Introduction to particle physics: experimental part

Searches for New Physics

Supersymmetry

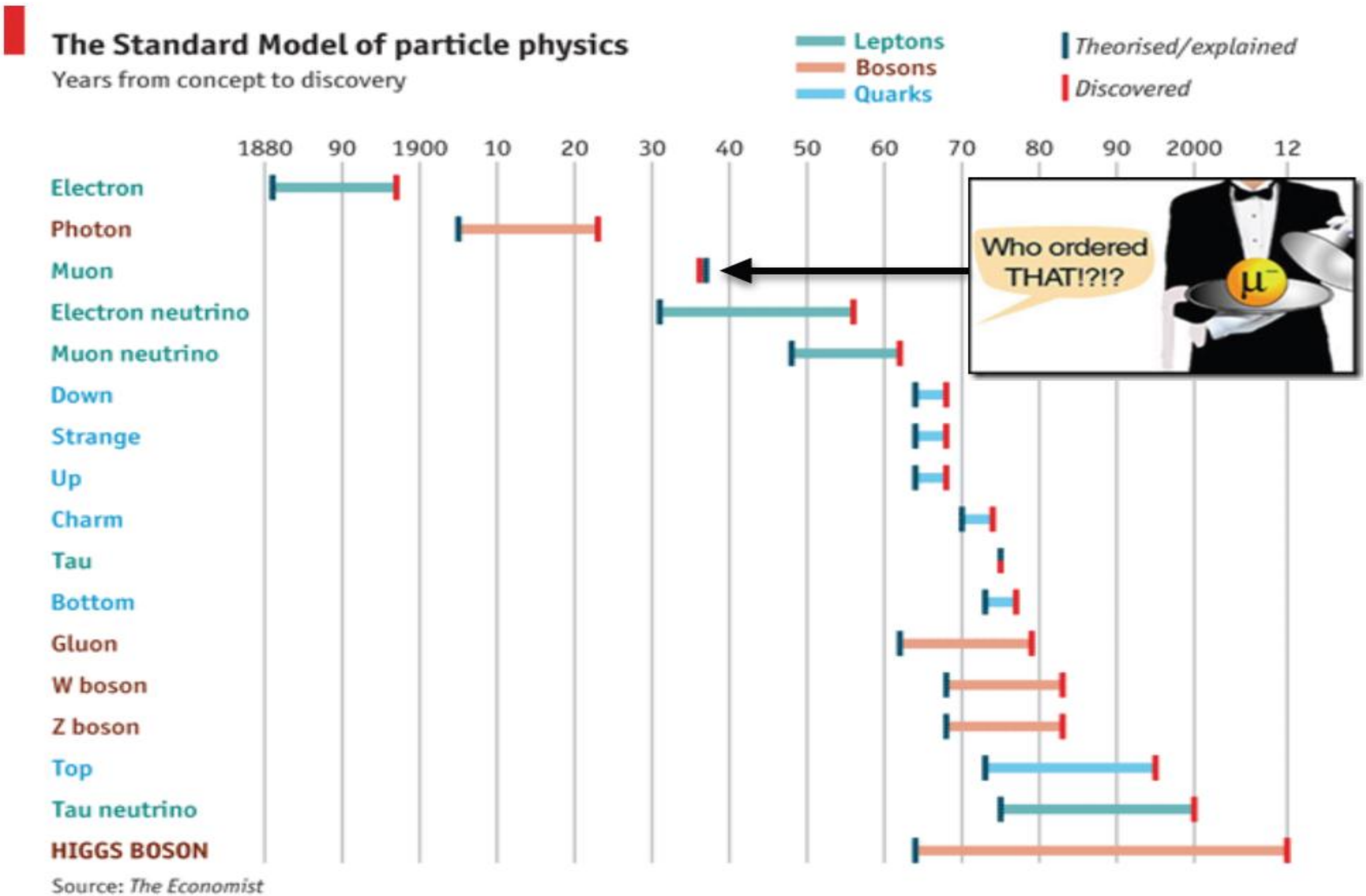
Exotic models

Dark Matter

Unconventional signatures

Prof. dr hab. Elżbieta Richter-Wąs

Uncharted discoveries?



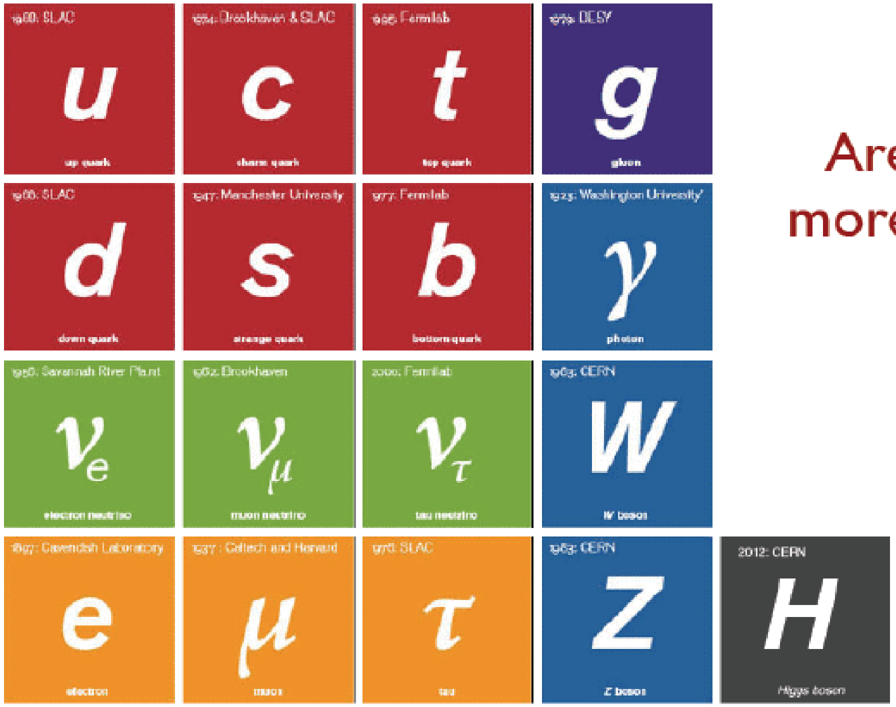
Many unanswered questions …

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?

How do neutrinos get mass?



Are there more forces?

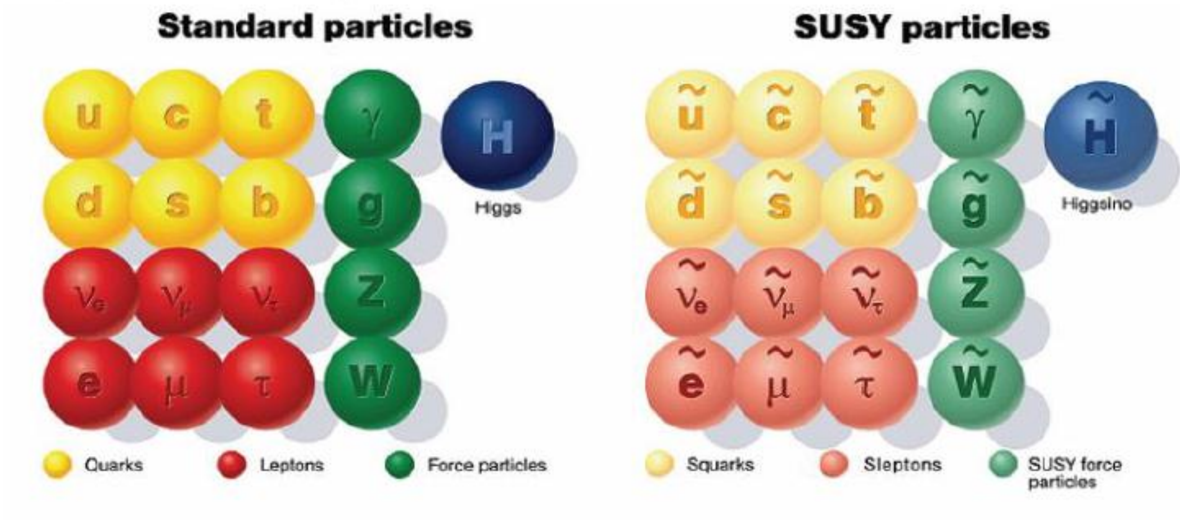
What keeps the Higgs mass so small?

How do we incorporate gravity?

What is Dark Matter?

… and as many possible answers to probe!

- Super-symmetry?



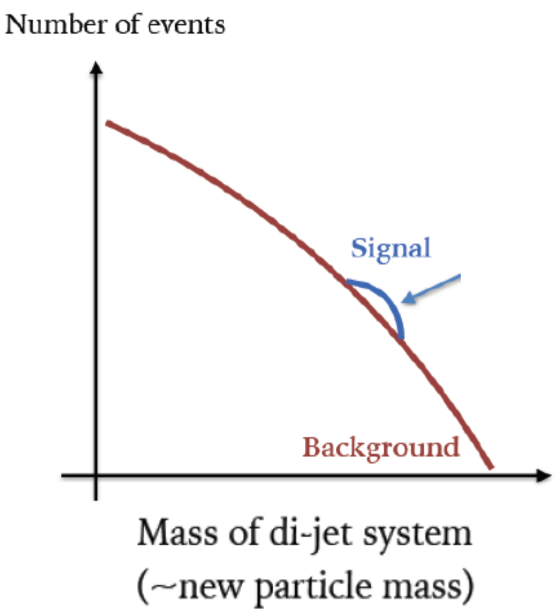
- Composite quark and/or leptons?
- New Heavy bosons?
- Gravitons?
- Dark Matter particles?
- …

Any new theory need to agree with the SM!

How would new phenomena manifest?

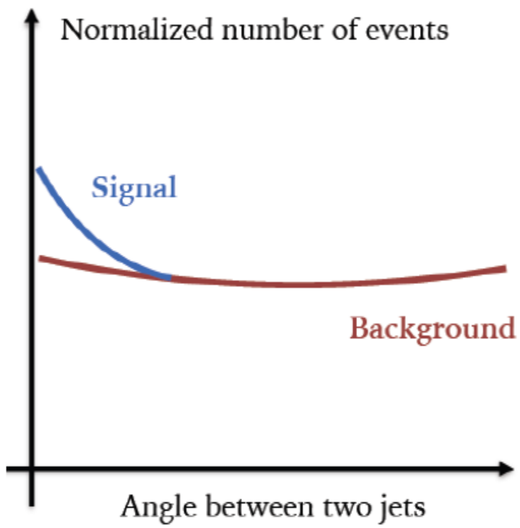
New particles:

resonant excess (bump) over Standard Model background



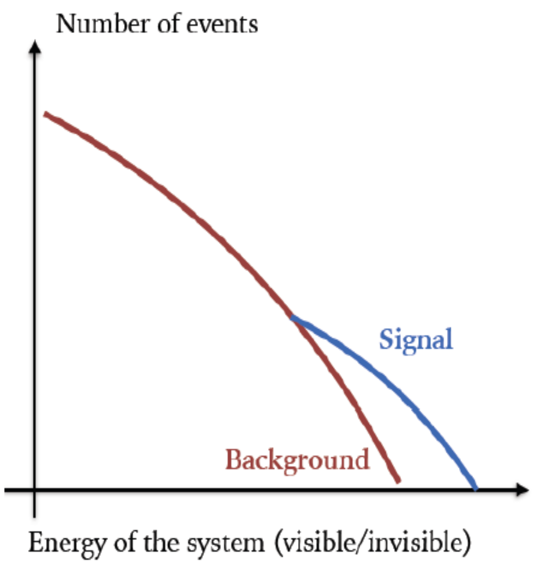
New interactions:

more central production (~Rutherford experiment)

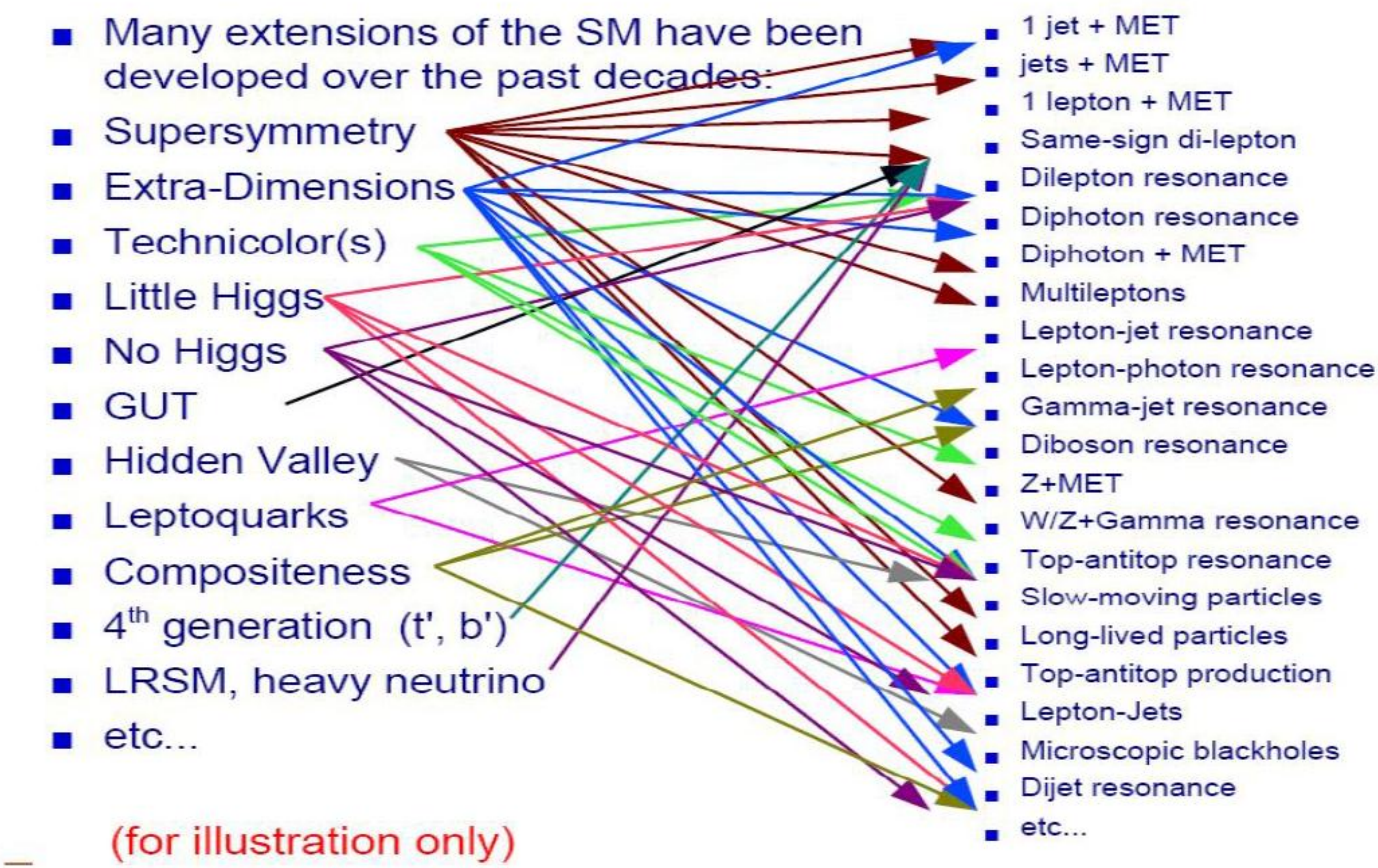


New particles and states:

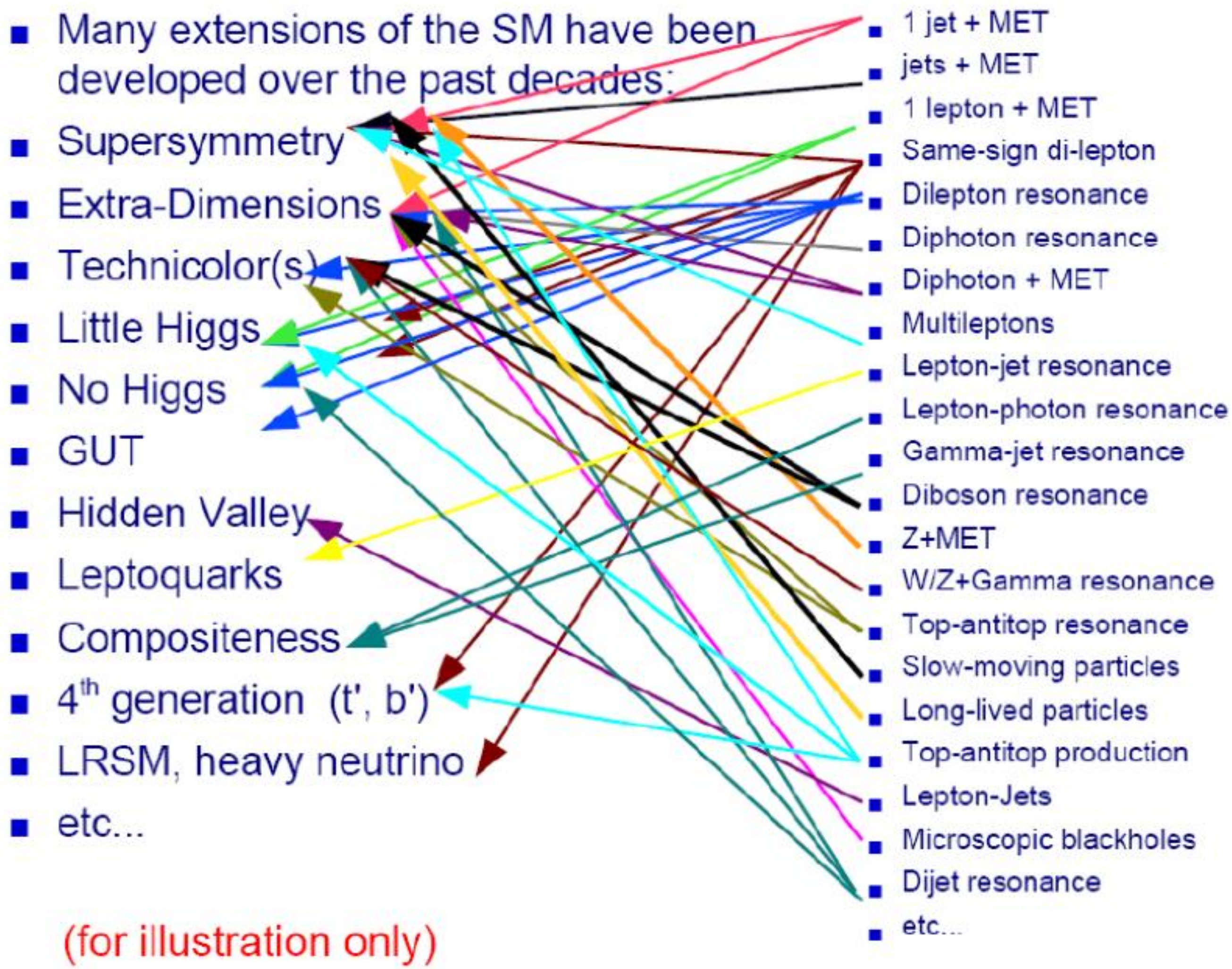
larger multiplicity of objects at high masses



Long list of models and signatures



Long list of models and signatures



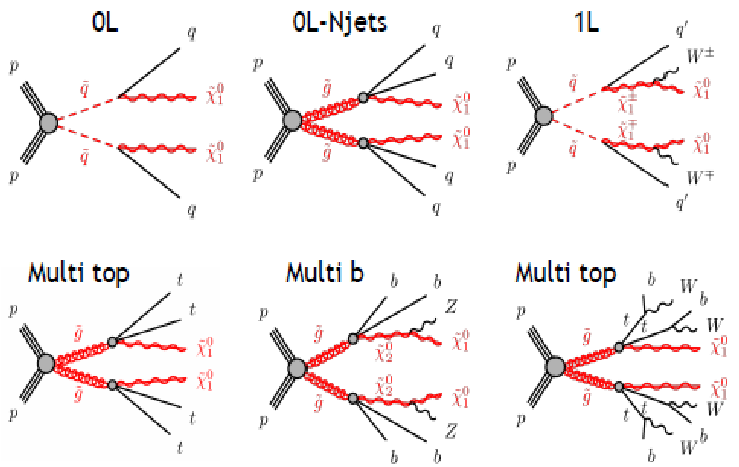
A complex 2D problem

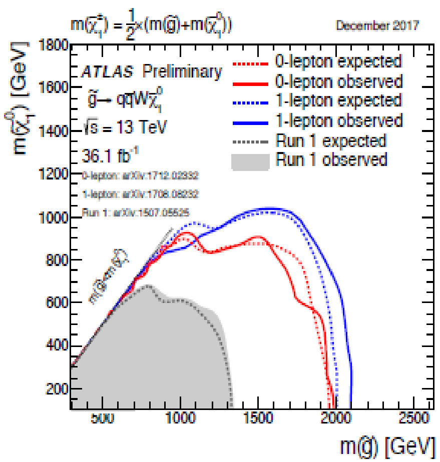
Experimentally, a **signature standpoint** makes a lot of sense:

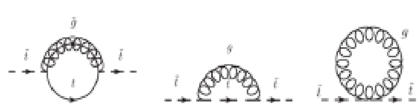
- → Practical
- → Less model-dependent
- → Important to cover every possible signature

Strongly produced SUSY searches

Squarks and gluinos

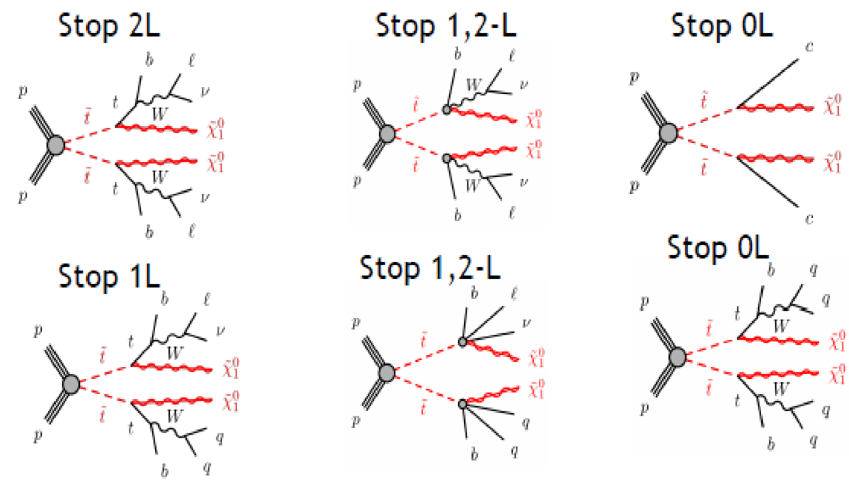


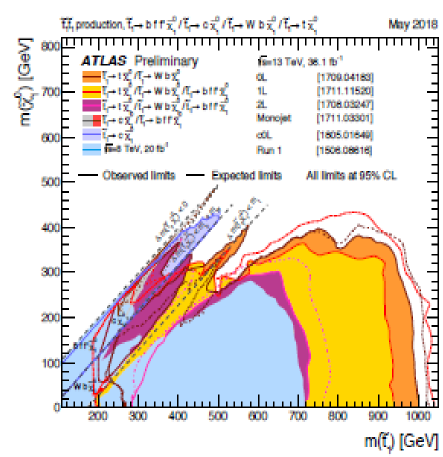




Stop also a scalar requires light gluinos to be light enough: for gluinos > 1.8 TeV ~tuning of Factor of 30

Stop





Not so natural SUSY: Stops > 800 GeV ~Tuning of factor 20, but these exclusions are under specific conditions, and there are unexcluded corridors.

Strongly produced SUSY searches

Squarks and gluinos

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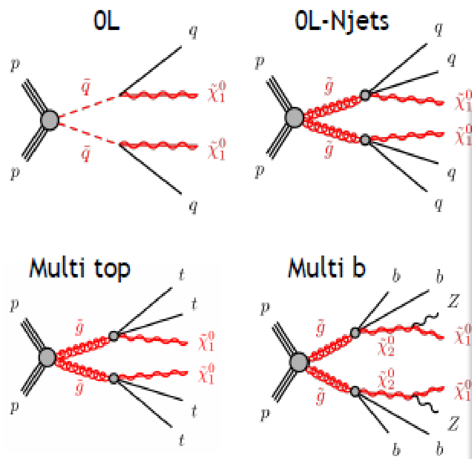
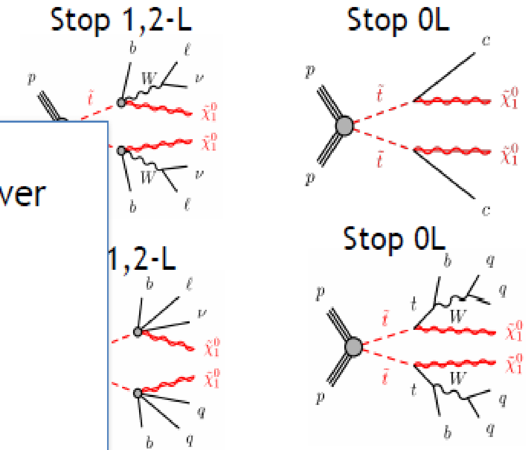
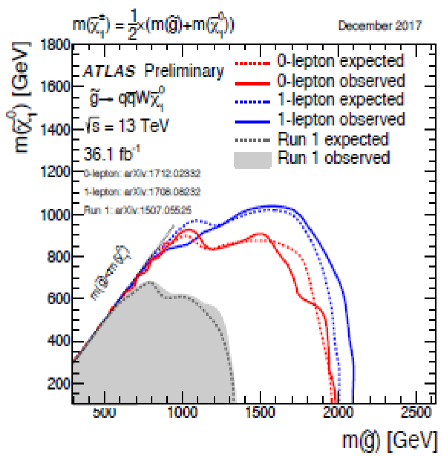
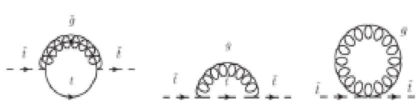




Large number of topologies which can cover different SUSY or other new physics scenarios

All signatures feature missing transverse energy!





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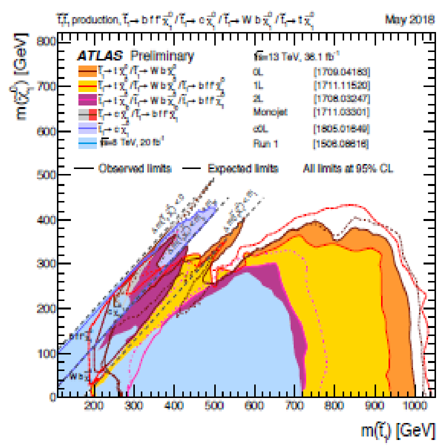
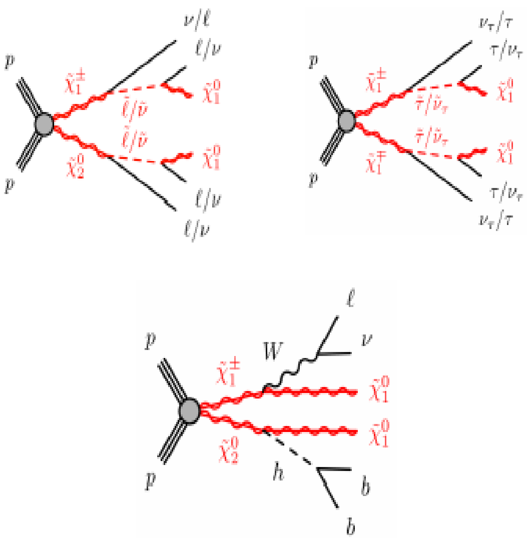


Not so natural SUSY: Stops > 800 GeV ~Tuning of factor 20, but these exclusions are under specific conditions, and there are unexcluded corridors.

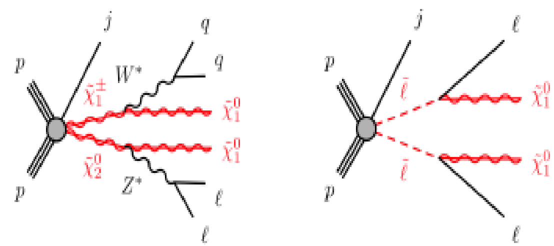
More intricate scenarios

Weak production of chagrinos, neutralinos and sleptons



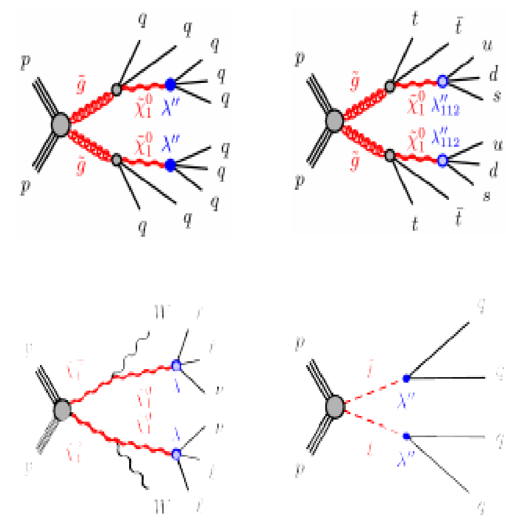
1 to 4 leptons (including taus) in the final state. Including decays to electroweak bosons.

Weak production in compressed scenarios



Scenarios where the charginos, neutralinos or sleptons are close to mass degenerate with the lightest SUSY particle (LSP).

R-Parity violating SUSY

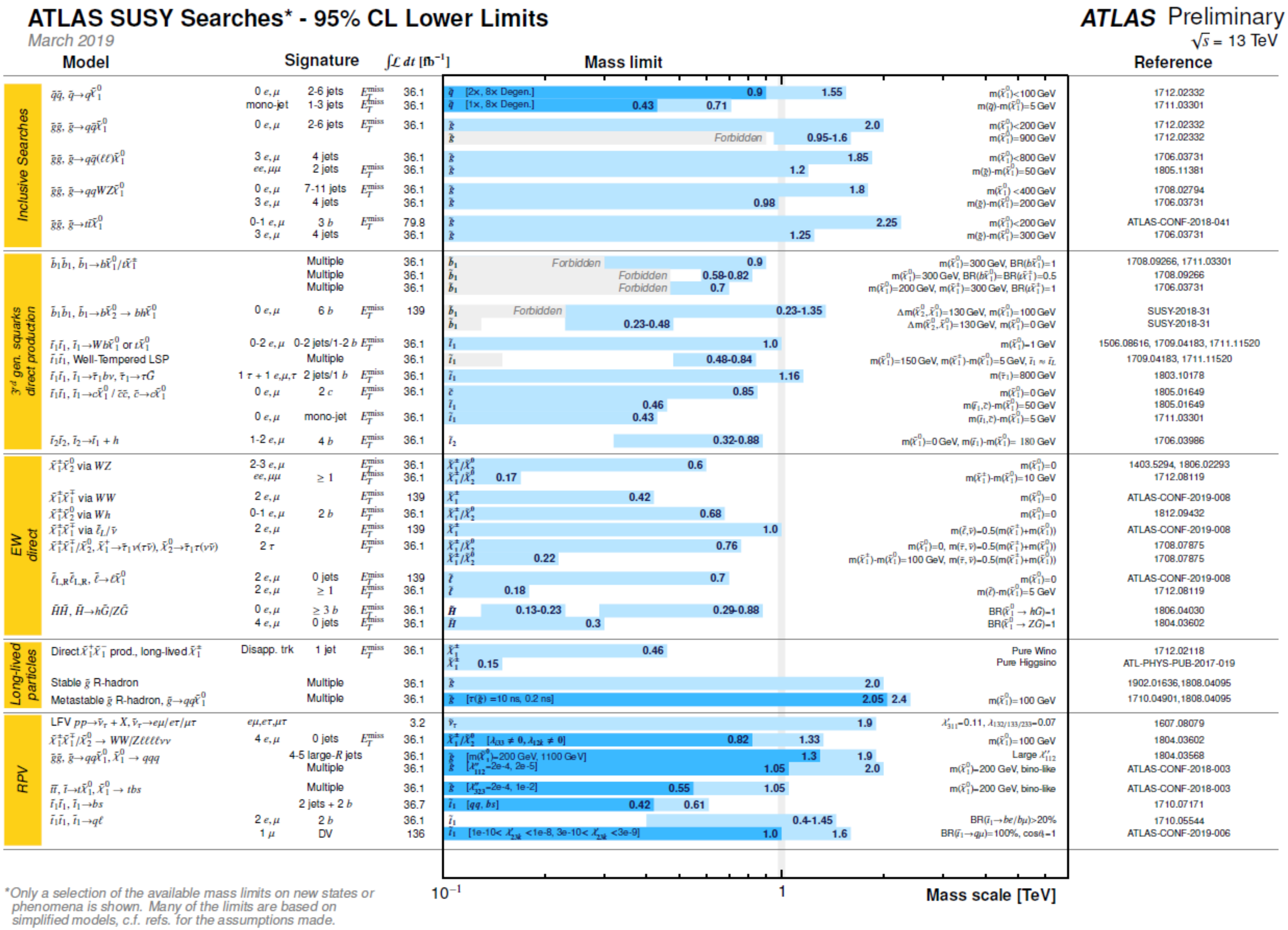


Resulting in topologies without LSP in the final state and therefore no MET.

$$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_i L_i H_2$$

RPV components of superpotential

SUSY Searches Overview

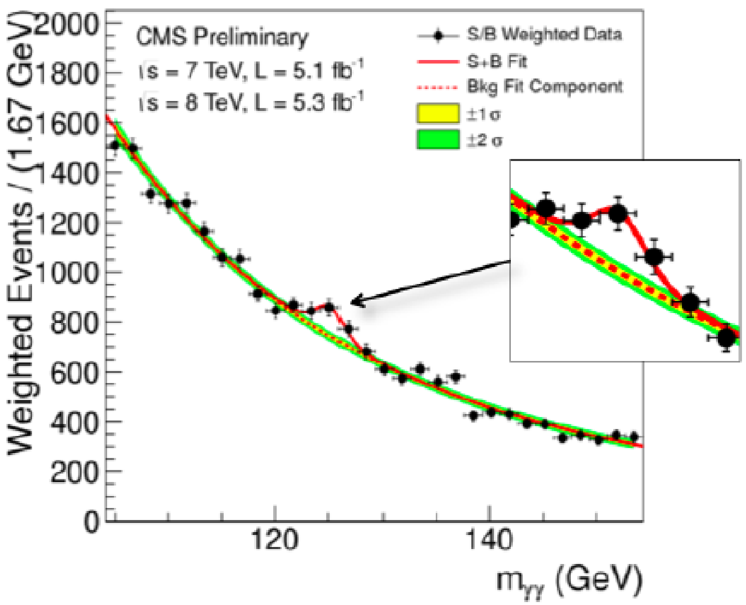


What characterizes Exotics Searches

No precise model to guide us

Standard Model:

Predicted Higgs boson

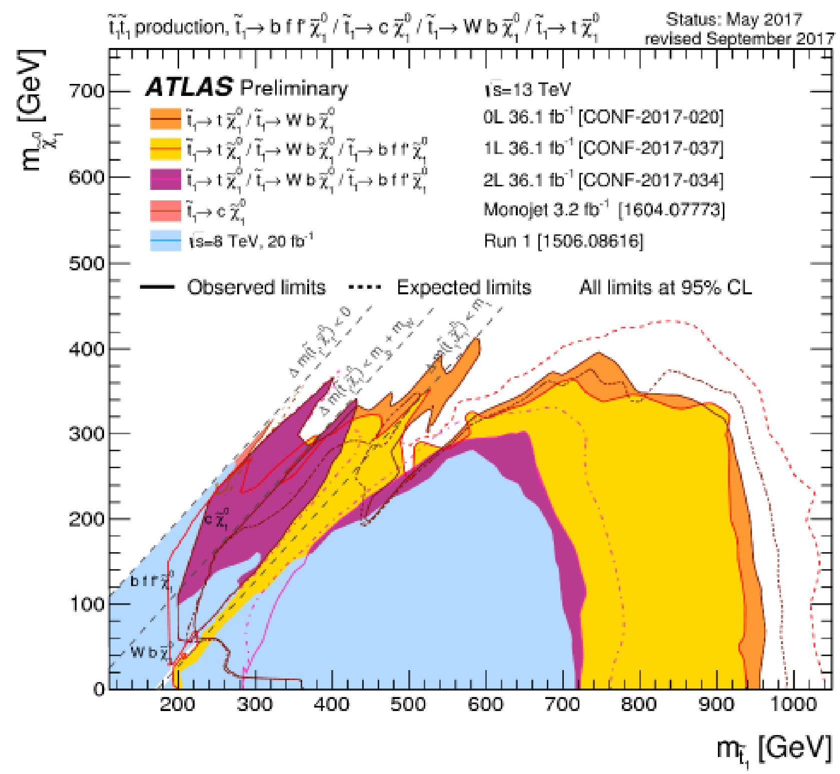


[Phys. Lett. B 716 (2012) 1-29](#)

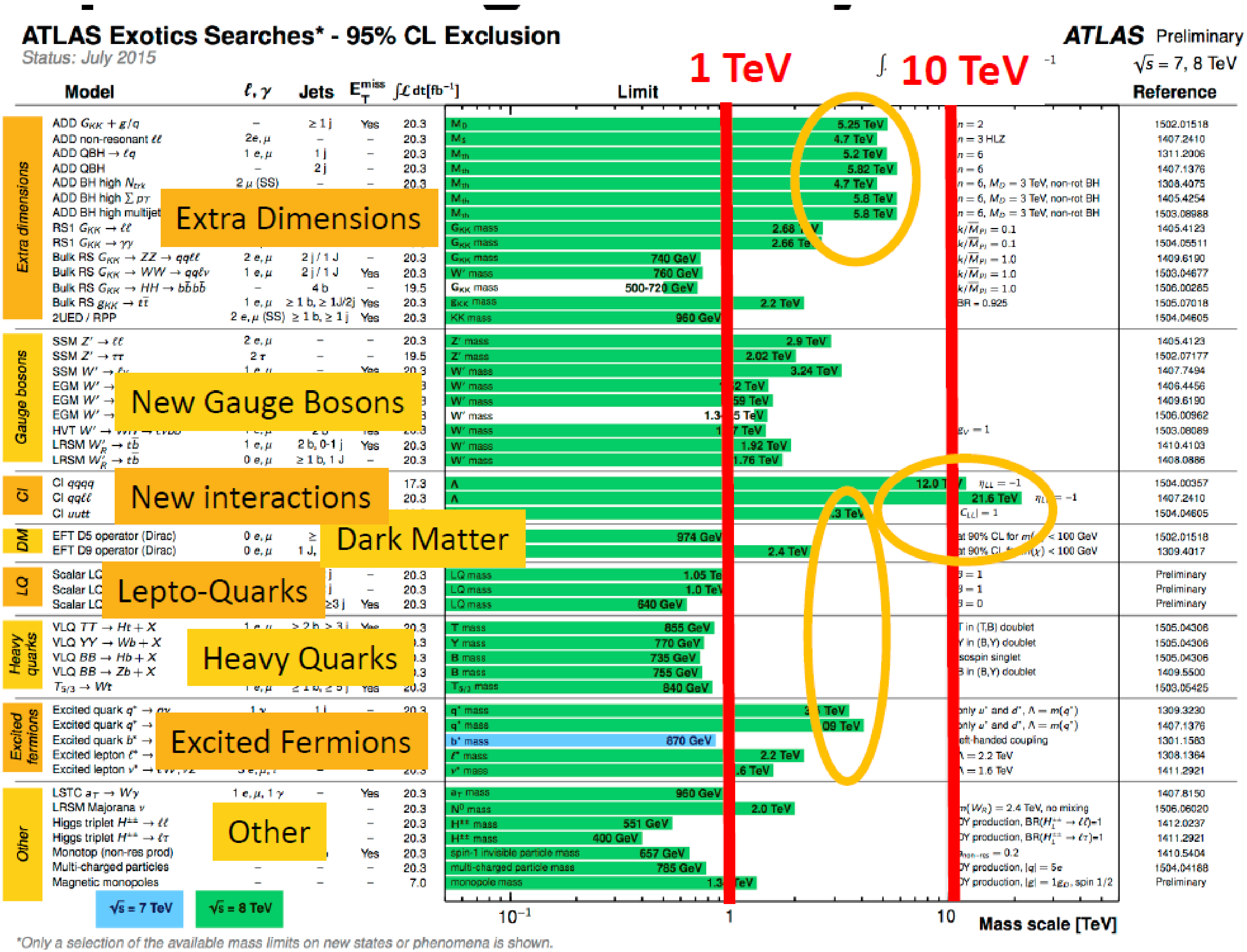
[Phys. Lett. B 716 (2012) 30-61](#)

No unified parameter phase space

Supersymmetry Searches:



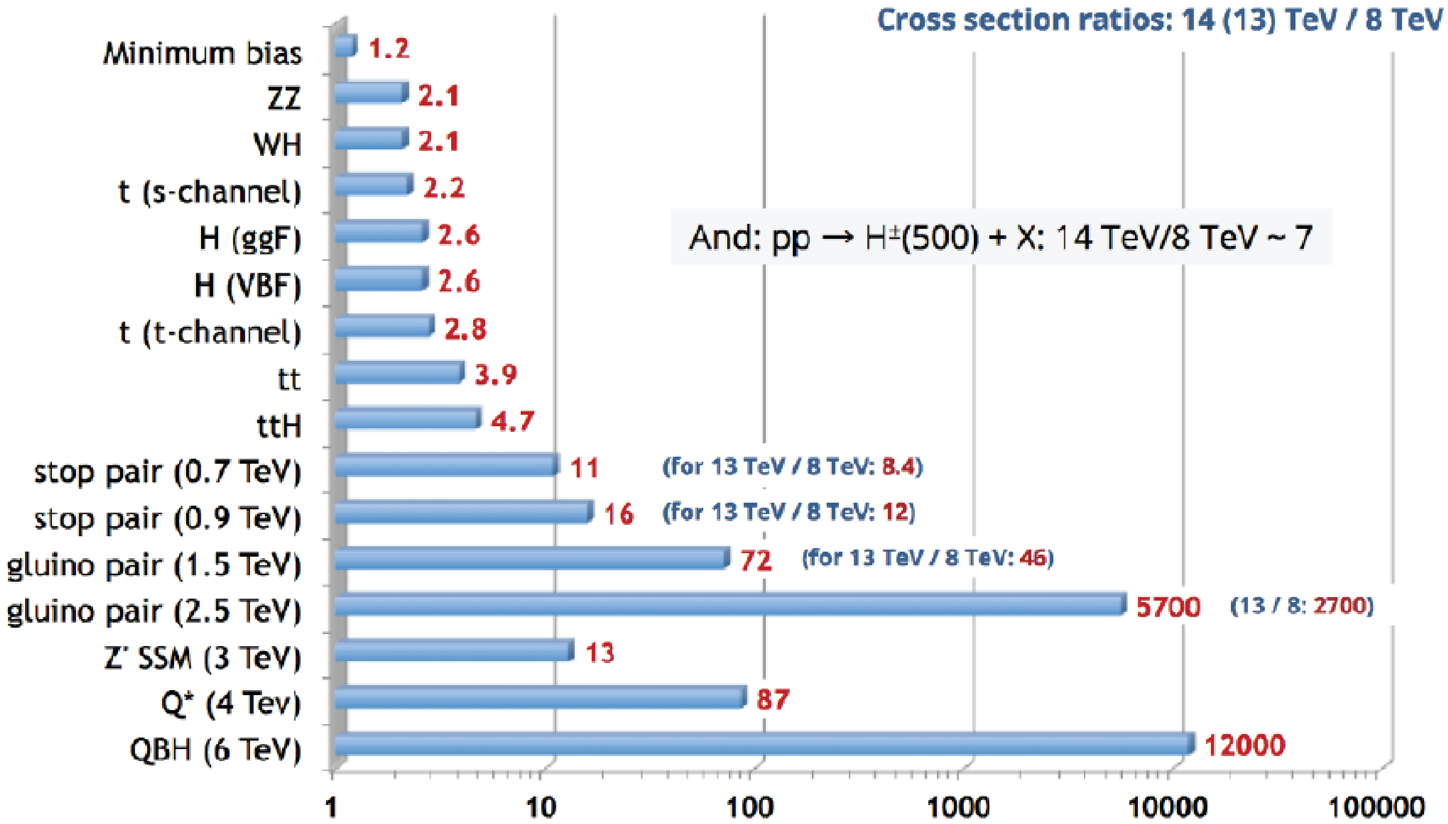
Exploration range of LHC by mid 2015



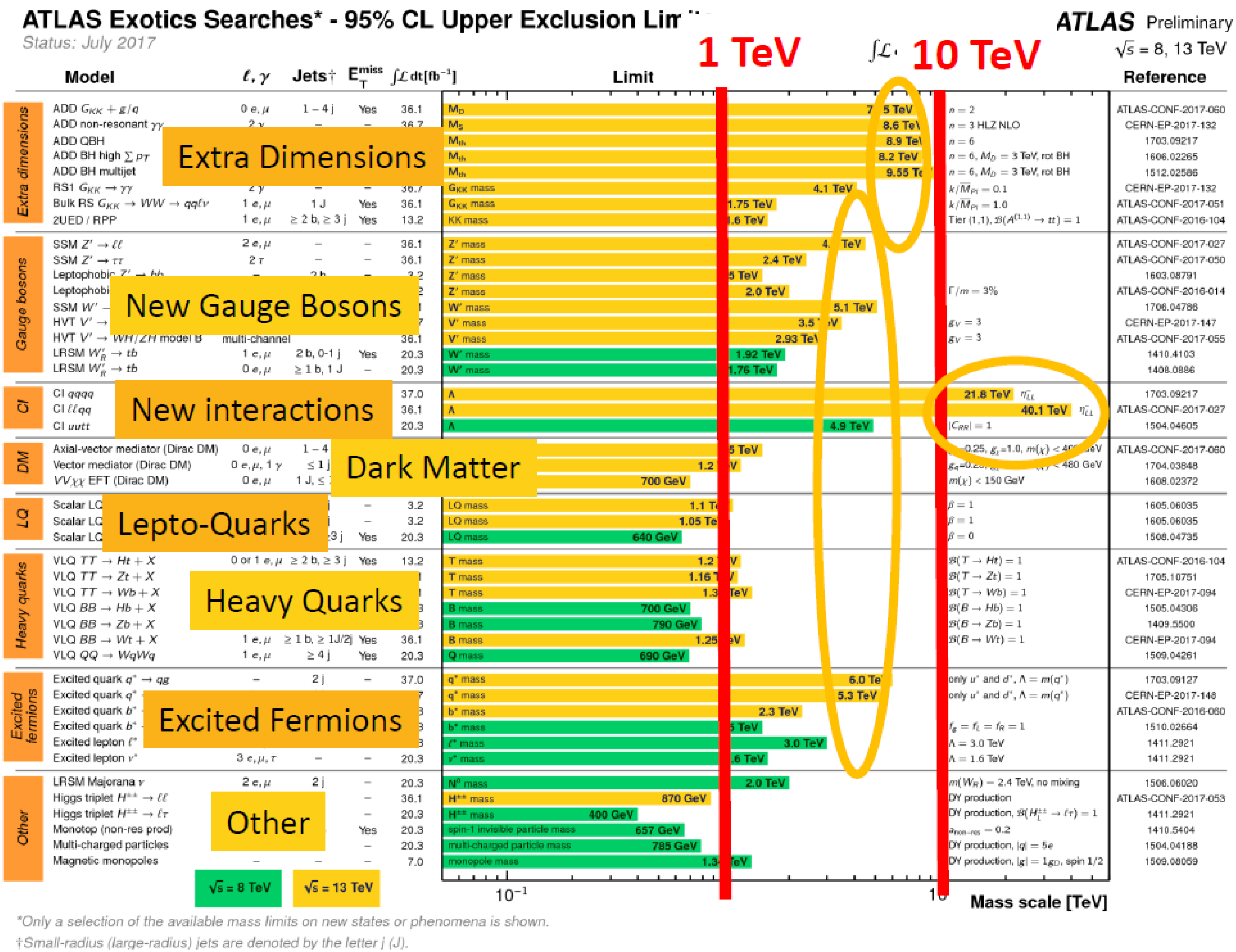
LHC Run II

Hugely increased potential for discovery of heavy particles at 13 TeV

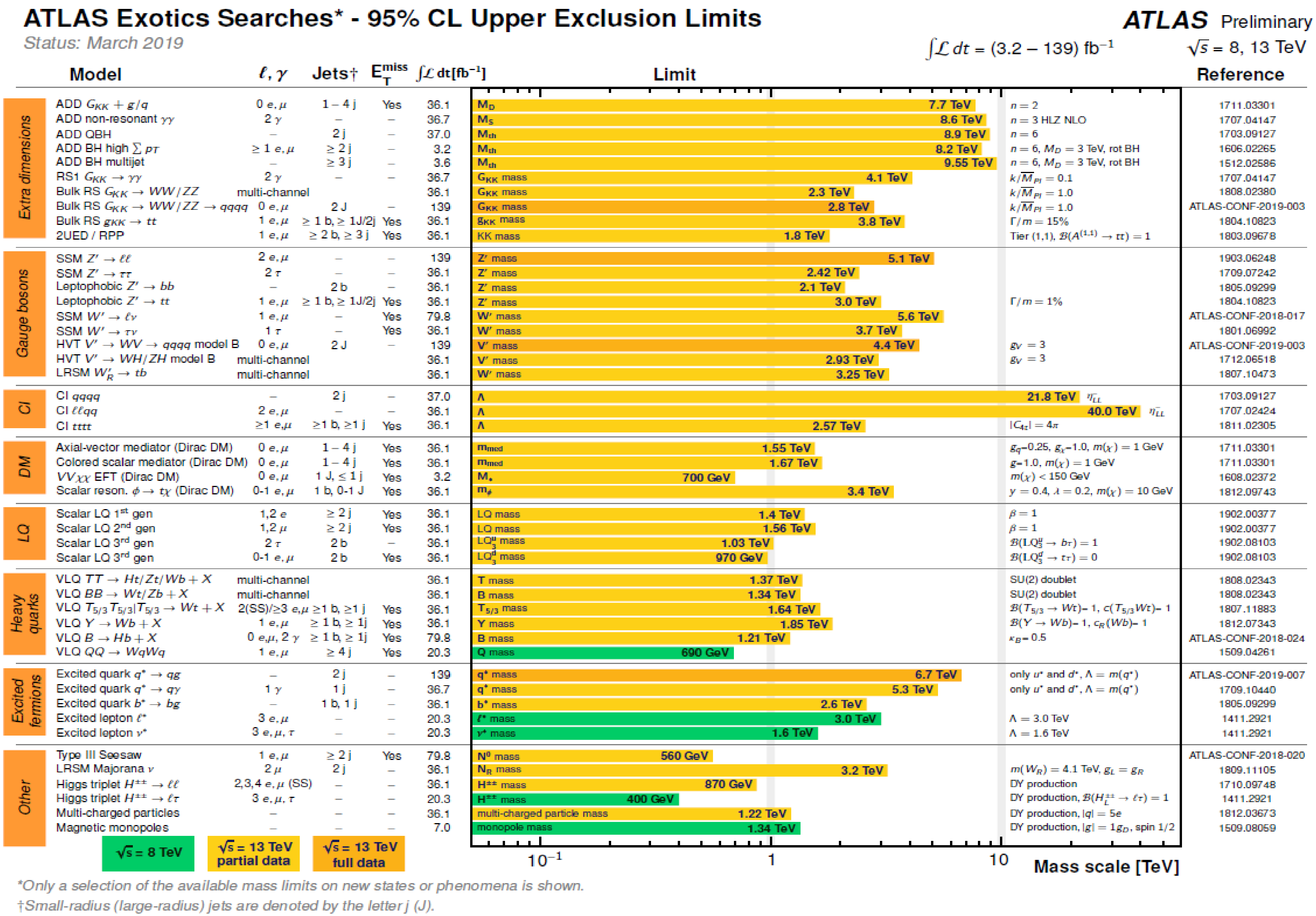
Perfect occasion for young motivated physicists: join the search!



Exploration range of LHC by mid 2017



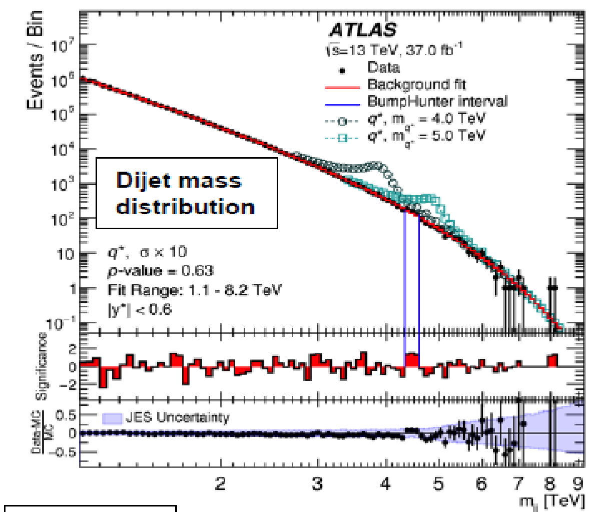
Exploration range of LHC by mid 2019



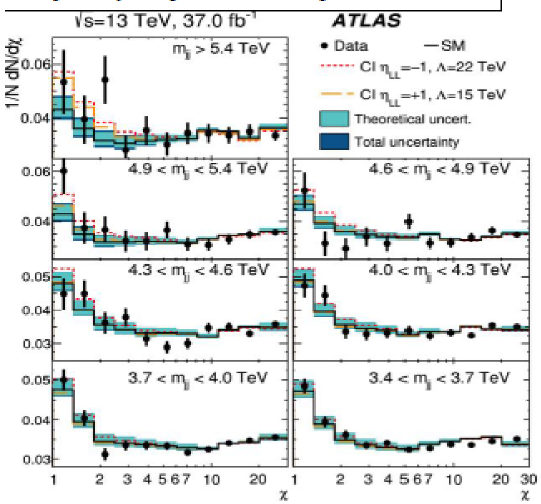
Searches with Dijets

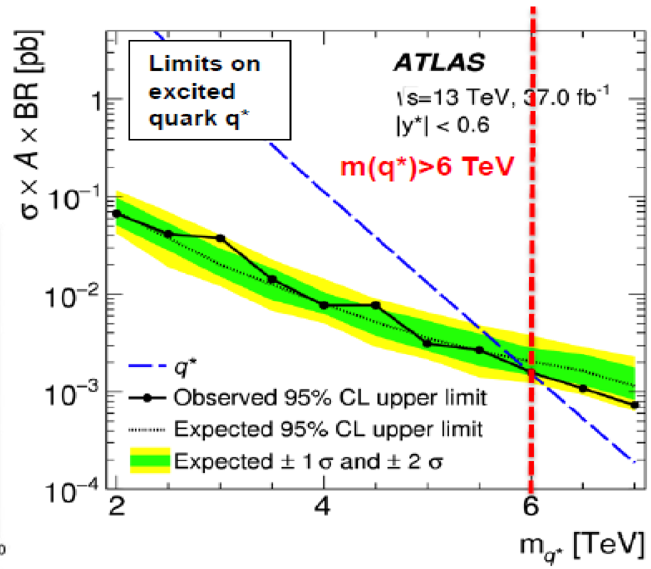
arXiv:1703.09127

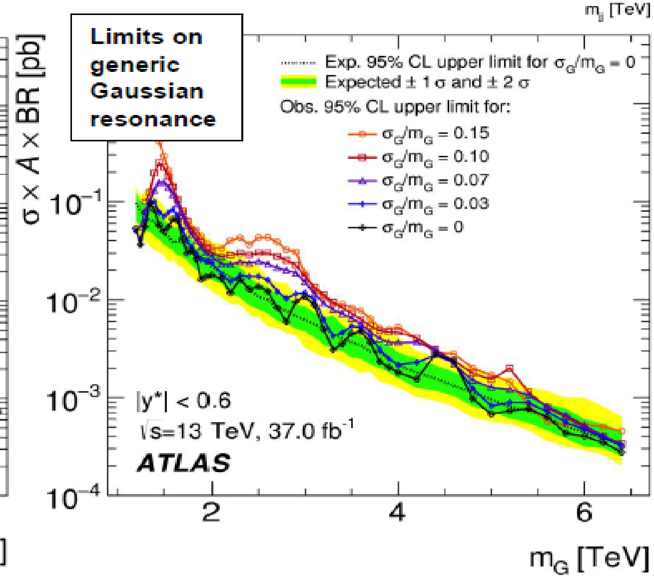
- Search for excess in dijet mass and angular distributions
- No significant excesses over SM expectation
- Extends limits significantly beyond 2015 results, on new gauge bosons and contact interactions, e.g.
  - Excited quarks: m(q*) > 6.0 TeV (5.8 TeV exp.)
  - Add. gauge bosons: m(W') > 3.6 TeV (3.7 TeV exp.)
  - Quantum Black Holes: m(BH) > 8.9 TeV (8.9 TeV exp.)
  - Contact Interactions: Λ > 13.1/21.8 TeV (η_{LL} = +1/-1)
- Limits also set on generic Gaussian resonances



Dijet angular distributions χ=exp(2|y*|) for jet rapidity difference y*



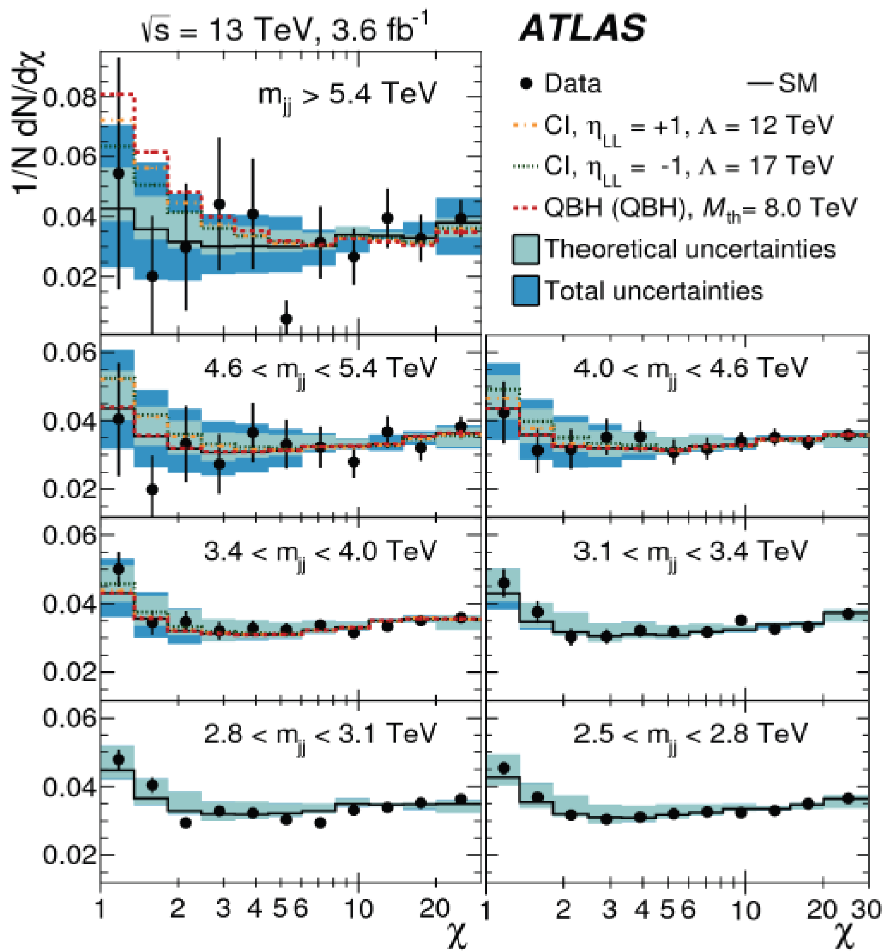




Dijet Angular Searches

Search in dijet mass bins using angular distribution

$$\chi = e^{2|y^*|} \sim \frac{1+\cos\theta^*}{1-\cos\theta^*}$$



1512.01530

Search for distortions of the dijet angular distribution from Contact Interactions of particles at much higher masses O(Λ) with color-singlet left-handed chiral couplings (in 4-fermion effective field theory)

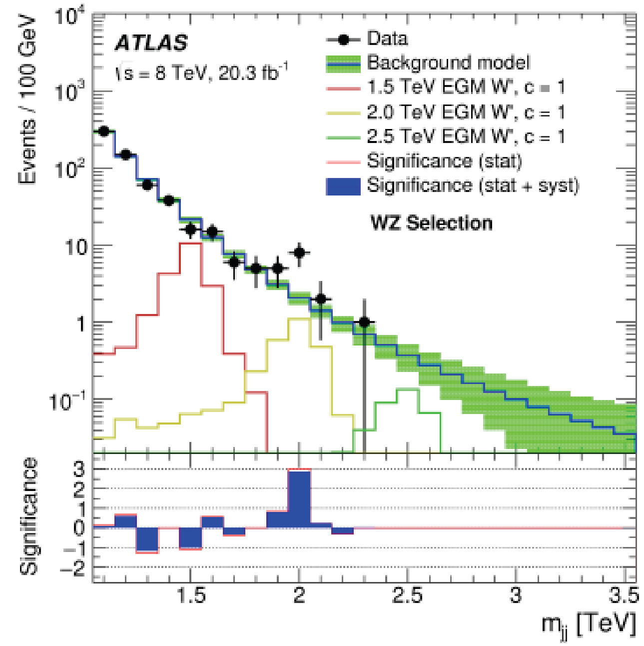
No deviations observed, limits set at 12 TeV on Λ (for η_{LL} = 1)

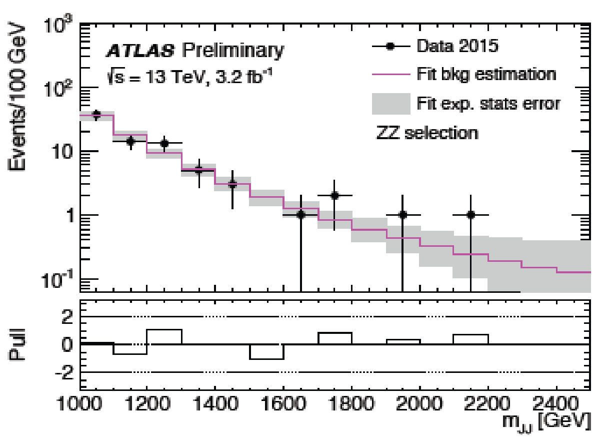
Fully hadronic JJ Diboson Searches

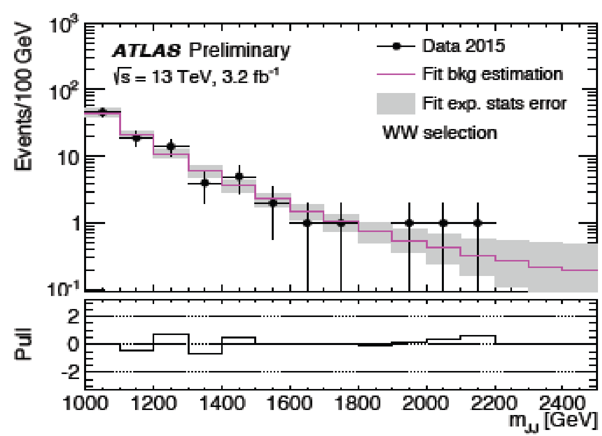
ATLAS-CONF-2015-073

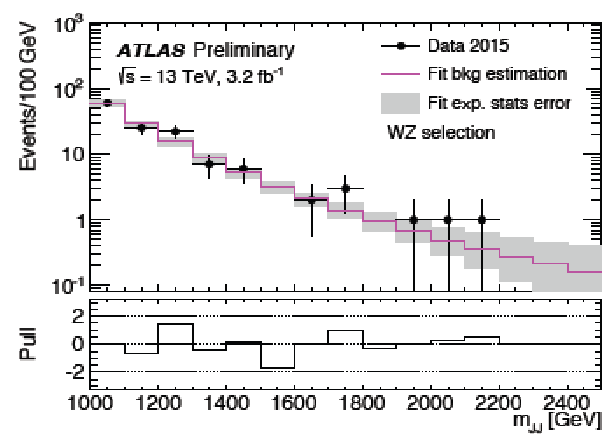
- **Modest excess at Run-1: 3.4σ** local / **2.5σ global**
- **Analysis very similar to Run 1**, with functional fit of the background
- **No significant excess is observed**
  however sensitivity not high enough for conclusive probe of the Run 1 excess

Run-1





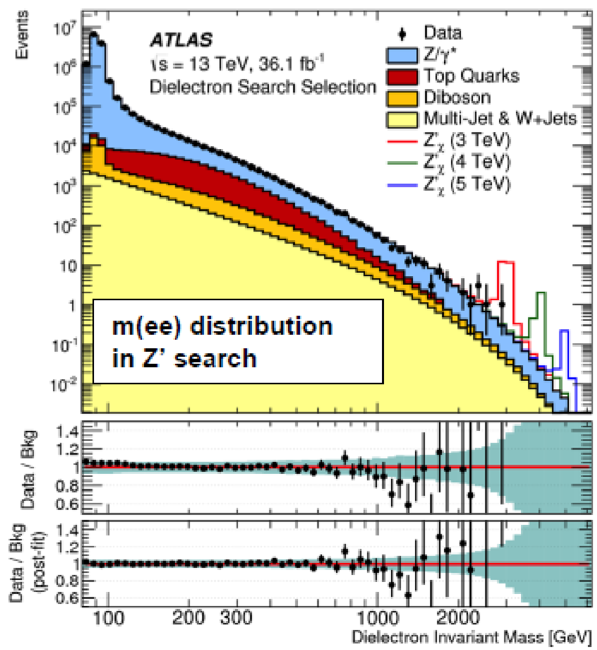


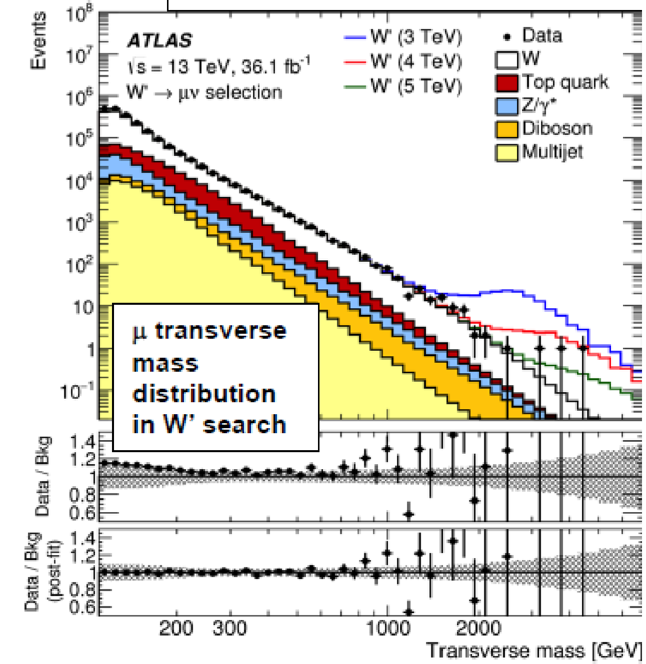


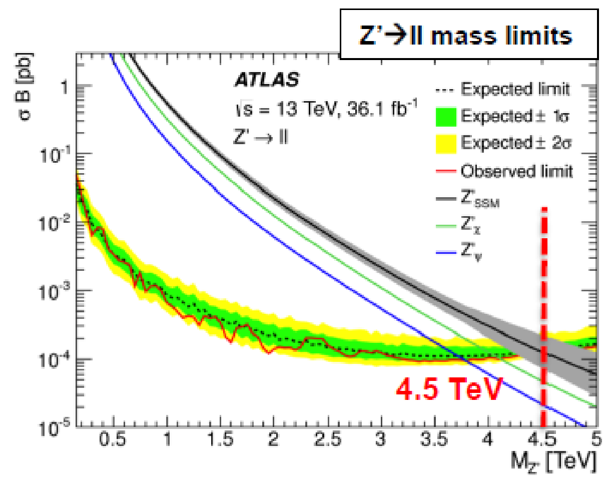
Resonance Searches (Dilepton, Lepton+ETmiss)

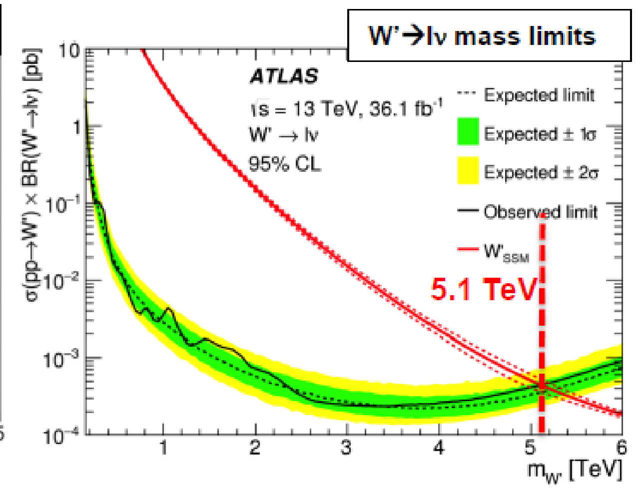
- Searches for new resonances decaying to lepton pairs (e.g. Z') or lepton+E_T^{miss} (e.g. W')
- Signature is peak in invariant mass distribution (dilepton) or tranverse mass distributions (lepton+E_T^{miss})
- No significant excess over SM expectation
- 95% CL exclusion limits extracted in various new physics Z' and W' scenarios, e.g. the Sequential Standard Model (SSM)

arXiv:1707.02424, arXiv:1706.04786



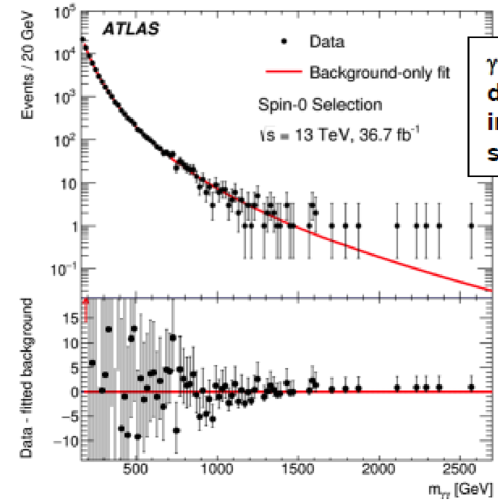




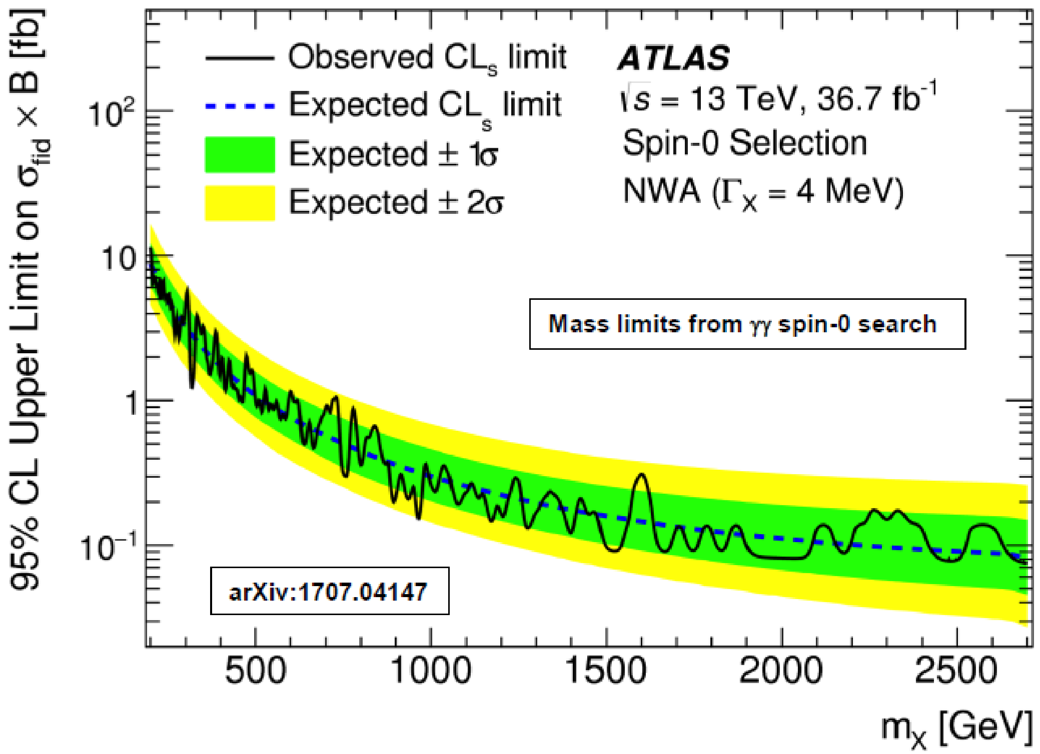


Resonance Searches ($\gamma\gamma$, $\tau\tau$)

- Diboson resonance searches also sensitive to new heavy scalars, e.g. Higgs bosons.
- Searches also conducted with $\gamma\gamma$ and $\tau\tau$ final states
- $\gamma\gamma$ search also targets spin-2 (graviton) production with a dedicated selection
- $\tau\tau$ searches sensitive to SUSY Higgs (H/A) models
- No significant excesses over SM expectation

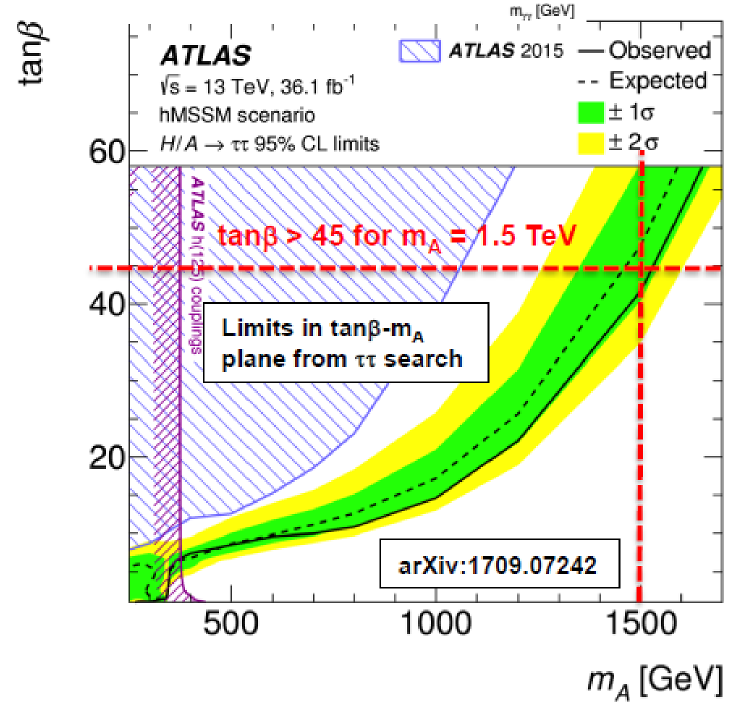


γγ mass distribution in spin-0 search



Mass limits from $\gamma\gamma$ spin-0 search

arXiv:1707.04147

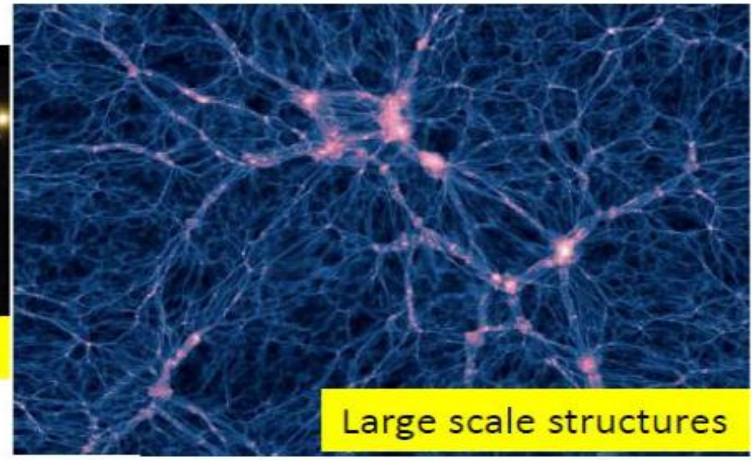


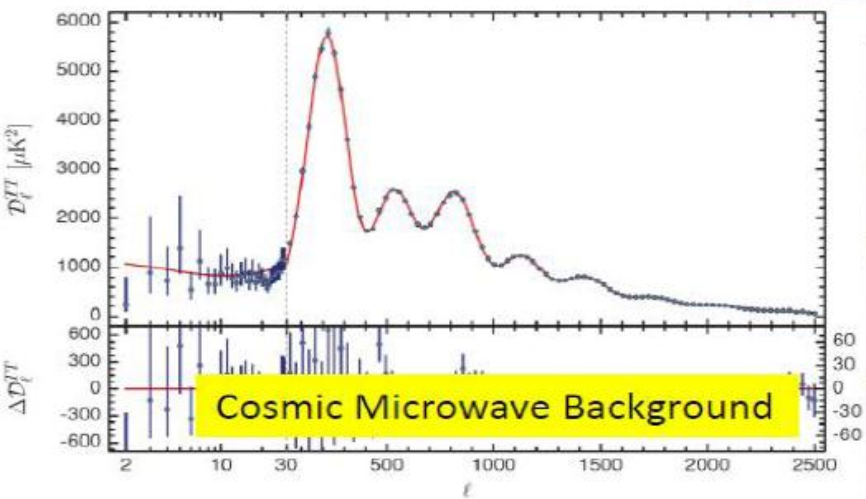
Limits in tanβ-m_A plane from $\tau\tau$ search

arXiv:1709.07242

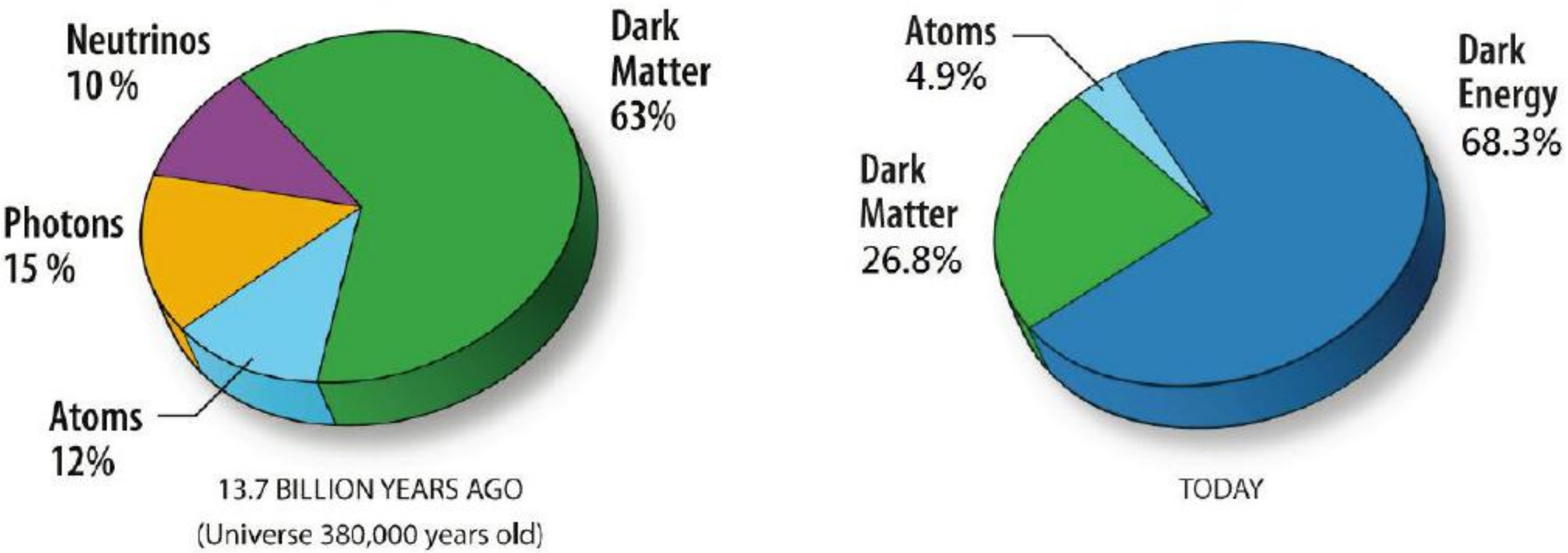
Why Dark Matter?

Evidence piling up…





What do we know about Dark Matter

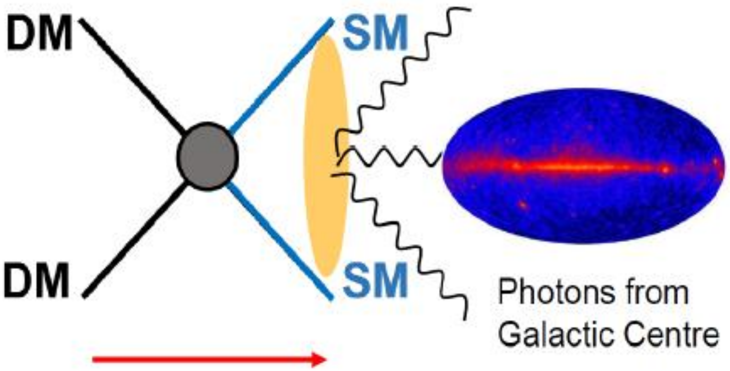


Strong astrophysical evidence for the existence of dark matter

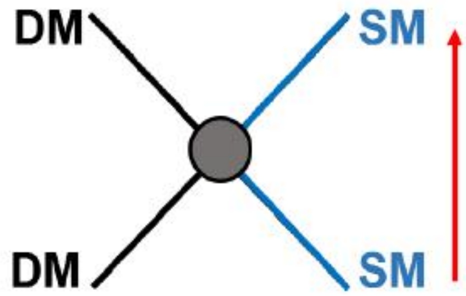
What do we know about Dark Matter

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

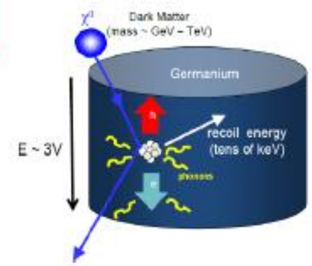
Experimental detection of Dark Matter



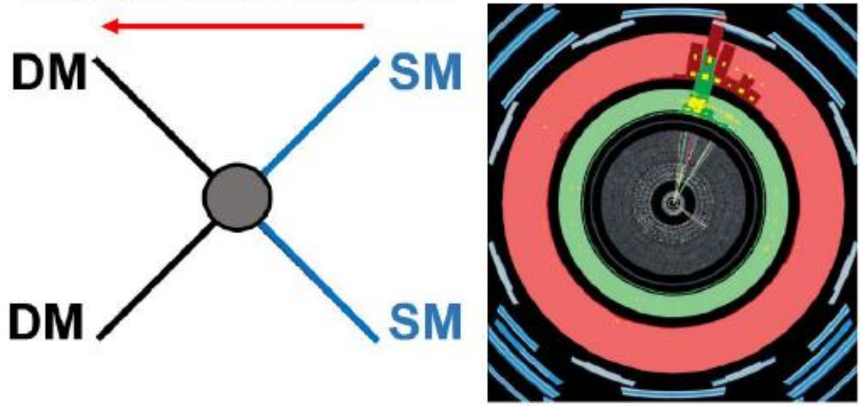
"break it": indirect detection



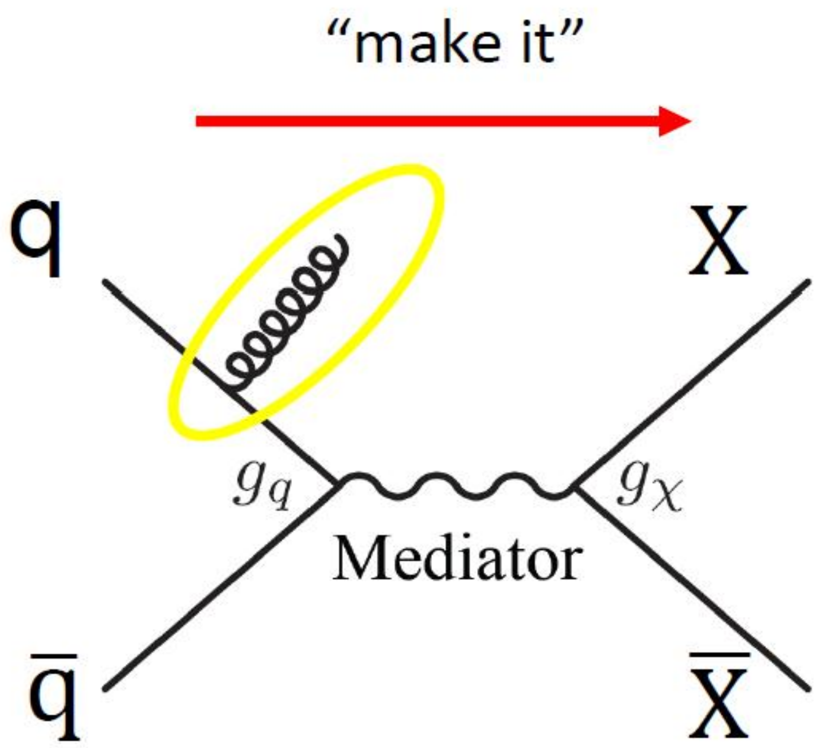
"shake it"
direct detection



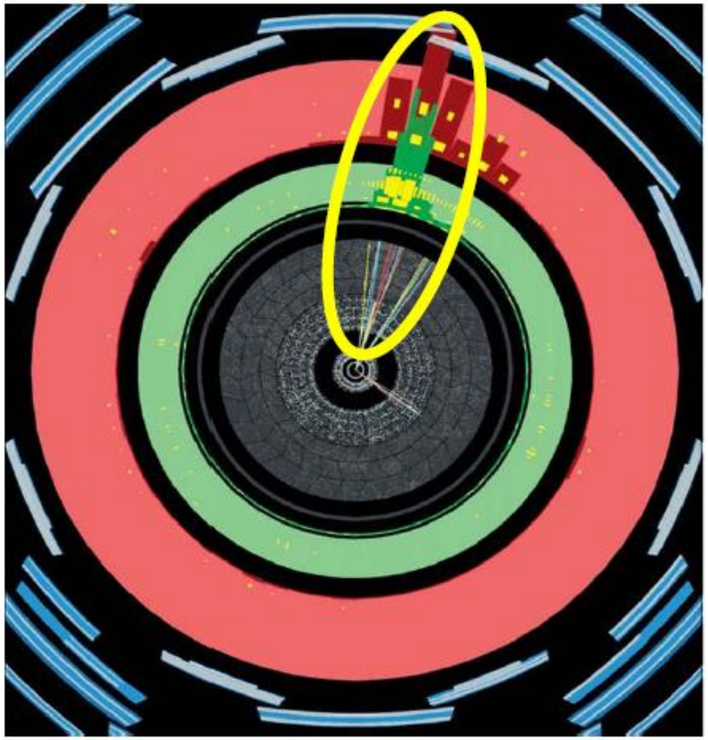
"make it": Collider Production



Dark Matter serches at Colliders

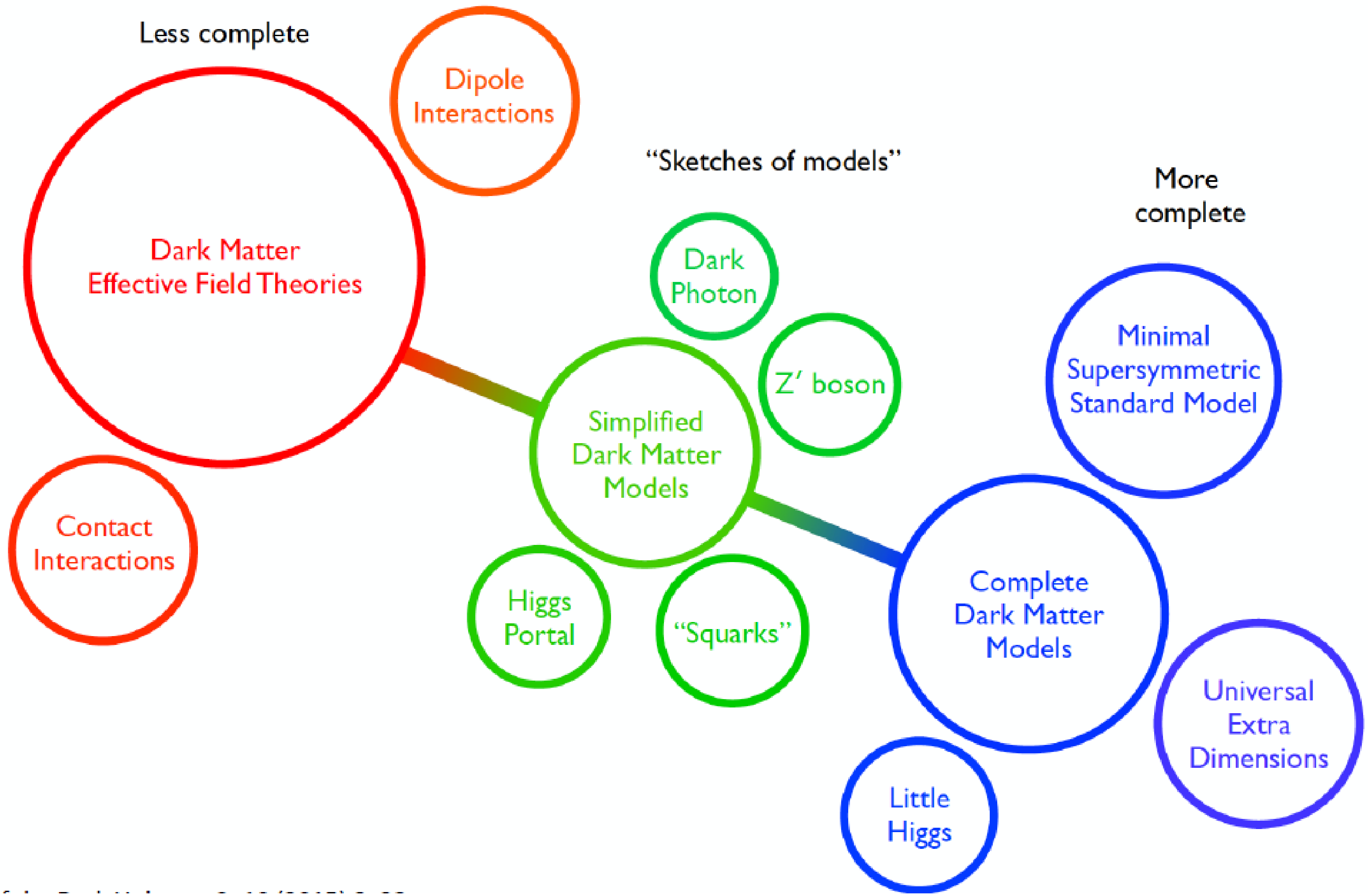


g_q and g_X coupling strengths

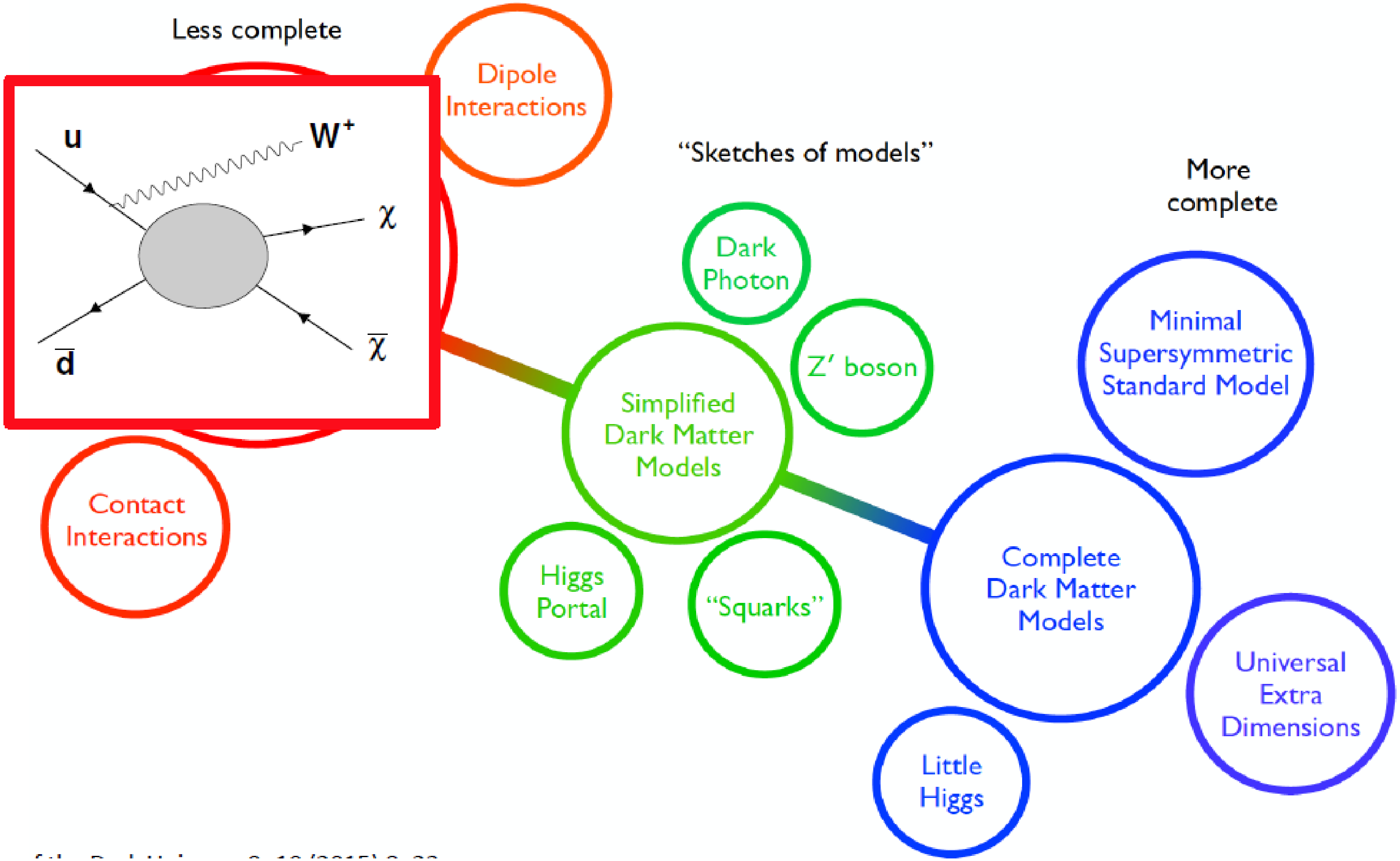


Empty detector + something

Dark Matter theory space



Dark Matter theory space



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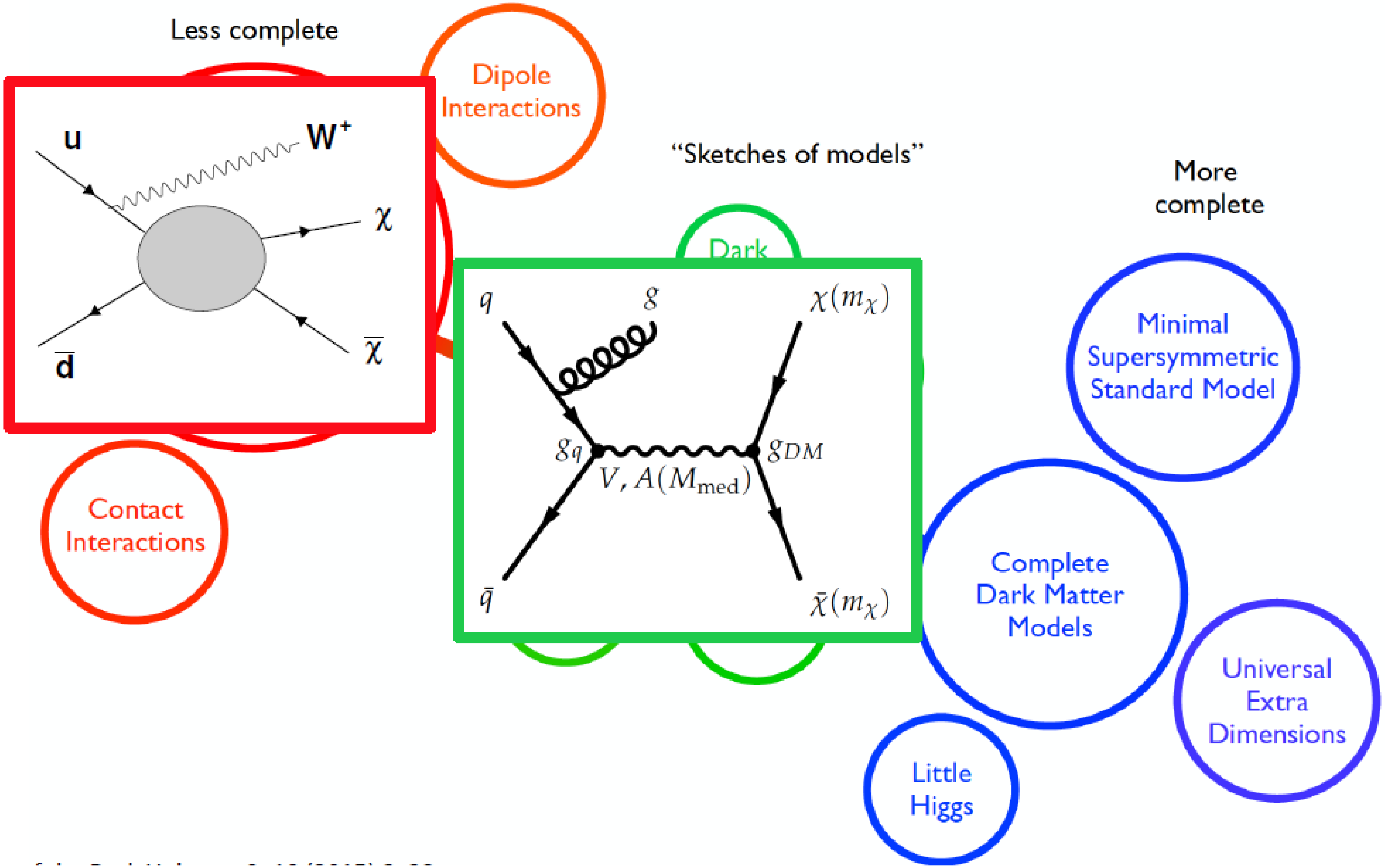
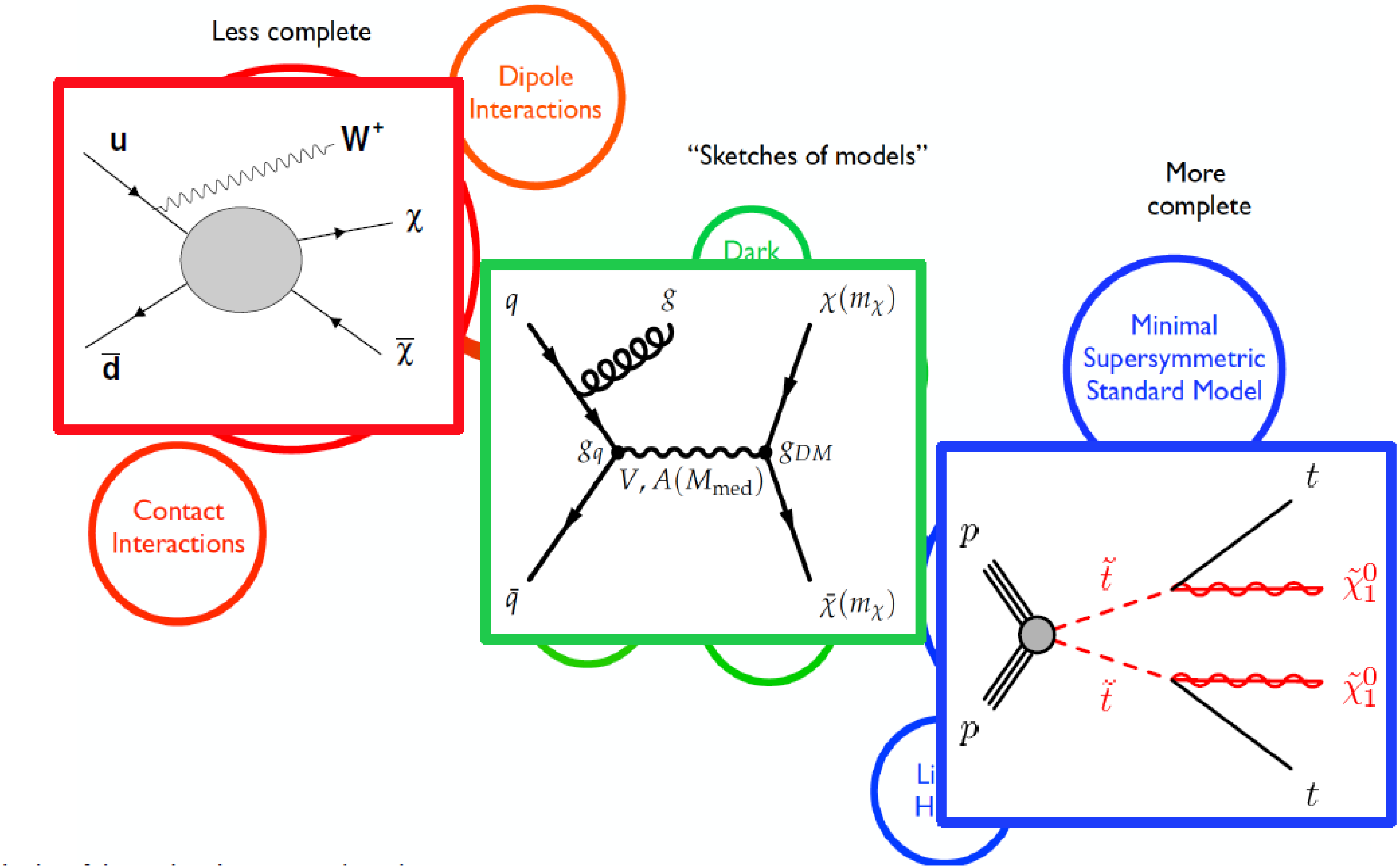
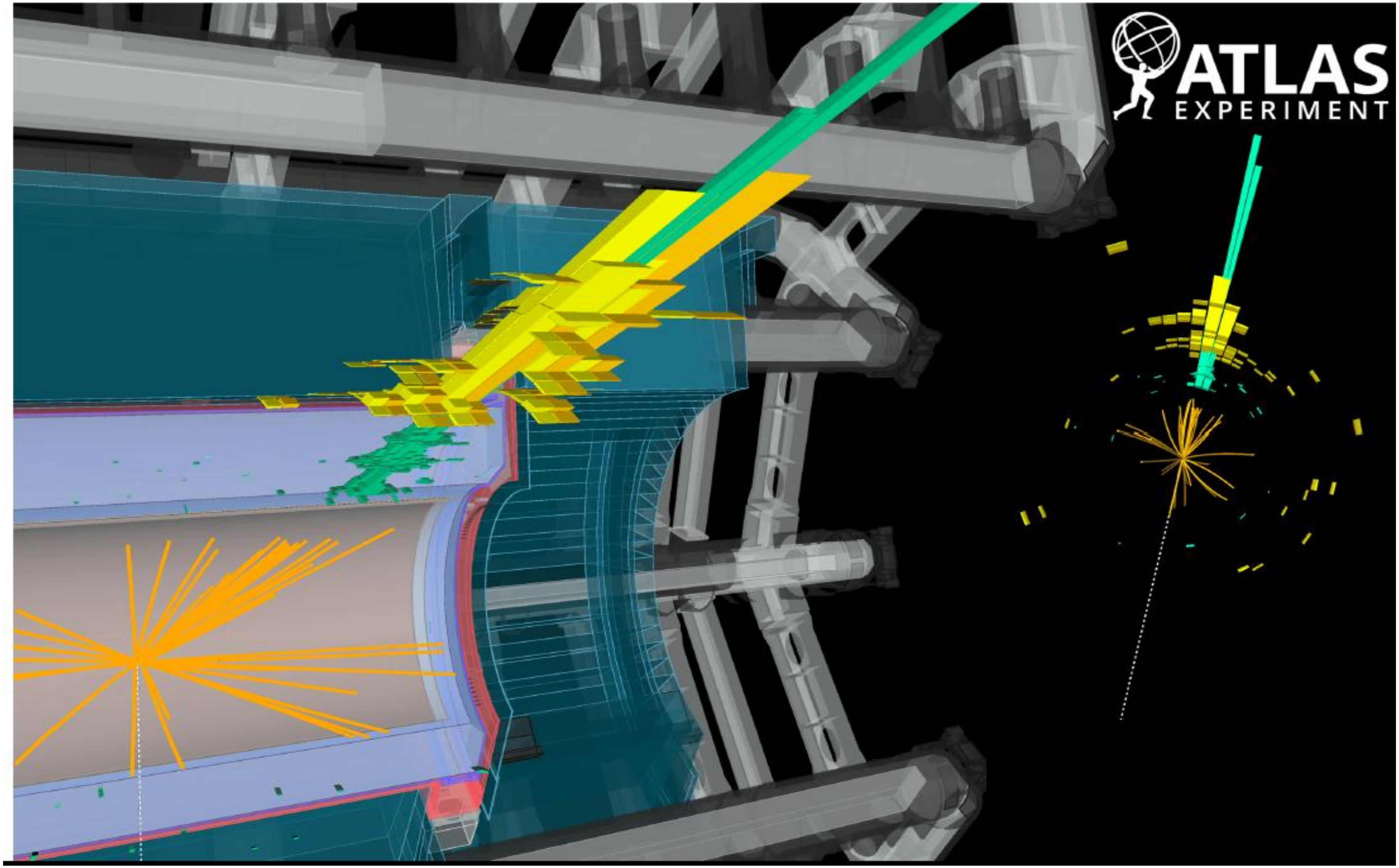


Dark Matter theory space

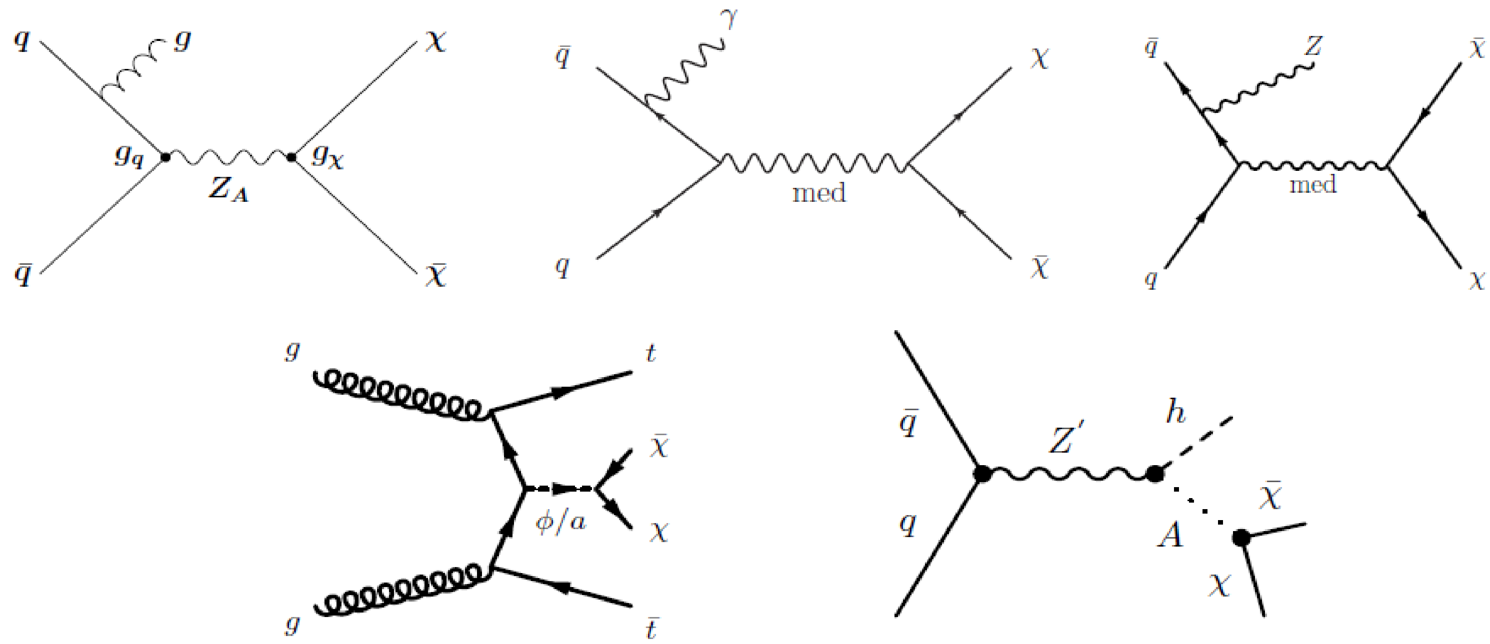


Searches for DM with (E_T^{miss} +X) Signatures



$(E_T^{miss} + X)$ 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, $X = \text{jet}, \gamma, V, t, b, h \ldots$

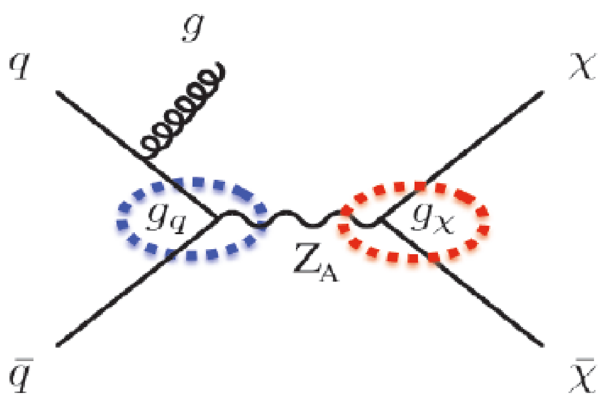


Mediators: vector, axial-vector, scalar, pseudoscalar
Parameters: $m_{\text{med}}, m_\chi, g_q, g_\chi$

Simplified Model

Simplified Model

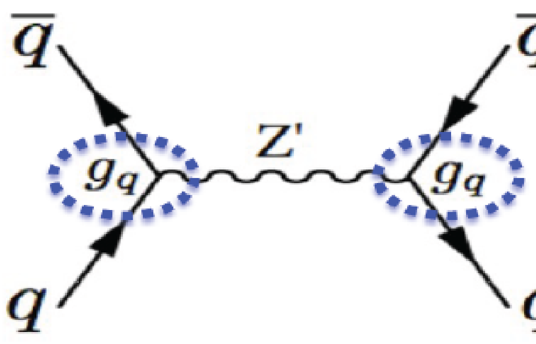
$SM \rightarrow mediator \rightarrow DM$



→Mono-X signature

E_T^{miss}+ jet, W/Z/H, γ, ...

$SM \rightarrow mediator \rightarrow SM$



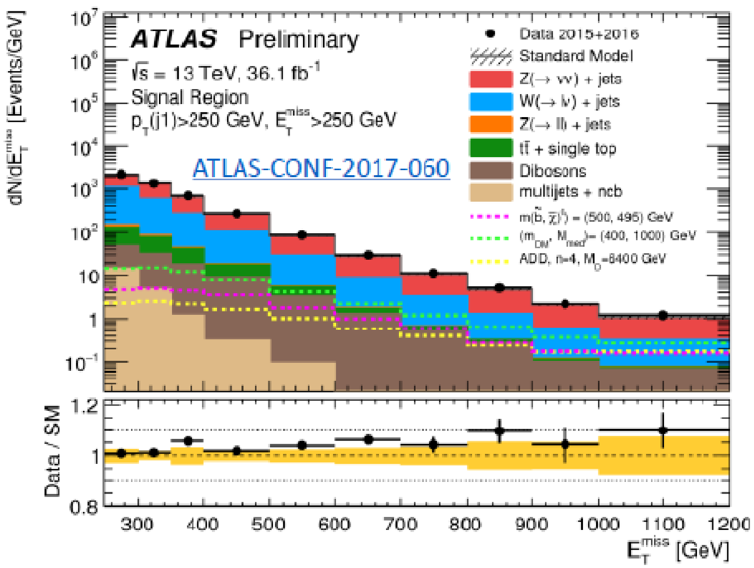
→resonant production

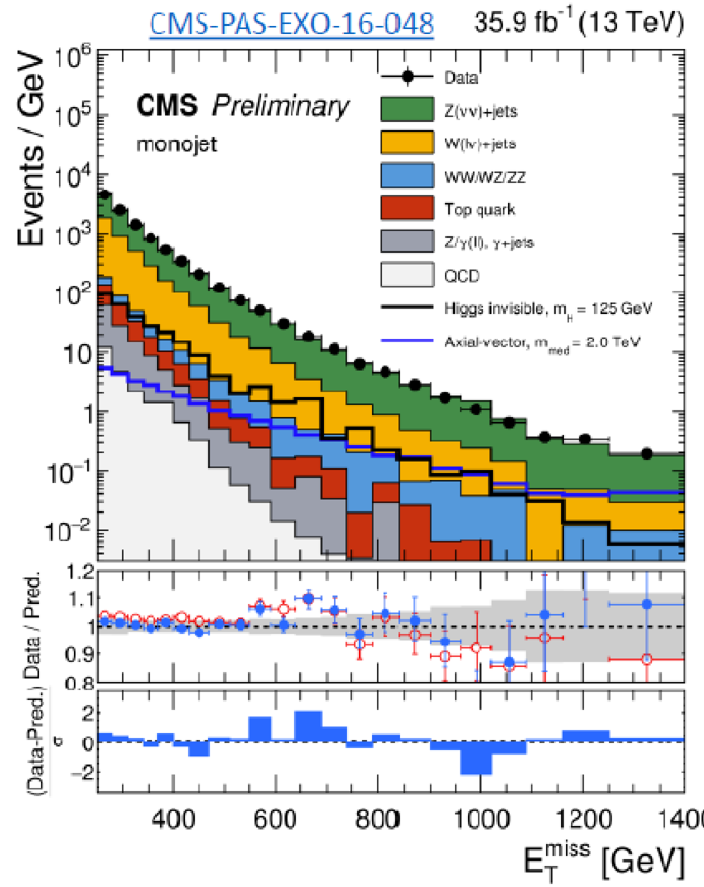
Dijet, ditop, dilepton.....

	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

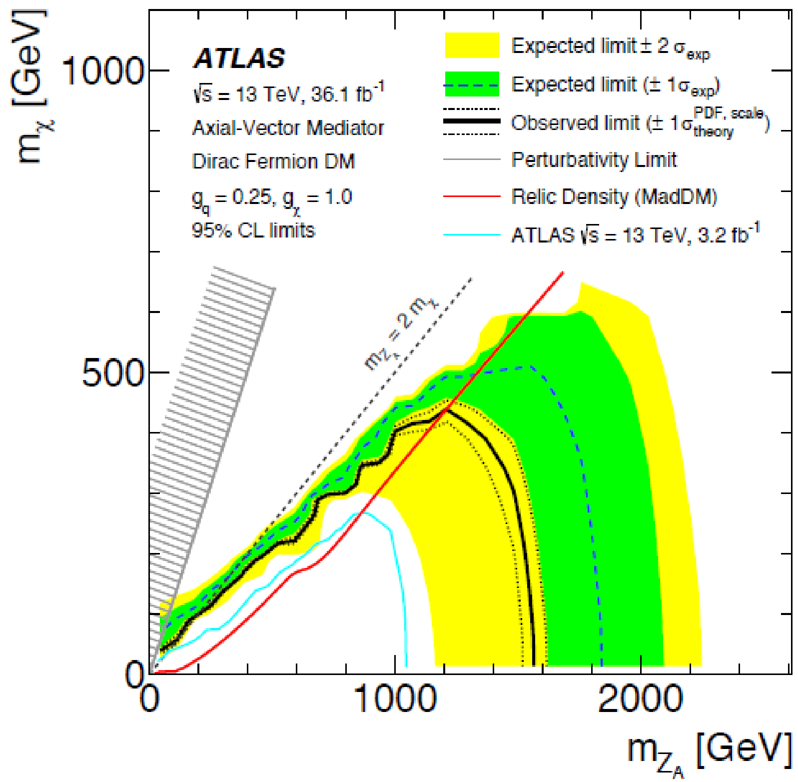
- $E_T^{miss} > 250$ GeV, $\Delta\varphi(\text{jet}, p_T^{miss}) > 0.4$
- Jet $p_T > 250$ GeV, $|\eta| < 2.4$
- $N_{jets} \leq 4$

CMS

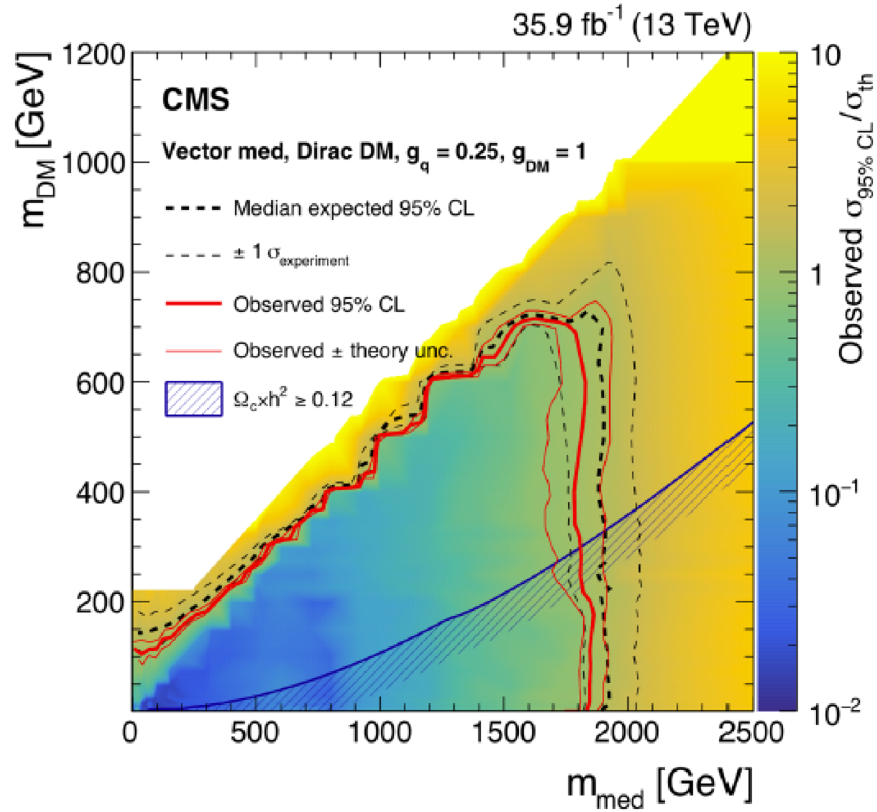
- $E_T^{miss} > 250$ GeV
- Jet $p_T > 100$ GeV, $|\eta| < 2.5$

Mono-X searches

Axial-Vector Mediator



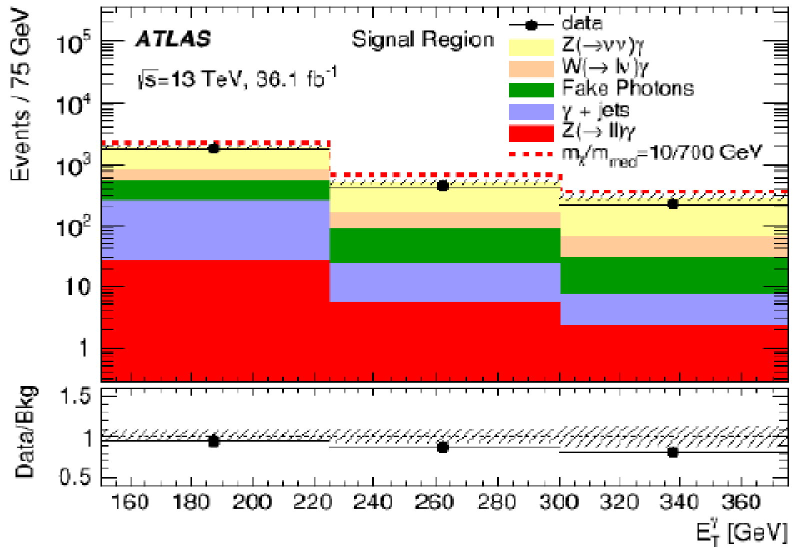
Vector Mediator

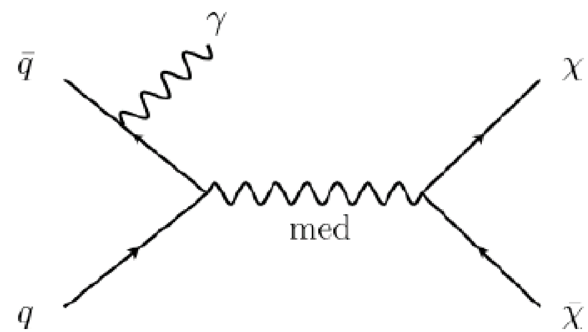


For couplings $g_q = 0.25,\ g_\chi = 1.0$, axial-vector and vector mediators excluded up to 1.8 TeV (1.55 TeV) by CMS (ATLAS) for $m_\chi \sim 1$ GeV.

JHEP 01 (2018) 126
arXiv:1712.02345

Mono-photon



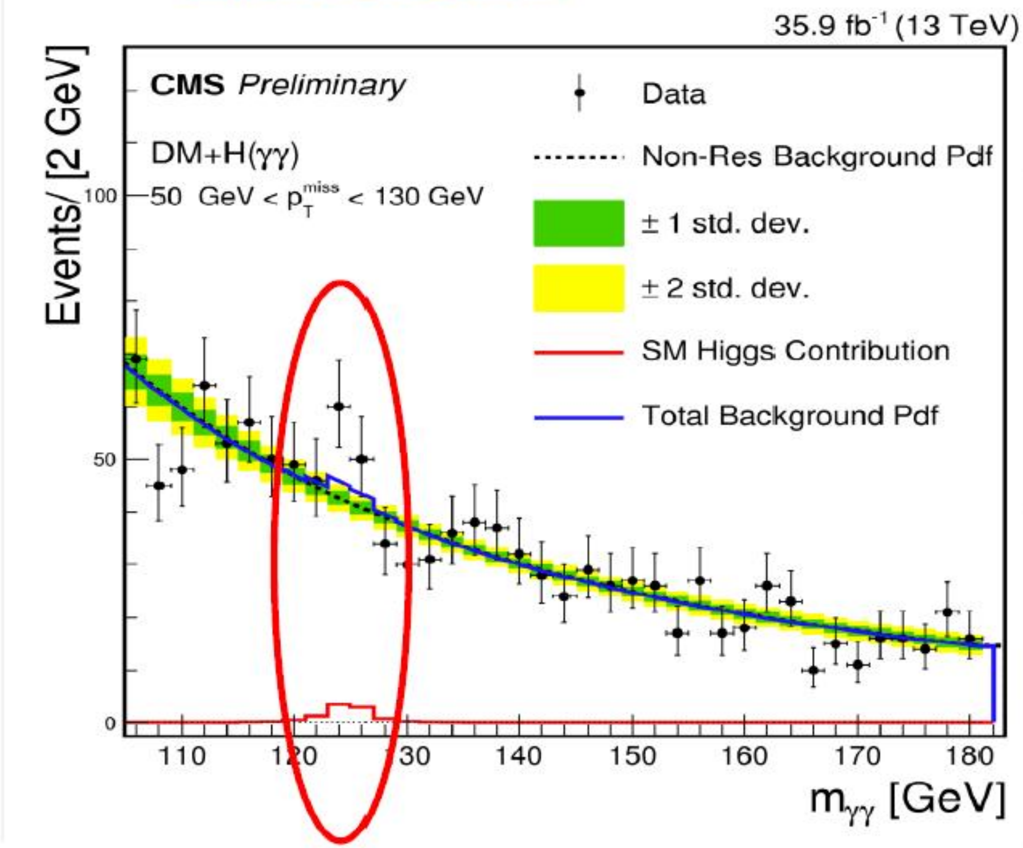


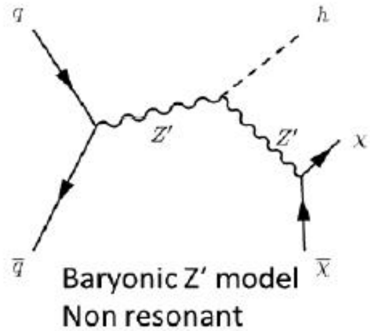
- Photon $E_T > 150$ GeV, $|\eta| < 2.37$
- $E_T^{miss}/\sqrt{\sum E_T} > 8.5\ \mathrm{GeV}^{1/2}$
- $\Delta\varphi(\mathrm{photon}, E_T^{miss}) > 0.4$
- $N_{jets}(p_T > 30\ \mathrm{GeV}, |\eta| < 4.5) \leq 1$

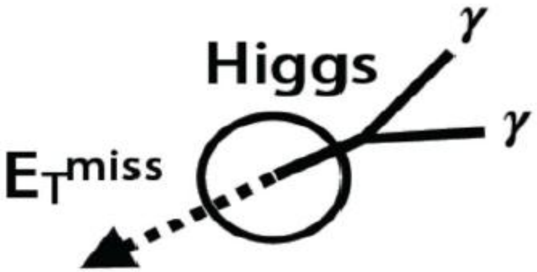
Mono-X searches

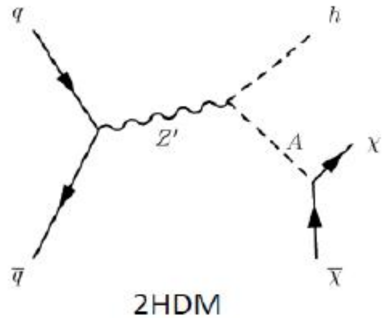
Mono-Higgs

CMS-PAS-EXO-16-054

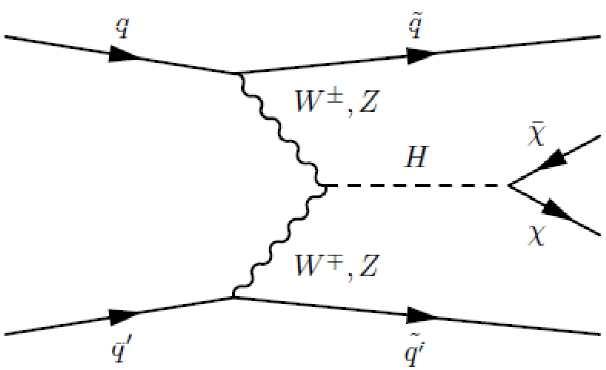






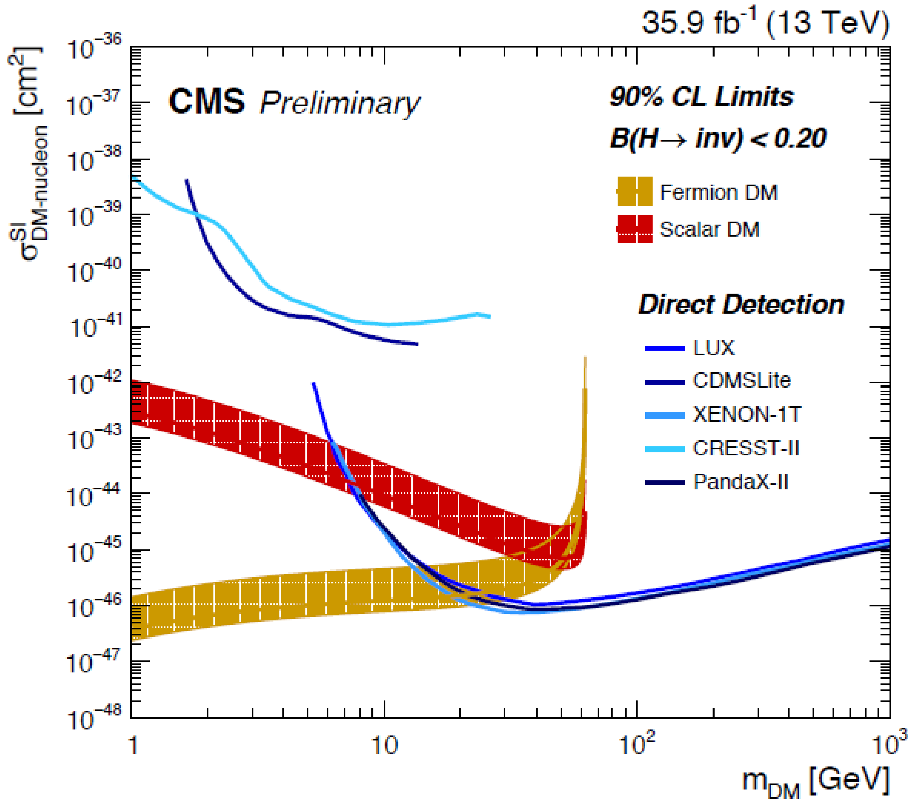


H-> invisible: Comparison with DD



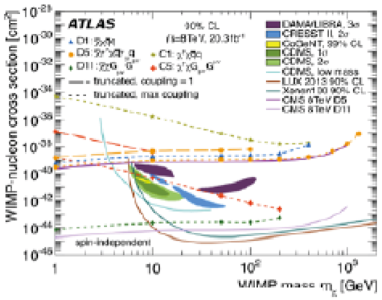
$\mathcal{B}(\mathrm{H}\to\mathrm{inv}) < 0.2$ at 90% CL interpreted in context of Higgs-portal DM model.

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

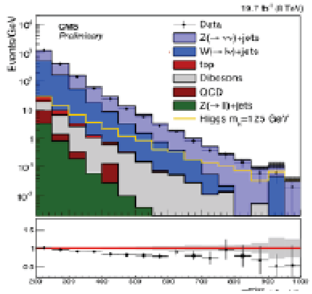


CMS-PAS-HIG-17-023 (14 March 2018)

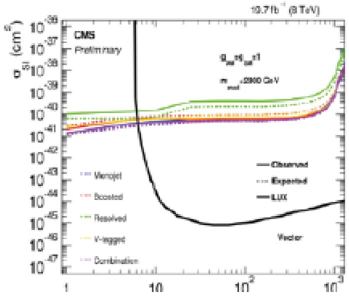
Plenty of mono-signatures



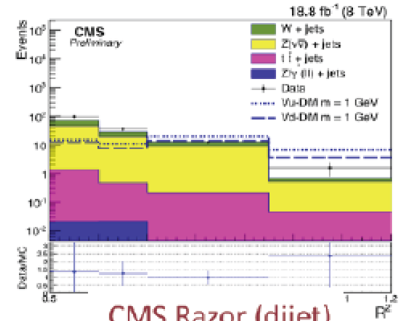
ATLAS Monojet
EPJC (2015) 75:299



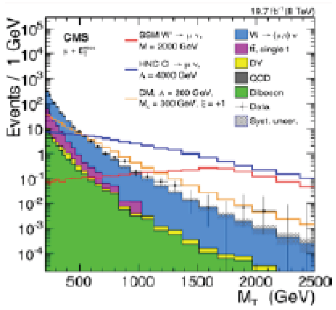
CMS j/V (mono/dijet)
PAS-EXO-12-055



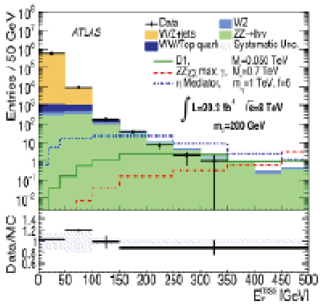
CMS j/V (mono/dijet)
PAS-EXO-12-055



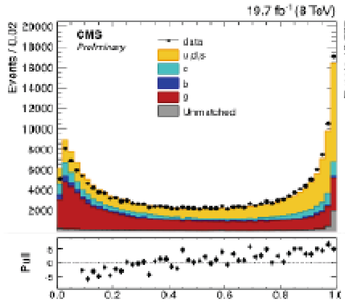
CMS Razor (dijet)
PAS-EXO-14-004



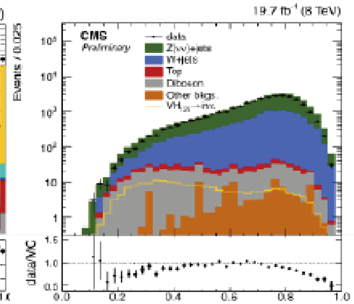
CMS, ATLAS MonoW
PRD 91, 092005, JHEP 09 (2014) 037 (2015)



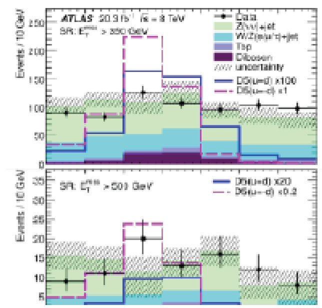
CMS, ATLAS MonoZ
EXO-12-054, PRD 90, 012004 (2014)



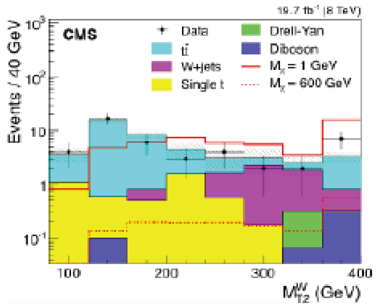
CMS MonoV (resolved)
PAS-EXO-12-005, PAS-JME-14-002



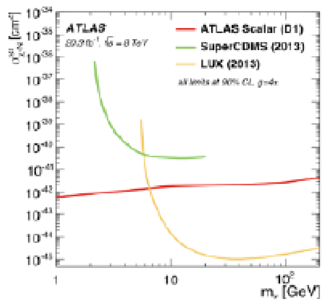
CMS MonoV (boosted)
EXO-12-005/JME-14-002



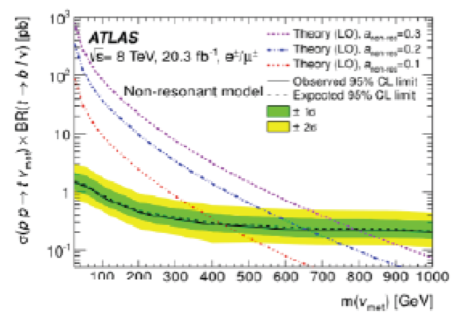
ATLAS MonoV (boosted)
ATLAS, PRL 112, 041802 (2014)



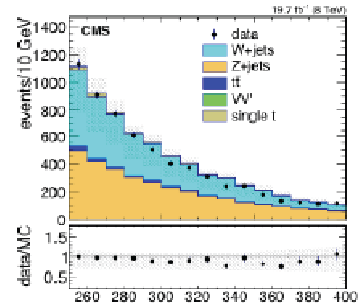
CMS TopPairs
CMS, JHEP 06 (2015) 121



ATLAS TopPairs
ATLAS, EPJC (2015) 75:92

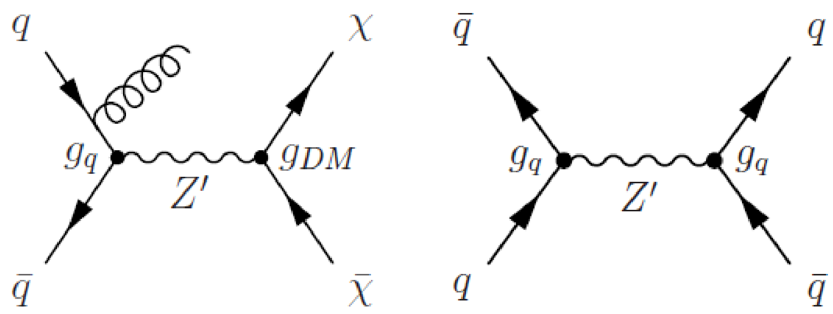


CMS MonoTop
CMS, PRL 114 (2015) 101801



ATLAS MonoTop
ATLAS, JHEP 11 (2014) 118

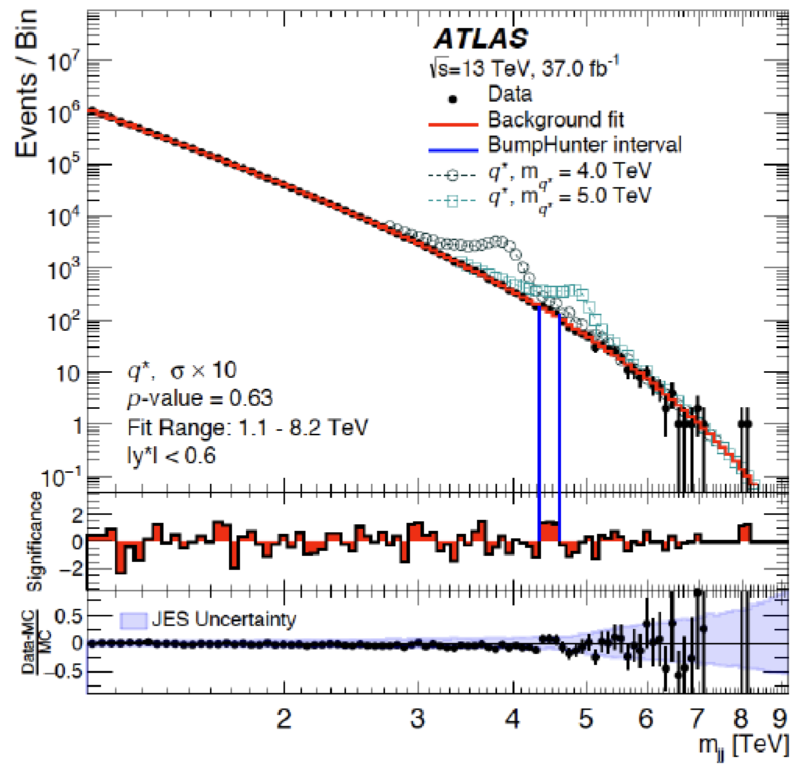
LHC is a mediator machine



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

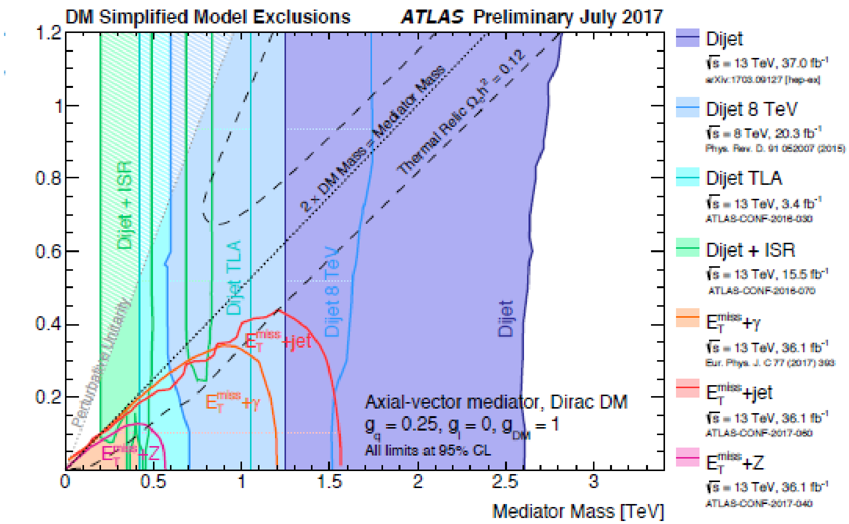
m_{jj} is the discriminant,
search for bump on a smooth,
falling background.

Background modeled by
a parameterized function.

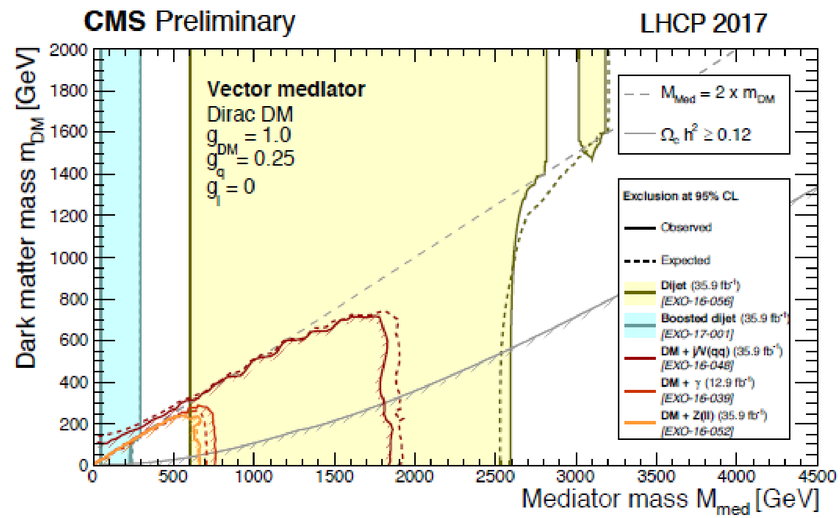


Limits on DM mass vs Mediator mass

Axial-Vector Mediator



Vector Mediator



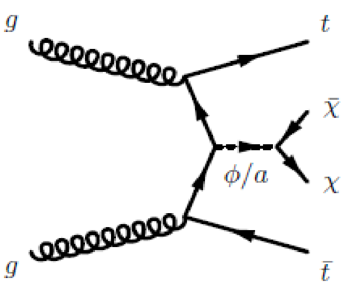
Couplings: $g_{\rm DM} = 1,\ g_q = 0.25,\ g_l = 0$ (leptophobic)

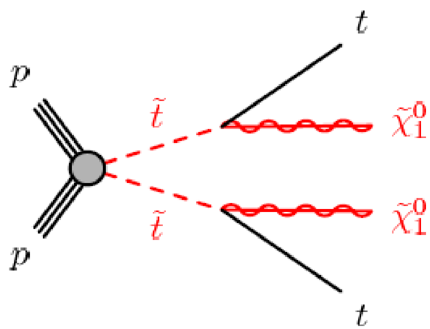
Dijet searches significantly extend DM reach, particularly for $m_{\rm DM} > M_{\rm med}/2$. Limits are same as leptophobic Z' search.

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

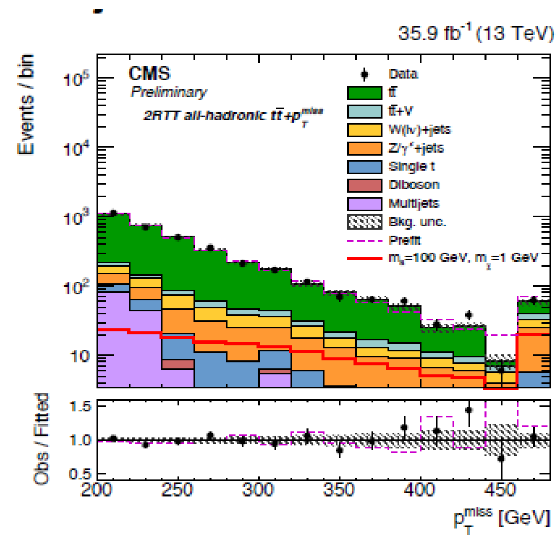


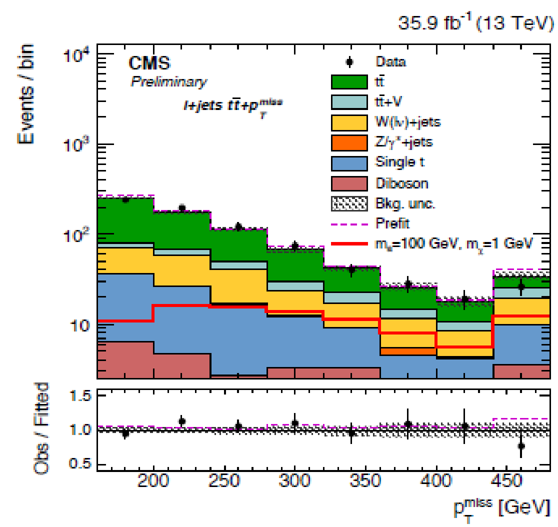


$(t\bar{t} + \chi\bar{\chi})$ discriminant is $p_{\mathrm{T}}^{\mathrm{miss}}$.

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

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





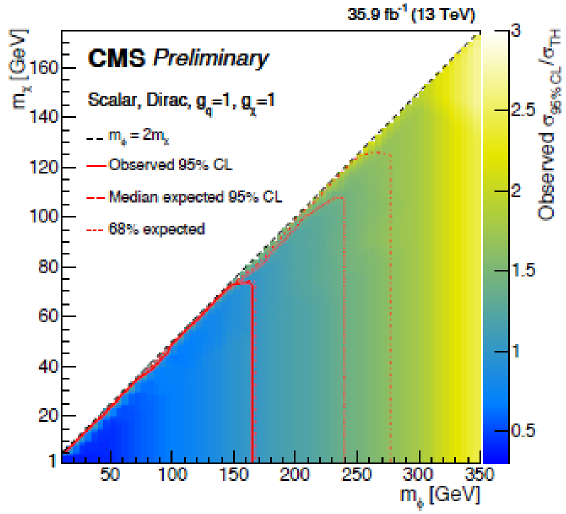
Search for DM + Heavy Flavor

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

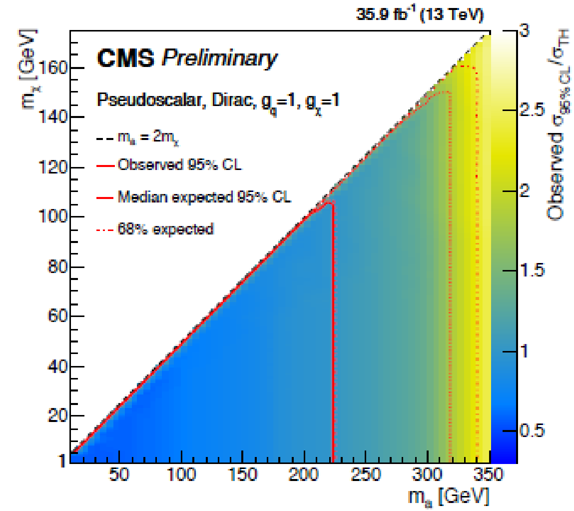
CMS-PAS-EXO-16-049 (3 April 2018)

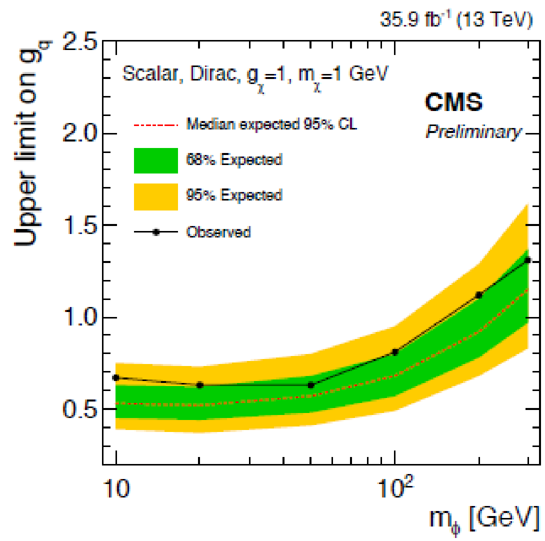
For $g_{\mathrm{DM}} = 1$, $m_\chi = 1$ GeV: limits on coupling of ϕ or a to SM quarks.

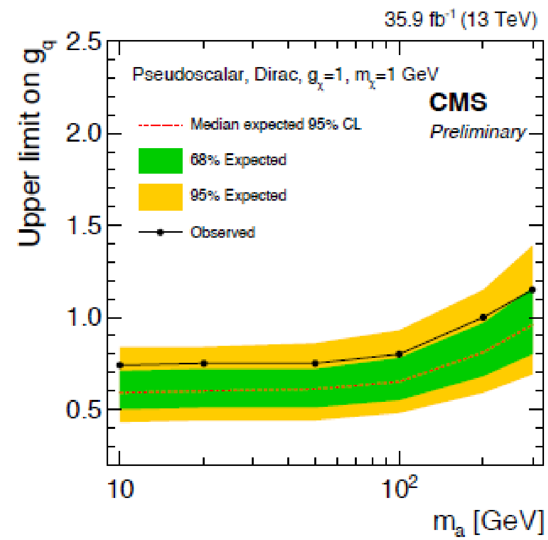
Scalar Mediator



Pseudoscalar Mediator

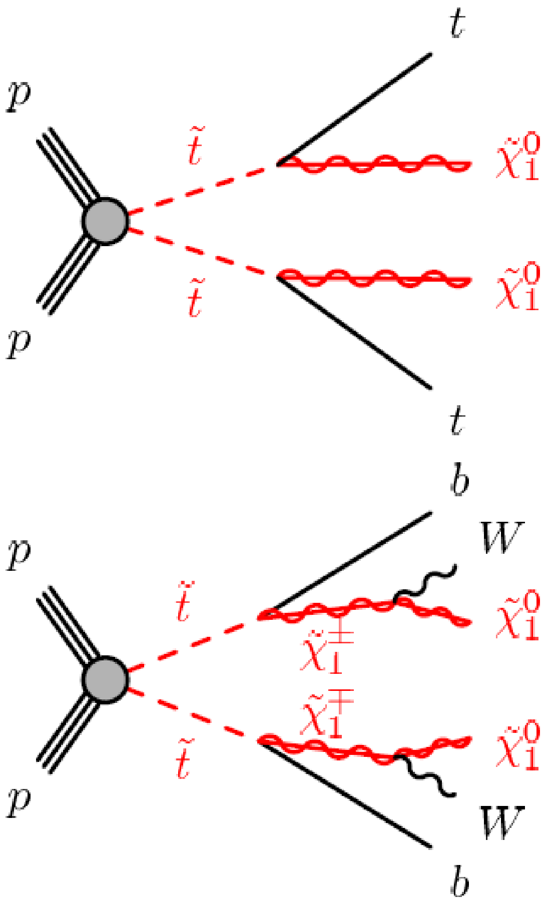


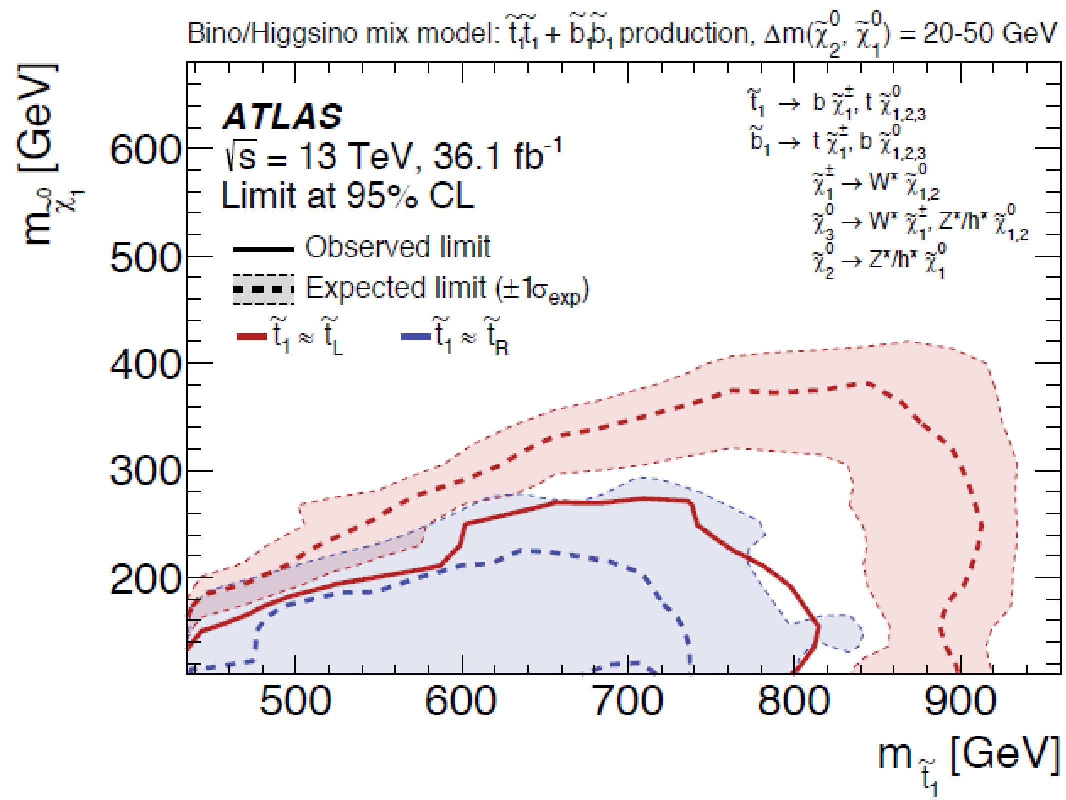




SUSY DM candidates

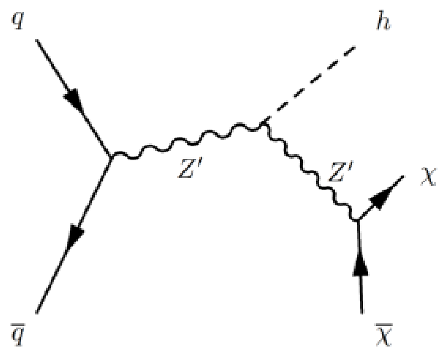
In many SUSY models the LSP is stable and weakly interacting $\Rightarrow$ a DM candidate. Some models are tuned to reproduce the DM relic density, e.g. the “well tempered neutralino” scenario.





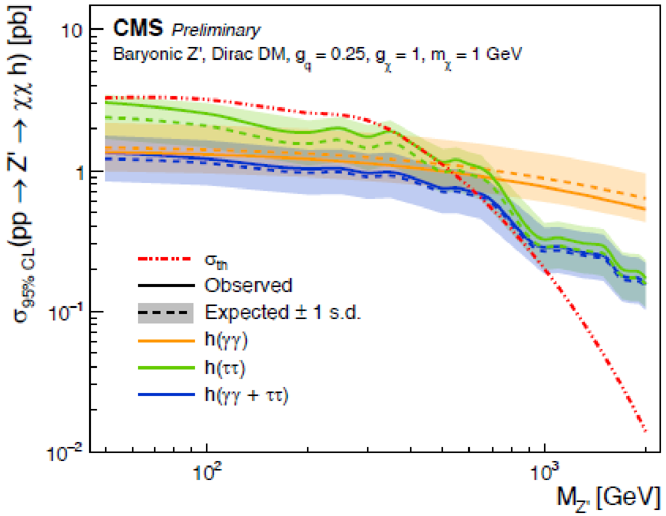
Search for DM + Higgs

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



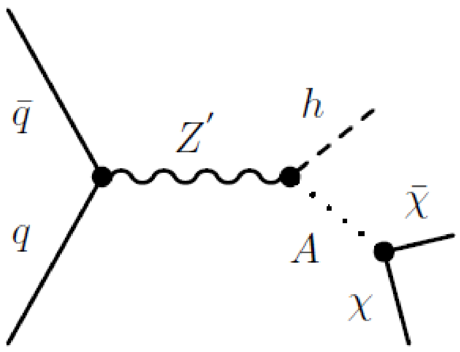
Baryonic Z' Model

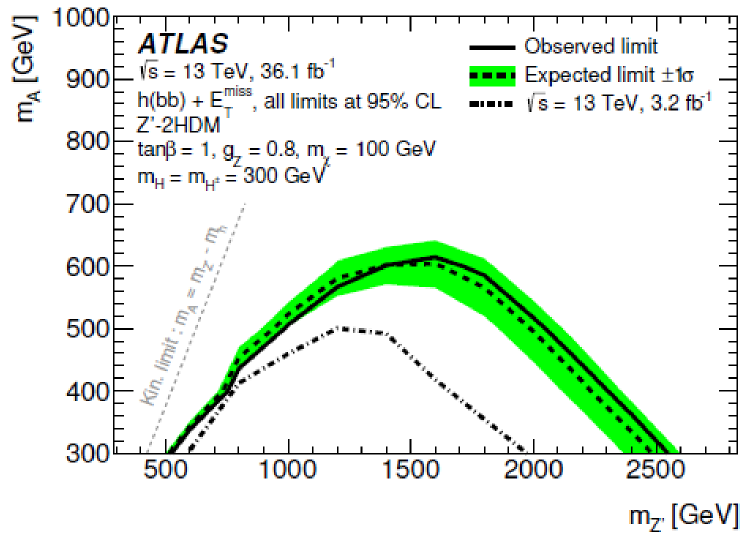
$h \to \gamma\gamma$ and $\tau^+\tau^-$
Z' excluded up to 815 GeV for low m_χ



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.



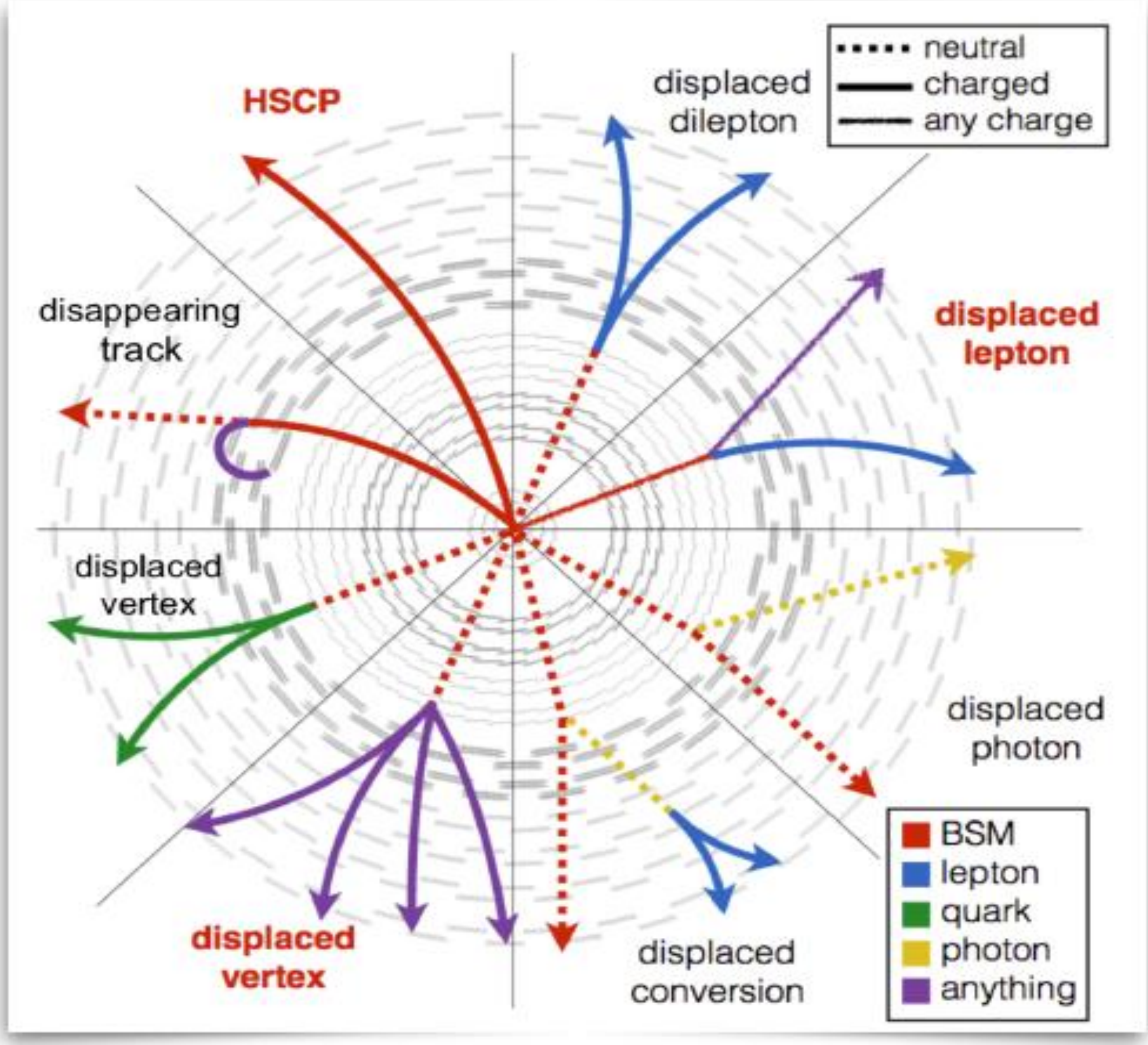


CMS PAS EXO-16-055 (13 March 2018)
PRL **119** (2017) 181804

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

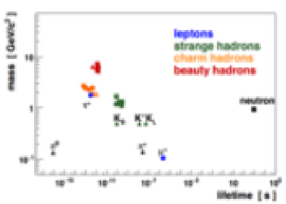


Unconventional signatures: challenges

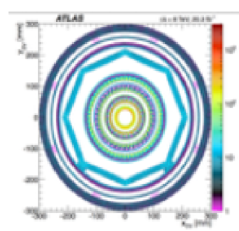
- Trigger: combination of hardware + software that must decide very quickly whether to save an event or lose it forever
  - First step in every search for LLPs: make sure that interesting events are saved!
    1. In associated production, trigger on prompt particle (Eg. WH prod. trigger on mu; ISR trigger 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

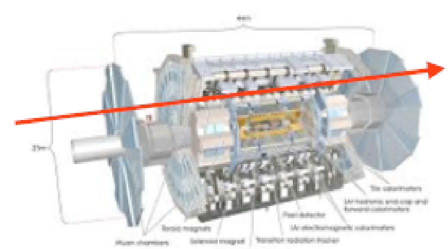
weak decays of heavy flavour



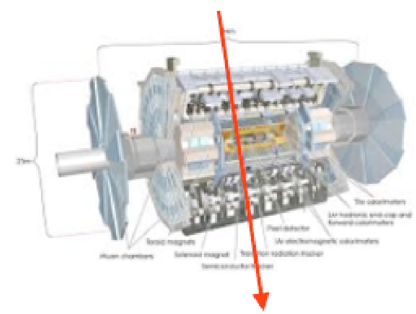
material interactions



beam halo muons



cosmic muons



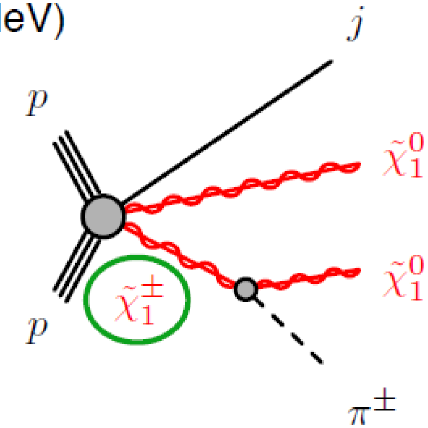
- Systematic uncertainties: can't use standard recommendations for object reconstruction nor trigger

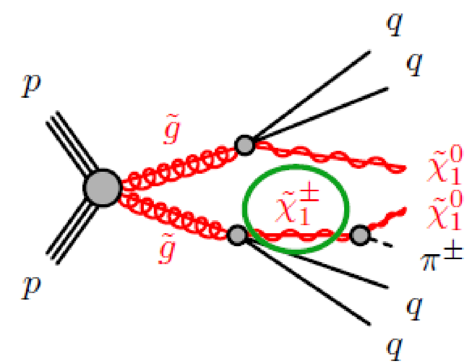
Unconventional signatures: disapearing tracks

LLP

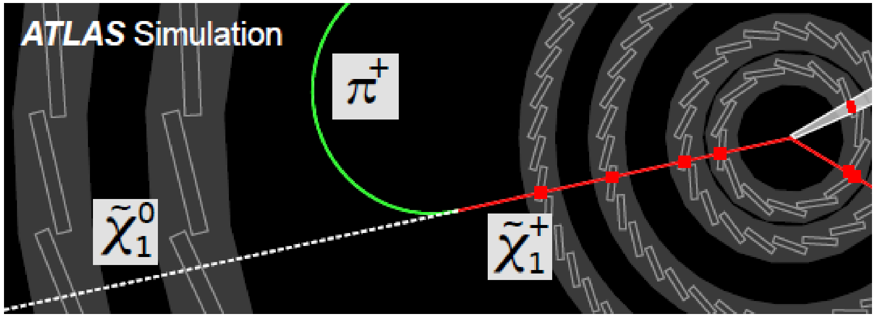
- Search for disappearing track + MET + jets
- Signature: Chargino track “disappears” when it decays, into MET
  - Low momentum pion track (~0.1 GeV) is hard to reconstruct
  - Challenge to identify the legitimate real tracklets (non-fake) using only a few measurement tracks

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





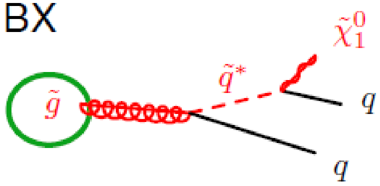
- Search sensitive to LLP lifetime of 10ps to 10 ns



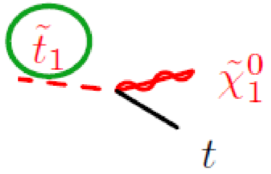
Unconventional signatures: stopped particles

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

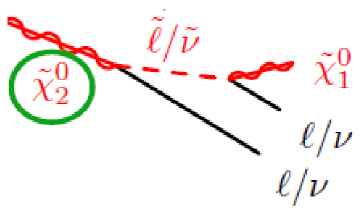
- Signature: LLPs come to rest in the detector and decays after the current BX
  - most likely to stop in the densest detector materials:
    - Calorimeters (ECAL, HCAL):
      a) Split SUSY: two-body and three-body decays of a gluino



      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 ($MCHAMP \rightarrow \mu^{\pm}\mu^{\pm}$)



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

Summary (Exotic Searches)

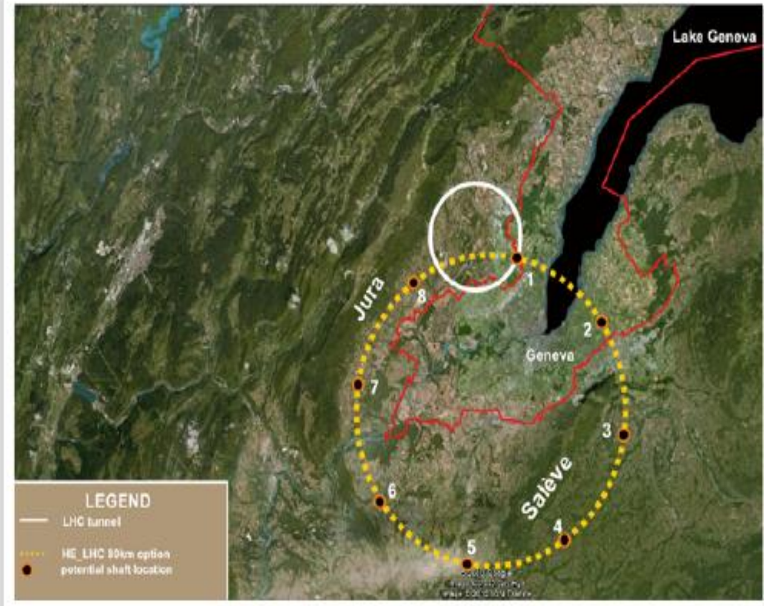
- Searches for Exotic searches
  - All major search channels reached 1 TeV scales
  - Quite a few at 10 TeV
  - New probe: Higgs boson → emerging field
- Dark Matter Searches are thriving at the LHC
- For vector and axial vector interactions
  - Dark Matter masses up 400 GeV – 700 GeV (mono-jet) excluded
  - Mediator mass up to 1.6 – 1.8 TeV (mono-jet) excluded
  - Mediator mass up to 1.2 TeV (mono-photon) excluded
  - Mediator mass up to 0.7 TeV (mono-Z) excluded
- LHC searches complement DD experiments
  - $m_{DM} < O(10\ GeV)$

Glimpse at Future Hadron Collider

The candidate machines in a tiny nutshell

Project	HL-LHC	HE-LHC	FCC-hh	SppC
Location	CERN	CERN	CERN	China TBD
Circ.	27 km	27 km	100 km	55 - 100 km
COM energy	14 (15?) TeV	27 TeV	100 TeV	70 -140 TeV
Luminosity	3 ab-1	15 ab-1	20-30 ab-1	TBD
PU	up to 200	up to 800	up to 1000	TBS
Bunch sp.	25 ns	25 ns	25 ns	25 ns
Field	8T	16T	16T	20T
When?	Until 2037	After 2037?	After 2037	TBS

Much much more in Lecture by R. Corsini



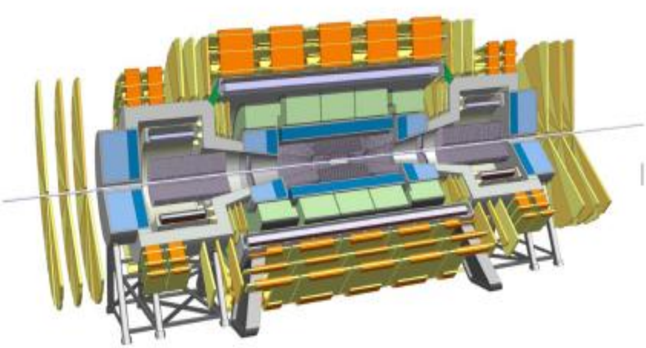
Detector, Trigger DAQ, Reconstruction challenges

Two challenges: higher PU (1000) higher pT

Answer: granularity and resolution

Decay products of a Z at 10 TeV are separated by $\Delta R = 0.01$

A b at 5 TeV can travel 50cm and a tau 10 cm



Glimpse at Future Hadron Collider

Numbers given here for FCC-hh and HL-LHC physics potential of HE-LHC is under study, however rule of thumbs scaling can give a fair estimate.

Direct searches

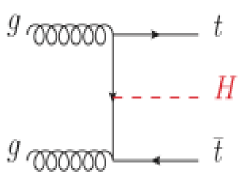
The reach in searches will range typically between a few TeV for weakly produced particles and **reach 20 TeV** for strongly interacting new particles as gluinos.

Precision SM and Higgs

- Precision EW measurements could reach unprecedented levels of accuracy with very high luminosity programs at the Z peak, the WW threshold and the tt threshold (MeV precision on the W mass, and tens of MeV on the top mass).

- Precision Higgs measurements will rely on a very complementary electron-positron collider which should reach sub percent level precision on most couplings (as well as measuring the total width of the Higgs boson)

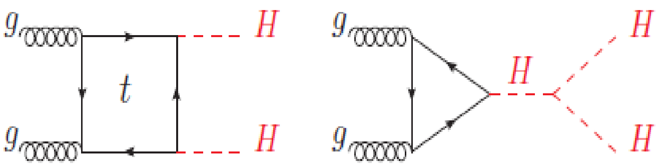
- Complementarity with the ee collider program



A production cross section 400 times larger than at LHC

O(5%) at HL-LHC

O(1%) at FCC-HH



Precision reach at HL-LHC O(100%) O(3%) at FCC-HH

Precision SM and Higgs

High energy FCC is a natural environment for measurements of SM processes, which will have first been measured at the HL-LHC.