Introduction to particle physics: experimental part

Searches for New Physics

Exotic models

Dark Matter

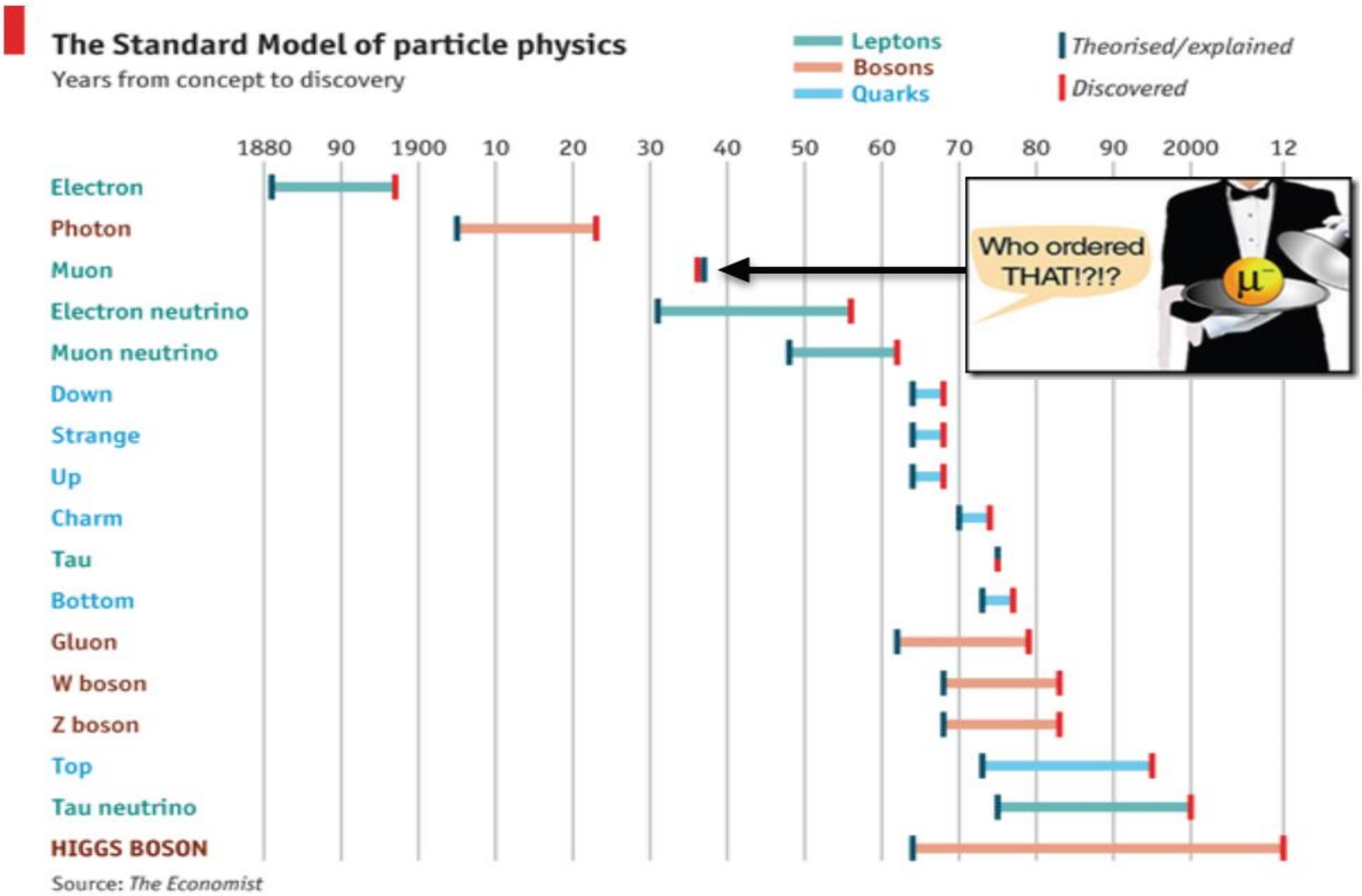
Uncomventional signatures

Sypersymmetry

ATLAS in statistics

Prof. dr hab. Elżbieta Richter-Wąs

Uncharted discoveries?

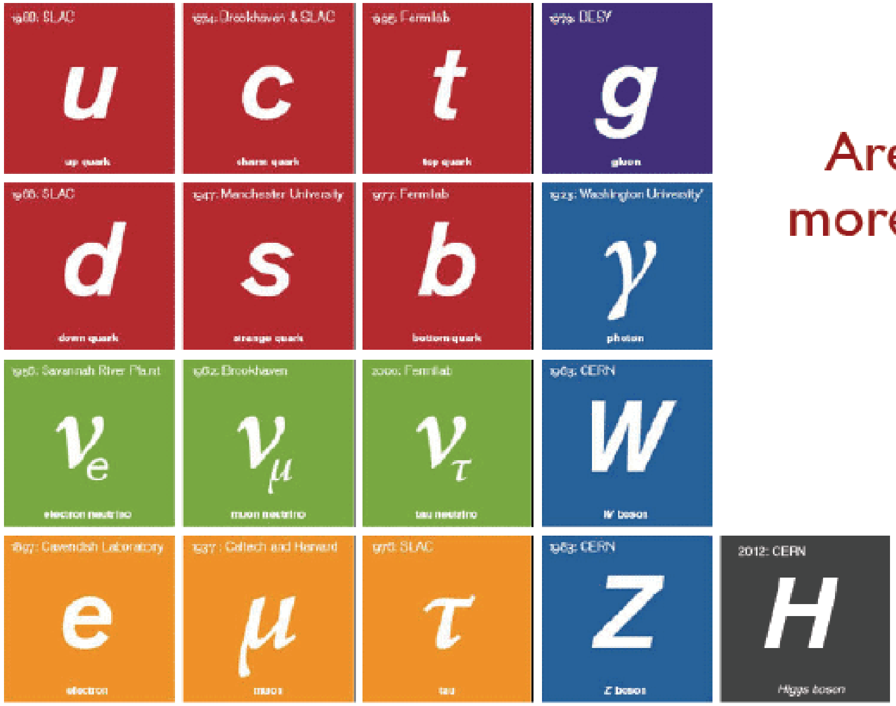


Many unanswered questions …

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?



Are there more forces?

How do neutrinos get mass?

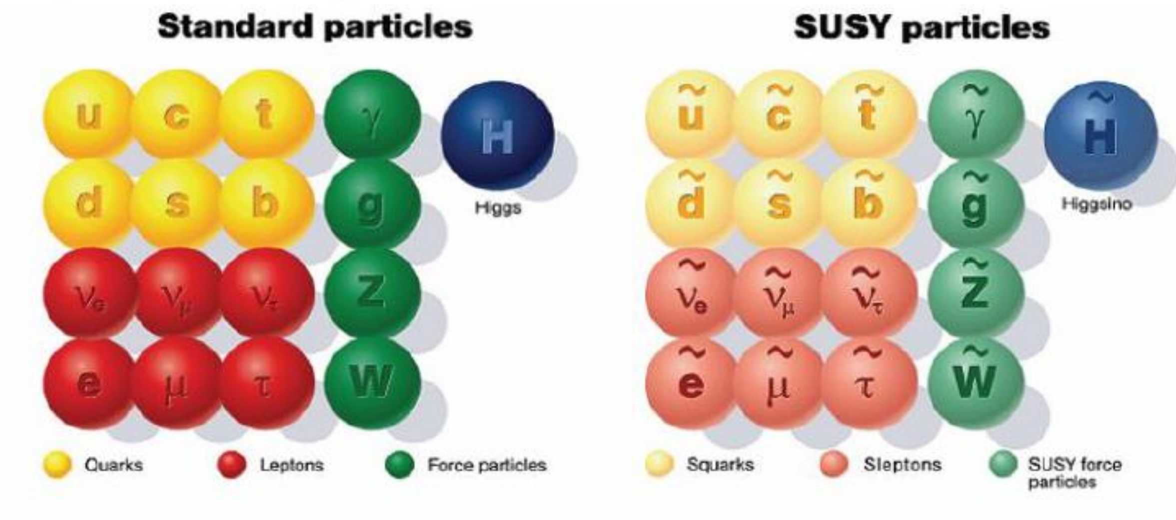
What keeps the Higgs mass so small?

How do we incorporate gravity?

What is Dark Matter?

… and as many possible answers to probe!

- Super-symmetry?

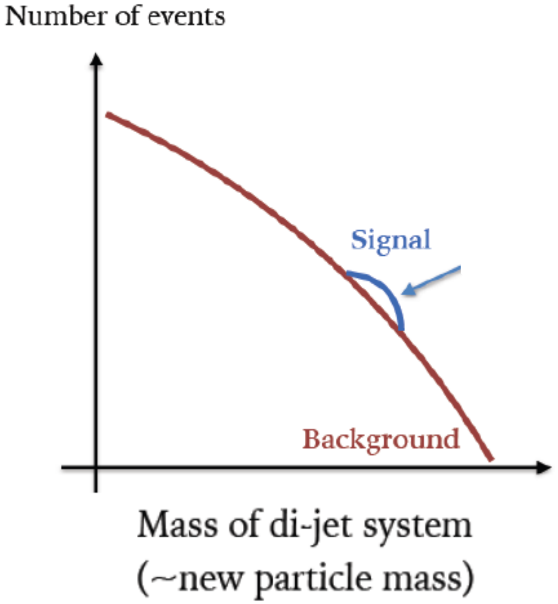


- Composite quark and/or leptons?
- New Heavy bosons?
- Gravitons?
- Dark Matter particles?
- …

How would new phenomena manifest?

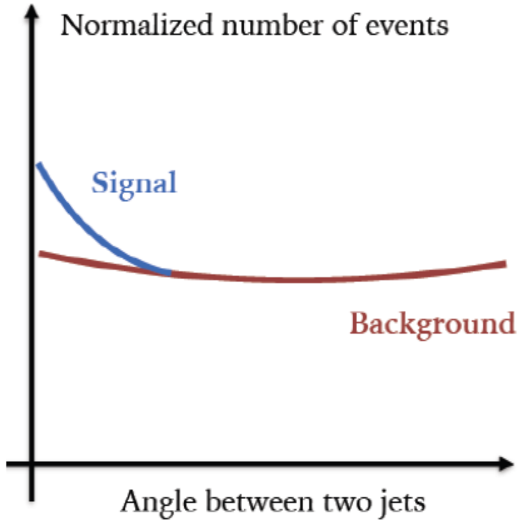
New particles:

resonant excess (bump) over Standard Model background



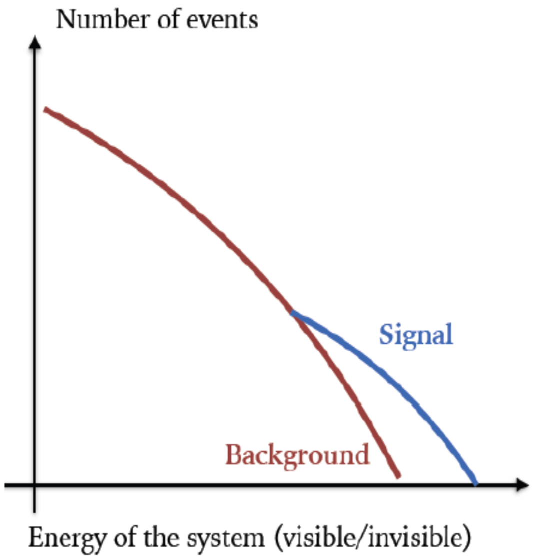
New interactions:

more central production (~Rutherford experiment)

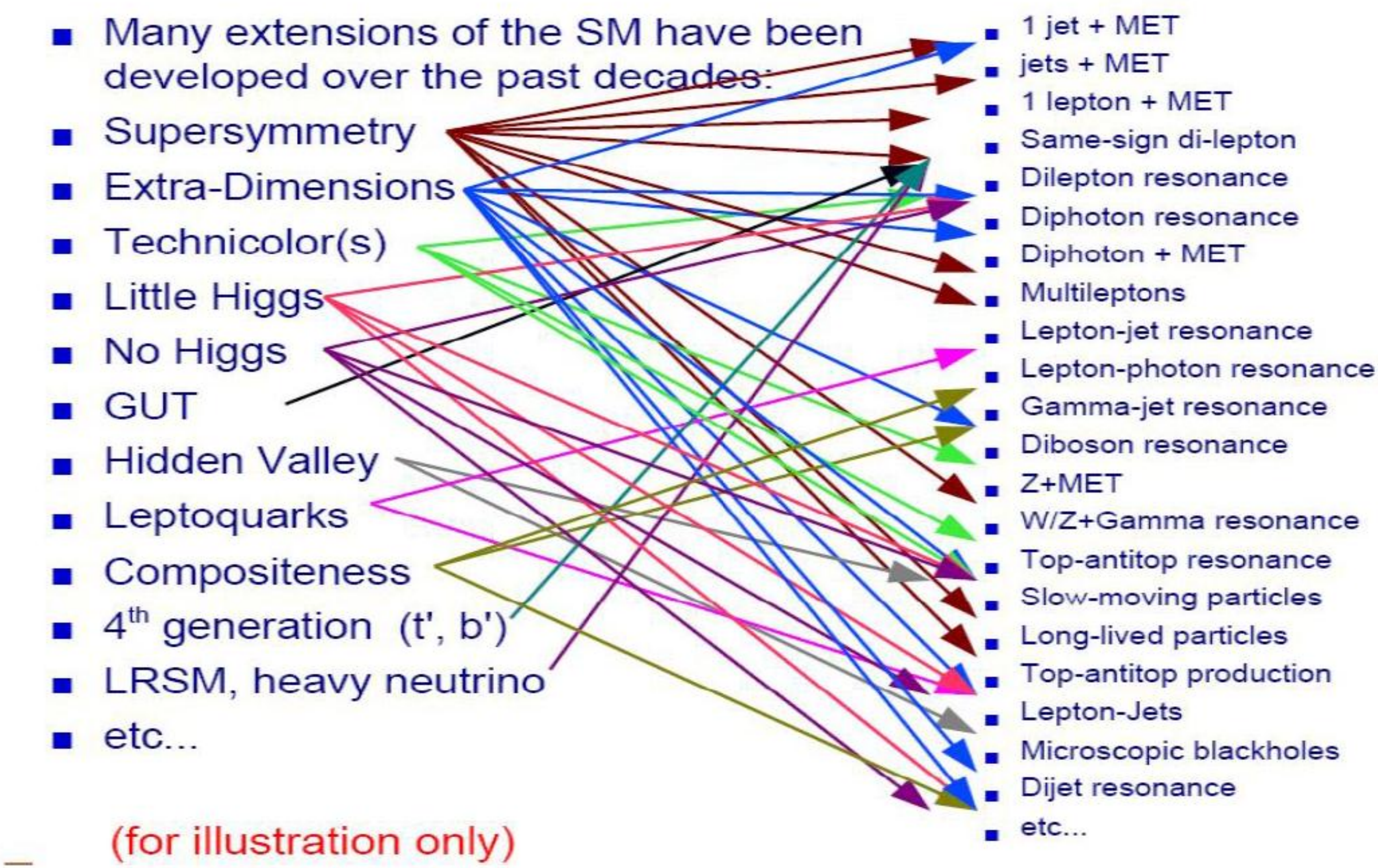


New particles and states:

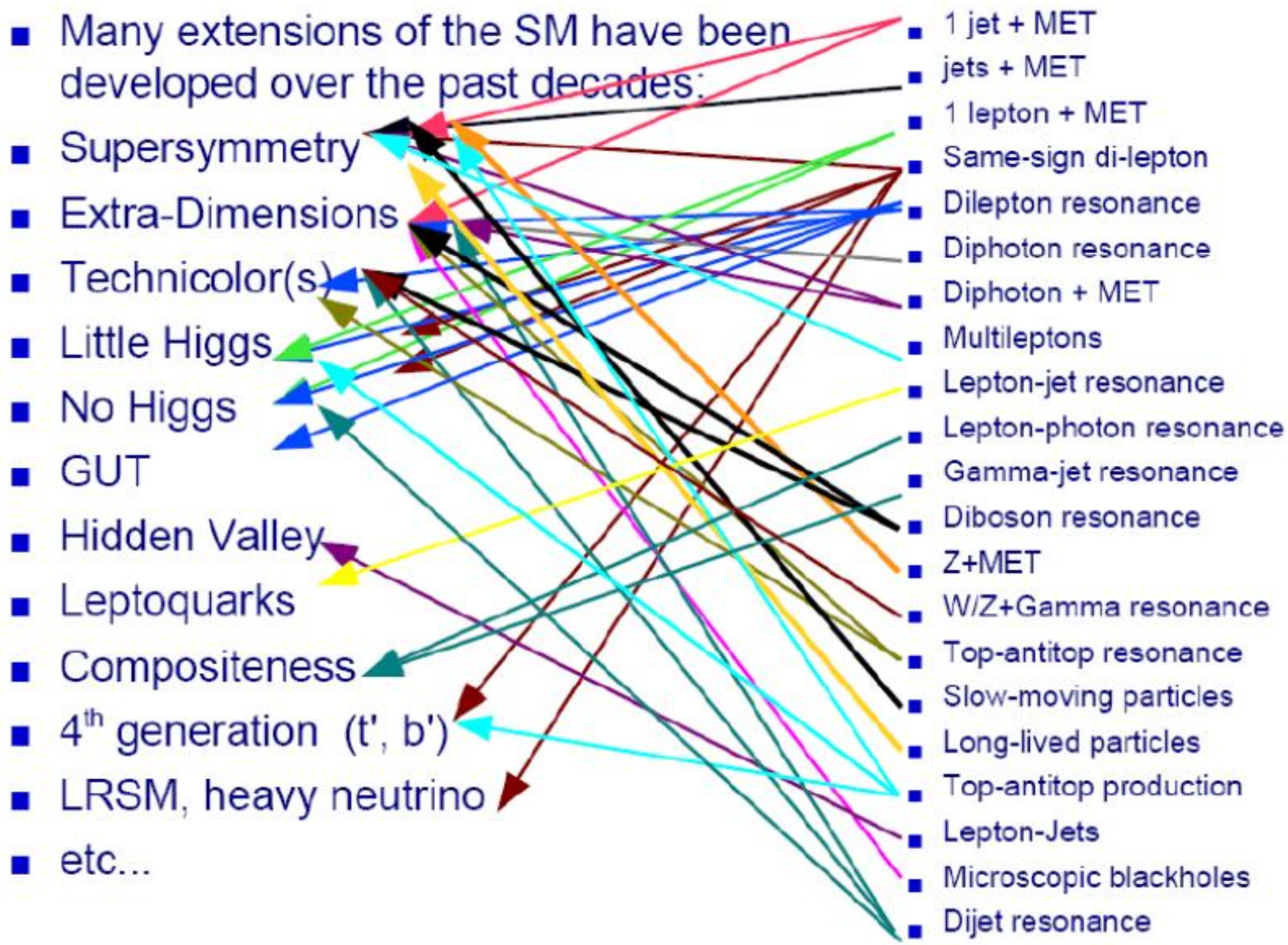
larger multiplicity of objects at high masses



Long list of models and signatures



Long list of models and signatures



(for illustration only)

A complex 2D problem

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

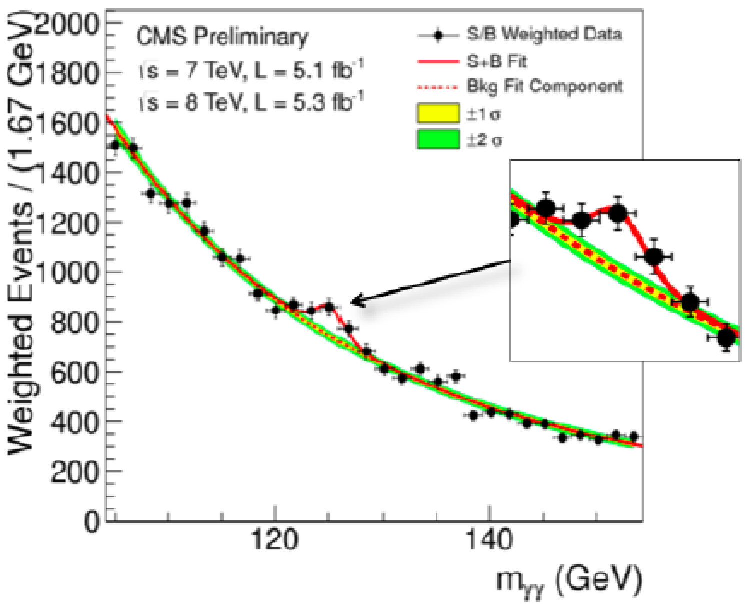
- → Practical
- → Less model-dependent
- → Important to cover every possible signature

What characterizes Exotics Searches

No precise model to guide us

Standard Model:

Predicted Higgs boson

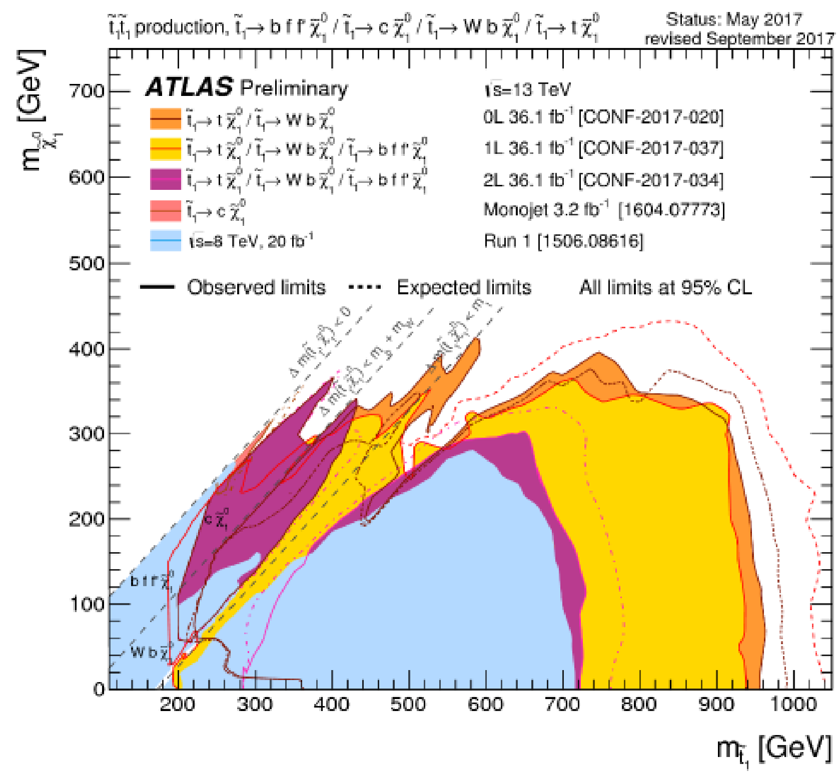


[Phys. Lett. B 716 (2012) 1-29]

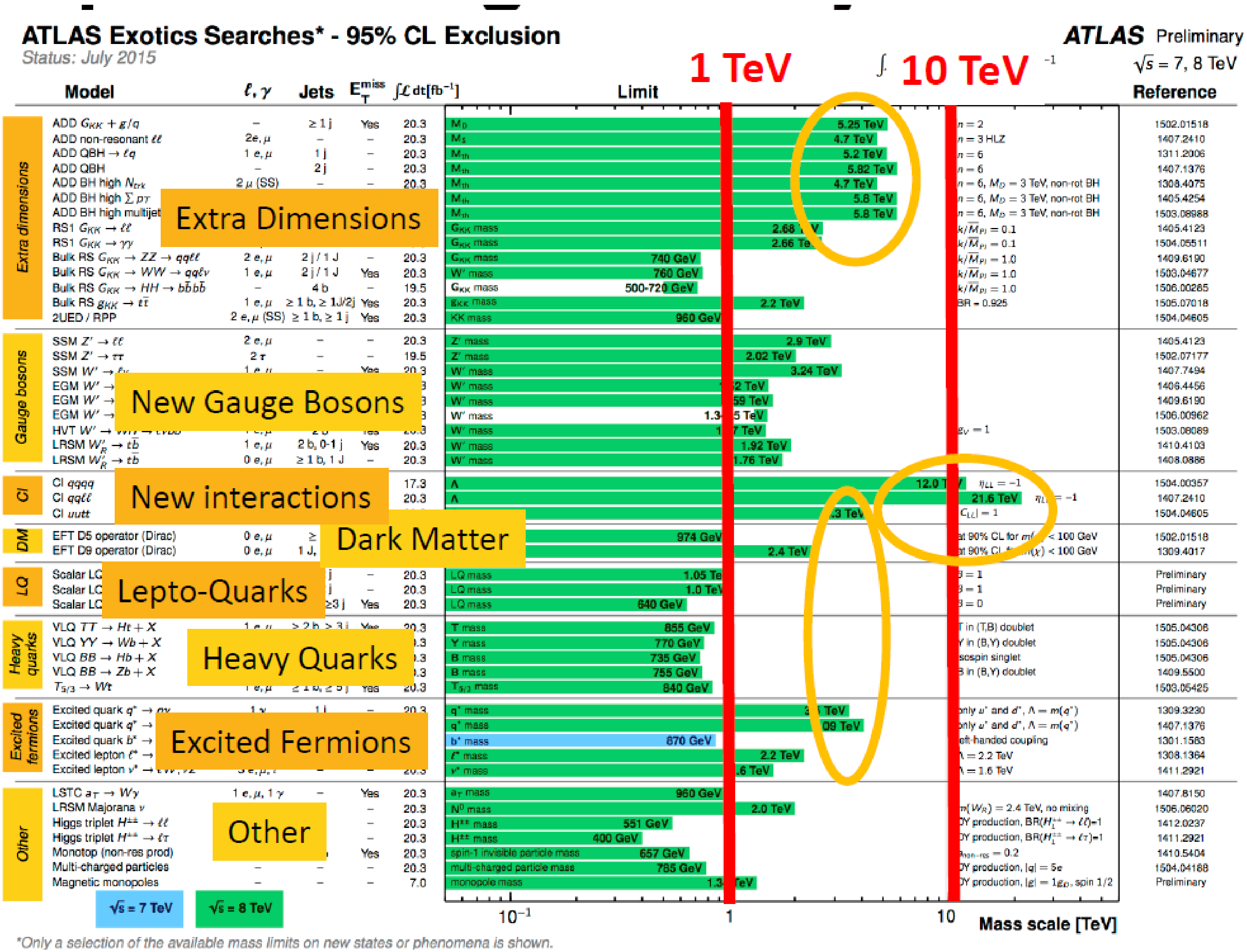
[Phys. Lett. B 716 (2012) 30-61]

No unified parameter phase space

Supersymmetry Searches:



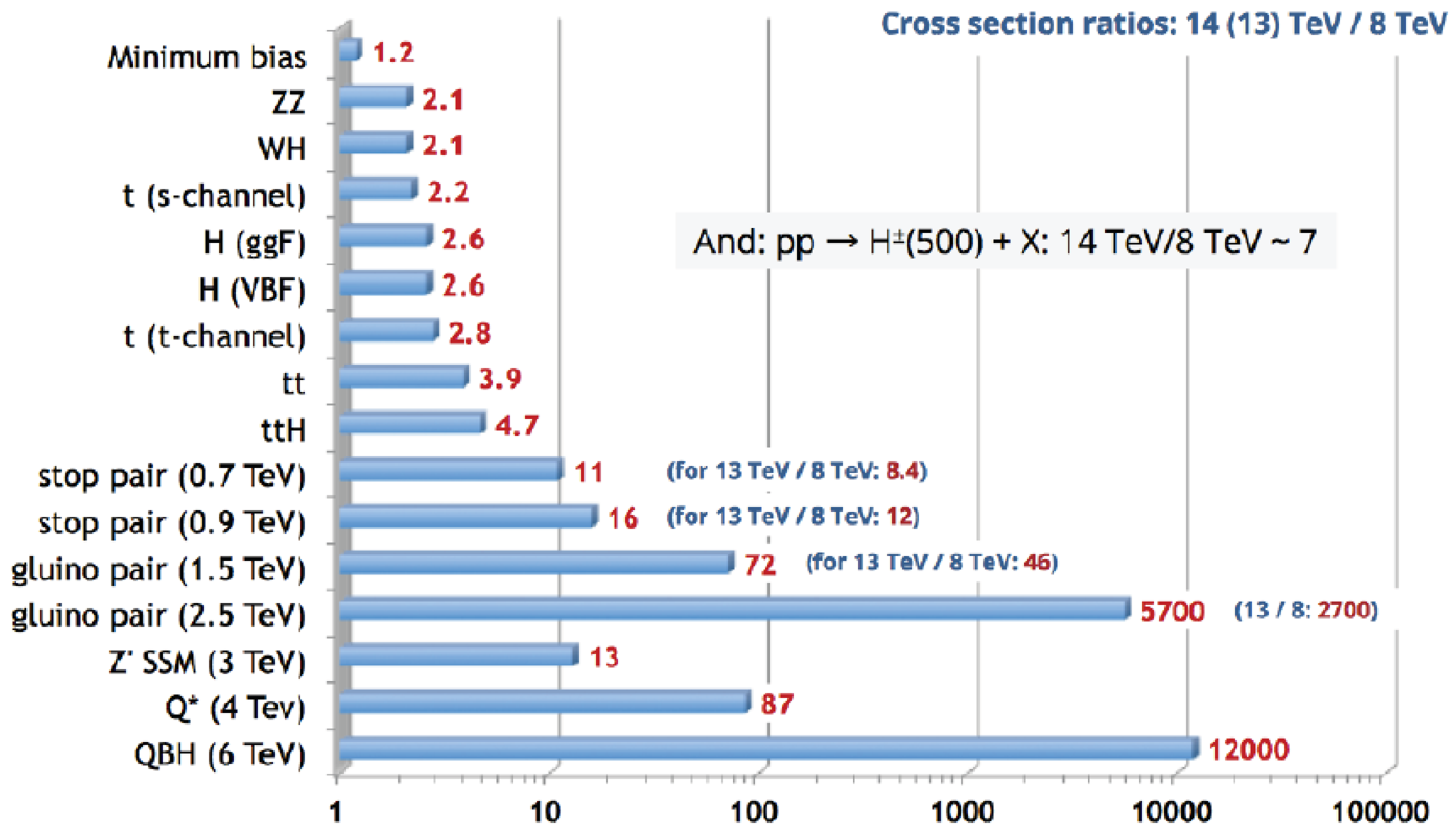
Exploration range of LHC by mid 2015



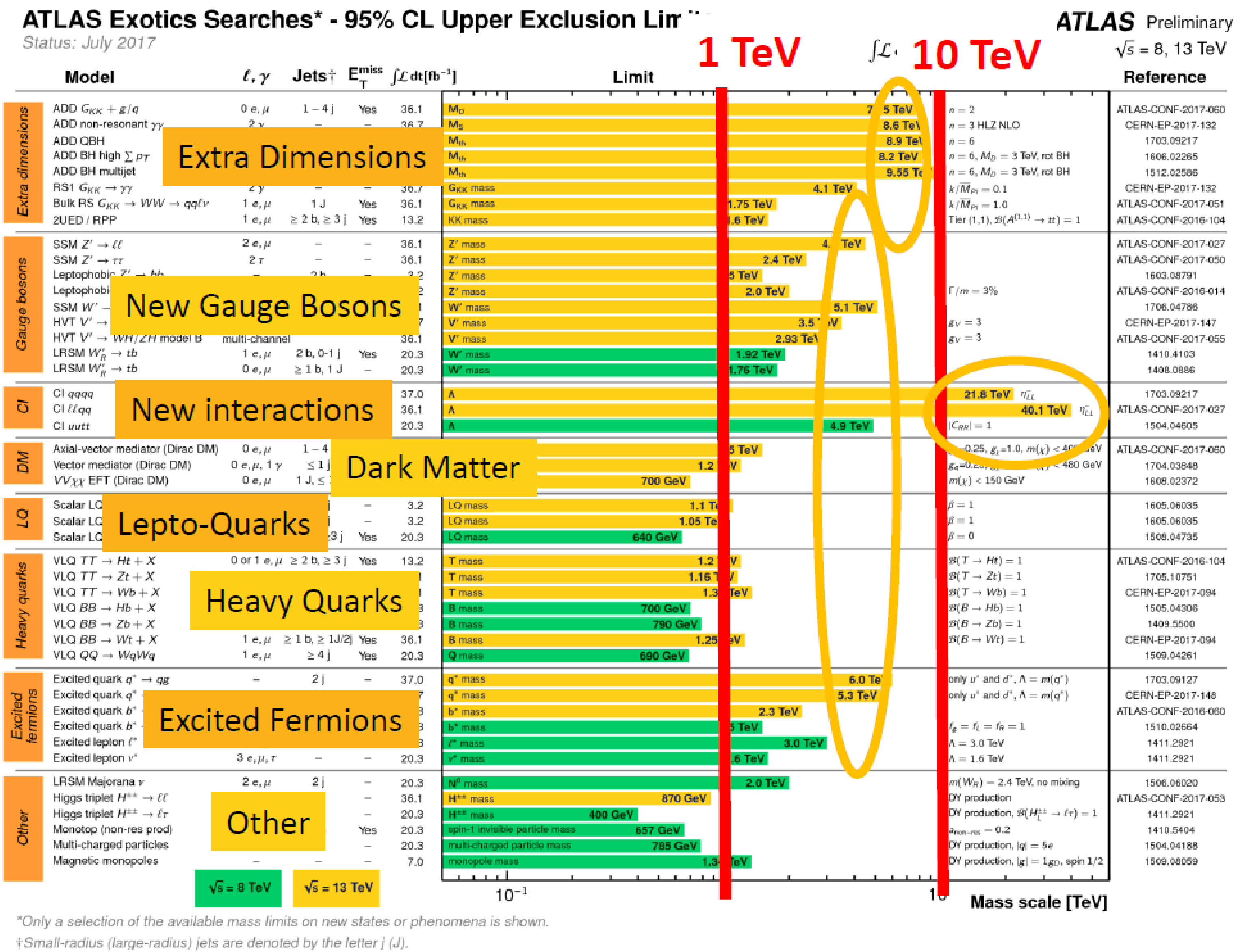
LHC Run II

Hugely increased potential for discovery of heavy particles at 13 TeV

Perfect occasion for young motivated physicists: join the search!



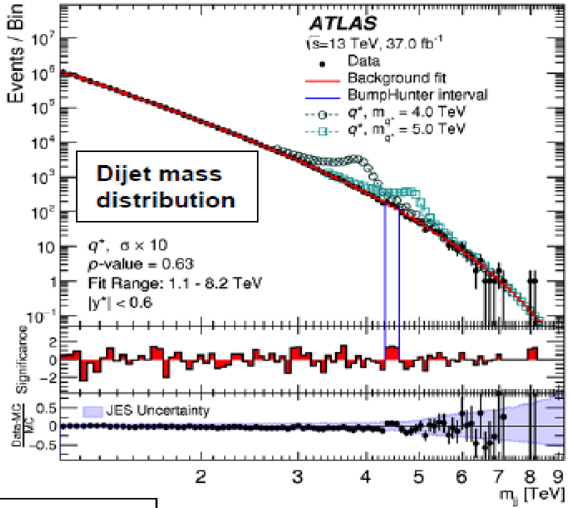
Exploration range of LHC by mid 2017

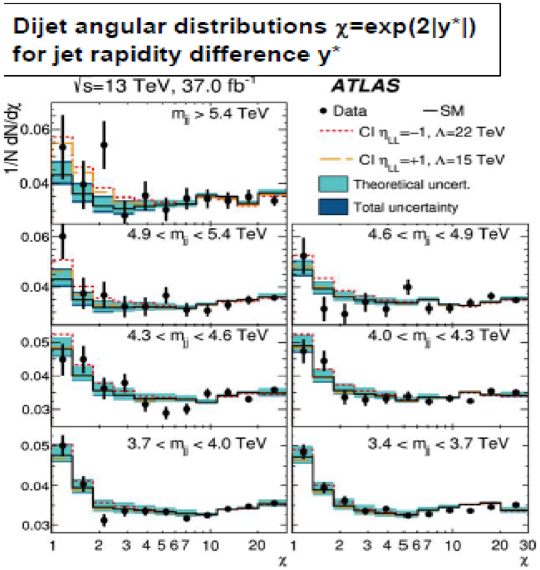


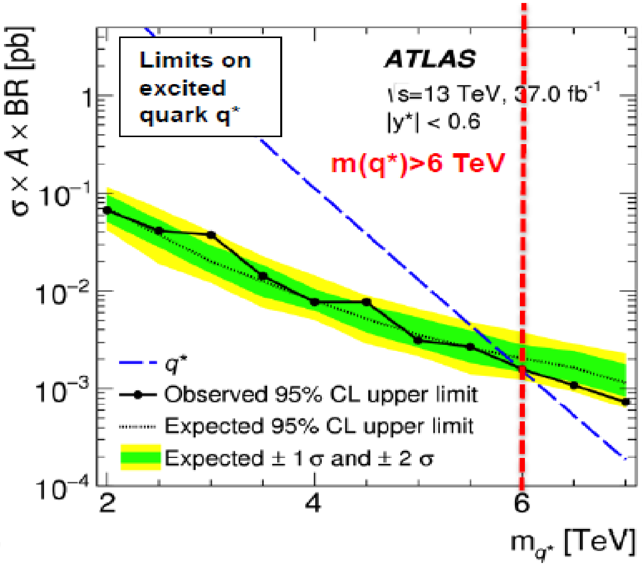
Searches with Dijets

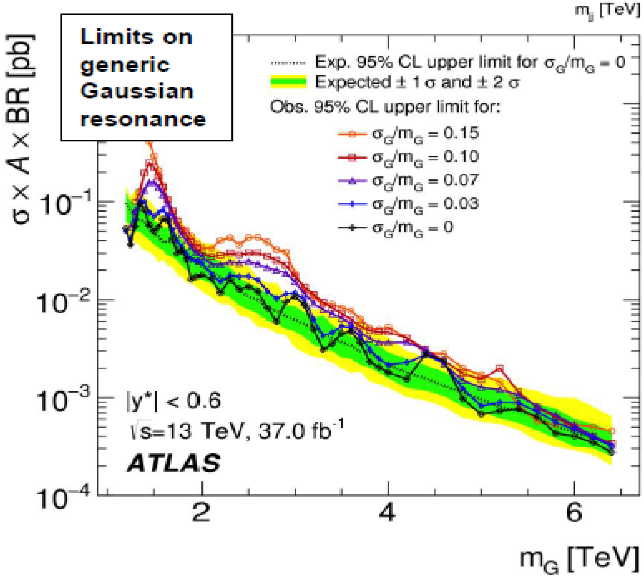
arXiv:1703.09127

- 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









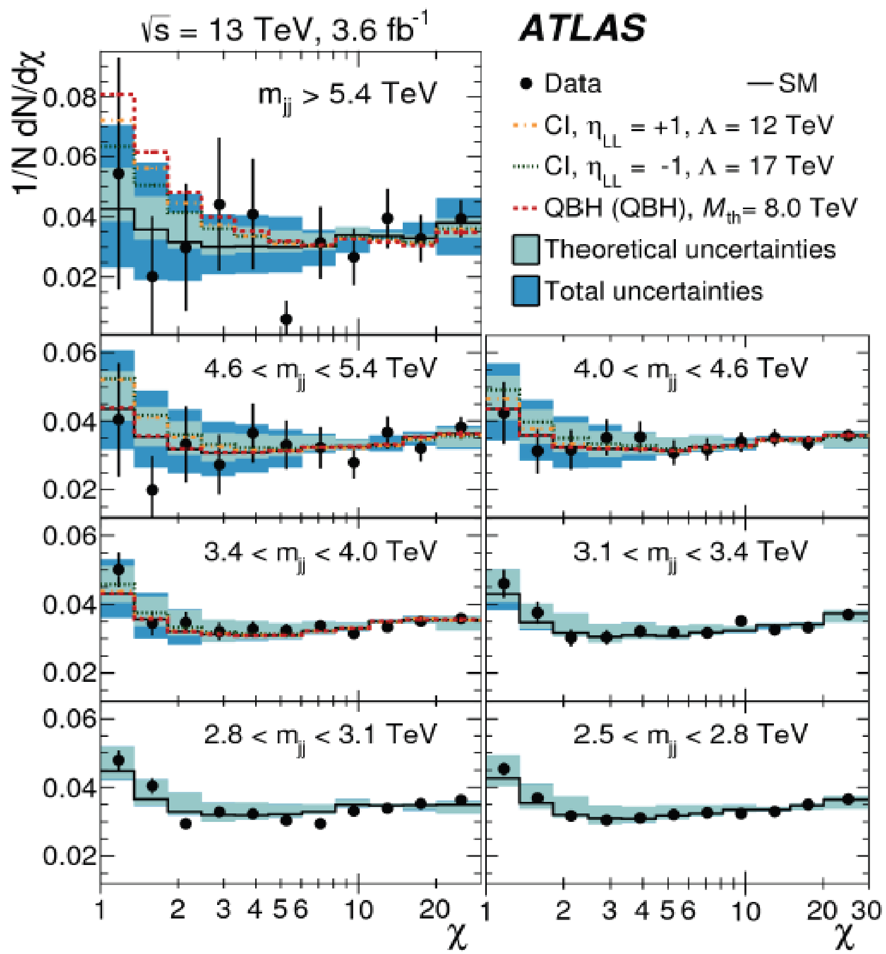
Dijet Angular Searches

Search in dijet mass bins using angular distribution

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

[1512.01530](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)



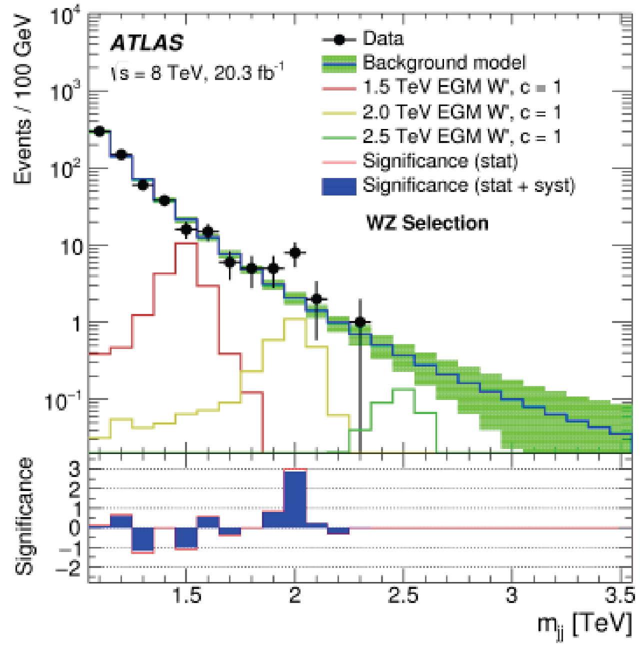
No deviations observed, limits set at 12 TeV on Λ (for η_{LL} = 1)

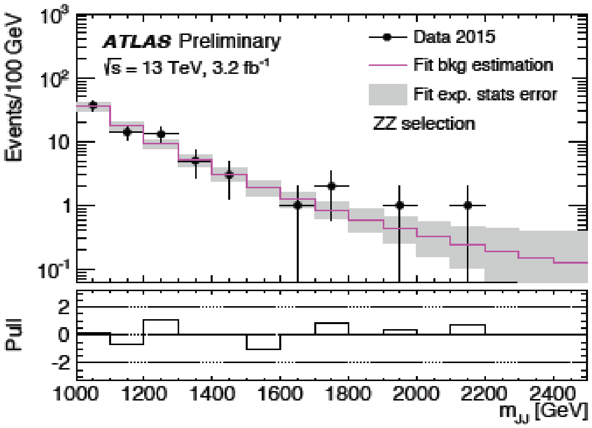
Fully hadronic JJ Diboson Searches

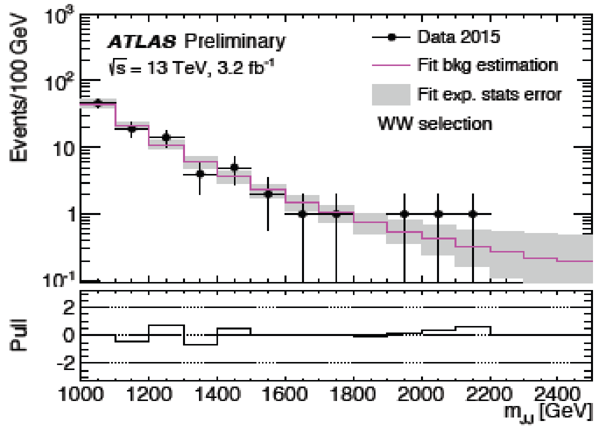
ATLAS-CONF-2015-073

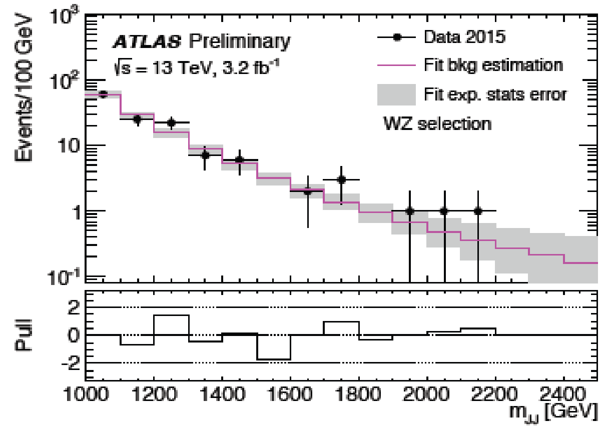
Run-1

- **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





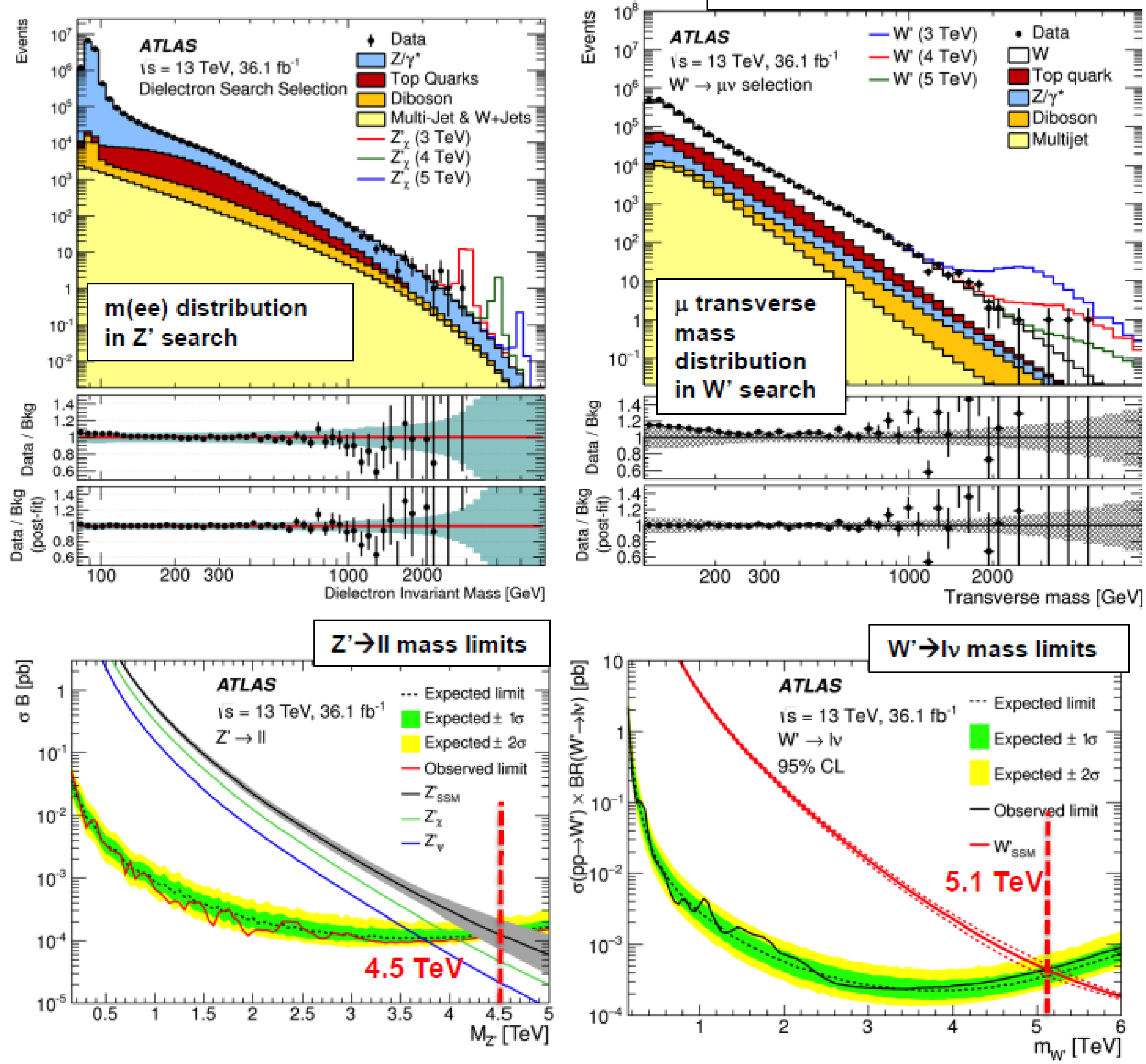




Resonance Searches (Dilepton, Lepton+ETmiss)

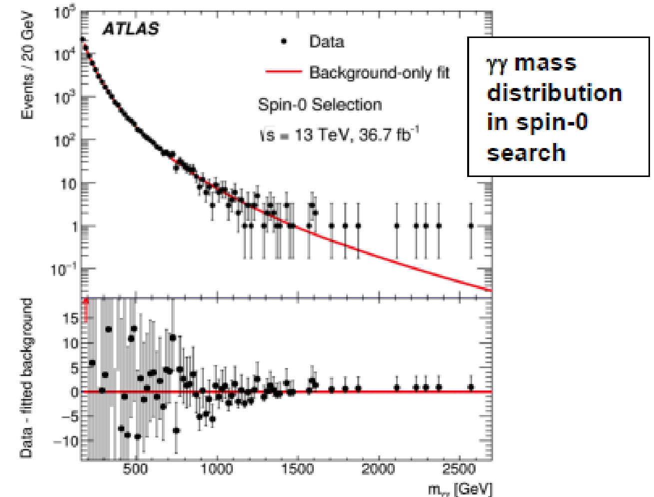
- Searches for new resonances decaying to lepton pairs (e.g. Z') or lepton+E_T^{miss} (e.g. W')
- Signature is peak in invariant mass distribution (dilepton) or tranverse mass distributions (lepton+E_T^{miss})
- No significant excess over SM expectation
- 95% CL exclusion limits extracted in various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

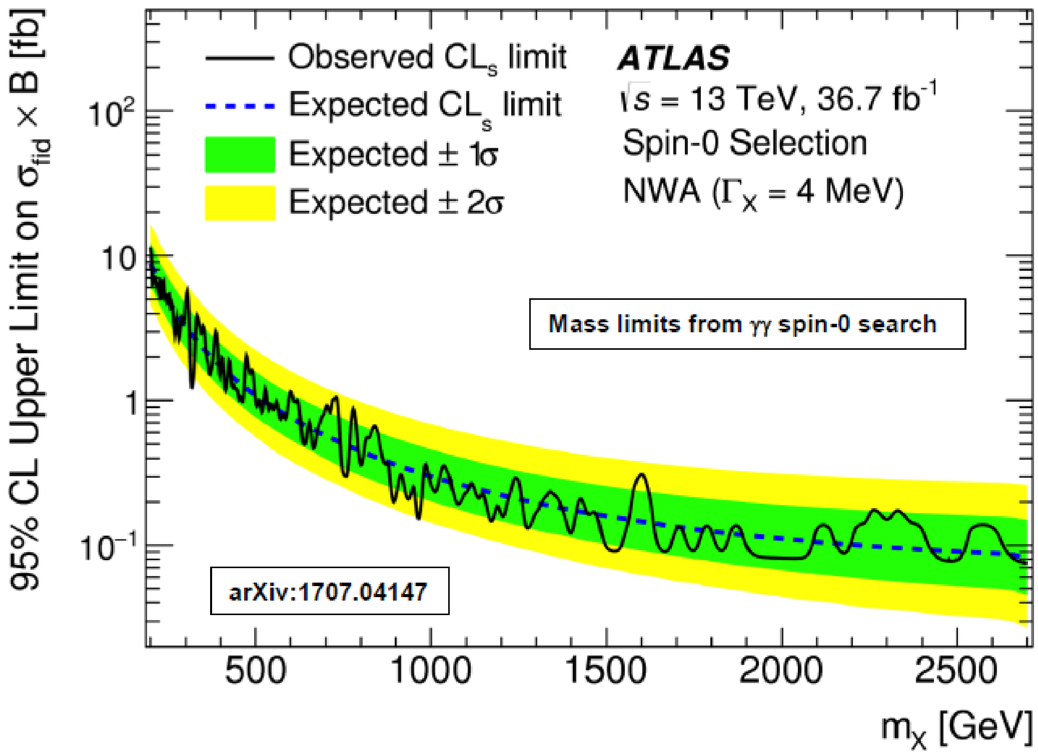
arXiv:1707.02424, arXiv:1706.04786

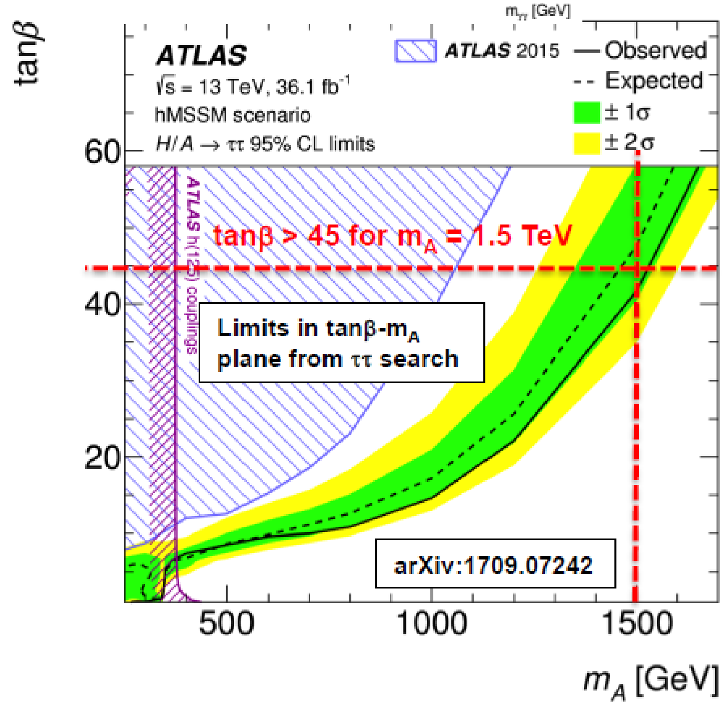


Resonance Searches ($\gamma\gamma$, $\tau\tau$)

- 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

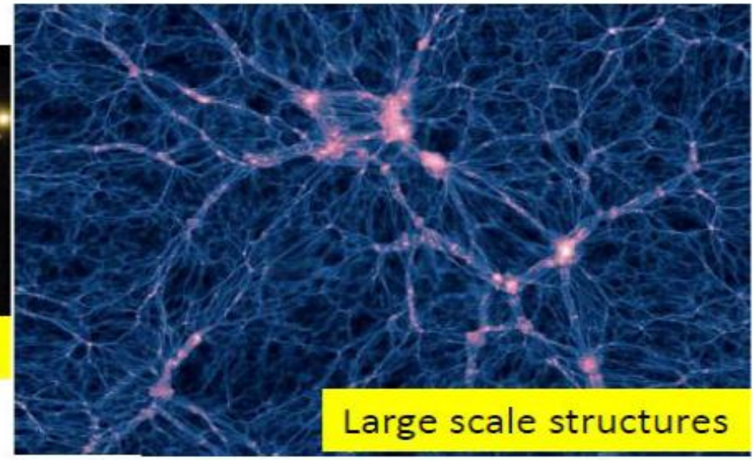


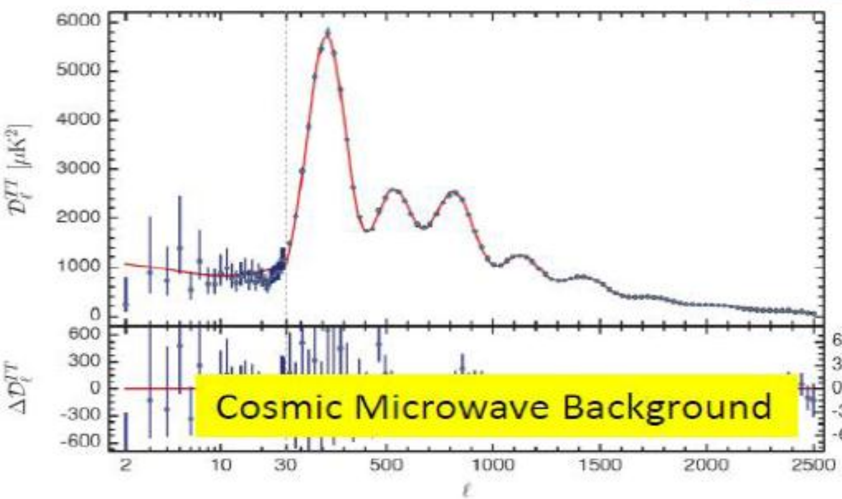


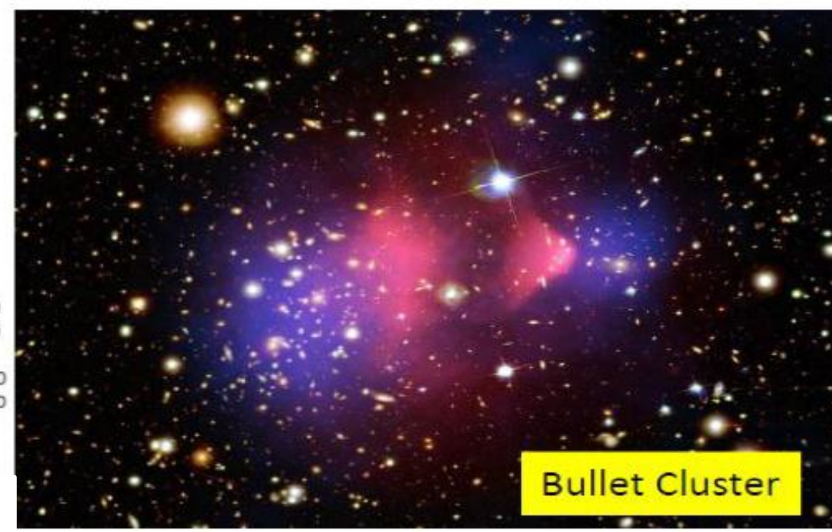


Why Dark Matter?

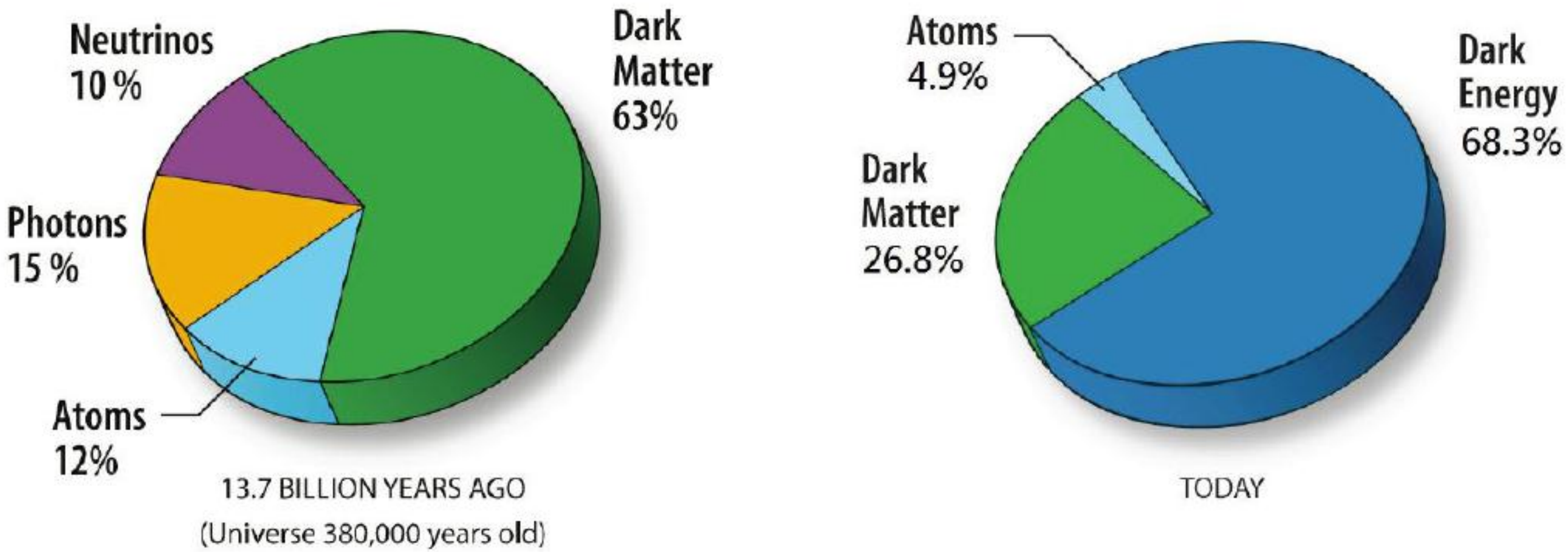
Evidence piling up…







What do we know about Dark Matter

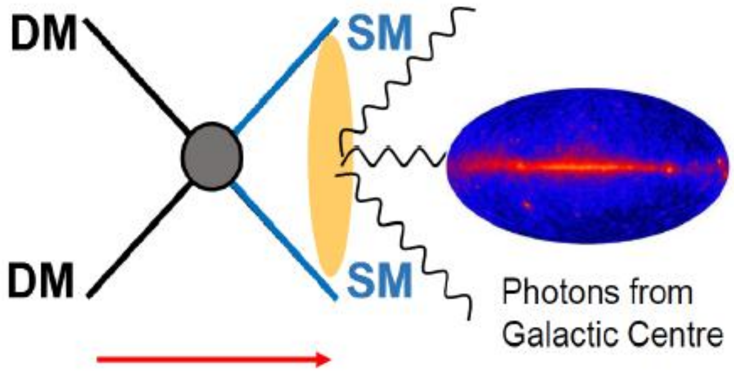


Strong astrophysical evidence for the existence of dark matter

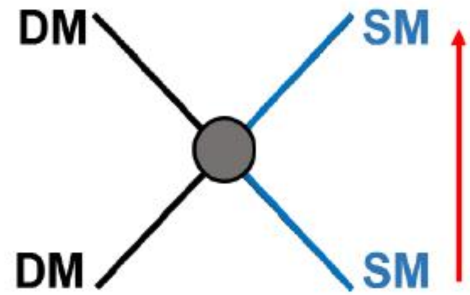
What do we know about Dark Matter

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

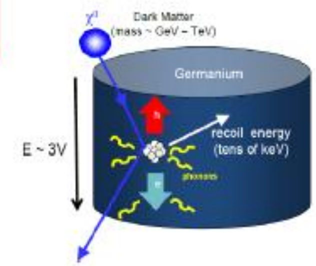
Experimental detection of Dark Matter



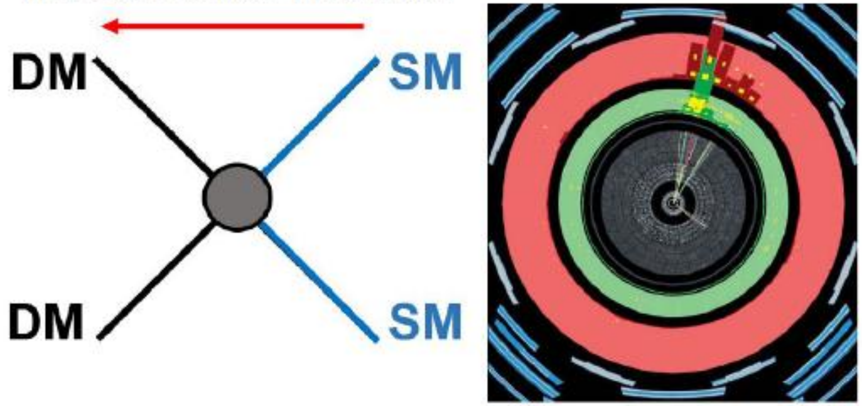
"break it": indirect detection



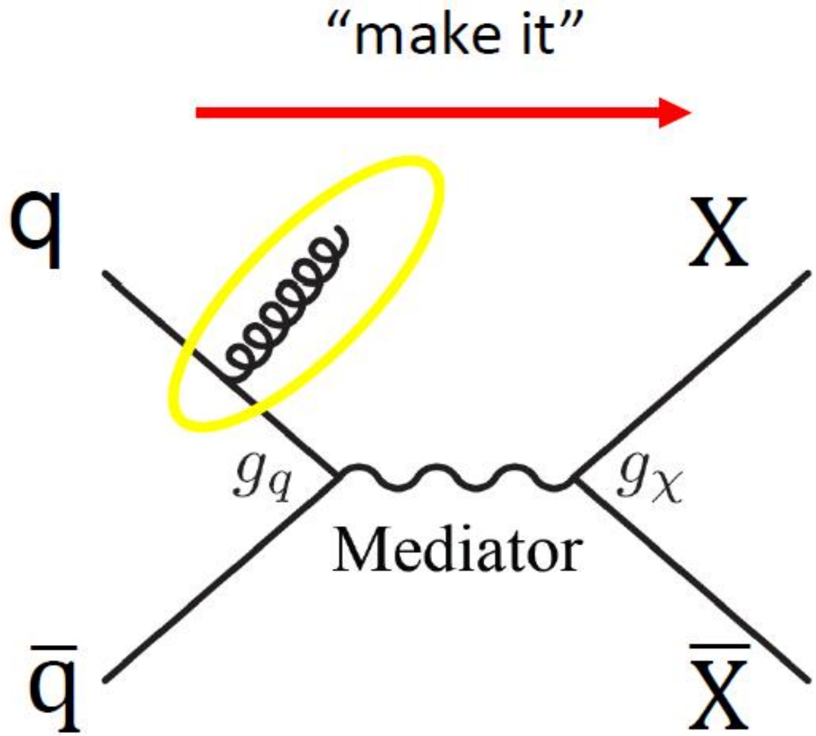
"shake it"
direct detection

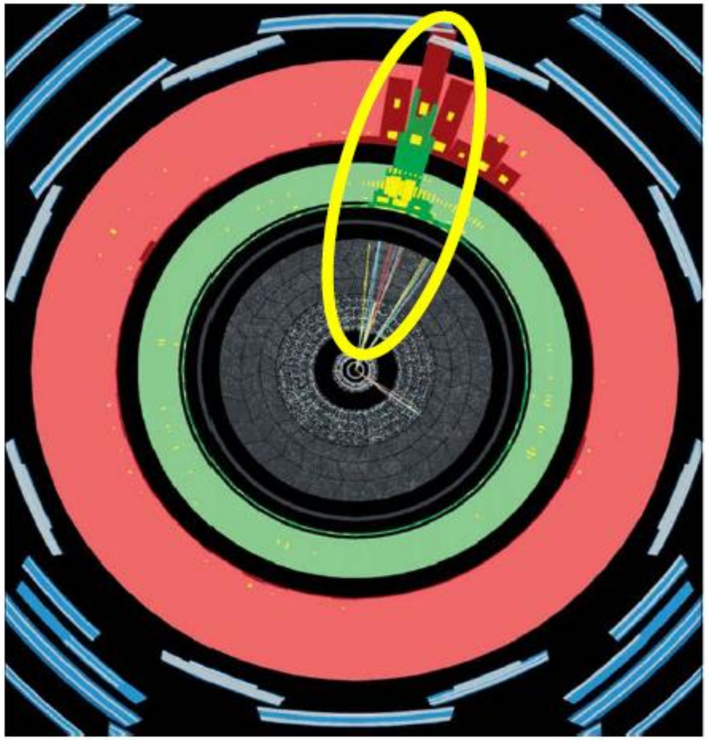


"make it": Collider Production



Dark Matter serches at Colliders

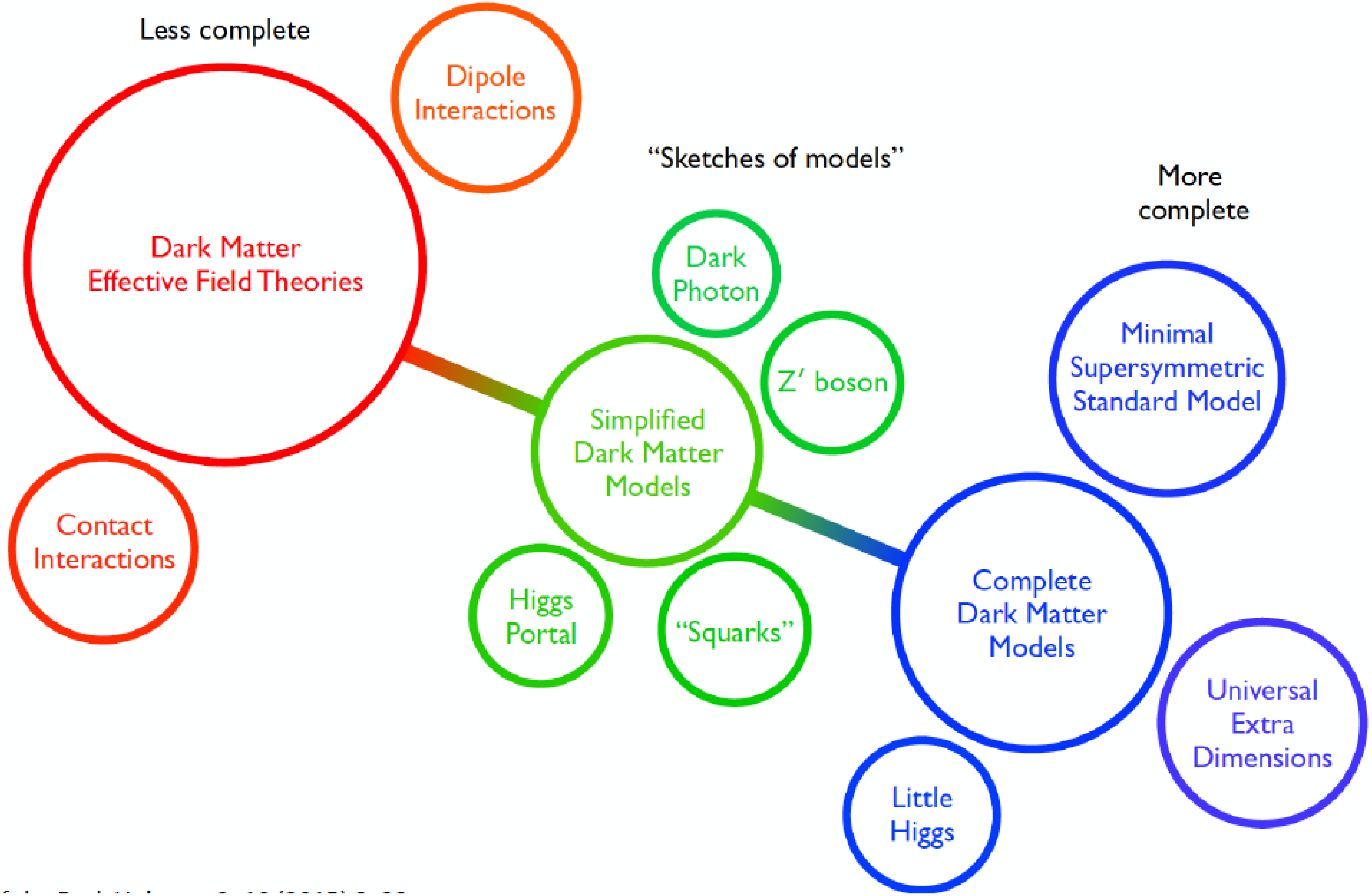




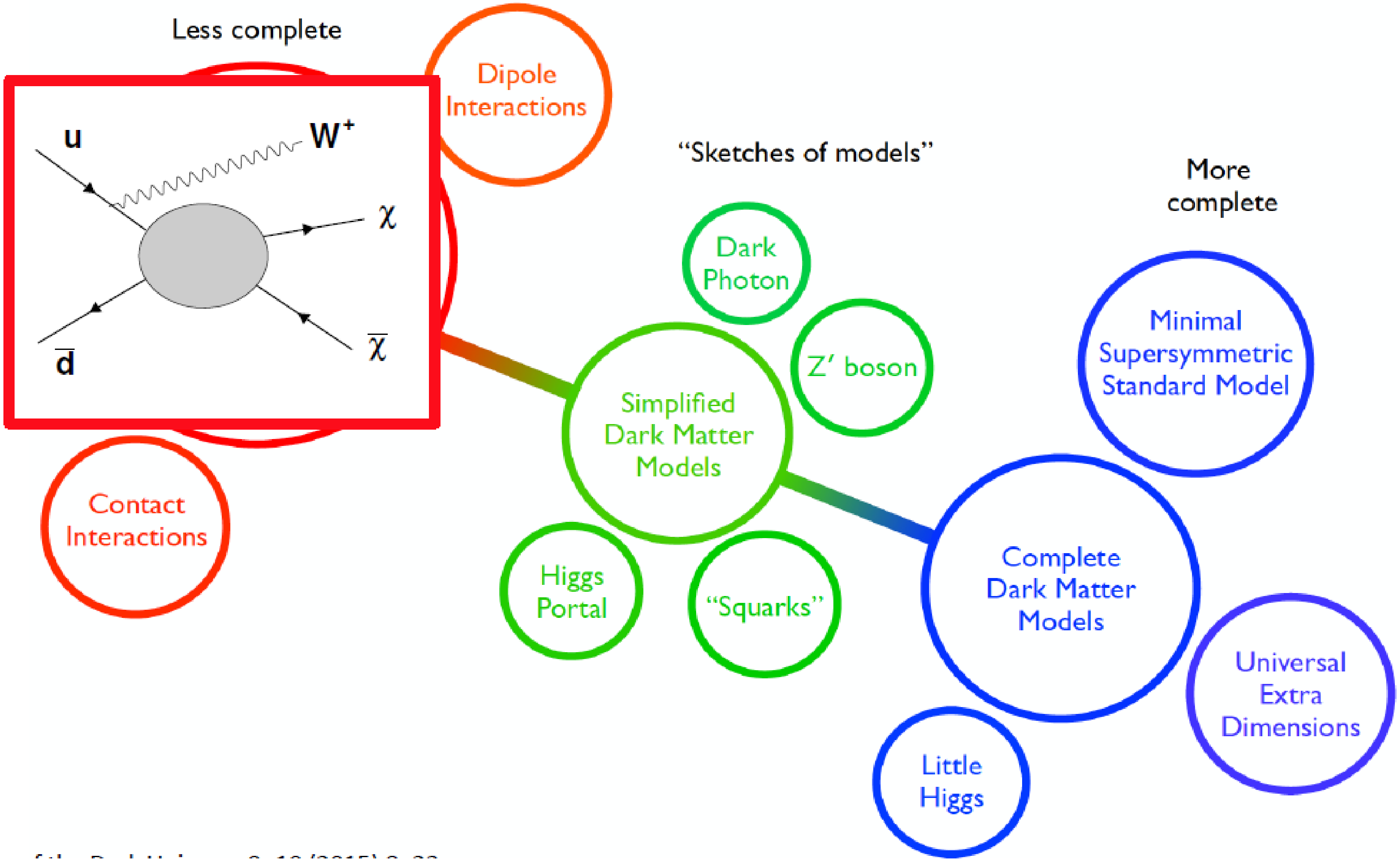
g_q and g_X coupling strengths

Empty detector + something

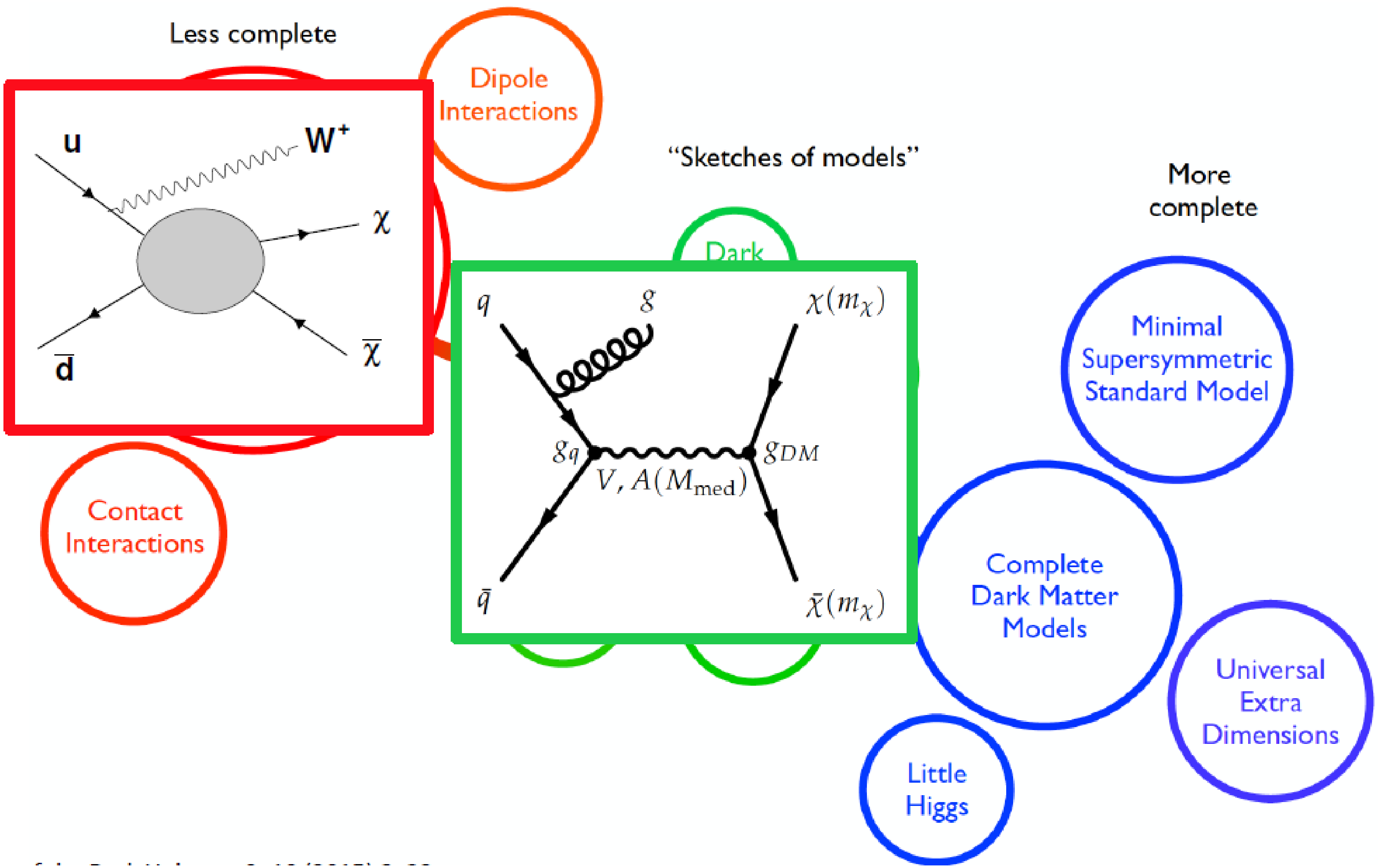
Dark Matter theory space



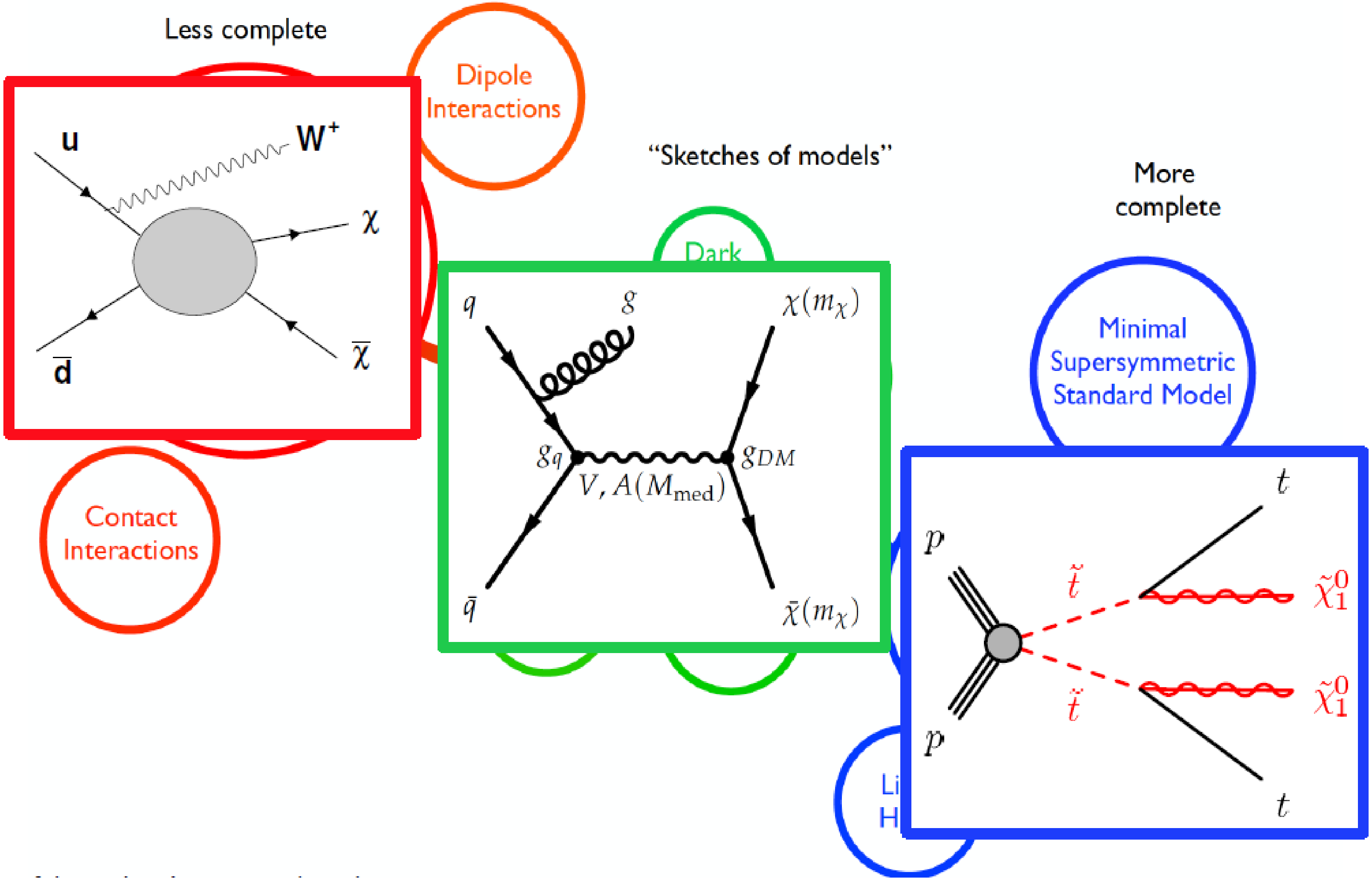
Dark Matter theory space



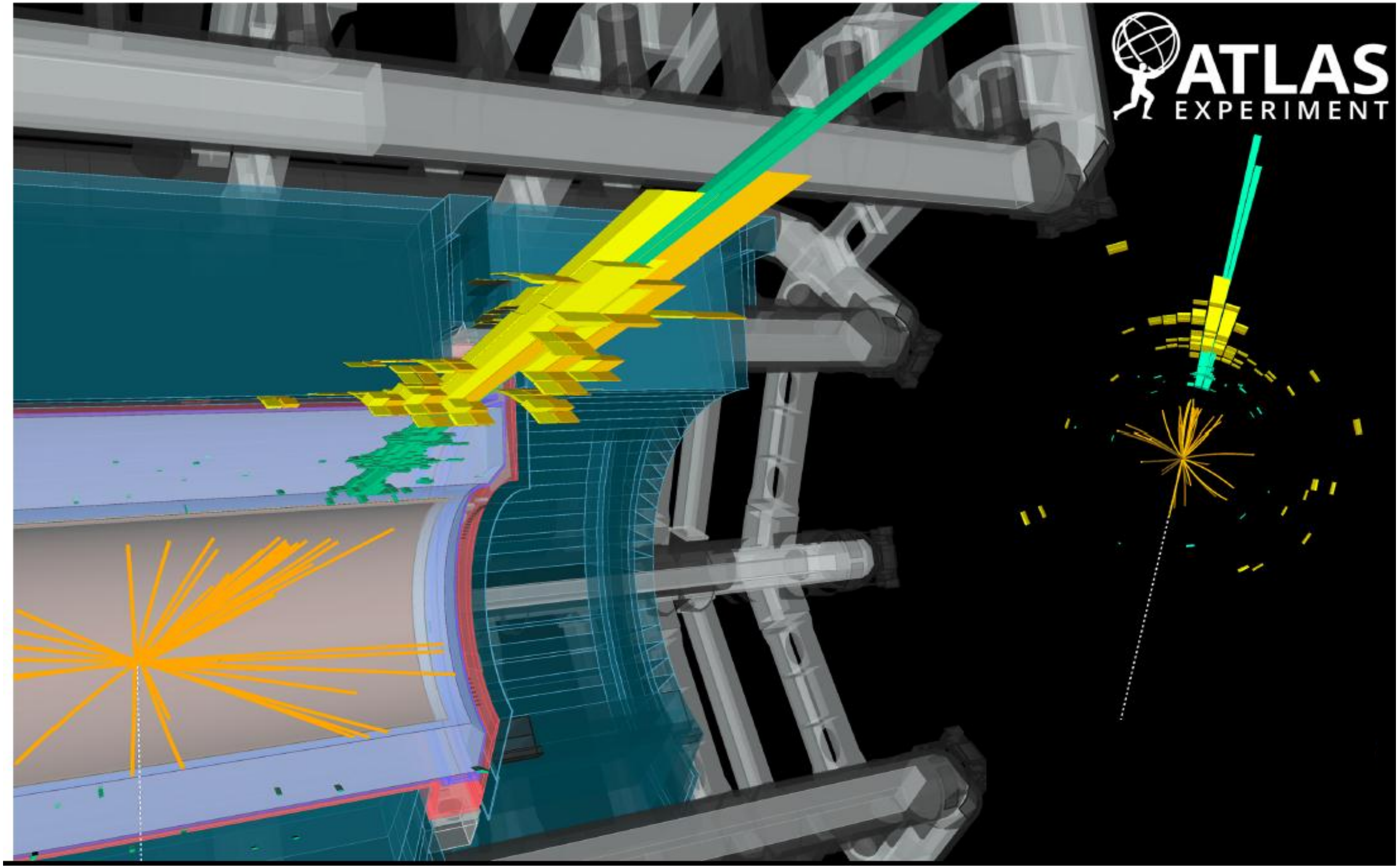
Dark Matter theory space



Dark Matter theory space

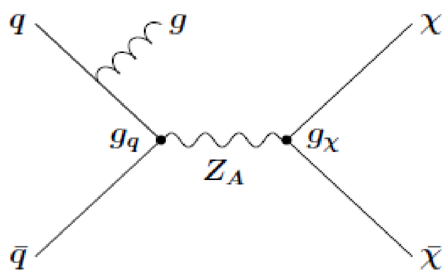


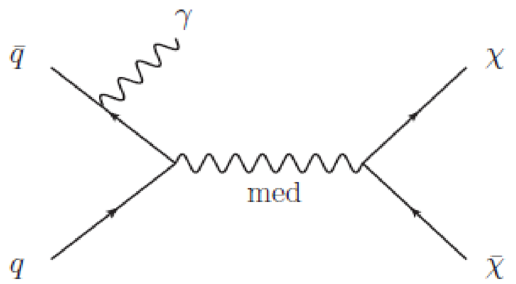
Searches for DM with (E_T^{miss} +X) Signatures

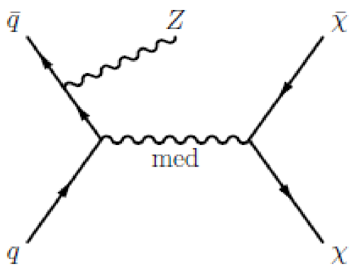


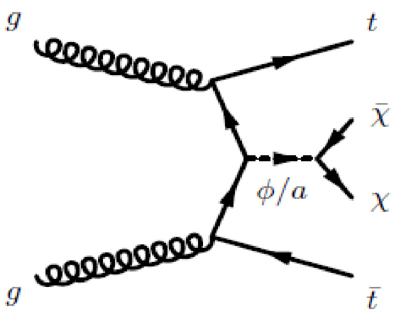
(E_T^{miss} +X) or Mono-X Signatures

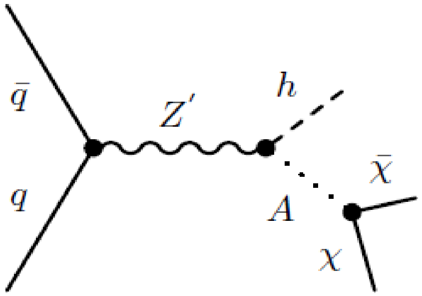
SM-DM mediator decays to DM pairs $\chi\bar{\chi}$ when $M_{\text{med}}/2 > m_\chi$.
DM escapes detection $\Rightarrow E_T^{\text{miss}} + X$ signature where
X = SM particles that tag the event, $X = \text{jet}, \gamma, V, t, b, h \ldots$







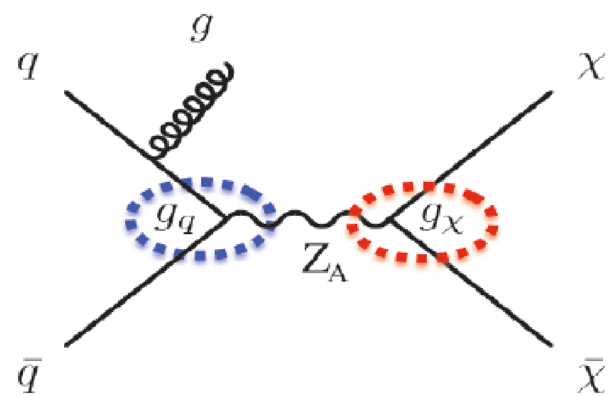




Mediators: vector, axial-vector, scalar, pseudoscalar
Parameters: $m_{\text{med}}, m_\chi, g_q, g_\chi$

Simplified Model

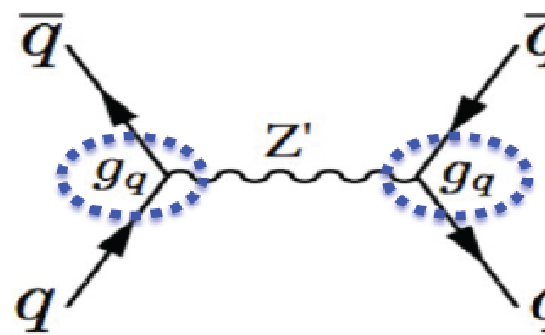
$SM \rightarrow mediator \rightarrow DM$



→Mono-X signature

E_T^{miss} + jet, W/Z/H, γ, ...

$SM \rightarrow mediator \rightarrow SM$



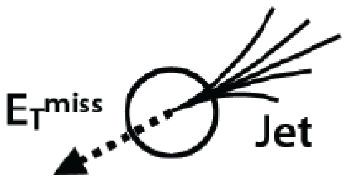
→resonant production

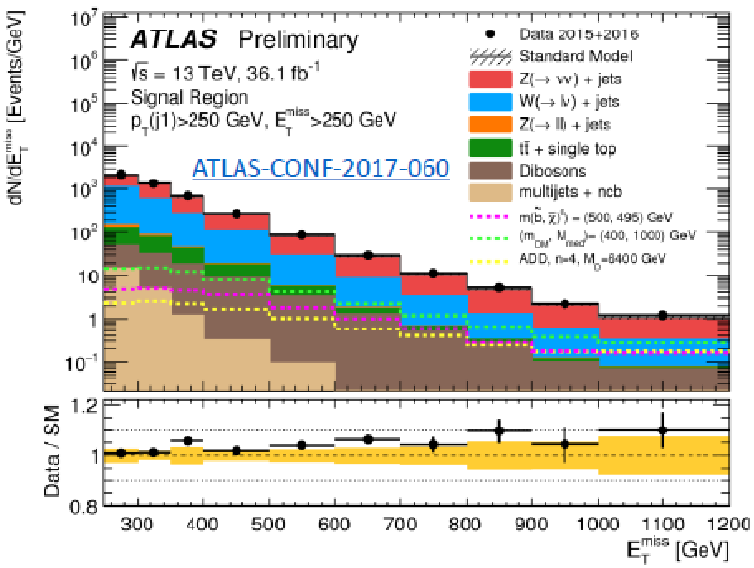
Dijet, ditop, dilepton.....

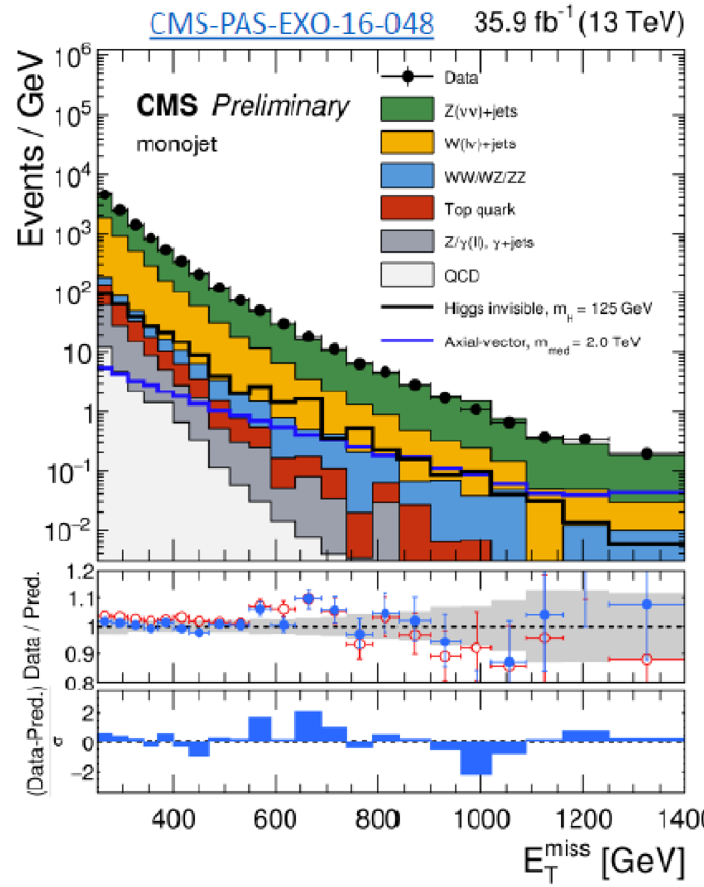
	spin 0	spin 1
Charge	Q=0 for s-channel	
Lorentz structure	Scalar $g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f$ Pseudoscalar $g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f} \gamma^5 f$	Vector $g_q \sum_q V_\mu \bar{q} \gamma^\mu q$ Axial-vector $g_q \sum_q A_\mu \bar{q} \gamma^\mu \gamma^5 q$
Coupling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

Mono-X searches

Mono-jet







ATLAS

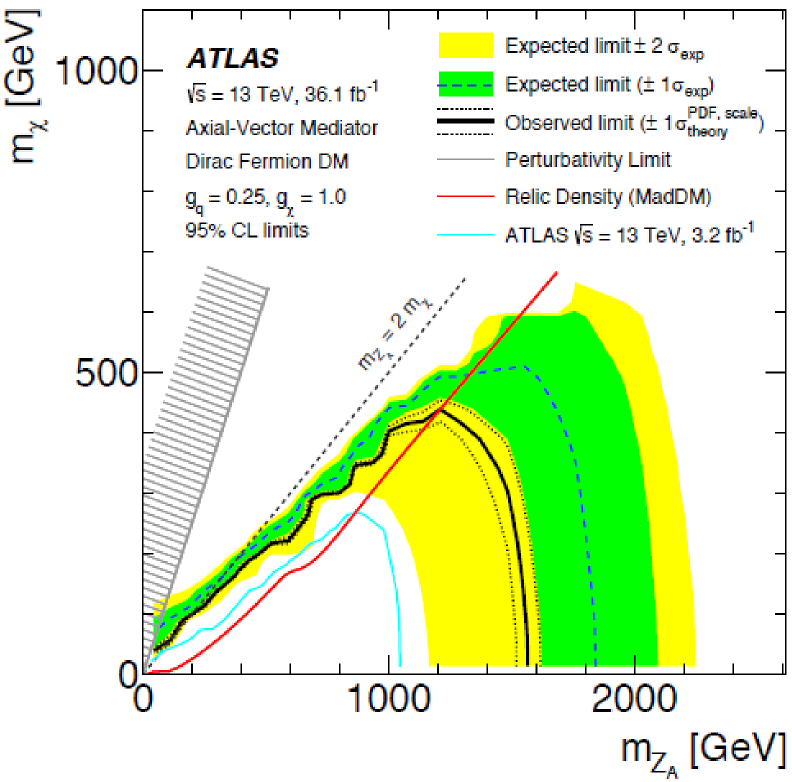
- $E_T^{miss} > 250$ GeV, $\Delta\varphi(\text{jet}, p_T^{miss}) > 0.4$
- Jet $p_T > 250$ GeV, $|\eta| < 2.4$
- $N_{jets} \leq 4$

CMS

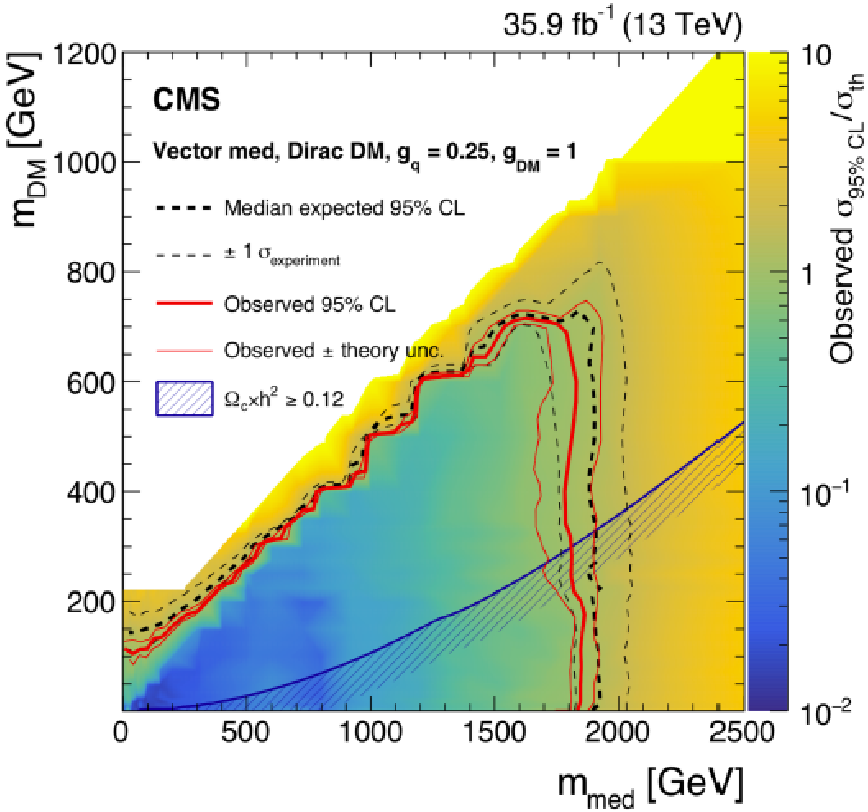
- $E_T^{miss} > 250$ GeV
- Jet $p_T > 100$ GeV, $|\eta| < 2.5$

Mono-X searches

Axial-Vector Mediator



Vector Mediator

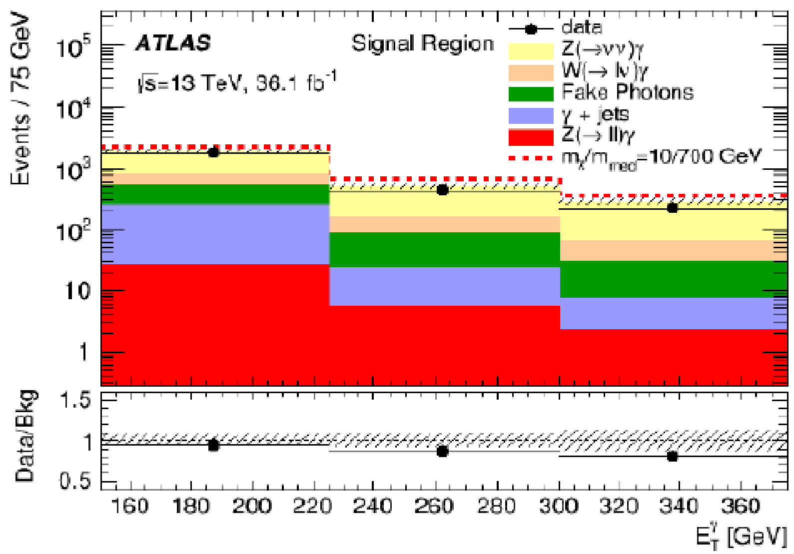


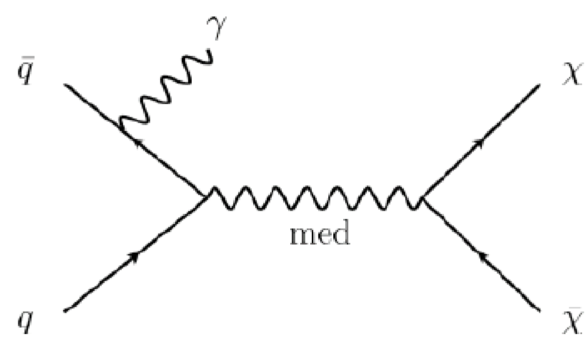
For couplings $g_q = 0.25,\ g_\chi = 1.0$, axial-vector and vector mediators excluded up to 1.8 TeV (1.55 TeV) by CMS (ATLAS) for $m_\chi \sim 1$ GeV.

JHEP 01 (2018) 126
arXiv:1712.02345

Mono-X searches

Mono-photon



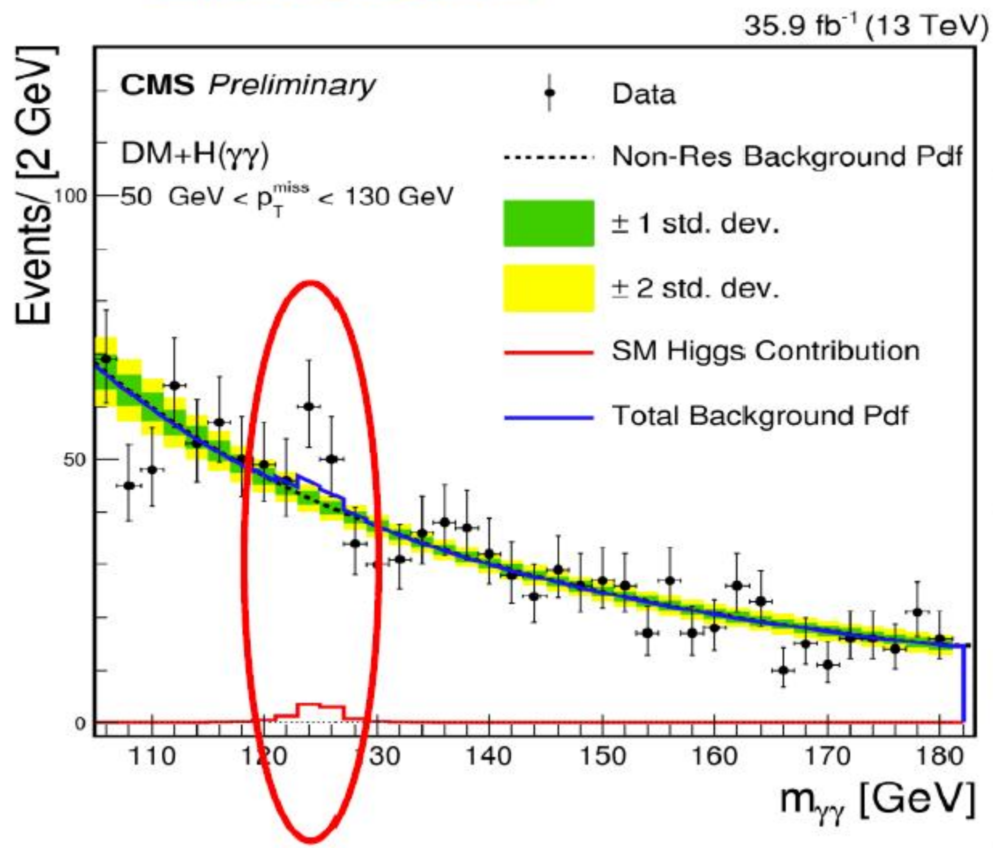


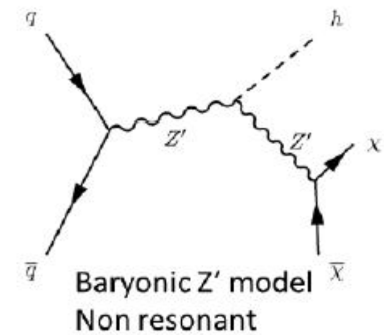
- Photon $E_T > 150$ GeV, $|\eta| < 2.37$
- $E_T^{miss}/\sqrt{\sum E_T} > 8.5\ GeV^{1/2}$
- $\Delta\varphi(\text{photon}, E_T^{miss}) > 0.4$
- $N_{jets}(p_T > 30\ GeV, |\eta| < 4.5) \leq 1$

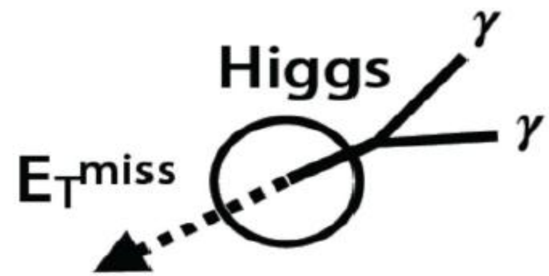
Mono-X searches

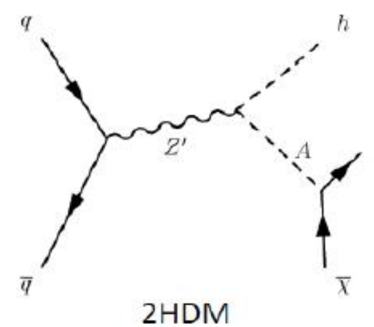
Mono-Higgs

CMS-PAS-EXO-16-054

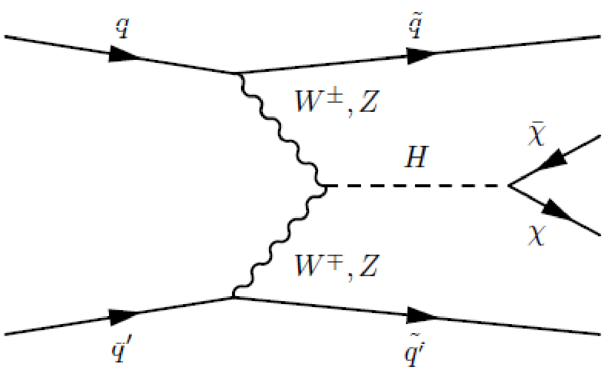






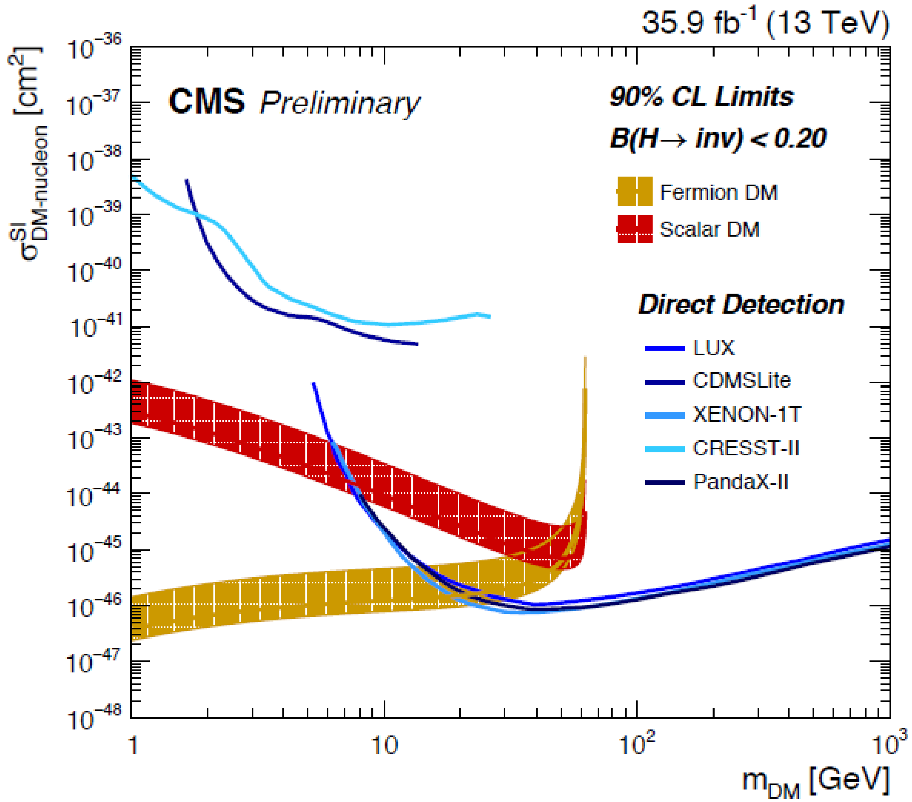


H-> invisible: Comaprison with DD



$\mathcal{B}$(H→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.

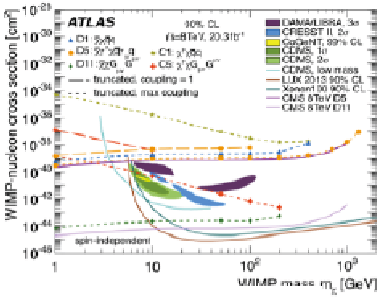


CMS-PAS-HIG-17-023 (14 March 2018)

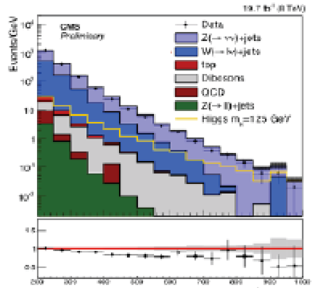
Mono-Mania!!

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

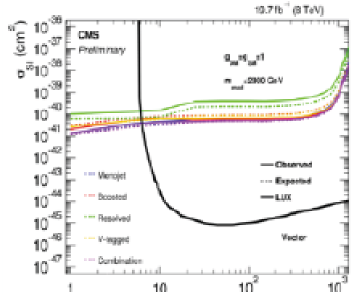
Mono-Mania!!



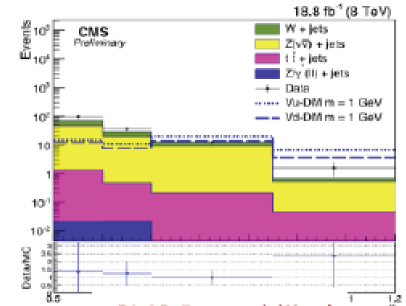
ATLAS Monojet
EPJC (2015) 75:299



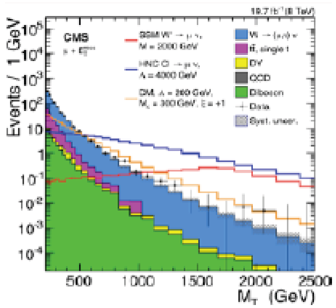
CMS j/V (mono/dijet)
PAS-EXO-12-055



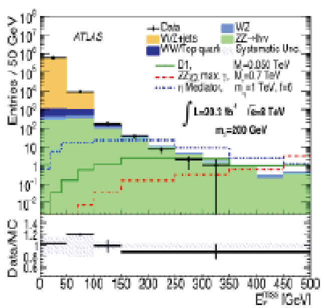
CMS j/V (mono/dijet)
PAS-EXO-12-055



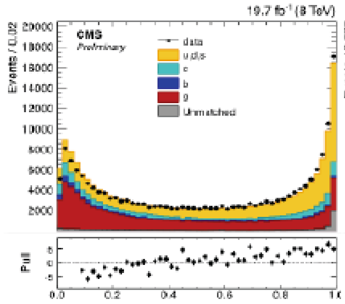
CMS Razor (dijet)
PAS-EXO-14-004



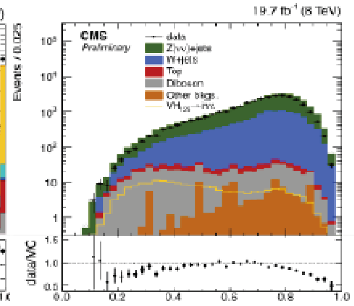
CMS, ATLAS MonoW
PRD 91, 092005, JHEP 09 (2014) 037 (2015)



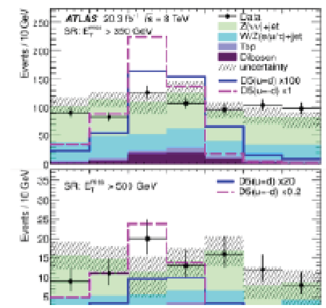
CMS, ATLAS MonoZ
EXO-12-054, PRD 90, 012004 (2014)



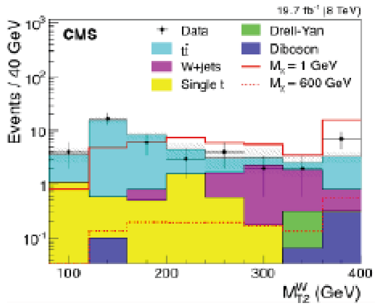
CMS MonoV (resolved)
PAS-EXO-12-005, PAS-JME-14-002



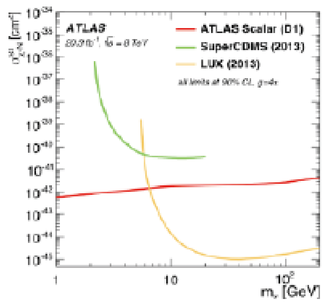
CMS MonoV (boosted)
EXO-12-005/JME-14-002



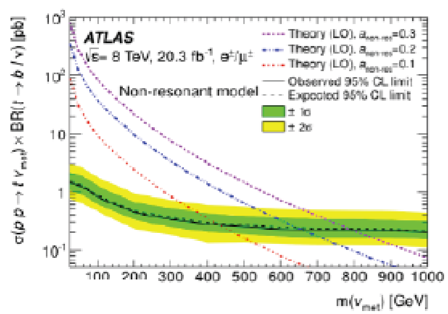
ATLAS MonoV (boosted)
ATLAS, PRL 112, 041802 (2014)



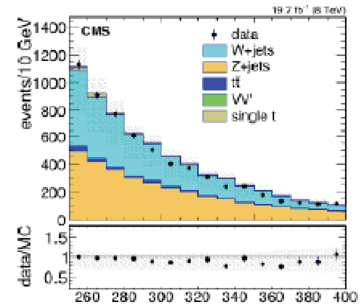
CMS TopPairs
CMS, JHEP 06 (2015) 121



ATLAS TopPairs
ATLAS, EPJC (2015) 75:92



CMS MonoTop
CMS, PRL 114 (2015) 101801



ATLAS MonoTop
ATLAS, JHEP 11 (2014) 118

LHC DM Working Group

Cornell University Library

arXiv.org > hep-ex > arXiv:1507.00966

arXiv:1507.00966

High Energy Physics – Experiment

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

Collection of DM models (simplified models, EFT), Model implementation

arXiv.org > hep-ex > arXiv:1603.04156

arXiv:1603.04156

High Energy Physics – Experiment

Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter

Guidelines to compare LHC results with DD/ID experiments

arXiv.org > hep-ex > arXiv:1703.05703

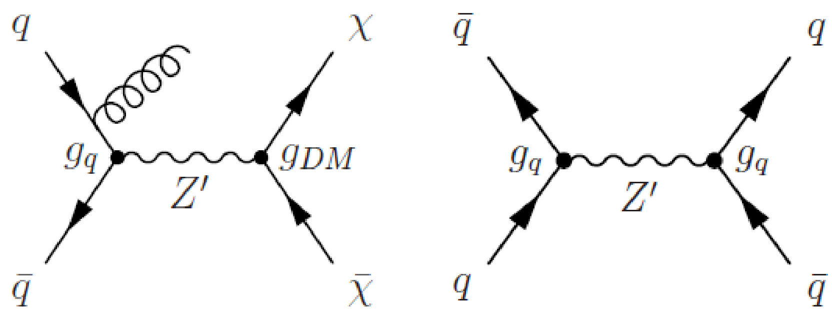
arXiv:1703.05703

High Energy Physics – Experiment

Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for heavy mediators of dark matter production in visible and invisible decay channels

Guidelines to present Mono-X and visible signatures for heavy mediators

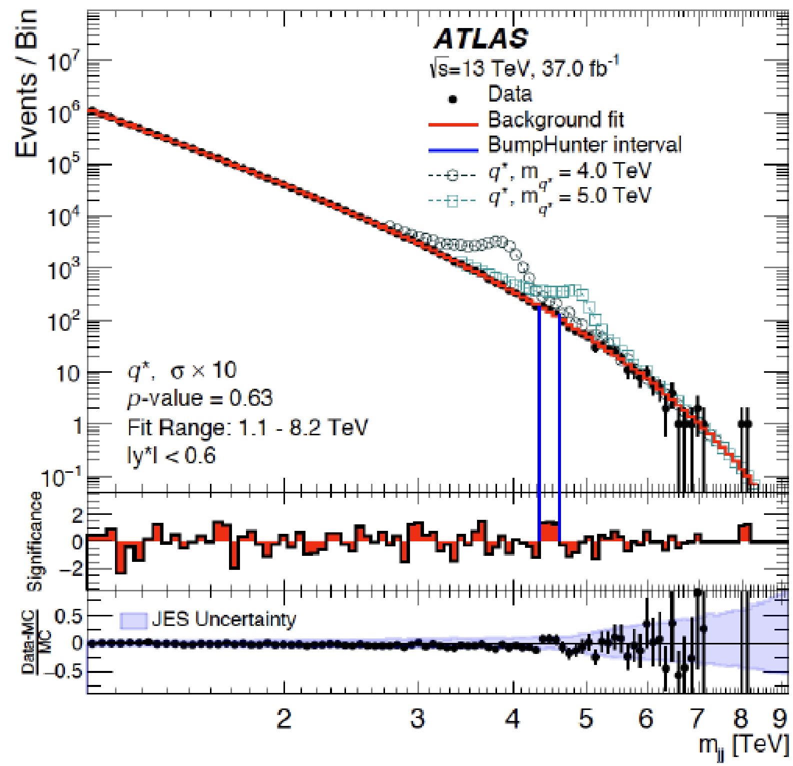
LHC is a mediator machine



Signature: 2 high p_T jets,
same as search for leptophobic Z'.

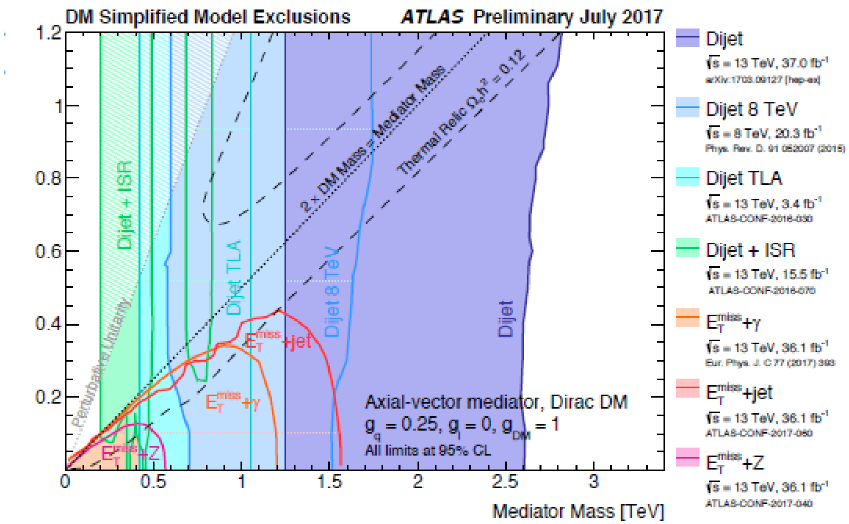
m_{jj} is the discriminant,
search for bump on a smooth,
falling background.

Background modeled by
a parameterized function.

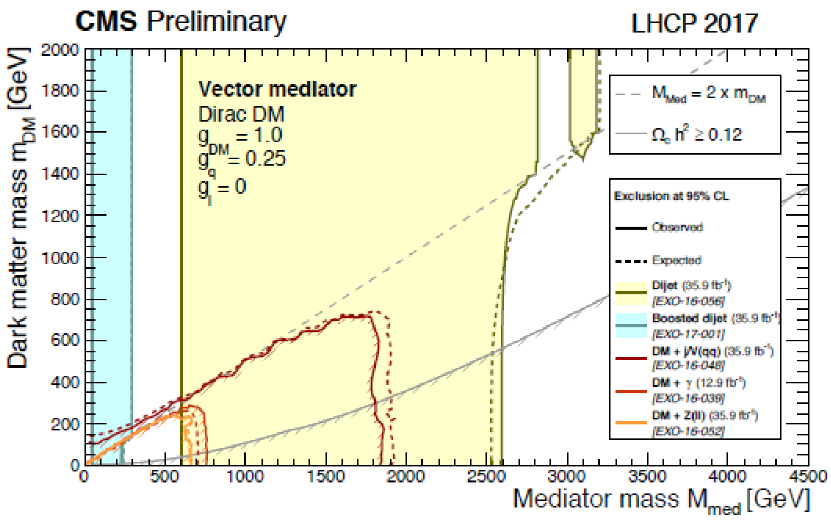


Limits on DM mass vs Mediator mass

Axial-Vector Mediator



Vector Mediator



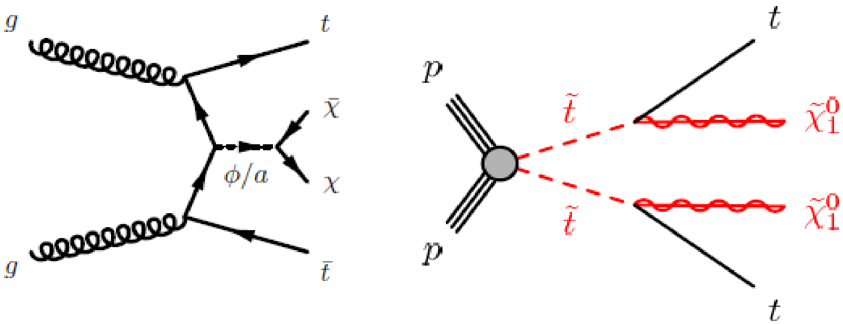
Couplings: $g_{\rm DM} = 1,\ g_q = 0.25,\ g_l = 0$ (leptophobic)

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

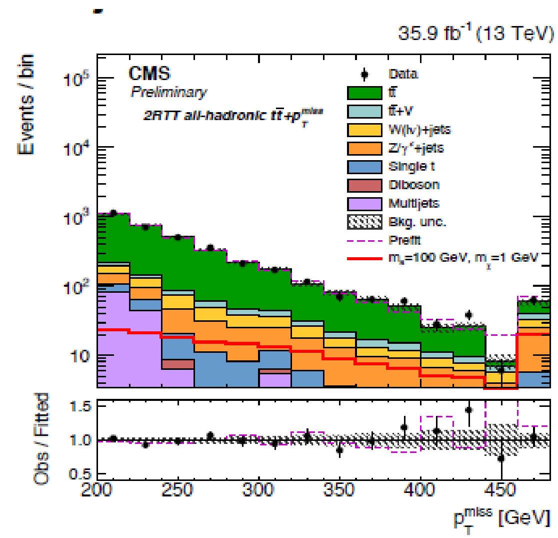
For spin-0 mediator ϕ or a,
MFV $\Rightarrow$ Yukawa couplings
ϕ and a couple strongly to t or b

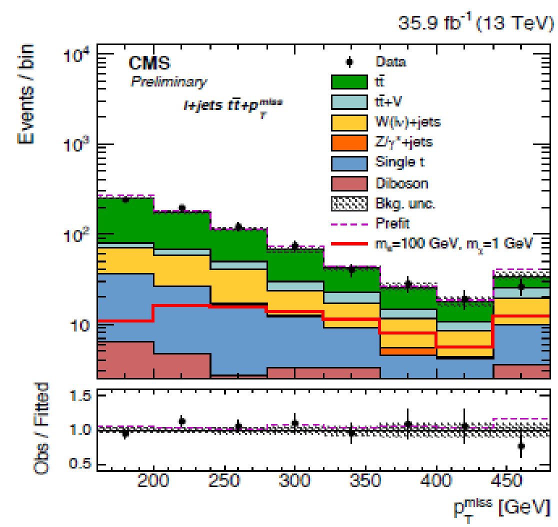


$(t\bar{t} + \chi\bar{\chi})$ discriminant is $p_{\mathrm{T}}^{\mathrm{miss}}$.

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

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





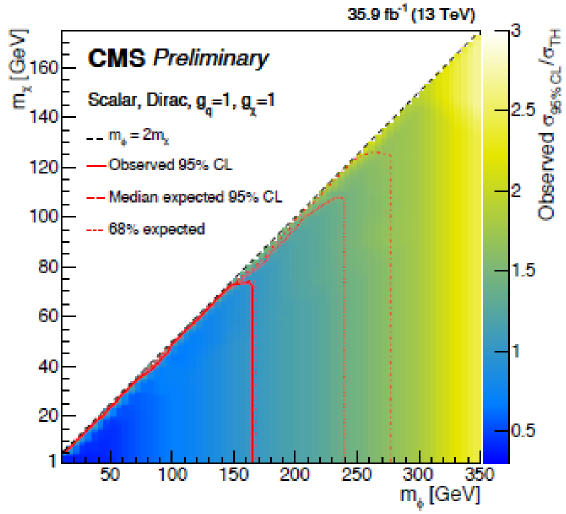
Search for DM + Heavy Flavor

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

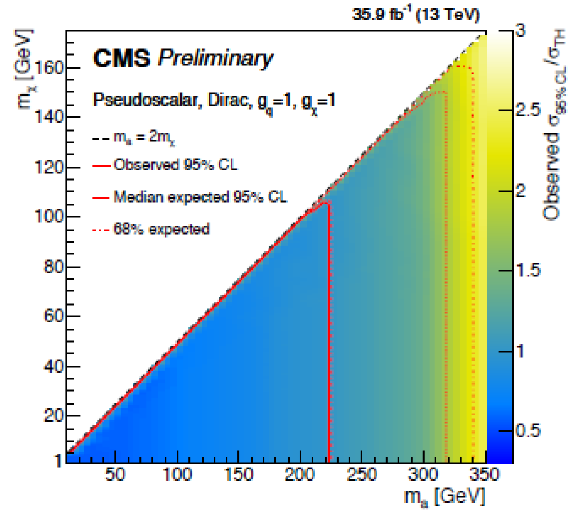
CMS-PAS-EXO-16-049 (3 April 2018)

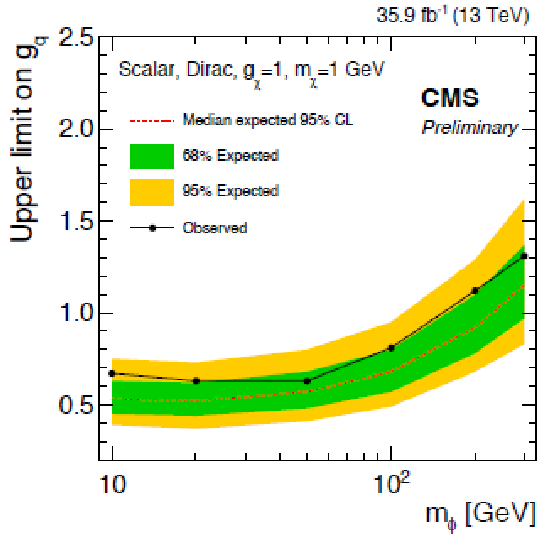
For $g_{\rm DM} = 1$, $m_\chi = 1$ GeV:
limits on coupling of ϕ or a
to SM quarks.

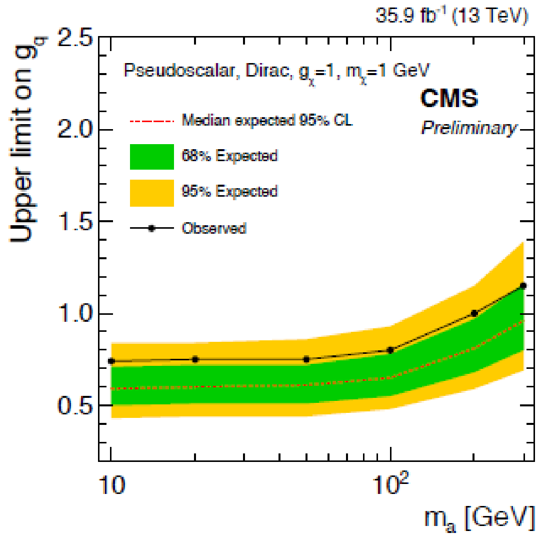
Scalar Mediator



Pseudoscalar Mediator

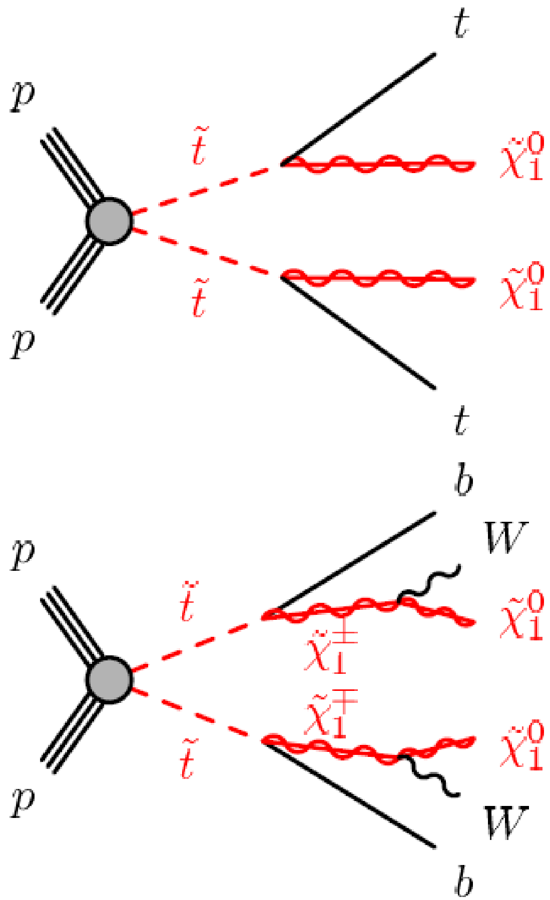


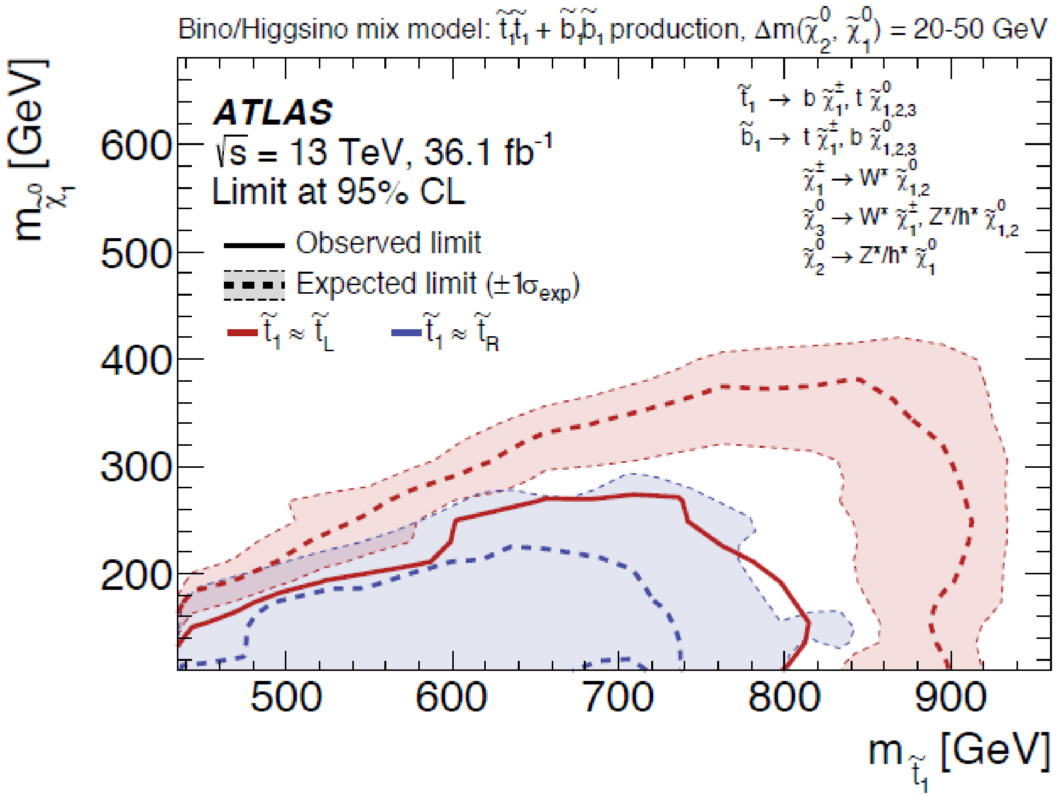




SUSY DM candidates

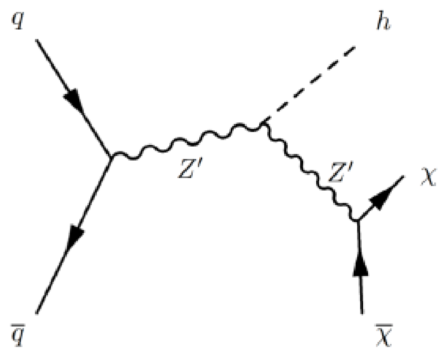
In many SUSY models the LSP is stable and weakly interacting $\Rightarrow$ a DM candidate. Some models are tuned to reproduce the DM relic density, e.g. the "well tempered neutralino" scenario.





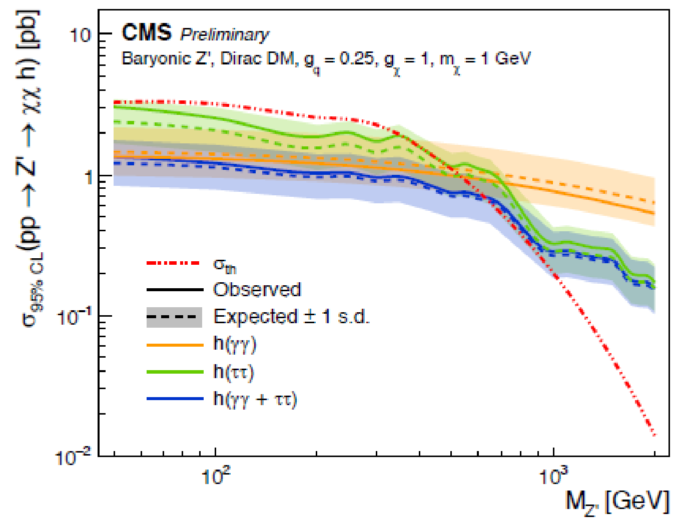
Search for DM + Higgs

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



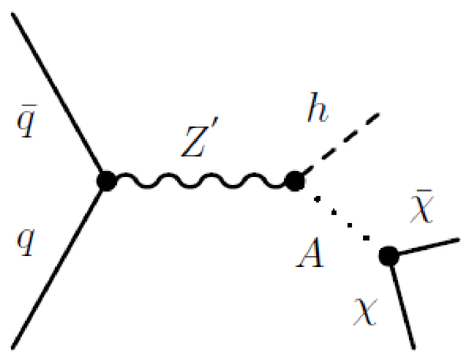
Baryonic Z' Model

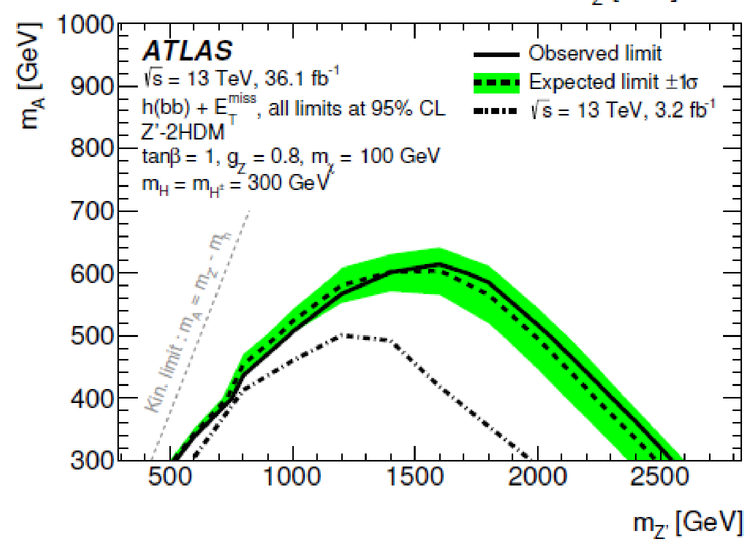
$h \to \gamma\gamma$ and $\tau^+\tau^-$
Z' excluded up to 815 GeV for low m_χ



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.



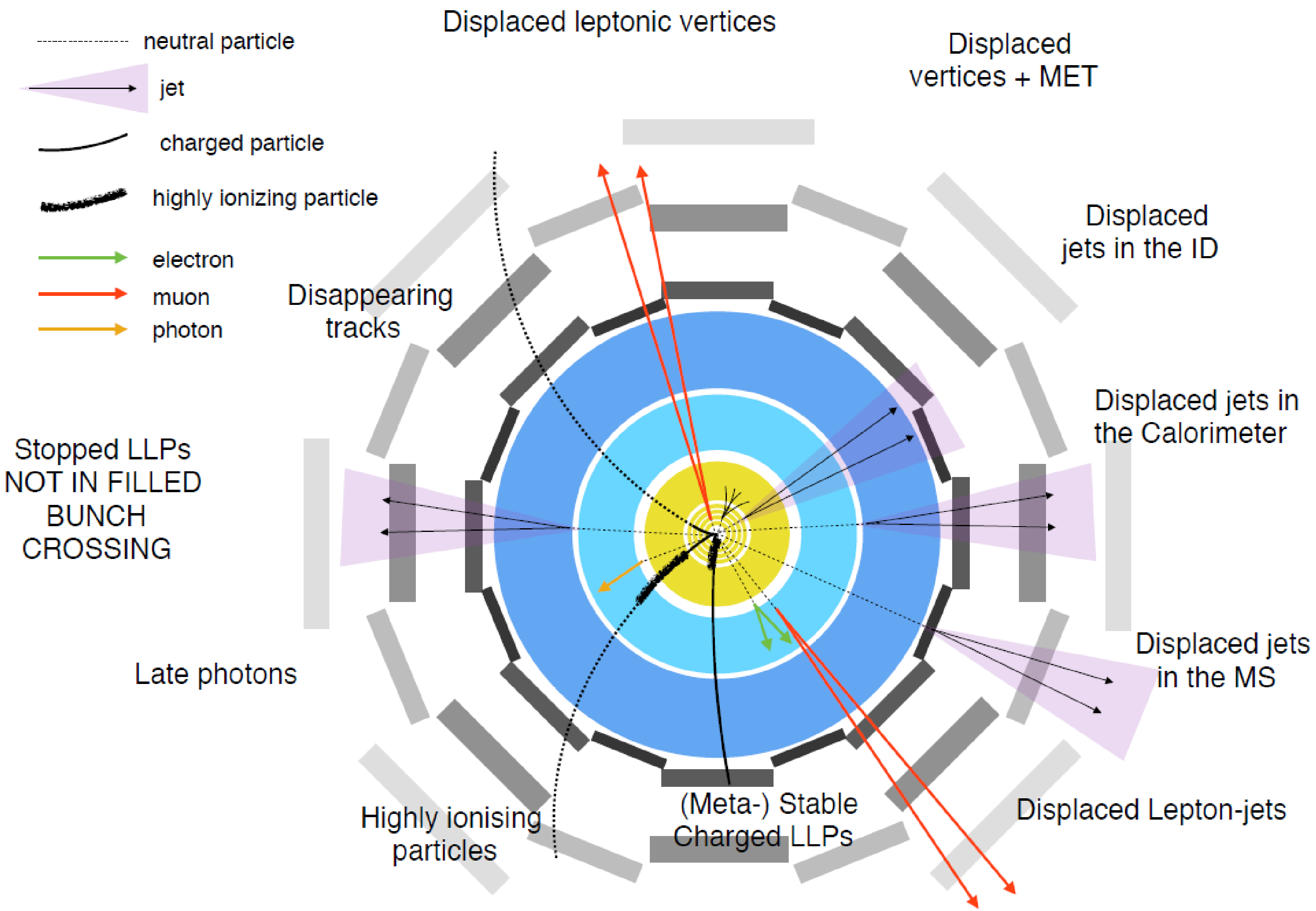


CMS PAS EXO-16-055 (13 March 2018)
PRL **119** (2017) 181804

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

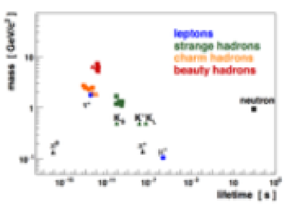


Unconventional signatures: challenges

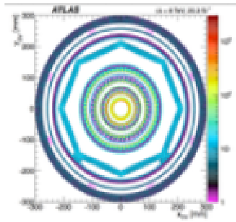
- Trigger: combination of hardware + software that must decide very quickly whether to save an event or lose it forever
  - First step in every search for LLPs: make sure that interesting events are saved!
    1. In associated production, trigger on prompt particle (Eg. WH prod. trigger on mu; ISR trigger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

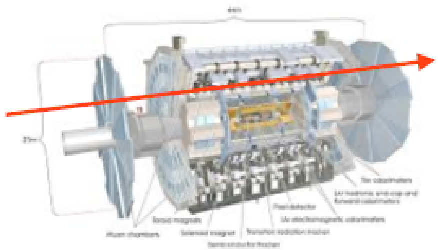
weak decays of heavy flavour



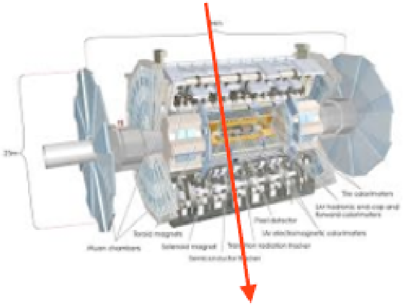
material interactions



beam halo muons



cosmic muons



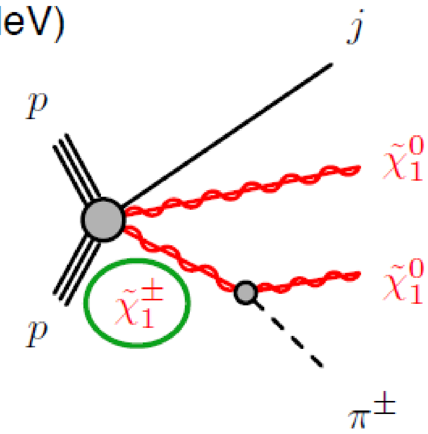
- Systematic uncertainties: can’t use standard recommendations for object reconstruction nor trigger

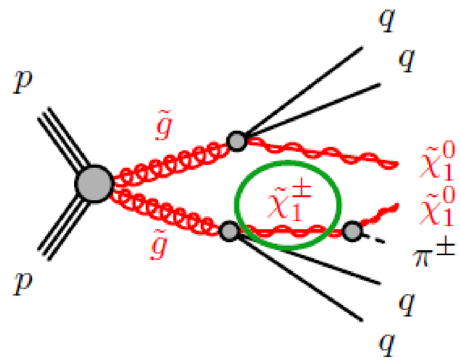
Unconventional signatures: disapearing tracks

LLP

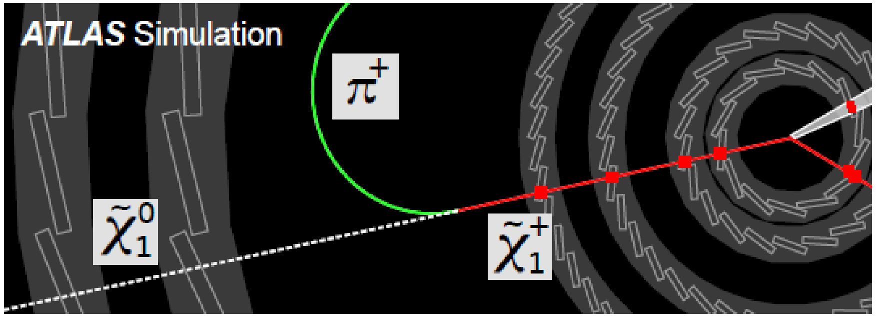
- Search for disappearing track + MET + jets
- Signature: Chargino track "disappears" when it decays, into MET
  - Low momentum pion track (~0.1 GeV) is hard to reconstruct
  - Challenge to identify the legitimate real tracklets (non-fake) using only a few measurement tracks

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



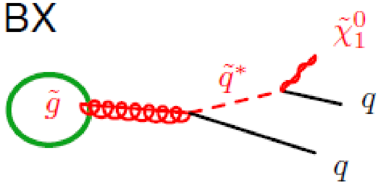


- Search sensitive to LLP lifetime of 10ps to 10 ns

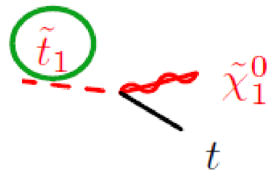


Unconventional signatures: stopped particles

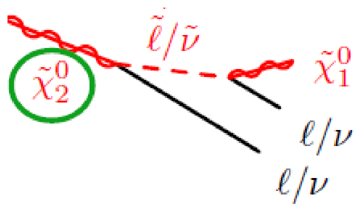
- Search for stopped LLPs decaying during non-collision bunch crossings (BX)
- Signature: LLPs come to rest in the detector and decays after the current BX
  - most likely to stop in the densest detector materials:
    - Calorimeters (ECAL, HCAL):
      a) Split SUSY: two-body and three-body decays of 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 lQl = 2e decays into two same-sign muons (MCHAMP → $\mu^{\pm}\mu^{\pm}$)



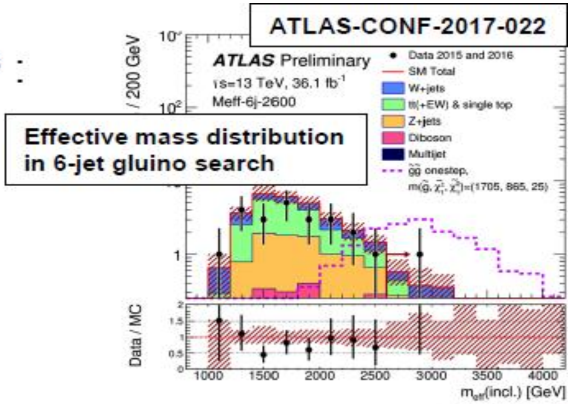
- Search sensitive to wide range of LLP lifetime: 10^{-5} to 10^{6} s

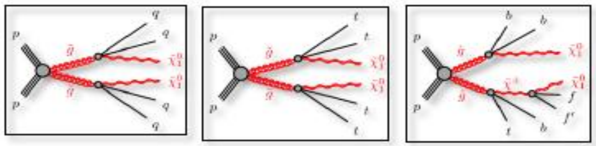
Summary (Exotic Searches)

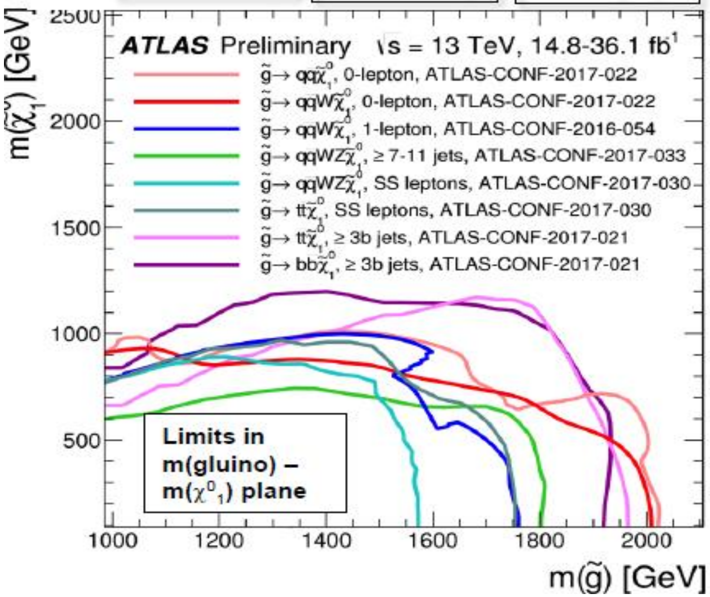
- Searches for Exotic searches
  - All major search channels reached 1 TeV scales
  - Quite a few at 10 TeV
  - New probe: Higgs boson → emerging field
- Dark Matter Searches are thriving at the LHC
- For vector and axial vector interactions
  - Dark Matter masses up 400 GeV – 700 GeV (mono-jet) excluded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

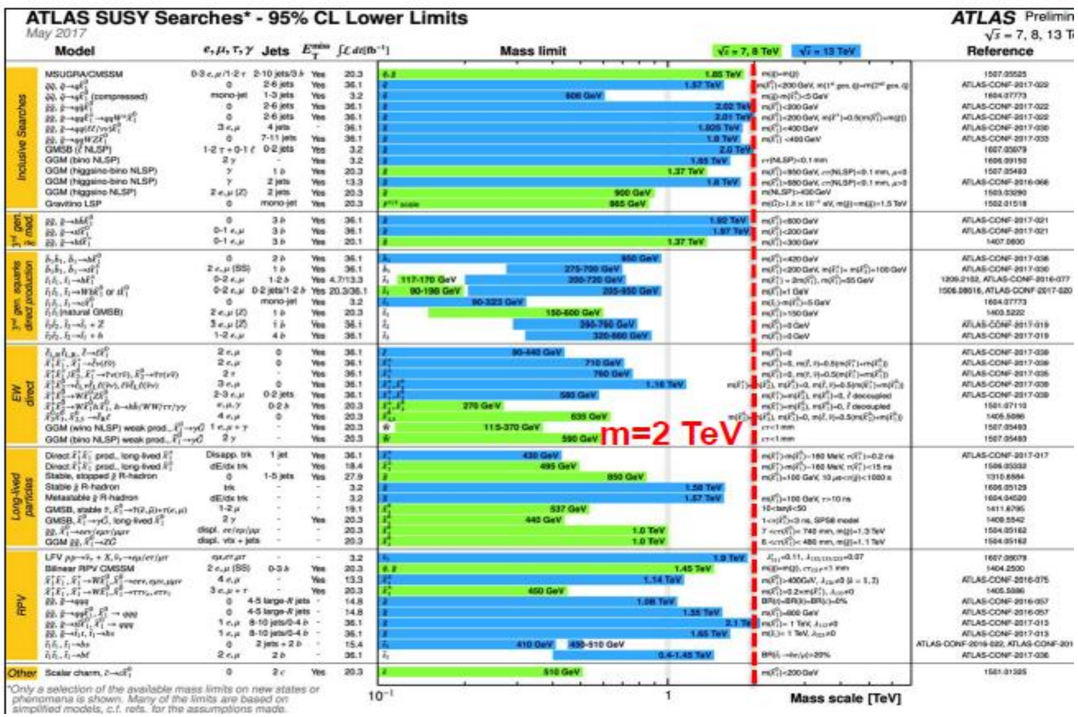
Searches for Supersymmetry

- Searches for light squarks and gluinos with jets and E_T^{miss} : sensitivity beyond 2 TeV for the first time
- Searches extended to stop and sbottom production in cascade decays of gluinos using final states with b-jets.
- No significant excesses over SM expectation
  - Limits extend up to 500 GeV beyond 2015 dataset limits

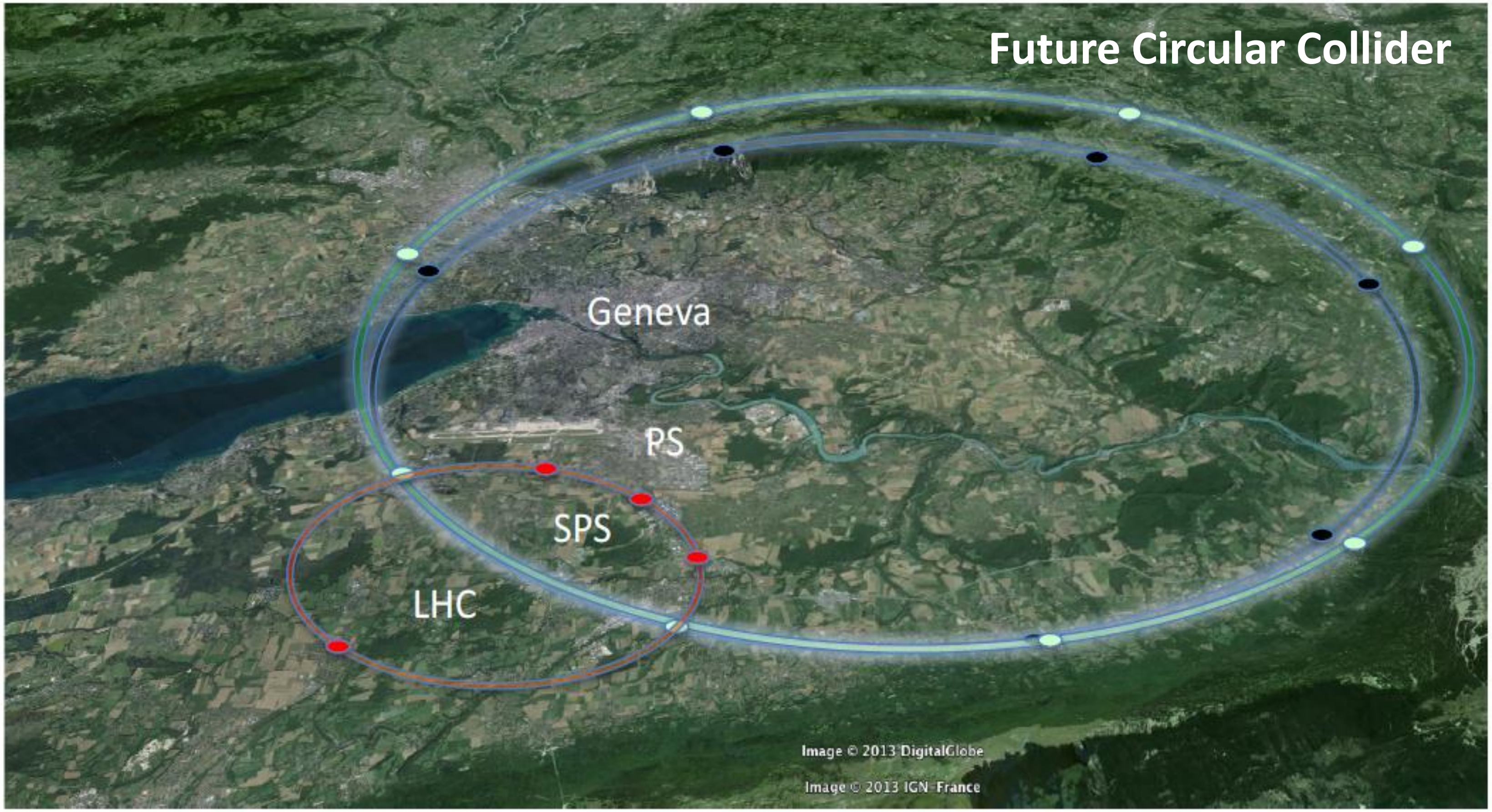








ECFA report 2016 (European Committee for Future Accelerators)



LHC	HE-LHC	FCC-hh	FCC-hh
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)

ATLAS Statistics

183 Institutions → 166 Institutes (single)
17 clusters (57 institutes in clusters)
14 associated institutes

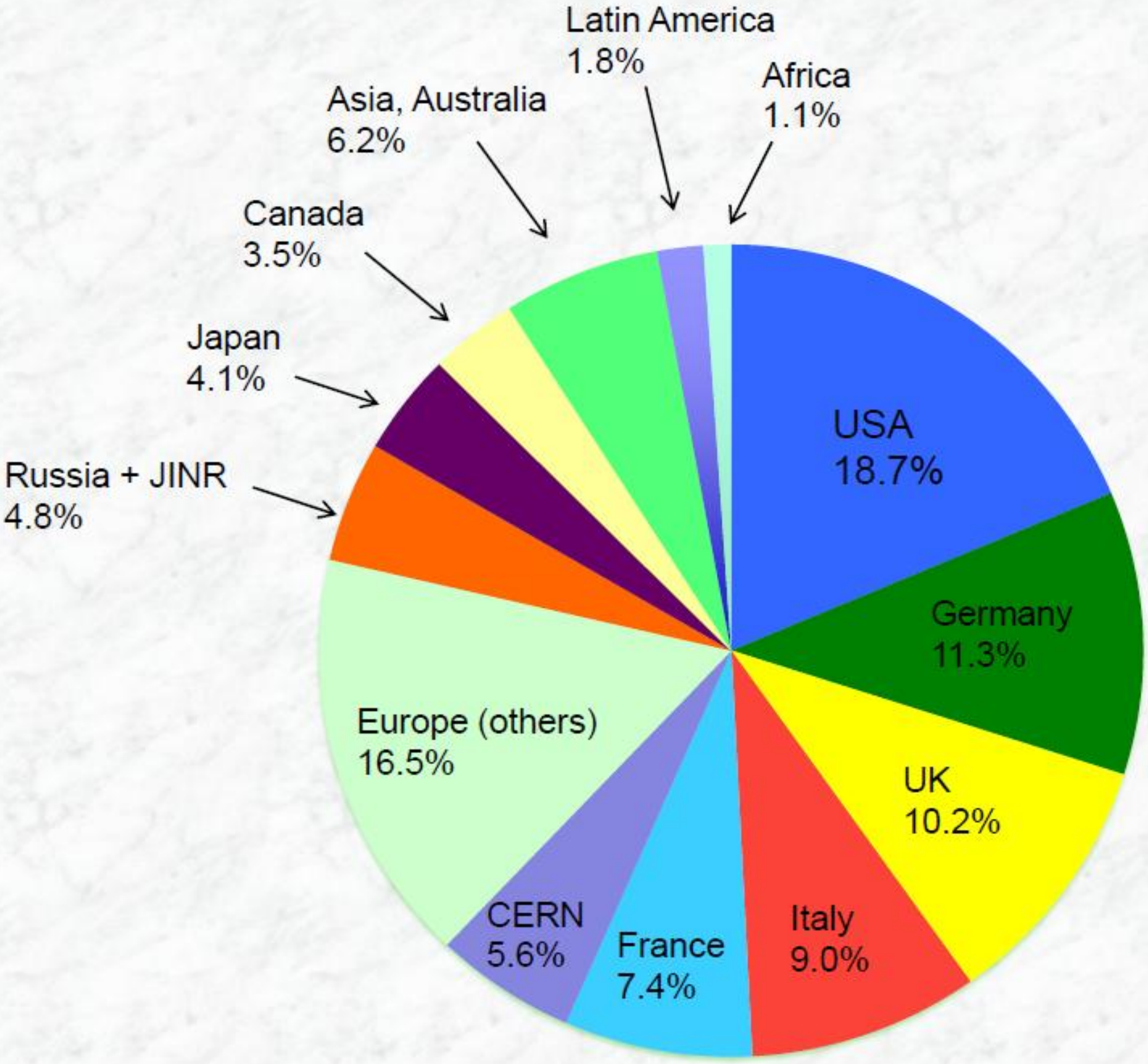
→ 237 Institutes (preliminary, to be cross-checked)

from 38 Countries

- Active ATLAS members ~5'500
  (Physicists, students, engineers, technicians, ...)

- Scientific authors ~2'900
- with PhD, contributing to M&O share ~1'900

- PhD students ~1'200
- Master / diploma students ~500



Fractions according to PhD physicists (M&O share)

USA	18,7%
Germany	11,3%
UK	10,2%
Italy	9,0%
France	7,4%
CERN	5,6%
Japan	4,1%
Canada	3,5%
Russia+ JINR	4,8%
Spain	2,6%
China	2,6%
Czech Republic	2,1%
Sweden	1,6%
Israel	1,6%
Poland	1,6%
Switzerland	1,3%
Netherlands	1,3%
Europe (others)	6,0%
Asia (others) + Australia	2,0%
Latin America	1,8%
Africa	1,1%