Elementary Particle Physics: theory and experiments

Searches for New Physics at LHC

Exotic models

Supersymmetry

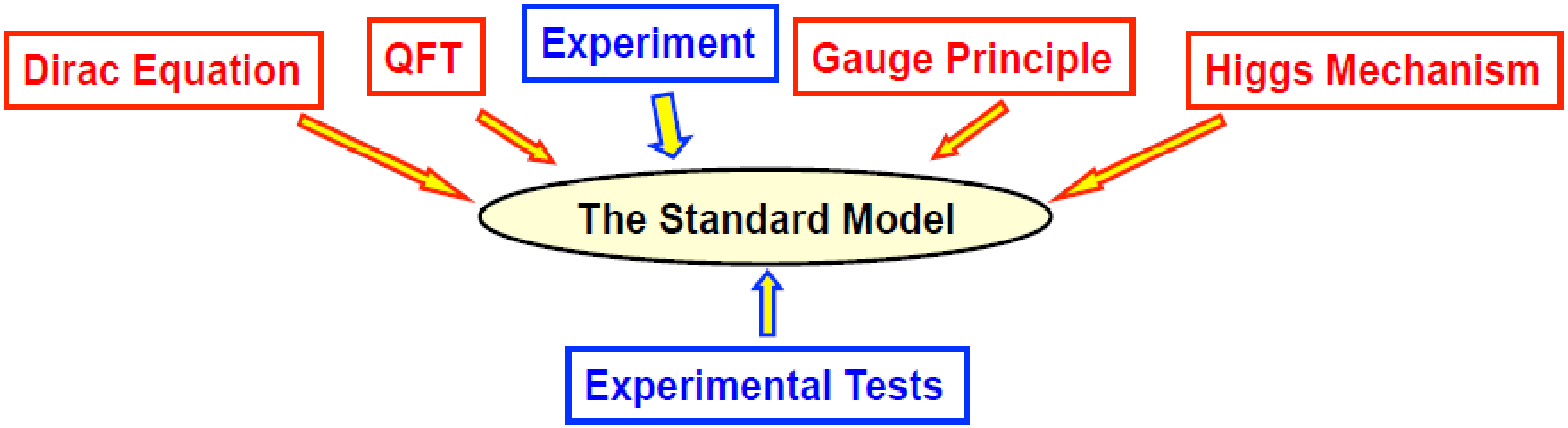
Dark Matter

Unconventional signatures

Prof. dr hab. Elżbieta Richter-Wąs

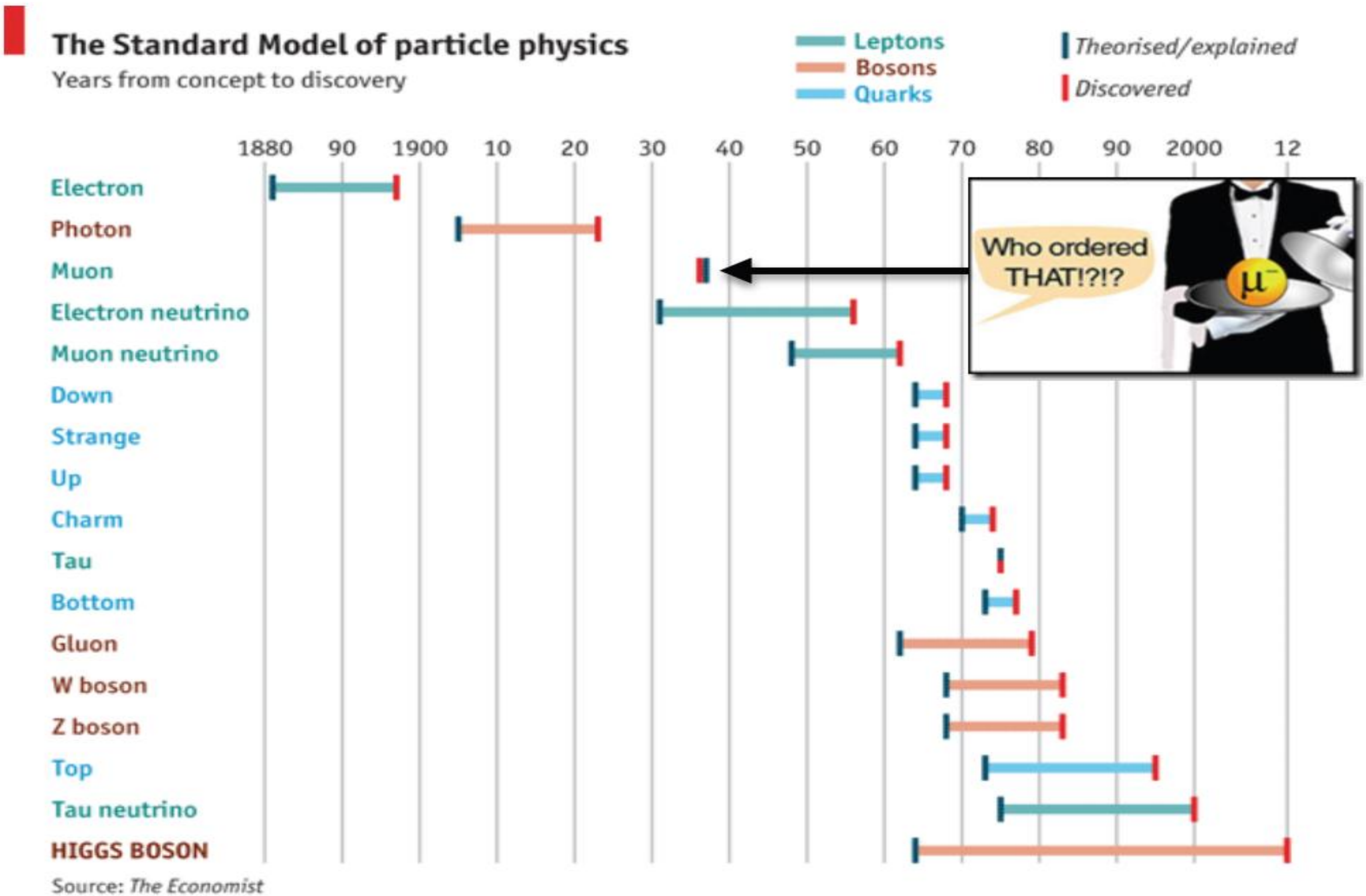
Standard Model

- The Standard Model of Particle Physics is one of the great scientific triumphs of the late 20th century
- Developed through close interplay of experiment and theory



- Modern experimental particle physics provides many precise measurements. and the **Standard Model** successfully describes all current data !
- Despite its great success, we should not forget that it is just a model; a collection of beautiful theoretical ideas cobbled together to fit with experimental data.
- There are many issues / open questions…

Uncharted discoveries?



Standard Model: Problems and Open Questions

- The Standard Model has too many free parameters:

$$m_{\nu_1}, m_{\nu_2}, m_{\nu_3}, m_e, m_\mu, m_\tau, m_d, m_s, m_b, m_u, m_c, m_t$$

$$\theta_{12}, \theta_{13}, \theta_{23}, \delta \quad + \quad \lambda, A, \rho, \eta \qquad e, G_F, \theta_W, \alpha_S \qquad \cancel{m_H}, \theta_{CP}$$

- Why three generations ?
- Why $SU(3)_c \times SU(2)_L \times U(1)$?
- Unification of the Forces
- Origin of CP violation in early universe ?
- What is Dark Matter ?
- Why is the weak interaction V-A ?
- Why are neutrinos so light ?
- ~~Does the Higgs exist ?~~ + gives rise to huge cosmological constant ?
- Ultimately need to include gravity

Over the last 25 years particle physics has progressed enormously.

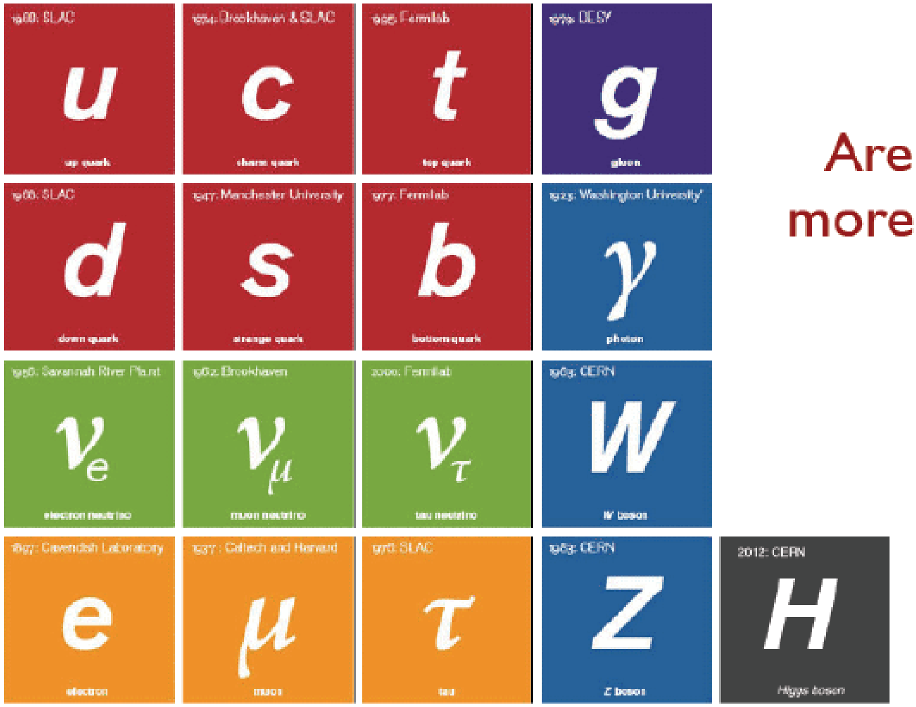
—— since year 2012

Many unanswered questions …

Why there are 3 families of particles? Are there more?

Why is the top quark so heavy?

Why there's more matter then anti-matter?



Are there more forces?

How do neutrinos get mass?

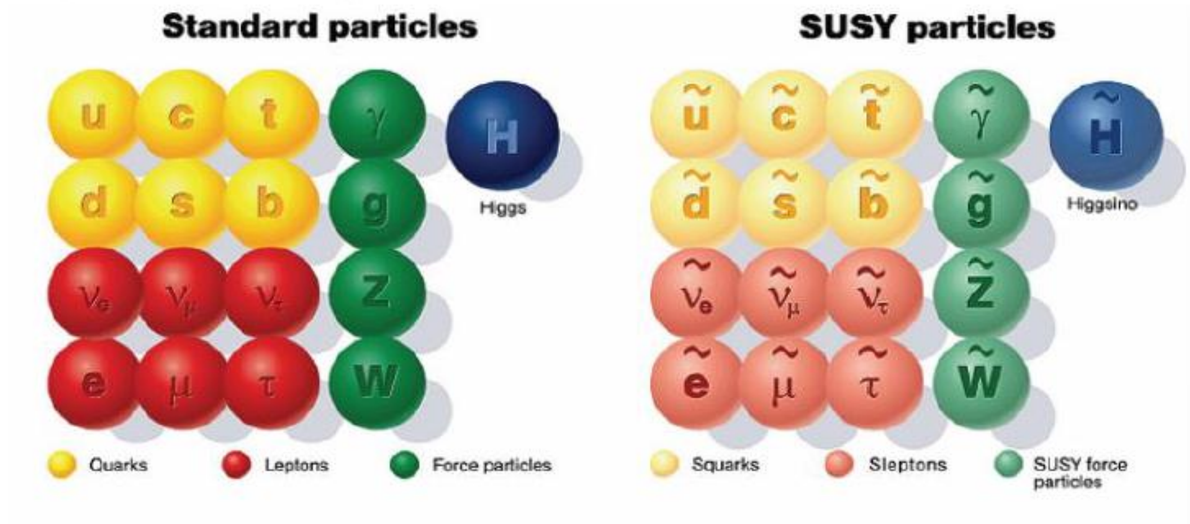
What keeps the Higgs mass so small?

How do we incorporate gravity?

What is Dark Matter?

… and as many possible answers to probe!

- Super-symmetry?



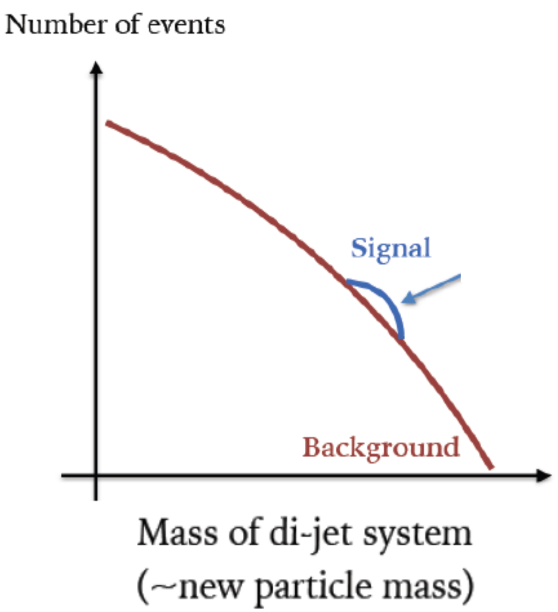
- Composite quark and/or leptons?
- New Heavy bosons?
- Gravitons?
- Dark Matter particles?
- …

Any new theory need to agree with the SM!

How would new phenomena manifest?

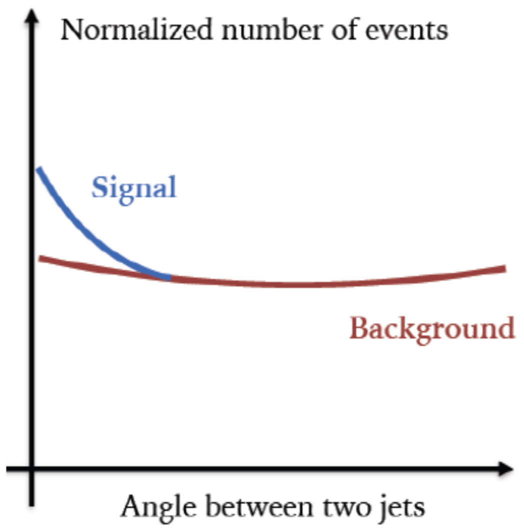
New particles:

resonant excess (bump) over Standard Model background



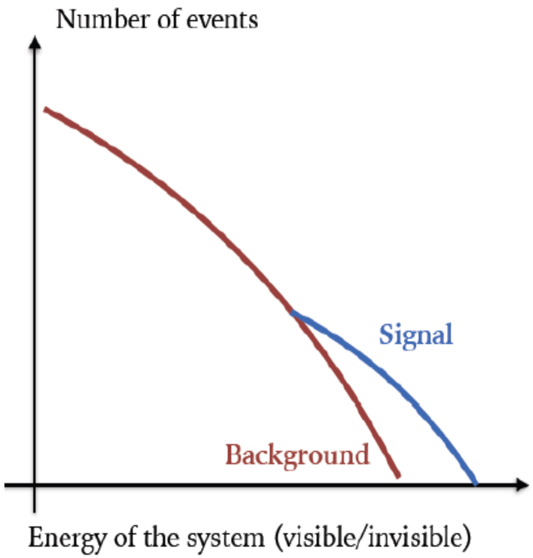
New interactions:

more central production (~Rutherford experiment)

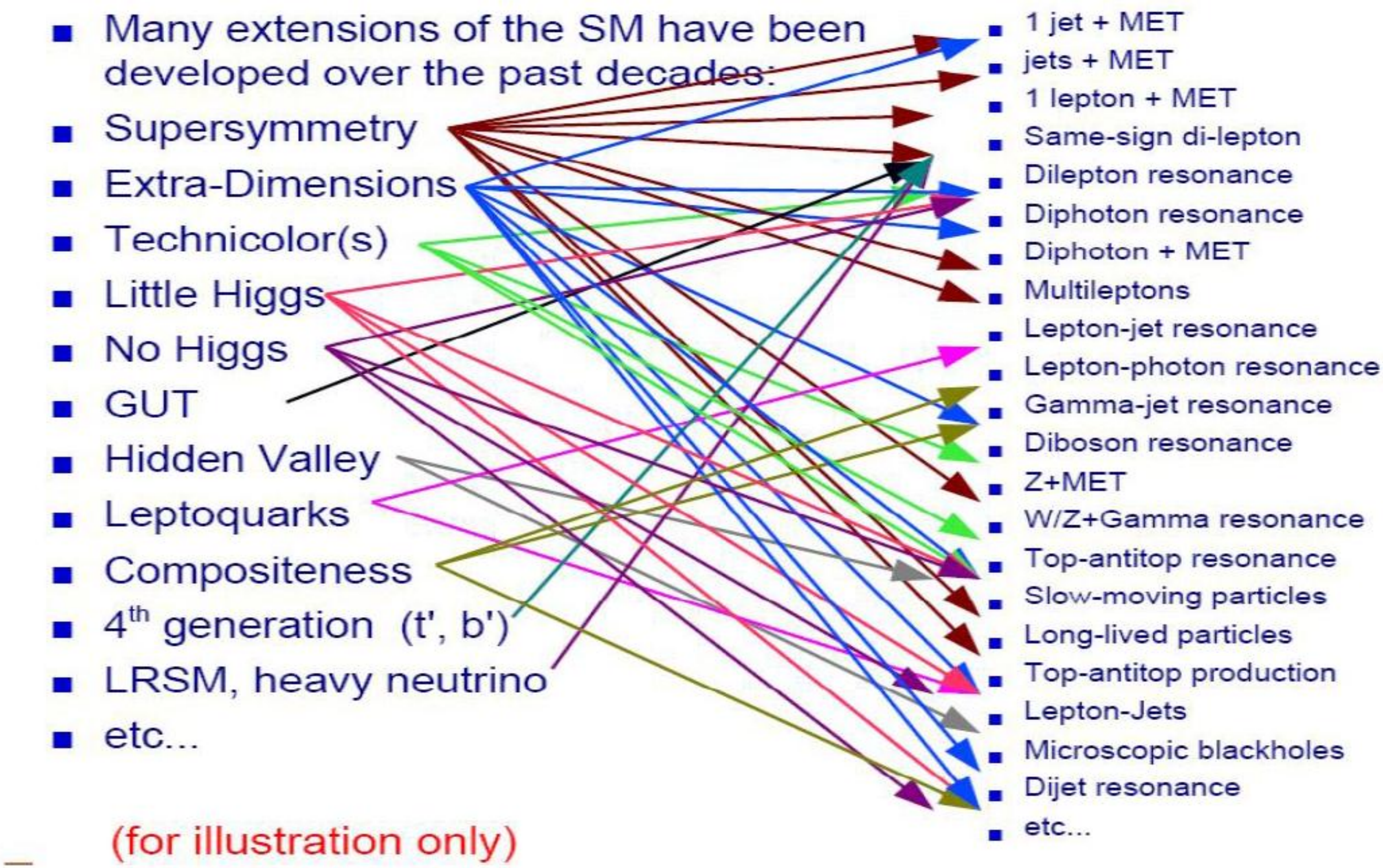


New particles and states:

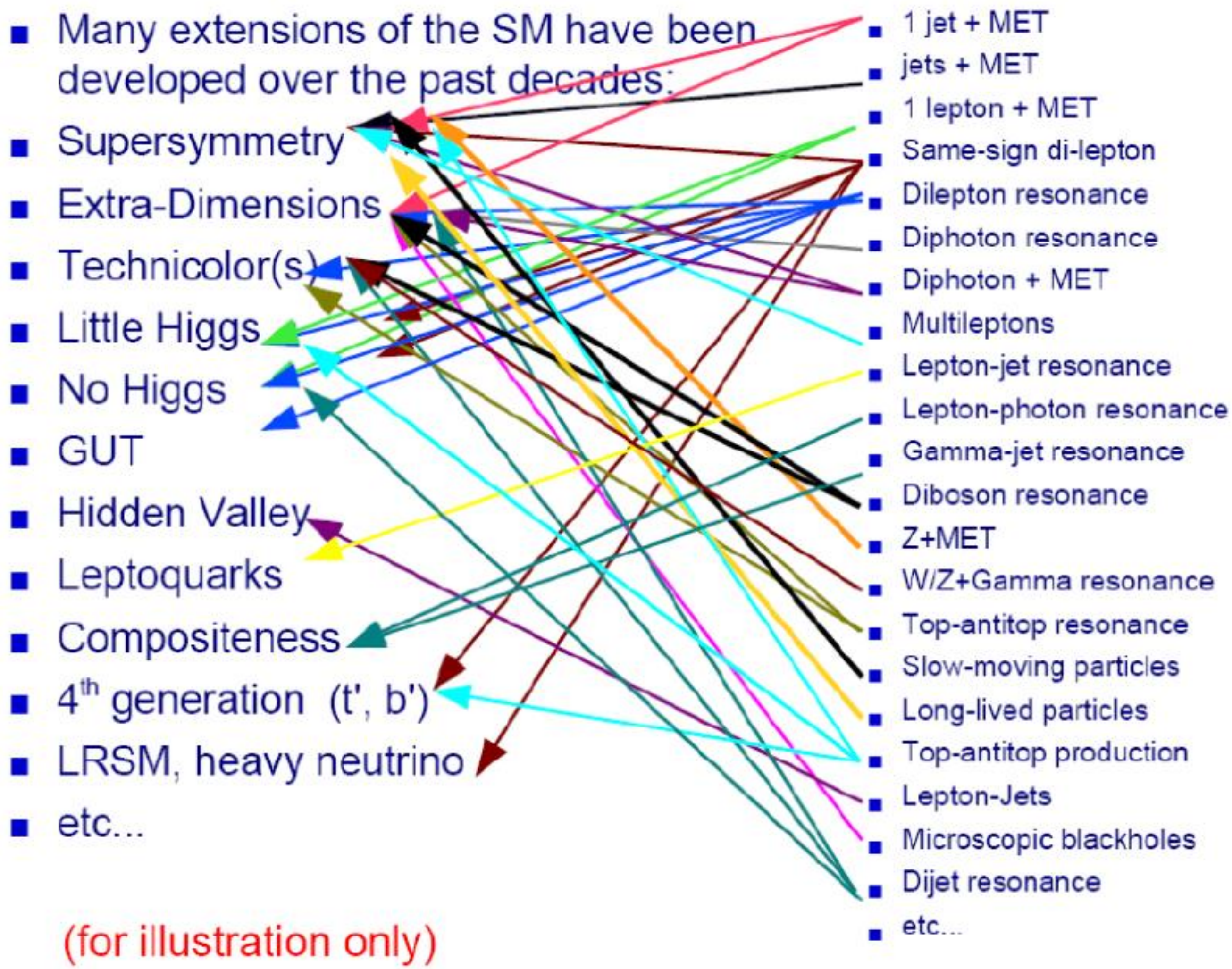
larger multiplicity of objects at high masses



Long list of models and signatures



Long list of models and signatures



A complex 2D problem

Experimentally, a **signature standpoint** makes a lot of sense:

→ Practical

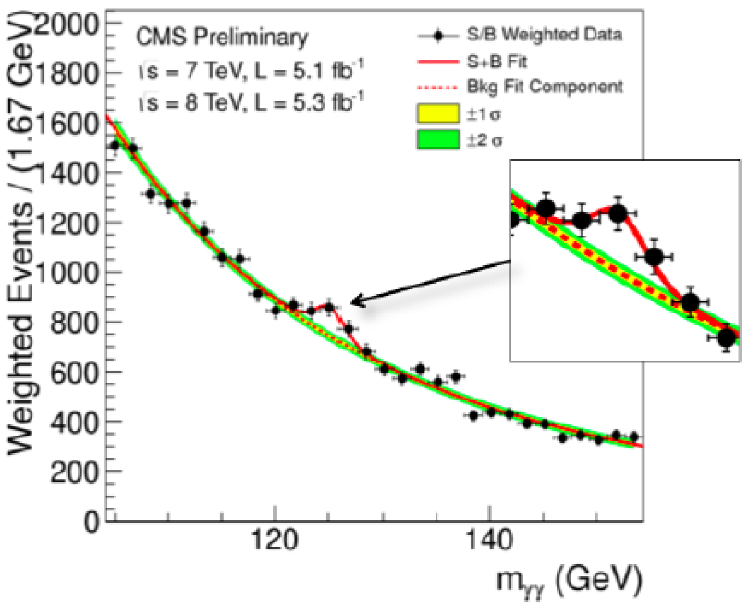
→ Less model-dependent

→ Important to cover every possible signature

What characterizes Exotics Searches

No precise model to guide us

Standard Model:
Predicted Higgs boson

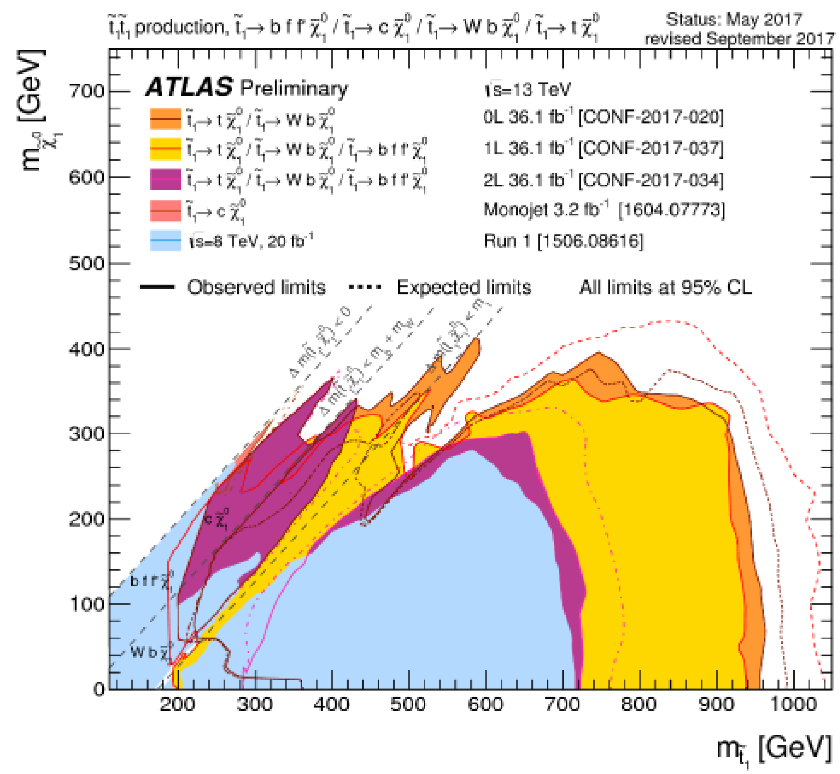


[Phys. Lett. B 716 (2012) 1-29]

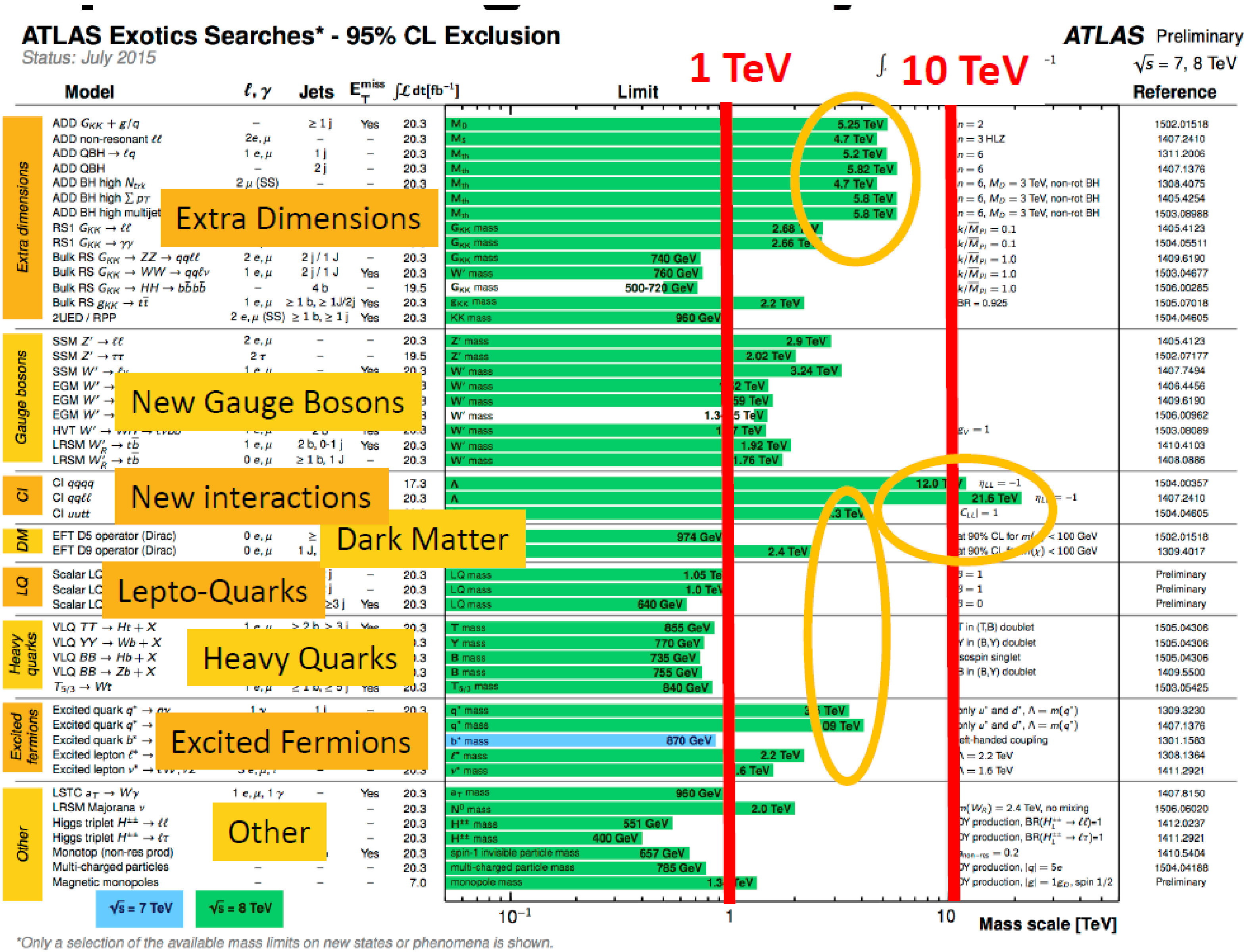
[Phys. Lett. B 716 (2012) 30-61]

No unified parameter phase space

Supersymmetry Searches:



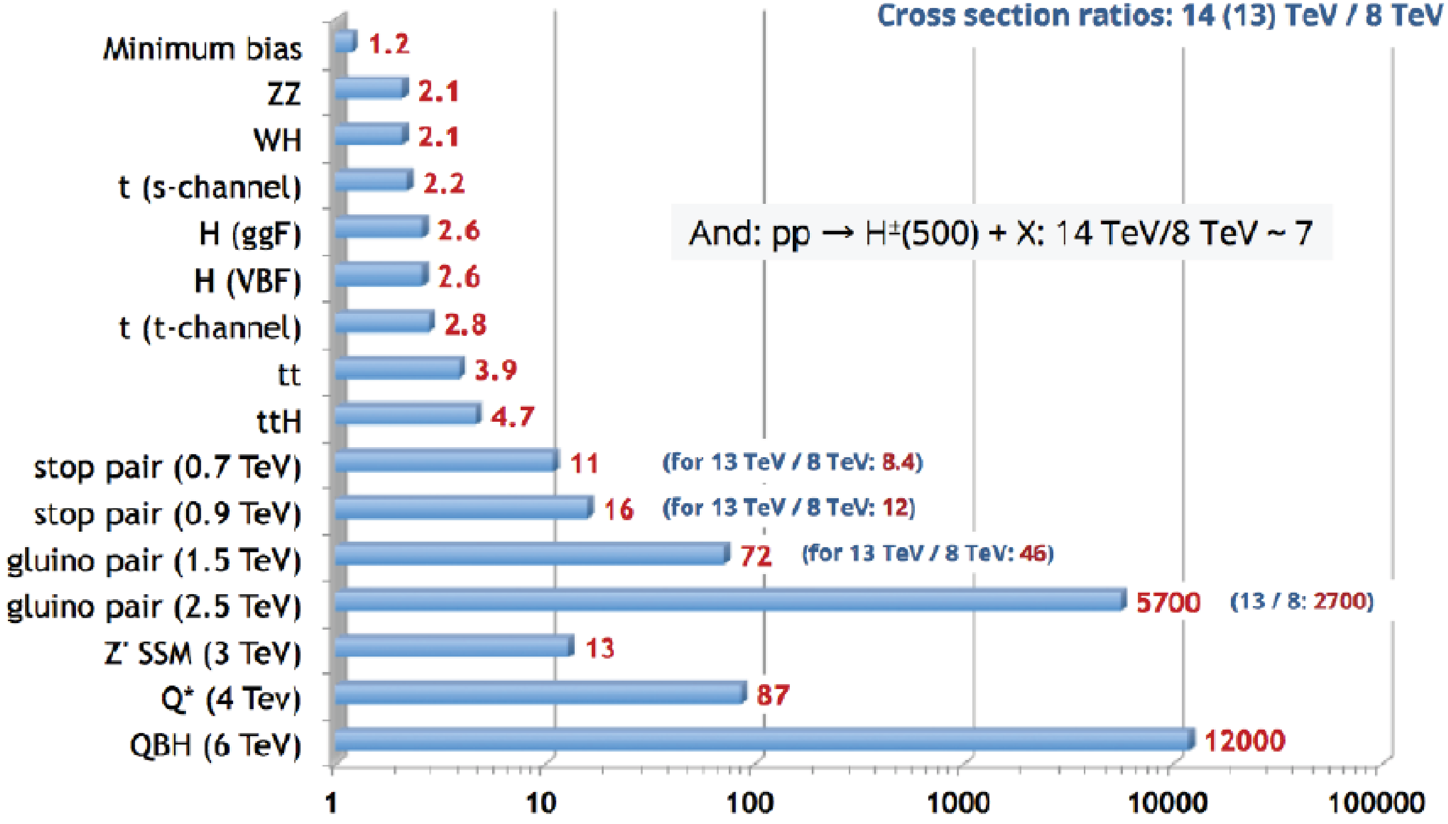
Exploration range of LHC by mid 2015



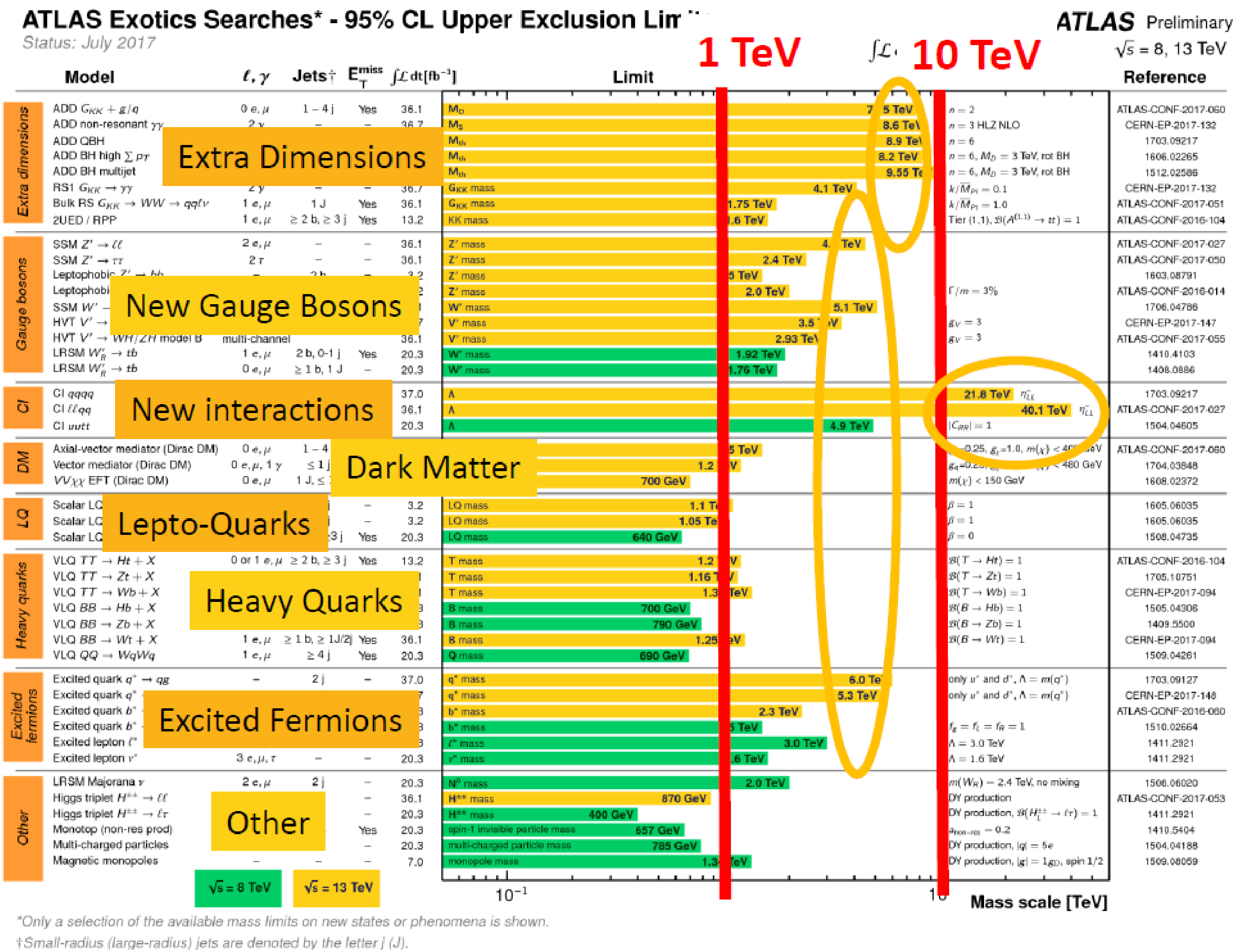
LHC Run II

Hugely increased potential for discovery of heavy particles at 13 TeV

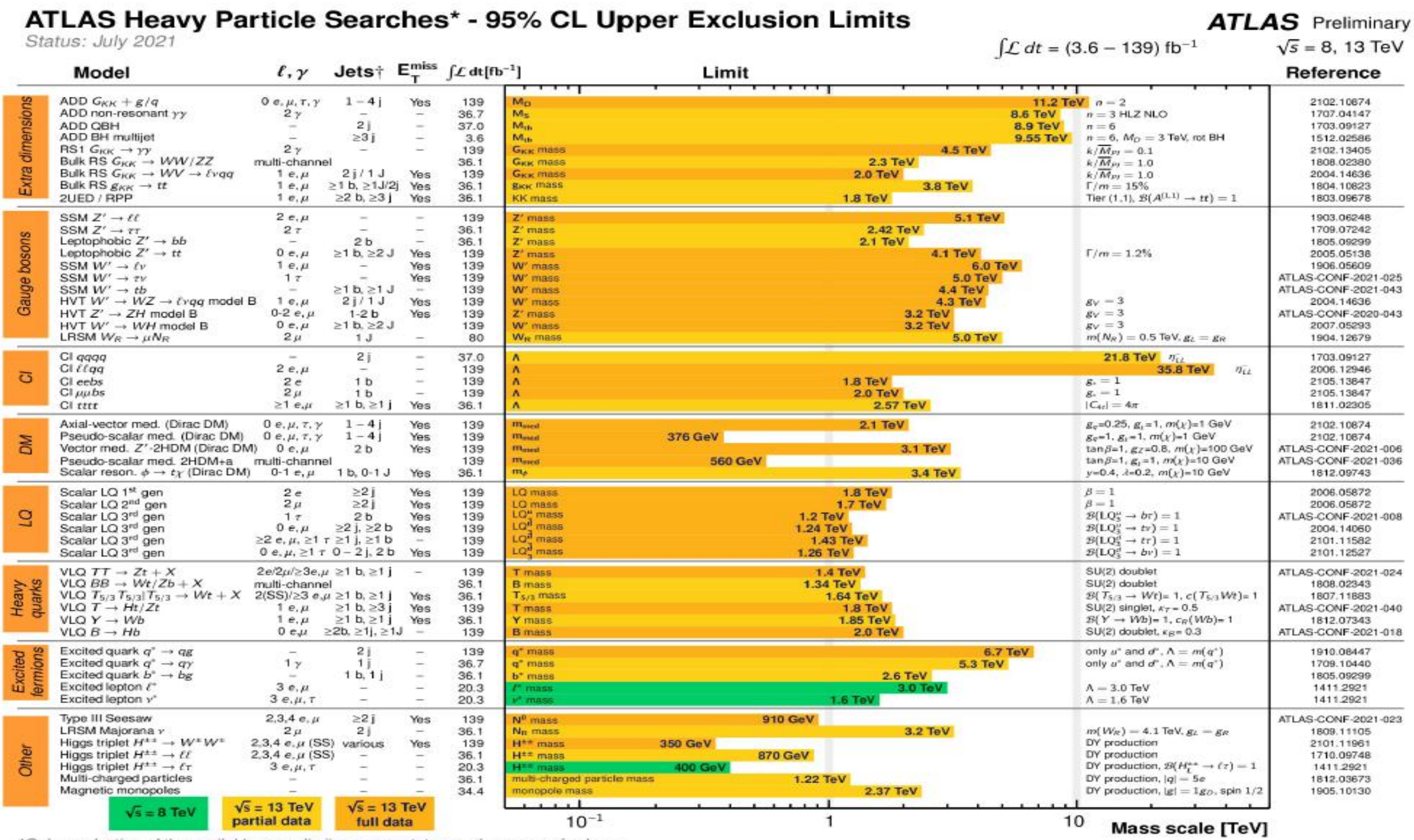
Perfect occasion for young motivated physicists: join the search!



Exploration range of LHC by mid 2017



Exploration range of LHC by mid 2021



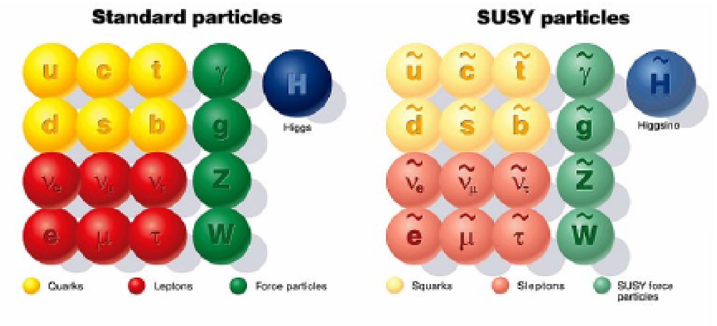
*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

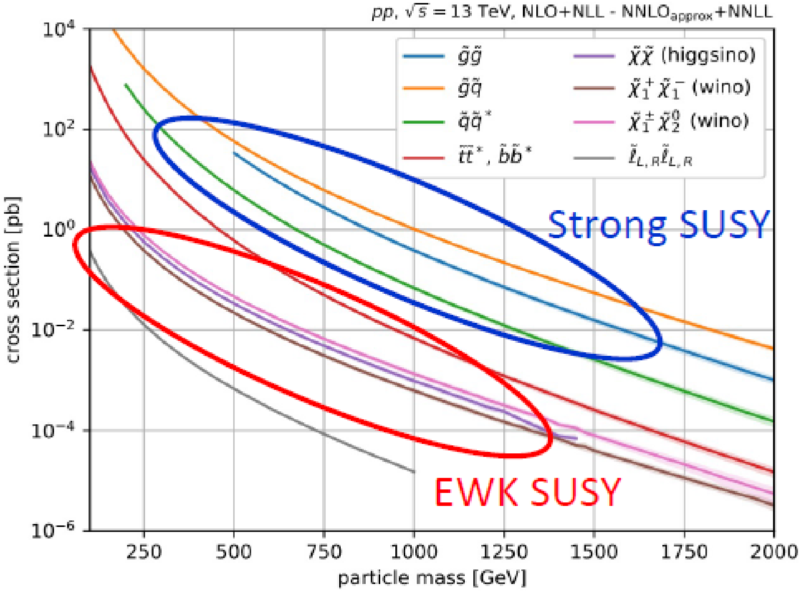
Beyond SM landscape at the LHC

- LHC built as a discovery machine
  - Hope to discover hints of BSM physics in measurements as well as direct searches
  - Ever-expanding portfolio of BSM searches
- Driven by theories and results
  - Solving some of the big problems
    - Dark matter/energy
    - Higgs boson mass calculation
    - Matter-antimatter asymmetry
    - ...
  - Getting hints from measurements
    - Cosmological constraints, direct searches for DM, SM measurements, muon g-2…
- Driven by signatures
  - Triggering and reconstruction crucial
  - Able to discriminate backgrounds
  - Continuously optimizing this with new techniques
    - Leads to new, more sensitive signatures

Supersymmetry

- One of the most popular BSM theories
  - Solves multiple open questions (DM, hierarchy problem…)
  - Every SM boson gets a fermion partner and vice versa
  - Wide variety of signatures
  - LHC data has put serious constraints but still exploring new phase space:
    - By targeting more challenging signatures
    - Beyond vanilla SUSY: RPV, NMSSM,…
- Expanding on previous exclusions
  - New final states
  - Improving existing tools
  - New decay modes
- Many new results
  - Focus on EWK SUSY
  - New cascade search with additional Higgs bosons

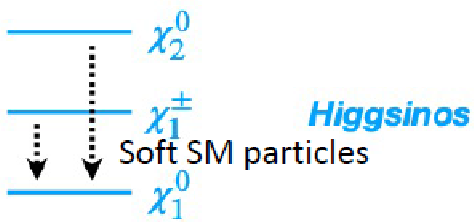


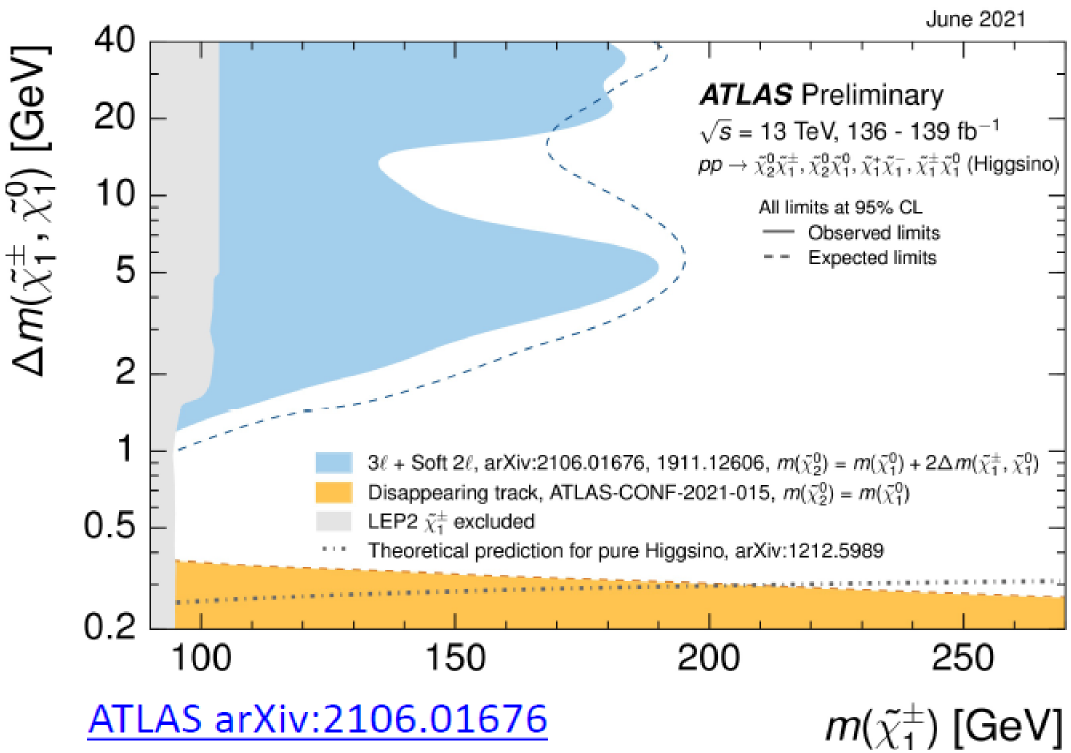


- Smaller production cross sections in EWK production lead to lower mass constraints

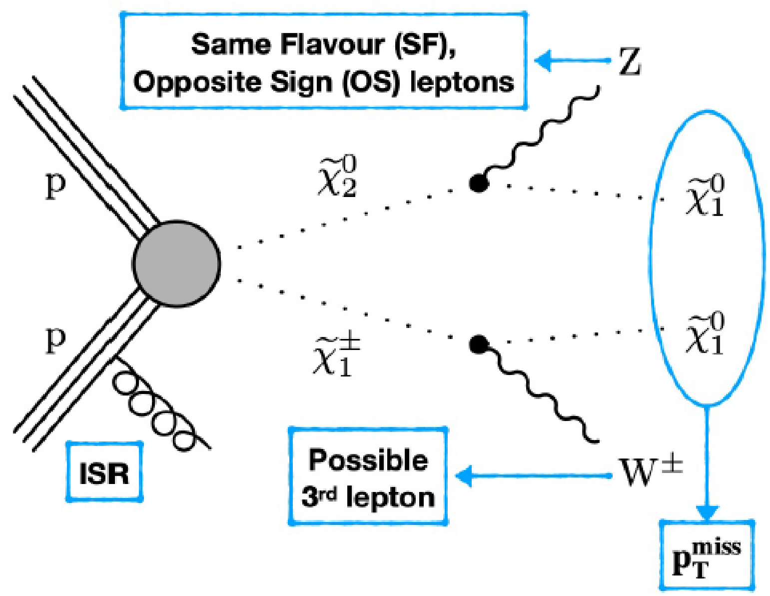
Compressed searches for charginos and neutralinos

- Special interest for compressed scenarios
  - Higgsino production with Higgsinos with similar mass close to the M_H scale
  - Rather challenging from experimental point of view
    - Boost final state to get enough pT to particles
    - Very soft leptons and missing transverse momentum
    - Lowering thresholds and looking for new ways to close the gaps





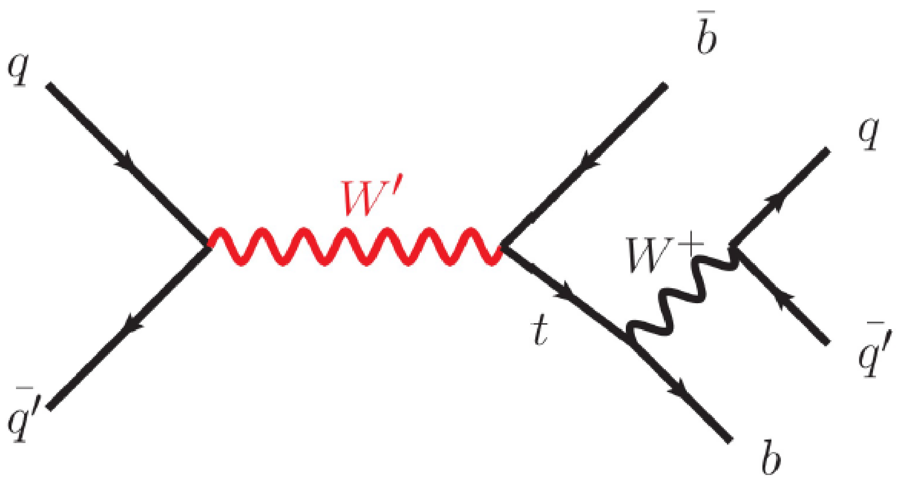
[ATLAS arXiv:2106.01676](https://arxiv.org/abs/2106.01676)

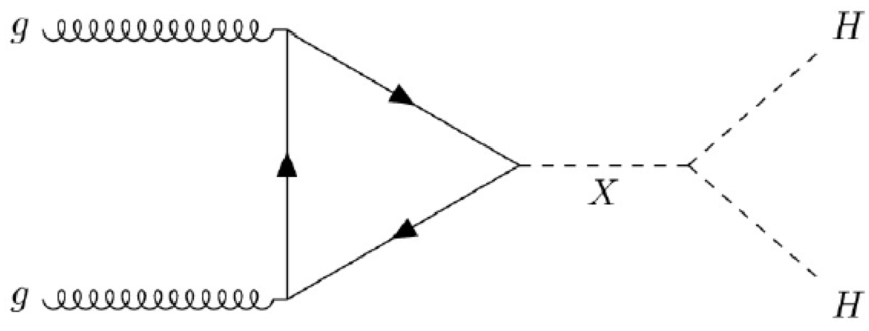


CMS-SUS-PAS-18-004

Heavy resonances

- Many BSM theories predict new heavy resonances
  - 2HDM models
    - Extension of SM Higgs sector
  - Extra dimension theories
    - Spin-2 gravitons, spin-0 radions
  - NMSSM
  - New vectorbosons
  - ...

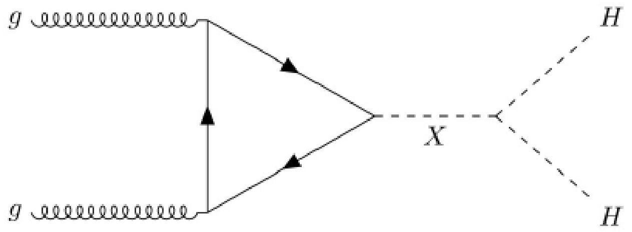


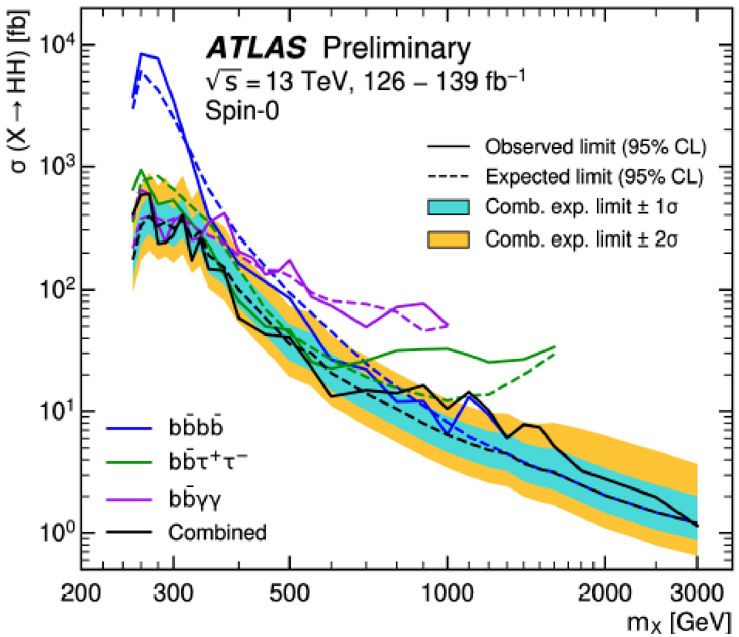


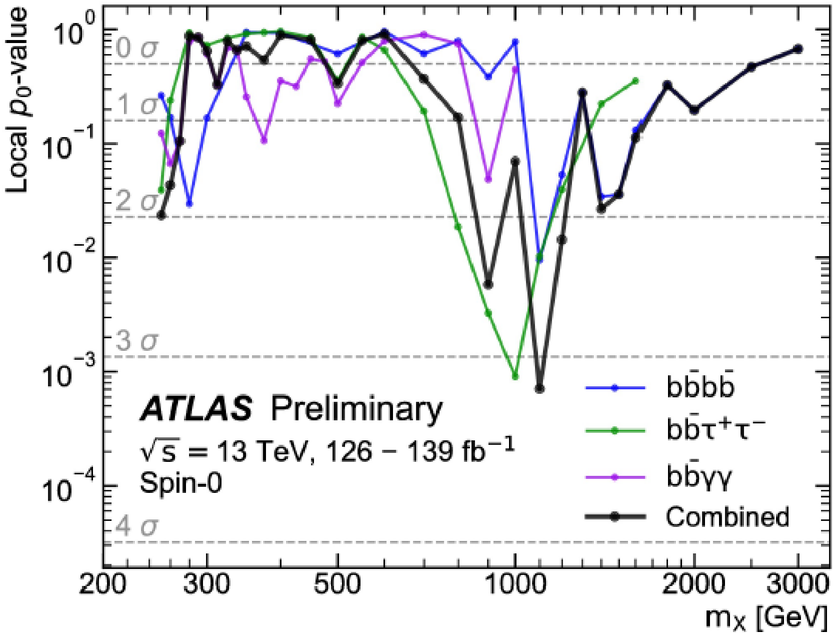
Resonances decaying to SM Higgs boson

NEW [ATLAS-CONF-2021-052]

- Combination of searches for Higgs boson pairs, resonant and non-resonant
  - $HH \rightarrow bbbb$
  - $HH \rightarrow bb\tau\tau$
  - $HH \rightarrow bb\gamma\gamma$
- Sensitivity of different channels in different mass ranges
  - Small excess at 1.1 TeV

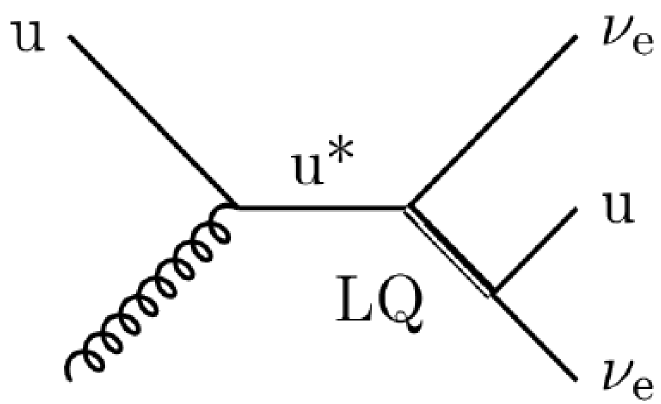


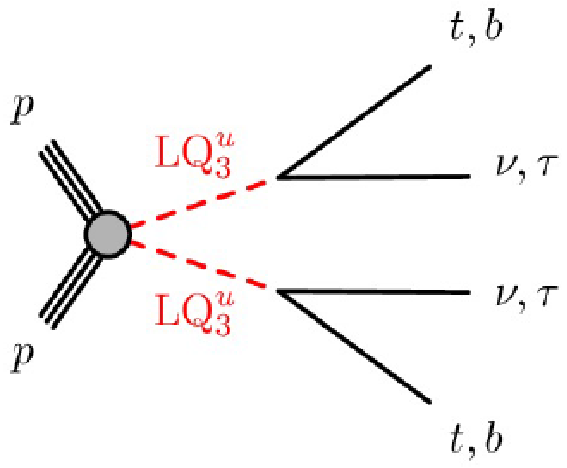




Leptoquarks

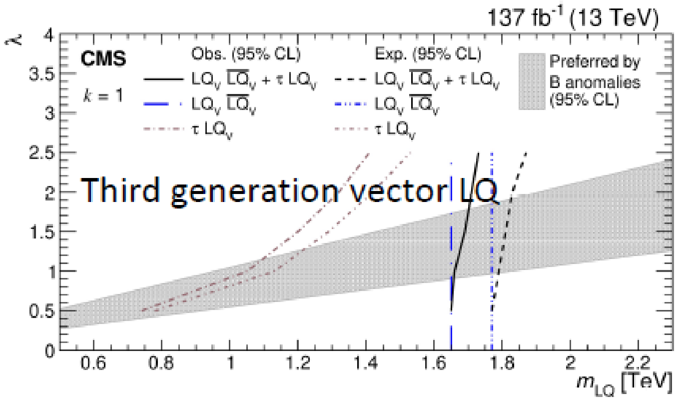
- Leptoquarks (LQs) are hypothetical particles which couple to both leptons and quarks
  - Both scalar and vector bosons
- Carry fractional electric charge
- Processes could violate lepton flavor universality
  - Possible explanation for B anomalies
- Predicted in GUTs and composite Higgs models
- Decay into lepton and quark

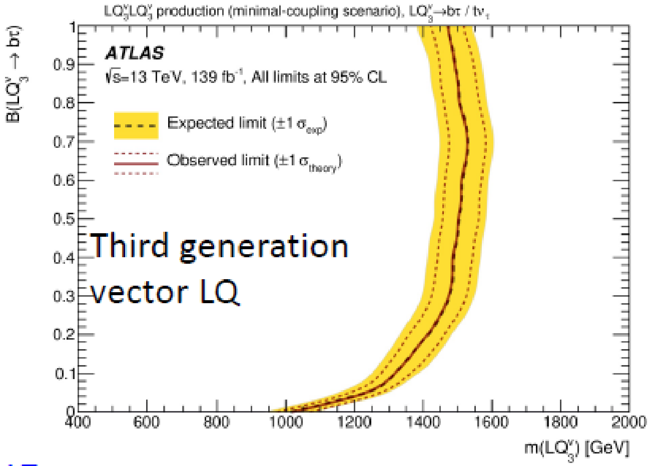




Leptoquark searches

- Dedicated searches and reinterpretations
- Both scalar and vector LQs
- 1st, 2nd, 3rd generation or mixed generations





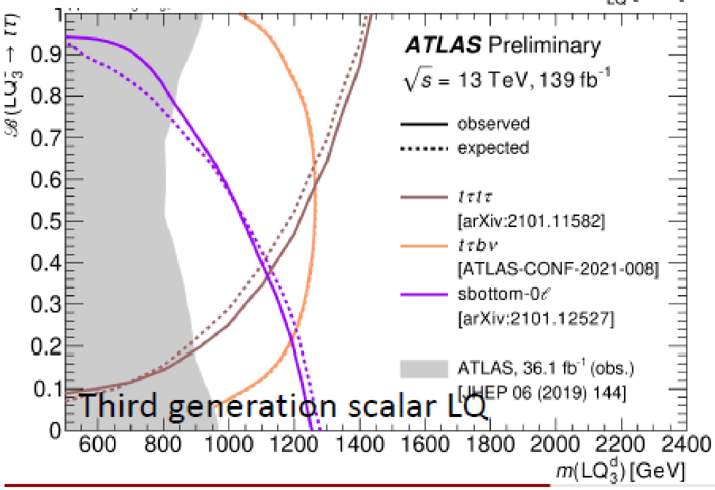
ATL-PHYS-PUB-2021-017

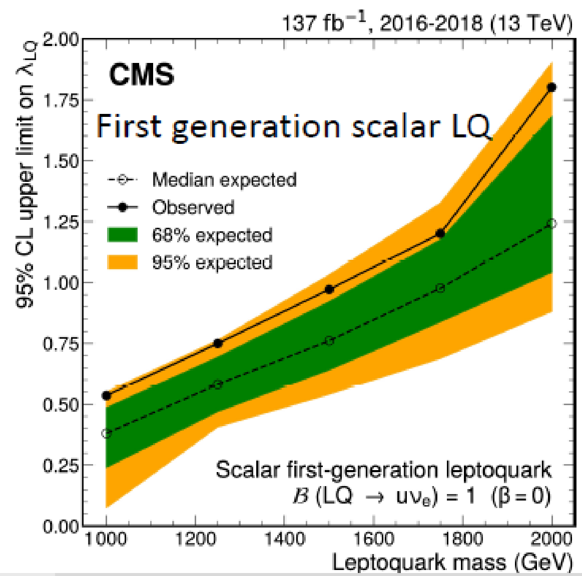
ATLAS arXiv:2006.05872

ATLAS arXiv:2108.07665

CMS arXiv:2107.13021

CMS arXiv:2012.04178

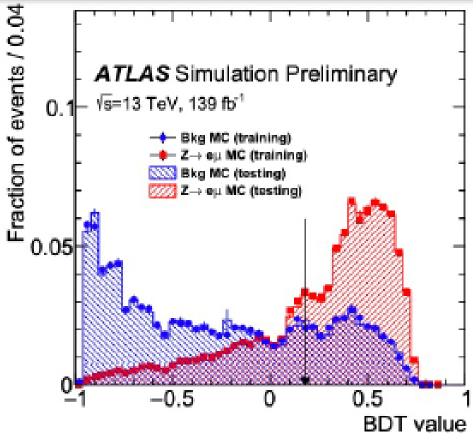


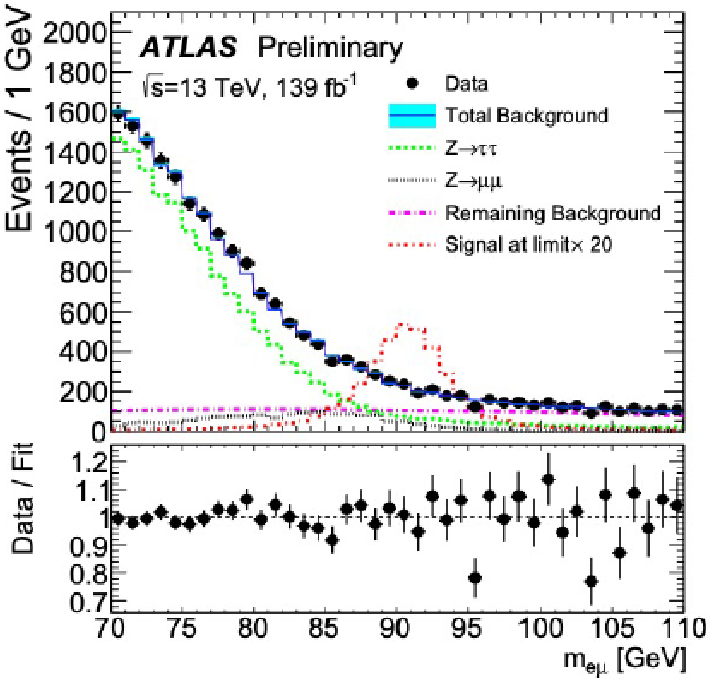


Lepton flavor violation in Z->eμ

ATLAS-CONF-2021-042

- Lepton-flavor violation has been observed in the neutrino sector
- Charged-lepton flavor violation would indicate BSM physics
- BDT trained in leading jet p_T, p_T^{miss} and $p_T^{e\mu}$
- Use ratio to the average of observed ee and μμ events to reduce systematic uncertainties
- Stringent direct constraint: $B(Z \to e\mu) < 3.04 \times 10^{-7}$
  - Driven by statistical uncertainties
  - Indirect searches: $B(Z \to e\mu) < 5 \times 10^{-13}$
  - LEP constraint: $B(Z \to e\mu) < 1.7 \times 10^{-6}$
  - ATLAS strongest limits on Z->l+tau
    - [ATLAS arXiv:2105.12491]





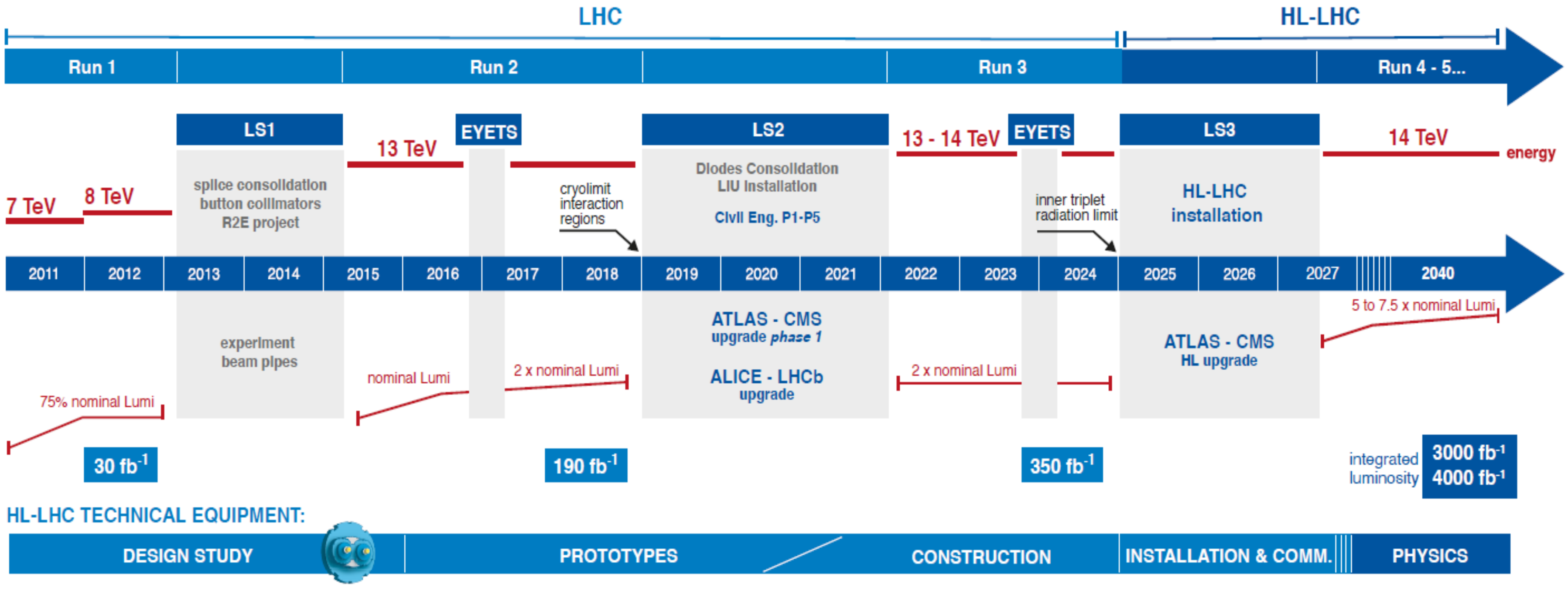
Conclusions

- Direct searches for new physics at LHC a thriving field
  - Increased sensitivity due to improved techniques
    - Well beyond pre-LHC projections
  - New models being explored for the first time
- Sadly enough no new evidence for BSM to report yet
  - But still learning by excluding more and more model phase space
- Still work for these searches in the future
  - Many new interesting hints of where to look for new physics (LFU, muon g-2,…)
  - New signal models
  - More targeted searches
  - More data
  - Improved detector and trigger capabilities
    - More challenging signatures

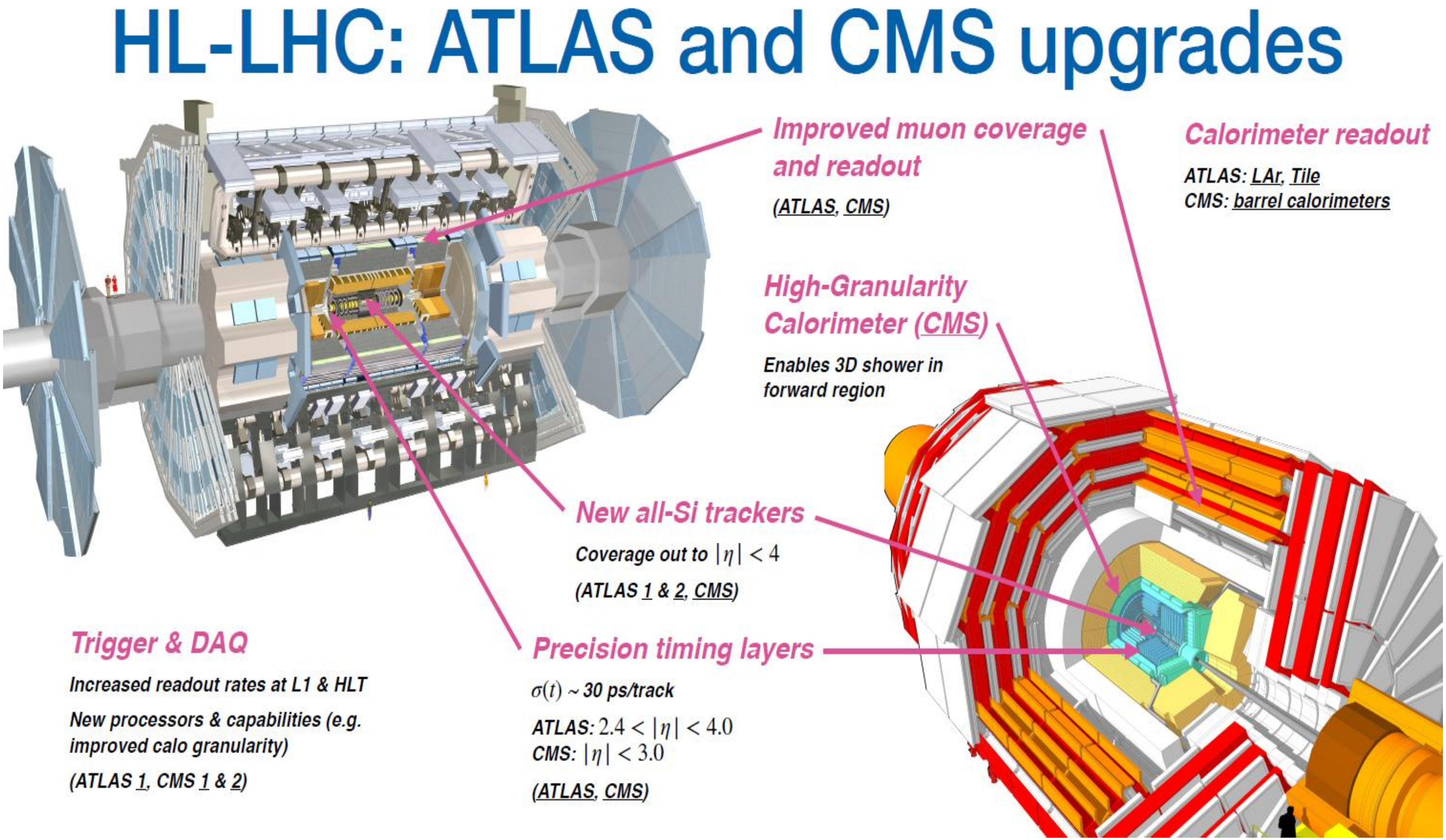
Near Future HE experiments

HL-LHC

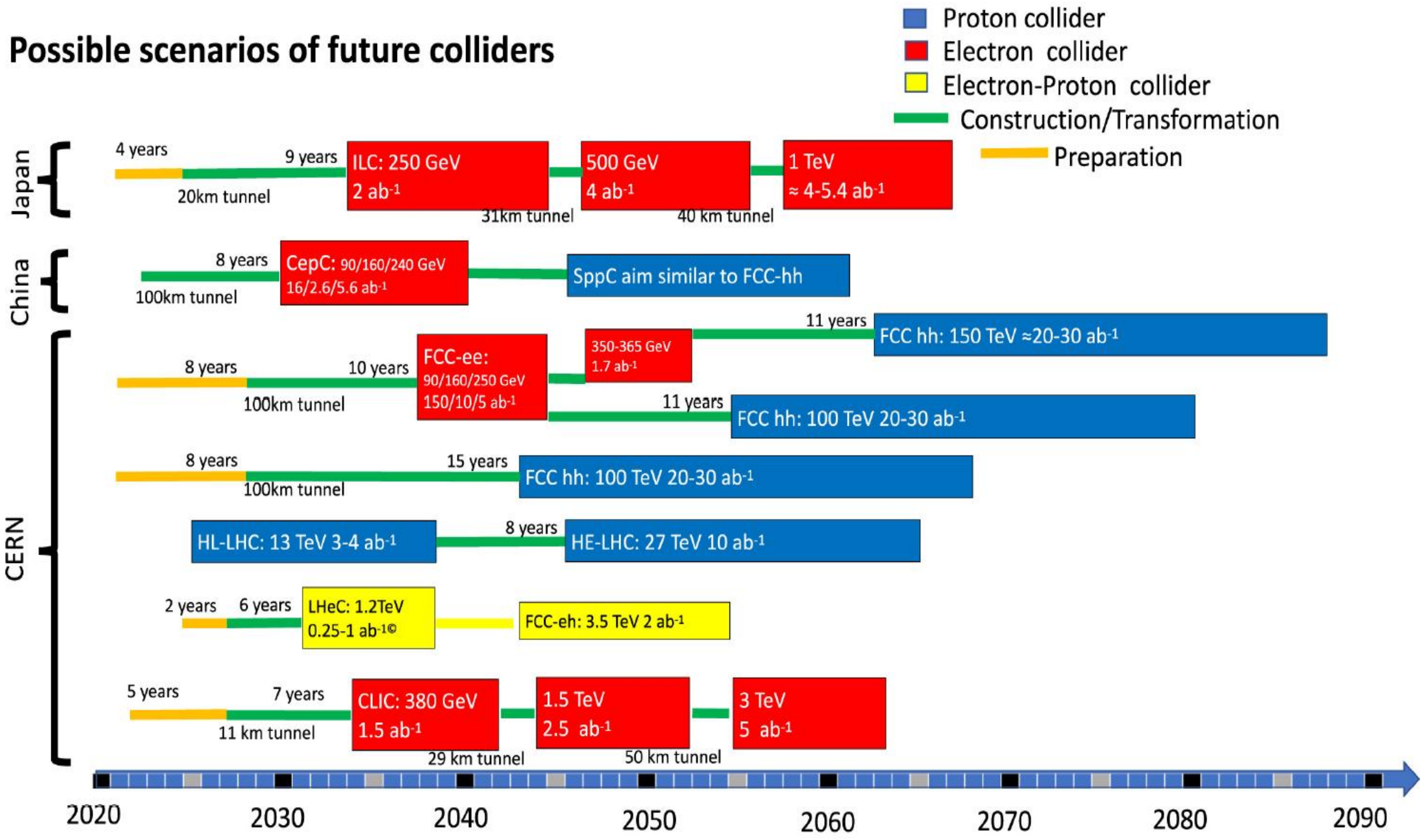
- Fully approved in 2016, technology available, construction well underway!



Near Future HE experiments



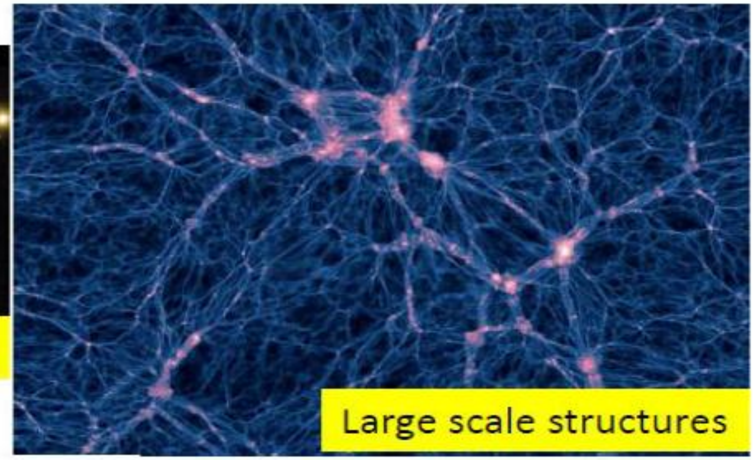
Future HE experiments

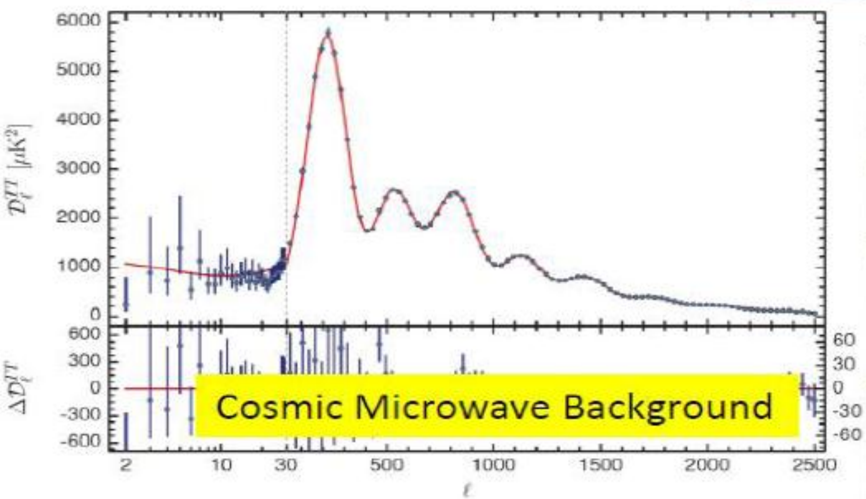


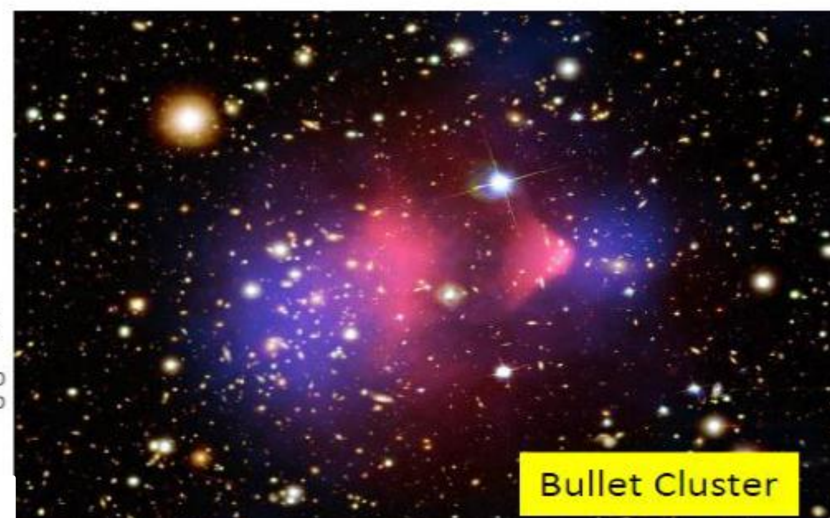
EXTRA SLIDES

Why Dark Matter?

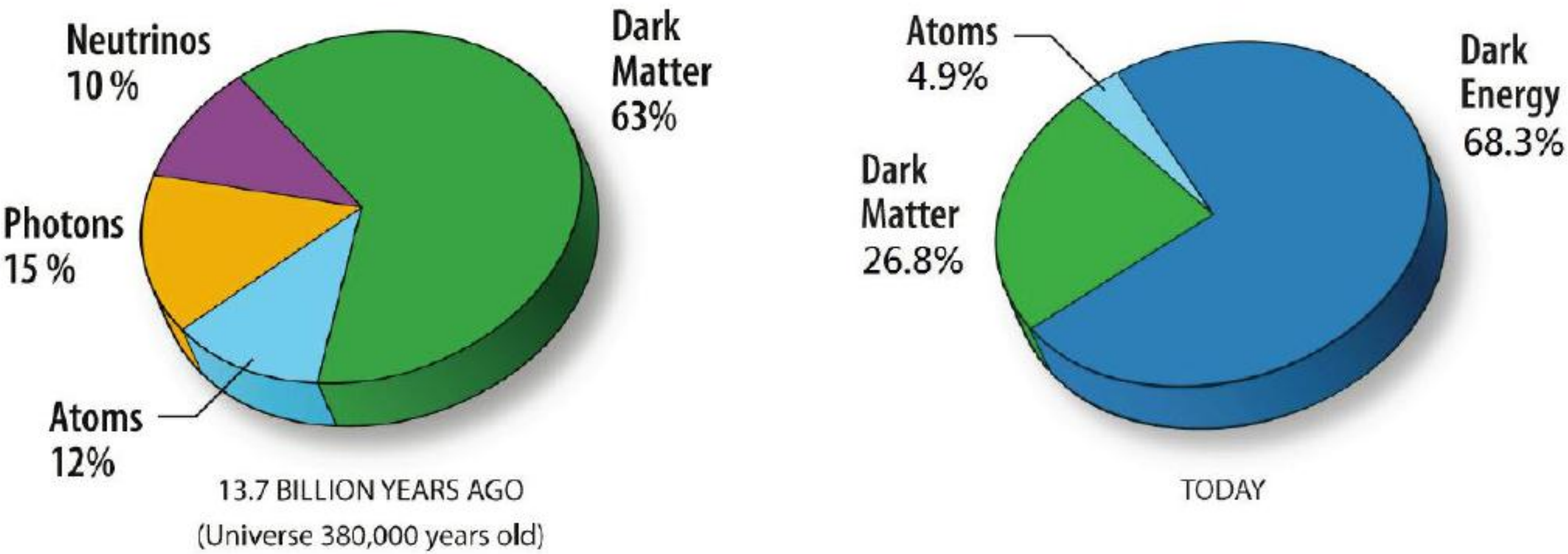
Evidence piling up...







What do we know about Dark Matter

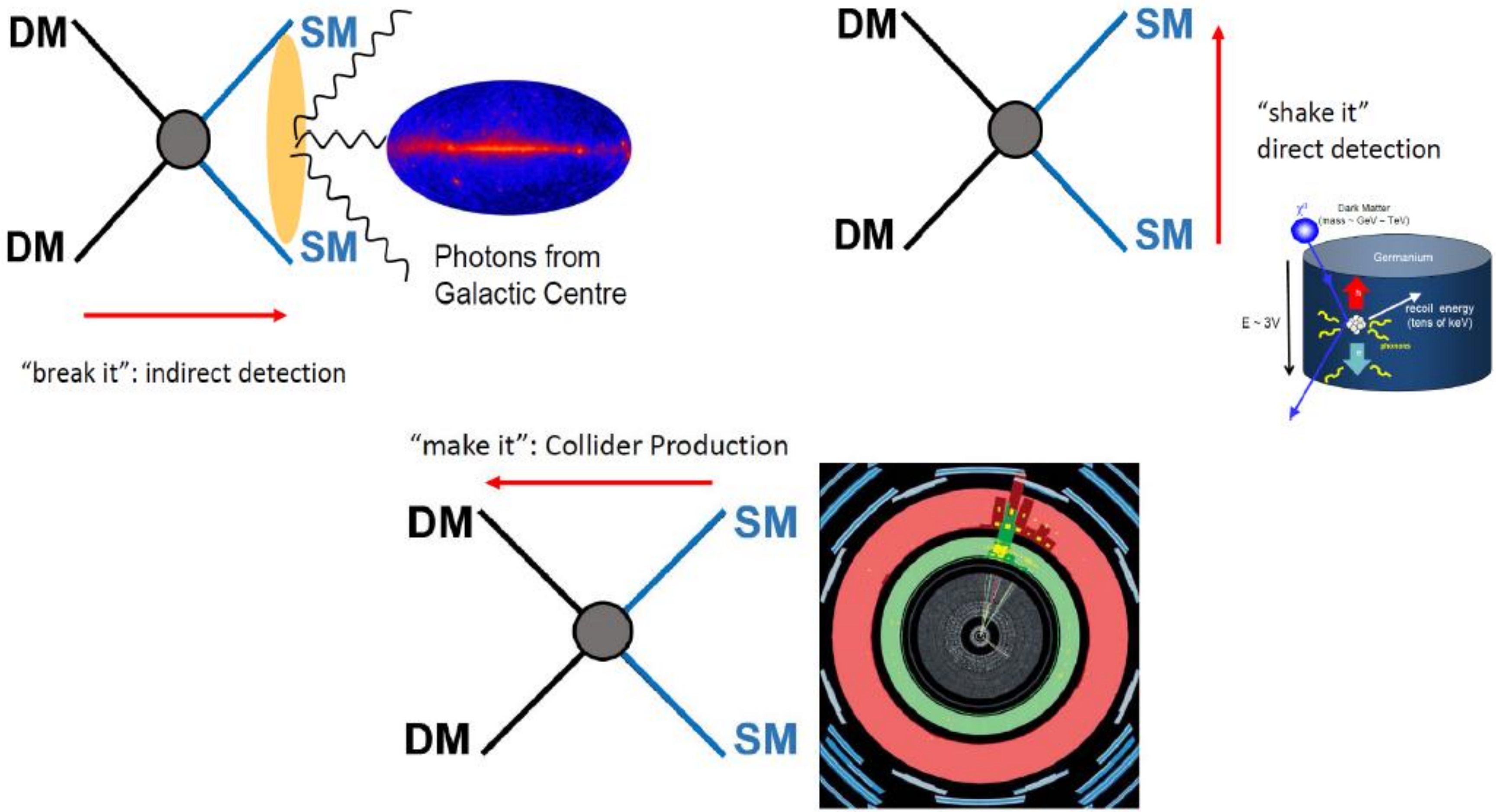


Strong astrophysical evidence for the existence of dark matter

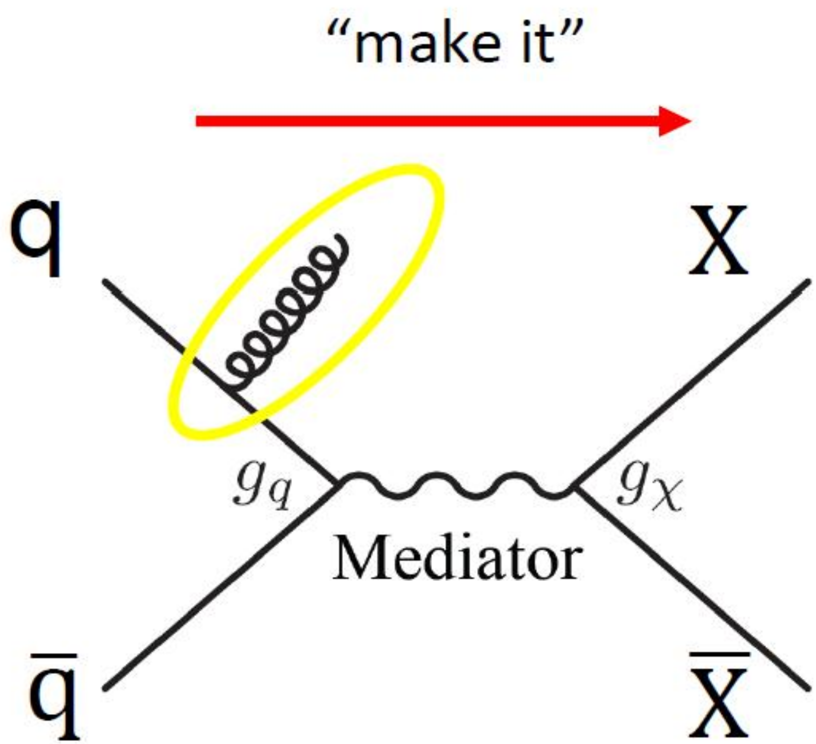
What do we know about Dark Matter

- Massive
- Non-relativistic (slow)
- Long lived (old)
- No electric or colour charge
- Very weakly interacting with ordinary matter
- Subject to gravity interactions

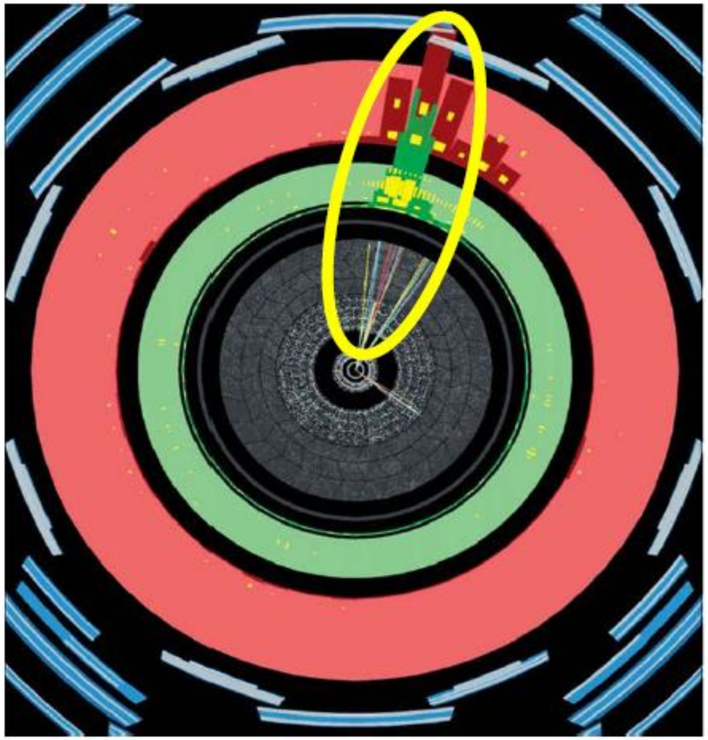
Experimental detection of Dark Matter



Dark Matter serches at Colliders

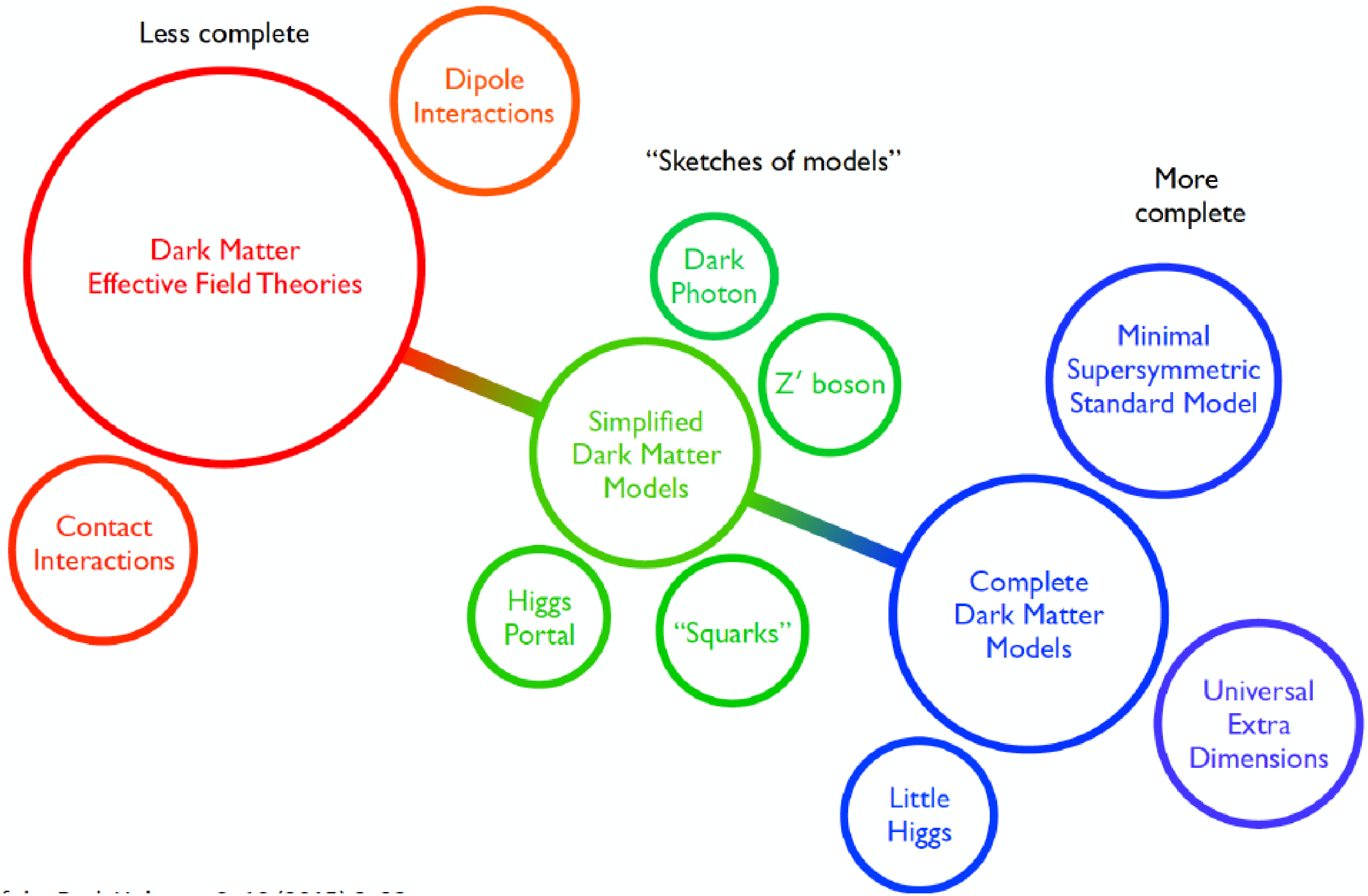


g_q and g_X coupling strengths

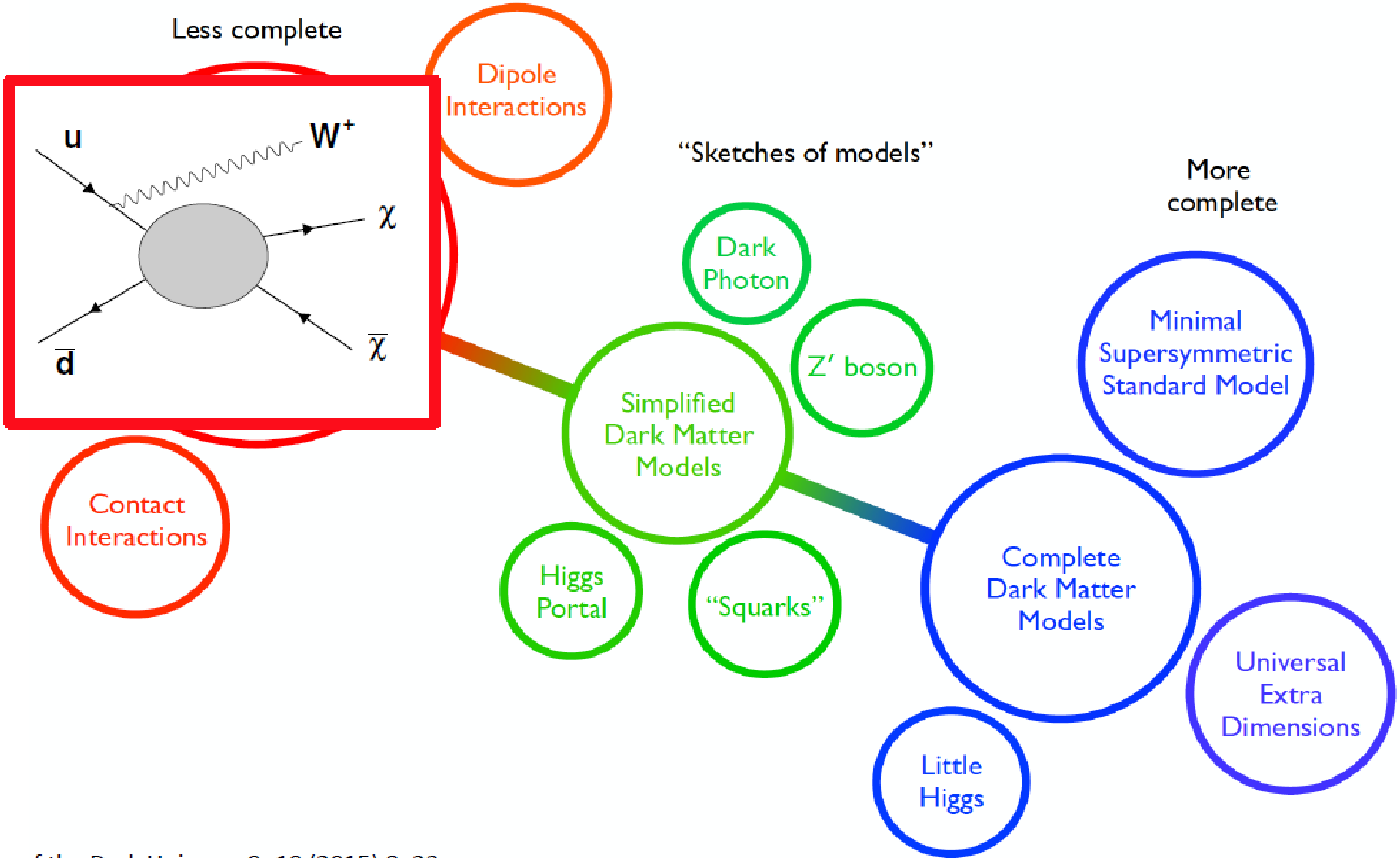


Empty detector + something

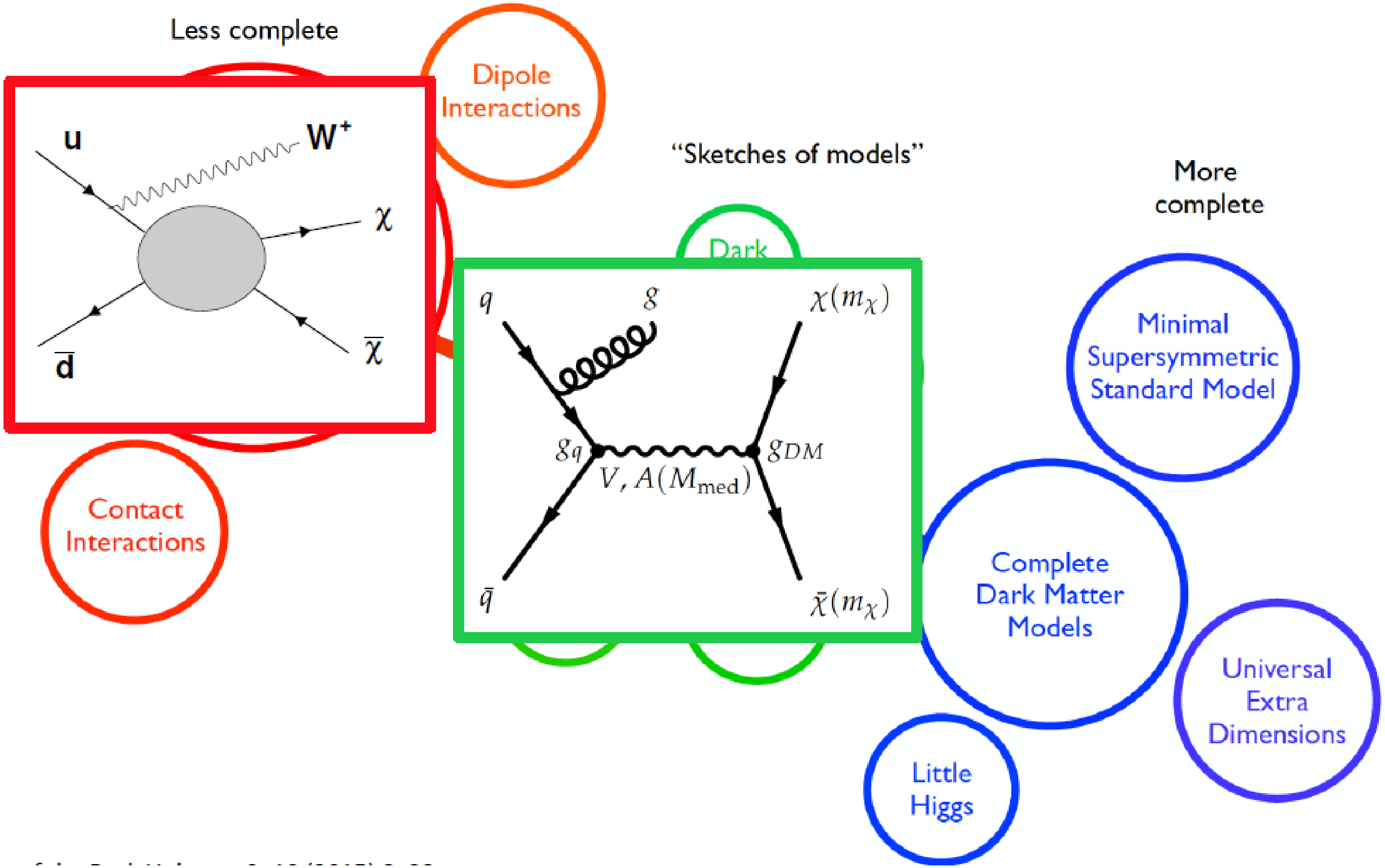
Dark Matter theory space



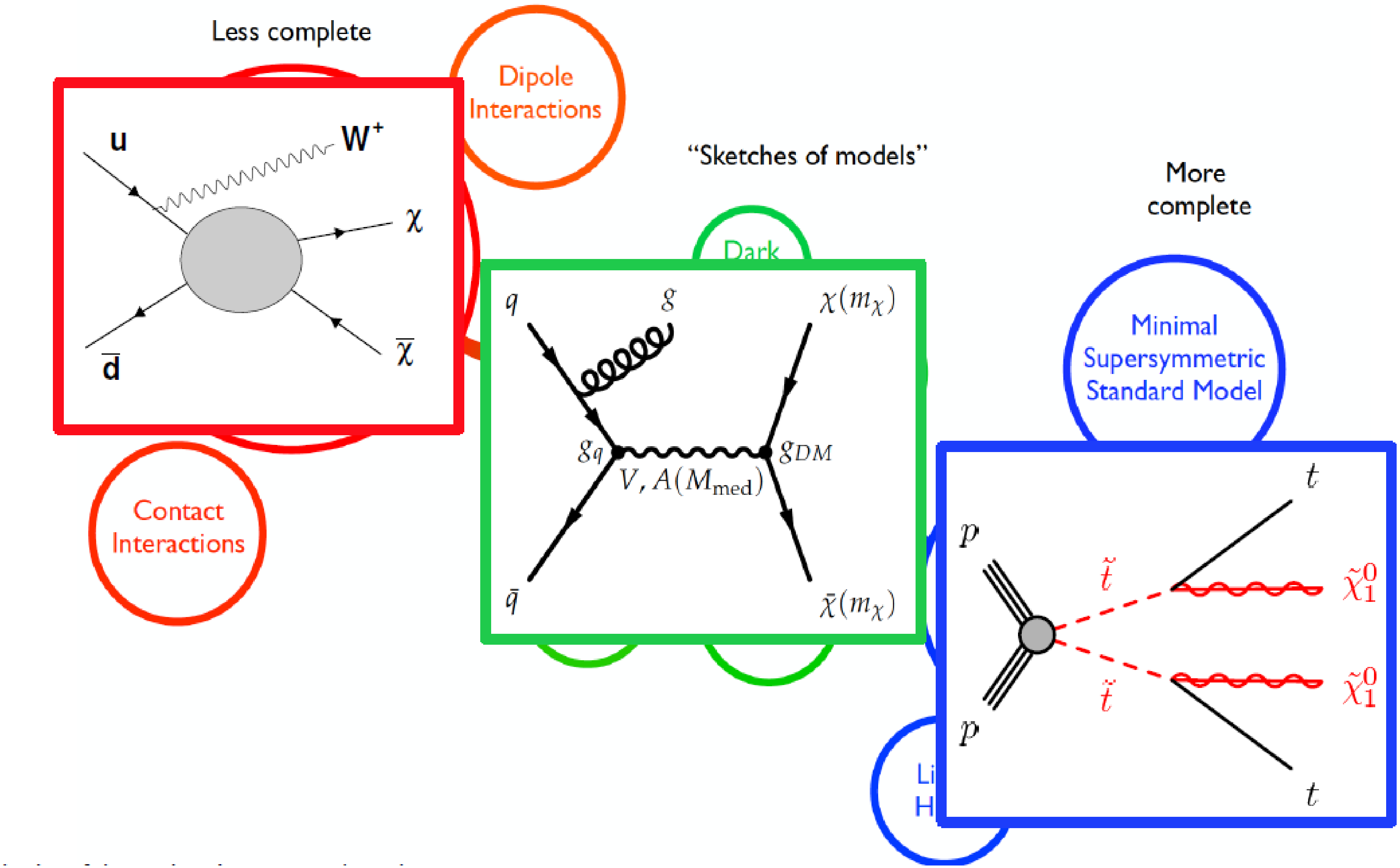
Dark Matter theory space



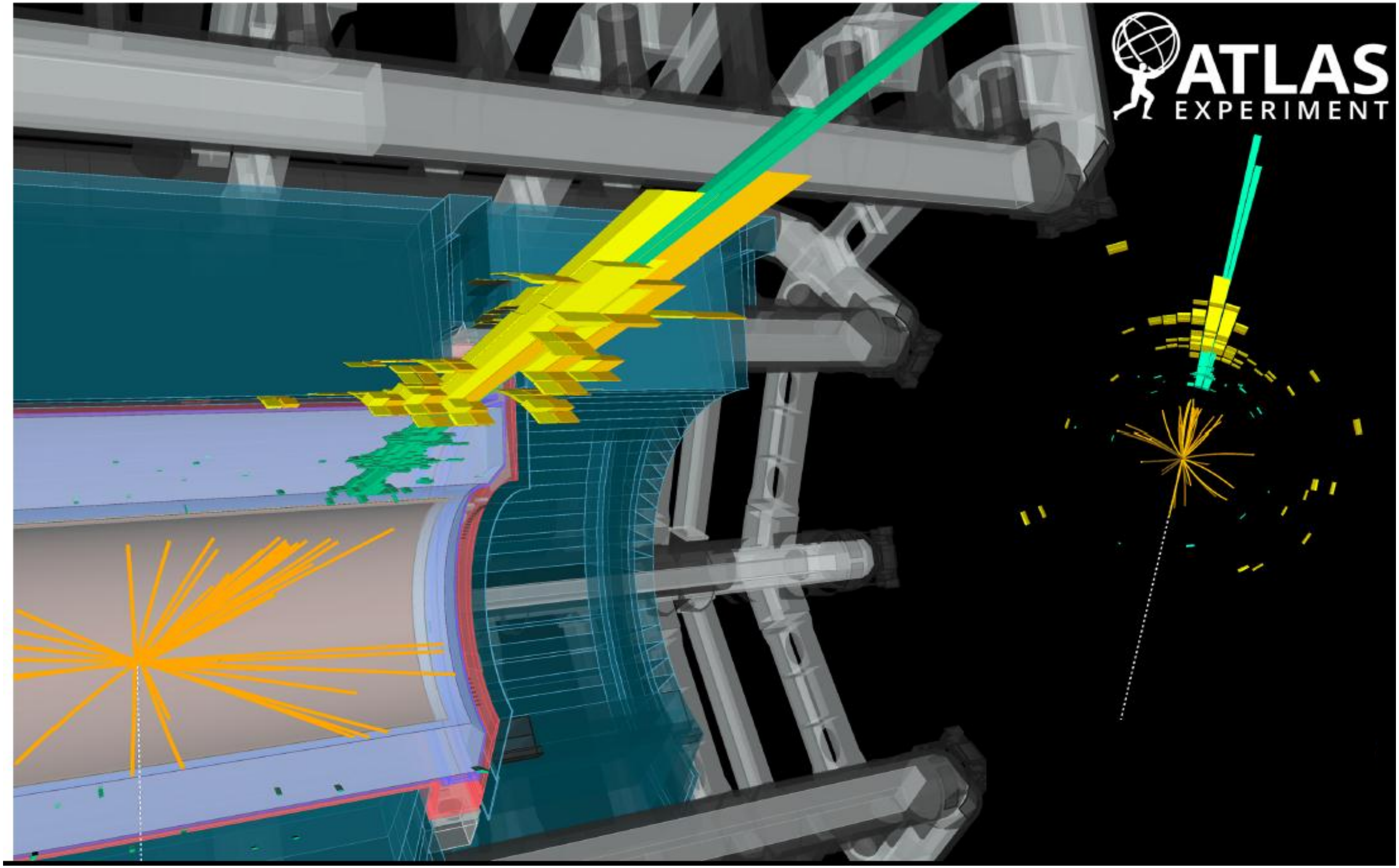
Dark Matter theory space



Dark Matter theory space

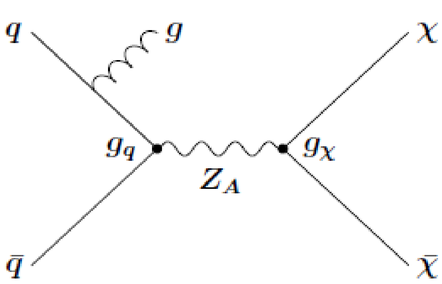


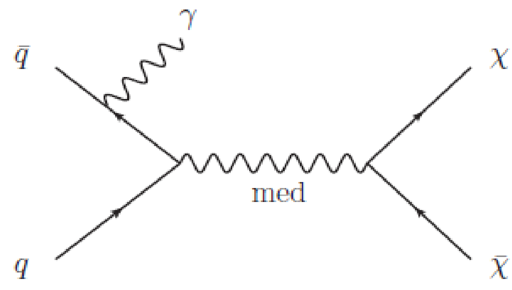
Searches for DM with (E_T^{miss} +X) Signatures

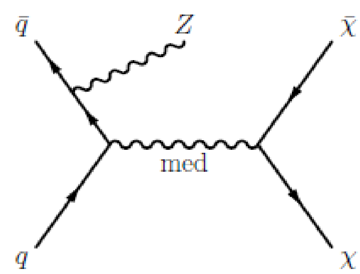


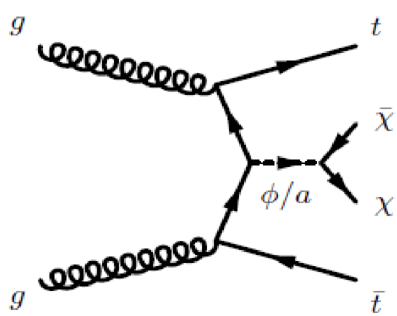
(E_T^{miss} +X) or Mono-X Signatures

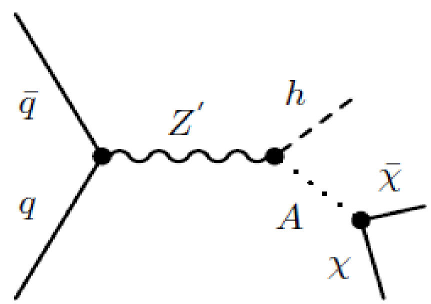
SM-DM mediator decays to DM pairs $\chi\bar{\chi}$ when $M_{\text{med}}/2 > m_\chi$.
DM escapes detection $\Rightarrow E_T^{\text{miss}} + X$ signature where
X = SM particles that tag the event, $X = \text{jet}, \gamma, V, t, b, h \ldots$









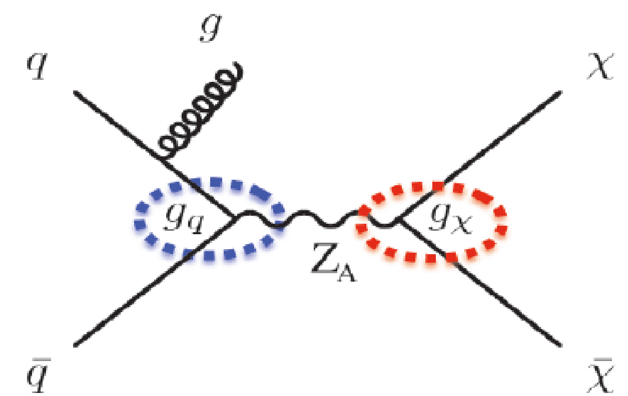


Mediators: vector, axial-vector, scalar, pseudoscalar
Parameters: $m_{\text{med}}, m_\chi, g_q, g_\chi$

Simplified Model

Simplified Model

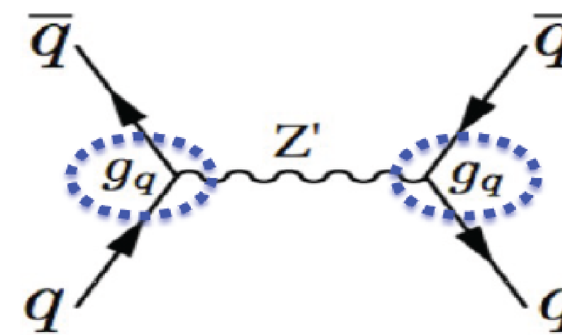
$SM \rightarrow mediator \rightarrow DM$



→Mono-X signature

E_T^{miss} + jet, W/Z/H, γ, …

$SM \rightarrow mediator \rightarrow SM$



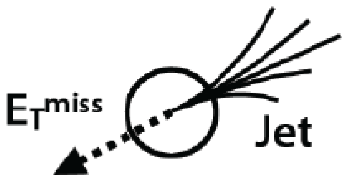
→resonant production

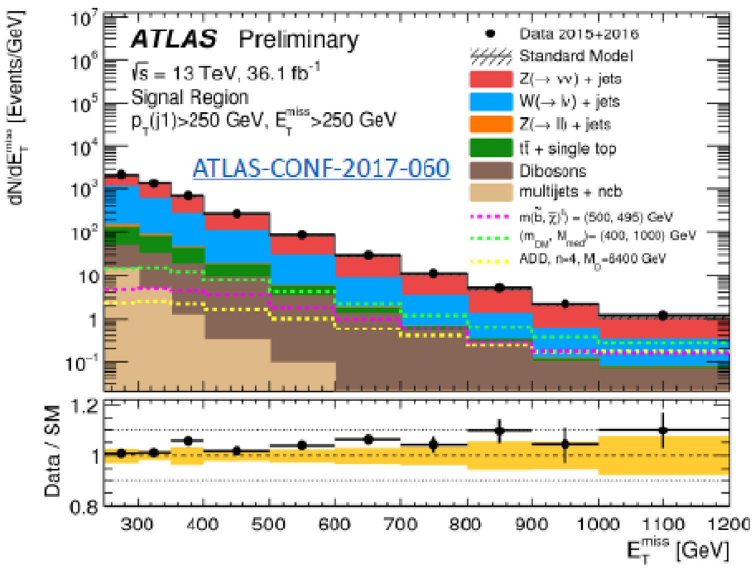
Dijet, ditop, dilepton.....

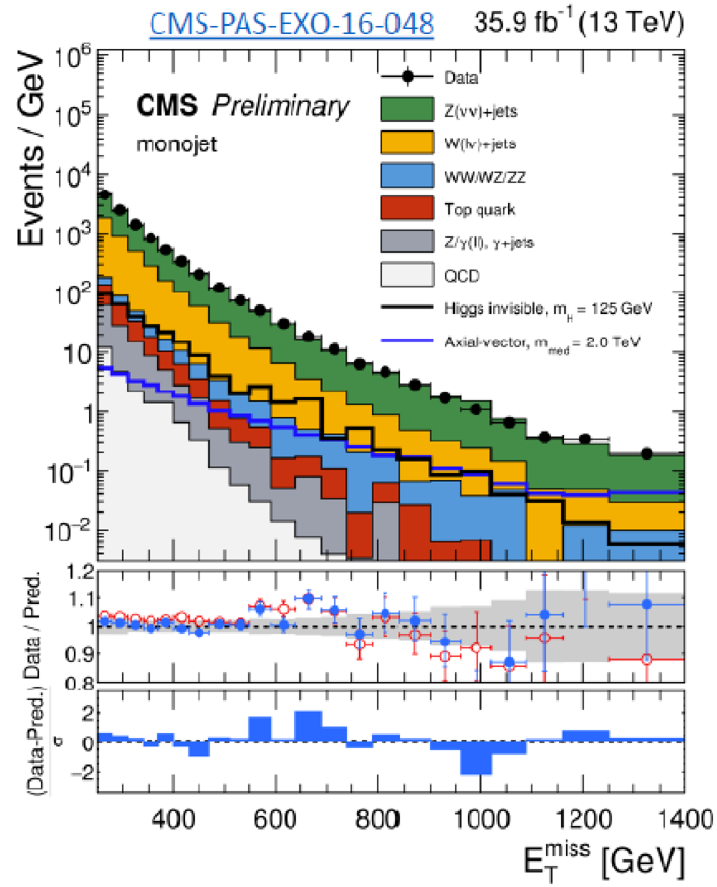
	spin 0	spin 1
Charge	Q=0 for s-channel	
Lorentz structure	Scalar $g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f$	Vector $g_q \sum_q V_\mu \bar{q} \gamma^\mu q$
	Pseudoscalar $g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f} \gamma^5 f$	Axial-vector $g_q \sum_q A_\mu \bar{q} \gamma^\mu \gamma^5 q$
Coupling	∝ mass	∝ charge

Mono-X searches

Mono-jet







ATLAS

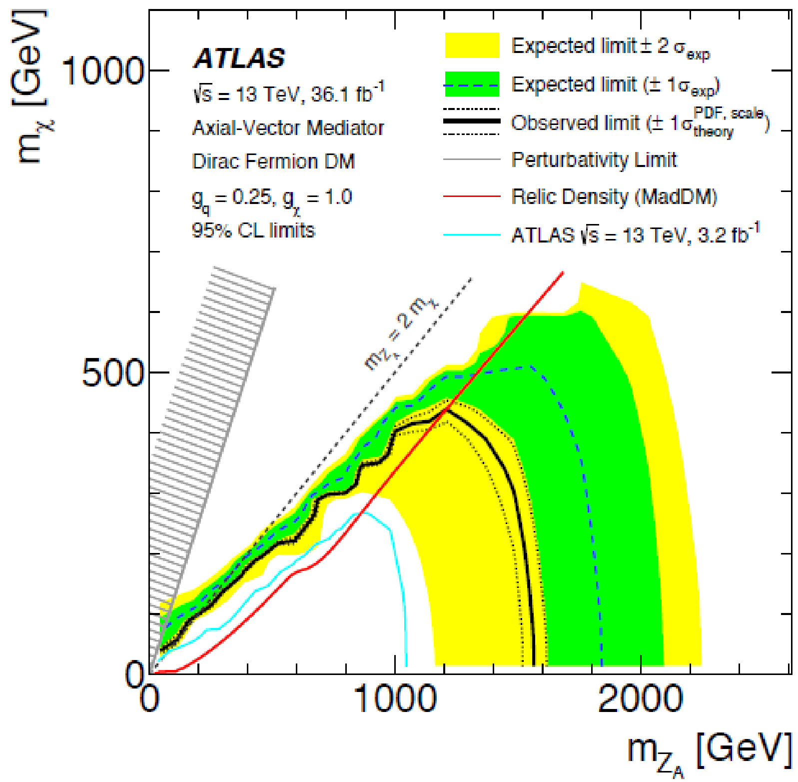
- $E_T^{miss} > 250$ GeV, $\Delta\varphi(\text{jet}, p_T^{miss}) > 0.4$
- Jet $p_T > 250$ GeV, $|\eta| < 2.4$
- $N_{jets} \leq 4$

CMS

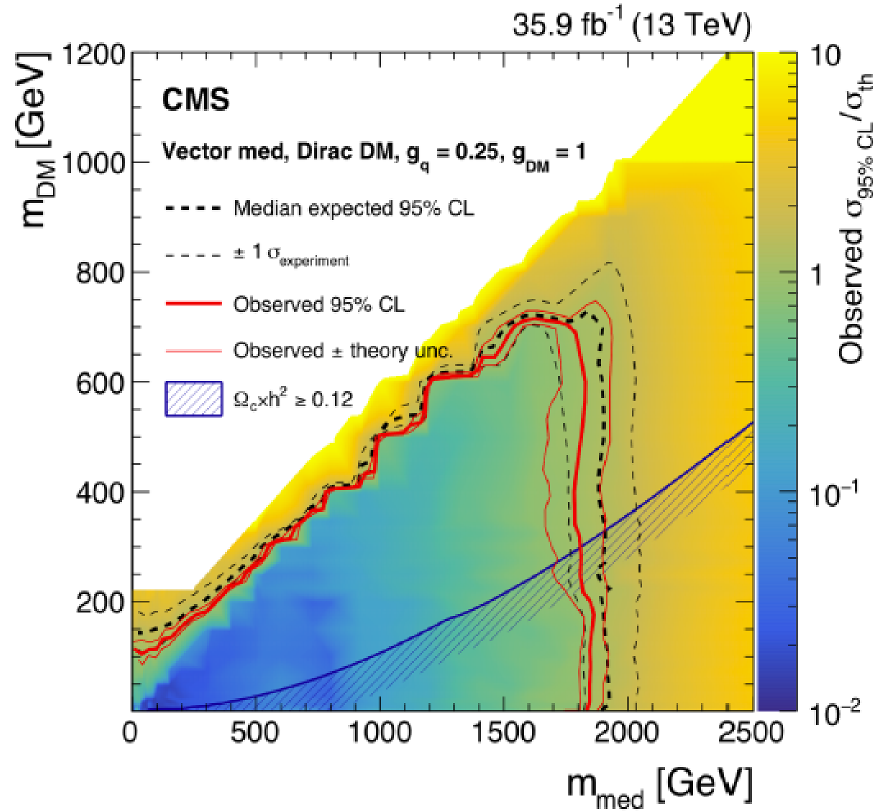
- $E_T^{miss} > 250$ GeV
- Jet $p_T > 100$ GeV, $|\eta| < 2.5$

Mono-X searches

Axial-Vector Mediator



Vector Mediator

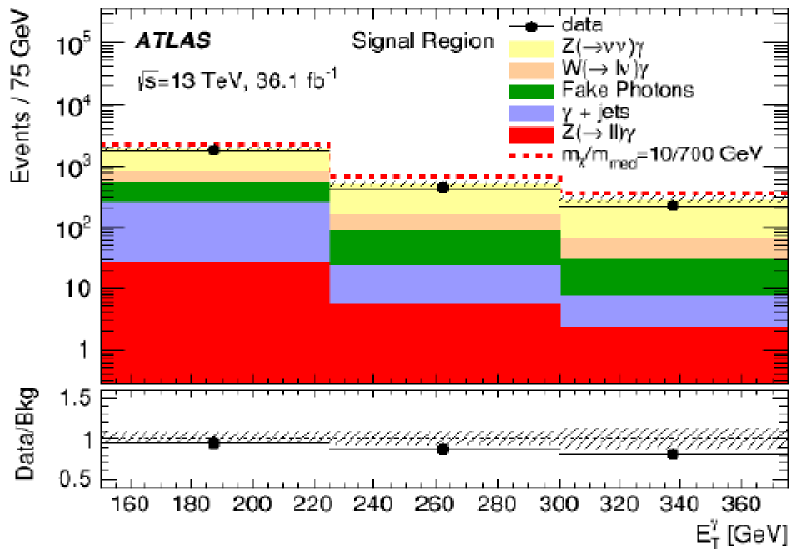


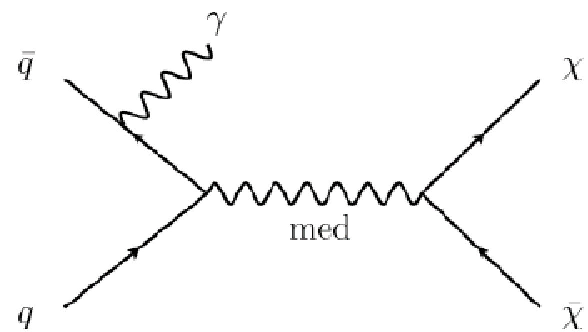
For couplings $g_q = 0.25,\ g_\chi = 1.0$, axial-vector and vector mediators excluded up to 1.8 TeV (1.55 TeV) by CMS (ATLAS) for $m_\chi \sim 1$ GeV.

JHEP 01 (2018) 126
arXiv:1712.02345

Mono-X searches

Mono-photon



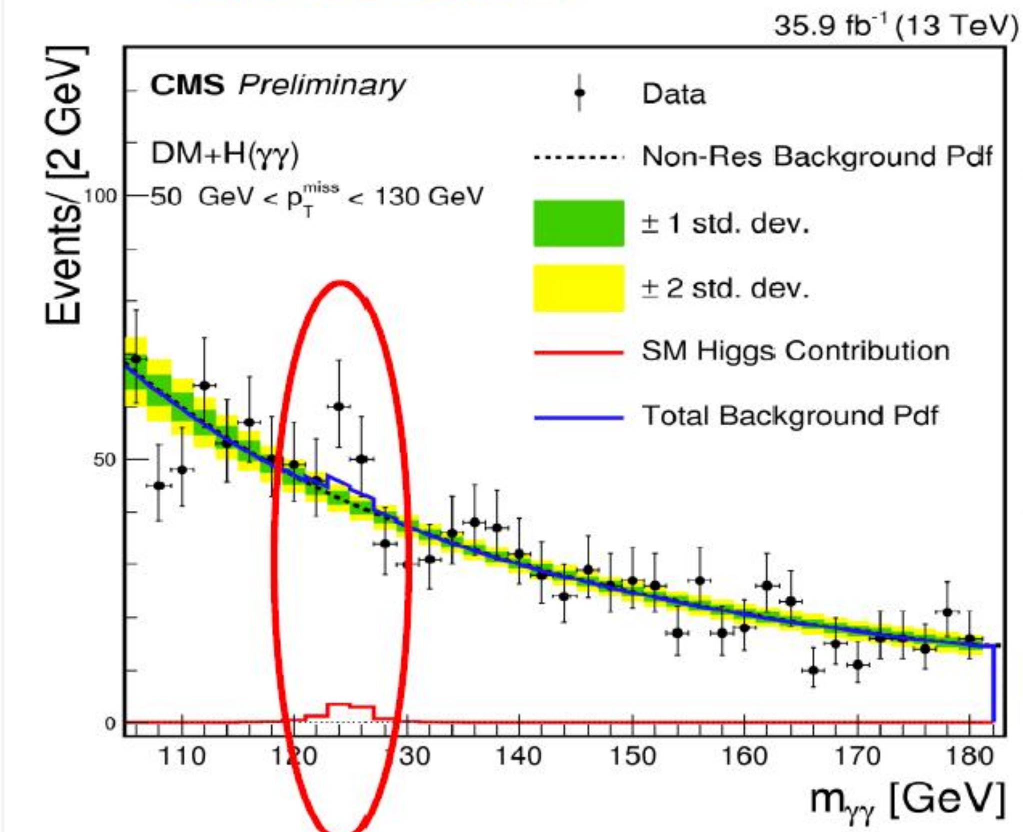


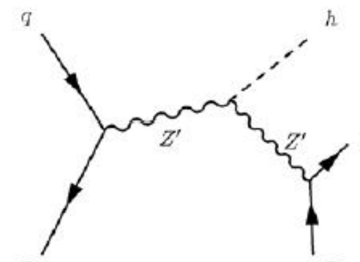
- Photon $E_T > 150$ GeV, $|\eta| < 2.37$
- $E_T^{miss}/\sqrt{\sum E_T} > 8.5\ \mathrm{GeV}^{1/2}$
- $\Delta\varphi(\mathrm{photon}, E_T^{miss}) > 0.4$
- $N_{jets}(p_T > 30\ \mathrm{GeV}, |\eta| < 4.5) \leq 1$

Mono-X searches

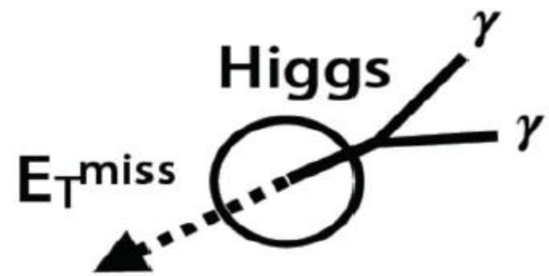
Mono-Higgs

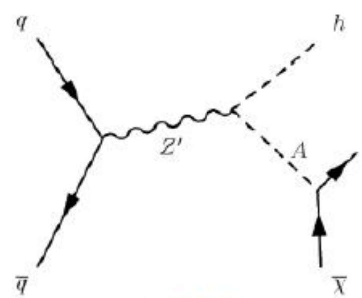
CMS-PAS-EXO-16-054





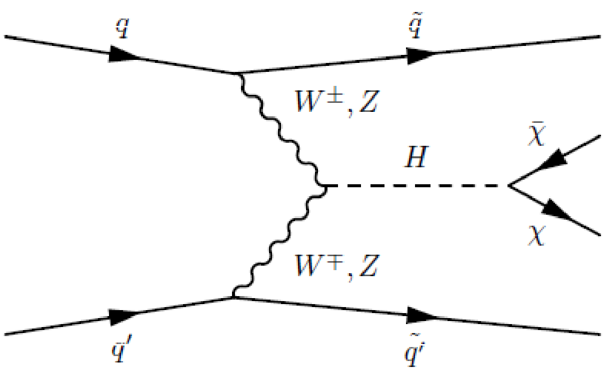
Baryonic Z' model
Non resonant





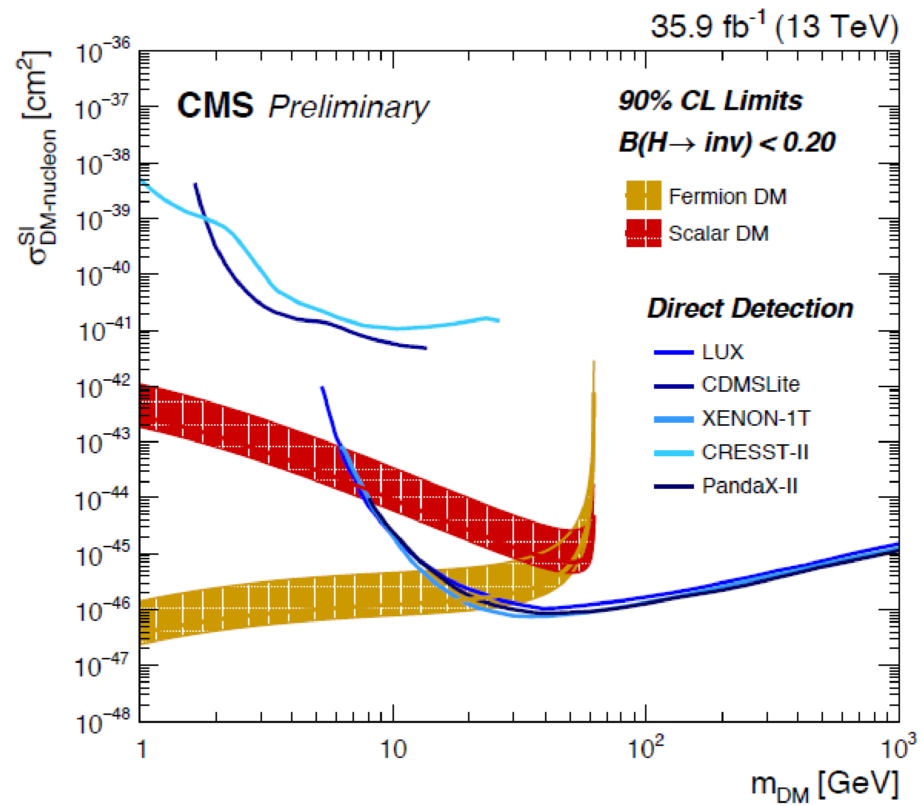
2HDM

H-> invisible: Comaprison with DD



$\mathcal{B}(\mathrm{H}\rightarrow\mathrm{inv}) < 0.2$ at 90% CL interpreted in context of Higgs-portal DM model.

Strongest limits for fermion (scalar) χ for $m_\chi < 20$ (7) GeV.

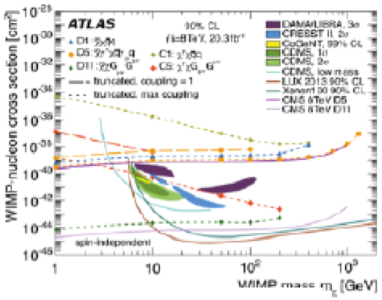


CMS-PAS-HIG-17-023 (14 March 2018)

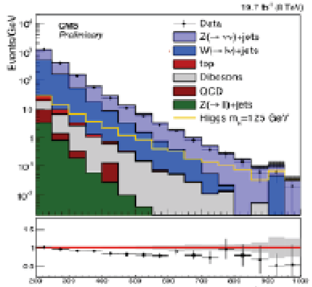
Mono-Mania!!

- Hundreds of phenomenology papers
- Thousands of citations of collider DM
- "ISR tagging" established technique for all new particle searches (not just DM)

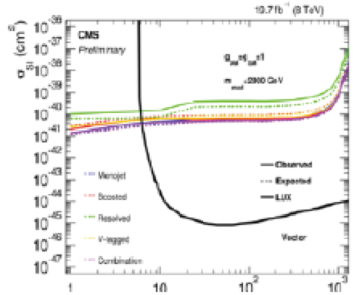
Mono-Mania!!



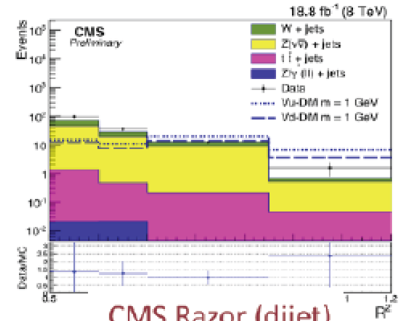
ATLAS Monojet
EPJC (2015) 75:299



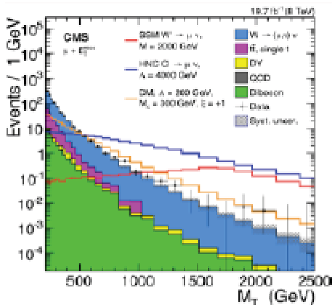
CMS j/V (mono/dijet)
PAS-EXO-12-055



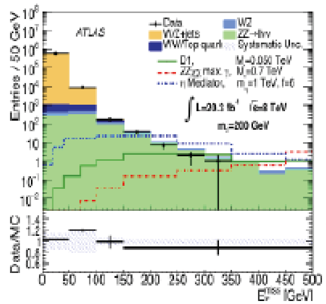
CMS j/V (mono/dijet)
PAS-EXO-12-055



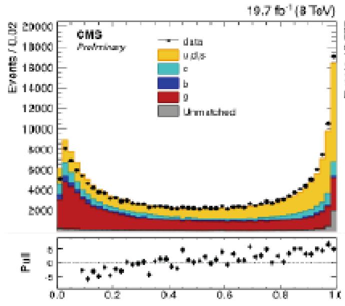
CMS Razor (dijet)
PAS-EXO-14-004



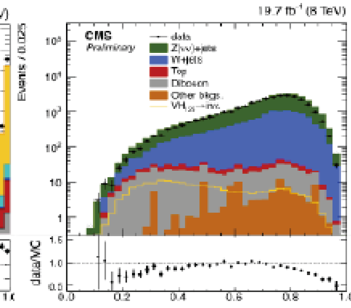
CMS, ATLAS MonoW
PRD 91, 092005, JHEP 09 (2014) 037 (2015)



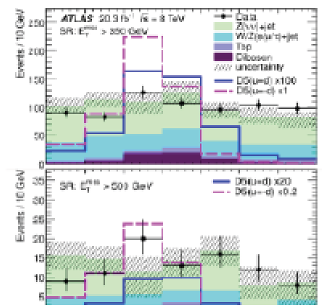
CMS, ATLAS MonoZ
EXO-12-054, PRD 90, 012004 (2014)



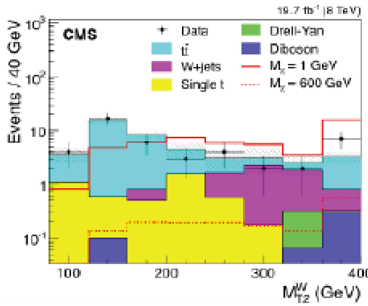
CMS MonoV (resolved)
PAS-EXO-12-005, PAS-JME-14-002



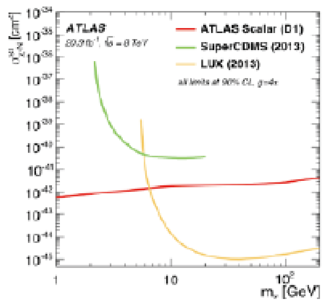
CMS MonoV (boosted)
EXO-12-005/JME-14-002



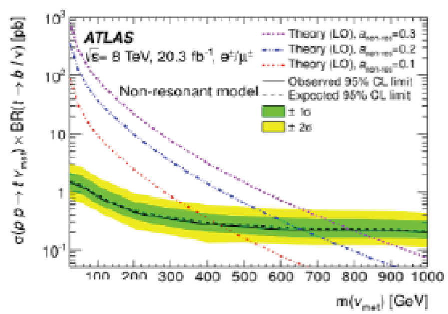
ATLAS MonoV (boosted)
ATLAS, PRL 112, 041802 (2014)



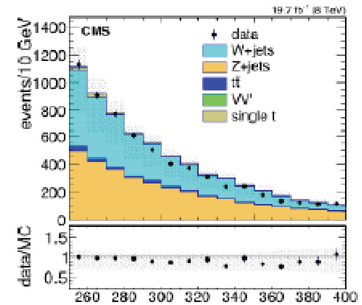
CMS TopPairs
CMS, JHEP 06 (2015) 121



ATLAS TopPairs
ATLAS, EPJC (2015) 75:92

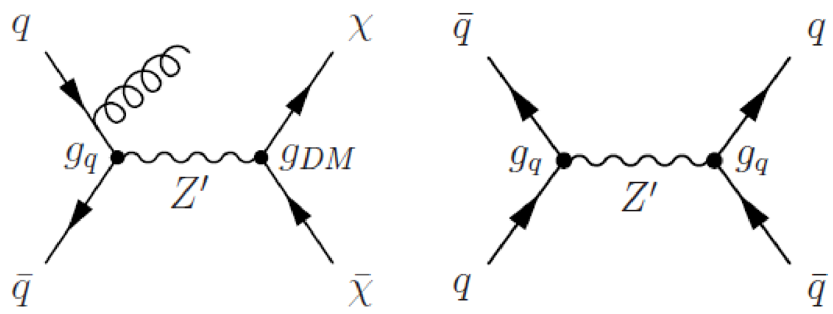


CMS MonoTop
CMS, PRL 114 (2015) 101801



ATLAS MonoTop
ATLAS, JHEP 11 (2014) 118

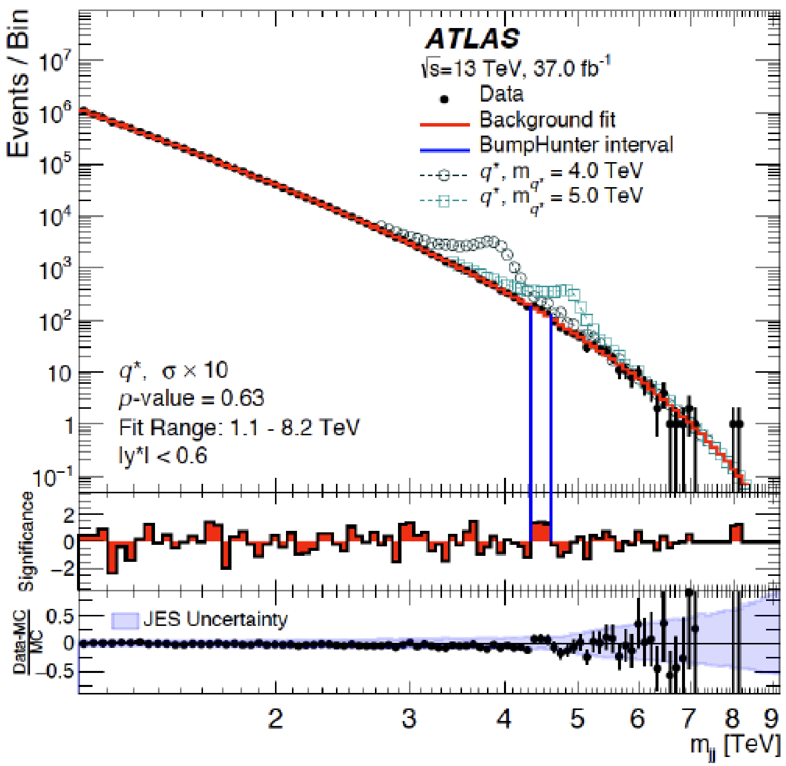
LHC is a mediator machine



Signature: 2 high $p_{\rm T}$ jets,
same as search for leptophobic Z'.

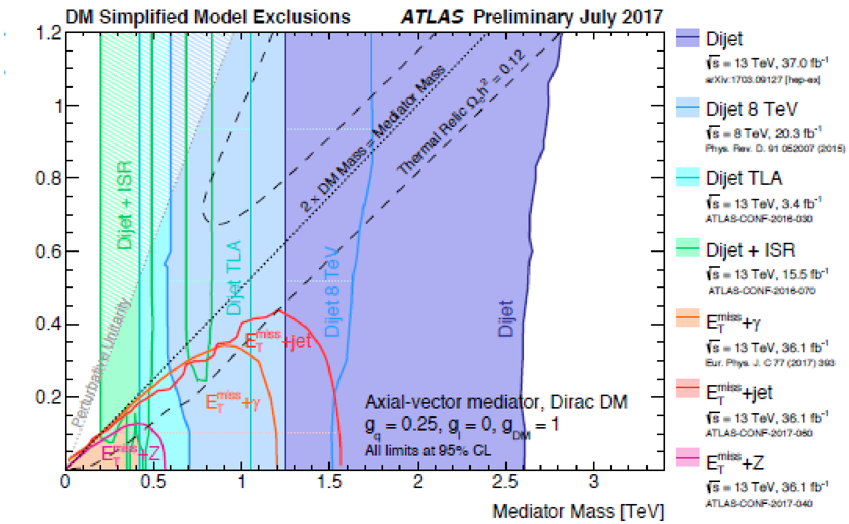
m_{jj} is the discriminant,
search for bump on a smooth,
falling background.

Background modeled by
a parameterized function.

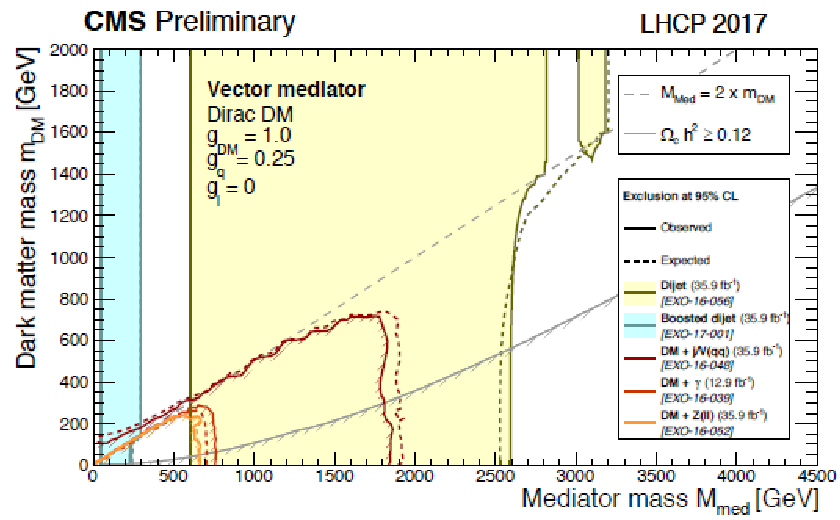


Limits on DM mass vs Mediator mass

Axial-Vector Mediator



Vector Mediator



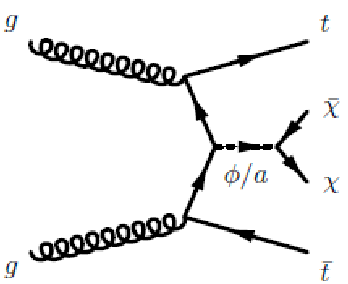
Couplings: $g_{\rm DM} = 1,\ g_q = 0.25,\ g_l = 0$ (leptophobic)

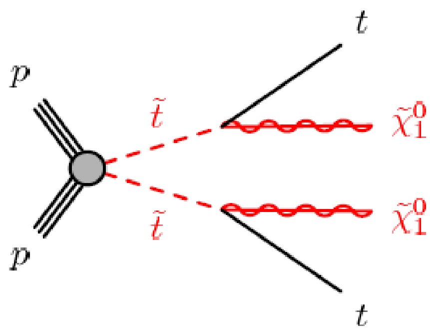
Dijet searches significantly extend DM reach, particularly for $m_{\rm DM} > M_{\rm med}/2$. Limits are same as leptophobic Z' search.

Mediator masses excluded up to about 2.6 TeV for low m_χ.

Search for DM + Heavy Flavor

For spin-0 mediator ϕ or a,
MFV $\Rightarrow$ Yukawa couplings
ϕ and a couple strongly to t or b

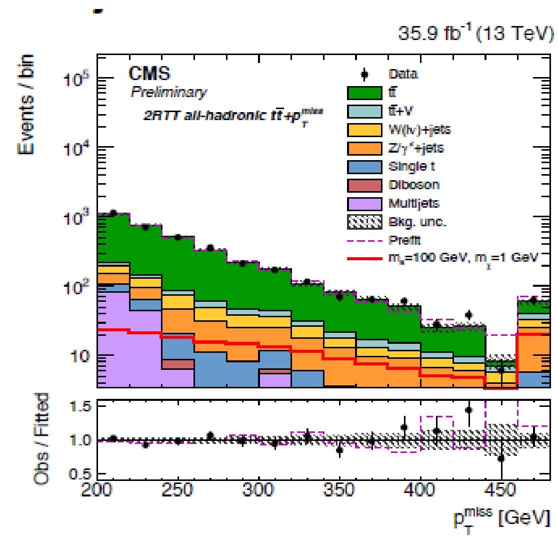


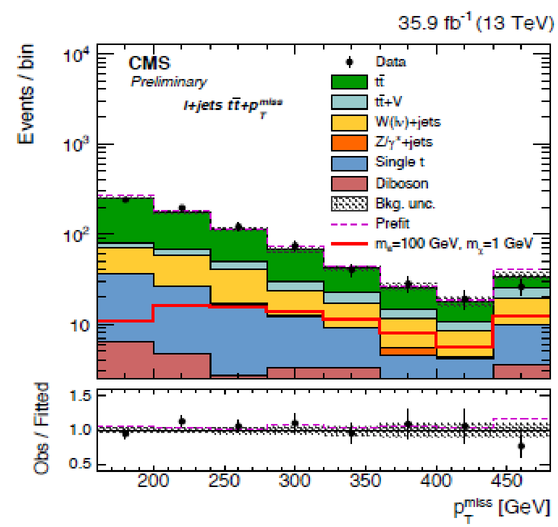


$(t\bar{t} + \chi\bar{\chi})$ discriminant is p_T^{miss}.

SRs based on $t\bar{t}$ decays:
all-hadronic, ℓ + jets, dileptonic
provide complementary sensitivity.

$t\bar{t}$, W + jets, Z + jets backgrounds
constrained by CRs.

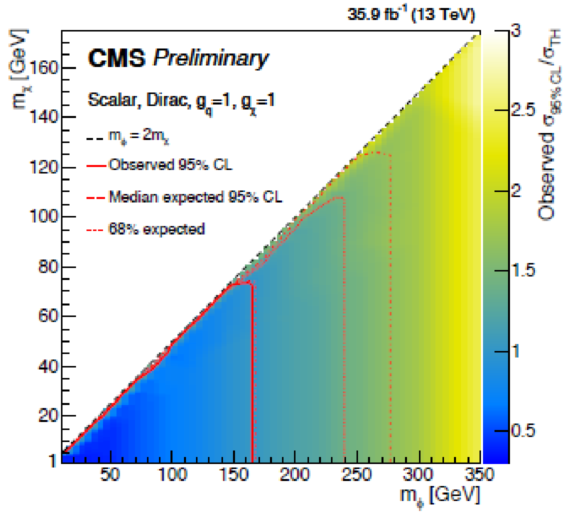




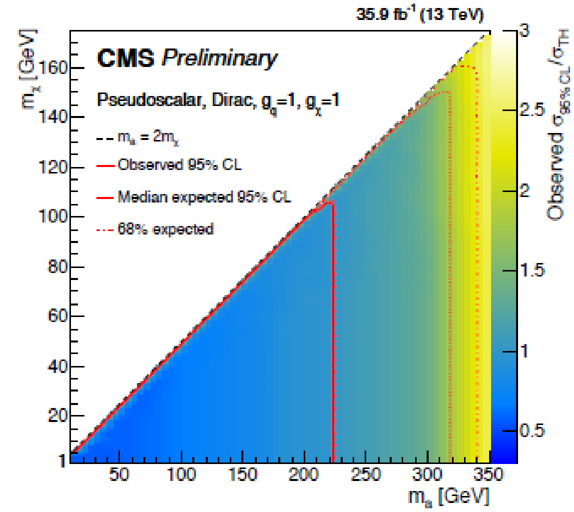
Search for DM + Heavy Flavor

For $g_q = 1,\ g_{\mathrm{DM}} = 1,$ $m_\chi = 1$ GeV: exclusion for $m_\phi < 165$ GeV and $m_a < 223$ GeV.

Scalar Mediator

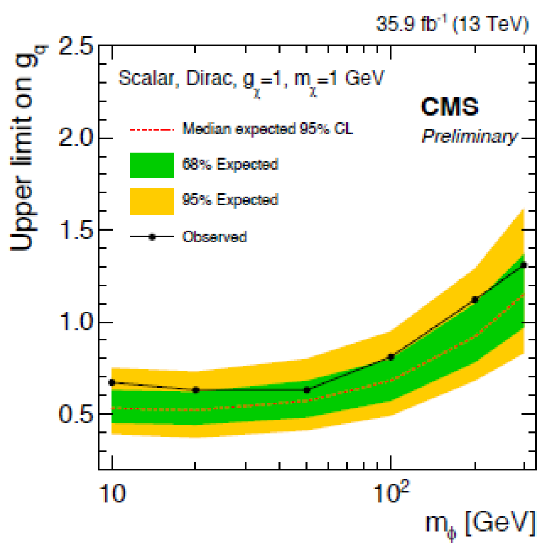


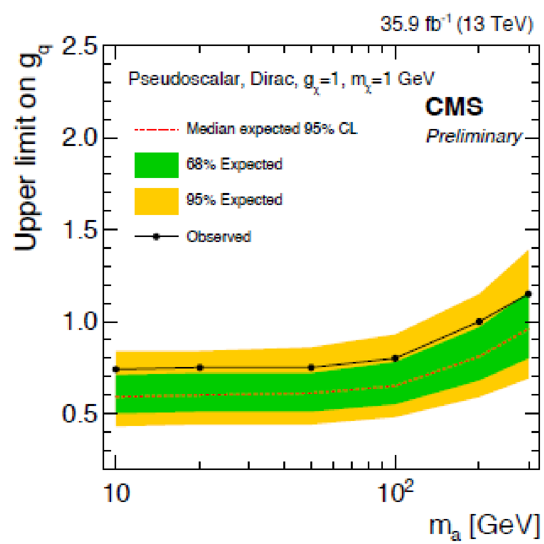
Pseudoscalar Mediator



CMS-PAS-EXO-16-049 (3 April 2018)

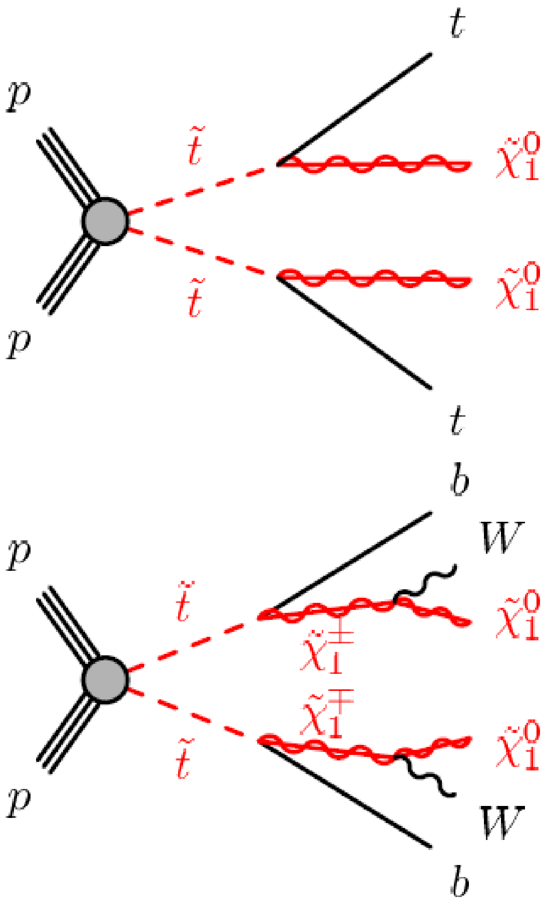
For $g_{\mathrm{DM}} = 1$, $m_\chi = 1$ GeV: limits on coupling of ϕ or a to SM quarks.

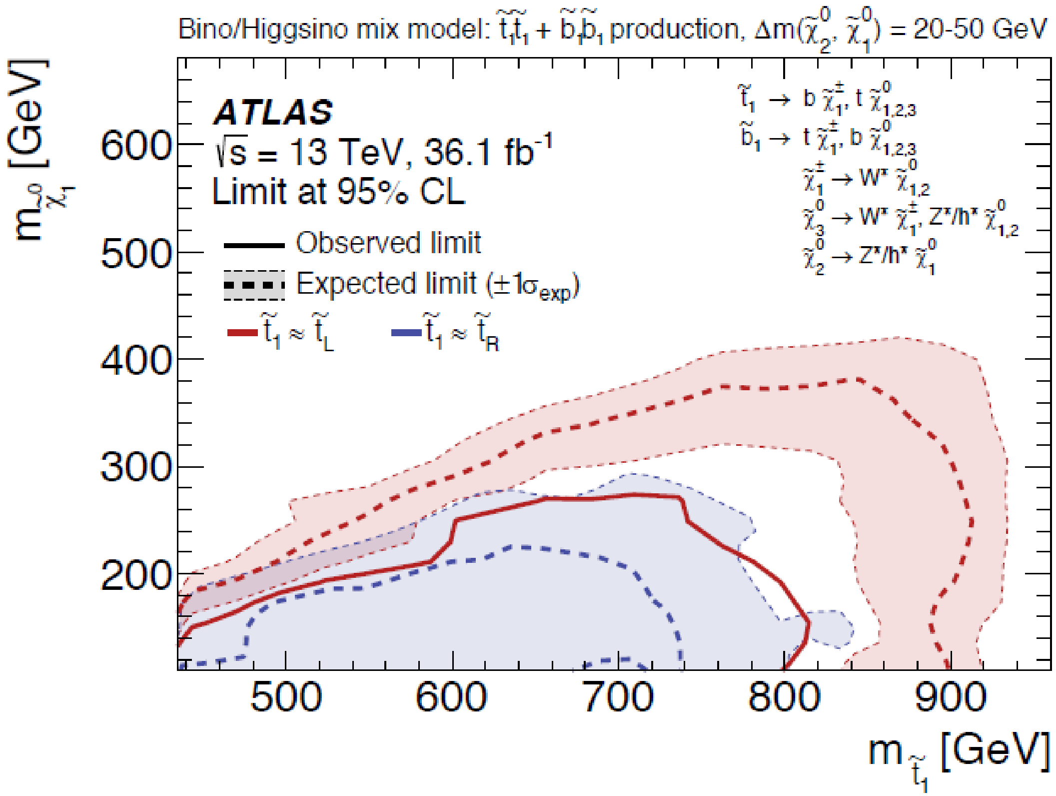




SUSY DM candidates

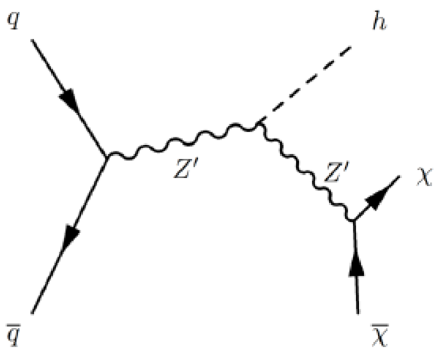
In many SUSY models the LSP is stable and weakly interacting $\Rightarrow$ a DM candidate. Some models are tuned to reproduce the DM relic density, e.g. the "well tempered neutralino" scenario.





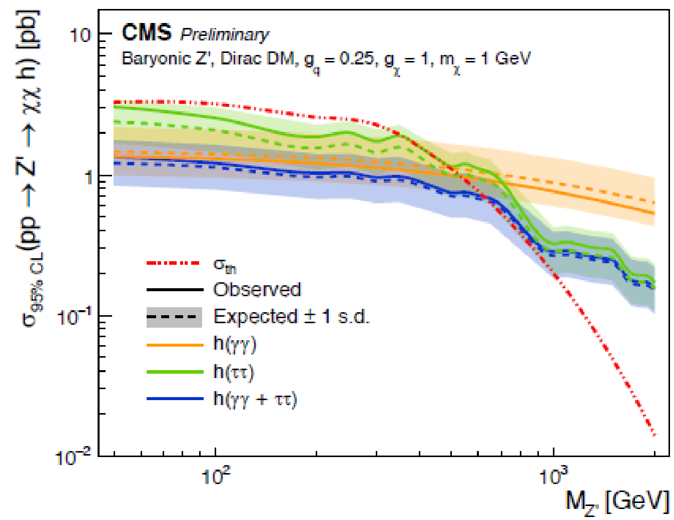
Search for DM + Higgs

$E_T^{miss} + h$ events tagged by Higgs boson.
h not from ISR but couples to the mediator.



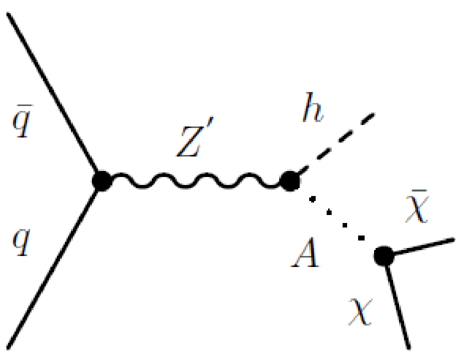
Baryonic Z' Model

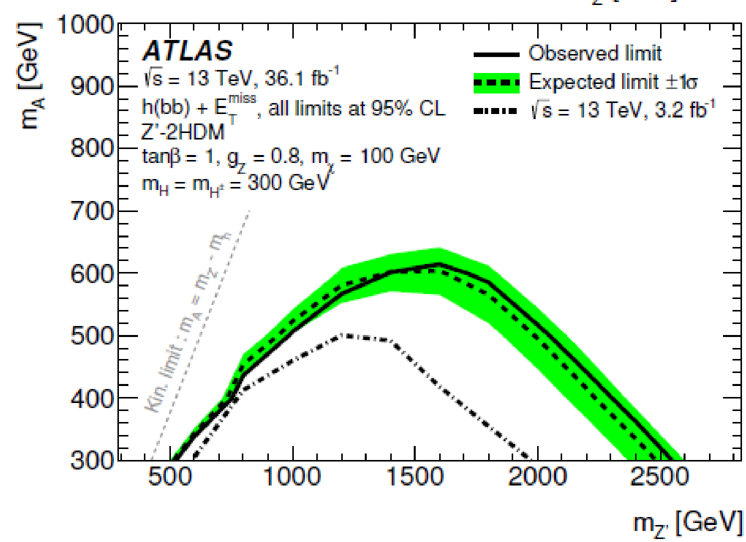
$h \to \gamma\gamma$ and $\tau^+\tau^-$
Z' excluded up to 815 GeV for low m_χ



Z'-2HDM Model

$h \to b\bar{b}$ with resolved or merged jets.
Z' excluded up to 2.6 TeV and A up to 600 GeV.



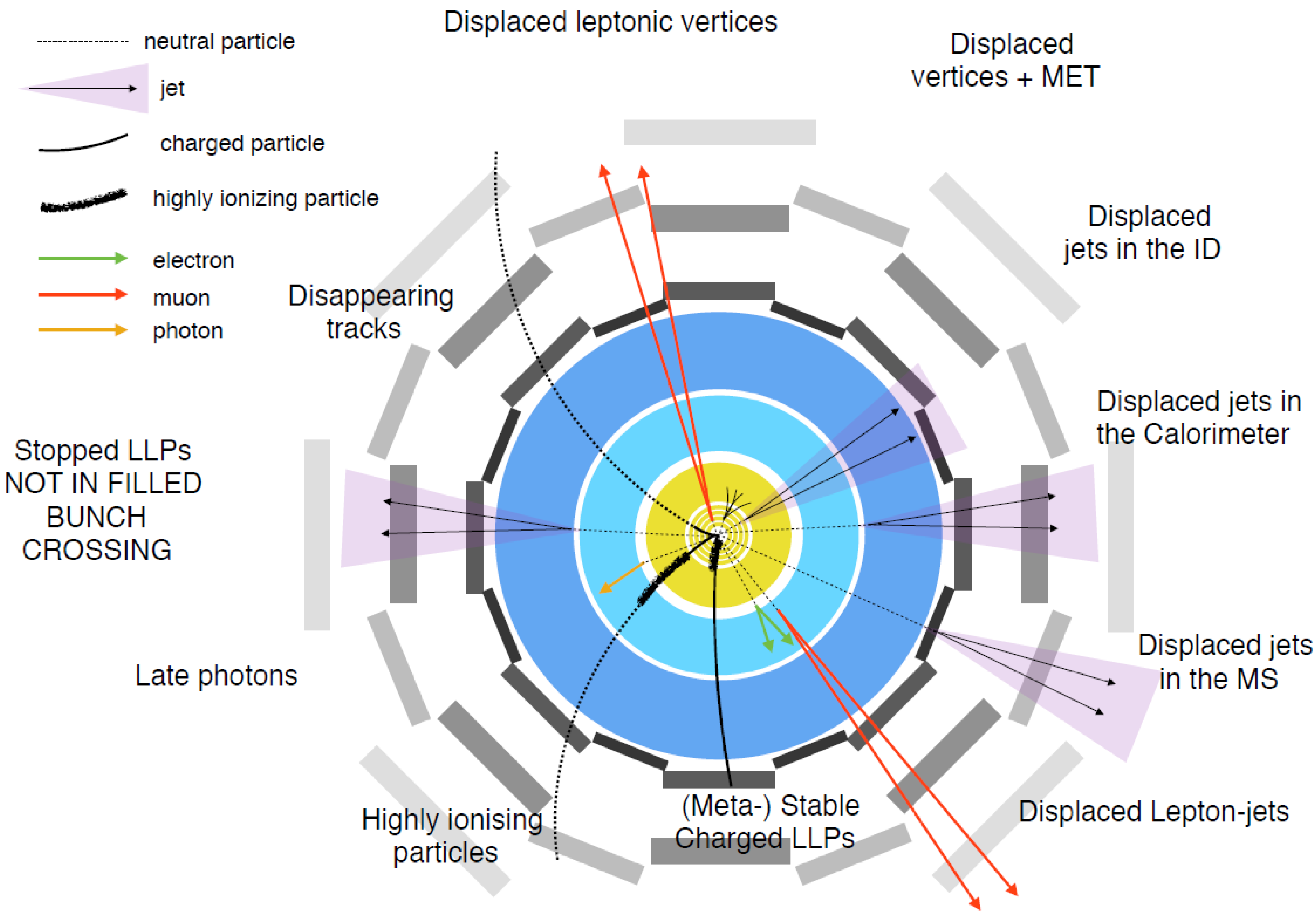


CMS PAS EXO-16-055 (13 March 2018)
PRL **119** (2017) 181804

Outlook for DM searches

- Experiments at the LHC are actively searching for DM
  - Sensitivity to DM under many model assumptions for the interaction and mediator
- No evidence for DM so far but there is much more phase space to be explored
- Outlook for DM Searches
  - Small fraction of total LHC data set in hand to date
  - New analysis techniques continuously being developed
  - New directions: models and signatures
- LHC is just getting started with DM searches

Unconventional signatures

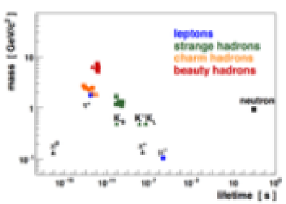


Unconventional signatures: challenges

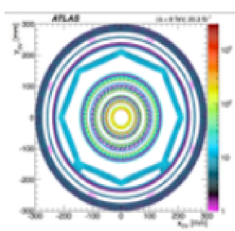
- Trigger: combination of hardware + software that must decide very quickly whether to save an event or lose it forever
  - First step in every search for LLPs: make sure that interesting events are saved!
    1. In associated production, trigger on prompt particle (Eg. WH prod. trigger on mu; ISR trigger on MET)
    2. Design and develop a new trigger. Need to keep trigger rates under control and within budget

- Object identification algorithms assume prompt particles. Need to adapt them
- Backgrounds: usually instrumental background such as miss-identified leptons ("fakes") and non-collision backgrounds (NCB) have to be taken into account

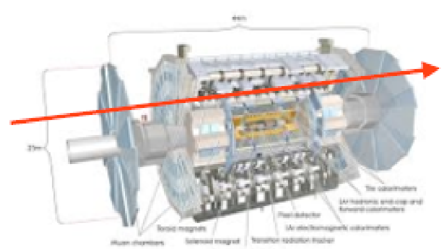
weak decays of heavy flavour



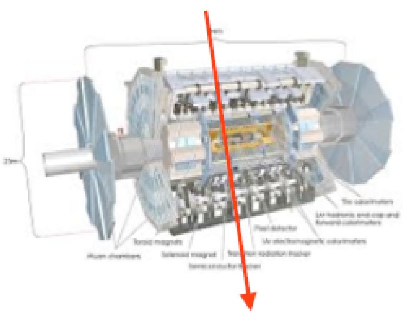
material interactions



beam halo muons



cosmic muons



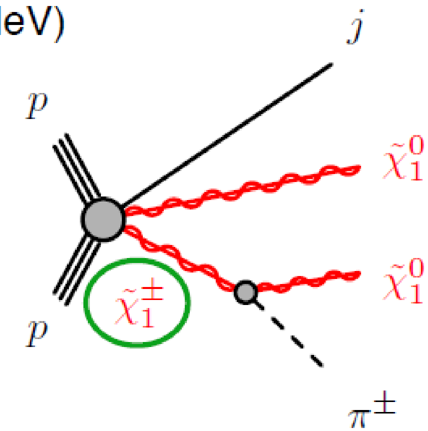
- Systematic uncertainties: can't use standard recommendations for object reconstruction nor trigger

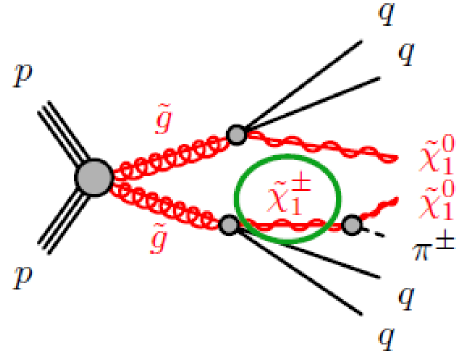
Unconventional signatures: disapearing tracks

LLP

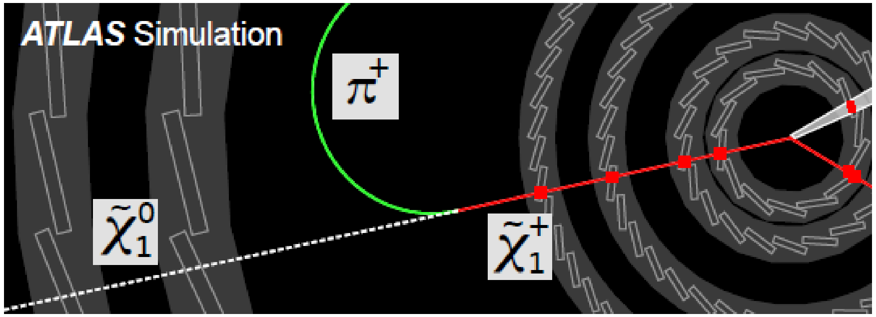
- Search for disappearing track + MET + jets
- Signature: Chargino track "disappears" when it decays, into MET
  - Low momentum pion track (~0.1 GeV) is hard to reconstruct
  - Challenge to identify the legitimate real tracklets (non-fake) using only a few measurement tracks

- Benchmark model: AMSB model with almost degenerate neutralino and chargino $\Delta m \sim O(100\ \mathrm{MeV})$





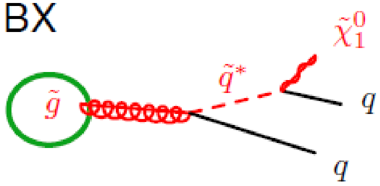
- Search sensitive to LLP lifetime of 10ps to 10 ns



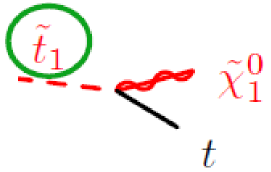
Unconventional signatures: stopped particles

- Search for stopped LLPs decaying during non-collision bunch crossings (BX)

- Signature: LLPs come to rest in the detector and decays after the current BX
  - most likely to stop in the densest detector materials:
    - Calorimeters (ECAL, HCAL):
      a) Split SUSY: two-body and three-body decays of a gluino

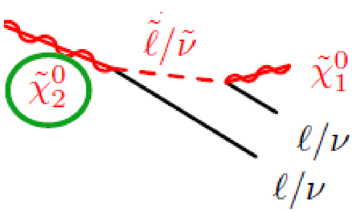


      b) top squark decay



    - Steel yoke in the muon system:
      a) three-body decay of the gluino ($g \rightarrow qq\chi_2$, $\chi_2 \rightarrow \mu\ \mu\ \chi_1$)

      b) MCHAMPs, with charge $|Q| = 2e$ decays into two same-sign muons ($\text{MCHAMP} \rightarrow \mu^{\pm}\mu^{\pm}$)



- Search sensitive to wide range of LLP lifetime: 10^{-5} to 10^{6} s