Beyond-cutoff effects in EFT limit-setting

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(with F. Pobbe and M. Zanetti, arXiv:1704.00736)

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Phenomenological Models

The Standard Higgs model was the only **compelling** and **predictive** new physics model to be searched for at the LHC

Consequently, the SM Higgs was the only hypothetical particle for which sharp (1 free par. only) theoretical predictions could be made

For all the rest, **including BSM Higgs properties**, no compelling and fully predictive model is available

Employing **conventional benchmark models is not an option**

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Few-parameters descriptions of a **limited set** of processes, representative of a **large class** of new physics scenarios

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Describe **resonant prod./decay,** e.g.

- Breit-Wigner
- SUSY simplified models
- ….

EFT-based Ph. M.

Describe **low-energy proc.** ,e.g.

- Flavour/EWPT physics
- Dark Matter
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OR, "good" events can be **identified** and **selected**

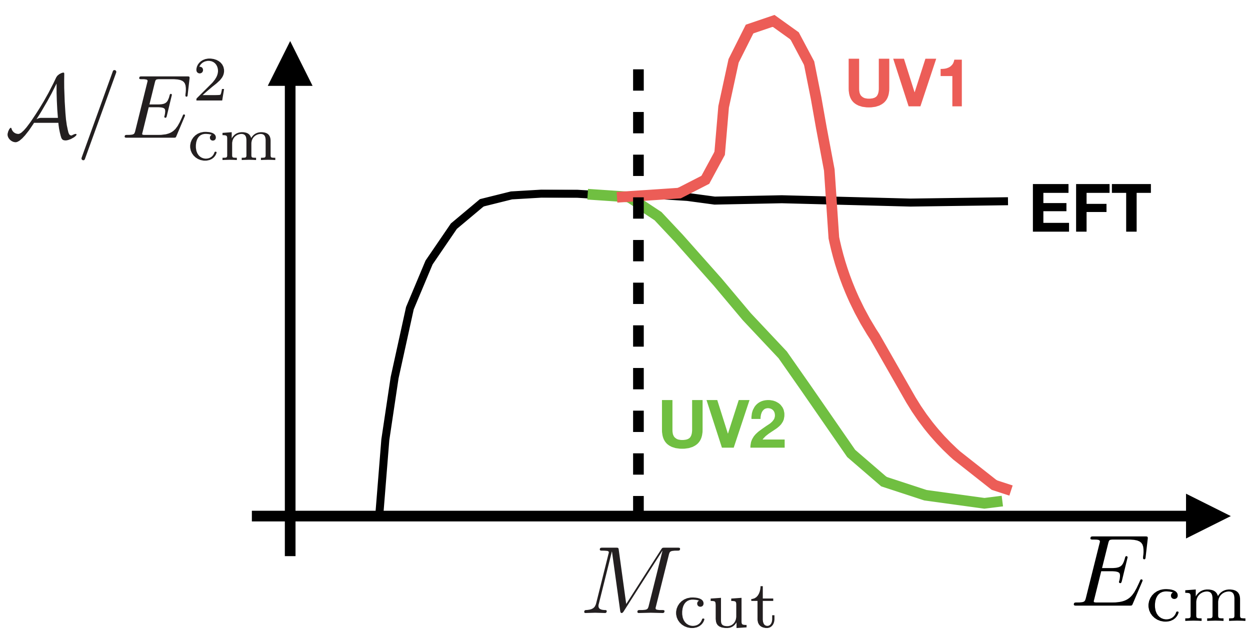
OR (e.g., **DM EFT**), no way to tell if event is good. What to do, then?

Beyond-cutoff Effects

EFT only holds below its cutoff: $M_{\rm cut}$

Reactions below are predictable, i.e. EFT reproduces the infinite set of UV theories they aim at describing

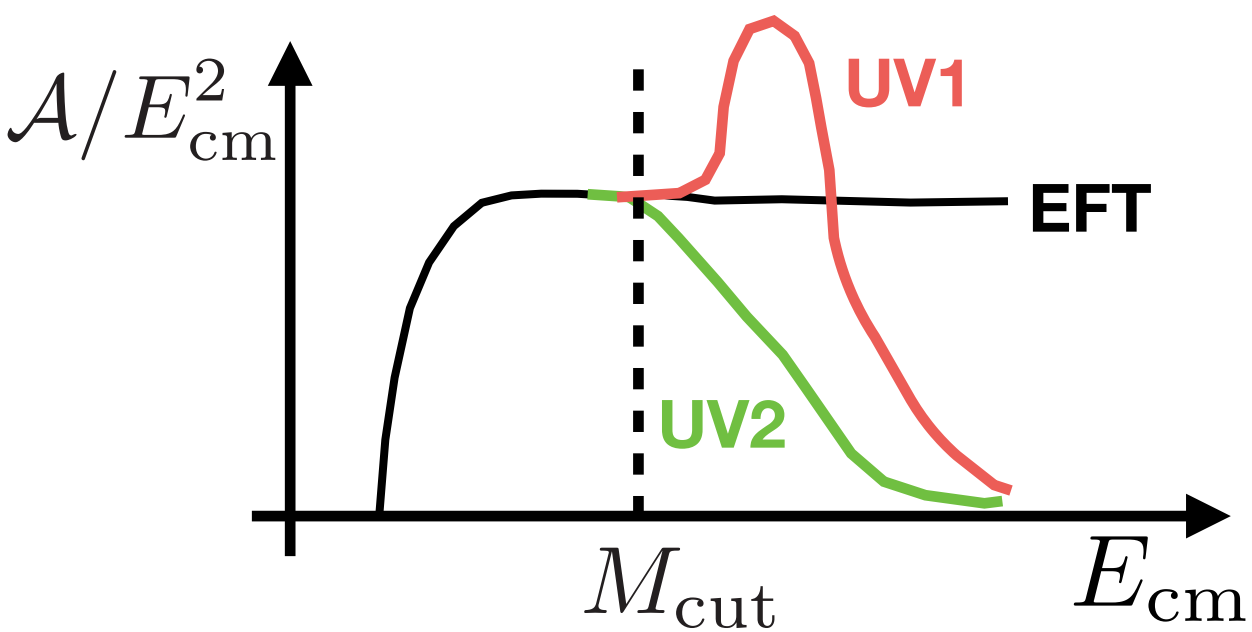
For reactions above, EFT looses any resemblance to UV ones:
(remark: unrestricted EFT can **underestimate or overestimate** signal)



Beyond-cutoff Effects

Three possibilities:

1. $M_{\rm cut} >$ available energy: nothing to worry about



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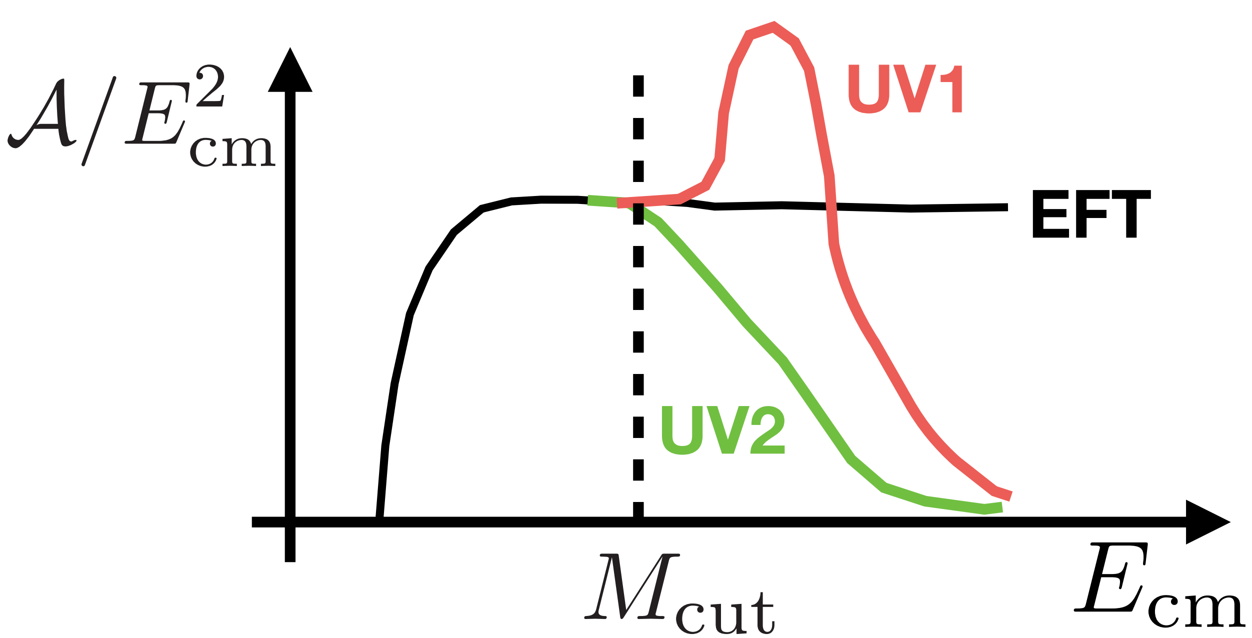
2. E_{cm} can be measured in data: place a cut $E_{\text{cm}} < M_{\text{cut}}$



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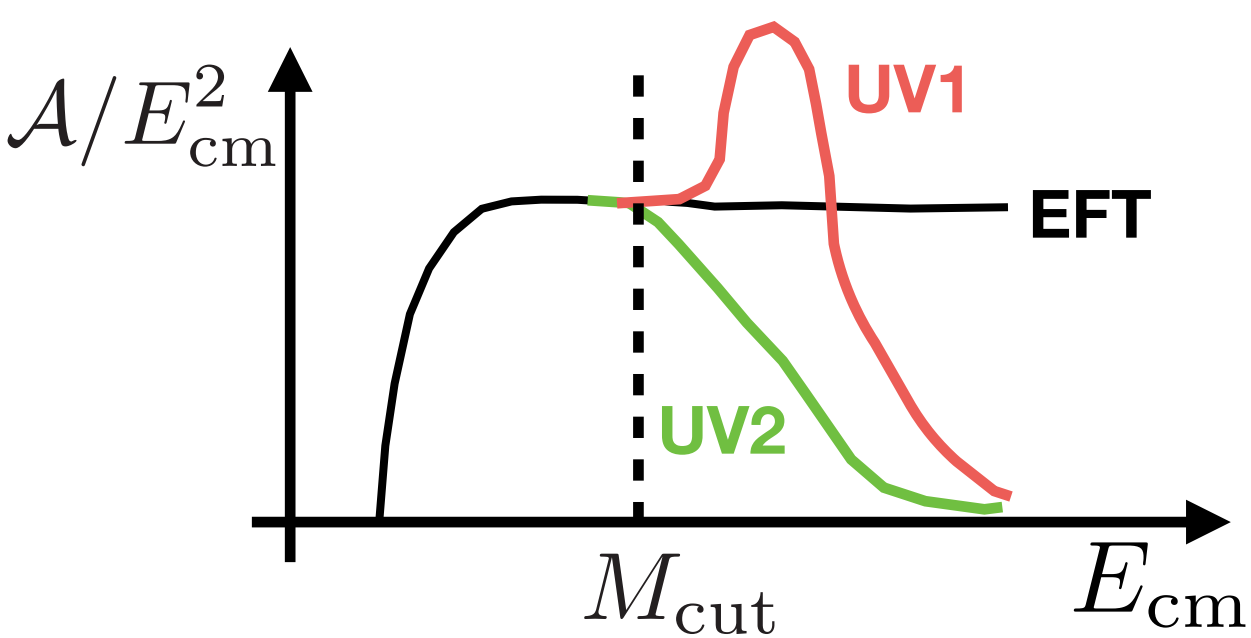
$$n_i^{\rm DM} = \int_{{\rm bin}_i} d\not{E}_T \int^{M_{\rm cut}} dE_{\rm cm} \frac{d^2 n_i^{\rm DM}}{dE_{\rm cm} d\not{E}_T} + \int_{{\rm bin}_i} d\not{E}_T \int_{M_{\rm cut}}^{\sqrt{S}} dE_{\rm cm} \frac{d^2 n_i^{\rm DM}}{dE_{\rm cm} d\not{E}_T} \equiv n_i^{\rm EFT} + \Delta n_i$$



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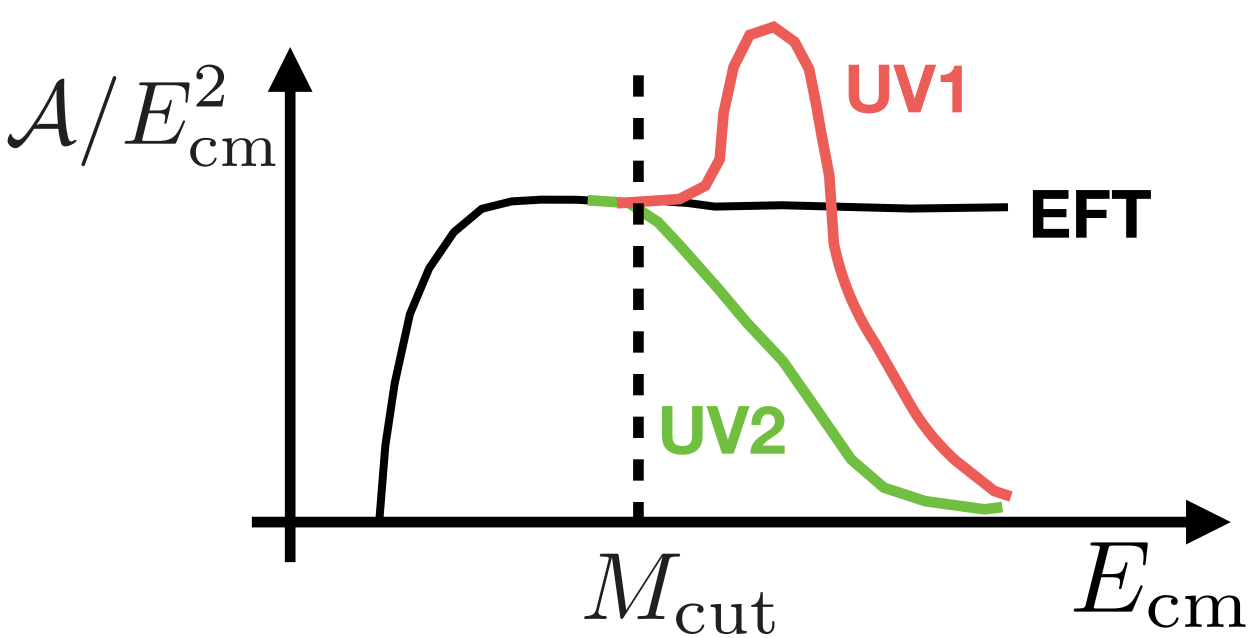

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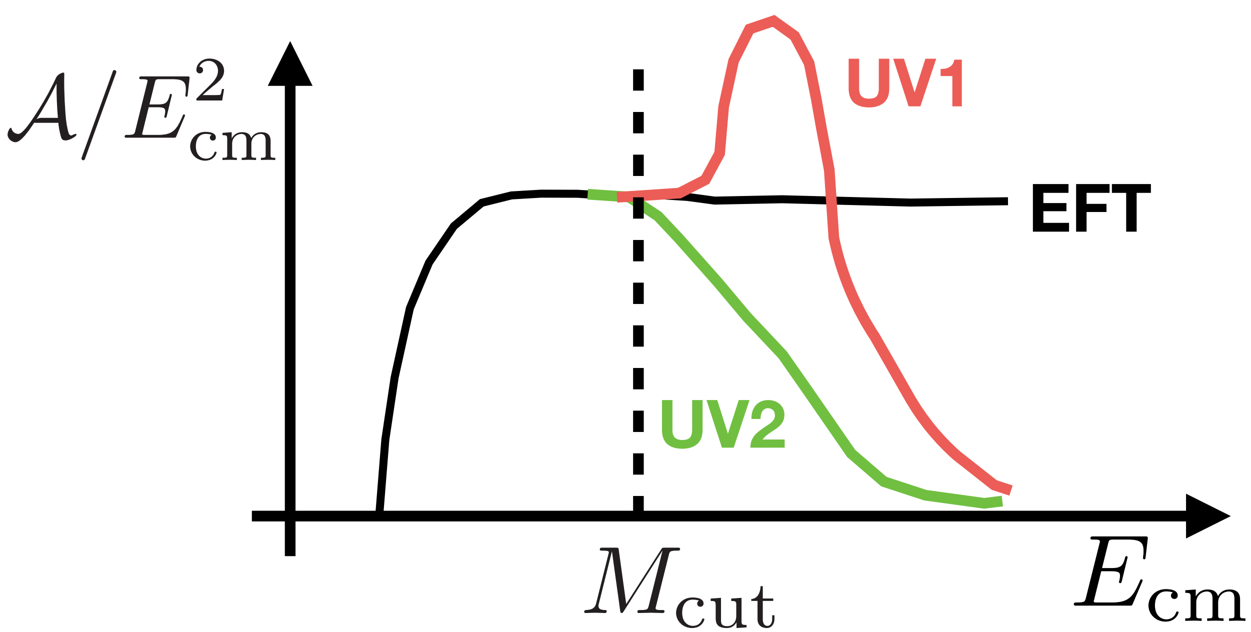

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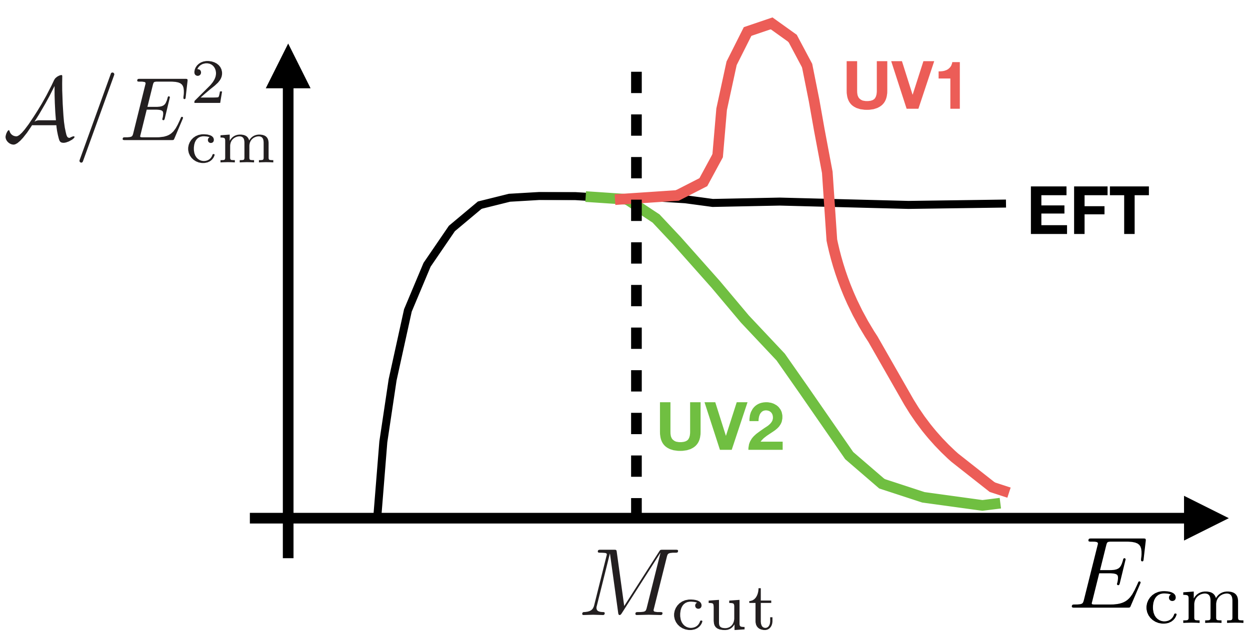

EFT signal restricted to $E_{\rm cm} < M_{\rm cut}$

"Additional signal" from $E_{\rm cm} > M_{\rm cut}$

No interference from kin. distinct region, add. signal is **positive**:

$$\Delta_i \geq 0$$

Limits with Unknown Additional Signal

Single-bin (cut-and-count) case is trivial: $\overline{n}^{\mathrm{EFT}} \leq \overline{n}^{\mathrm{DM}} \leq \overline{n}^{\mathrm{DM}}_{\mathrm{exc.}}$

Ordinary bin. hist. test with $\mathrm{S}_i^{\mathrm{tot}} = \mathrm{S}_i$ is clearly inconsistent, as the EFT provides **no** definite **prediction** of signal **shape**

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Conceptually simple way out:

1. Apply "ordinary" test for any given $\Delta_i \geq 0$:

$$\underbrace{\mathrm{S}_i^{\mathrm{tot}} = \mathrm{S}_i + \Delta_i}_{\text{signal}} \longrightarrow \underbrace{L = L(\vec{\mathrm{S}}, \vec{\Delta}; \vec{O}\,) = \mathcal{P}(\vec{O}\,|\vec{\mathrm{S}} + \vec{\Delta})}_{\text{likelihood}}$$

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3. Test: $p_{\max} \lessgtr 1 - \alpha$

Limits with Unknown Additional Signal

Practically **feasible** only if $\vec{\Delta}$-independent t distribution.
True in the Asymptotic Limit (~3 exp. count.s/bin is enough)

$$t \sim f(t\,|\vec{\mathrm{S}},\vec{\Delta}) \quad \longrightarrow \quad t \overset{\mathrm{AL}}{\sim} f_{\chi^2}(t;N) = \frac{1}{2^{N/2}\Gamma(N/2)} t^{N/2-1}\mathrm{e}^{-t/2}$$

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$$\Downarrow$$

$$p_{\max} \overset{\mathrm{AL}}{=} \sup_{\Delta_i\geq 0}\left\{\int_{t(\vec{\mathrm{S}}+\vec{\Delta};\vec{O}\,)}^{\infty} dt'\, f(t')\right\} = \int_{t_{\min}}^{\infty} dt'\, f(t')$$

$$t_{\min}(\vec{\mathrm{S}};\vec{O}\,) = \inf_{\Delta_i\geq 0}\{t(\vec{\mathrm{S}},\vec{\Delta};\vec{O}\,)\}$$

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We identified four possible ways to proceed:

1. **Full Story:** Poisson likelihood with exact nuisance profiling

$$t_{\min} = \inf_{\vec{\nu}} \left[\sum_{\{\mathrm{S}_i + \mathrm{B}_i > O_i\}} 2 \left(\mathrm{S}_i(\vec{s}, \vec{\nu}) + \mathrm{B}_i(\vec{\nu}) - O_i - O_i \log \frac{\mathrm{S}_i(\vec{s}, \vec{\nu}) + \mathrm{B}_i(\vec{\nu})}{O_i} \right) - 2 \log \frac{\mathcal{L}_{\vec{\nu}}}{\mathcal{L}_{\vec{\nu}_0}} \right]$$

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2. **Chi-Squared:** Gaussian countings and nuisance (large stat.)

$$t \simeq \chi^2 = \sum_{i,j=1}^{N} (\mathrm{M}_i^0 - O_i)(\Sigma_{\mathrm{tot}}^{-1})_{ij}(\mathrm{M}_j^0 - O_j)\,, \qquad \Sigma_{\mathrm{tot}} = \Sigma_{\mathrm{M}} + \Sigma_\nu$$

$$\begin{aligned}(\Sigma_\nu)_{ij} = \; & \mu^2\, E[(\overline{\mathrm{S}}_i - \overline{\mathrm{S}}_i^0)(\overline{\mathrm{S}}_j - \overline{\mathrm{S}}_j^0)] + \mu\, E[(\overline{\mathrm{S}}_i - \overline{\mathrm{S}}_i^0)(B_j - B_j^0) + i \leftrightarrow j] \\ & + E\left[(\mathrm{B}_i - \mathrm{B}_i^0)(\mathrm{B}_j - \mathrm{B}_j^0)\right] \;.\end{aligned}$$

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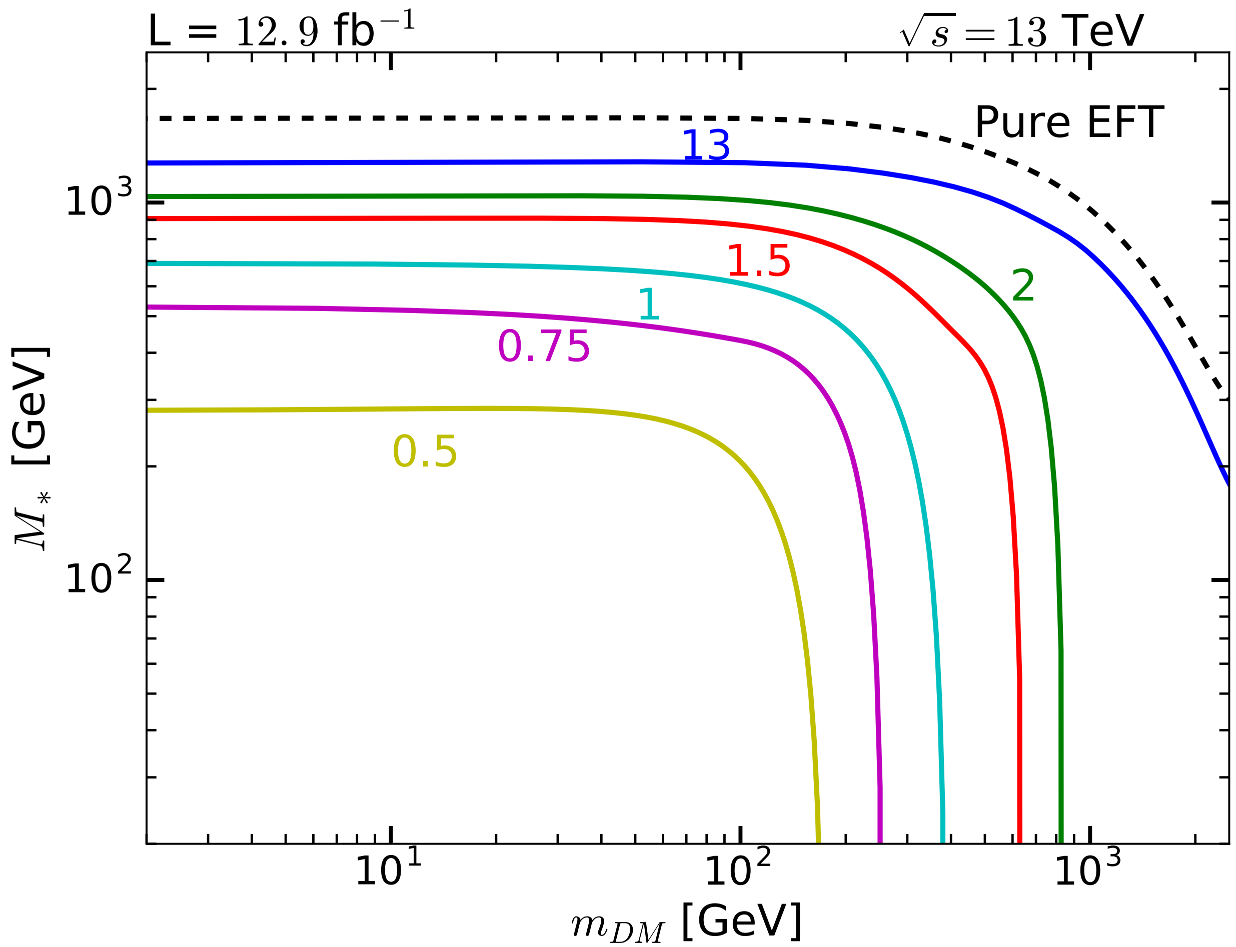
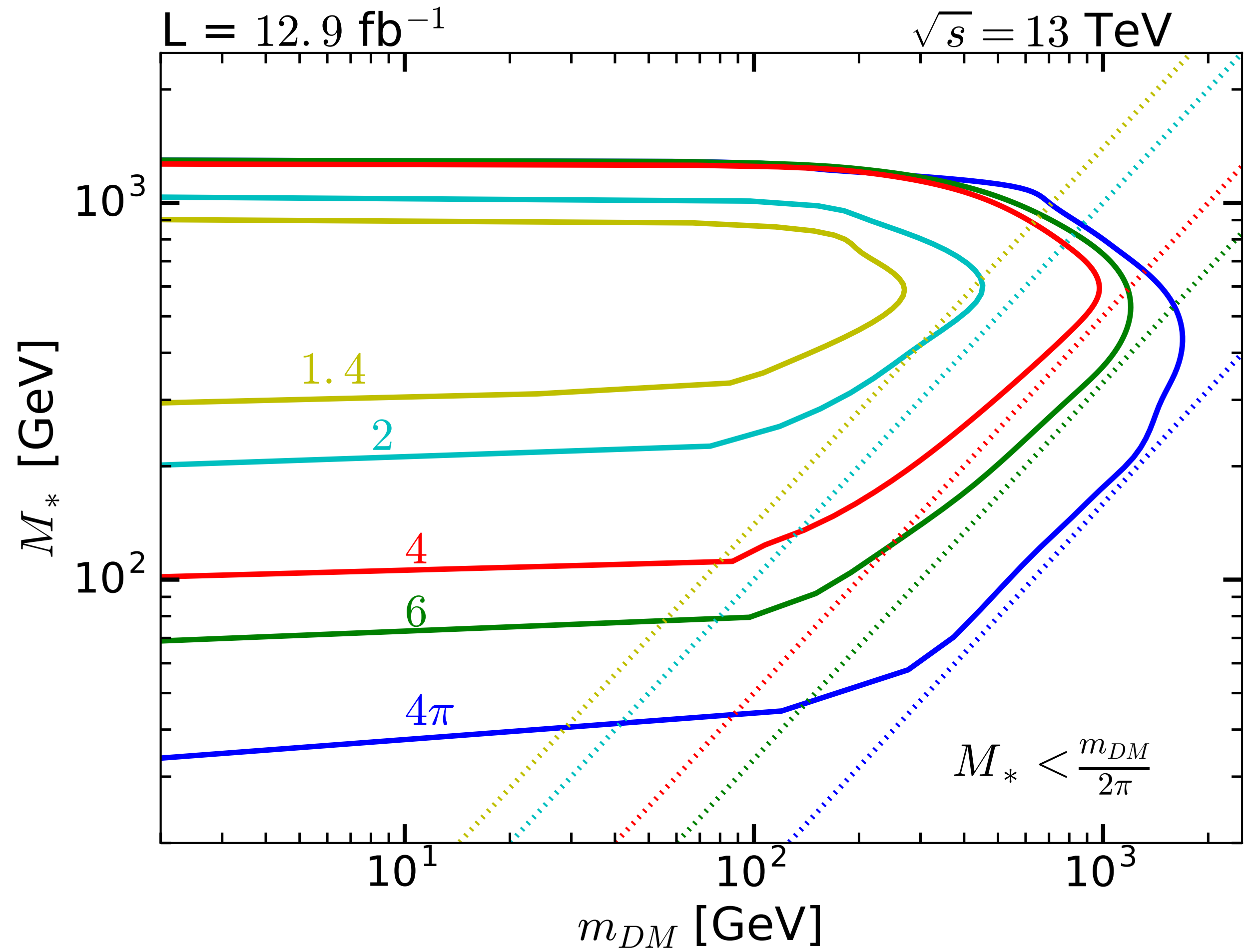
4. **Cross-section Measurements:**

$$t(\vec{\mathrm{S}}, \vec{\Delta}; \vec{O}\,) = \chi^2 = \sum_{i,j=1}^{N} (\vec{\sigma}^{\rm EFT} + \vec{\Delta} + \vec{b} - \vec{\sigma}^{\rm m})_i \Sigma_{ij}^{-1} (\vec{\sigma}^{\rm EFT} + \vec{\Delta} + \vec{b} - \vec{\sigma}^{\rm m})_j$$

CMS DM Mono-jet Reinterpretation





$$\mathcal{L}_{\rm int} = -\frac{1}{M_*^2}(\overline{X}\gamma^\mu\gamma^5 X)(\sum_q \bar{q}\gamma_\mu\gamma^5 q)$$

$$\frac{1}{M_*^2} = \frac{g_*^2}{M_{\rm cut}^2}$$

Conclusions

- EFT's can be also used under **extreme conditions** where
  1. Beyond-cutoff effects can be large
  2. Center-of-mass energy not experimentally detectable

- Our dedicated stat. method **only needed** in these extreme cases

- No assumption whatsoever made on beyond-cutoff contribution
  Hence limits always weaker than those for $\Delta_i = 0$, even if $M_{\mathrm{cut}} = \infty$
  Whenever possible, standard limit-setting should performed