$SCET_{BSM}$ for Scalar Leptoquarks

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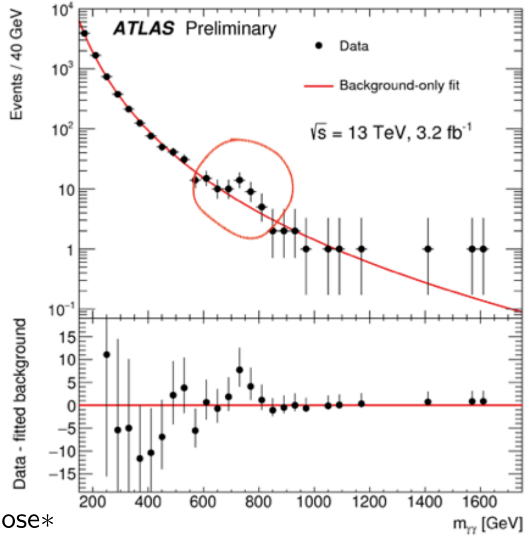
Work in progress with M.Neubert

In case of a new heavy resonance. How would we describe it?



Illustrative purpose∗

What's next?

In case of a new heavy resonance. How would we describe it?

use "some kind" of $\mathcal{EFT}$

$$\mathcal{L}_{eff} = \sum_{n \geq 1} \sum_{i} \frac{C_{n,i}(\Lambda, \mu)}{\Lambda^n} \mathcal{O}_{n,i}(M, \mu, v)$$

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- **Separate scales** $\Rightarrow$ **logs of large ratios :** $\alpha_s^n \log^{2n}(\frac{M}{v})$

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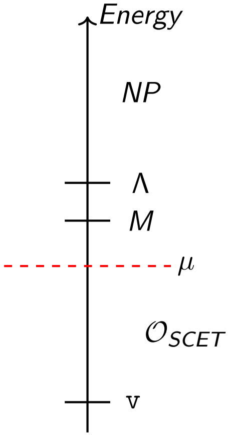
$$\mathcal{L}_{eff} = \sum_{n\geq 1}\sum_{i} \frac{C_{n,i}(\Lambda,\mu)}{\Lambda^n} \underbrace{\mathcal{O}_{n,i}(M,\mu,v)}_{\sim\Lambda^{n-k}v^k}$$

- **Separate scales** $\Rightarrow$ **logs of large ratios :** $\alpha_s^n \log^{2n}(\frac{M}{v})$
- **A tower of infinite number of effective operators for** $M \sim \Lambda$

SCET as the EFT

Bauer, Fleming, Pirjol, Stewart 2001;
Bauer, Pirjol, Stewart 2002;
Beneke, Chapovsky, Diehl, Feldmann 2002;



Run the scale to resum the logs

$$\mu\frac{d}{\mu}\mathcal{O}_{SCET} = \Gamma(\alpha, M, \mu)\mathcal{O}_{SCET}$$

SCET ingredients

Describe the interaction of collinear particles emitted in n_i directions: collinear - soft interactions

$$p^\mu = \bar{n} \cdot p \frac{n^\mu}{2} + n \cdot p \frac{\bar{n}^\mu}{2} + p_\perp^\mu$$

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- Each field has a corresponding scaling with λ at leading order

$$\Psi_c \sim \lambda$$
$$\Phi_{n_i} \sim \lambda$$
$$\mathcal{A}^\mu_{n_i,\perp} \sim \lambda$$
$$n_i \cdot \mathcal{A}_{n_i} \sim \lambda^2$$

$\hookrightarrow \lambda$ **is the power counting for leading and suppressed operators**

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- Fields are described by gauge invariant building blocks

$$\Psi_{n_i}(x) = \frac{\not{n}_i \bar{\not{n}}_i}{4} \underbrace{\left(P \exp \left[i \sum_k g^{(k)} \int_{-\infty}^{0} ds \bar{n}_i \cdot G_{n_i}^{(k)}(x + s\bar{n}_i) \right] \right)^\dagger}_{\text{Wilson line}} \psi(x)$$

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$$\Phi_{n_i}(x) = \mathcal{W}_{n_i}^\dagger(x)\phi(x), \Phi_0 \to (0,v)^T$$

$$\mathcal{A}_{n_i}^\mu = \mathcal{W}_{n_i}^{(A)\dagger}\left[i\mathcal{D}_{n_i}^\mu\mathcal{W}_{n_i}^{(A)}(x)\right]$$

Application to a scalar singlet

[S.Alte, M.König,M. Neubert; arXiv:1806.01278 & 1902.04593]

$$\mathcal{L}_{\text{eff}}^{(2)} = M\, C_{\phi\phi}(M_S, M, \mu)\, O_{\phi\phi}(\mu) + M \sum_{A=G,W,B} \Big[C_{AA}(M_S, M, \mu)\, O_{AA}(\mu) + \widetilde{C}_{AA}(M_S, M, \mu)\, \widetilde{O}_{AA}(\mu) \Big]$$

with:

$$O_{\phi\phi} = S\left(\Phi_{n_1}^\dagger \Phi_{n_2} + \Phi_{n_2}^\dagger \Phi_{n_1}\right)$$

$$O_{AA} = S\, g_{\mu\nu}^{\perp}\, \mathcal{A}_{n_1}^{\mu,a}\, \mathcal{A}_{n_2}^{\nu,a}$$

$$\widetilde{O}_{AA} = S\, \epsilon_{\mu\nu}^{\perp}\, \mathcal{A}_{n_1}^{\mu,a} \mathcal{A}_{n_2}^{\nu,a}$$

Matched into a UV complete model of a heavy vector-like quark:

$$\begin{aligned} \mathcal{L}_{\text{UV}} = \mathcal{L}_{\text{SM}} &+ \frac{1}{2}(\partial_\mu S)(\partial^\mu S) - \frac{M_S^2}{2} S^2 - \frac{\lambda_3}{3!} S^3 - \frac{\lambda_4}{4!} S^4 \\ &+ \bar{\Psi}(i\not{D} - \boldsymbol{M})\Psi - \left(\bar{\Psi}\tilde{\phi}\, \boldsymbol{G}_u u_R + \bar{\Psi}\phi\, \boldsymbol{G}_d d_R + \text{h.c.}\right) \\ &- \kappa_1 S\, \phi^\dagger\phi - \frac{\kappa_2}{2} S^2 \phi^\dagger \phi \\ &- S\, \bar{\Psi}\big(\boldsymbol{X} - i\gamma_5 \tilde{\boldsymbol{X}}\big)\Psi - S\left(\bar{\Psi}\, \boldsymbol{V}_Q\, Q_L + \text{h.c.}\right) \end{aligned}$$

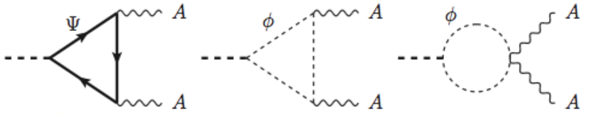
Application to a scalar singlet

Matching yields non-trivial Wilson coefficients.

Example: Production of diboson final state:

$$C_{AA} = \frac{d_A}{\pi^2}\,\mathrm{Tr}(\boldsymbol{X})\left[\frac{4-\xi}{\xi}\,g^2(\xi) - 1\right] + \frac{d'_A}{4\pi^2}\,\frac{\kappa_1}{M}$$

$$\widetilde{C}_{AA} = \frac{d_A}{\pi^2}\,\mathrm{Tr}(\tilde{\boldsymbol{X}})\,g^2(\xi)\,; \quad \xi = M_S^2/M^2$$



$$d_B = N_c Y_\psi^2 = \frac{1}{12}\,, \quad d_W = \frac{T_F N_c}{2} = \frac{3}{4}\,, \quad d_G = T_F = \frac{1}{2}$$

$$d'_B = Y_\phi^2 = \frac{1}{4}\,, \quad d'_W = \frac{T_F}{2} = \frac{1}{4}\,, \quad d'_G = 0$$

Application to a scalar singlet

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$$\widetilde{C}_{AA} = \frac{d_A}{\pi^2}\,\mathrm{Tr}(\tilde{\boldsymbol{X}})\,g^2(\xi); \quad \xi = M_S^2/M^2$$

A resummation of an infinite tower of operators in EFT!

$$\widetilde{C}_{AA} = \frac{d_A}{2\pi^2}\,\mathrm{Tr}(\tilde{\boldsymbol{X}})\sum_{k=1}^{\infty}\frac{\Gamma\left(\frac{1}{2}\right)\Gamma(k)}{k\,\Gamma\left(\frac{1}{2}+k\right)}\left(\frac{M_S^2}{4M^2}\right)^k$$

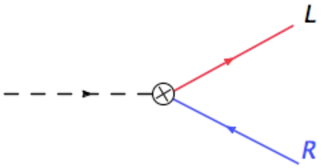
Leptoquark application-motivation from B-anomalies

Effective Lagrangian at $\mathcal{O}(\lambda^2)$ for the $S_1(3,1,-\frac{1}{3})$

$$\mathcal{L}^{(\lambda^2)}_{SCET} = C^R_{u\ell}\mathcal{O}^R_{u\ell} + C^L_{QL}\mathcal{O}^L_{QL} + h.c,$$

with the gauge invariant operators:

$$\mathcal{O}^R_{u\ell} = \bar{u}^c_{R,n_1}\ell_{R,n_2}\phi^*_1 + (n_1 \leftrightarrow n_2)$$
$$\mathcal{O}^L_{QL} = \bar{u}^c_{L,n_1}\bar{Q}^{c,a}_{L,n_1}\epsilon_{a,b}L^b_{L,n_2}\phi^*_1$$



Effective Lagrangian at $\mathcal{O}(\lambda^2)$ for the $S_1(3,1,-\frac{1}{3})$

$$\mathcal{L}_{SCET}^{(\lambda^2)} = C_{u\ell}^R \mathcal{O}_{u\ell}^R + C_{QL}^L \mathcal{O}_{QL}^L + h.c,$$

with the gauge invariant operators:

$$\mathcal{O}_{u\ell}^R = \bar{u}_{R,n_1}^c \ell_{R,n_2} \phi_1^* + (n_1 \leftrightarrow n_2)$$
$$\mathcal{O}_{QL}^L = \bar{u}_{L,n_1}^c \bar{Q}_{L,n_1}^{c,a} \epsilon_{a,b} L_{L,n_2}^b \phi_1^*$$

Adding a light right handed neutrino:

$$\mathcal{L}_{SCET}^{(\lambda^2)} = C_{u\ell}^R \mathcal{O}_{u\ell}^R + C_{QL}^L \mathcal{O}_{QL}^L + C_{d\nu}^R \mathcal{O}_{d\nu}^R + h.c.$$

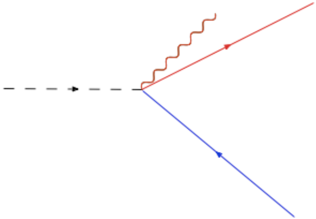
$$\mathcal{O}_{d\nu}^R = \bar{d}_{R,n_1}^c \nu_{R,n_2} \phi_1^* + +(n_1 \leftrightarrow n_2)$$

Its interactions with SM and a ν_R at leading order are described by only 3 Wilson Coefficients.

Effective $\mathcal{L}$ at $\mathcal{O}(\lambda^3)$ for the S_1

Two jet Lagrangian

$$\mathcal{L}_{SCET}^{(\lambda^3)} = \frac{1}{\Lambda}\sum_{j=1,2}\int_0^1 du\left[C_1^{(j)}{}_{Ld}^{LR}\mathcal{O}^{(j)}{}_{Ld}^{LR} + C_1^{(j)}{}_{Q\nu}^{LR}\mathcal{O}^{(j)}{}_{Q\nu}^{LR} + C_1^{(j)}{}_{d\nu}^{R}\mathcal{O}^{(j)}{}_{d\nu}^{R}\right]$$
$$+\frac{1}{\Lambda}C_1^{(0)}{}_{Ld}^{LR}\mathcal{O}^{(0)}{}_{Ld}^{LR} + \frac{1}{\Lambda}C_1^{(0)}{}_{Q\nu}^{LR}\mathcal{O}^{(0)}{}_{Q\nu}^{LR} + h.c$$



Effective $\mathcal{L}$ at $\mathcal{O}(\lambda^3)$ for the S_1

Two jet Lagrangian

$$\mathcal{L}^{(\lambda^3)}_{SCET} = \frac{1}{\Lambda}\sum_{j=1,2}\int_0^1 du\left[C^{(j)\,LR}_{1\;\;Ld}\mathcal{O}^{(j)\,LR}_{Ld} + C^{(j)\,LR}_{1\;\;Q\nu}\mathcal{O}^{(j)\,LR}_{Q\nu} + C^{(j)\,R}_{1\;\;d\nu}\mathcal{O}^{(j)\,R}_{d\nu}\right] + \frac{1}{\Lambda}C^{(0)\,LR}_{1\;\;Ld}\mathcal{O}^{(0)\,LR}_{Ld} + \frac{1}{\Lambda}C^{(0)\,LR}_{1\;\;Q\nu}\mathcal{O}^{(0)\,LR}_{Q\nu} + h.c$$

$$\mathcal{O}^{(0)\,LR}_{Ld} = \bar{L}_{n_1}\tilde{\Phi}^0 d_{R,n_2}\phi_1^* + (n_1 \leftrightarrow n_2)$$

$$\mathcal{O}^{(0)\,LR}_{Q\nu} = \bar{Q}_{L,n_1}\Phi^0 \nu_{R,n_2}\phi_1 + (n_1 \leftrightarrow n_2)$$

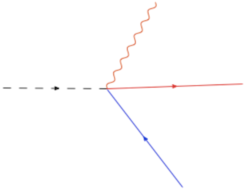
$$\mathcal{O}^{(j)\,LR}_{Ld} = \bar{L}_{n_1}\tilde{H}^u_{n_j} d_{R,n_2}\phi_1^* + (n_1 \leftrightarrow n_2)$$

$$\mathcal{O}^{(j)\,LR}_{Q\nu} = \bar{Q}_{L,n_1}H^u_{n_j}\nu_{R,n_2}\phi_1 + (n_1 \leftrightarrow n_2)$$

$$\mathcal{O}^{(j)\,R}_{d\nu} = \bar{d}_{R,n_1}\not{\mathcal{B}}^{\perp}_{n_j}\nu_{R,n_2}\phi_1 + (n_1 \leftrightarrow n_2)$$

Effective $\mathcal{L}$ at $\mathcal{O}(\lambda^3)$ for the S_1

- Similarly can build a Lagrangian with 3-jet operators



The $\mathcal{L}$ at $\mathcal{O}(\lambda^2)$ breaks the fermion number while the $\mathcal{O}(\lambda^3)$ conserves the fermion number. Therefore no mixing between $\mathcal{O}(\lambda^2)$ and $\mathcal{O}(\lambda^3)$ operators $\Rightarrow$ decay rates from $\mathcal{L}^{(\lambda^3)}$ are $\left(\frac{v}{\Lambda}\right)^2$ suppressed. $3 - jet$ operators $\mathcal{L}^{(\lambda^3)}$ further suppressed due to the phase space.

Decay rates at $\mathcal{O}(\lambda^2)$

The logs need to be resummed to get reliable prediction in perturbation theory.

$$\Gamma(\phi_1 \to \bar{\ell}_L u_L^c) = N_f \frac{M_{\phi_1}}{32\pi} |C_{u\ell}^R|^2$$

$$\mu \frac{d}{d\mu} C_{u\ell}^R = \left[\left(-C_F \gamma_{cusp}^{(3)} - \frac{1}{9} \gamma_{cusp}^{(1)} \right) \ln \frac{\mu}{M_{\phi_1}} - \frac{4}{3} \gamma_{cusp}^{(1)} \ln\left(\frac{\mu^2}{M_{\phi_1}^2} - i\pi \right) + \gamma^{\phi_1} + \gamma^{\ell_R} + \gamma^{u_R^c} \right] C_{u\ell}^R$$

$$\Gamma(\phi_1 \to Q_R^c \bar{L}_R) = N_f \frac{M_{\phi_1}}{32\pi} |C_{QL}^L|^2$$

$$\mu \frac{d}{d\mu} C_{QL}^L = \left[\left(-C_F \gamma_{cusp}^{(3)} + \frac{1}{9} \gamma_{cusp}^{(1)} \right) \ln \frac{\mu}{M_{\phi_1}} + \left(-\frac{3}{4} \gamma_{cusp}^{(2)} - \frac{1}{9} \gamma_{cusp}^{(1)} \right) \left(\ln \frac{\mu^2}{M_{\phi_1^2}} - i\pi \right) + \gamma^{\phi_1} + \gamma^{L} + \gamma^{Q} \right] C_{QL}^L$$

$$\Gamma(\phi_1 \to d_L^c \bar{\nu}_L) = N_f \frac{M_{\phi_1}}{32\pi} |C_{d\nu}^R|^2$$

$$\mu \frac{d}{d\mu} C_{d\nu}^R = \left[\left(-C_F \gamma_{cusp}(\alpha_s) - \frac{1}{9} \gamma_{cusp}(\alpha_1) \right) \ln \frac{\mu}{M_{\phi_1}} + \gamma^{\phi_1} + \gamma^{d_R} \right] C_{d\nu}^R$$

Decay rates at $\mathcal{O}(\lambda^2)$

The logs need to be resummed to get reliable prediction in perturbation theory.

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$$\Gamma(\phi_1 \to Q_R^c \bar{L}_R) = N_f \frac{M_{\phi_1}}{32\pi} |C_{QL}^L|^2$$

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$$\Gamma(\phi_1^* \to \bar{d}_R^c \nu_R) = N_f \frac{M_{\phi_1}}{32\pi} |C_{d\nu}^R|^2$$

$$\mu \frac{d}{d\mu} C_{d\nu}^R = \left[\left(C_F \gamma_{cusp}(\alpha_s) - \frac{1}{9}\gamma_{cusp}(\alpha_1) \right) \ln \frac{\mu}{M_{\phi_1}} + \gamma^{\phi_1} + \gamma^{d_R} \right] C_{d\nu}^R$$

Next: Solve the RGE to resum the logs.

Effective Lagrangian for a scalar triplet $S_3(3, 3, -\frac{1}{3})$

$$\mathcal{L}^{(\lambda^2)}_{SCET} = C_3{}^{L}_{QL} \mathcal{O}^{L}_{QL} + h.c$$

where: $\mathcal{O}^{L}_{QL} = \bar{Q}^{c}_{L,n_1} L_{L,n_2} \phi^{*}_{3} + (n_1 \leftrightarrow n_2)$

$$\mathcal{L}^{(\lambda^3)}_{SCET} = \frac{1}{\Lambda} \sum_{j=1,2} \left[\int_0^1 du\, C_3^{(j)}{}^{LR}_{Q\nu} \mathcal{O}^{(j)}{}^{LR}_{Q\nu} + C_3^{(j)}{}^{RL}_{dL} \mathcal{O}^{(j)}{}^{RL}_{dL} + C_3^{(j)}{}^{R}_{d\nu\mathcal{W}} \mathcal{O}^{(j)}{}^{R}_{d\nu\mathcal{W}} \right]$$
$$\frac{1}{\Lambda} C_3^{(0)}{}^{LR}_{Q\nu} \mathcal{O}^{(0)}{}^{LR}_{Q\nu} + \frac{1}{\Lambda} C_3^{(0)}{}^{RL}_{dL} \mathcal{O}^{(0)}{}^{RL}_{dL} + h.c.$$

$$\mathcal{L}^{(\lambda^3)}_{SCET} = \frac{1}{\Lambda}\sum_{j=1,2}\left[\int_0^1 du\, C^{(j)}_3{}^{LR}_{Q\nu}\mathcal{O}^{(j)}{}^{LR}_{Q\nu} + C^{(j)}_3{}^{RL}_{dL}\mathcal{O}^{(j)}{}^{RL}_{dL} + C^{(j)}_3{}^{R}_{d\nu\mathcal{W}}\mathcal{O}^{(j)}{}^{R}_{d\nu\mathcal{W}}\right]$$
$$\frac{1}{\Lambda}C^{(0)}_3{}^{LR}_{Q\nu}\mathcal{O}^{(0)}{}^{LR}_{Q\nu} + \frac{1}{\Lambda}C^{(0)}_3{}^{RL}_{dL}\mathcal{O}^{(0)}{}^{RL}_{dL} + h.c.$$

$$\mathcal{O}^{(0)}{}^{LR}_{Q\nu} = \bar{Q}_{L,n_1}\phi_3\Phi_0\nu_{R,n_2} + (n_1 \leftrightarrow n_2)$$
$$\mathcal{O}^{(j)}{}^{LR}_{Q\nu} = \bar{Q}_{L,n_1}\phi_3 H^{(u)}_{n_j}\nu_{R,n_2} + (n_1 \leftrightarrow n_2)$$
$$\mathcal{O}^{(0)}{}^{RL}_{dL} = \bar{d}_{R,n_1}\Phi^{0,a}\epsilon_{a,b}\phi_3 L^b_{n_2} + (n_1 \leftrightarrow n_2)$$
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$$\mathcal{O}^{(j)}{}^{R}_{d\nu} = \bar{d}_{R,n_1}\phi_3 \not{\mathcal{W}}^{\perp,u}_{n_j}\nu_{R,n_2} + (n_1 \leftrightarrow n_2)$$

Conclusion

- SCET offers a consistent way to describe the decay of heavy particles into SM particles
- Deal with a finite number of operators to describe the decay of the heavy particle
- The presence of multi scales makes it possible to sum the large logarithmic contributions

Thank you!