

Discovery Stories at FCC

(A personal, incomplete perspective)

Tevong You



Contents

- **Introduction:** Once upon a time in particle physics
- **Story 1:** No BSM, still a success story
- **Story 2:** Everyone's a flavour physicist
- **Story 3:** Naturalness and BSM outcomes
- **Bedtime:** Dreams of a final theory

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Introduction

- 1900: Almost all data agree spectacularly with the fundamental framework of the time, *no reason to doubt its universal applicability or completeness.*
- 1920s: A combination of **precision measurements** (Mercury), **aesthetic arguments** (relativity) supported by **null experimental results** (Michelson-Morley), and **theoretical inconsistencies** (Rayleigh-Jeans UV catastrophe) lead to an overhaul of the fundamental picture at **smaller scales** and **higher energies** after *pushing the frontiers of technology and theory into new regimes.*

Introduction

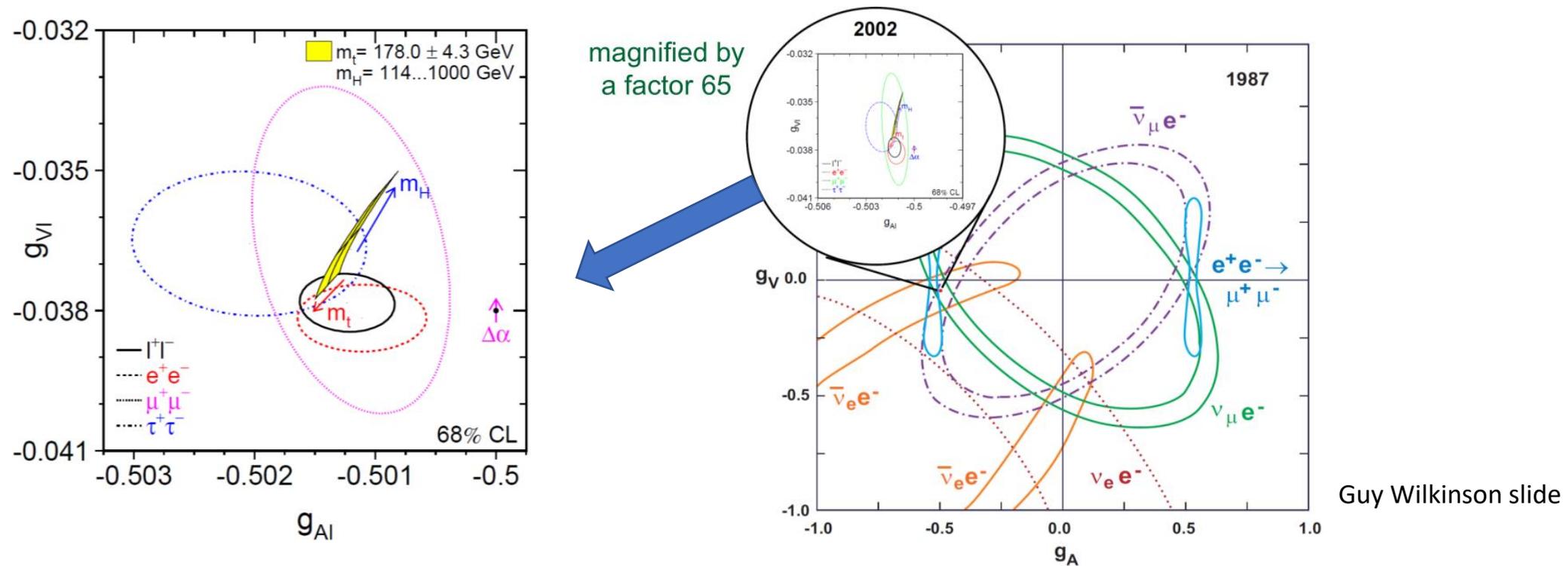
- 1930-40s: Success of QED. **QFT** emerges as the *new fundamental description of Nature*.
- 1960s: QFT is **unfashionable**, non-Abelian theory dismissed as an **unrealistic generalisation** of local symmetry-based forces. Widely believed a **radically new framework** will be required *e.g. to understand the strong force*.
- 1970s: **QFT triumphs** following Yang-Mills+Higgs+asymptotic freedom+renormalisation. Nature is **radically conservative**, *but more unified than ever*.
- 1980s: Success of SM. QFT understood as **most general EFT consistent with symmetry**. Higgs and cosmological constant *violate this symmetry principle*.
- **Tremendous progress since, despite lack of BSM** (Would we take back the last 40 years of particle physics just because everything agreed with the SM?)

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No BSM or new discoveries at LEP

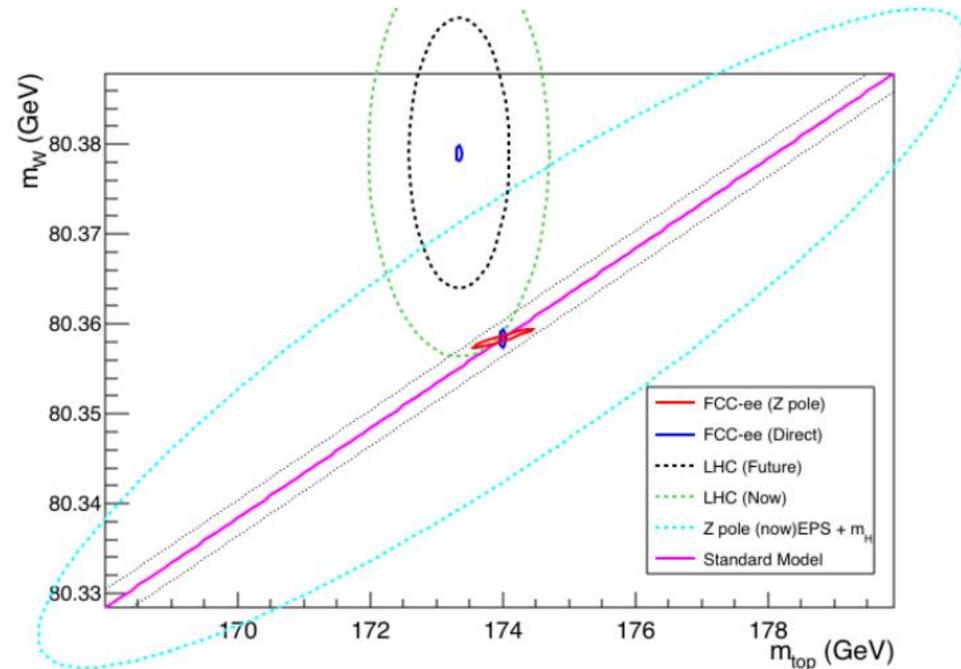
- 1980-1990s: LEP physics programme a **resounding success**
- Improved our fundamental picture of nature *by orders of magnitude*



- *Indirect precision probe* of physics at **higher energies**

No BSM or new discoveries at FCC-ee

- Further **zooming in** on our fundamental picture of nature



- **Rich physics programme** covering Higgs, top, electroweak, multi-bosons, flavour, rare decays, neutrinos, QCD, heavy ions *and more*.

No guarantee of new discoveries at FCC-hh

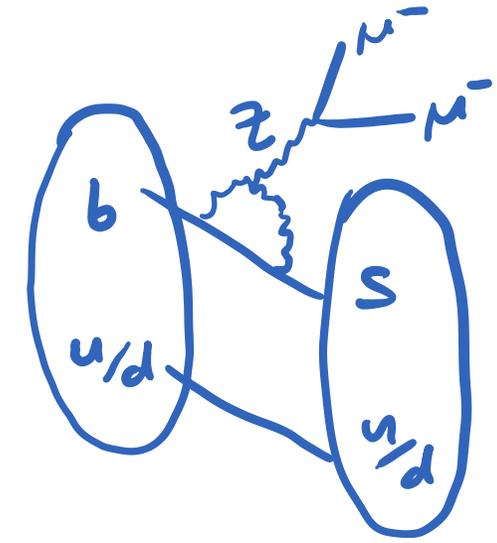
- **No guarantee of discovery** at Tevatron either. Hadron collisions thought by some *to be too messy to do physics.*
- **Value in pushing frontiers:** we learn something *regardless of outcome*
- **Definite questions** are answered, *even if in the negative*
- Science is about *continually refining existing knowledge and exploring the unknown*
- **A new generation** of data management, analysis techniques, improved measurements, theoretical calculational tools, hardware development, cutting-edge engineering, large international collaboration, popular culture inspiration, and spirit of fundamental exploration, **can only benefit humanity** regardless of our own short-sighted disappointment at lack of BSM. *Doing good science is its own reward.*

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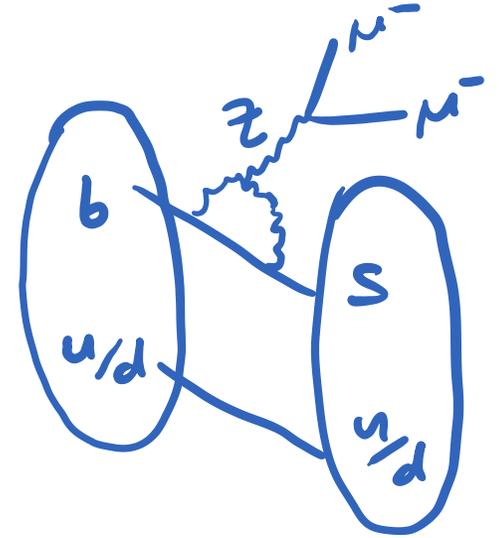
Flavour anomalies in B physics

- New physics **beyond the Standard Model** in processes involving $b \rightarrow s \mu^+ \mu^-$ transitions?



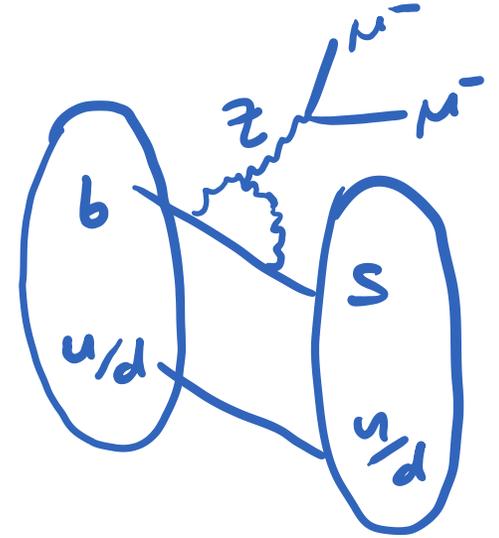
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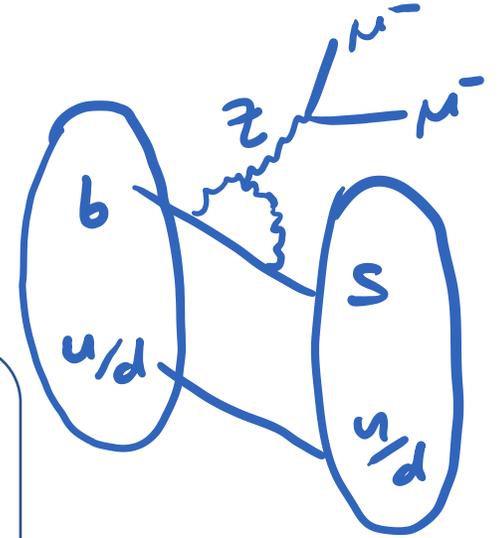
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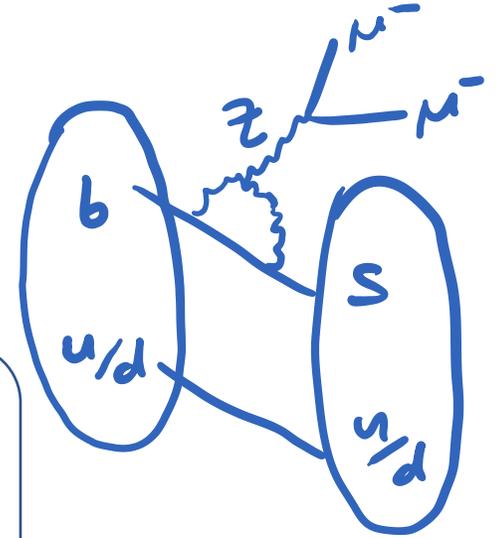


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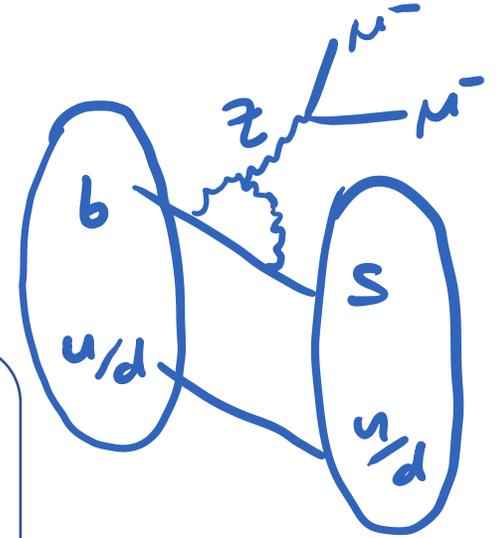
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- *Consistency* of all these various anomalies is **extremely non-trivial**



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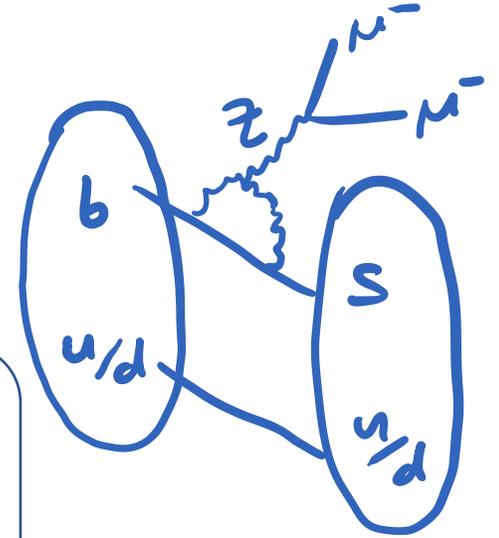
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(19/10/2021): **1.4 σ** in $R_{K_S^0}$, **1.5 σ** in $R_{K^{*+}}$

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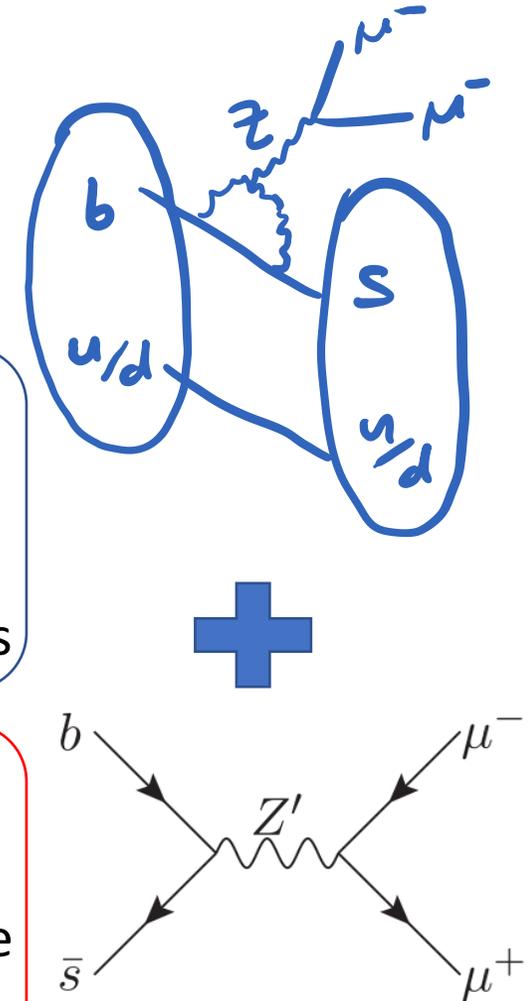
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- Could be due to a new *fundamental particle* e.g. **Z'**



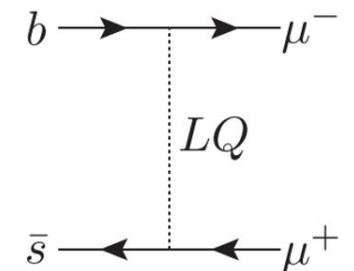
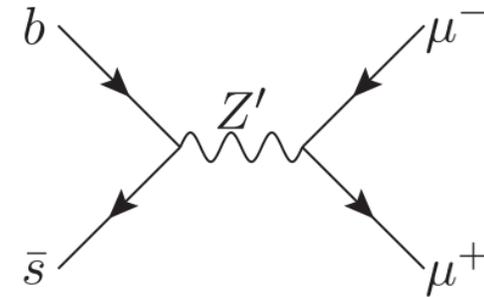
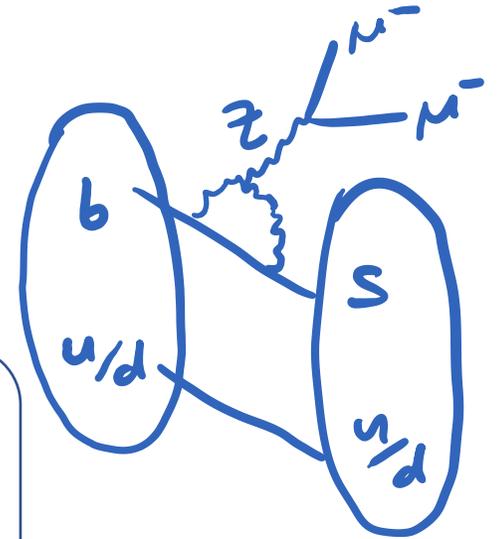
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- Could be due to a new *fundamental particle* e.g. **Z'**, **leptoquark**, ...

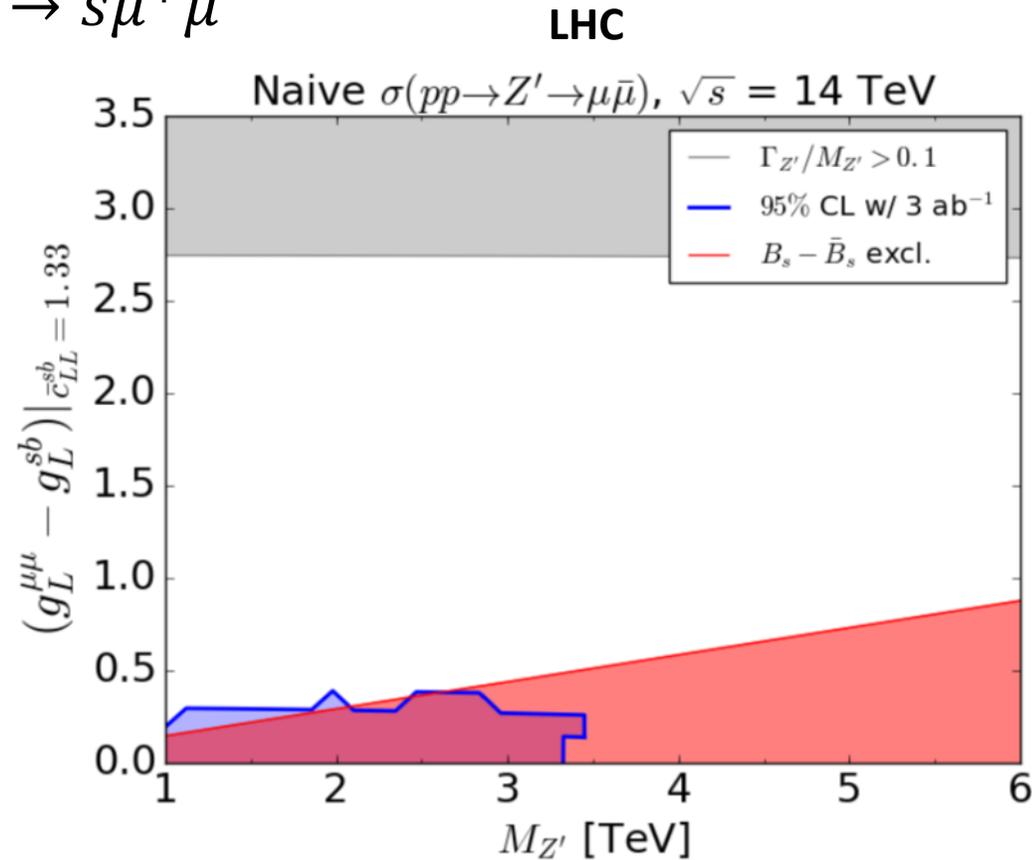


Flavour anomalies in B physics

- If confirmed, *can we guarantee a discovery at FCC-hh?*

80 TeV unitarity limit = **no general no-lose theorem** at FCC-hh [Di Luzio, Nardecchia, 1706.01868]

- Project **Z'** sensitivity in most pessimistic scenario assuming only couplings required for $b \rightarrow s\mu^+\mu^-$



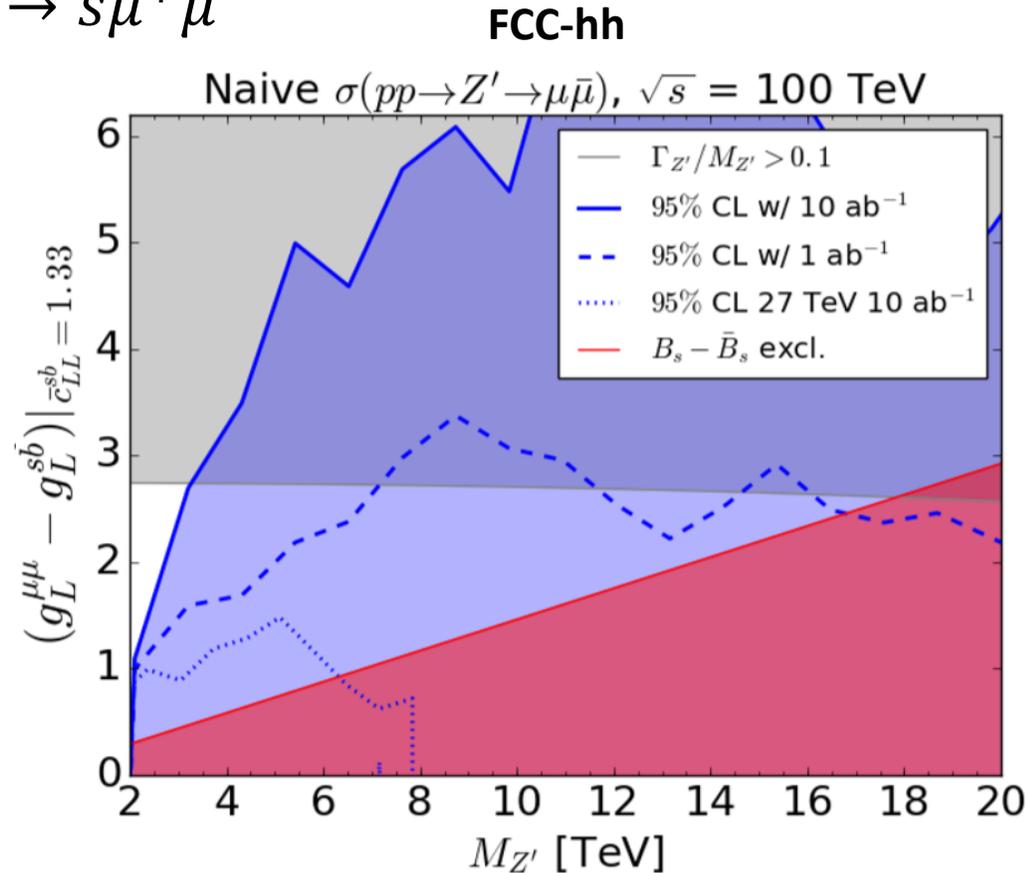
Allanach, Gripaio, TY [1710.06363]
TY [1805.04418]

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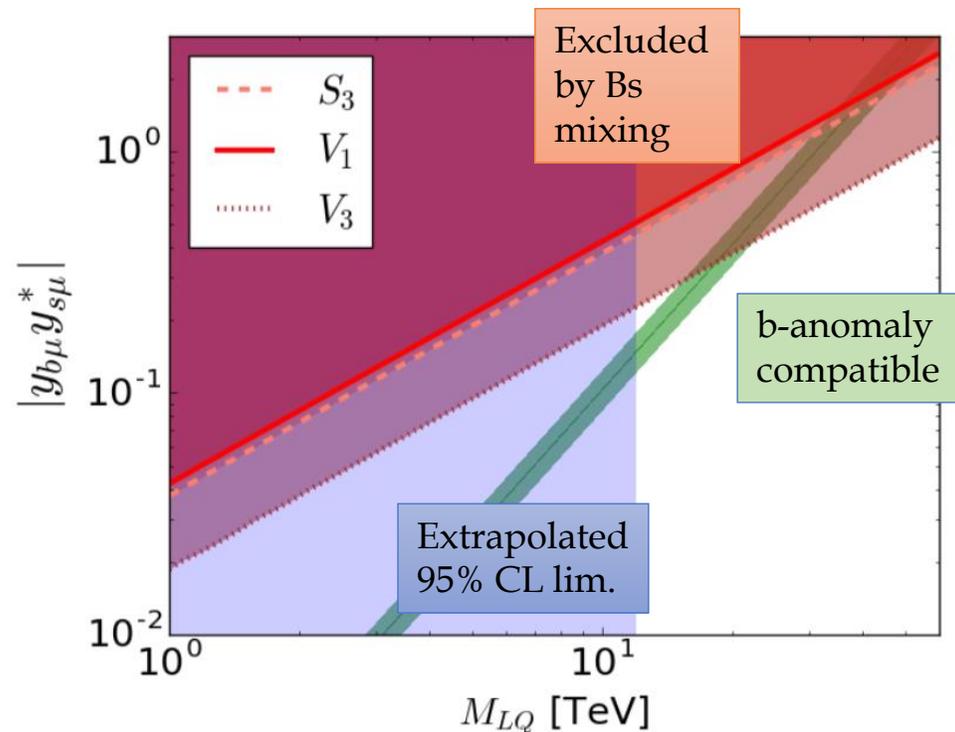
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- Project **LQ** sensitivity in most pessimistic scenario assuming only couplings required for $b \rightarrow s\mu^+\mu^-$



Allanach, Gripaio, TY [1710.06363]
TY [1805.04418]

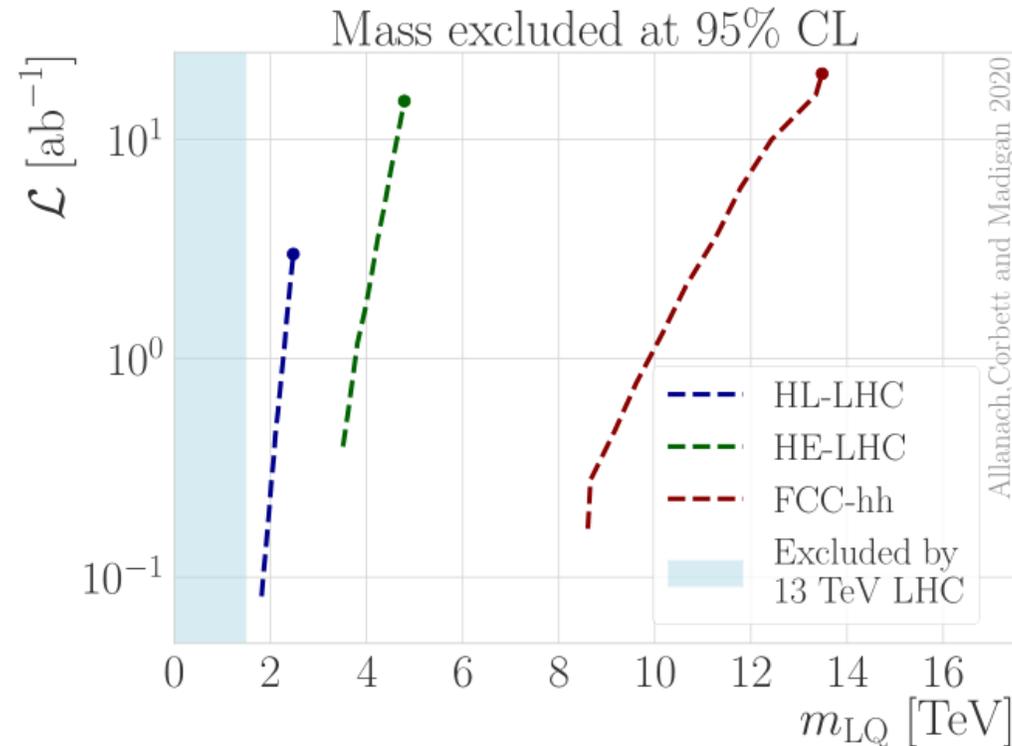
Max $M_{LQ} = 37, 41, 18$ TeV for S_3, V_1, V_3 .

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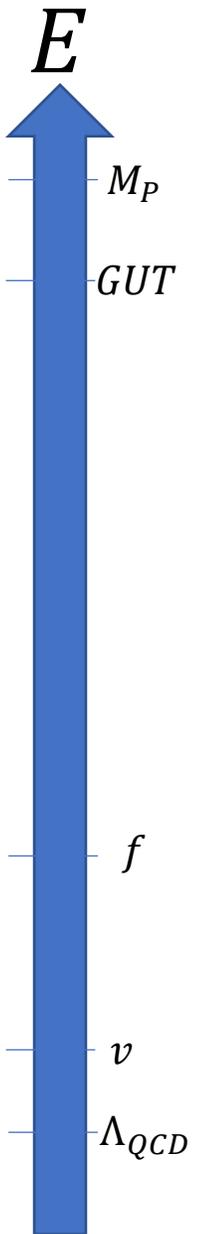
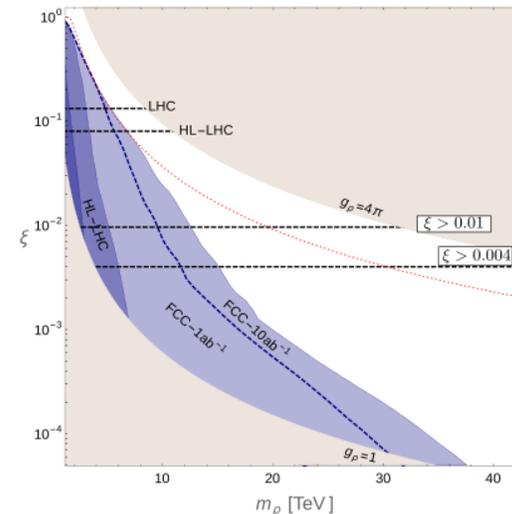
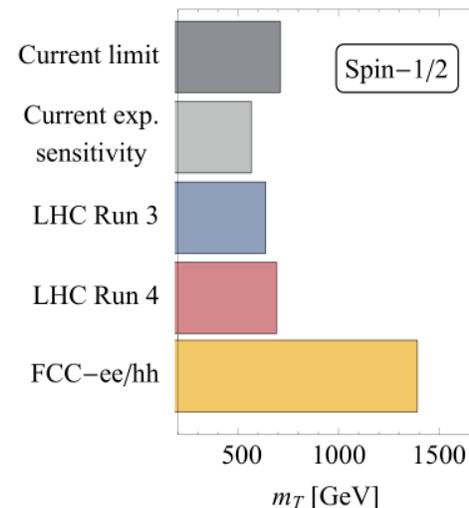
Allanach, Corbett, Madigan [1911.04455]

Flavour anomalies in B physics

- Leptoquarks pointing towards composite Higgs models?
- Confinement of **new strong sector** at scale $f \sim \text{TeV}$
- **Flavour structure** from linear mixing with composite operators

$$\mathcal{L} \supset \epsilon_Q \bar{Q}_L \mathcal{O}_Q + \epsilon_U \bar{U}_R \mathcal{O}_U + \epsilon_D \bar{D}_R \mathcal{O}_D. \quad \Rightarrow \quad Y_{U(D)}_{ij} \sim \epsilon_Q^i \epsilon_{U(D)}^j$$

- Requires new sector to be **coloured** and **electroweak-charged** \Rightarrow *TeV-scale leptoquark resonances*
- Expect **third generation** couples strongest to new sector
- Potential **direct exploration** of compositeness at FCC-hh



Flavour anomalies in B physics

- Z' pointing towards **new gauge symmetries**?
- Explanation of **fermion masses** and **flavour structure**?
- Connection to other **LFU violation** and **muon g-2**?
- *If confirmed by Belle II*, FCC-ee can **improve flavour measurements** and have **unprecedented indirect sensitivity** to new physics responsible

Table S.4: Expected production yields for b-flavoured particles at FCC-ee at the Z run, and at Belle II (50 ab^{-1}) for comparison.

| particle production (10^9) | B^0/\bar{B}^0 | B^+/B^- | B_s^0/\bar{B}_s^0 | $\Lambda_b/\bar{\Lambda}_b$ | $c\bar{c}$ | $\tau^+\tau^-$ |
|--------------------------------|-----------------|-----------|---------------------|-----------------------------|------------|----------------|
| Belle II | 27.5 | 27.5 | n/a | n/a | 65 | 45 |
| FCC-ee | 1000 | 1000 | 250 | 250 | 550 | 170 |

FCC CDR Vol. 1

- *Even if anomalies go away*, it illustrates how **generic new physics** at the edge of current sensitivity will require FCC-hh to **fully explore directly**

Flavour anomalies in B physics

- More generally, **indirect hints** typically *precede* direct discovery
- **Global SMEFT fits** will play a crucial role

FCC CDR Vol. 1

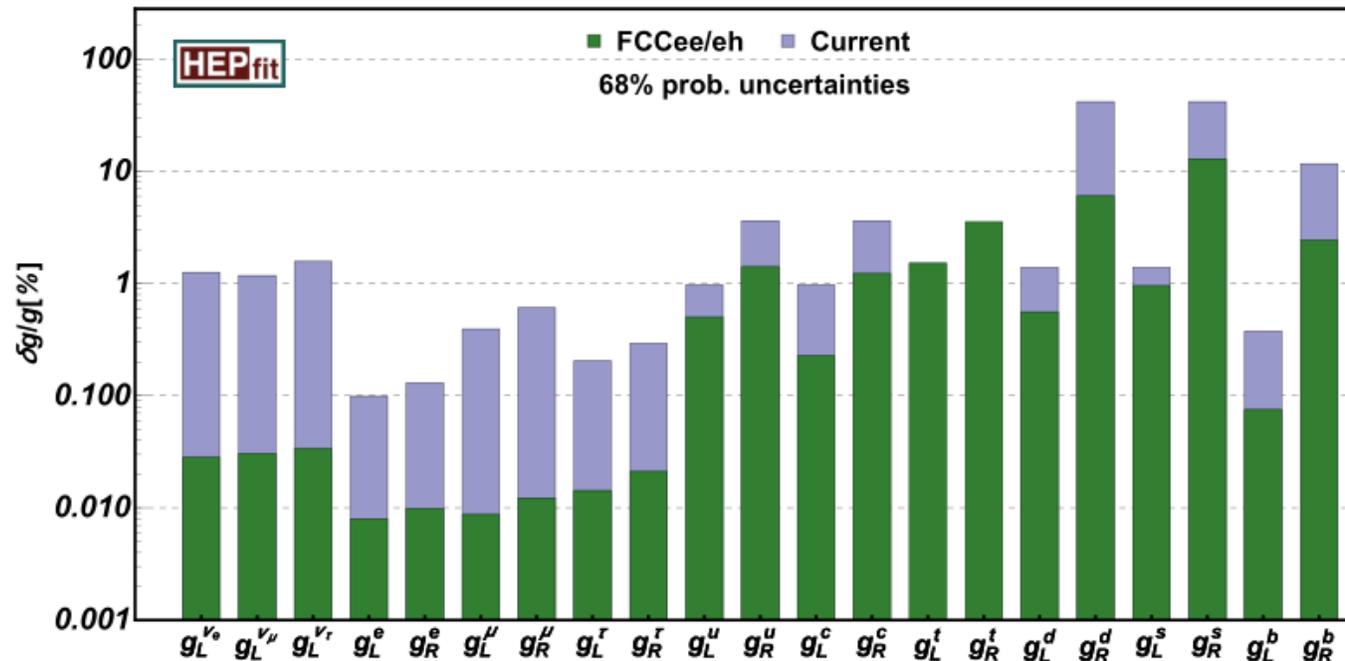


Figure 8.2: Sensitivity, at the 1- σ level, to deviations of the neutral current couplings resulting from a global EFT fit at the dimension-6 level to EW precision measurements at FCC-ee and FCC-eh.

Flavour anomalies in B physics

- In the future **we may all be flavour physicists!**



Donal Hill

@DonalHill

Looking into [@ManUtd](#)'s new manager Ralf Rangnick, and noticed he has a picture of the $b \rightarrow s$ transition on his wall! He clearly knows what's most important, [@LHCbExperiment](#) 😊



14:54 · 29 Nov 21 · Twitter Web App

← Thread



Alexey Petrov

@AlexeyPetrov

Why does Michael Rangnick, a coach of Manchester United soccer club, have a penguin diagram as art on his wall?

This was a surprise for me - I watched a review of the results of Winter transfer window in Europe on YouTube and noticed it.



19:44 · 08 Feb 22 · Twitter for iPhone

8 Retweets 3 Quote Tweets 60 Likes



Alexey Petrov @AlexeyPetrov · 3h

#Physics #ManUnited



Alexey Petrov @AlexeyPetrov · 1h

Correction: it's Ralf Rangnick. I apologize to all #ManchesterUnited fans. For some reason I was thinking of Michael Carrick. Still, the penguin diagram is a mystery.

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Effective Field Theory

$$\mathcal{L} = \Lambda^4 + \Lambda^2 \mathcal{O}^{(2)} + m \mathcal{O}^{(3)} + \mathcal{O}^{(4)} + \frac{1}{\Lambda^2} \mathcal{O}^{(6)} + \frac{1}{\Lambda^4} \mathcal{O}^{(8)} + \dots$$

- Incredibly successful
- Explains many features of our theories
- **Natural expectations** for sizes of parameters
- Sound reasoning, vindicated many times in the past
- However: **hierarchy problem** and **cosmological constant**

The Hierarchy Problem

- Hierarchy problem *is still a problem*: $(m_h)_{\text{tree}}^2 + (m_h)_{\text{radiative}}^2 = (m_h)_{\text{v}}^2$

[If Higgs mass is *calculable* in underlying UV theory]

$$\delta m_\phi^2 \propto m_{\text{heavy}}^2, \quad \delta m_\psi \propto m_\psi \log\left(\frac{m_{\text{heavy}}}{\mu}\right)$$

Historical precedent

- Take aesthetic issues seriously
- Earliest example of an unnatural, **arbitrary** feature of a fundamental theory:

$$m_{\text{inertial}} = m_{\text{gravity}}$$

- Classical electromagnetism fine-tuning:

$$(m_e c^2)_{\text{obs}} = (m_e c^2)_{\text{bare}} + \Delta E_{\text{coulomb}}, \quad \Delta E_{\text{coulomb}} = \frac{e^2}{4\pi\epsilon_0 r_e}$$

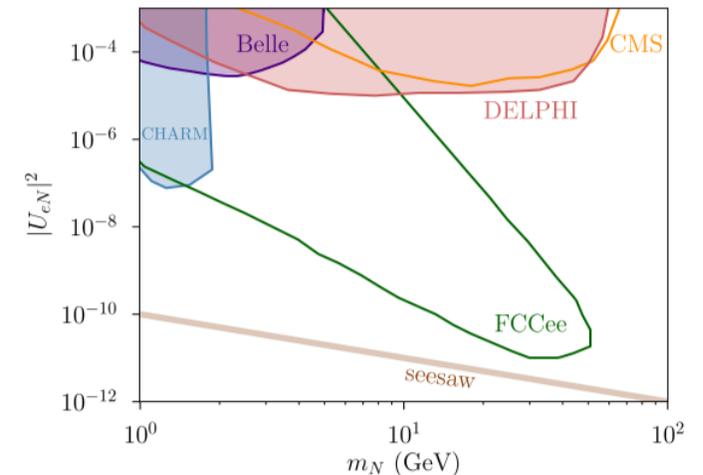
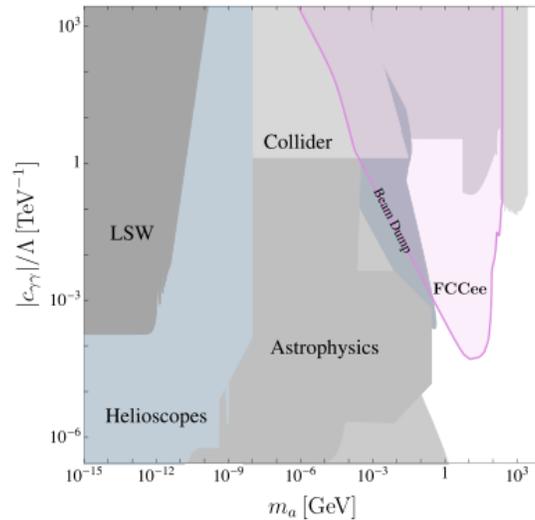
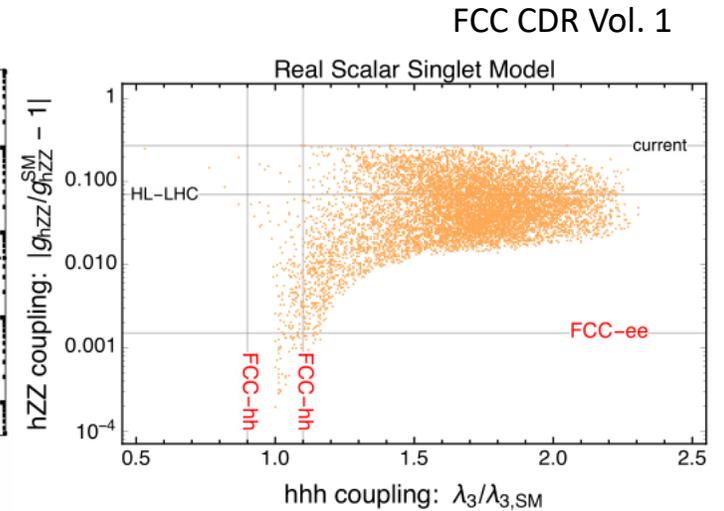
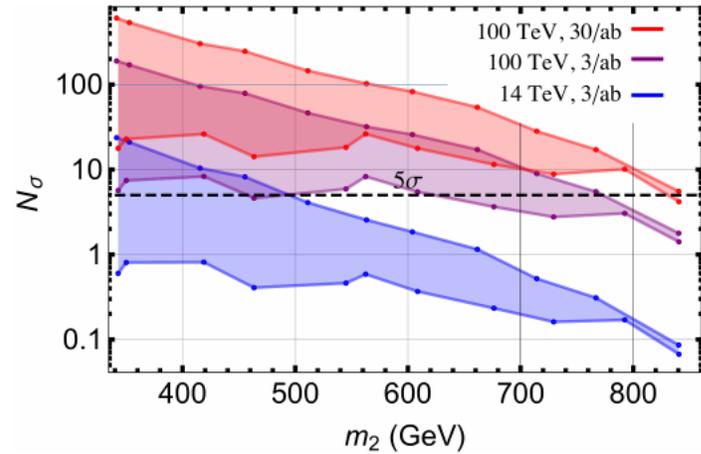
- Pions, GIM mechanism, etc.
- Higgs? Expect new physics close to weak scale

Understanding the origin of EWSB

- The SM has many *arbitrary* features put in by hand which hint at **underlying structure**
 - *Pattern of Yukawa couplings, CKM*
 - *QCD Theta term*
 - *Neutrino mass*
 - *Higgs potential*
 - ...
- Maybe it just is what it is $_ _ (_ _) _ / _$
- but we would like a **deeper understanding** i.e. an *explanation* for why things are the way they are
 - *e.g. PQ axion for Theta term, see-saw for neutrino mass, Froggat-Nielsen for Yukawas...*
- In SM, **no understanding** of Higgs sector: Higgs potential and couplings *put in by hand and unexplained*
- We feel there must be some underlying system that **explains the origin of EWSB**
- In any such theory *in which the Higgs potential is calculable*, there is a **UV sensitivity** to the Higgs mass (*that is no longer a free parameter*) which requires fine-tuned cancellations
- Unlike solutions to other arbitrary features, this one points to **weak-scale new physics**

Potential BSM discoveries at FCC

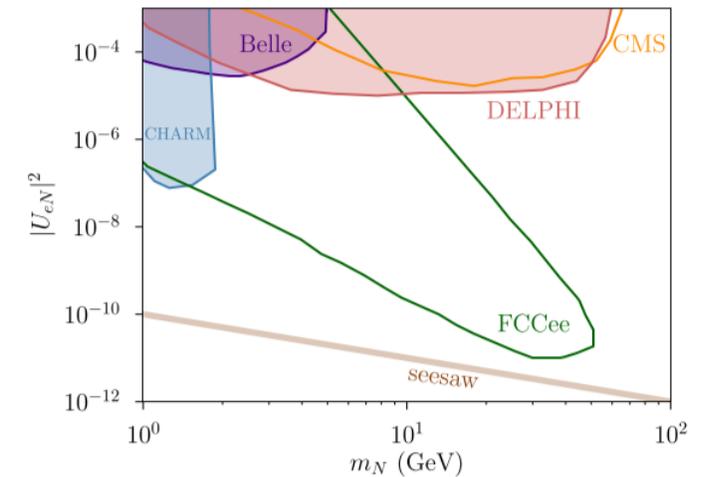
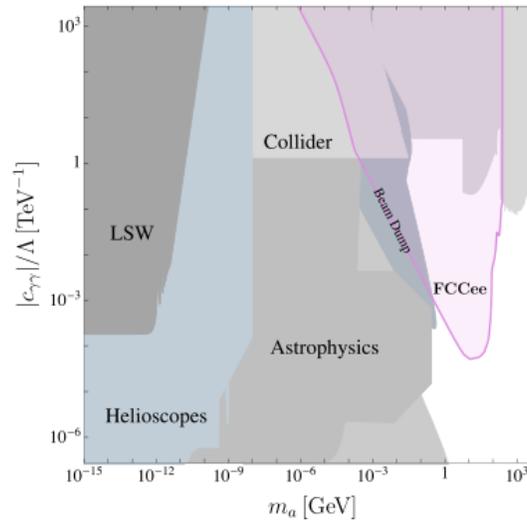
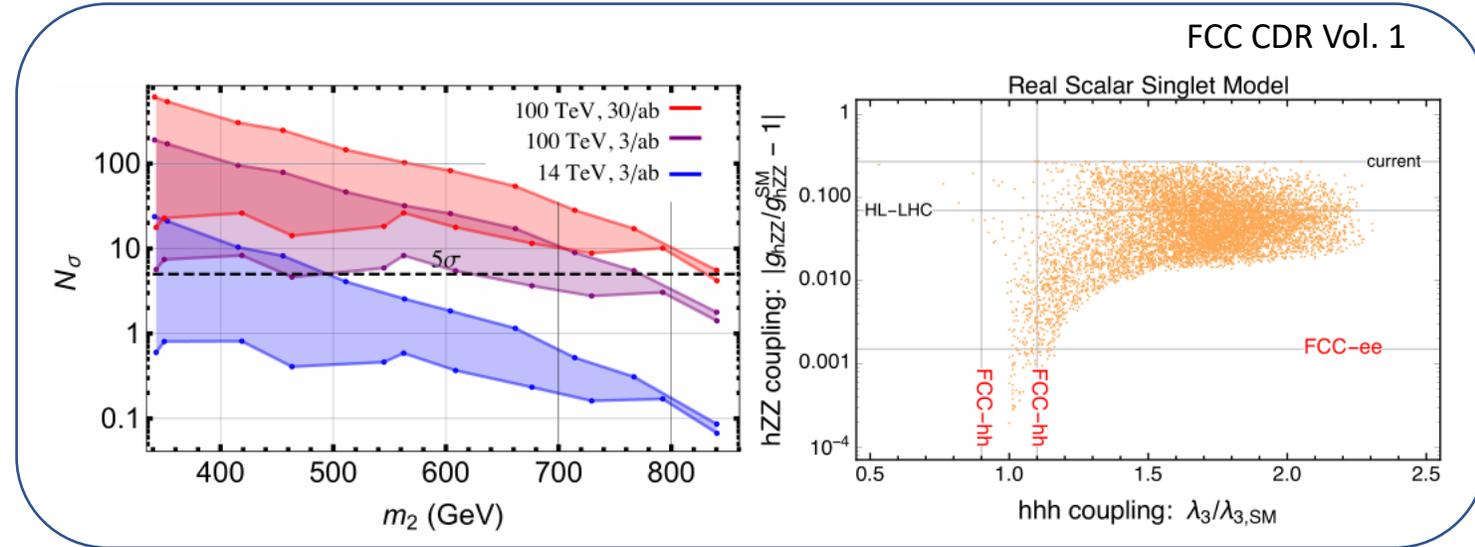
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- CP violation
- Dark matter
- Light dark sectors
- Axion-like particles
- Sterile neutrinos
- Higgs portal
- BSM Higgs couplings
- Additional Higgs doublets
- Supersymmetric partners
- Top partners
- Leptoquarks
- New forces
- ...
- Implications for naturalness?



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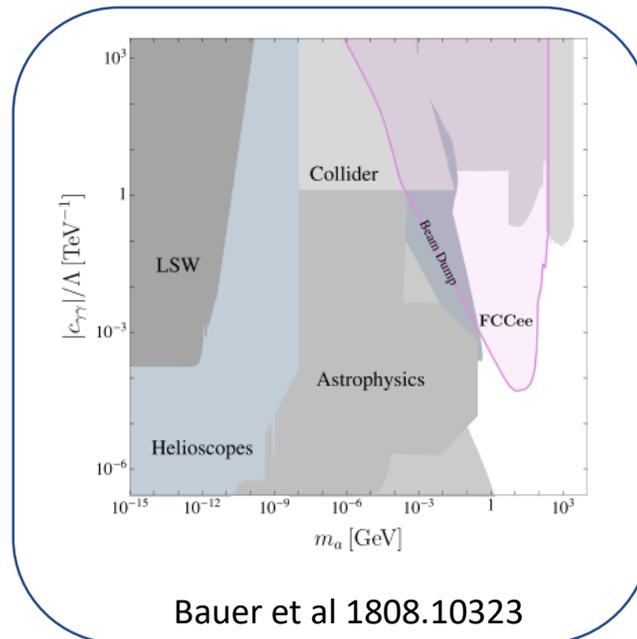
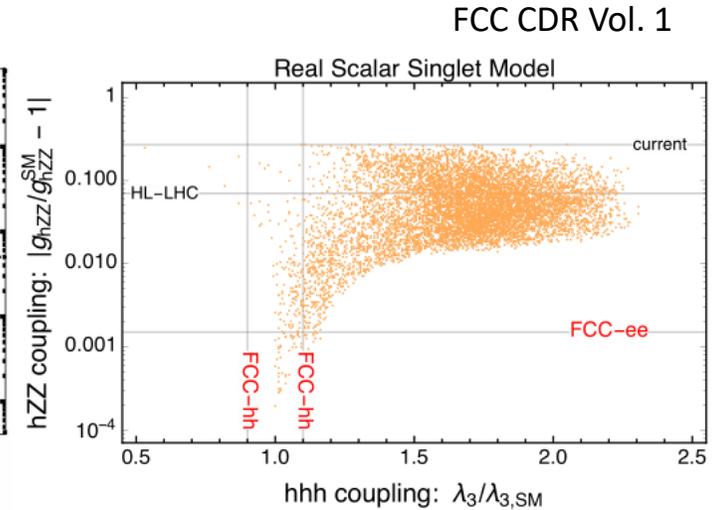
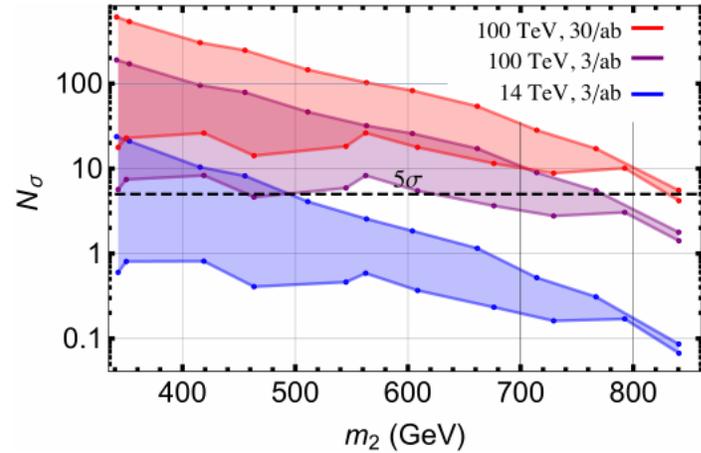
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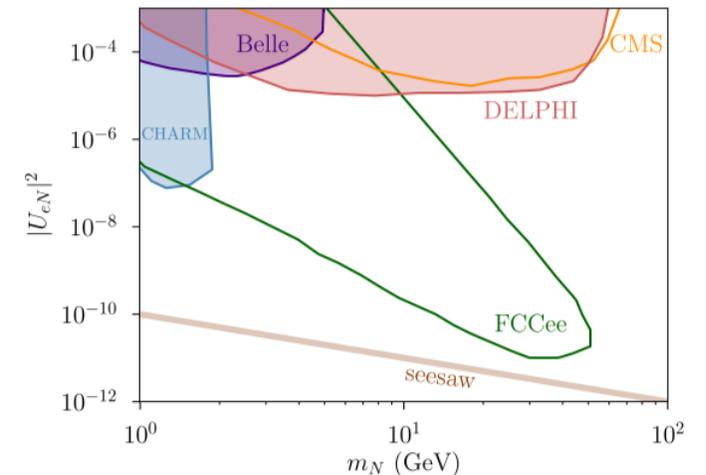


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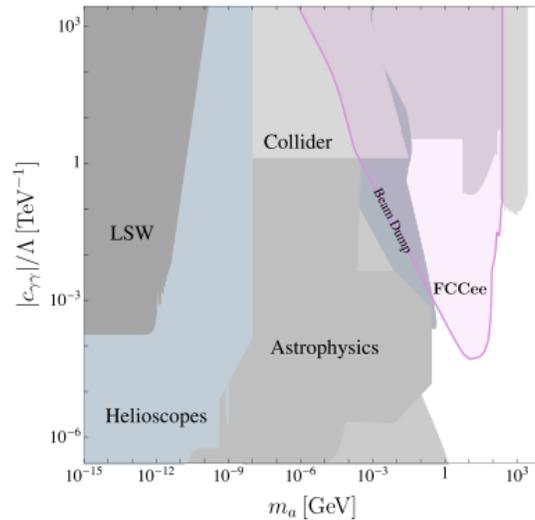
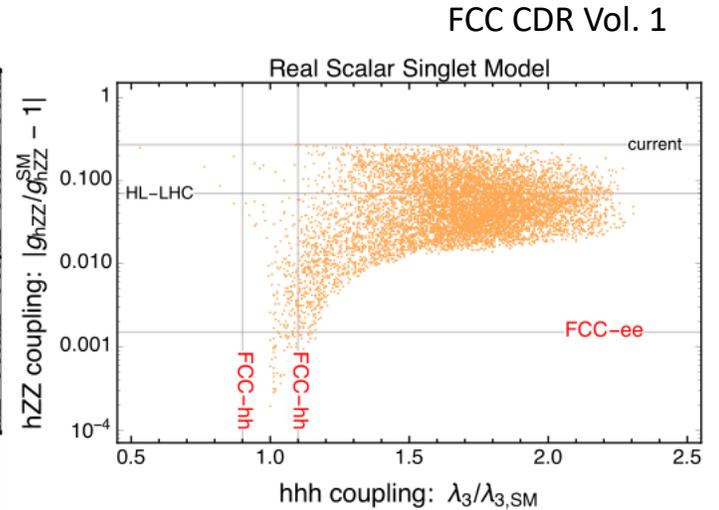
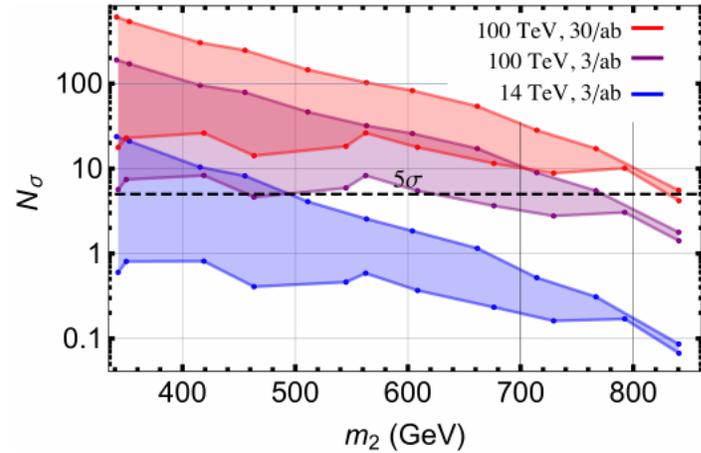
Bauer et al 1808.10323



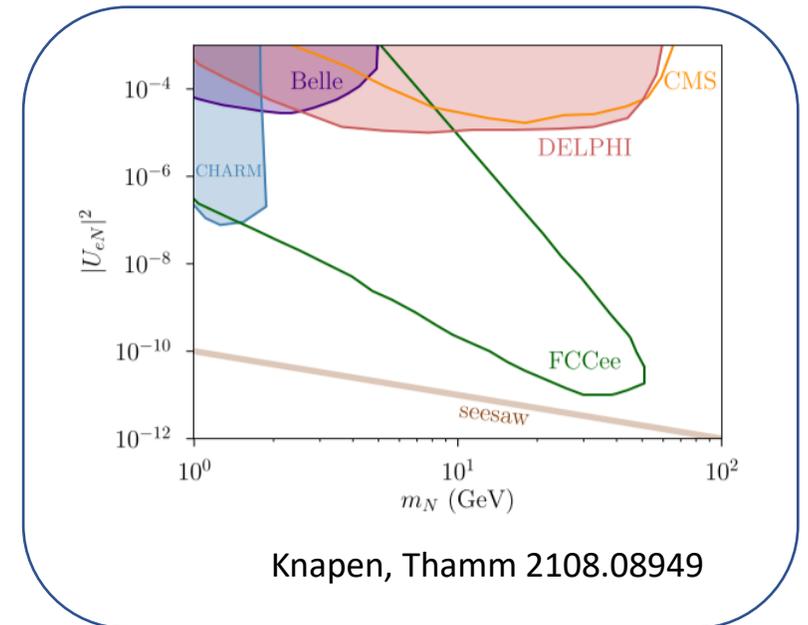
Knapen, Thamm 2108.08949

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- CP violation
- Dark matter
- Light dark sectors
- Axion-like particles
- **Sterile neutrinos**
- Higgs portal
- BSM Higgs couplings
- Additional Higgs doublets
- Supersymmetric partners
- Top partners
- Leptoquarks
- New forces
- ...
- Implications for naturalness?



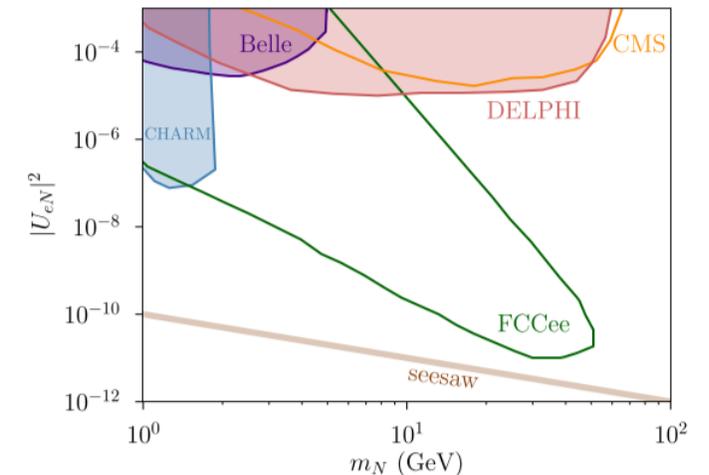
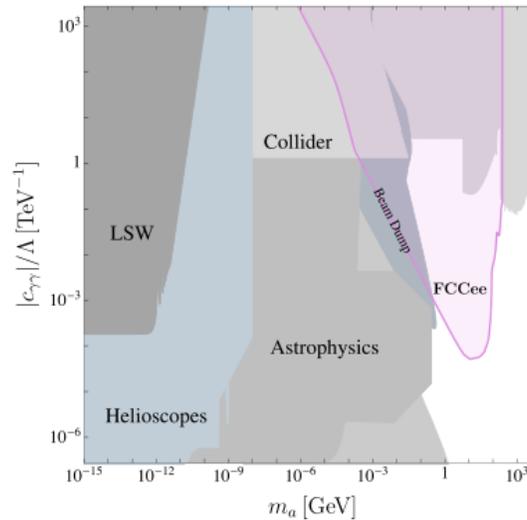
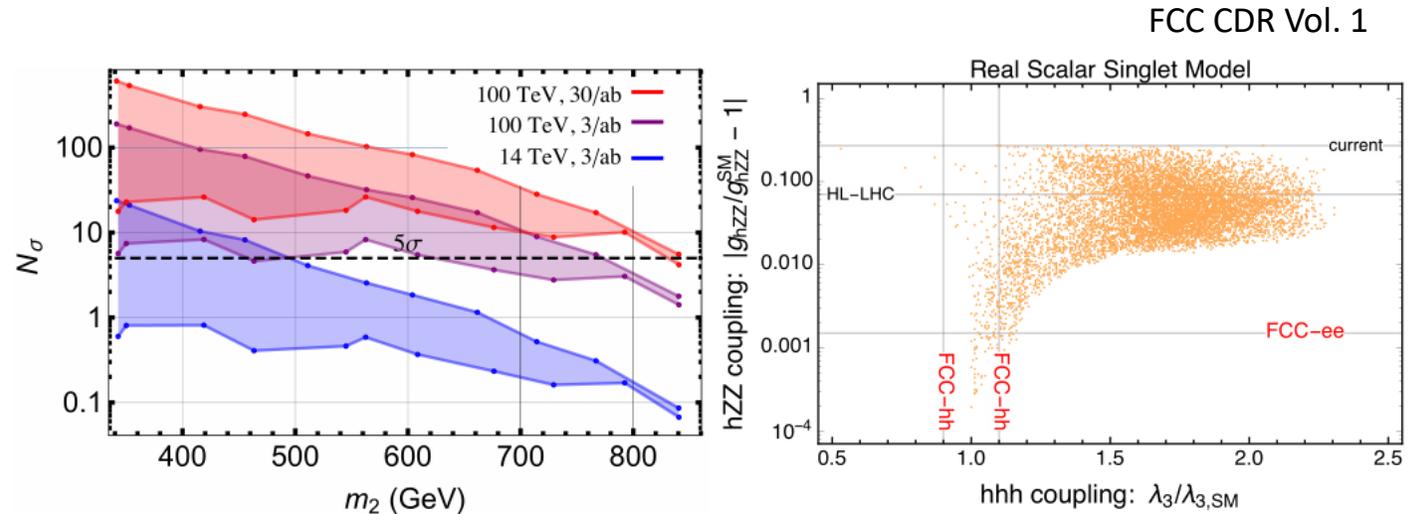
Bauer et al 1808.10323



Knapen, Thamm 2108.08949

Potential BSM discoveries at FCC

- First order electroweak phase transition
- CP violation
- Dark matter
- Light dark sectors
- Axion-like particles
- Sterile neutrinos
- Higgs portal
- BSM Higgs couplings
- Additional Higgs doublets
- Supersymmetric partners
- Top partners
- Leptoquarks
- New forces
- ...
- **Implications for naturalness?**



Potential BSM outcomes at FCC

- 1930-40s: Success of QED. **QFT** emerges as the *new fundamental description of Nature*.
- 1960s: QFT is **unfashionable**, non-Abelian theory dismissed as an **unrealistic generalisation** of local symmetry-based forces. Widely believed a **radically new framework** will be required *e.g. to understand the strong force*.
- 1970s: **QFT triumphs** following Yang-Mills+Higgs+asymptotic freedom+renormalisation. Nature is **radically conservative**, *but more unified than ever*.
- 1980s: Success of SM. QFT understood as **most general EFT consistent with symmetry**. Higgs and cosmological constant *violate this symmetry principle*.

Potential BSM outcomes at FCC

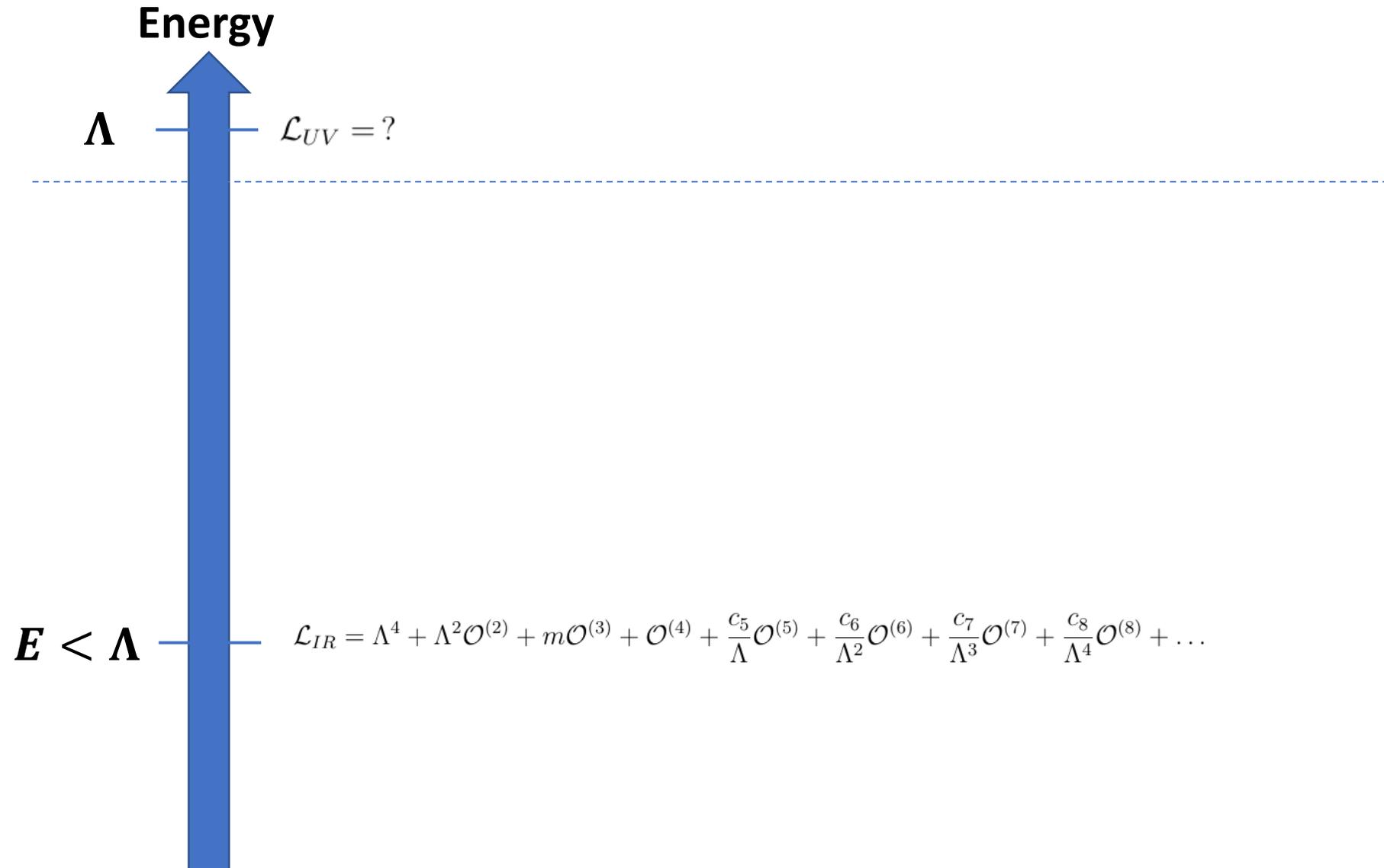
- 1980-2020s: Success of SM, established as the *fundamental description of Nature up to TeV scale*.
- 2040s: QFT is **unfashionable**, supersymmetry theory dismissed as an **unrealistic generalisation** of symmetry principles. Widely believed a **radically new framework** will be required *e.g. to understand naturalness*.
- 2060s: **QFT triumphs** following Yang-Mills+Higgs+asymptotic freedom+renormalisation+**supersymmetry**. Nature is **radically conservative**, *but more unified than ever*.
- 2080s: Success of MSSM

This slightly facetious example is nevertheless one possible scenario...

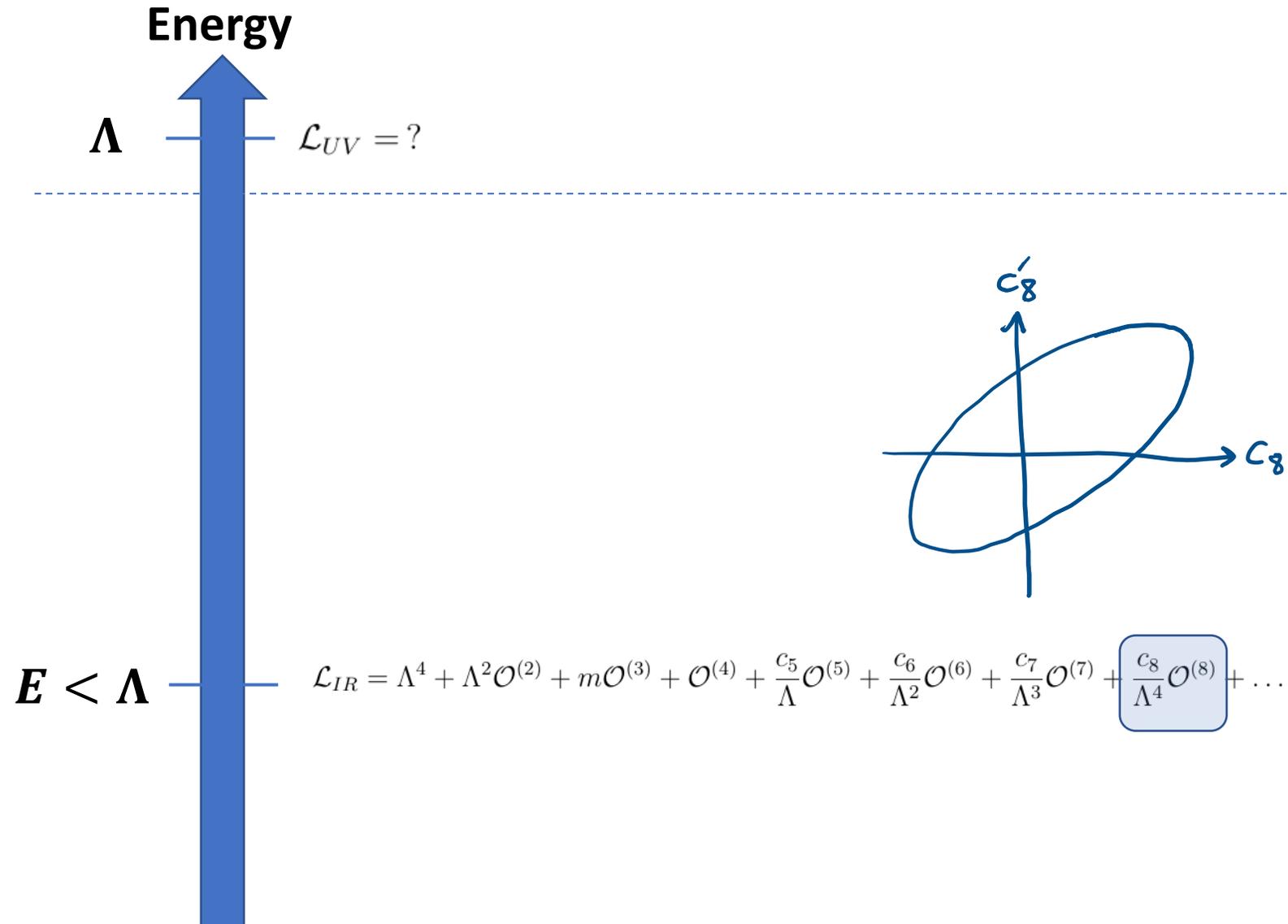
Potential BSM outcomes at FCC

- **Radically conservative:** naturalness restored just around the corner
 - Natural supersymmetry
 - Composite Higgs/extra dimensions
- **Creatively conservative**
 - Twin Higgs
 - Stealth supersymmetry
- **Post-naturalness BSM**
 - Split supersymmetry
 - Vector-like fermions only
 - Lowered vacuum instability scale
 - Weak-scale new physics for cosmological dynamics
- **Radically new?**
 - Hard to imagine what form this might take, by definition
 - How might this show up?

Radically new BSM?

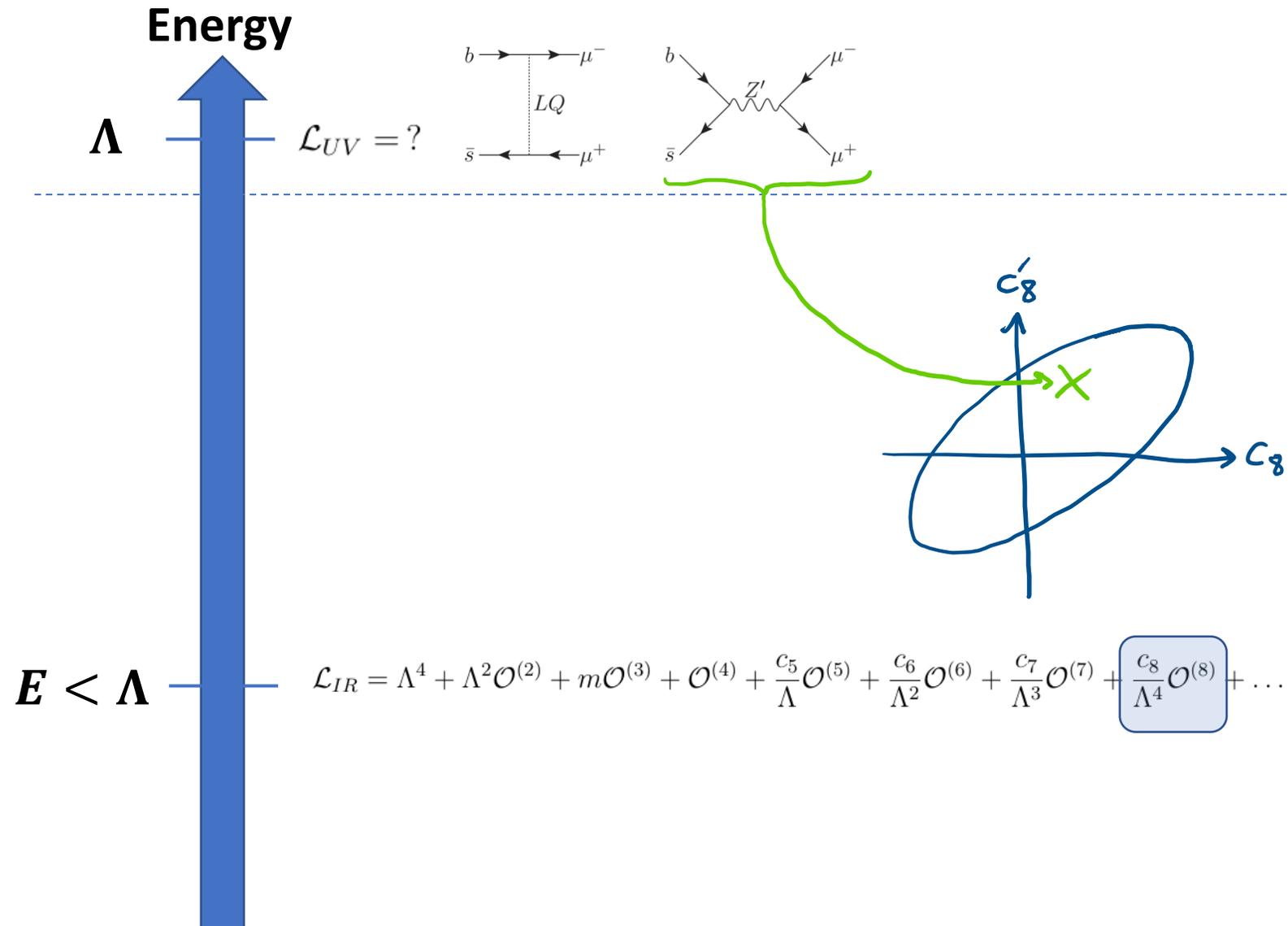


Radically new BSM?



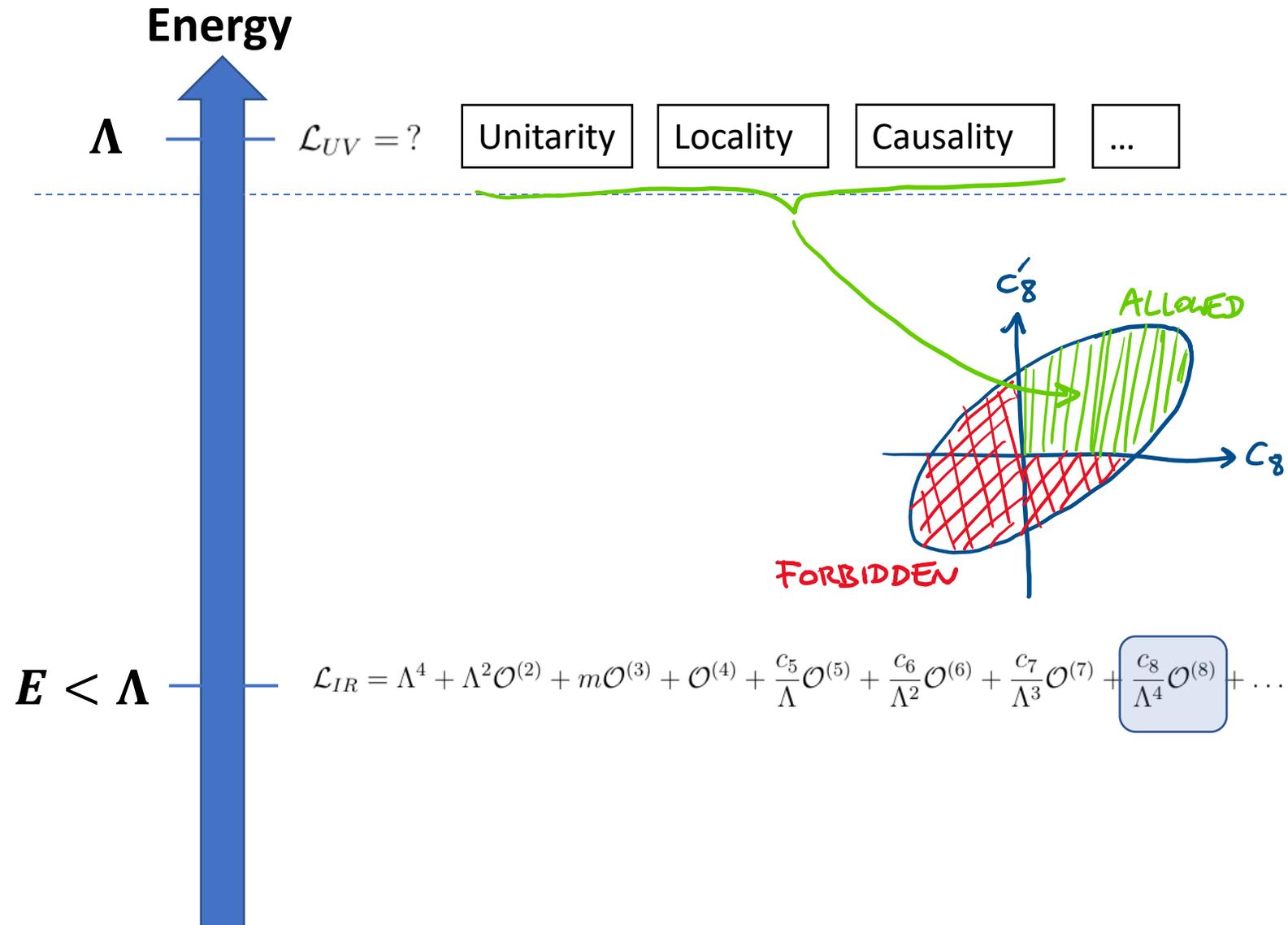
e.g. Consider indirect sensitivity to UV theory

Radically new BSM?



Matching explicit UV models populates a **subspace** of SMEFT coefficient space

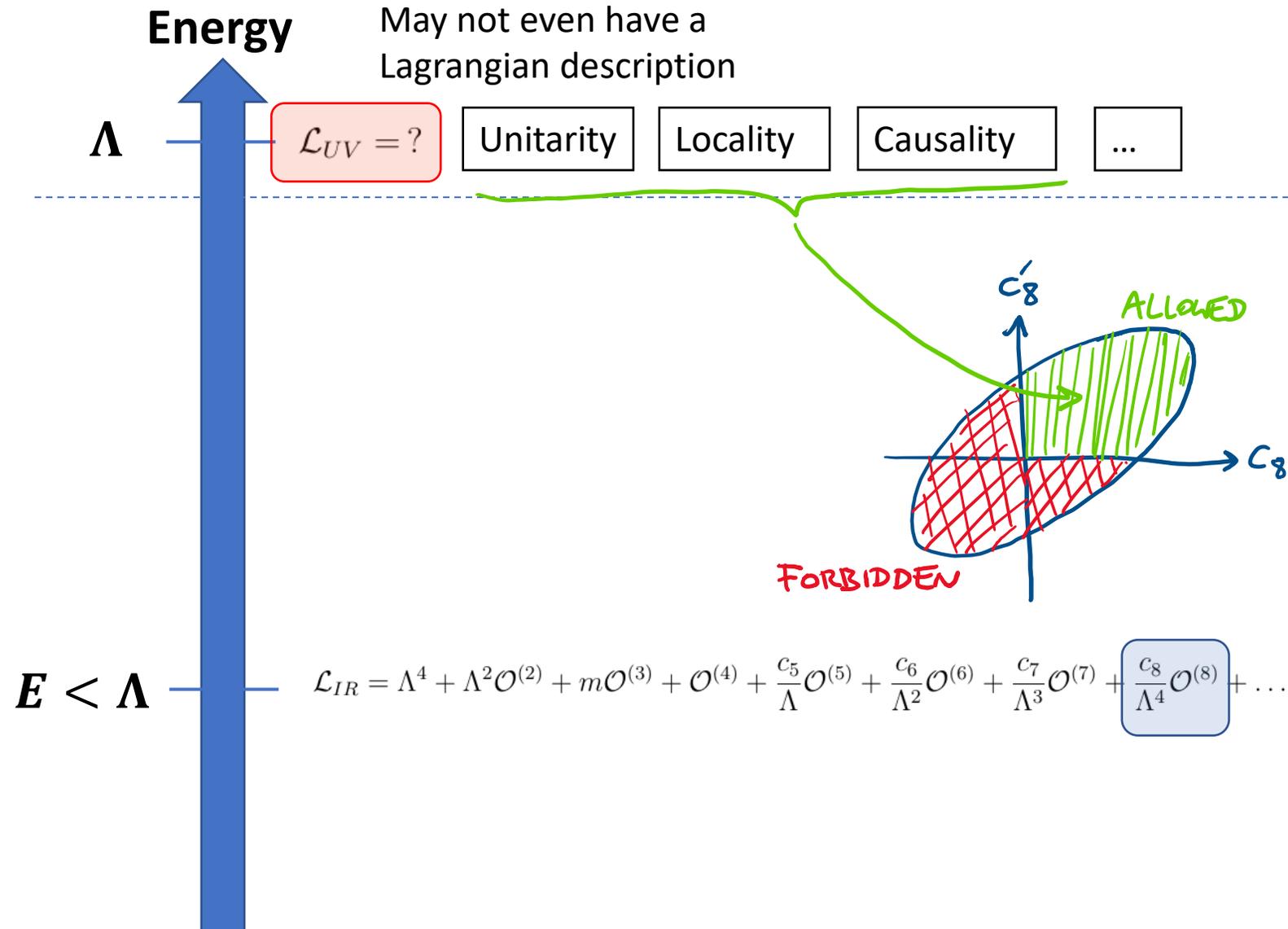
Radically new BSM?



Positivity bounds forbid **negative signs** of SMEFT coefficients *assuming only general fundamental principles* in the UV

Measuring the “*wrong*” sign experimentally would have **truly revolutionary** consequences for the underlying theory!

Radically new BSM?



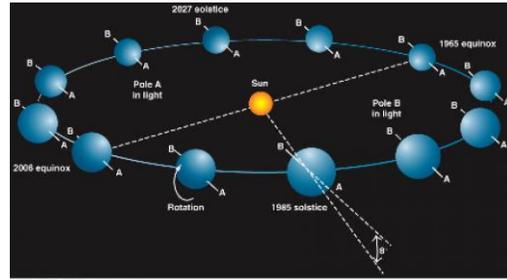
Positivity bounds forbid **negative signs** of SMEFT coefficients *assuming only general fundamental principles* in the UV

Measuring the “*wrong*” sign experimentally would have **truly revolutionary** consequences for the underlying theory!

Radically new BSM?

- Sometimes an anomaly in **indirect precision** measurement = *something missing*

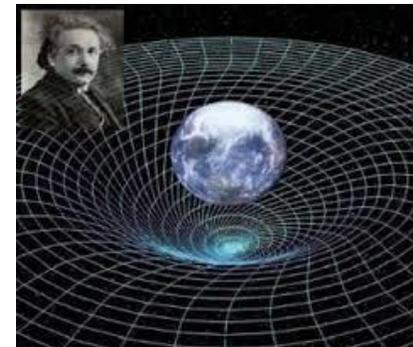
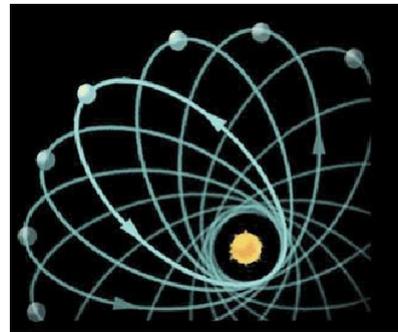
Anomaly in orbit of Uranus



Discovery of Neptune

- Sometimes its implications are *far more radical*

Anomaly in orbit of Mercury

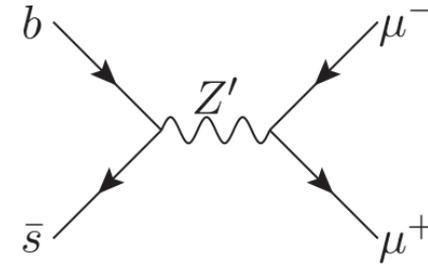
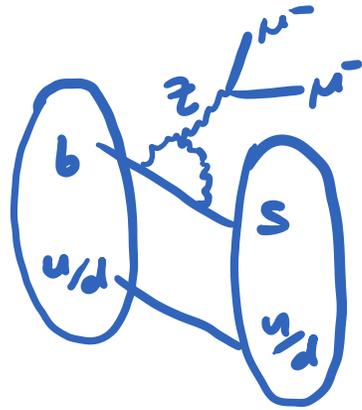


Explained by General Relativity

Radically new BSM?

- Sometimes an anomaly in **indirect precision** measurement = *something missing*

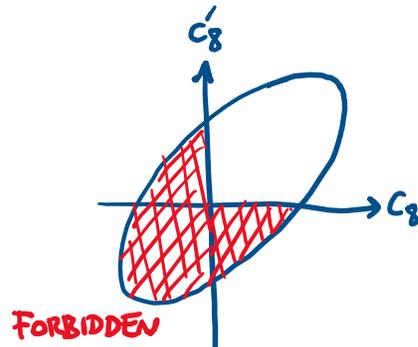
Anomaly in Flavour physics



Discovery of Z'?

- Sometimes its implications are *far more radical*

Anomaly in positivity bounds?



$\mathcal{L}_{UV} = ?$

Explained by ???

Contents

- **Introduction:** Once upon a time in particle physics
- **Story 1:** No BSM, still a success story
- **Story 2:** Everyone's a flavour physicist
- **Story 3:** Naturalness and BSM outcomes
- **Bedtime:** Dreams of a final theory

Conclusion

- 1900: Almost all data agree spectacularly with the fundamental framework of the time, *no reason to doubt its universal applicability or completeness.*
- 1920s: A combination of **precision measurements** (Mercury), **aesthetic arguments** (relativity) supported by **null experimental results** (Michelson-Morley), and **theoretical inconsistencies** (Rayleigh-Jeans UV catastrophe) lead to an overhaul of the fundamental picture at **smaller scales** and **higher energies** after *pushing the frontiers of technology and theory into new regimes.*

Conclusion

- 2020: Almost all data agree spectacularly with the fundamental framework of the time, *no reason to doubt its universal applicability or completeness.*
- 2050s: A combination of **precision measurements** (B mesons, Hubble), **aesthetic arguments** (naturalness) supported by **null experimental results** (LHC), and **theoretical inconsistencies** (black hole information paradox) lead to an overhaul of the fundamental picture at **smaller scales** and **higher energies** after *pushing the frontiers of technology and theory into new regimes.*

Conclusion

- FCC is a **general purpose particle observatory** for fundamental physics with a *wide-ranging and comprehensive physics programme*
- Keep the spirit of **fundamental science and exploration** alive for the next century and *pass the baton on to future generations*
- Why have we not discovered BSM so far?

Conclusion



---Ralf Rangnick, Manchester United manager