QCD and Flavour physics at future lepton colliders

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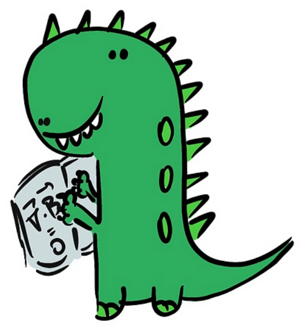
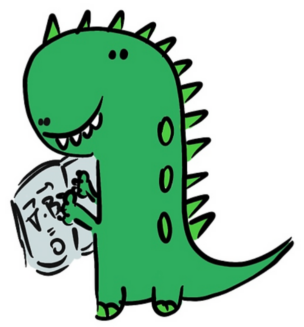


09.10.2024
QCD Conference
Freiburg

My personal summary of the upcoming European Strategy for Particle Physics

“QCD is what will keep us busy for the next hundred years.”

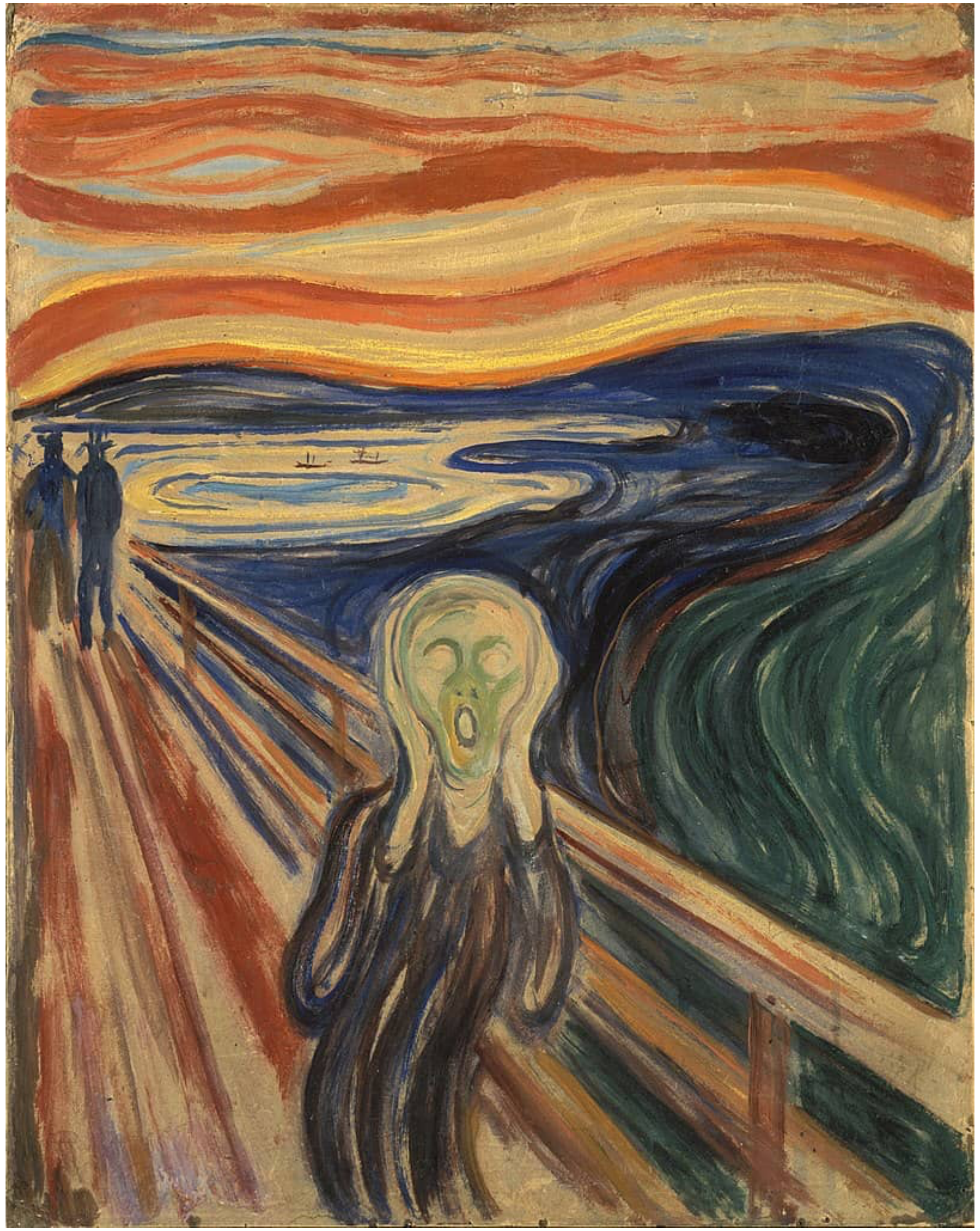


Trigger warning

What follows is by no means

a complete review of the topic.

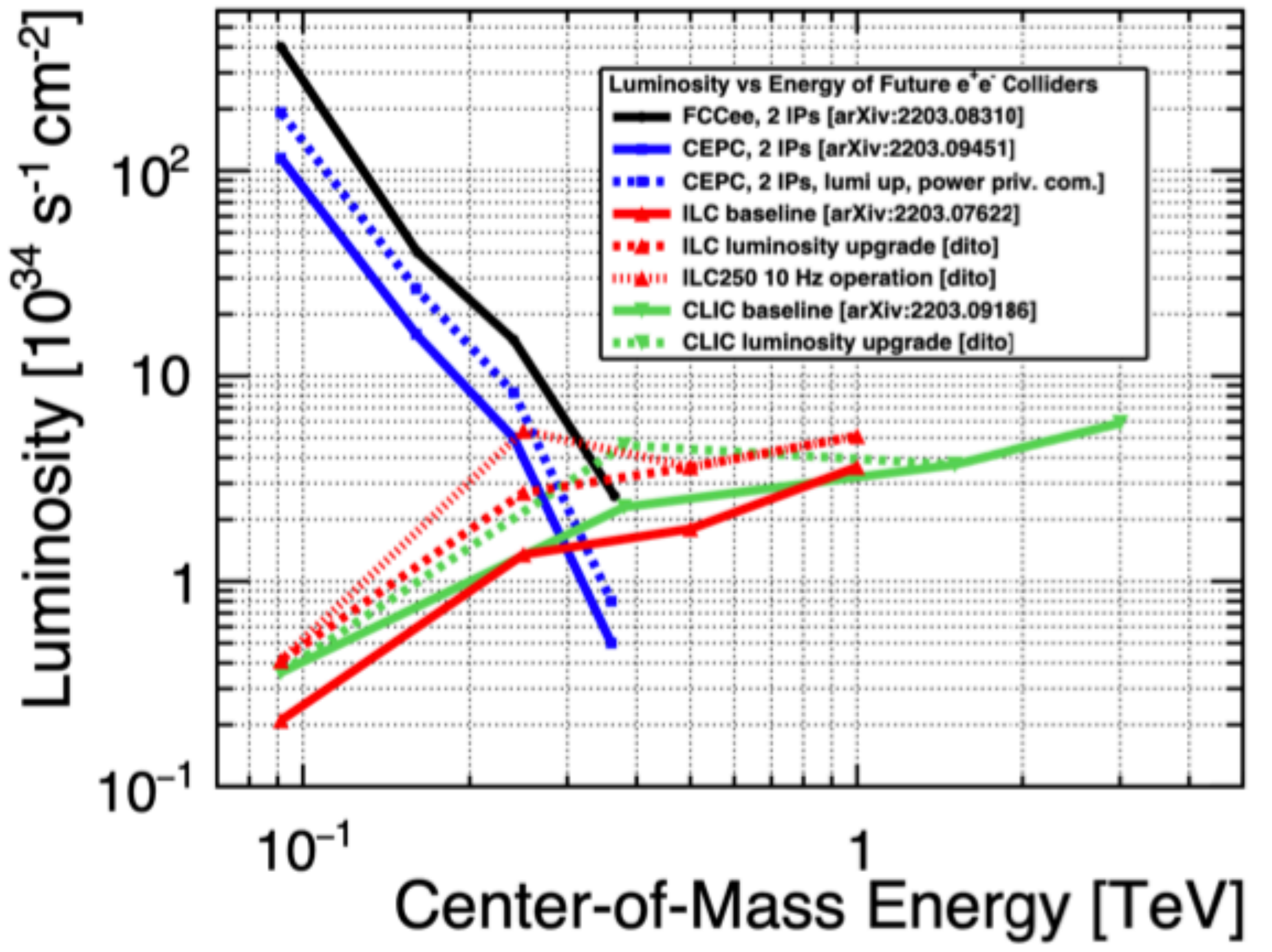
However, I will cover selected examples.



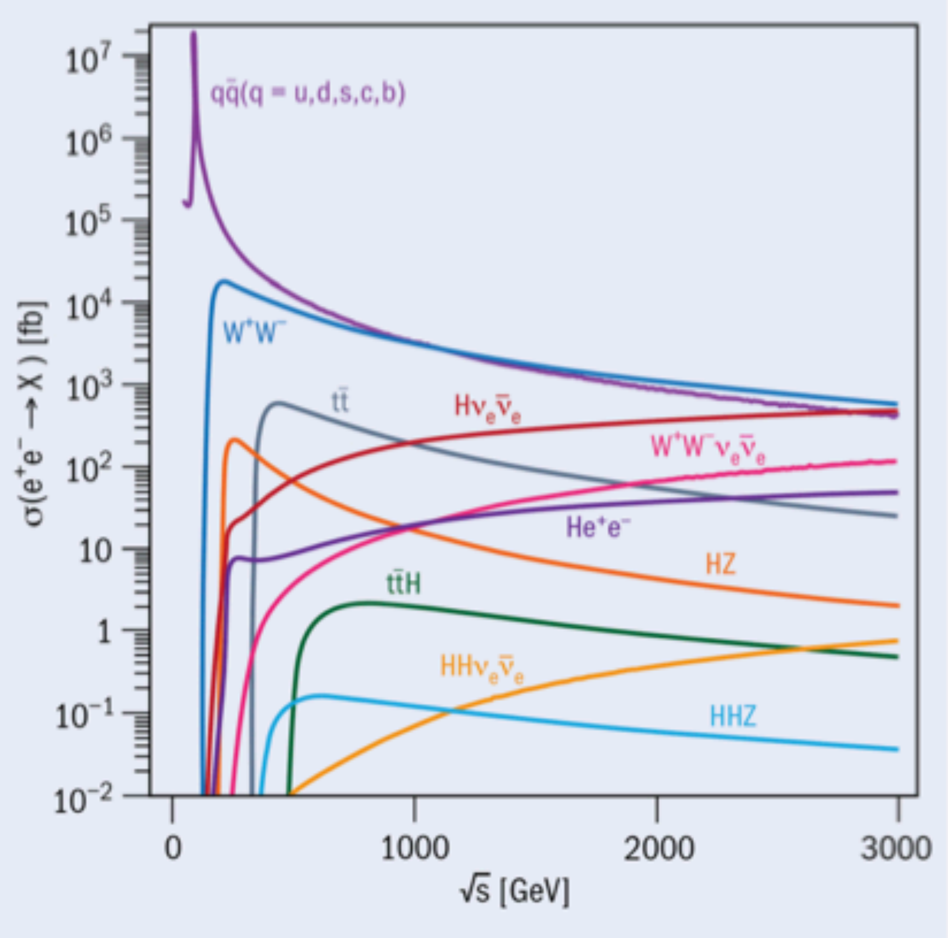
Circular or linear e^+e^- colliders?

Circular e^+e^- colliders

- FCC-ee, CEPC
- Circumference: 90 - 100 km
- High luminosity & power efficiency at **low energies;** → huge rates at Z pole (table below)
- Less luminosity at higher E_{CM} (synchrotron radiation)
- Multiple interaction regions
- Very clean: little beamstrahlung



per detector in e⁺e⁻	# Z	# B	# τ	# charm	# WW
LEP	4 x 10⁶	1 x 10⁶	3 x 10⁵	1 x 10⁶	2 x 10⁴
SuperKEKB	-	10¹¹	10¹¹	10¹¹	-
FCC-ee	2.5 x 10¹²	7.5 x 10¹¹	2 x 10¹¹	6 x 10¹¹	1.5 x 10⁸



Linear e^+e^- colliders

- ILC, CLIC, C^3 (new idea)

  C^3 arXiv:2110.15800
- Length

  ILC: 250 GeV – 1 TeV: 20.5 → 40 km

  CLIC: 380 GeV – 3 TeV: 11.4 → 50 km
- High luminosity & power efficiency at **high energies;**
- **Longitudinally spin-polarised beams**
- Long-term energy upgrades possible
  - longer tunnel, same technology and/or
  - replacing accelerating structure with advanced technologies (RF cavities with higher gradients, plasma acceleration?)

Let's see how Flavour Physics and understanding QCD can help us go beyond the Standard Model ?

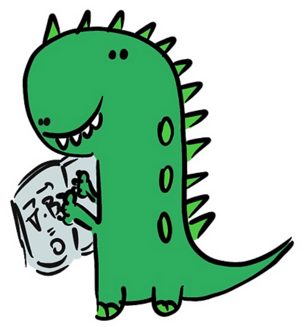
Beyond the SM

L12

* Need to add neutrino mass (Majorana or Dirac?)

Motivation for BSM

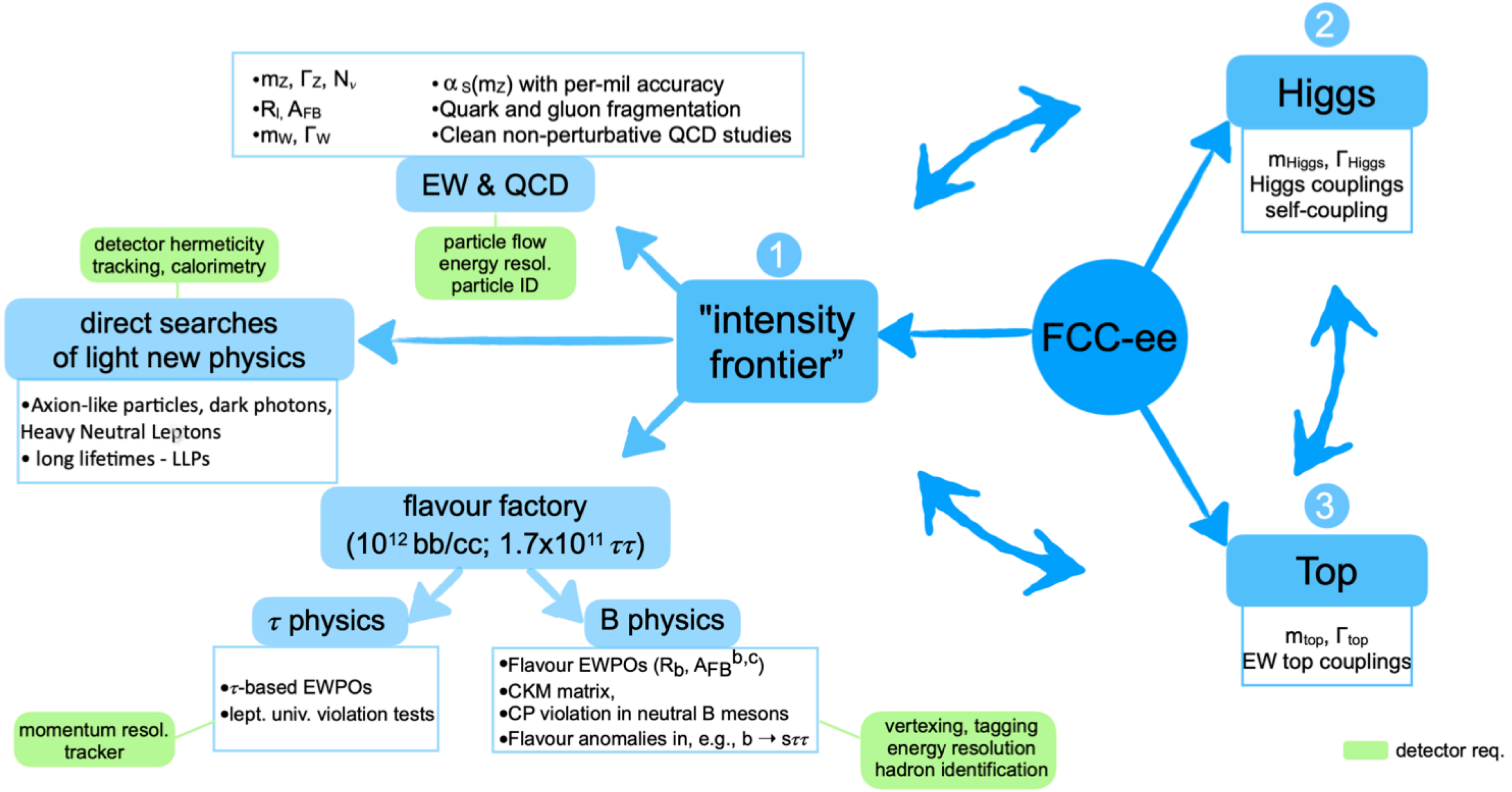
Plausable EFT Solutions	Challenge EFT Paradigm
• Dark matter	• Hierarchy problem
• Baryon asymmetry	• Cosmological constant
• Strong CP	• Initial conditions for inflation / Eternal inflation
• Fermion masses and mixings	
• Grand unification	• UV completion of gravity



Tim Cohen
CERN/Fermilab
School 2023

FCC-ee (and CEPC) Z-physics programme

Christophe Grojean, FCC week 2022



K. Jakobs, CERN-Fermilab HCP Summer School, 31st Aug. 2023

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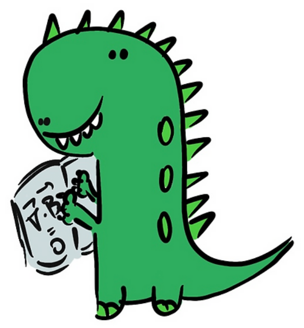
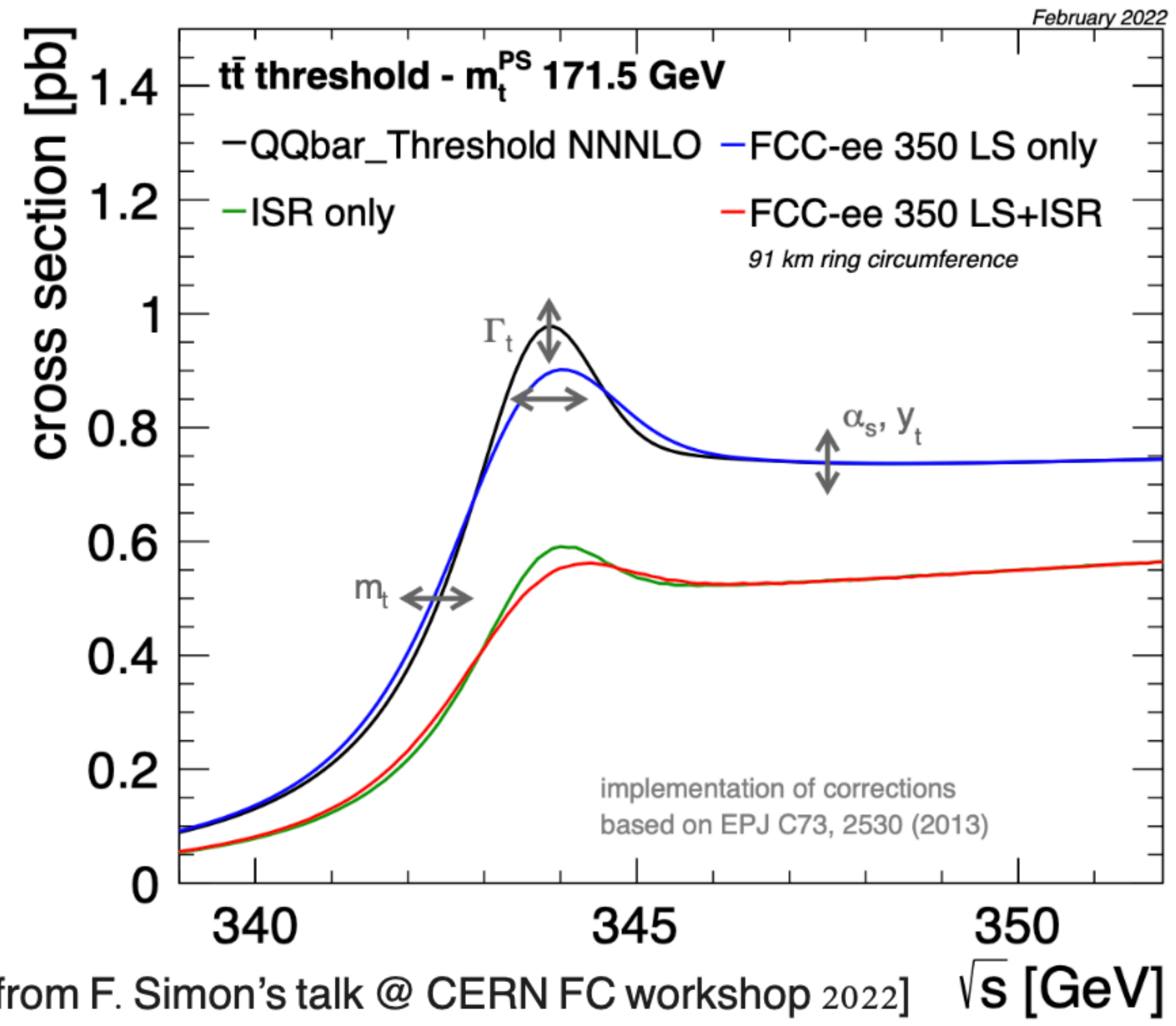


Naturally one need o fold into this thought process the fact that we have recently started the third run of the LHC and there is still HL-LHC

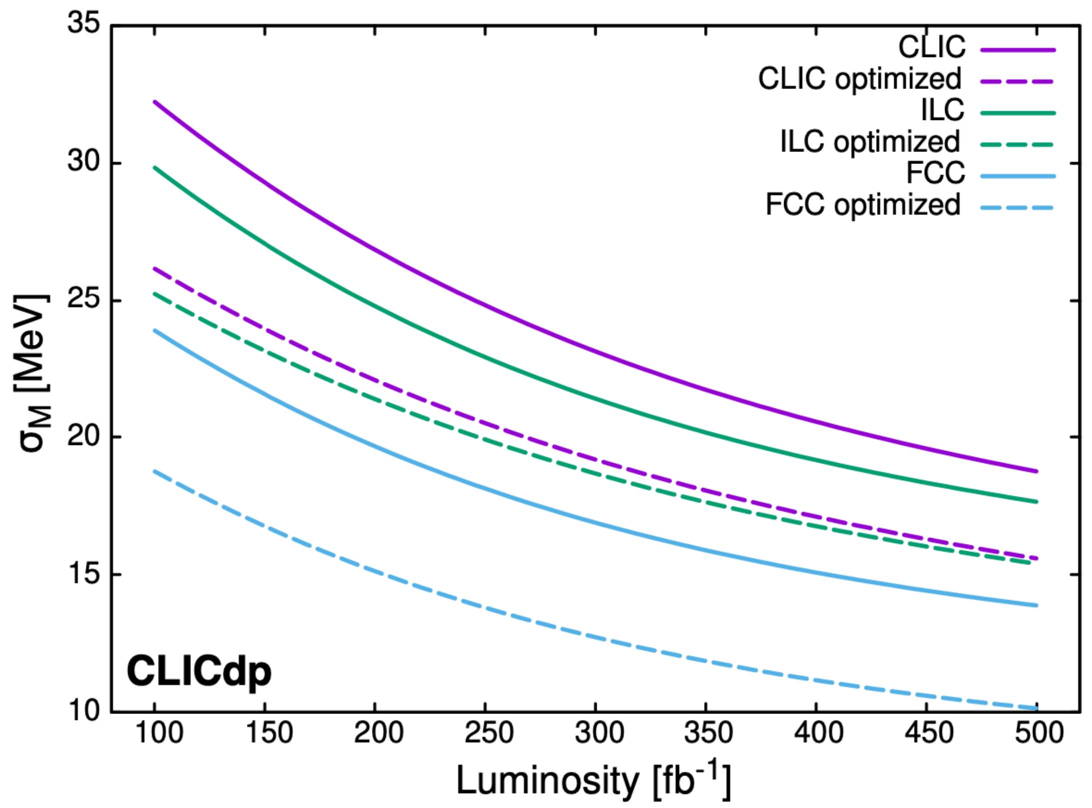
Top physics

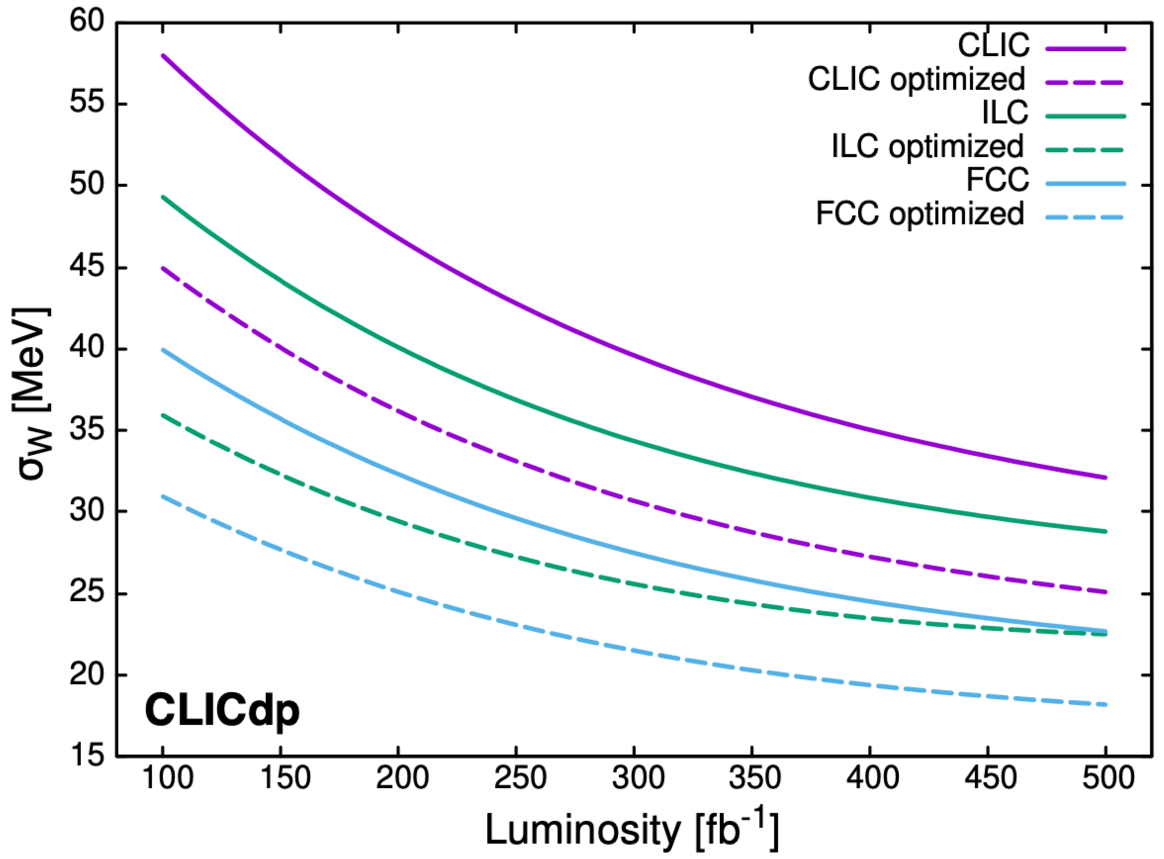
Linear
Circular

The top quark mass is a key SM parameter for precision tests at linear colliders
Huge potential from threshold scan: up to per-mille accuracy on cross section & asymmetries

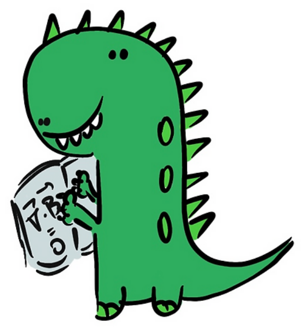


[Plot from F. Simon's talk @ CERN FC workshop 2022]



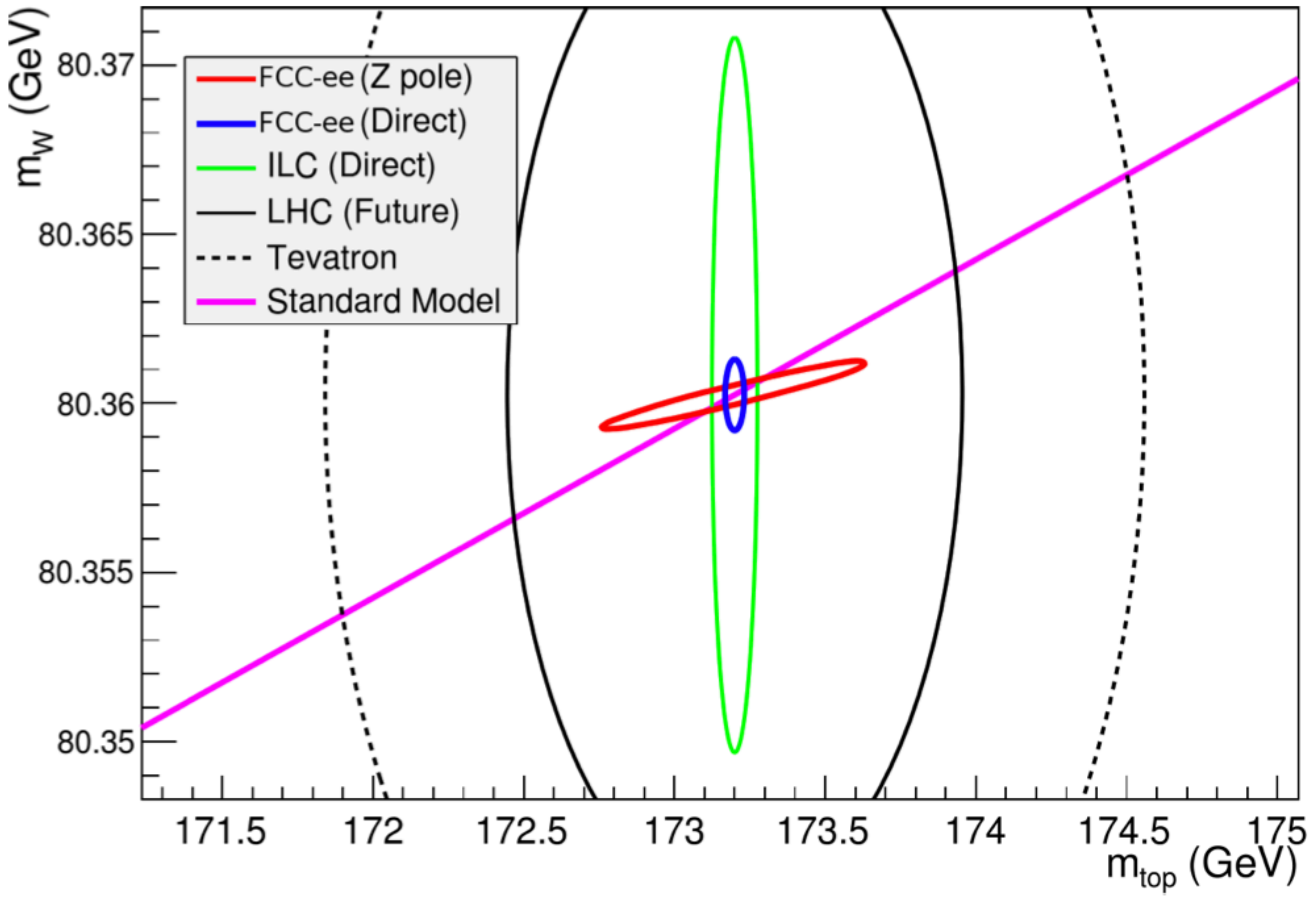


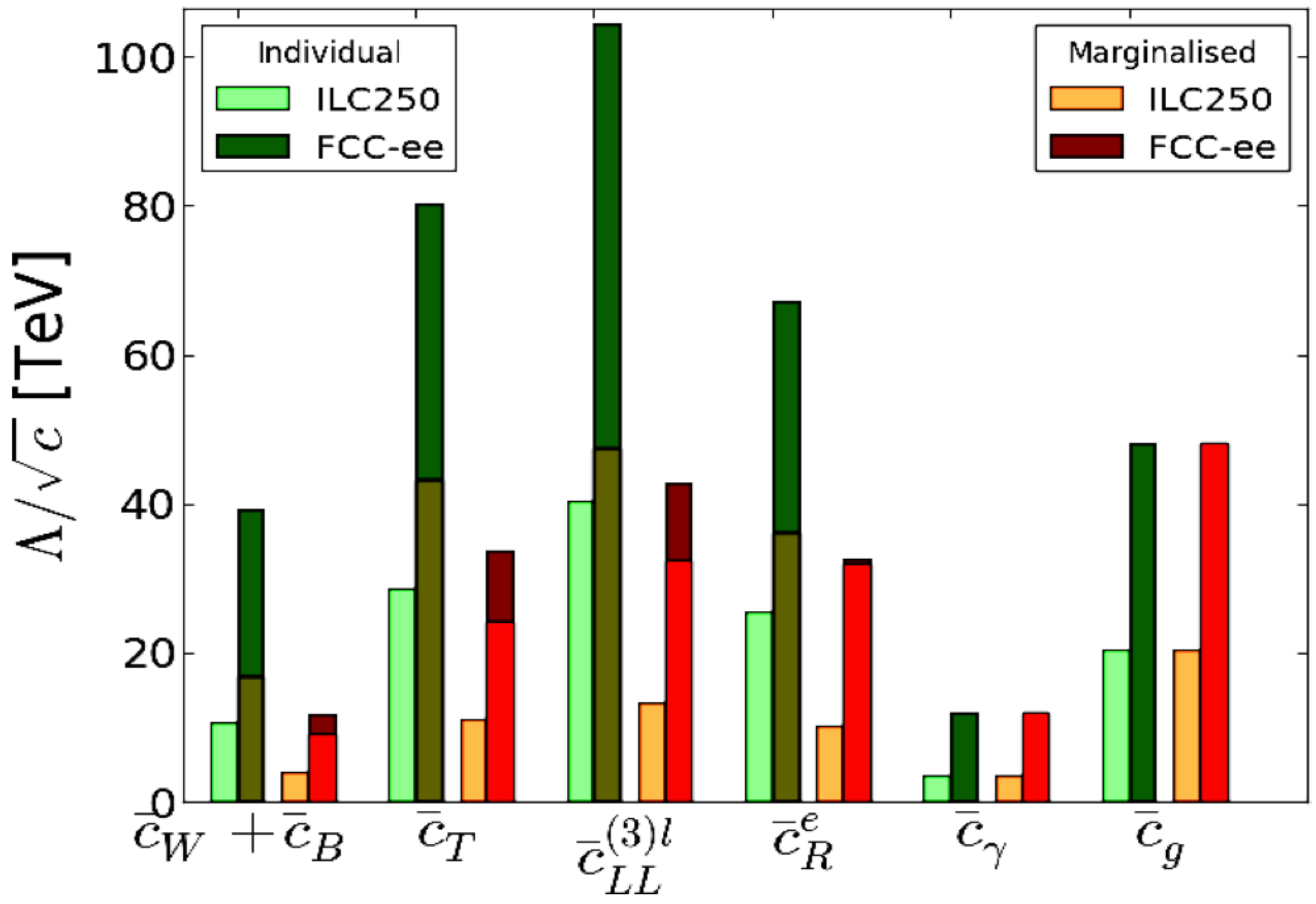
arXiv:2103.00522



Access to top mass and width, as well as strong coupling and top Yukawa coupling

Indirect constraints on BSM via high-precision





Energy reaches of a subset of dimension-6 operators SMEFT

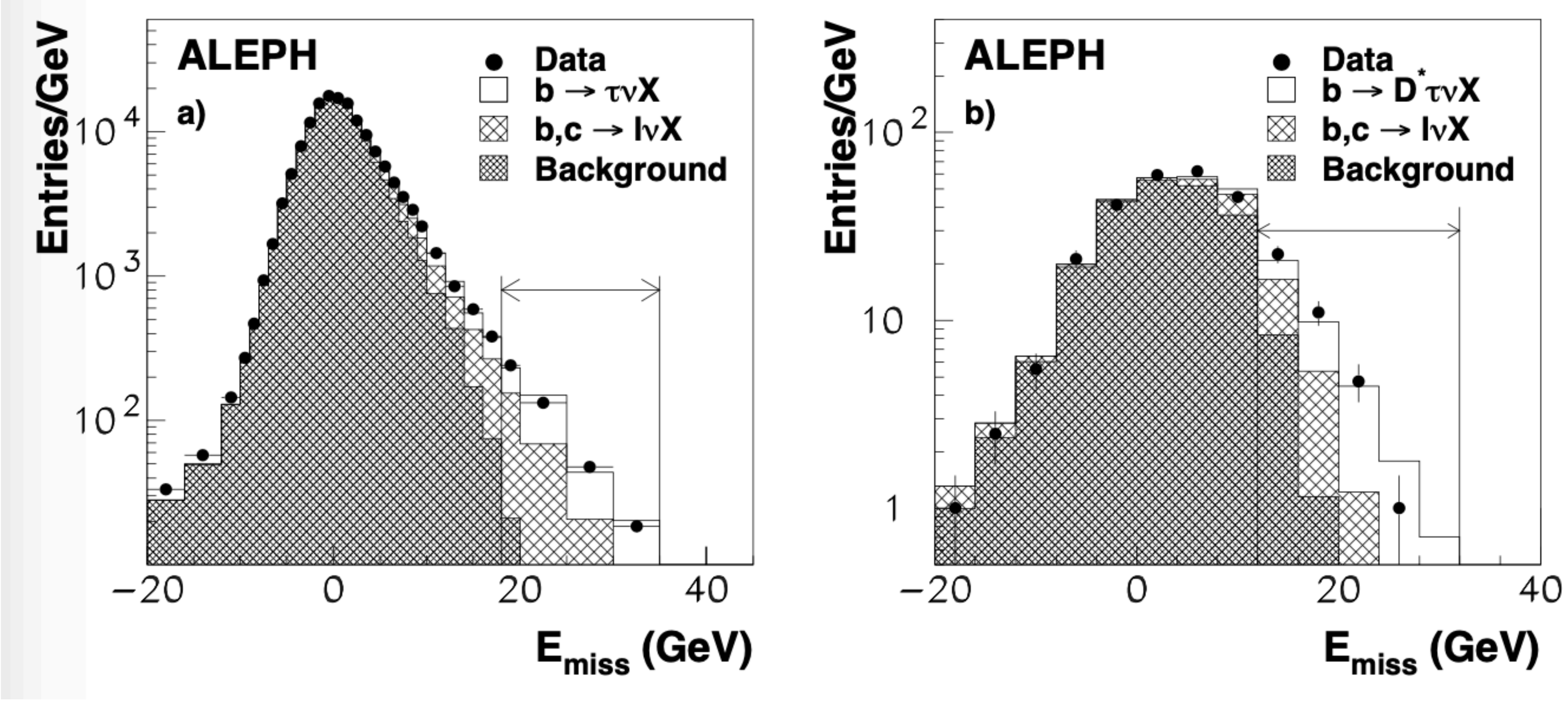
Linear
Circular

arXiv:1601.06640 and arXiv:1510.04561

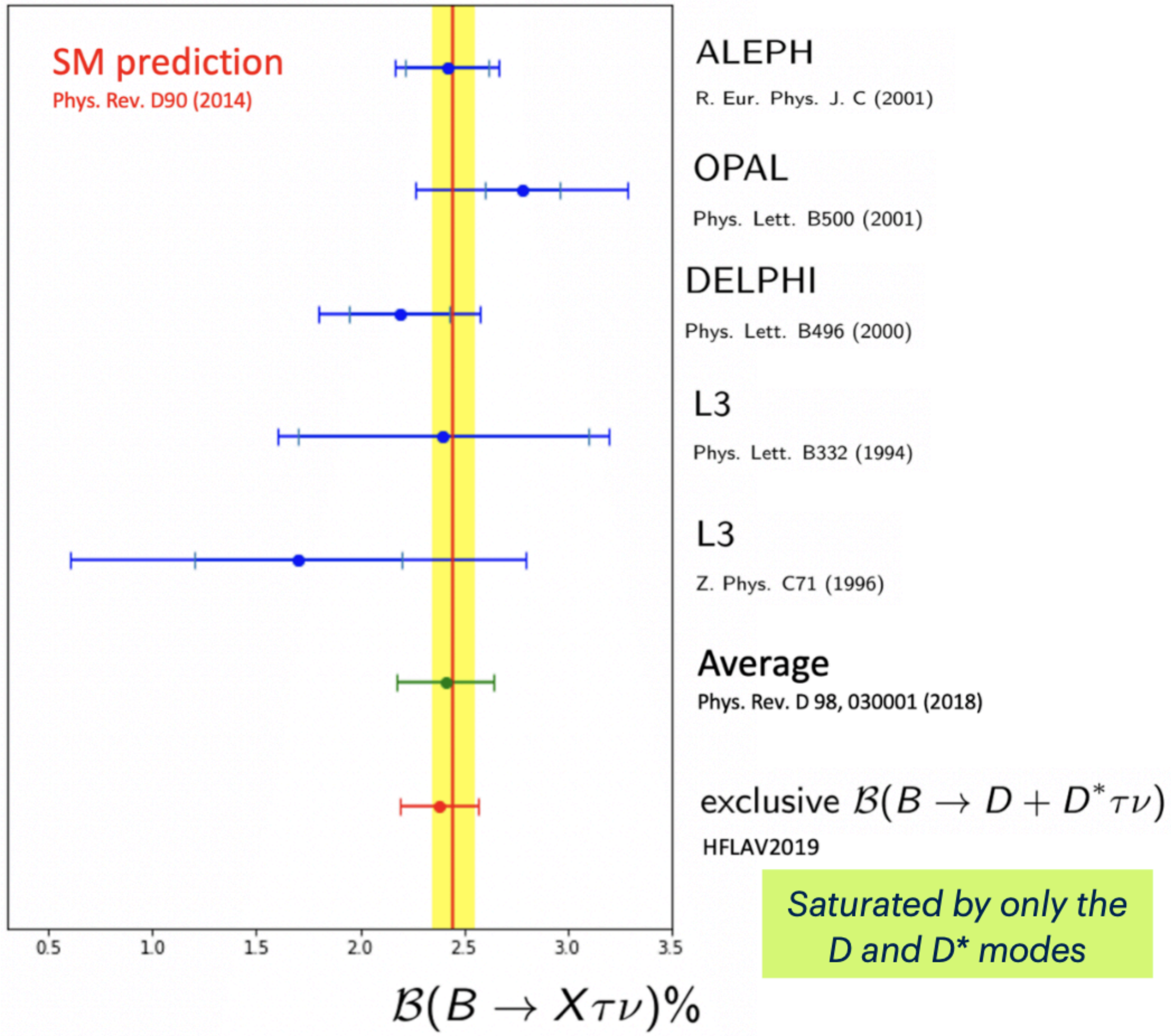
b-physics @ Z pole

Linear

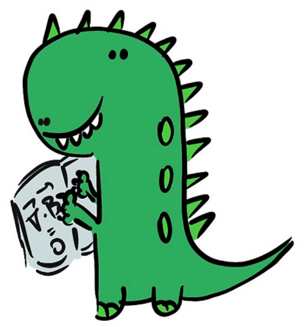
Large boost for *b* hadrons (<P_B> = 32 GeV/c), very well separated b produced in opposite hemispheres



EPJC 19 (2001) 213-227



Saturated by only the D and D modes*



Various *b*-decays modes with τ could be accessible, inclusive and exclusive.

FCCee aka LEP in one minute

About 20 times the nominal Belle II anticipated statistics for B^0 and B^+.

All species of *b*-hadrons are produced.

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]

$$\langle E_{X_b} \rangle = 75\% \times E_{\text{beam}}; \langle \beta\gamma \rangle \sim 6.$$

Particle species	B^0	B^-	B^0_s	Λ_b	B^+_c	$c\bar{c}$	$\tau^-\tau^+$
Yield (10^9)	740	740	180	160	3.6	720	200

Table 1: Particle abundances for $6 \cdot 10^{12}$ Z decays. Charge conjugation is implied.

Circular

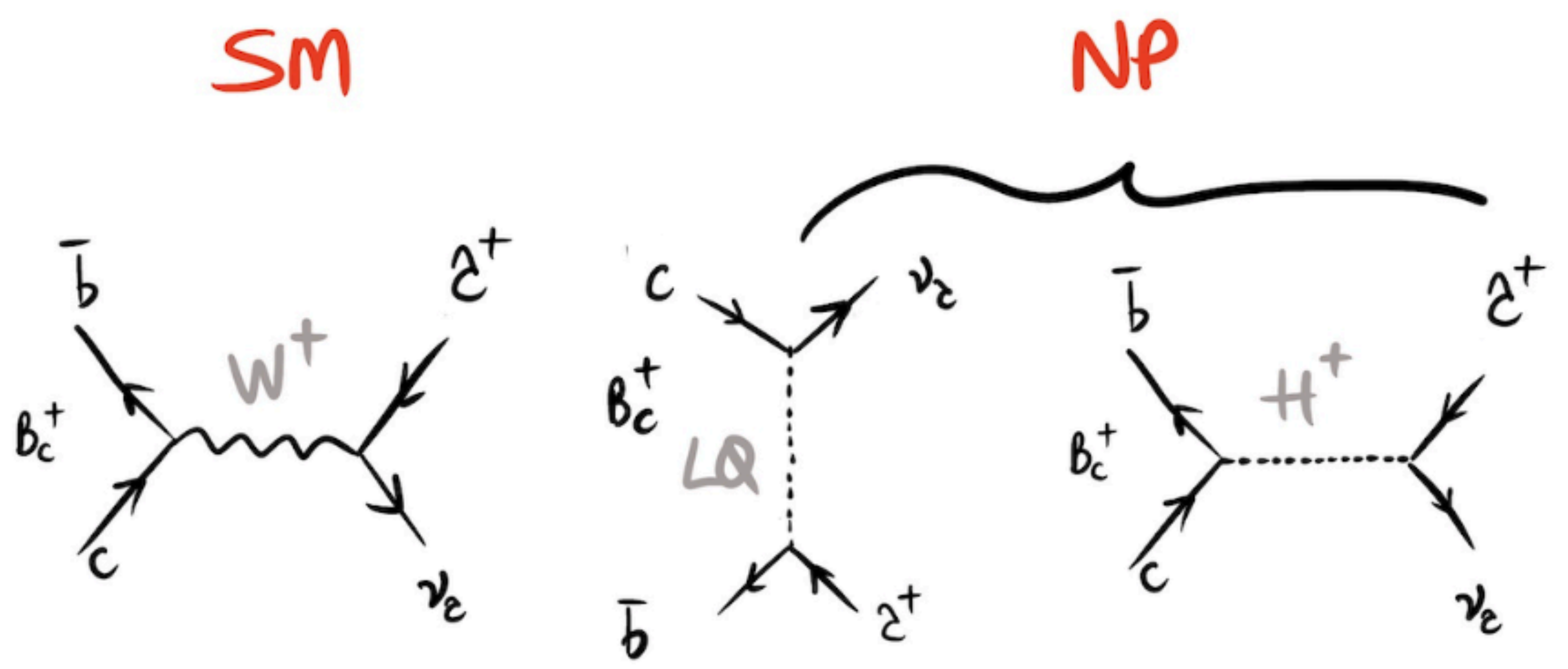
3) Reviews of current / foreseen activities (Feas. Study)

FCC

- Rare semileptonic decays and leptonic decays:
  - $b \to s\tau^+\tau^-$, e.g. $B^0 \to K^{*0}\ \tau^+\tau^-$. (vertexing case for mid-term review)
  - $b \to s\nu\nu$, e.g. $B_s \to \phi\nu\nu$
  - $Bc \to \tau\nu$; $b \to s(d)\ \ell\ell$
- *CP* violation studies:
  - The CKM γ angle, e.g. $B_s \to D_s K$.
  - The semileptonic asymmetries (*CP* breaking in mixing).
  - The CKM α angle, e.g. $B^0 \to (\pi^0\pi^0)$.
  - The matrix elements V_{ub} and V_{cb} ….
- Tau Physics:
  - Lepton flavour violating τ decays
  - Lepton-universality tests in τ decays.
- Charm Physics:
  - The rare decays, e.g. $D \to \pi\nu\nu$, $D^0 \to \gamma\gamma$
  - The hadronic decays, $D^+ \to \pi^+\pi^0$ …

Circular

What's interesting about $B^+_{(c)} \to \tau^+ \nu_\tau$?

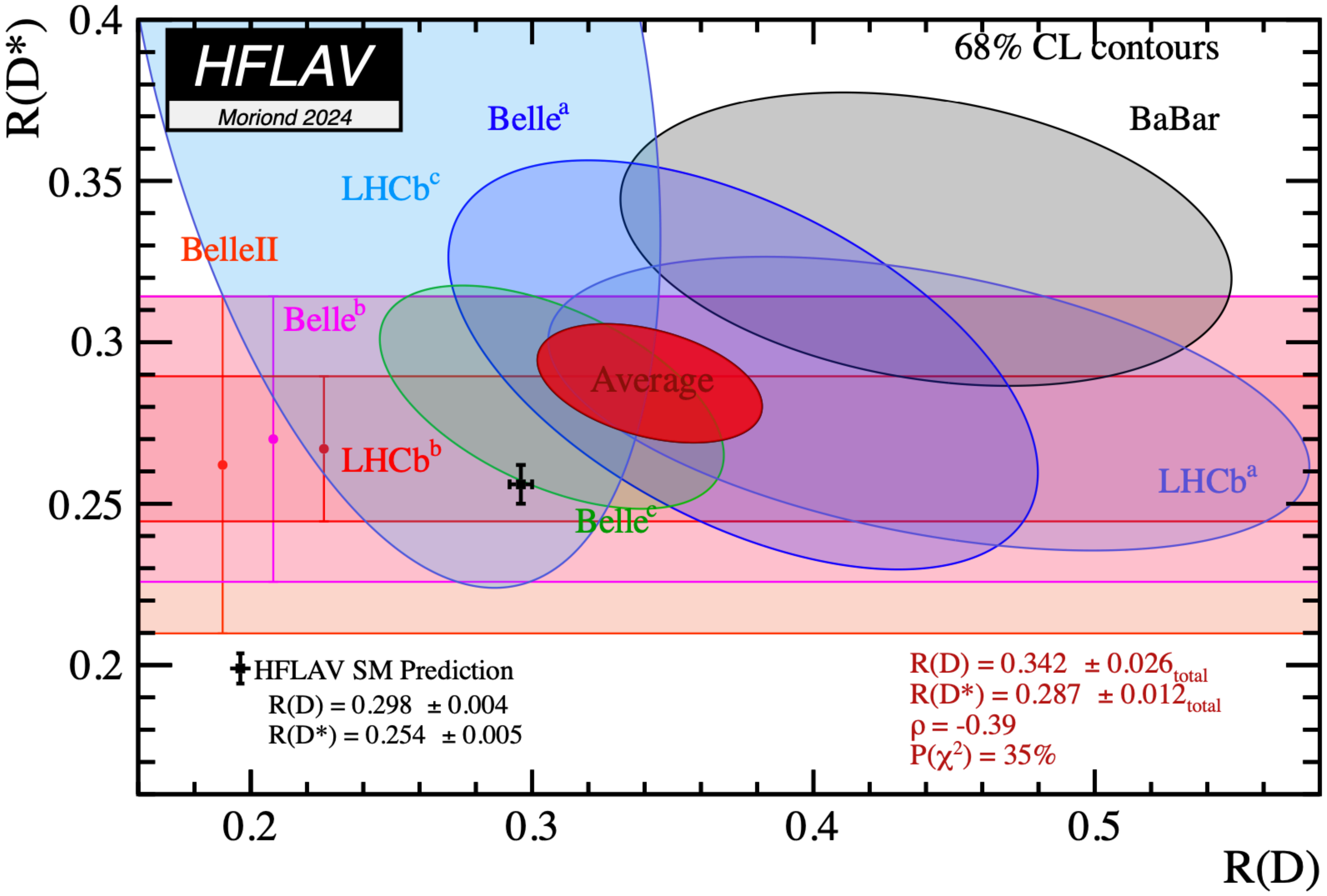


- Can be used to measure the CKM element $|V_{cb}|$ and highly sensitive to scalar contributions from NP.
- No possible at LHCb due to missing energy-lack of constraints and reconstructed information.
- No B_c production at Belle II.

[arxiv:2105.13330, arxiv:2305.02998]
[arxiv:2007.08234]

Circular

Charged currents



https://hflav.web.cern.ch/content/semileptonic-b-decays

With an EFT at $\mu = m_b$

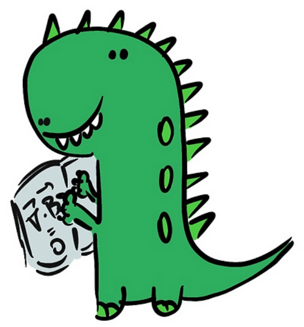
$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[(1+C_{V_L})(\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L) + C_{V_R}(\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_L) + C_{S_L}(\bar{c}_L b_R)(\bar{\tau}_R \nu_L) + C_{S_R}(\bar{c}_R b_L)(\bar{\tau}_R \nu_L) \Big] + h.c.$$

C_i are the Wilson coefficients, null in the SM using this convention.

If one uses : $C_{V(A)} = C_{V_R} \pm C_{V_L}$ and $C_{S(P)} = C_{S_R} \pm C_{S_L}$.

$$\mathcal{B}(B_c \to \tau\nu) = \mathcal{B}^{SM}(B_c \to \tau\nu) \left| 1 - C_A - C_P \frac{m_{B_c}^2}{m_\tau (m_b + m_c)} \right|^2$$

C_P lifts the SM helicity suppression sizeable enhancement !

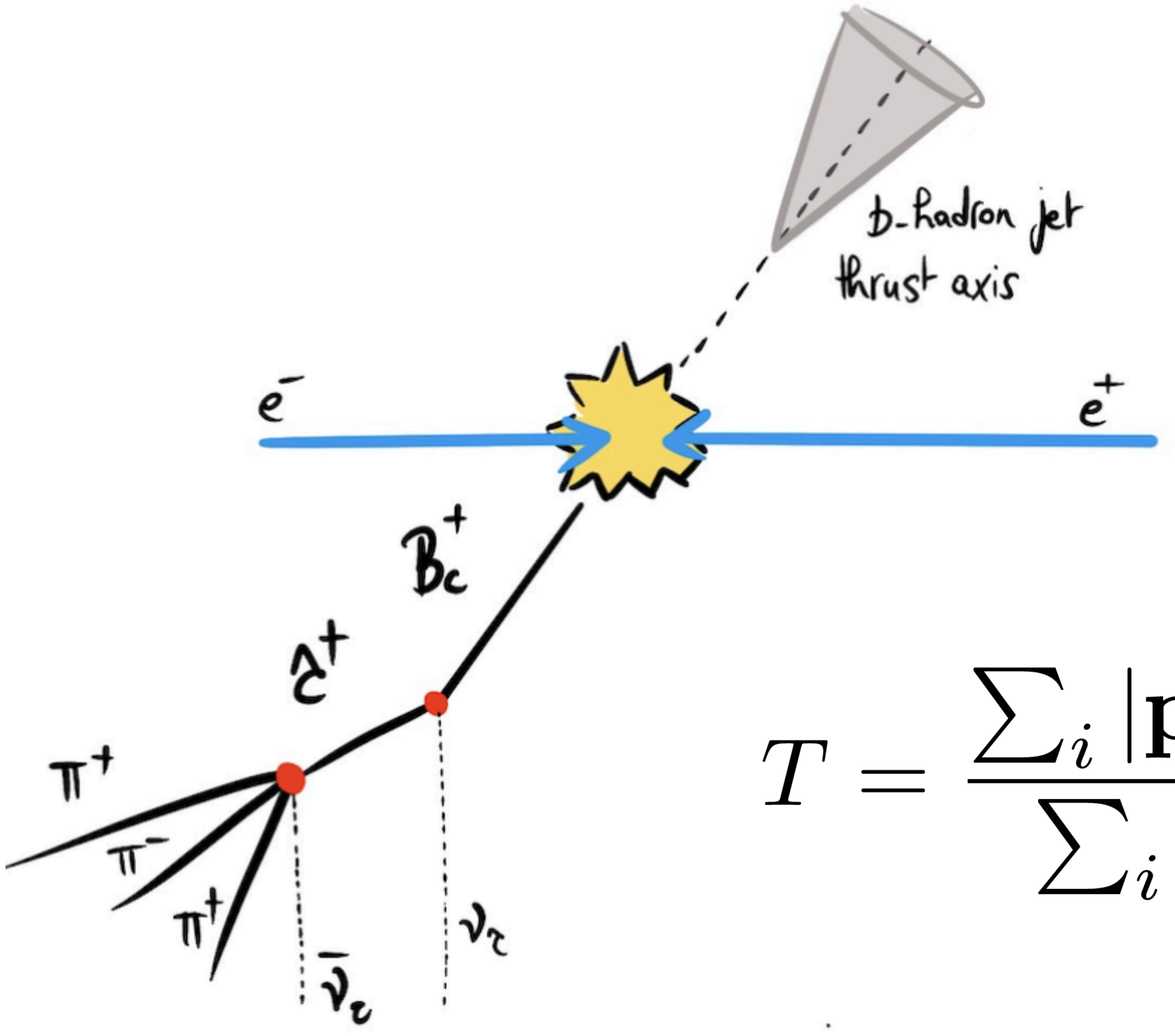


Circular

Decay topology

B_c lifetime very short ~ 0.5 ps,
i.e too many degrees of freedom to fully reconstruct the decay.

Explore the thrust axis properties and the hadronic τ decays.



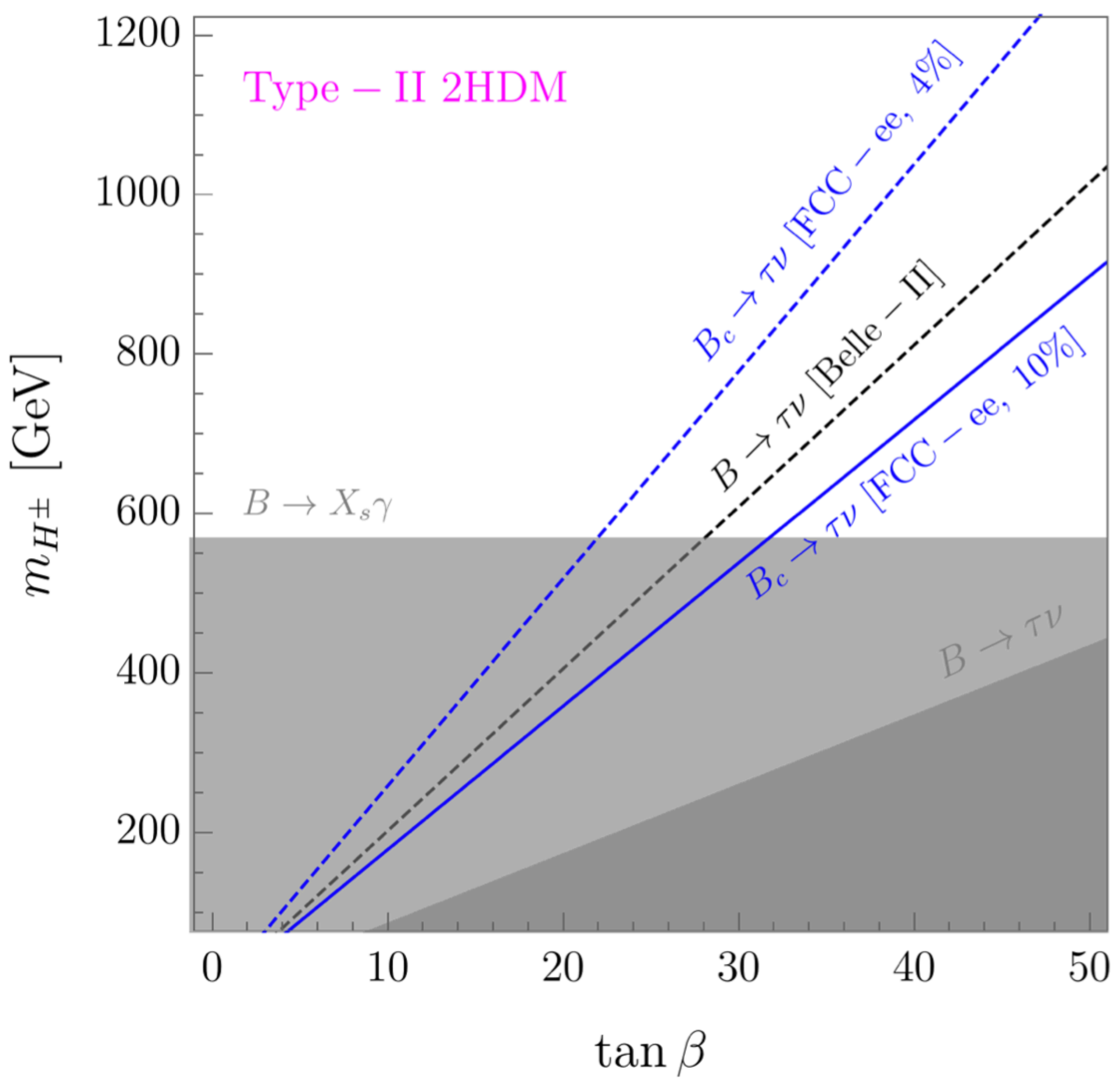
$$T = \frac{\sum_i |\mathbf{p}_i \cdot \hat{\mathbf{n}}|}{\sum_i |\mathbf{p}_i|}$$

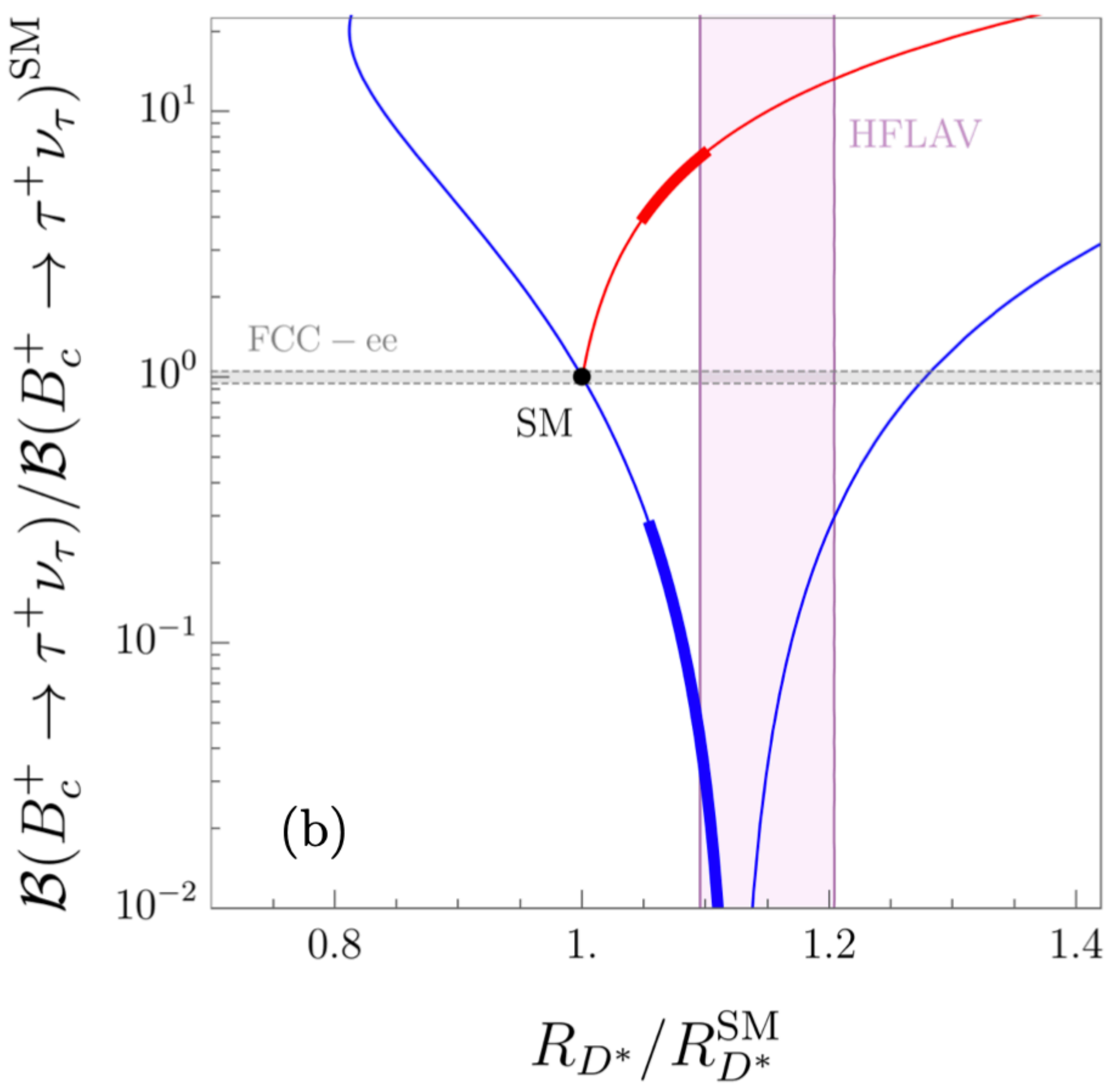
Note : arXiv:2007.08234 explored leptonic τ decays.

Results

Circular

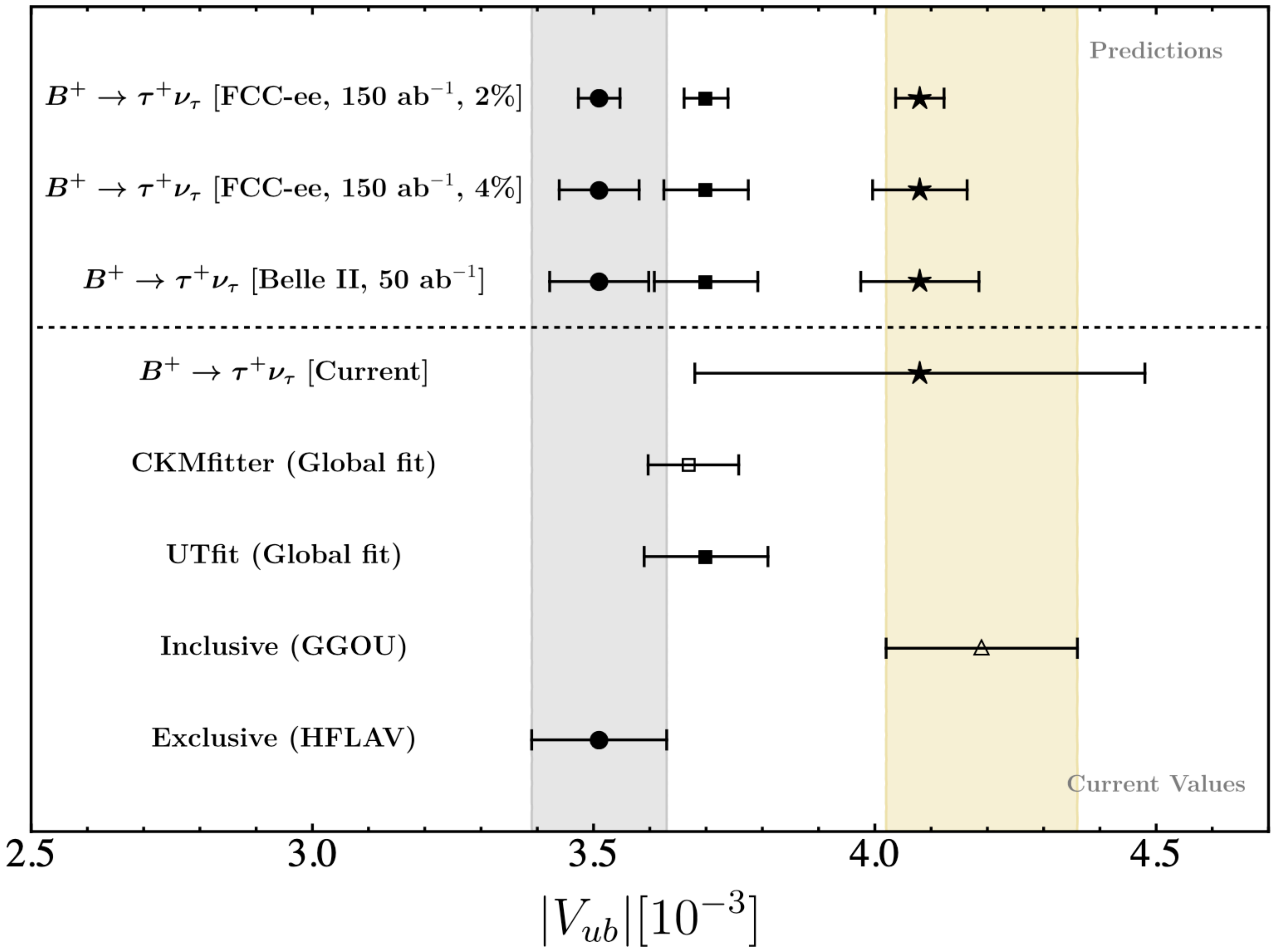
Impact evaluated on NP models and Lepton Universality observables



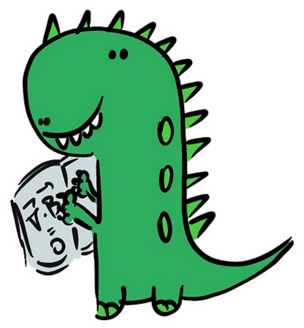


But also… $B^+ \to \tau^+\nu_\tau$

arXiv:2305.02998



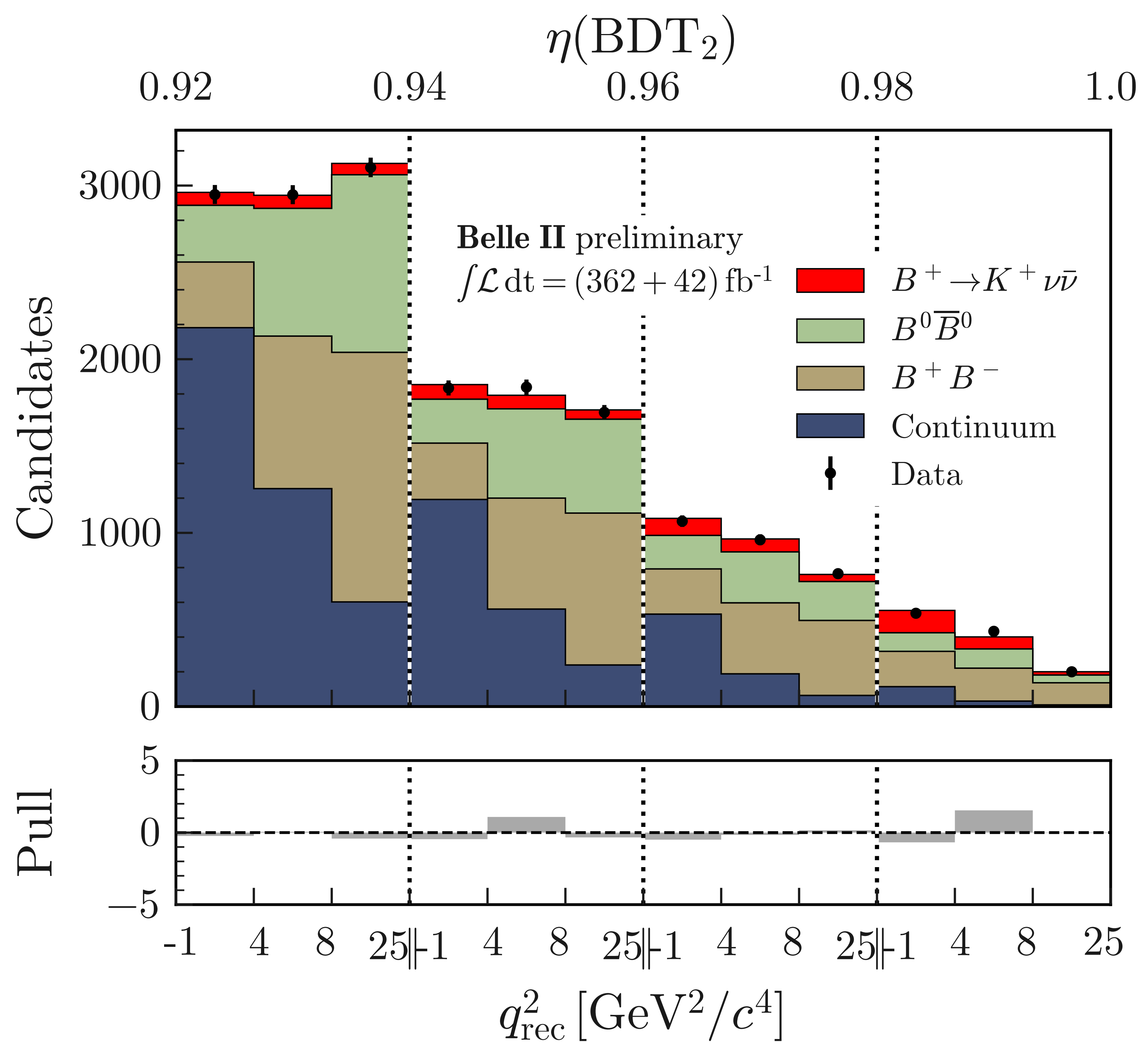
Comparison between current determinations of $|V_{ub}|$ and predicted determinations from Belle II and FCC-ee, where the FCC-ee values correspond to 2% and 4% uncertainty on $\mathscr{B}(B^+ \to \tau^+\nu_\tau)$. Different central values are taken from the current Exclusive, Global and $B^+ \to \tau^+\nu_\tau$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



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

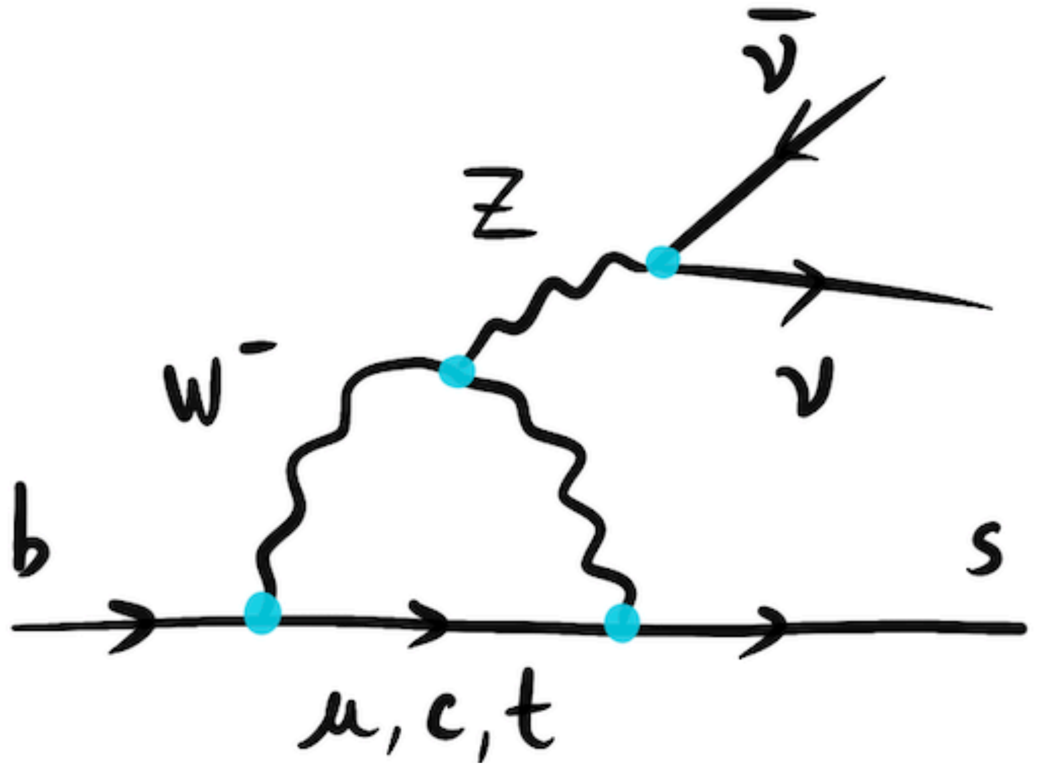
Circular

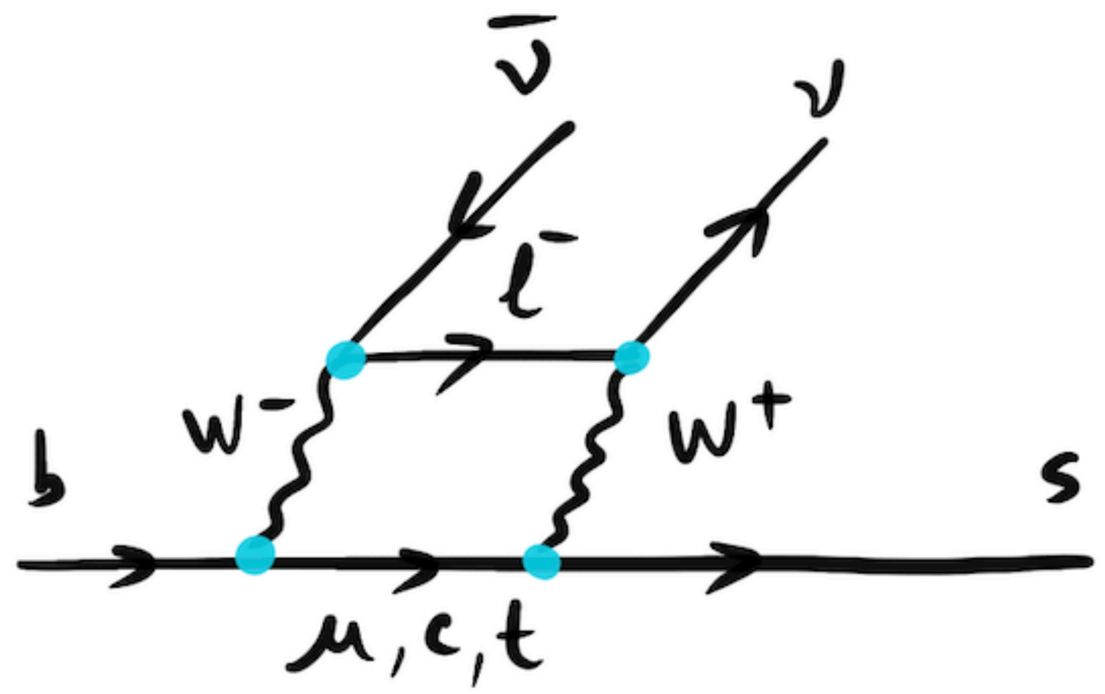
- Most probably impossible at LHCb
- Belle II cannot do all B flavours
- Yet to be observed, besides evidence for $B^+ \to K^+\nu\bar{\nu}$
  - 2.7σ tension with SM [arxiv:2311.14647]
- Theoretically cleaner than the corresponding $b \to sl^+l^-$
- Can be used to extract the CKM factor and hadronic form 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
$B^+ \to K^+\nu\bar{\nu}$	✔	✔
$B^+ \to K^{*+}\nu\bar{\nu}$	✔	✔
$B^0 \to K^0_S\nu\bar{\nu}$	✔	✔
$B^0 \to K^{*0}\nu\bar{\nu}$	✔	✔
$B^0_s \to \phi\nu\bar{\nu}$	✗	✔
$\Lambda^0_b \to \Lambda^{(*)0}\nu\bar{\nu}$	✗	✔



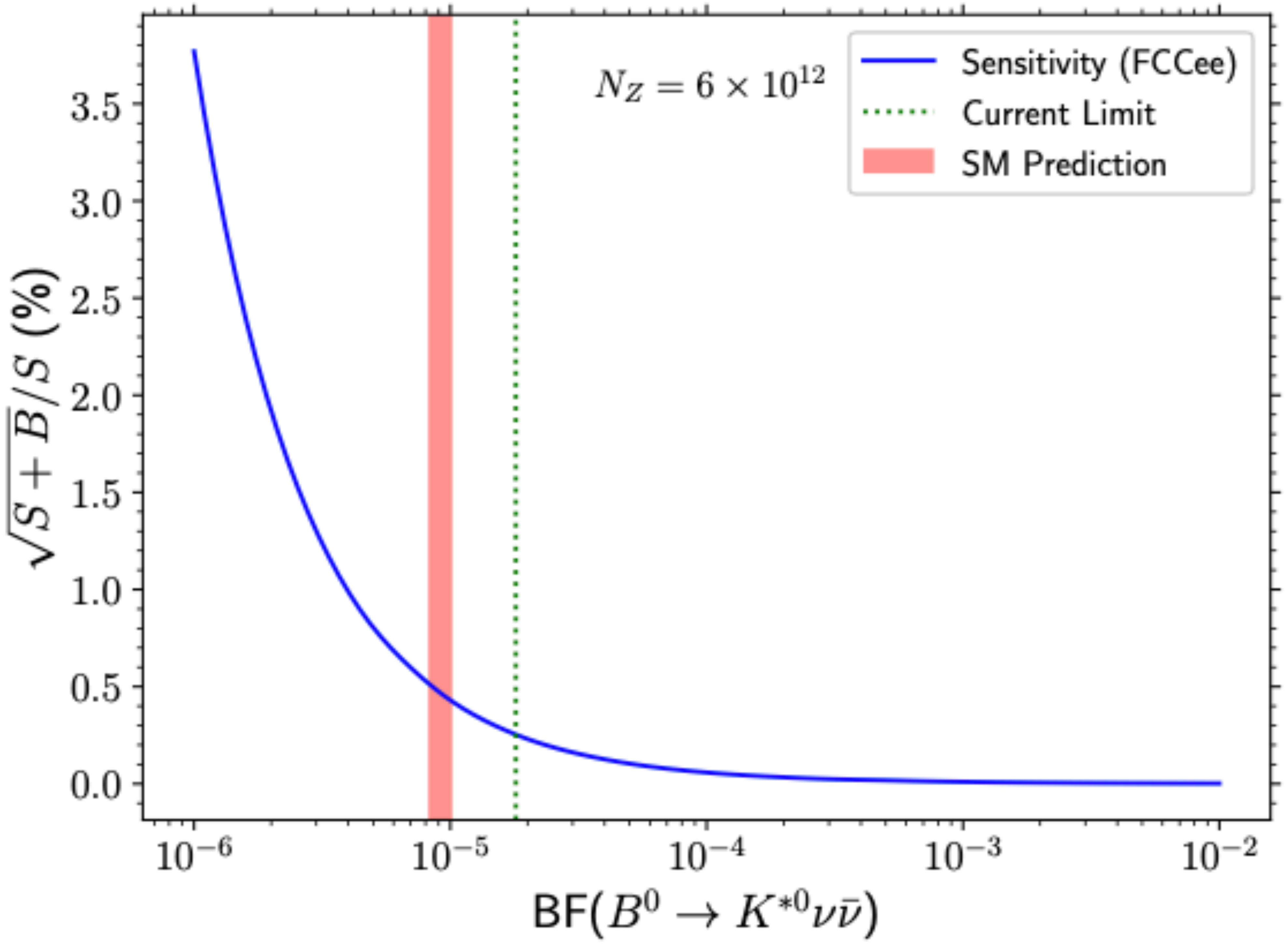


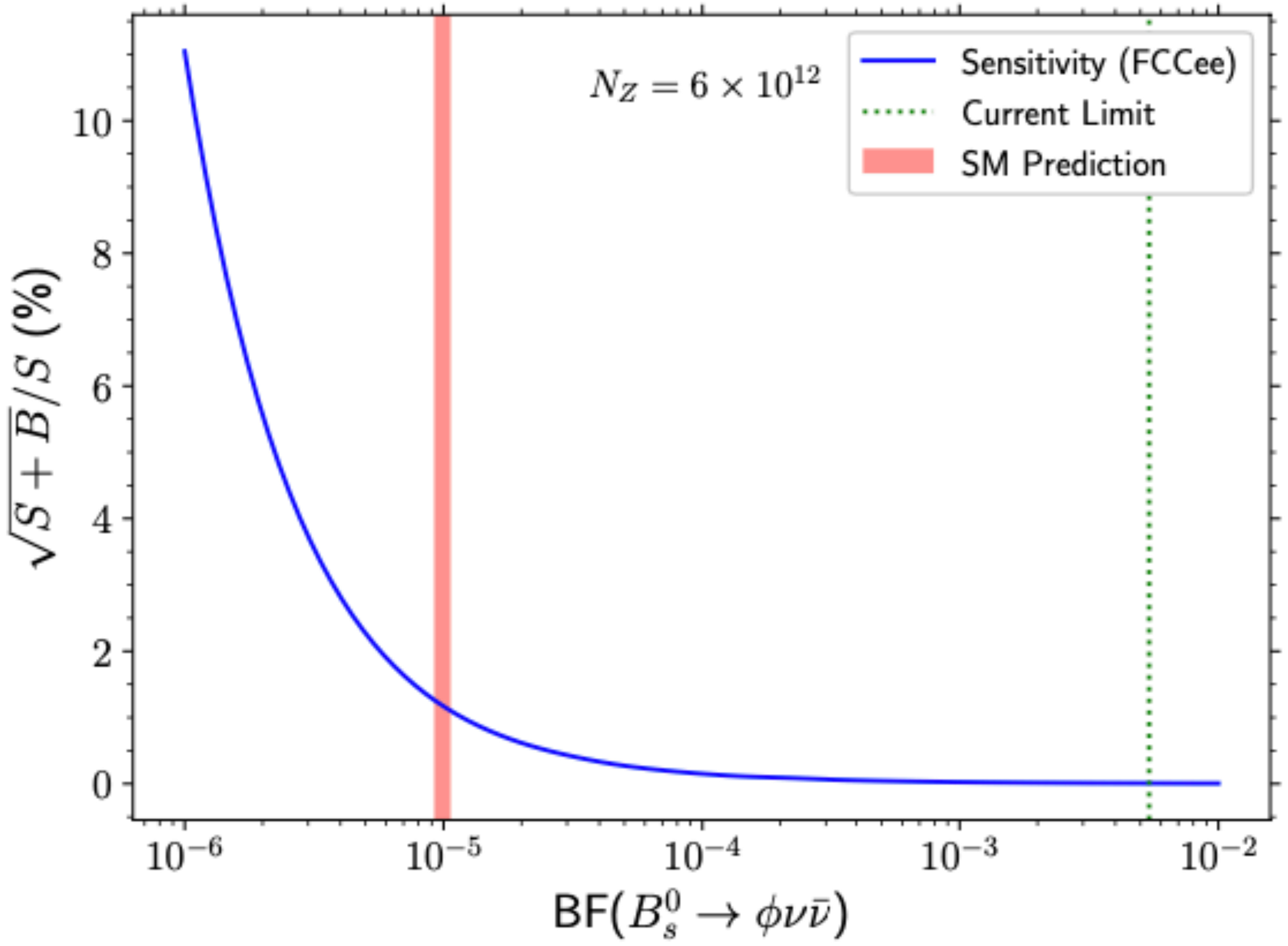
arxiv:2309.11353

Circular

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

Studies on sensitivity at FCC-ee [JHEP 01 (2024) 144] and at CEPC [PRD 105 (2022) 114036]



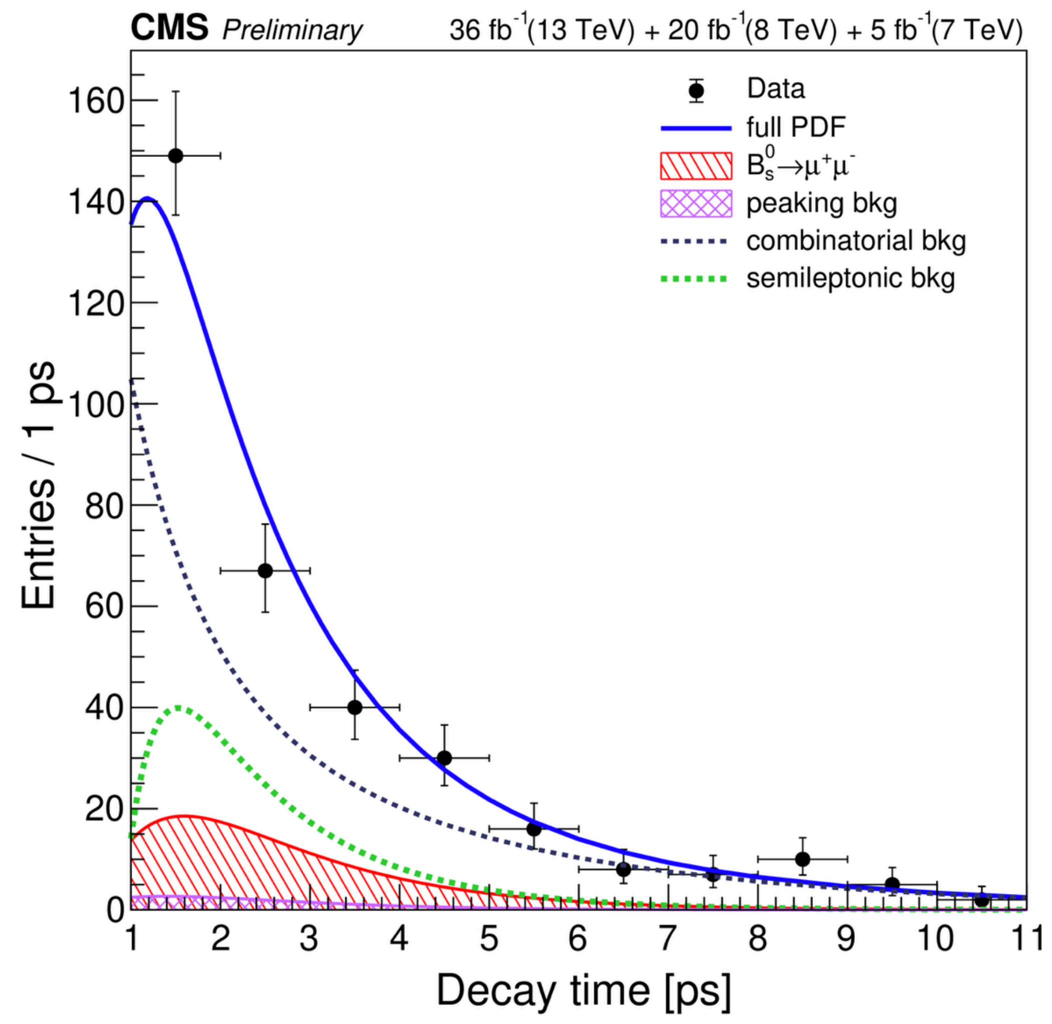


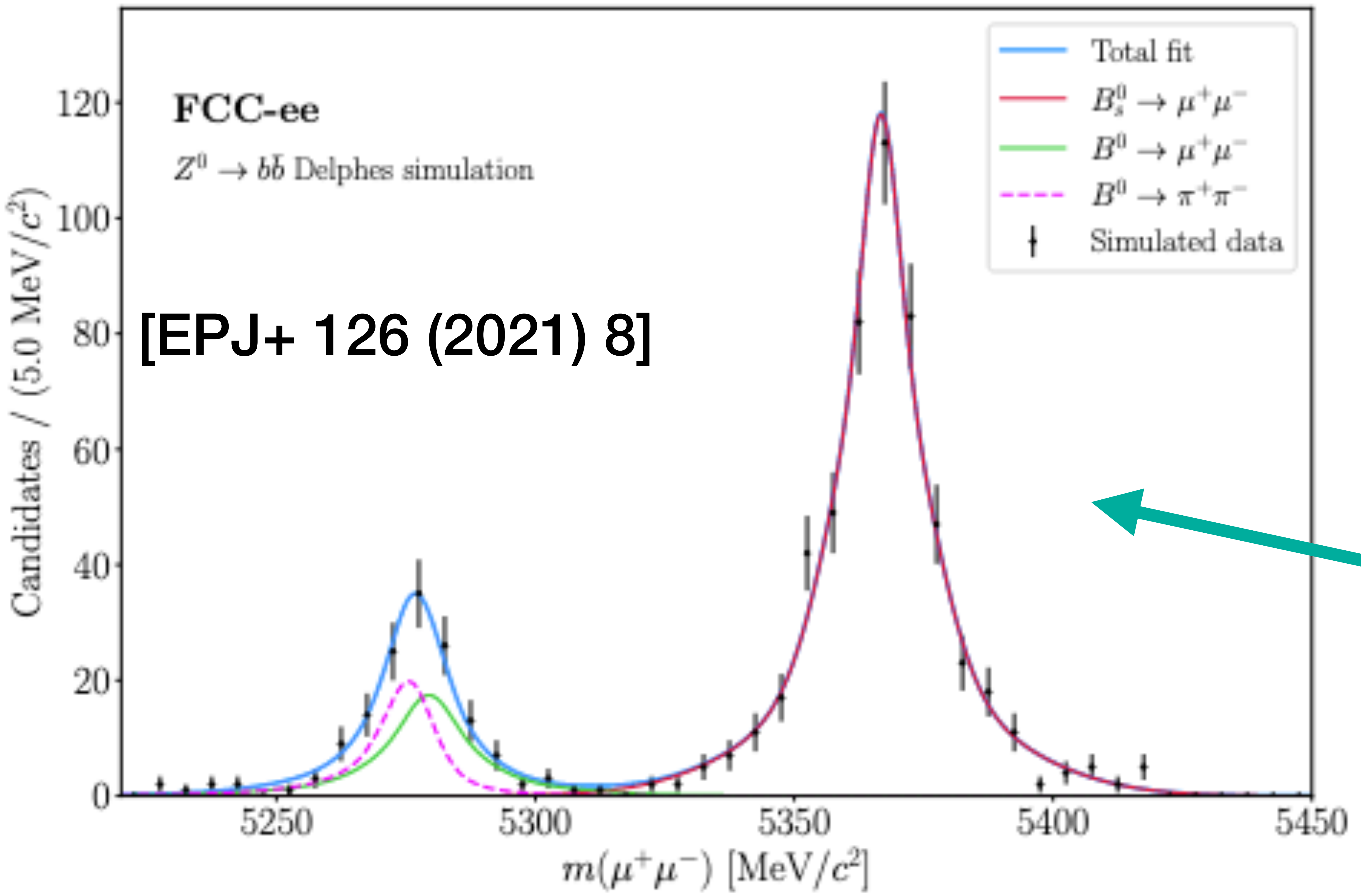
This kind of precision means that differential measurements will be possible

Very rare decays $B_s \to \mu^+\mu^-$

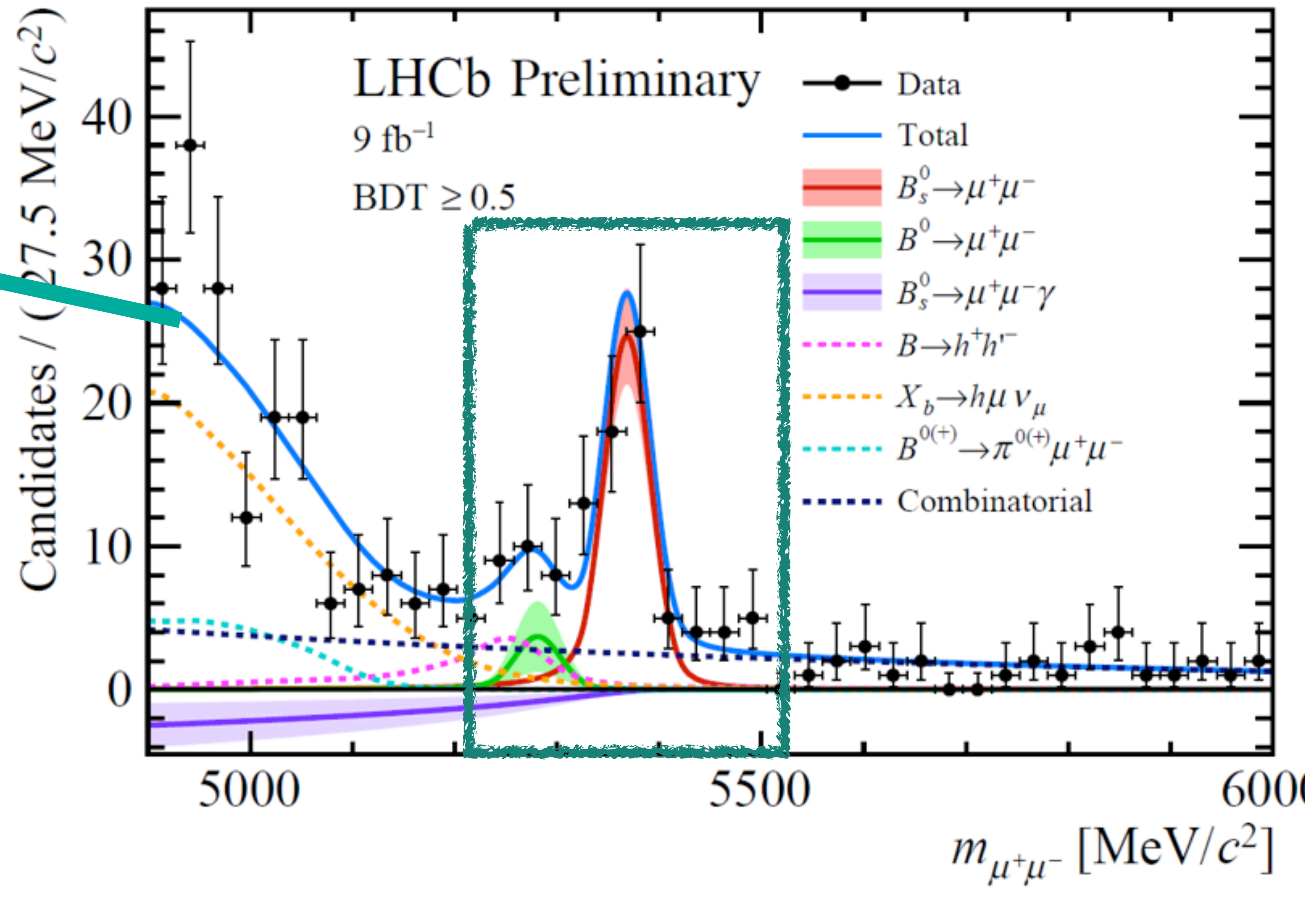
Circular

Invariant-mass resolution is a must - Ultra-high resolution calorimetry is in addition desirable to touch high performance for modes w/ neutrals

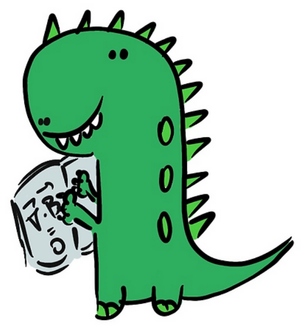




[EPJ+ 126 (2021) 8]

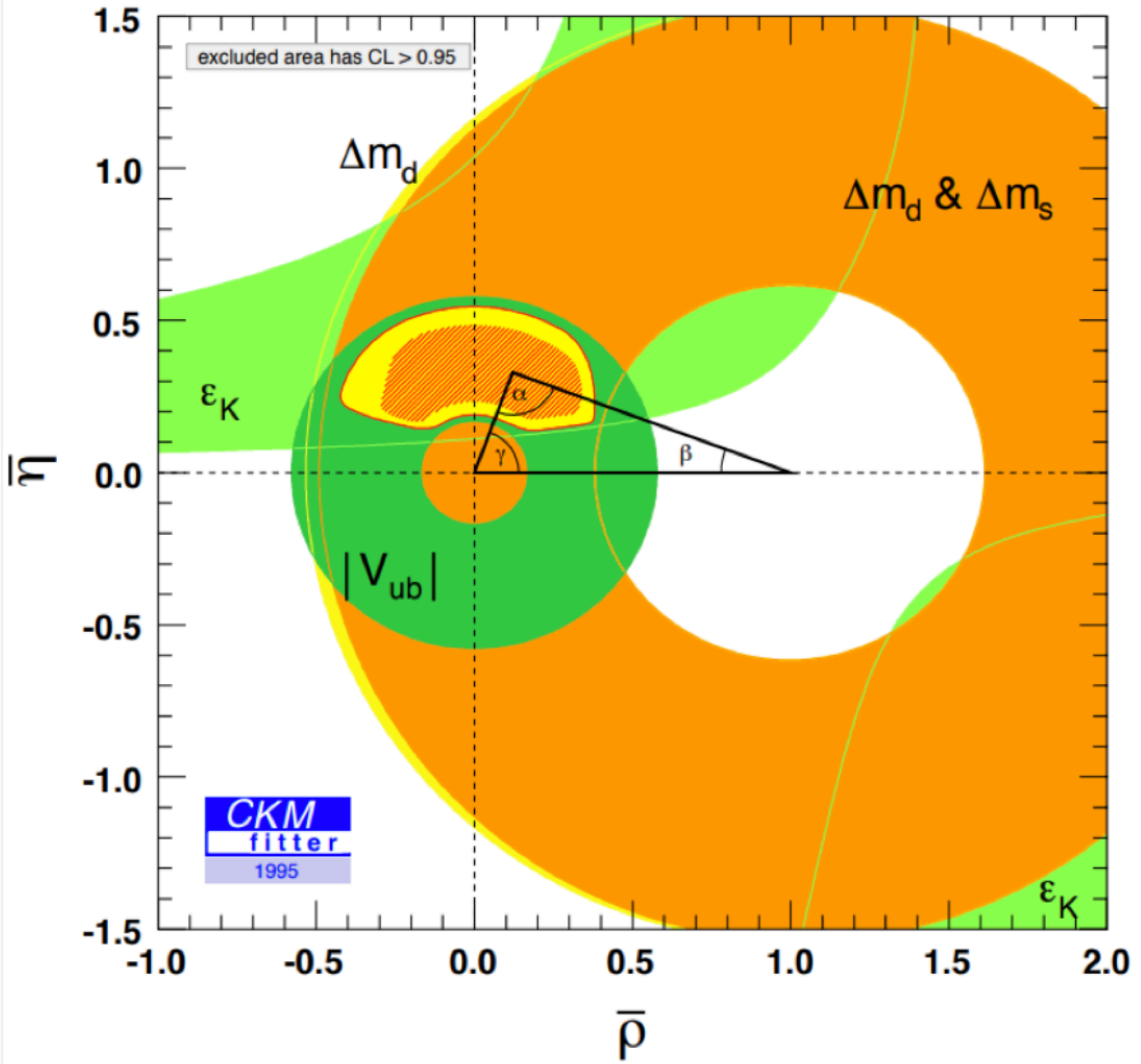


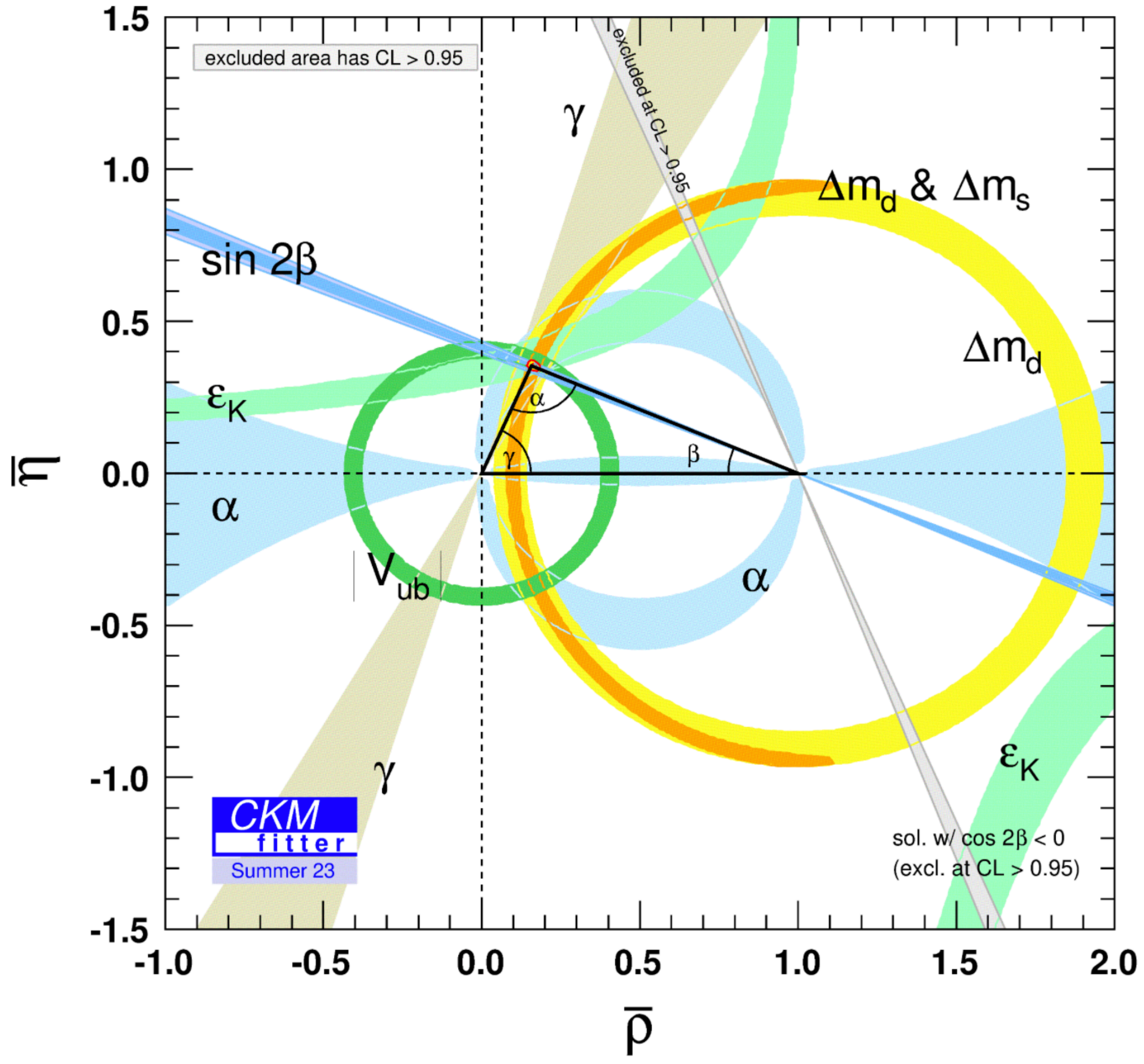
Run 1 & 2 LHCb data



Effective lifetimes and *CP* asymmetries are possible

CKM metrology





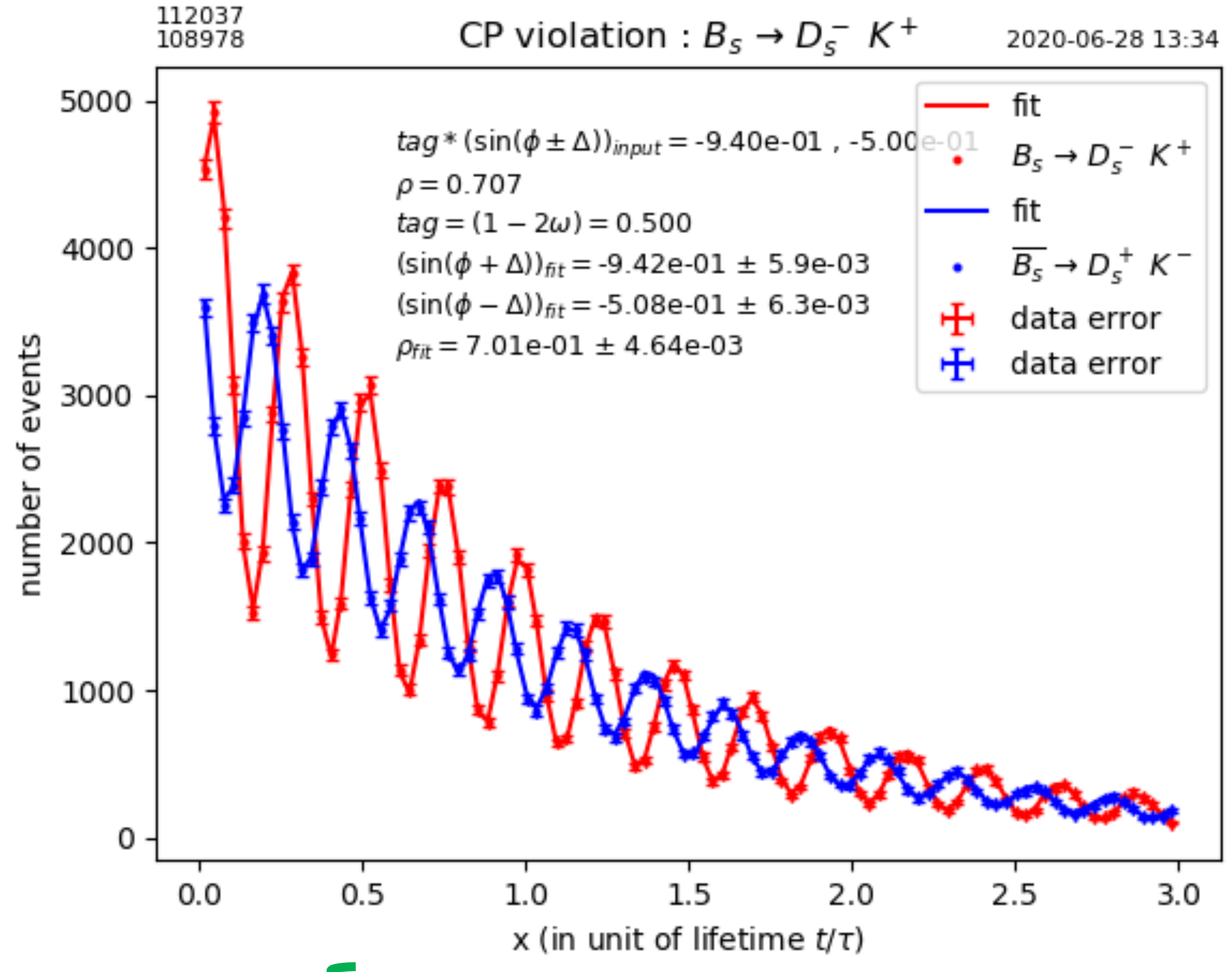
At the horizon of the next electron collider, the knowledge of the CKM profile is expected to have been deeply revisited by LHCb and Belle II/III.

Let's not forget about γ

Circular

Measurement of CP violation with $B_s \to D_s K$

$$\int Ldt = 150\ ab^{-1}$$



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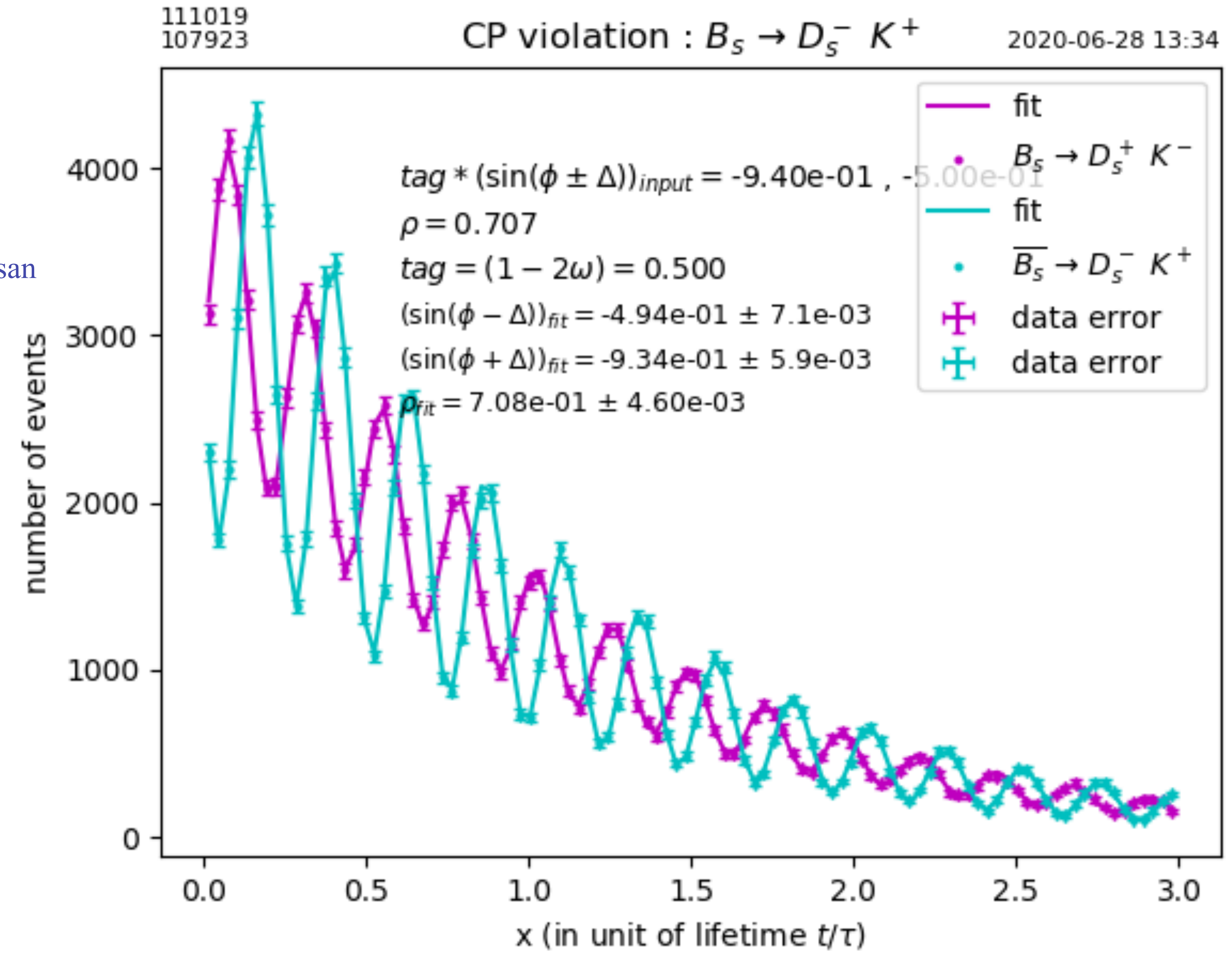
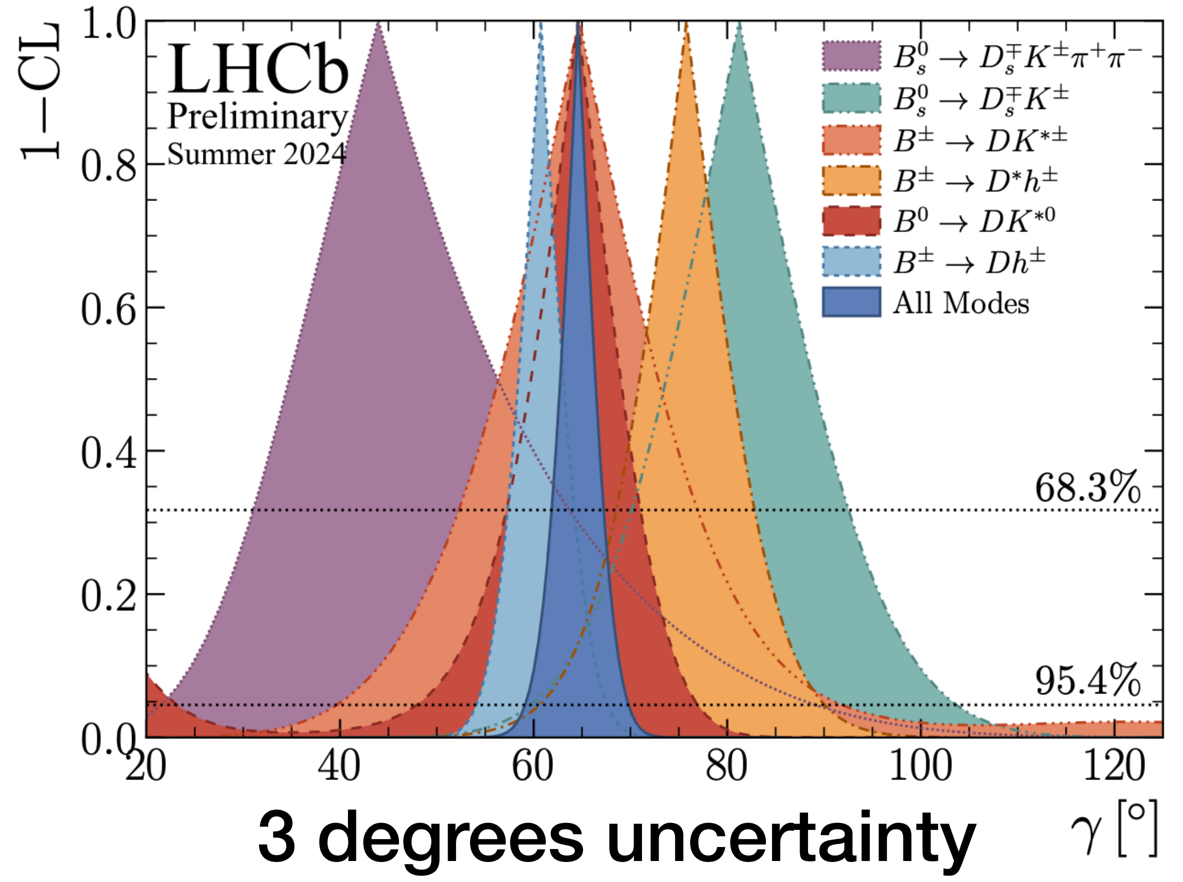




3 degrees uncertainty

Result 3 :

$$\delta(\rho) \approx 3.2 \times 10^{-3} (stat.)$$

$$\delta(\sin^2\phi_{CKM}) \approx \delta(\sin^2\gamma) \approx 5 \times 10^{-3} (stat.) \cong \delta(\gamma) \approx 0.4° \ (stat.)$$

Potential statistical gain of factor 4-5 with $D_s^\pm \to K^{*0}K^\pm, \phi\rho^\pm$, … but background needs to be studied (see later)+

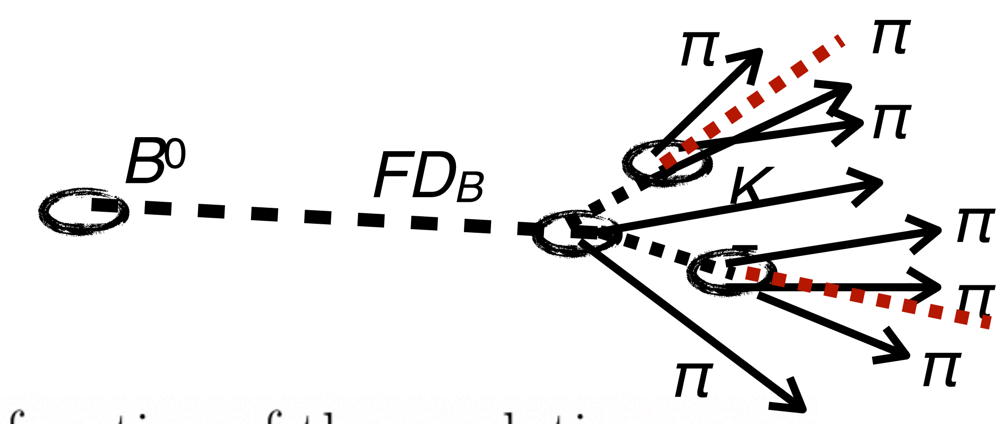
Additionnal potential gain (another factor ~2) with $B_s \to D_s^{*\pm}K^\mp, D_s^\pm K^{*\mp}, D_s^{*\pm}K^{*\mp}$, most modes including γ(s)

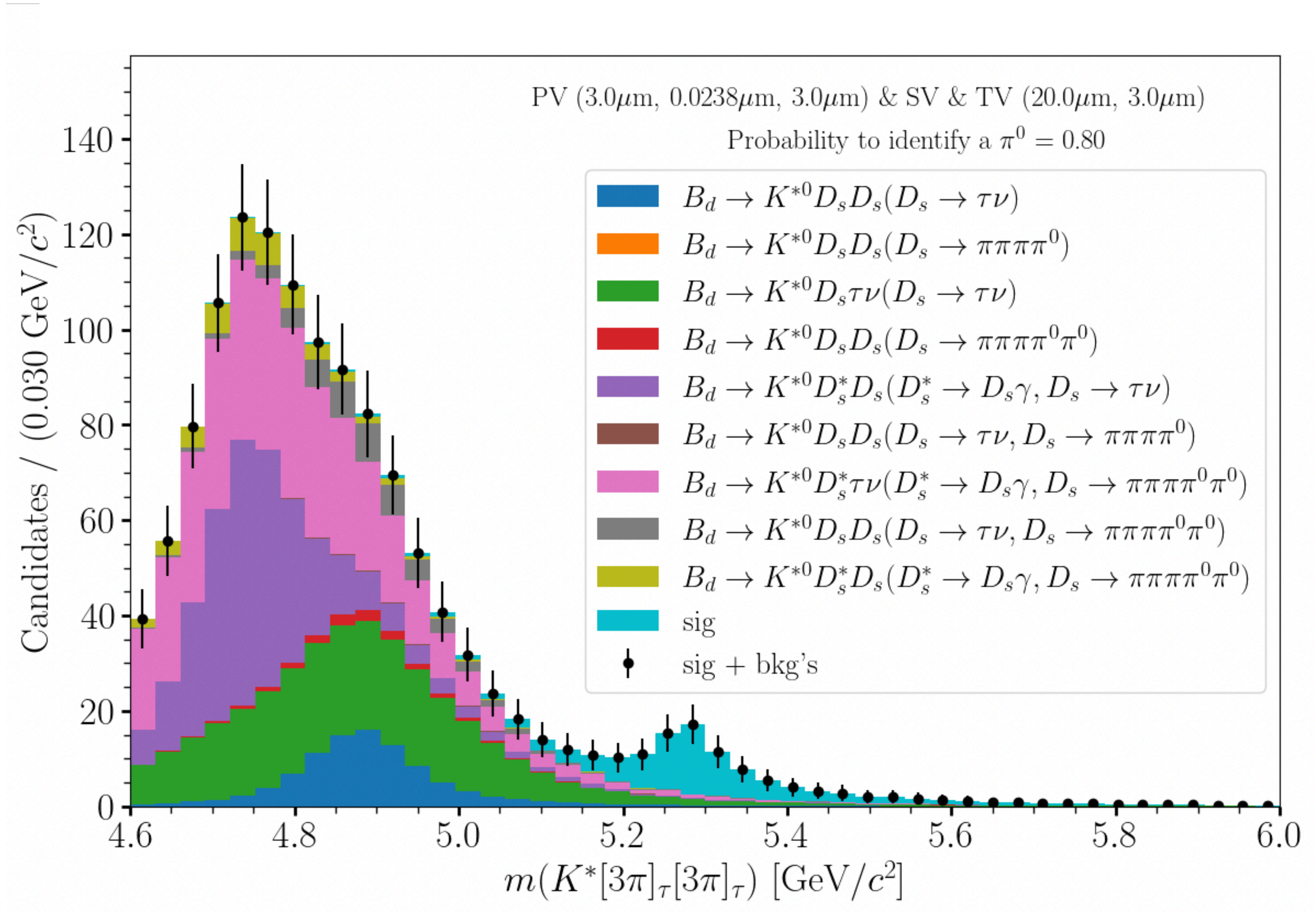
Several null tests of the SM accessible at the highest precision, e.g. semileptonic asymmetries, ϕ_s in penguin-dominated diagrams …

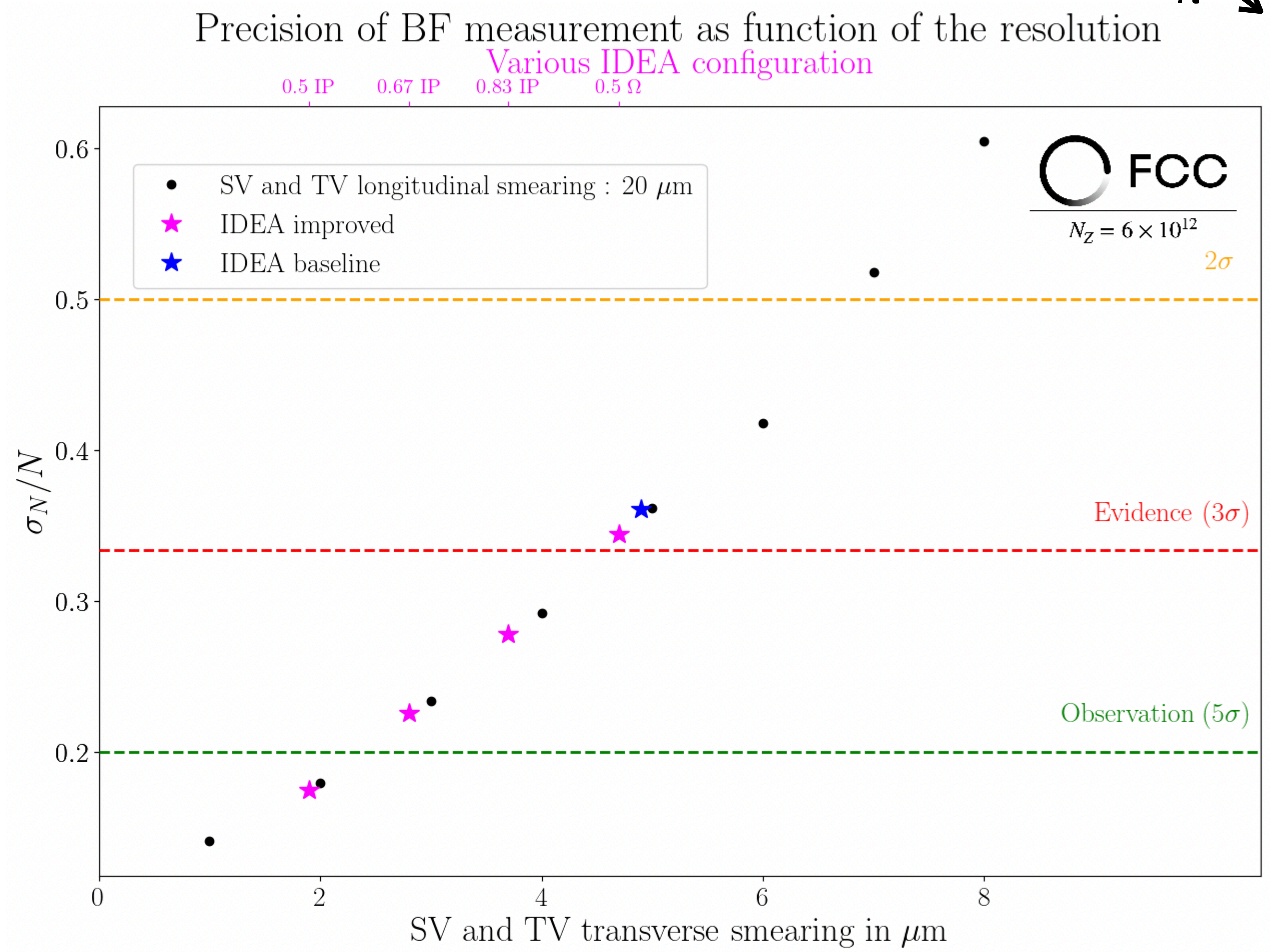
Circular

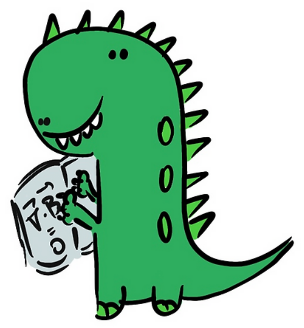
$B \to K^{*}\tau^{+}\tau^{-}$ decays

A fairly complex topology to study $b \to s\ell^{+}\ell^{-}$ transitions









We could see unambiguously the SM signal with this emulated detector

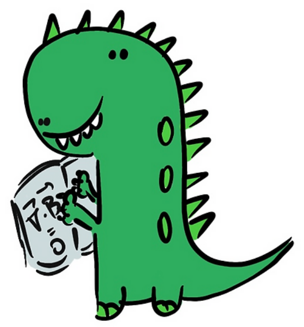
τ measurements

Circular

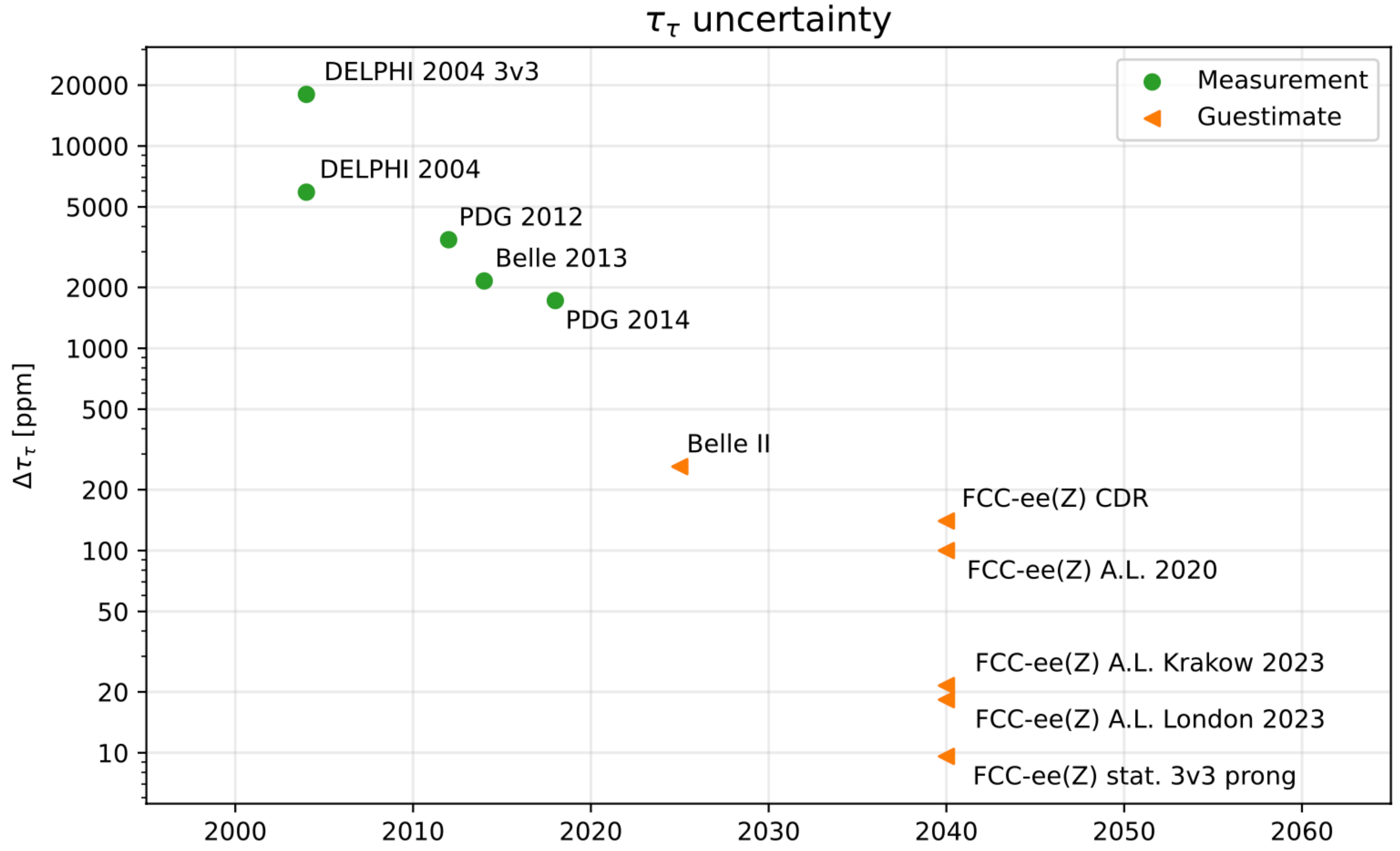
- $\sim 10^{11}\ Z \to \tau^+\tau^-$ at the FCC-ee
- m_τ is a SM parameter - must push experimental sensitivity as far as possible
  - Required for many SM predictions
    - Charged weak currents
    - CKM elements
  - Enters LFU tests at the fifth power
    - LFV searches complement that of μ
- Can 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]

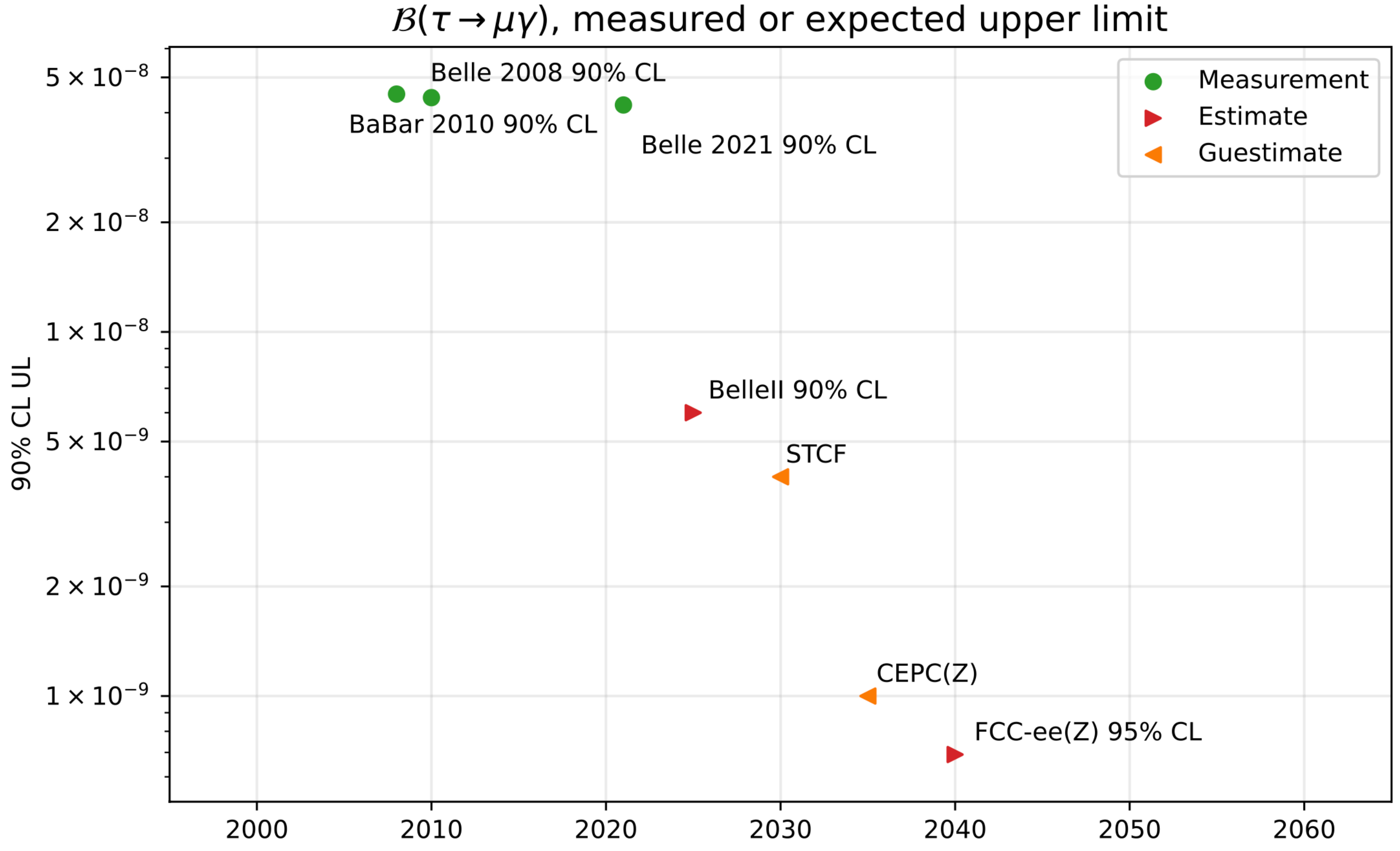
$\tau^{\pm}$ lifetime and BFs

- 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, $< 20\,\% / \sqrt{E(\text{GeV})}$ (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





Conclusions

Precision flavour measurements set powerful constraints on New Physics

There are a number of interesting opportunities at lepton colliders

A number of challenges both theoretical and experimental will have to be overcome

Hopefully exciting times and potentially discoveries ahead of us

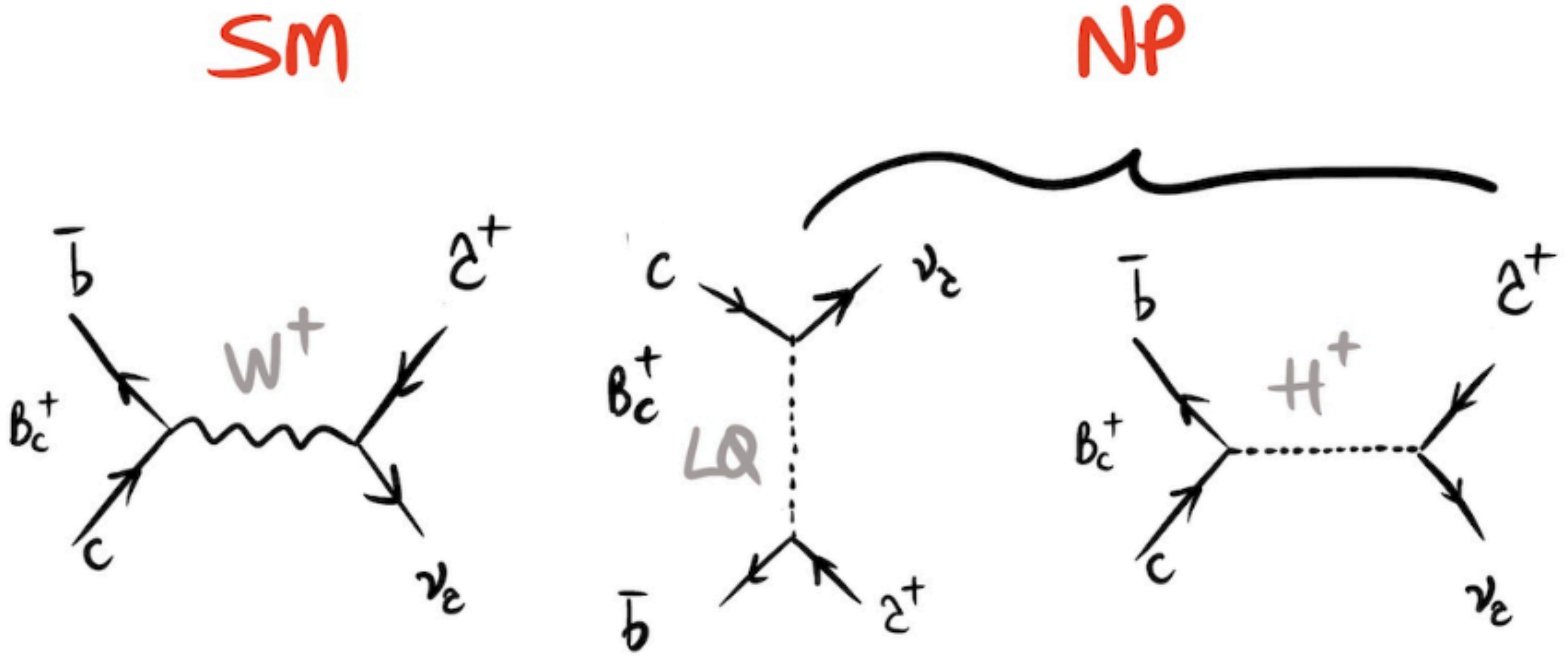
One final note

“Mum, which question are you trying to answer? I mean in physics? ”

Material heavily inspired by

- Karl Jakobs - CERN/Fermilab school 2023
- Pier Monni - Zurich Phenomenology Workshop 2024
- Stephane Monteil - LHCb meeting 2024
- Philip Urquijo - ECFA 2022
- Matthew Kenzie - ECFA-UK Meeting 2024
- Aidan Wiederhold - ICHEP 2024

Why do we care about this decay?



- Can be used to measure the CKM element $|V_{cb}|$ and highly sensitive to scalar contributions from NP.
- No possible at LHCb due to missing energy-lack of constraints and reconstructed information.
- No B_c production at Belle II.
- A Tera-Z machine is an ideal machine to study this decay.

With an EFT at $\mu = m_b$

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[(1+C_{V_L})(\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L) + C_{V_R}(\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_L) + C_{S_L}(\bar{c}_L b_R)(\bar{\tau}_R \nu_L) + C_{S_R}(\bar{c}_R b_L)(\bar{\tau}_R \nu_L) \Big] + h.c.$$

C_i are the Wilson coefficients,
null in the SM using this convention.

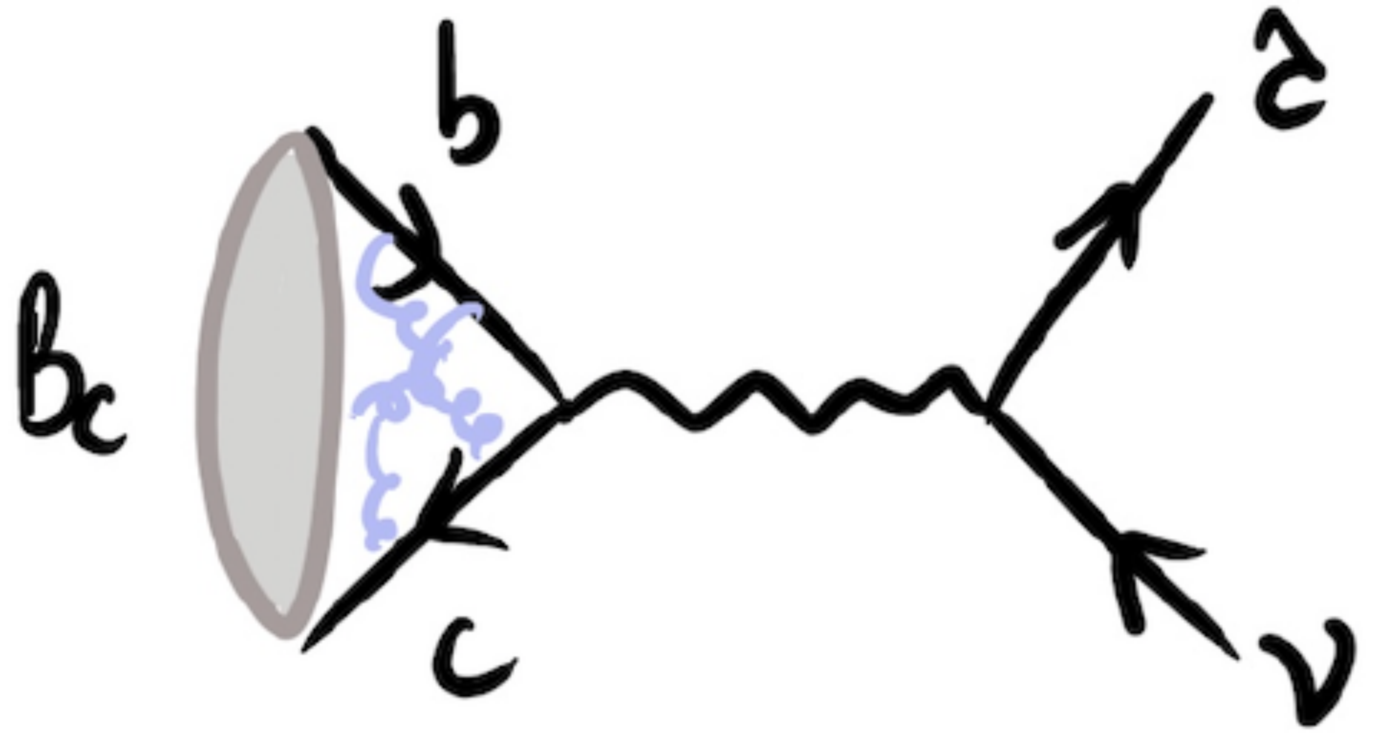
If one uses : $C_{V(A)} = C_{V_R} \pm C_{V_L}$ and $C_{S(P)} = C_{S_R} \pm C_{S_L}$.

$$\mathcal{B}(B_c \to \tau\nu) = \mathcal{B}^{SM}(B_c \to \tau\nu) \left| 1 - C_A - C_P \frac{m_{B_c}^2}{m_\tau (m_b + m_c)} \right|^2$$

C_P lifts the SM helicity suppression
sizeable enhancement !

SM prediction

Tree-level Feynman diagram in the SM



$$\mathcal{B}(B_c \to \tau\nu)^{SM} = \tau_{B_c} \frac{G_F^2 |V_{cb}|^2 f_{B_c} m_{B_c}}{8\pi} \cdot m_\tau^2 \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2$$

$$\mathcal{B}(B_c^+ \to \tau^+ \nu_\tau)^{\mathrm{SM}} = 1.95(9) \times 10^{-2}$$

Decay constant from HPQCD and V_{cb} exclusive HFLAV.
Looking forward to improvements of the decay constant computation with LQCD techniques.