Physics Beyond the Standard Model (experimental) - Part 2

CATERINA DOGLIONI - LUND UNIVERSITY

Outline for these three BSM lectures

Lecture 1

The Standard Model has no apparent major problem!
Why should we look beyond, and how? Direct and indirect BSM searches

Lecture 2

The Standard Model has some problems!
Solving many problems at once: *supersymmetry*
Solving one problem at a time: *generic dark matter searches* (at the LHC, for today)

Lecture 3

Connecting DM@LHC with DM beyond the LHC (direct and indirect detection)
Darker matter: the rare and the unexpected (at the LHC and beyond)
Outline of other BSM theories & results
(Almost) back to the SM: neutrino physics

Recap of Lecture 1

The SM has no problems (...just wait until today's lecture...)!

- Measurements and agreement with theory

✅Energy frontier => exploration of the unknown

"Generic" ***direct search strategies***:

look for (sizable) deviations signaling the presence of new particles

A simple BSM search in more detail

❌Energy frontier => but we're not upgrading the LHC energy anytime soon!

Indirect search strategies:

look for (small) deviations from the presence of new particles in loops

Wordcloud #1

Wordcloud #2

Future: poll results

Lecture 2

More detailed outline of lecture 2

The SM has some problems!

- the Higgs and the hierarchy problem [some solutions: this afternoon]
- dark matter and dark energy [some solutions: this afternoon]
- neutrino masses [problem & solutions: tomorrow]

Solving many problems at once: **Supersymmetry (SUSY)**

How to search for SUSY & interpret results

SUSY @ LHC: where we are, where we are going

Solving at least one big problem: not-necessarily-SUSY **Dark Matter, part 1**

~~Dark matter~~ Invisible particles at colliders

Benchmark models and searches

Standard Model? Here are its problems!

A list of problems with the SM

Aesthetic

- Fine-tuning needed for Higgs mass
- Large difference in scales of forces (hierarchy problem)
- Free SM parameters
- ...

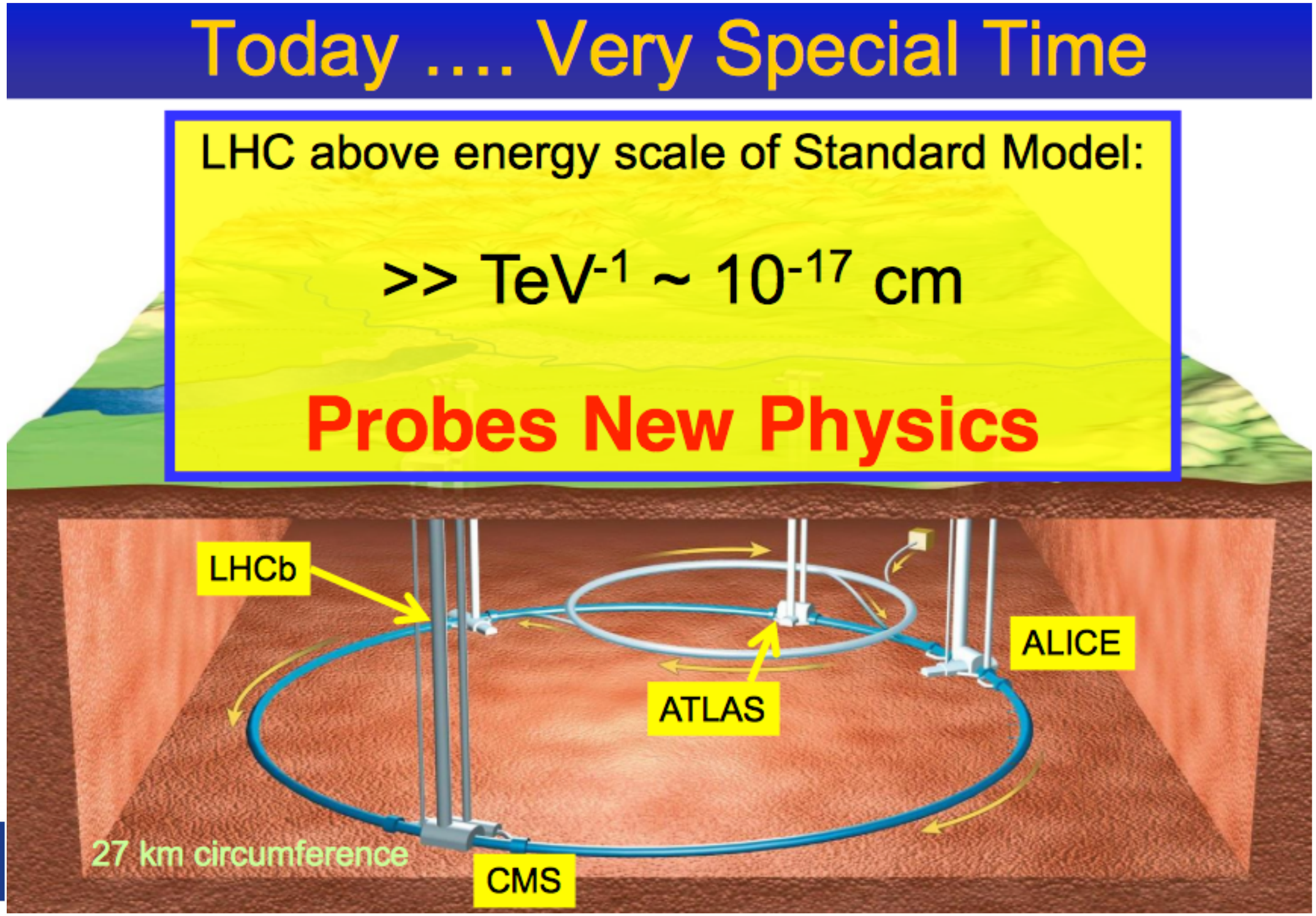
Empirical

- Dark matter (DM)
- Dark energy
- Matter vs antimatter
- Weakness of gravity
- Neutrino masses

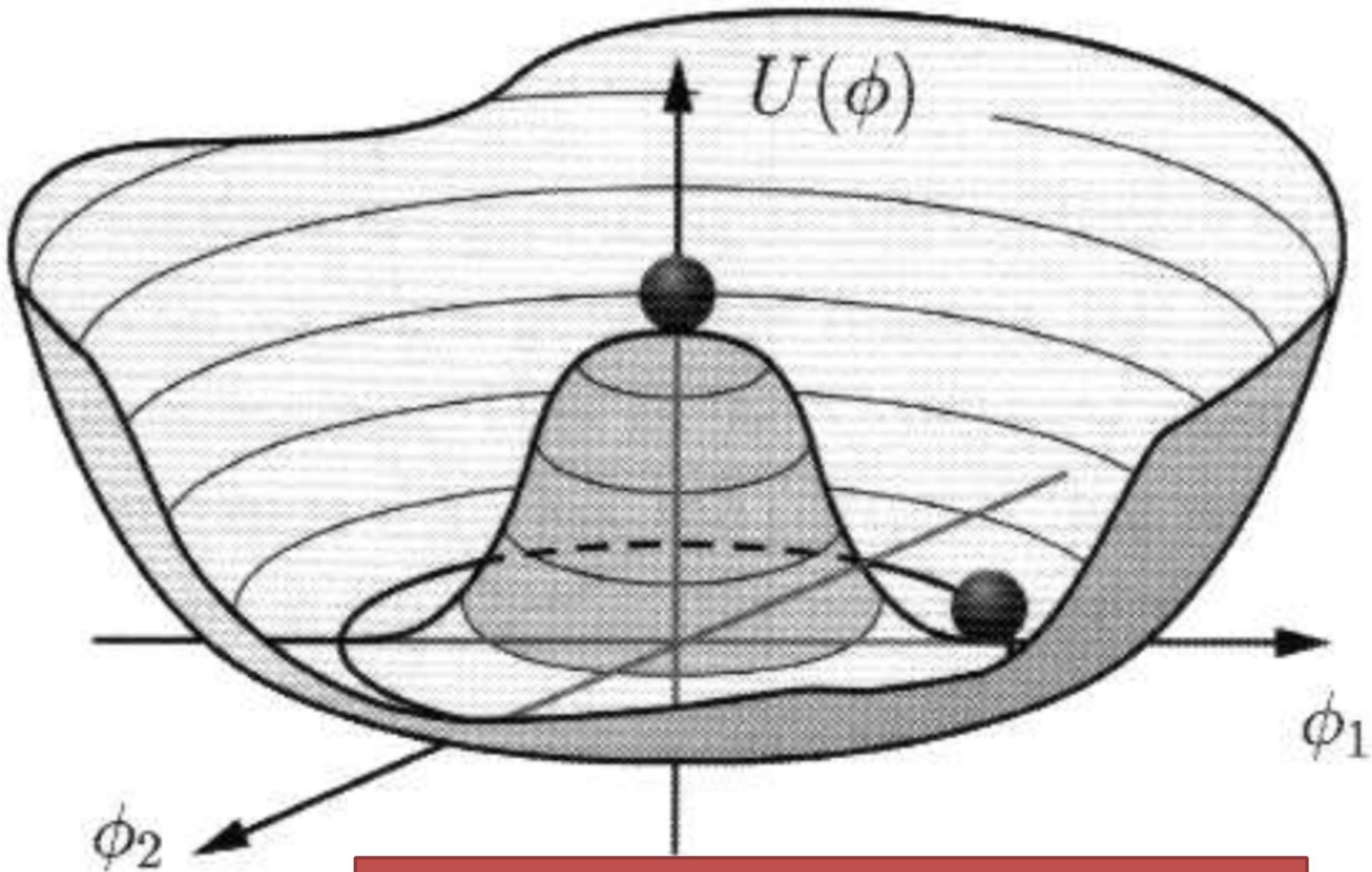
Preferred (by whom?) mass range for answers: **TeV-scale**

Preference also due to a special time in history

C. Issever



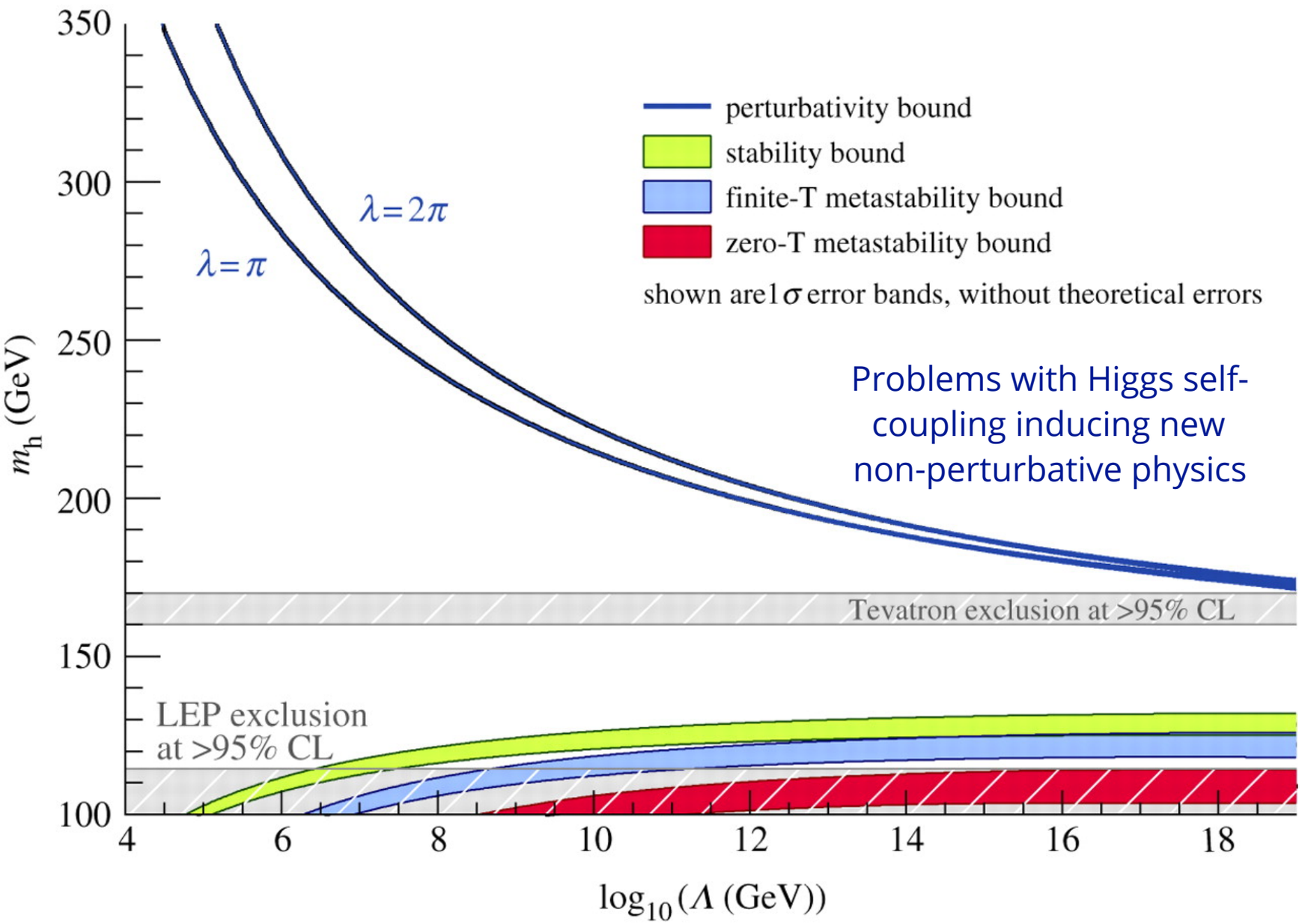
Preference also due to a special time in history



Higgs Vacuum Expectation Value: 246 GeV ~10^-16 cm

Can the Higgs indicate the scale of new physics? Not

http://rsta.royalsocietypublishing.org/content/370/1961/818 (2012)



Problems with Higgs self-coupling inducing new non-perturbative physics

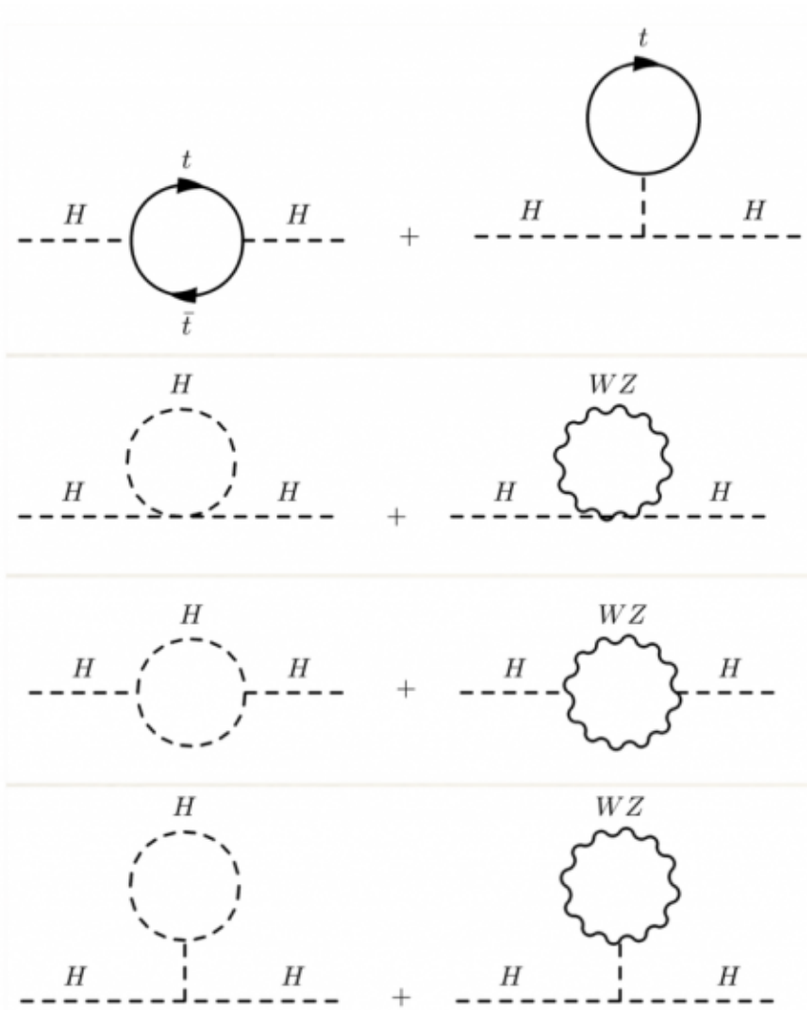
"Only a narrow range of $m_h \in (130,180)$ GeV is compatible with the survival of the Standard Model at all scales up to the Planck mass. This could be the 'maximal conceivable disaster' scenario for the LHC: a single Standard Model Higgs boson and nothing else!"

Problems with stability of the vacuum

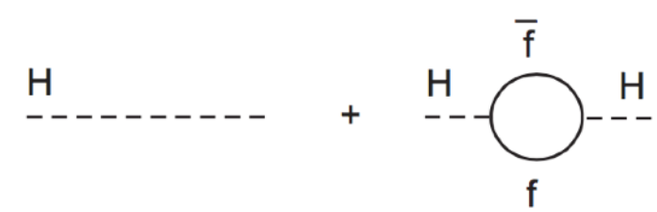
Higgs mass and fine tuning

Slides by P. Athron, D. Miller

Observed (Higgs mass)^2: 10^{32} times smaller than predicted



Think **renormalisation**:
Large loop corrections needed
to the Higgs mass
OR
cut-ff the theory at scale Λ



$$m_H^2 = m_o^2 + \delta m^2$$

$$\delta m^2 \sim \Lambda^2,$$

No indication of what this scale Λ is (from previous slide)…
could be limit of current physics knowledge (Planck scale)

Higgs mass and fine tuning

Tobias Golling's talk

Is this natural?

$$36127890984789307394520932878928933023 -$$
$$36127890984789307394520932878928917398 =$$
$$= m^2_H = 125^2$$

Unnatural cancellation or fine-tuning: $O(10^{32}) - O(10^{32}) = O(1)$

In analogy to: $0.7 - 0.4 \neq O(10^{-32})$

Higgs mass and fine tuning

Slides by P. Athron, D. Miller

Is this natural?

Fine-tuning in nature:

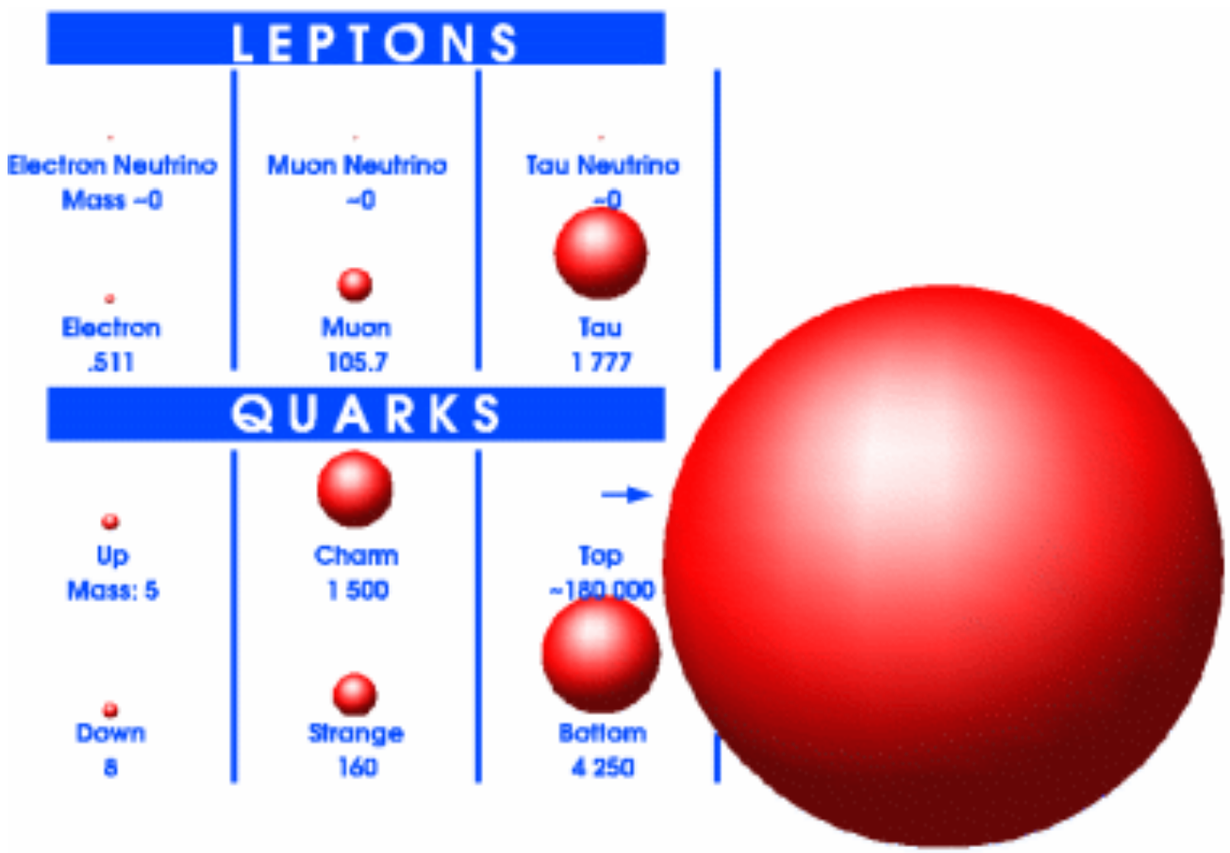
- Eclipse (moon and sun aligned to 1 %)
- A pen perfectly balanced on its tip

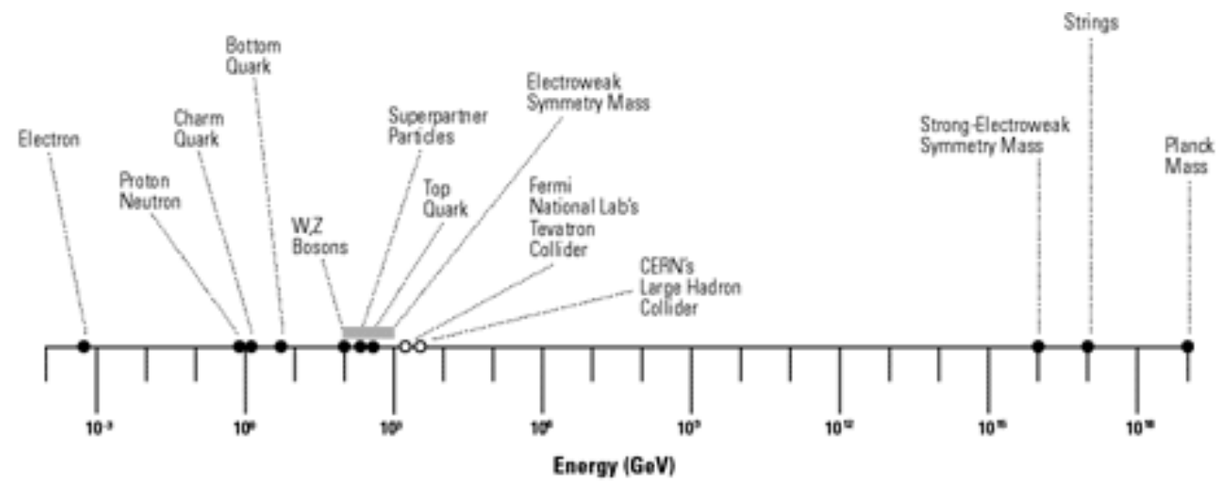
For further digressions: see http://discovermagazine.com/2000/nov/cover/

But also: *"Whatever combination of physical constants may exist, it would be one of a kind."* T. Drange

Hierarchy problems

More of this in BSM theory lectures





Why are the scales of the SM forces and the masses of its particles so far apart?
[Why three families? Why masses not predicted?]

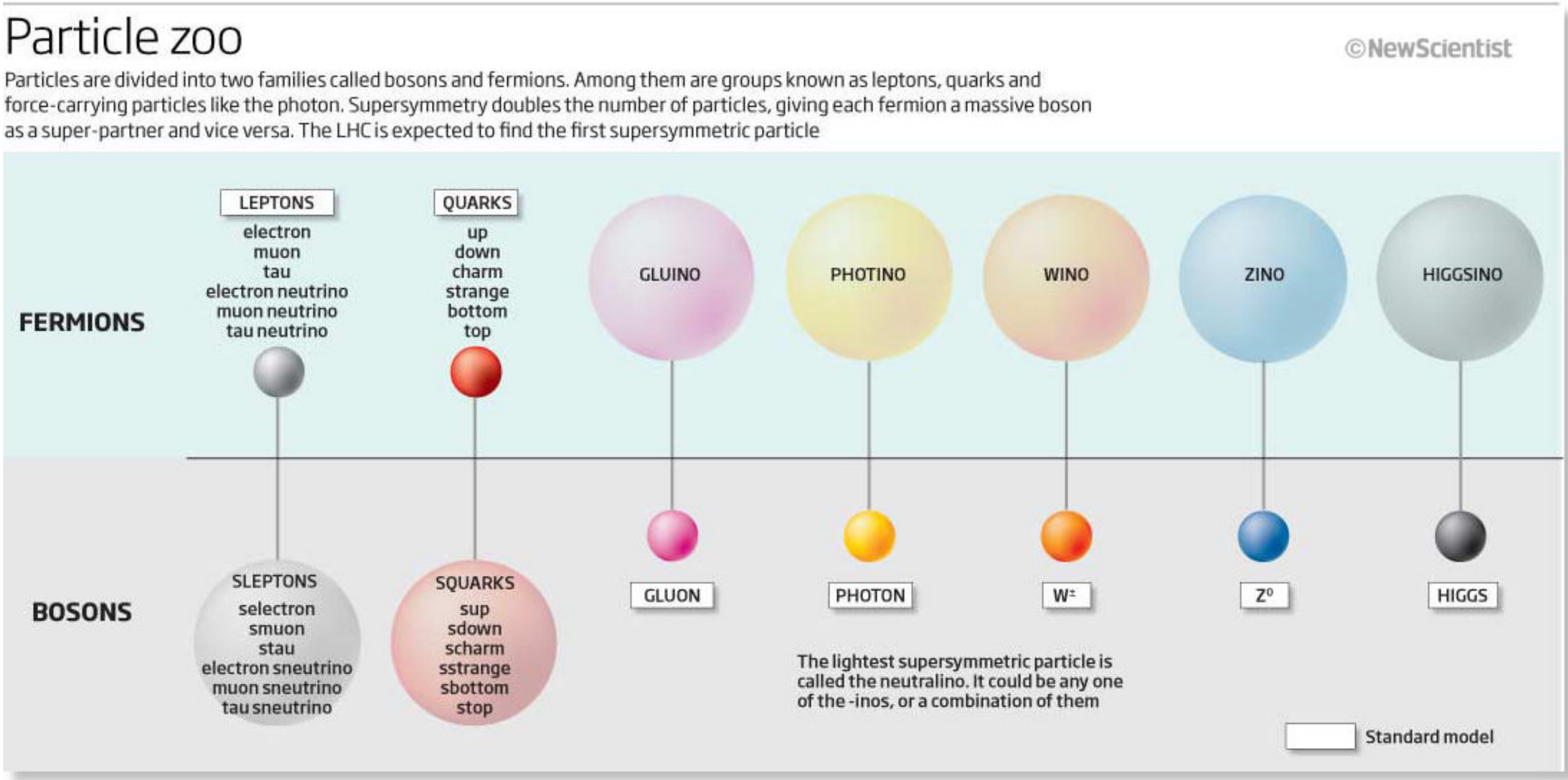
Take-home point #1:

The SM has problems that are both aesthetic
(observations not matching a "beautiful" theory)
and empirical
(observations not explained)

These motivate the search for BSM physics at the scales reachable by the LHC

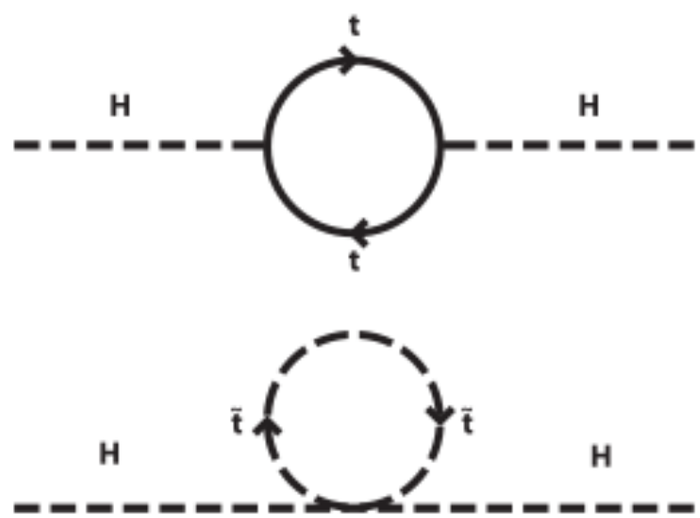
A solution with many benefits: Supersymmetry

Supersymmetry: a new particle zoo



A solution with benefits

Every supersymmetric partner can compensate a loop that would increase the Higgs mass



$$m_H^2 = m_o^2 + \delta m^2 + \delta \tilde{m}^2$$

Cancellation ~exact only if equal masses

Note: need to apply R-parity conservation to avoid proton decays (not experimentally observed)

$R = (-1)^{(3B+L+2s)}$

SM particles: R=+1

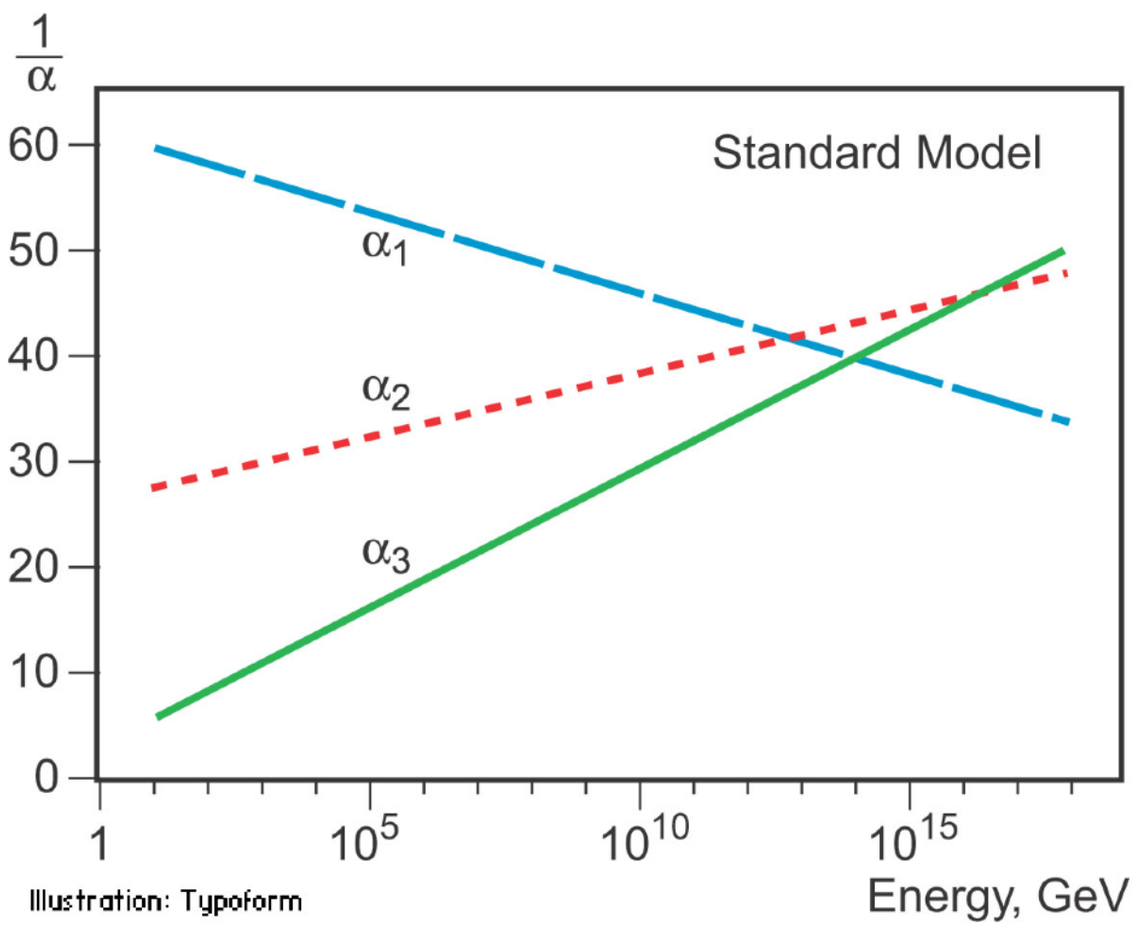
SUSY particles: R=-1

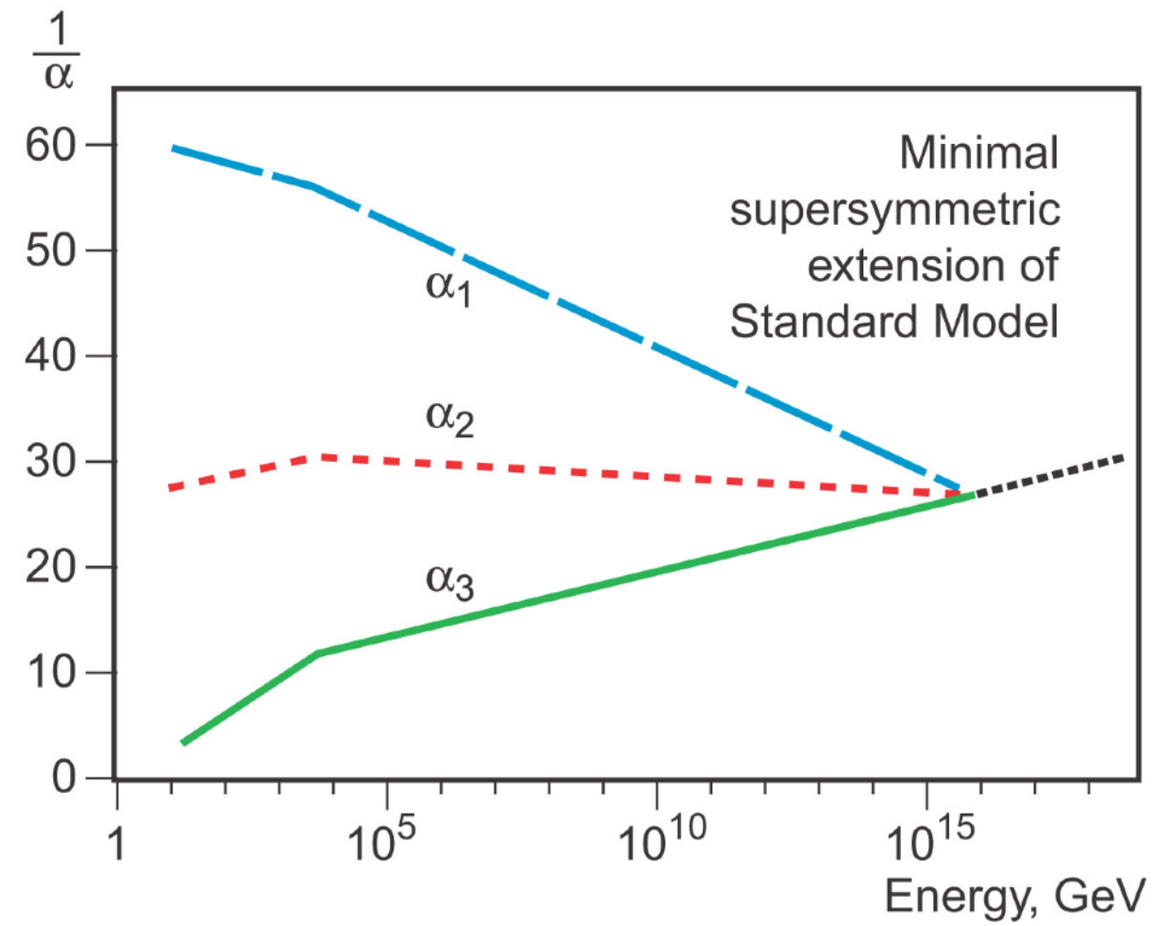
Consequence: decay chains, until pair-production of stable remnant (lightest supersymmetric particle, LSP)

—> benefit: this is a dark matter candidate (see later)

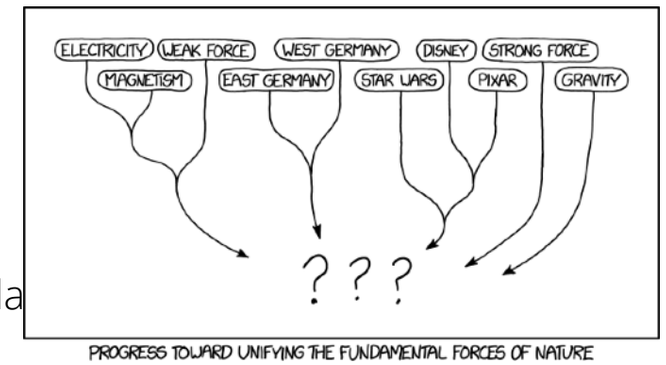
Additional benefit: force unification

Coupling constants run with energy
if (TeV-scale) SUSY particles, they all run to the same value





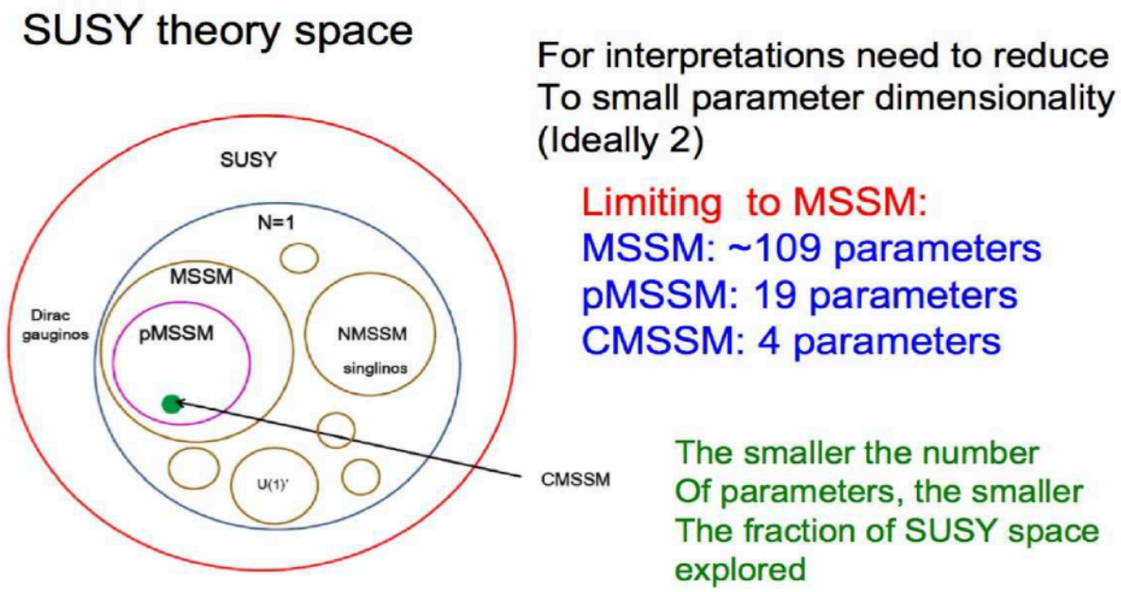
https://xkcd.com/1956/



PDG review

How to look for SUSY particles? Depends...

SUSY has many realizations: many new particles bring many parameter choices



Number of parameters reduced applying constraints, e.g. imposing a certain mass hierarchy / equalities

G. Polesello

Phenomenology depends on how the supersymmetry is broken

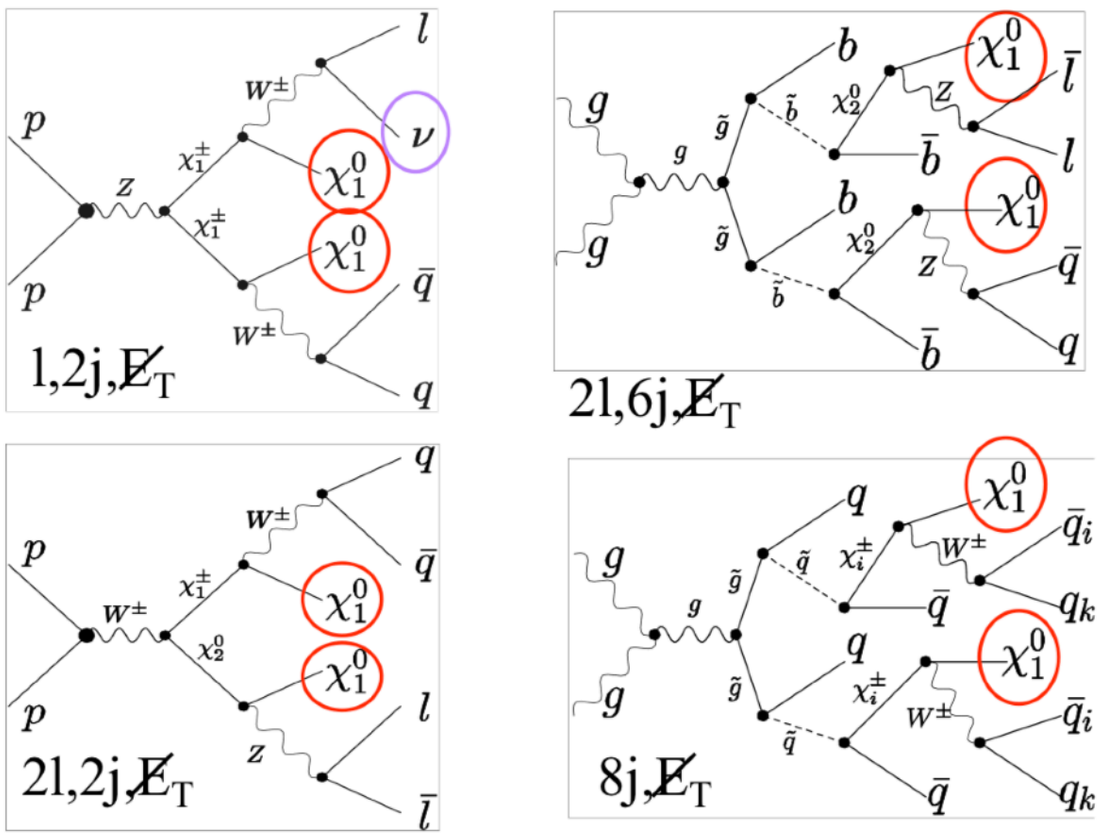
In a "naive experimental" picture the model depends on:

- Particle content and mass hierarchy (e.g. small/large mass splittings)
- Type of SUSY particle considered
- Coupling constants to SM particles, mixing angles (=decays)
- R-parity conservation/violation

Experiments "brand" searches for **strong/electroweak/compressed/3rd gen (..) SUSY**

How to look for SUSY particles? Depends...

Some "typical" SUSY decay chains



https://arxiv.org/pdf/1306.6420.pdf

Table 110.1: Typical search signatures at hadron colliders for direct gluino and first- and second-generation squark production assuming different mass hierarchies.

Mass Hierarchy	Main Production	Dominant Decay	Typical Signature
$m_{\tilde{q}} \ll m_{\tilde{g}}$	$\tilde{q}\tilde{q}, \tilde{q}\bar{\tilde{q}}$	$\tilde{q} \to q\tilde{\chi}_1^0$	≥ 2 jets + E_T^{miss} + X
$m_{\tilde{q}} \approx m_{\tilde{g}}$	$\tilde{q}\tilde{g}, \bar{\tilde{q}}\tilde{g}$	$\tilde{q} \to q\tilde{\chi}_1^0$ $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$	≥ 3 jets + E_T^{miss} + X
$m_{\tilde{q}} \gg m_{\tilde{g}}$	$\tilde{g}\tilde{g}$	$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$	≥ 4 jets + E_T^{miss} + X

PDG review

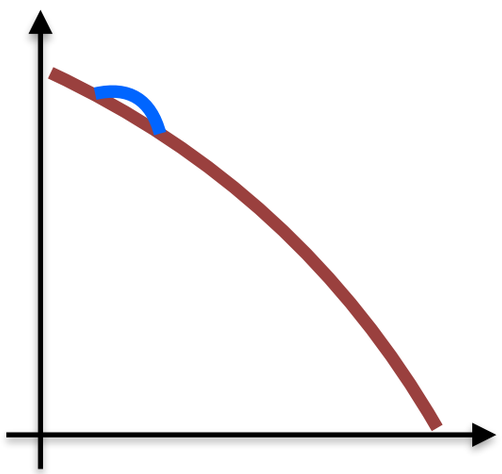
Event characteristics:

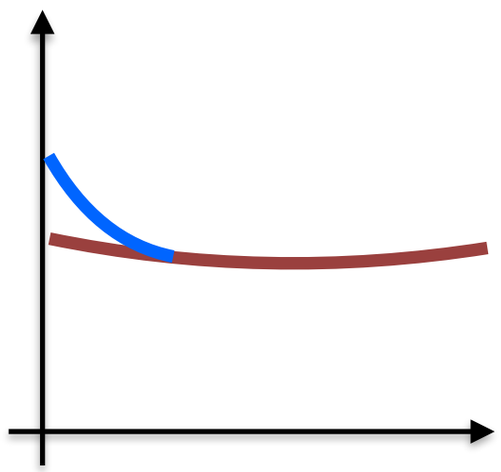
- High object multiplicity
- Missing transverse momentum

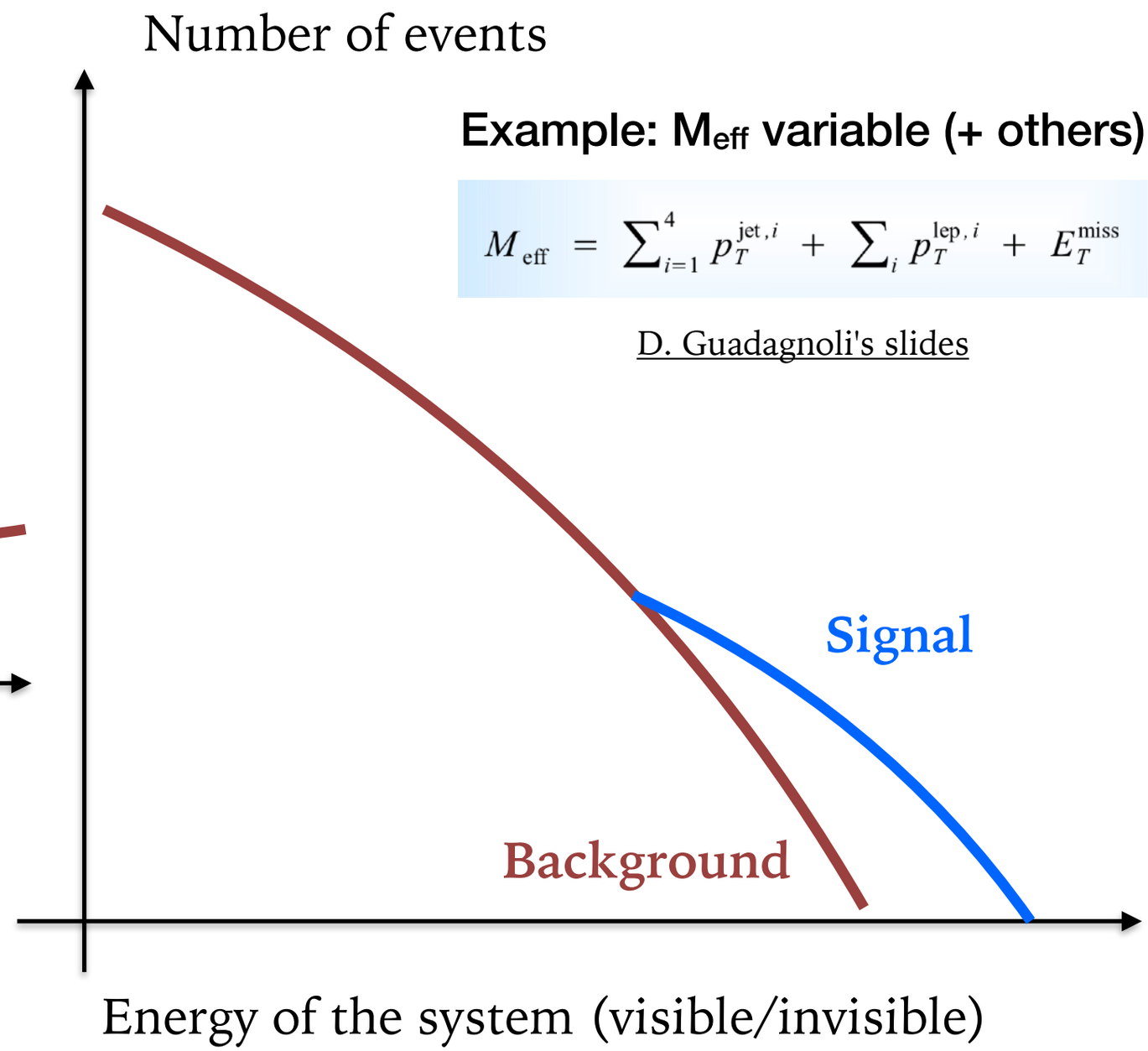
Backgrounds:

- QCD, with mis-measured jets
- W+jets
- top quarks

RPC SUSY variables: include the MET in the ET







Example: M_{eff} variable (+ others)

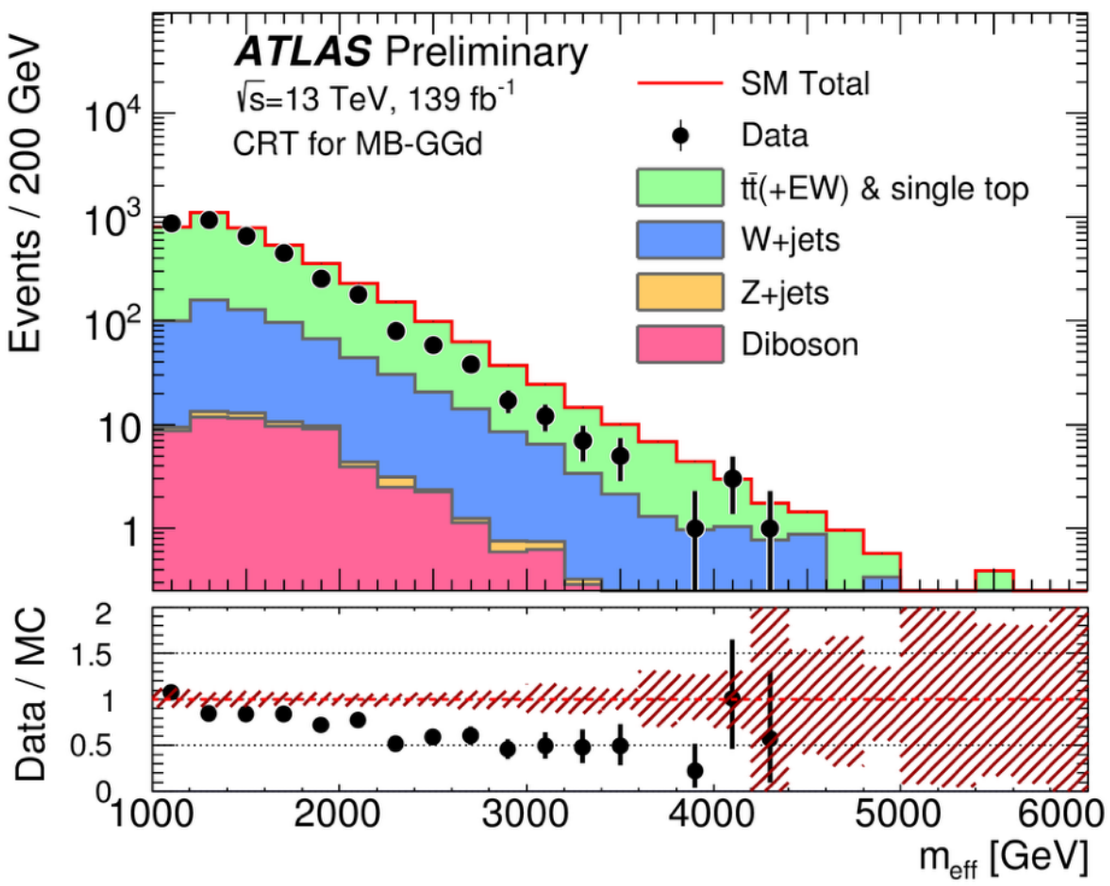
$$M_{\text{eff}} = \sum_{i=1}^{4} p_T^{\text{jet},i} + \sum_i p_T^{\text{lep},i} + E_T^{\text{miss}}$$

D. Guadagnoli's slides

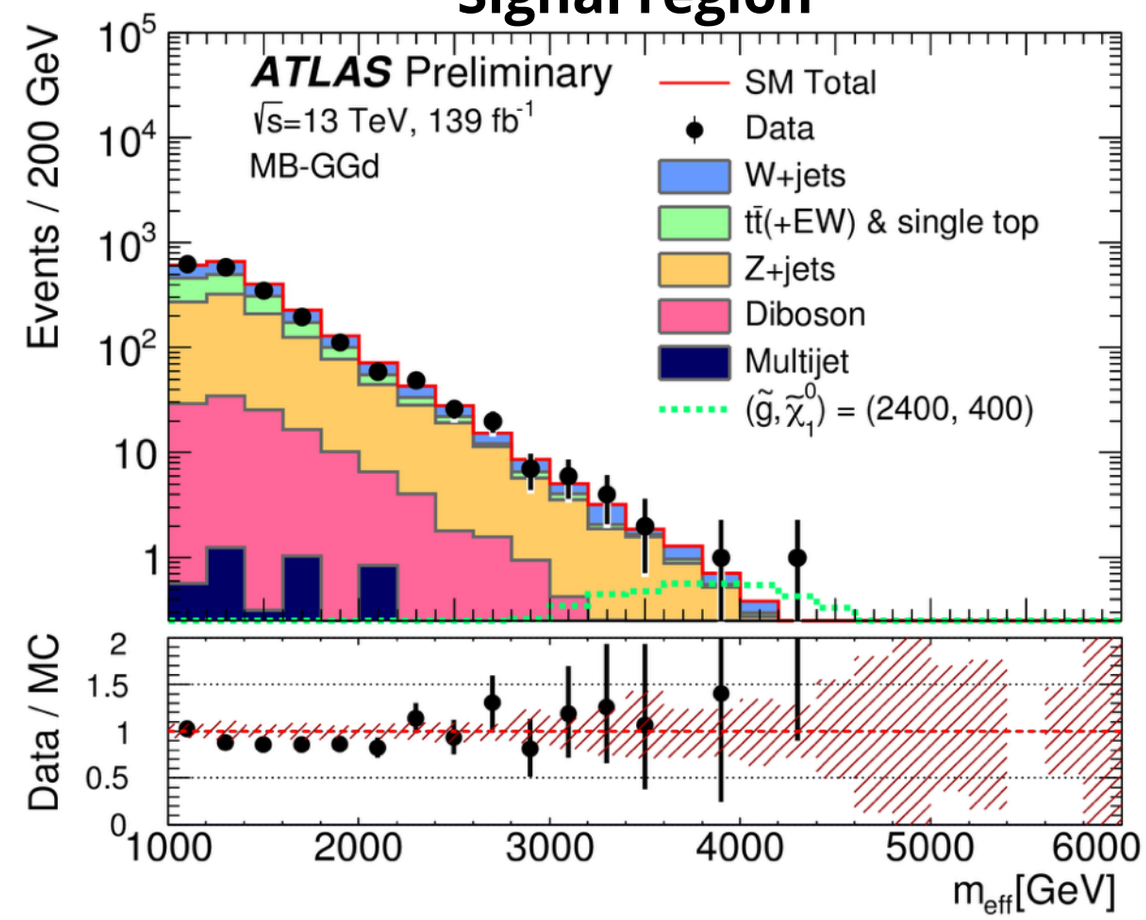
Background estimation: use control regions

Recent search for squarks and gluinos: ATLAS-CONF-2019-040

Control region



Signal region



Define to be signal-depleted

Can serve as normalization for MC, reducing theory uncertainties

Define to be signal-rich

This search: also use a second variable related to MET for multi-bin approach

Can make use of CR normalizations

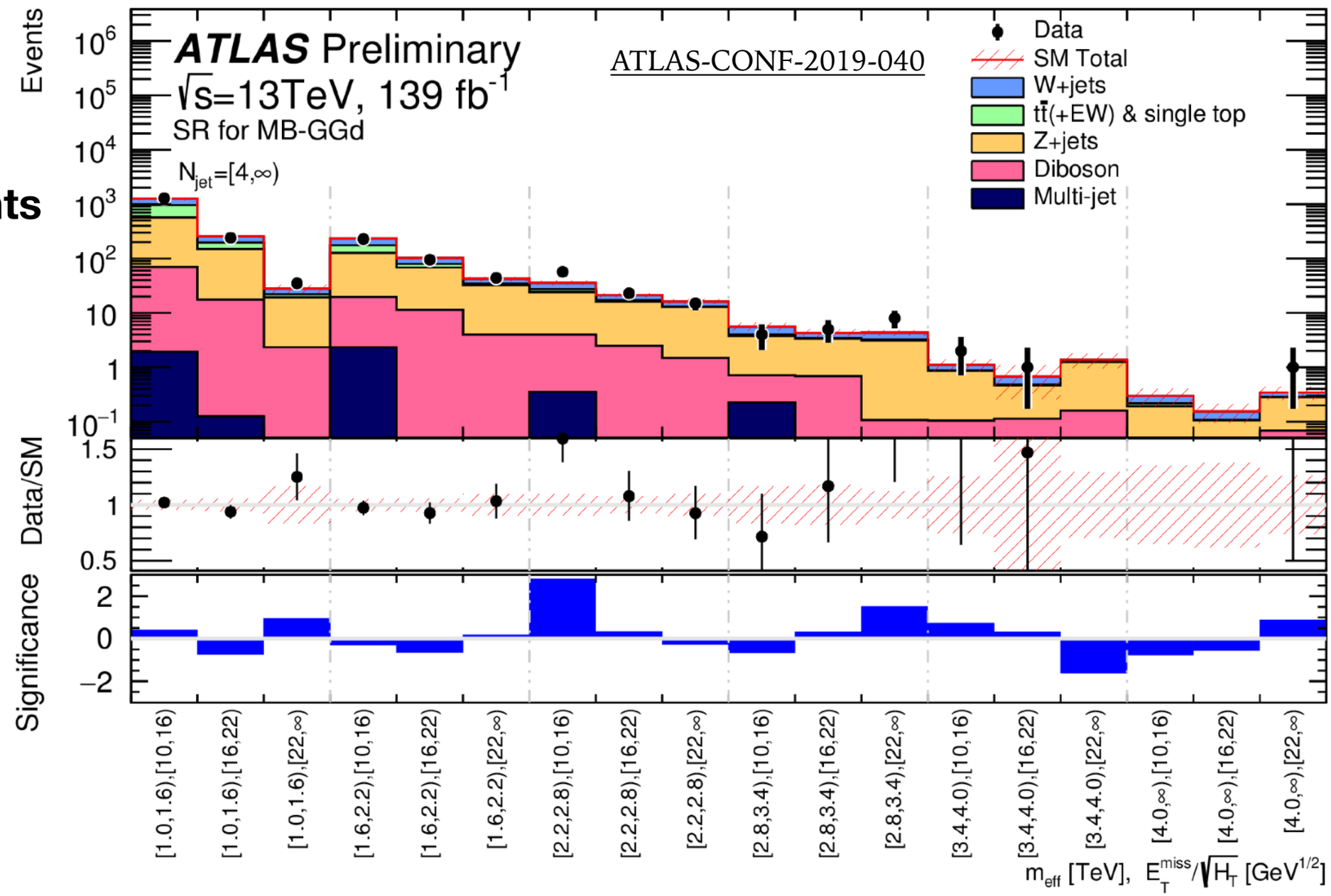
Apply cut to increase signal/background

Compare data and background estimation in SR

Cumulative number of events in bin

Profile likelihood ratio

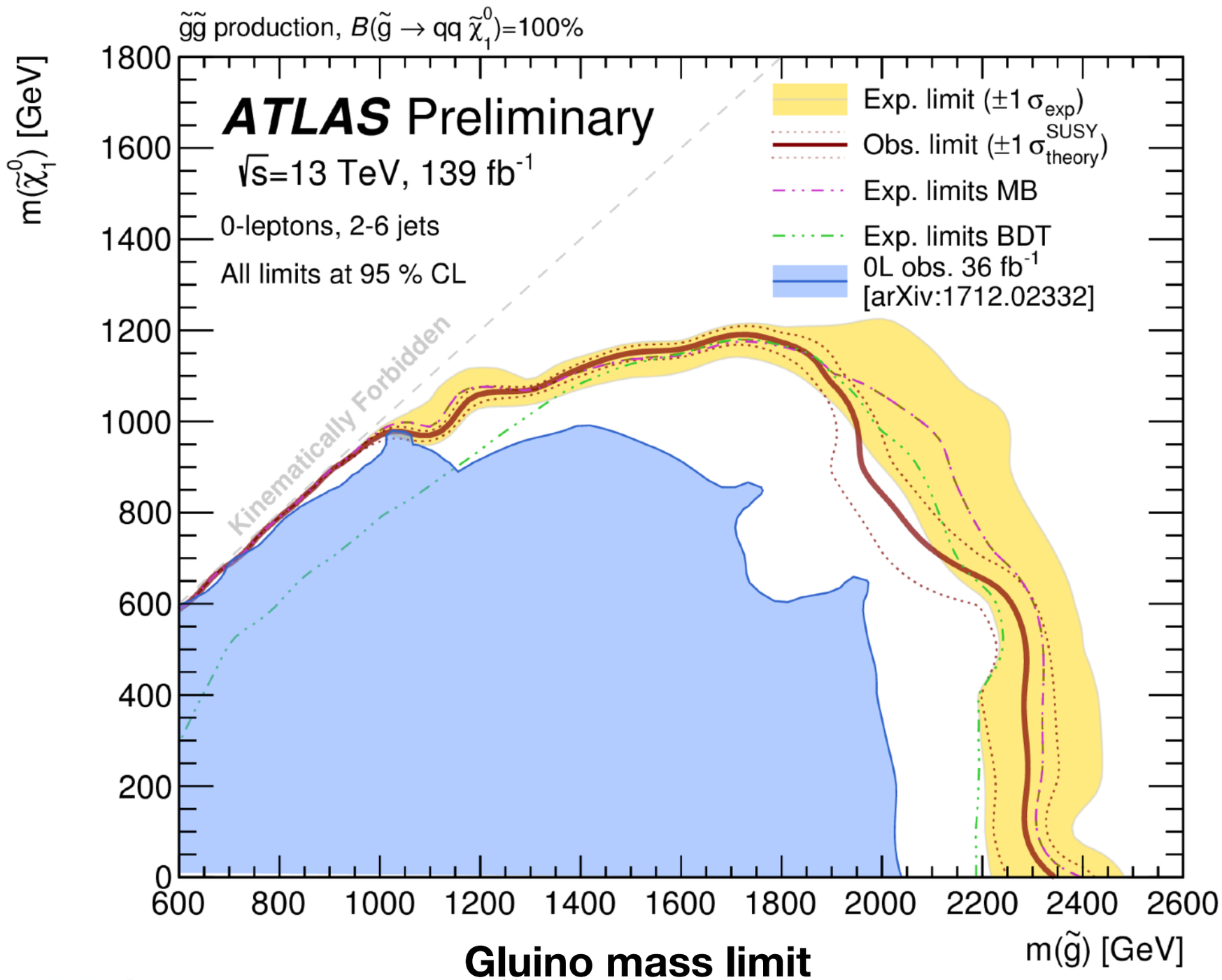
Bin bounds



An example SUSY limit plot

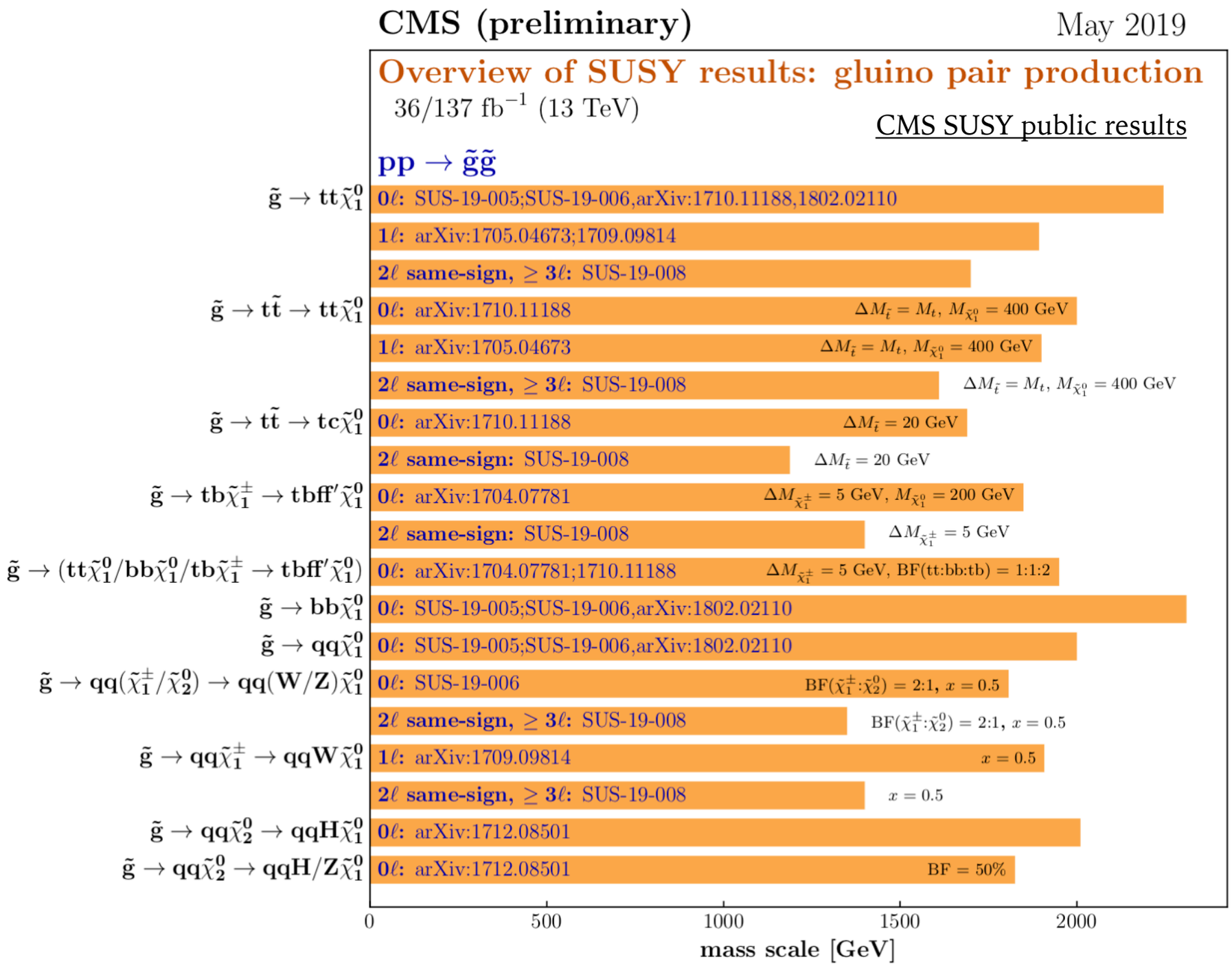
ATLAS-CONF-2019-040

Mass limit for lightest stable neutralino (LSP)



Gluino mass limit

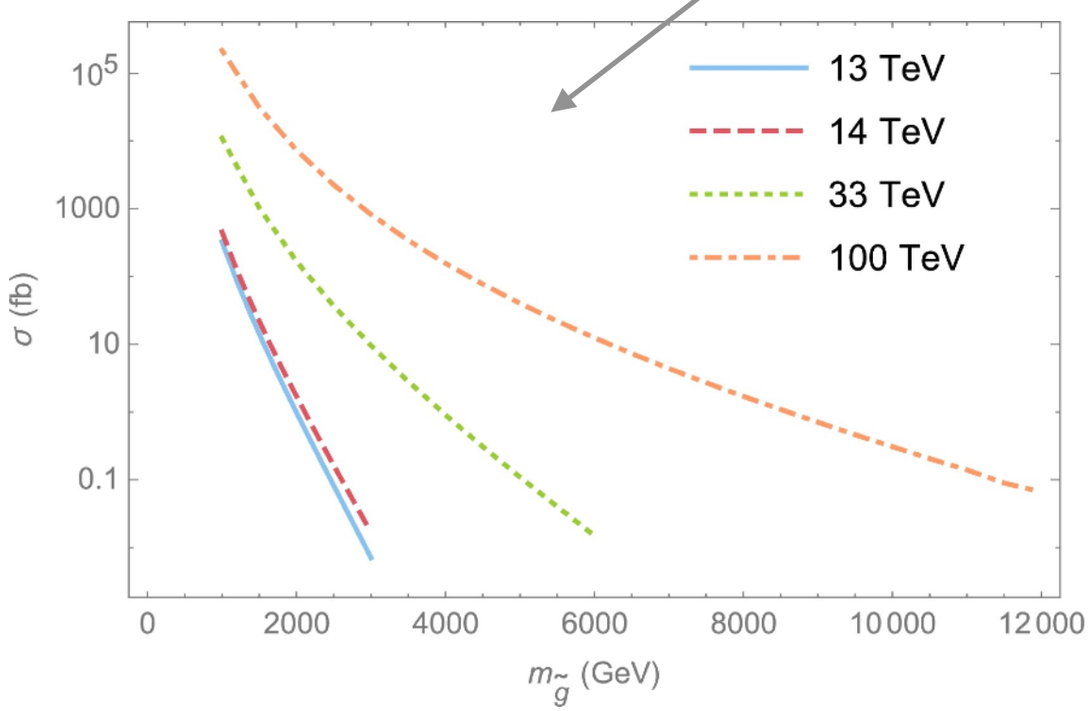
Strong SUSY limits (= the "problem" with natural SUSY)



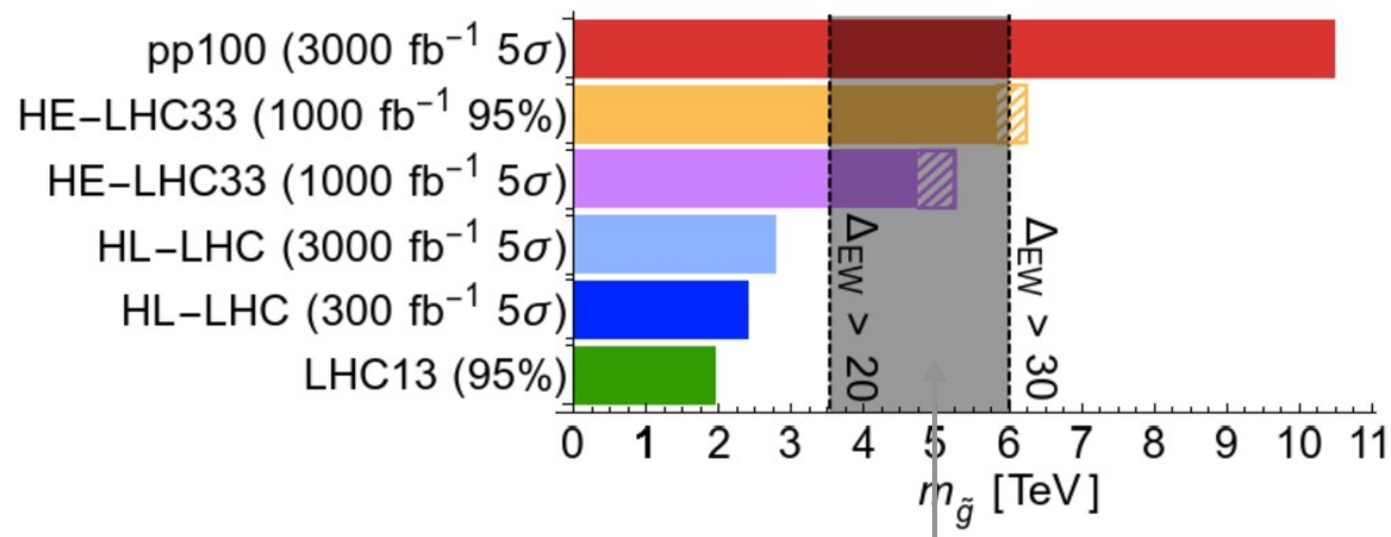
Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

Gluinos at future hadron colliders

Worth asking what will be the reach for gluinos at future hadron colliders (but the answer is intuitive)



https://arxiv.org/abs/1702.06588



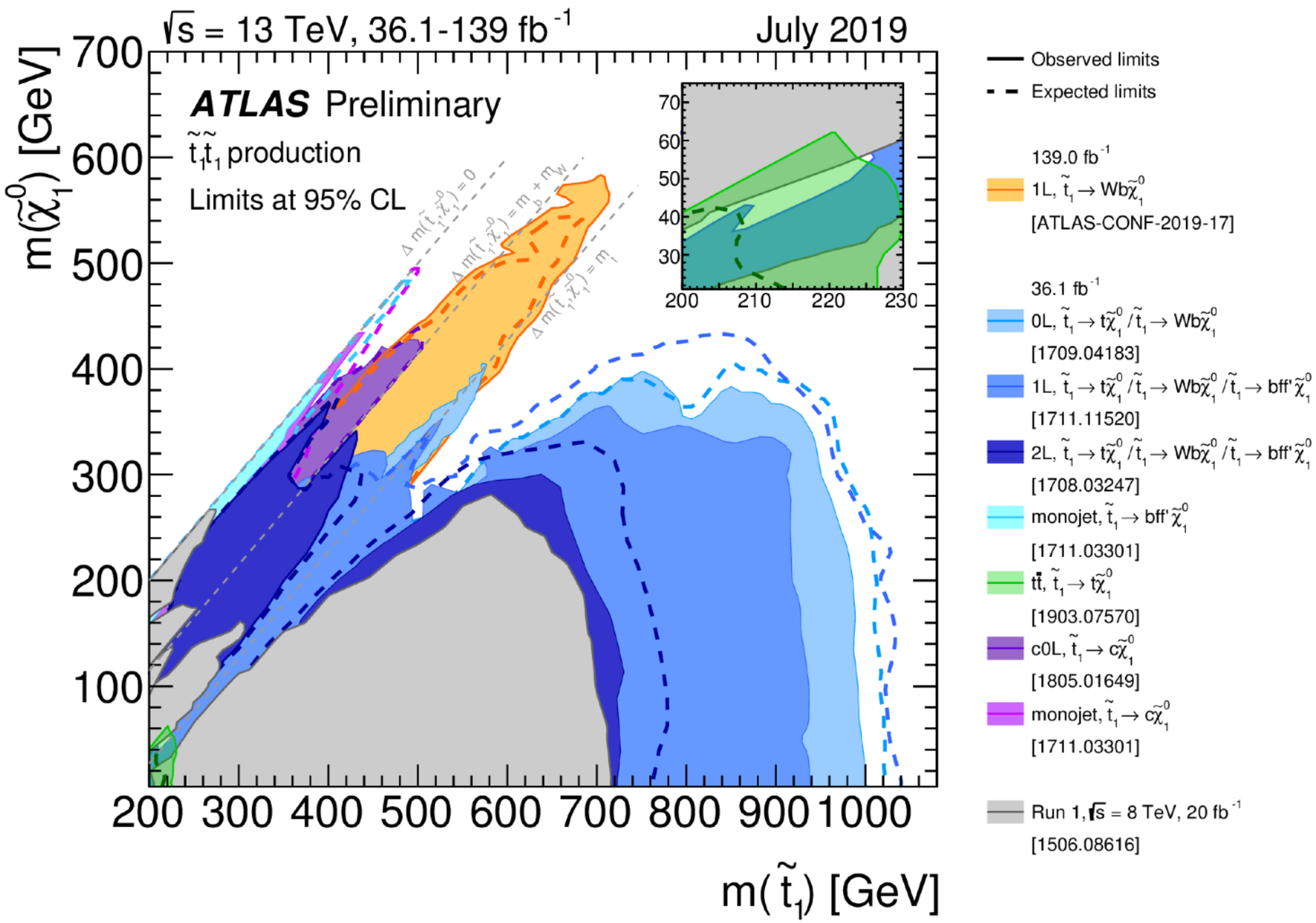
Measure of "naturalness"

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 .$$

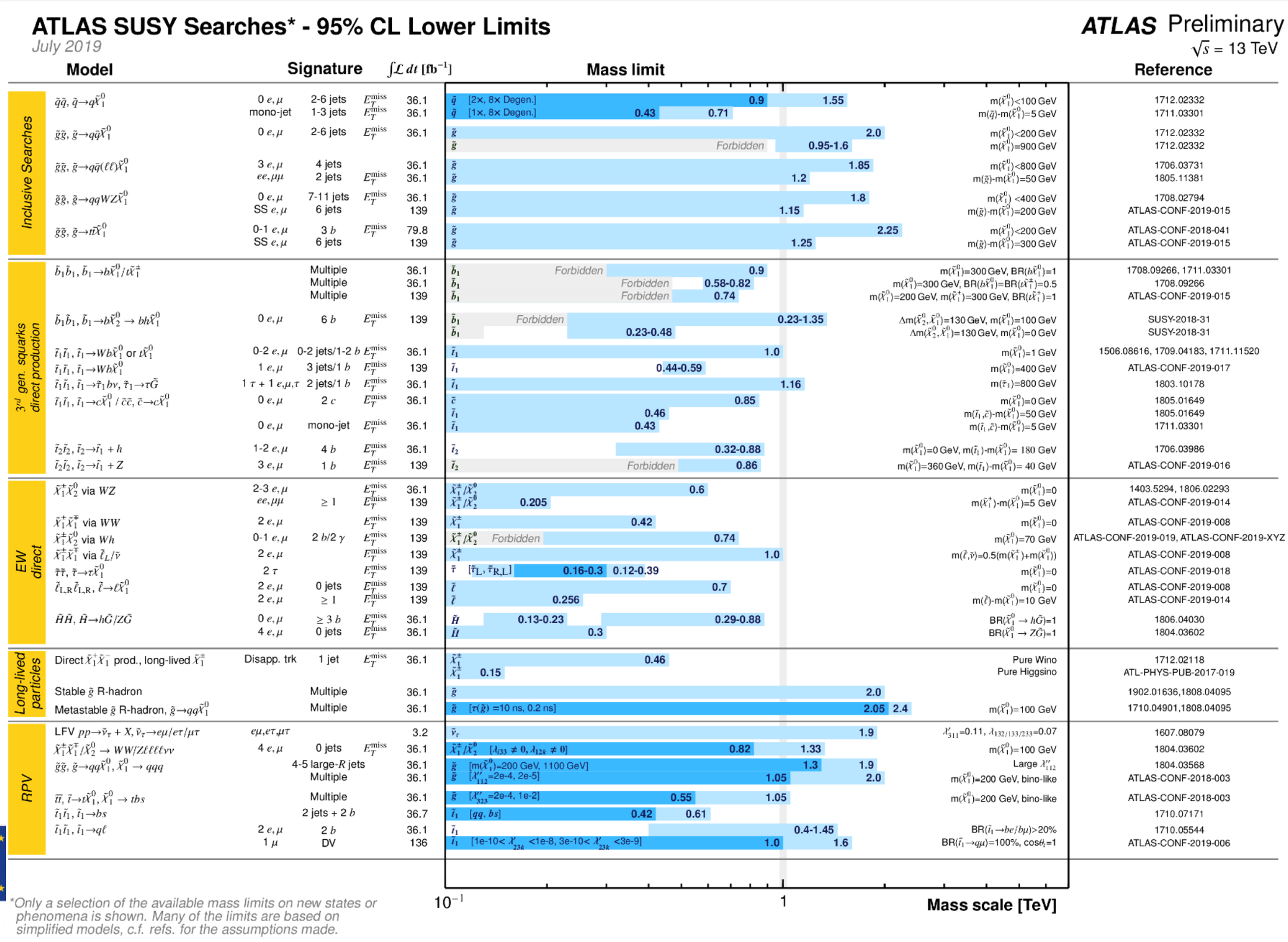
$$\Delta_{\rm EW} \equiv \max|\text{each term on RHS of Eq. (1)}|/(m_Z^2/2)$$

Limits on masses of 3rd generation SUSY partners

ATLAS SUSY public results

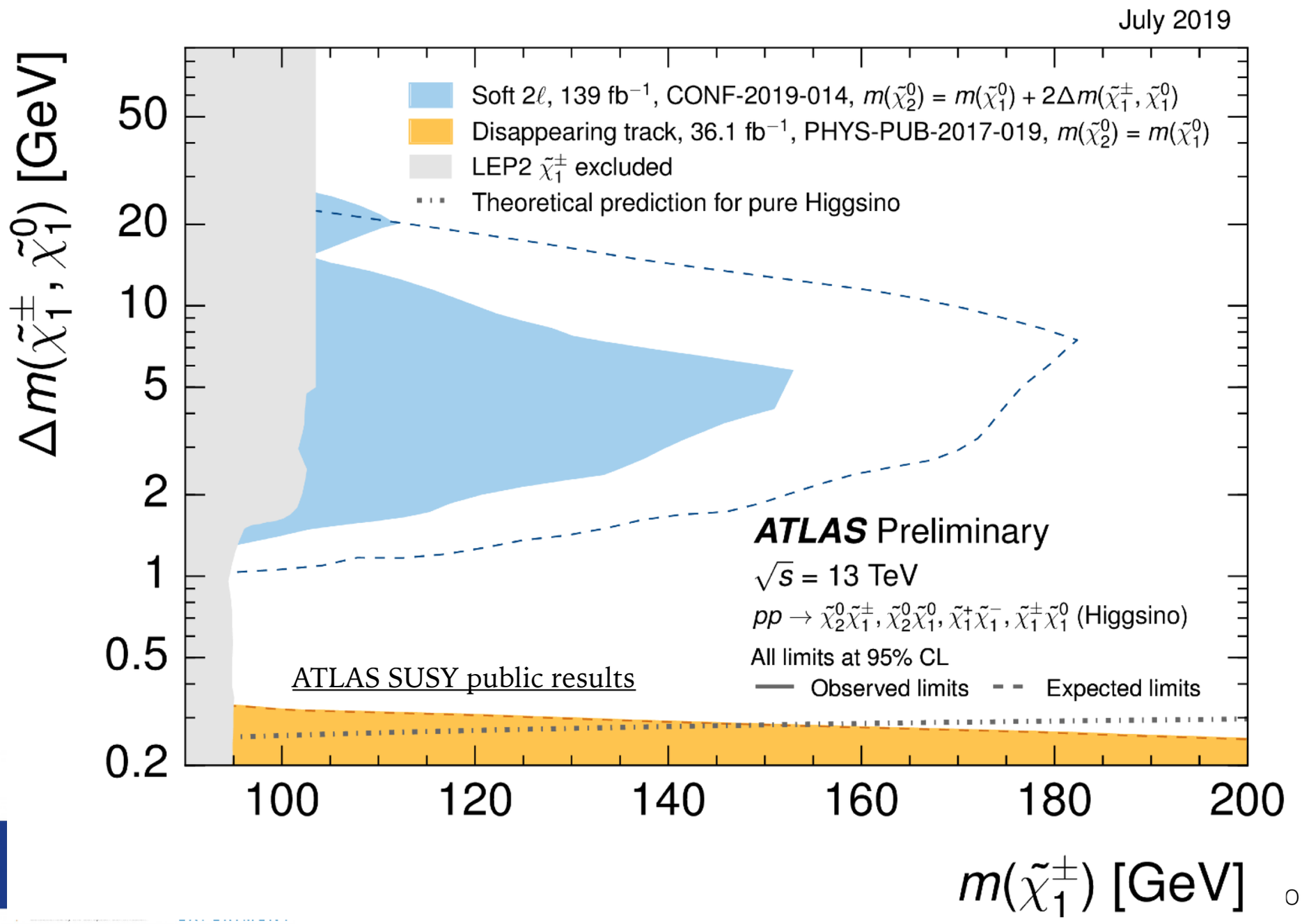


Limits on masses of 3rd generation SUSY partners



Are we done with SUSY? Not yet

Electroweak SUSY particles, especially those with **challenging signatures**, are not yet excluded in many **viable** SUSY models (e.g. those explaining dark matter)



Final word: the importance of reinterpretability

Given the many SUSY incarnations, very important to **allow theorists to reinterpret search results** in terms of different models

(see also discussion on simplified models in next section of lecture)

Available on the CMS information server **CMS NOTE-2017/001**

The Compact Muon Solenoid Experiment

CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

2017/11/07

https://cds.cern.ch/record/2242860

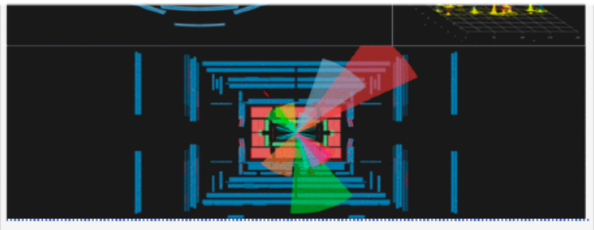
Simplified likelihood for the re-interpretation of public CMS results

The CMS Collaboration

Auxiliary material ATLAS SUSY public results

As part of ATLAS SUSY journal publications auxiliary material is made available in digital format via the HEPData project. This can be accessed via the "Documents" and then "Data points" links. The information in HEPData includes:

- the observed and expected exclusion contour lines,
- the observed upper limits on the signal model cross-section,
- the acceptance and the efficiency (encapsulating detector effects) numbers for selected signal models,
- detailed cut-flows for selected signal models (sometimes only in the "Auxiliary figures and tables" section of the public results webpage),
- with the corresponding SLHA files (new HEPData: click on "Resources"-"Common Resources"),
- [starting in 2017] code snippet with the implementation of the analysis selection at truth-level, as used to produce the acceptance numbers (new HEPData: click on "Resources"-"Common Resources").



Higgsino exclusion summary (Dec 2017). Stop exclusion summary (Dec 2017). High jet multiplicity event from SUSY-2016-13.

The acceptance is calculated using objects at truth-level following the definitions in ATL-PHYS-PUB-2015-013 with the following choices / minor modifications:

- using `undressed' leptons,
- jets: excluding muons and neutrinos,
- missing transverse momentum: include neutrinos from hadrons (e.g. from semi-leptonic b decays).

All experimental effects are absorbed in the so-called "efficiency", which is defined such that the product of acceptance and efficiency is the full selection efficiency calculated using reconstructed objects i.e. including all detector effects.

Take-home point #2:

SUSY: elegant solution to many SM problems, including dark matter

No signs of SUSY @ LHC yet (but not all parameter space yet excluded):
worth considering SUSY models that are harder to find, or models that solve only a few problems at a time

https://arxiv.org/pdf/1512.06819.pdf

Empirical problems of the SM

- **Dark matter (DM)**
- Dark energy
- Matter vs antimatter
- Weakness of gravity
- Neutrino masses

Dark Matter, what do we know about it?

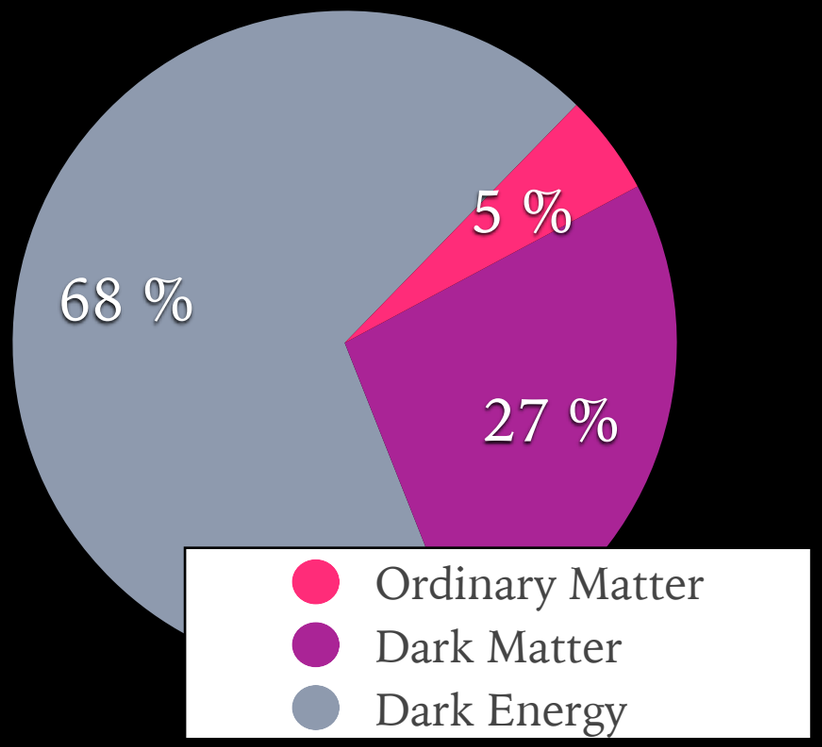
it is dark

it is dark

it has mass

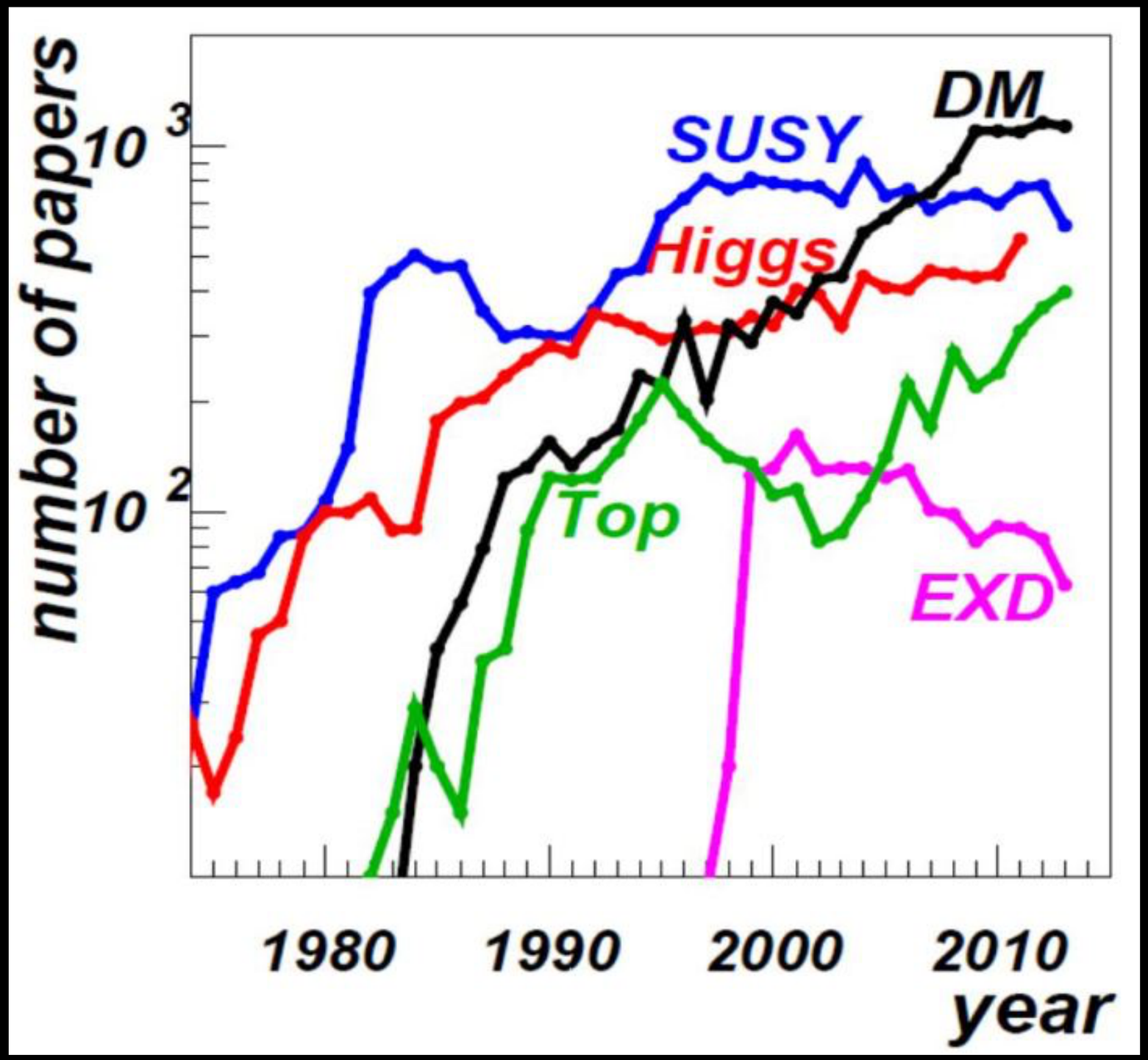
it is dark

it has mass

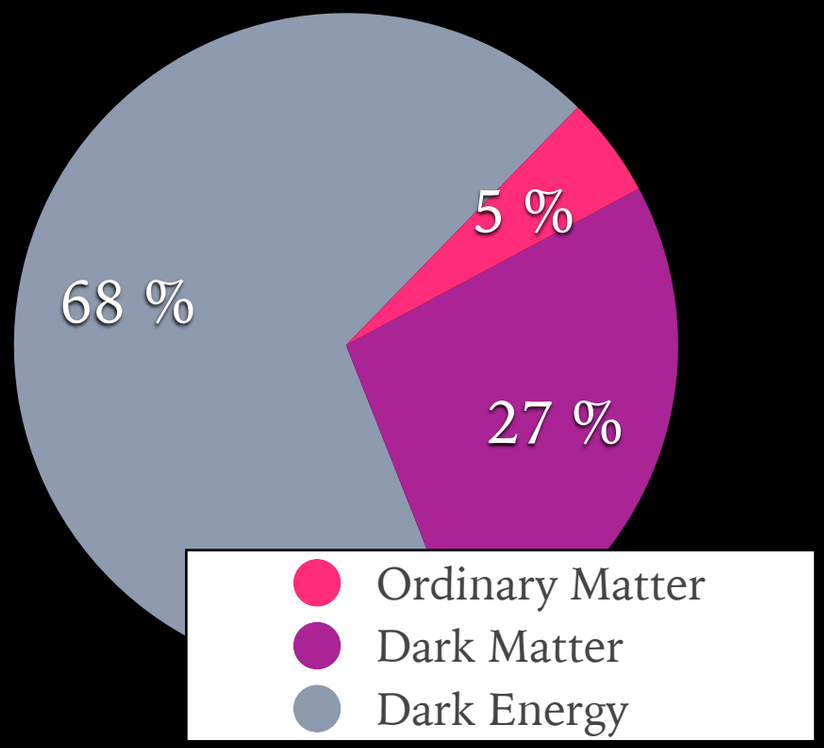


it constitutes
most of the matter
in the universe

many physicists are talking about it



A. Belyaev



it constitutes
most of the matter
in the universe

↓

relic density

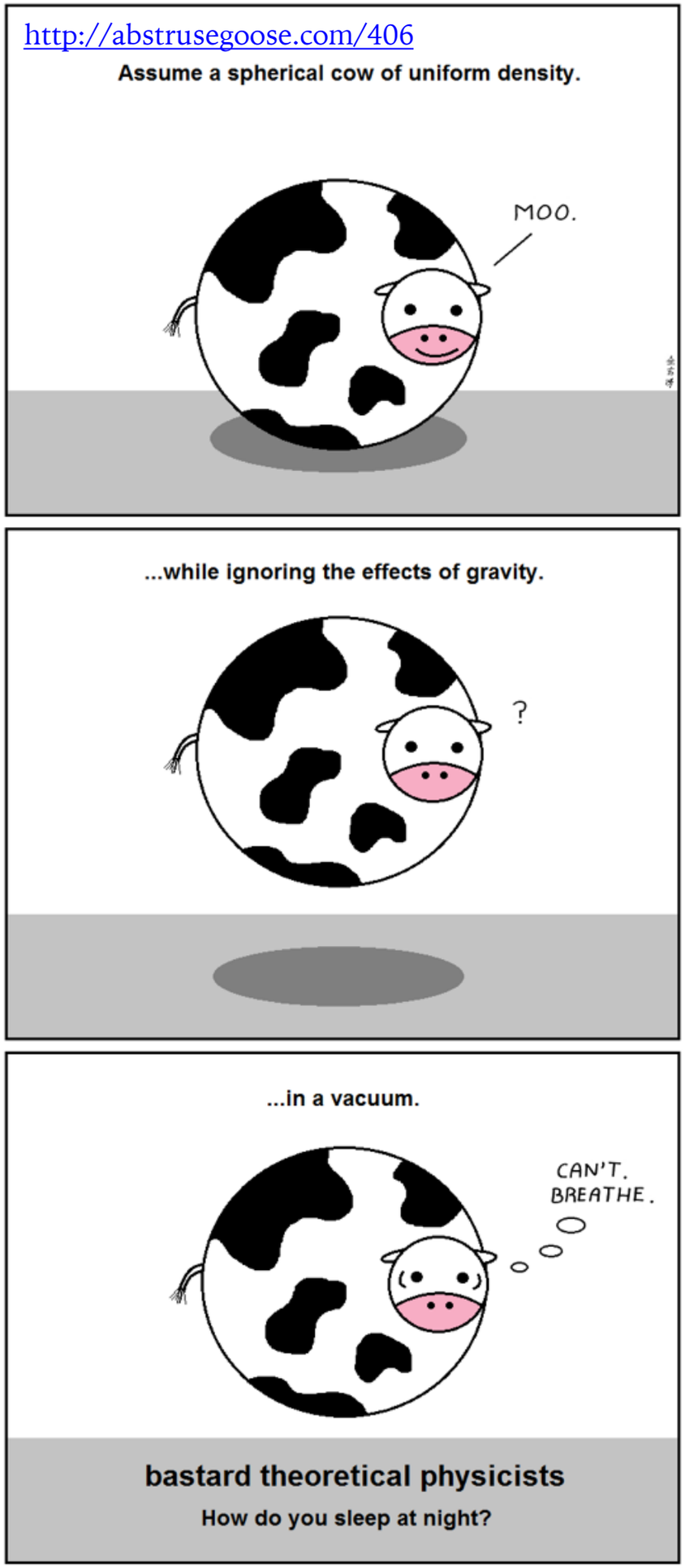
many caveats and options on how to get it:
see J. Harz's talk

This relic density can be explained with

a new particle

- that interacts only weakly with known matter
- with mass in the range of current experiments (WIMP)

Under these assumptions…



...we could discover Dark Matter in the next decade!

Unless…

(this is here just to avoid constantly singling out theorists in jokes)

Take-home point #3:

we don't know very much about DM beyond its gravitational interactions and astrophysics abundance

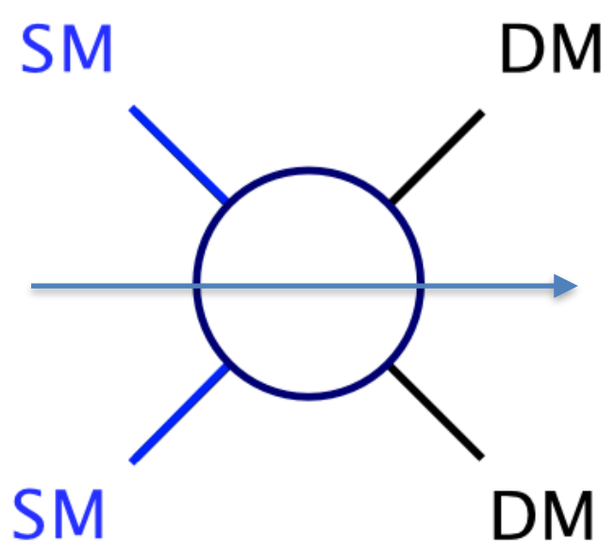
any ~~LHC~~ search will necessarily contain some hypotheses (e.g. about interactions/model) so that DM can be observed experimentally

Motivation for DM@colliders

How do we search for DM at colliders, depending on its properties?

- Generally assume some properties for the DM particle, our assumptions:
  - interacts with SM particles → we can **produce it at colliders**

known particle collision



production of DM particles

Caveat: very simplified diagram

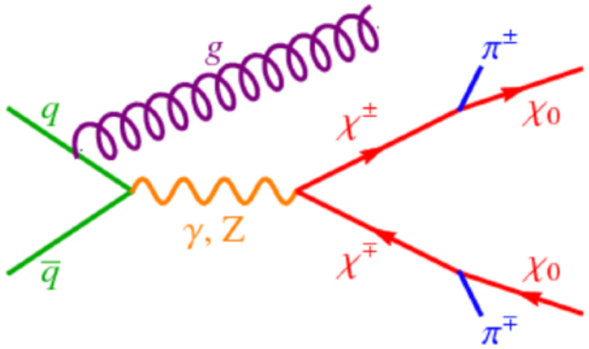
- [a matter of preference] is a thermal relic → **WIMP**
- dark, stable → **invisible to detectors**

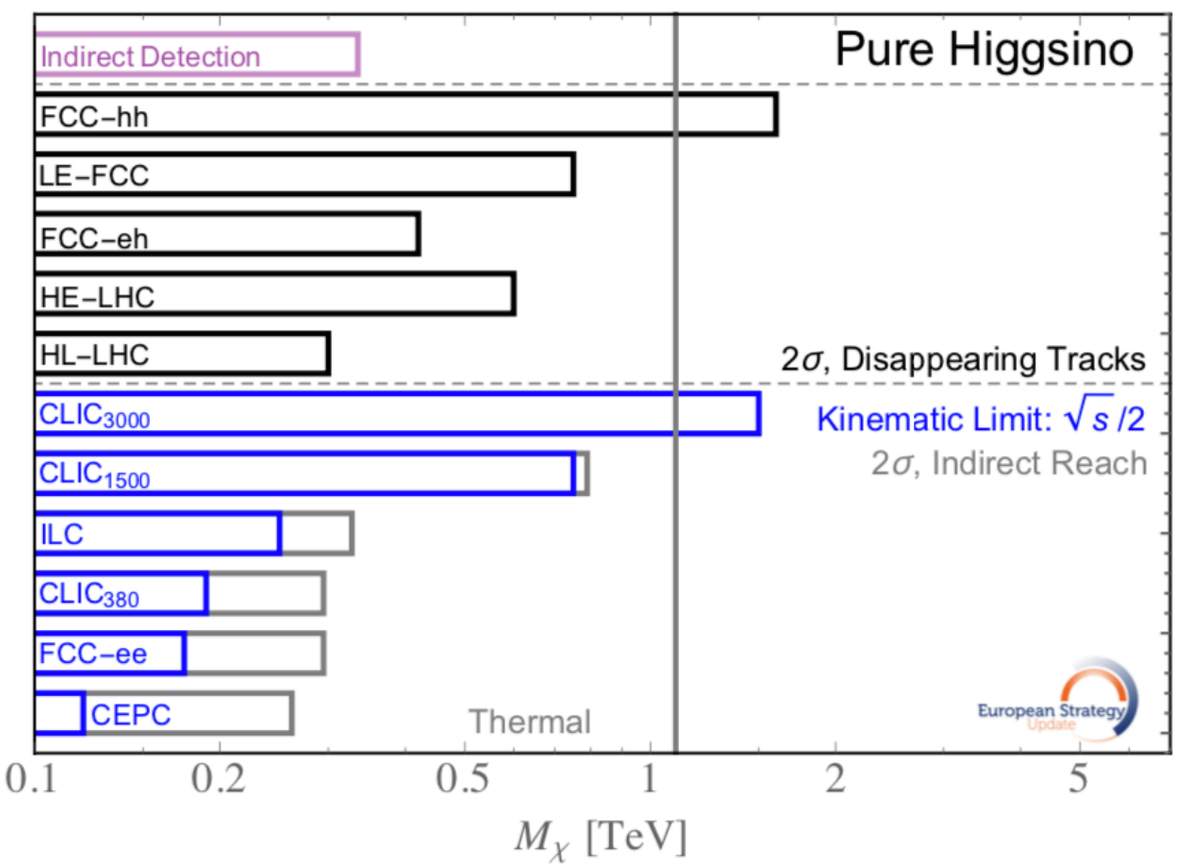
a **SUSY LSP** is a good candidate!

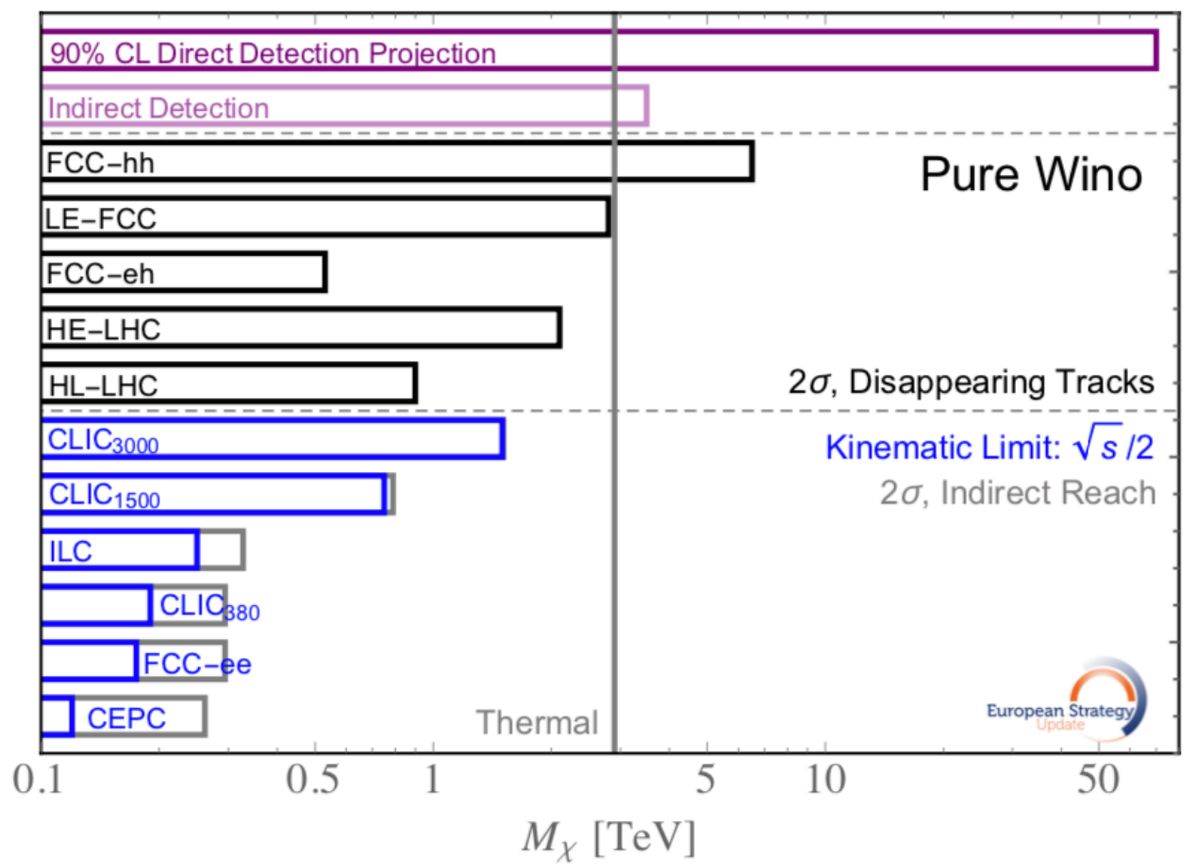
An example of SUSY as DM @ future colliders

arXiv:1802.04097, arXiv:0706.4071, arXiv:1705.04843

- Viable thermal relic WIMP candidate in SUSY terms: lightest neutralino - pure Wino/Higgsino
  - Also standalone model of "minimal DM"



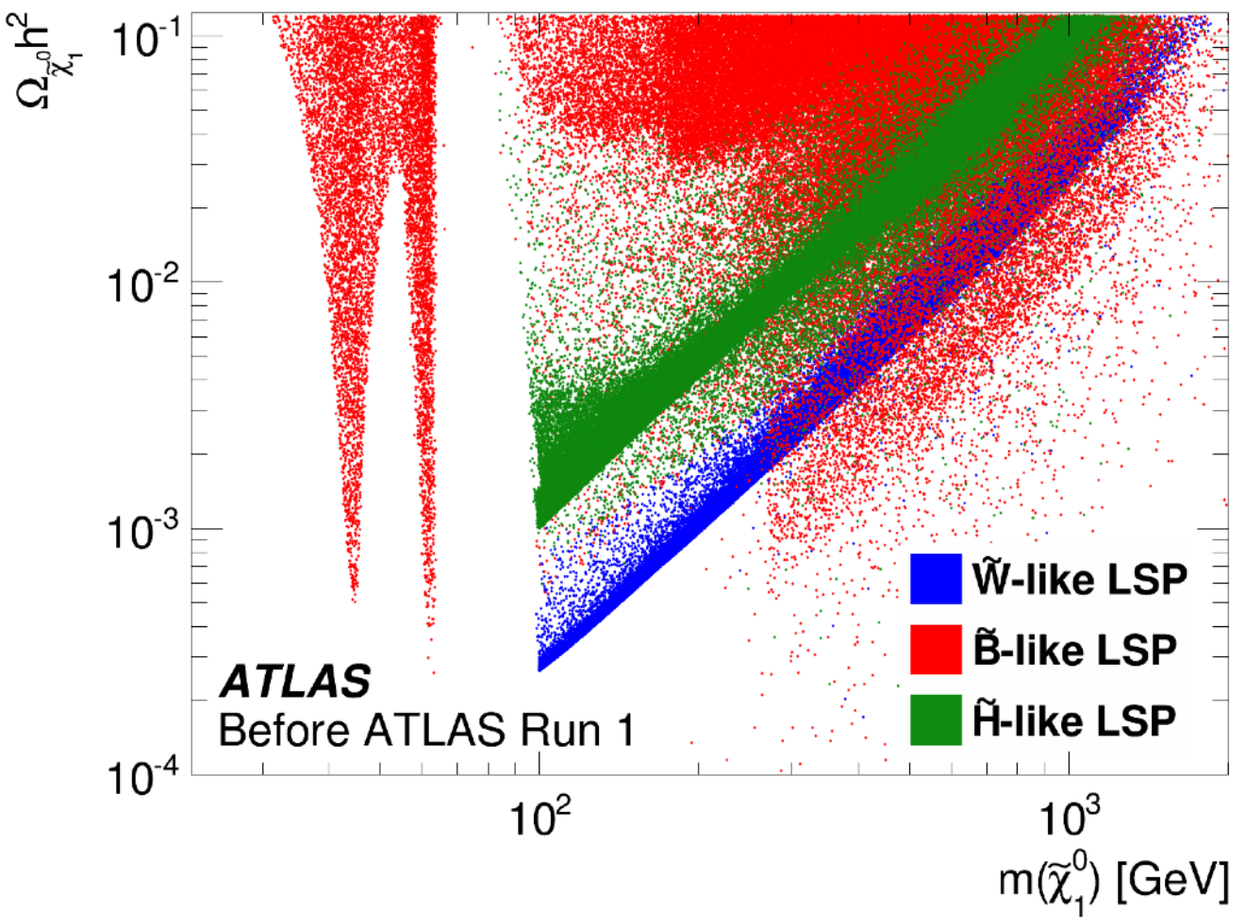


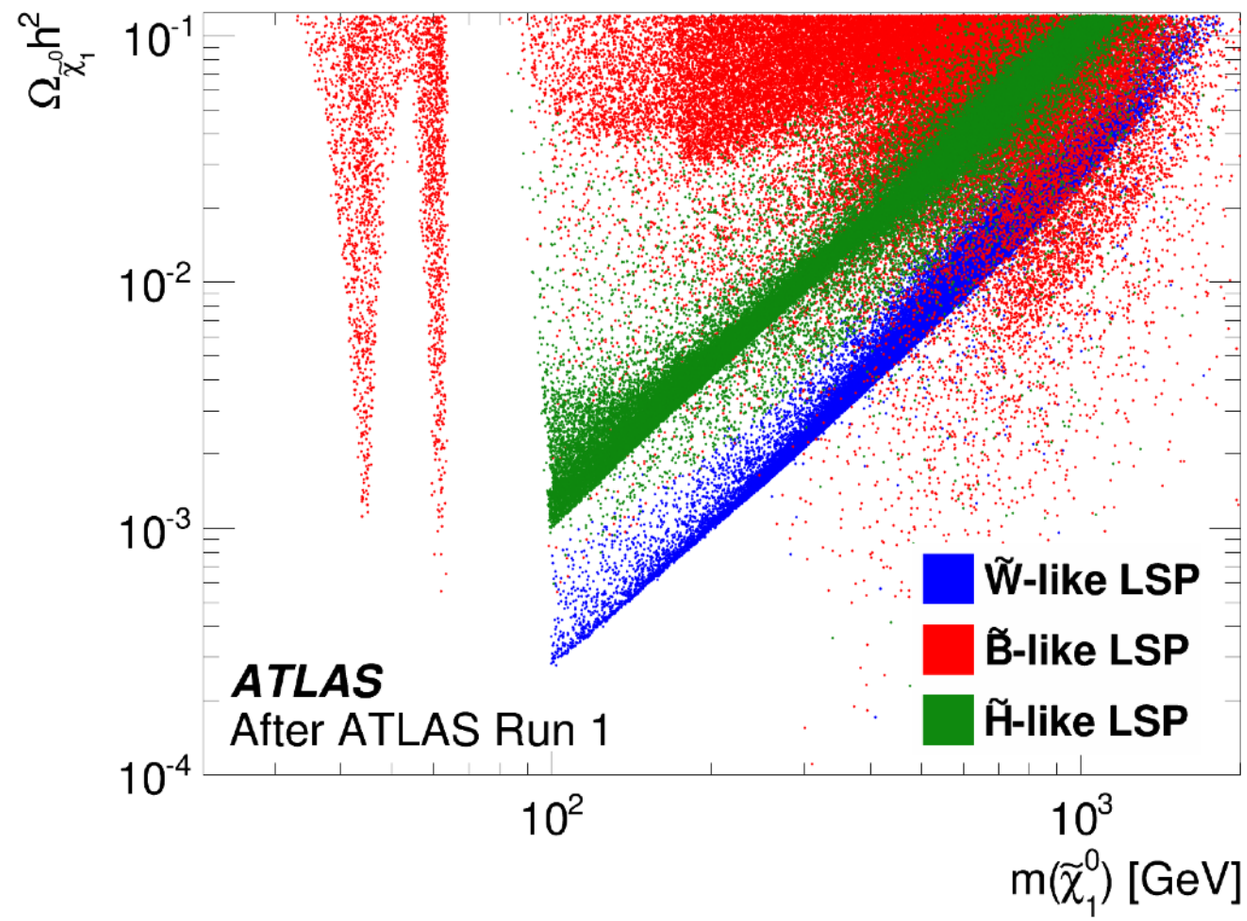


Plots by M. McCullough (more theory in his lectures/discussion)

Another SUSY example in DM context: pMSSM scan

Start from parameter scan of a SUSY model, point corresponds to set of choices
Plot on a plane including the DM relic density, use searches to constrain
Points on very top of the plot (= observed relic): LSP makes up 100% of the DM
Points below: another kind of DM needed to complement this one





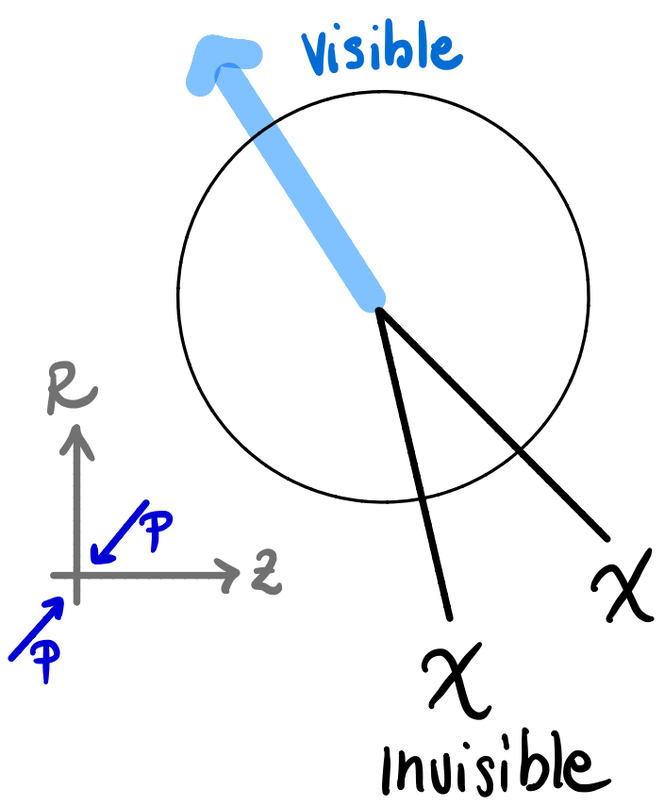
Searches for ~~DM~~ invisible particles at colliders

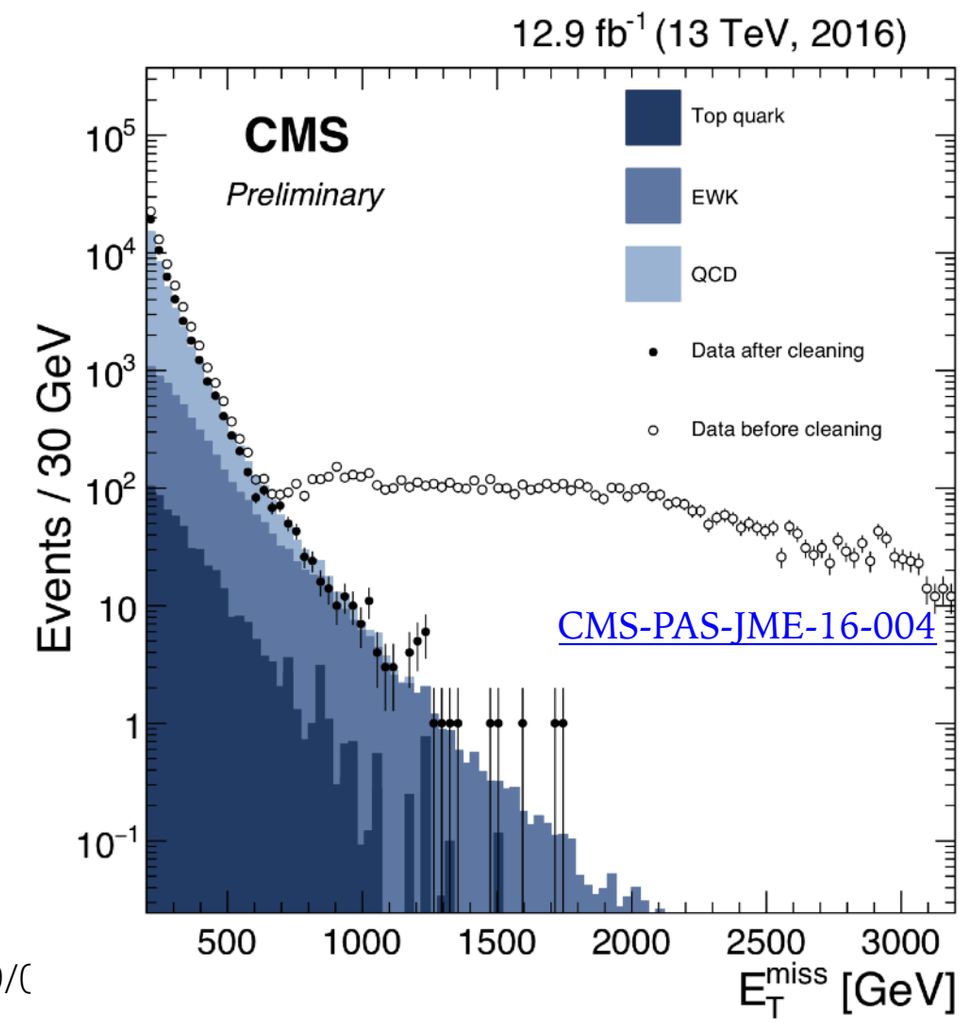
- Switch to non-SUSY searches && switch terminology from DM to invisible particle
  - if we discover a new particle, we don't know how stable it is (also in SUSY) (it could decay outside the detector)

Good performance of missing transverse momentum crucial for DM searches e.g. reject fake E_T^{miss}

Signature of invisible particles (like Dark Matter):

missing transverse momentum (E_T^{miss})





What visible to detect the invisible?

Standard Model Particles interact with *Dark Matter*

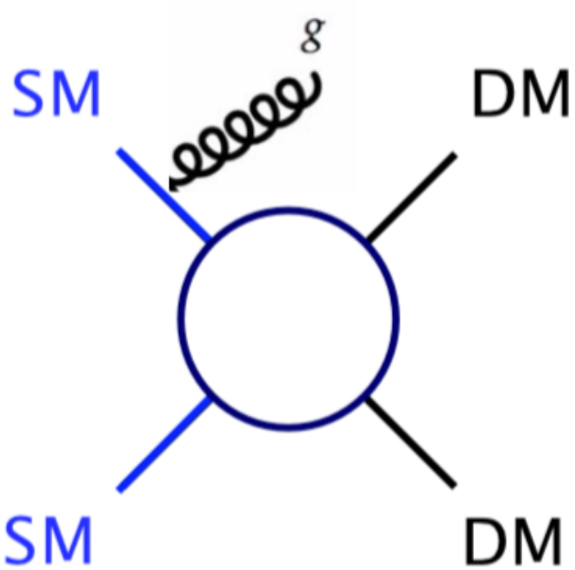
insert known particle(s) here

insert new particle(s) here

in signatures including

insert ISR/FSR boson, or additional particles

"monojet"



"mono-everything-mania"

also: a nomenclature problem for searches

(think of e.g. QCD corrections to simple picture,

other more complex diagrams...)

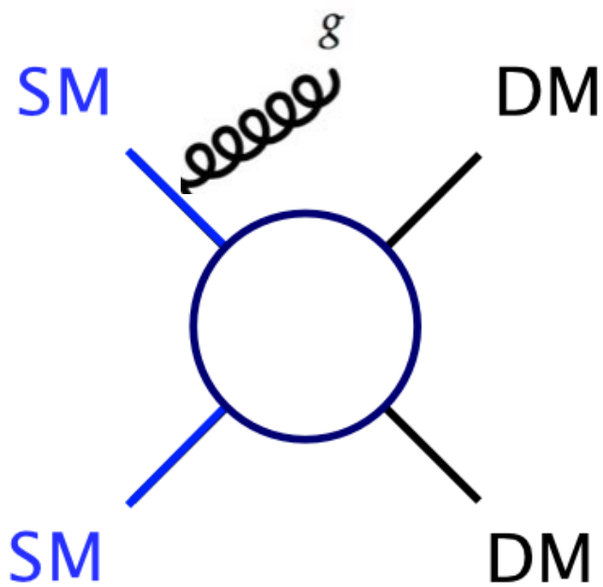
better name: **Missing transverse momentum + X**

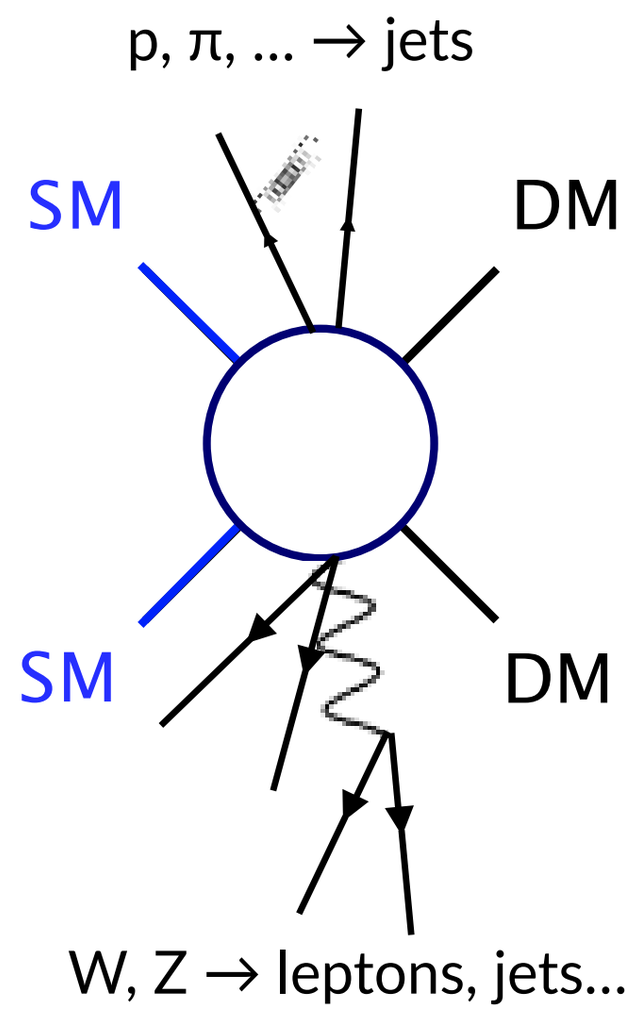
Broad categories of searches for DM@colliders

Generic searches → More specific searches

- Good for **simple models** with **sizable cross-sections**
- **Fewer assumptions** on specific model characteristics

- More sensitive to **specific models**
- More reliant on **model assumptions**





→ the way we think of benchmark models **influences searches**

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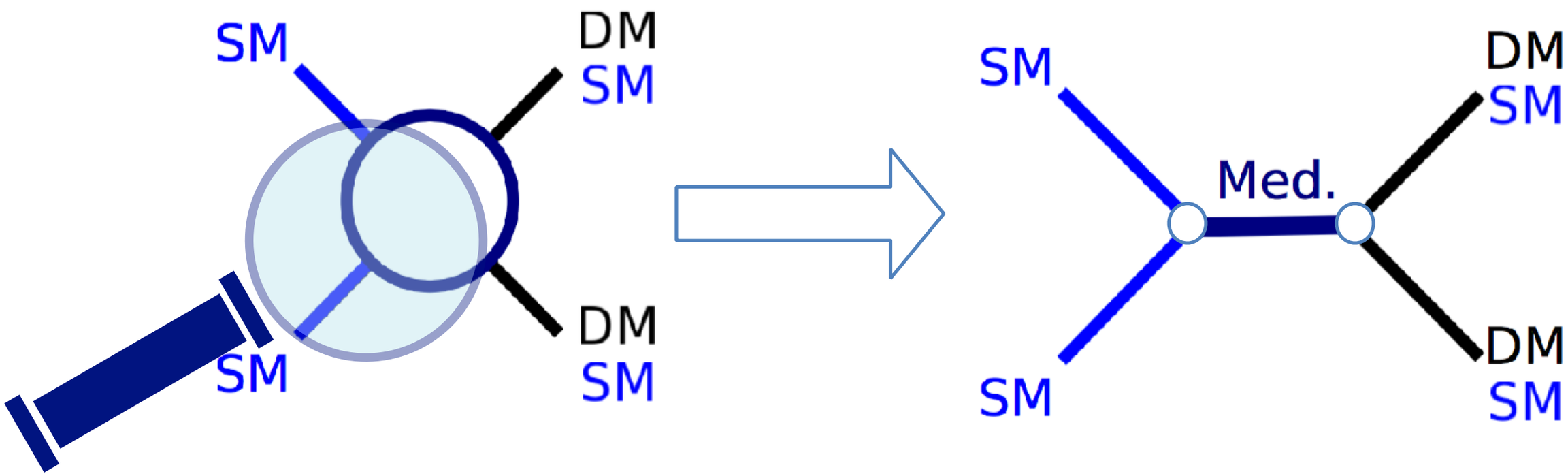
Dark Matter mediators at the LHC

If there's a force there's a mediator, and the LHC can see it: simplified models became Run-2 LHC search benchmarks



Consequences for colliders:

1. Can **probe the dark interaction** even if DM is inaccessible
2. Can look for both **invisible and visible decays** of the mediator

(cf lecture about direct searches for new particles)

Some side thoughts on EFT

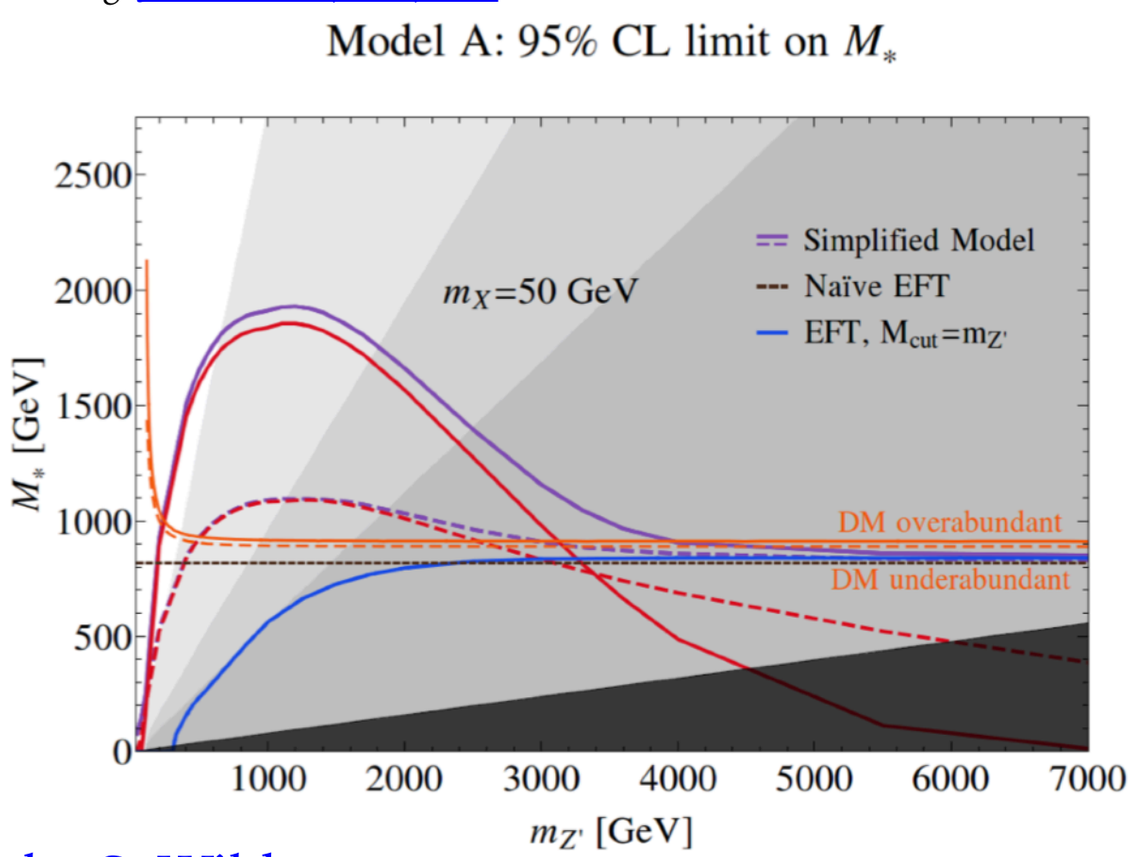
"EFTs are not evil, they just (model-)build them that way"

EFTs are very versatile (and necessary, when there's no alternative)

EFTs are viable benchmarks that motivate new signatures

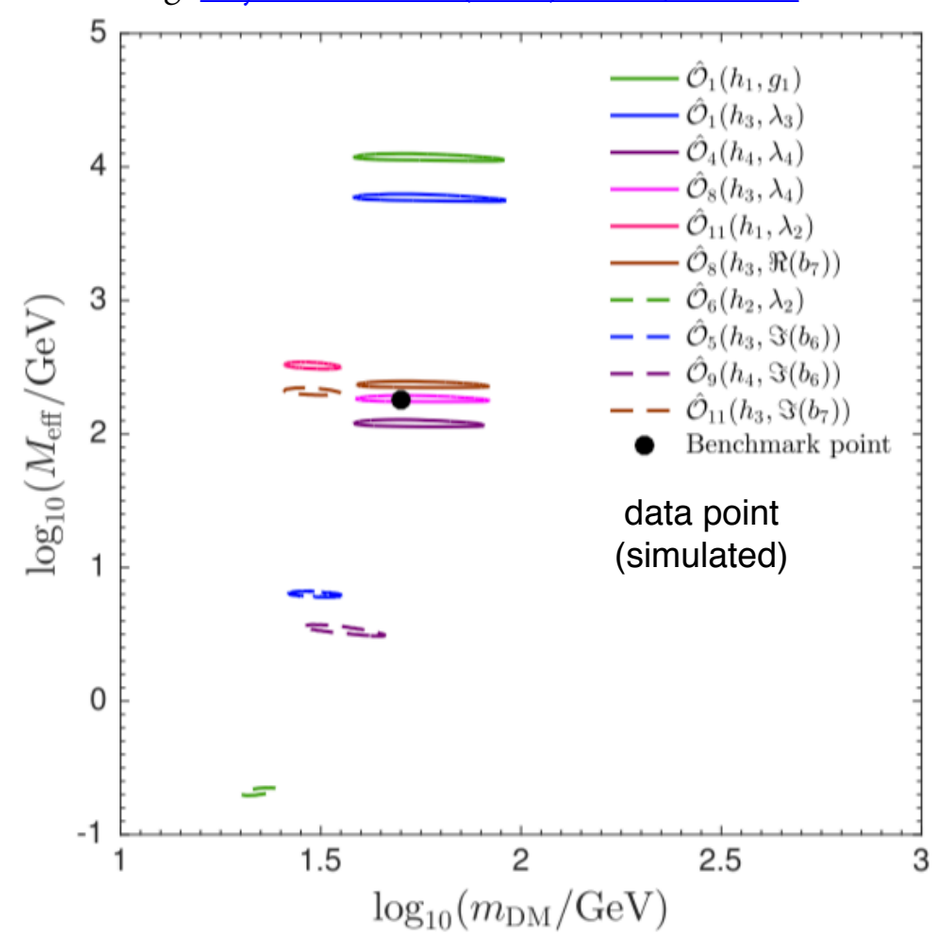
The "problematic parts" of EFTs can be removed

e.g. JHEP 1505 (2015) 009



Non-relativistic EFTs are a useful tool to break down signals and understanding their compatibility of future signals with models and compare LHC/DD

e.g. Phys. Rev. D 97 (2018) no.10, 103002



list of possible operators (simulated)

data point (simulated)

Talk by S. Wild

Cornell University Library

We gratefully acknowledge s
the Simons
and Lund Univers

arXiv.org > hep-ex > arXiv:1507.00966
https://arxiv.org/abs/1507.00966

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High Energy Physics – Experiment

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, Barbara Alvarez Gonzalez, Jeremy Andrea, Alexandre Arbey, Georges Azuelos, Patrizia Azzi, Mihailo Backović, Yang Bai, Swagato Banerjee, James Beacham, Alexander Belyaev, Antonio Boveia, Amelia Jean Brennan, Oliver Buchmueller, Matthew R. Buckley, Giorgio Busoni, Michael Buttignol, Giacomo Cacciapaglia, Regina Caputo, Linda Carpenter, Nuno Filipe Castro, Guillelmo Gomez Ceballos, Yangyang Cheng, John Paul Chou, Arely Cortes Gonzalez, Chris Cowden, Francesco D'Eramo, Annapaola De Cosa, Michele De Gruttola, Albert De Roeck, Andrea De Simone, Aldo Deandrea, Zeynep Demiragli, Anthony DiFranzo, Caterina Doglioni, Tristan du Pree, Robin Erbacher, Johannes Erdmann, Cora Fischer, Henning Flaecher, Patrick J. Fox, et al. (94 additional authors not shown)

(Submitted on 3 Jul 2015)

This document is the final report of the ATLAS-CMS Dark Matter Forum, a forum organized by the ATLAS and CMS collaborations with the participation of experts on theories of Dark Matter, to select a minimal basis set of dark matter simplified models that should support the design of the early LHC Run-2 searches. A prioritized, compact set of benchmark models is proposed, accompanied by studies of the parameter space of these models and a repository of generator implementations. This report also addresses how to apply the Effective Field Theory formalism for collider searches and present the results of such interpretations.

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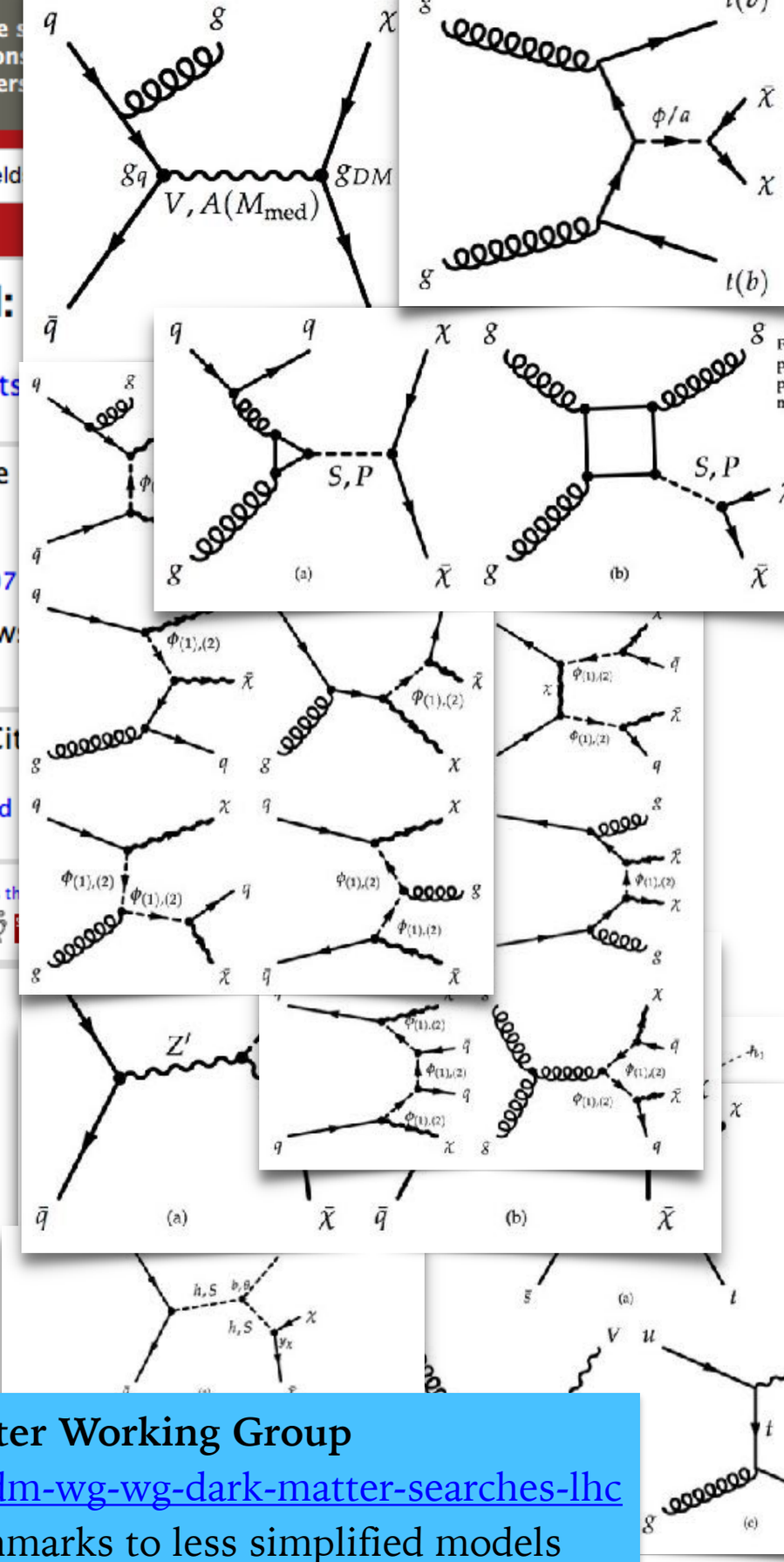
Cite as: **arXiv:1507.00966 [hep-ex]**
(or **arXiv:1507.00966v1 [hep-ex]** for this version)

Submission history

From: Antonio Boveia [view email]
[v1] Fri, 3 Jul 2015 16:54:32 GMT (3860kb,D)

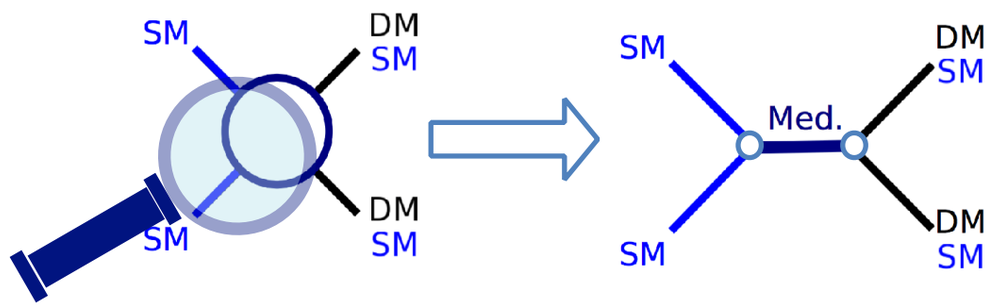


Now: **LHC Dark Matter Working Group**
http://lpcc.web.cern.ch/content/lhc-dm-wg-wg-dark-matter-searches-lhc
extending the menu of LHC benchmarks to less simplified models

Common benchmarks for collider WIMP searches

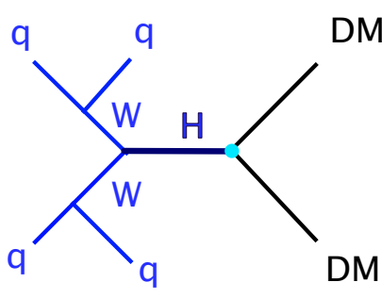
Simple models ⟷ More complex/complete models

Simple DM mediation



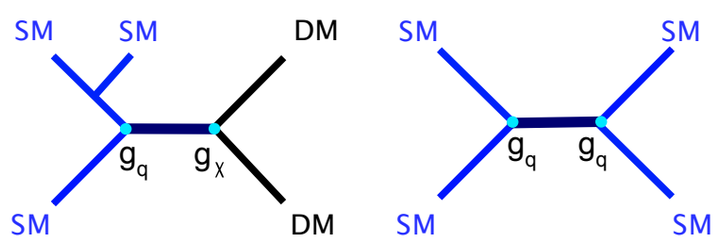
SM mediator

- **Z/Higgs** portals

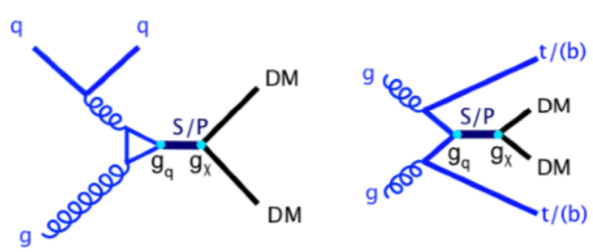


Beyond-SM mediator

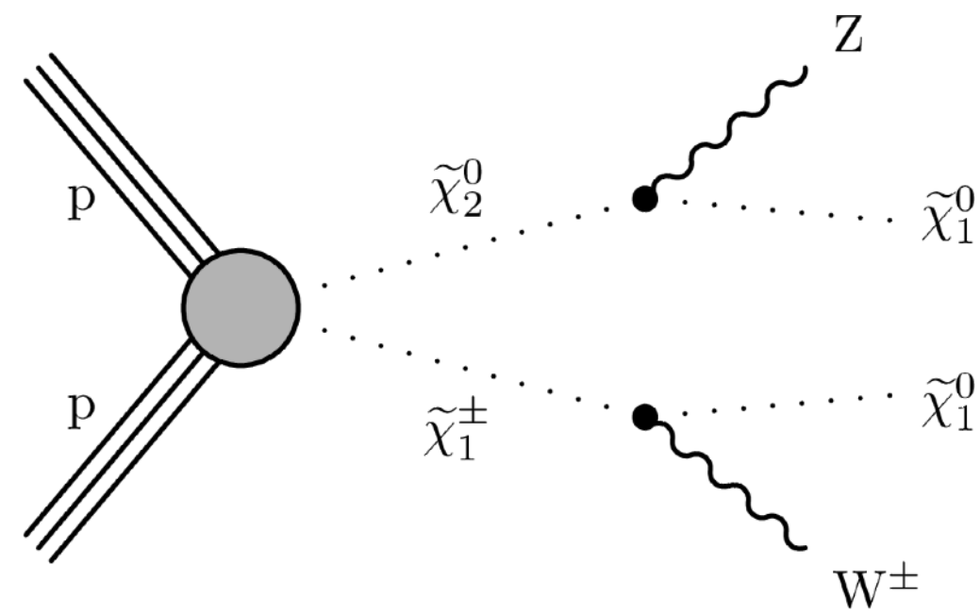
- **Vector-like** mediator



- **Scalar-like** mediator and Two Higgs Doublet Models



Supersymmetry



(*Simplified model* diagram)

JHEP 03 (2018) 160

Also: DM models with long-lived particles [tomorrow's lecture]

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Choice of benchmarks

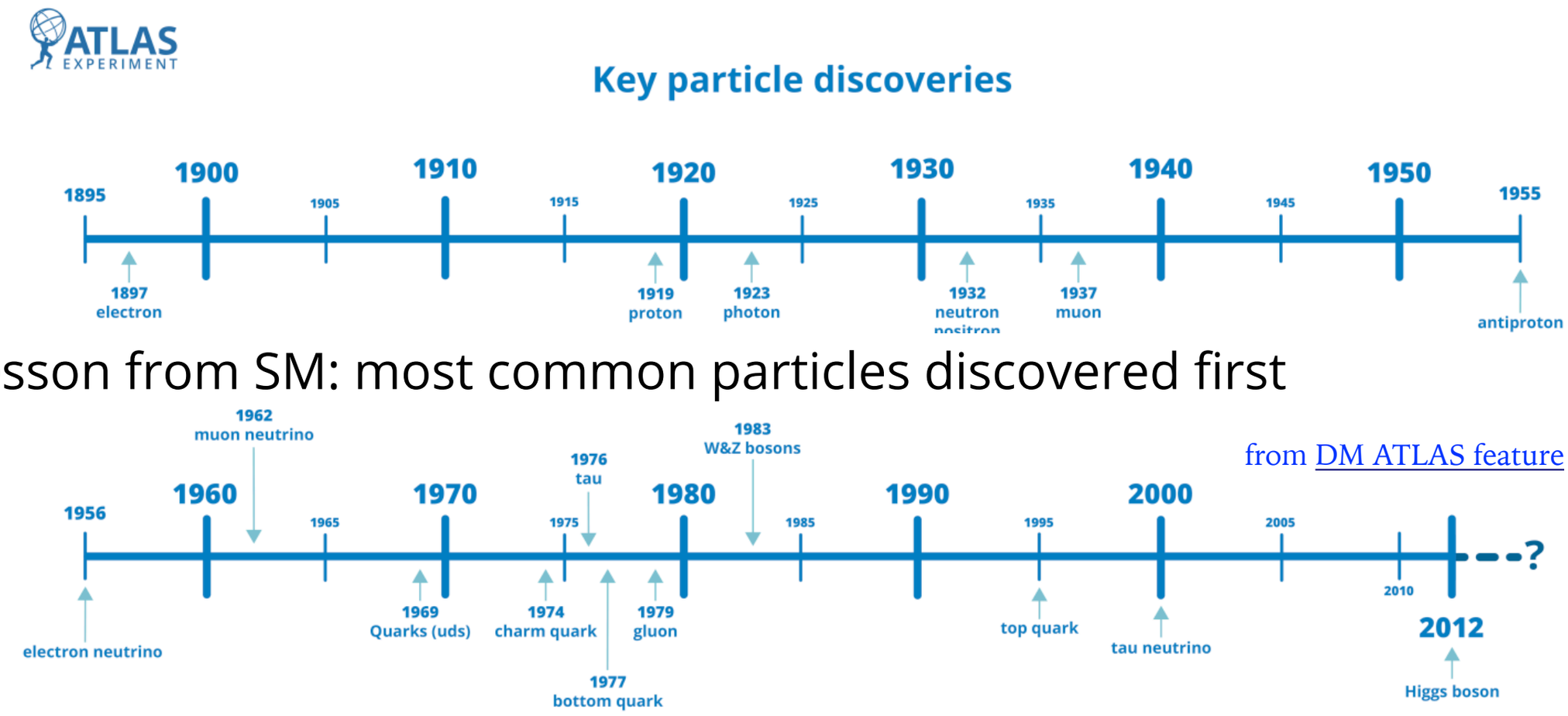
Why bother? Because:

https://abstrusegoose.com/406

"Why should we believe such simple models?"

"Do we think DM is all made of a single WIMP model?"

(not necessarily)



from DM ATLAS feature

- Lesson from SM: most common particles discovered first
- Simplified models can encapsulate relevant experimental characteristics representing wider classes of theories

Start simple: Higgs portal models

arXiv:1903.03616

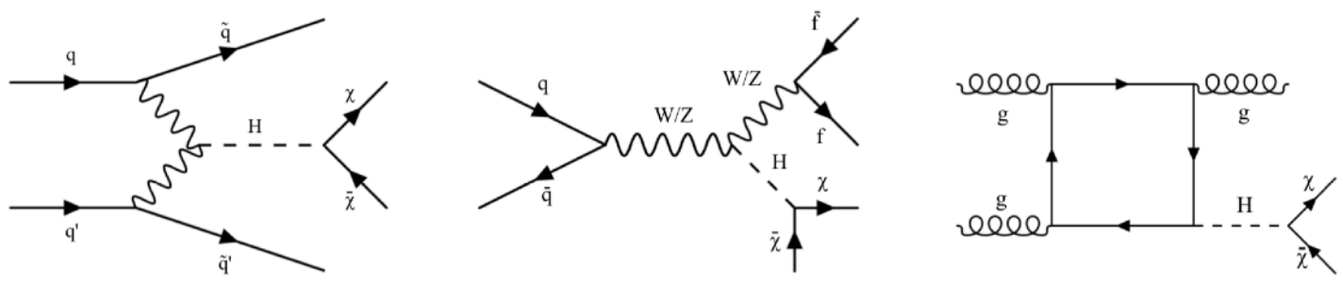
$$\Delta\mathcal{L}_\chi = -\frac{1}{2}M_\chi\bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{H\chi\chi}}{\Lambda}\Phi^\dagger\Phi\bar{\chi}\chi\,.$$

$$\Delta\mathcal{L}_S = -\frac{1}{2}M_S^2S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HSS}\Phi^\dagger\Phi S^2\,,$$

Lambda for fermion EFT: assumed 1 TeV

- Only add the DM particle to SM
- Test different kinds of dark matter
  - Majorana fermion/scalar
  - Vector not there for historical reasons

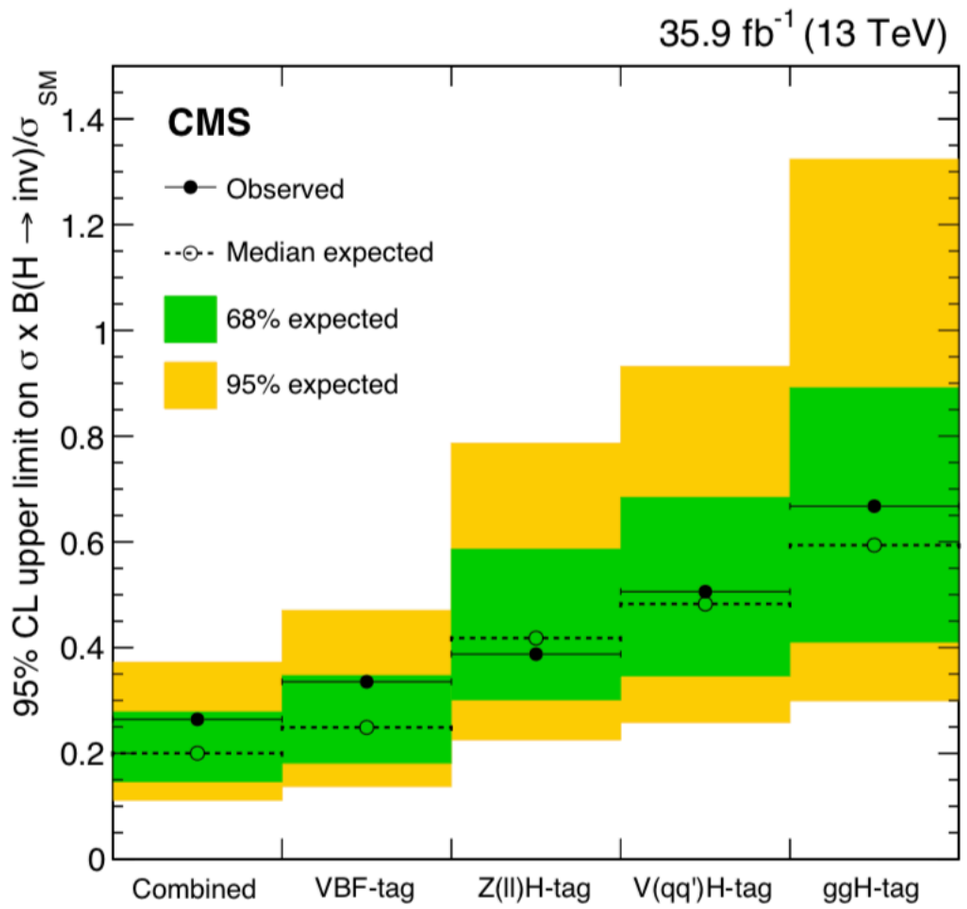
- How to detect invisibly decaying Higgs:
  - **directly** (MET searches)

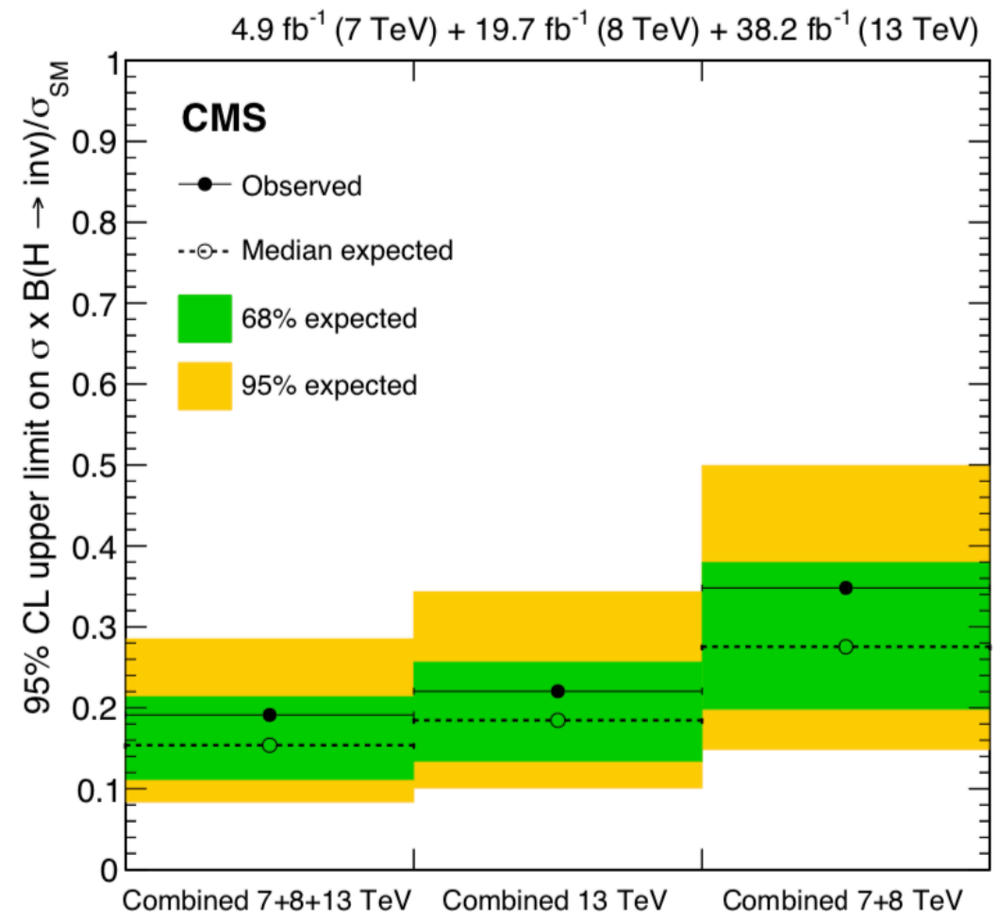


  - **indirectly** (deviation of SM coupling through fits, using κ-framework)
    - including only σ x Branching Ratio (BR) measurements/ratios, no high-pT Higgs keeping SM BR fixed, only allow invisible BR to float in the fit (subtracting SM)

Higgs portal DM results with partial Run-2 data

https://arxiv.org/abs/1809.05937





LHC sensitive to a Higgs to invisible BR of ~0.2

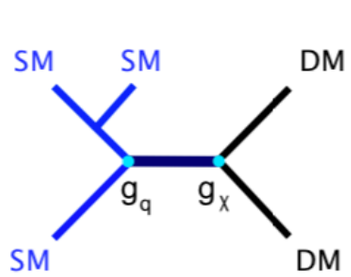
(SM value: invisible BR ~ 10^{-3}, reachable by future colliders)

Add a BSM mediator: s-channel vector/scalar models

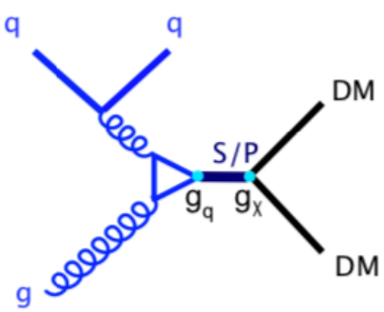
arXiv:1708.02245 & references Ann.Rev.Nucl.Part.Sci. 68 (2018) 429-459

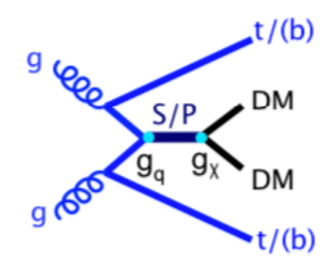
Map possible types of s-channel mediator exchanges between DM and SM: vector, axial-vector, scalar, pseudo-scalar mediators

- How to detect them:
  - **invisible decays** (MET searches)



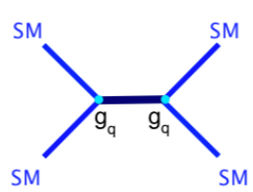
Mono-jet search (or mono-photon)



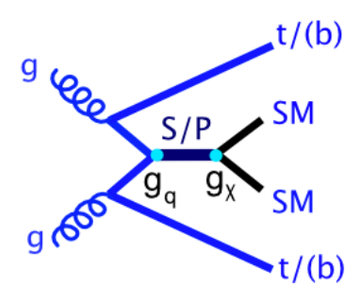


MET in association with heavy flavor quarks
(also: single top, Wt signatures)

- **visible decays of mediators**



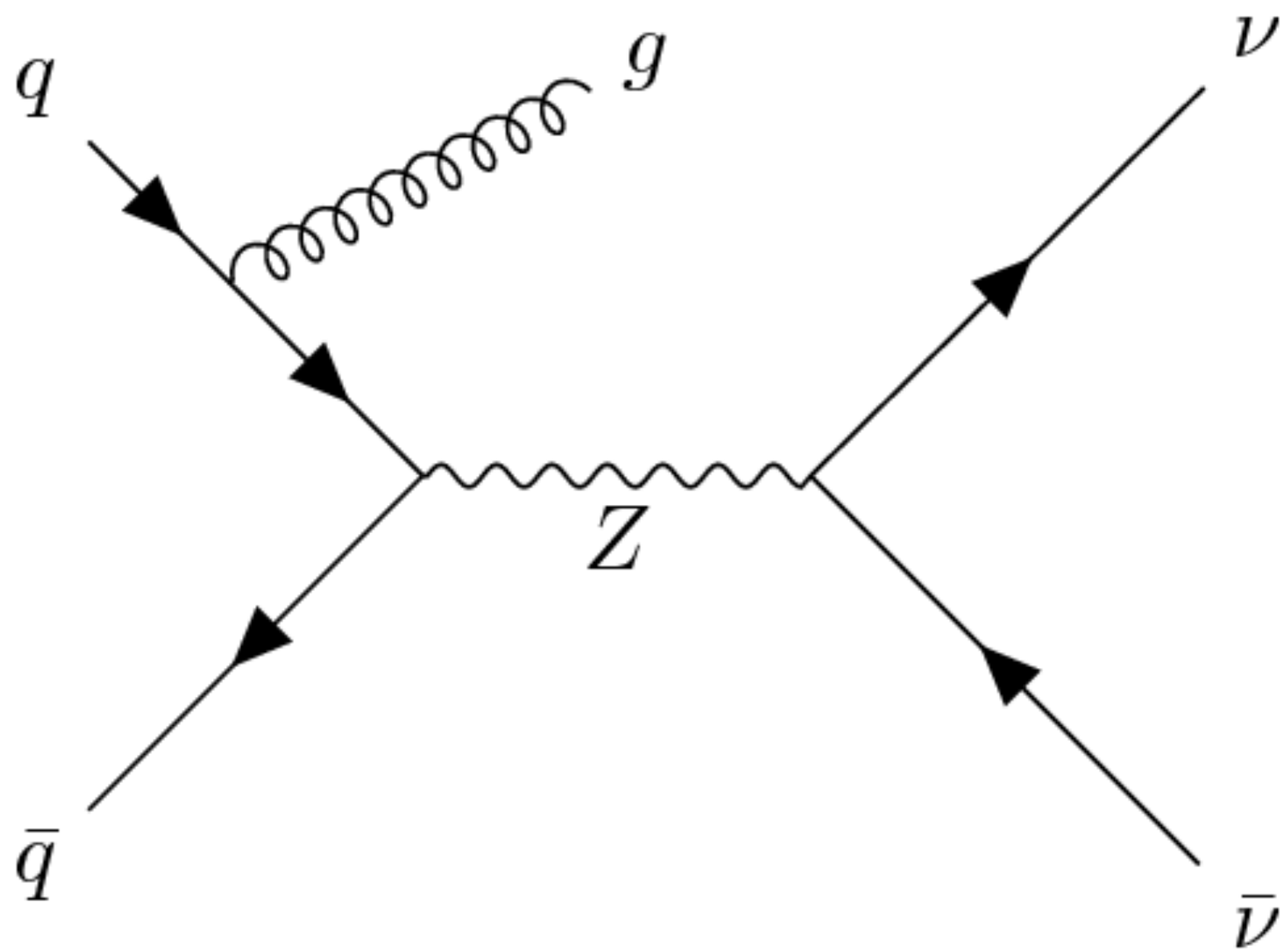
Di-object searches



Rare 4-top signatures

LHC production of invisible particles

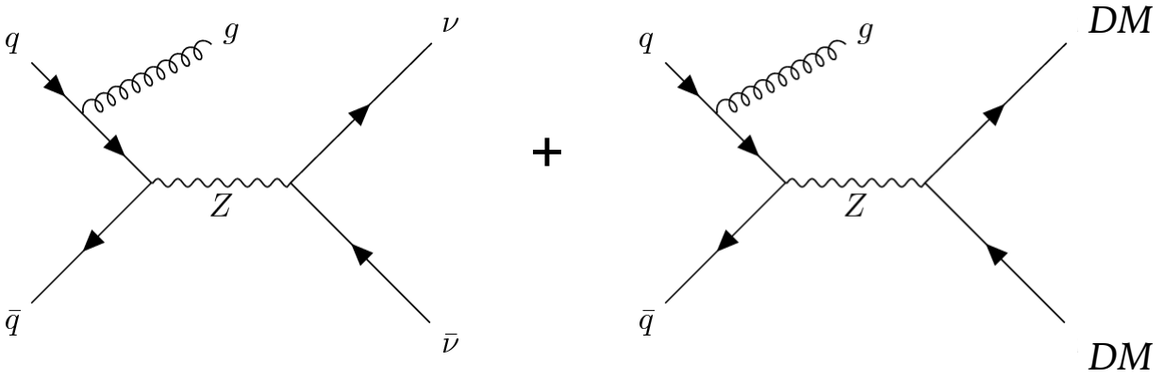
Production of invisible particles is common in the SM

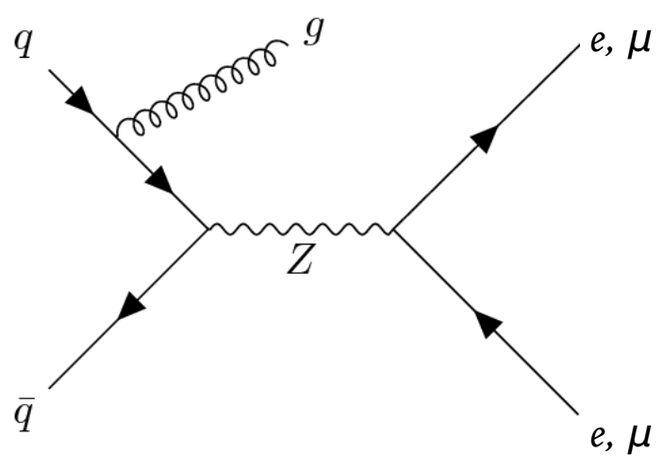


Eur. Phys. J. C 77 (2017) 765

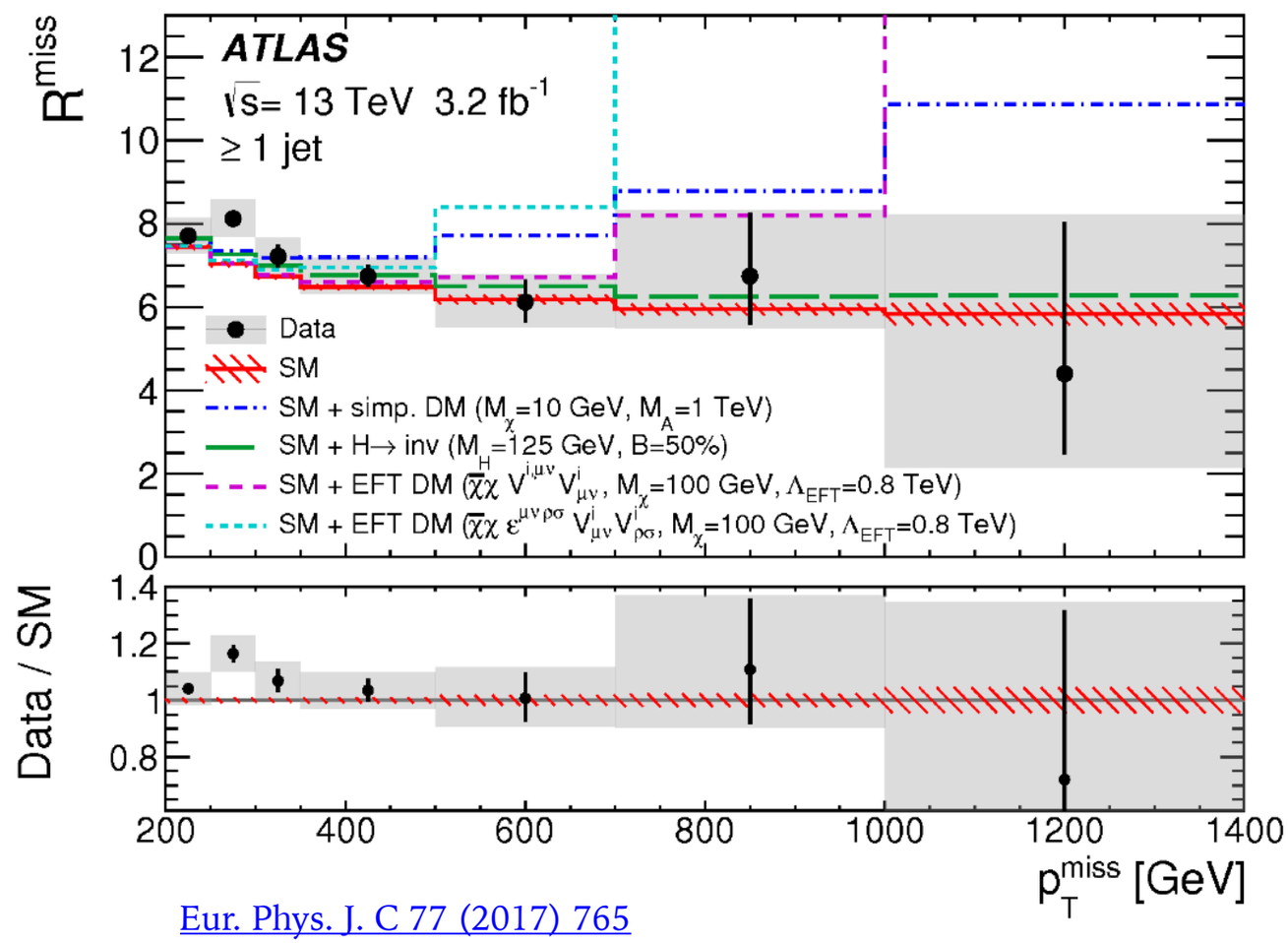
LHC production of new invisible particles

Production of invisible particles can be common in the SM
use **standard candles** (Z boson) to search for non-SM production





$$R^{\text{miss}} = \frac{\sigma_{\text{fid}}\left(p_{\text{T}}^{\text{miss}} + \text{jets}\right)}{\sigma_{\text{fid}}\left(\ell^+\ell^- + \text{jets}\right)}$$



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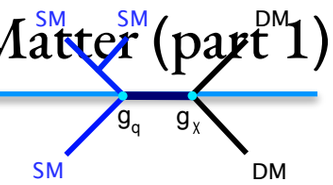


Generic searches for DM: "*X+MET*"

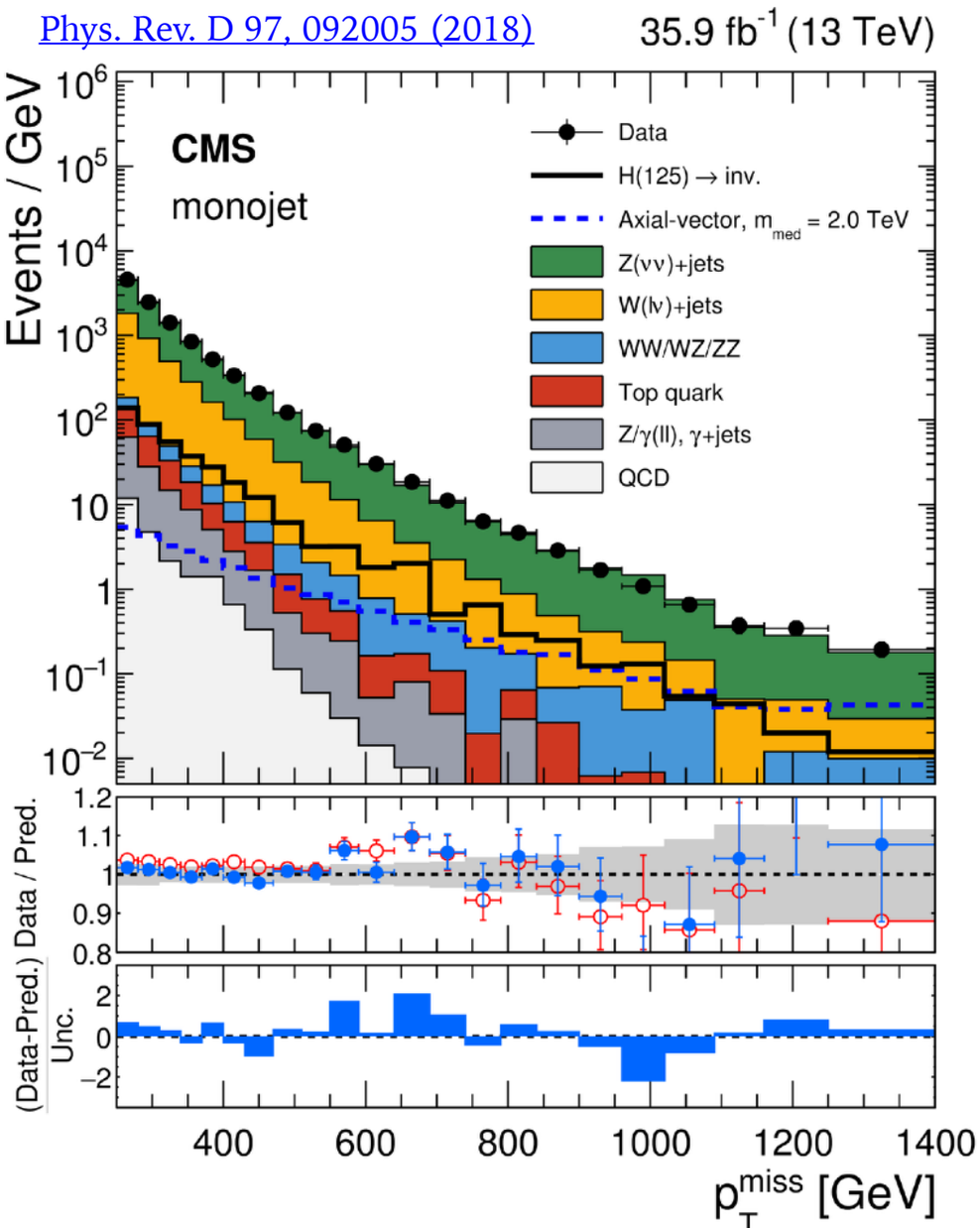
ISR (jet, photon, V boson...) + MET signature

Background normalized using data

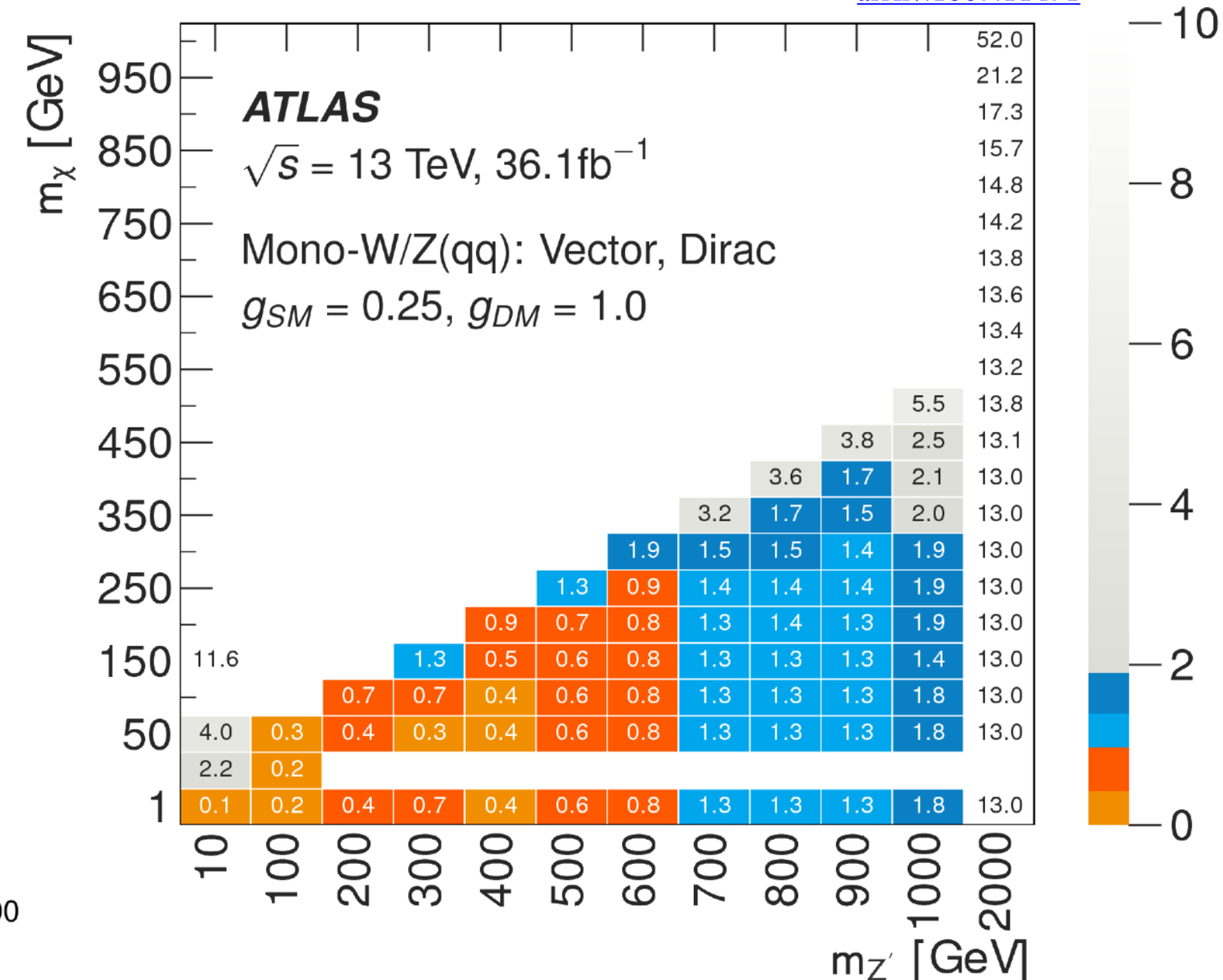
Background shapes need precise theory predictions EPJC 2017 77:829

Results can be interpreted in a variety of models

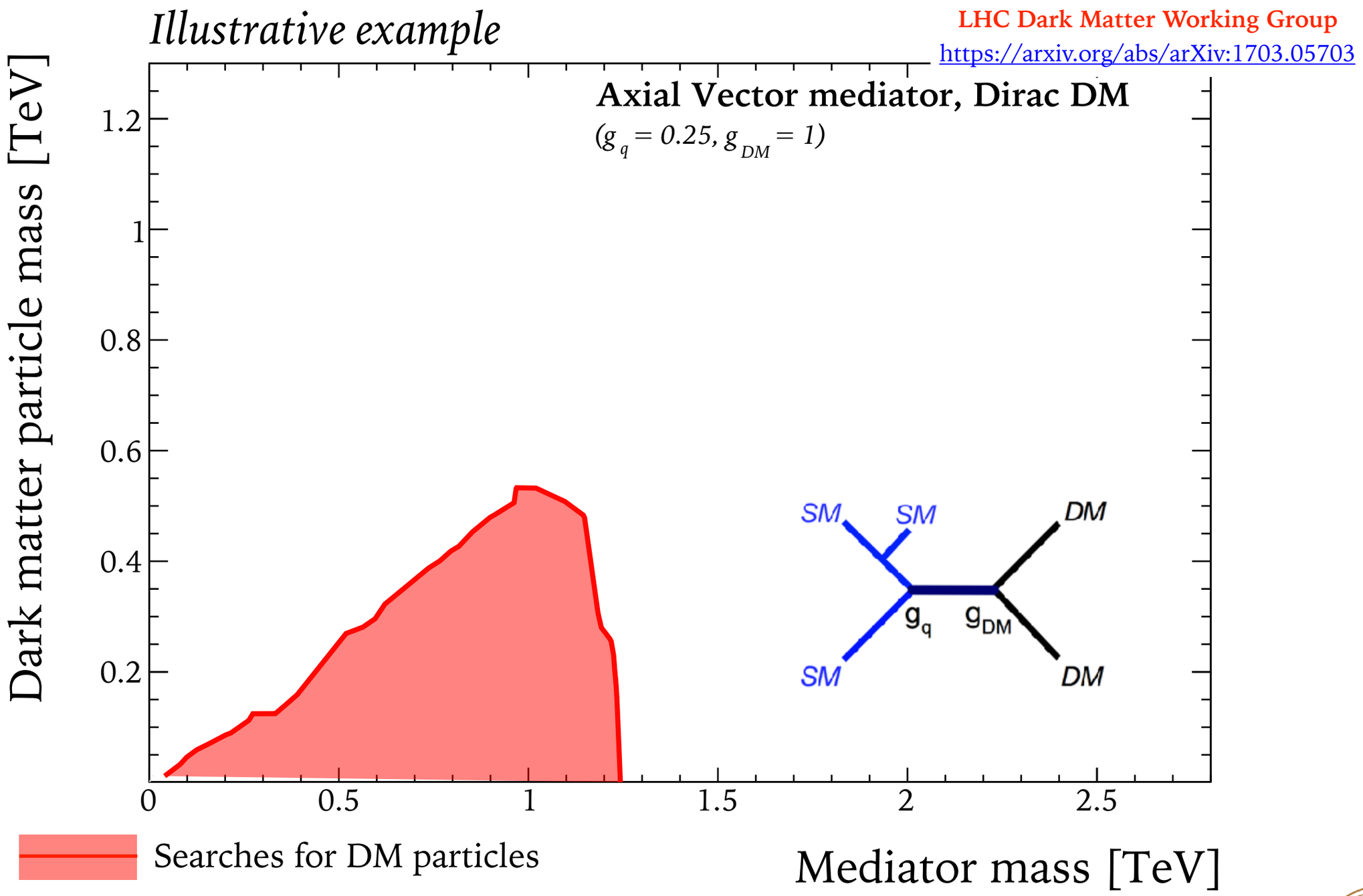
Phys. Rev. D 97, 092005 (2018)



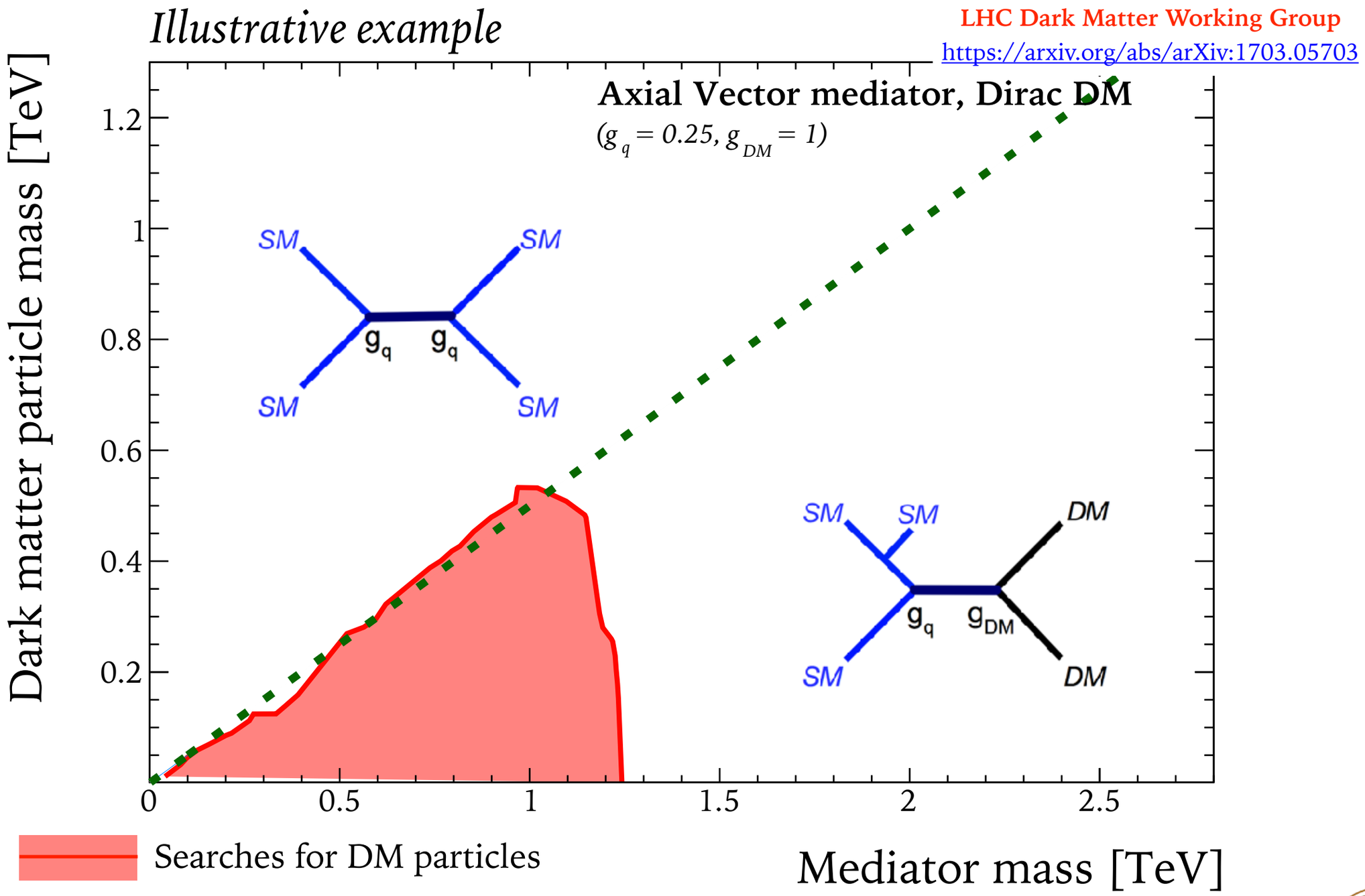
arXiv:1807.11471



Complementarity of visible/invisible searches

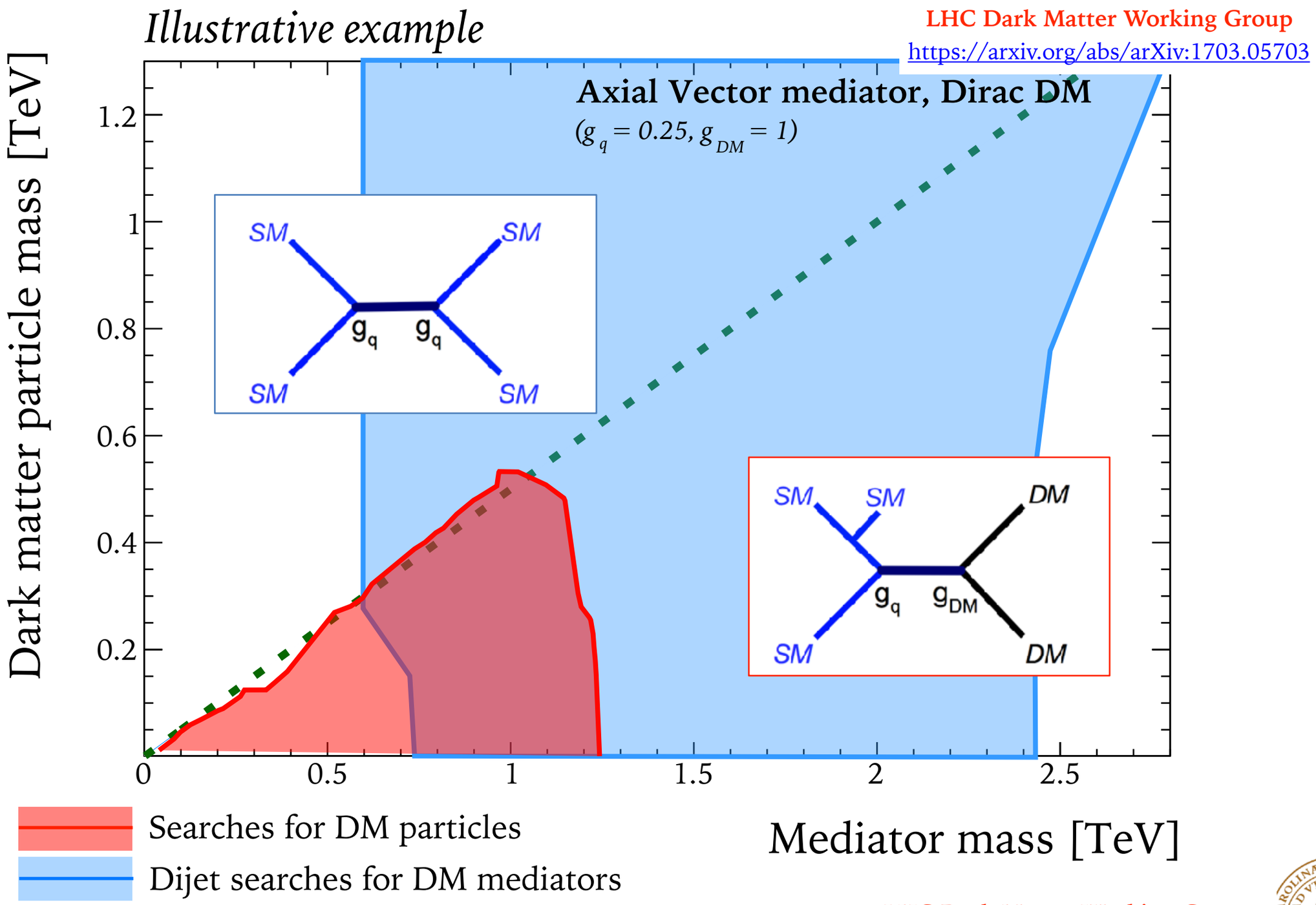


Complementarity of visible/invisible searches



LHC Dark Matter Working Group
https://arxiv.org/abs/arXiv:1703.05703

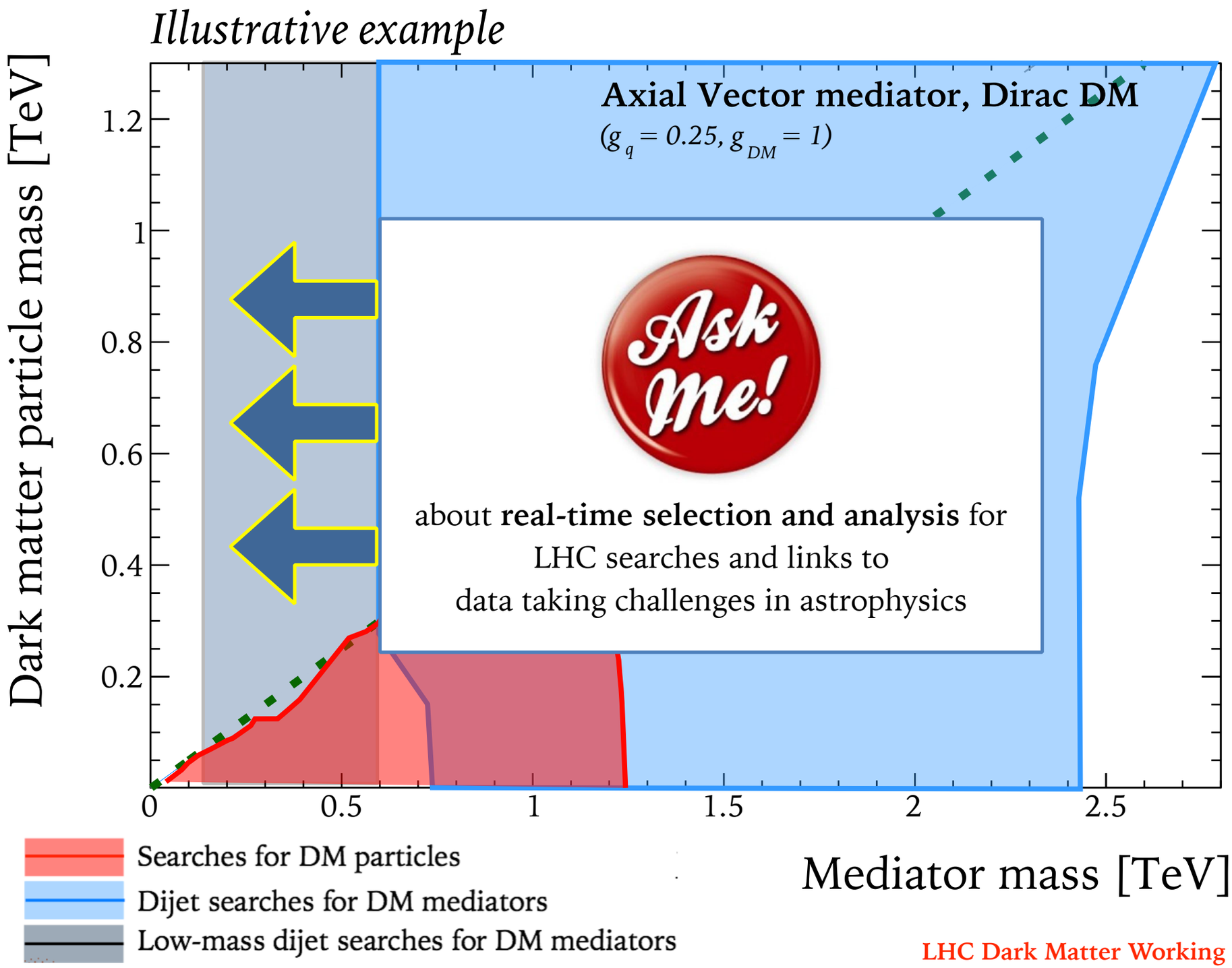
Complementarity of visible/invisible searches



LHC Dark Matter Working Group
https://arxiv.org/abs/arXiv:1703.05703

Collider strength for these models: searches for visible mediator decays

Complementarity of visible/invisible searches



LHC Dark Matter Working Group
https://arxiv.org/abs/arXiv:1703.05703

Collider strength for these models: searches for visible mediator decays

Take-home point #4:

Generic searches for DM particles targeting simple (simplified) models show the unique LHC ability to look into the SM-DM interactions, but they are only a starting point

Recap of Lecture 2
& wordclouds & another poll

Go to www.menti.com and use the code 21 90 19

Take-home point #1:

The SM has problems that are both aesthetic
(observations not matching a "beautiful" theory)
and empirical
(observations not explained)

These motivate the search for BSM physics at the scales reachable by the LHC

Take-home point #2:

SUSY: elegant solution to many SM problems, including dark matter

No signs of SUSY @ LHC yet (but not all parameter space yet excluded):
worth considering SUSY models that are harder to find, or models that solve only a few problems at a time

https://arxiv.org/pdf/1512.06819.pdf

Take-home point #3:

we don't know very much about DM beyond its gravitational interactions and astrophysics abundance

any ~~LHC~~ search will necessarily contain some hypotheses (e.g. about interactions/model) so that DM can be observed experimentally

Take-home point #4:

Generic searches for DM particles targeting simple (simplified) models show the unique LHC ability to look into the SM-DM interactions, but they are only a starting point