From theory to observation in the LHC era: summary of BSM searches

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What kinds of directions in BSM collider physics?

1. "Traditional" BSM physics
2. Tackling the inverse problem
3. Designing "blind" searches
4. Finding signatures that detectors would miss

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  - DM (e.g. SUSY, Z')
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Tackling the inverse problem

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- Use **simplified models** + **reinterpretation** of search limits
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Motivations for BSM models and searches

"Traditional" searches

- "Naturalness" & Unification ⇒ learn more about the higgs sector, new BSM Higgses?

  Higgs self-coupling? Top partners? Light gluon partners (gluino, KK-excitation)? New scalars?

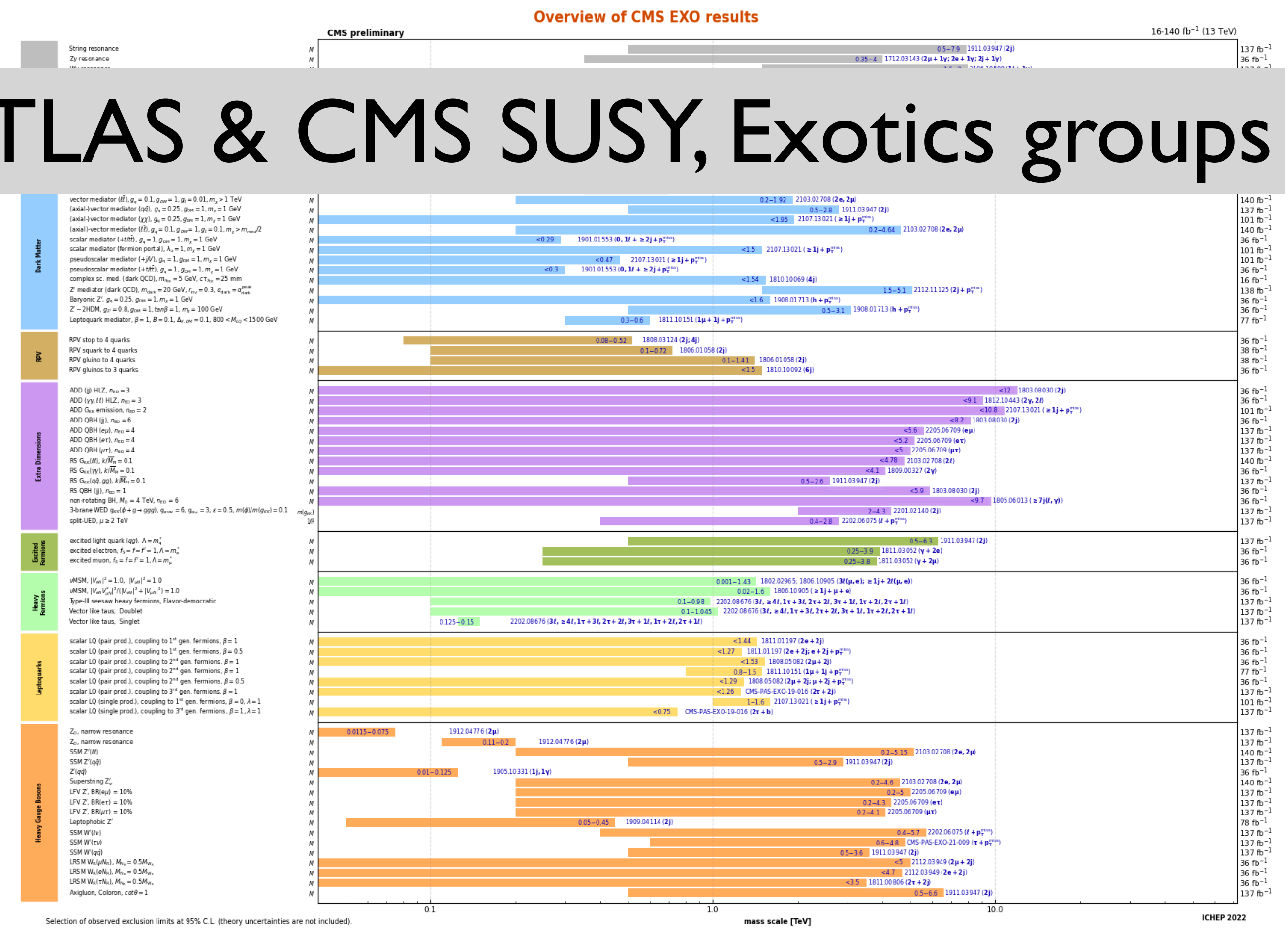
- Flavour anomalies ⇒ New Z' with FCNC? Leptoquarks? EFT-based bsll searches?

- Dark Matter motivated ⇒ MET, mono-X, mediator searches, electroweakino, …

- Neutrino mass ⇒ HNL, new W', Z', …

- Because we see nothing ⇒ Axion-like particles,

  stopped charged particles, heavy tracks, …



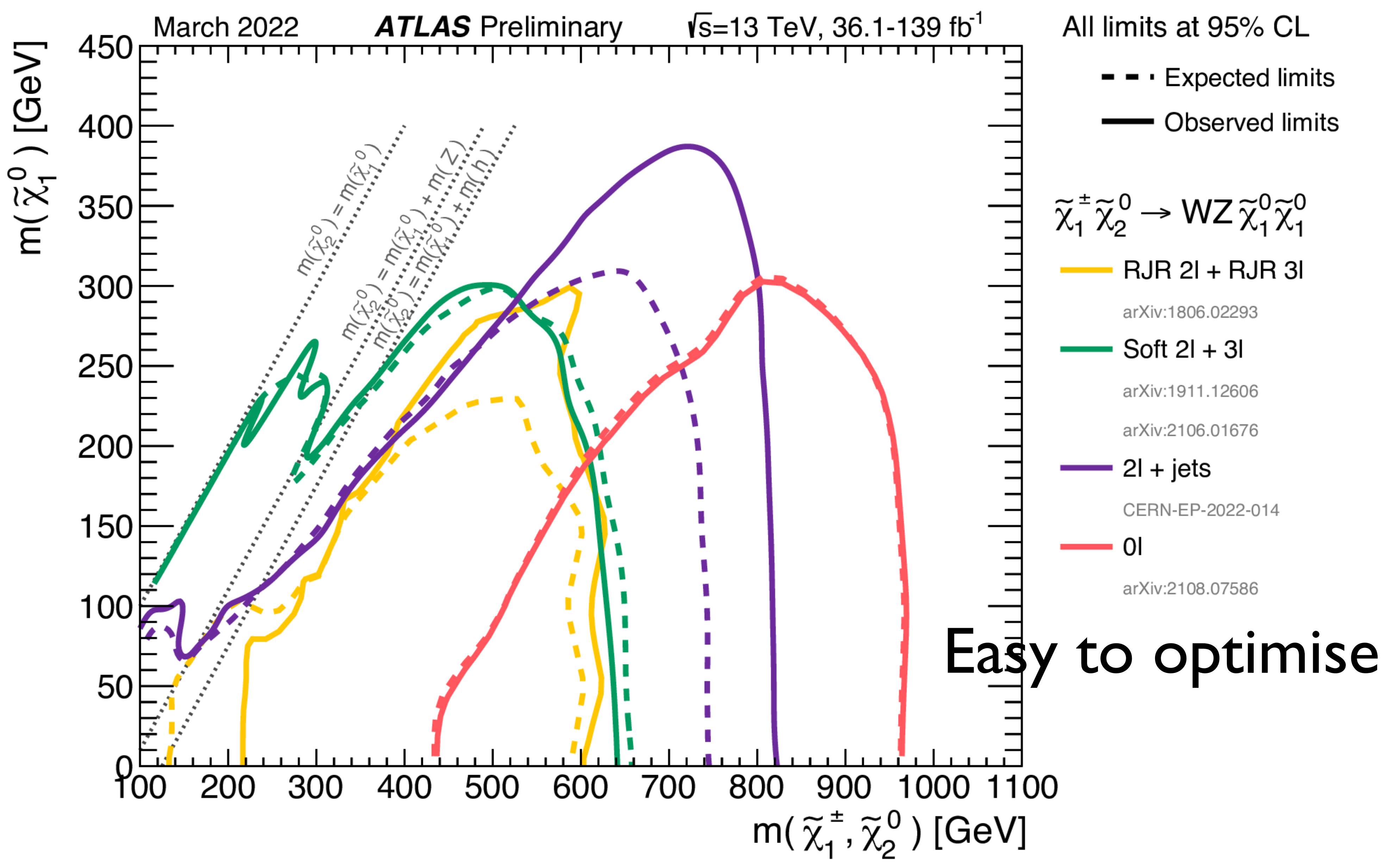
Over 300 searches from ATLAS & CMS SUSY, Exotics groups

[See talks by V. Hegde, + 27 WG2 talks + ?? Posters]

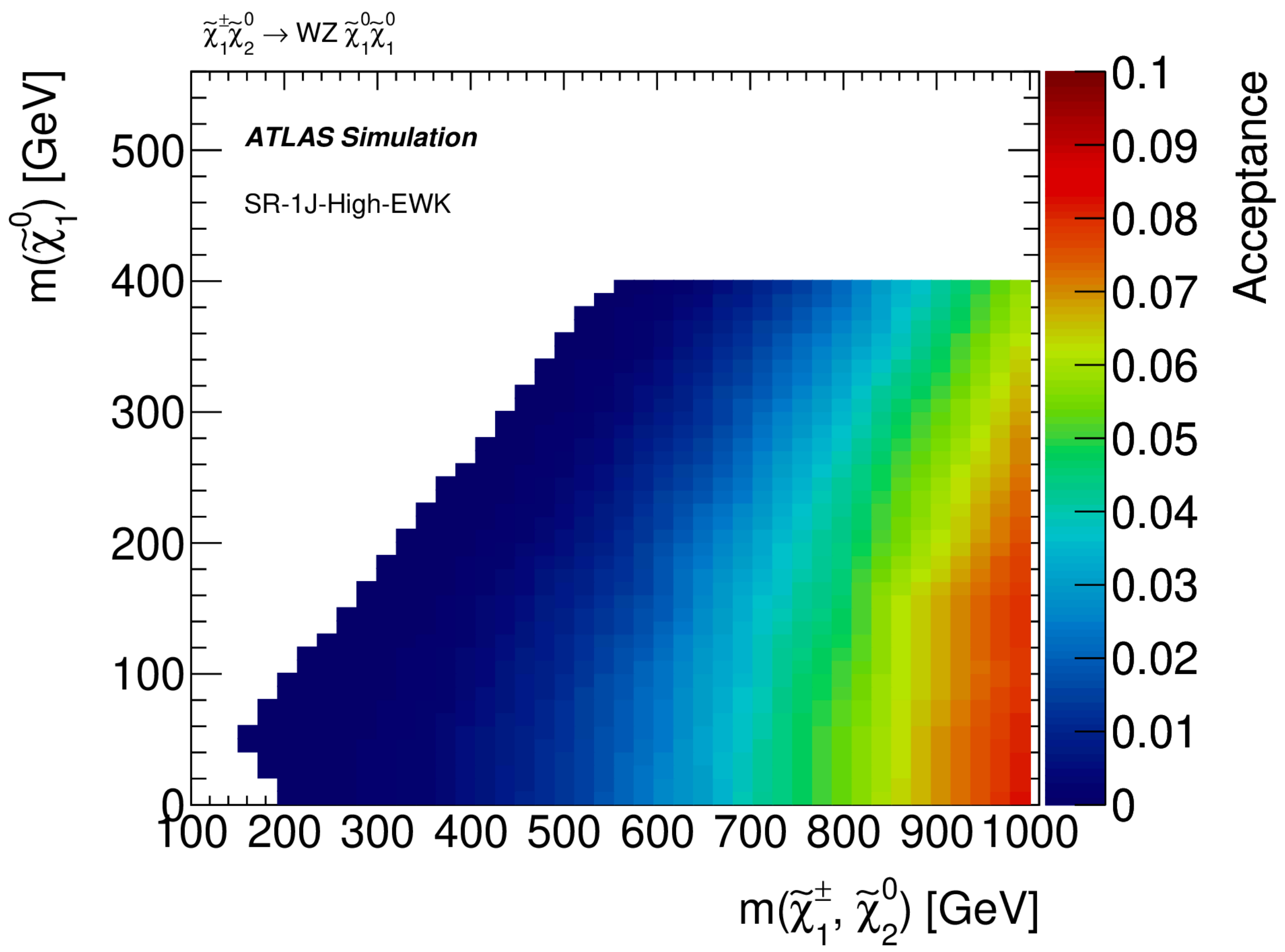
What does it take to test a theory at the LHC?

- **Write down the general Lagrangian** + find parameter space the gets you the right phenomenology (e.g. DM density)
- Identify the corresponding LHC production + decay modes; make a "**simplified model**" based on this (this is so we can capture the general features)
  - Pick particles + interactions & **scan over Masses, couplings**, (or lifetimes)
- Identify if any existing searches (LHC + DD etc.) are sensitive to this model; **reinterpret all existing limits**; do they leave off some interesting phase space?
- Provide a **proof-of-concept search strategy**; useful if cut-and-count because more transparent

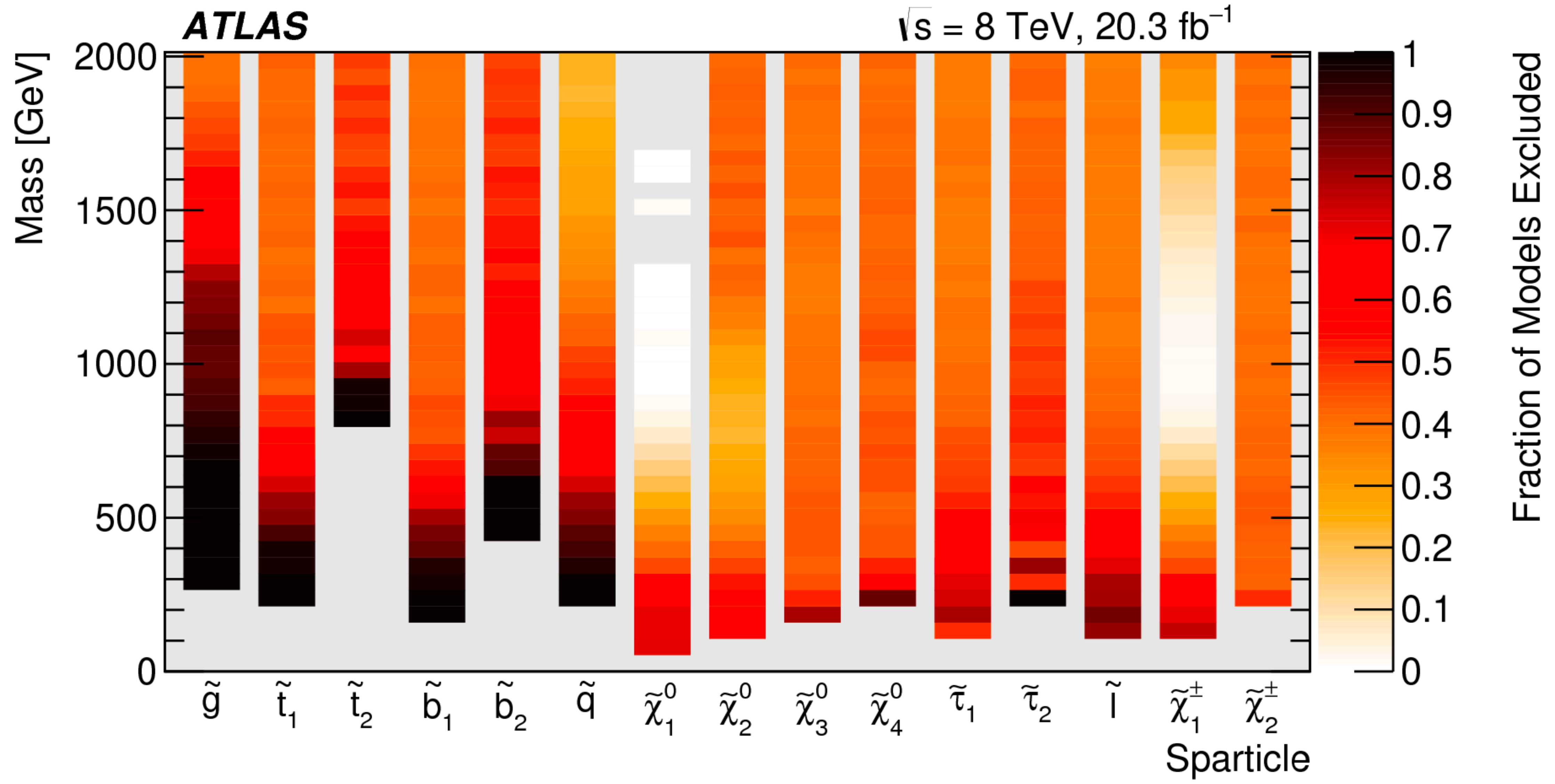
Simplified models — a blessing and a curse



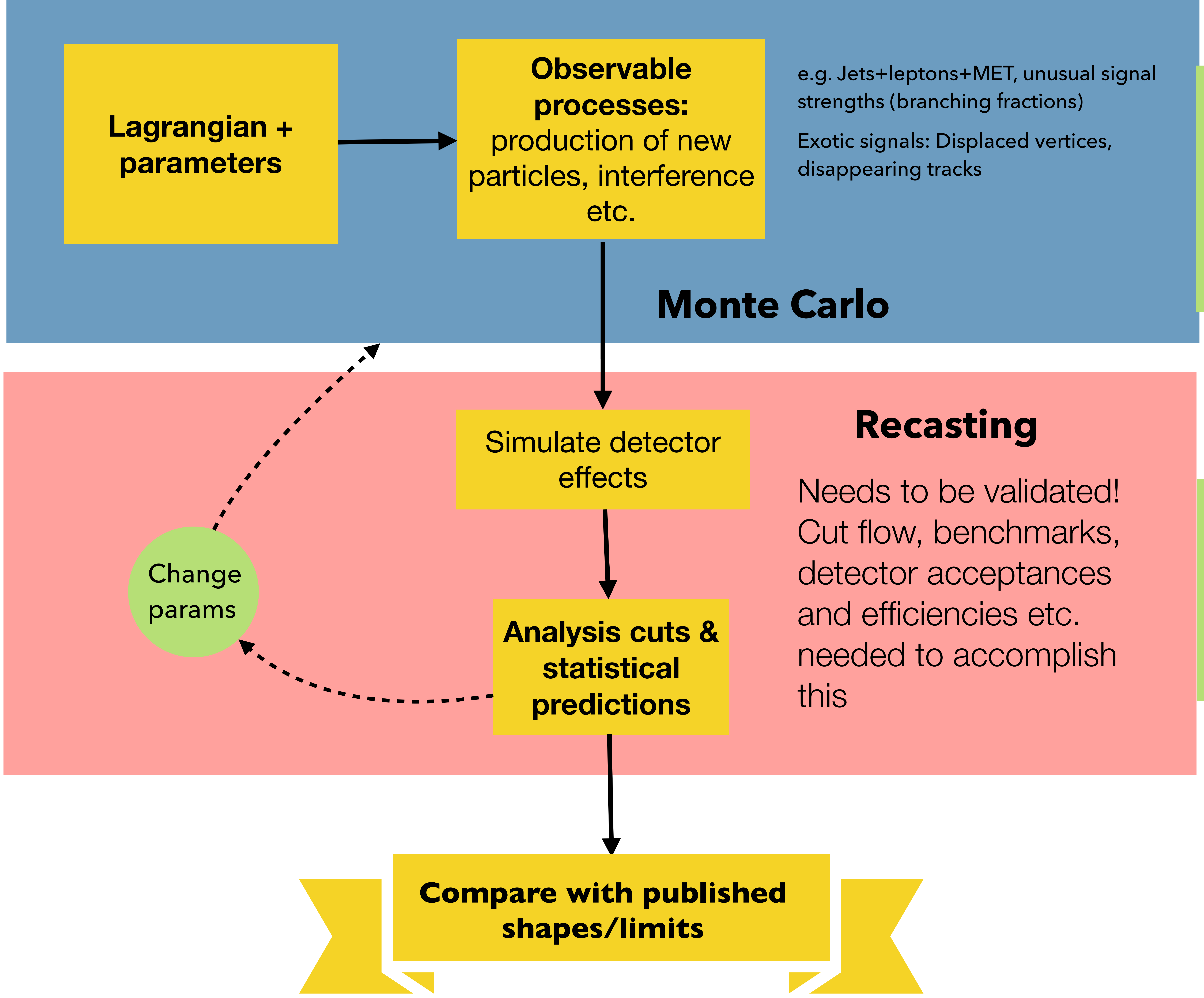
Easy to optimise your analysis



Few model parameters, easy to provide efficiencies to recombine



Rely on having the same "topology" and angular distributions



MONTE CARLO

Pythia8

Pythia 8.2 Manual (2015)
SUSY & SLHA (2012)
Dark Matter in Pythia8 (2018)
Pythia 8.3 Manual (2022)

RECAST

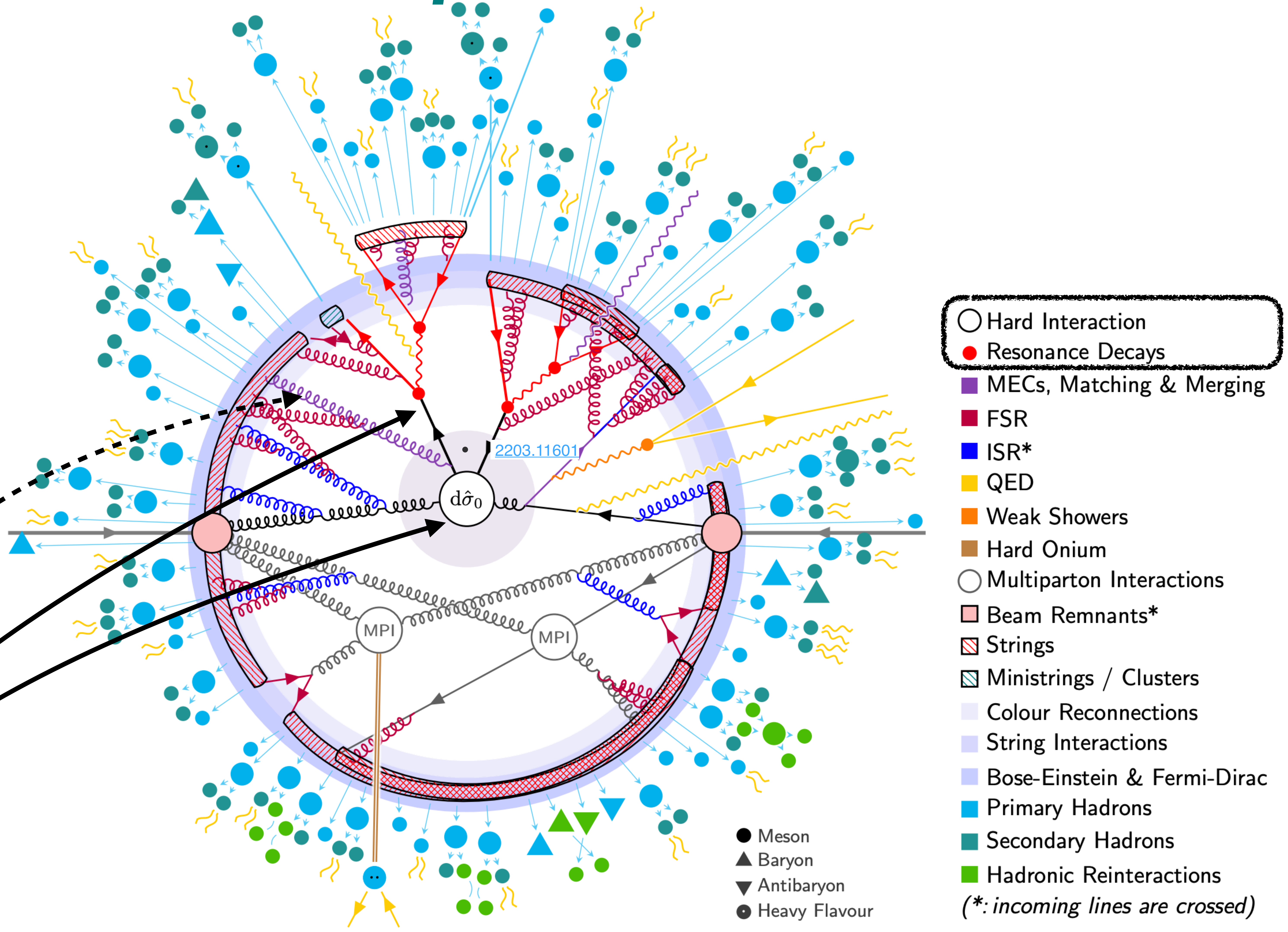
CheckMATE2

Dercks, Desai, et al (2017)
LLP searches (2021)

Pythia8 Coll. 2203.11601

MC generators are complicated beasts

Changes in showering?



BSM models

Flowchart for Recasting analyses

Dercks, ND et al. Comp. Phys. Comm. (2017)

Write the Lagrangian

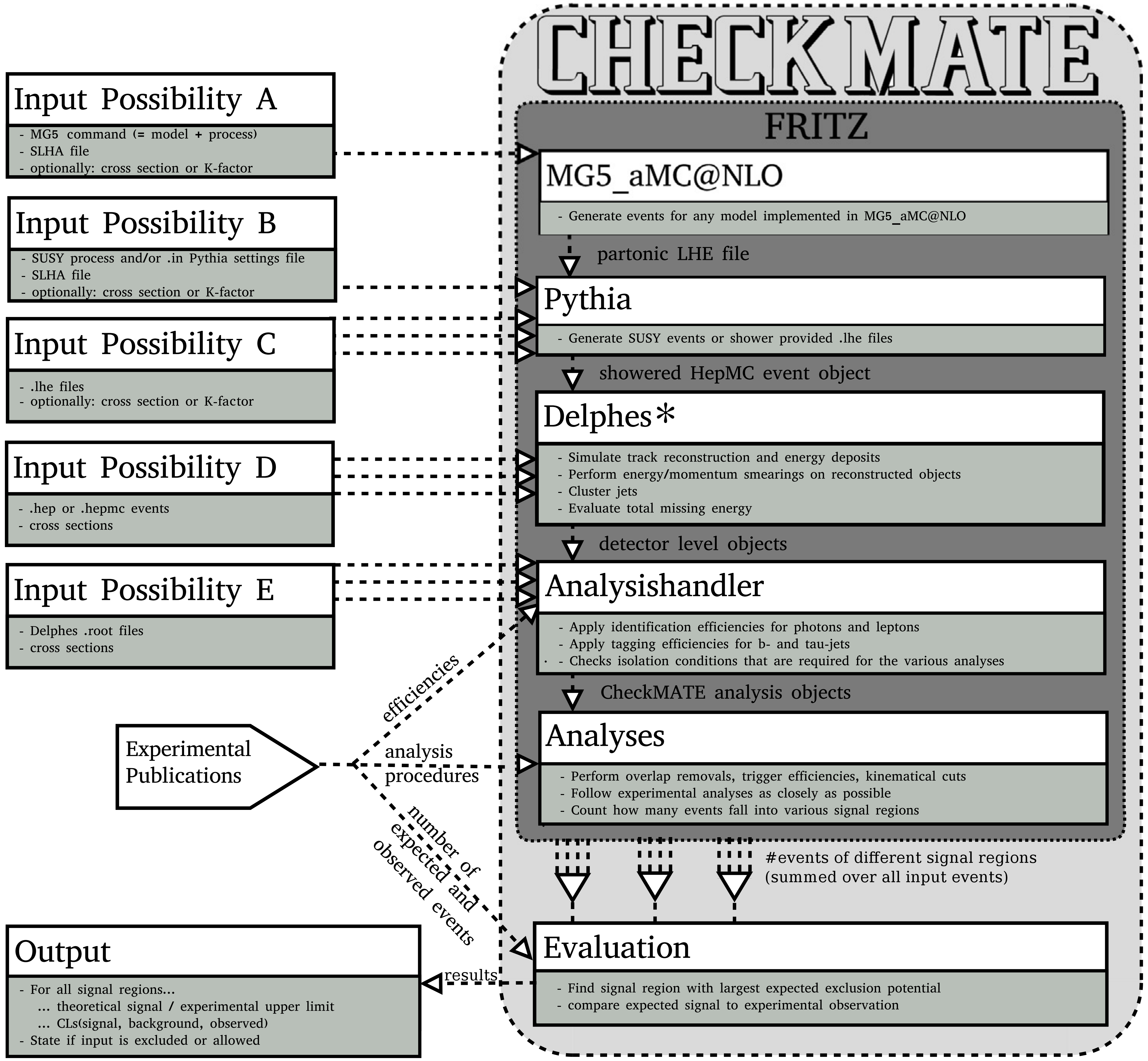
Generate signal events

Include QCD effects

Include detector effects

Simulate kinematic cuts

Compare to published upper limits



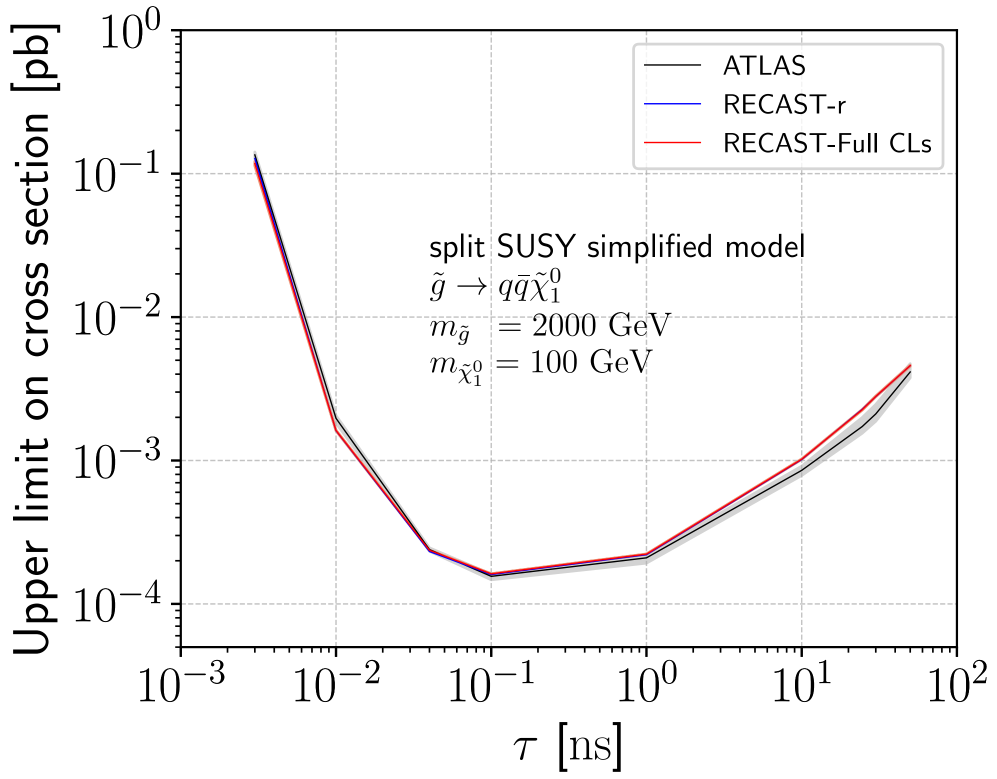
* Delphes output is not sufficient to do LLPs; we do our own vertexing/efficiencies to validate

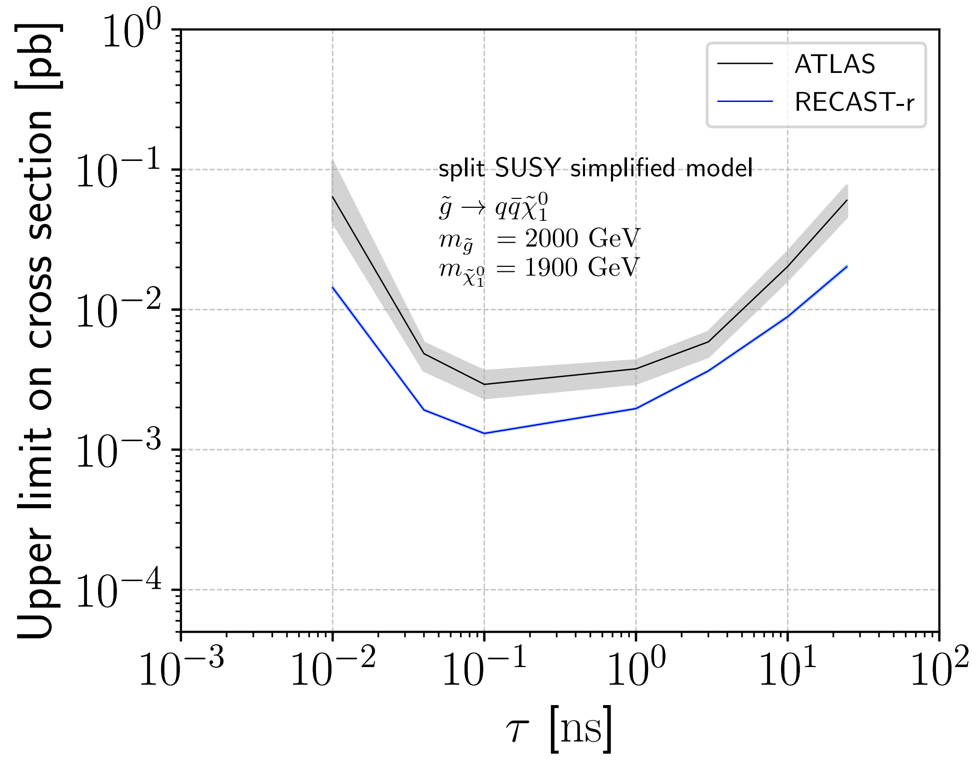
What are issues in Reinterpretation?

See also ongoing workshop of the Re-interpretation Forum: https://indico.cern.ch/event/1197680/

- Make sure that published results are actually usable; multiple topologies, no missing efficiencies; check you can validate

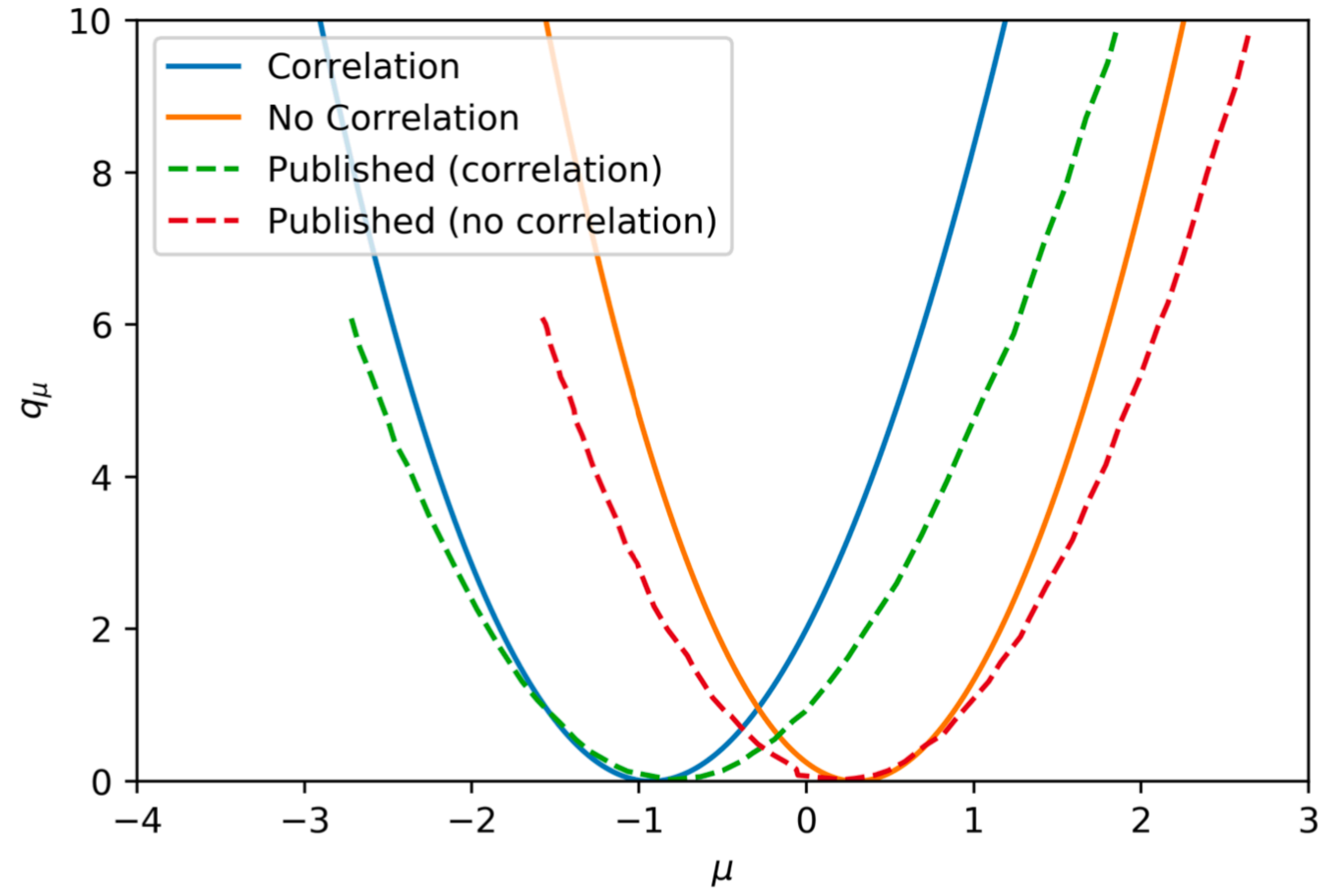
ND et al. (CheckMATE coll.) 2104.04542





- Publication of correlations, full likelihoods where possible
  Formats are complicated, only just started

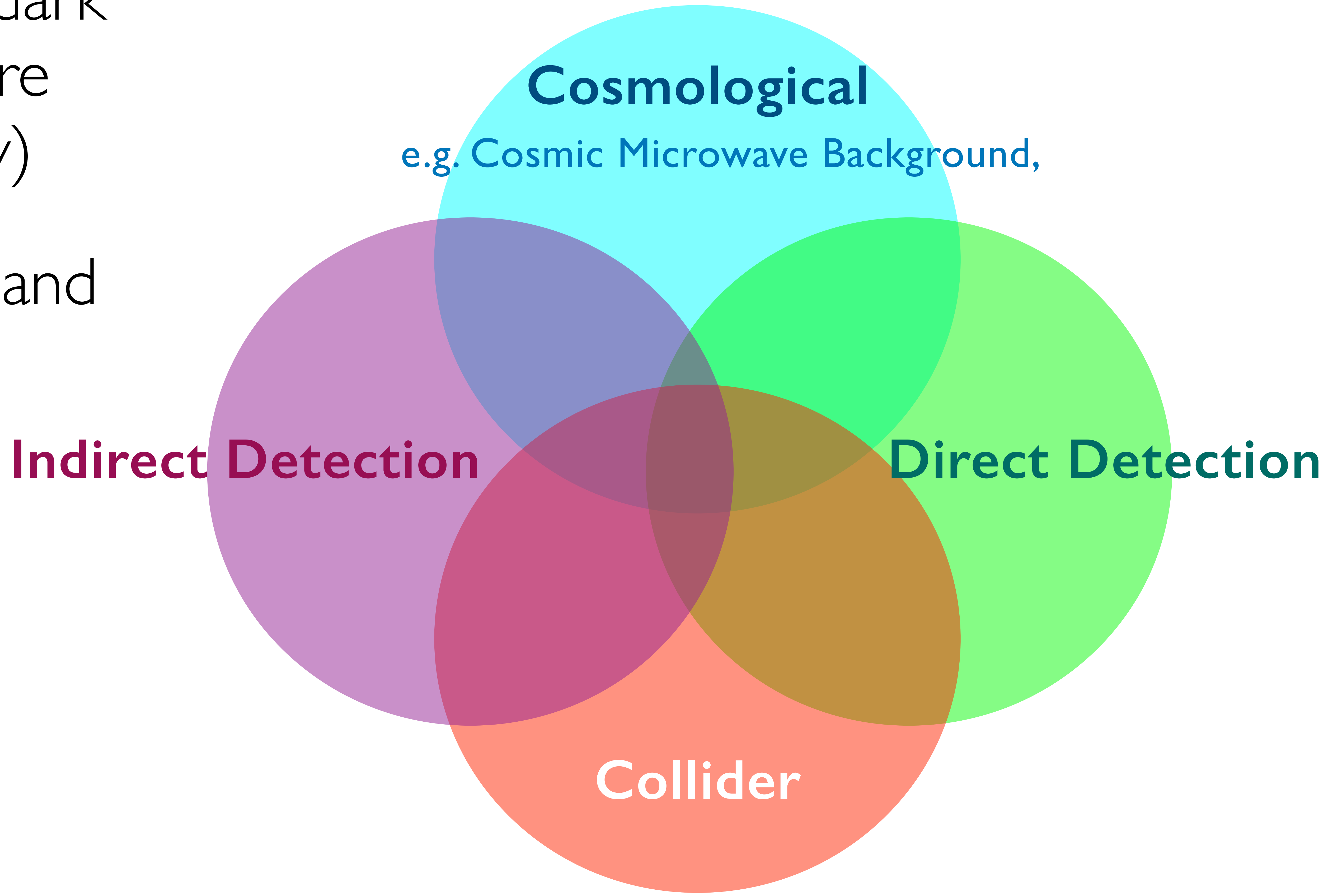
CMS simplified likelihood for mono-jet; Plot from A. Verma



- **NEW** How to reuse ML/BDT based searches?

Recap: A case for DM searches @ LHC through LLPs

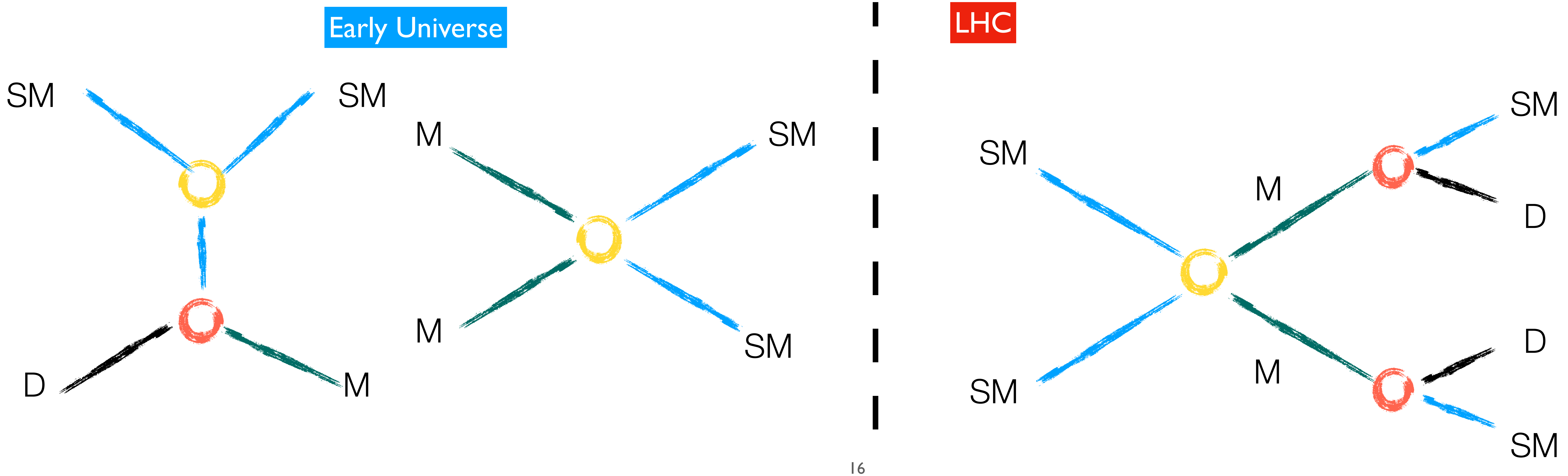
- Direct and Indirect DM searches rely of dark matter that is already existing and therefore sensitive to uncertainties (e.g. local density)
- Producing at colliders is complementary and does not rely on astrophysical estimates



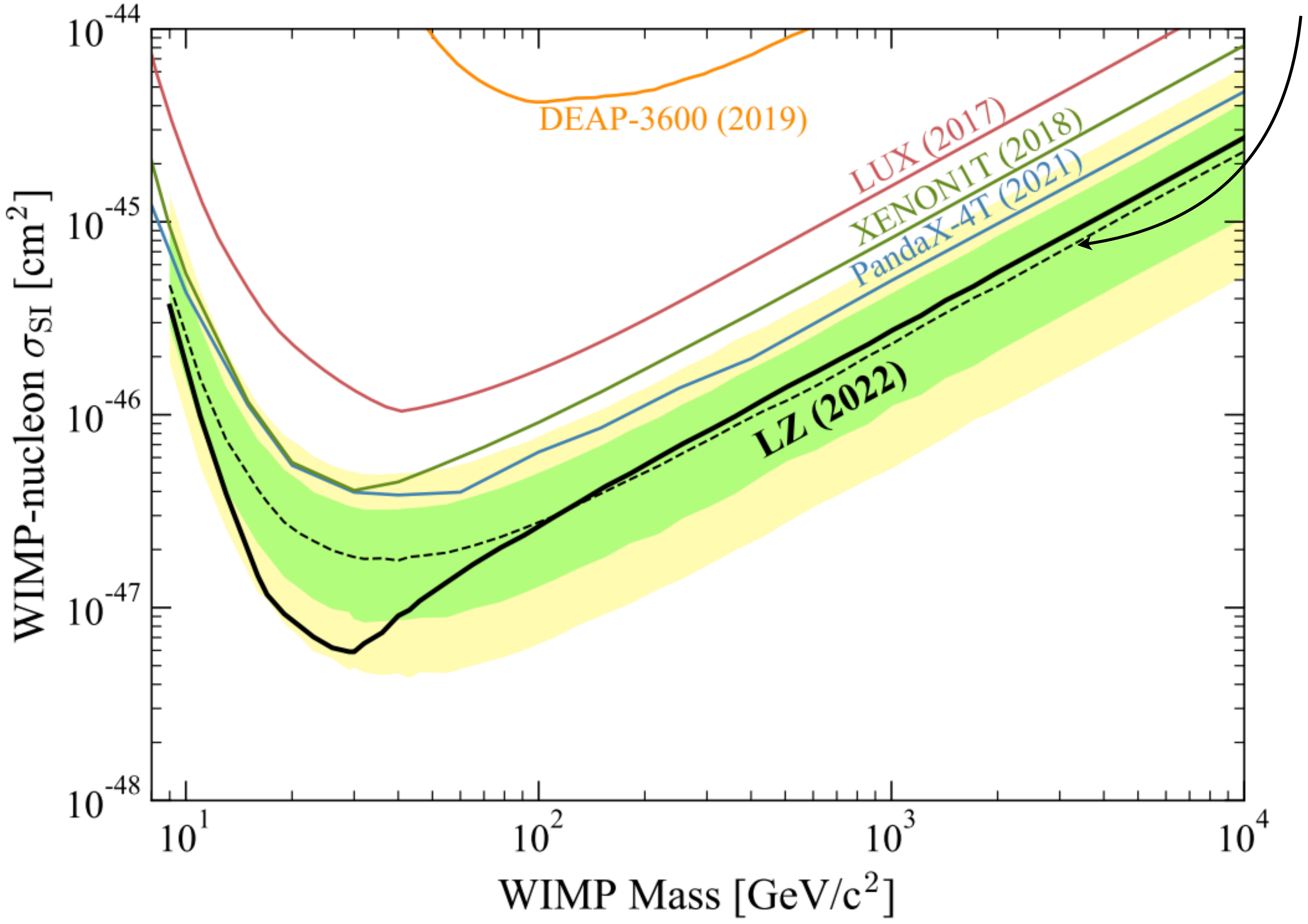
Recap: A case for DM searches @ LHC through LLPs

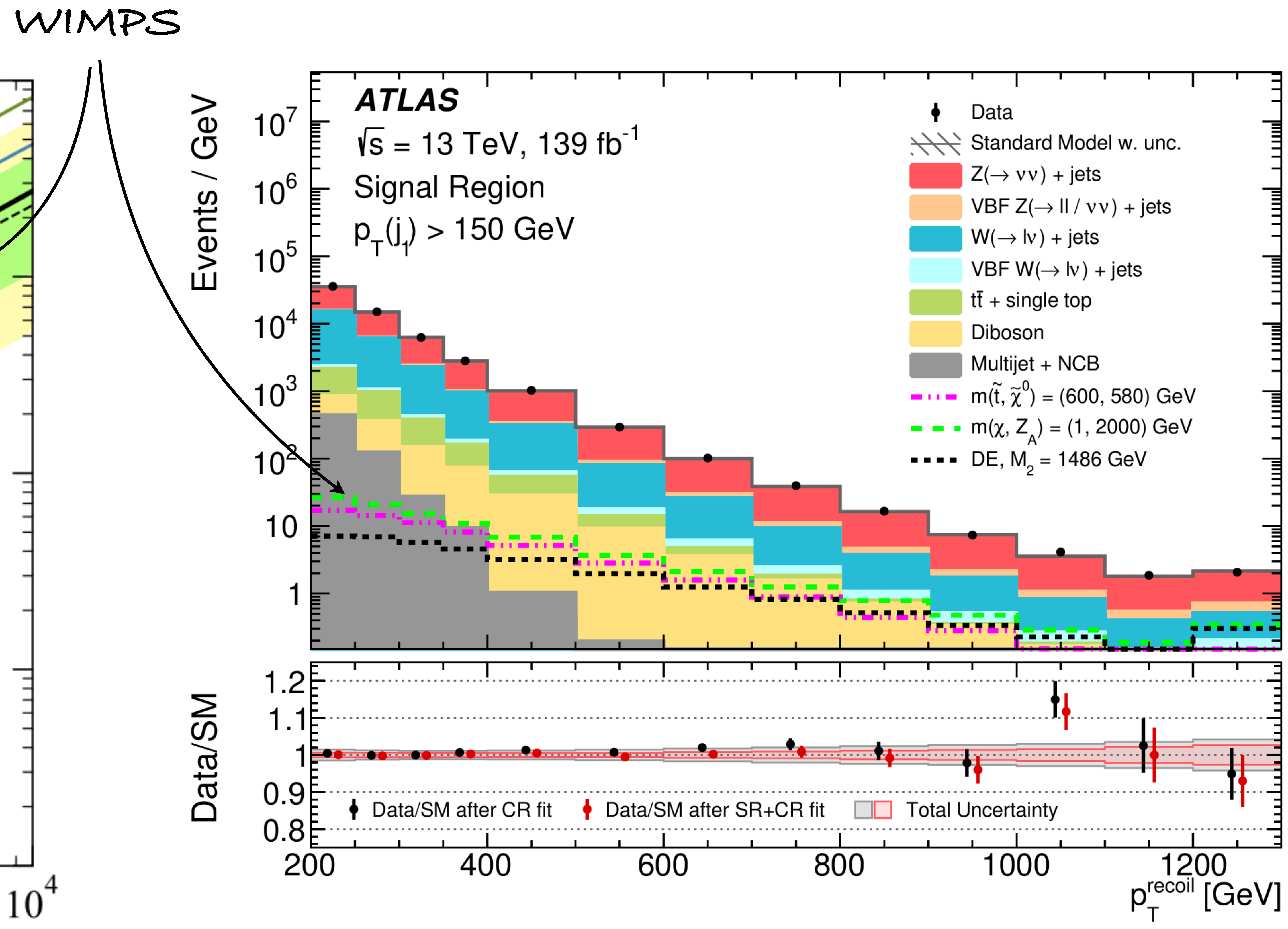
- LHC Production mode + lifetimes of particles directly predicted by how DM produced in early universe

- Well-motivated cosmological regimes (freeze-in, co-scattering) can be tested by LLPs because they predict small couplings.



No WIMPs seen in Direct Detection or LHC so far





ATLAS MET search with full Run 2: 2102.10874

CMS Run 2 Jets + MET: 2107.1302

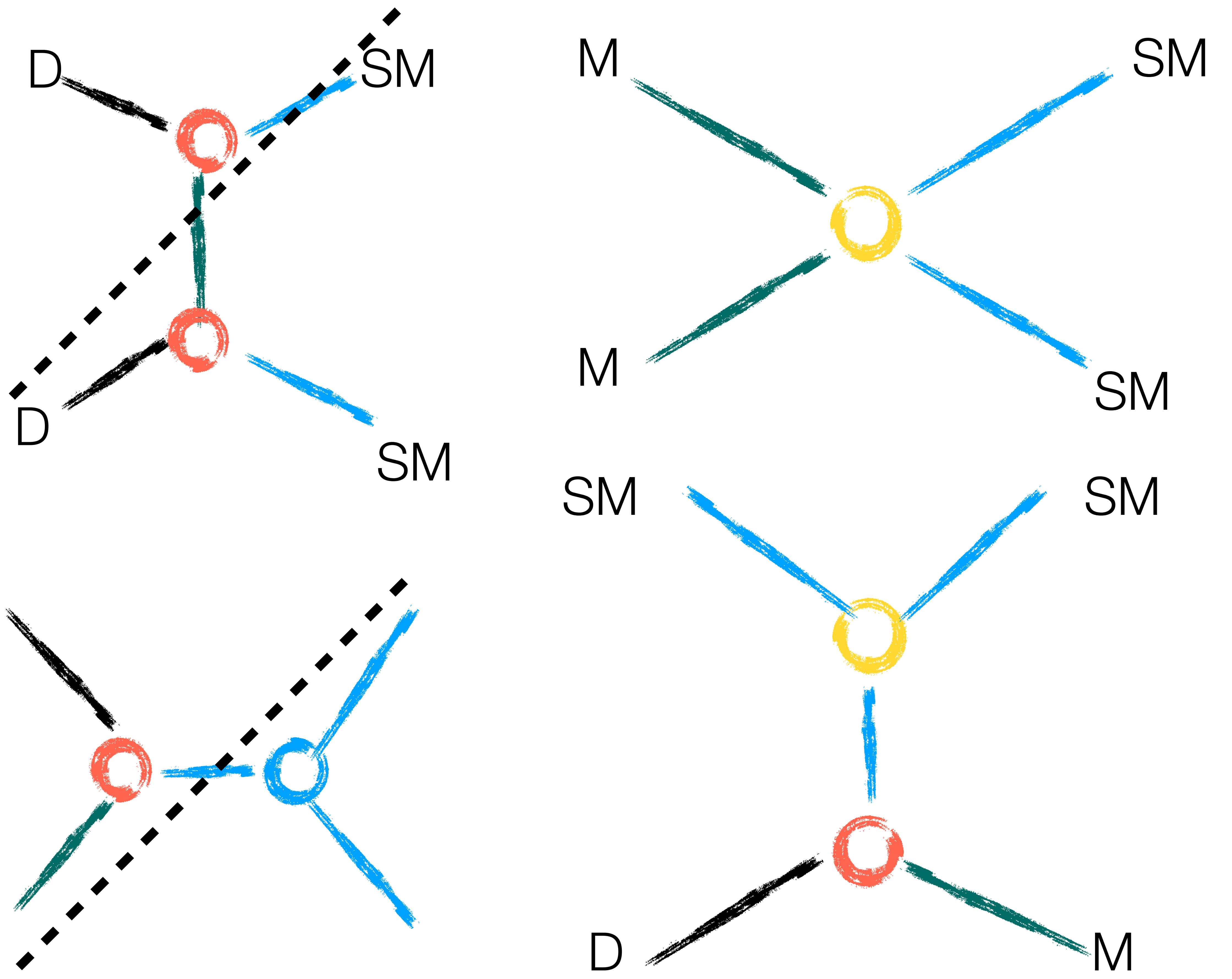
Motivation for LLPs: Co-scattering Dark Matter

Co-scattering = small coupling + some compression:

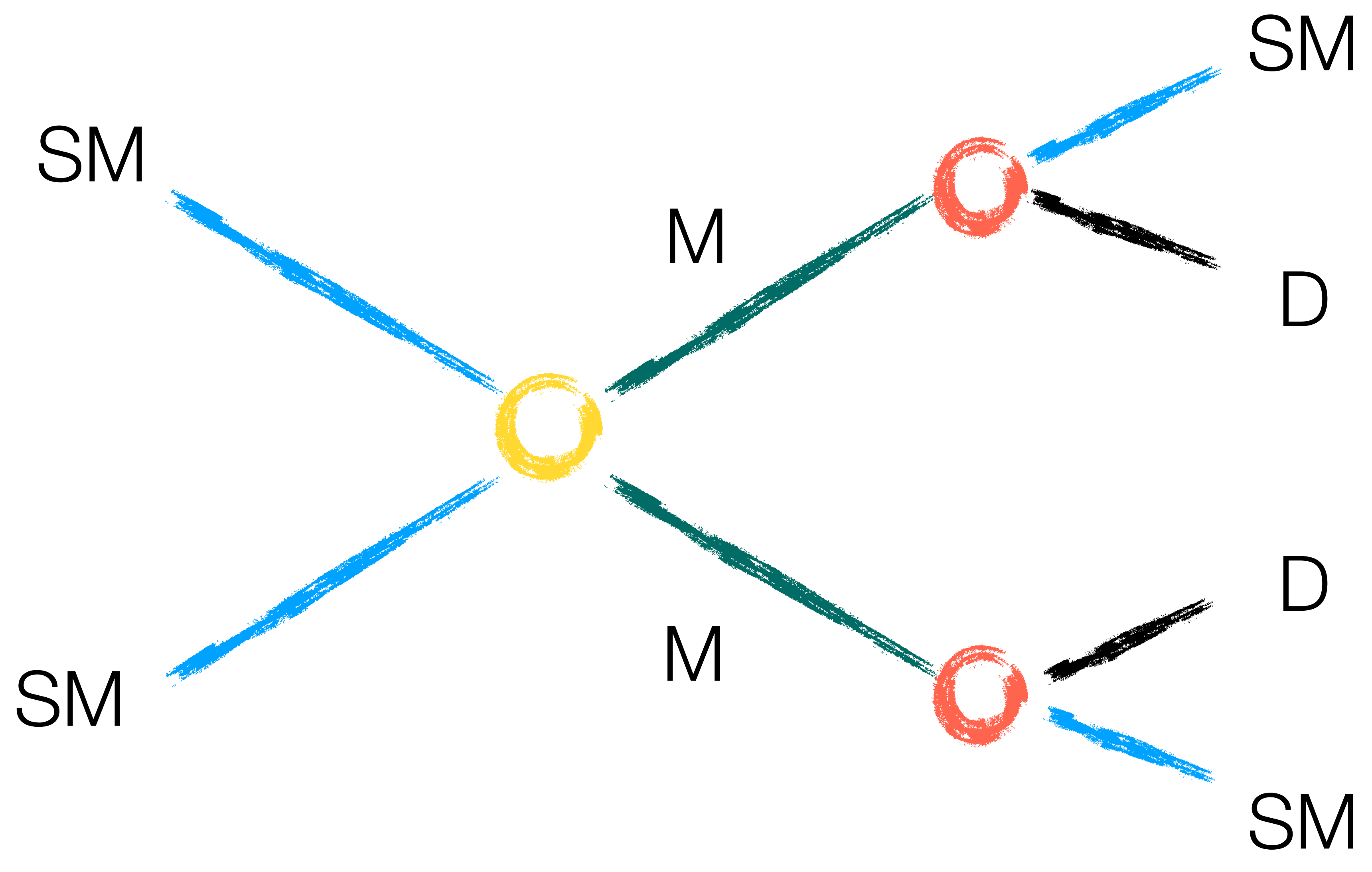
D'Agnolo et al. 1705.08450

Garny et al. 1705.09292

Early Universe



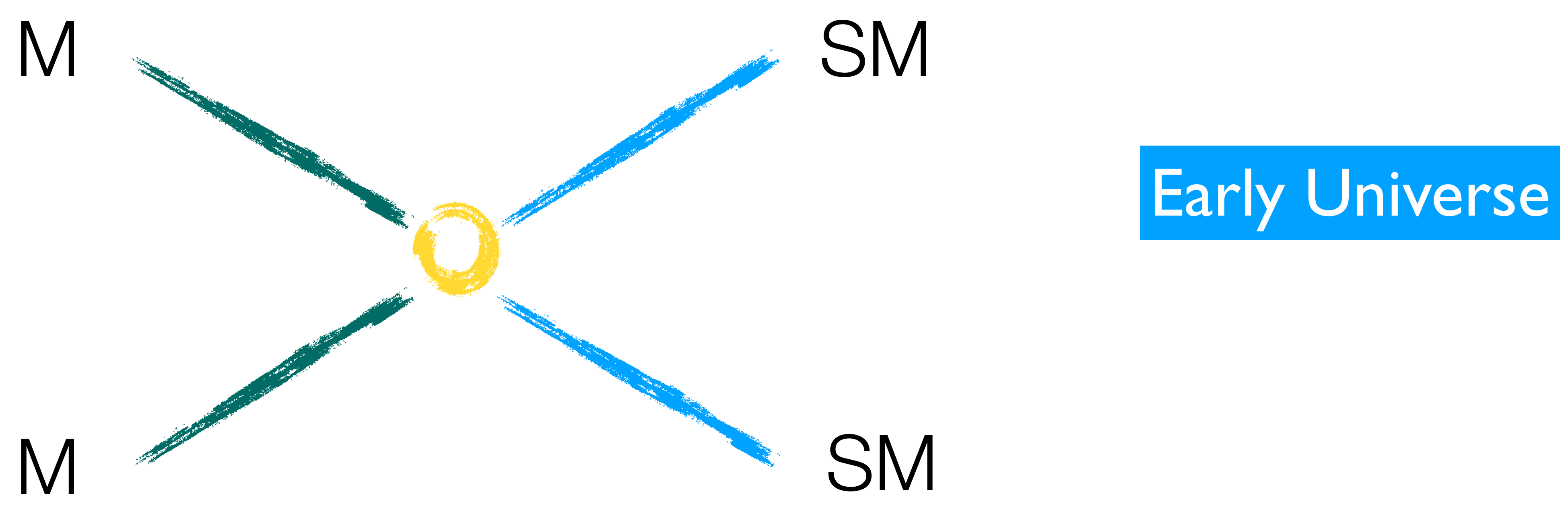
LHC

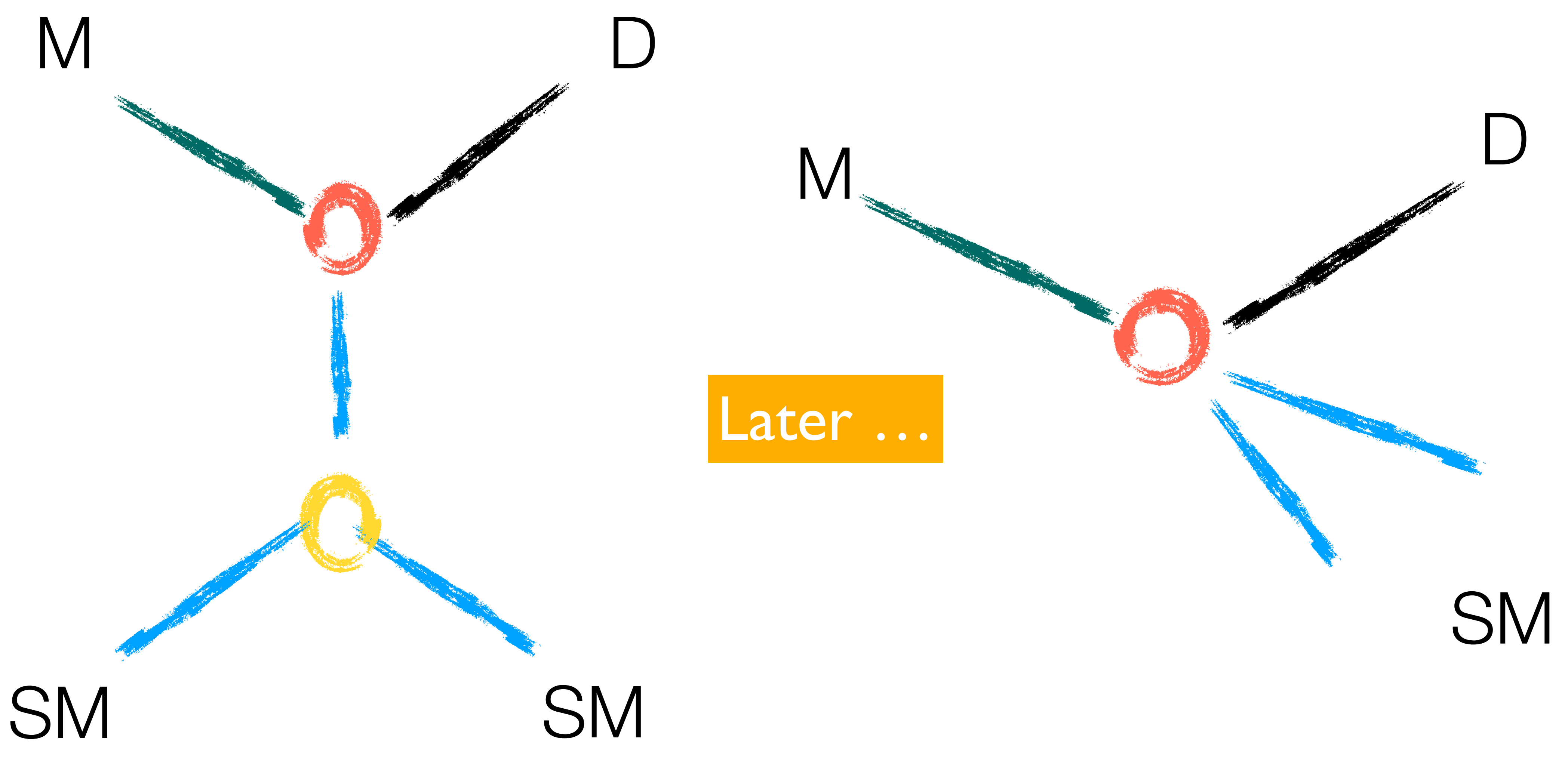


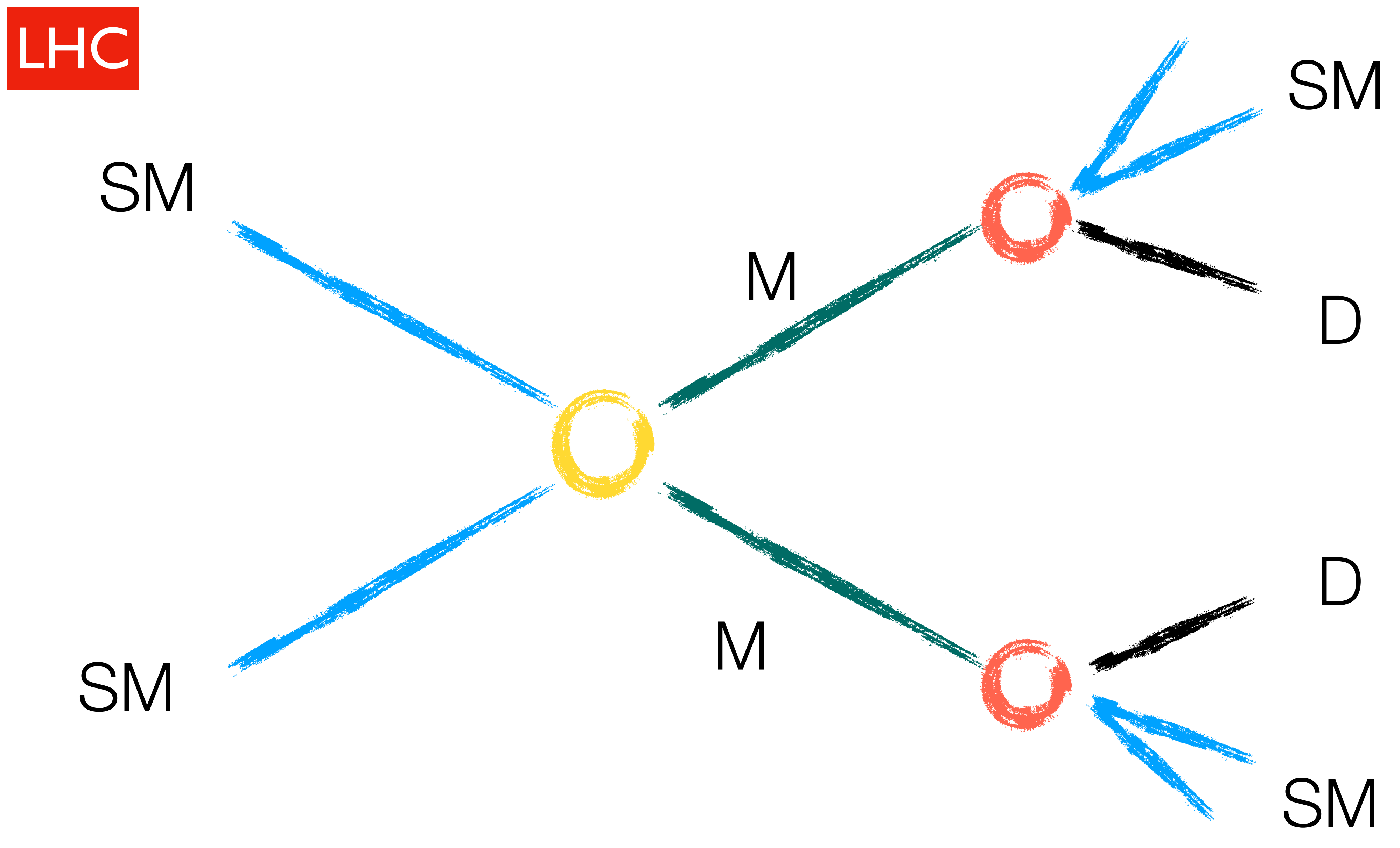
Hall et al. 0911.1120

Motivation for LLPs: Freeze-in Dark Matter

Freeze-in: start with zero DM density, populate later via mediator decay/interactions







Co-scattering and Freeze-in

	Co-scattering	Freeze-in
DD	✗	✗
ID	✗	✗
Collider	✓	(✓)

DM has feeble couplings with SM

Needs mediator with SM

Mediator likely has very small decay width and is long-lived

Look for long-lived mediators

What does long lifetime signify?

Three ways to get a long-lived particle (i.e. very small decay width):

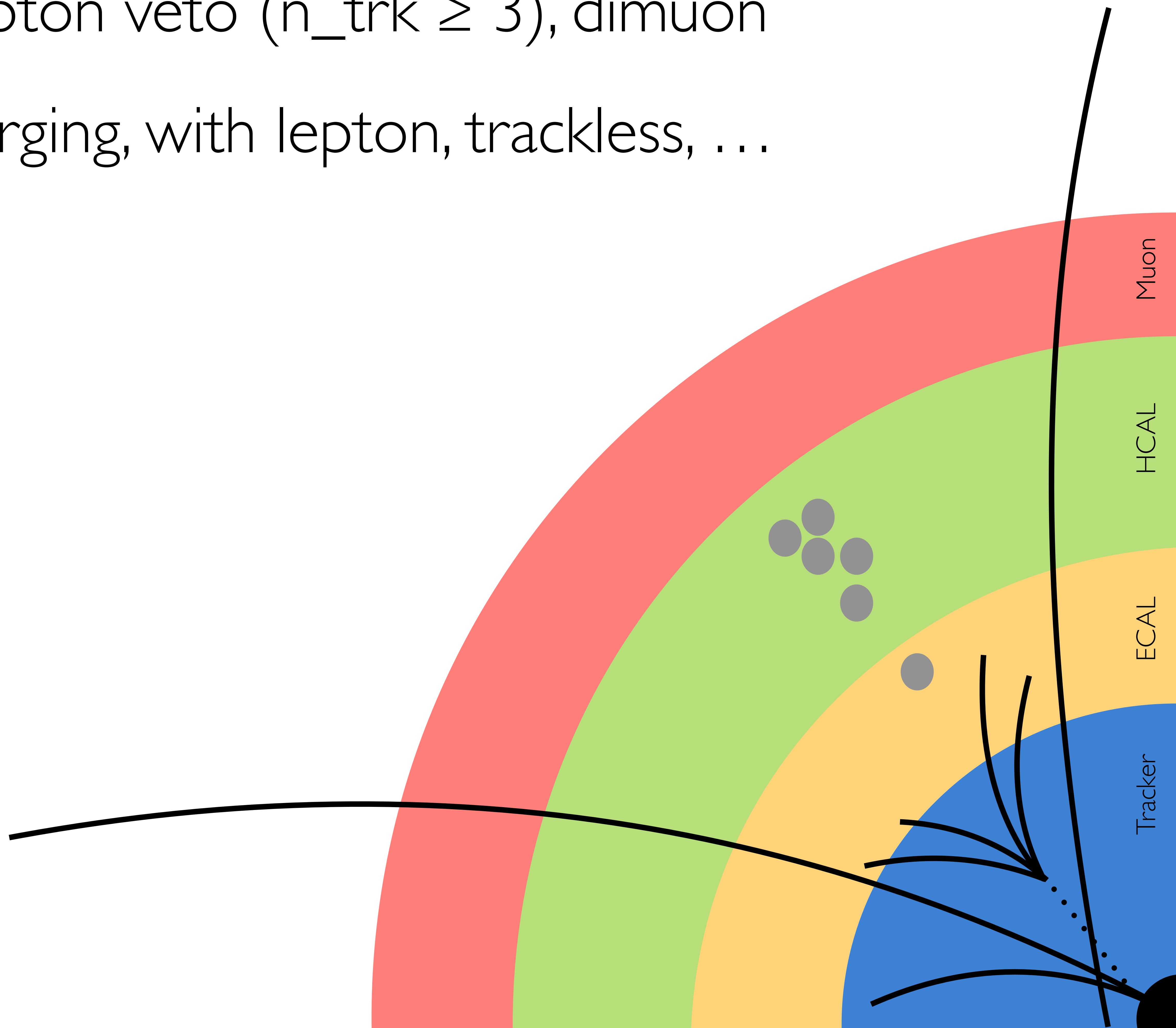
1. Small couplings
2. Heavy intermediate particle (e.g. mesons in SM, mediator doesn't have to be super heavy)
3. Compressed spectrum (e.g. new SU(2) Triplet fermion)

Ways to produce a particle at the LHC:

1. Needs to have colour/EW-charge to be produced directly
2. Can be produced in decays of another particle if it does not have SM charges

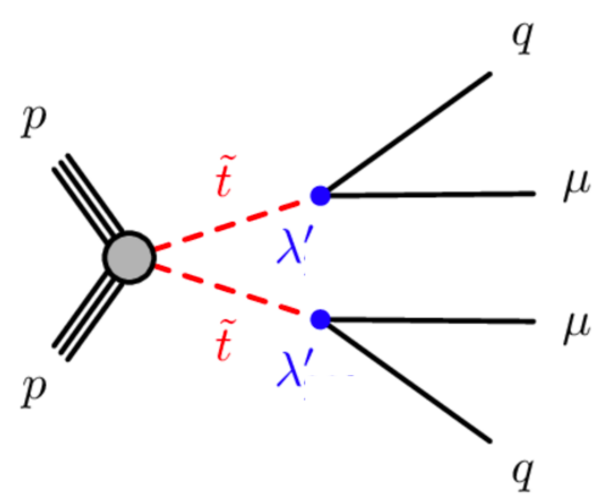
LLP Signature vocabulary

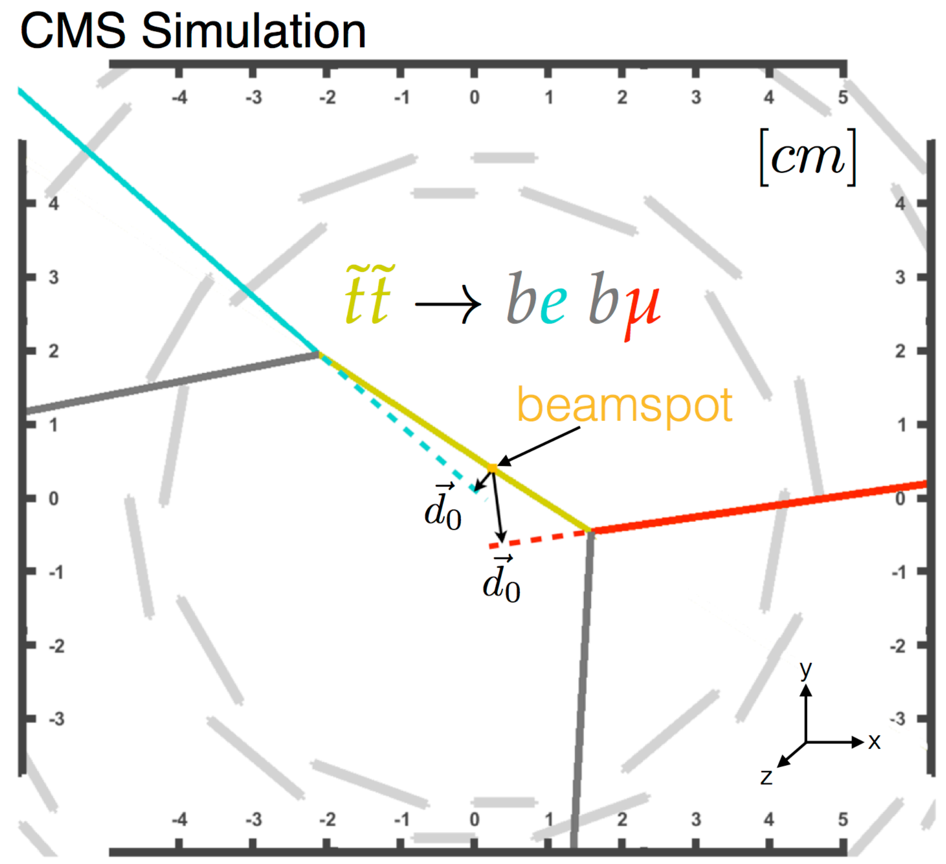
Displaced	Leptons	eμ, μμ
	Vertices	with muons, lepton veto (n_trk ≥ 3), dimuon
	Jets	Displaced, emerging, with lepton, trackless, …
"Prompt"	Heavy charged track	
	Disappearing track	



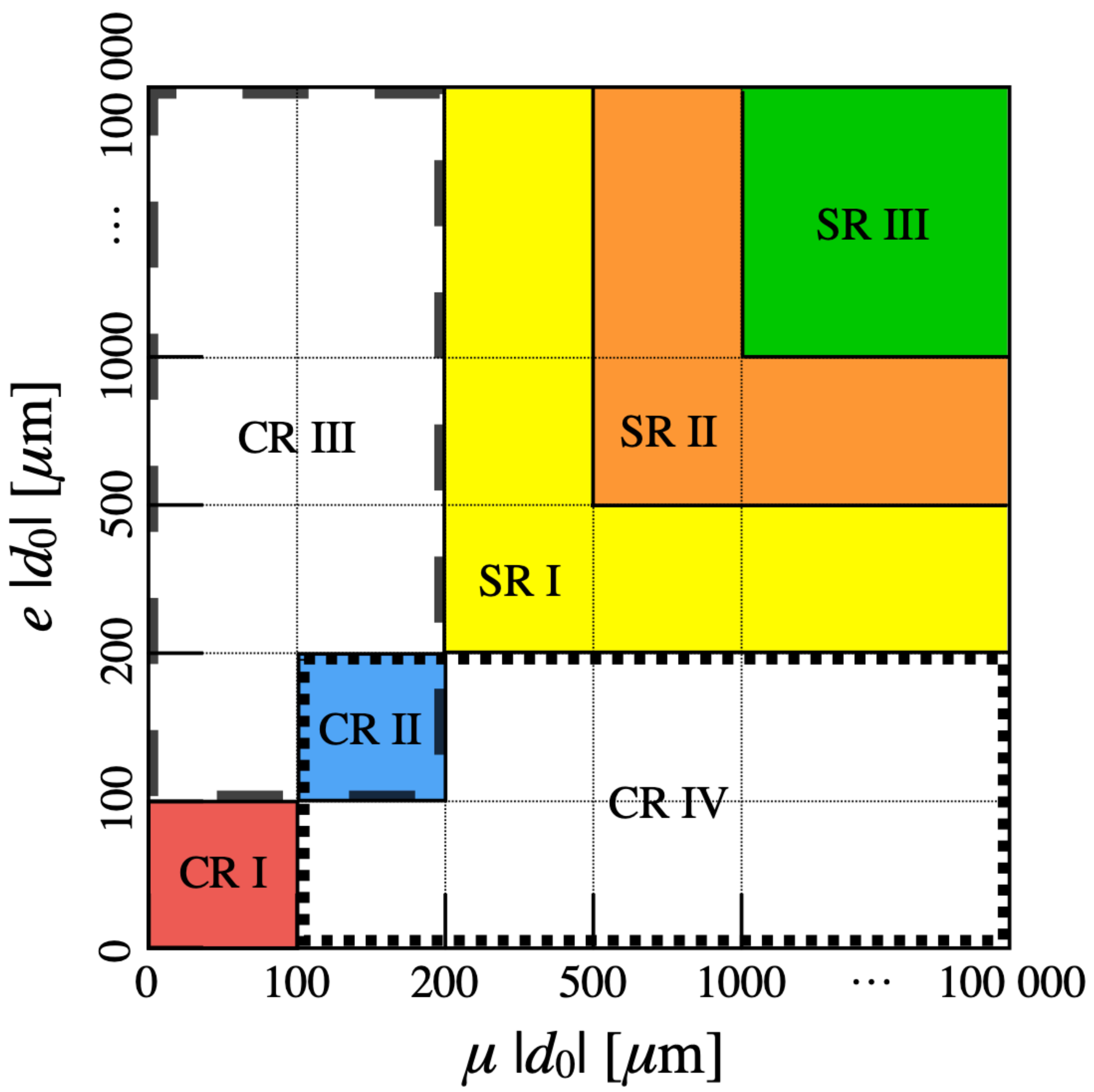
CMS LLP searches include all of these

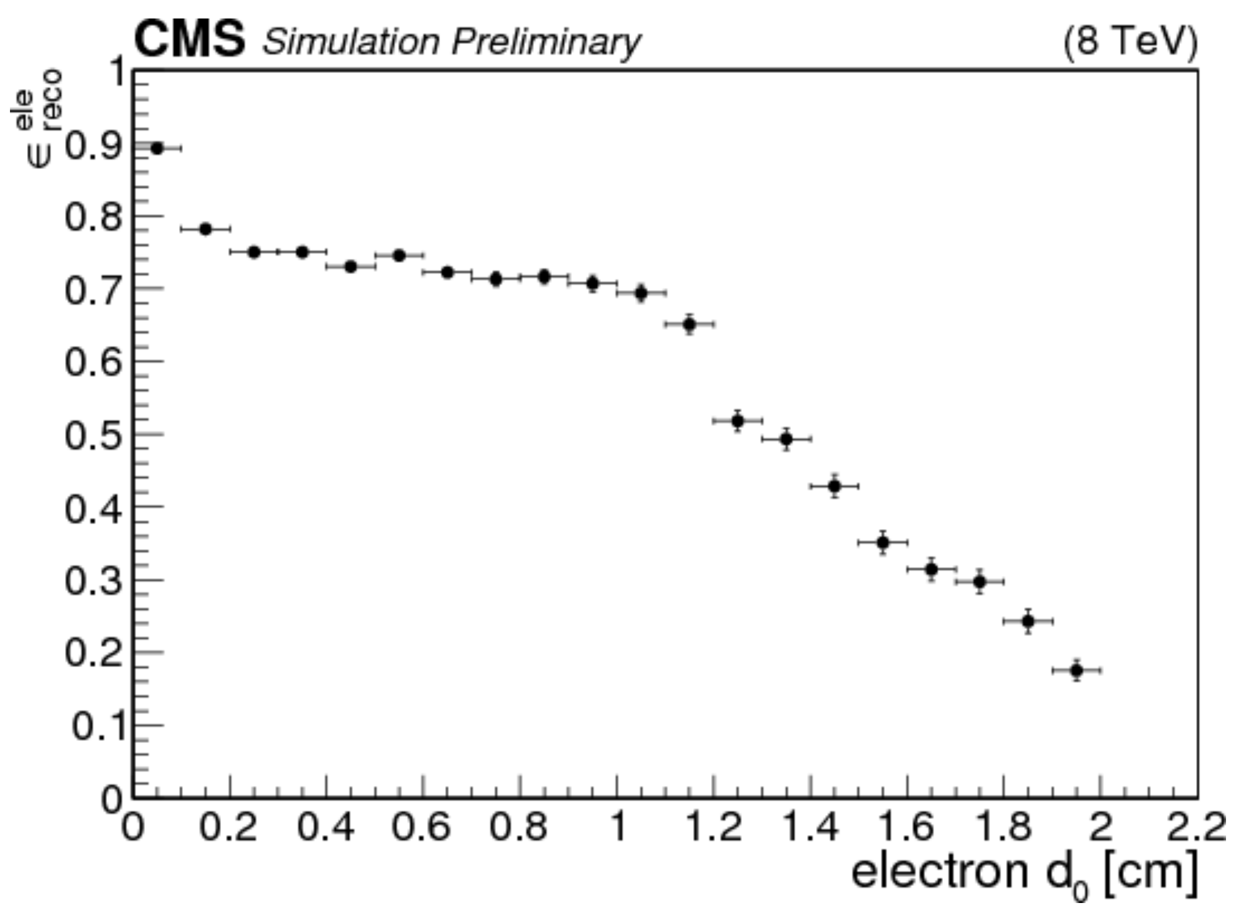
Understanding the CMS displaced lepton search

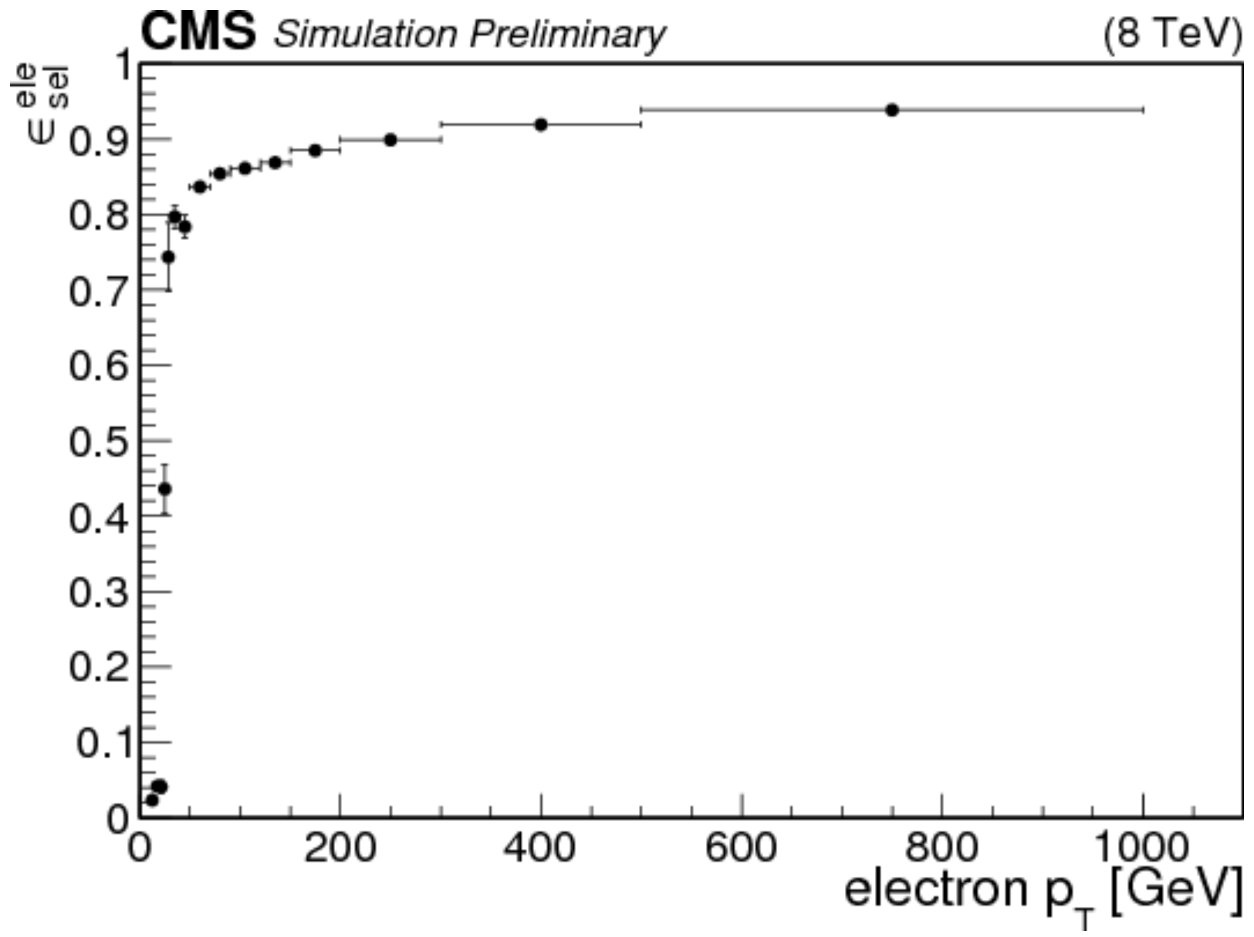


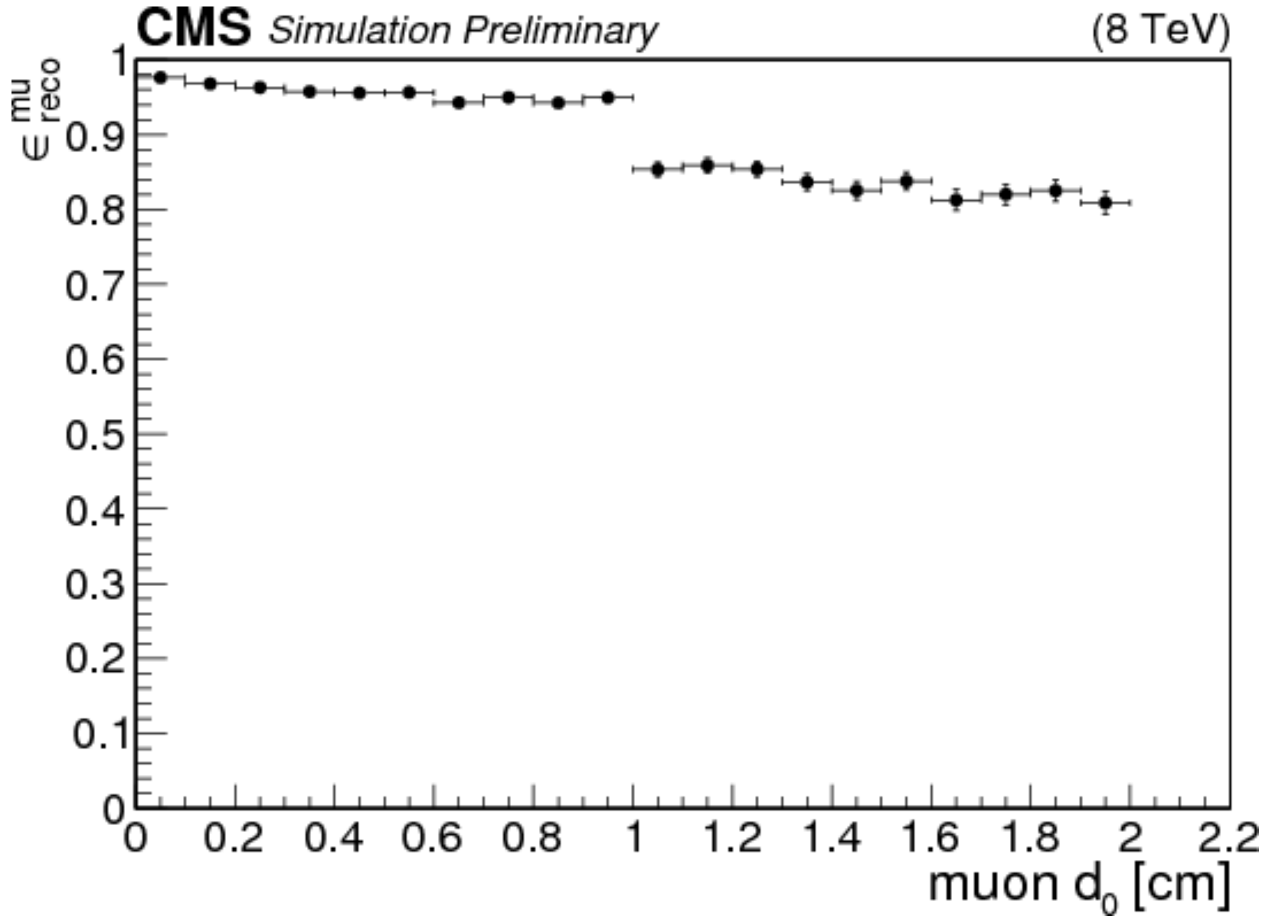


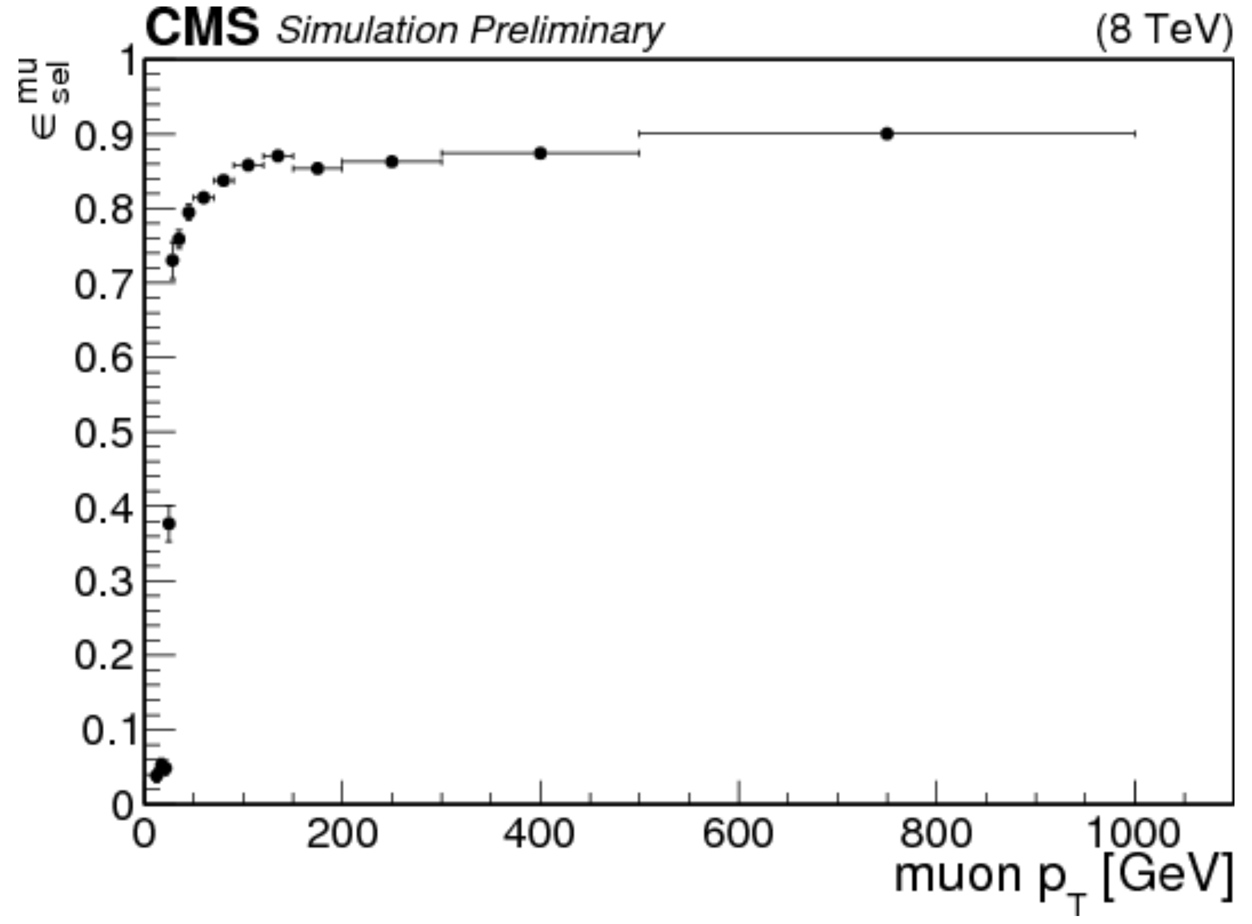
CMS-PAS-EXO-16-022







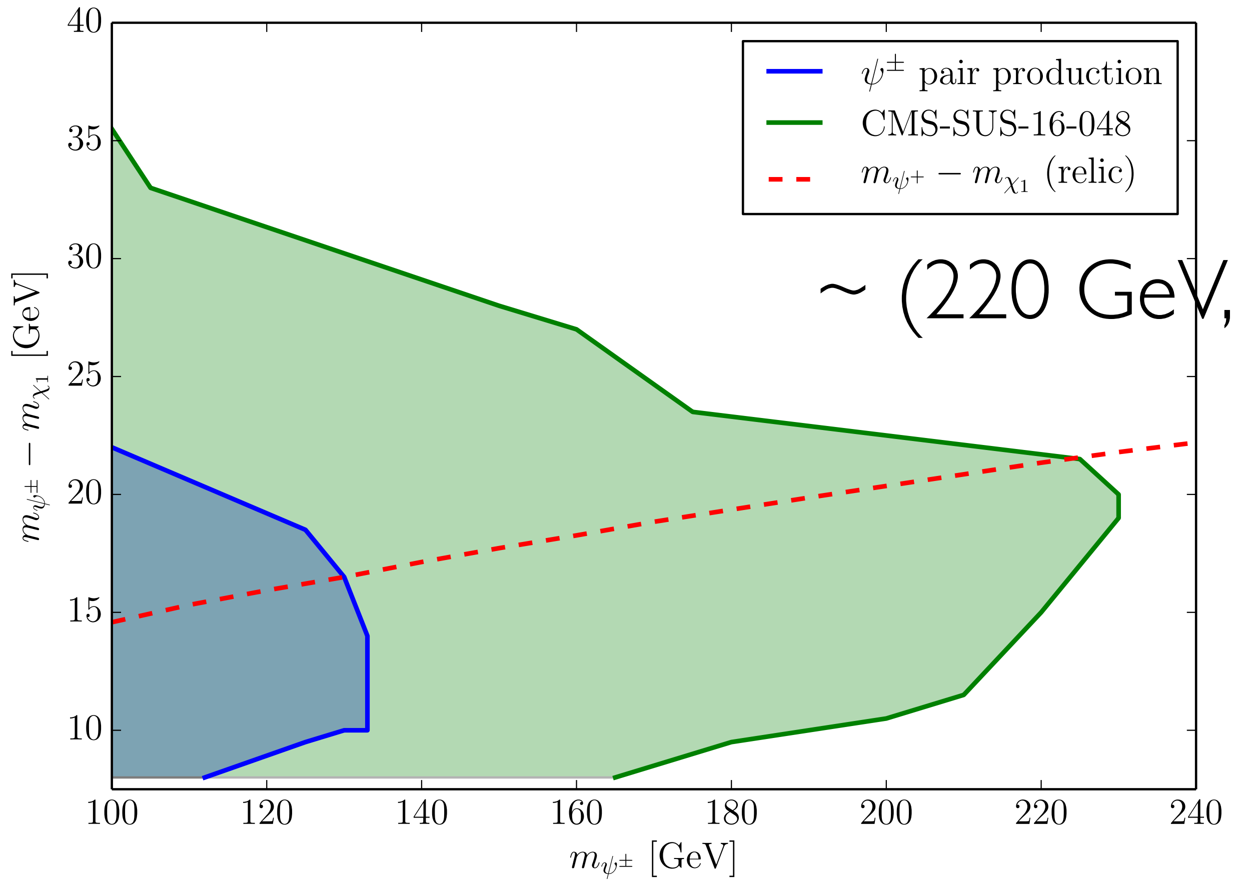




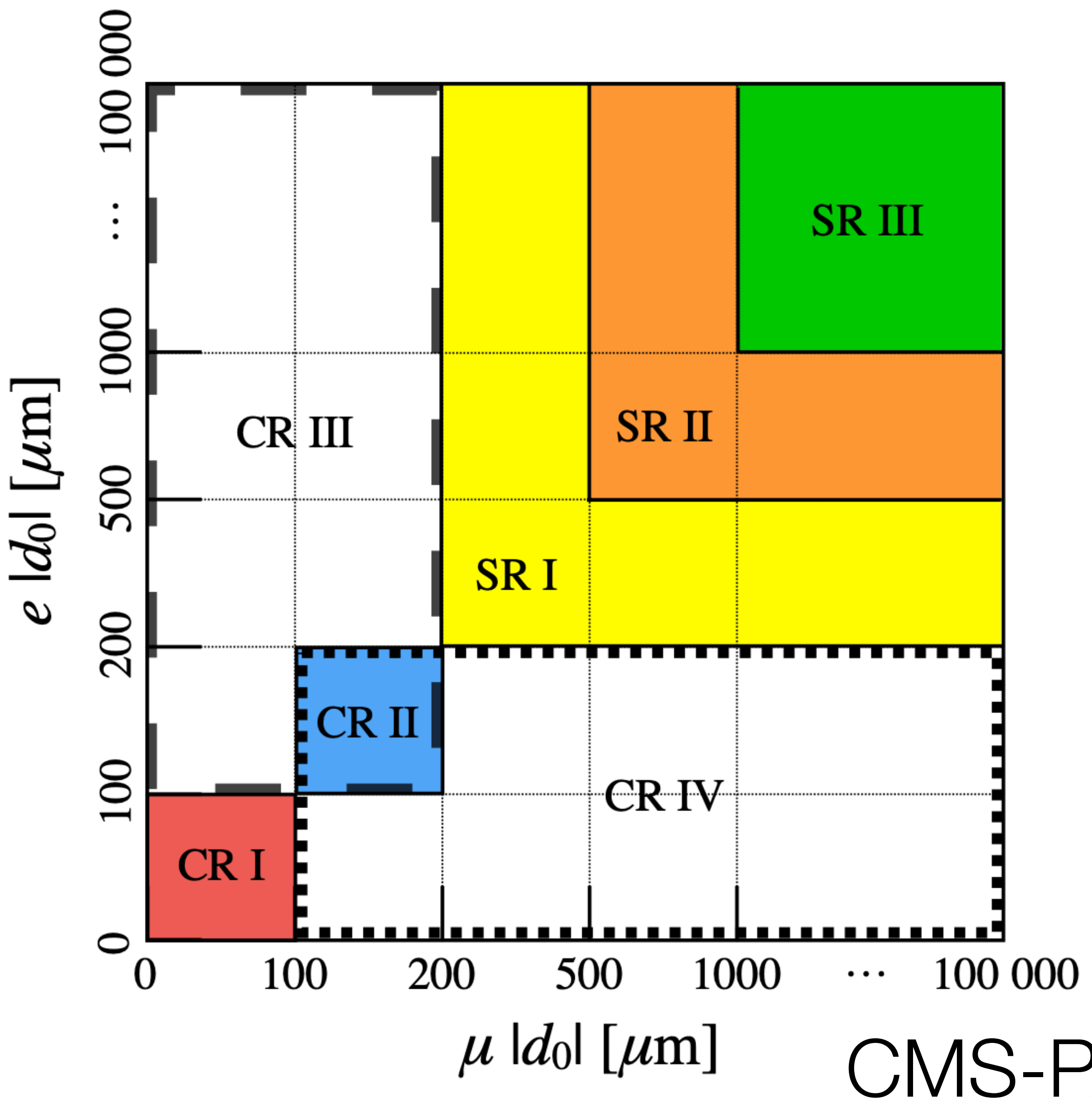
Theoretically motivated but fall through search cracks!

Bharucha, Brümmer, ND 1804.02357

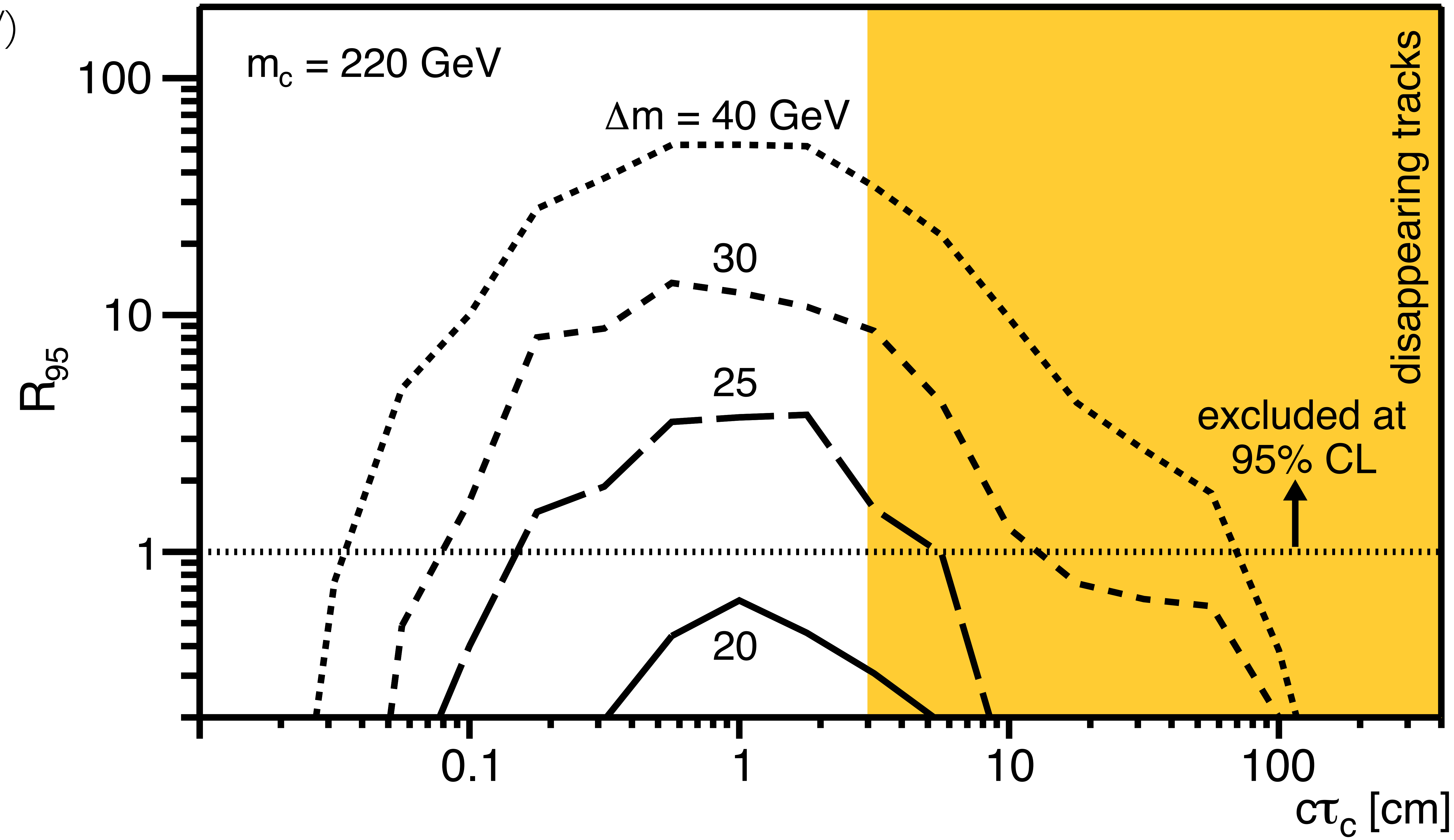
Blekman, ND, et al 2007.03708



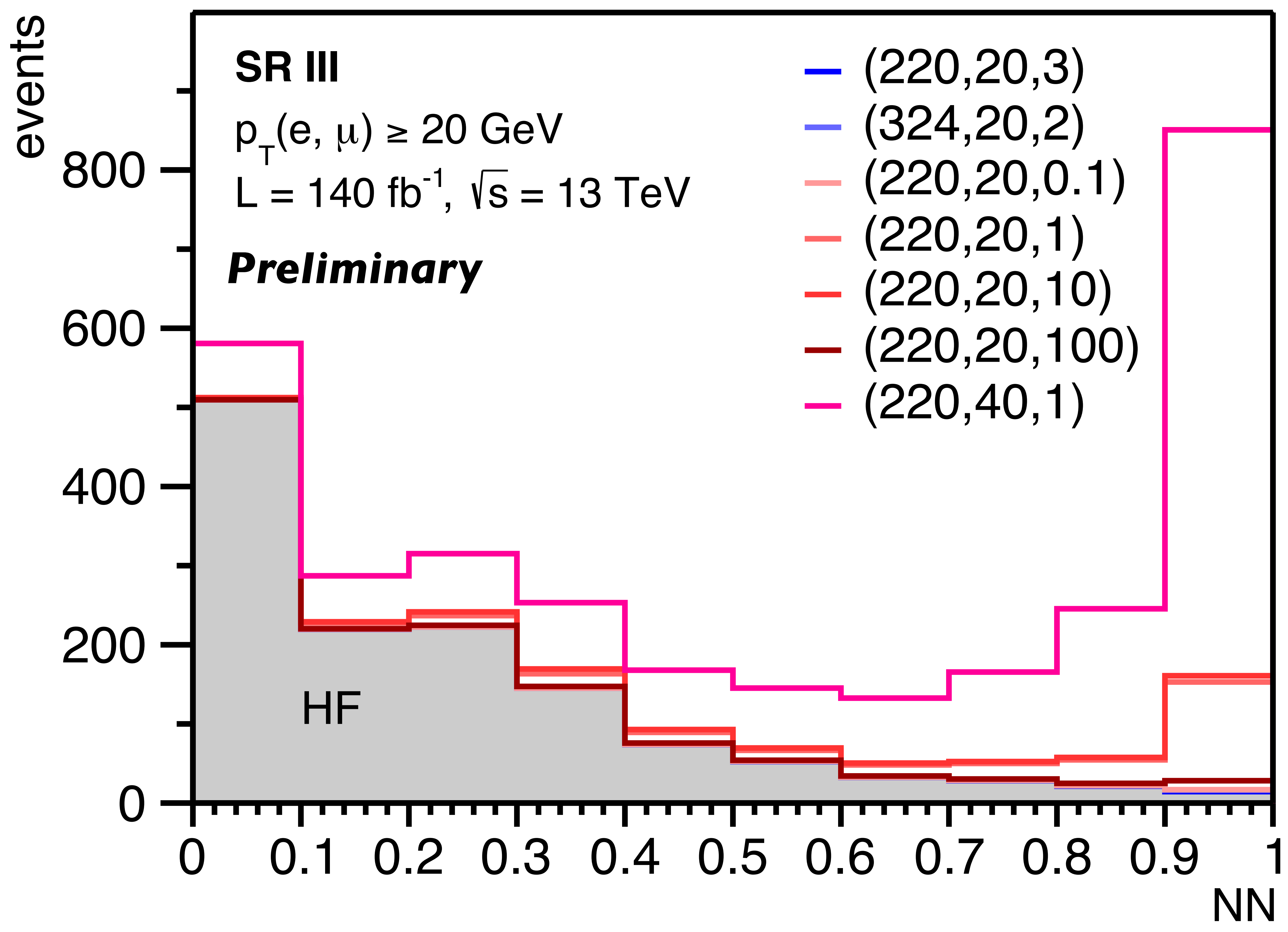
~ (220 GeV, 20 GeV)



CMS-PAS-EXO-16-022



NN improves sensitivity many fold!

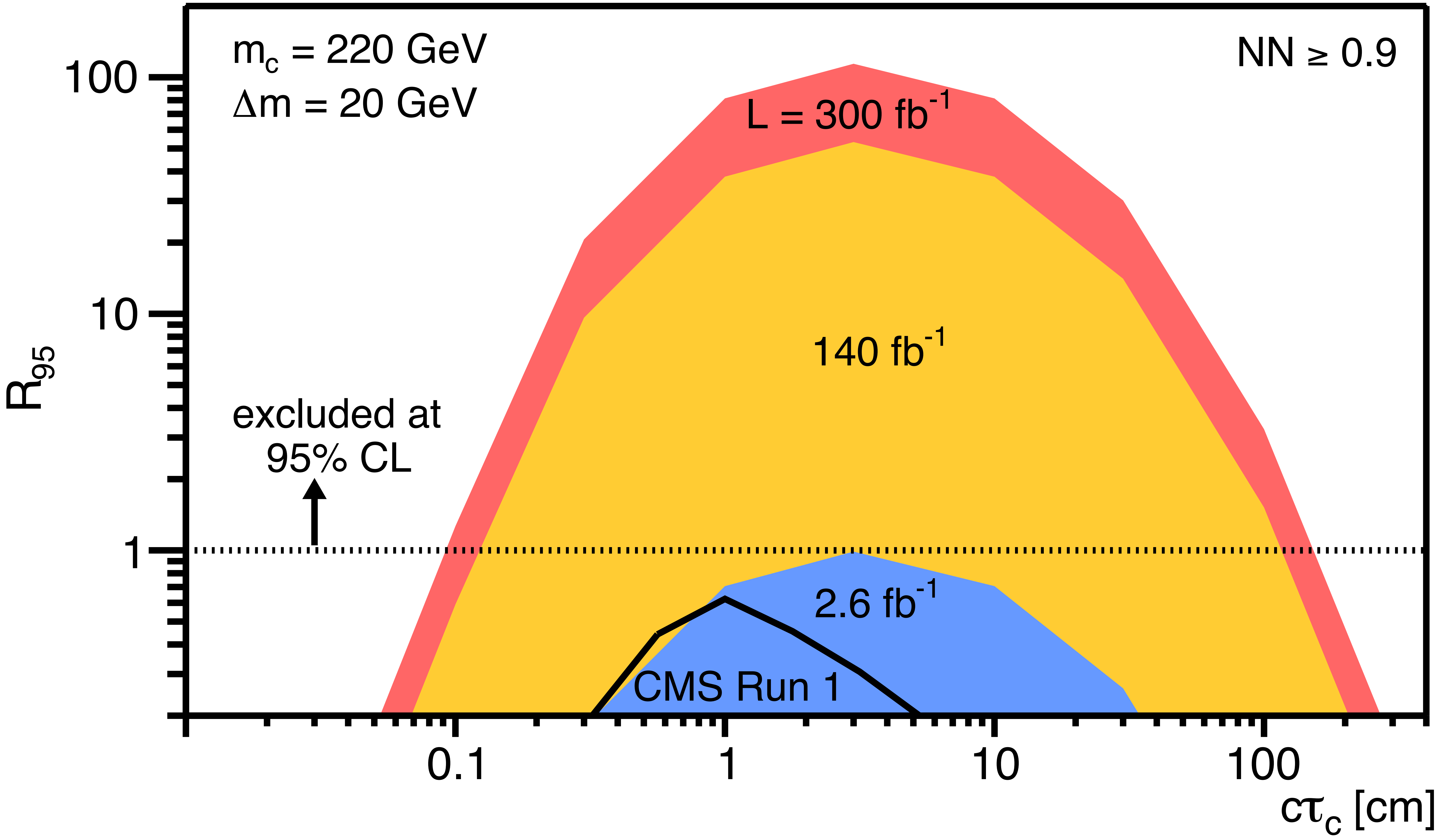


#	(m_c [GeV], Δm [GeV], $c\tau_c$ [cm])	$S_{\rm I}$	$S_{\rm II}$	$S_{\rm III}$
1	(324, 20, 2)	0.21	0.23	0.64
2	(220, 20, 3)	0.57	0.67	2.71
3	(220, 20, 0.1)	68	19	3.06
4	(220, 20, 1)	84	72	139
5	(220, 20, 10)	15	20	147
6	(220, 20, 100)	0.79	0.70	14
7	(220, 40, 1)	449	427	837
	HF background	2323	363	14

Blekman, ND, et al 2007.03708

Extrapolation of near-future reach

Blekman, ND, et al 2007.03708



What triggers?

The LLP WG has identified multiple avenues where more work is necessary

2110.14675, CERN-LPCC-2021-01

During Run 2, CMS had several triggers designed to target events with two displaced leptons [23–25]. These triggers selected ee, $e\mu$ and $\mu\mu$ events with a p_T threshold on each lepton of 30–50 GeV, and no primary vertex requirement. A trigger requiring a photon and a displaced muon was used to select events with a displaced muon and displaced electron, or the equivalent with two displaced electrons (i.e., trigger on two photons). The thresholds for these triggers were substantially increased when the performance of the LHC increased during Run 2. To achieve low-p_T thresholds during Run 3 further work will be necessary.

L1	Present in Run 2	HLT	Present in Run 2	Physics motivation example	Section
Jet or MET	Yes	* Number of tracker hits "below" jet	No	Hadronically decaying LLPs with low-HT where displaced track reconstruction is particularly difficult	3.1.2
* HCAL timing	No	Various	Yes	Slow LLPs (heavy or produced near threshold)	3.2.1
* HCAL timing + CalRatio type	No	Various	Yes	LLPs decaying in calorimeter	
$1j$, $3j$, H_T, 2τ	Yes	* Calo timing (+ tracking?) + dramatic reduction of HLT thresholds	No	Various LLP scenarios	3.2.2
Photon	Yes	Displaced γ + * timing	No	GMSB	
Single muon	Yes	*Displaced track(s) in inner detector (*add calo timing for electrons?)	No	Soft displaced leptons; GMSB staus, freeze-in DM, LLPs from Higgs boson decays	3.3.1
Single electron	Yes				
Di- (or tri-) muon	Yes			Soft displaced multi-lepton, e.g. dark photons, dark shower	
Muon system	Yes	* Muon system timing	No	Fractionally charged particles	3.4.1
* Displaced muons	No	Muon system and inner tracker	Yes	Displaced muons with impact parameter $>$ 10s of cm	3.5.1, 3.5.2

Table 1. Summary of ideas for new Run-3 triggers for ATLAS. We assume that Run-2 triggers [29, 57] will be retained or improved for Run 3. The new component of each trigger is marked with a star *. Question marks indicate possibilities that need further investigation. Please refer to text for further details.

Hidden Valley & Dark Showers

Hidden Valley: Strassler & Zurek hep-ph/0604261
Emerging jets: 1502.05409
Semi-visible jets: 1503.00009

SM (pp)

↓ Heavy Mediator

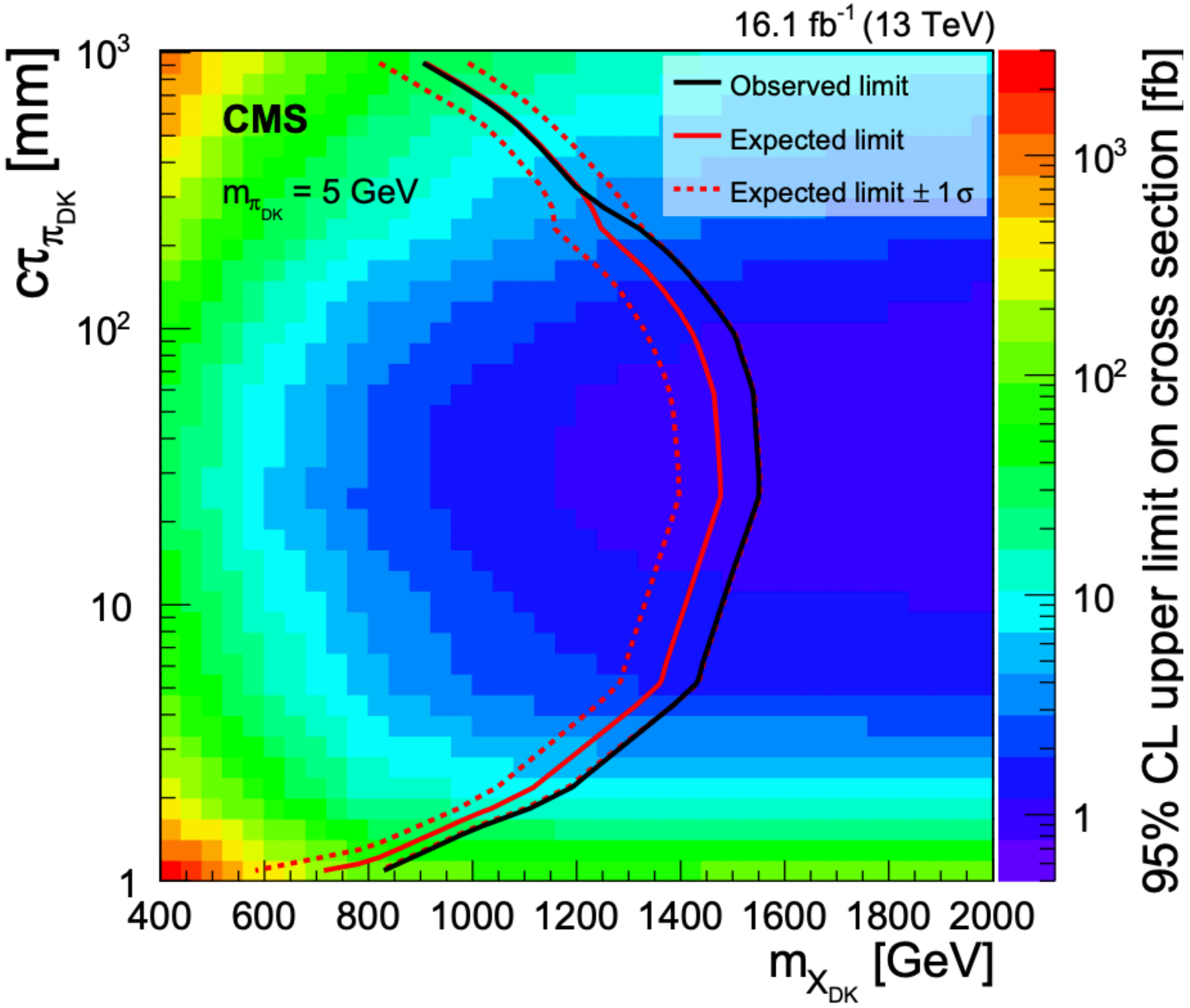
Hidden sector "quarks"

↓ Dark shower + Hadronisation

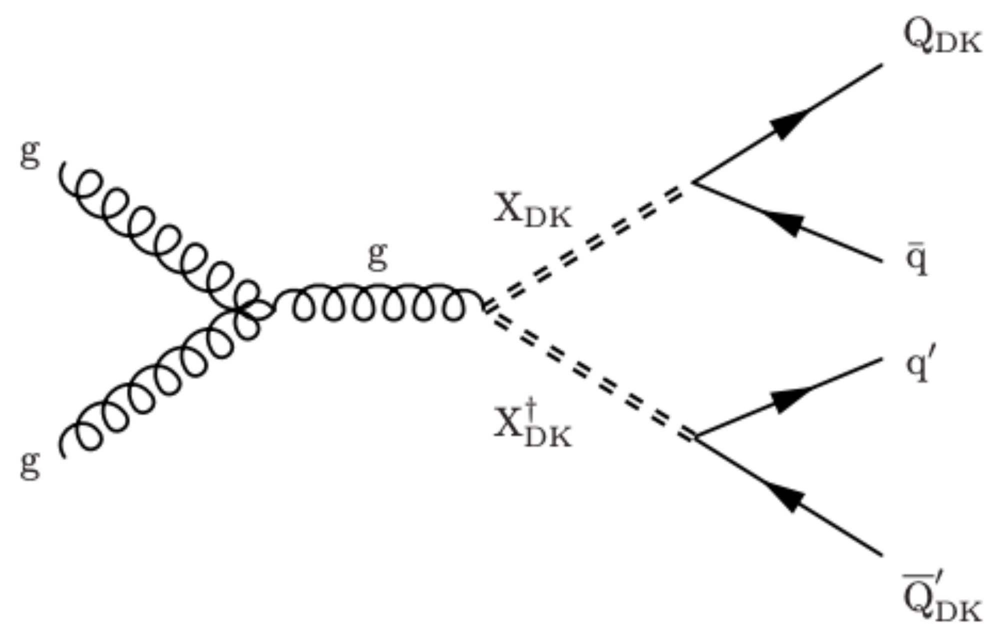
Hidden sector hadrons

↓ Off-shell Heavy Mediator

SM



CMS 1810.10069



Trick of using strongly charged production

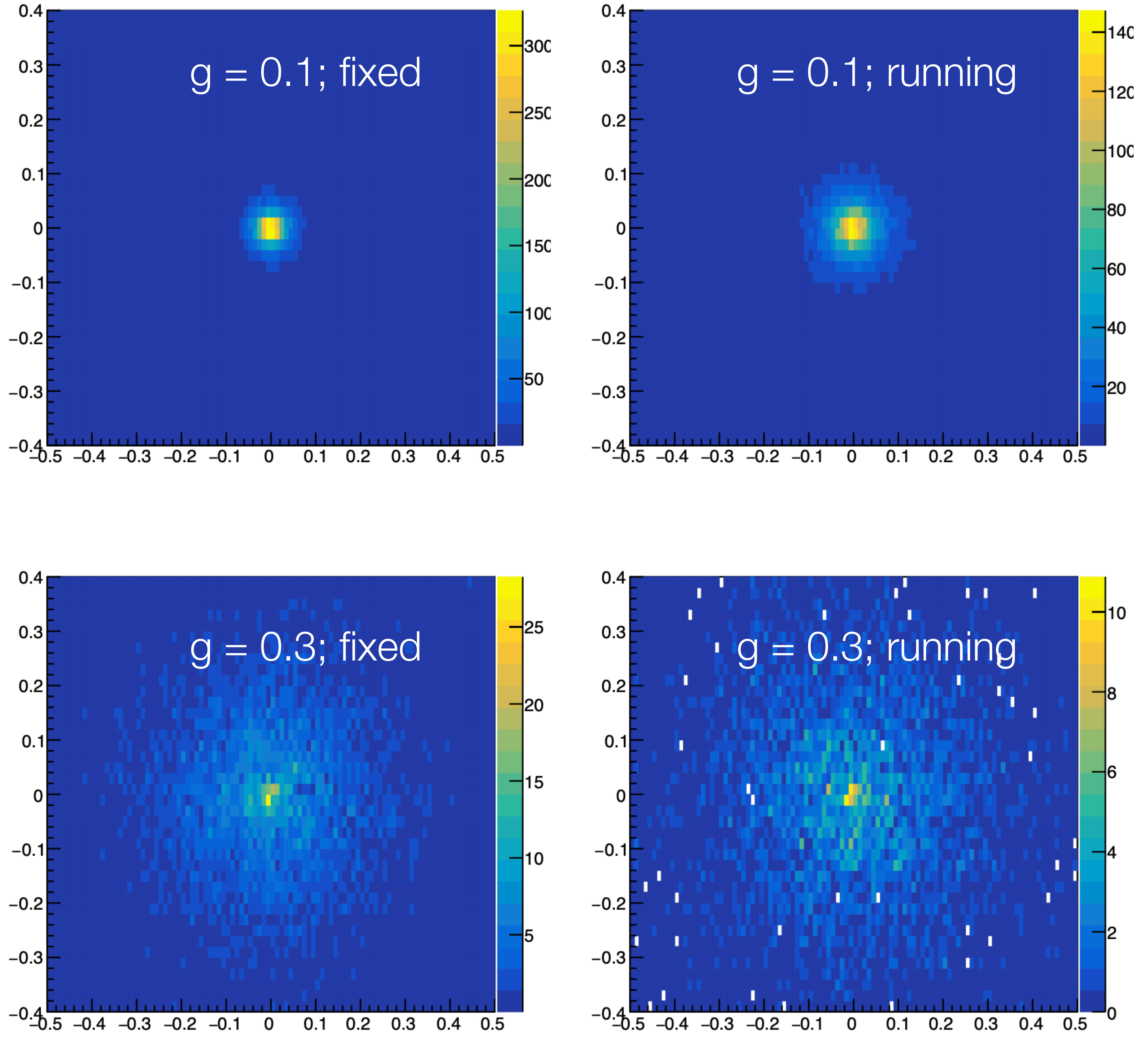
Potentially strong interactions between SM & DM

[See also talk by S. Kulkarni]

What would be the best way to describe these?

- Current use of full Pythia8 machinery results in too many parameters (at a minimum, a scan in 8 dim; partly "tuning")
- But clearly, many choices result in non-distinguishable* phenomenology
- Can we encapsulate the difference meaningfully? —
  - **Mass of resonance** to set production kinematics
  - Simplified model-like **one kind of dark hadron decay at a time**
  - Encapsulate the **jet shape** using our understanding of extremes

Jets from a 1 TeV resonance with different coupling & running



Take away —

- BSM search techniques at LHC are really quite mature now. Innovation has shifted to finding really exotic signatures and preservation + reinterpretation of analyses.
- ML/BDT studies gaining popularity because what can be discoverable at Run 3 is clearly very hard to see (else we would have had an indication).
- New focus on improving coverage in LLPs and finding gaps in coverage

Not in this talk

- ML ideas to find anomalies — autoencoders, energy mover distance, etc.
- Jet substructure techniques + QCD resummation improvements for heavy new particle searches
- …