Elementary Particle Physics: theory and experiments

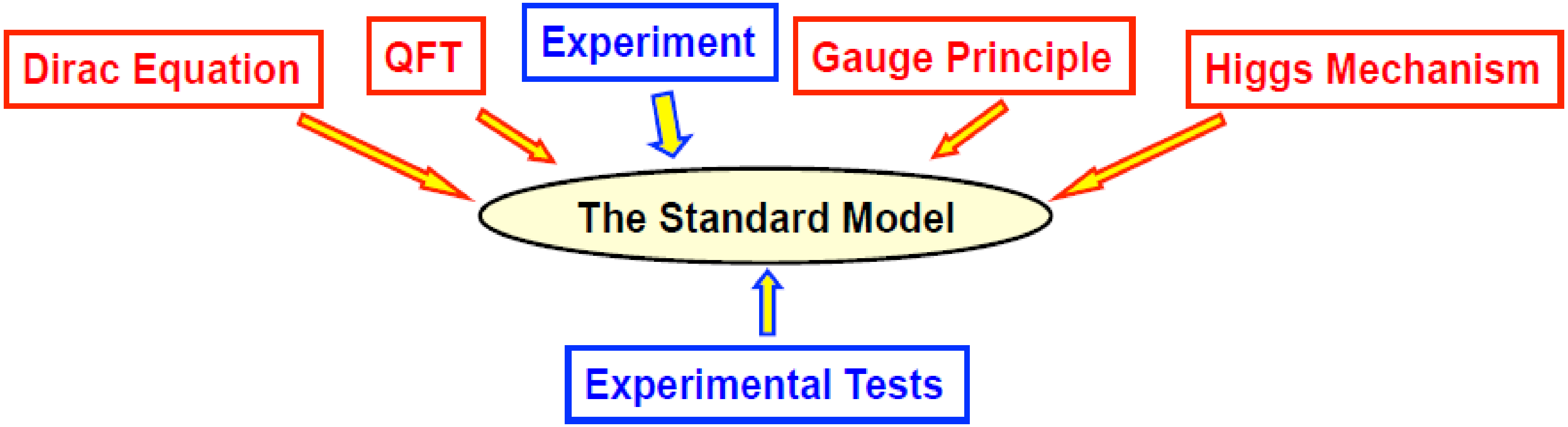
Searches for New Physics at LHC

Exotic models
Dark Matter
Uncomventional signatures
Sypersymmetry

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



Dirac Equation

QFT

Experiment

Gauge Principle

Higgs Mechanism

The Standard Model

Experimental Tests

- 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…

Standard Model: Problems and Open Questions

- The Standard Model has too many free parameters:

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

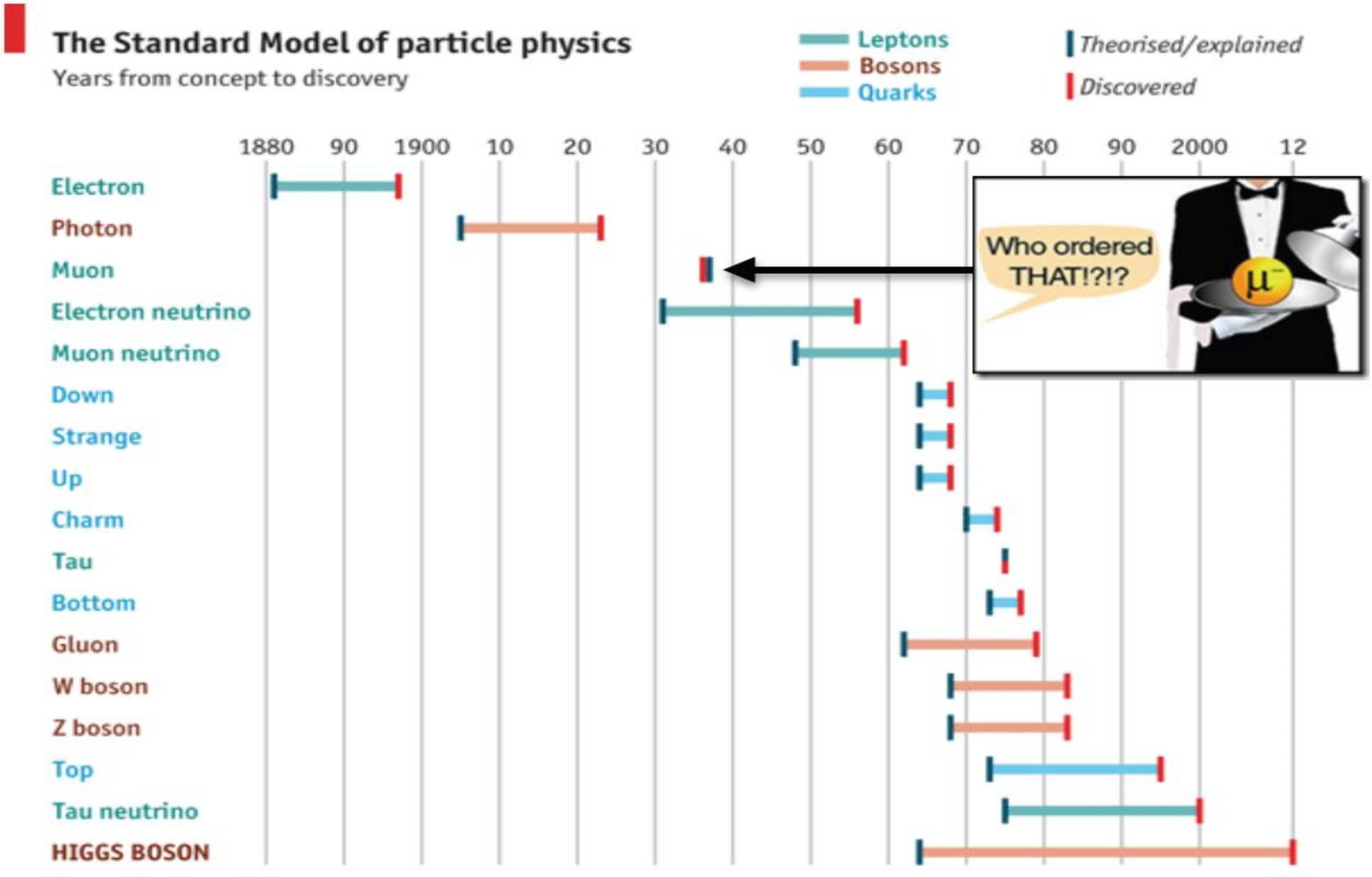
$$\theta_{12}, \theta_{13}, \theta_{23}, \delta \quad + \quad \lambda, A, \rho, \eta \qquad e, G_F, \theta_W, \alpha_S \qquad \cancel{m_H}, \theta_{CP}$$

- Why three generations ?
- Why SU(3)$_c$ x SU(2)$_L$ x 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

Uncharted discoveries?



Source: *The Economist*

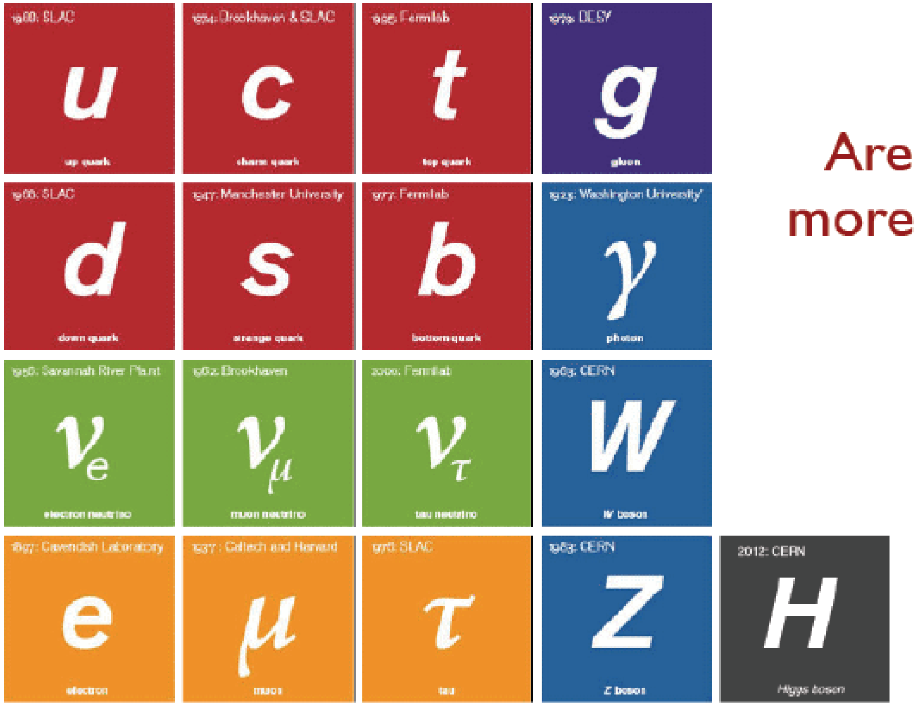
Many unanswered questions …

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?

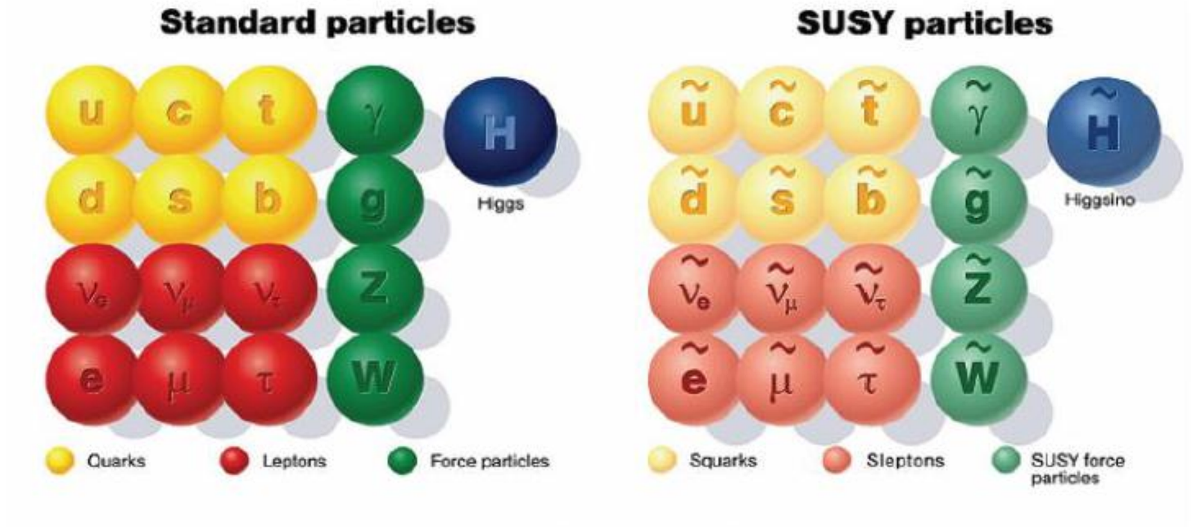
What keeps the Higgs mass so small?

How do we incorporate gravity?

What is Dark Matter?

… and as many possible answers to probe!

- Super-symmetry?



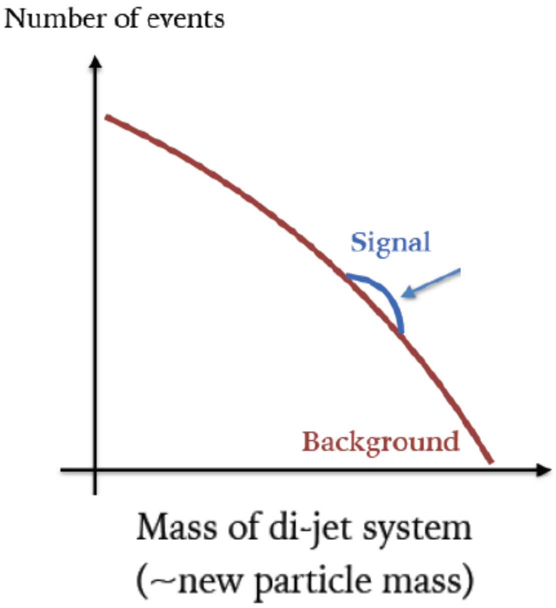
- Composite quark and/or leptons?
- New Heavy bosons?
- Gravitons?
- Dark Matter particles?
- …

Any new theory need to agree with the SM!

How would new phenomena manifest?

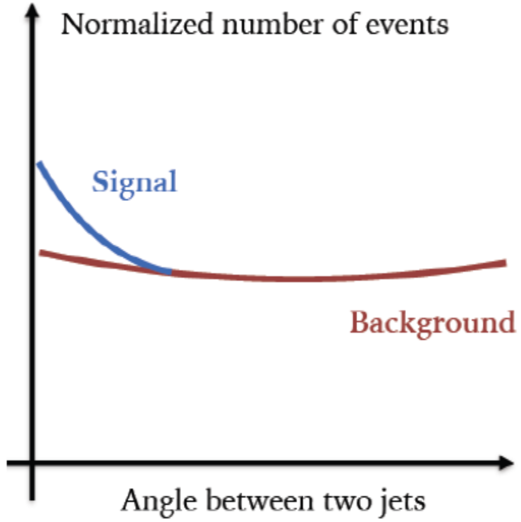
New particles:

resonant excess (bump) over Standard Model background



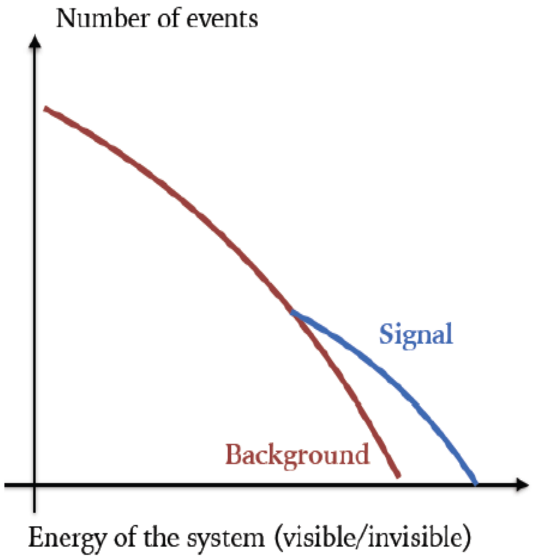
New interactions:

more central production (~Rutherford experiment)

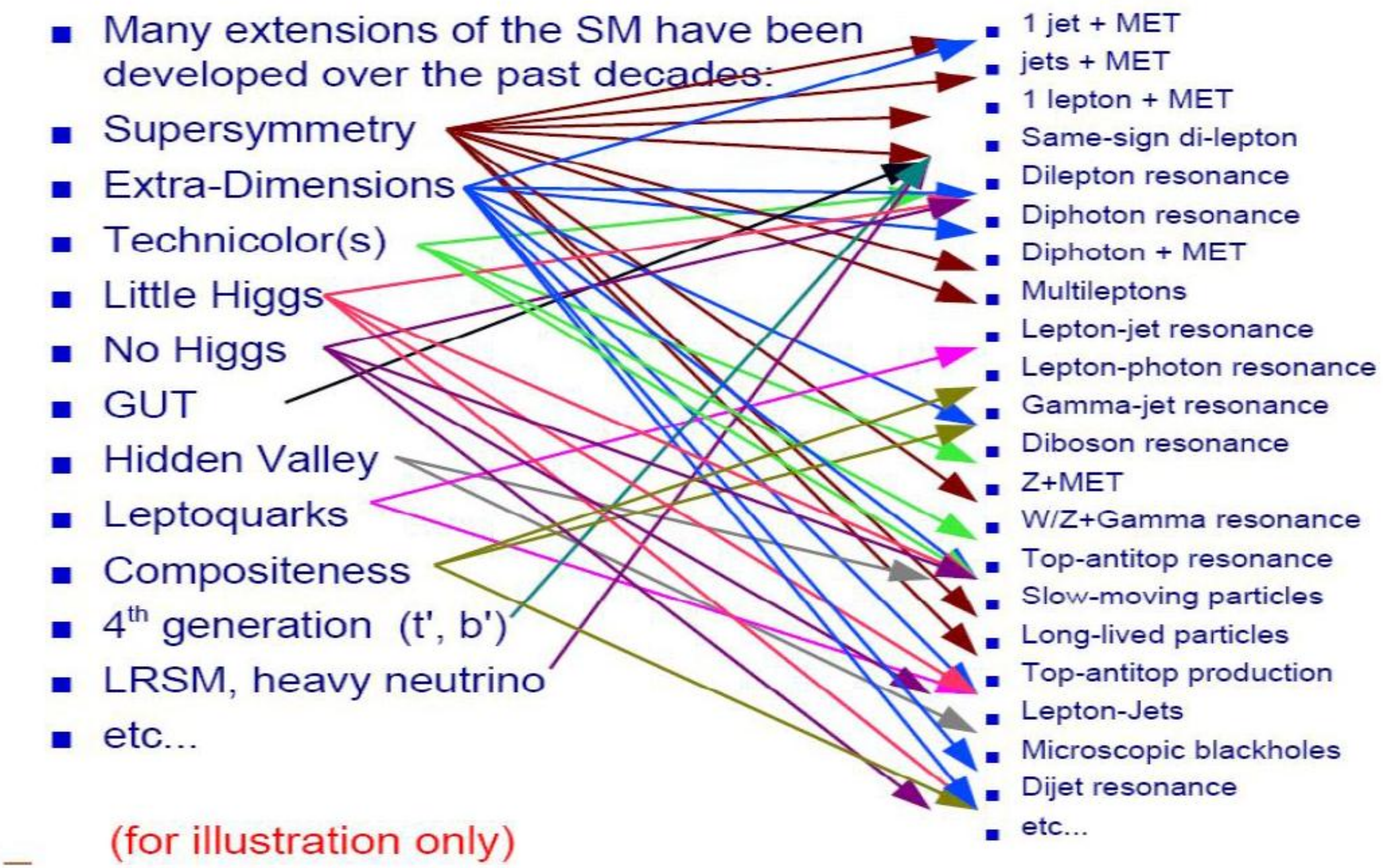


New particles and states:

larger multiplicity of objects at high masses



Long list of models and signatures

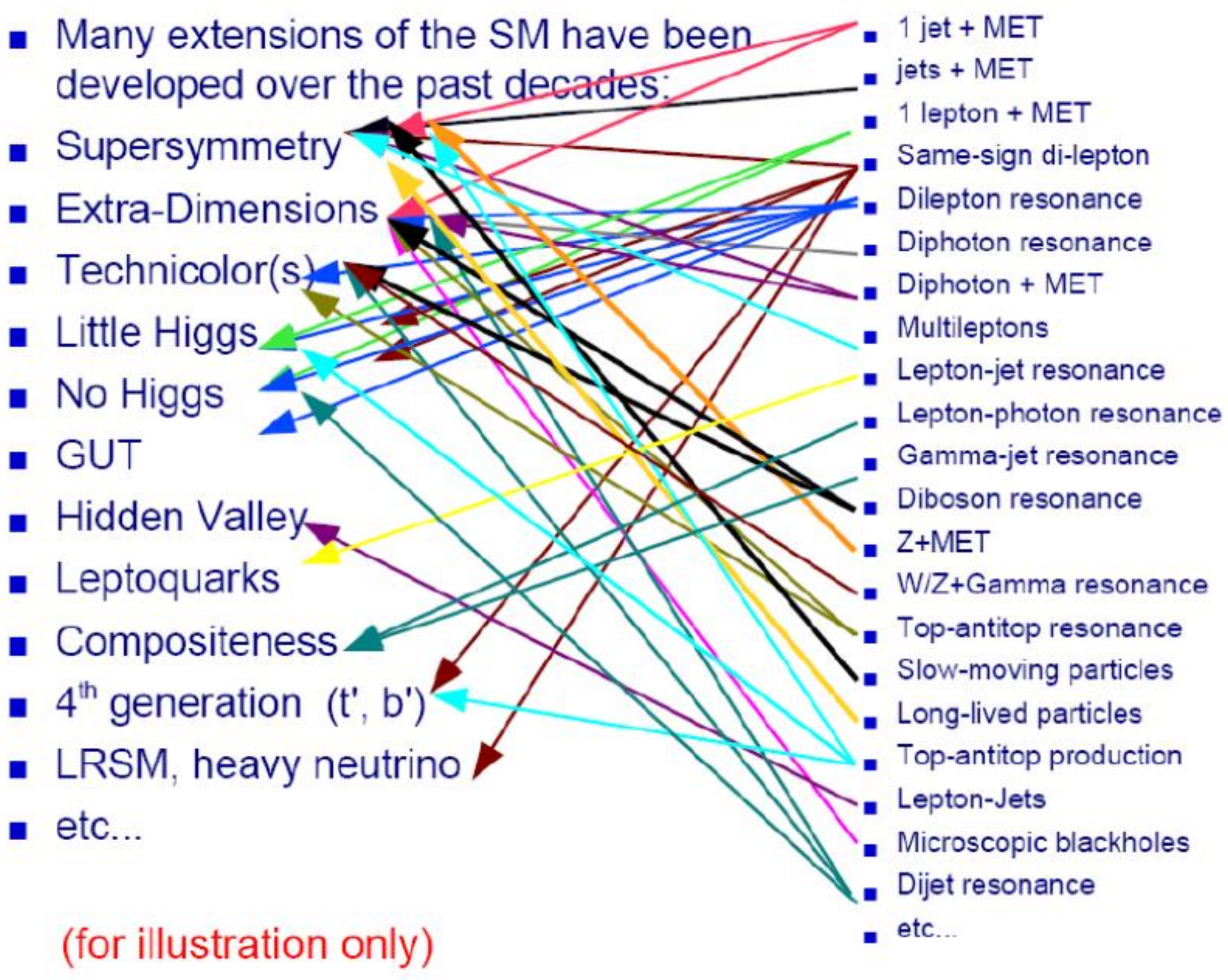


- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4th generation (t', b')
- LRSM, heavy neutrino
- etc...

(for illustration only)

- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

Long list of models and signatures



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A complex 2D problem

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

→ Practical

→ Less model-dependent

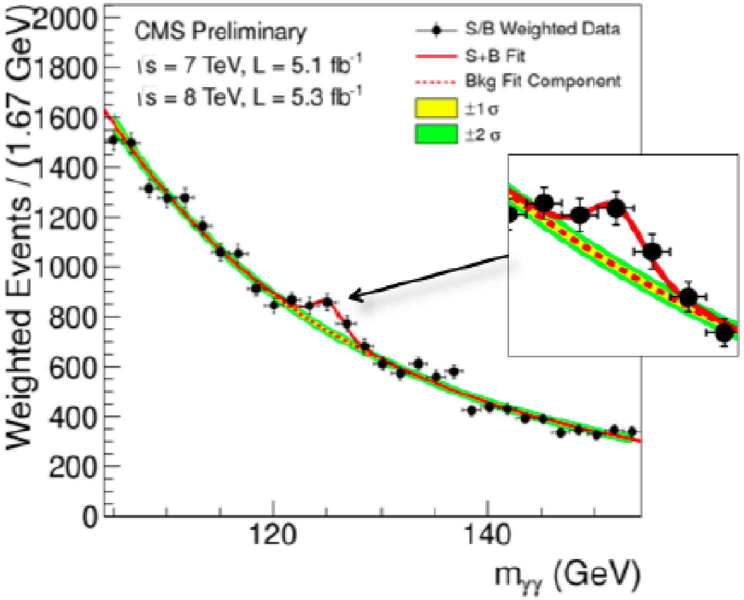
→ Important to cover every possible signature

What characterizes Exotics Searches

No precise model to guide us

Standard Model:

Predicted Higgs boson

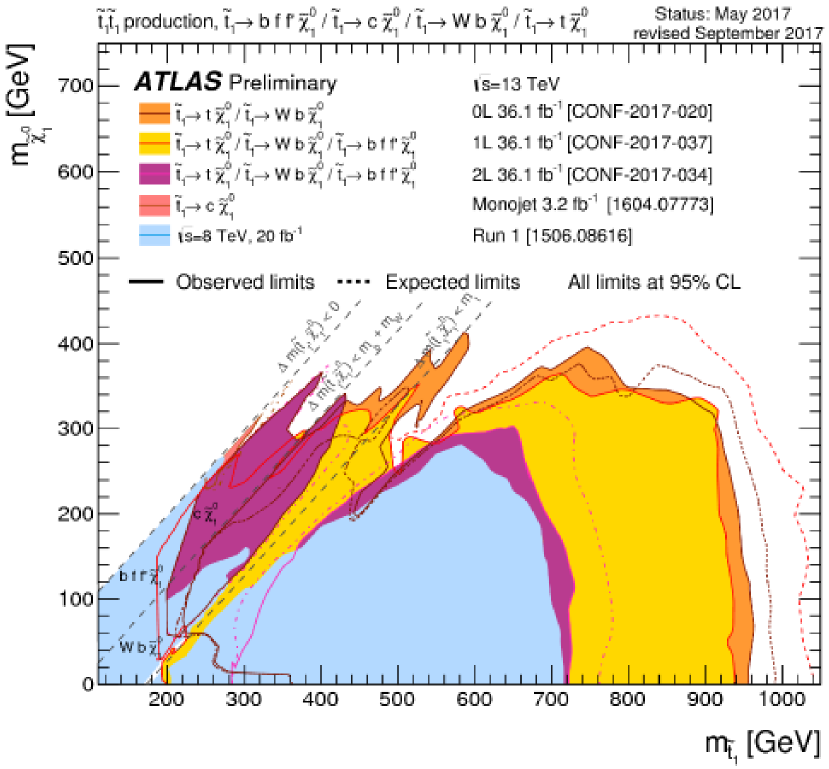


Phys. Lett. B 716 (2012) 1-29

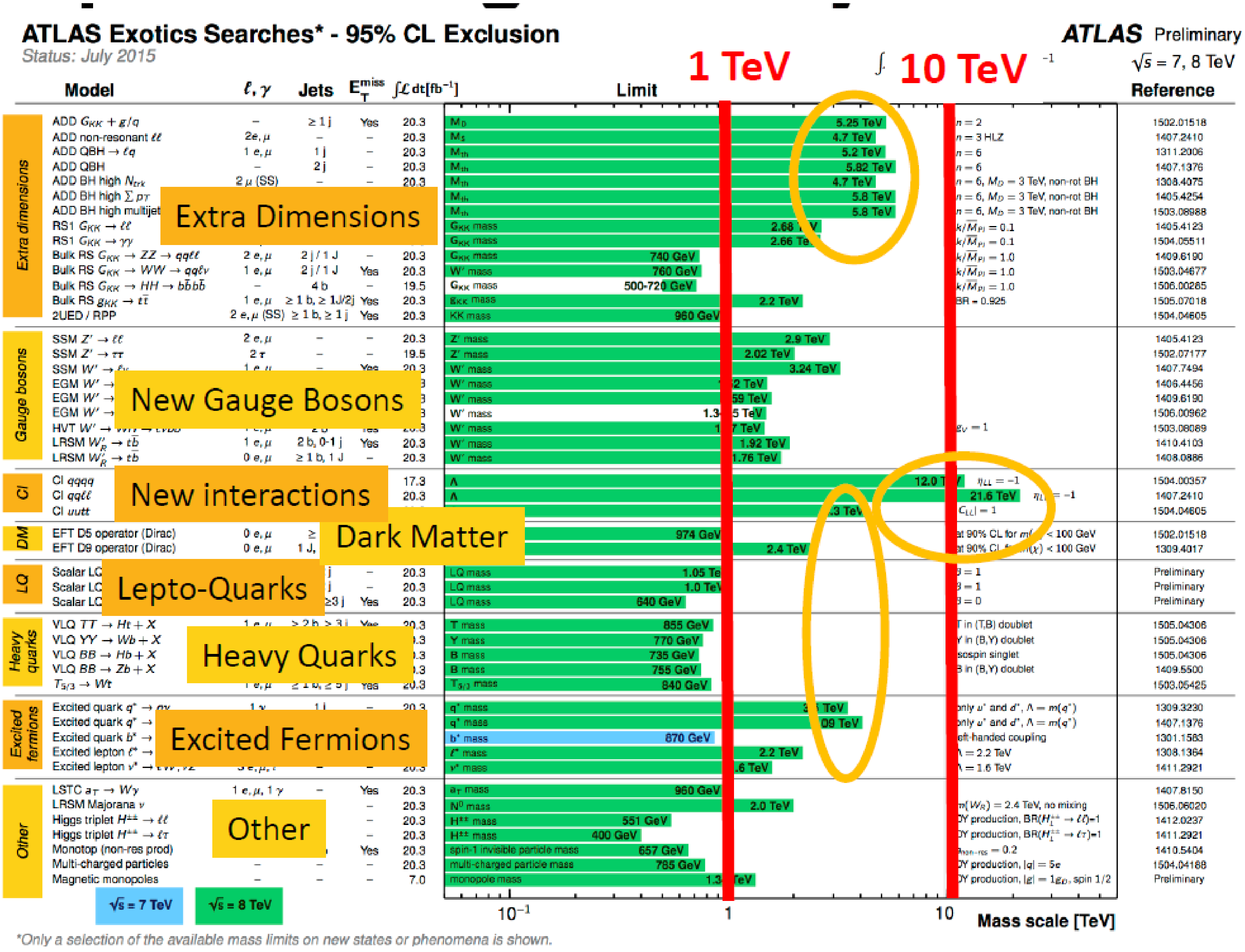
Phys. Lett. B 716 (2012) 30-61

No unified parameter phase space

Supersymmetry Searches:



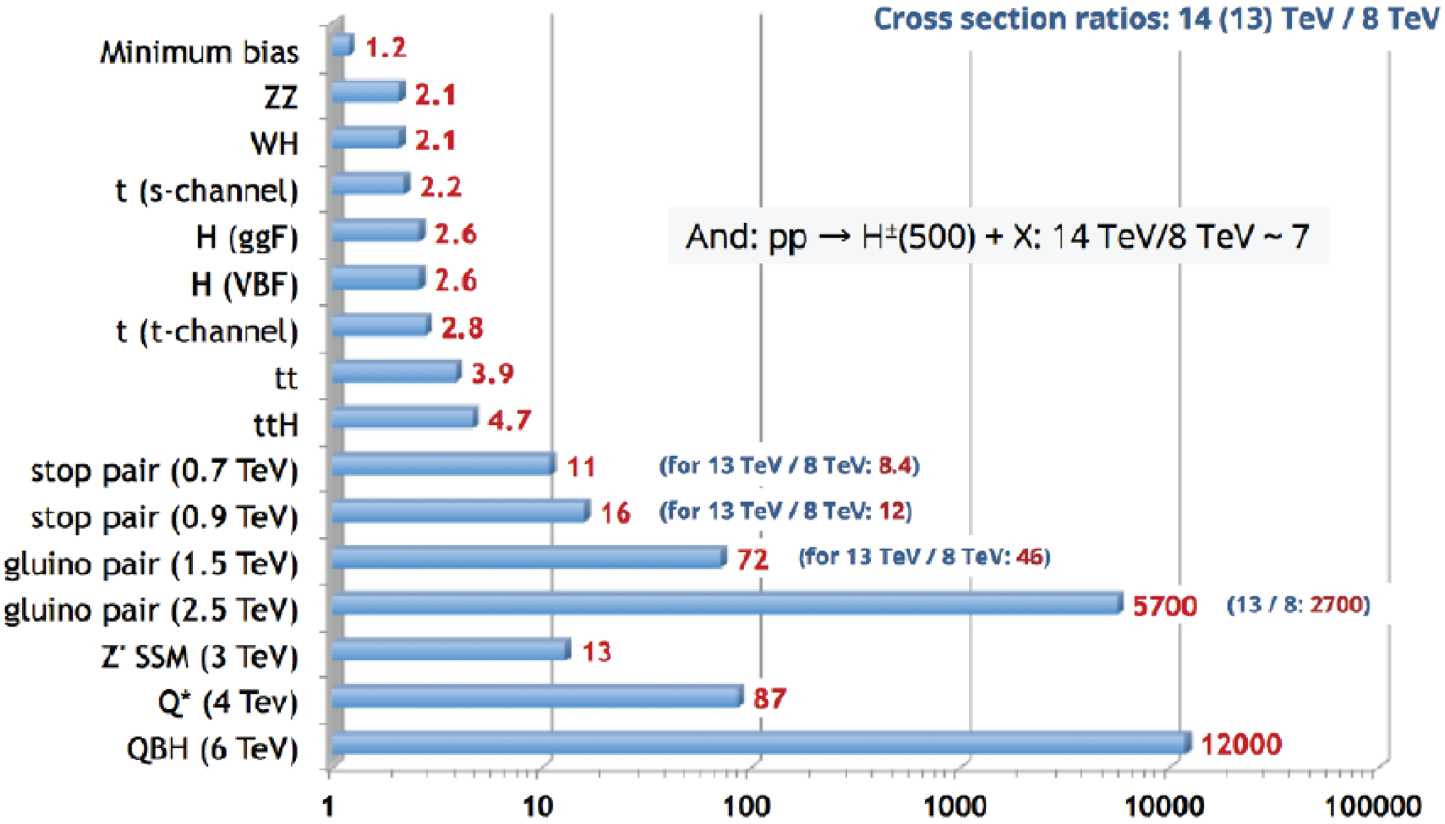
Exploration range of LHC by mid 2015



LHC Run II

Hugely increased potential for discovery of heavy particles at 13 TeV

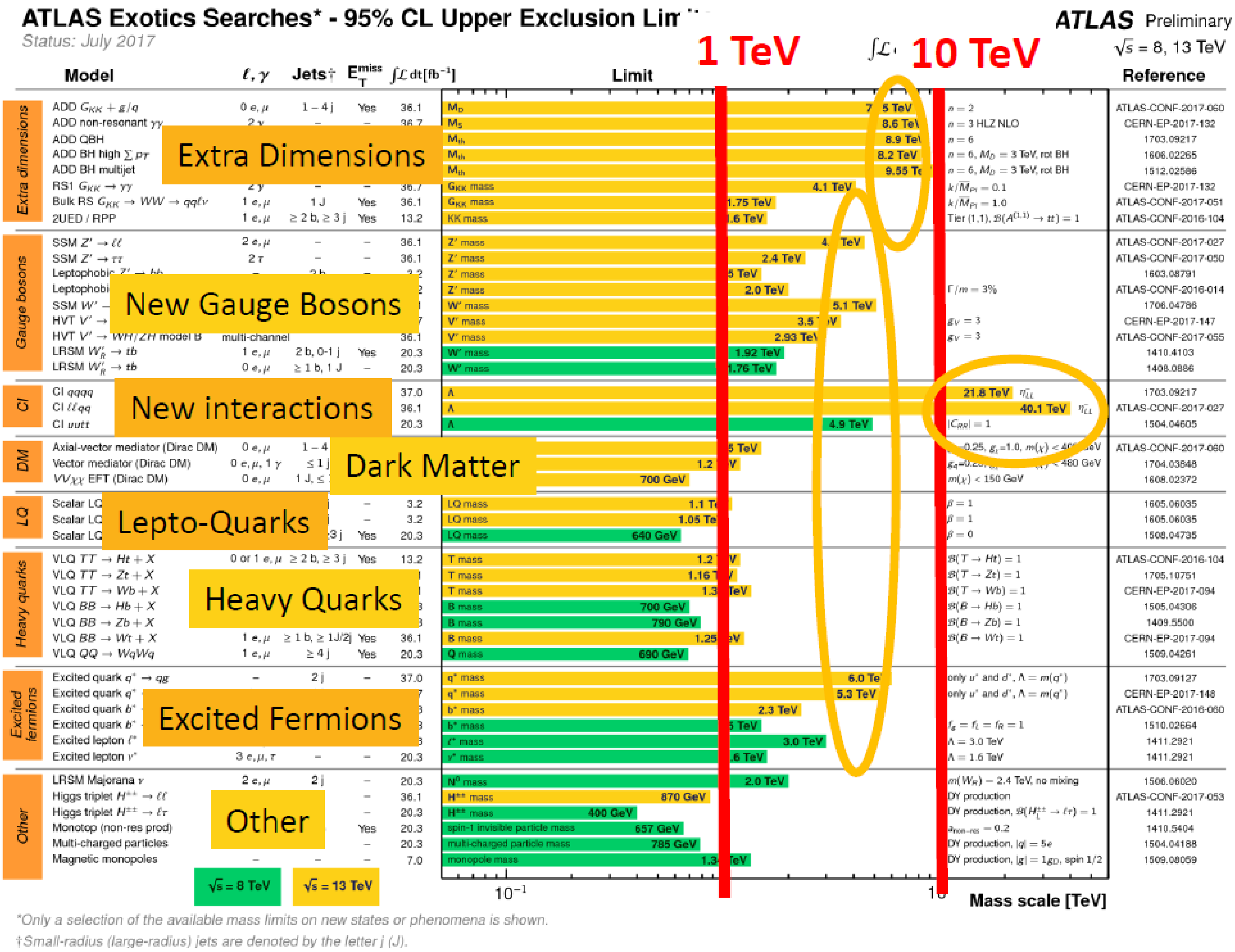
Perfect occasion for young motivated physicists: join the search!



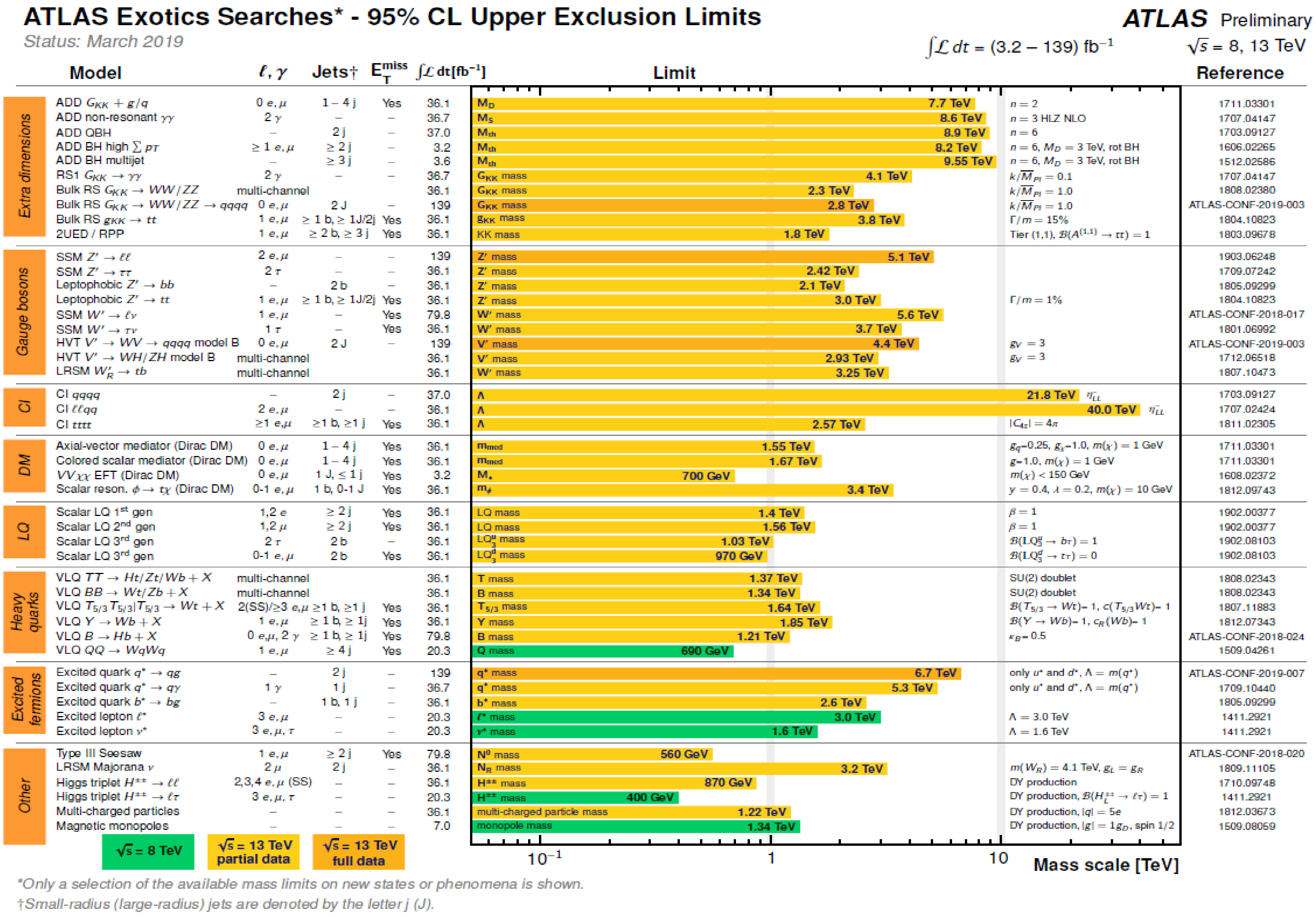
Cross section ratios: 14 (13) TeV / 8 TeV

And: pp → H±(500) + X: 14 TeV/8 TeV ~ 7

Exploration range of LHC by mid 2017



Exploration range of LHC by mid 2019



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: March 2019

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 139)\ \text{fb}^{-1}$

$\sqrt{s} = 8,\ 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WW/ZZ \to qqqq$	0 e, μ	2 J	–	139	G_{KK} mass 2.8 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2019-003
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	79.8	W' mass 5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	139	V' mass 4.4 TeV	$g_V = 3$	ATLAS-CONF-2019-003
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	W' mass 3.25 TeV		1807.10473
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η^-_{LL}	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.0 TeV	η^-_{LL}	1707.02424
	CI $tttt$	$\geq$1 e,μ	$\geq$1 b, $\geq$1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1$^{\text{st}}$ gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2$^{\text{nd}}$ gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3$^{\text{rd}}$ gen	2 τ	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(\text{LQ}_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3$^{\text{rd}}$ gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(\text{LQ}_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2019-007
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV partial data

🟧 $\sqrt{s}$ = 13 TeV full data

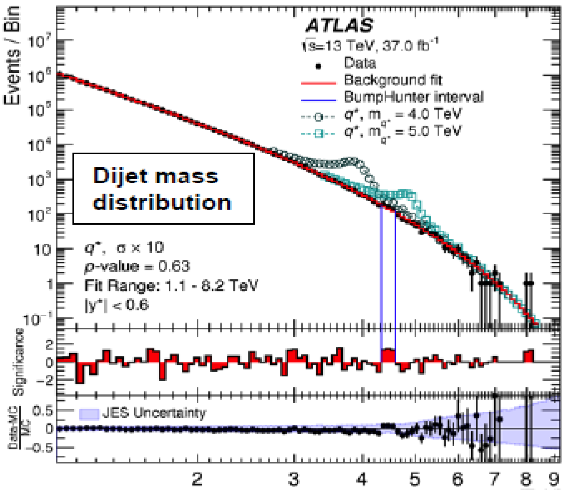
**Only a selection of the available mass limits on new states or phenomena is shown.*

†Small-radius (large-radius) jets are denoted by the letter j (J).

Searches with Dijets

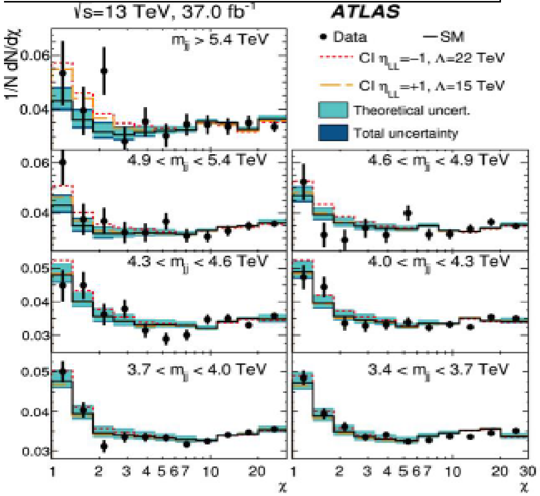
- Search for excess in dijet mass and angular distributions
- No significant excesses over SM expectation
- Extends limits significantly beyond 2015 results, on new gauge bosons and contact interactions, e.g.
  - Excited quarks: m(q*) > 6.0 TeV (5.8 TeV exp.)
  - Add. gauge bosons: m(W') > 3.6 TeV (3.7 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

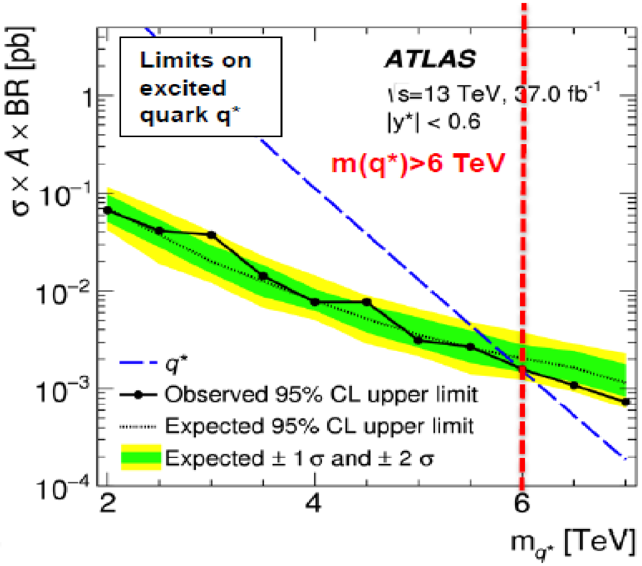
arXiv:1703.09127



Dijet mass distribution

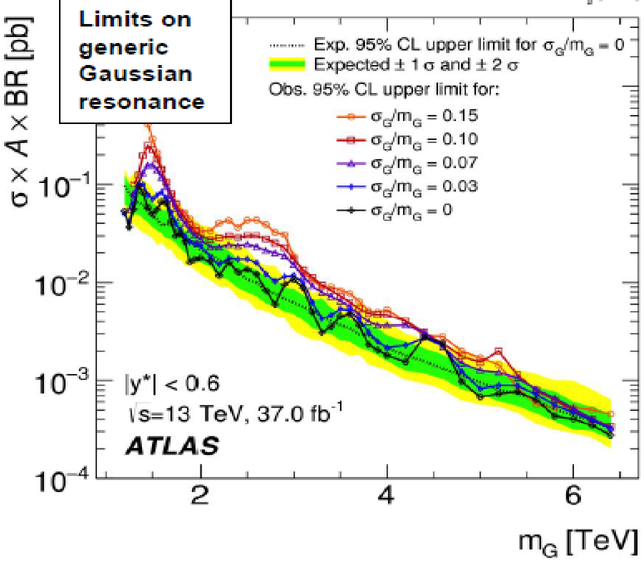
Dijet angular distributions χ=exp(2|y*|) for jet rapidity difference y*





Limits on excited quark q*

m(q*)>6 TeV



Limits on generic Gaussian resonance

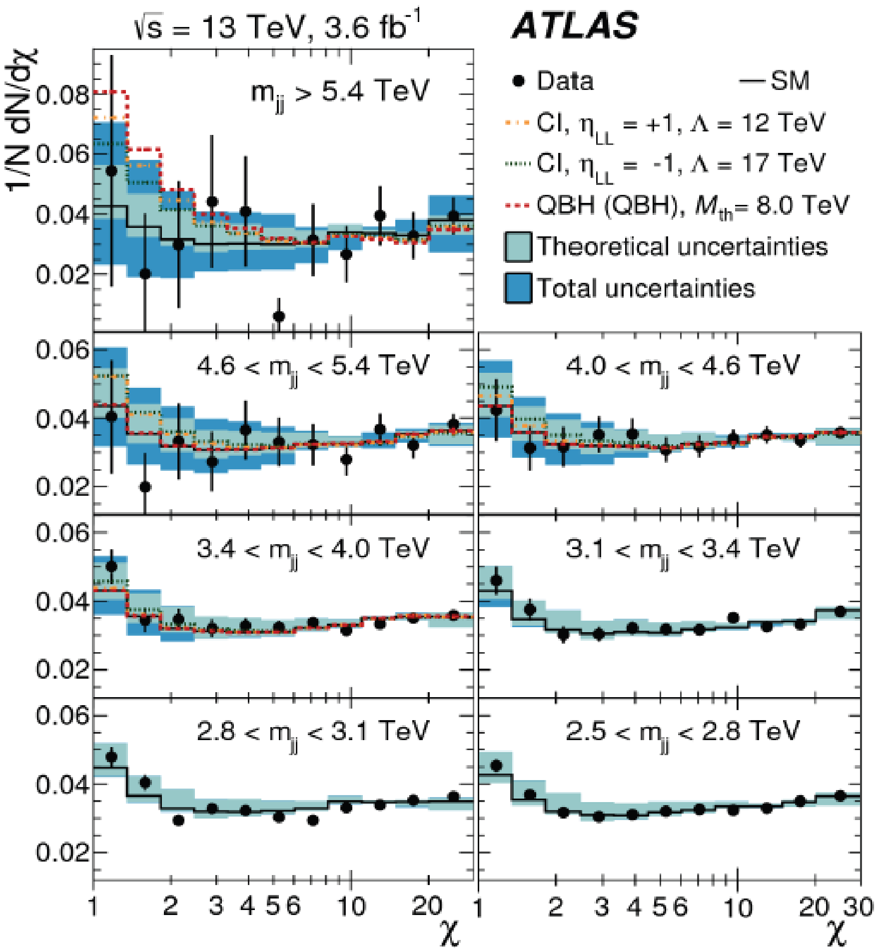
Dijet Angular Searches

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

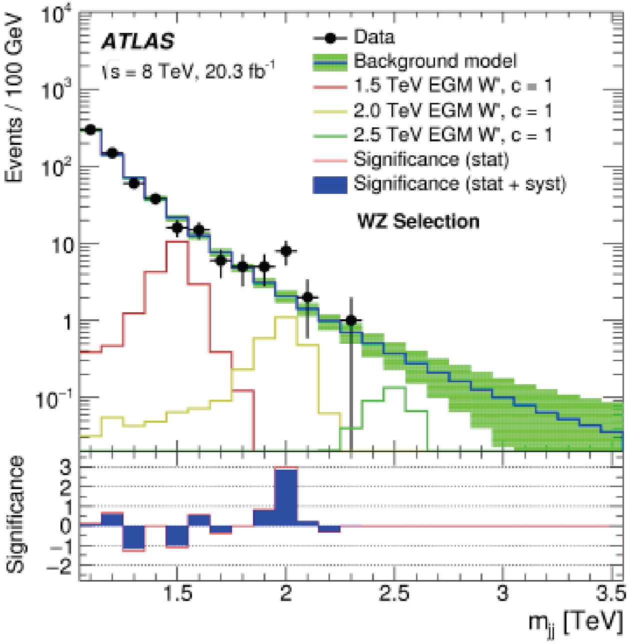
ATLAS-CONF-2015-073

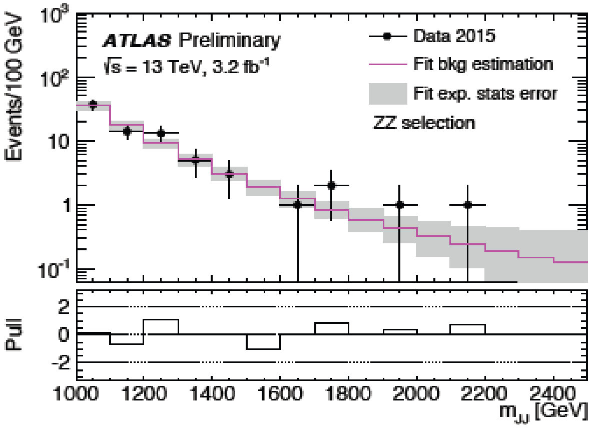
- **Modest excess at Run-1: 3.4σ** local / **2.5σ global**

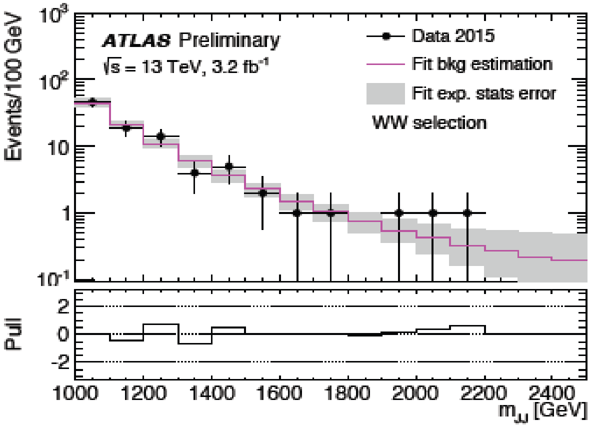
- **Analysis very similar to Run 1**, with functional fit of the background

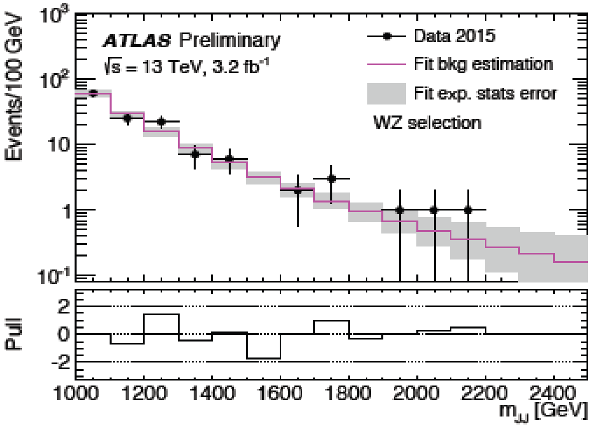
- **No significant excess is observed** however sensitivity not high enough for conclusive probe of the Run 1 excess

Run-1





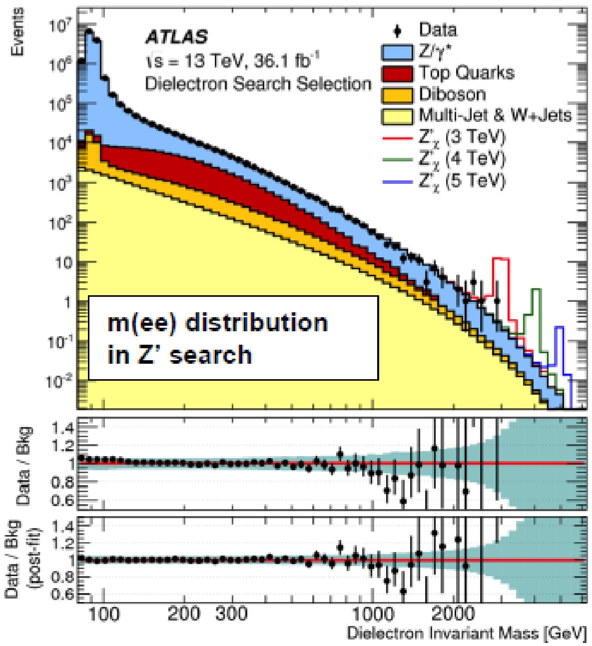


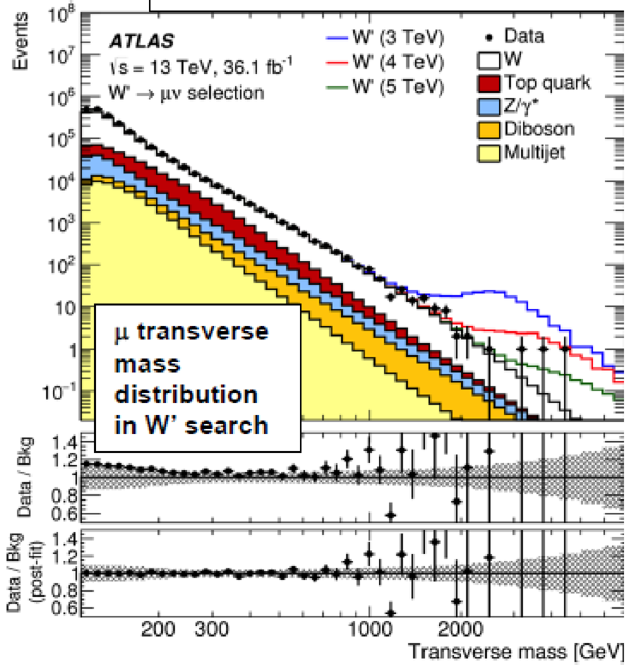


Resonance Searches (Dilepton, Lepton+ETmiss)

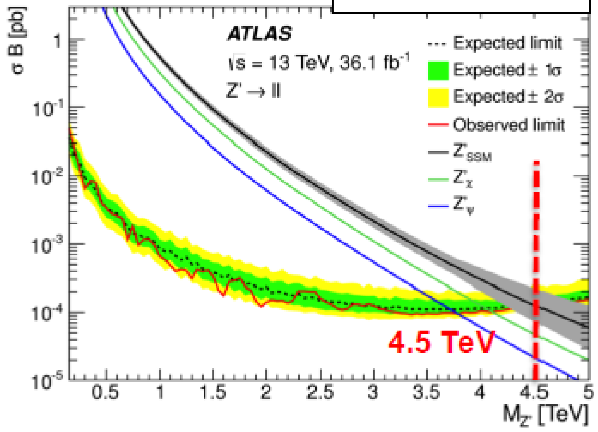
- Searches for new resonances decaying to lepton pairs (e.g. Z’) or lepton+E_T^{miss} (e.g. W’)
- Signature is peak in invariant mass distribution (dilepton) or tranverse mass distributions (lepton+E_T^{miss})
- No significant excess over SM expectation
- 95% CL exclusion limits extracted in various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

arXiv:1707.02424, arXiv:1706.04786

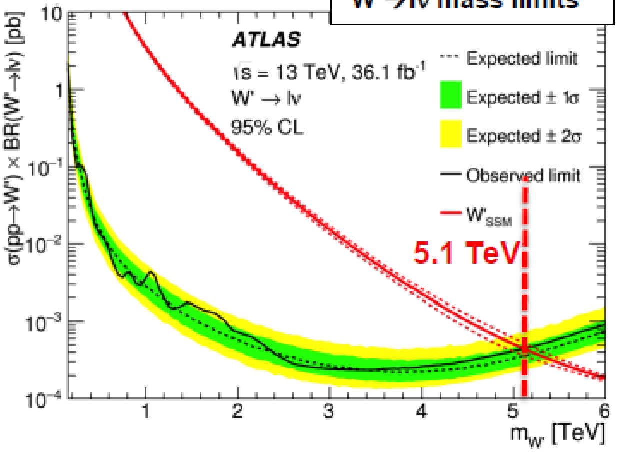

m(ee) distribution in Z’ search


μ transverse mass distribution in W’ search

Z’→ll mass limits

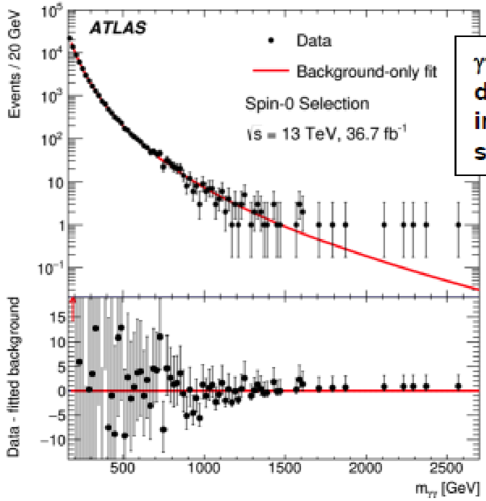


W’→lν mass limits

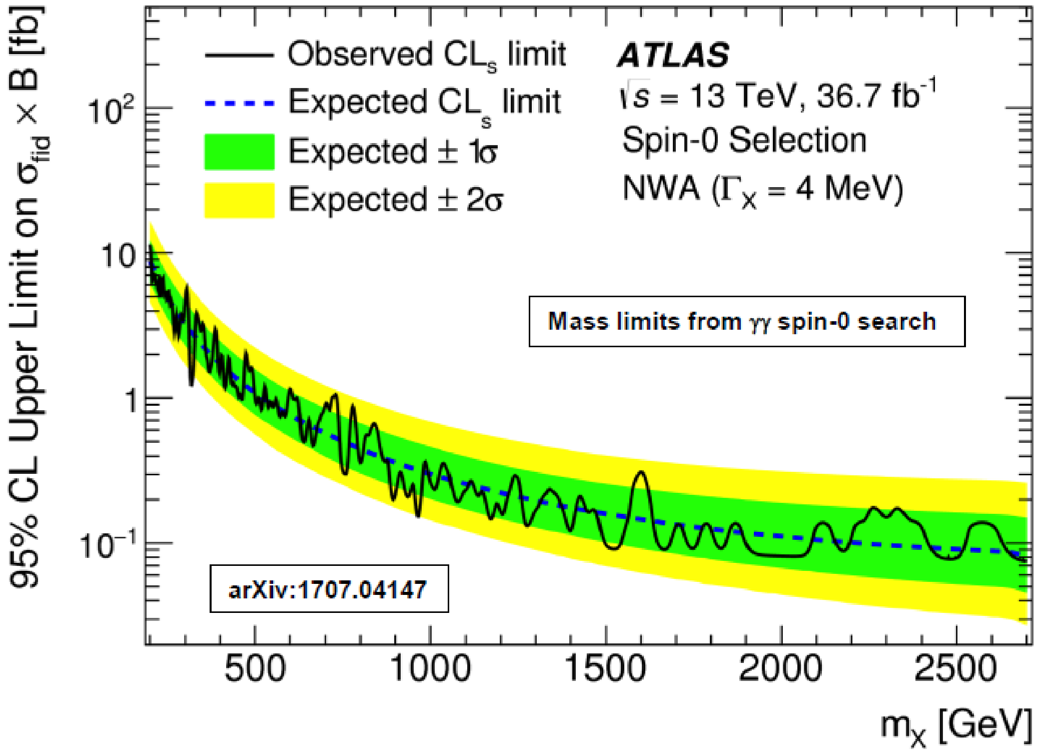


Resonance Searches ($\gamma\gamma$, $\tau\tau$)

- 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

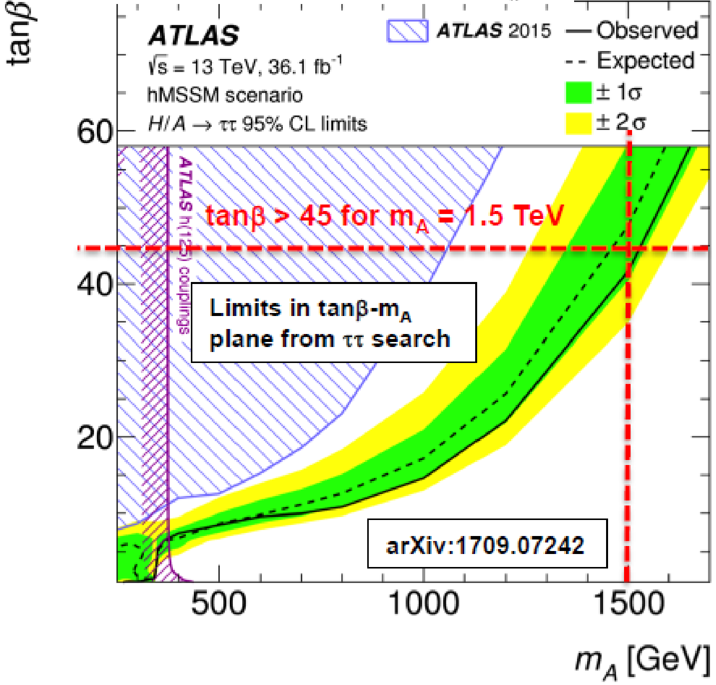


$\gamma\gamma$ mass distribution in spin-0 search



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

arXiv:1707.04147



tanβ > 45 for m_A = 1.5 TeV

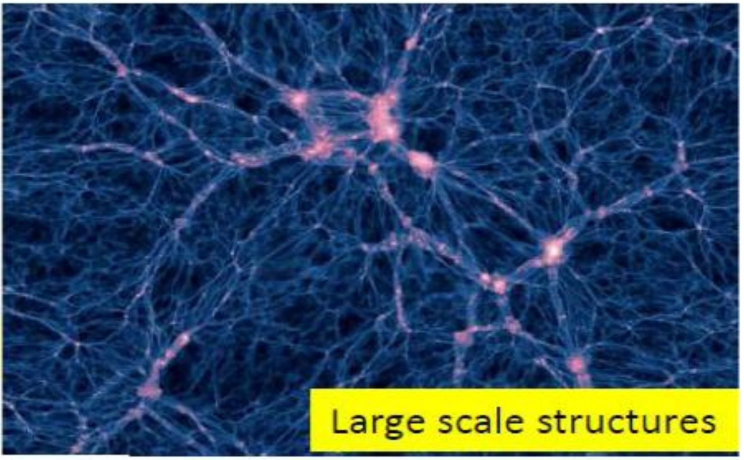
Limits in tanβ-m_A plane from $\tau\tau$ search

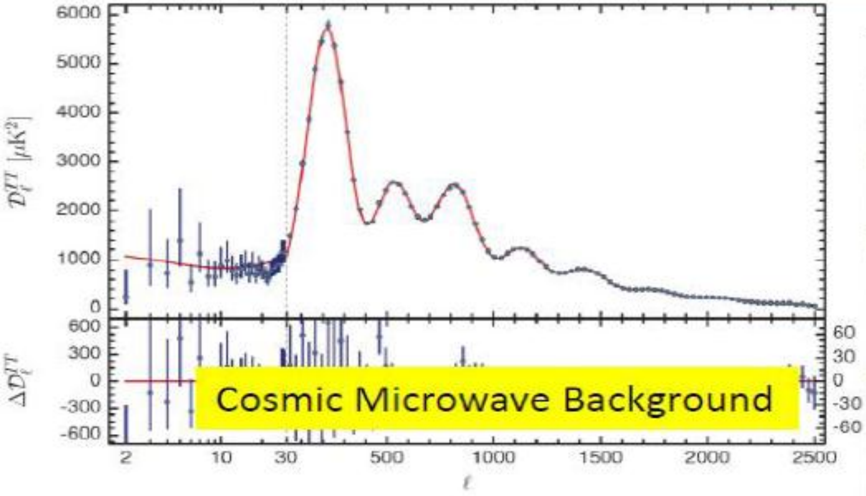
arXiv:1709.07242

Why Dark Matter?

Evidence piling up…


Gravitational Lensing

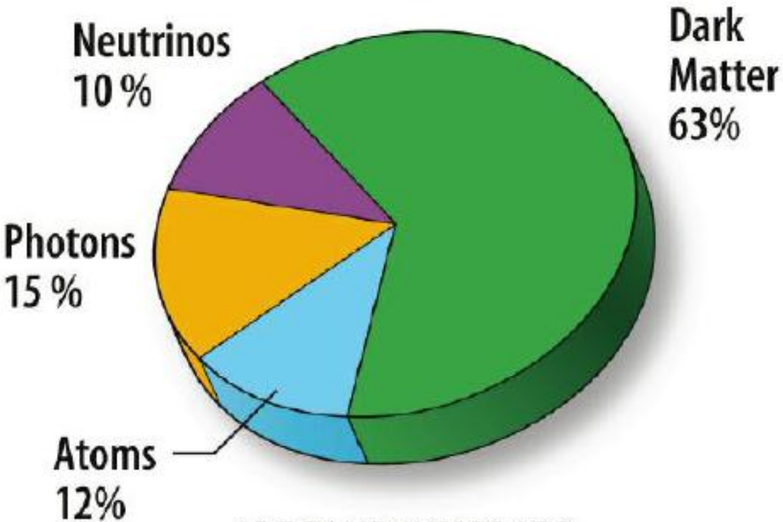

Large scale structures



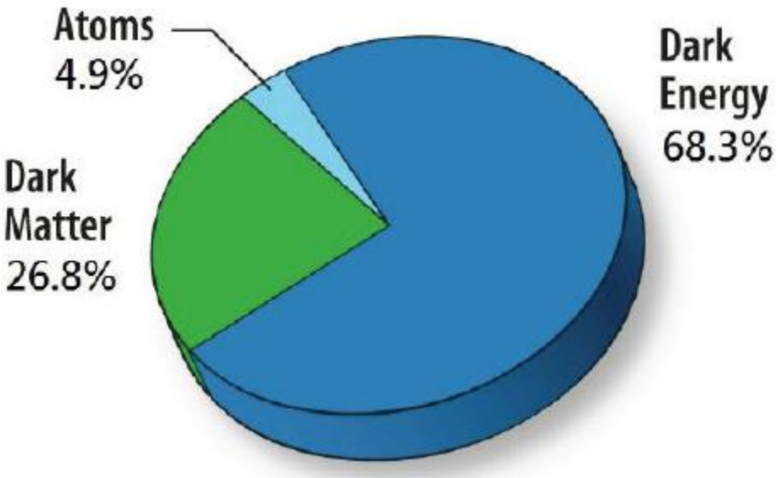
Cosmic Microwave Background


Bullet Cluster

What do we know about Dark Matter



13.7 BILLION YEARS AGO
(Universe 380,000 years old)



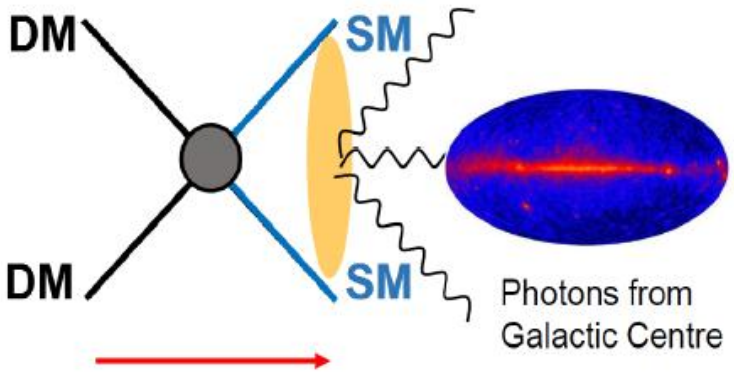
TODAY

Strong astrophysical evidence for the existence of dark matter

What do we know about Dark Matter

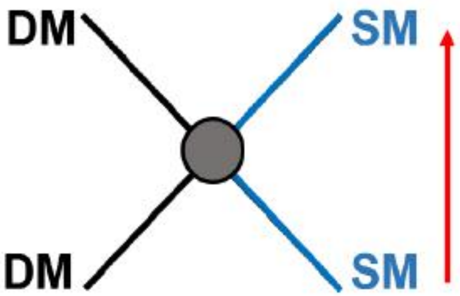
- Massive
- Non-relativistic (slow)
- Long lived (old)
- No electric or colour charge
- Very weakly interacting with ordinary matter
- Subject to gravity interactions

Experimental detection of Dark Matter

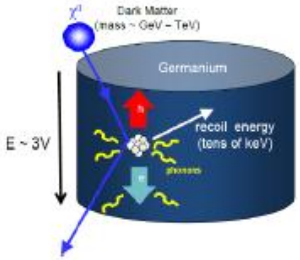


Photons from Galactic Centre

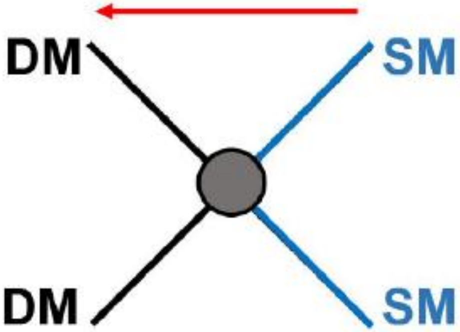
"break it": indirect detection

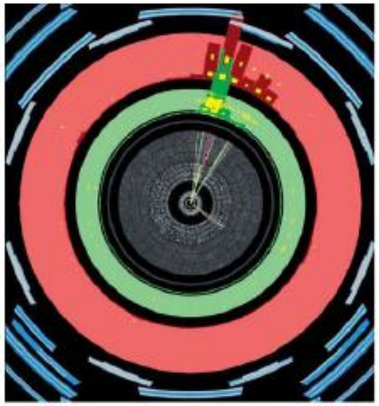


"shake it" direct detection

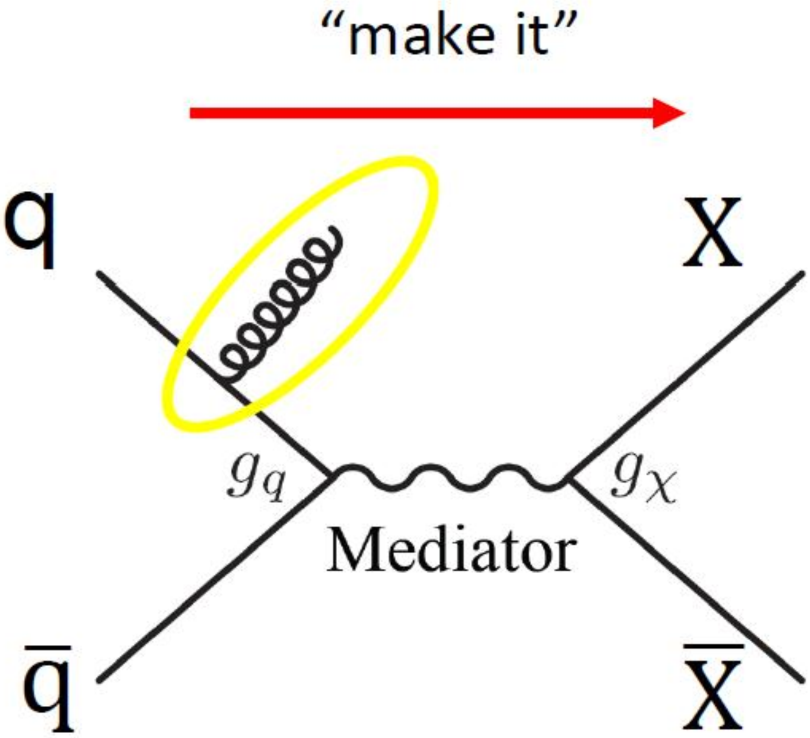


"make it": Collider Production

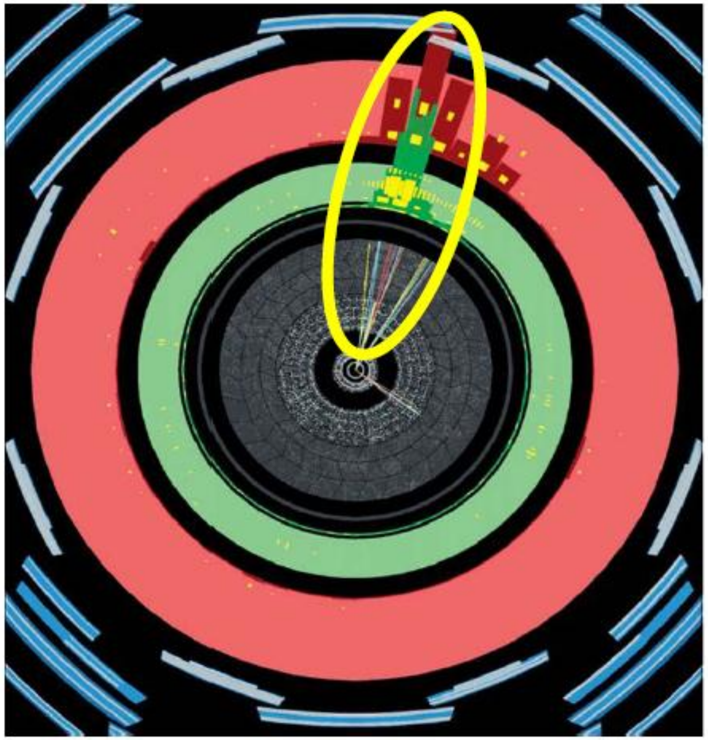




Dark Matter serches at Colliders

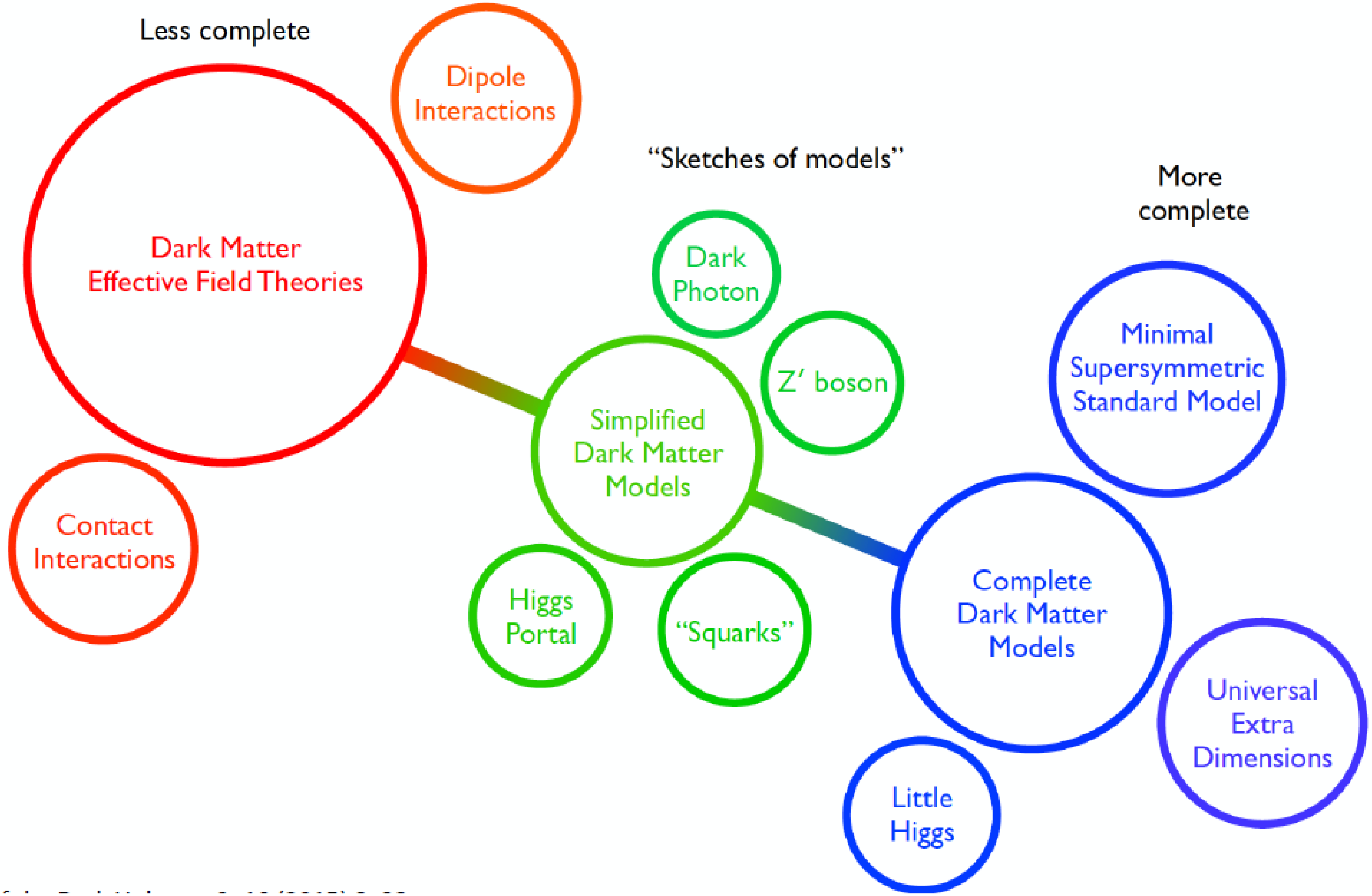


g_q and g_χ coupling strengths



Empty detector + something

Dark Matter theory space



Less complete

Dipole Interactions

Dark Matter Effective Field Theories

Contact Interactions

"Sketches of models"

Dark Photon

Z′ boson

Simplified Dark Matter Models

Higgs Portal

"Squarks"

More complete

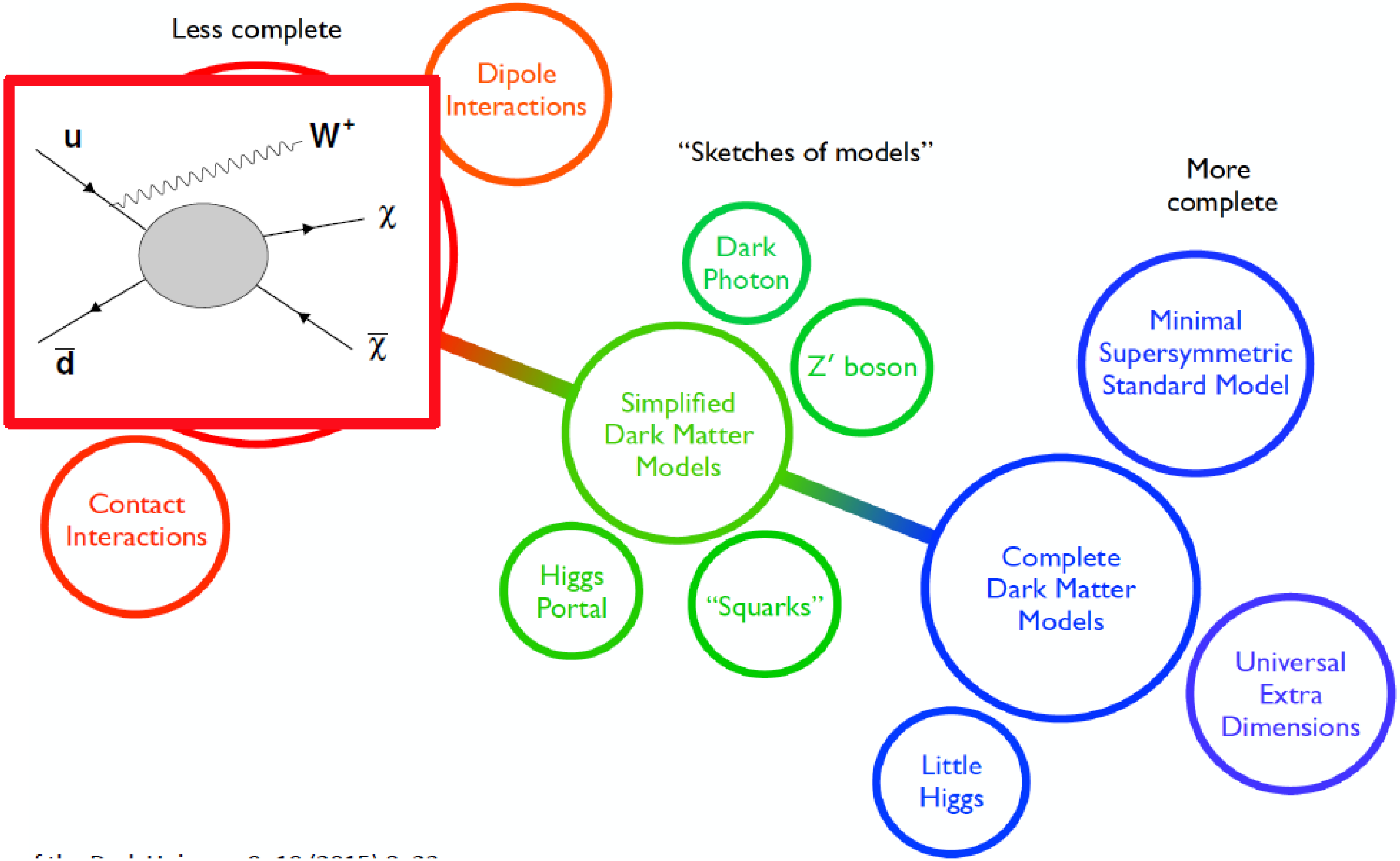
Minimal Supersymmetric Standard Model

Complete Dark Matter Models

Universal Extra Dimensions

Little Higgs

Dark Matter theory space



Less complete

Dipole Interactions

Contact Interactions

"Sketches of models"

Simplified Dark Matter Models

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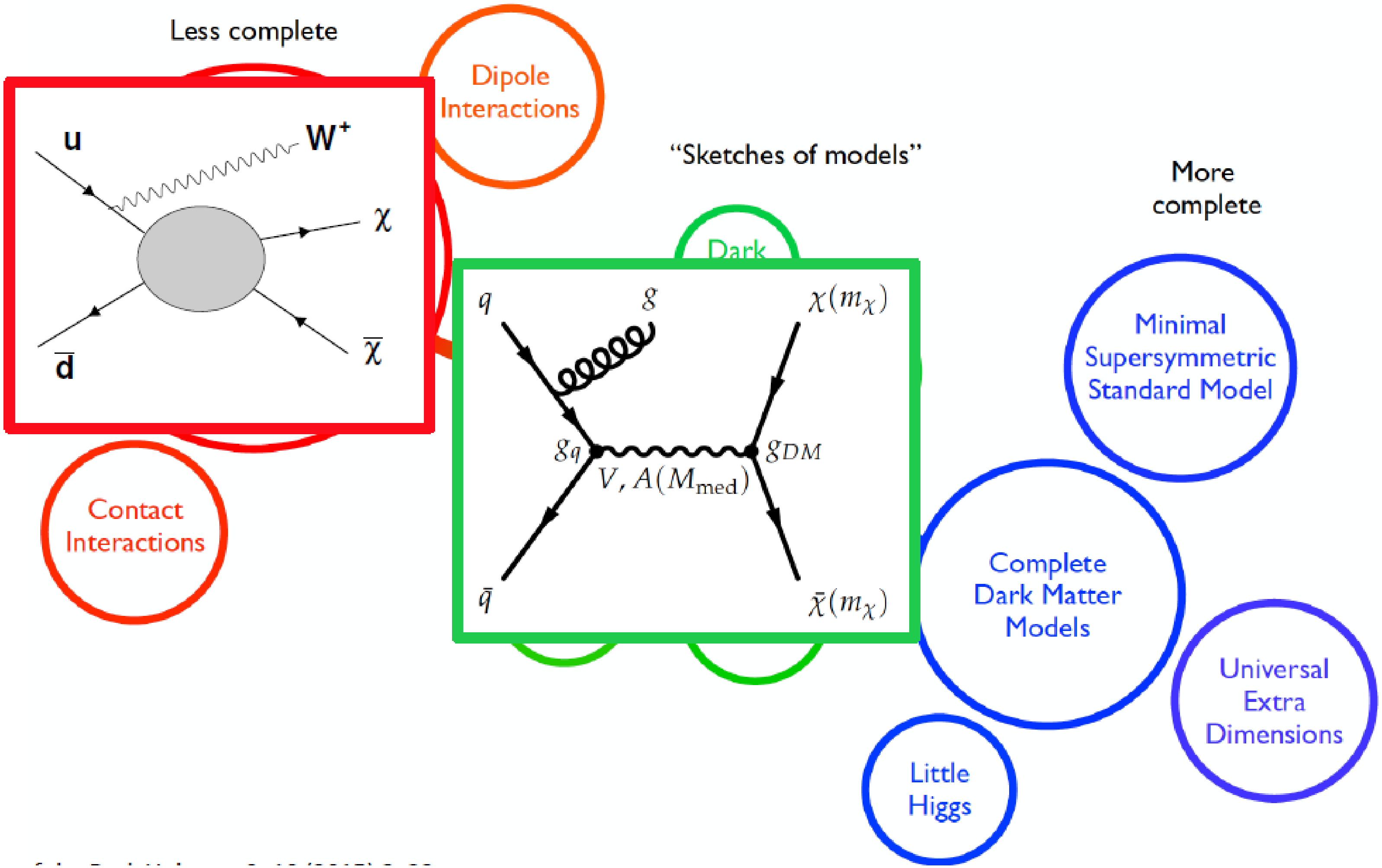

Less complete

Dipole Interactions

Contact Interactions

"Sketches of models"

Dark

More complete

Minimal Supersymmetric Standard Model

Complete Dark Matter Models

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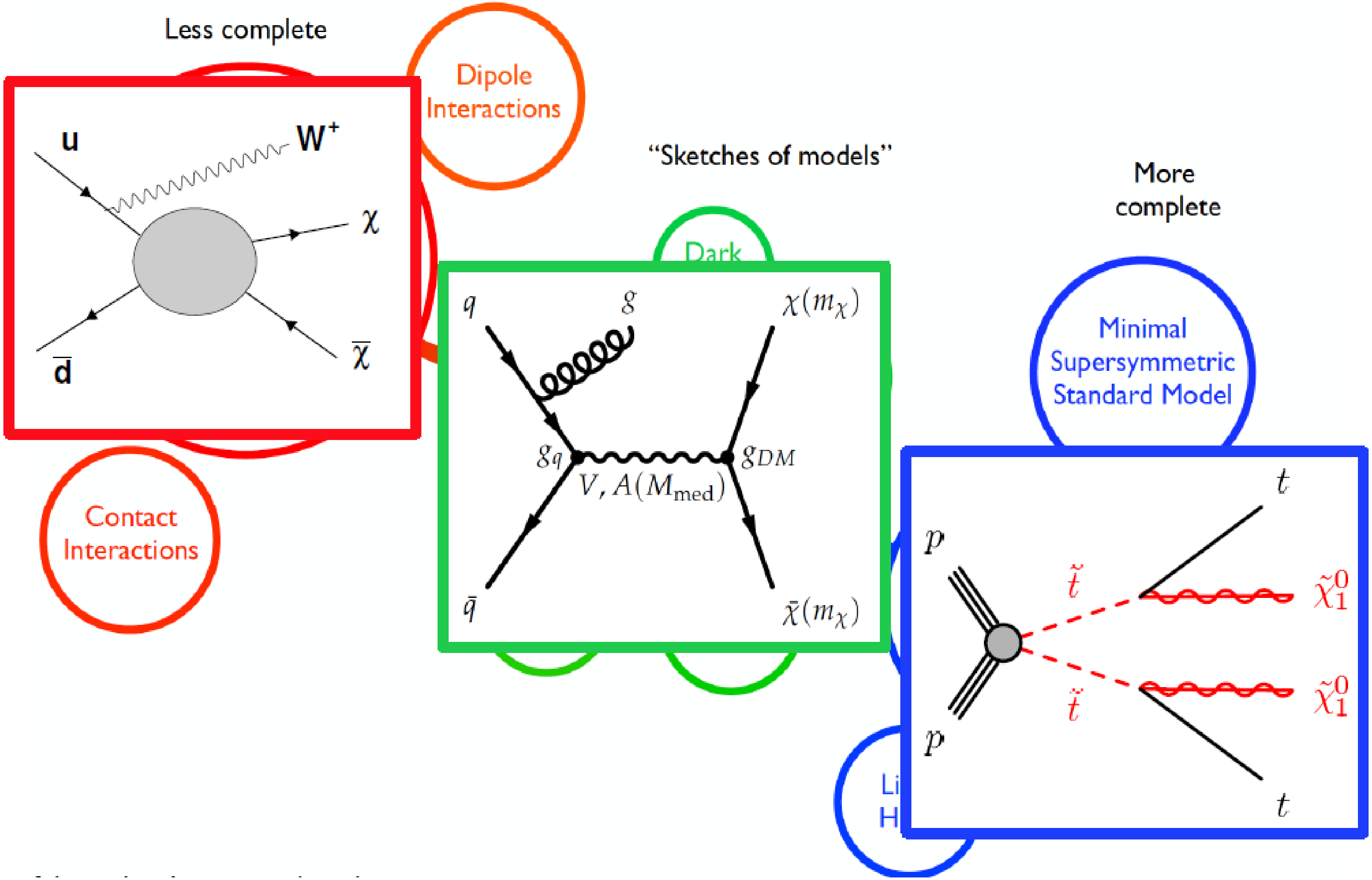
Dark Matter theory space



Less complete

Dipole Interactions

"Sketches of models"

More complete

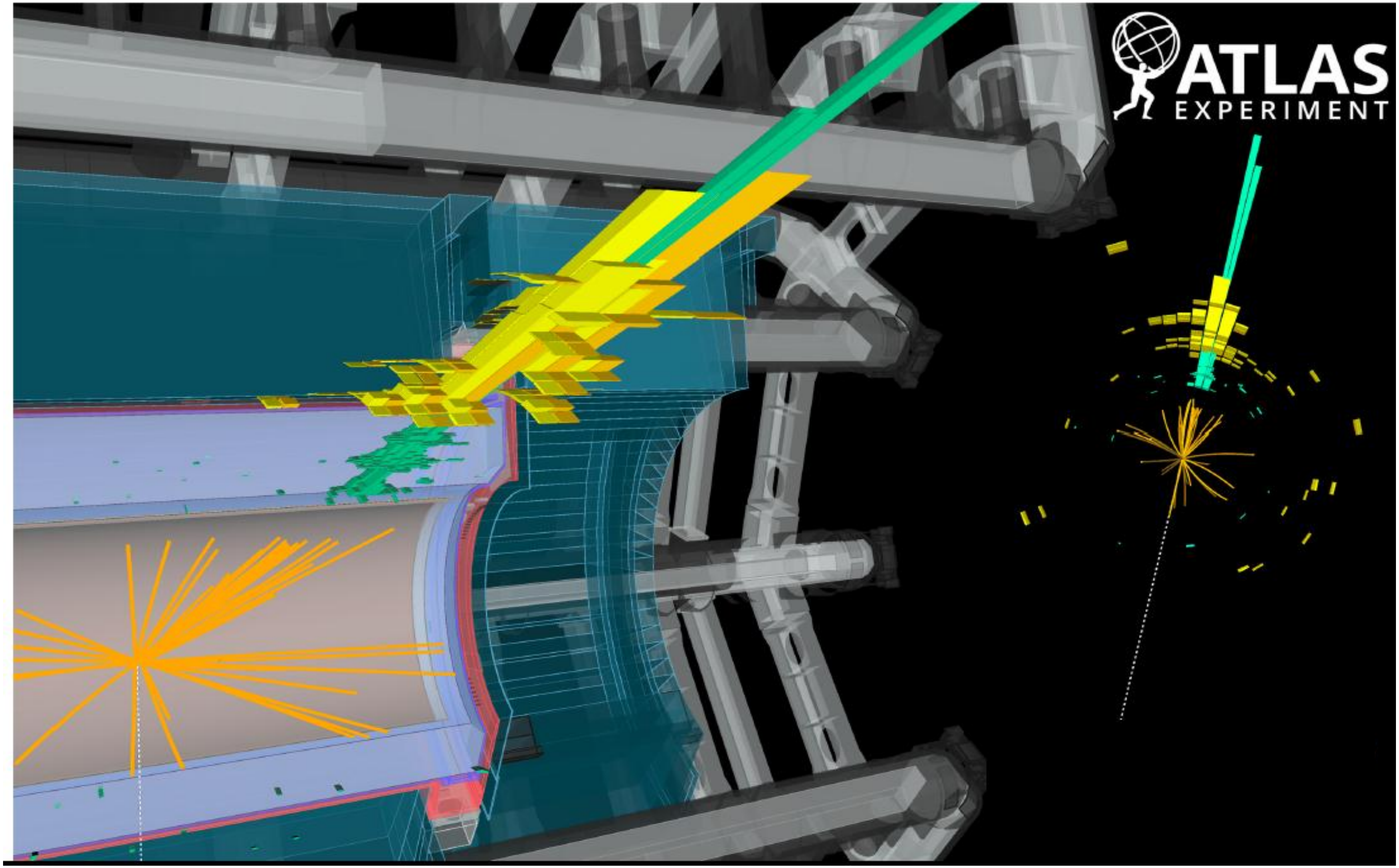
Contact Interactions

Dark

Minimal Supersymmetric Standard Model

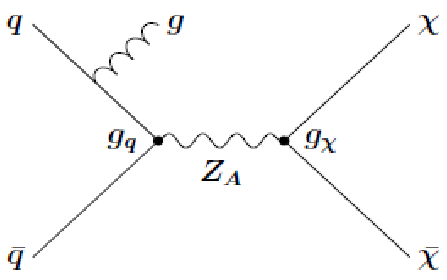
Li
H

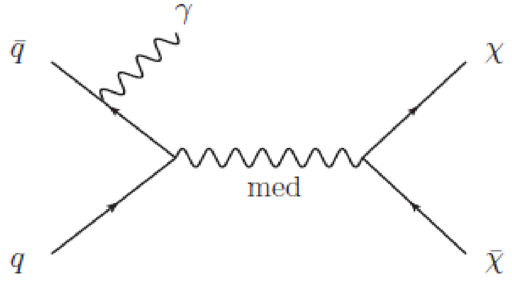
Searches for DM with (E_T^{miss} +X) Signatures

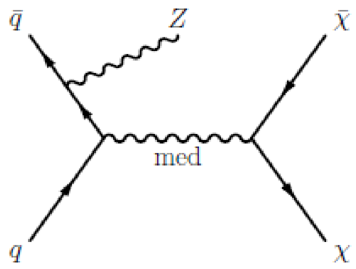


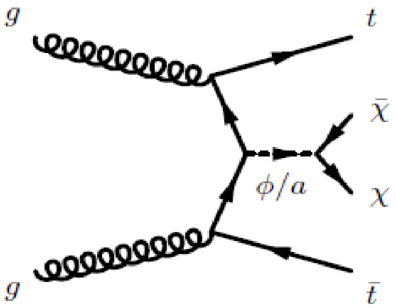
(E_T^{miss} +X) or Mono-X Signatures

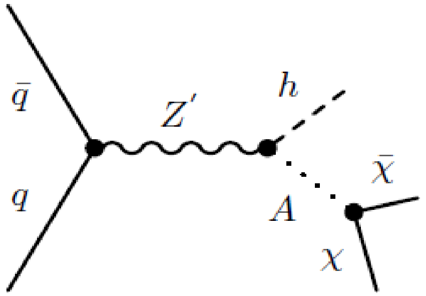
SM-DM mediator decays to DM pairs $\chi\bar{\chi}$ when $M_{\rm med}/2 > m_\chi$. DM escapes detection $\Rightarrow E_T^{\rm miss} + X$ signature where X = SM particles that tag the event, $X = {\rm jet}, \gamma, V, t, b, h \ldots$







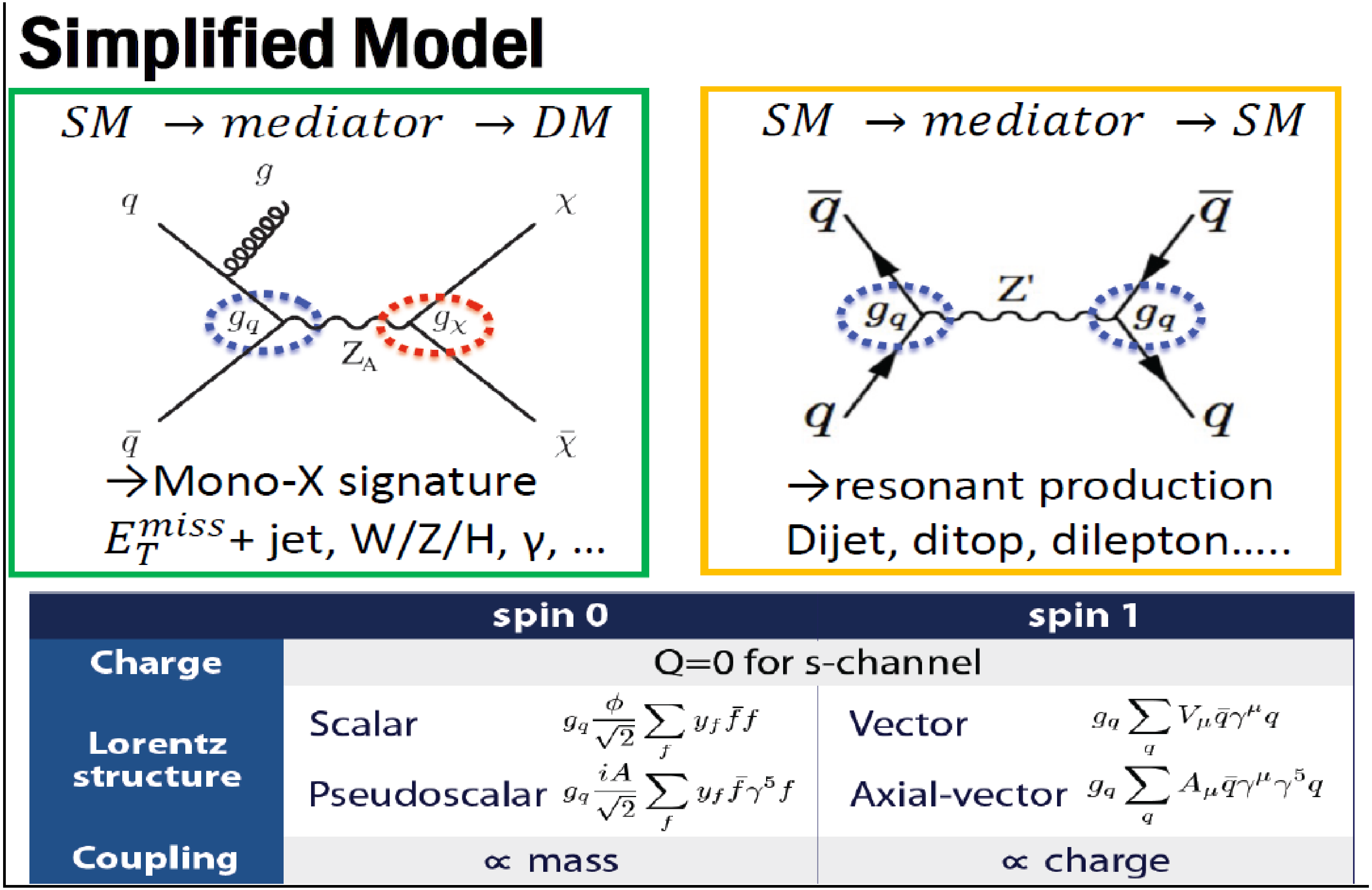




Mediators: vector, axial-vector, scalar, pseudoscalar

Parameters: $m_{\rm med}, m_\chi, g_q, g_\chi$

Simplified Model



Simplified Model

$SM \rightarrow mediator \rightarrow DM$

→Mono-X signature

E_T^{miss} + jet, W/Z/H, γ, ...

$SM \rightarrow mediator \rightarrow SM$

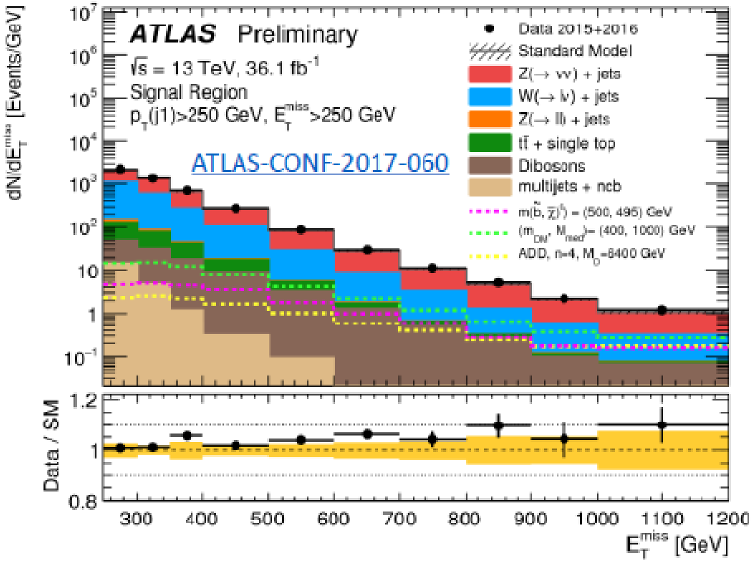
→resonant production

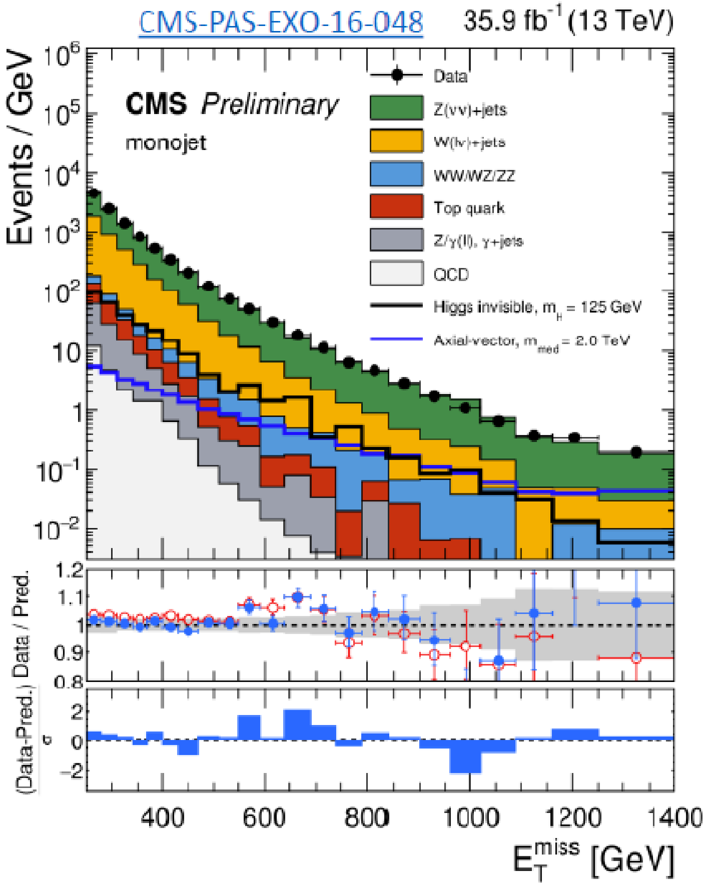
Dijet, ditop, dilepton.....

	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

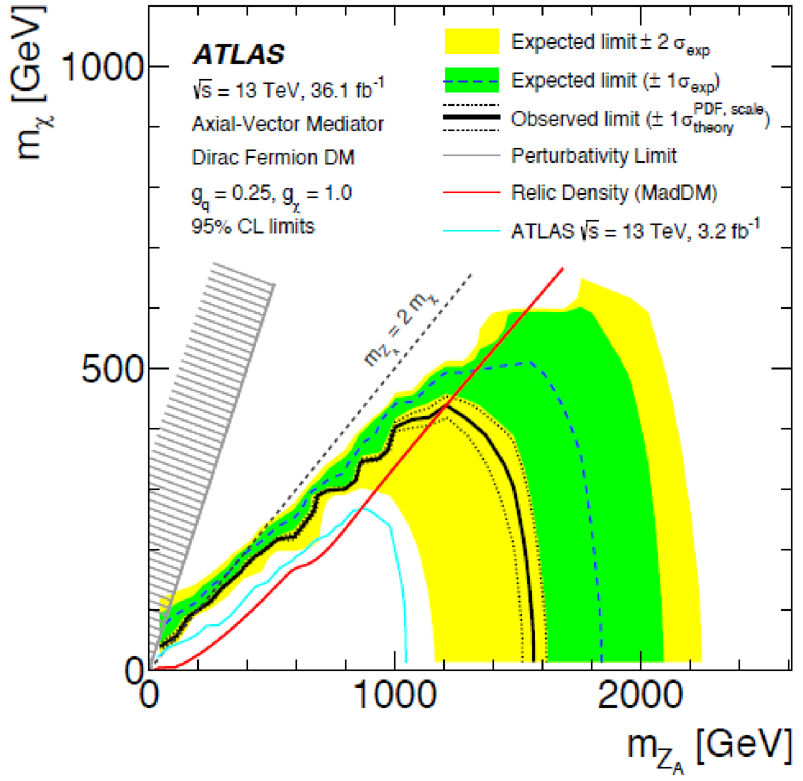
- $E_T^{miss} > 250$ GeV, $\Delta\varphi(\mathrm{jet}, p_T^{miss}) > 0.4$
- Jet $p_T > 250$ GeV, $|\eta| < 2.4$
- $N_{jets} \leq 4$

CMS

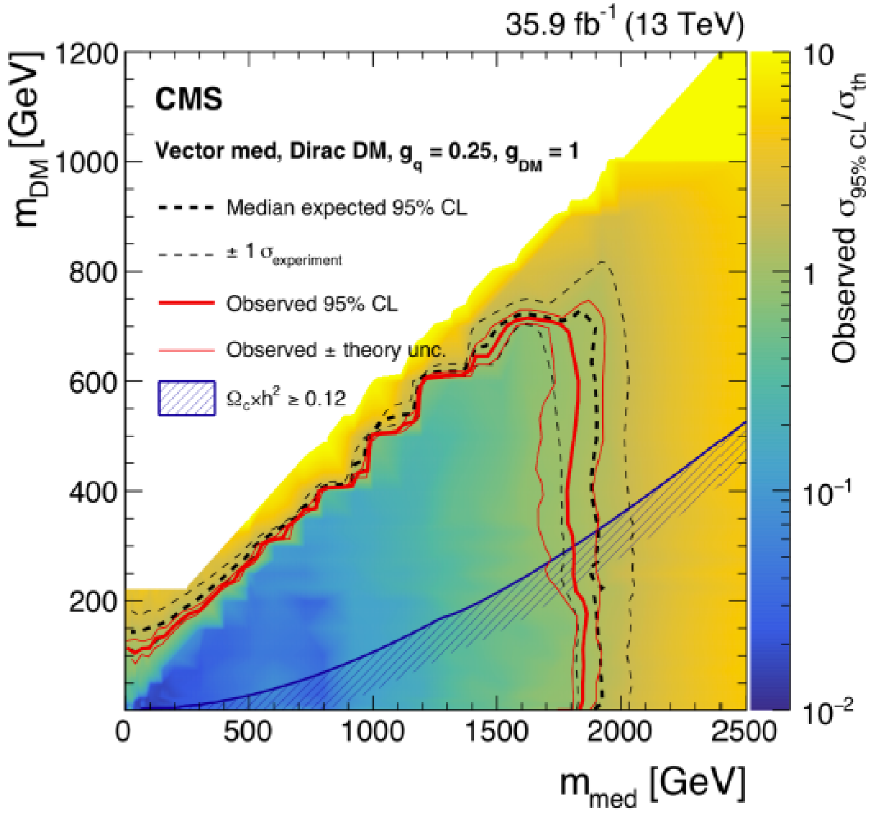
- $E_T^{miss} > 250$ GeV
- Jet $p_T > 100$ GeV, $|\eta| < 2.5$

Mono-X searches

Axial-Vector Mediator



Vector Mediator

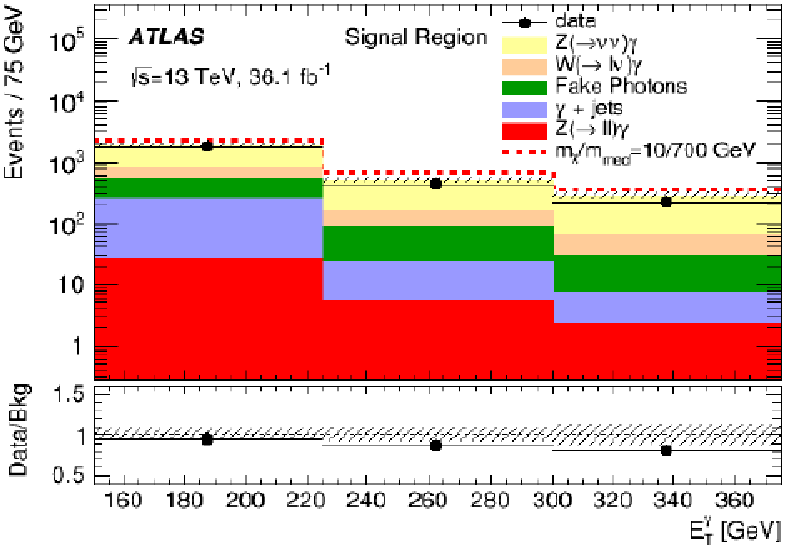


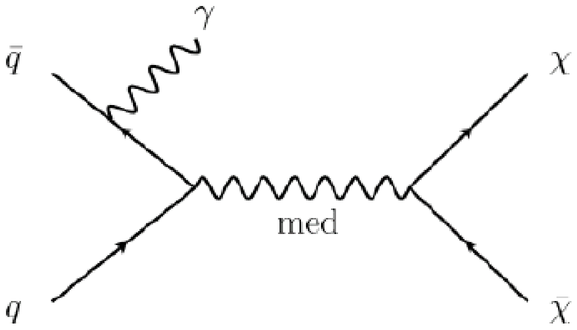
For couplings $g_q = 0.25$, $g_\chi = 1.0$, axial-vector and vector mediators excluded up to 1.8 TeV (1.55 TeV) by CMS (ATLAS) for $m_\chi \sim 1$ GeV.

JHEP 01 (2018) 126
arXiv:1712.02345

Mono-X searches

Mono-photon



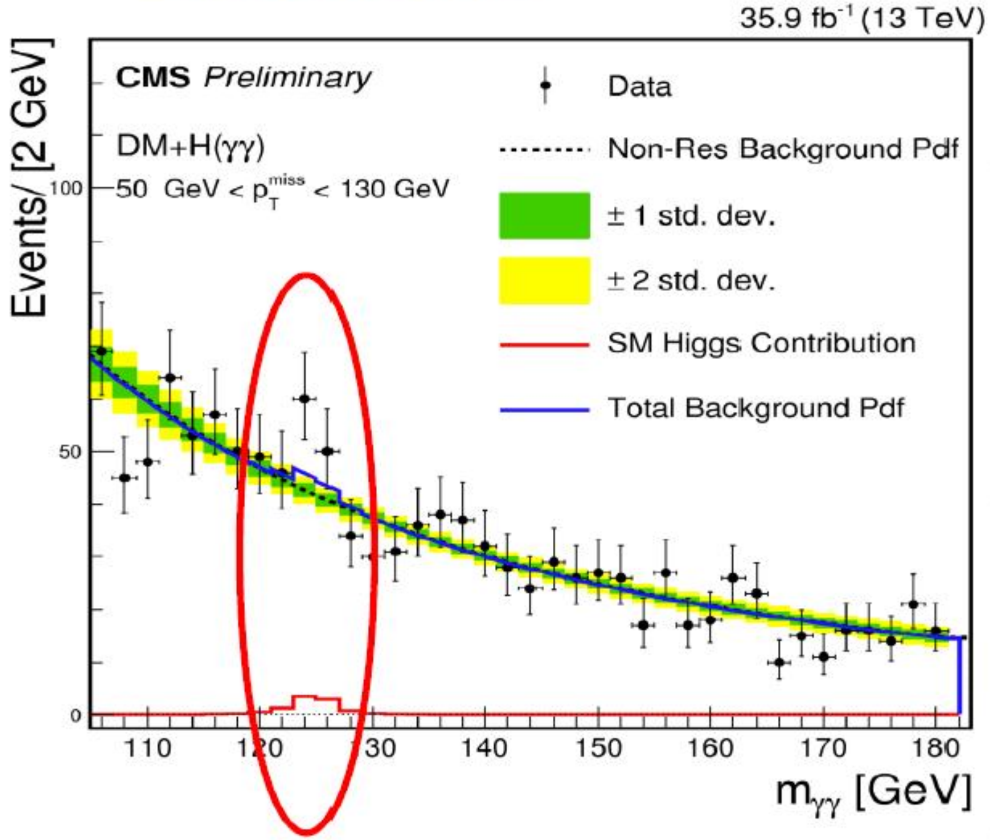


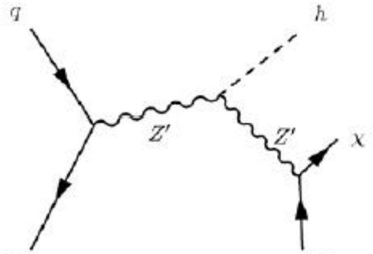
- Photon $E_T > 150$ GeV, $|\eta| < 2.37$
- $E_T^{miss}/\sqrt{\sum E_T} > 8.5\ \text{GeV}^{1/2}$
- $\Delta\varphi(\text{photon}, E_T^{miss}) > 0.4$
- $N_{jets}(p_T > 30\ \text{GeV}, |\eta| < 4.5) \leq 1$

Mono-X searches

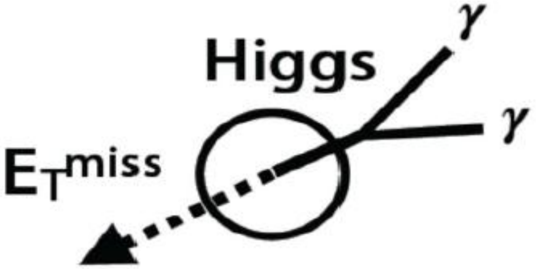
Mono-Higgs

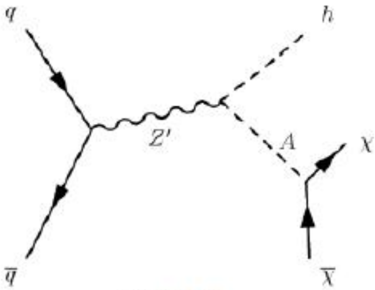
CMS-PAS-EXO-16-054





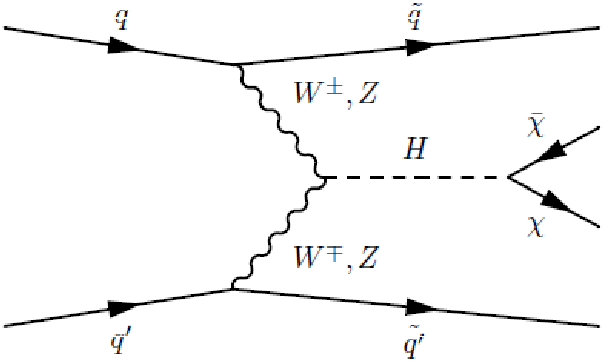
Baryonic Z' model
Non resonant





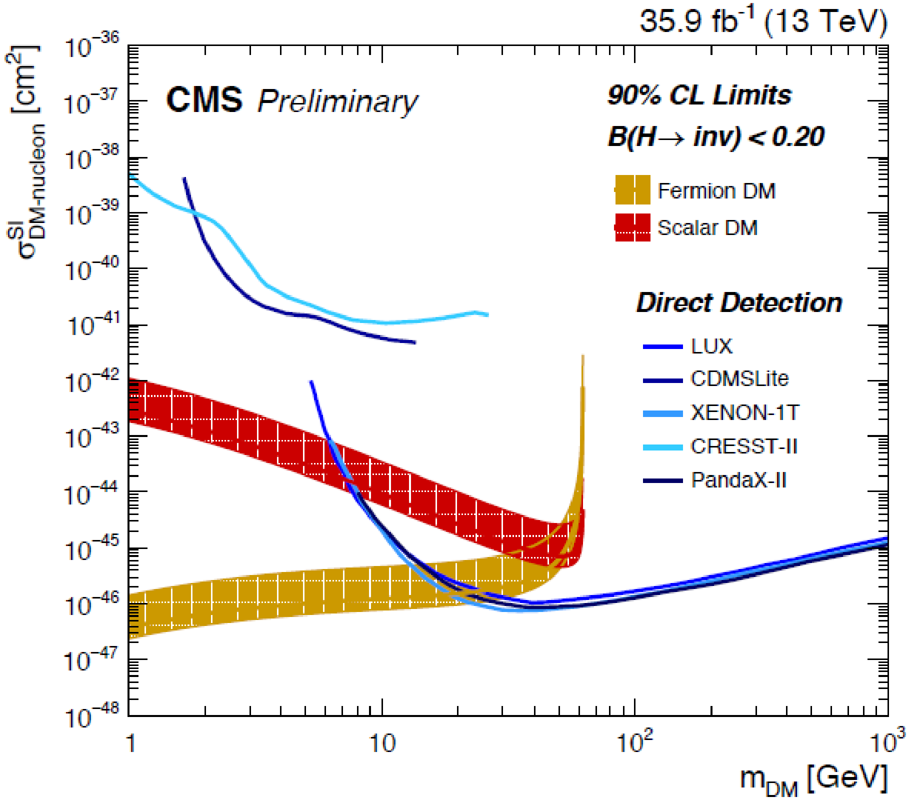
2HDM

H-> invisible: Comaprison with DD



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

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

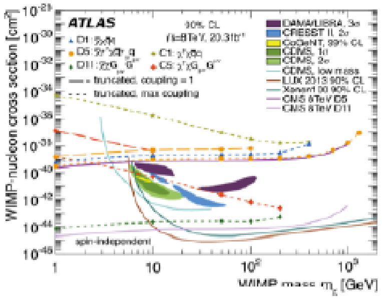


CMS-PAS-HIG-17-023 (14 March 2018)

Mono-Mania!!

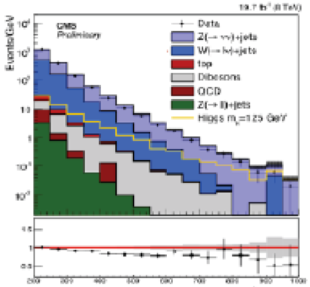
- Hundreds of phenomenology papers
- Thousands of citations of collider DM
- “ISR tagging” established technique for all new particle searches (not just DM)

Mono-Mania!!



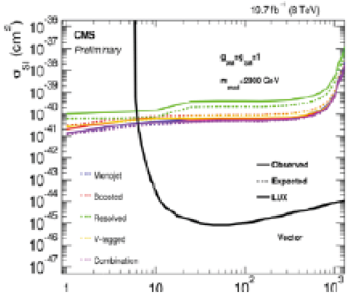
ATLAS Monojet

EPJC (2015) 75:299



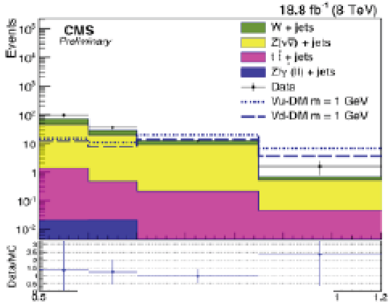
CMS j/V (mono/dijet)

PAS-EXO-12-055



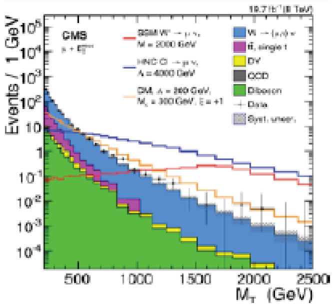
CMS j/V (mono/dijet)

PAS-EXO-12-055



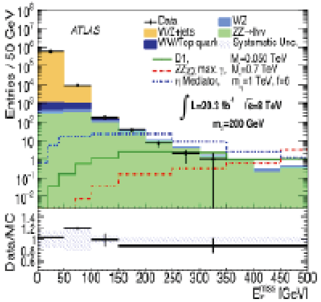
CMS Razor (dijet)

PAS-EXO-14-004



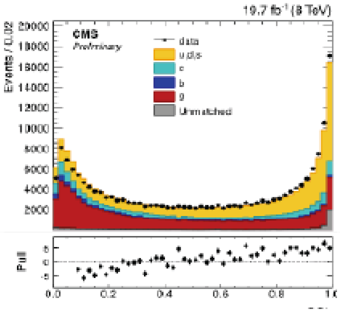
CMS, ATLAS MonoW

PRD 91, 092005, JHEP 09 (2014) 037 (2015)



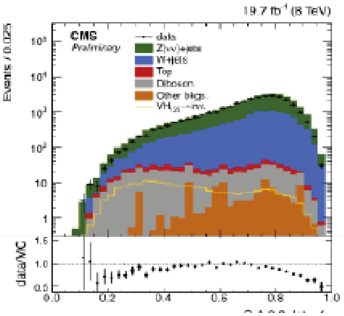
CMS, ATLAS MonoZ

EXO-12-054, PRD 90, 012004 (2014)



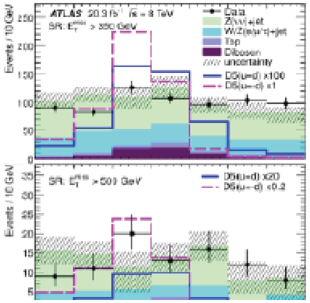
CMS MonoV (resolved)

PAS-EXO-12-005, PAS-JME-14-002



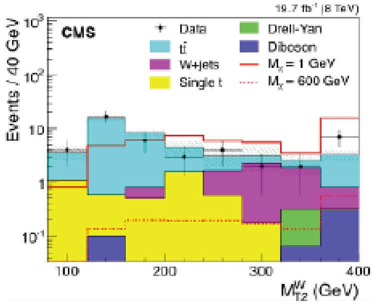
CMS MonoV (boosted)

EXO-12-005/JME-14-002



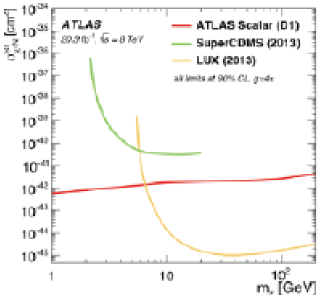
ATLAS MonoV (boosted)

ATLAS, PRL 112, 041802 (2014)



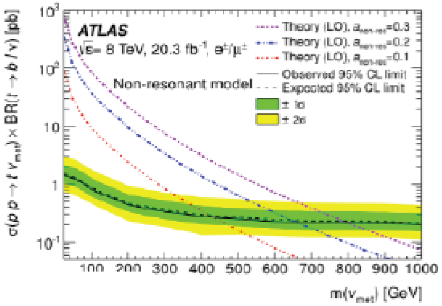
CMS TopPairs

CMS, JHEP 06 (2015) 121



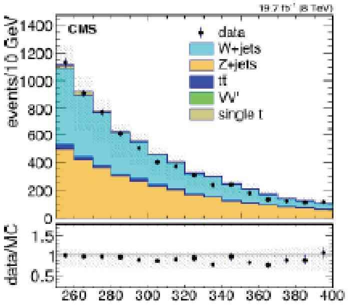
ATLAS TopPairs

ATLAS, EPJC (2015) 75:92



CMS MonoTop

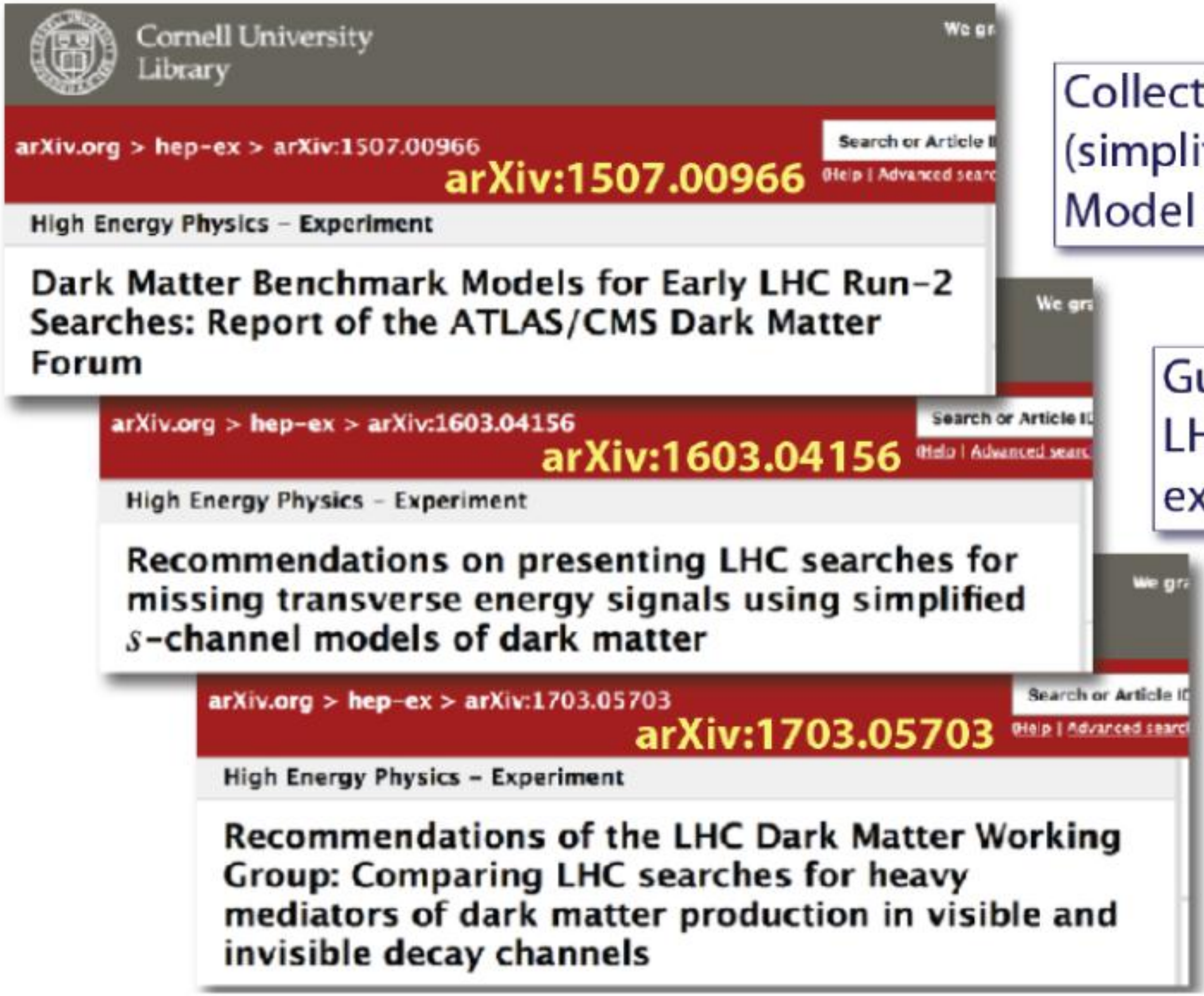
CMS, PRL 114 (2015) 101801



ATLAS MonoTop

ATLAS, JHEP 11 (2014) 118

LHC DM Working Group



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

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

arXiv.org > hep-ex > arXiv:1703.05703

arXiv:1703.05703

High Energy Physics – Experiment

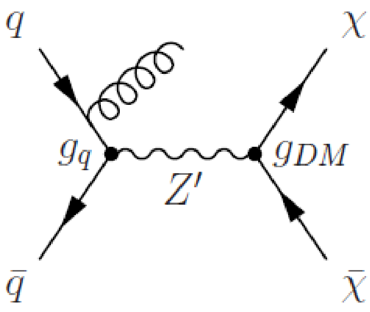
Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for heavy mediators of dark matter production in visible and invisible decay channels

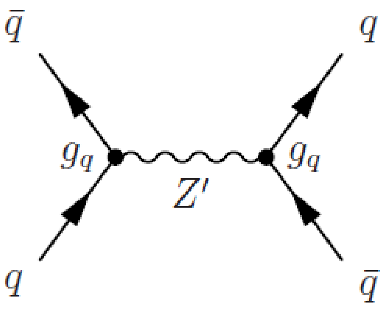
Collection of DM models (simplified models, EFT), Model implementation

Guidelines to compare LHC results with DD/ID experiments

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

LHC is a mediator machine

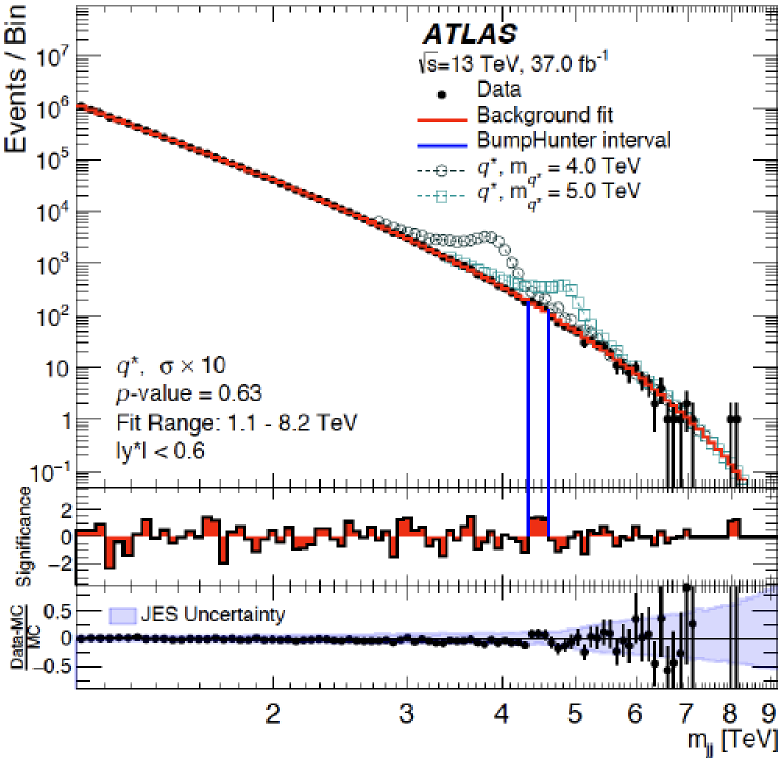




Signature: 2 high p_{T} jets, same as search for leptophobic Z'.

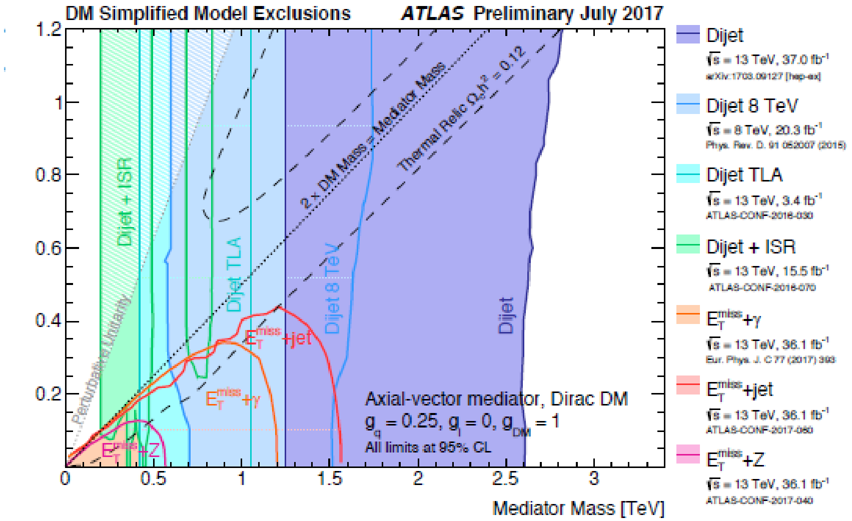
m_{jj} is the discriminant, search for bump on a smooth, falling background.

Background modeled by a parameterized function.

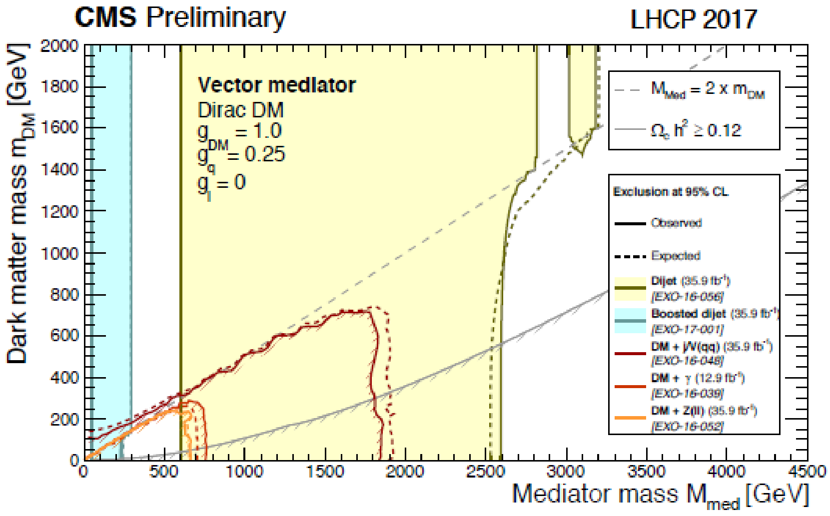


Limits on DM mass vs Mediator mass

Axial-Vector Mediator



Vector Mediator



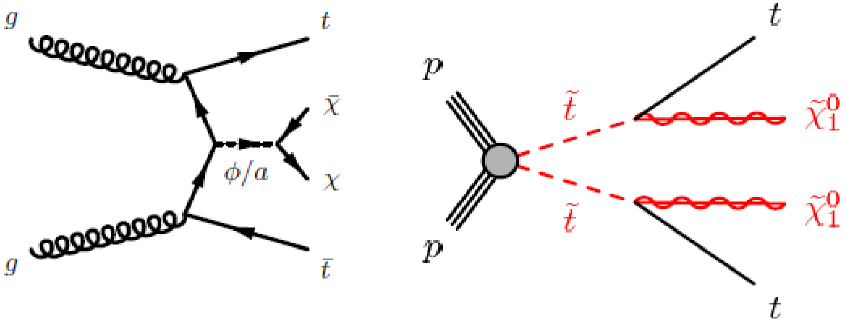
Couplings: $g_{\text{DM}} = 1,\ g_q = 0.25,\ g_l = 0$ (leptophobic)

Dijet searches significantly extend DM reach, particularly for $m_{\text{DM}} > M_{\text{med}}/2$. 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

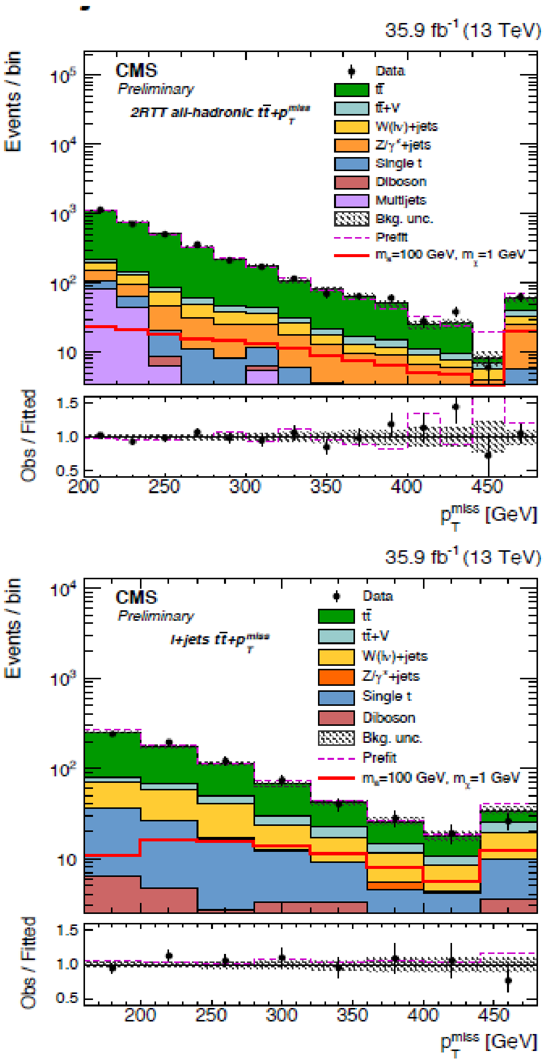
For spin-0 mediator ϕ or a,
MFV $\Rightarrow$ Yukawa couplings
ϕ and a couple strongly to t or b



$(t\bar{t} + \chi\bar{\chi})$ 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.

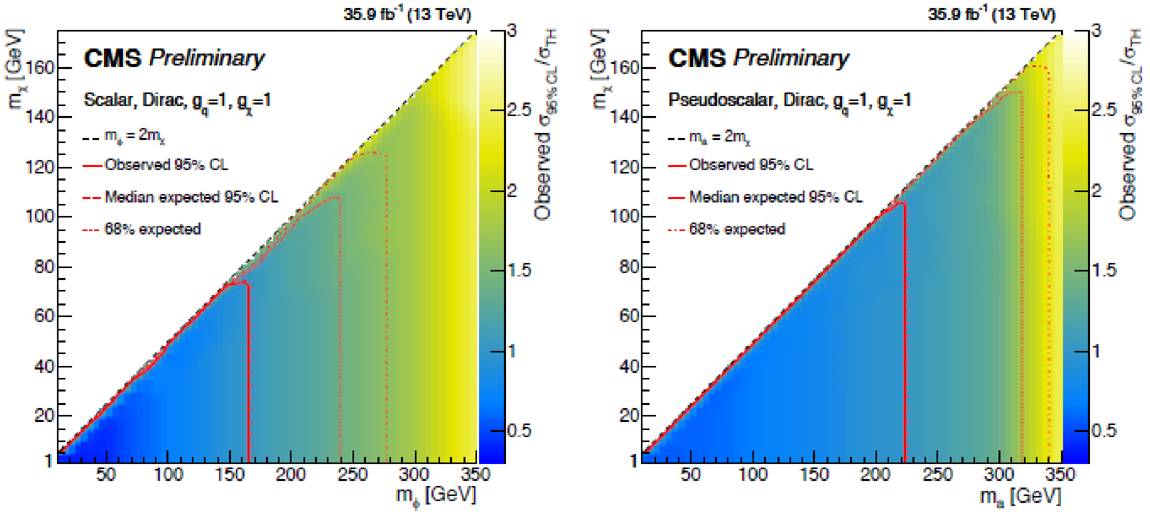


Search for DM + Heavy Flavor

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

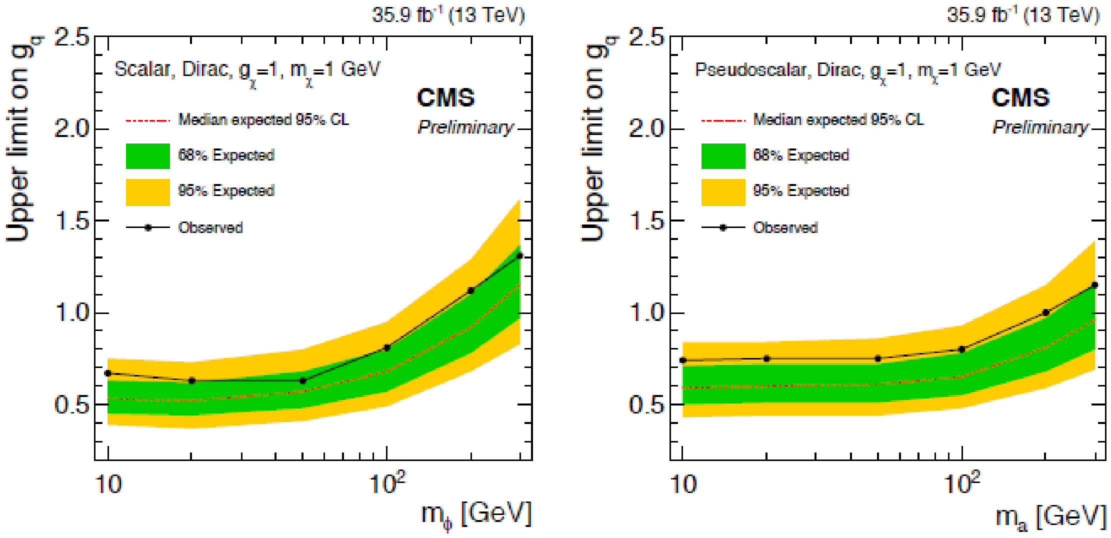
Scalar Mediator

Pseudoscalar Mediator



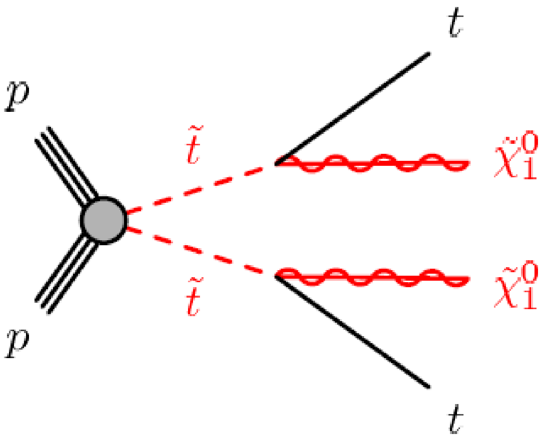
CMS-PAS-EXO-16-049 (3 April 2018)

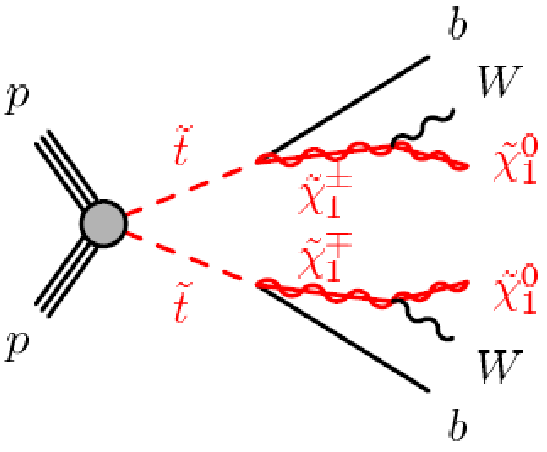
For $g_{\mathrm{DM}} = 1,\ m_\chi = 1$ GeV: limits on coupling of ϕ or a to SM quarks.

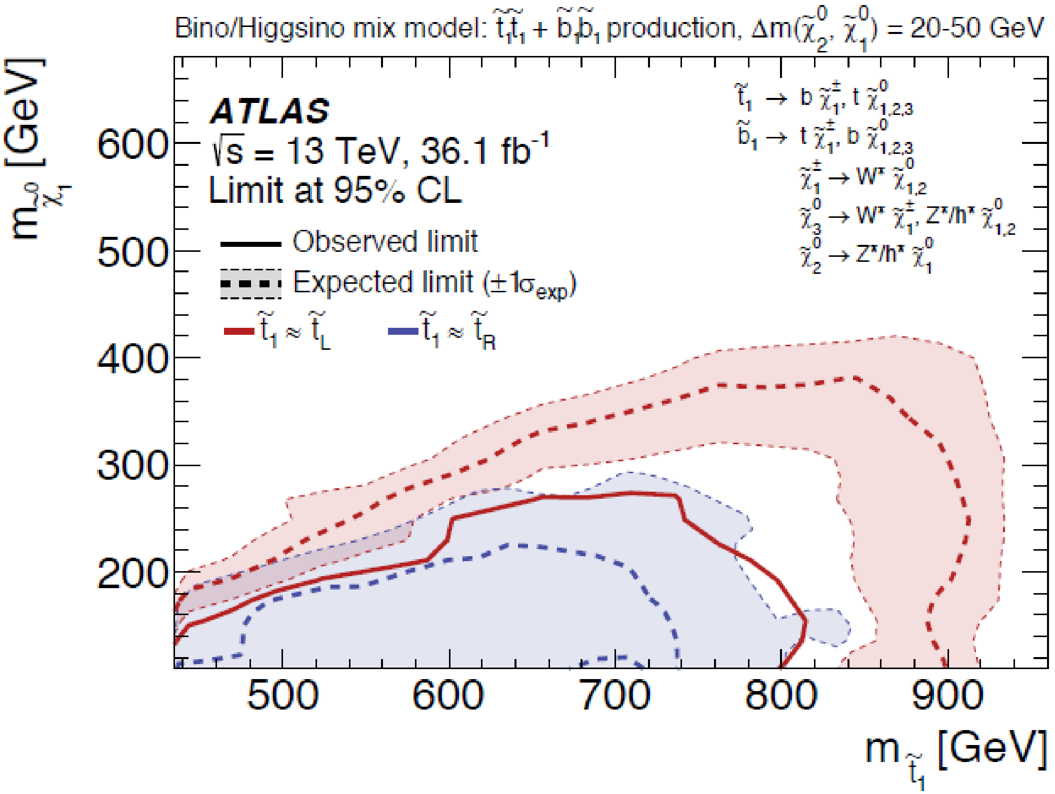


SUSY DM candidates

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.

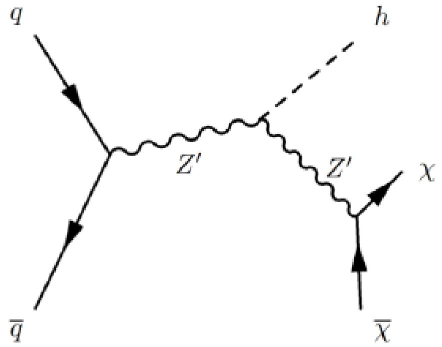






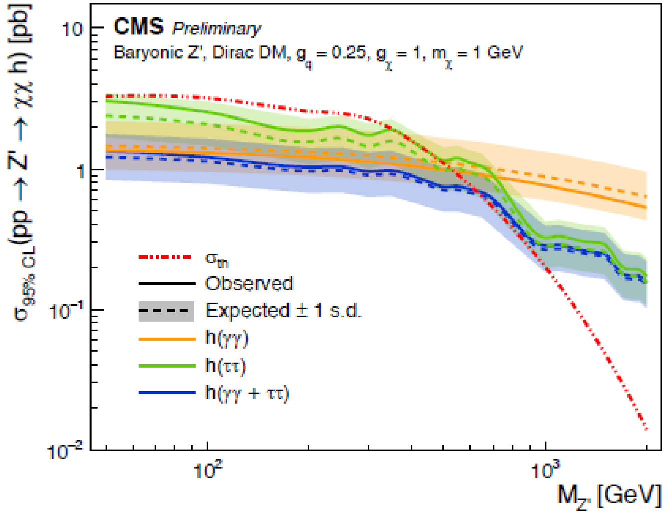
Search for DM + Higgs

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



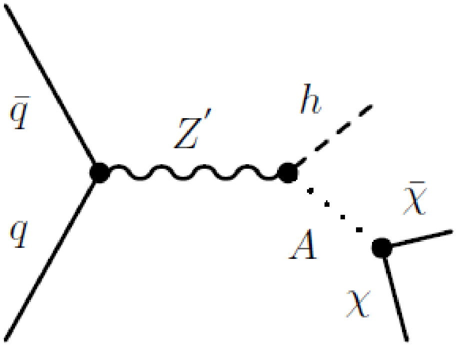
Baryonic Z' Model

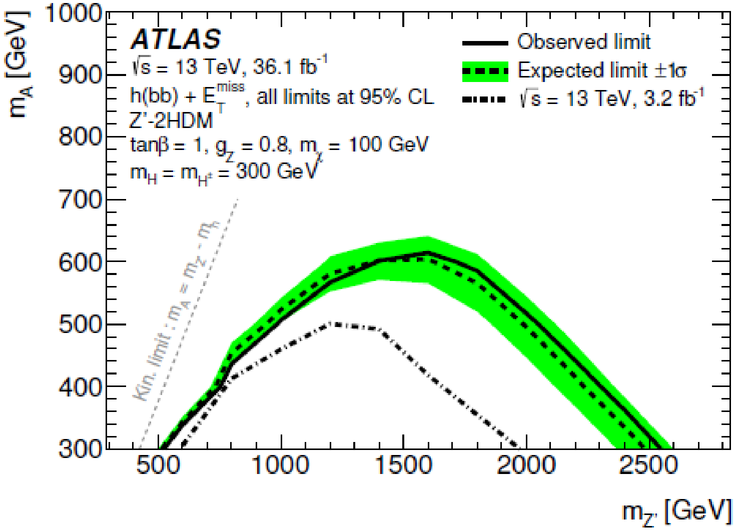
$h \to \gamma\gamma$ and $\tau^+\tau^-$
Z' excluded up to
815 GeV for low m_χ



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.



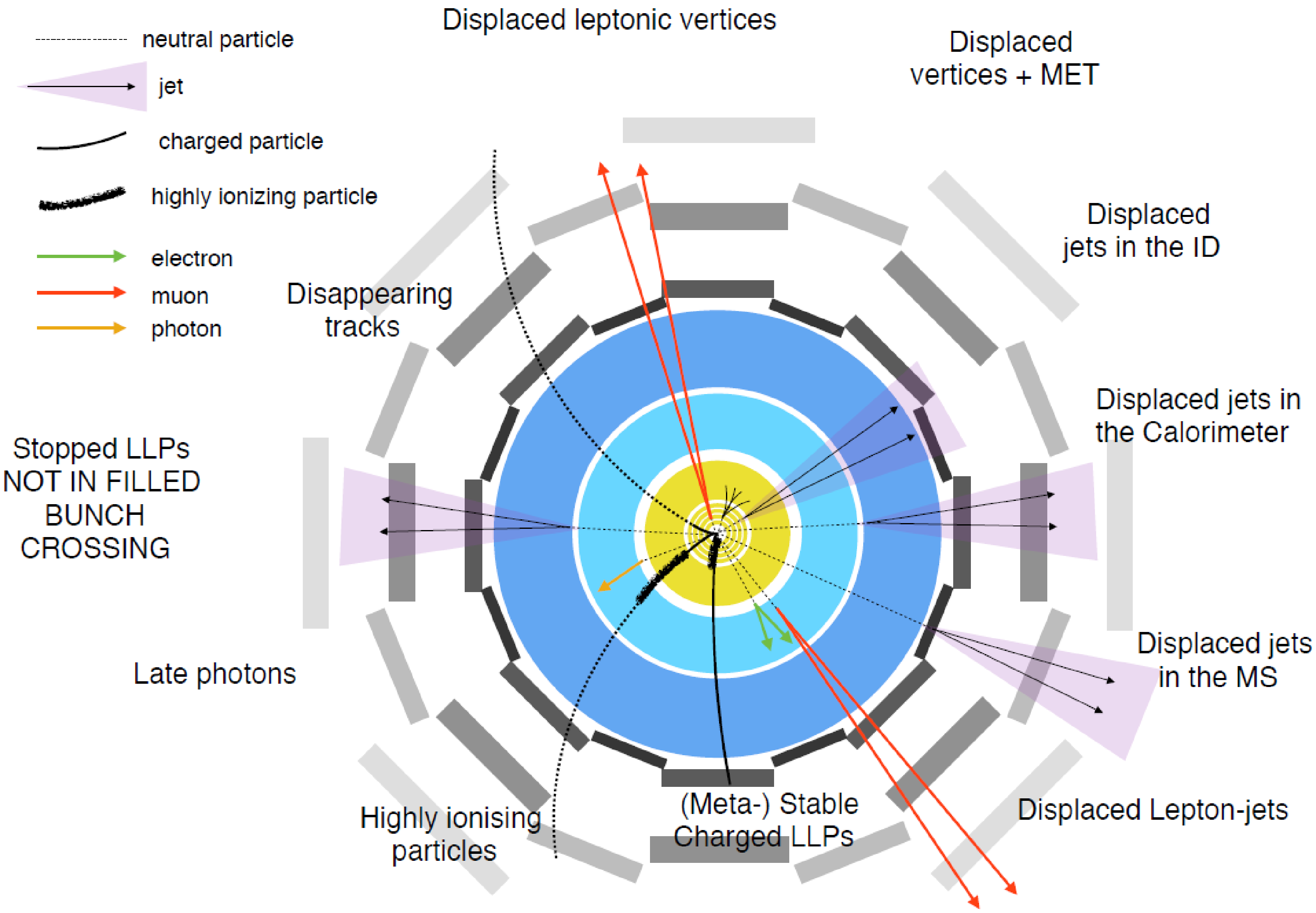


CMS PAS EXO-16-055 (13 March 2018)
PRL **119** (2017) 181804

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

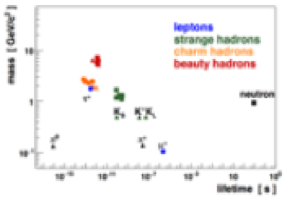


Unconventional signatures: challenges

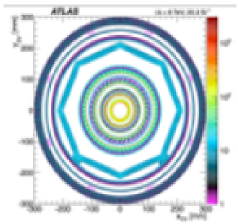
- Trigger: combination of hardware + software that must decide very quickly whether to save an event or lose it forever
  - First step in every search for LLPs: make sure that interesting events are saved!
    1. In associated production, trigger on prompt particle (Eg. WH prod. trigger on mu; ISR trigger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

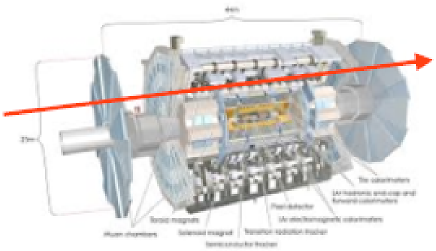
weak decays of heavy flavour



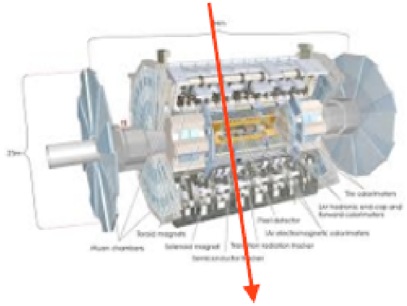
material interactions



beam halo muons



cosmic muons



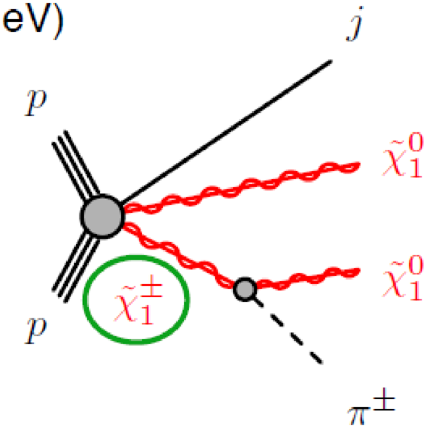
- Systematic uncertainties: can't use standard recommendations for object reconstruction nor trigger

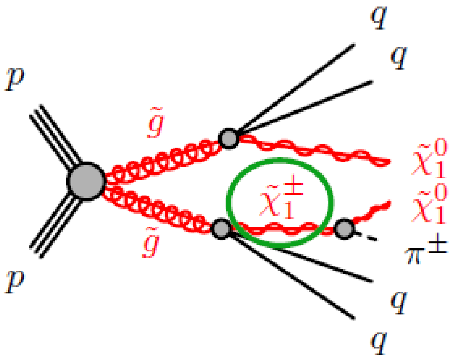
Unconventional signatures: disapearing tracks

LLP

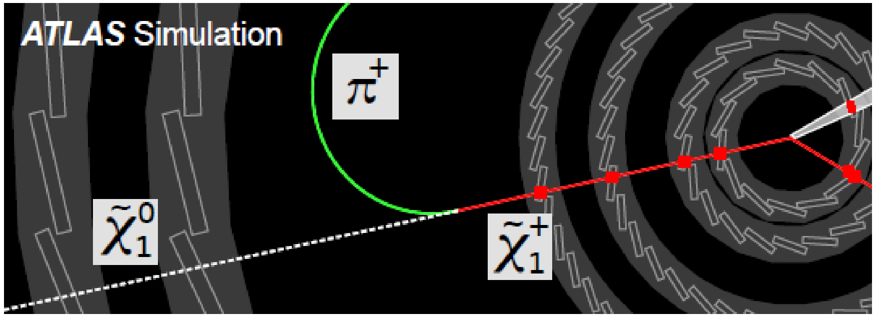
- Search for disappearing track + MET + jets
- Signature: Chargino track “disappears” when it decays, into MET
  - Low momentum pion track (~0.1 GeV) is hard to reconstruct
  - Challenge to identify the legitimate real tracklets (non-fake) using only a few measurement tracks

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





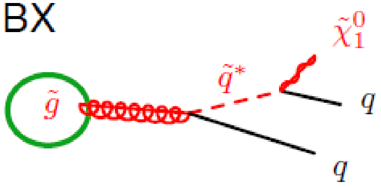
- Search sensitive to LLP lifetime of 10ps to 10 ns



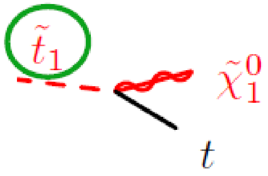
Unconventional signatures: stopped particles

- 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

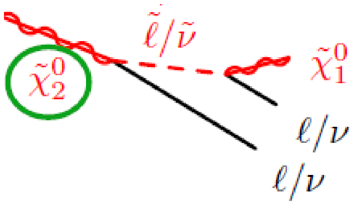


      b) top squark decay



    - 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 lQl = 2e decays into two same-sign muons (MCHAMP → $\mu^{\pm}\mu^{\pm}$)



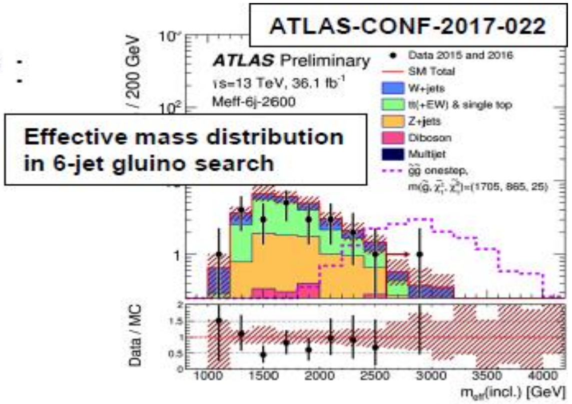
- Search sensitive to wide range of LLP lifetime: 10^{-5} to 10^{6} s

Summary (Exotic Searches)

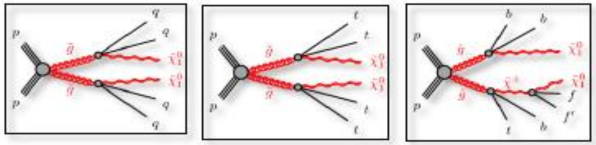
- Searches for Exotic searches
  - All major search channels reached 1 TeV scales
  - Quite a few at 10 TeV
  - New probe: Higgs boson → emerging field
- Dark Matter Searches are thriving at the LHC
- For vector and axial vector interactions
  - Dark Matter masses up 400 GeV – 700 GeV (mono-jet) excluded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

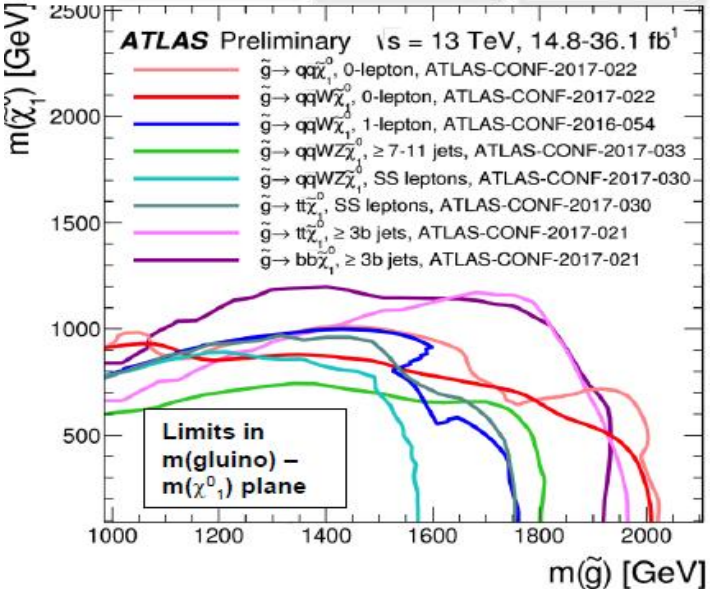
Searches for Supersymmetry

- 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

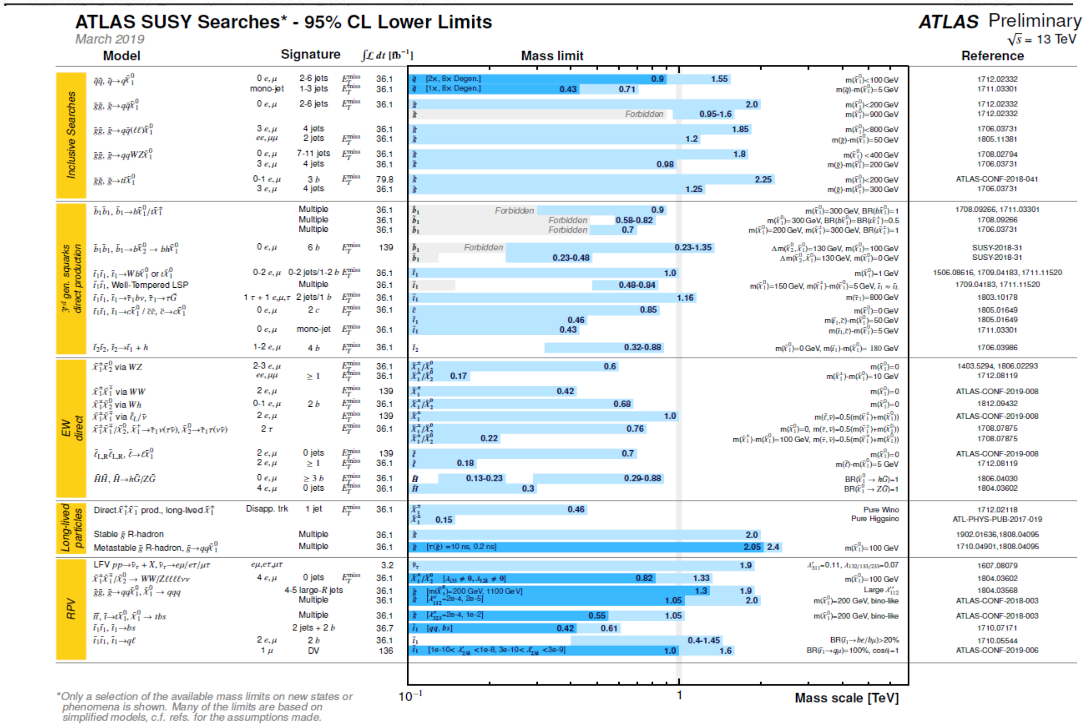

ATLAS-CONF-2017-022

Effective mass distribution in 6-jet gluino search





Limits in m(gluino) – m(χ^0_1) plane



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.