



SCUOLA
NORMALE
SUPERIORE

General bounds on hidden CFTs

SUSY 2018 – 25/07/2018

Kevin Max, SNS & INFN Pisa

18xx.xxx with Roberto Contino & Rashmish Mishra.

What this talk is about

Generic setup:

approximate CFT with cut-off Λ_{UV} (+ IR breaking scale Λ_{IR})

What this talk is about

Generic setup:

approximate CFT with cut-off Λ_{UV} (+ IR breaking scale Λ_{IR})

Weakly coupled to SM:

SM \longleftrightarrow CFT

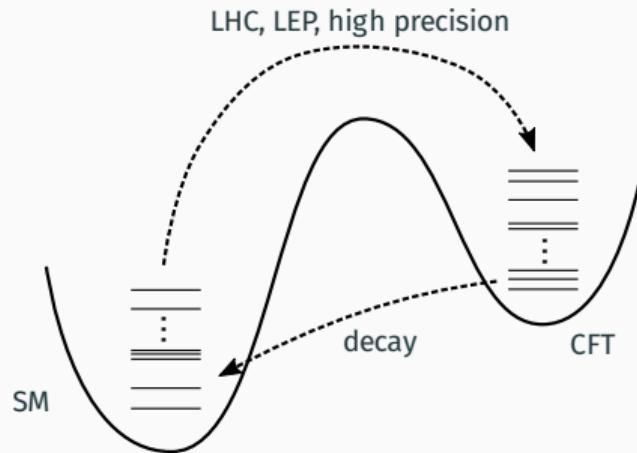
What this talk is about

Generic setup:

approximate CFT with cut-off Λ_{UV} (+ IR breaking scale Λ_{IR})

Weakly coupled to SM:

$\text{SM} \longleftrightarrow \text{CFT}$



What this talk is about

Generic setup:

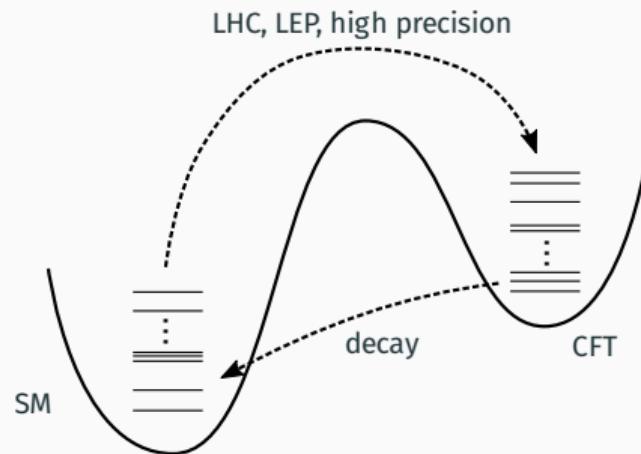
approximate CFT with cut-off Λ_{UV} (+ IR breaking scale Λ_{IR})

Weakly coupled to SM:

$\text{SM} \longleftrightarrow \text{CFT}$

Given:

- # particles
- coupling to SM

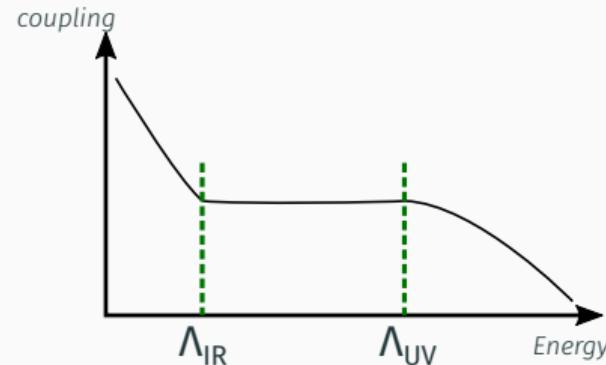


⇒ Can we put **generic bounds** on this large class of theories?

Defining the CFTs

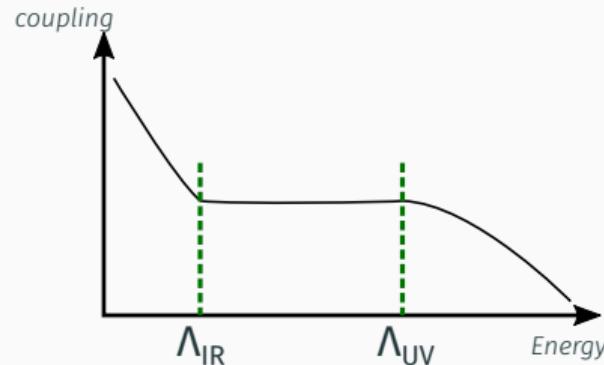
Defining the CFTs

Assume BSM sector with scale invariance between Λ_{UV} and Λ_{IR}



Defining the CFTs

Assume BSM sector with scale invariance between Λ_{UV} and Λ_{IR}

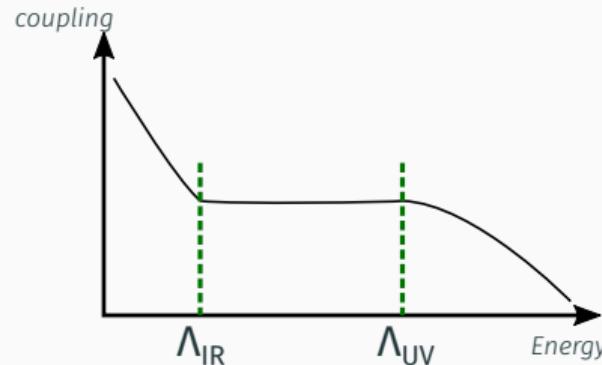


Examples:

- QCD-like in conformal window
- Supersymmetric models ($\mathcal{N} = 4$ or SQCD)
- Randall-Sundrum

Defining the CFTs

Assume BSM sector with scale invariance between Λ_{UV} and Λ_{IR}



Examples:

- QCD-like in conformal window
- Supersymmetric models ($\mathcal{N} = 4$ or SQCD)
- Randall-Sundrum

For illustration, assume Banks-Zaks IR fixed point.

Defining the CFTs

Theory content:

- fundamental fields χ
- operators \mathcal{O} formed from χ 's

Defining the CFTs

Theory content:

- fundamental fields χ
- operators \mathcal{O} formed from χ 's

Which operators must be in a CFT?

→ Any conserved current J_μ of a symmetry, e.g. Conformal symmetry

Defining the CFTs

Theory content:

- fundamental fields χ
- operators \mathcal{O} formed from χ 's

Which operators must be in a CFT?

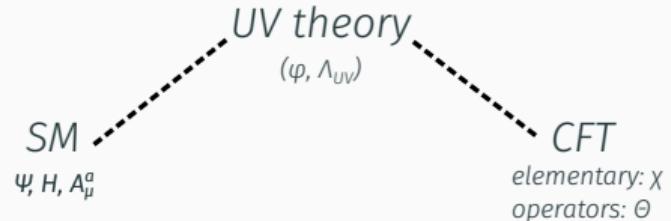
→ Any conserved current J_μ of a symmetry, e.g. Conformal symmetry

Generically: Energy-momentum tensor $T_{\mu\nu}^{\text{CFT}}$

⇒ In the following: assume only $T_{\mu\nu}^{\text{CFT}} \in \{\mathcal{O}_{\text{CFT}}\}$

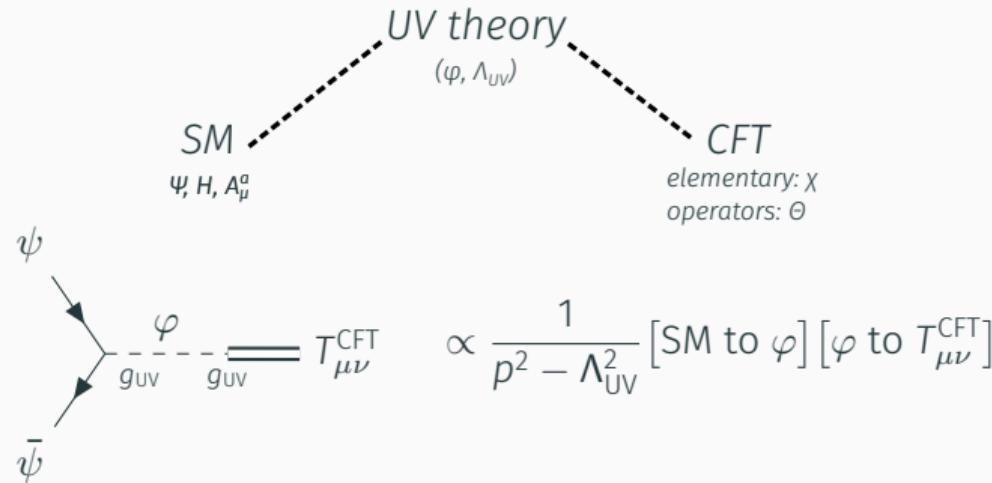
Coupling to the SM

Seclude CFT from SM – generic weakly coupling φ , mass $\mathcal{O}(\Lambda_{\text{UV}})$



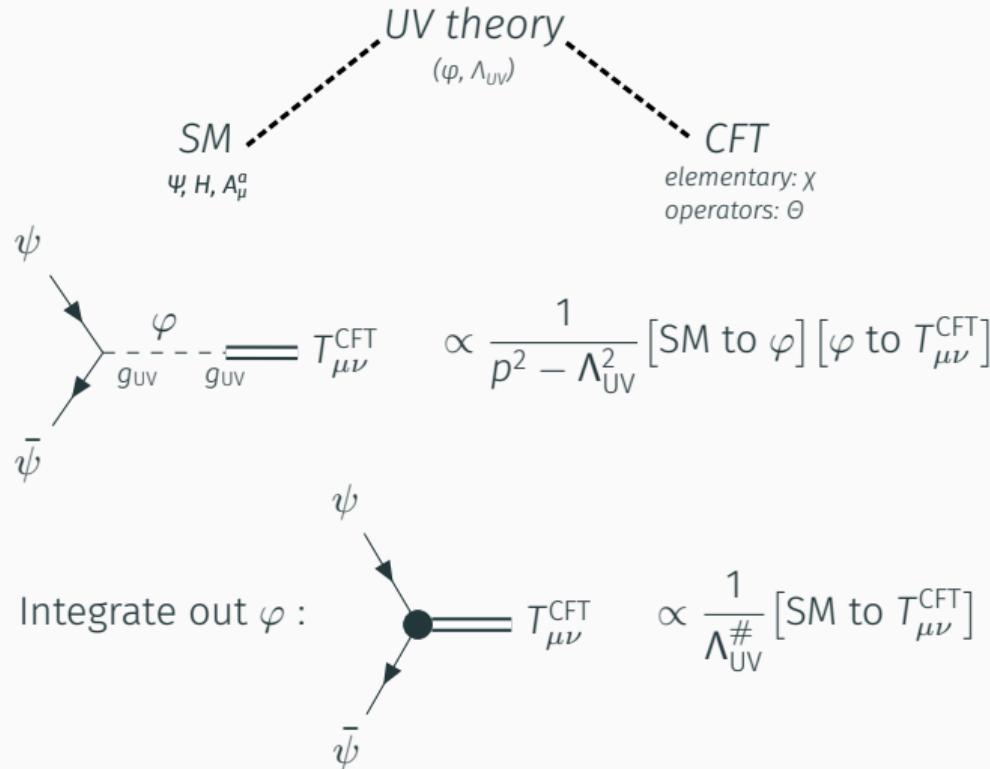
Coupling to the SM

Seclude CFT from SM – generic weakly coupling φ , mass $\mathcal{O}(\Lambda_{\text{UV}})$



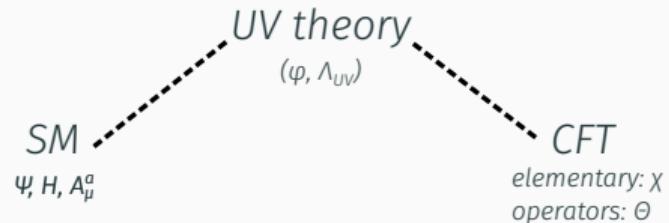
Coupling to the SM

Seclude CFT from SM – generic weakly coupling φ , mass $\mathcal{O}(\Lambda_{\text{UV}})$



Coupling to the SM

Seclude CFT from SM – generic weakly coupling φ , mass $\mathcal{O}(\Lambda_{\text{UV}})$



EFT interaction:

A Feynman diagram showing a vertex where two external lines, labeled ψ and $\bar{\psi}$, meet. They interact with a central black dot representing the operator $T_{\mu\nu}^{\text{CFT}}$. This interaction is equivalent to the term $\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}}$, where $C_0 \equiv g_{\text{UV}}^2$.

$$\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}}, \quad C_0 \equiv g_{\text{UV}}^2$$

How to describe dynamics of $T_{\mu\nu}^{CFT}$?

The Unparticle formalism

The Unparticle formalism

Operator in the CFT \mathcal{O}_U of mass dim. d_U – **spectral decomposition**:

$$d_U \in \mathbb{R}$$

$$\langle \Omega | \mathcal{O}_U(x) \mathcal{O}_U^\dagger(0) | \Omega \rangle = \int \frac{d^4 P_U}{(2\pi)^4} \left| \langle \Omega | \mathcal{O}_U(0) \underbrace{|P_U\rangle}_{\text{'unparticle' state}} \right|^2 \rho(P_U^2)$$

The Unparticle formalism

Operator in the CFT \mathcal{O}_U of mass dim. d_U – **spectral decomposition**:

$$d_U \in \mathbb{R}$$

$$\langle \Omega | \mathcal{O}_U(x) \mathcal{O}_U^\dagger(0) | \Omega \rangle = \int \frac{d^4 P_U}{(2\pi)^4} \left| \langle \Omega | \mathcal{O}_U(0) \underbrace{|P_U\rangle}_{\text{'unparticle' state}} \right|^2 \rho(P_U^2)$$

Can we guess the spectrum?

1. Scale invariance \Rightarrow no mass scale in $\left| \langle \Omega | \mathcal{O}_U(0) | P_U \rangle \right|^2 \rho(P_U^2)$
2. Mass dimension $(2d_U - 4)$

The Unparticle formalism

Operator in the CFT \mathcal{O}_U of mass dim. d_U – spectral decomposition:

$$d_U \in \mathbb{R}$$

$$\langle \Omega | \mathcal{O}_U(x) \mathcal{O}_U^\dagger(0) | \Omega \rangle = \int \frac{d^4 P_U}{(2\pi)^4} \left| \langle \Omega | \mathcal{O}_U(0) \underbrace{|P_U\rangle}_{\text{'unparticle' state}} \right|^2 \rho(P_U^2)$$

Can we guess the spectrum?

1. Scale invariance \Rightarrow no mass scale in $\left| \langle \Omega | \mathcal{O}_U(0) | P_U \rangle \right|^2 \rho(P_U^2)$
2. Mass dimension $(2d_U - 4)$

$$\Rightarrow \left| \langle \Omega | \mathcal{O}_U(0) | P_U \rangle \right|^2 \rho(P_U^2) = A_{d_U} \theta(p_U^0) \theta(p_U^2) (p_U^2)^{d_U - 2} \quad (1)$$

The Unparticle formalism

Scalar unparticle:

$$\left| \langle \Omega | \mathcal{O}_U(0) | P_U \rangle \right|^2 \rho(P_U^2) = \underbrace{A_{d_U}}_? \theta(p_U^0) \theta(p_U^2) (p_U^2)^{d_U - 2}$$

$$d_U \in \mathbb{R}$$

The Unparticle formalism

Scalar unparticle:

$$\left| \langle \Omega | \mathcal{O}_U(0) | P_U \rangle \right|^2 \rho(P_U^2) = \underbrace{A_{d_U}}_? \theta(p_U^0) \theta(p_U^2) (p_U^2)^{d_U - 2}$$

$$d_U \in \mathbb{R}$$

Cf. phase space factor A_n for n massless particles:

$$A_n = \frac{16\pi^{5/2}}{(2\pi)^{2n}} \frac{\Gamma(n + 1/2)}{\Gamma(n - 1)\Gamma(2n)}$$

The Unparticle formalism

Scalar unparticle:

$$\left| \langle \Omega | \mathcal{O}_U(0) | P_U \rangle \right|^2 \rho(P_U^2) = \underbrace{A_{d_U}}_? \theta(p_U^0) \theta(p_U^2) (p_U^2)^{d_U - 2}$$

$$d_U \in \mathbb{R}$$

Cf. phase space factor A_n for n massless particles:

$$A_n = \frac{16\pi^{5/2}}{(2\pi)^{2n}} \frac{\Gamma(n + 1/2)}{\Gamma(n - 1)\Gamma(2n)}$$

Georgi '07:

“Unparticle $\hat{=}$ phase space of d_U (massless) particles”

The Unparticle formalism

Scalar unparticle:

$$\left| \langle \Omega | \mathcal{O}_U(0) | P_U \rangle \right|^2 \rho(P_U^2) = \underbrace{A_{d_U}}_? \theta(p_U^0) \theta(p_U^2) (p_U^2)^{d_U-2}$$

$$d_U \in \mathbb{R}$$

Cf. phase space factor A_n for n massless particles:

$$A_n = \frac{16\pi^{5/2}}{(2\pi)^{2n}} \frac{\Gamma(n + 1/2)}{\Gamma(n - 1)\Gamma(2n)}$$

Georgi '07:

“Unparticle $\hat{=}$ phase space of d_U (massless) particles”

Phase space factor A_{d_U} reduces to free massless scalar for $d_U \rightarrow 1$:

$$A_{d_U} (P_U^2)^{d_U-2} \theta(P_U^2) \xrightarrow[d_U \rightarrow 1]{\epsilon \rightarrow 0} (2\pi) \frac{\epsilon \theta(P_U^2)}{(P_U^2)^{1-\epsilon}} = (2\pi) \delta(P_U^2) \quad \checkmark$$

The Unparticle formalism

Scalar unparticle:

$$\left| \langle \Omega | \mathcal{O}_U(0) | P_U \rangle \right|^2 \rho(P_U^2) = \underbrace{A_{d_U}}_? \theta(p_U^0) \theta(p_U^2) (p_U^2)^{d_U-2}$$

$$d_U \in \mathbb{R}$$

Cf. phase space factor A_n for n massless particles:

$$A_n = \frac{16\pi^{5/2}}{(2\pi)^{2n}} \frac{\Gamma(n + 1/2)}{\Gamma(n - 1)\Gamma(2n)}$$

Georgi '07:

"Unparticle $\hat{=}$ phase space of d_U (massless) particles"

Phase space factor A_{d_U} reduces to free massless scalar for $d_U \rightarrow 1$:

$$A_{d_U} (P_U^2)^{d_U-2} \theta(P_U^2) \xrightarrow[d_U \rightarrow 1]{\epsilon \rightarrow 0} (2\pi) \frac{\epsilon \theta(P_U^2)}{(P_U^2)^{1-\epsilon}} = (2\pi) \delta(P_U^2) \quad \checkmark$$

Note: No on-shell condition $\delta(P_U^2)$ for Unparticles! (spectrum is scale invariant)

Application to $\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}}$

Production at colliders:

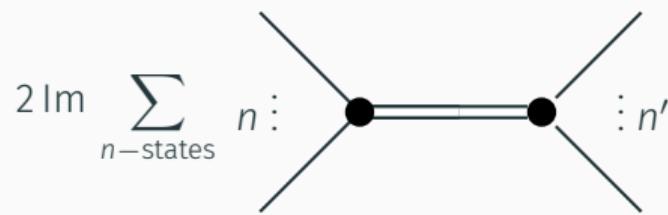
$$|\mathcal{M}_U|^2 = \left| \begin{array}{c} p \\ \diagup \\ \text{---} \\ \diagdown \\ p \end{array} \right. \text{---} \left. \begin{array}{c} U \\ \diagup \\ \text{---} \\ \diagdown \\ X \end{array} \right|^2 \propto \sum_{n-\text{states}} \left| \begin{array}{c} n : \\ \diagup \\ \text{---} \\ \diagdown \\ n' : \end{array} \right. \text{---} \left. \begin{array}{c} U \\ \diagup \\ \text{---} \\ \diagdown \\ \end{array} \right|^2$$

Apply optical theorem:

$$\begin{aligned} &= 2 \text{Im} \sum_{n-\text{states}} \left| \begin{array}{c} n : \\ \diagup \\ \text{---} \\ \diagdown \\ n' : \end{array} \right. \text{---} \left. \begin{array}{c} n' : \\ \diagup \\ \text{---} \\ \diagdown \\ n : \end{array} \right| \\ &\propto 2 \text{Im} \langle 0 | \mathcal{T}[T_{\mu\nu}^{\text{CFT}}(p) T_{\rho\sigma}^{\text{CFT}}(-p)] | 0 \rangle \end{aligned}$$

Application to $\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}}$

We need the propagator $\langle 0 | \mathcal{T}[T_{\mu\nu}^{\text{CFT}}(p) T_{\rho\sigma}^{\text{CFT}}(-p)] | 0 \rangle$.



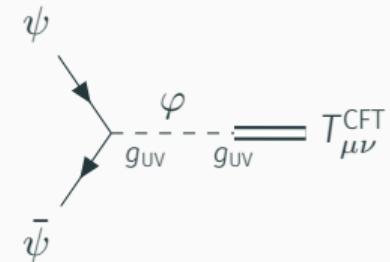
→ Using the Unparticle description & results on CFT correlators: (Grinstein et al. '08)

$$\langle 0 | \mathcal{T}[T_{\mu\nu}^{\text{CFT}}(p) T_{\rho\sigma}^{\text{CFT}}(-p)] | 0 \rangle = i \mathbf{C}_T N_T P_{\mu\nu\rho\sigma}^4(p) (\mathbf{p}^2 + i\epsilon)^2 \log(-p^2 - i\epsilon) \quad (2)$$

Unparticle production at LHC and LEP

Parameters for collider searches

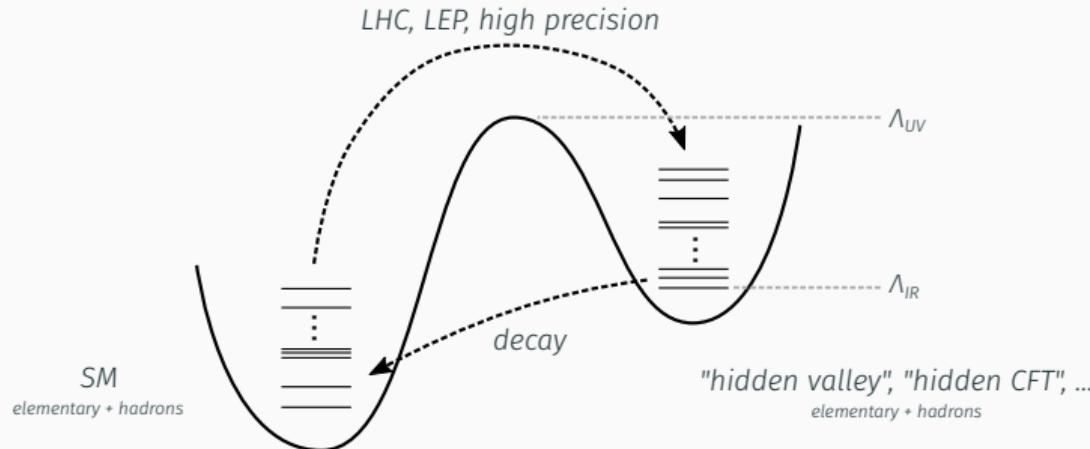
- UV cut-off Λ_{UV}
- IR breaking scale Λ_{IR}
- Perturbative coupling to SM $C_0 \sim g_{\text{UV}}^2$
- Coefficient of EMT 2-correlator, central charge C_T



$$\langle 0 | \mathcal{T}[T_{\mu\nu}^{\text{CFT}}(p) T_{\rho\sigma}^{\text{CFT}}(-p)] | 0 \rangle \propto C_T (p^2 + i\epsilon)^2 \dots$$

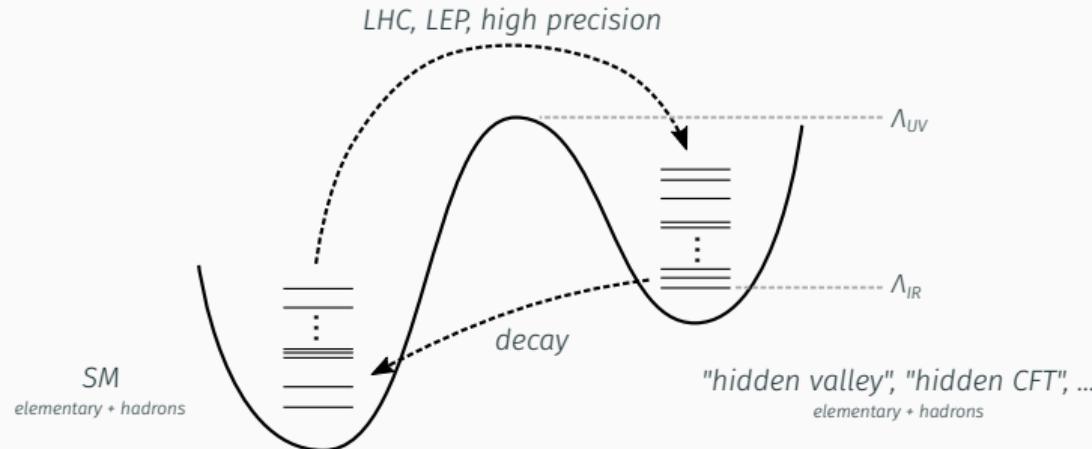
E.g. QCD-like theory: $C_T \times C_0^2 \sim \frac{N_c^2}{16\pi^2} \times g_{\text{UV}}^4$

Collider signals of hidden CFTs



(inspired by M. Strassler, 0801.0629)

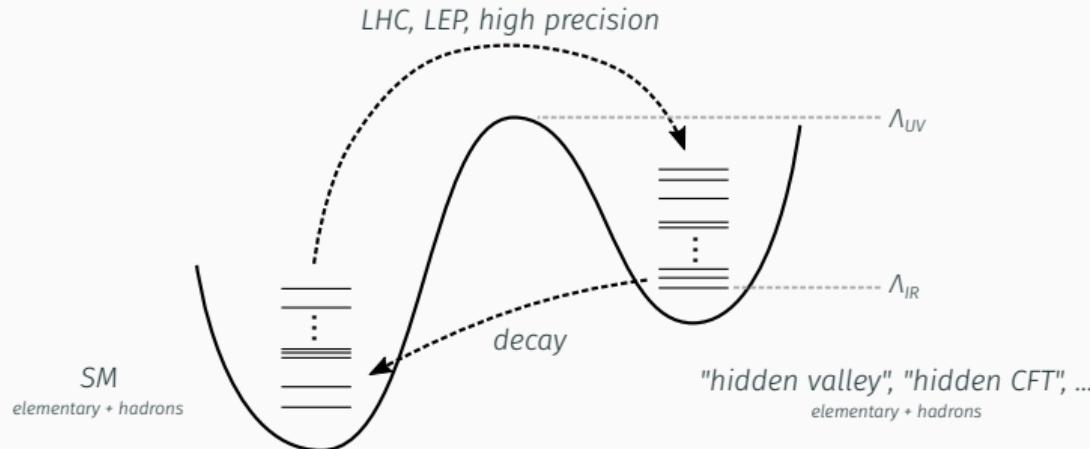
Collider signals of hidden CFTs



- $\sqrt{S} \ll \Lambda_{\text{IR}} \ll \Lambda_{\text{UV}}$: point like interactions – indirect searches

(inspired by M. Strassler, 0801.0629)

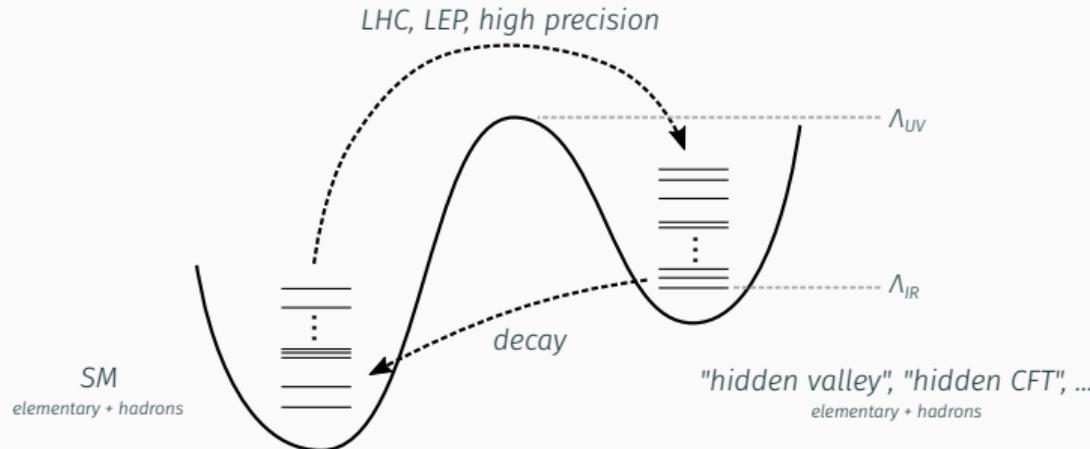
Collider signals of hidden CFTs



(inspired by M. Strassler, 0801.0629)

- $\sqrt{S} \ll \Lambda_{IR} \ll \Lambda_{UV}$: point like interactions – indirect searches
- $\Lambda_{IR} \lesssim \sqrt{S} \ll \Lambda_{UV}$: hidden valley-like, dark jets (Strassler '08, ...)

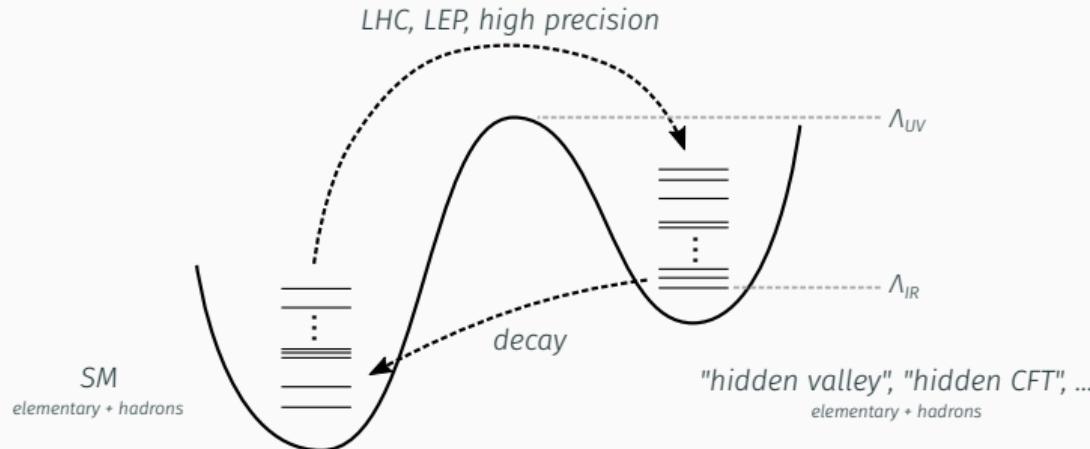
Collider signals of hidden CFTs



(inspired by M. Strassler, 0801.0629)

- $\sqrt{S} \ll \Lambda_{IR} \ll \Lambda_{UV}$: point like interactions – indirect searches
- $\Lambda_{IR} \lesssim \sqrt{S} \ll \Lambda_{UV}$: hidden valley-like, dark jets (Strassler '08, ...)
- $\Lambda_{IR} \ll \sqrt{S} \ll \Lambda_{UV}$: Unparticles as missing (transverse) momentum (\vec{p}_T)

Collider signals of hidden CFTs

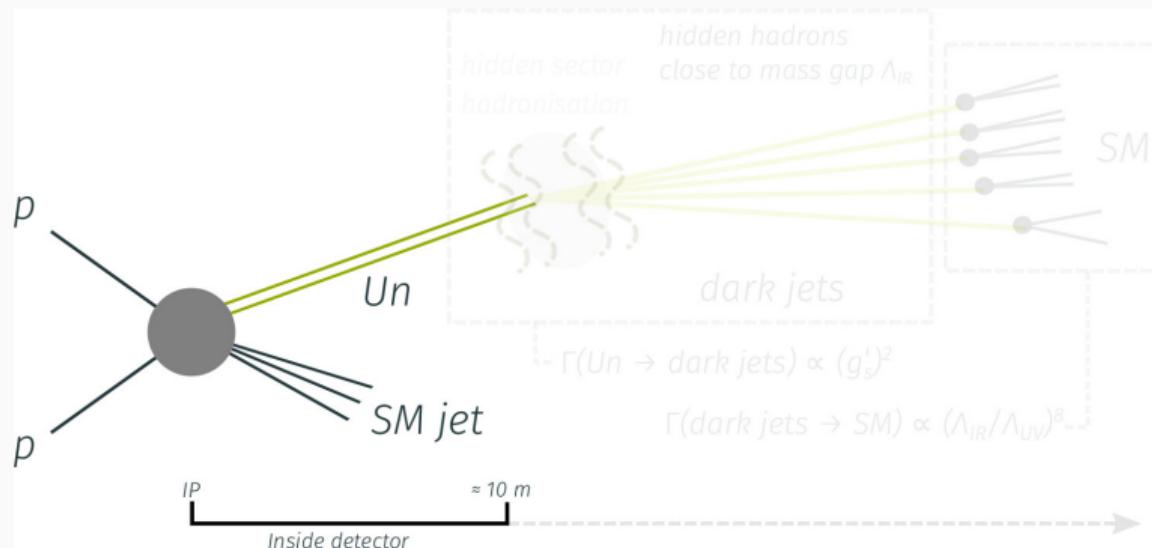


(inspired by M. Strassler, 0801.0629)

- $\sqrt{S} \ll \Lambda_{\text{IR}} \ll \Lambda_{\text{UV}}$: point like interactions – indirect searches
- $\Lambda_{\text{IR}} \lesssim \sqrt{S} \ll \Lambda_{\text{UV}}$: hidden valley-like, dark jets (Strassler '08, ...)
- $\Lambda_{\text{IR}} \ll \sqrt{S} \ll \Lambda_{\text{UV}}$: Unparticles as **missing (transverse) momentum (\vec{p}_T)** ← this talk

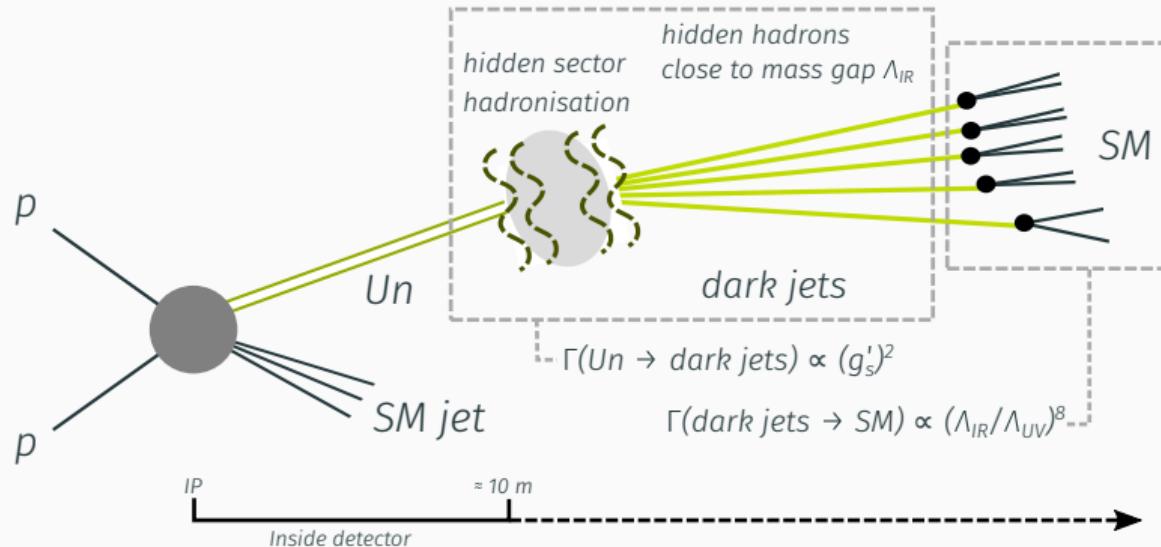
Unparticle production at colliders

What we simulate



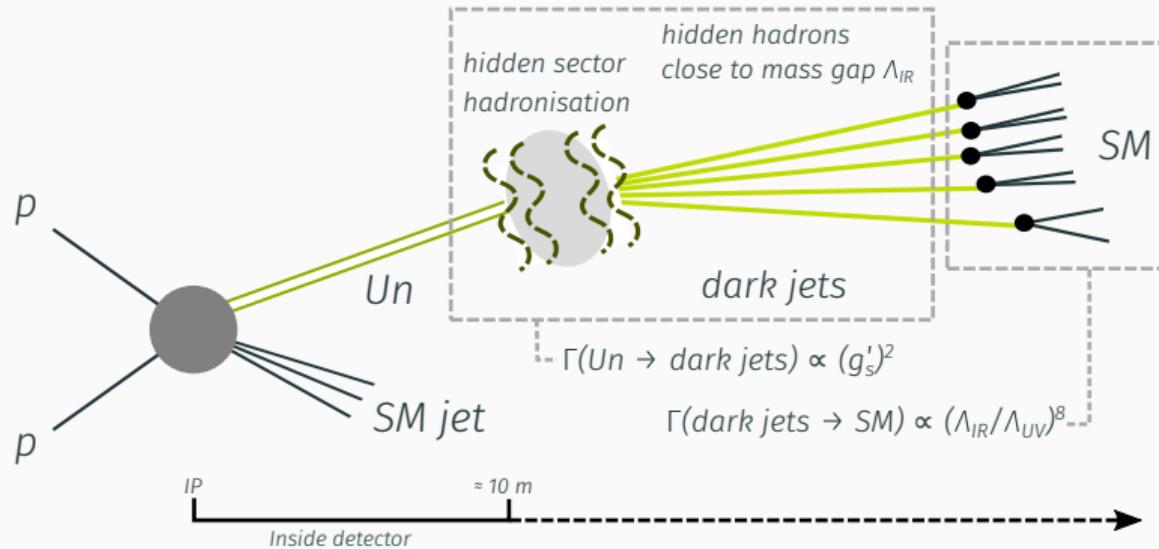
Unparticle production at colliders

What we simulate vs. what we estimate:



Unparticle production at colliders

What we simulate vs. what we estimate:



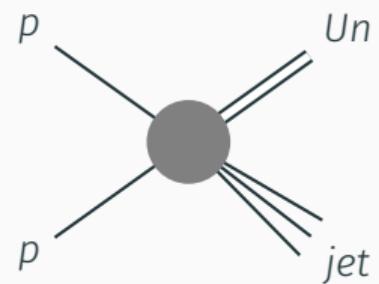
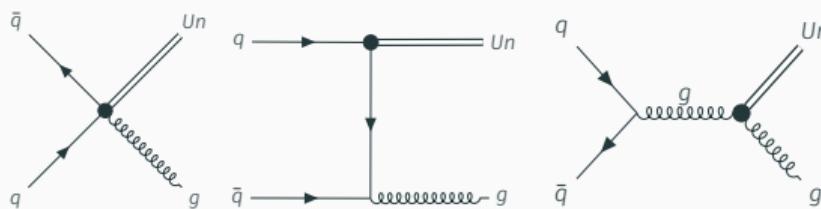
For \vec{p}_T searches, estimate:

$$\Gamma(\text{lightest dark hadrons} \rightarrow \text{SM}) \approx \frac{1}{8\pi} \frac{\Lambda_{IR}^9}{\Lambda_{UV}^8} \gtrsim (10\text{m})^{-1}$$

Unparticle production at colliders

From $\mathcal{L} = \frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}}$:

1. Feynman rules*: [FeynRules 2](#) for MMA
2. Diagrams & $|\mathcal{M}|^2$: [FeynArts 3.10](#) for MMA & FormCalc



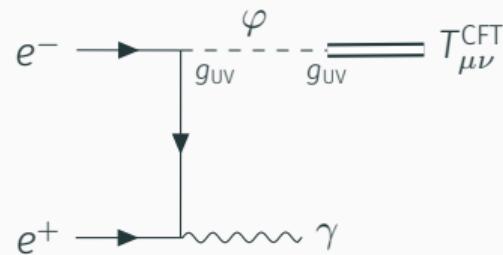
3. Take $\frac{d\sigma}{d|\vec{p}_T|}$, PDF

* Model file based on 1605.09359.

Effective field theory validity

Higher-dim. operator → check EFT validity!

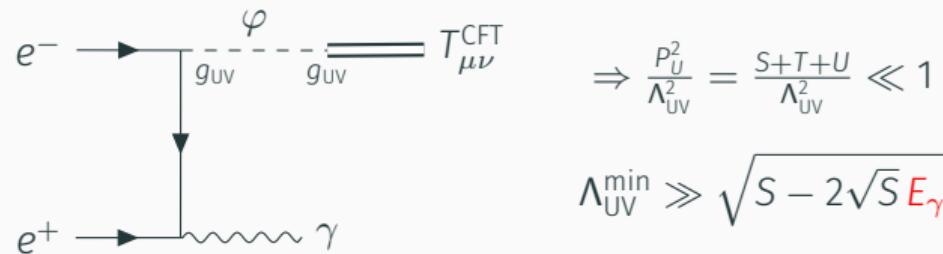
(See Contino et al., 1604.06444)



Effective field theory validity

Higher-dim. operator → check EFT validity!

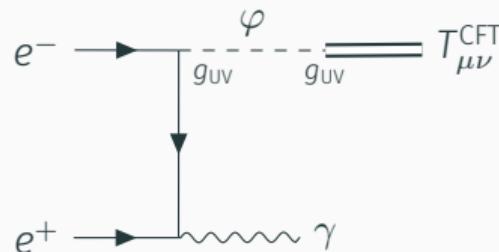
(See Contino et al., 1604.06444)



Effective field theory validity

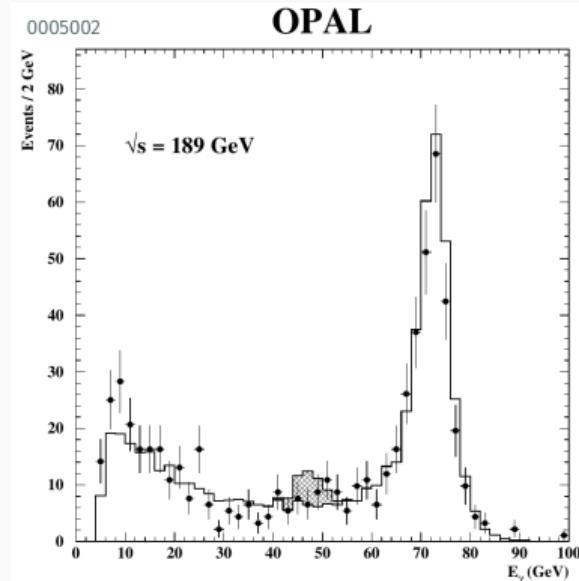
Higher-dim. operator → check EFT validity!

(See Contino et al., 1604.06444)



$$\Rightarrow \frac{P_U^2}{\Lambda_{UV}^2} = \frac{S+T+U}{\Lambda_{UV}^2} \ll 1$$

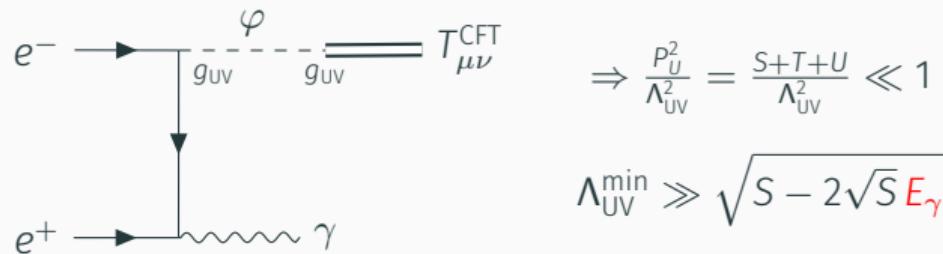
$$\Lambda_{UV}^{\min} \gg \sqrt{S - 2\sqrt{S} E_\gamma}$$



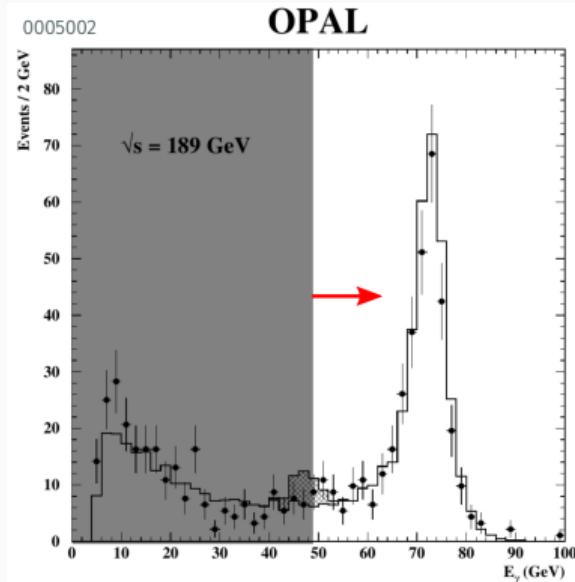
Effective field theory validity

Higher-dim. operator → check EFT validity!

(See Contino et al., 1604.06444)



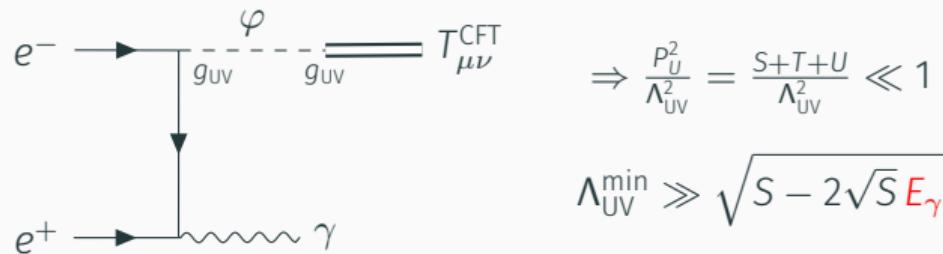
use fewer bins \Leftrightarrow bound Λ_{UV} degrades
 \Leftrightarrow but: better validity Λ_{UV}^{\min}



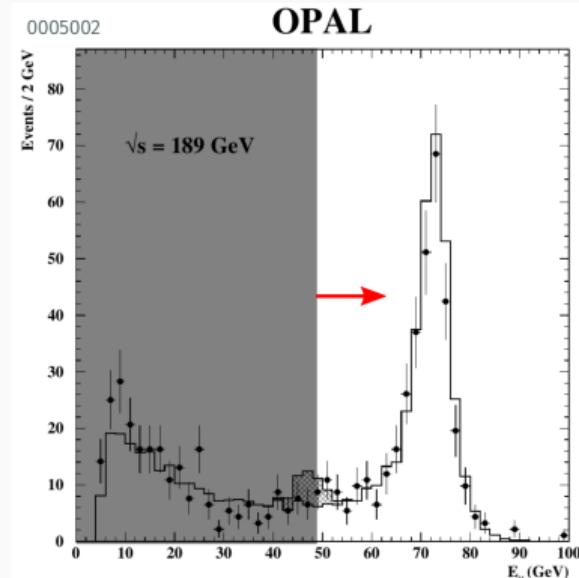
Effective field theory validity

Higher-dim. operator → check EFT validity!

(See Contino et al., 1604.06444)



use fewer bins \Leftrightarrow bound Λ_{UV} degrades
 \Leftrightarrow but: better validity $\Lambda_{\text{UV}}^{\min}$

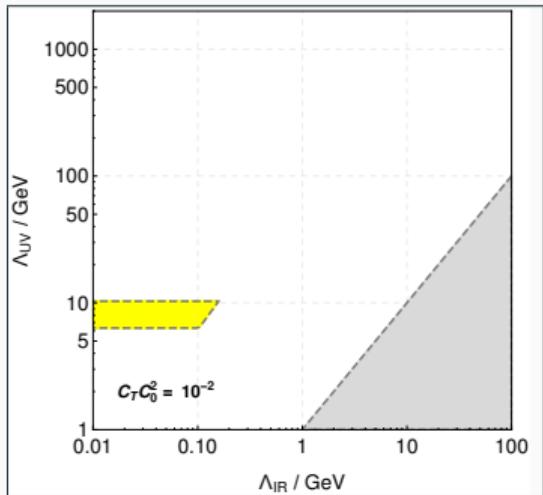


Perform statistical analysis using all possible bin configurations.

Bounds from LEP and LHC

Bounds on $\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}} - (\Lambda_{\text{IR}}, \Lambda_{\text{UV}})$

Shaded regions are excluded at 95% probability



- EFT validity
- LHC13 monojet (ATLAS 1711.03301)
- LEP mono- γ (L3 PLB 587) High-E
- LEP mono- γ (OPAL 0005002)
- LEP mono- γ (L3 PLB 587) Low-E

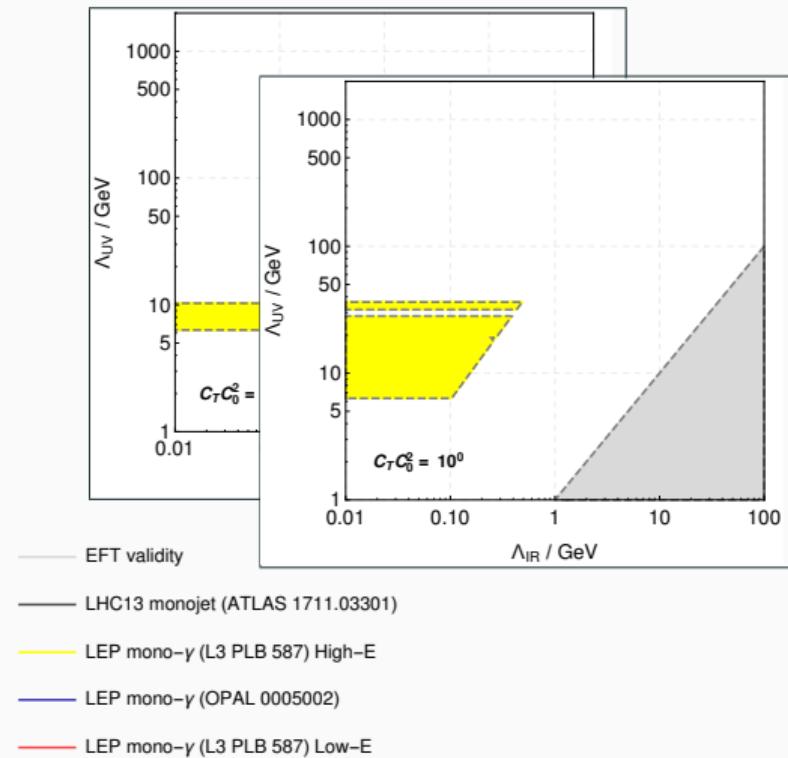
preliminary

YM: $C_T \times C_0^2 \sim \frac{N_c^2}{16\pi^2} \times g_{\text{UV}}^4$

The diagram shows a gauge boson loop with two fermion lines. The gauge boson is labeled $T_{\mu\nu}^{\text{CFT}}$ and has a coupling g_{UV} . The fermion lines are labeled ψ and $\bar{\psi}$. The angle between the gauge boson and the fermion lines is φ .

Bounds on $\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}} - (\Lambda_{\text{IR}}, \Lambda_{\text{UV}})$

Shaded regions are excluded at 95% probability



YM: $C_T \times C_0^2 \sim \frac{N_c^2}{16\pi^2} \times g_{\text{UV}}^4$

ψ

$\bar{\psi}$

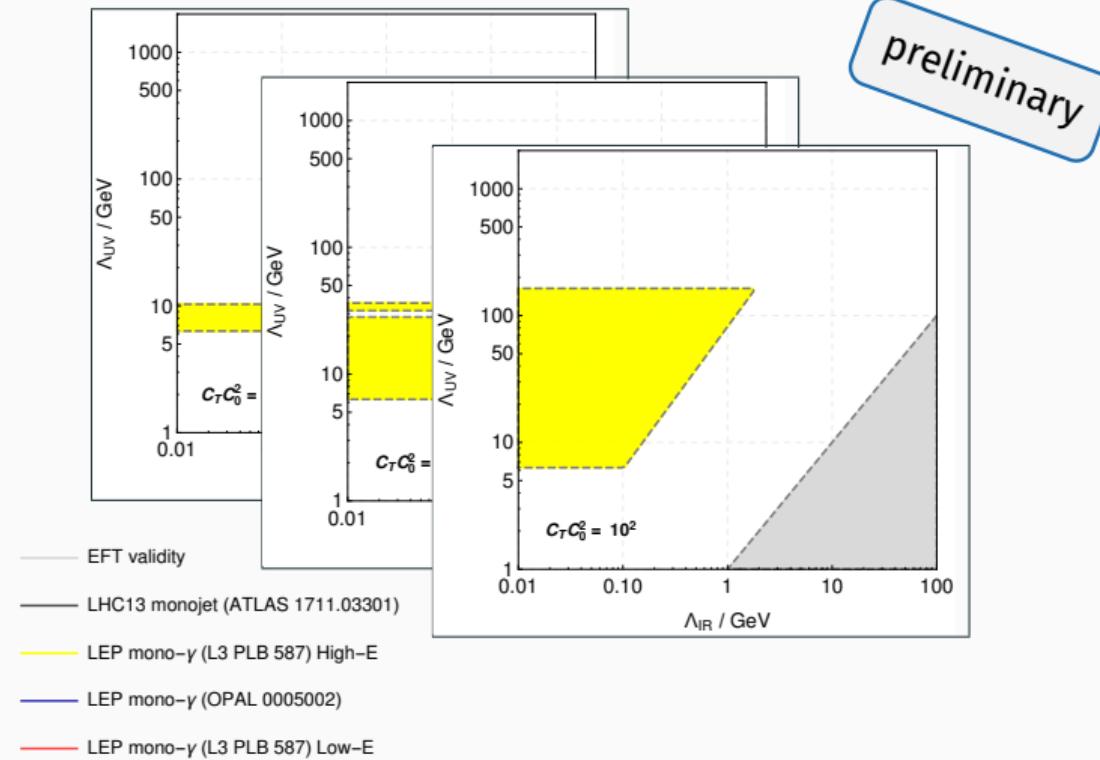
φ

g_{UV}

$T_{\mu\nu}^{\text{CFT}}$

Bounds on $\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}} - (\Lambda_{\text{IR}}, \Lambda_{\text{UV}})$

Shaded regions are excluded at 95% probability

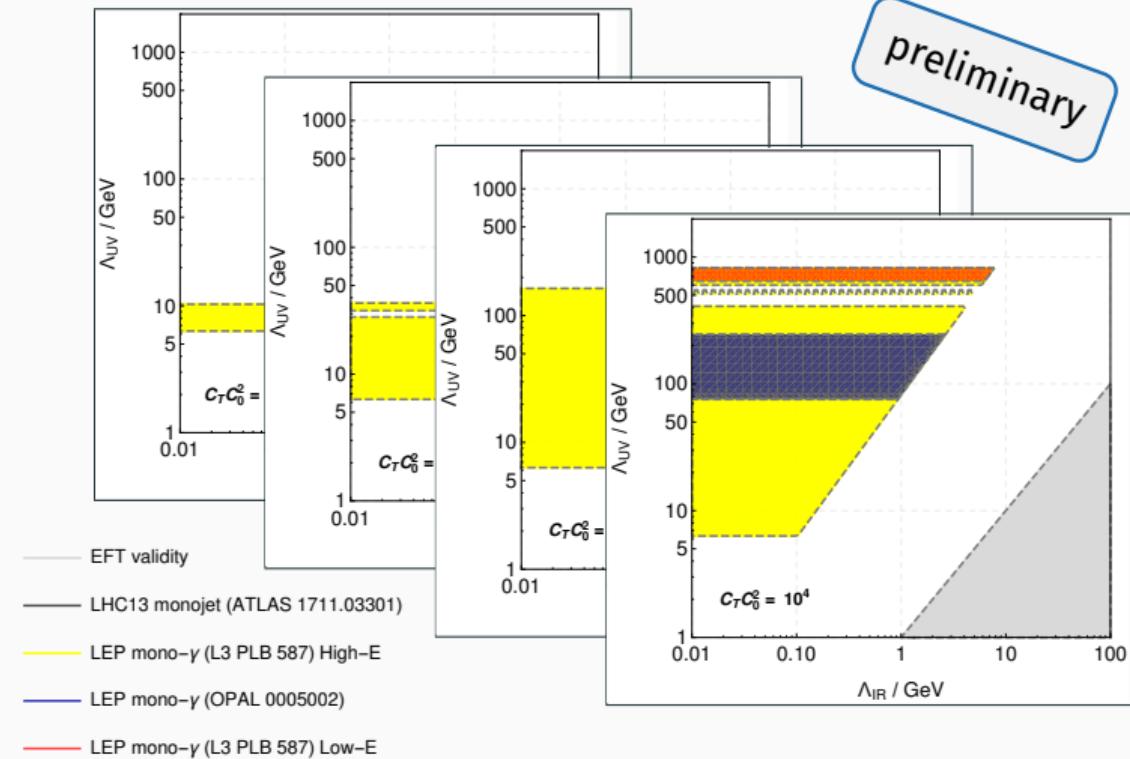


YM: $C_T \times C_0^2 \sim \frac{N_c^2}{16\pi^2} \times g_{\text{UV}}^4$

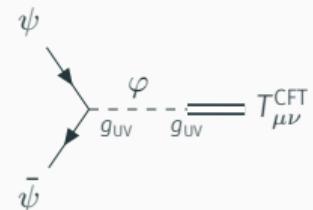
ψ φ g_{UV} $T_{\mu\nu}^{\text{CFT}}$

Bounds on $\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}} - (\Lambda_{\text{IR}}, \Lambda_{\text{UV}})$

Shaded regions are excluded at 95% probability

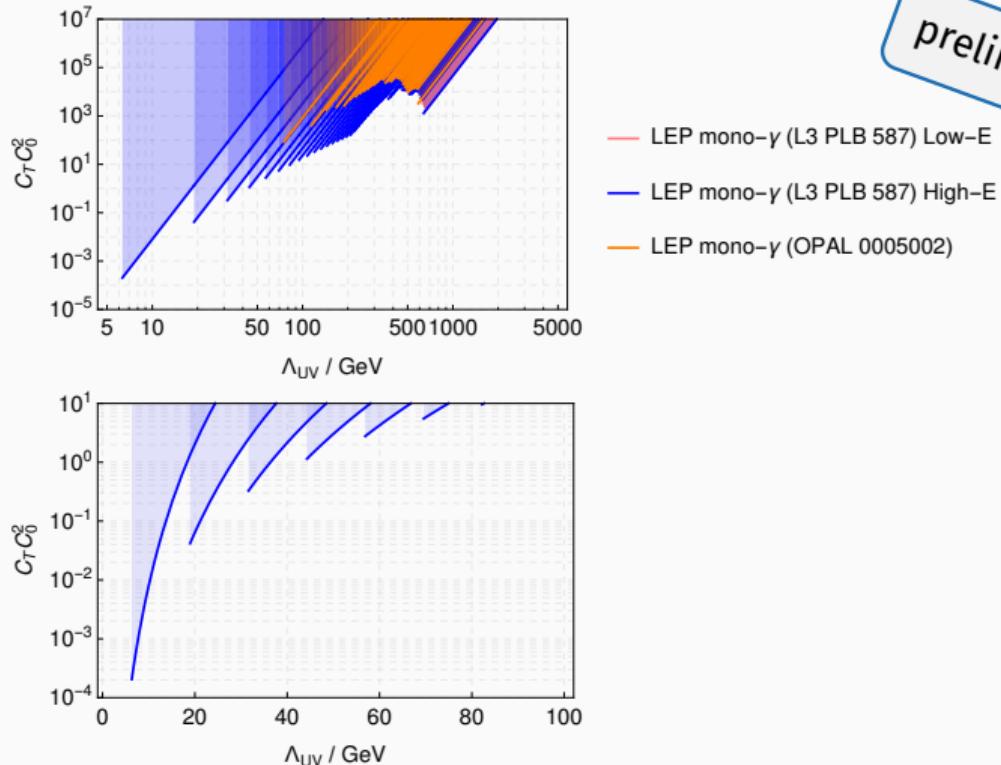


$$\text{YM: } C_T \times C_0^2 \sim \frac{N_c^2}{16\pi^2} \times g_{\text{UV}}^4$$



Bounds on $\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}} - (\Lambda_{\text{UV}}, C_T C_0^2)$

Shaded regions are excluded at 95% probability



preliminary

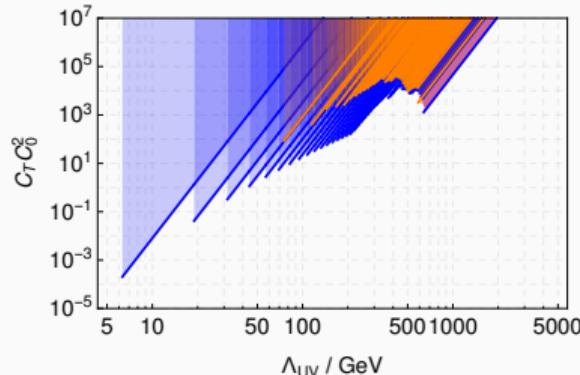
YM: $C_T \times C_0^2 \sim \frac{N_c^2}{16\pi^2} \times g_{\text{UV}}^4$

ψ φ g_{UV} $T_{\mu\nu}^{\text{CFT}}$

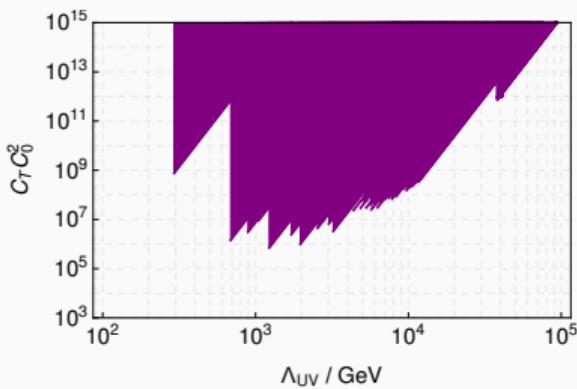
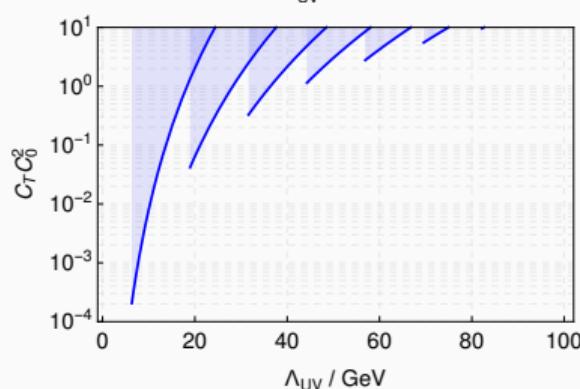
$\bar{\psi}$

Bounds on $\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}} - (\Lambda_{\text{UV}}, C_T C_0^2)$

Shaded regions are excluded at 95% probability



preliminary



YM: $C_T \times C_0^2 \sim \frac{N_c^2}{16\pi^2} \times g_{\text{UV}}^4$

Testing a model

Example: QCD-like $SU(N_c)$ with N_f fundamental fermions

N_f in conformal window, $\beta_g \rightarrow 0$ in IR

Testing a model

Example: QCD-like $SU(N_c)$ with N_f fundamental fermions

N_f in conformal window, $\beta_g \rightarrow 0$ in IR

From OPE at $Q^2 \rightarrow \infty$: (see Zoller & Chetyrkina '14)

$$\begin{aligned} & \langle 0 | \mathcal{T}[T_{\mu\nu}^{\text{CFT}}(p) T_{\rho\sigma}^{\text{CFT}}(-p)] | 0 \rangle \\ & \approx \frac{1}{16\pi^2} (\#N_c^2 + \#N_f N_c) Q^4 \log Q^2 \end{aligned}$$

Testing a model

Example: QCD-like $SU(N_c)$ with N_f fundamental fermions

N_f in conformal window, $\beta_g \rightarrow 0$ in IR

From OPE at $Q^2 \rightarrow \infty$: (see Zoller & Chetyrkina '14)

$$\begin{aligned} & \langle 0 | \mathcal{T}[T_{\mu\nu}^{\text{CFT}}(p) T_{\rho\sigma}^{\text{CFT}}(-p)] | 0 \rangle \\ & \approx \frac{1}{16\pi^2} (\#N_c^2 + \#N_f N_c) Q^4 \log Q^2 \end{aligned}$$

Pick e.g. $g_{UV} = 1$

$$\Rightarrow C_T C_0^2 \approx 10^{-2} N_c^2$$

Testing a model

Example: QCD-like $SU(N_c)$ with N_f fundamental fermions

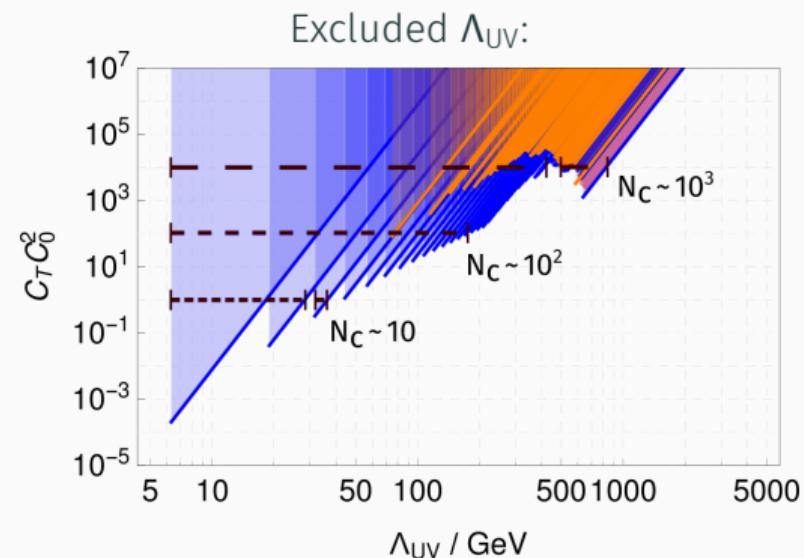
N_f in conformal window, $\beta_g \rightarrow 0$ in IR

From OPE at $Q^2 \rightarrow \infty$: (see Zoller & Chetyrkina '14)

$$\begin{aligned} & \langle 0 | \mathcal{T}[T_{\mu\nu}^{\text{CFT}}(p) T_{\rho\sigma}^{\text{CFT}}(-p)] | 0 \rangle \\ & \approx \frac{1}{16\pi^2} (\#N_c^2 + \#N_f N_c) Q^4 \log Q^2 \end{aligned}$$

Pick e.g. $g_{\text{UV}} = 1$

$$\Rightarrow C_T C_0^2 \approx 10^{-2} N_c^2$$



Caveats to present analysis

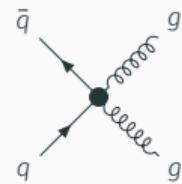
“But what about...”



Caveats to present analysis

“But what about...”

- generating $T_{\text{SM}}^2 > T_{\text{SM}} T_{\text{CFT}}$?
- lower (< 8)-dim. ops^a?
- exotic jet signatures?
- stable hidden sector particles?


$$= \frac{1}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^2$$

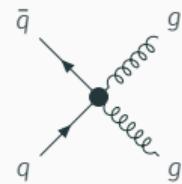
^aCheck that decay to SM happens out of detector before applying our bounds.

Caveats to present analysis

“But what about...”

- generating $T_{\text{SM}}^2 > T_{\text{SM}} T_{\text{CFT}}$?
- lower (< 8)-dim. ops^a?
- exotic jet signatures?
- stable hidden sector particles?

}


$$= \frac{1}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^2$$

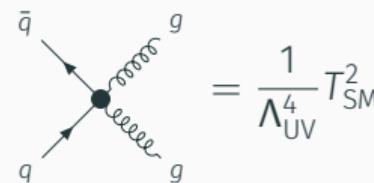
Great! Improves bounds beyond generic analysis.

^aCheck that decay to SM happens out of detector before applying our bounds.

Caveats to present analysis

“But what about...”

- generating $T_{\text{SM}}^2 > T_{\text{SM}} T_{\text{CFT}}$?
- lower (< 8)-dim. ops^a?
- exotic jet signatures?
- stable hidden sector particles?
- coupling only to $g/\gamma/q/l$? \Rightarrow *work in progress*
- $\Lambda_{\text{IR}} \approx \sqrt{S_{\text{LHC}}} \text{ or } \sqrt{S_{\text{LEP}}}$ \Rightarrow ~~Unparticles~~ **hidden valley**
- CFT breaking operators, e.g. $|H|^2 \mathcal{O}$?
- $\Lambda_{\text{IR}} \rightarrow 0$?



$$= \frac{1}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^2$$

Great! Improves bounds beyond generic analysis.

^aCheck that decay to SM happens out of detector before applying our bounds.

Conclusions.

Conclusions.

- Coupling to $T_{\mu\nu} \Rightarrow$ generic bounds on many BSM models

Conclusions.

- Coupling to $T_{\mu\nu} \Rightarrow$ generic bounds on many BSM models
- Unparticles are a (mathematical) tool to describe its dynamics

Conclusions.

- Coupling to $T_{\mu\nu} \Rightarrow$ generic bounds on many BSM models
- Unparticles are a (mathematical) tool to describe its dynamics
- Many QCD-like models: $\Lambda_{\text{UV}} \gtrsim \mathcal{O}(10^2 - 10^3)$ GeV

Conclusions.

- Coupling to $T_{\mu\nu} \Rightarrow$ generic bounds on many BSM models
- Unparticles are a (mathematical) tool to describe its dynamics
- Many QCD-like models: $\Lambda_{\text{UV}} \gtrsim \mathcal{O}(10^2 - 10^3)$ GeV
- Results: LEP \gg LHC due to validity constraints of EFT

$$\Lambda_{\text{UV}}^{\min} \gg \sqrt{S - 2\sqrt{S} E_X} \quad \Rightarrow \quad \text{Need } \vec{p}_T \text{ measurement close to } E_X \approx \sqrt{S}/2!$$

Conclusions.

- Coupling to $T_{\mu\nu} \Rightarrow$ generic bounds on many BSM models
- Unparticles are a (mathematical) tool to describe its dynamics
- Many QCD-like models: $\Lambda_{\text{UV}} \gtrsim \mathcal{O}(10^2 - 10^3)$ GeV
- Results: LEP \gg LHC due to validity constraints of EFT

$$\Lambda_{\text{UV}}^{\min} \gg \sqrt{S - 2\sqrt{S} E_X} \quad \Rightarrow \quad \text{Need } \vec{p}_T \text{ measurement close to } E_X \approx \sqrt{S}/2!$$

fin.

Furthermore...

Application to $\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}}$

We need the propagator $\langle 0 | \mathcal{T}[T_{\mu\nu}^{\text{CFT}}(p) T_{\rho\sigma}^{\text{CFT}}(-p)] | 0 \rangle$.

Application to $\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}}$

We need the propagator $\langle 0 | \mathcal{T}[T_{\mu\nu}^{\text{CFT}}(p) T_{\rho\sigma}^{\text{CFT}}(-p)] | 0 \rangle$.

→ From conformal symmetry (Grinstein et al. '08):

$$\langle 0 | \mathcal{T}[\mathcal{O}_{\mu\nu}(p) \mathcal{O}_{\rho\sigma}(-p)] | 0 \rangle = -i C_T \frac{\Gamma(2 - d_U)}{4^{d_U - 1} \Gamma(d_U + 2)} (-p^2 - i\epsilon)^{d_U - 2} P_{\mu\nu\rho\sigma}^{d_U}(p) \quad (3)$$

Application to $\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}}$

We need the propagator $\langle 0 | \mathcal{T}[T_{\mu\nu}^{\text{CFT}}(p) T_{\rho\sigma}^{\text{CFT}}(-p)] | 0 \rangle$.

→ From conformal symmetry (Grinstein et al. '08):

$$\langle 0 | \mathcal{T}[\mathcal{O}_{\mu\nu}(p) \mathcal{O}_{\rho\sigma}(-p)] | 0 \rangle = -i C_T \frac{\Gamma(2 - d_U)}{4^{d_U-1} \Gamma(d_U + 2)} (-p^2 - i\epsilon)^{d_U-2} P_{\mu\nu\rho\sigma}^{d_U}(p) \quad (3)$$

with Lorentz index structure

$$\begin{aligned} P_{\mu\nu\rho\sigma}^{d_U}(p) &= d_U (d_U - 1) (\eta_{\mu\rho} \eta_{\nu\sigma} + \mu \leftrightarrow \nu) + \frac{1}{2} \left[4 - d_U (d_U + 1) \right] \eta_{\mu\nu} \eta_{\rho\sigma} \\ &\quad - 2(d_U - 1)(d_U - 2) \left(\eta_{\mu\rho} \frac{p_\nu p_\sigma}{p^2} + \eta_{\mu\sigma} \frac{p_\nu p_\rho}{p^2} + \mu \leftrightarrow \nu \right) \\ &\quad + 4(d_U - 2) \left(\eta_{\mu\nu} \frac{p_\rho p_\sigma}{p^2} + \eta_{\rho\sigma} \frac{p_\mu p_\nu}{p^2} \right) + 8(d_U - 2)(d_U - 3) \frac{p_\mu p_\nu p_\rho p_\sigma}{(p^2)^2}. \end{aligned}$$

Application to $\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}}$

We need the propagator $\langle 0 | \mathcal{T}[T_{\mu\nu}^{\text{CFT}}(p) T_{\rho\sigma}^{\text{CFT}}(-p)] | 0 \rangle$.

→ From conformal symmetry (Grinstein et al. '08):

$$\langle 0 | \mathcal{T}[\mathcal{O}_{\mu\nu}(p) \mathcal{O}_{\rho\sigma}(-p)] | 0 \rangle = -i C_T \frac{\Gamma(2 - d_U)}{4^{d_U - 1} \Gamma(d_U + 2)} (-p^2 - i\epsilon)^{d_U - 2} P_{\mu\nu\rho\sigma}^{d_U}(p) \quad (3)$$

with Lorentz index structure

$$P_{\mu\nu\rho\sigma}^{d_U}(p) = d_U (d_U - 1) (\eta_{\mu\rho} \eta_{\nu\sigma} + \mu \leftrightarrow \nu) + \frac{1}{2} \left[\begin{aligned} & \left. \eta_{\mu\nu} \eta_{\rho\sigma} \right] (d_U + 1) \\ & - 2(d_U - 1) \left. \eta_{\mu\nu} \eta_{\rho\sigma} \right] \left(\eta_{\mu\sigma} \frac{p_\rho p_\nu}{p^2} + \mu \leftrightarrow \nu \right) \\ & + 4(d_U - 2) \left(\eta_{\mu\nu} \frac{p_\rho p_\sigma}{p^2} + \eta_{\rho\sigma} \frac{p_\mu p_\nu}{p^2} \right) + 8(d_U - 2)(d_U - 3) \frac{p_\mu p_\nu p_\rho p_\sigma}{(p^2)^2}. \end{aligned} \right]$$

Take away: not $(P_T)_{\mu\nu} = \eta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}$

Application to $\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}}$

We need the propagator $\langle 0 | \mathcal{T}[T_{\mu\nu}^{\text{CFT}}(p) T_{\rho\sigma}^{\text{CFT}}(-p)] | 0 \rangle$.

→ From conformal symmetry (Grinstein et al. '08):

$$\langle 0 | \mathcal{T}[\mathcal{O}_{\mu\nu}(p) \mathcal{O}_{\rho\sigma}(-p)] | 0 \rangle = -i C_T \frac{\Gamma(2 - d_U)}{4^{d_U - 1} \Gamma(d_U + 2)} (-p^2 - i\epsilon)^{d_U - 2} P_{\mu\nu\rho\sigma}^{d_U}(p) \quad (3)$$

Take $d_U \rightarrow 4$:

Application to $\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}}$

We need the propagator $\langle 0 | \mathcal{T}[T_{\mu\nu}^{\text{CFT}}(p) T_{\rho\sigma}^{\text{CFT}}(-p)] | 0 \rangle$.

→ From conformal symmetry (Grinstein et al. '08):

$$\langle 0 | \mathcal{T}[\mathcal{O}_{\mu\nu}(p) \mathcal{O}_{\rho\sigma}(-p)] | 0 \rangle = -i C_T \frac{\Gamma(2 - d_U)}{4^{d_U-1} \Gamma(d_U + 2)} (-p^2 - i\epsilon)^{d_U-2} P_{\mu\nu\rho\sigma}^{d_U}(p) \quad (3)$$

Take $d_U \rightarrow 4$:

$$\lim_{d_U \rightarrow 4} \frac{\Gamma(2 - d_U)}{4^{d_U-1} \Gamma(d_U + 2)} (-p^2)^{d_U-2} \propto \lim_{\delta \rightarrow 0} \left[\frac{1}{\delta} + \text{const.} \right] \left[1 + \delta \log(-p^2 - i\epsilon) \right] (p^2 + i\epsilon)^2 + \mathcal{O}(\delta).$$

Application to $\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}}$

We need the propagator $\langle 0 | \mathcal{T}[T_{\mu\nu}^{\text{CFT}}(p) T_{\rho\sigma}^{\text{CFT}}(-p)] | 0 \rangle$.

→ From conformal symmetry (Grinstein et al. '08):

$$\langle 0 | \mathcal{T}[\mathcal{O}_{\mu\nu}(p) \mathcal{O}_{\rho\sigma}(-p)] | 0 \rangle = -i C_T \frac{\Gamma(2 - d_U)}{4^{d_U-1} \Gamma(d_U + 2)} (-p^2 - i\epsilon)^{d_U-2} P_{\mu\nu\rho\sigma}^{d_U}(p) \quad (3)$$

Take $d_U \rightarrow 4$:

$$\lim_{d_U \rightarrow 4} \frac{\Gamma(2 - d_U)}{4^{d_U-1} \Gamma(d_U + 2)} (-p^2)^{d_U-2} \propto \lim_{\delta \rightarrow 0} \left[\frac{1}{\delta} + \text{const.} \right] \left[1 + \delta \log(-p^2 - i\epsilon) \right] (p^2 + i\epsilon)^2 + \mathcal{O}(\delta).$$

⇒ local term $\partial^2 \delta(x)$

Application to $\frac{C_0}{\Lambda_{\text{UV}}^4} T_{\text{SM}}^{\mu\nu} T_{\mu\nu}^{\text{CFT}}$

We need the propagator $\langle 0 | \mathcal{T}[T_{\mu\nu}^{\text{CFT}}(p) T_{\rho\sigma}^{\text{CFT}}(-p)] | 0 \rangle$.

→ From conformal symmetry (Grinstein et al. '08):

$$\langle 0 | \mathcal{T}[\mathcal{O}_{\mu\nu}(p) \mathcal{O}_{\rho\sigma}(-p)] | 0 \rangle = -i C_T \frac{\Gamma(2 - d_U)}{4^{d_U-1} \Gamma(d_U + 2)} (-p^2 - i\epsilon)^{d_U-2} P_{\mu\nu\rho\sigma}^{d_U}(p) \quad (3)$$

Take $d_U \rightarrow 4$:

$$\lim_{d_U \rightarrow 4} \frac{\Gamma(2 - d_U)}{4^{d_U-1} \Gamma(d_U + 2)} (-p^2)^{d_U-2} \propto \lim_{\delta \rightarrow 0} \left[\frac{1}{\delta} + \text{const.} \right] \left[1 + \delta \log(-p^2 - i\epsilon) \right] (p^2 + i\epsilon)^2 + \mathcal{O}(\delta).$$

⇒ local term $\partial^2 \delta(x)$

⇒ finite piece:

$$\langle 0 | \mathcal{T}[T_{\mu\nu}^{\text{CFT}}(p) T_{\rho\sigma}^{\text{CFT}}(-p)] | 0 \rangle = i C_T N_T P_{\mu\nu\rho\sigma}^4(p) (p^2 + i\epsilon)^2 \log(-p^2 - i\epsilon) \quad (4)$$

Inputs:

- n_{BSM} (predicted @ $\Lambda_{\text{UV}} = 1 \text{ TeV}$), n_{SM} (from data), n_{obs} for i different bins
- Parameters to optimise, here: Λ_{UV}
- Prior $\pi(\Lambda_{\text{UV}})$, here: $\pi(\Lambda_{\text{UV}}) = \Theta(\Lambda_{\text{UV}})$

Bayesian likelihood analysis:

$$\underbrace{p(\Lambda_{\text{UV}}|n_{\text{obs}})}_{\text{Posterior prob.}} = \text{Norm} \cdot \underbrace{\left(\prod_i L_i \right)}_{\text{Likelihoods}} \cdot \pi(\Lambda_{\text{UV}}) \quad \text{w/ } L_i \equiv p(n_{\text{obs}}^i | \Lambda_{\text{UV}}) = \text{Poisson}\left(n_{\text{SM}}^i + \frac{n_{\text{BSM}}^i}{\Lambda_{\text{UV}}^8}, n_{\text{data}}^i\right)$$

$$0.95 \stackrel{!}{=} \int_{\Lambda_{\text{UV}}^{95\%}}^{\infty} d\Lambda_{\text{UV}} p(\Lambda_{\text{UV}}|n_{\text{obs}})$$

see *Bayesian reasoning in data analysis* by D'Agostini