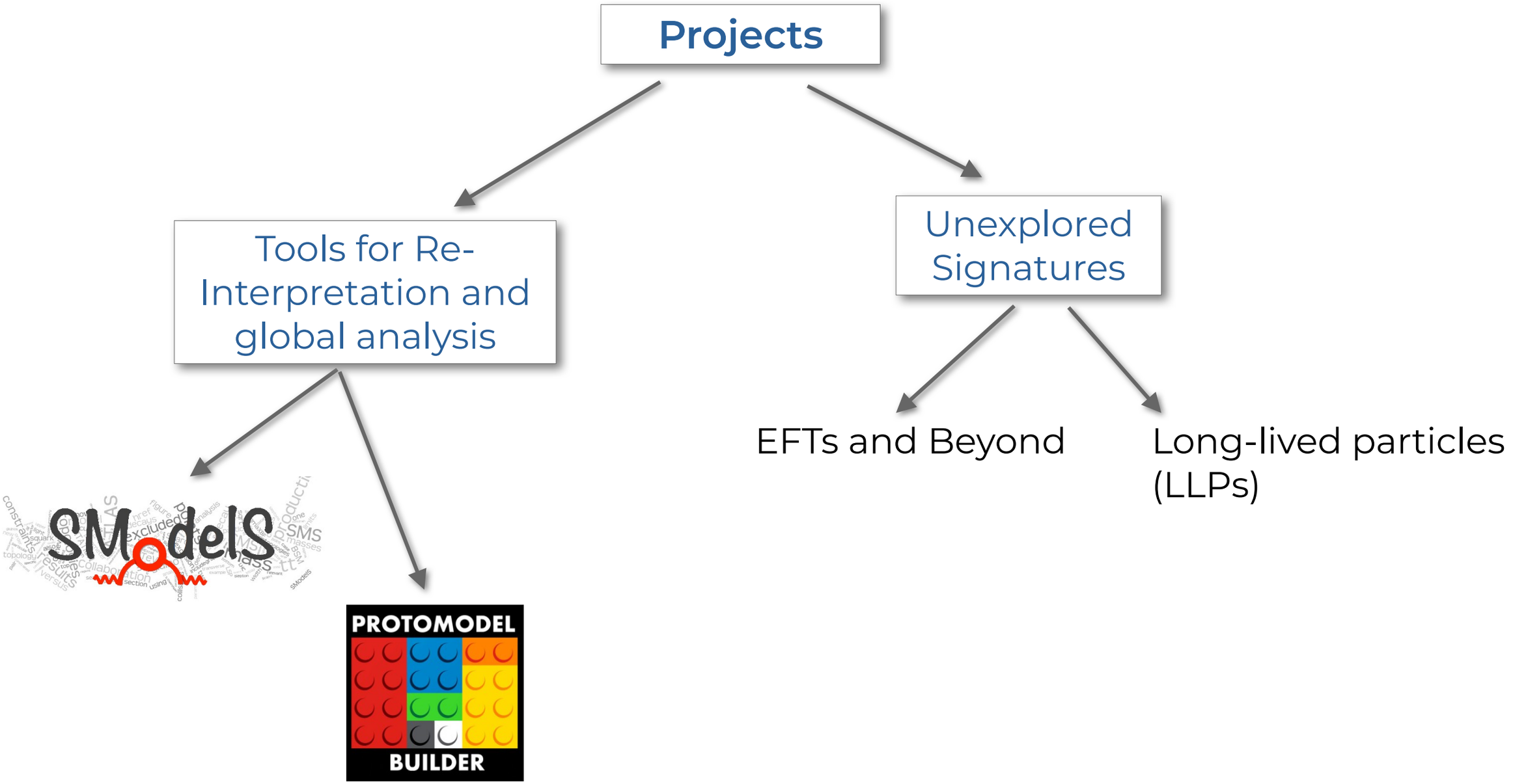
BSM Theory

André Lessa
(UFABC – São Paulo)

SPACE Workshop

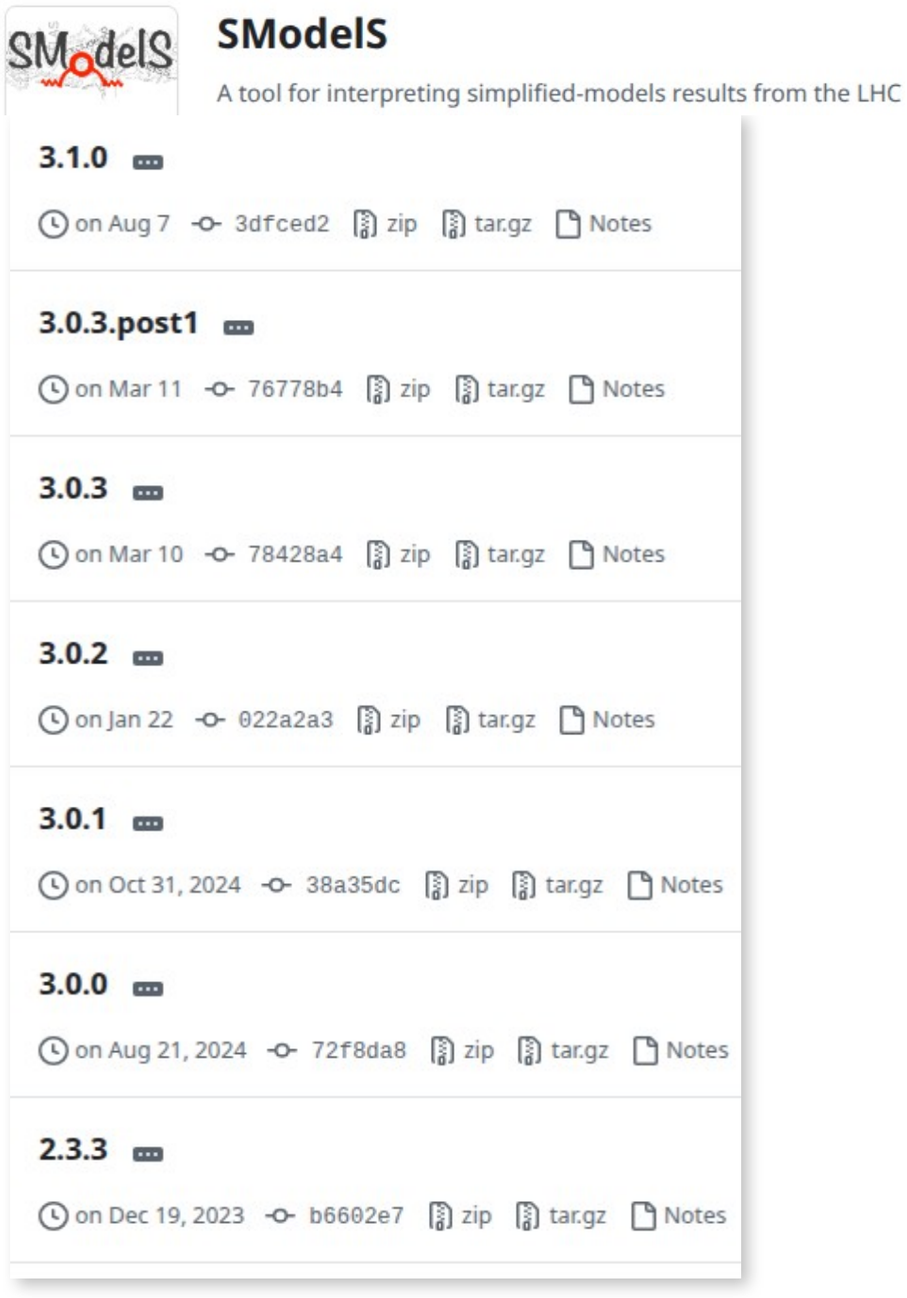
October 24th, 2025

Research Projects



Tools: SModelS

- The tool was developed by theorists and experimentalists
- It has an active group of collaborators
- It is in constant development



- Largest database of BSM searches:
  - 61 ATLAS results
  - 64 CMS results

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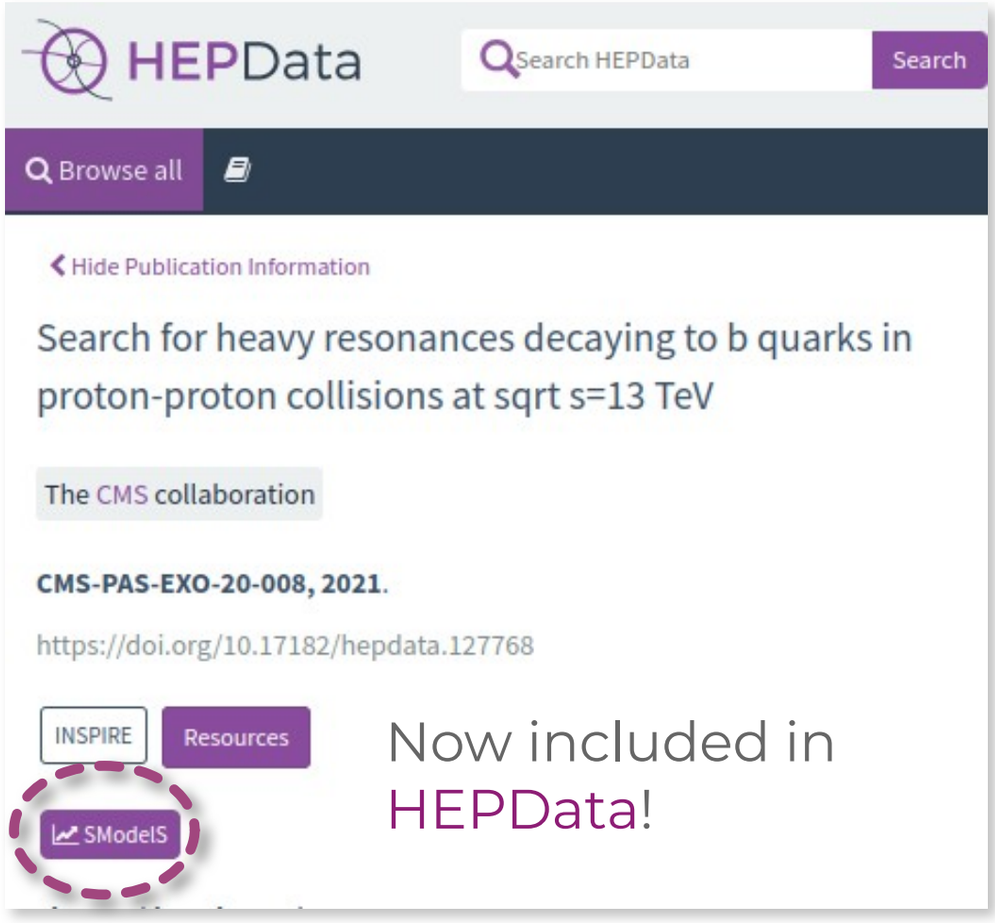

Now included in HEPData!

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- Recent developments
  - Full statistical models (Pyhf)
  - Global analysis combination
  - Arbitrary models → graph theory

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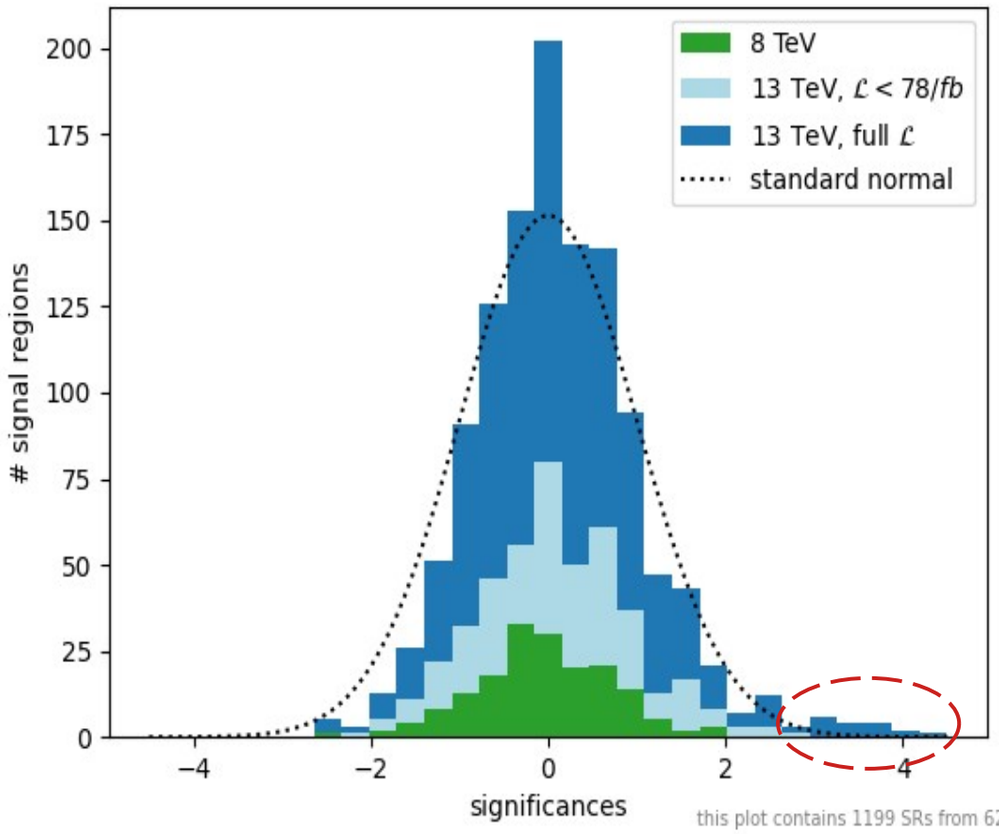
- Future plans:
  - Inclusion of Run 3 results
  - More LLP (non-SUSY) results
  - Impact of analysis combination
  - ...

Building the Next SM

- The large database of ATLAS and CMS results allow for a meta-analysis:



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- These are expected due to the huge number of searches! (~1200 bins)

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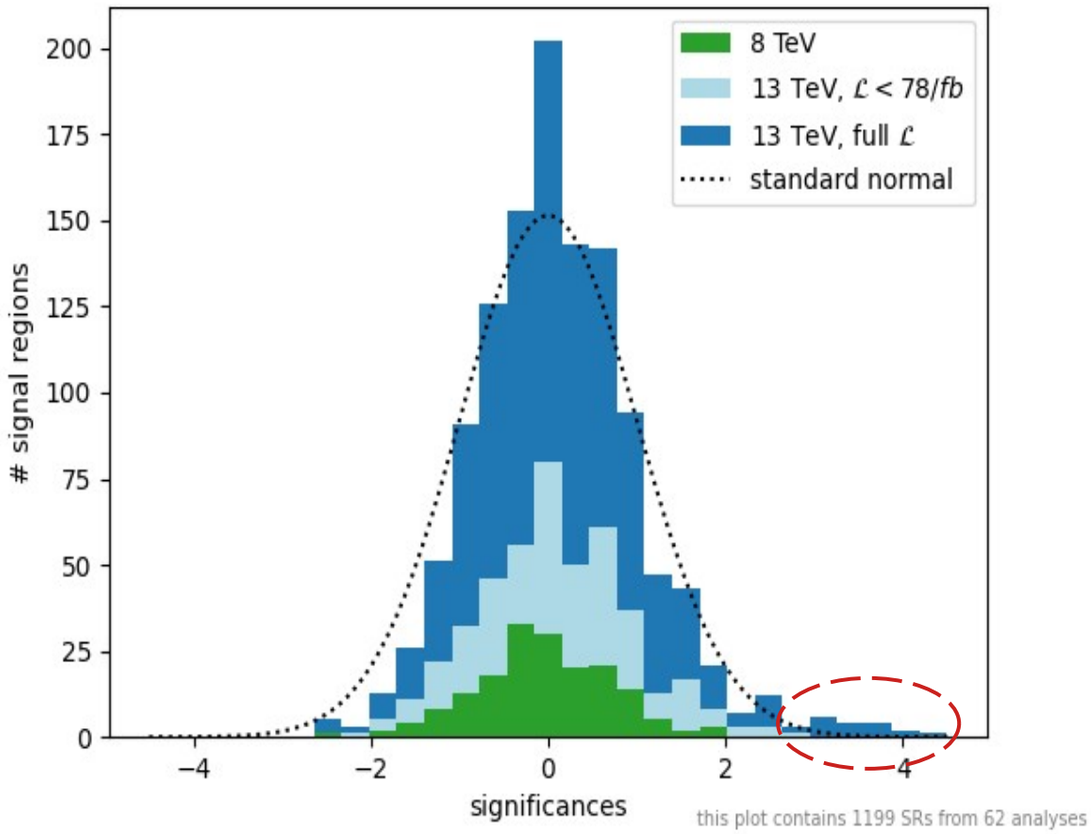

- Currently the largest excess are at ~ 3-4σ
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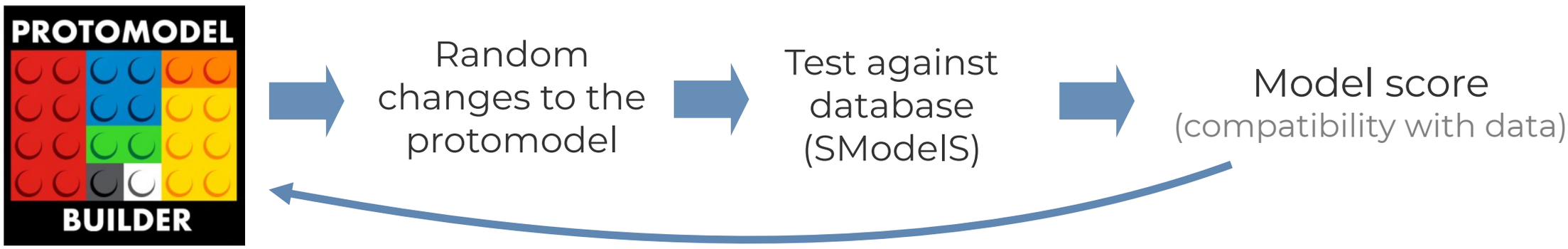
- However, what if:
  - Signal is dispersed over many final states (not easily visible by individual searches)?
  - The Next SM (NSM) does not match any of the UV models considered so far?

→ How to infer the NSM from data?

Building the Next SM

- We have built a prototype algorithm based on a MCMC for a dimensional space of varying dimensions.
- The algorithm looks for dispersed signals which can be simultaneously explained by minimal number of new particles.



S. Kraml, AL, W. Waltenberger, *JHEP 03 (2021) 207*

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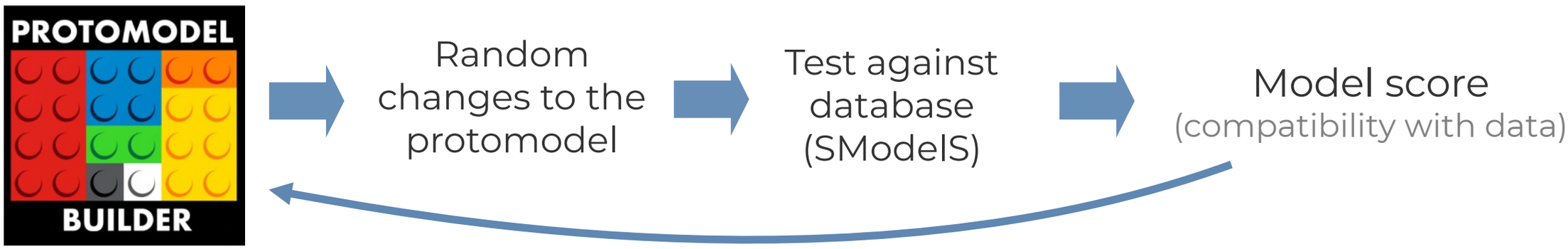

S. Kraml, AL, W. Waltenberger, *JHEP 03 (2021) 207*

- Future plans:
  - New version under development
  - Reversible-Jump MCMC
  - Better statistical interpretation
  - Experimental bias
  - How to automatically build a Lagragian (FeynRules → UFO)?
  - ....

Effective Field Theories

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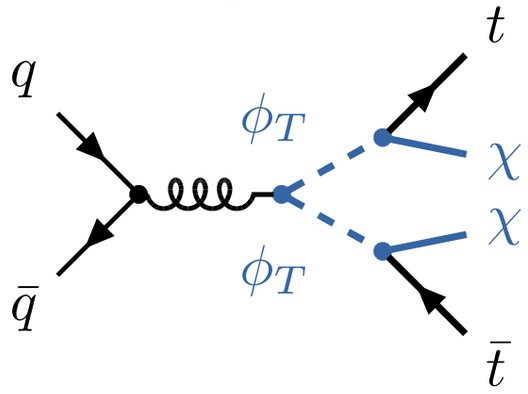
  - What happens in the transition regime? $\left(\Lambda_{\rm BSM} \gtrsim \sqrt{\hat{s}}\right)$

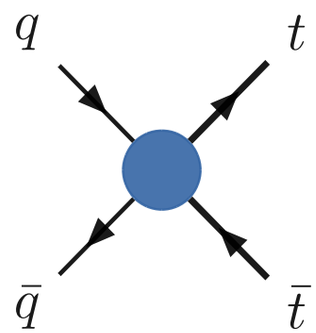
$2m_T < \sqrt{\hat{s}}$



$\mathcal{L}_{BSM} = |D_\mu \phi_T|^2 - y_{\rm DM} \phi_T^\dagger \bar{\chi} t_R + ...$

On-shell

$2m_T \gg \sqrt{\hat{s}}$



$\mathcal{L}_{\rm SMEFT} = \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + ...$

EFT

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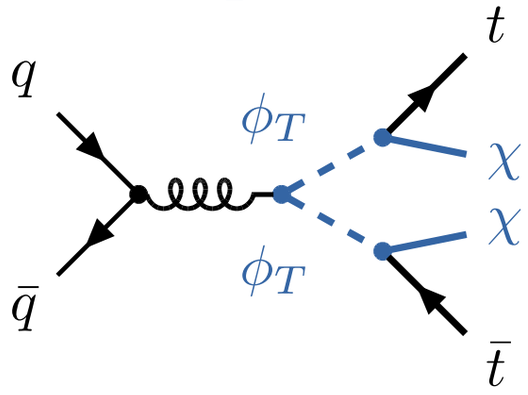

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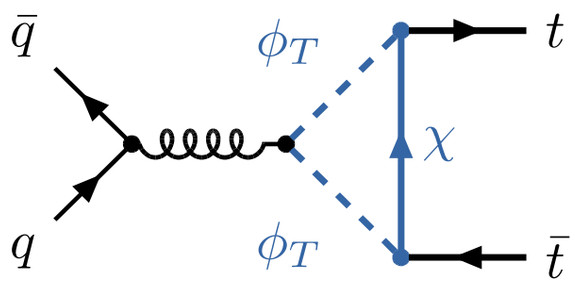
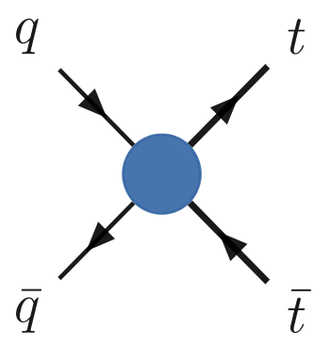


$\mathcal{L}_{\rm FF} = \sum_i \mathcal{F}_i(q^2, \Lambda^2, ...) O_i^{(6)} + ...$

Form factors

$2m_T \gg \sqrt{\hat{s}}$



$\mathcal{L}_{\rm SMEFT} = \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + ...$

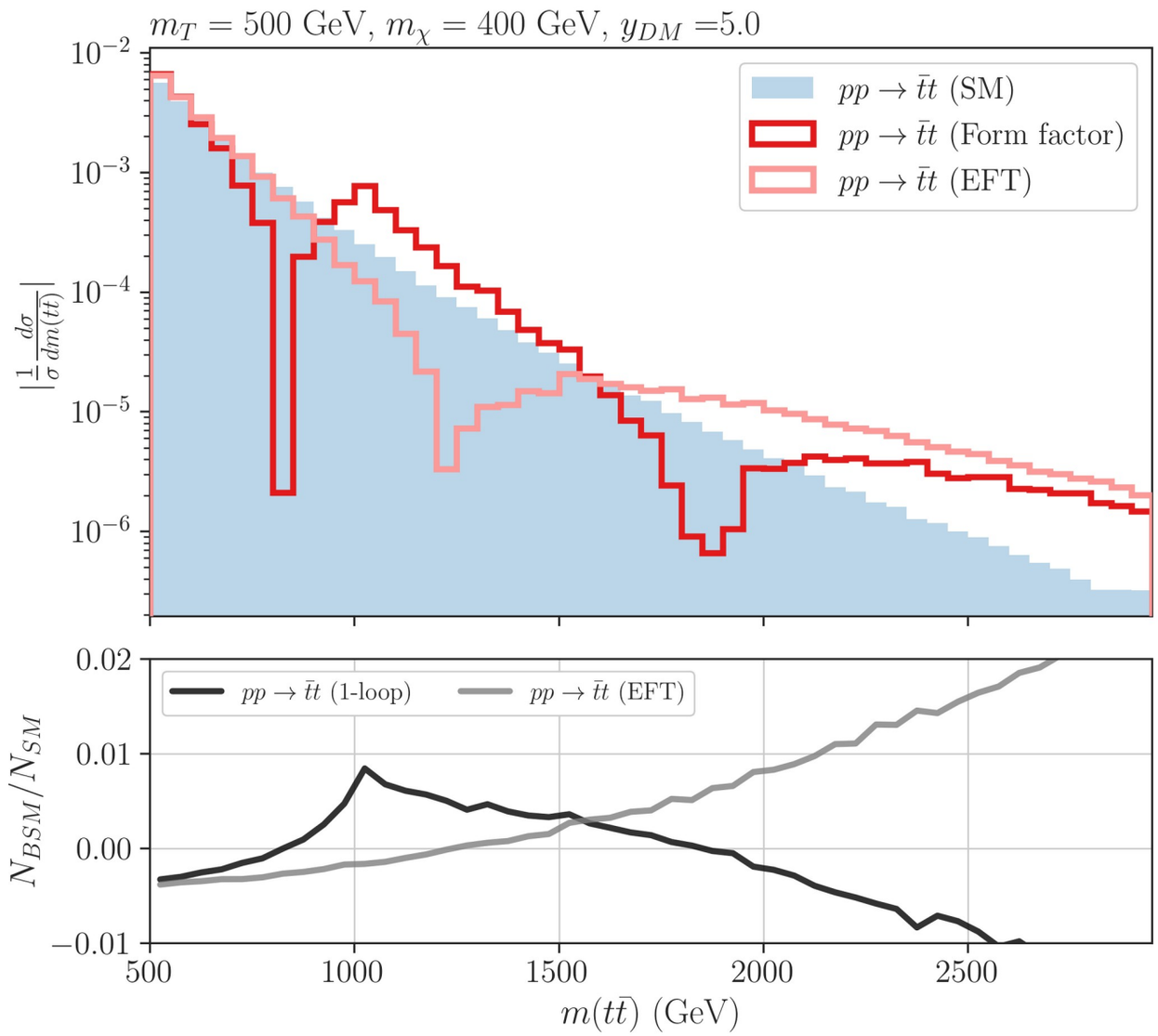
EFT

Beyond EFTs

- Form factors encode the full kinematical dependence at any energy:

$$\mathcal{F}_i(q^2, \Lambda^2, ...) \sim c_i^0 \frac{1}{\Lambda^2} + c_i^1 \frac{q^2}{\Lambda^4} + ...$$

→ New features not captured by EFTs!



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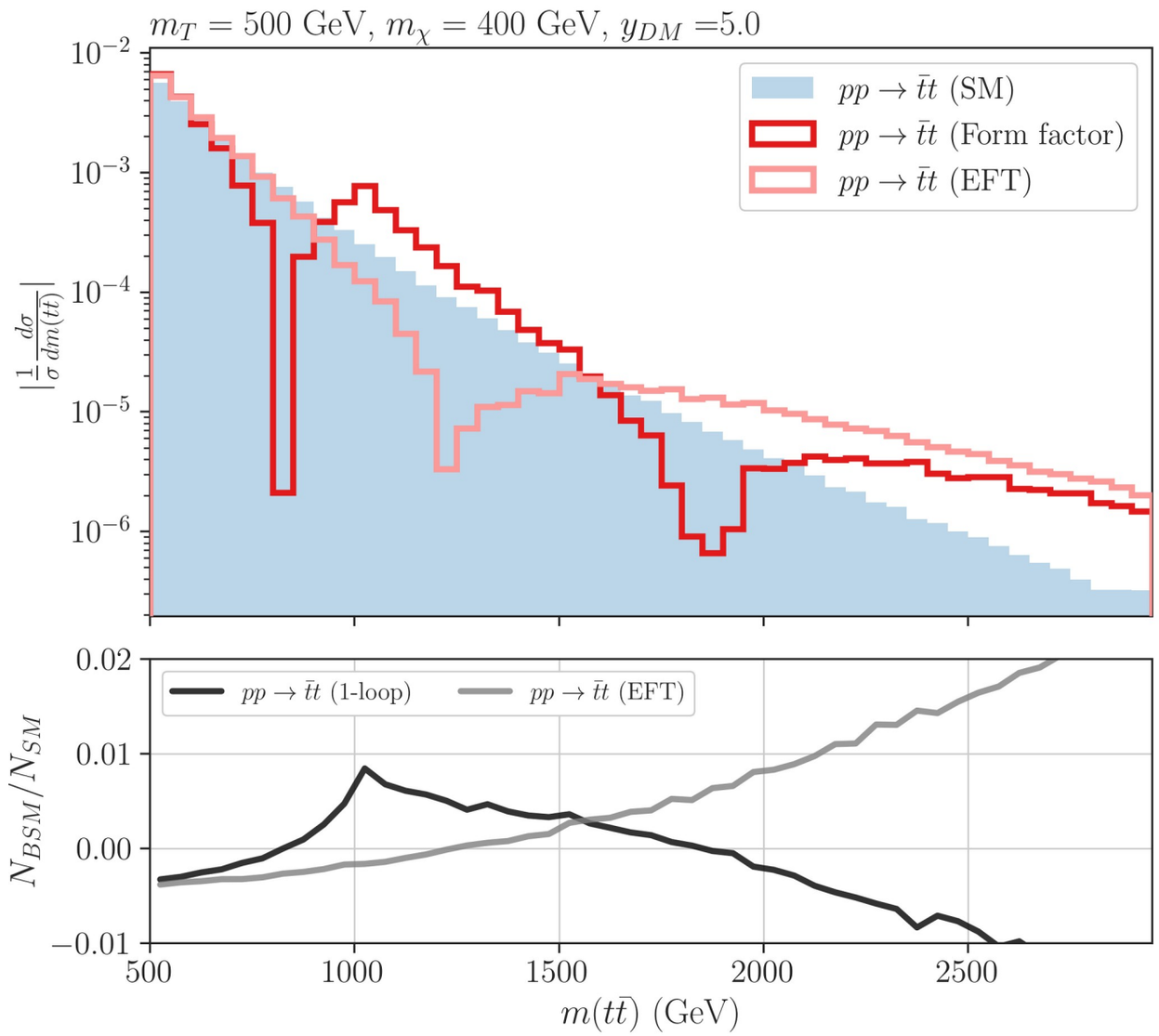

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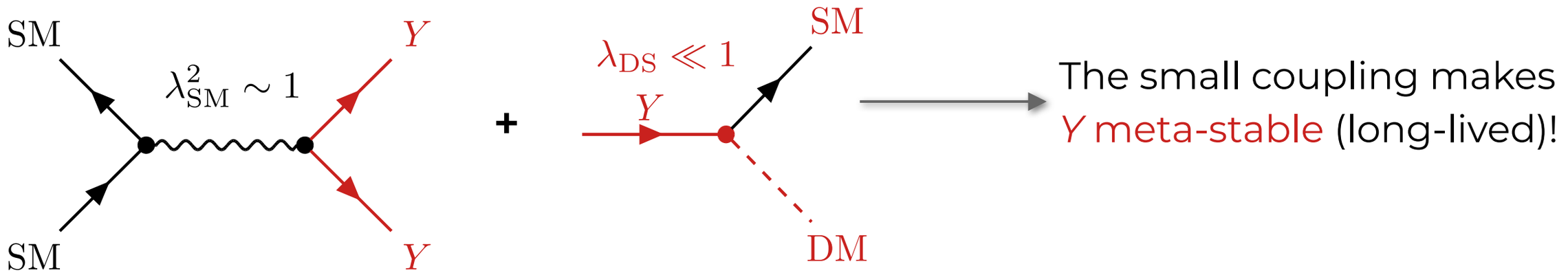
- Future plans
  - New search strategies (Anomaly detection?)
  - Combining EFT (low energy) and form factors (high energy) constraints
  - Model dependence → generic features?
  - Other observables?

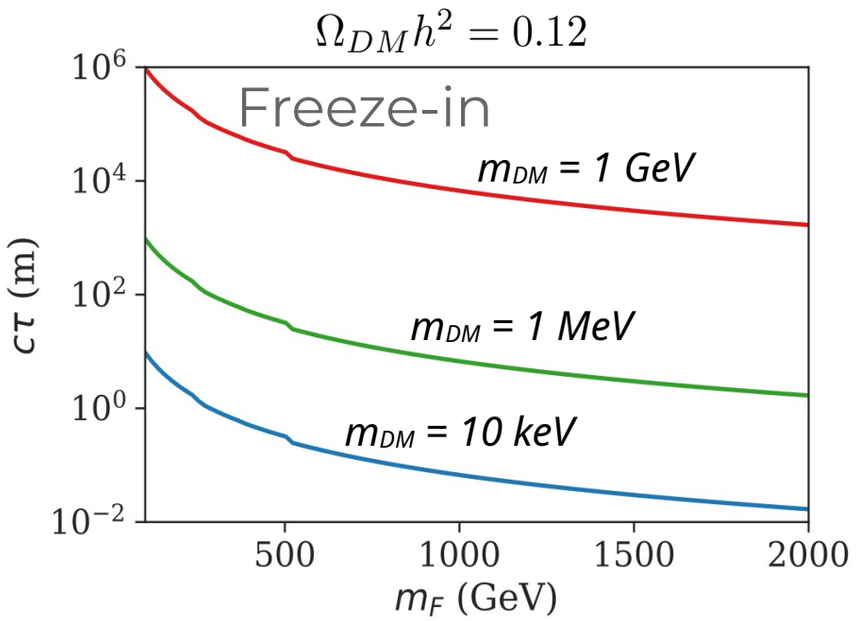
New Signatures - LLPs



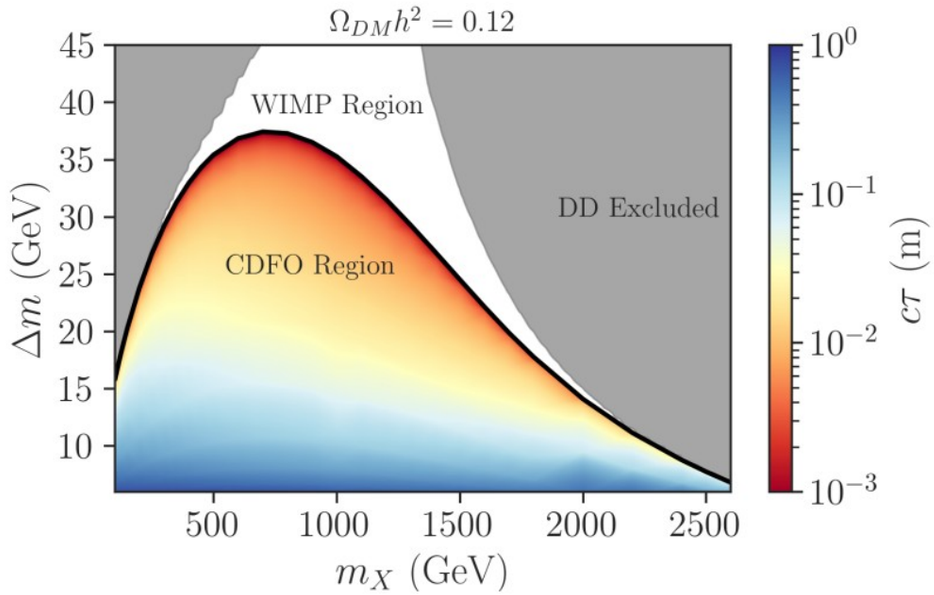
Large cross-section

Small decay width
(large lifetime)

- There are several “minimal” scenarios which lead to LLP signatures.



AL et al, *JHEP 02 (2019) 186*



J. Heisig, AL, L. Magno, PRD *110 (2024) 1*

New Signatures - LLPs

- Many of these scenarios are not yet fully explored by searches.
- In the last years searches for LLPs have increased considerably at the LHC.
- The collaboration between the experimental and theory communities has been key for developing the program.

- **LLP Working Group (CERN-LPCC):**
  - Theory: André Lessa
  - ALICE: Mesut Arslandok
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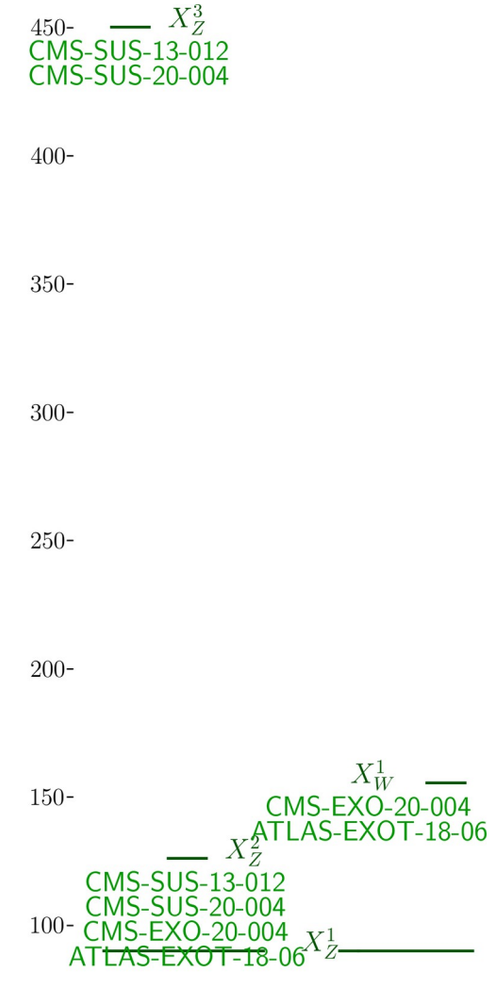
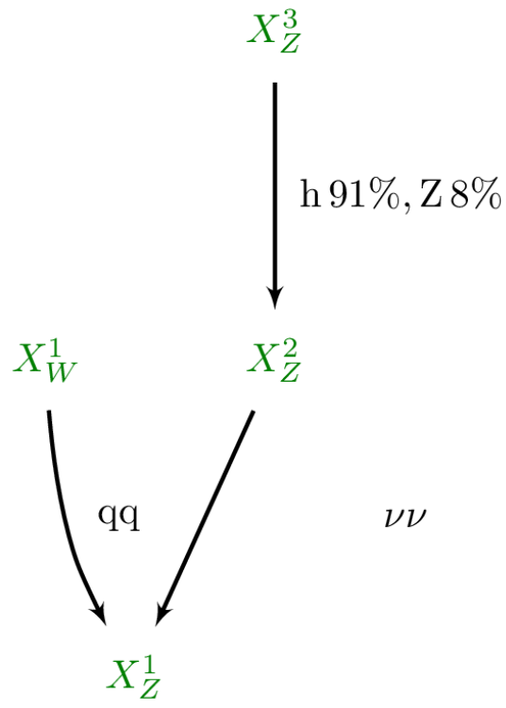
- Future plans
  - New trigger strategies
  - Coordination of benchmarks for searches
  - Complementarity between prompt and LLP searches
  - New signatures/gaps in coverage

Backup

Building the Next SM

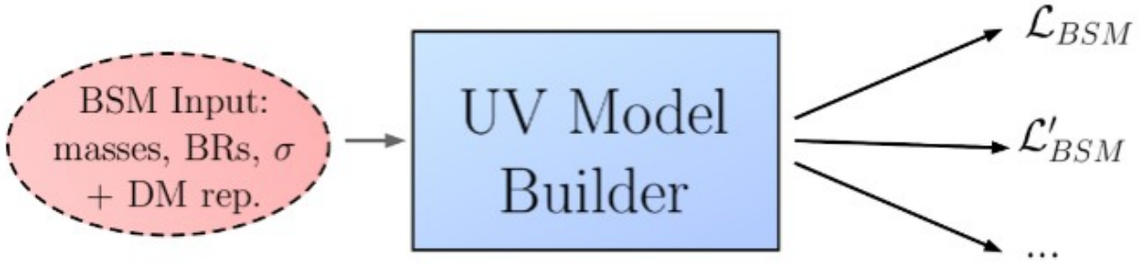
- Current run:

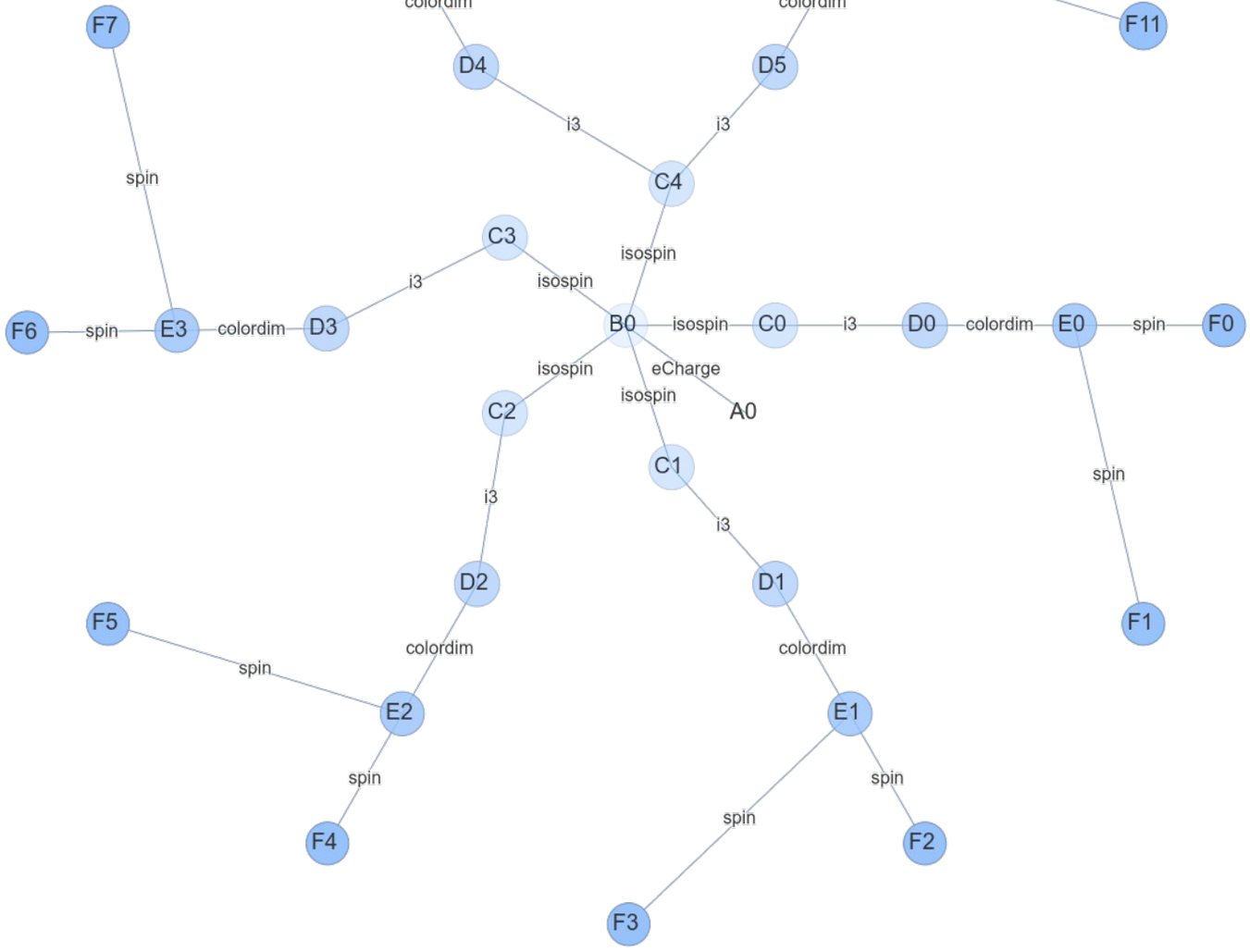




Analysis Name	Type	Dataset	Topos	Observed	Expected	Approx σ
CMS-EXO-20-004	comb	-	TChiISR, TChiZISRqq	2e+02 fb	1e+02 fb	4.6 σ
ATLAS-EXOT-2018-06	em	EM10	TChiISR, TChiZISRqq	413	359.00 +/- 10.00	2.5 σ
CMS-SUS-20-004	comb	-	TChiHH	0.3 fb	0.2 fb	2.2 σ
CMS-SUS-13-012	em	3NJet6_1000HT12 ...	TChiZZ	32	22.80 +/- 5.20	1.3 σ

Building the Next SM





EFT vs Direct Searches

- What happens when we consider complex scenarios? (MSSM)
- Are the EFT constraints valid/competitive?

$$\mathcal{L}_{\rm MSSM}(m_{\tilde{q}},...) \Rightarrow \mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)}(m_{\tilde{q}},...)}{\Lambda^2} O_i^{(6)} + \mathcal{O}\left(\Lambda^{-4}\right)$$

MSSM
(4-component spinors, diagonal Higgs basis)

MATCHETE

Functional methods (CDE)

SMEFT
(Warsaw basis)

S. Kraml, AL, S. Prakash, F. Wilsch, arXiv:2506.05201

$C_{HB} \to \hbar \left(\frac{1}{36} \sum_p c_{2\beta}\, g_1^4\, LF_{3,0}[m_d^p] - \frac{1}{36} \sum_p c_{2\beta}\, g_1^4\, LF_{4,-1}[m_d^p] - \right.$
$\frac{1}{6}\, g_1^2\, c_\beta^2\, \overline{y_d}^{pr}\, y_d^{pr}\, LF_{3,0}[m_d^r] + \frac{1}{6}\, g_1^2\, c_\beta^2\, \overline{y_d}^{pr}\, y_d^{pr}\, LF_{4,-1}[m_d^r] +$
$\frac{1}{4} \sum_p c_{2\beta}\, g_1^4\, LF_{3,0}[m_e^p] - \frac{1}{4} \sum_p c_{2\beta}\, g_1^4\, LF_{4,-1}[m_e^p] - \frac{1}{2}\, g_1^2\, c_\beta^2\, \overline{y_e}^{pr}\, y_e^{pr}\, LF_{3,0}[m_e^r] +$
$\frac{1}{2}\, g_1^2\, c_\beta^2\, \overline{y_e}^{pr}\, y_e^{pr}\, LF_{4,-1}[m_e^r] - \frac{1}{16}\, g_1^2\, (2\, c$
$\frac{1}{16} \left(2\, g_1^2\, c_\beta^2\, \overline{y_e}^{pr}\, y_e^{pr} + \sum_p c_{2\beta}\, g_1^4\right) LF_{4,-1}[$
$\frac{1}{144}\, g_1^2 \left(-6\, c_\beta^2\, \overline{y_d}^{pr}\, y_d^{pr} - 6\, s_\beta^2\, \overline{y_u}^{pr}\, y_u^{pr} +$
$\frac{1}{144}\, g_1^2 \left(6\, c_\beta^2\, \overline{y_d}^{pr}\, y_d^{pr} + 6\, s_\beta^2\, \overline{y_u}^{pr}\, y_u^{pr} - \sum$
$\frac{2}{9} \sum_p c_{2\beta}\, g_1^4\, LF_{3,0}[m_u^p] + \frac{2}{9} \sum_p c_{2\beta}\, g_1^4\, LF_{4,}$
$\frac{2}{3}\, g_1^2\, s_\beta^2\, \overline{y_u}^{pr}\, y_u^{pr}\, LF_{4,-1}[m_u^r] + \frac{1}{64} \left(g_1^4\, (1$
$\frac{1}{64}\, g_1^2 \left(g_1^2\, (1 + 3\, c_{4\beta}) + 3\, g_2^2\, (-1 + c_{4\beta})\right) L$
$\frac{1}{6}\, g_1^2 \left(c_\beta\, \overline{a_d}^{pr} - s_\beta\, \tilde{\mu}\, \overline{y_d}^{pr}\right) \left(c_\beta\, a_d^{pr} - s_\beta\, \tilde{\mu}\, y_d\right.$
$\frac{1}{6}\, g_1^2 \left(c_\beta\, \overline{a_d}^{pr} - s_\beta\, \tilde{\mu}\, \overline{y_d}^{pr}\right) \left(c_\beta\, a_d^{pr} - s_\beta\, \tilde{\mu}\, y_d^{pr}\right) LF_{3,1,0}[m_d^r, m_q^p] +$

$\frac{1}{4}\, g_1^2 \left(c_\beta\, \overline{a_e}^{pr} - s_\beta\, \tilde{\mu}\, \overline{y_e}^{pr}\right) \left(c_\beta\, a_e^{pr} - s_\beta\, \tilde{\mu}\, y_e^{pr}\right) LF_{5,1,-2}[m_l^p, m_e^r] +$
$\frac{1}{3}\, g_1^2 \left(c_\beta\, \overline{a_d}^{pr} - s_\beta\, \tilde{\mu}\, \overline{y_d}^{pr}\right) \left(c_\beta\, a_d^{pr} - s_\beta\, \tilde{\mu}\, y_d^{pr}\right) LF_{3,1,0}[m_q^p, m_d^r] +$
$\left(c_\beta\, a_d^{pr} - s_\beta\, \tilde{\mu}\, y_d^{pr}\right) LF_{3,2,-1}[m_q^p, m_d^r] -$
$\left(c_\beta\, a_d^{pr} - s_\beta\, \tilde{\mu}\, y_d^{pr}\right) LF_{4,1,-1}[m_q^p, m_d^r] +$
$\left(c_\beta\, a_d^{pr} - s_\beta\, \tilde{\mu}\, y_d^{pr}\right) LF_{5,1,-2}[m_q^p, m_d^r] -$
$\left(s_\beta\, a_u^{pr} - \tilde{\mu}\, c_\beta\, y_u^{pr}\right) LF_{2,2,0}[m_q^p, m_u^r] -$
$\left(s_\beta\, a_u^{pr} - \tilde{\mu}\, c_\beta\, y_u^{pr}\right) LF_{3,1,0}[m_q^p, m_u^r] +$
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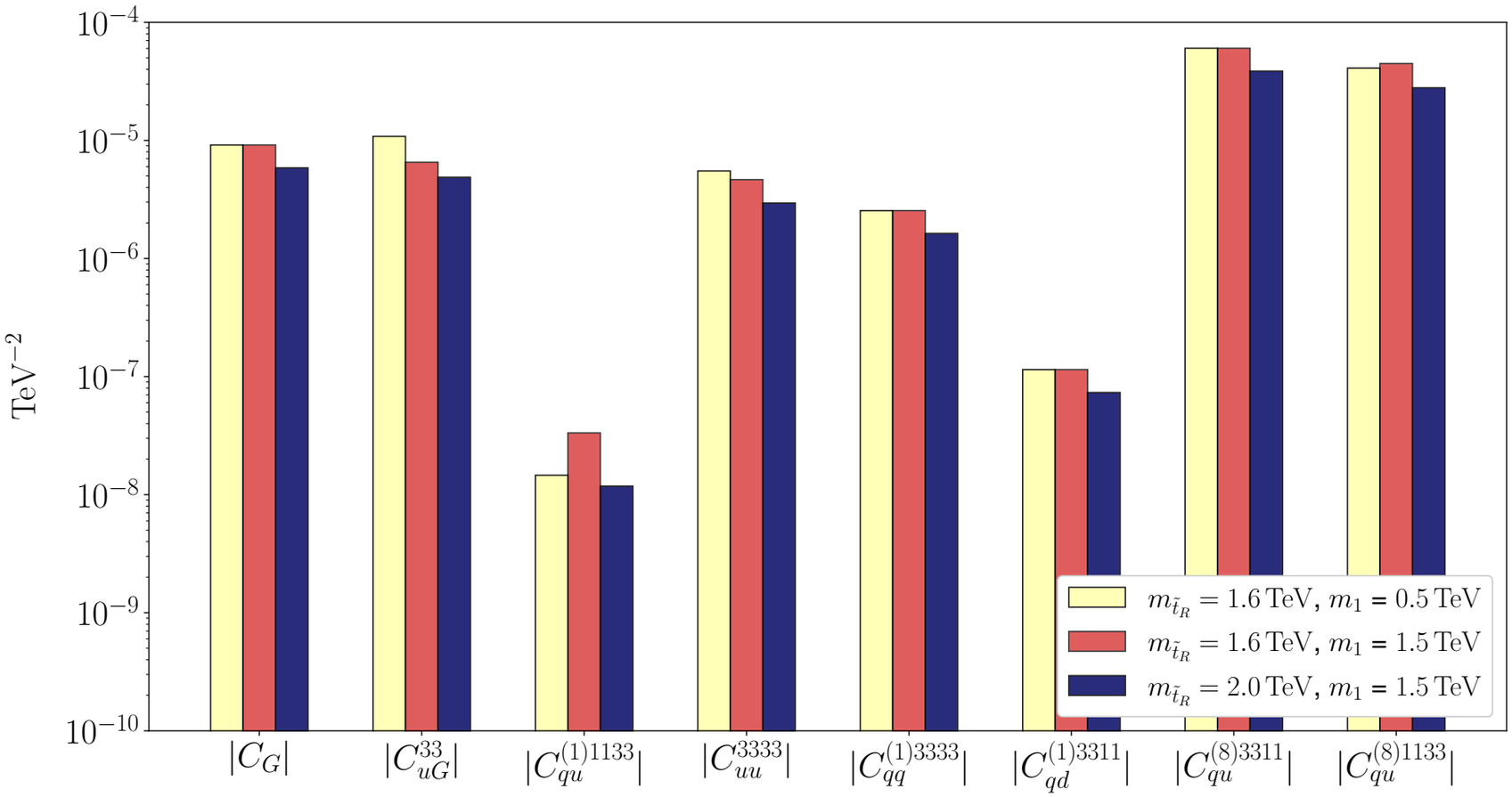
$\frac{1}{24}\, g_1^2 \left(s_\beta\, \overline{a_u}^{pr} - \tilde{\mu}\, c_\beta\, \overline{y_u}^{pr}\right) \left(s_\beta\, a_u^{pr} - \tilde{\mu}\, c_\beta\, y_u^{pr}\right) LF_{3,2,-1}[m_u^r, m_q^p] -$

OperatorToC++
allows for the numerical evaluation of coefficients given the input parameters

EFT vs Direct Searches

S. Kraml, AL, S. Prakash, F. Wilsch, arXiv:2506.05201



- **Future plans**
  - EFT constraints vs direct searches
  - Higgs sector (2HDM) vs EFT
  - Multi-scale MSSM

Main collaborators:
S. Kraml (LPSC-Grenoble)
S. Prakash (IFIC)
F. Wilsch (RWTH-Aachen)

Tools: SModelS

- What is the real impact of LHC data on BSM models?

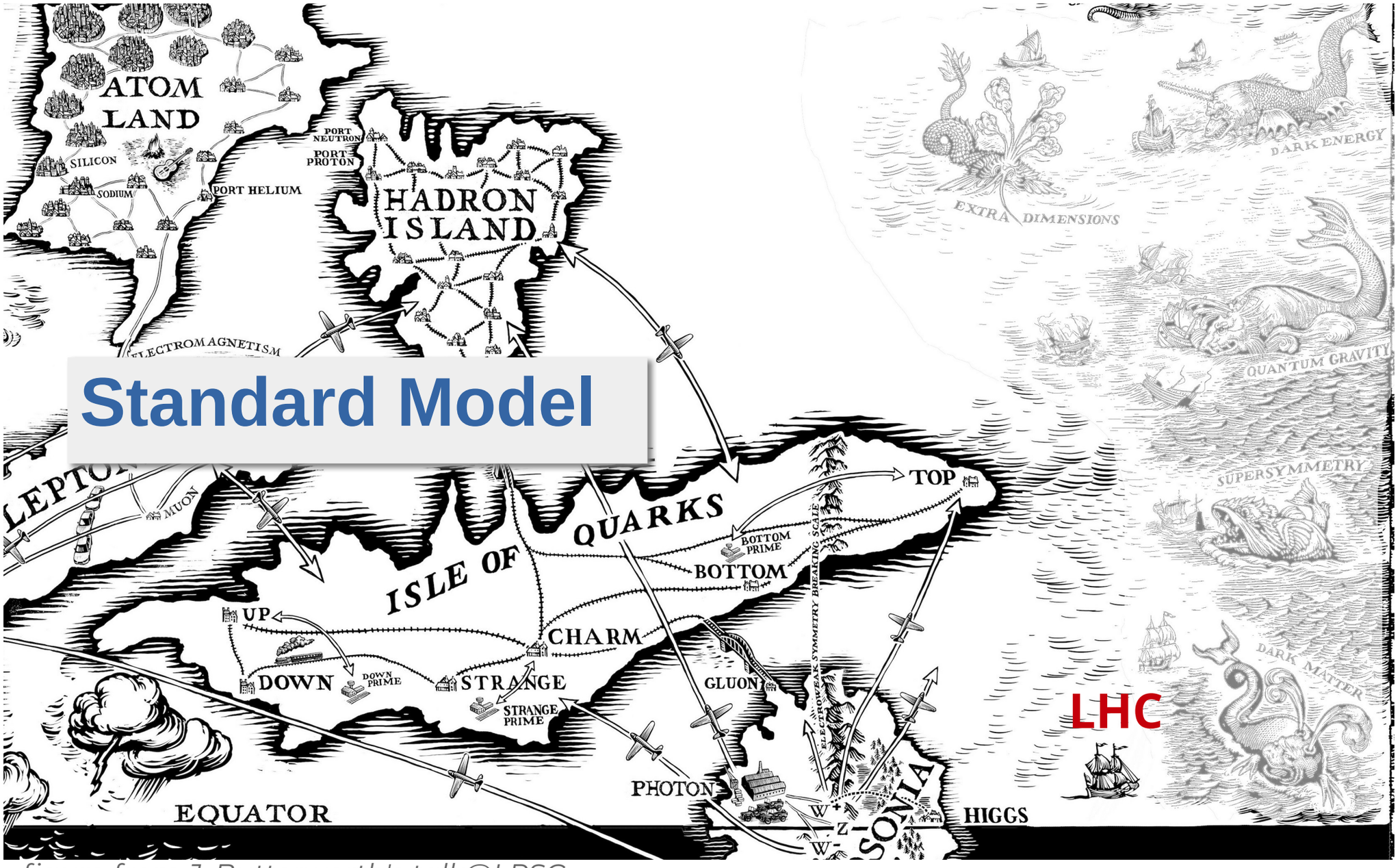


figure from J. Butterworth's talk@LPSC

Tools: SModelS

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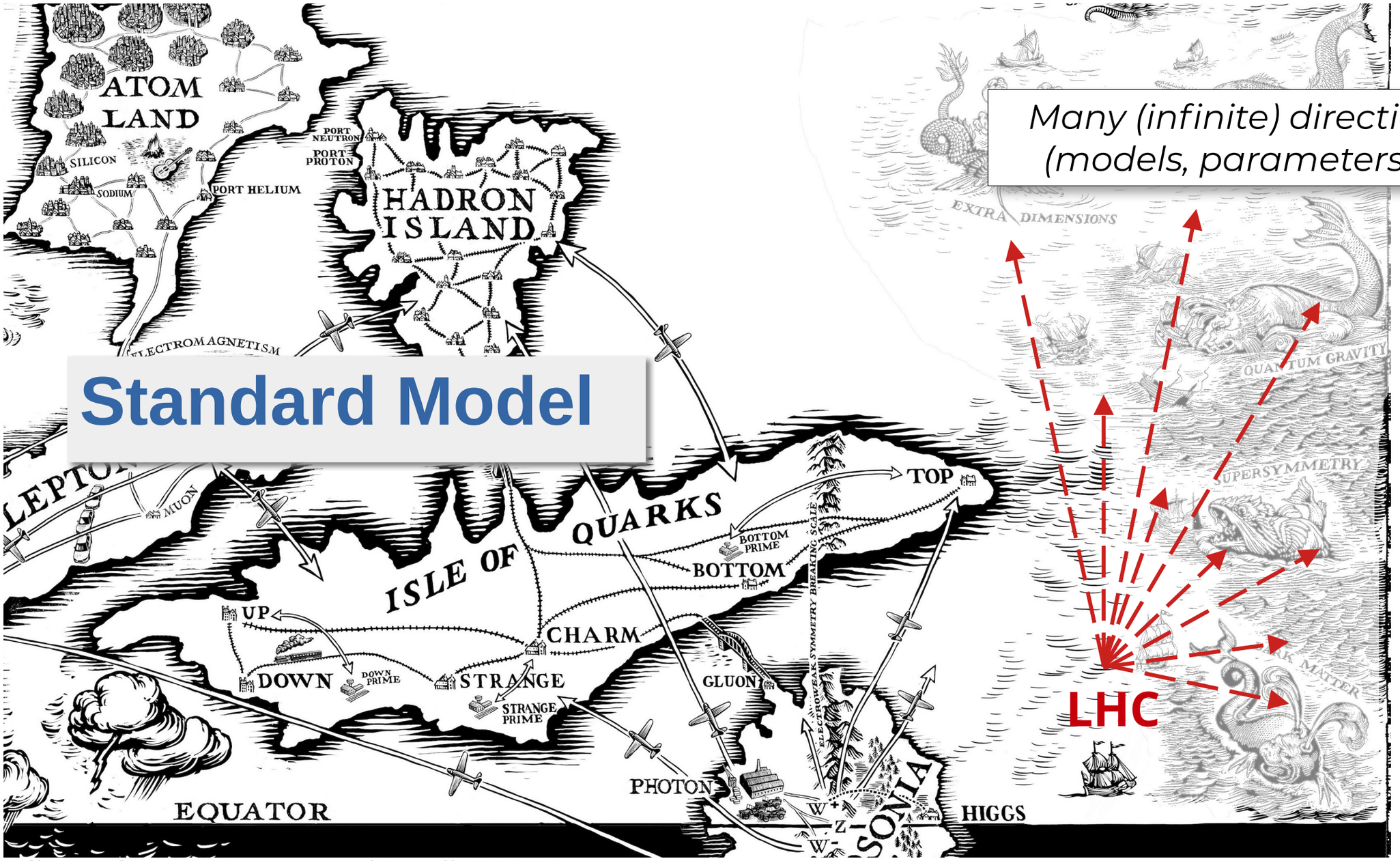
  → Not an easy question!



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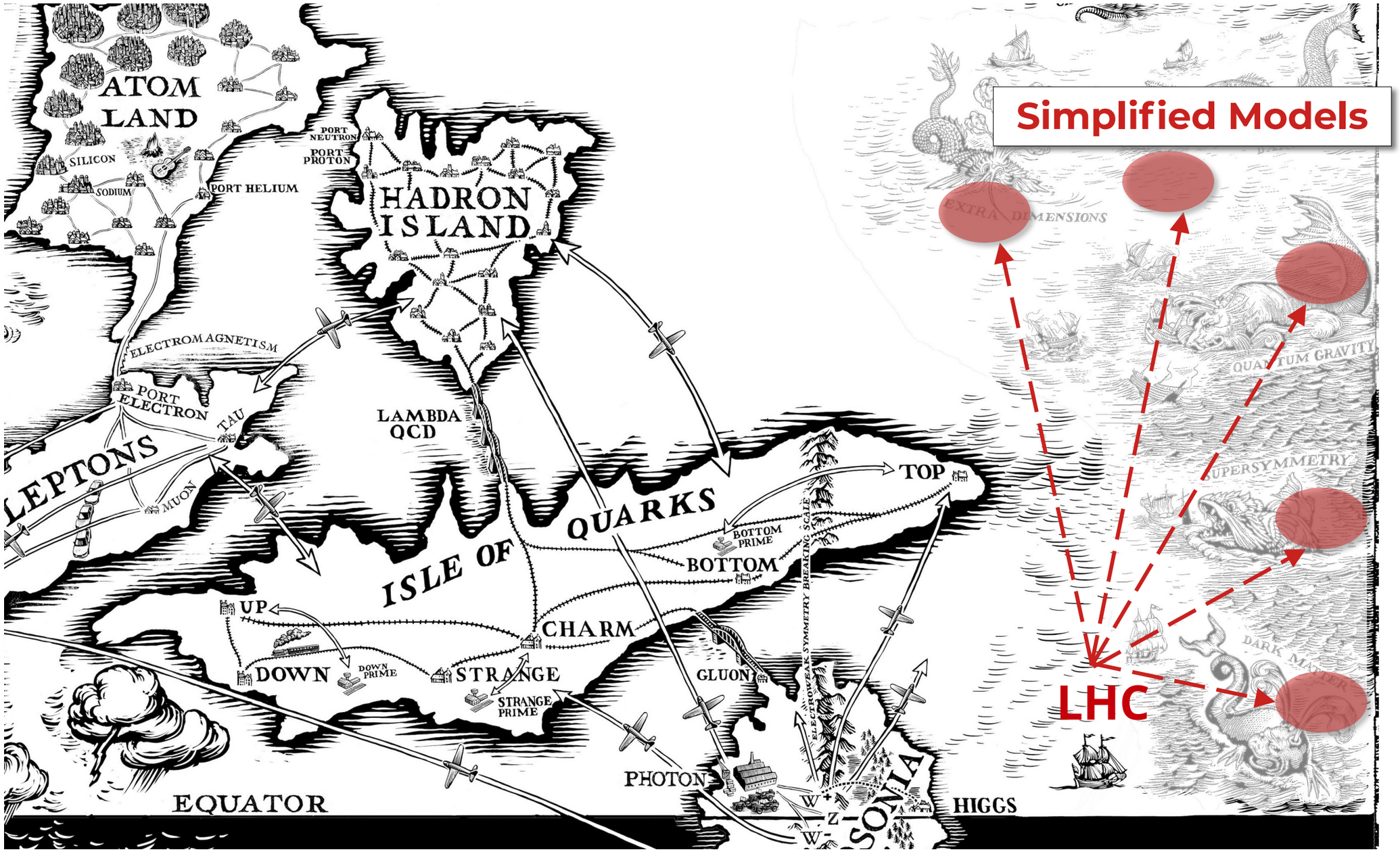

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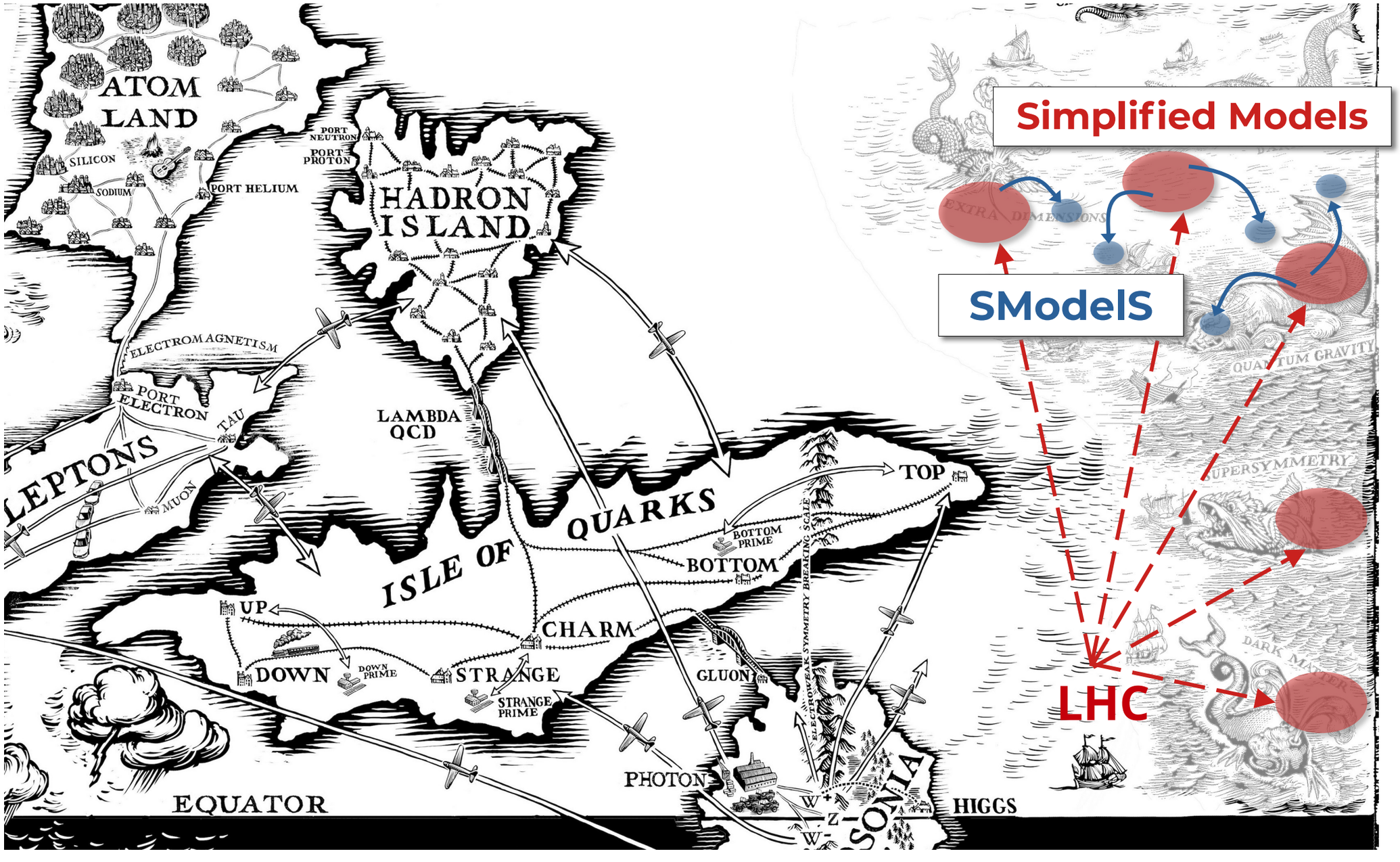
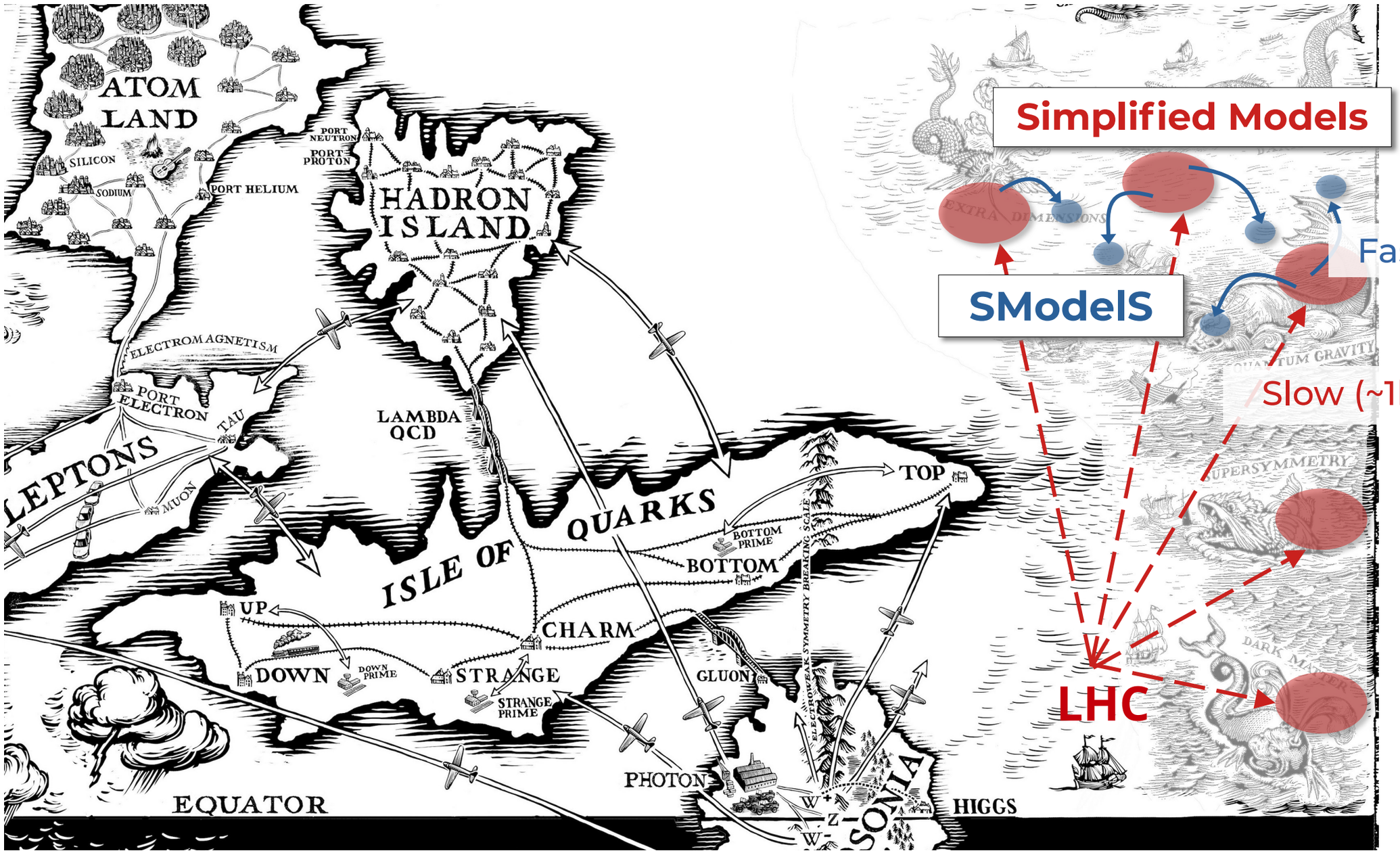


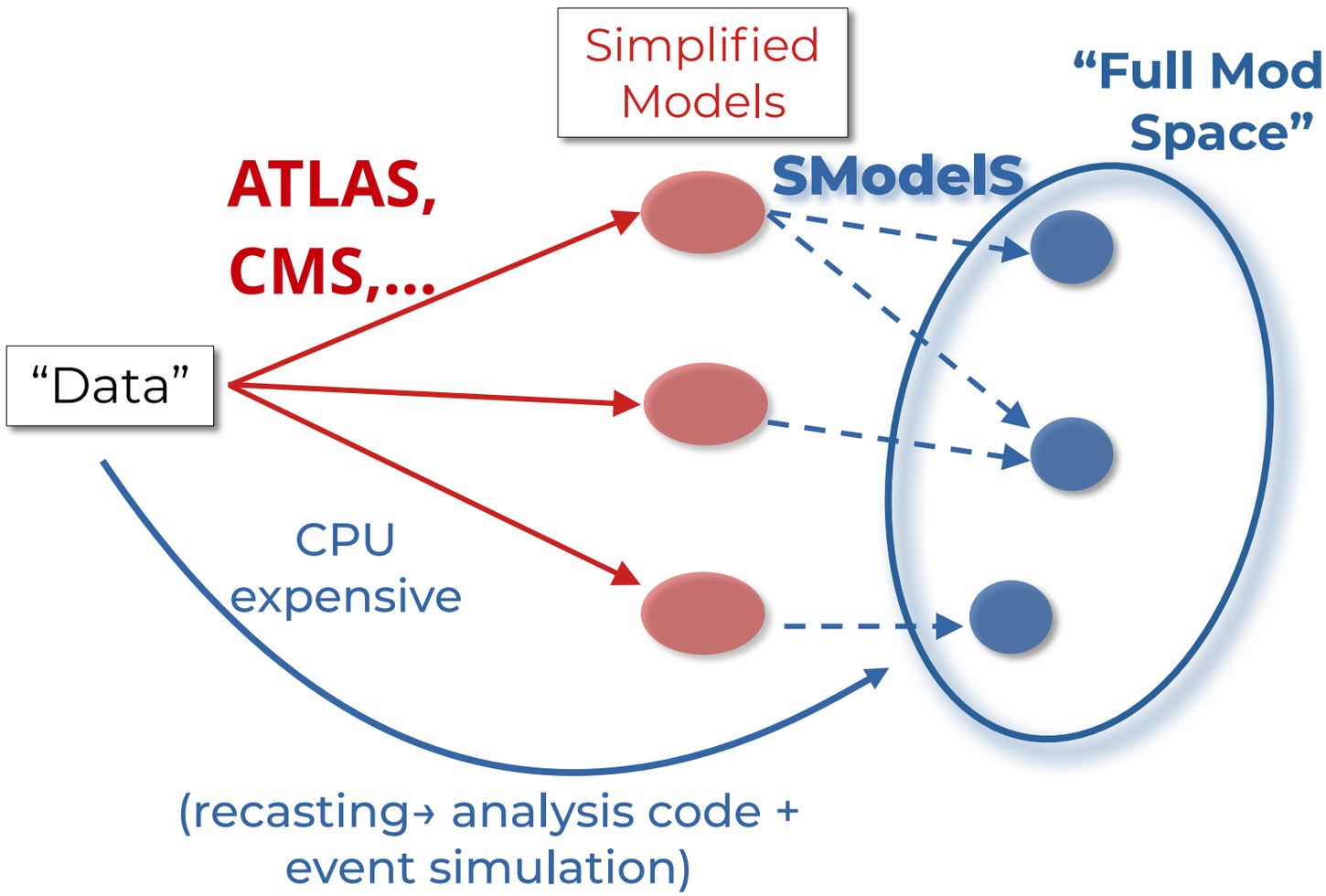
Tools: SModelS

- SModelS → software tool for collecting experimental results and allowing for a quick assessment of constraints to BSM scenarios



SModelS: Basics

- Tool for reintrepretation of LHC results based on rescaling of simplified model (SMS) results:

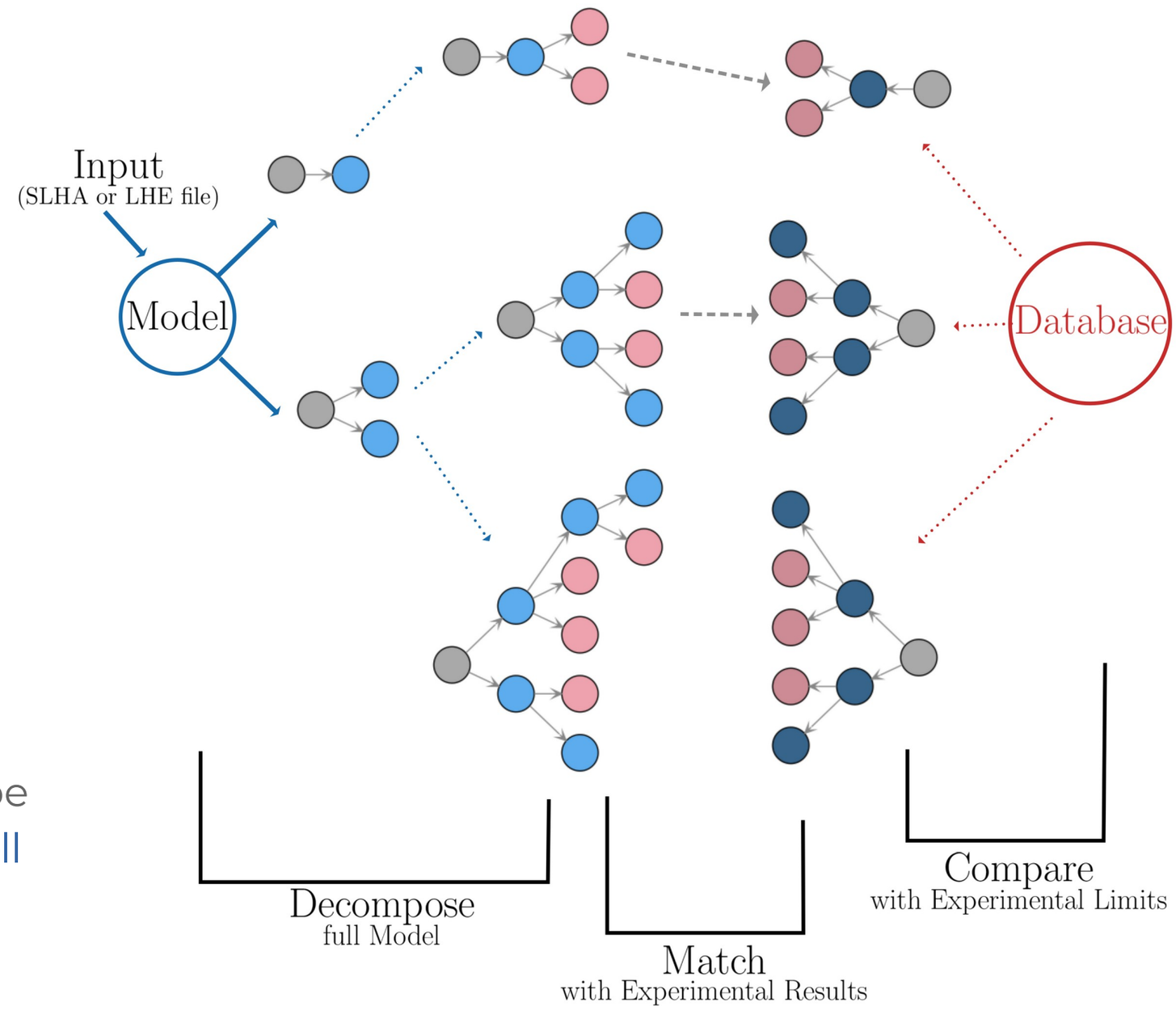


- Pros:
  - Many SMS results have been produced by the experimental collaborations
  - No need for recasting or event simulation
  - Sometimes the only alternative for complex searches
  - Very fast!
- Cons:
  - The rescaling extrapolates/interpolates signal efficiencies
  - Results are limited by the available simplified models
  - Results tend to be conservative and underestimate the experimental sensitivity

SModelS: Basics

- SModelS performs 3 main tasks:

1. UV model → sum of SMS
2. Find the matching results in the database
3. Compute constraints (limit setting)

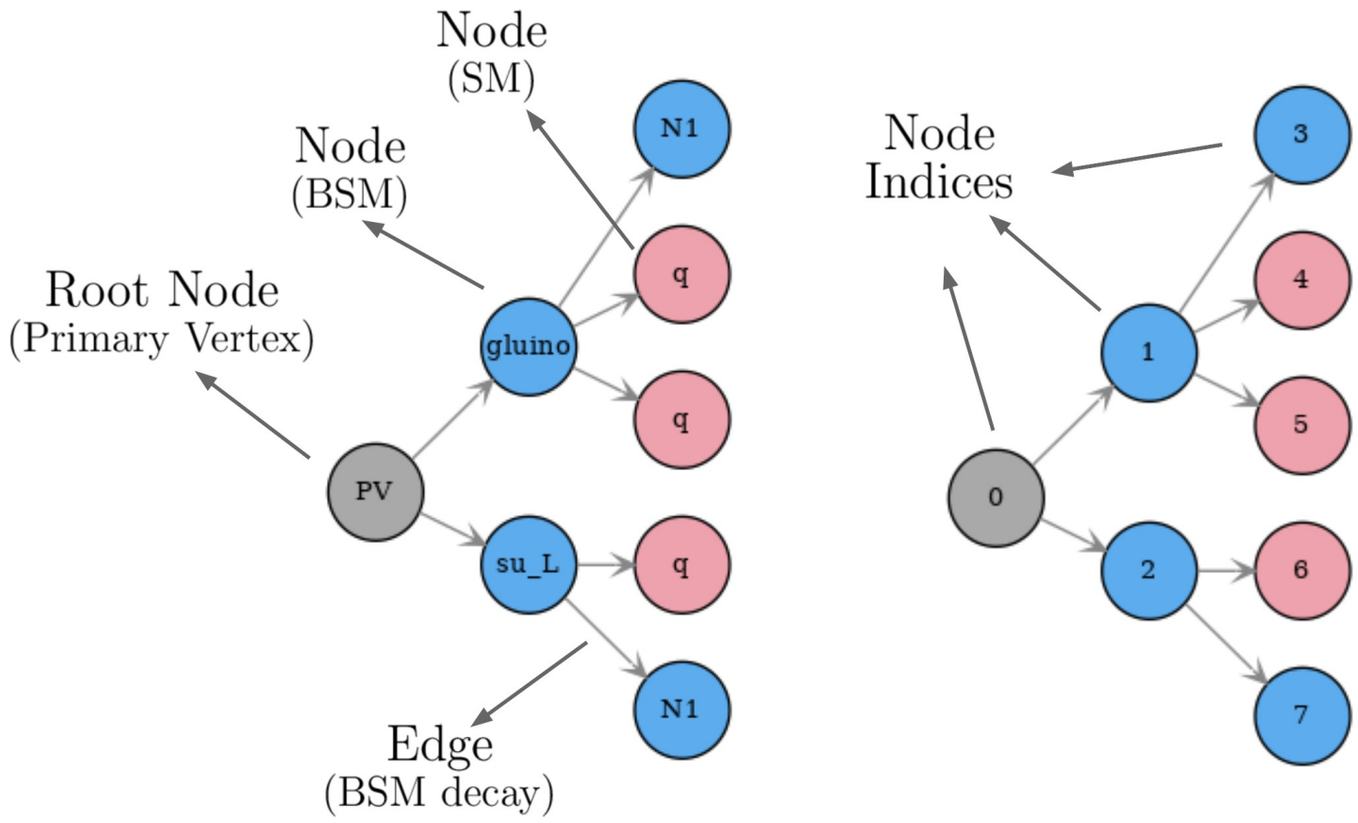


- Main approximation:

SMS efficiencies are assumed to be driven by the properties of on-shell particles → masses, widths and quantum numbers

SModelS Graphs

- Graph Representation:



- Text Representation:

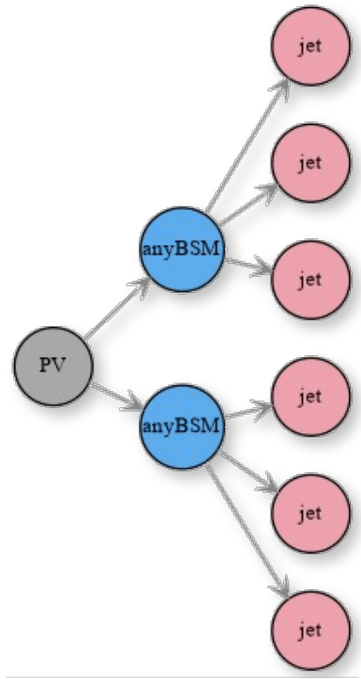
```
(PV > gluino(1),su_L(2)), (gluino(1) > N1(3),q(4),q(5)), (su_L(2) > q(6),N1(7))
```

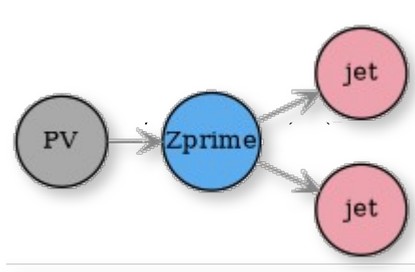
node number

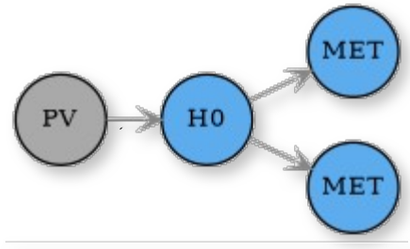
SModelS v3: Database

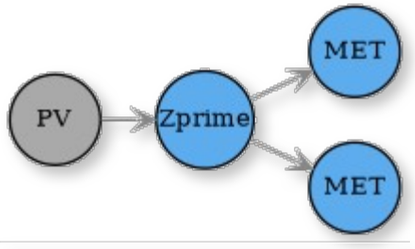
- Non-Z_2 results:

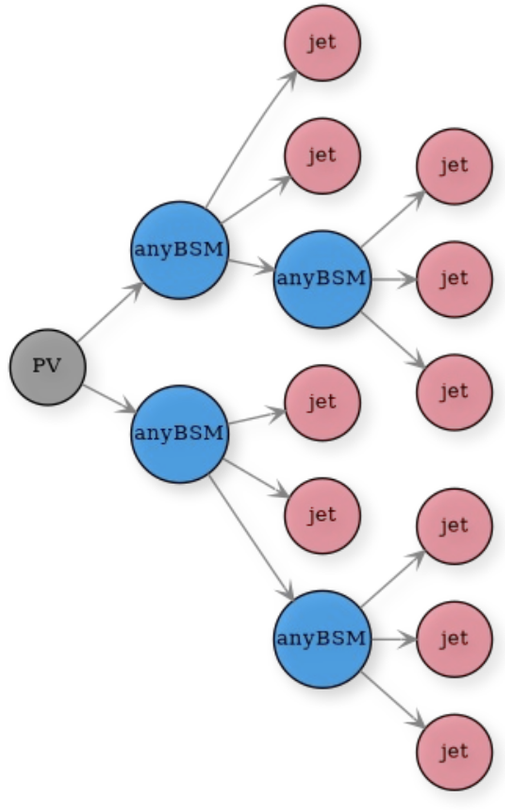
ID	Signature	Luminosity	SMS Topology	Type
		Run 2 - 13 TeV		
ATLAS-EXOT-2019-03	Dijet resonance	139 fb^{-1}	$pp \to Z' \to jj, b\bar{b}$	UL
ATLAS-EXOT-2018-48	$t\bar{t}$ resonance	139 fb^{-1}	$pp \to Z' \to t\bar{t}$	UL
CMS-EXO-19-012	Dijet resonance	137 fb^{-1}	$pp \to Z' \to jj, b\bar{b}$	UL
CMS-EXO-20-008	b-jet resonance	138 fb^{-1}	$pp \to Z' \to b\bar{b}$	UL
CMS-EXO-20-004	Monojet	137 fb^{-1}	$pp \to Z', S \to \chi\chi$	EM
ATLAS-EXOT-2018-06	Monojet	139 fb^{-1}	$pp \to Z' \to \chi\chi$	UL
ATLAS-SUSY-2018-22	Multi-jet plus	139 fb^{-1}	$pp \to Z' \to \chi\chi$	EM
ATLAS-SUSY-2018-13	Displaced jets	139 fb^{-1}	$pp \to \tilde{\chi}\tilde{\chi} \to jjj, jjj; \ldots$	EM
		Run 1 - 8 TeV		
CMS-EXO-16-057	b-jet resonance	19.7 fb^{-1}	$pp \to Z' \to b\bar{b}$	UL
CMS-EXO-12-059	Dijet resonance	19.7 fb^{-1}	$pp \to Z' \to jj$	UL
ATLAS-EXOT-2013-11	Dijet resonance	20.3 fb^{-1}	$pp \to Z' \to jj$	UL

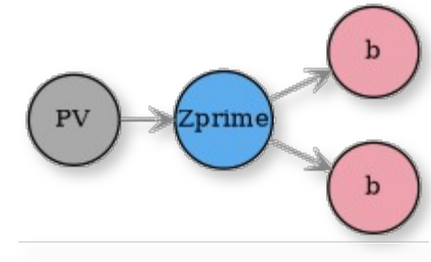


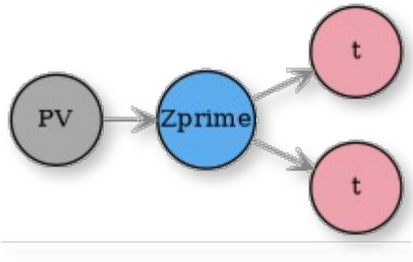






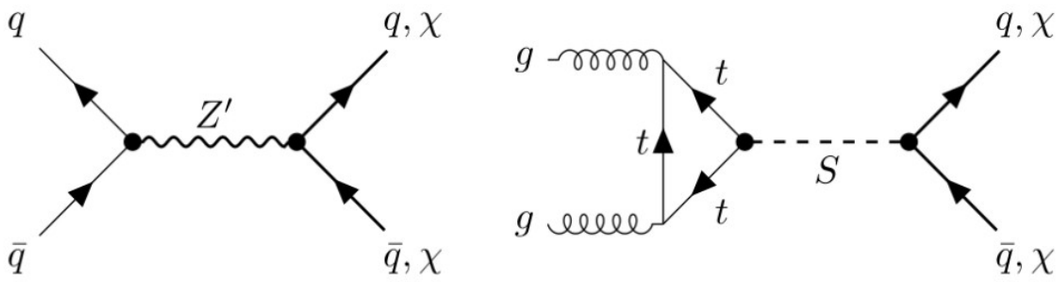


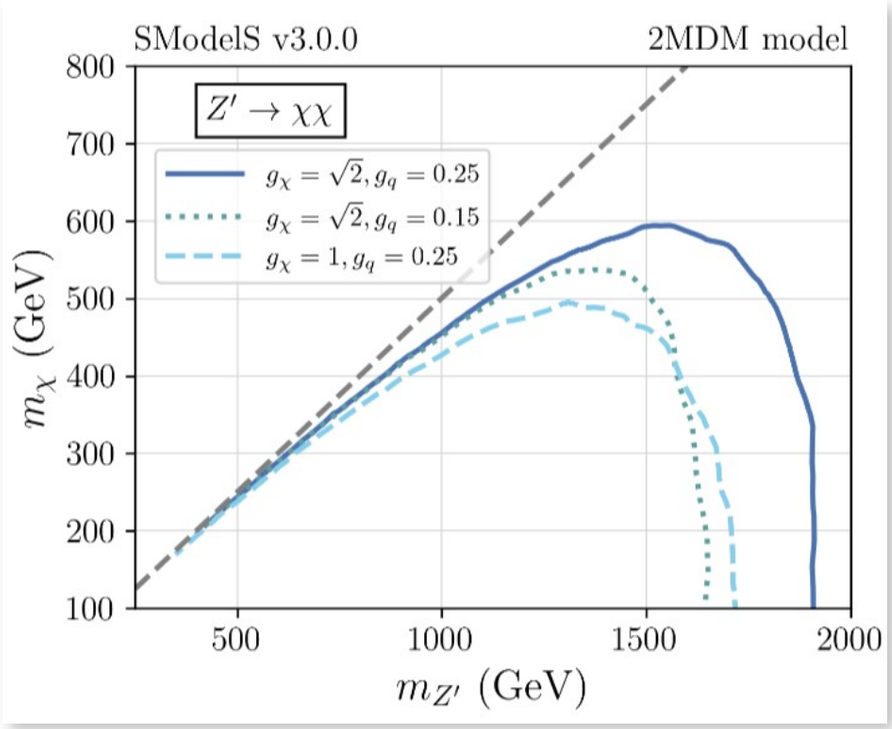




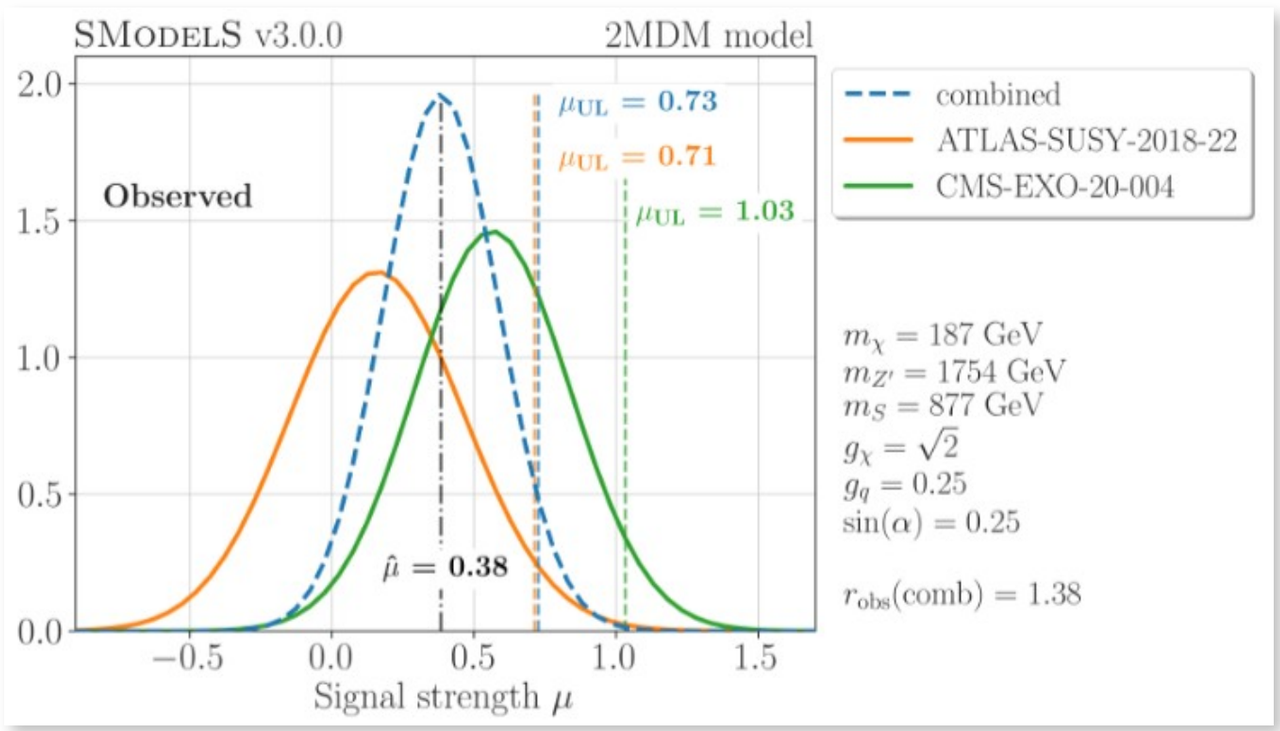
Physics Study: 2MDM

- Two mediator DM





Statistical Combination of ATLAS + CMS



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- We have built a prototype algorithm based on a MCMC for a dimensional space of varying dimensions.
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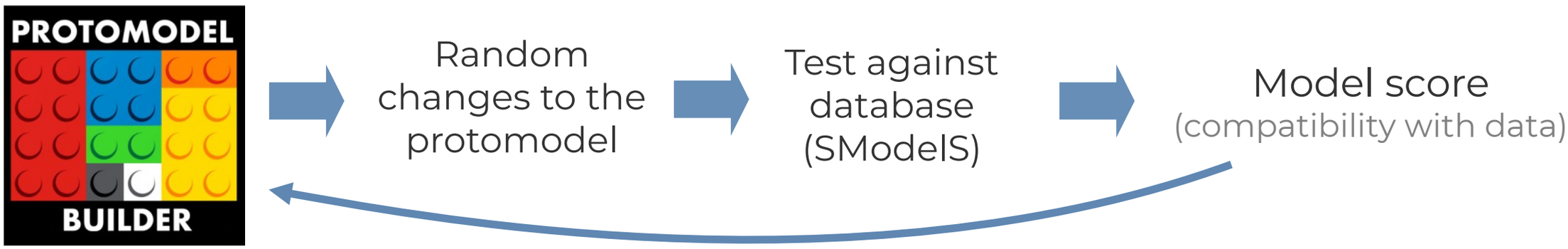

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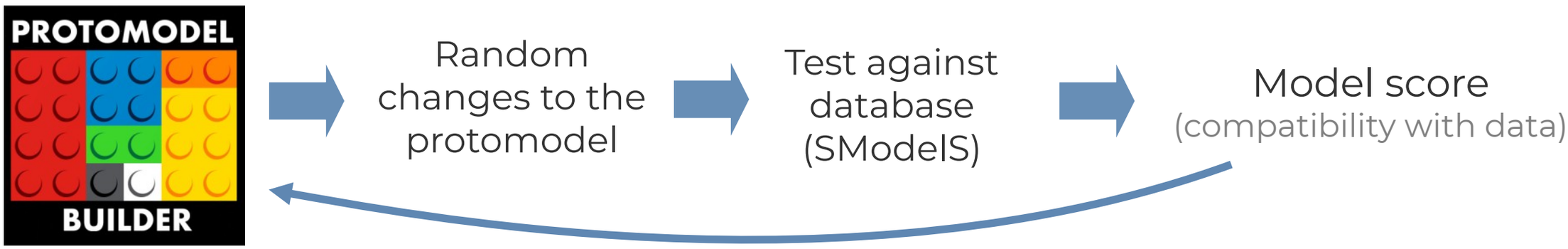

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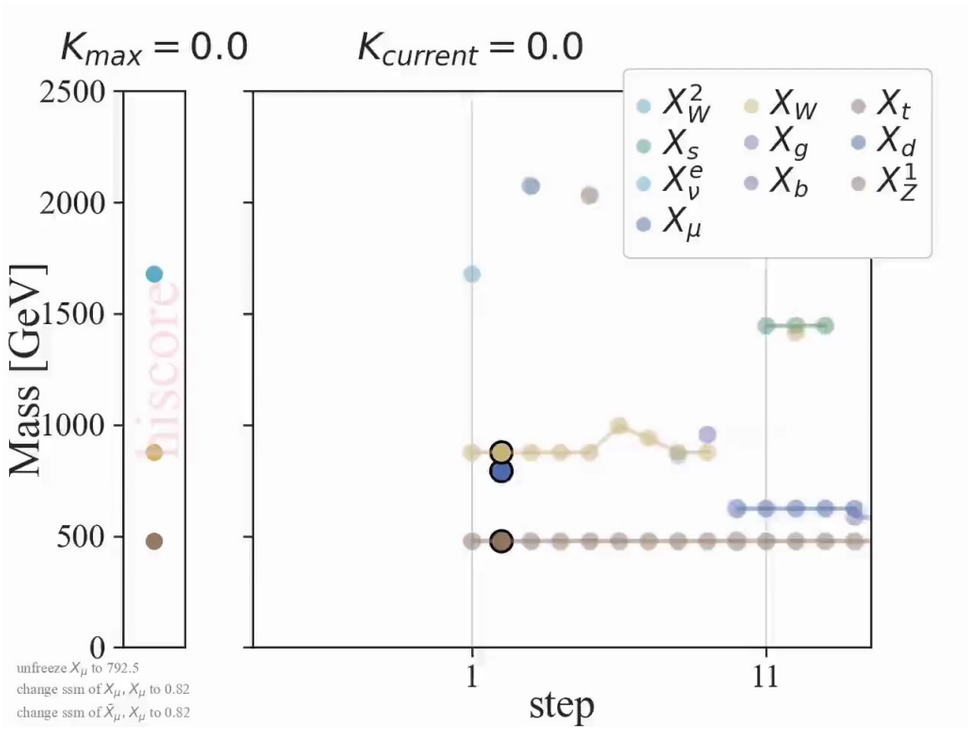

Effective Field Theories

- With the increase of data (HL-LHC)
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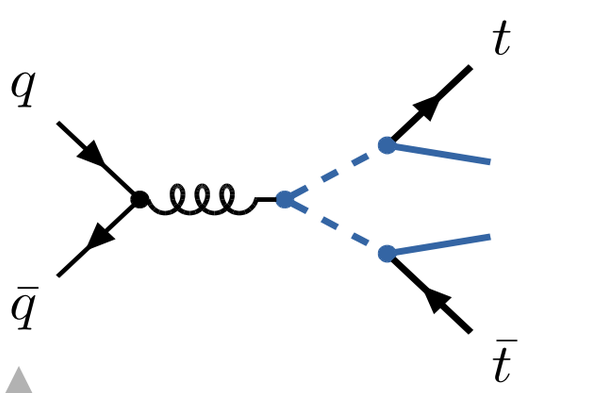
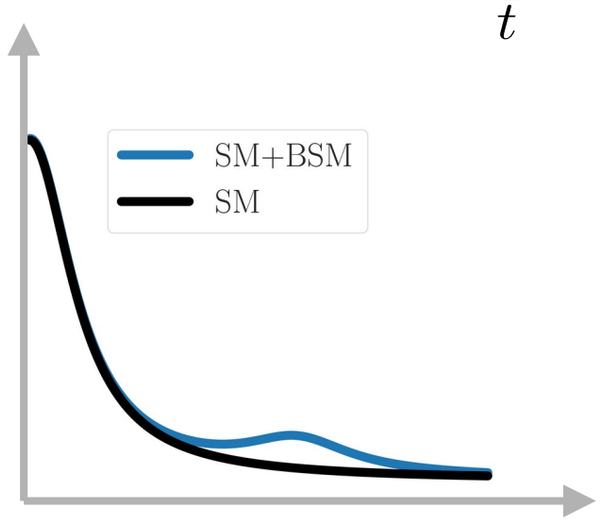
$\Lambda_{\rm BSM} < \sqrt{\hat{s}}$

On-Shell (BSM Searches)

$\mathcal{L}_{BSM} = |D_\mu \phi_T|^2 - y_{\rm DM} \phi_T^\dagger \bar{\chi} t_R + ...$





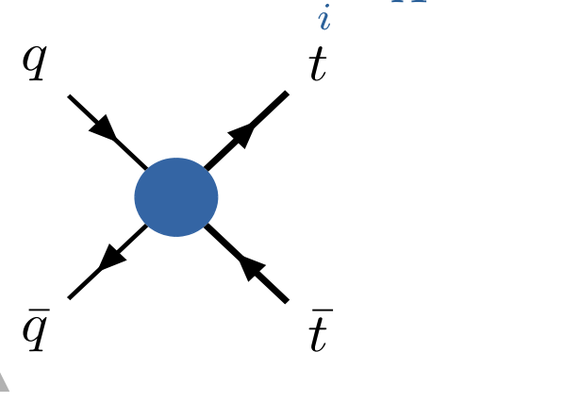
More data

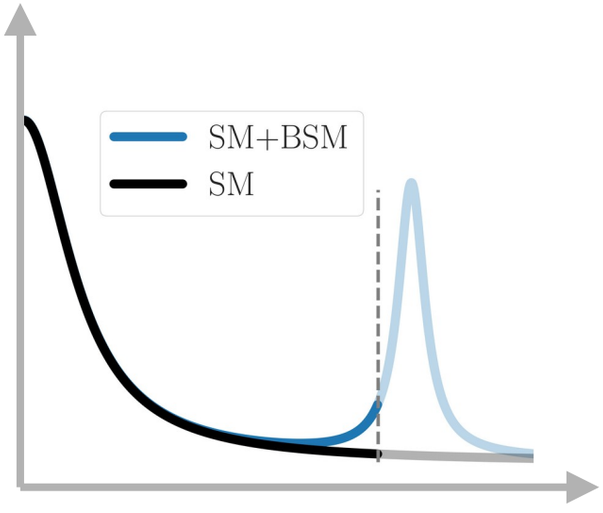
higher precision

$\Lambda_{\rm BSM} \gg \sqrt{\hat{s}}$

EFT (SM Measurements)

$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + ...$





Beyont EFTs

- Form factors:

$$\mathcal{F}^{\mu} = i\frac{T^A}{32\pi^4}\left[2\left(\not{p}_2 p_1^{\mu} + \not{p}_1 p_2^{\mu}\right) - s\gamma^{\mu}\right] P_R \mathcal{F}(s, m_T^2) \quad (m_\chi \to m_T,\, m_t \to 0),$$

where:

$$\mathcal{F}(s, m_T^2) \equiv \frac{1}{s^2}\left[m_T^2 L^2(s, m_T^2) + \sqrt{s\left(s - 4m_T^2\right)} L(s, m_T^2) + 3s\right] \text{ and}$$

$$L(s, m_T^2) \equiv \log\left[\left(\sqrt{s\left(s - 4m_T^2\right)} + 2m_T^2 - s\right)/(2m_T^2)\right]$$

EFT regime