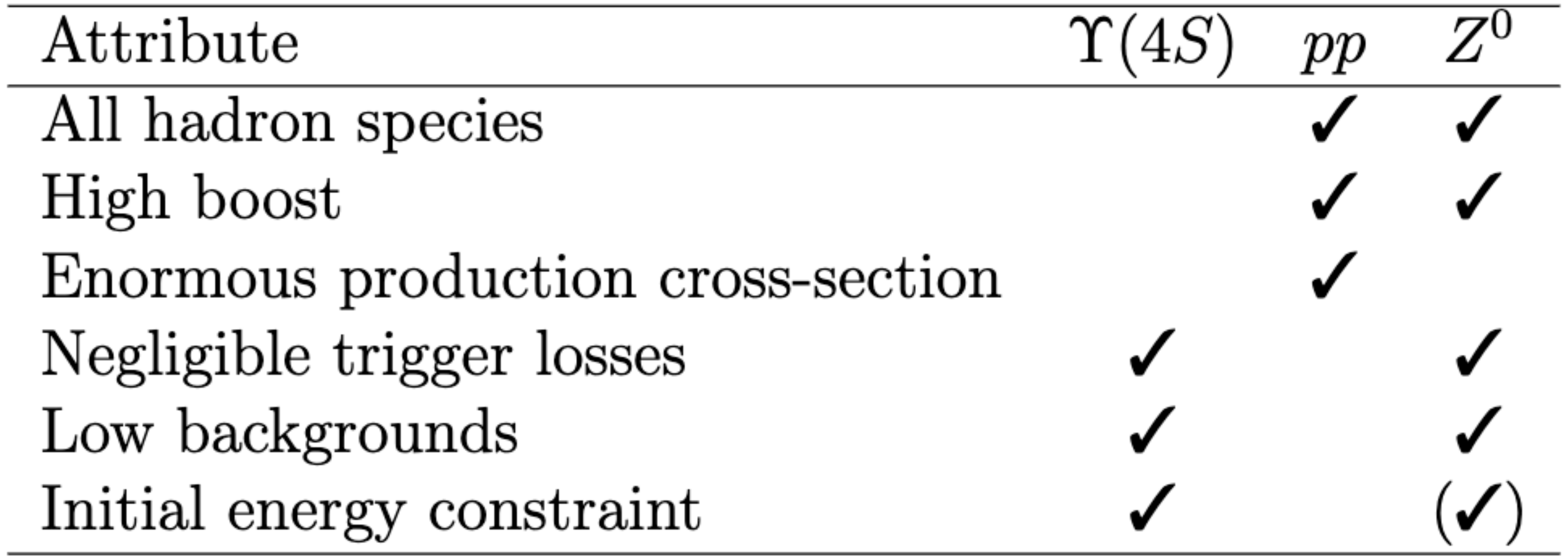
The FCC-ee

- 91 km circumference
- 4 collision points
- 16 years operation
- Plan to operate at a number of energy levels; Z^0-pole, W^+W^-, Z^0H, $t\bar{t}$
- I will primarily cover the latest Z^0-pole prospects



The FCC-ee

- Z^0-pole run will deliver 6×10^{12} Z^0s in total
  - “LEP in a minute”
- W^+W^- run will deliver 2.4×10^8 $W^\pm$ pairs in total
- Almost a “best of both worlds” scenario compared to Belle II and LHCb
- We must determine what kind of detectors we need…



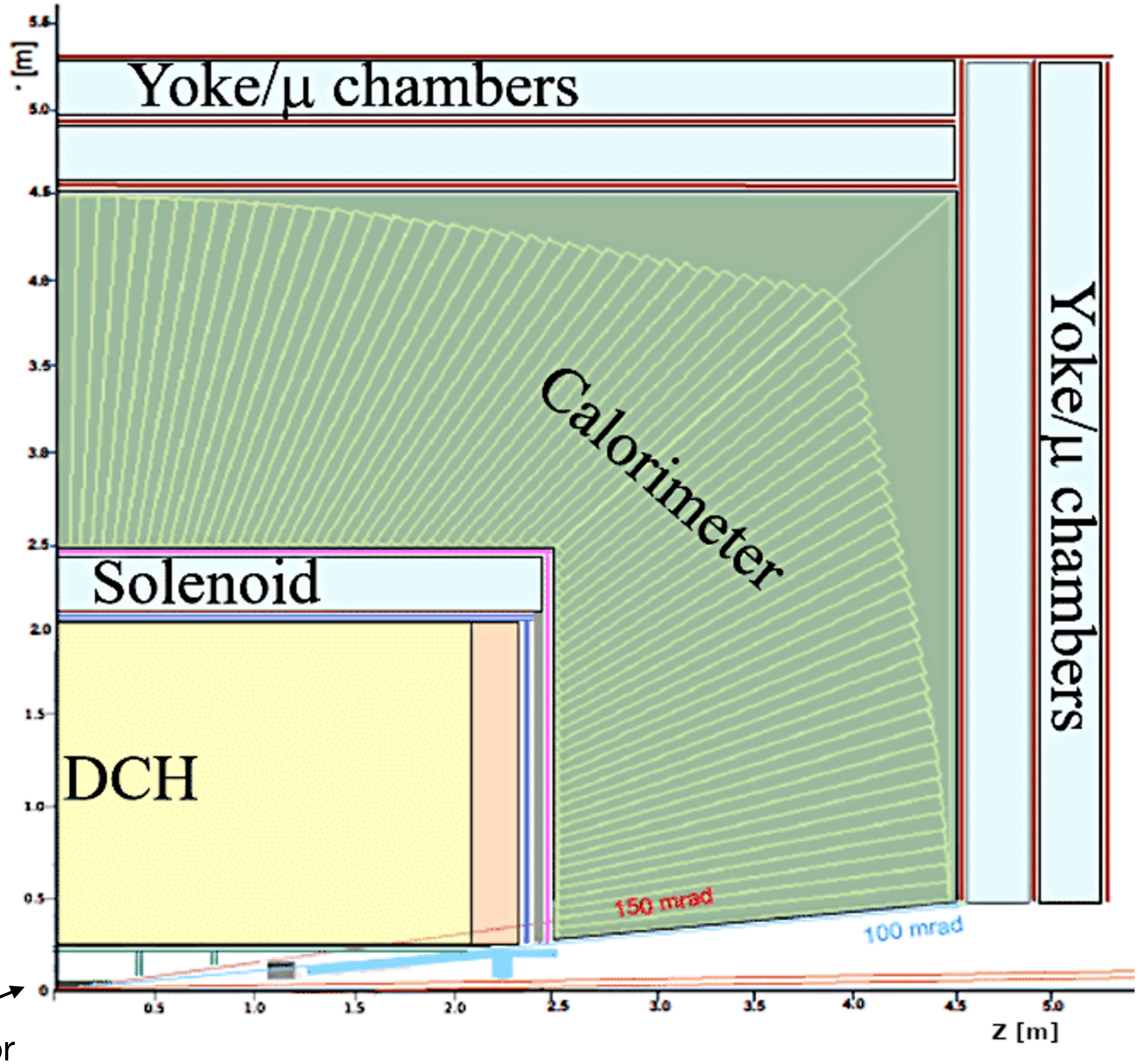
Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

Advantageous properties of Belle II ($\Upsilon(4S)$), LHC (pp) and FCC-ee (Z^0)
[arxiv:2106.01259]

The IDEA detector

Gabriella Gaudia: ICHEP 2022

- One of the candidates for a future detector design
- Plenty development activity over the past few years
  - See talks at the FCC weeks and ECFA meetings
- Need to marry this work by detector experts with the physics requirements



Silicon vertex detector

Quarter cross-section of the IDEA design

V_{ub} and V_{cb}

David Marzocca: 2nd ECFA Workshop 2023

Crucial inputs for constraining new physics from rare meson decays and meson mixing - the largest source of uncertainty

Systematic uncertainties will eventually dominate
the semileptonic V_{cb} measurements

Present Day		LHCb Upgrade II & Belle III
$\sigma(V_{cb}) \sim 1.4\,\%$ $\sigma(V_{ub}) \sim 6.2\,\%$	→	$\sigma(V_{cb}) \sim 1.0\,\%$ $\sigma(V_{ub}) \sim 0.9\,\%$

Can we improve on this?

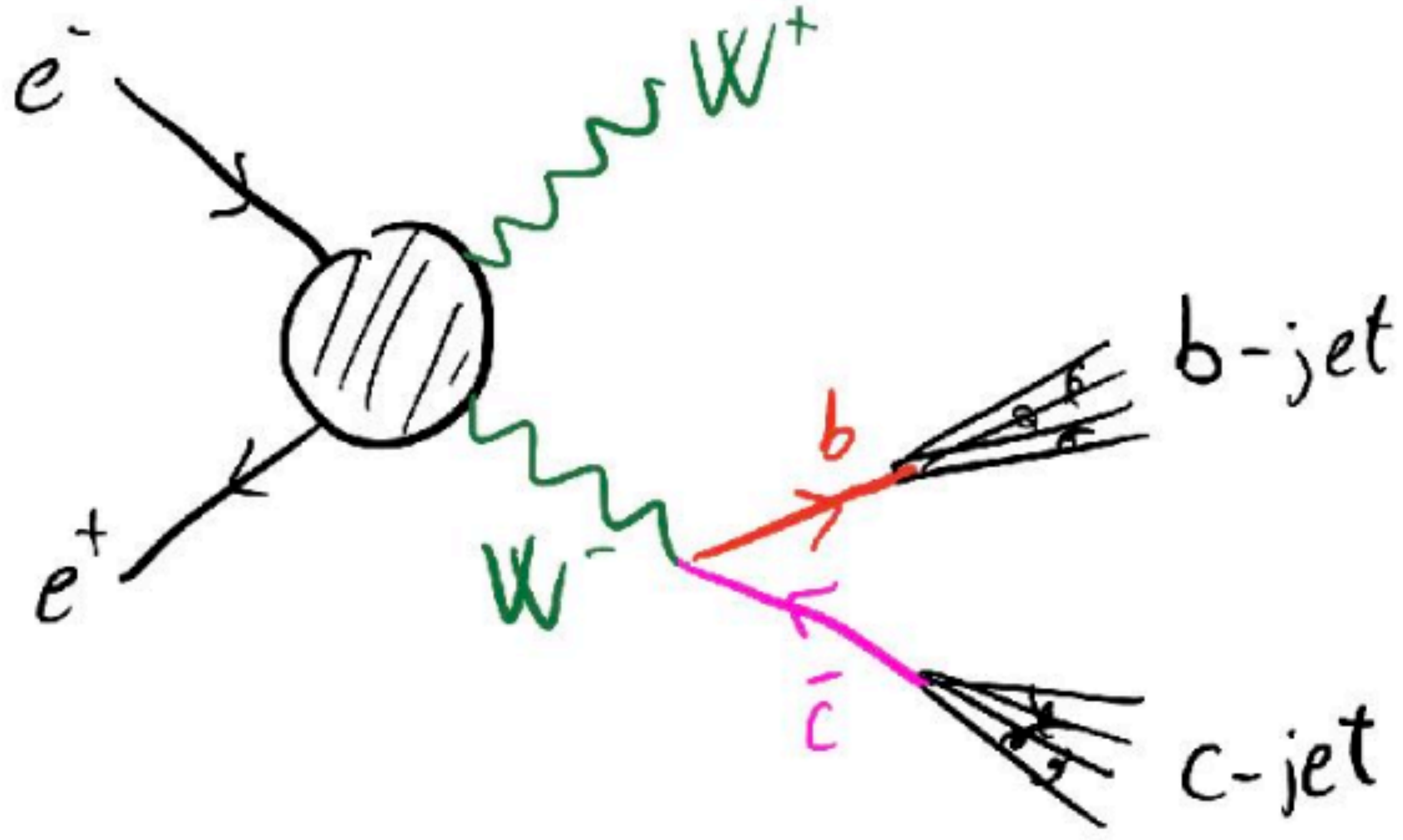
V_{cb} from on-shell $W^{\pm}$ decays

David Marzocca: 2nd ECFA Workshop 2023

- Independent of the semileptonic measurements
- Independent of Lattice QCD inputs

$\Longrightarrow$ improved precision

- For 10^8 $W^{\pm}$ pairs $\boxed{\sim 0.14\,\%\text{ relative uncertainty}}$ with perfect jet flavour tagging



	b	c	uds
Eff b-jet tagger	25%		
Eff c-jet tagger	10%	50%	2%

Marie-Hélène Schune: 3rd FCC Workshop 2020

Numbers inspired by:

ILD@ILC
Tracking and Vertexing at Future Linear Colliders: Applications in Flavour Tagging
Tomohiko Tanabe (U Tokyo)
IAS Program on High Energy Physics 2017, HKUST

$\Longrightarrow$ $\boxed{\sim 0.4\,\%\text{ relative uncertainty}}$

Can even be slightly more optimistic given there may be twice as many $W^{\pm}$ pairs in the nominal running plan

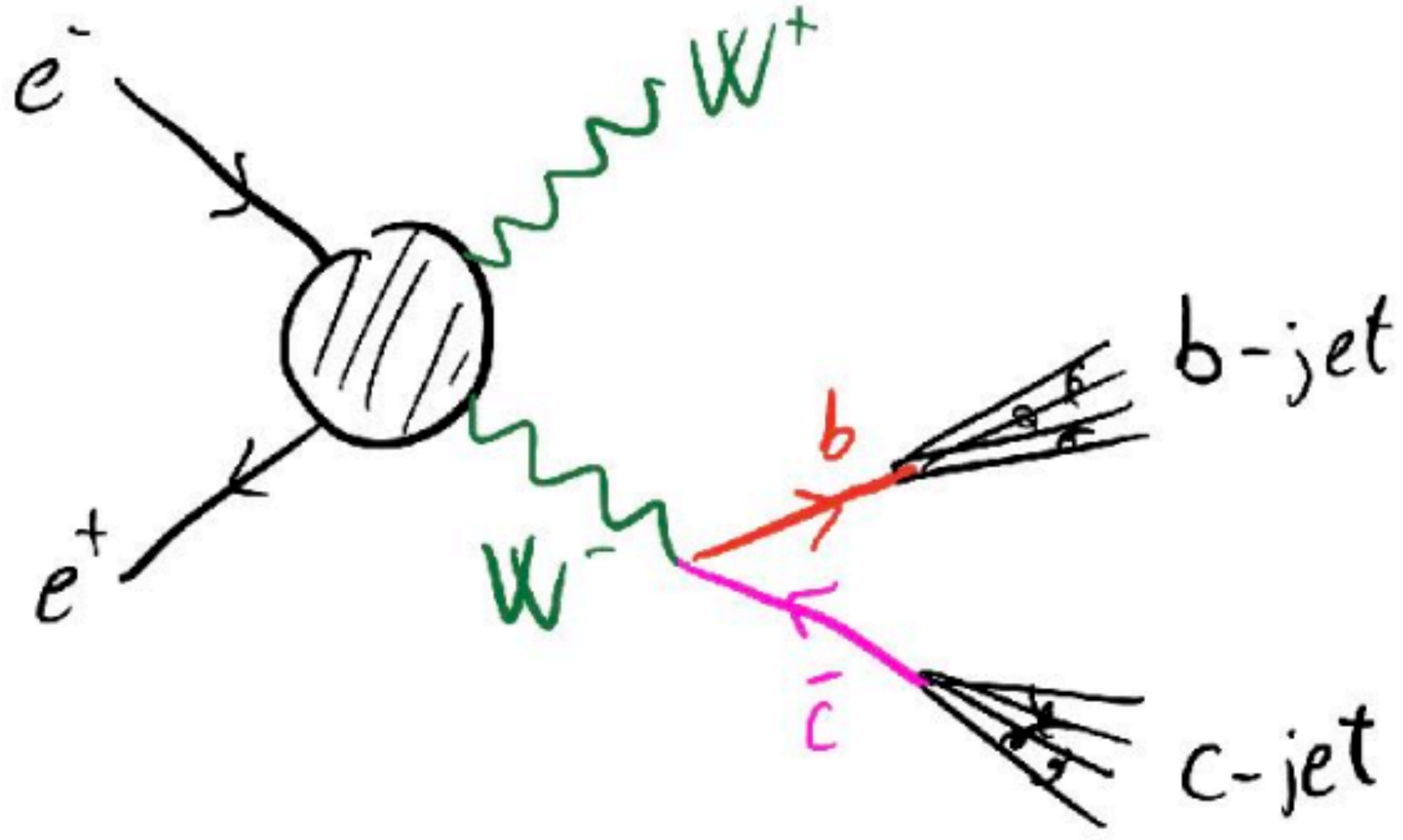
V_{cb} from on-shell $W^{\pm}$ decays

Stephane Monteil: FCC Week January 2024

- Independent of the semileptonic measurements
- Independent of Lattice QCD inputs

$\Longrightarrow$ improved precision

- For 10^8 $W^{\pm}$ pairs $\boxed{\sim 0.14\,\%\text{ relative uncertainty}}$ with perfect jet flavour tagging
- Will need to calibrate with data - the main challenge



	~~b~~	~~c~~	~~uds~~
~~Eff b-jet tagger~~	~~25%~~		
~~Eff c-jet tagger~~	~~10%~~	~~50%~~	~~2%~~

	b	c	uds
Eff b-jet tagger	87%		
Eff c-jet tagger	100%	65%	0.01%

$\Longrightarrow$ $\boxed{\begin{array}{c}\sim 0.15\,\% \\ \text{relative uncertainty}\end{array}}$

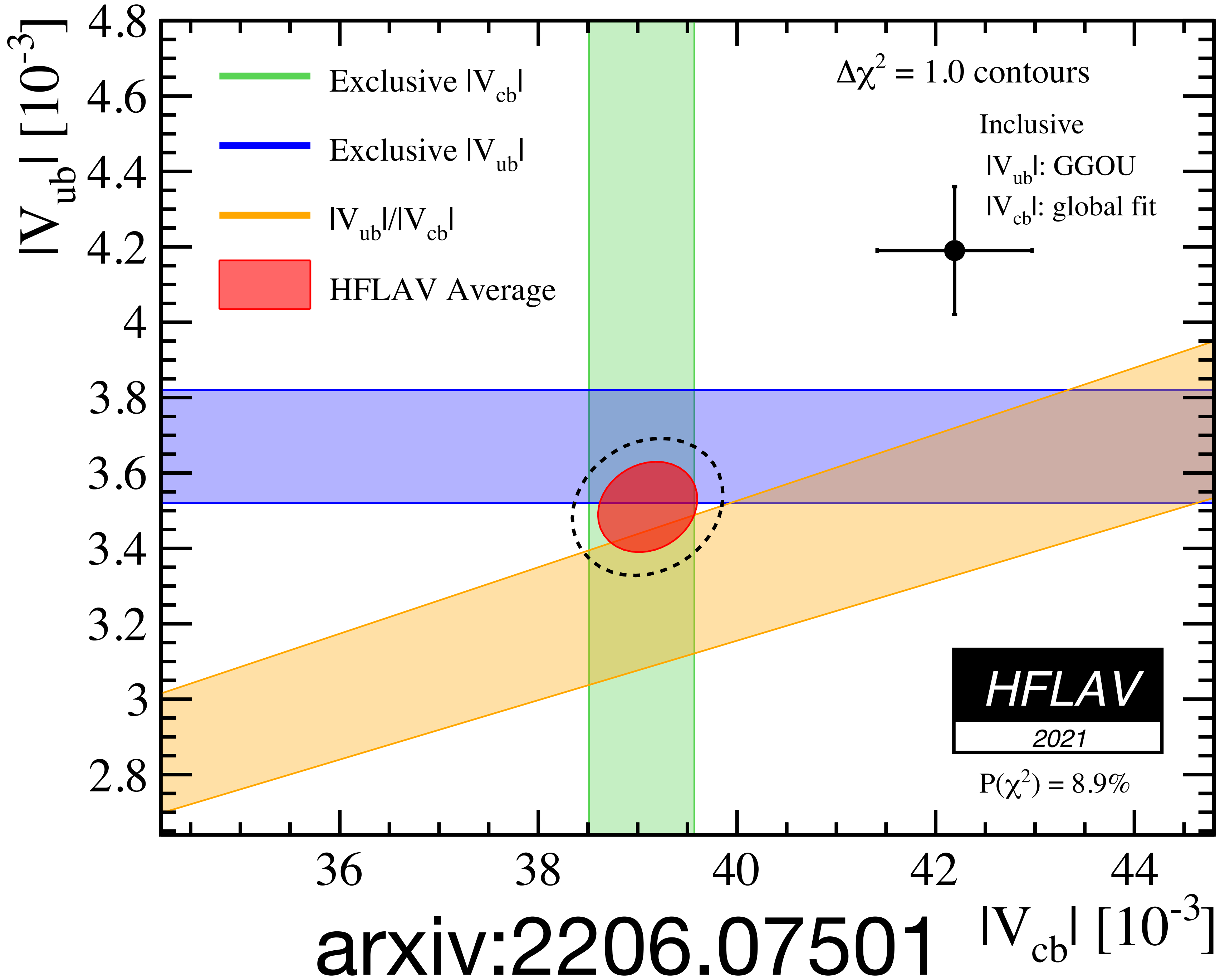
Update based on FCC performance study [Michele Selvaggi: FCC Week June 2023]

Can even be slightly more optimistic given there may be twice as many $W^{\pm}$ pairs in the nominal running plan

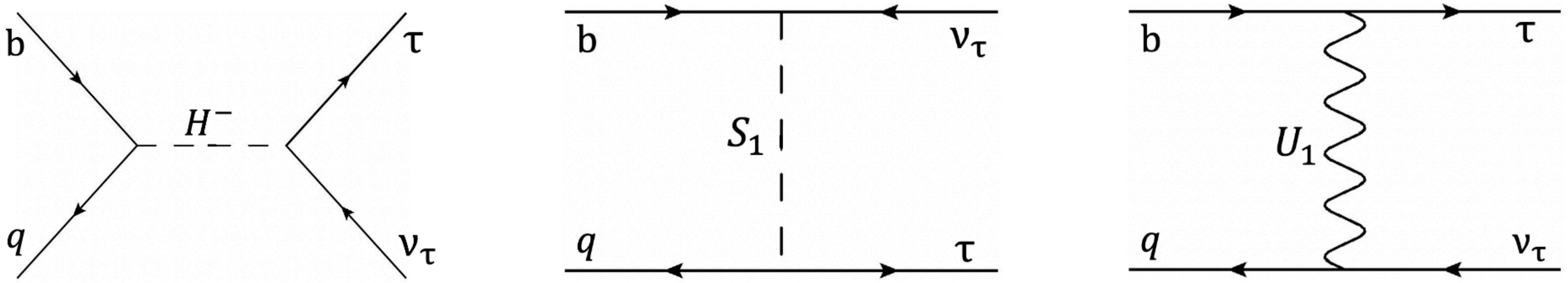
$B^+_{(c)} \to \tau^+\nu_\tau$

[arxiv:2105.13330, arxiv:2305.02998]

- Independent clean probes of V_{ub} and V_{cb}
  - May help resolve the tension between exclusive and inclusive measurements
- Can also probe various NP models
  - Charged Higgs
  - Scalar leptoquarks
  - Vector leptoquarks



arxiv:2206.07501

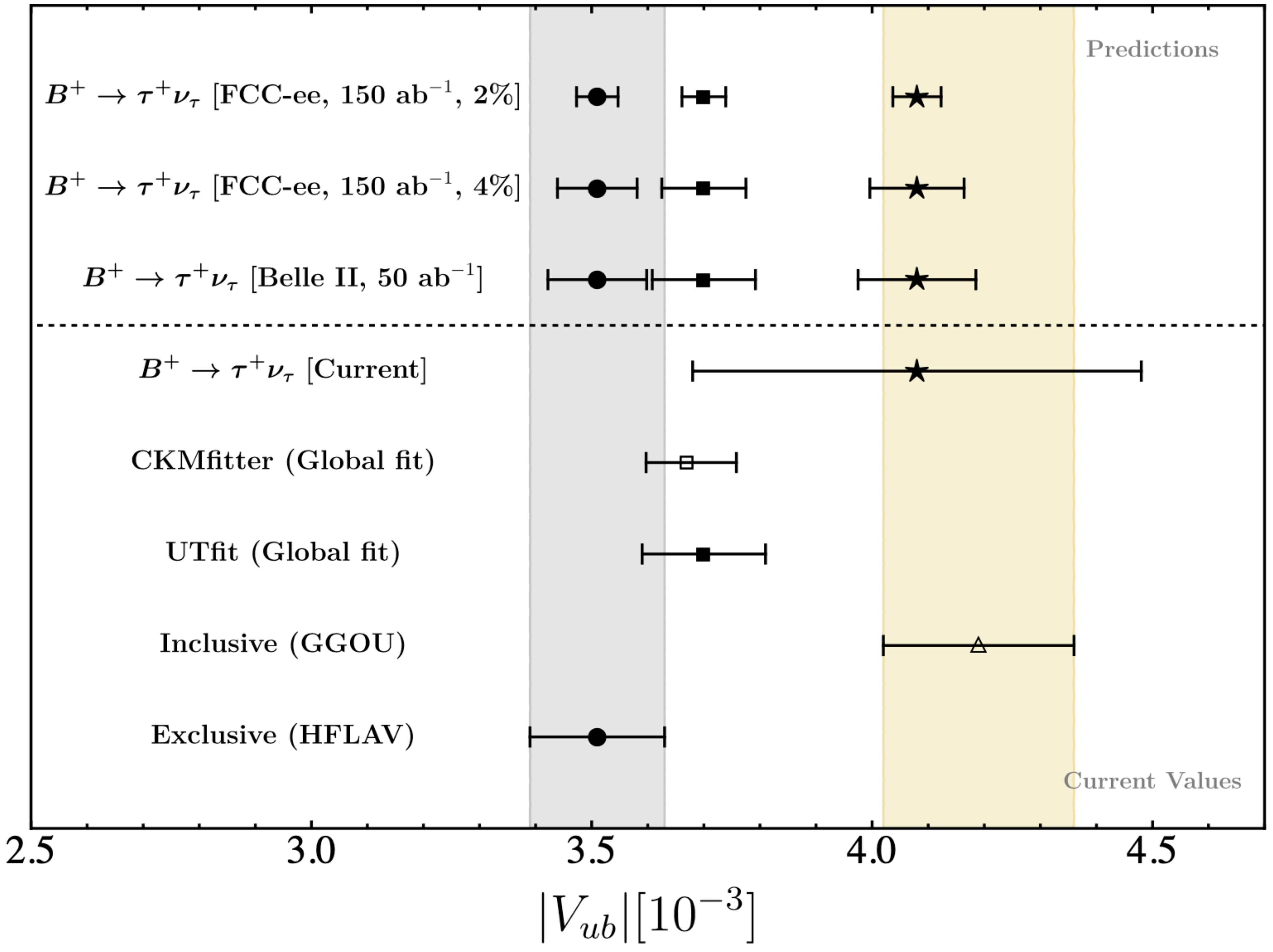


Feynman diagrams for tree-level contributions from: charged Higgs (left), scalar leptoquarks (middle) and vector leptoquarks (right)

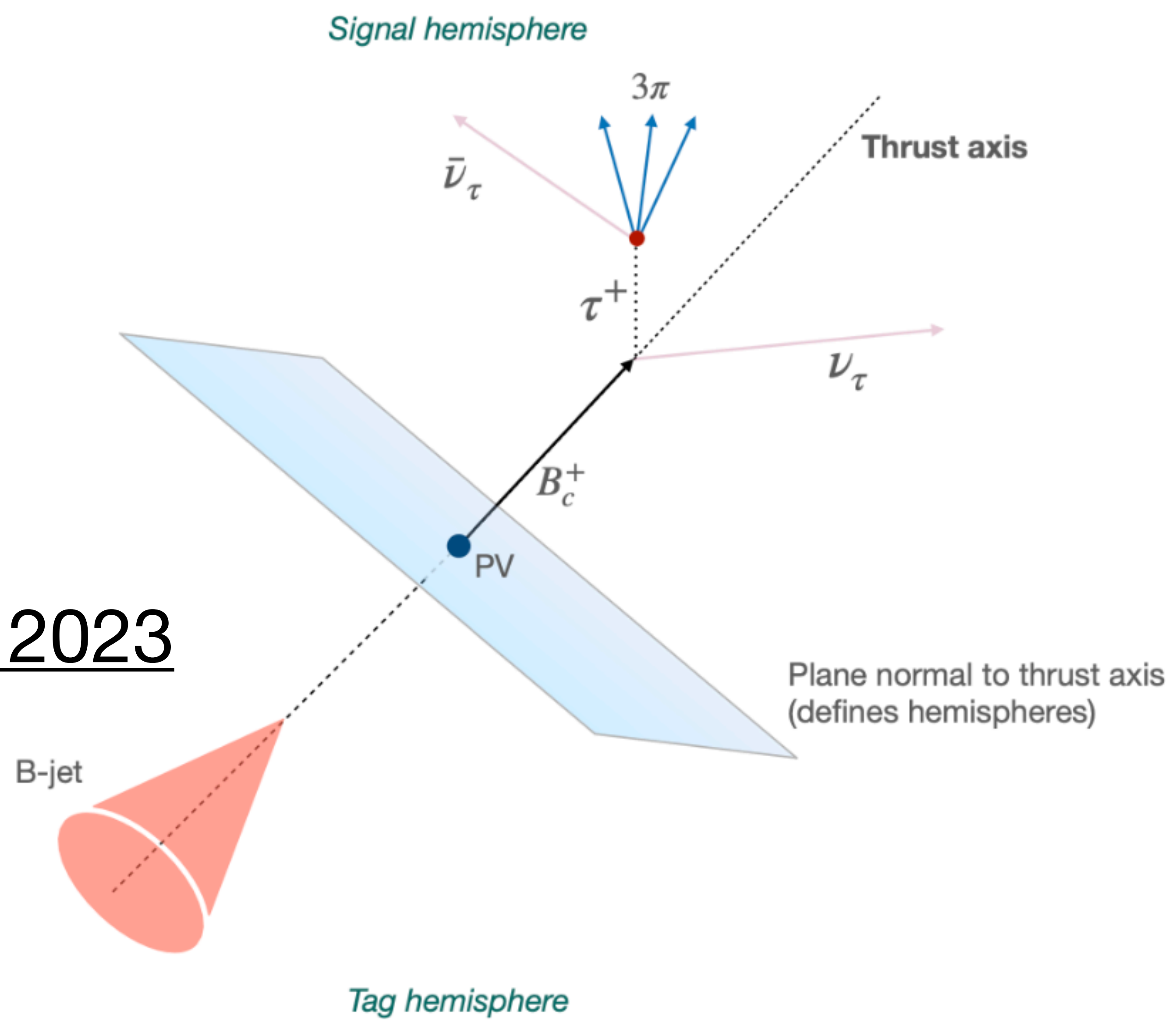
$B^+_{(c)} \to \tau^+\nu_\tau$

[arxiv:2105.13330, arxiv:2305.02998]

- Reconstruct $\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$ decay
- Decay topology split into high- and low-energy hemispheres
- 2-stage BDT selection: Hemisphere properties followed by candidate properties
- Determine ideal and pessimistic BF uncertainties
    - 2% and 4% respectively



Comparison between current determinations of $|V_{ub}|$ and predicted determinations from Belle II and FCC-ee, where the FCC-ee values correspond to 2% and 4% uncertainty on $\mathscr{B}(B^+ \to \tau^+\nu_\tau)$. Different central values are taken from the current Exclusive, Global and $B^+ \to \tau^+\nu_\tau$ values.



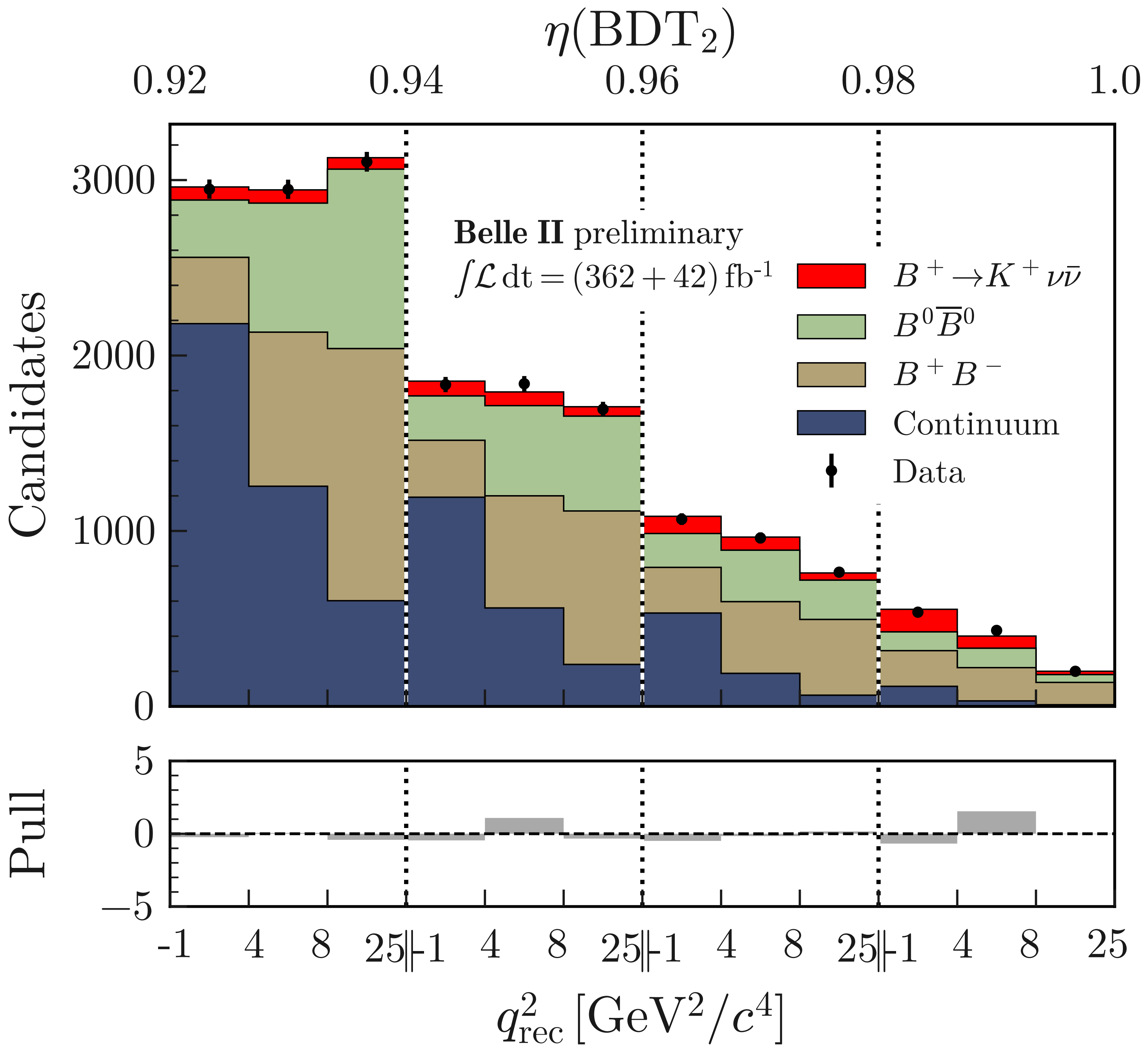
Xunwu Zuo: EPS-HEP 2023

This study assumes 5×10^{12} Z^0s so we could actually push it a little further!

$b \to s\nu\bar{\nu}$ motivation

[arxiv:2309.11353]

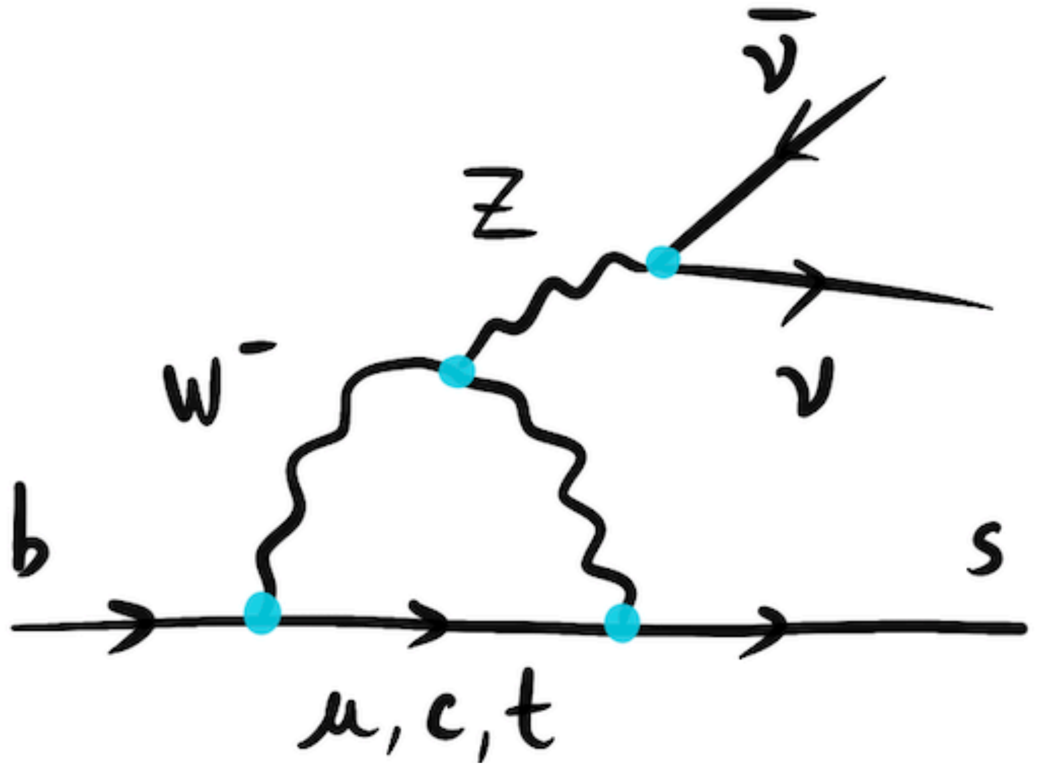
- Impossible at LHCb
- Belle II cannot do *all* B flavours
- Yet to be observed, besides evidence for $B^+ \to K^+\nu\bar{\nu}$
  - 2.7σ tension with SM [arxiv:2311.14647]
- Theoretically cleaner than the corresponding $b \to sl^+l^-$
  - No long-distance charm loops!
- Can be used to extract the CKM factor and hadronic form factors, and constrain Wilson coefficients
- Novel probes of CPV from new physics [arxiv:2208.10880]

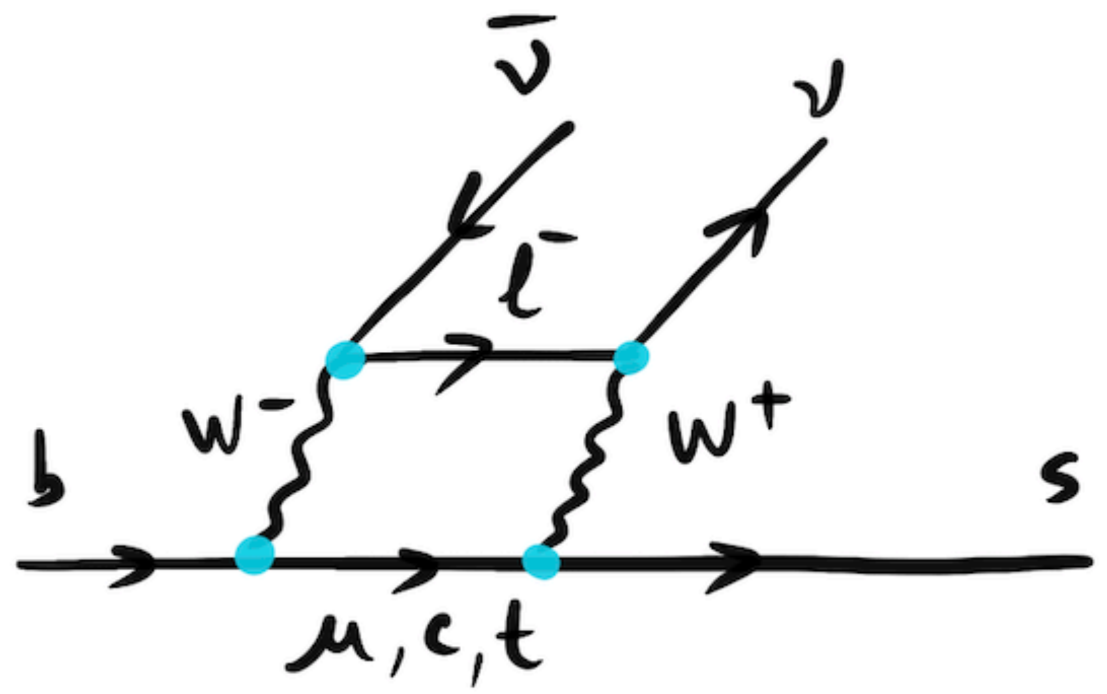


Plot of the maximum likelihood fit for $B^+ \to K^+\nu\bar{\nu}$ from inclusive tagging

Decay	B-factories	FCC-ee
$B^+ \to K^+\nu\bar{\nu}$	✔	✔
$B^+ \to K^{*+}\nu\bar{\nu}$	✔	✔
$B^0 \to K^0_S\nu\bar{\nu}$	✔	✔
$B^0 \to K^{*0}\nu\bar{\nu}$	✔	✔
$B^0_s \to \phi\nu\bar{\nu}$	✗	✔
$\Lambda^0_b \to \Lambda^{(*)0}\nu\bar{\nu}$	✗	✔

B decays accessible by B-factories and FCC-ee

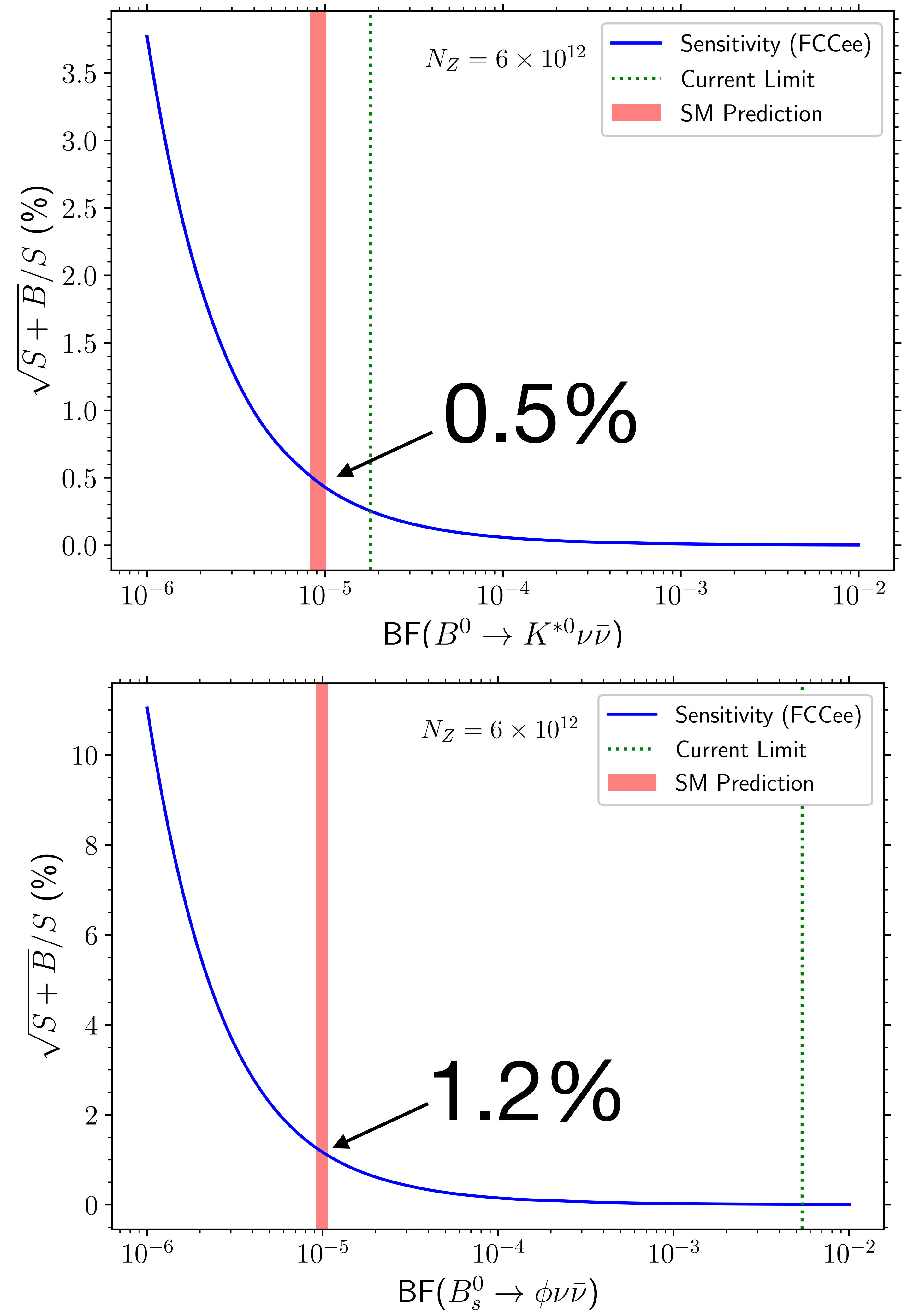




$b \to s\nu\bar{\nu}$ BF sensitivity

[arxiv:2309.11353]

- Belle II expects $\mathcal{O}(10\%)$ uncertainty on $\mathscr{B}(B \to K^{(*)}\nu\bar{\nu})$ with 50 ab^{-1}
  - Let's see where they go with $B^+ \to K^+\nu\bar{\nu}$…
- Follow a similar analysis procedure to $B_{(c)} \to \tau^+\nu_\tau$
- FCC-ee assuming perfect vertex seeding and PID:
  - $\mathcal{O}(1\%)$ uncertainty for $B^0 \to K^{*0}\nu\bar{\nu}$ & $B_s^0 \to \phi\nu\bar{\nu}$
  - $\mathcal{O}(3\%)$ uncertainty for $B^0 \to K_S^0\nu\bar{\nu}$
  - $\mathcal{O}(10\%)$ uncertainty for $\Lambda_b^0 \to \Lambda^0\nu\bar{\nu}$

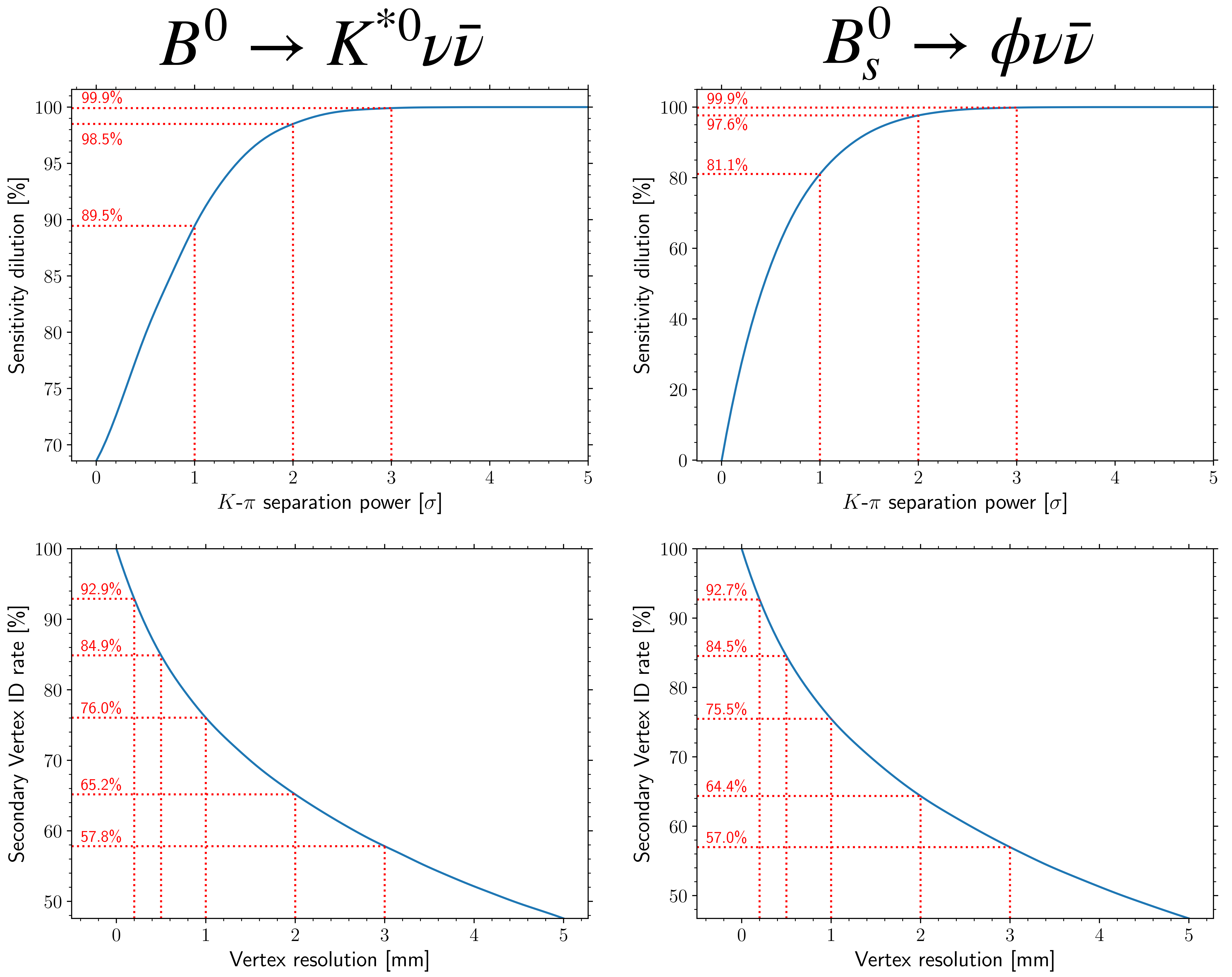


Sensitivity estimate plots for a range of BFs of $B^0 \to K^{*0}\nu\bar{\nu}$ (top) & $B_s^0 \to \phi\nu\bar{\nu}$ (bottom)

$b \to s\nu\bar{\nu}$ detector requirements

[arxiv:2309.11353]

- Robust against $\pi - K$ mis-ID with at least $\sim 2\sigma$ separation
- Require ≤ 0.2mm vertex resolution
    - Well above the expected resolution $\mathcal{O}(10\mu$m)
- More detailed studies in the future to evaluate the full detector requirements

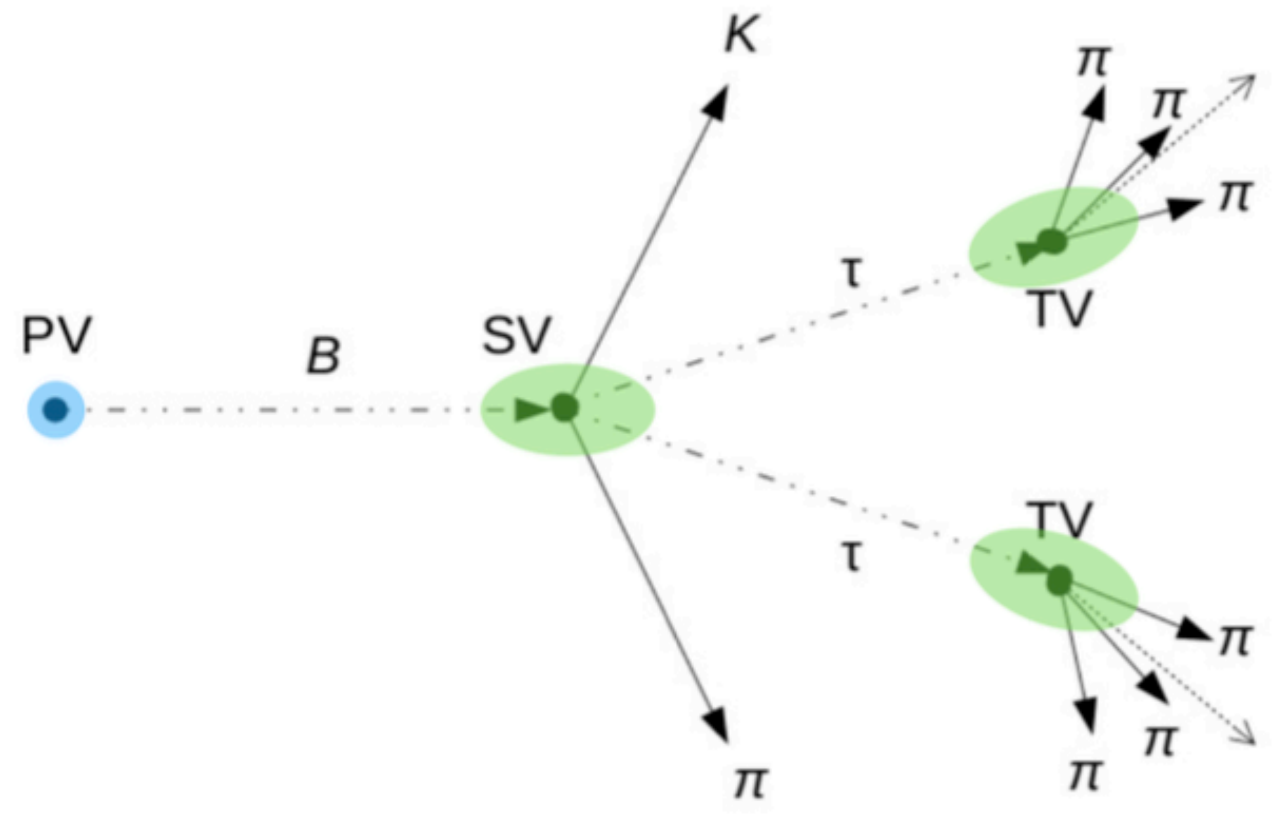

$B^0 \to K^{*0}\nu\bar{\nu}$

$B_s^0 \to \phi\nu\bar{\nu}$

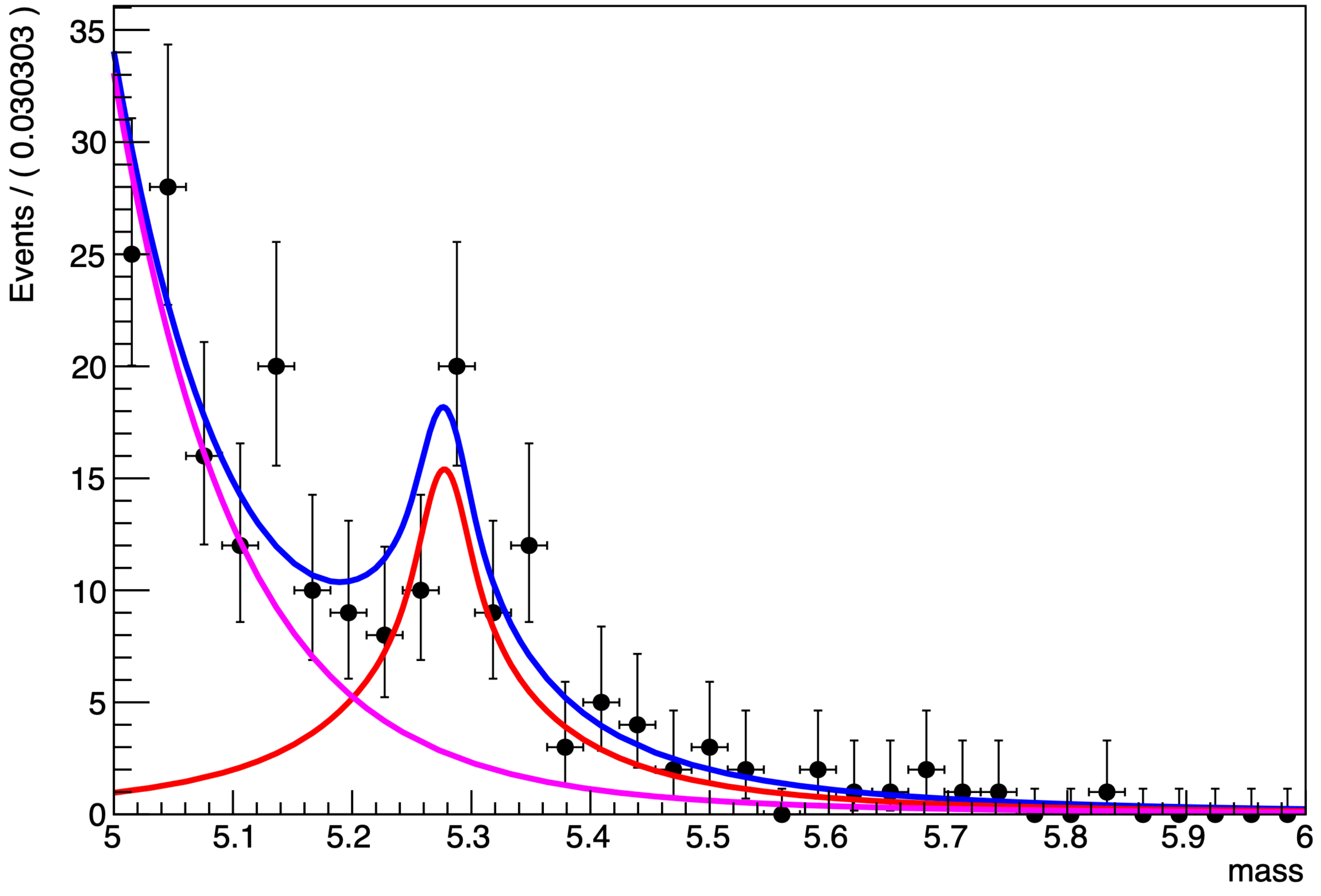
$B^0 \to K^{*0}\tau^+\tau^-$

Tristan Miralles: FCC Week January 2024

- Yet to be observed - $\mathcal{O}(10^{-7})$ BF
  - Current limit $\mathcal{O}(10^{-4}) - \mathcal{O}(10^{-3})$
- Many NP models expect NP to couple primarily to the Higgs and the third generation Ben Stefanek: 2nd ECFA Workshop 2023
- Focus again on the the 3-prong $\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}$ decay
- Use energy-momentum conservation to resolve ν kinematics
- BDT trained with candidate kinematics to reduce backgrounds
- Signal yield extracted with an unbinned ML fit to the candidate B mass



Schematic of the signal decay

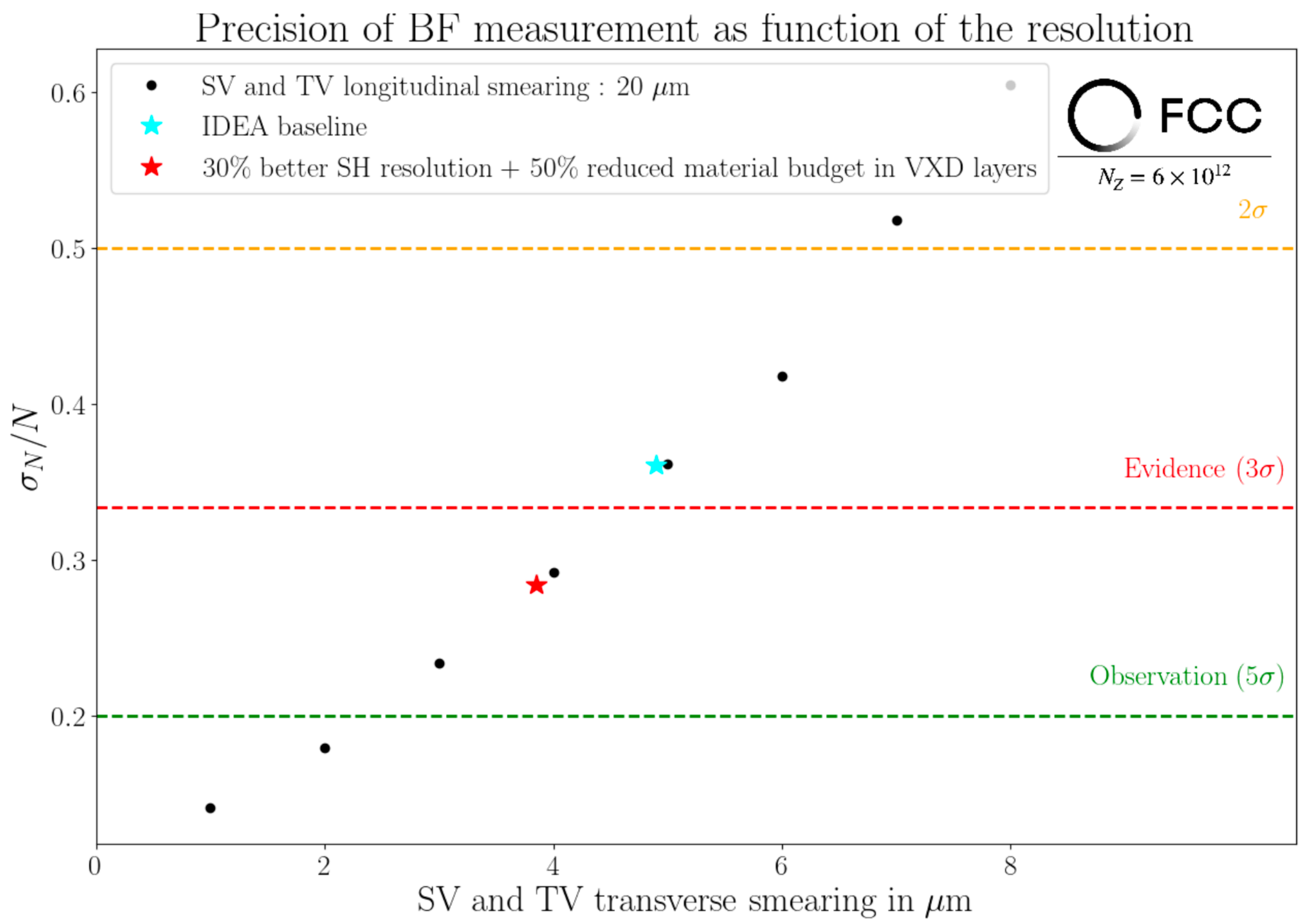


B^0 candidate invariant mass fit to rescaled signal and background MC

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

Tristan Miralles: FCC Week January 2024

- Current FCC-ee and IDEA would not allow for discovery of this mode
  - Trying to play with detector performance $\implies 3.5\sigma$
- Clearly some work to do!
  - Better vertexing?
    - Easier said than done
  - Higher luminosity/longer run period?
    - Difficult/competition with other runs
  - Consider other τ decays?
    - Leptonics harder to handle but would produce $\mathcal{O}(10)$ times the data



Dependence of the relative signal yield uncertainty on the vertex resolution of the IDEA detector

Motivations for τ measurements

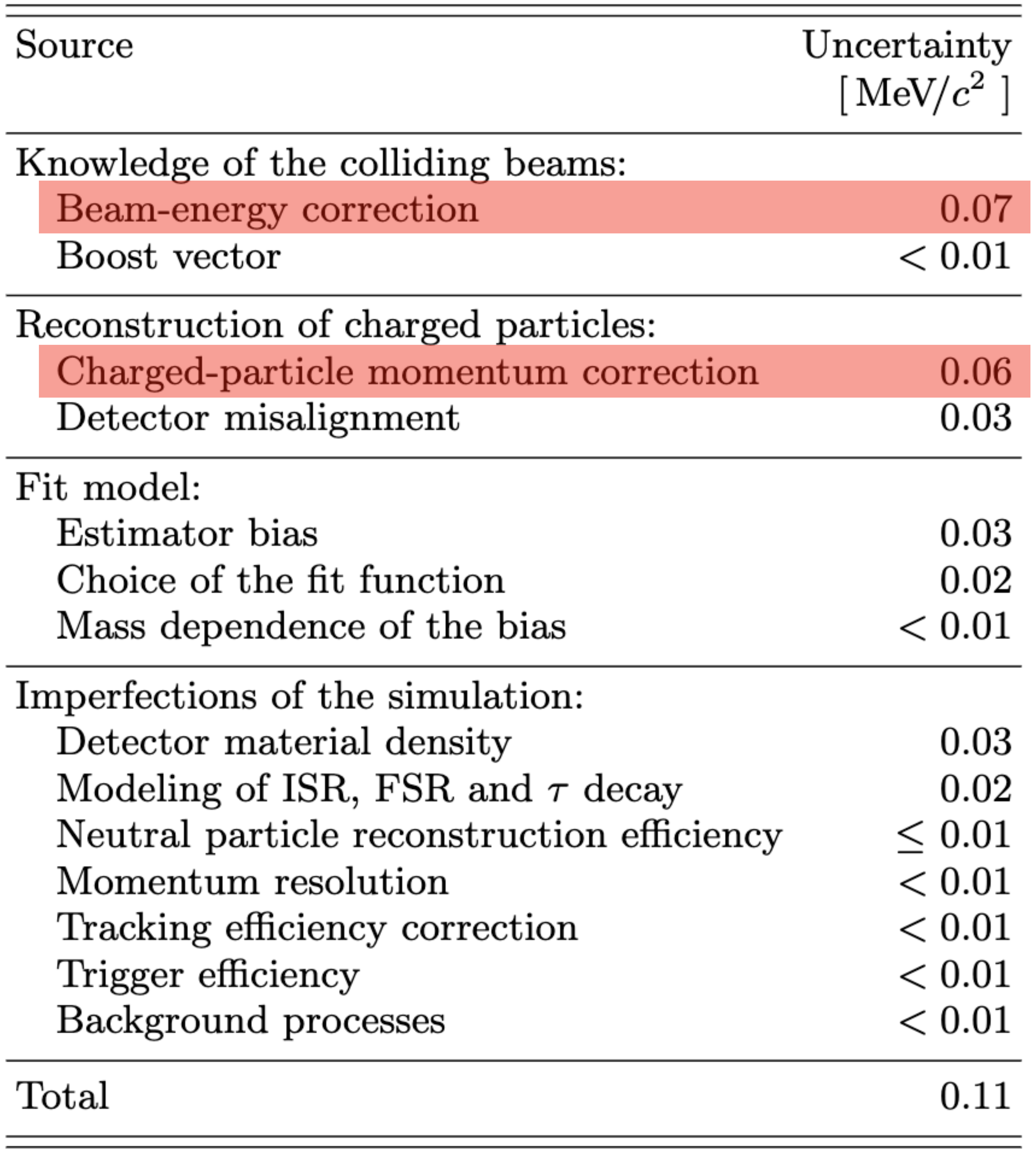
Alberto Lusiani: FCC Week 2023

- $\sim 10^{11}\ Z \to \tau^+\tau^-$ at the FCC-ee
- m_τ is a SM parameter - must push experimental sensitivity as far as possible
  - Required for many SM predictions
    - Charged weak currents
    - CKM elements
  - Enters LFU tests at the fifth power
    - LFV searches complement that of μ
- Can also directly measure lifetime and BFs (extract $\alpha_s(m_\tau)$)
- τ coupling $\implies$ ν_τ coupling - link to oscillations and LFV, probe orders of magnitude better than current experiments [arXiv:1612.02728, arXiv:2203.05502v2, arXiv:2203.06520]

m_τ systematics

Alberto Lusiani: FCC Week 2023

- A recent Belle II analysis, arxiv:2305.19116, gives the most precise measurement $m_\tau = 1777.09 \pm 0.08$(stat.) $\pm\, 0.11$(syst.) MeV/c^2
- Systematically limited
  - Knowledge of the beam energy
  - Momentum corrections due to scale factor dependence on p_T
- FCC-ee should be able to significantly reduce these effects
  - Beam energy should be known to within 1ppm
  - ~2ppm momentum scale calibration should be possible using $m_{j/\psi}$
- Baseline IDEA should be sufficient to obtain 14ppm measurement of $\sigma_{m_\tau} \sim 0.02$ MeV/c^2



Source	Uncertainty [MeV/c^2]
Knowledge of the colliding beams:	
Beam-energy correction	0.07
Boost vector	< 0.01
Reconstruction of charged particles:	
Charged-particle momentum correction	0.06
Detector misalignment	0.03
Fit model:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	< 0.01
Imperfections of the simulation:	
Detector material density	0.03
Modeling of ISR, FSR and τ decay	0.02
Neutral particle reconstruction efficiency	≤ 0.01
Momentum resolution	< 0.01
Tracking efficiency correction	< 0.01
Trigger efficiency	< 0.01
Background processes	< 0.01
Total	0.11

Systematic uncertainties in the Belle II m_τ measurement
arxiv:2305.19116

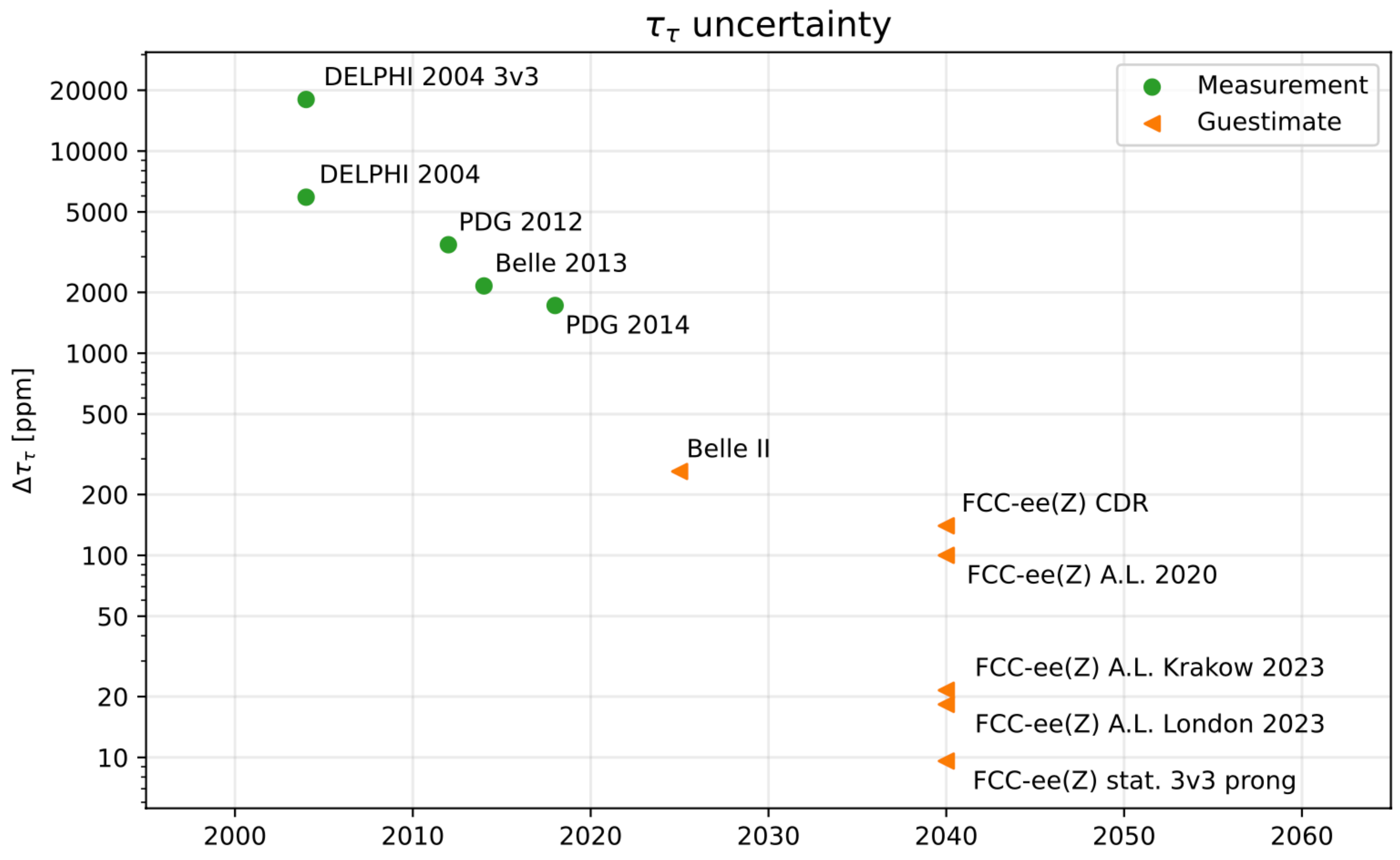
$\tau^{\pm}$ lifetime and BFs

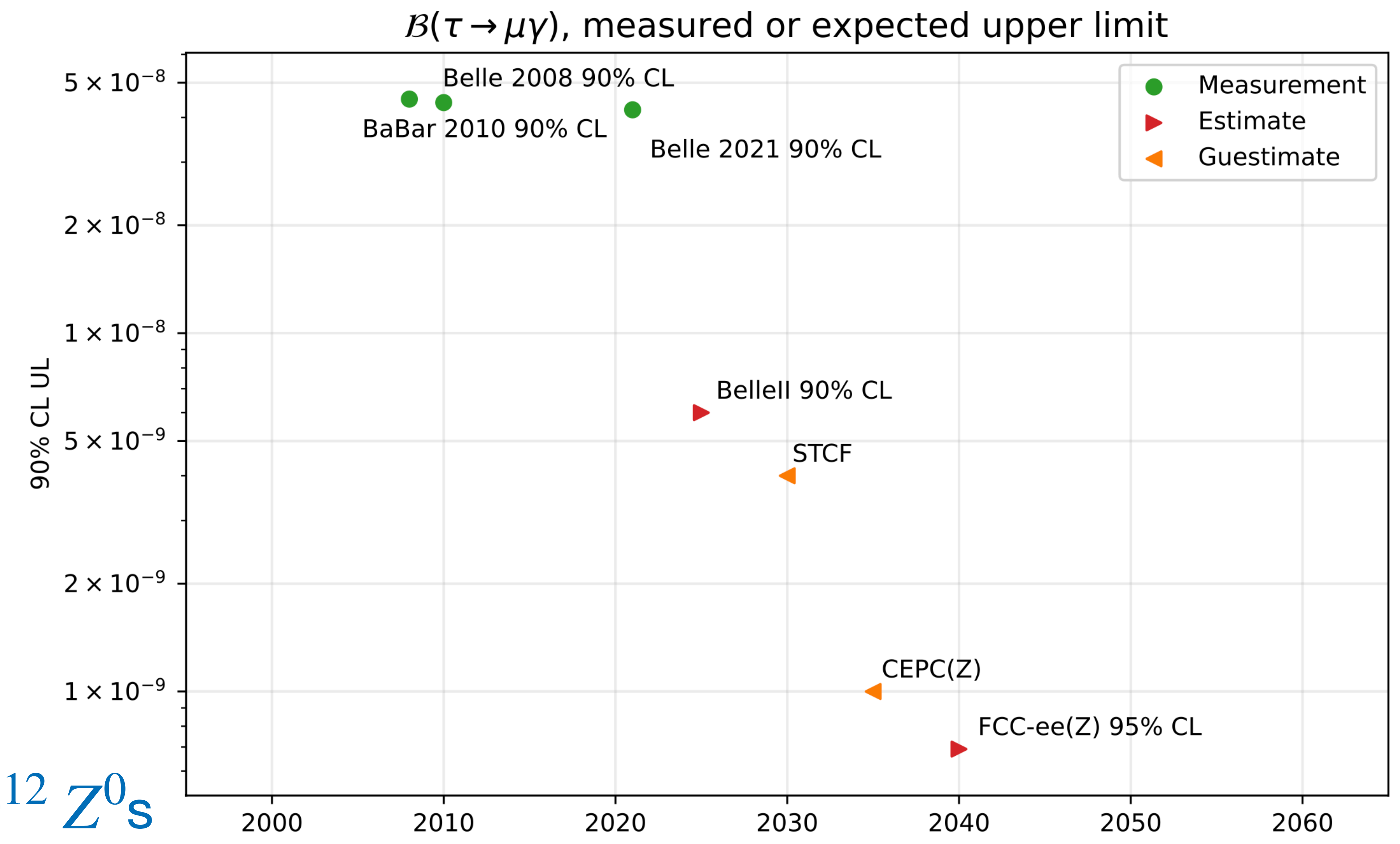
Alberto Lusiani: FCC Week 2023

- FCC-ee should provide the most precise measurements of τ lifetimes and BFs

- For lifetime
  - Impact parameter is $\sim 70\ \mu$m, much greater than the FCC IP resolution and beam spot size
  - Uncertainty on the average length scale of vertex detector elements ≤ 4.8 ppm

- For BFs
  - Good EM energy resolution, $< 20\,\% / \sqrt{E(\mathrm{GeV})}$ (LEP)
  - Granular EM calorimeter $> 15 \times 15$ mrad^2 (LEP)





Should temper expectations a little as these plots assume $8 \times 10^{12}\ Z^0$s

That’s not all…

- Obviously there is much more flavour physics to explore in the future
  - CKM measurements - the “flattest” unitarity triangle arxiv:2402.09987
  - Lepton flavour violation, e.g. $e^+e^- \rightarrow \tau^\pm\mu^\mp$ arxiv:2305.03869
  - Lepton number violation and heavy neutral leptons Stefan Antusch: 2nd ECFA Workshop 2023, Jürgen Reuter: 2nd ECFA Workshop 2023
  - t flavour changing neutral currents arxiv:1904.10956
- We need to do our best to ensure we build something that lets us do as much as possible — What would you want to do that current experiments cannot?
  - More ideas are welcome
  - And more people to do studies!

Summary

- CKM measurements far more precise than possible at current experiments
- Can perform extensive studies of (semi-)invisible final states
  - Impossible at LHCb due to missing energy
  - Possible at Belle II but limited to $\sigma_{\mathscr{B}} \sim \mathcal{O}(10\%)$ and B^0, B^+
  - FCC-ee should get $\sigma_{\mathscr{B}} \sim \mathcal{O}(1\%)$ BF measurements
- Can push $\tau^{\pm}$ measurements further
  - Difficult at LHCb
  - Limited at Belle II by sample size, species and systematics
  - $\sigma_{m_\tau} \sim 14$ppm, $\sigma_{\tau_\tau} \sim 12$ppm,
- More papers on the way - focus on detailed detector requirements increasing!
- More ideas and collaborators are welcome!

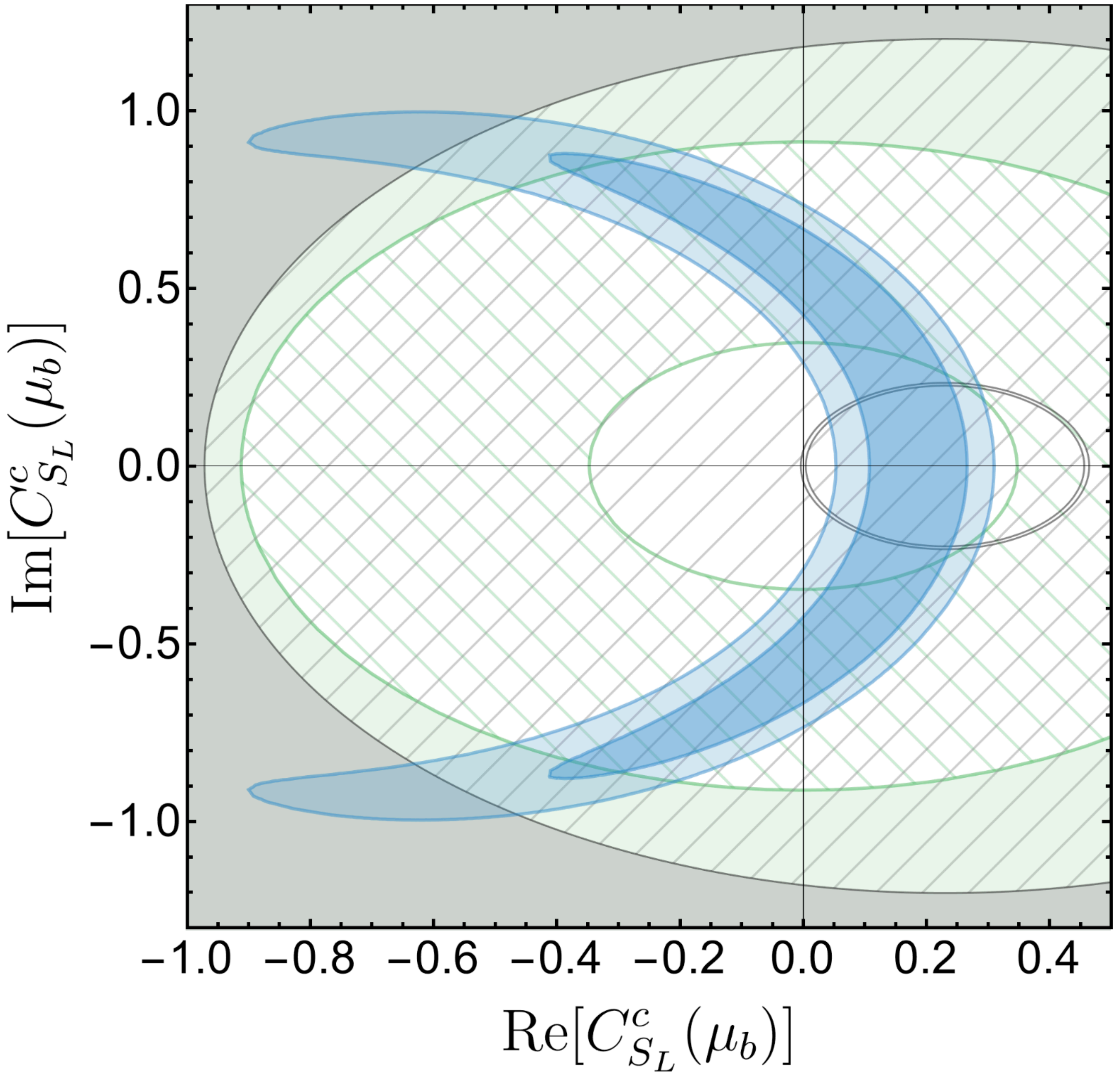
GitHub: FCCeePhysicsPerformance

Backup

$B_{(c)} \rightarrow \tau^+\nu_\tau$: analysis and leptoquarks

[arxiv:2105.13330, arxiv:2305.02998]

- Subsequent $\tau^+ \rightarrow \pi^+\pi^-\pi^+\bar{\nu}_\tau$ decay
- Decay topology split into high- and low-energy hemispheres
- 2-stage BDT selection: Hemisphere properties followed by candidate properties
- First stage BDT trained with hemisphere properties of signal and inclusive background MC
  - Total energy, charged energy, neutral energy, multiplicities, number of tracks, etc…
- Second stage BDT trained with the candidate properties
  - Mass, vertex χ^2, momentum, impact parameters…
- Signal yield determined by a fit to the maximum hemisphere energy



- Grey shade is the exclusion by current results
- Green hash is the exclusion expected for HL-LHC
- Grey hash is the exclusion by FCC-ee (the thin annulus survives)
- Blue shades are 1σ,2σ,3σ bands from current $b \rightarrow c$ anomalies