Probing QFT bedrock principles and the inverse problem @ the FCC-ee

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arXiv:2009.02212 [in press in Chinese Physics C]

Outline

1. Dim-6 and dim-8 SMEFT operators at future lepton colliders

2. Positivity bounds

3. Applications
   - ★ Testing positivity and core QFT principles
   - ★ Inferring BSM in a model-independent way

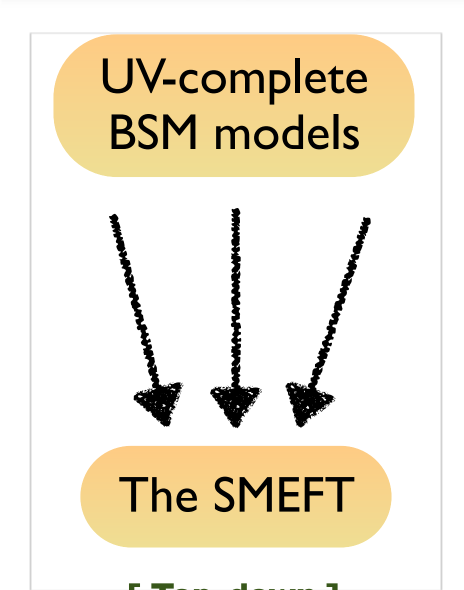
4. Summary

Theoretical context: the SMEFT

✦ The SMEFT: new physics is parametrised as small deviations to the SM

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \dots$$

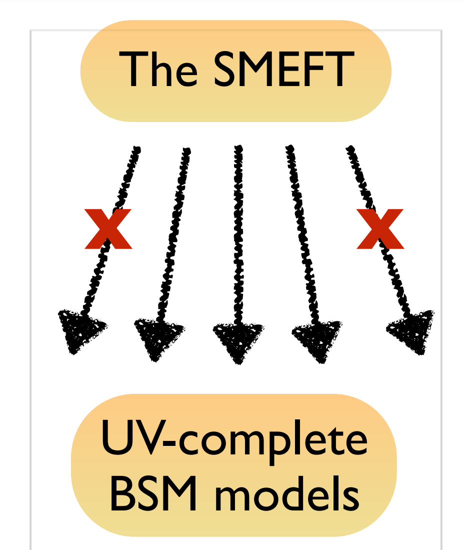
- ✤ Solely involves the SM fields
- ✤ Leading effects usually assumed to be dim-6
- ✤ UV-complete setups also yield higher-order operators
  - ★ No *a priori* reason to neglect them
  - ★ Other types of powerful constraints [to which dim-6 operators are insensitive]



[Top-down]

✦ Choice for the Wilson coefficients

- ✤ Coefficients are dictated by the UV
  - ★ Taken as free parameters in the SMEFT
  - ★ Not all arbitrary values physical (positivity bounds)



[Bottom-up]

Four-electron operators

Four-electron operators

- Barely constrained (LEP+SLD): at best 1TeV bounds on dim-6 operators
- Excellent case for future lepton colliders ($e^+e^- \to e^+e^-$ scattering)

[Han & Skiba (PRD`05)]

Relevant operators at the dim-6 and dim-8 level

$$O_{ee} = (\bar{e}\gamma^\mu e)\ (\bar{e}\gamma_\mu e)$$
$$O_{el} = (\bar{e}\gamma^\mu e)\ (\bar{l}\gamma_\mu l)$$
$$O_{ll} = (\bar{l}\gamma^\mu l)\ (\bar{l}\gamma_\mu l)$$

Dim-6

$$O_1 = \partial^\alpha(\bar{e}\gamma^\mu e)\partial_\alpha(\bar{e}\gamma_\mu e)$$
$$O_2 = \partial^\alpha(\bar{e}\gamma^\mu e)\partial_\alpha(\bar{l}\gamma_\mu l)$$
$$O_3 = D^\alpha(\bar{e}l)\ D_\alpha(\bar{l}e)$$
$$O_4 = \partial^\alpha(\bar{l}\gamma^\mu l)\ \partial_\alpha(\bar{l}\gamma_\mu l)$$
$$O_5 = D^\alpha(\bar{l}\gamma^\mu\tau^I l)\ D_\alpha(\bar{l}\gamma_\mu\tau^I l)$$

Dim-8

- Other dim-8 operators omitted
  - ★ $\psi^4\phi^2$: dim-6 structure (when $\phi \to v$)
  - ★ $\psi^4 D\phi$: ignored from flavour symmetry

Constraining the SMEFT at future ee colliders

✦ Differential $e^+e^- \to e^+e^-$ cross section at the dim-8 level

- ✤ Interferences between the SM and the SMEFT operators
- ✤ Squared dim-6 contributions (no interferences for $m_e \to 0$)

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\rm SM} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathrm{d}\sigma_i^{(6)} + \sum_i \frac{{C_i^{(6)}}^2}{\Lambda^4}\mathrm{d}\sigma_{ii}^{(6)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4}\mathrm{d}\sigma_i^{(8)}$$

✦ Setup for computations of the cos θ spectrum

- ✤ LEP2: measurements at 2%
  - → Assumption: 1% at future colliders for each cos θ bin
- ✤ 25 bins, we ignore the most forward bin
- ✤ All future colliders considered (except $\sqrt{s} = m_Z$), full luminosity
- ✤ Statistical uncertainties included

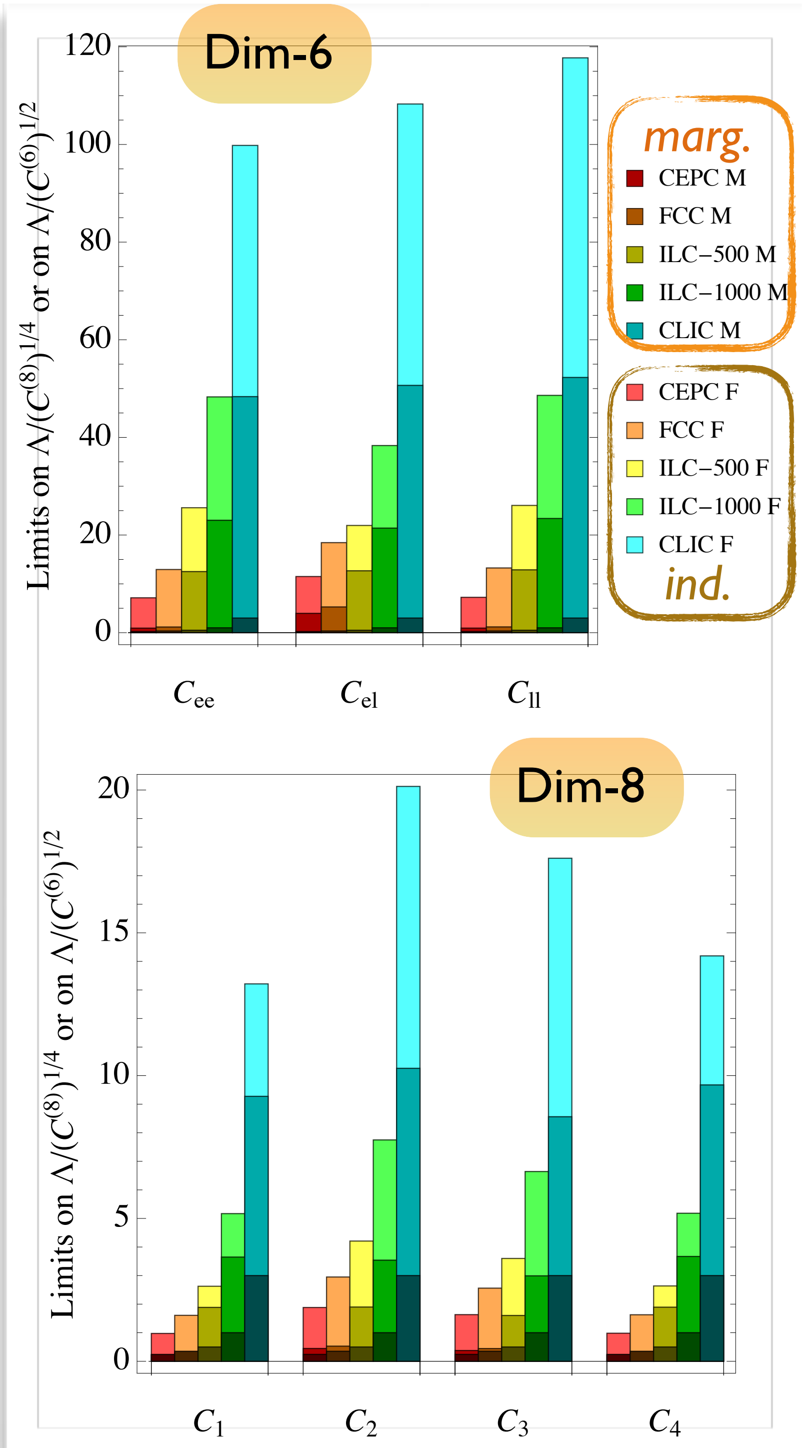
[ILC white paper (2013)]
[De Blas, Durieux, Grojean, Gu & Paul (JHEP`19)]

✦ Constraints on the vector of Wilson coefficients $\boldsymbol{C}$

- ✤ Hypothesis $\boldsymbol{C}_0$
- ✤ Would-be observation $\boldsymbol{C}$

→ $\chi^2(\mathbf{C}, \mathbf{C_0})$ → $[\mathbf{C}_{\rm min}, \mathbf{C}_{\rm max}]$ range at 2σ ⇝ BSM scale Λ_c

Results for the SM hypothesis $C_0 = 0$



✦ Dimension-6 coefficients

- ✤ Sensitivity to very large scales
  - ★ 1–2 orders of magnitude larger than $\sqrt{s}$
- ✤ Similar findings as for LEP2
- ✤ Marginalised limits a factor of a few weaker
  - ★ OK wrt to the EFT validity

✦ Dimension-8 coefficients

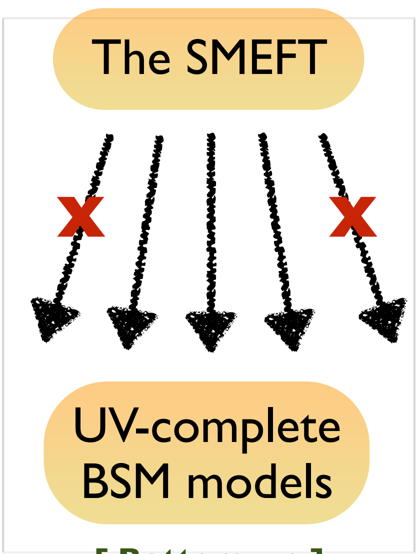
- ✤ Sensitivity to scales of 1–10 TeV
  - ★ 5 times larger than $\sqrt{s}$
- ✤ Marginalised limits a factor of a few weaker
  - ★ CEPC/FCC-ee: smaller than $\sqrt{s}$ for C_1/C_4
    - → almost identical LLLL and RRRR cross sections
    - → almost flat direction
  - ★ The EFT is valid (check of the next terms in $d\sigma$)

$$O_1 = \partial^\alpha(\bar{e}\gamma^\mu e)\partial_\alpha(\bar{e}\gamma_\mu e) \quad O_4 = \partial^\alpha(\bar{l}\gamma^\mu l)\,\partial_\alpha(\bar{l}\gamma_\mu l)$$

- ✤ Implications for UV physics: positivity bounds

Positivity bounds: generalities

- ✦ Not all SMEFT scenarios ≡ UV completions
  - ✤ Wilson coefficients not arbitrary
  - ✤ Some non-physical regions in the SMEFT parameter space
- ✦ Core QFT principles (analyticity, unitarity, locality, Lorentz)
  - ✤ The optical theorem + dispersion relation: positivity bounds
  - ✤ Constraints on the allowed SMEFT scenarios



[Bottom-up]

- ✦ Positivity bounds and future measurements: applications
  - ✤ Measurement of a positivity bound violation
    - → breakdown of the fundamental principles of QFT
    - → the SMEFT invalid (TeV scale new physics)
  - ✤ Observations in agreement with the positivity bounds
    - → Inferring / excluding the existence of UV new physics model-independently
    - → Towards solving the inverse problem

[Zhang & Zhou (2020)]

Positivity bounds - interpretations

✦ Conditions on the Wilson coefficients

$$M^{ijkl} = \int_{(\epsilon\Lambda)^2}^{\infty} \mathrm{d}\mu \sum_{Z \text{ in } \mathbf{r}}{}' \frac{|\langle Z|\mathcal{M}|\mathbf{r}\rangle|^2}{\pi\left(\mu - \frac{1}{2}M^2\right)^3} P_{\mathbf{r}}^{i(j|k|l)}$$

Quadratic in $C^{(8)}$ — Positive

Direct calculations: derivation of the viable SMEFT space regions

Geometry: additional model-independent constraints on new physics

✤ We can compute M^{ijkl} in the SMEFT
- ★ From any elastic fwd scattering amp.
- ★ The second-order derivative > 0
- ★ Arbitrary superpositions
- ★ Constraints on the coefficients

✤ We can use convex geometry
- ★ The rhs written with $C^{(8)}$ (for given $\mathbf{r}$)
  - → $\{\mathbf{c_r}\}$ forms a convex cone
- ★ The lhs written with $C^{(8)}$: $\mathbf{C}$
  - → $\mathbf{C} \in \text{cone}(\mathbf{c_r})$

Positivity bounds for $e^+e^- \to e^+e^-$ collisions

✦ Direct computations (reproduced with convex geometry)

From specific helicities

$$M(e_R e_R \to e_R e_R) \to C_1 \leq 0$$

$$M(e_L e_L \to e_L e_L) \to C_4 + C_5 \leq 0$$

$$M(e_R \bar{e}_L \to e_R \bar{e}_L) \to C_3 \geq 0$$

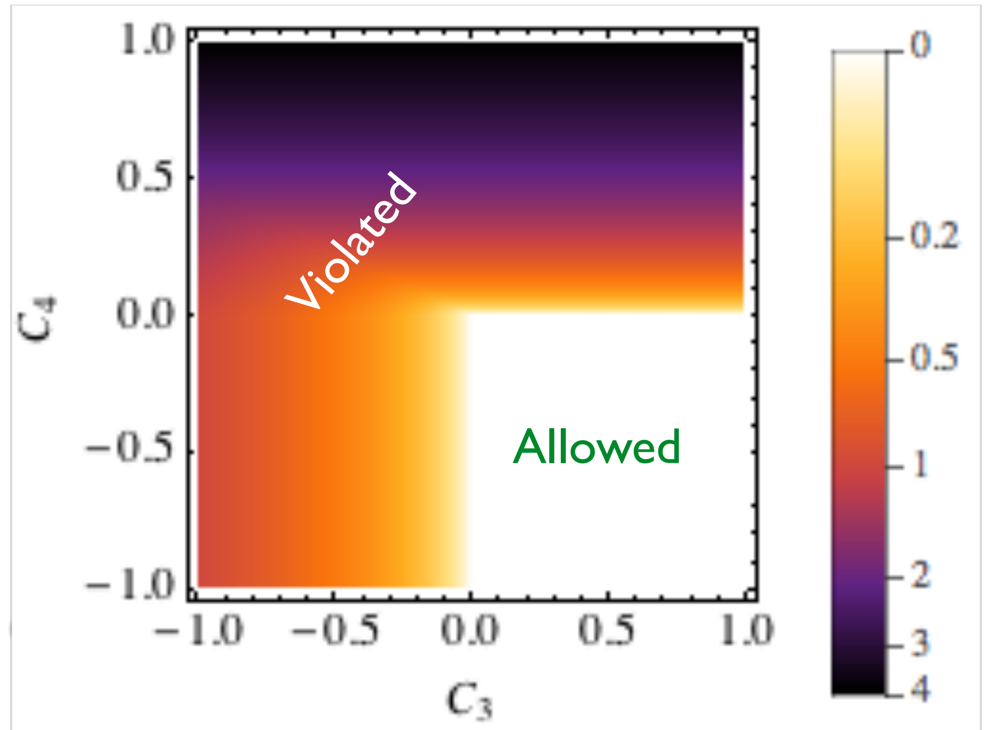
$$M(e_L \nu_L \to e_L \nu_L) \to C_5 \leq 0$$

From given superpositions

$$|f_\pm\rangle \propto (C_4 + C_5)^{1/4} |e_R\rangle + C_1^{1/4} |\bar{e}_L\rangle$$

$$2\sqrt{C_1(C_4 + C_5)} > C_2$$

$$2\sqrt{C_1(C_4 + C_5)} > -(C_2 + C_3)$$



The constraints define a cone in the SMEFT space
Distance of a point outside ≡ amount of positivity violation

Positivity bounds at the FCC-ee

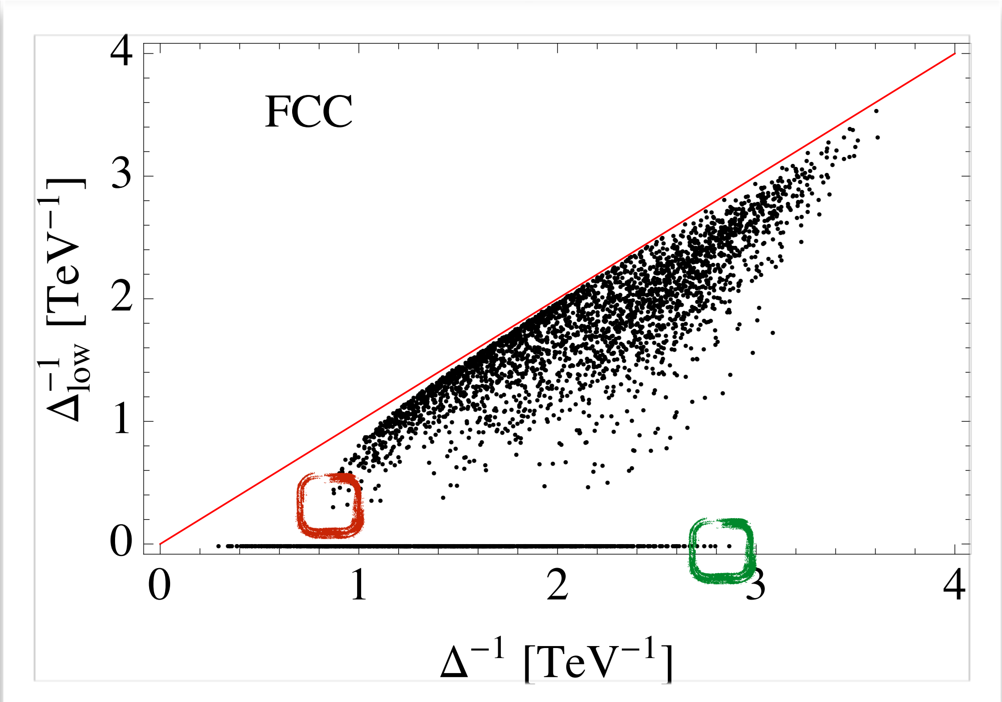
✦ Assumptions

- Assumption 1: nature picks a given $\boldsymbol{C_0} = (C_1, C_2, \ldots, C_5)$ [within the bounds or not]
- Assumption 2: $\boldsymbol{C_{exp}}$ is measured at the FCC-ee and is consistent with $\boldsymbol{C_0}$

✦ Strategy

- The measurements yield bounds for positivity violation $\Delta^{-1} \in [\Delta^{-1}_{\rm low}, \Delta^{-1}_{\rm high}]$
- The lower bound is a conservative estimate
  - ★ = 0: Compatible with the positivity bounds
  - ★ > 0: Observation of positivity violation

✦ FCC-ee sensitivity to a positivity violation scale Δ *[scan over **C₀**]*



- **Δ** connected with the scale at which QFT bedrock principles are violated
- Smallest $\boldsymbol{\Delta^{-1}}$ for a non-zero $(\boldsymbol{\Delta}_{\rm low})^{-1}$
  - ★ Positivity violation occurring below 1.2 TeV has a chance to be detected
- Largest $\boldsymbol{\Delta^{-1}}$ for a zero $(\boldsymbol{\Delta}_{\rm low})^{-1}$
  - ★ Positivity violation occurring below 360 GeV is guaranteed to be detected

UV physics from precision at future ee colliders

✦ Assumptions

- ✤ Assumption 1: nature picks a given $\mathbf{C}_0 = (C_1, C_2, \ldots, C_5)$ [blue dot]
- ✤ Assumption 2: $\mathbf{C}_{exp}$ is measured at some lepton collider [green area]
- ✤ The positivity bounds define a convex cone in the SMEFT space [yellow cone]

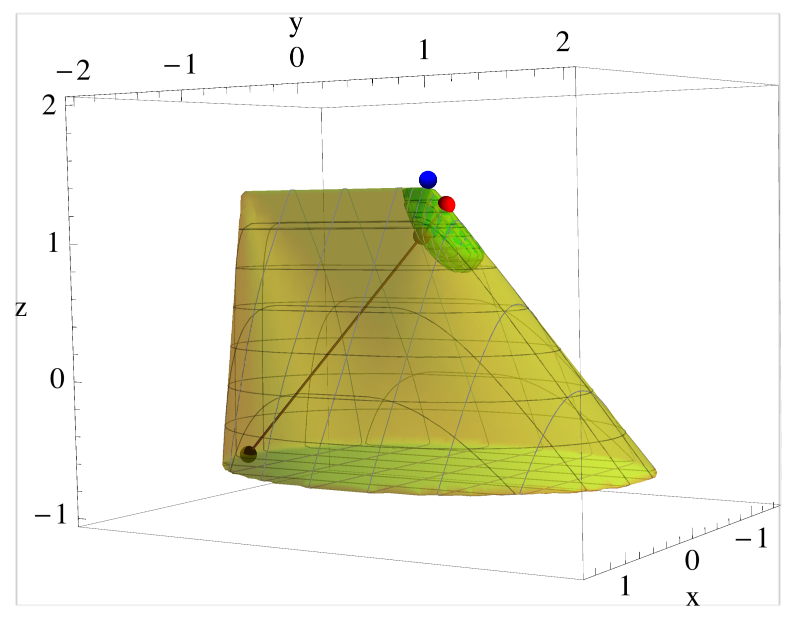
✦ Towards excluding a class of particle X'

- ✤ The extremal ray corresponding to X': $\mathbf{c}_{X'}$ [black dot]
- ✤ We determine $\mathbf{C}_{max}$ so that λ is maximised

$$\max_{\lambda}\left[\vec{C}^{(8)}_{\text{exp}} - \lambda \vec{c}^{\,(8)}_{X'} \in \mathcal{C}\right]$$

[brown dot; red dot]

- ✤ $\lambda_{\text{max}} \equiv$ the max X' contribution to $\mathbf{C}_0$



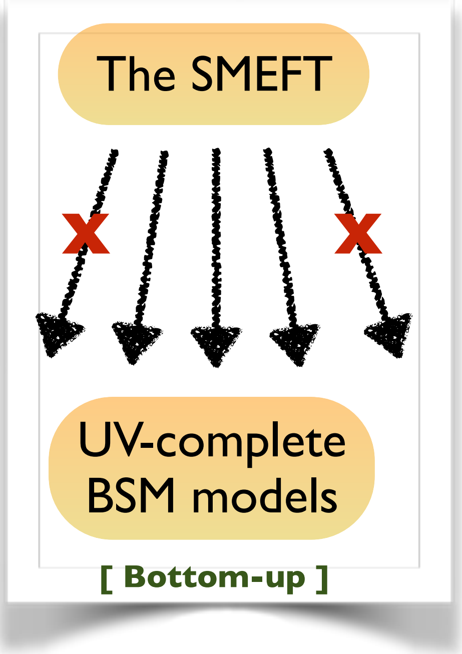
✦ Examples: the no new physics case $\mathbf{C}_0 \equiv (0,0,0,0,0)$ @ FCC-ee

X'	λ_{max}	$M_{X'}/\sqrt{g_{X'}}$	X'	λ_{max}	$M_{X'}/\sqrt{g_{X'}}$
$\mathbf{2}_{1/2}$ scalar	0.4267	≥ 1.23 TeV	$\mathbf{1}_2$ scalar	0.7257	≥ 1.08 TeV
$\mathbf{1}_1$ scalar	0.6897	≥ 1.09 TeV	$\mathbf{1}_0$ vector	0.3627	≥ 1.29 TeV
$\mathbf{2}_{-3/2}$ vector	0.2427	≥ 1.42 TeV	$\mathbf{1}_0$ axial-vector	0.3551	≥ 1.30 TeV

Model-independent bounds!

Summary

- ✦ The SMEFT parameter space not entirely physical
  - ✤ Wilson coefficients not arbitrary
  - ✤ Some configurations have no UV completion
- ✦ Positivity bounds built from:
  - ✤ Core QFT principles (analyticity, unitarity, locality, Lorentz inv.)
  - ✤ Optical theorem and dispersion relation
- ✦ Applications
  - ✤ Testing fundamentals of QFT
  - ✤ Model-independent inference of the existence of new physics
  - ✤ Solution to the inverse problem



- ✦ Example: ee→ee scattering at the FCC-ee
  - ✤ Probing positivity violation at 360 GeV (guaranteed) and 1.2 TeV (possible)
  - ✤ Exclusion of UV physics model-independently (for scales up to about 1 TeV)

Backup

Derivation of the positivity bounds

[Zhang & Zhou (PRD`19)]

✦ Context: forward scattering amplitudes $M_{ij\to kl}(s)$

- Dispersion relation from Cauchy's integral formula, analyticity, unitarity of $M_{ij\to kl}$
- Subtraction of the poles and the low-energy part ($Q \ll \epsilon\Lambda$)

$$M^{ijkl} = \frac{1}{2}\frac{\mathrm{d}^2}{\mathrm{d}s^2} M_{ij\to kl}(s = Q^2/2) - \text{poles} - \text{low energy}$$
$$= \int_{(\epsilon\Lambda)^2}^{\infty} \frac{\mathrm{d}\mu}{2i\pi} \frac{\mathrm{Disc} M_{ij\to kl}(\mu)}{\left(\mu - \frac{1}{2}Q^2\right)^3} + [\mathrm{j} \leftrightarrow \mathrm{l}]$$

Positive

✦ Re-organisation of the dispersion relation

- Hermiticity
- Optical theorem

$$M_{ij\to kl}(s - i\epsilon) = M^*_{kl\to ij}(s + i\epsilon)$$
$$M_{ij\to kl} - M_{kl\to ij} = i \sum_X{}' M_{ij\to X} M^*_{kl\to X}$$

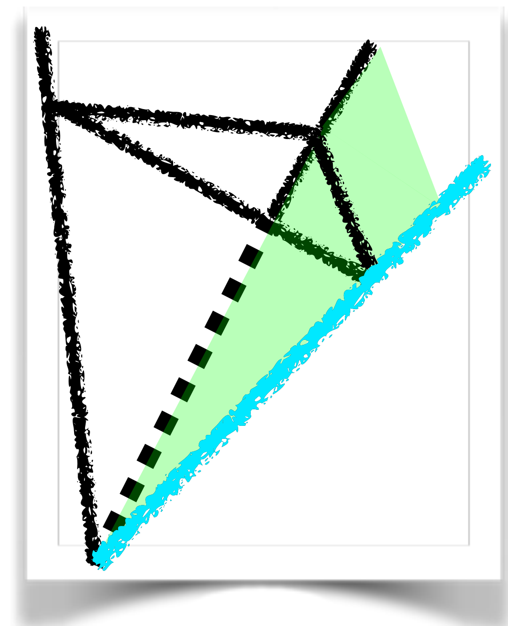
✦ Final formula

$$M^{ijkl} = \int_{(\epsilon\Lambda)^2}^{\infty} \mathrm{d}\mu \sum_{Z \text{ in } \mathbf{r}}{}' \frac{|\langle Z|\mathcal{M}|\mathbf{r}\rangle|^2}{\pi\left(\mu - \frac{1}{2}Q^2\right)^3} P_{\mathbf{r}}^{i(j|k|l)}$$

- Sum over intermediate Z-states
- Decomposition over SO(2) rotation reps. around the scattering axis

Convex geometry an its link to UV completions

✦ More about convex geometry



- ✤ Positivity defines a convex cone in the SMEFT space
  [set closed under additions and positive scalar multiplications]

- ✤ Two representations
  - ★ Faces: the positivity bounds themselves
    - → Hahn-Banach separation theorem: a convex cone can be specified by a set of linear inequalities
  - ★ Convex hull of extremal rays (Krein-Milman theorem)
    [An extremal ray cannot be trivially split into other cone elements]
    - → The extremal rays are the cone generators

[Bi, Zhang & Zhou (JHEP`19)]

✦ Extremal rays and physics

- ✤ Convex hull of {$\mathbf{x}_i$} ($\mathbf{x}_i$ denoting the extremal rays)

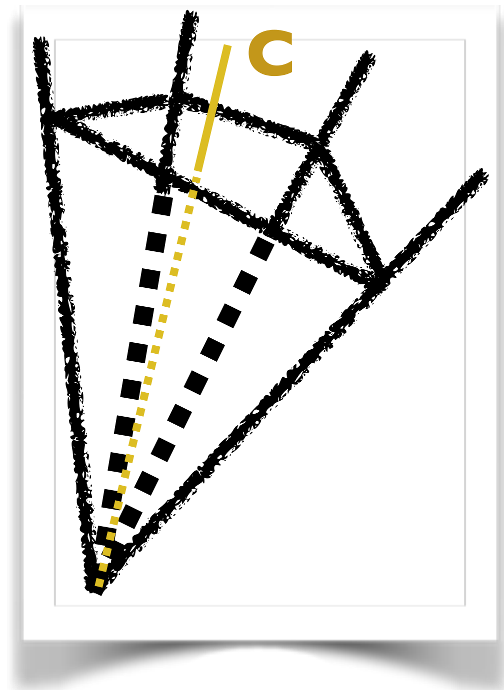
$$\text{all } \mathbf{x} \quad \text{such that} \quad \mathbf{x} = \sum_i \omega_i \mathbf{x}_i$$
$$\text{with } \omega_i \geq 0 \text{ and } \sum_i \omega_i = 1$$

- ★ Extremal rays ≡ generators of all UV-completable SMEFT setups
- ★ Extremal ray ≡ SM + one particle species

Seeking UV physics with convex geometry

✦ ‘SM + *n* particles’ setup

- ✤ Integrating out → **C** = (C_1, C_2, …, C_5)
  - ★ n > 1: not an extremal ray (extremal rays cannot be split)
- ✤ UV models generated from ‘SM + 1 particle’ extensions
- ✤ Localisation within the cone
  - ★ Extremal rays: one particle SM extensions
    - → One ray for different EW/spin reps.
  - ★ Faces of the cone: two-particle SM extensions
  - ★ Inside the cone: more complex SM extensions
  - ★ Outside the cone: violation of positivity, QFT core principles



Model-independent conclusions after adding future lepton collider expectations