Simplified Models for Heavy Stable Charged Particles

based on JH, A. Lessa, L. Quertenmont: JHEP 12 (2015) 087 [1509.00473]

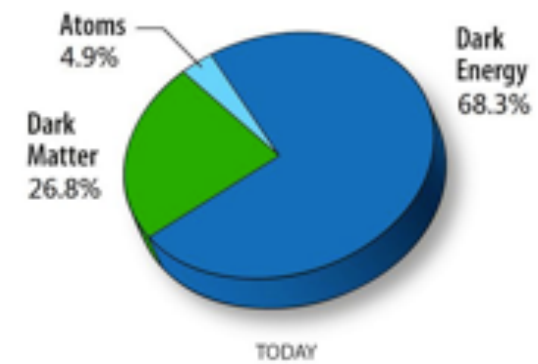
Jan Heisig (RWTH Aachen)

Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

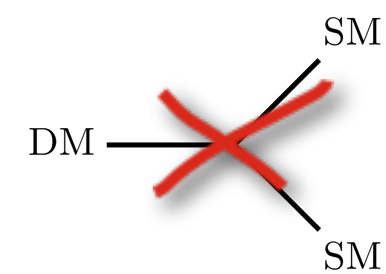
CERN

(Re)interpreting the results of new physics searches at the LHC
CERN, June 15−17, 2016

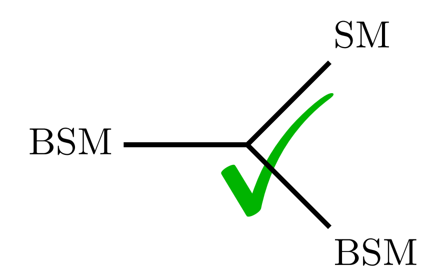
Why looking at heavy stable charged particels?
(HSCPs)



- Most BSM theories motivated by Dark Matter
  Need for a stable candidate!
- Impose a Z_2-symmetry: Dark matter Z_2-odd
- Only vertices with even numbers ⇒ no decay



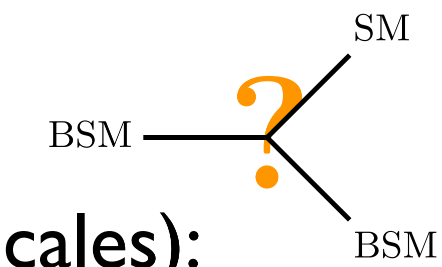
- Full theories: complete Z_2-odd sector
  (R-parity, KK-parity)
  ⇒ Cascade decays in the Z_2-odd sector



- Lightest Z_2-odd particle neutral
  For prompt decays ⇒ missing energy signature at the LHC

Why looking at heavy stable charged particels?

(HSCPs)



- Two situations in which not all decays are promt, charged particle can become stable (on collider time-scales):

I. Suppressed coupling of lightest Z_2-odd particle

- SUSY: Axino/gravitino LSP → NLSP long-lived

II. Decay of a heavier Z_2-odd particle is kinematically suppressed

- SUSY: Wino/Higgsino-LSP [e.g. Bomark, Kvellestad, Lola, Osland, Raklev, 1310.2788]
- Extra Dimensions [Byrne, hep-ph/0311160]
- SUSY: Stau-neutralino degeneracy (co-annihilation strip, Li-Problem) [e.g. Jittoh, Sato, Shimomura, Yamanaka, hep-ph/0512197]

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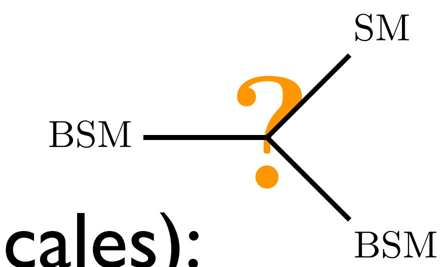

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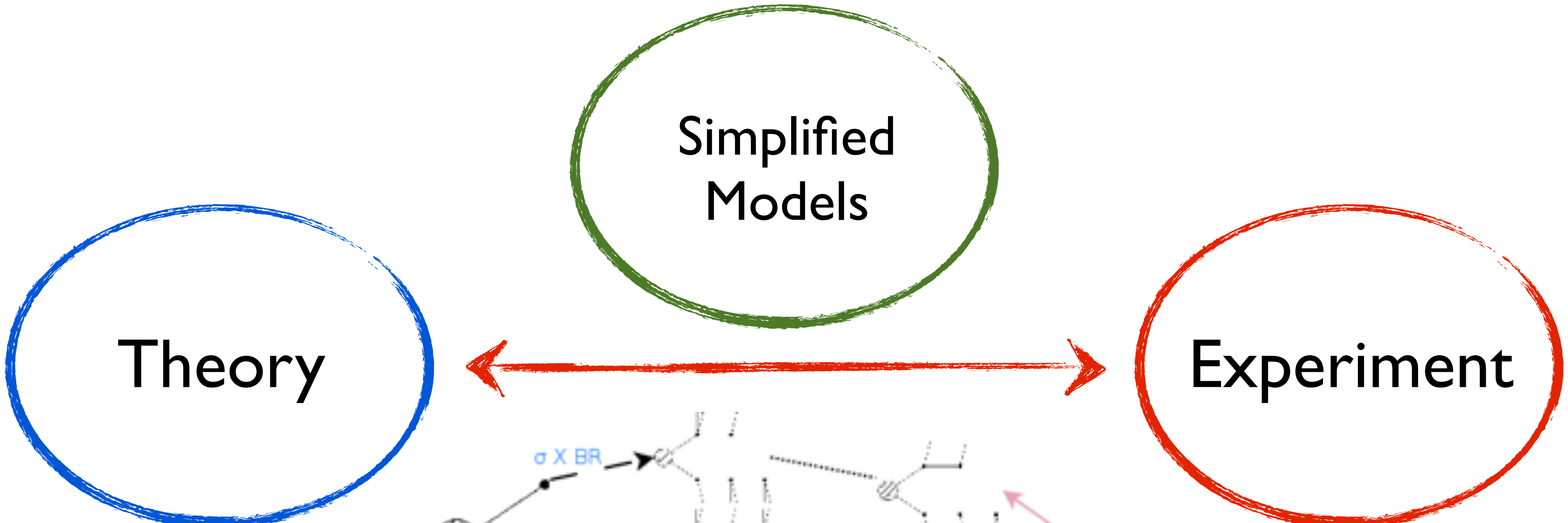
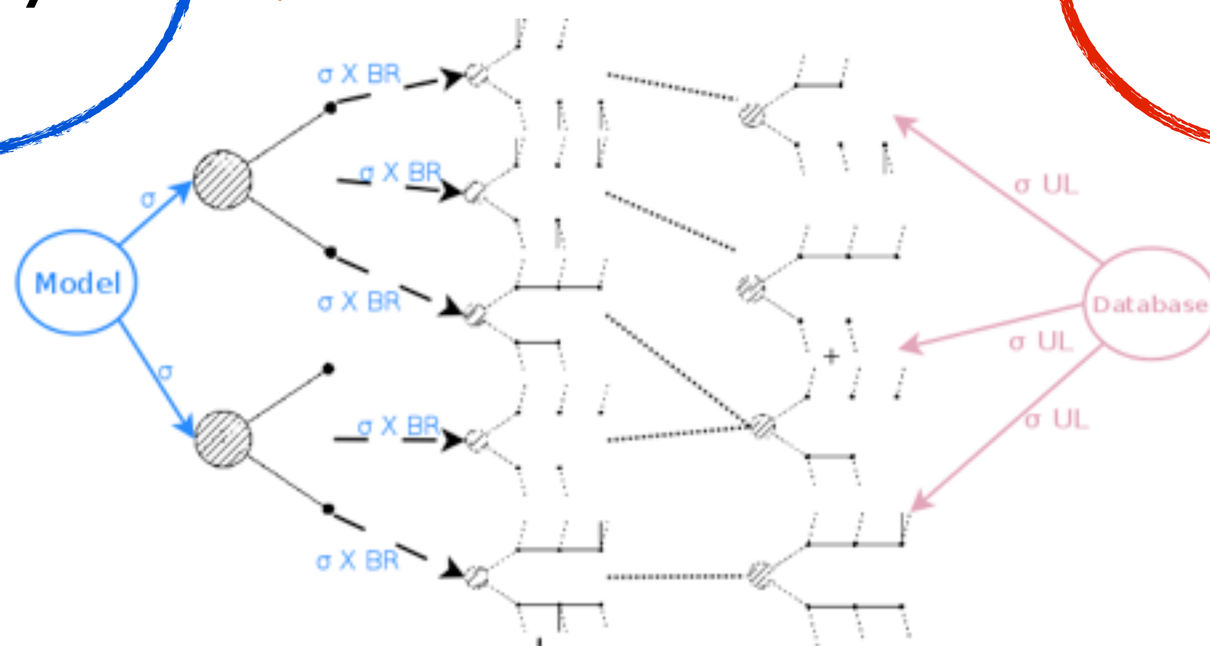
Why Simplified Models?





Pros:

- Applicable to any BSM model
- No MC simu → Fast!
- Tools avaibale

Cons:

- Limited by database
- Uses approximations (only masses, topologies)
  [see e.g. Edelhäuser *et al.* 1410.0965, 1501.03942]

[SModelS: Kraml, Kulkarni, Laa, Lessa, Magerl, Proschofsky, Waltenberger, 1312.4175] → Andre's Talk

[Fastlim: Papucci, Sakurai, Weiler, and Zeune, 1402.0492] → Kazuki's Talk

[XQCAT: Barducci, Belyaev, Buchkremer, O'Brien, Marrouche, Moretti, Panizzi, Prager] → Luca's Talk

Simplified Models

- So far: Missing Transverse Energy (MET) searches only
- But: more exotic signatures can be important!

  → Heavy Stable charged particles (HSCP)

This work:

Implement HSCP searches into SModelS

(stable = decays outside the detector
Disappearing Tracks → Jared's talk)

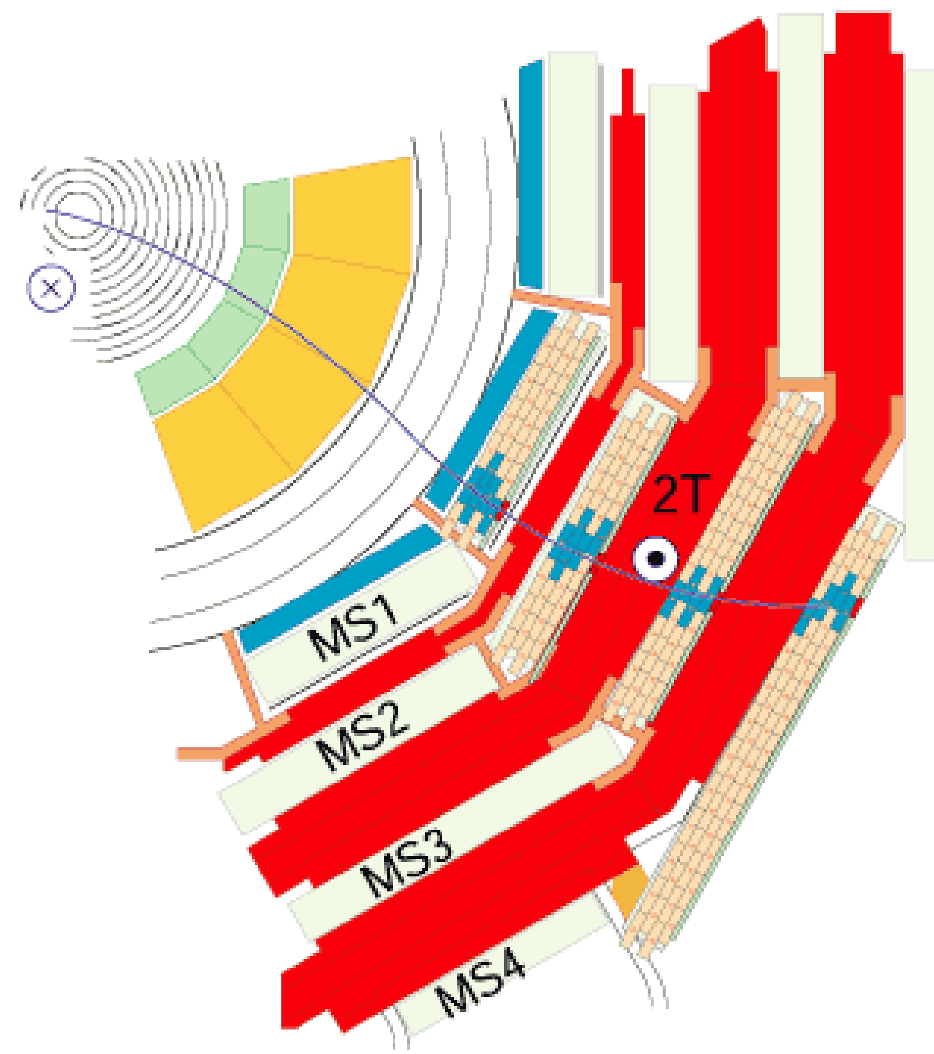
Outline

- HSCP searches at the LHC
- Implementation into SModelS
- Application to BSM scenario

HSCP searches at the LHC

HSCP at the LHC: a prominent signature

- Pass the whole detector: muon-like signature
- Two disctinct features



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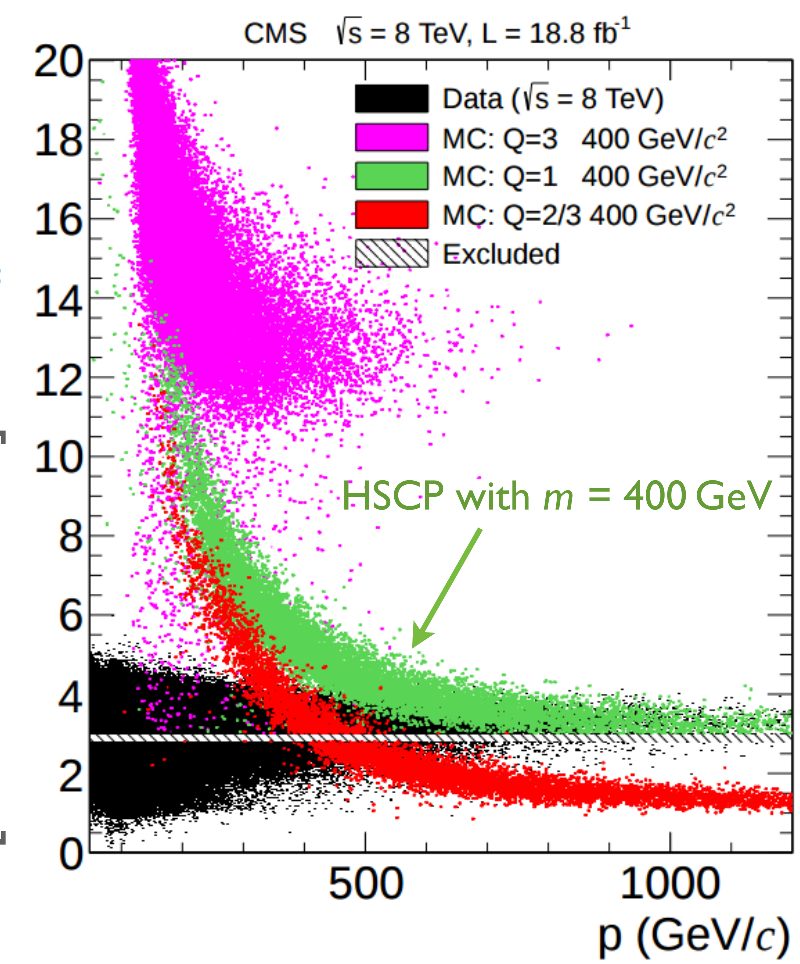
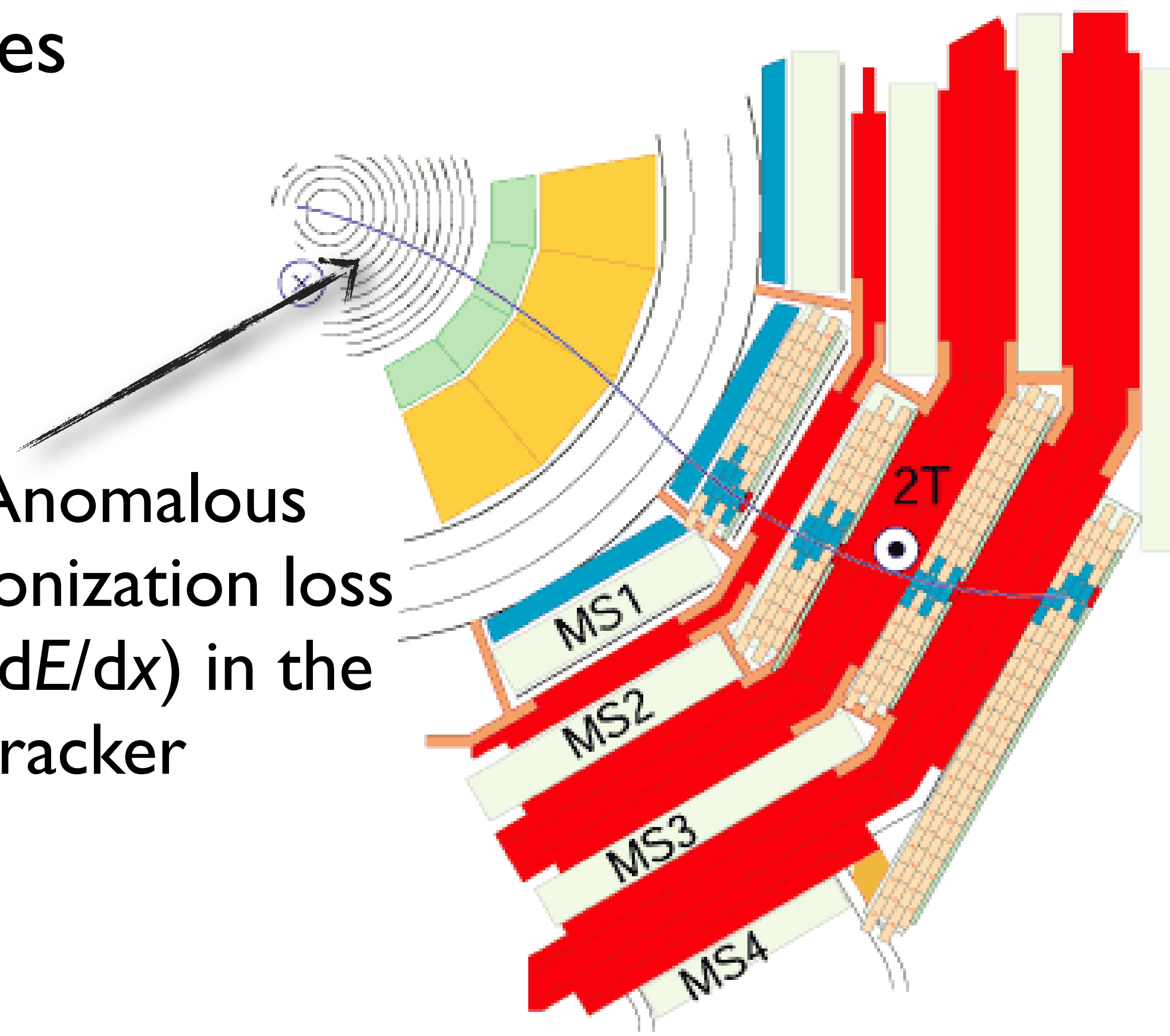


[CMS: 1305.0491]

Anomalous ionization loss (dE/dx) in the tracker



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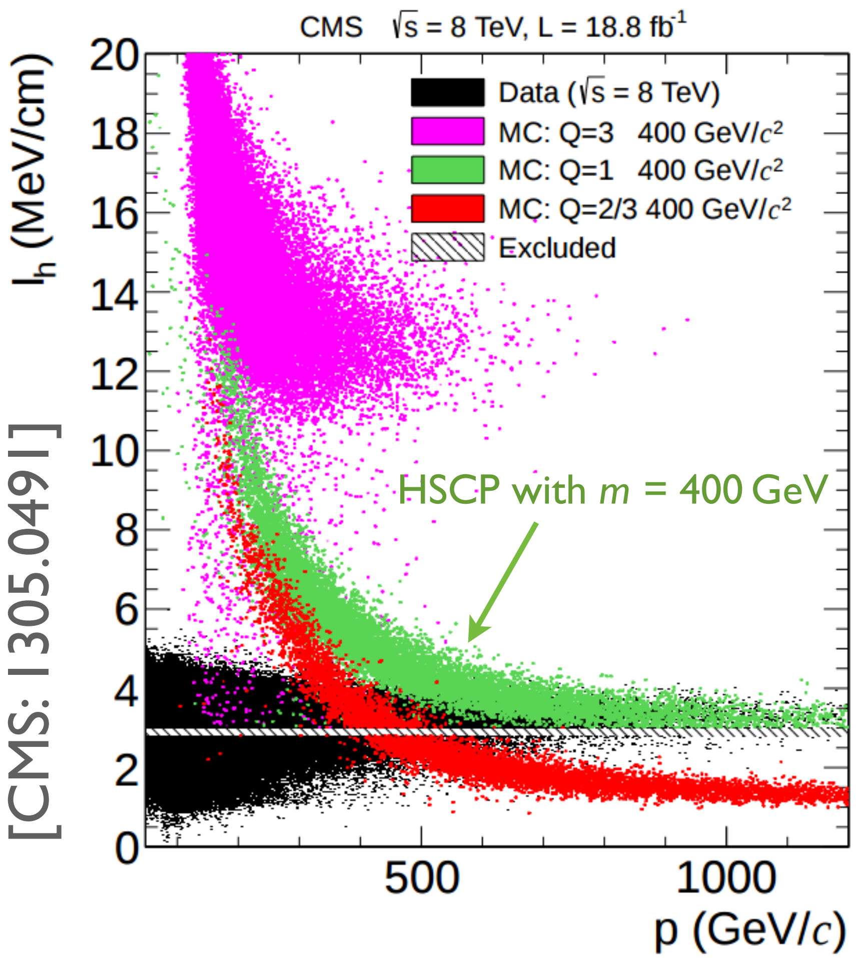

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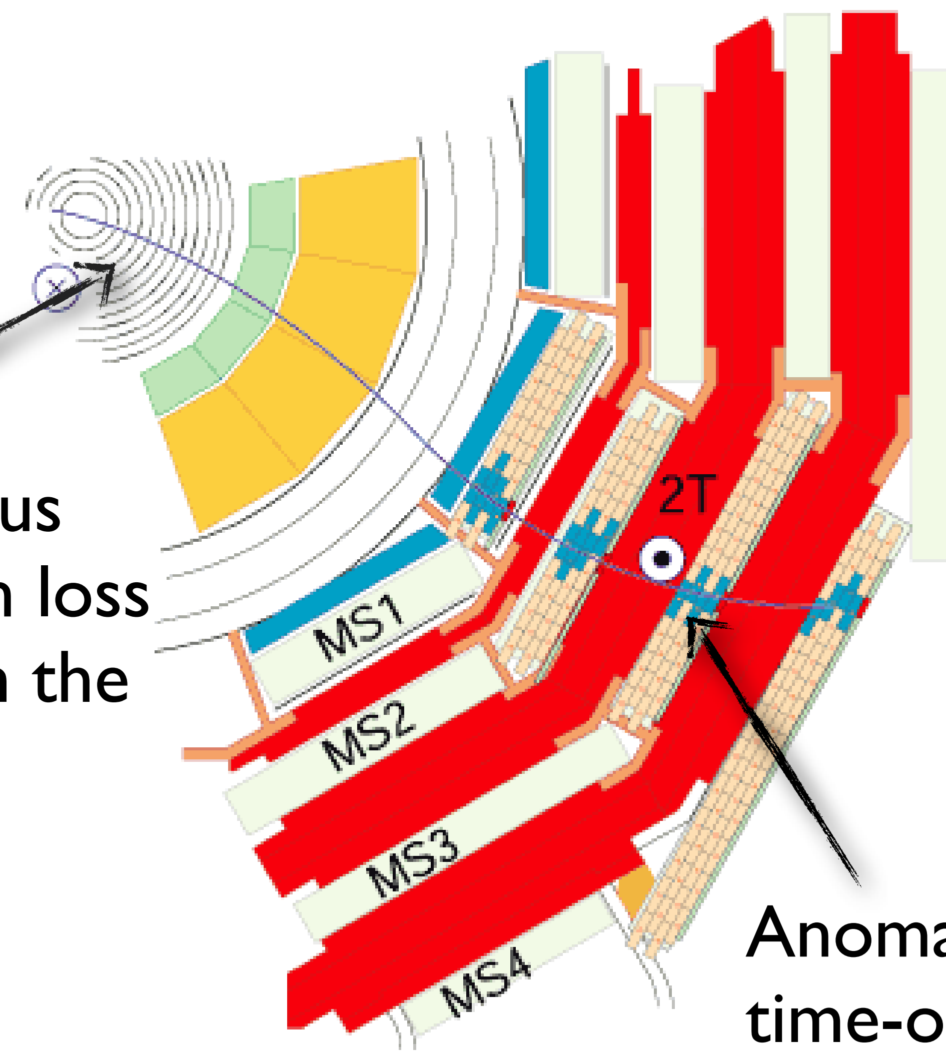

Anomalous time-of-flight in the muon-system

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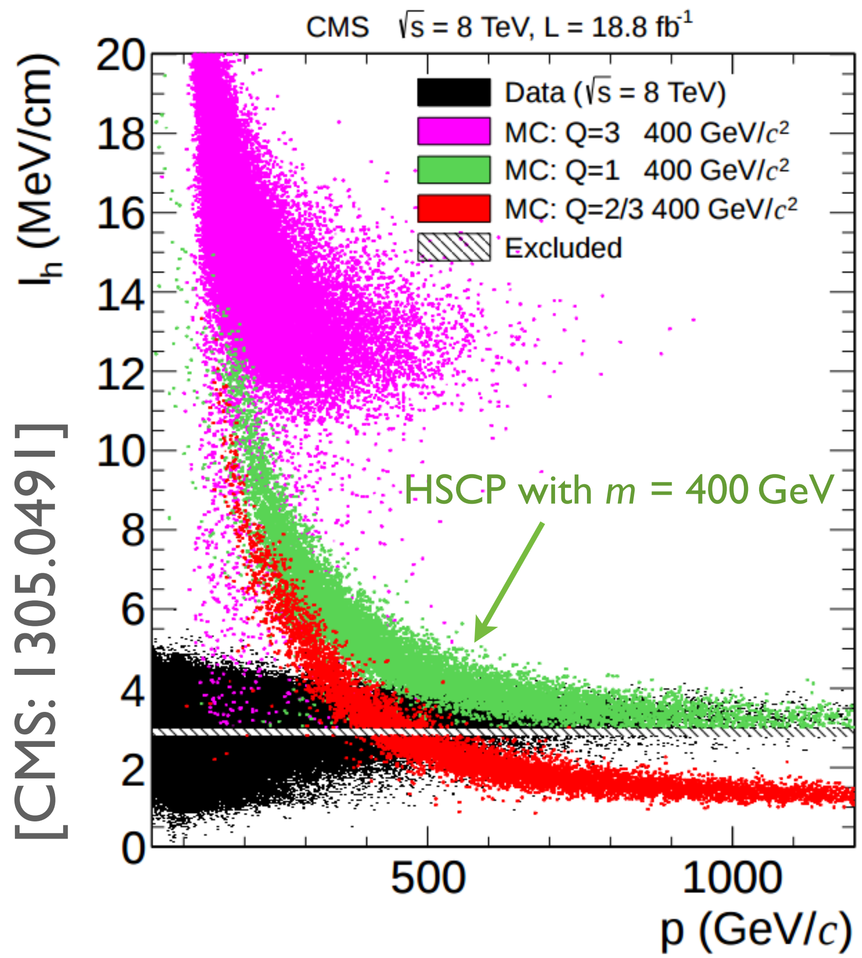

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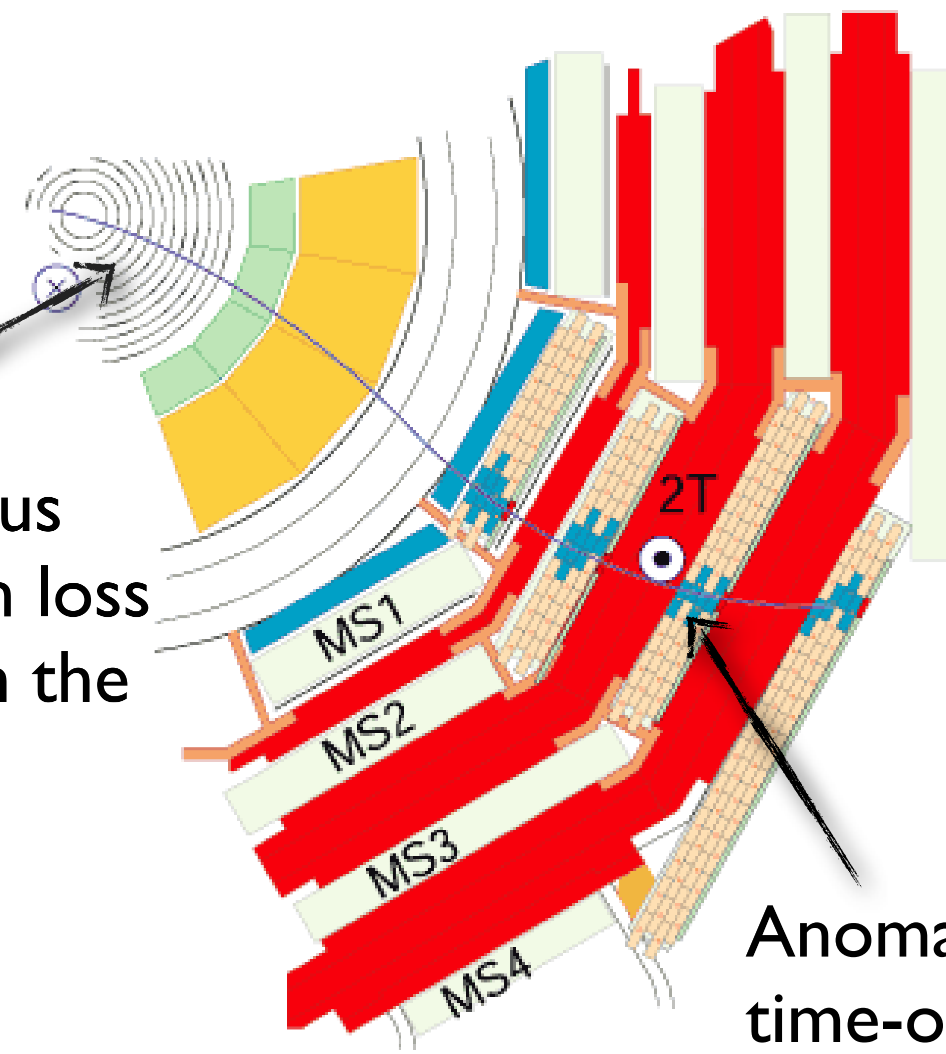

Anomalous time-of-flight in the muon-system

High sensitivity!

Interpretation of HSCP searches

- Hyper-kaon/rho (vector-like confinement model)
  [CMS 7TeV data; 1205.0272]
- SUSY staus (GMSB/direct production)
  [CMS, ATLAS 7,8 TeV data; 1205.0272, 1305.0491, 1211.1597, 1411.6795;
  13 TeV data (preliminary); CMS PAS EXO-15-010]
- SUSY charginos (AMSB/pMSSM/direct production)
  [CMS, ATLAS 8 TeV data; 1502.02522, 1506.0533]

→ Non-standard signature: Difficult to re-interprete

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→ Non-standard signature: Difficult to re-interprete

Novel method to recast HSCP analysis:

- Compute efficiences reliably directly from hadron-level events
- Provides probabilities for hadron-level events passing selection
- Incorporates detector effects (no simu needed)

Re-interpretation of HSCP searches

[CMS: 1502.02522]

Novel method to recast HSCP analysis:

- Acceptance depends on kinematics $\boldsymbol{k}_i = (\eta_i, p_{\mathrm{T}i}, \beta_i)$ of isolated HSCP candidates in the events
- 1502.02522 provides on- and offline probabilities $P_{\mathrm{on}}(\boldsymbol{k}_i)$ and $P_{\mathrm{off}}(\boldsymbol{k}_i)$ for an event to pass selection criteria
- Acceptance computed by averaging over all hadron-level events

$$\epsilon = \frac{1}{N}\sum_{i}^{N} P_{\mathrm{on}}(\boldsymbol{k}_i) \times P_{\mathrm{off}}(\boldsymbol{k}_i)$$

- For events with two HSCP candates $P_{\mathrm{on/off}}$ becomes

$$P^{(2)}_{\mathrm{on/off}}(\boldsymbol{k}_i^1, \boldsymbol{k}_i^2) = P_{\mathrm{on/off}}(\boldsymbol{k}_i^1) + P_{\mathrm{on/off}}(\boldsymbol{k}_i^2) - P_{\mathrm{on/off}}(\boldsymbol{k}_i^1) P_{\mathrm{on/off}}(\boldsymbol{k}_i^2)$$

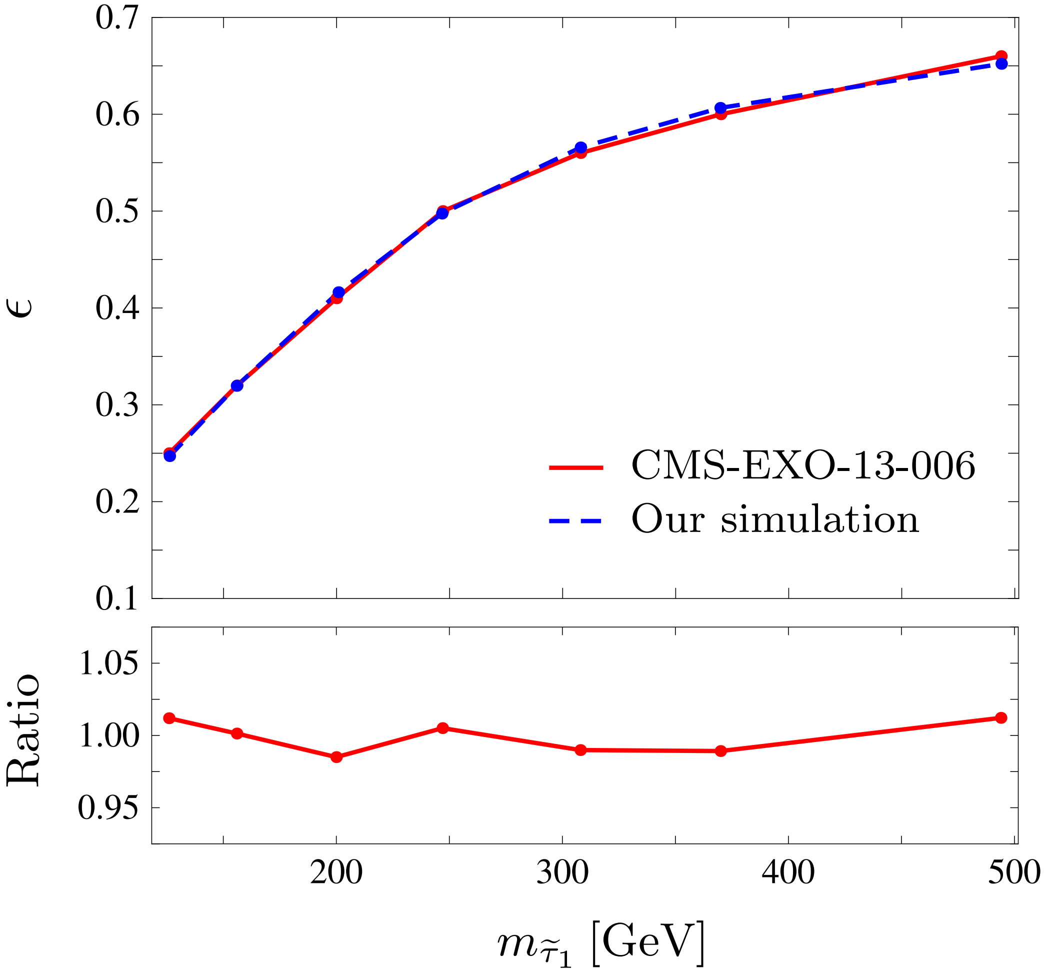
Re-interpretation of HSCP searches

[CMS: 1502.02522]

Novel method to recast HSCP analysis:

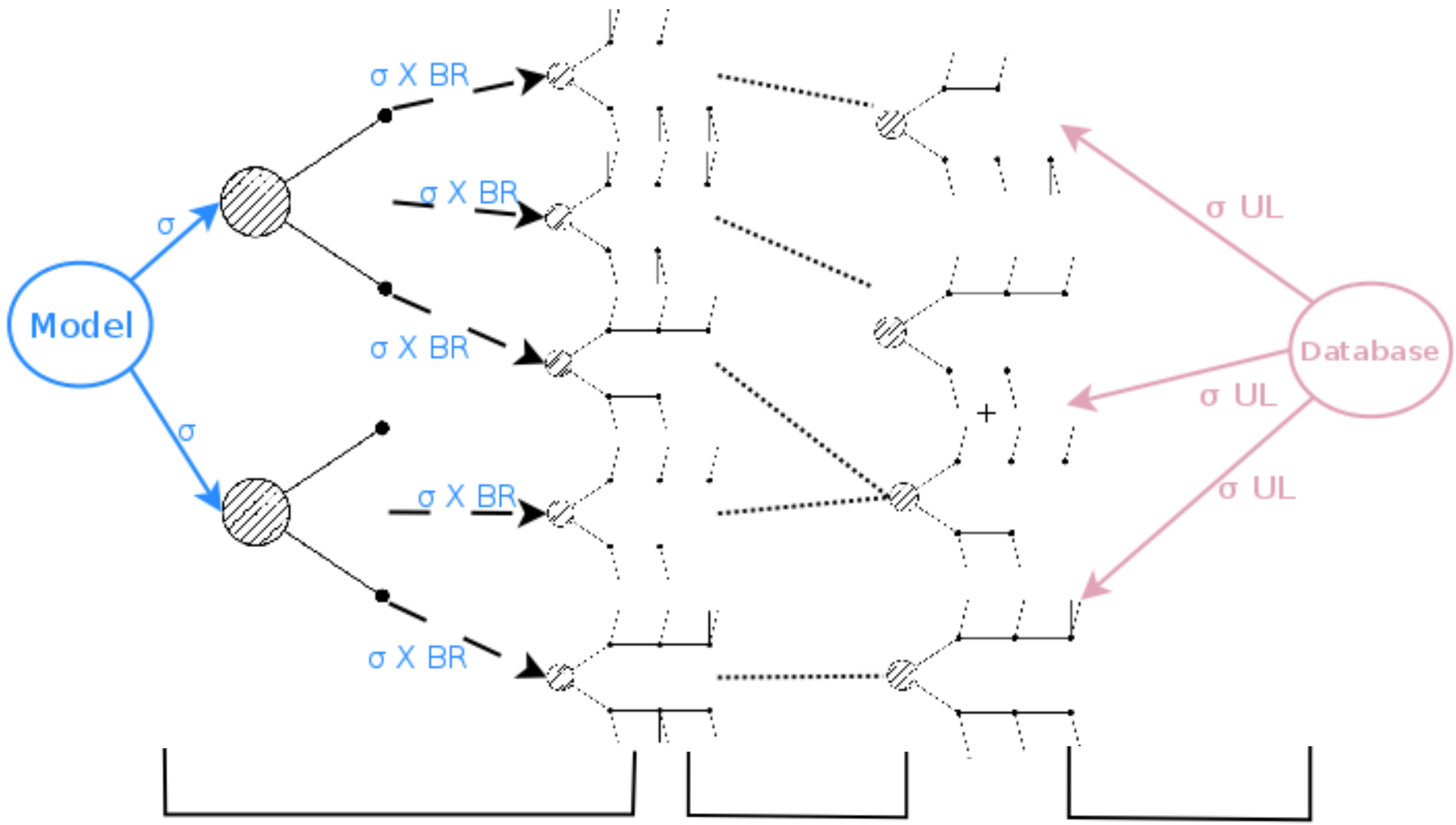
- Simulate events (MadGraph/Phythia) → apply isolation criteria → directly compute signal efficiency

- Validation GMSB model
- Less than 5% deviation →



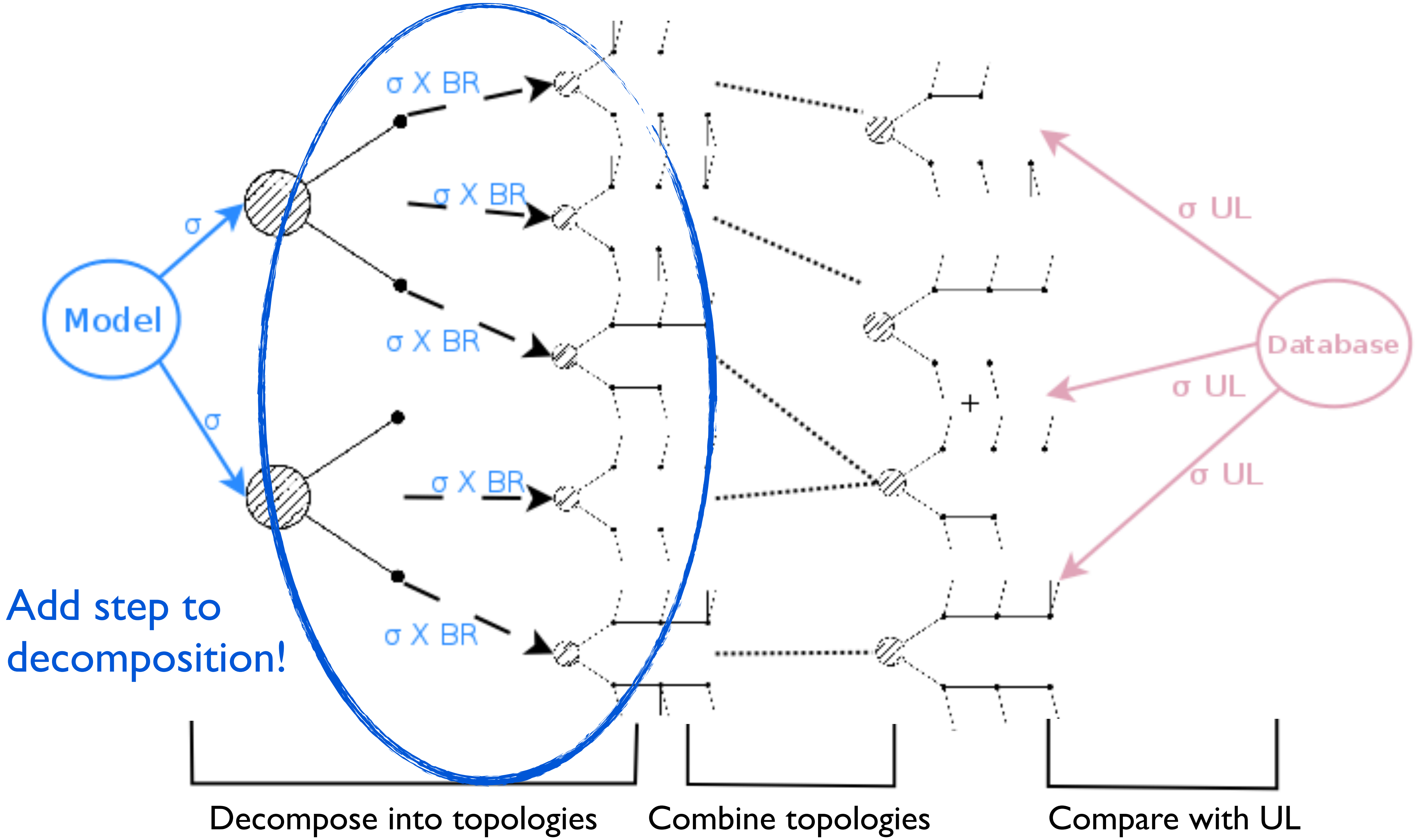
Implementation into SModelS

Extending SModelS



Decompose into topologies | Combine topologies | Compare with UL

Extending SModelS



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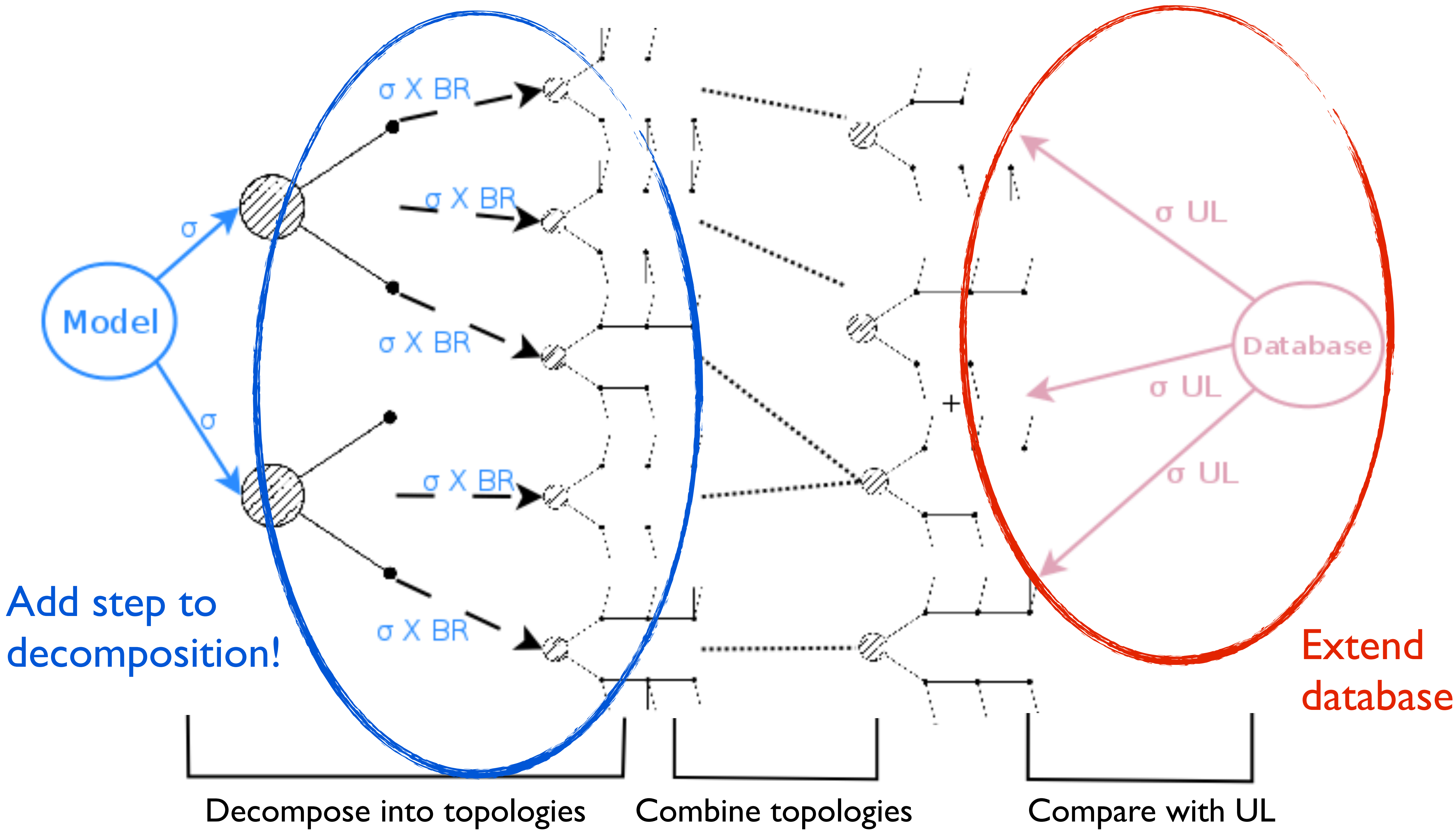
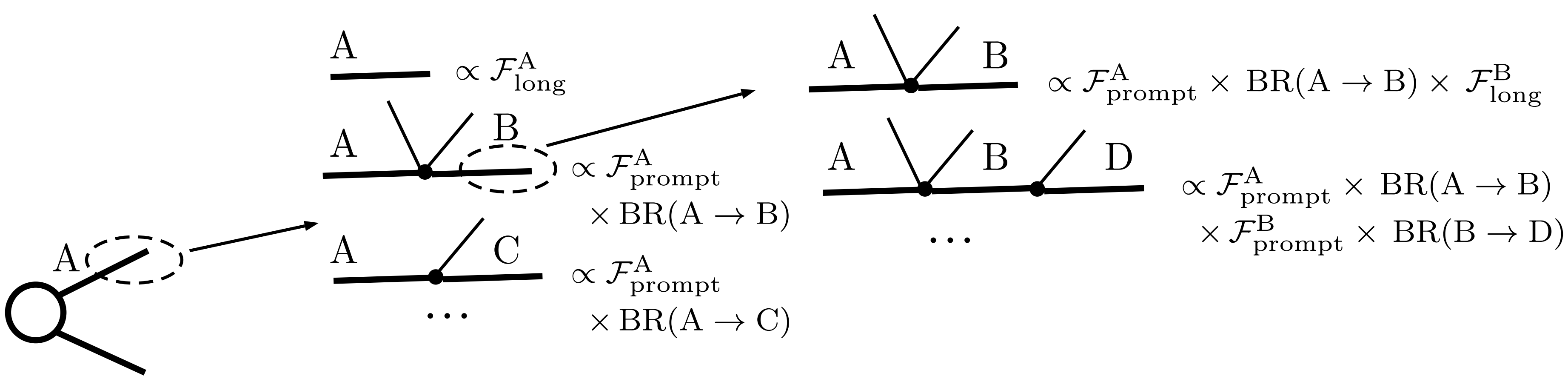


Extending SModelS

- Add step to decomposition:

  Probability to decay prompt: $\mathcal{F}_{\text{prompt}} = 1 - e^{-\Gamma l_{\text{inner}}/(\gamma\beta)}$,

  or appear metastable: $\mathcal{F}_{\text{long}} = e^{-\Gamma l_{\text{outer}}/(\gamma\beta)}$,



- End up with:

  pure MET, mixed MET/HSCP and pure HSCP

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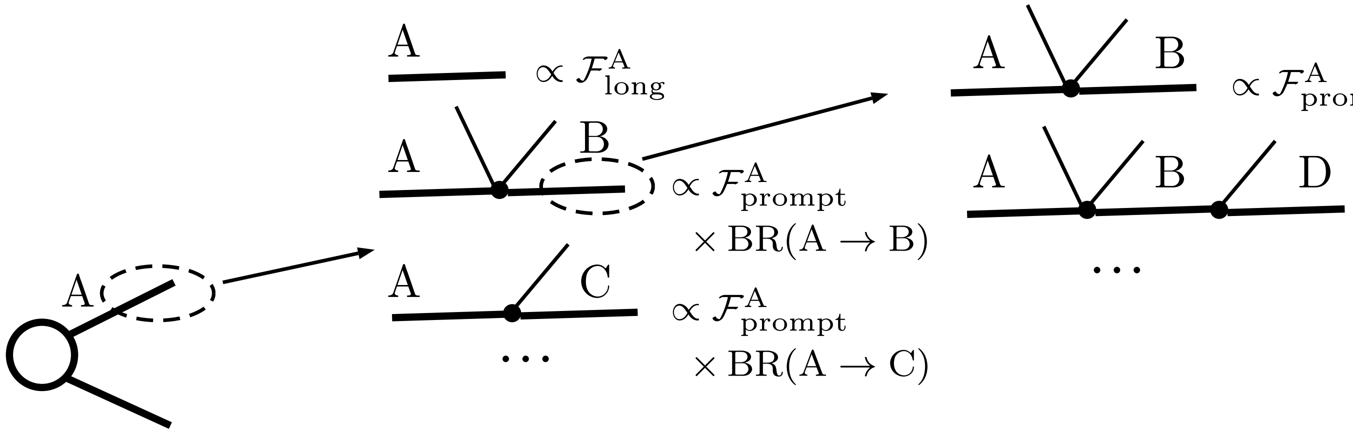


$\propto \mathcal{F}^{\mathrm{A}}_{\mathrm{long}}$

$\propto \mathcal{F}^{\mathrm{A}}_{\mathrm{prompt}} \times \mathrm{BR}(\mathrm{A} \to \mathrm{B})$

$\propto \mathcal{F}^{\mathrm{A}}_{\mathrm{prompt}} \times \mathrm{BR}(\mathrm{A} \to \mathrm{C})$

$\propto \mathcal{F}^{\mathrm{A}}_{\mathrm{prompt}} \times \mathrm{BR}(\mathrm{A} \to \mathrm{B}) \times \mathcal{F}^{\mathrm{B}}_{\mathrm{long}}$

$\propto \mathcal{F}^{\mathrm{A}}_{\mathrm{prompt}} \times \mathrm{BR}(\mathrm{A} \to \mathrm{B}) \times \mathcal{F}^{\mathrm{B}}_{\mathrm{prompt}} \times \mathrm{BR}(\mathrm{B} \to \mathrm{D})$

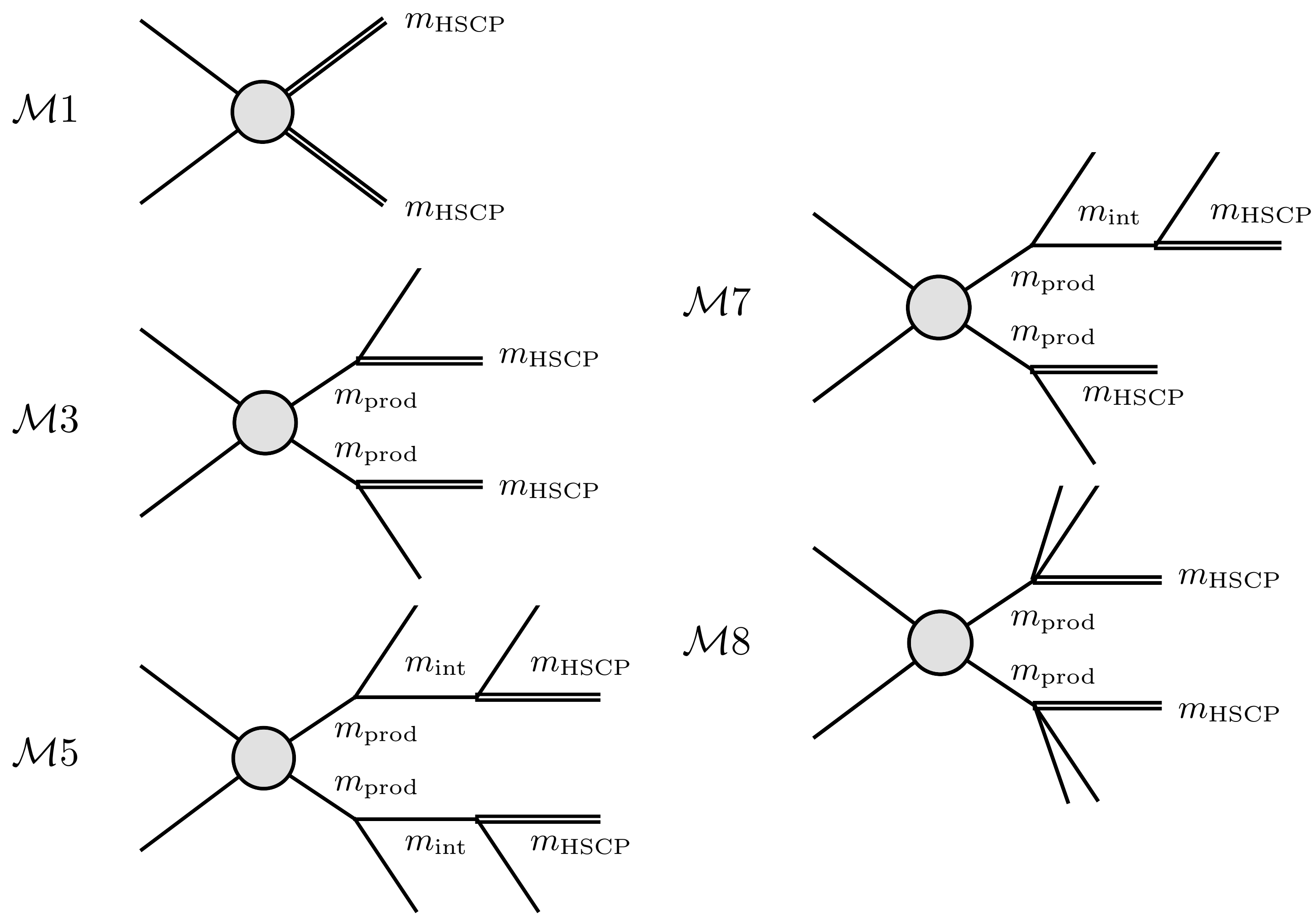
- End up with:

pure MET, mixed MET/HSCP and pure HSCP

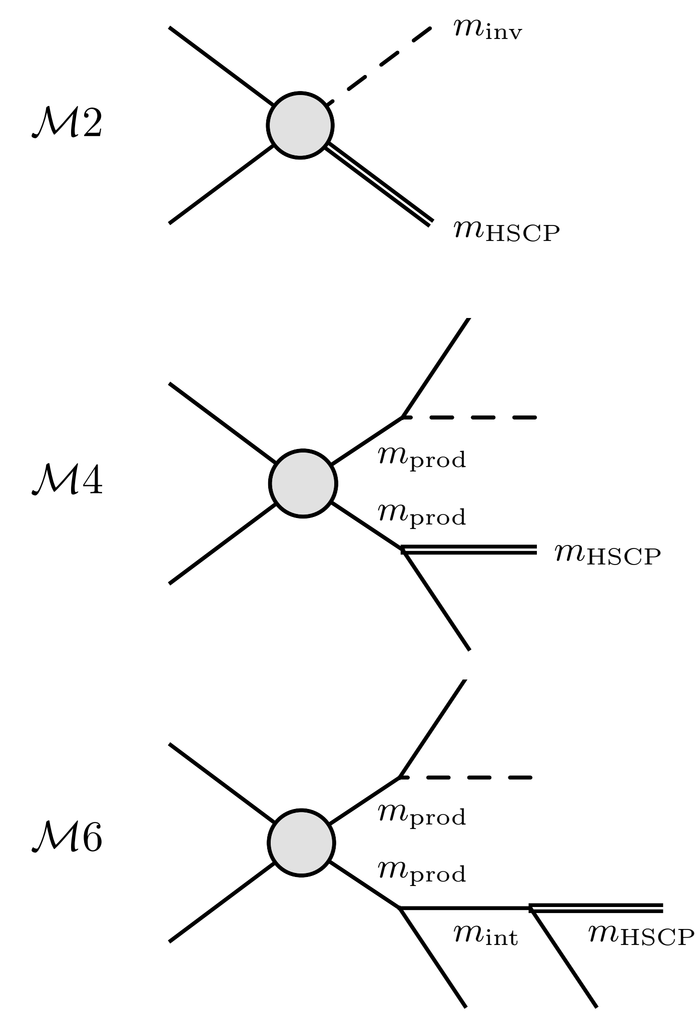
Extend database!

Extending SModelS: Considered Topologies

Pure HSCP:



MET/HSCP:



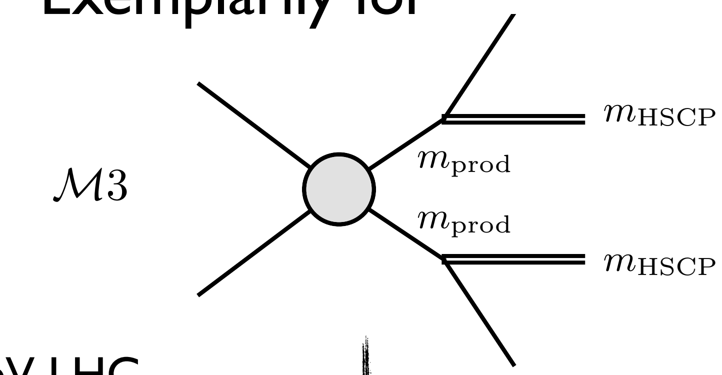
Extending SModelS: Efficiencies

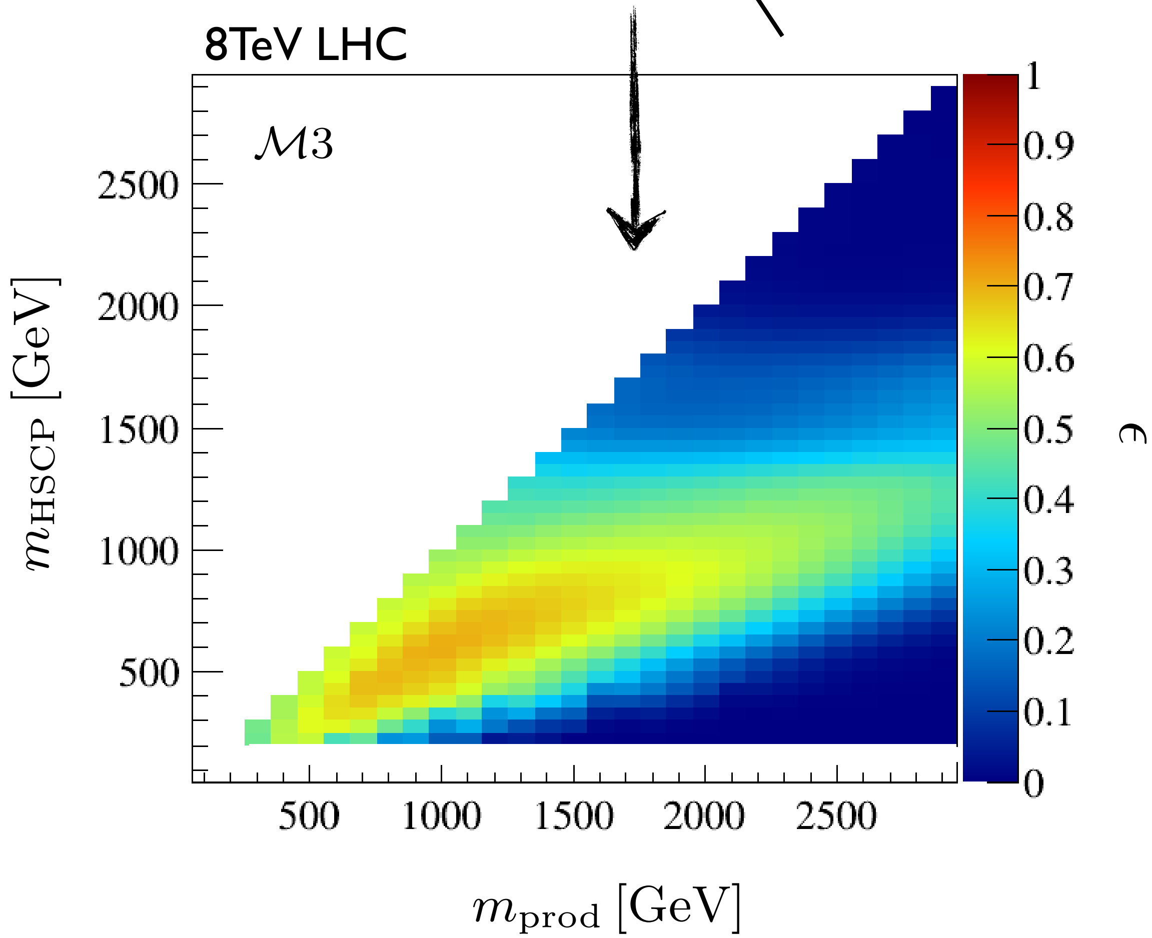
- Extend database:
  Compute efficiencies for 8 topologies
- Simulation: MadGraph/Phythia
    - Signal efficiencies up to 70%
    - Efficiencies drop for
        - $\beta \to 1$ (muon-background)
        - $\beta \lesssim 0.45$ (trigger)

      [cf. JH, Kersten, 1203.1581]

→ Use efficiencies for general model

Exemplarily for





Application to BSM scenario

The Tip of the CMSSM Co-annihilation Strip

[see also: Desai, Ellis, Luo, Marrouche, 1404.5061]

- CMSSM with neutralino LSP, stau NLSP
- Monte Carlo scan over

$$m_0, M_{1/2}, A_0$$

  for fixed $\tan\beta$ and $\mu > 0$

- Require $\delta m = m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} < 0.1 \text{ GeV}$, $\tau_{\tilde{\tau}} \gtrsim 1 - 100s$

  → long-lived stau is HSCP candidate

Additional motivation: cosmology

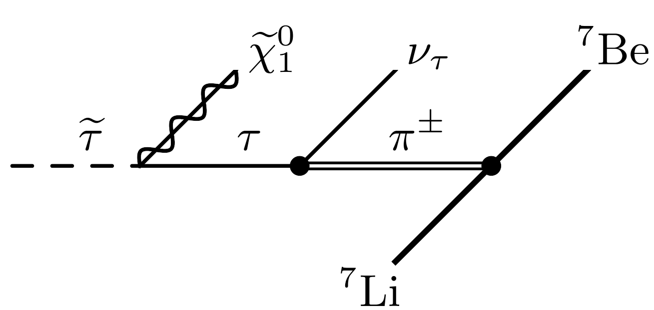
- possible solution to the ^{7}Li-Problem [Konishi et al. 1309.2067]

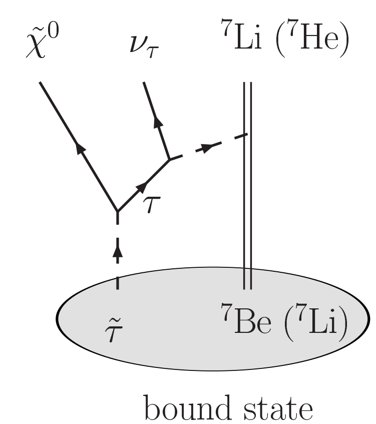
Additional motivation: Cosmology

- Big Bang Nucleosynthesis (BBN): Intriguing test of particle physics at temperatures $T \sim 1\,\mathrm{MeV}$ or times $t \sim 1\,\mathrm{min}$
- Standard BBN: Consistence for D, ^{3}He, ^{4}He
- But: Significant discrepancy for ^{7}Li:

$$\left(\frac{^7\mathrm{Li}}{\mathrm{H}}\right)_{\mathrm{theo}} = (4.68 \pm 0.67) \times 10^{-10}, \quad \left(\frac{\mathrm{Li}}{\mathrm{H}}\right)_{\mathrm{exp}} = (1.6 \pm 0.3) \times 10^{-10}\,.$$

- Depletion of ^{7}Li via HSCPs one proposed solution





[see e.g. Jittoh, Kohri, Koike, Sato, Shimomura, Yamanaka, 0704.2914]

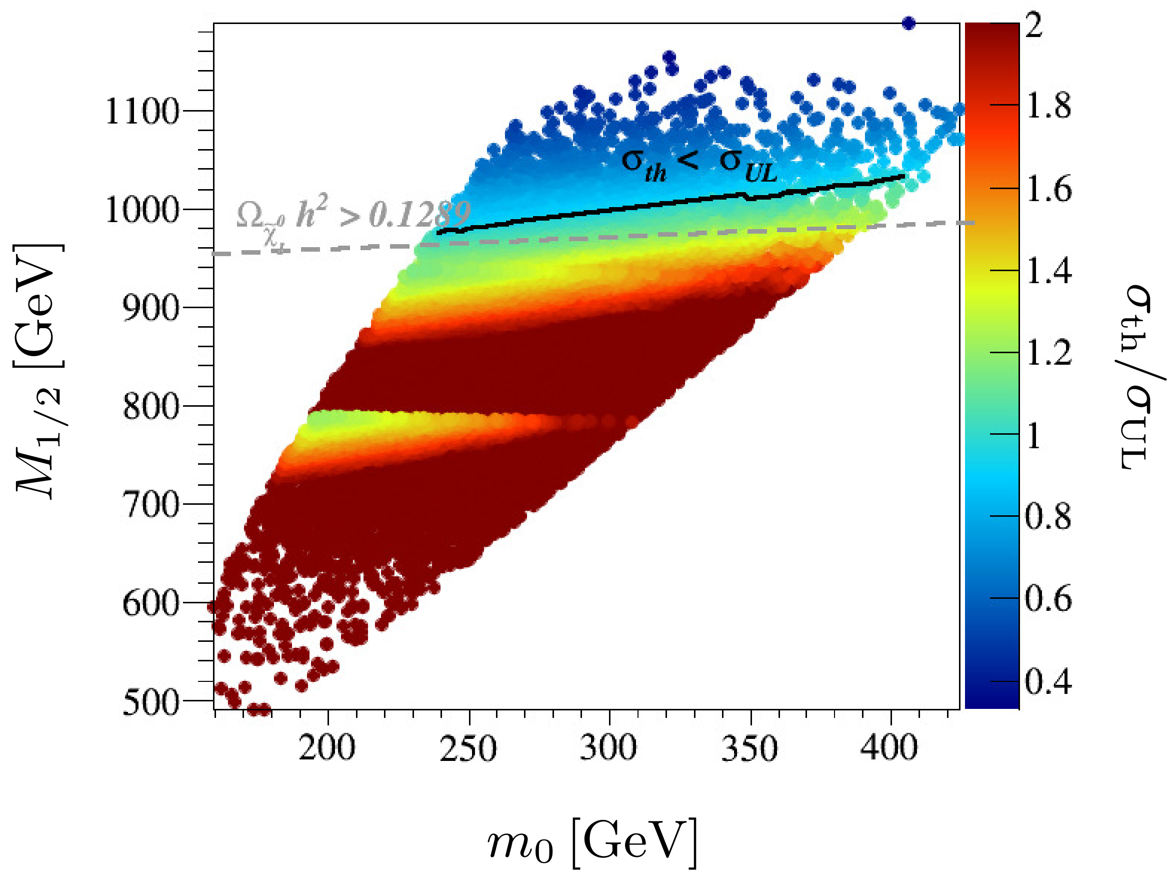
The Tip of the CMSSM Co-annihilation Strip

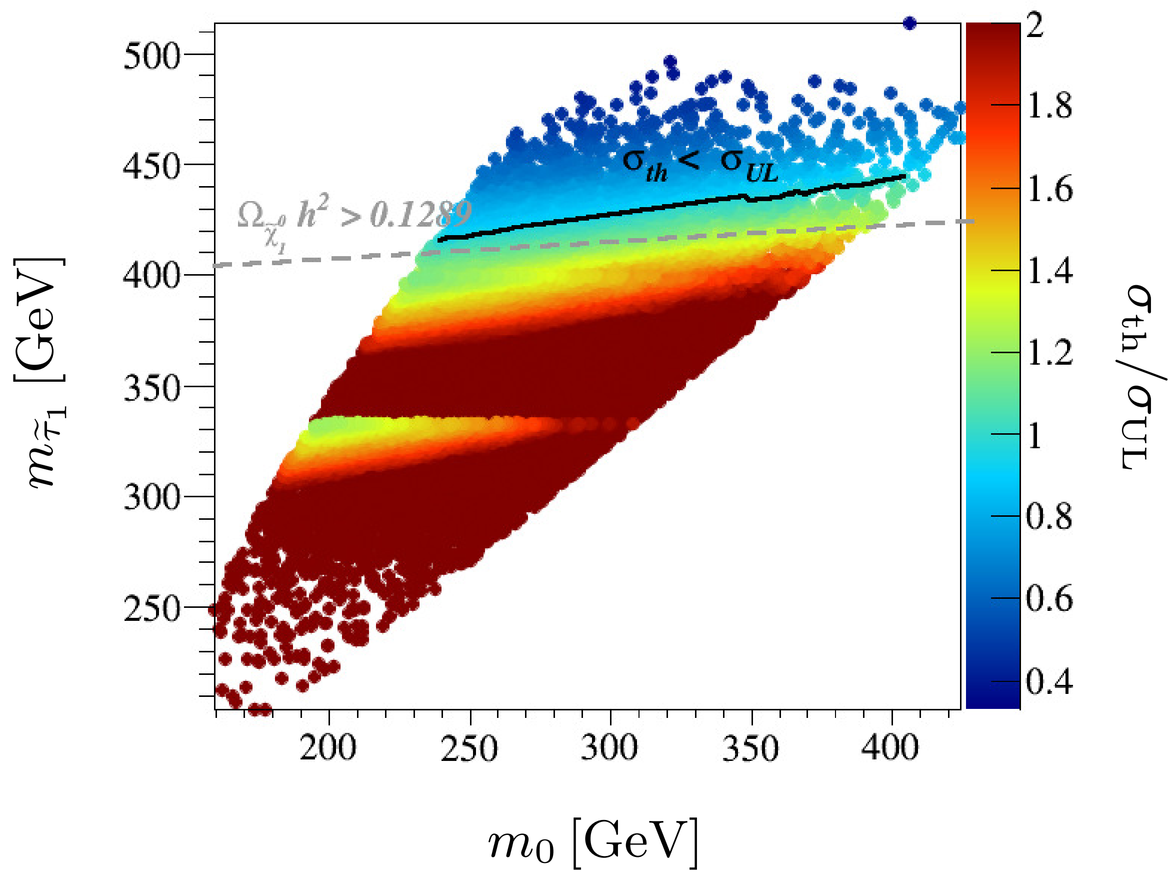
- Decomposition:
  - ~70% signal: MET signatures (dominant $\widetilde{q}\widetilde{q} \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0 + 2j$)
  - ~20% signal: mixed MET/HSCP (dominant $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0 \to \widetilde{\tau}_1^{\pm}\widetilde{\chi}_1^0 + \nu_\tau Z$)
  - ~10% signal: pure HSCP (dominant $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\pm} \to \widetilde{\tau}_1^{\pm}\widetilde{\tau}_1^{\pm} + 2\nu_\tau$)
- For HSCP and mixed: Efficiency database (8 topologies)
- For pure MET: Apply upper limit from most sensitive topology from SModelS MET-database

The Tip of the CMSSM Co-annihilation Strip

- LHC sensitivity (for $\tan\beta = 10$):

[JH, Lessa, Quertenmont, 1509.00473]

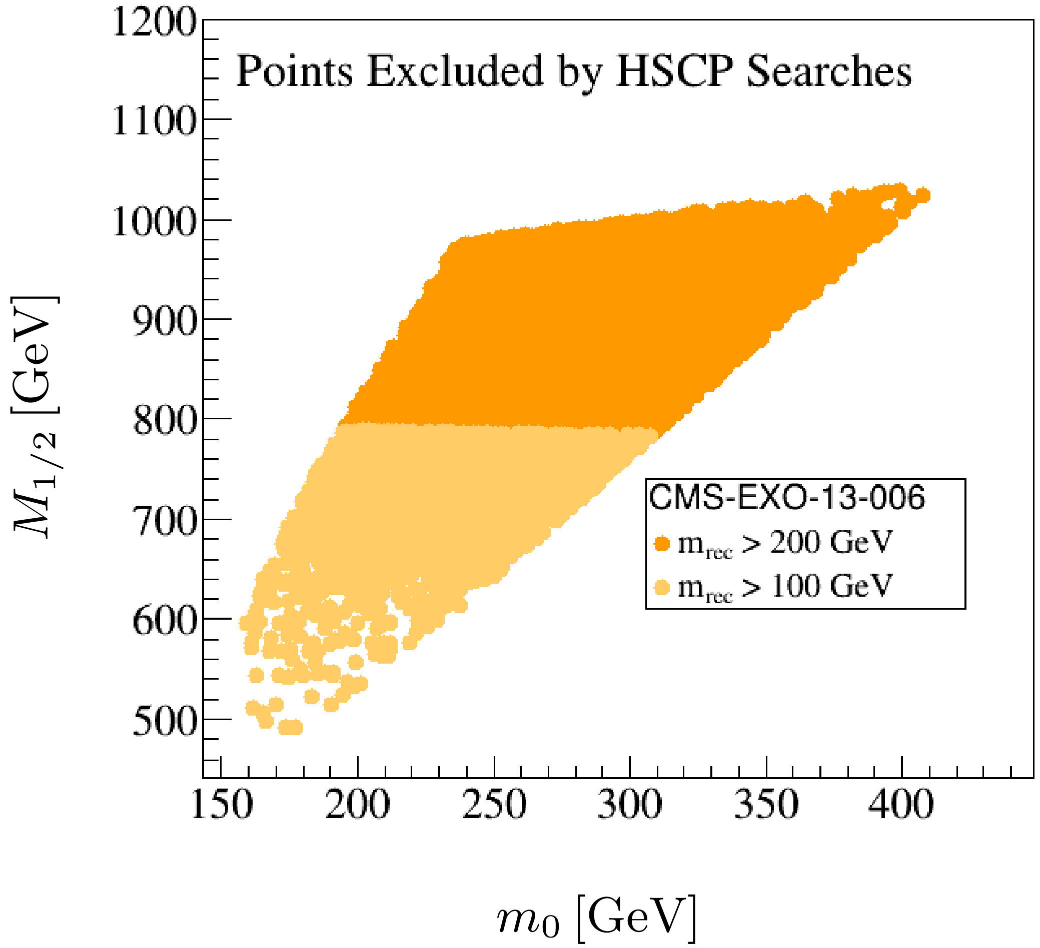


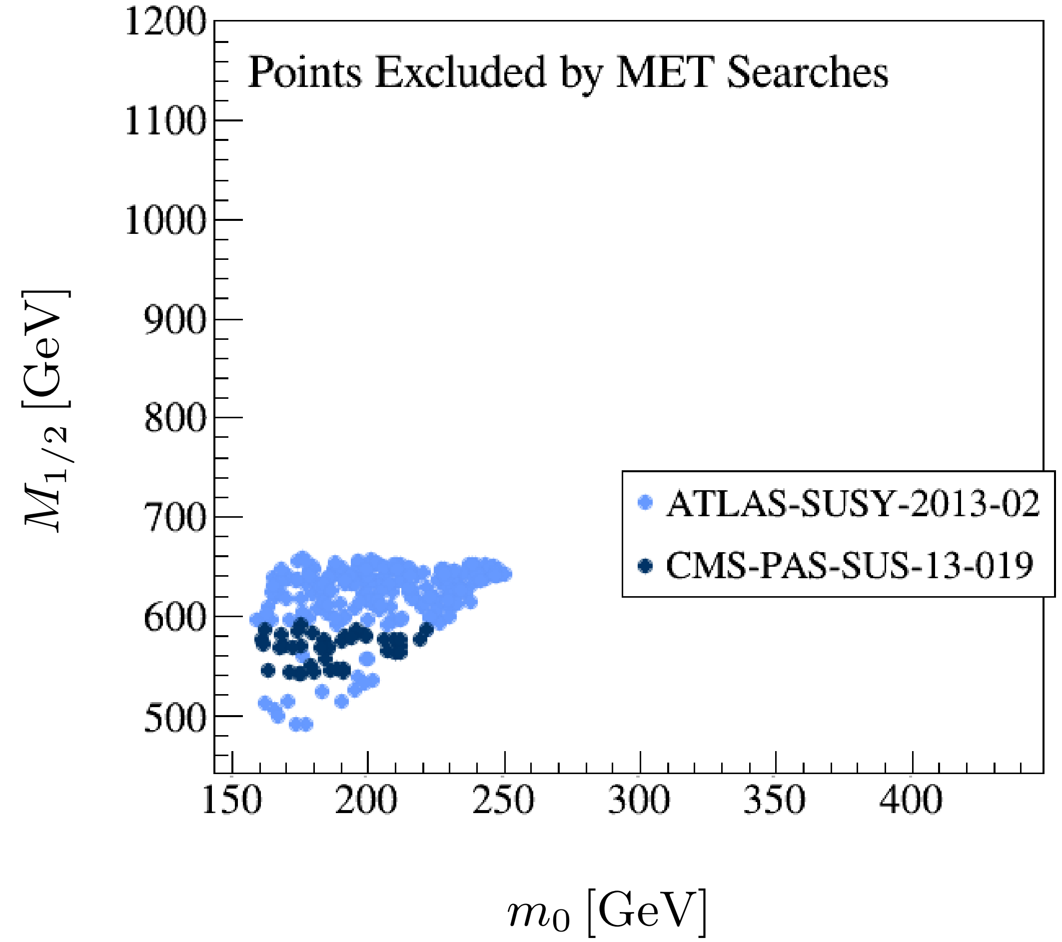


The Tip of the CMSSM Co-annihilation Strip

- LHC: HSCP versus MET sensitivity

[JH, Lessa, Quertenmont, 1509.00473]

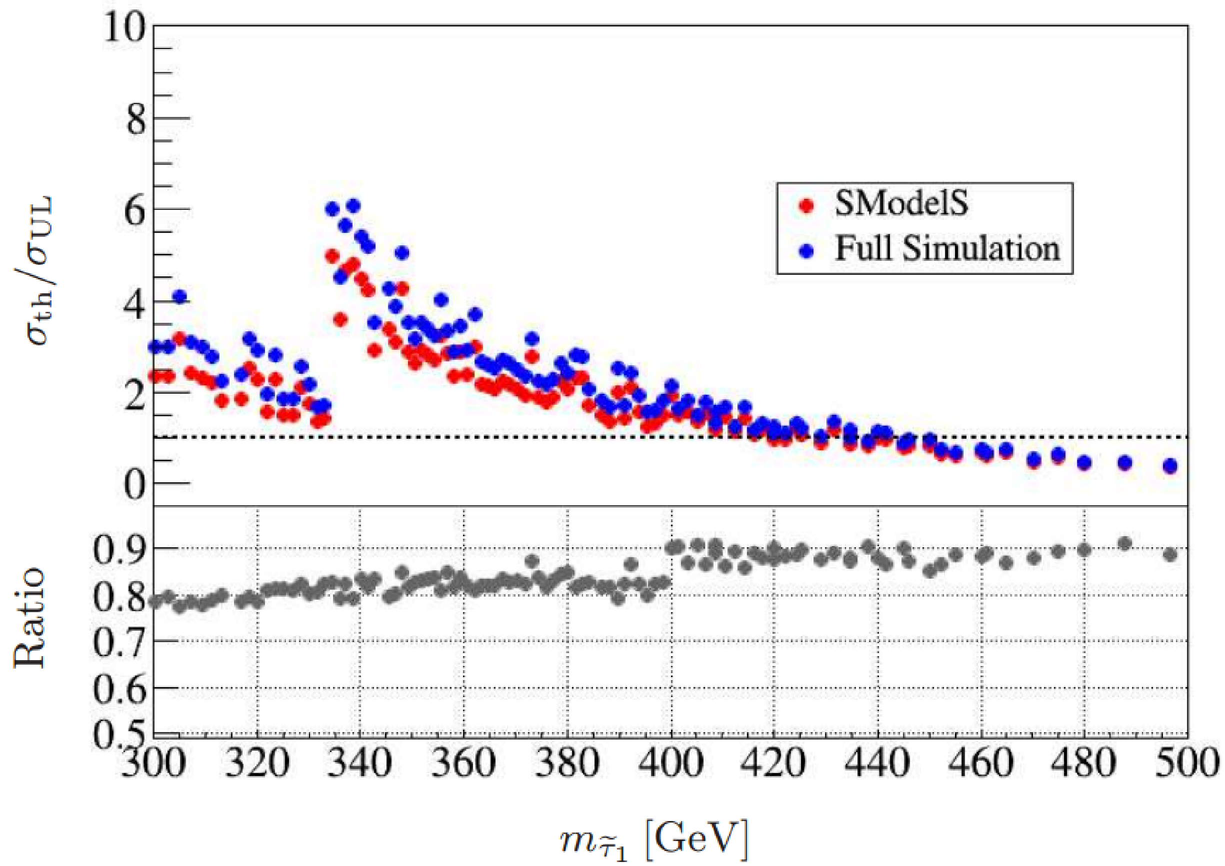




The Tip of the CMSSM Co-annihilation Strip

- Simplified models versus full simulation:

[JH, Lessa, Quertenmont, 1509.00473]



- SModelS conservative
- Signal coverage: ~90%

Summary

- Heavy stable charged particles (HSCP) occur in
  - mass degenerate scenarios (co-annihilation)
  - very weakly interacting DM (axinos/gravitinos)
- LHC high sensitivity to HSCPs
- CMS: novel method to compute efficiencies
- Implementation of HSCP searches into SModelS
- HSCP highest sensitivity although only ~30% of signal
- Work in progress: *R*-hadron searches

  Stay tuned! → smodels.hephy.at

Thank you for your attention!

The Tip of the CMSSM Co-annihilation Strip

- Scan (for $\tan\beta = 10$):

[JH, Lessa, Quertenmont, 1509.00473]