Direct Detection and Collider Searches of Dark Matter
Lecture 5

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Dark Matter School, Lund, Sept. 26-30, 2016

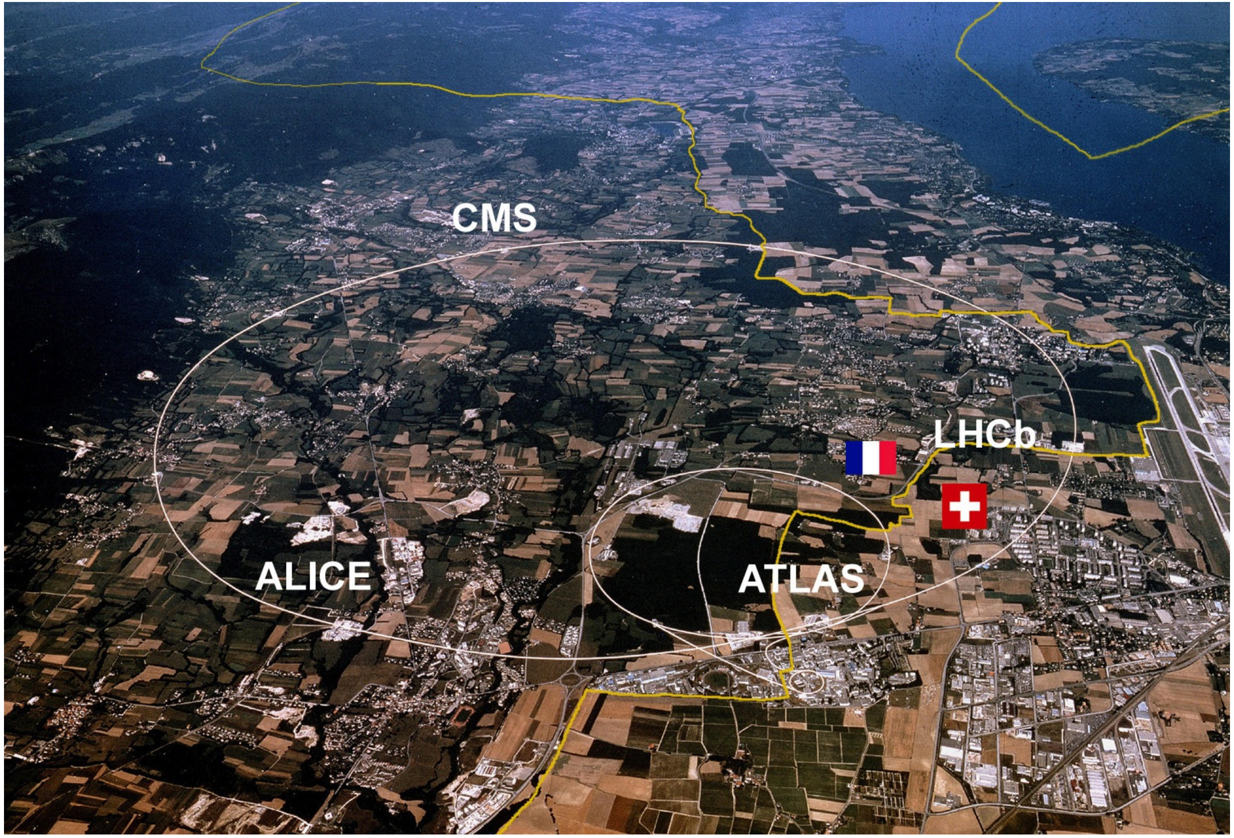
Content of Lecture 5

- Introduction to search strategies at the LHC
- Complete and simplified DM models, their searches at the LHC and complementarity with other DM searches

Subject is very vast, so idiosyncratic choice of subjects + citations disclaimer

The Large Hadron Collider (LHC)

- The most powerful particle accelerator in the world, 27 km around, 100 m below ground
- 1600 superconducting magnets operating at 1.9 K



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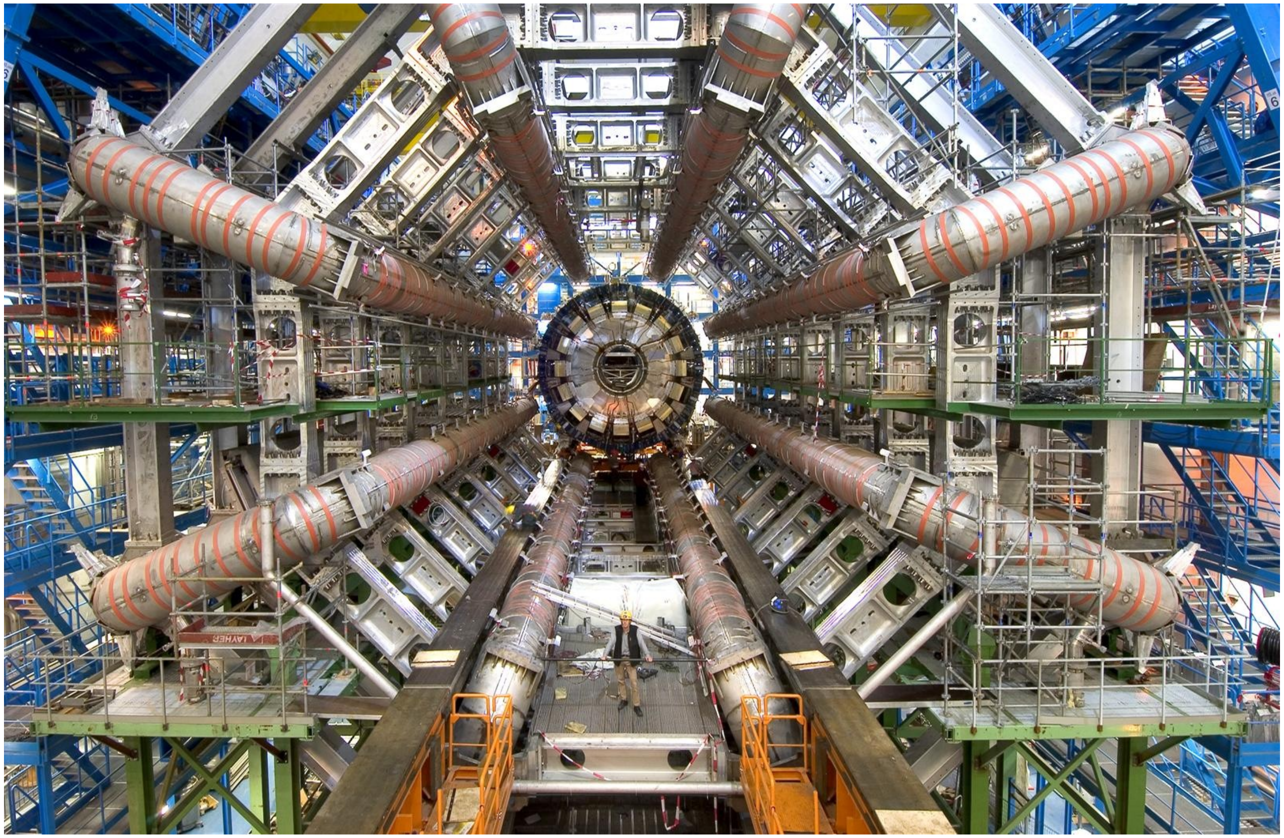
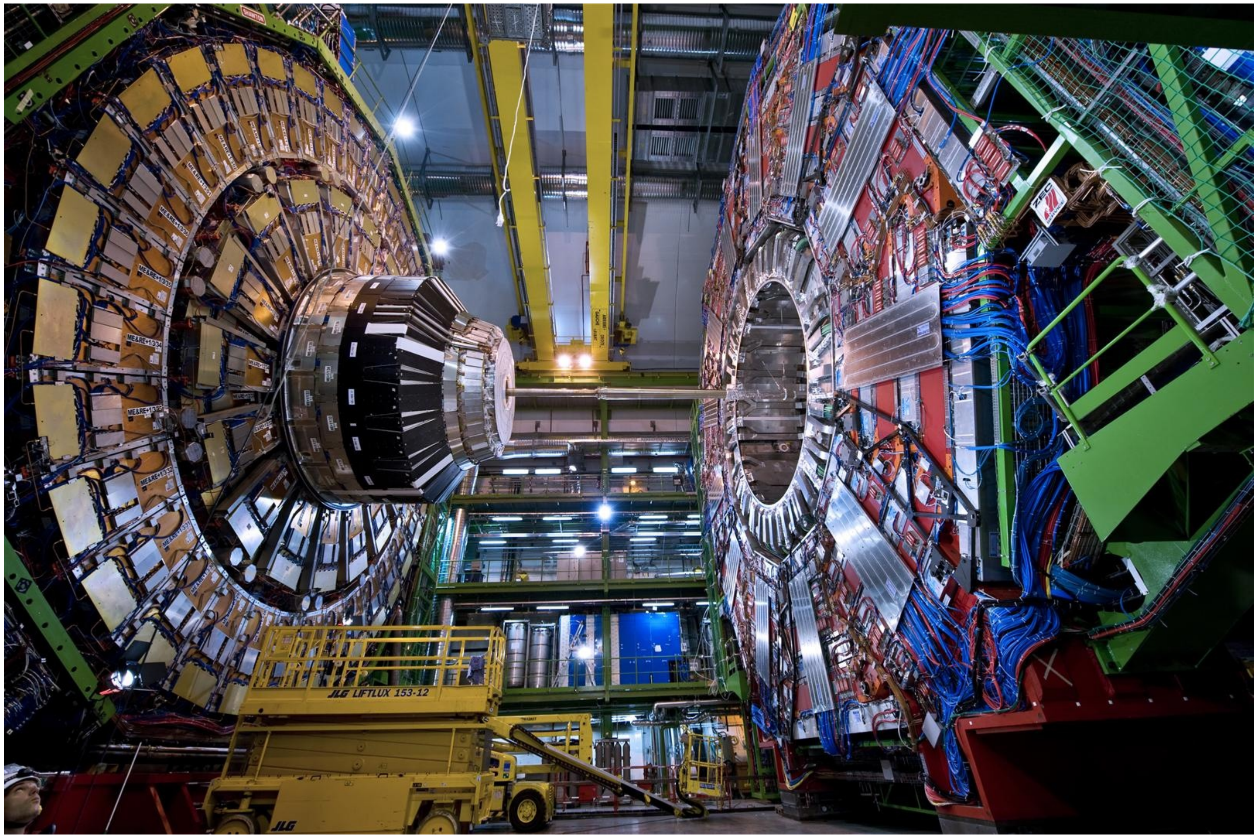
DM search strategies at the LHC

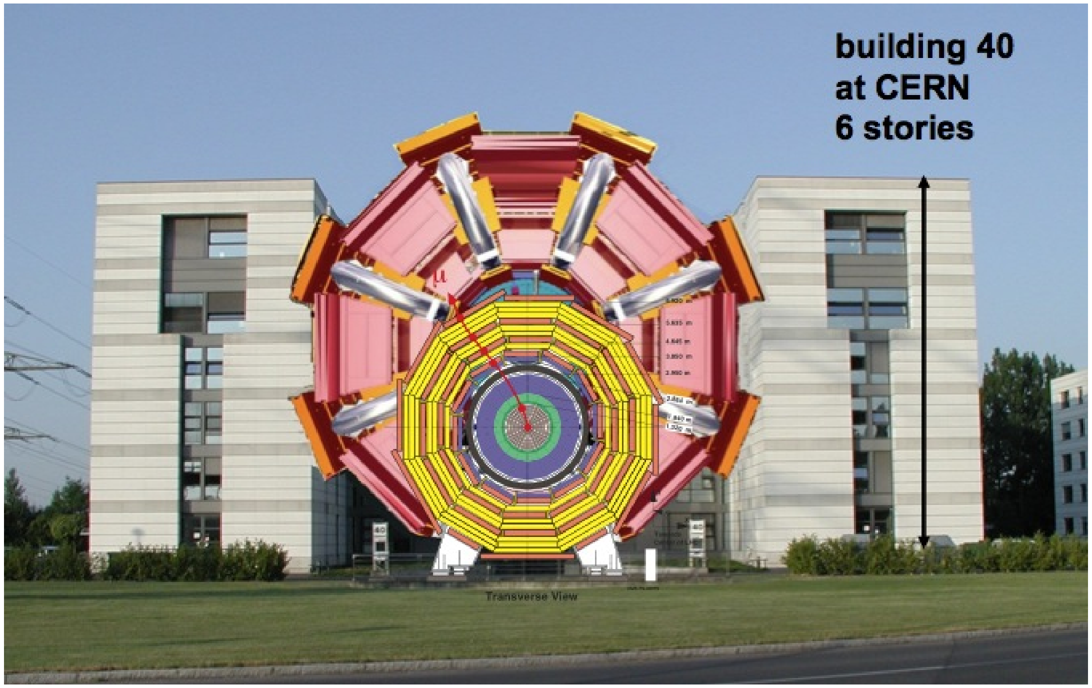
ATLAS



CMS

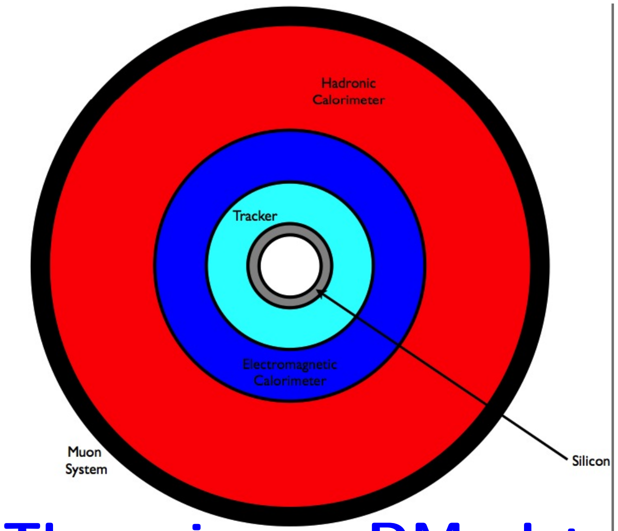


LHC multipurpose experiments: ATLAS and CMS



Are very large and very complicated detectors!!

Theorist version of an LHC detector



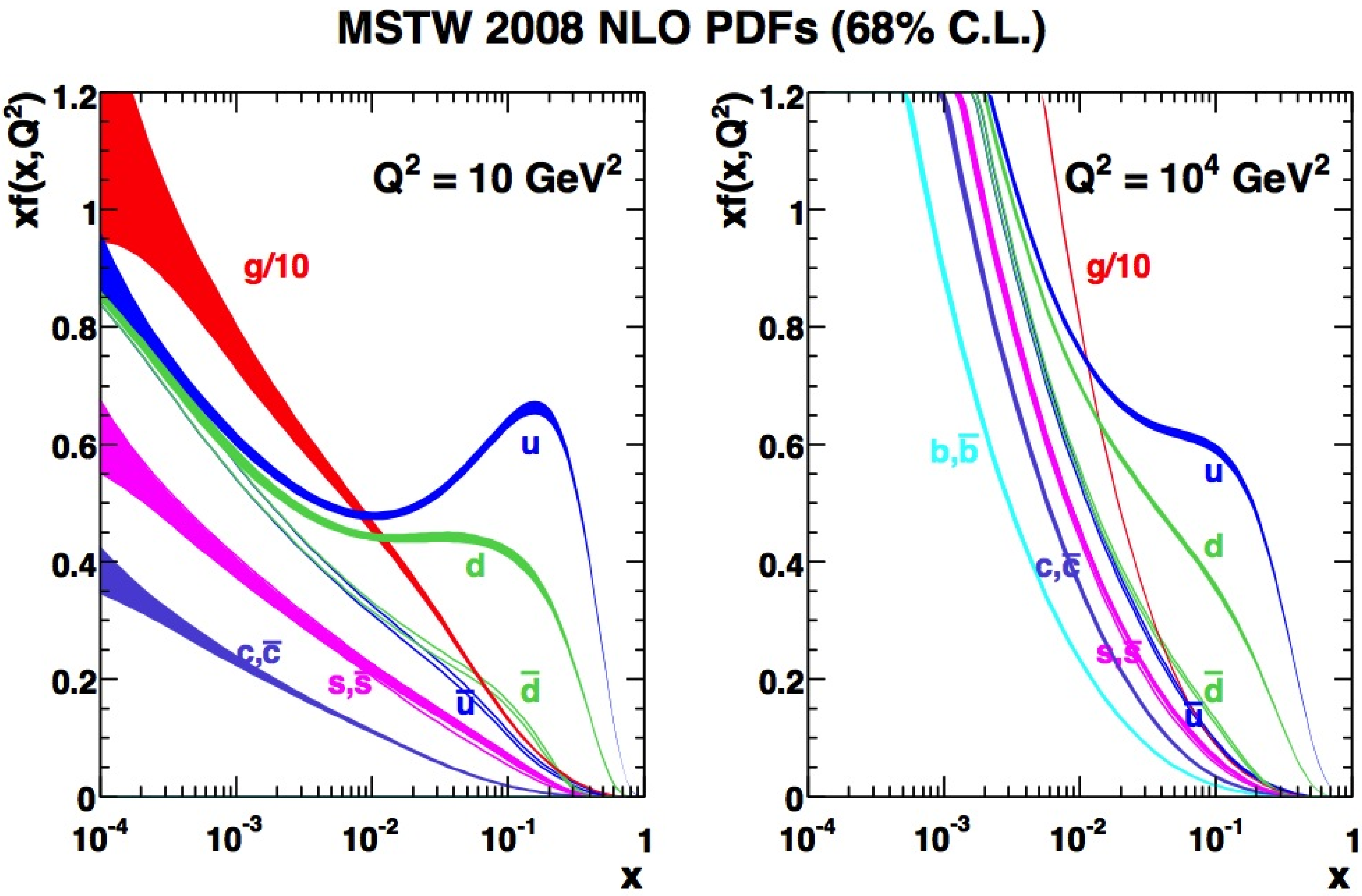
- Inner layer of silicon detectors: displaced vertices
- EM tracker: path of charged particles
- Calorimeters: stop e, γ and hadrons
- Outer radius of μ detectors: muon momenta
- Magnetic fields bend charged particle paths: measure momentum

There is no DM detector! DM signal is missing energy and momentum, actually MET (p_T). But so is for neutrinos!

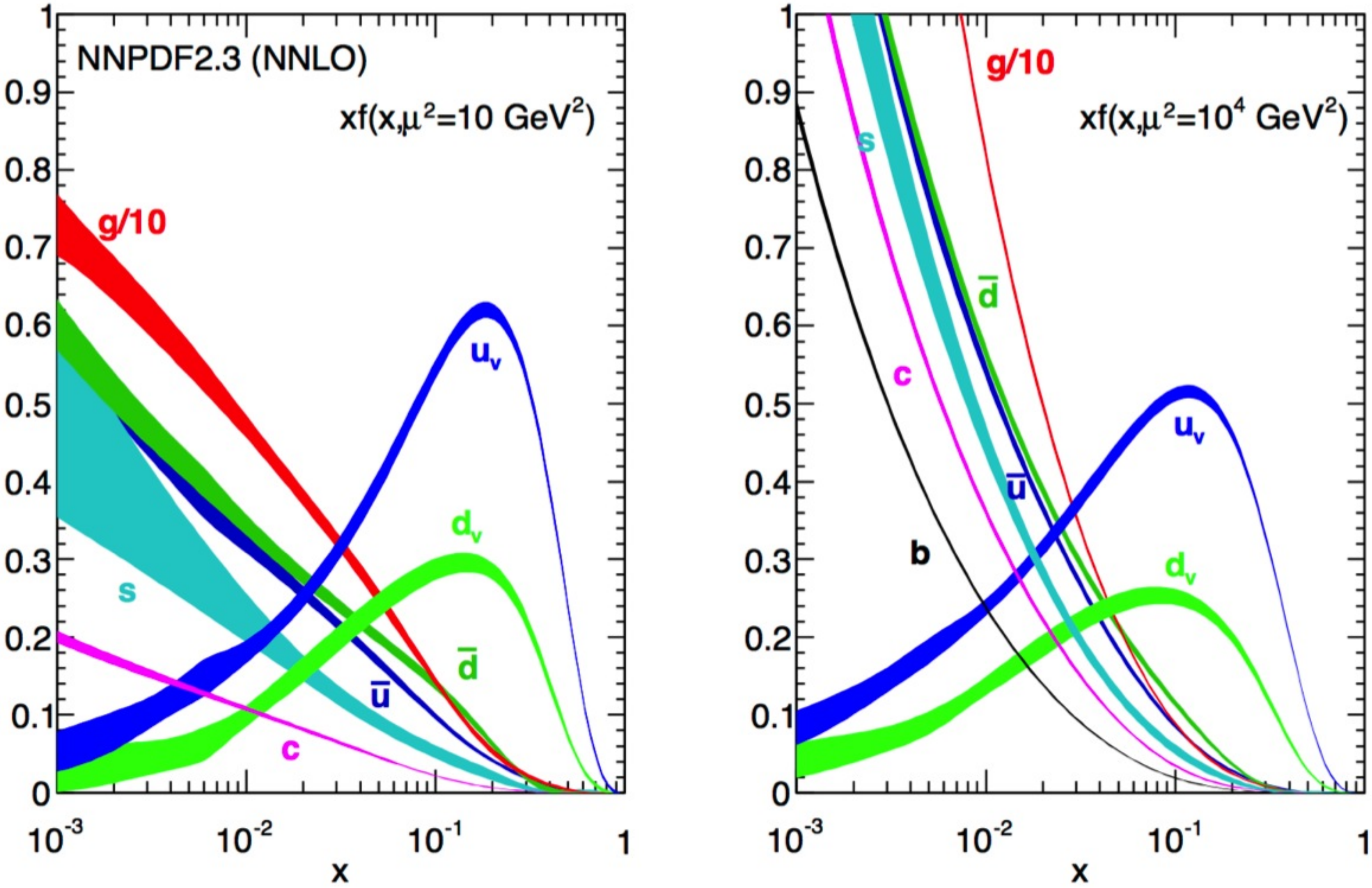
In hadron colliders, the initial momentum along the beam axis $x p_{had}$ of the colliding partons is not known so the amount of TOTAL missing energy/momentum cannot be determined. However, the initial par tonic momentum transverse to the beam axis $p_T = 0$, so any net momentum in the transverse plane indicates Missing Transverse Energy (MET) really p_T

(advantage of lepton colliders: can measure the total missing energy/momentum)

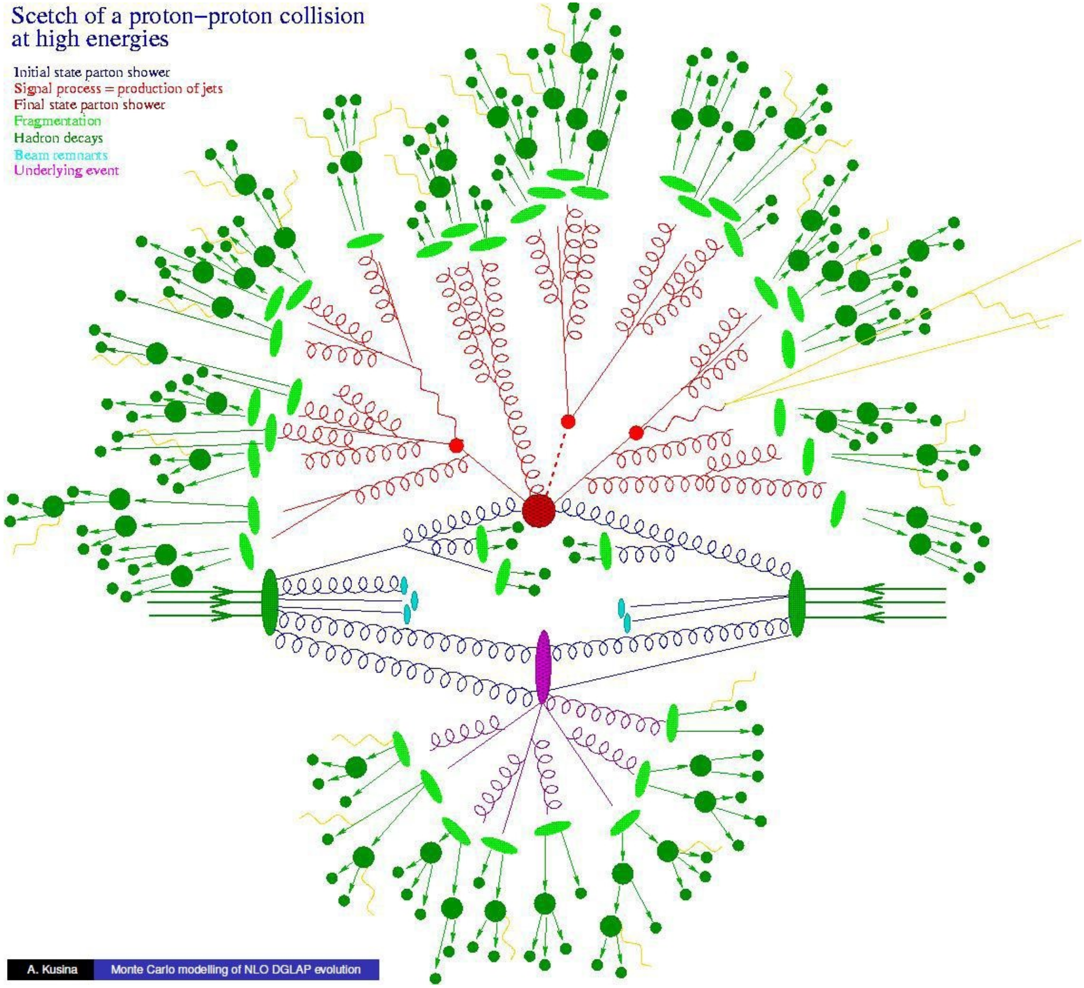
Protons are bags of partons



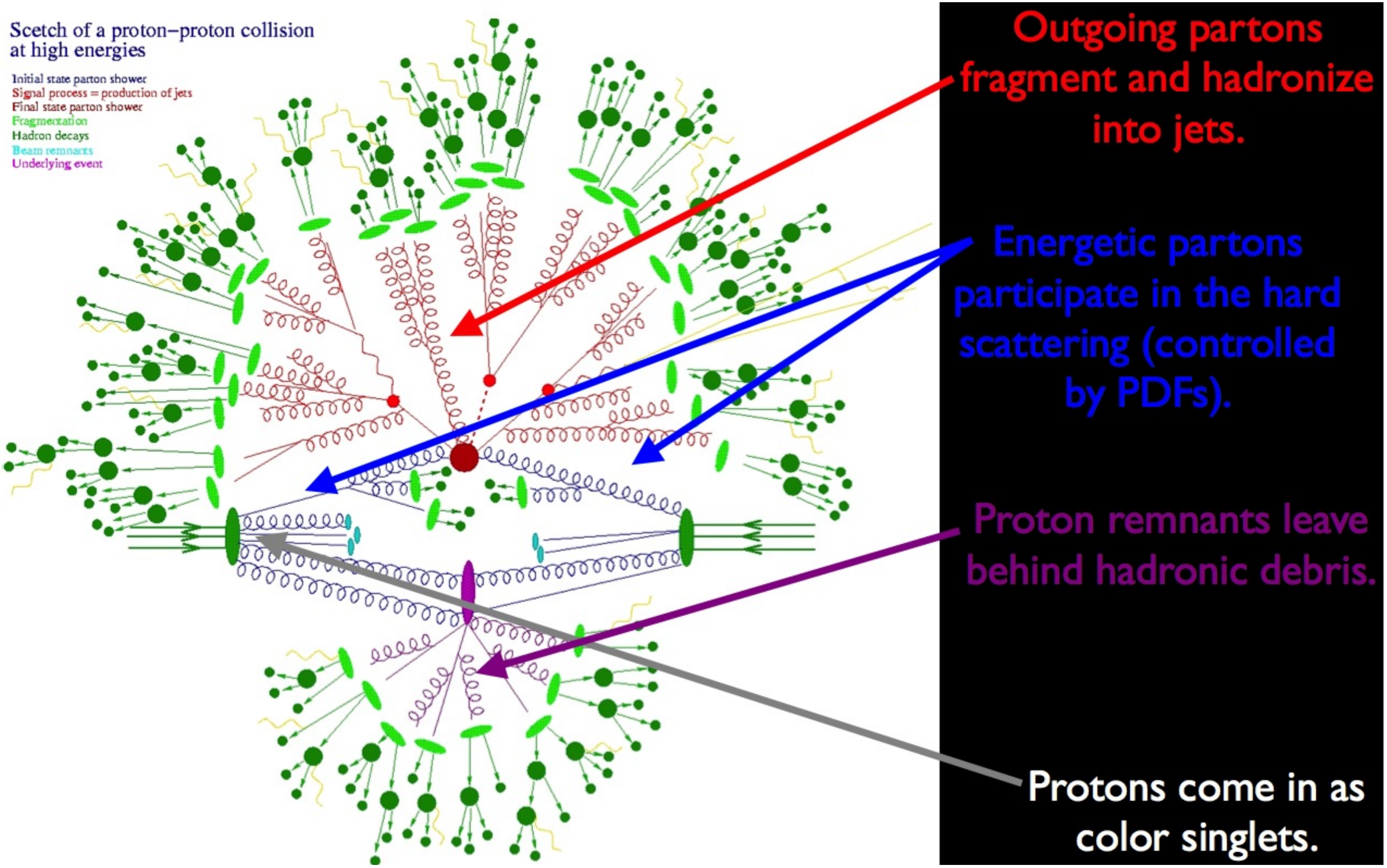
Protons are bags of partons But not sure the content of the bag



p-p collisions are very complicated



p-p collisions are very complicated Fig. from T. Tait



Outgoing partons fragment and hadronize into jets.

Energetic partons participate in the hard scattering (controlled by PDFs).

Proton remnants leave behind hadronic debris.

Protons come in as color singlets.

DM searches at the LHC

Main signature:

DM particles escape detection at colliders, thus they are characterized by missing transverse energy (missing E_T, MET) in collider events.

Caveats:

- The DM particles may be too heavy to be produced (above a few TeV).

- A signal produced by a particle escaping the detectors with lifetime $\simeq 100$ ns cannot be distinguished from one with lifetime $> 10^{17}$ s as required for DM particles.

- Hadron colliders are relatively insensitive to DM that interacts only with leptons.

- A DM signal may be hidden by backgrounds.

Main backgrounds for DM MET search

- “QCD background”

Measuring MET is difficult because requires measuring accurately EVERYTHING VISIBLE. Miss-measurement of jet energies is a source of fake missing momentum.

- Neutrinos are a background if they cannot be identified

- Z → $\nu\nu$ 20% of the time - look like DM MET.

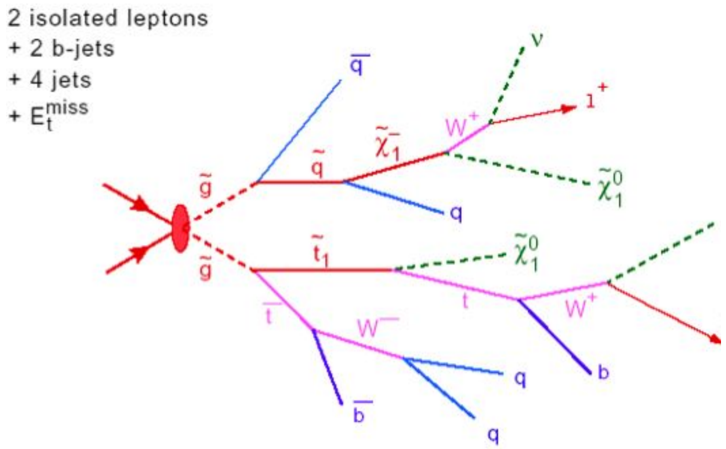
- W → $\nu\ell$, if the charged lepton ℓ is missed, ν cannot be identified and looks like DM MET.

- Same for τ decays, also produce ν's and ℓ's

Searches at the LHC

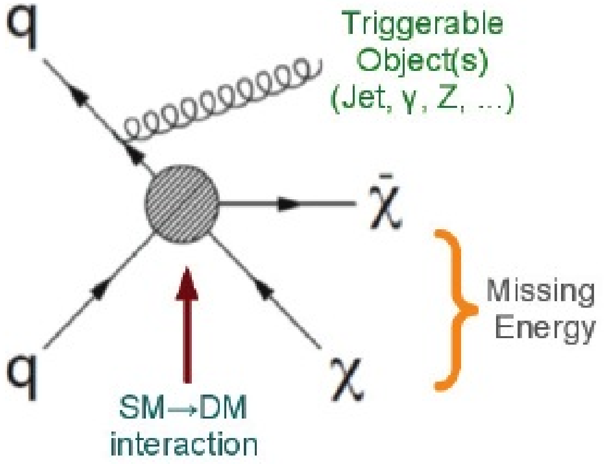
- Either in complete theories
DM through known decay chain

(specific UV complete models e.g. SUSY, or simplified topologies)

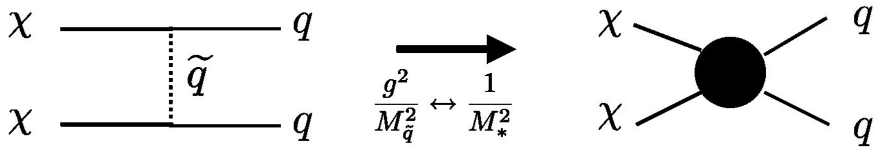


- Or direct DM production plus a visible particle either in effective field theories (EFT) or simplified DM models

photon or gluon ("monophoton" or "monojet" signal) or mono-W's (leptons), mono-Z's (dileptons), or mono-Higgses.

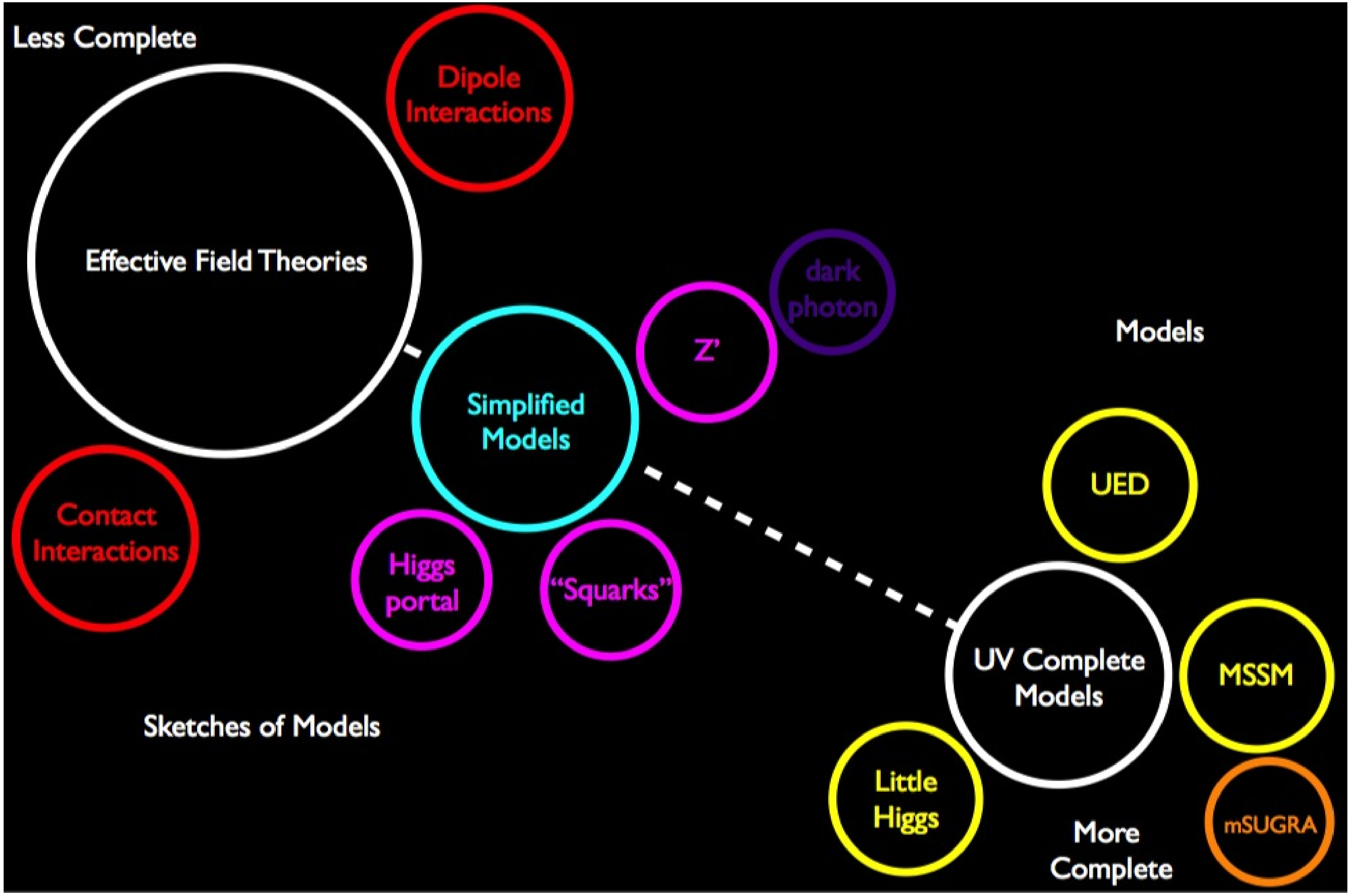


Initially done only for EFT



Spectrum of DM Theory Space

Fig. from T. Tait



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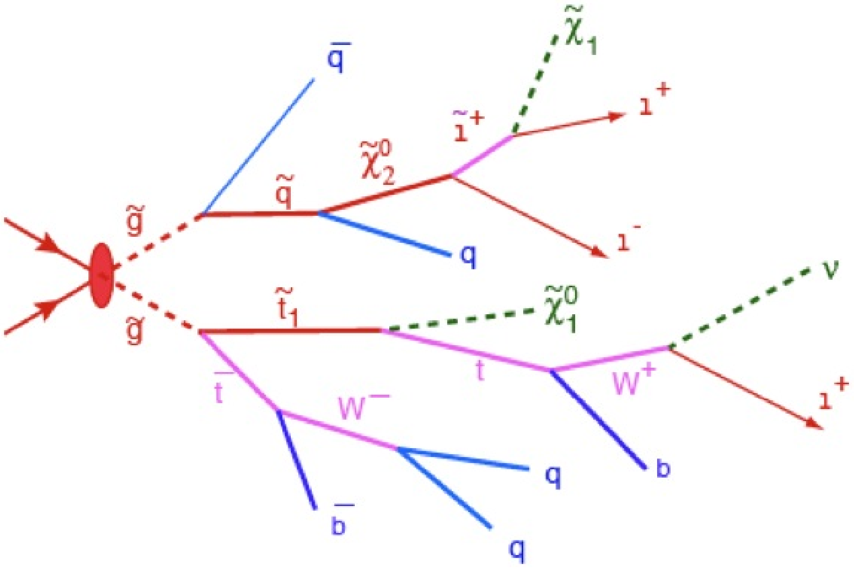
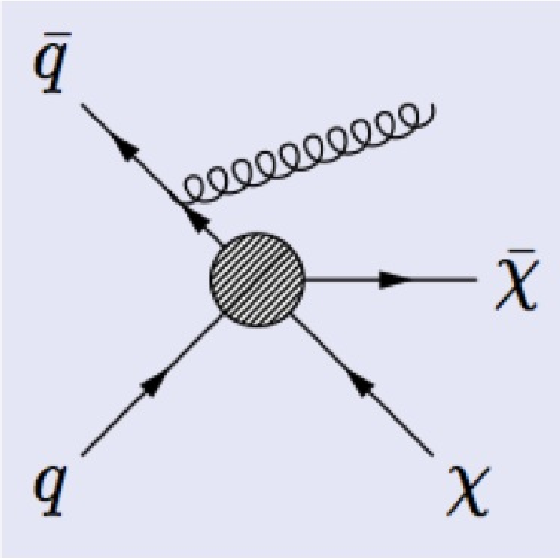
Complete and simplified DM models, searches at the LHC and complementarity with other DM searches

SUSY



Effective Field Theory



UV complete models - E.g. Supersymmetry (SUSY)

Most studied model

- Symmetry between bosons and fermions.
- Models are completely calculable
- Hierarchy: maintains EW scale $\ll$ GUT scale
- Requires two Higgs doublets minimum.
- Every known particle has supersymmetric partner(s)

Fermions:	**Bosons:**
SM fermions: ℓ, q	sfermions: $\widetilde{\ell}$, $\tilde{q}$
gauginos: $\widetilde{B}, \widetilde{W}, \tilde{g}$	SM gauge bosons: B, W, g
Gravitinos: $\widetilde{G}$	graviton
higgsinos: $\widetilde{H}$	Higgs bosons

- R-parity$= (-1)^{3B+L+2S}$ is $P_{SM} = +1$, $P_{SUSY} = -1$ distinguishes SM particles and SUSY partners

Many versions of SUSY- Many parameters

MSSM

- Minimum number of particles (SUSY partners+ two Higgs doublets)
- Number of parameters: those of the SM + 106!!!
- Parameter reduction:
  - pMSSM: simplified weak-scale MSSM: SM + 19 p.
  - CMSSM: constrained MSSM: SM+5 parameters ($m_0, A_0, m_{1/2}$, tanβ, μ)
  - mSUGRA: minimal supergravity: SM+5 parameters ($m_0, A_0, m_{1/2}$,tanβ, sign of μ)

NMSSM

- Non Minimum number of particles (extra singlet Higgs, etc)

Many versions of SUSY- Many parameters

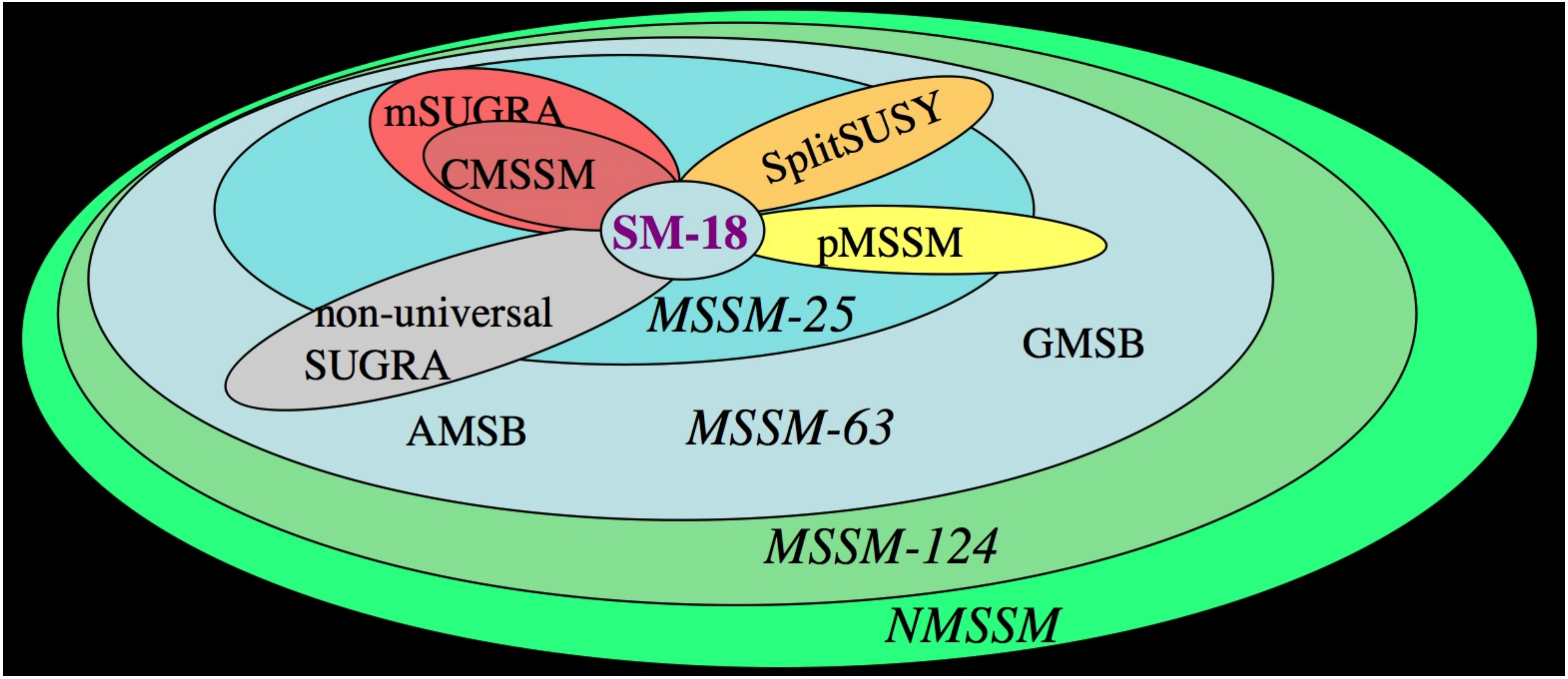


Fig. from P. Gondolo

SUSY models

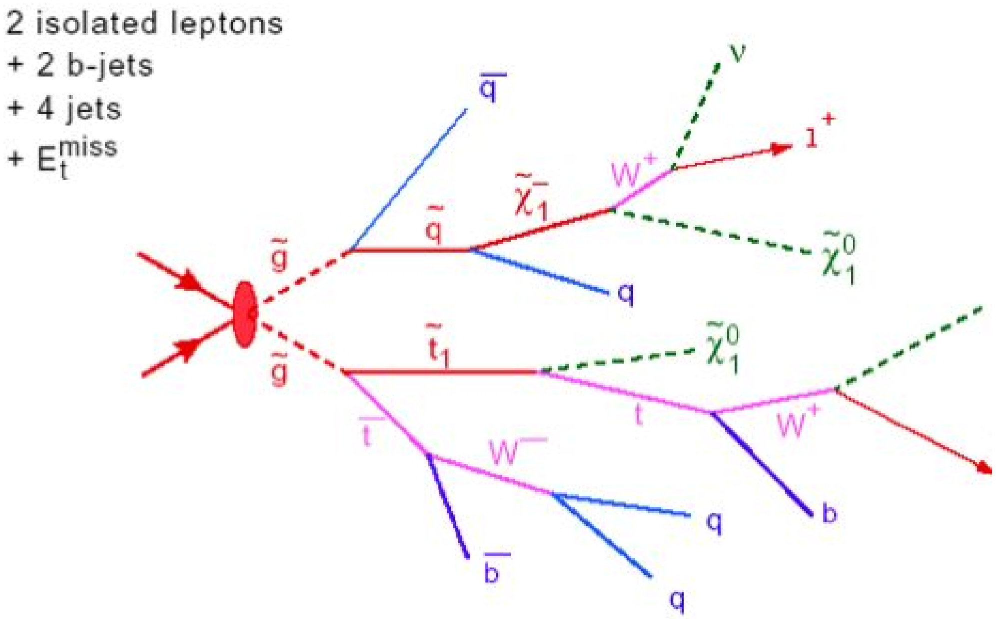
- If R-parity is conserved, the Lightest Supersymmetric Partner (LSP) is stable, thus a good WIMP dark matter candidate (if neutral and colorless):
  - $\tilde{\nu}$ sneutrino, $\widetilde{G}$ Gravitino (partner of graviton), $\tilde{a}$ axino (partner of the axion) or $\widetilde{\chi}^0$ neutralino (gaugino/ higgssino, partner of neutral gauge boson/Higgs boson)
- In the **MSSM** the usual LSP is the lightest neutralino. In the basis $\widetilde{B}$, $\widetilde{W}_3$, $\widetilde{H}_1^0$, $\widetilde{H}_2^0$ the mass matrix is

$$\begin{bmatrix} M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 \end{bmatrix}$$

tan$\beta = v_2/v_1$, M_1 : Bino mass, M_2 : Wino$_3$ mass, μ : mixes H_1 H_2

- If one stage unification of fundamental forces: $M_2 = 2M_1$,
  if $M_1 < |\mu|$, LSP$=$ $\widetilde{B}$ typical **cMSSM**, if $M_1 \simeq |\mu|$, LSP $=$ mixed $\widetilde{B}$-$\widetilde{H}$ OK
- If R-parity is conserved, an unstable SUSY particle decays into another SUSY particle and SUSY particles are only produced in pairs from SM particles.

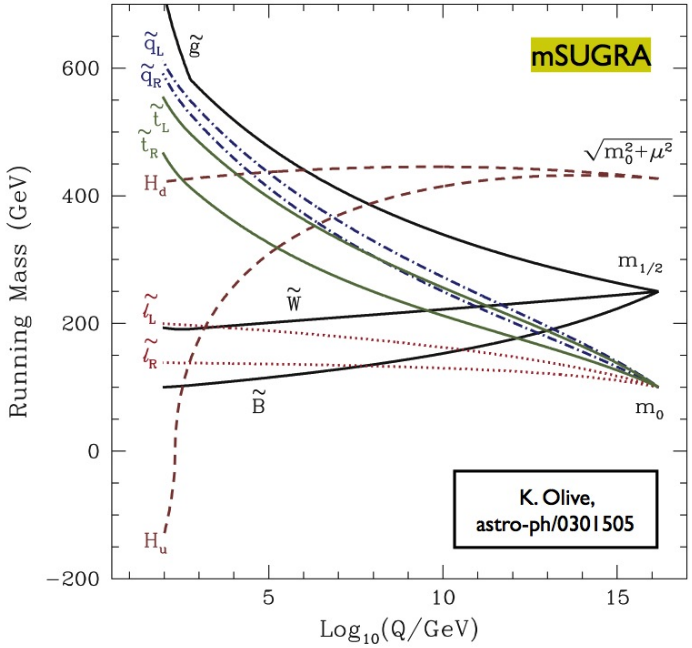
LHC typical SUSY decay chain



Typical topology:

- missing energy
- multiple hadronic jets
- number of leptons

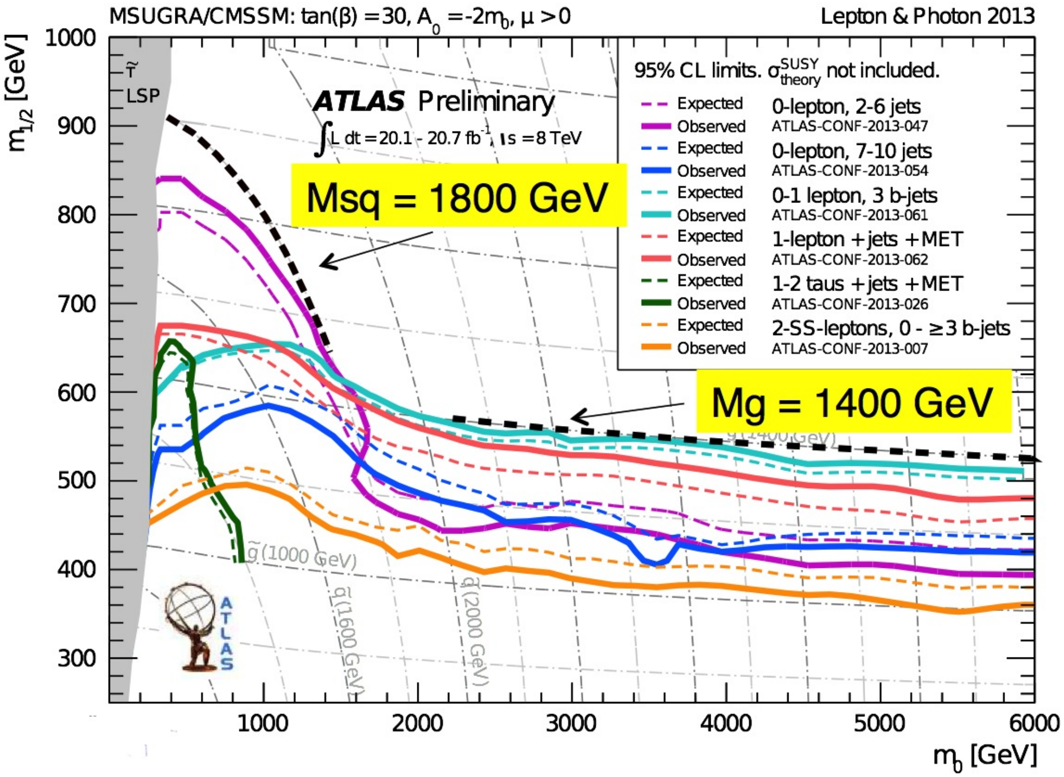
mSUGRA Start at the GUT scale with few parameters and use renormalization group equations to get to the electroweak scale.



K. Olive, astro-ph/0301505

pMSSM (phenomenological MSSM) Has 19 SUSY parameters directly defined at the electroweak scale: μ, m_A, tan β, A_b, A_t, A_τ, M_1, M_2, M_3, m_{Q1}, m_{Q3}, m_{u1}, m_{d1}, m_{u3}, m_{d3}, m_{L1}, m_{L3}, m_{e1}, m_{e3}

mSUGRA/cMSSM were in serious troubles by 2013



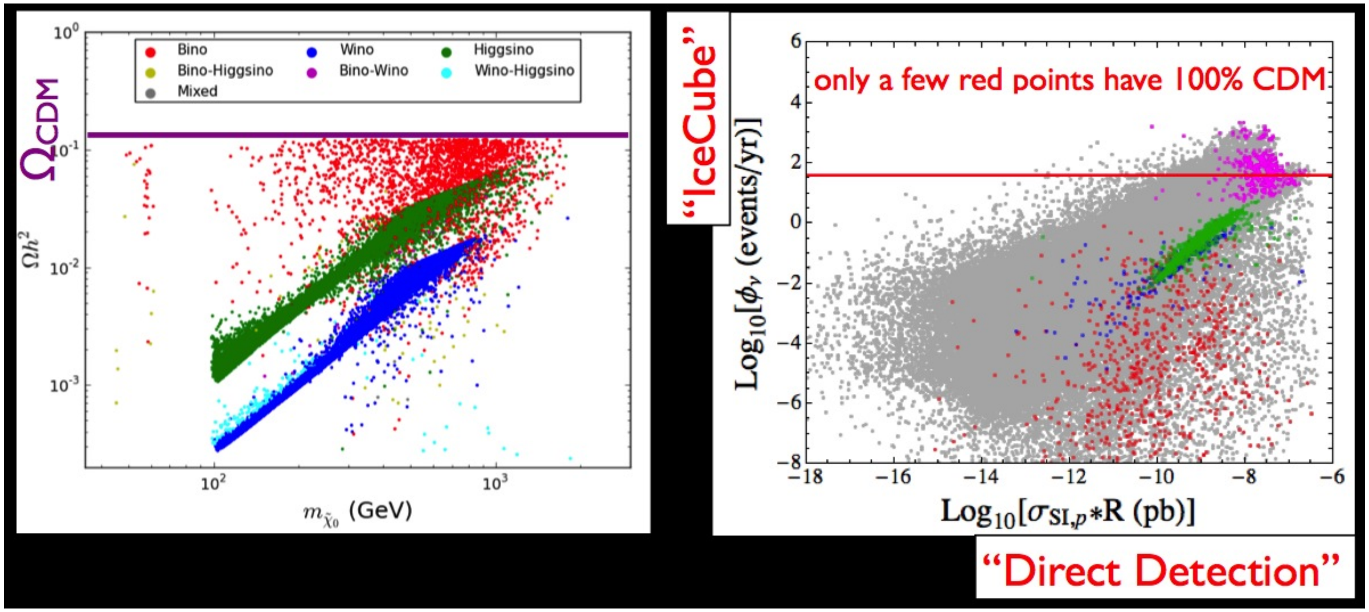
SO:• Use more parameters, pMSSM, or more particles NMSSM or

• Simplified SUSY model spectrum (SMS) with 100% BR for decay chain considered

pMSSM (phenomenological MSSM) LHC bounds

Cahill-Rowell et al 1305.6921

Only a few Bino LSP models with coannihilation can still constitute all the DM



"IceCube"

only a few red points have 100% CDM

"Direct Detection"

LSP $\widetilde{B}$-like (typical in CMSSM) is overdensed - or fine-tunned

(σ_{annih} into $f\bar{f}$ through $\widetilde{f}$ exchange is helicity suppressed $\sim m_f$)

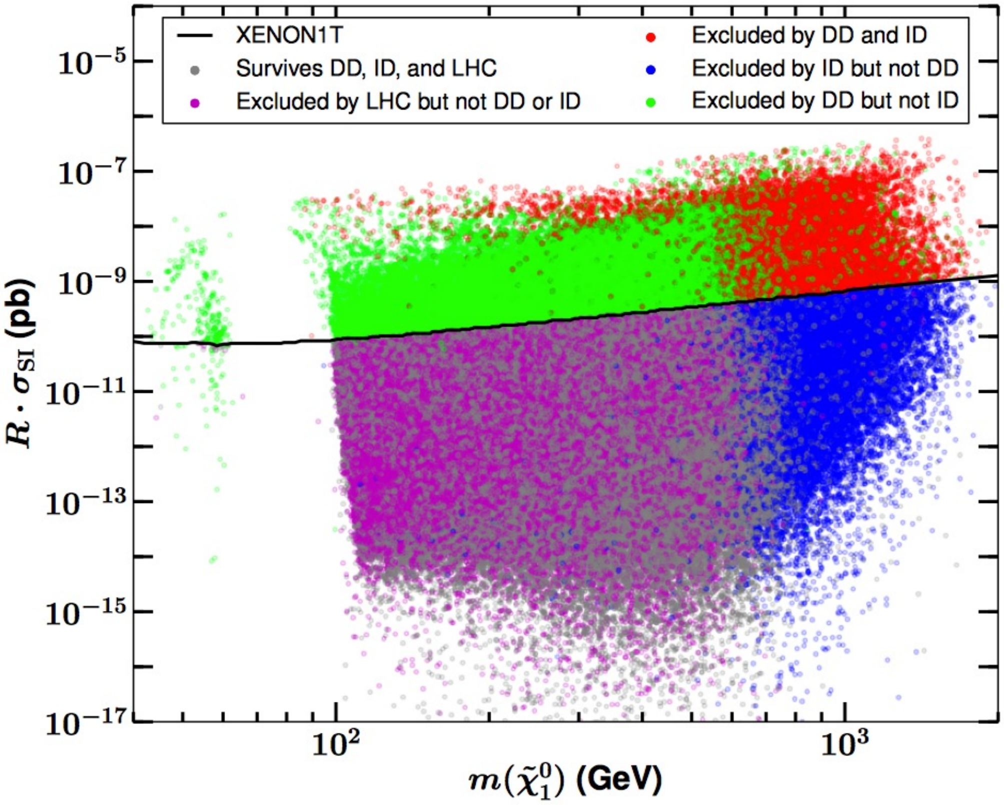
LSP $\widetilde{H}$-like and $\widetilde{W}$-like are underdensed unless $m \simeq$ TeV's (large σ_{annih} to W^+W^-, ZZ or $f\bar{f}$)

pMSSM - Complementarity of Searches

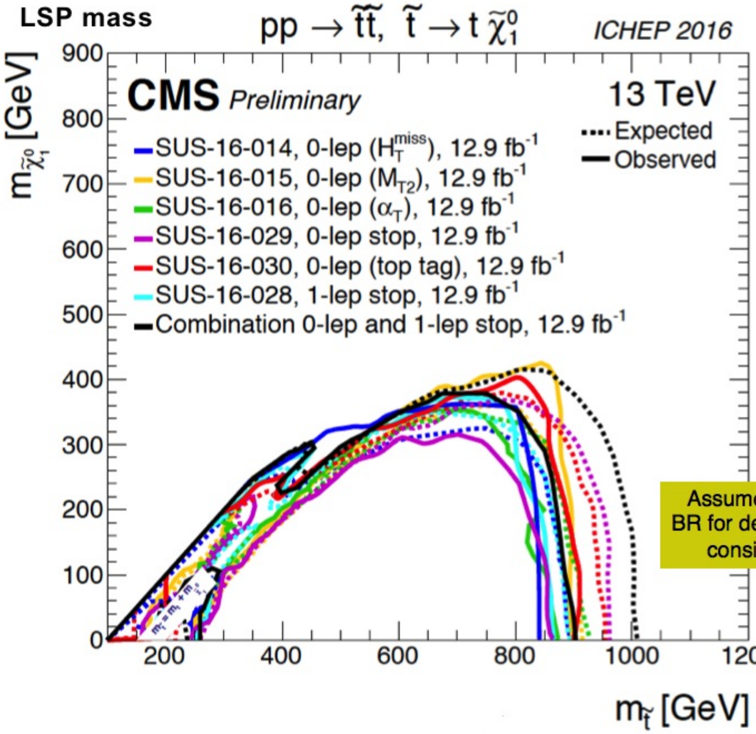
neutralino in the phenomenological MSSM with 19 free parameters, 50 GeV<m< 4 TeV, 2 10^5 points, each a model- Notice $R = \Omega_\chi/\Omega_{DM}$: fraction of DM density. $R\sigma$ in vert.axis. Cahill-Rowley et al. 1405.6716

Models will be tested by:

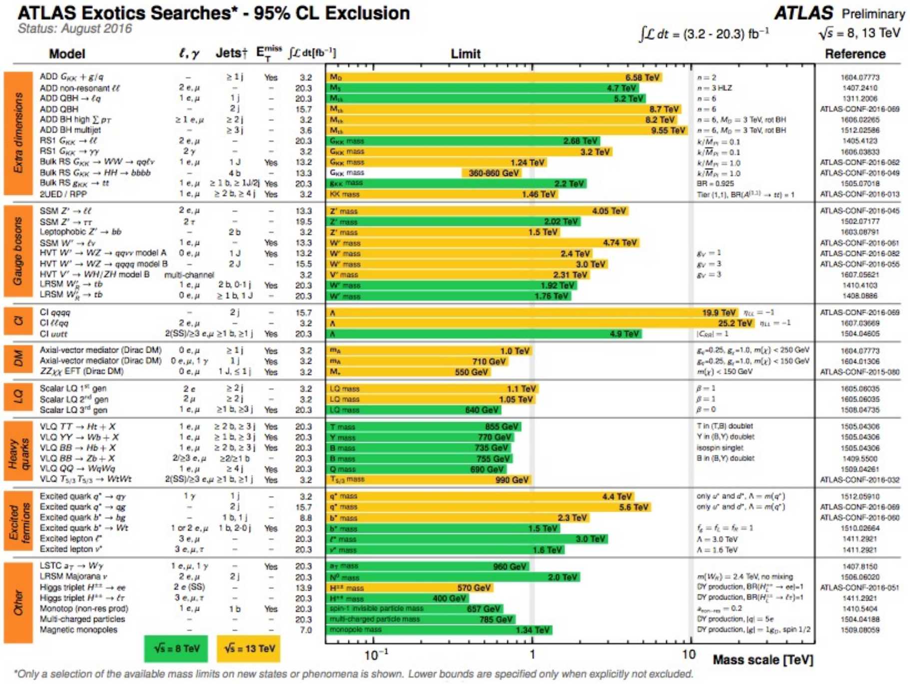
- direct detection (green) - black line is reach of LZ
- indirect detection with FermiLAT and future CTA (red)
- other indirect detection (blue)
- escape all other searches and will be tested only at the LHC (magenta).
- Gray regions will survive all searches in the near future.



SUSY Simplified Models Spectrum (SMS)



Assumes 100% BR for decay chain considered.



ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

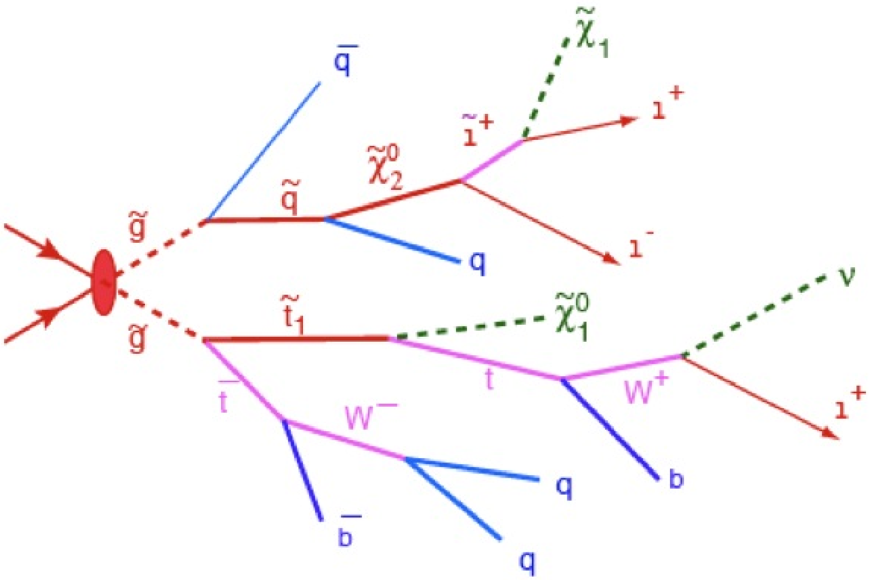
$\int \mathcal{L}\, dt = (3.2 - 20.3)\ fb^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt [fb^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	🟨 M_D 6.58 TeV	$n = 2$	1604.07773
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	🟩 M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\to \ell q$	1 e, μ	1 j	–	20.3	🟩 M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	15.7	🟨 M_{th} 8.7 TeV	$n = 6$	ATLAS-CONF-2016-069
	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 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	🟩 G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	3.2	🟨 G_{KK} mass 3.2 TeV	$k/\overline{M}_{Pl} = 0.1$	1606.03833
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	13.2	🟨 G_{KK} mass 1.24 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-062
	Bulk RS $G_{KK} \to HH \to bbbb$	–	4 b	–	13.3	🟨 G_{KK} mass 360-860 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-049
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	🟩 g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 4 j	Yes	3.2	🟨 KK mass 1.46 TeV	Tier (1,1), BR($A^{(1,1)} \to tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	13.3	🟨 Z' mass 4.05 TeV		ATLAS-CONF-2016-045
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	🟩 Z' mass 2.02 TeV		1502.07177
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	🟨 Z' mass 1.5 TeV		1603.08791
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	13.3	🟨 W' mass 4.74 TeV		ATLAS-CONF-2016-061
	HVT $W' \to WZ \to qq\nu\nu$ model A	0 e, μ	1 J	Yes	13.2	🟨 W' mass 2.4 TeV	$g_V = 1$	ATLAS-CONF-2016-082
	HVT $W' \to WZ \to qqqq$ model B	–	2 J	–	15.5	🟨 W' mass 3.0 TeV	$g_V = 3$	ATLAS-CONF-2016-055
	HVT $V' \to WH/ZH$ model B	multi-channel			3.2	🟨 V' mass 2.31 TeV	$g_V = 3$	1607.05621
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	🟩 W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	🟩 W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	15.7	🟨 Λ 19.9 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2016-069
	CI $\ell\ell qq$	2 e, μ	–	–	3.2	🟨 Λ 25.2 TeV	$\eta_{LL} = -1$	1607.03669
	CI $uutt$	2(SS)/≥3 e, μ	≥1 b, ≥1 j	Yes	20.3	🟩 Λ 4.9 TeV	$\lvert C_{RR} \rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	≥ 1 j	Yes	3.2	🟨 m_A 1.0 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 250$ GeV	1604.07773
	Axial-vector mediator (Dirac DM)	0 e, μ, 1 γ	1 j	Yes	3.2	🟨 m_A 710 GeV	g_q=0.25, g_χ=1.0, $m(\chi) < 150$ GeV	1604.01306
	$ZZ\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 550 GeV	$m(\chi) < 150$ GeV	ATLAS-CONF-2015-080
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	🟨 LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	🟨 LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	🟩 LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	🟩 Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	🟩 B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	🟩 Q mass 690 GeV		1509.04261
	VLQ $T_{5/3} T_{5/3} \to WtWt$	2(SS)/≥3 e, μ	≥1 b, ≥1 j	Yes	3.2	🟨 $T_{5/3}$ mass 990 GeV		ATLAS-CONF-2016-032
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	3.2	🟨 q* mass 4.4 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.05910
	Excited quark $q^* \to qg$	–	2 j	–	15.7	🟨 q* mass 5.6 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2016-069
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	8.8	🟨 b* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	🟩 b* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	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	LSTC $a_T \to W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	🟩 a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	🟩 N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to ee$	2 e (SS)	–	–	13.9	🟨 $H^{\pm\pm}$ mass 570 GeV	DY production, BR($H_L^{\pm\pm} \to ee$)=1	ATLAS-CONF-2016-051
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass 1.34 TeV	DY production, $\lvert g \rvert = 1g_D$, spin 1/2	1509.08059

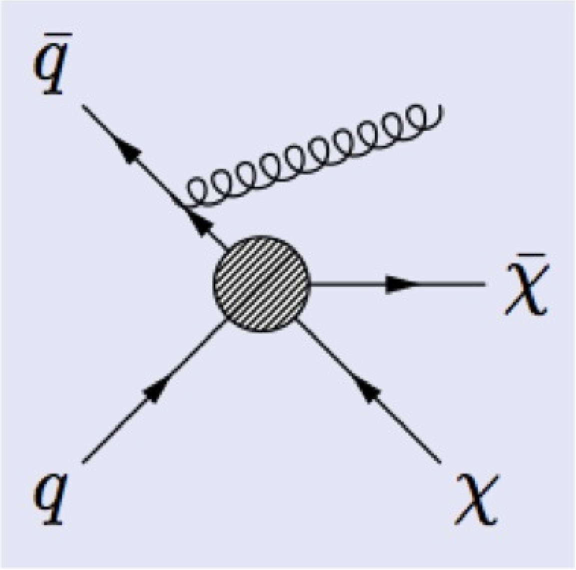
🟩 $\sqrt{s} = 8$ TeV 🟨 $\sqrt{s} = 13$ TeV

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

SUSY



Effective Field Theory



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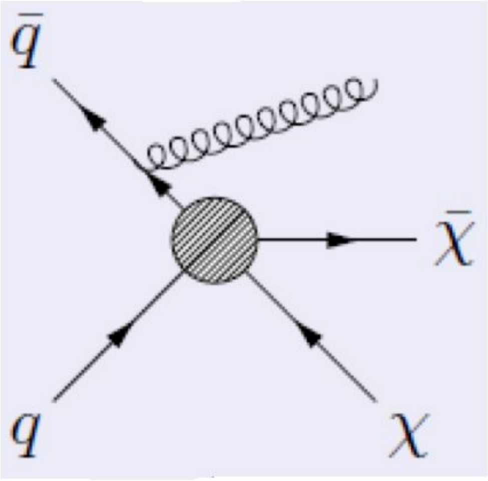
At the other extreme of a complete theory is Effective Field Theory.

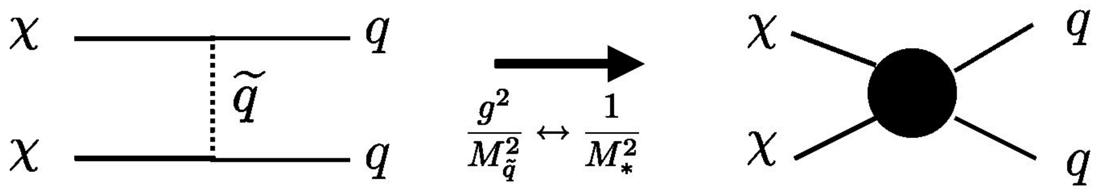
“MONO”-Searches at the LHC

Direct DM production plus a photon or gluon (“monophoton” or “monojet” signal) or mono-W’s (leptons), mono-Z’s (dileptons), or even mono-Higgses.



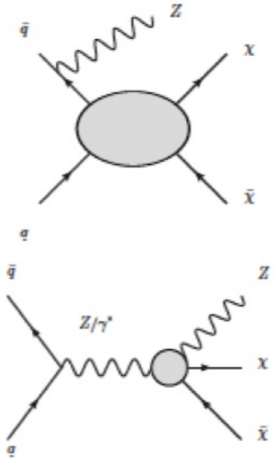
qq	scalar	$\frac{m_q}{M_\star^3}\bar\chi\chi\bar q q$
qq	vector	$\frac{1}{M_\star^2}\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q$
qq	axial-vector	$\frac{1}{M_\star^2}\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$
qq	tensor	$\frac{1}{M_\star^2}\bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\mu\nu} q$
gg	scalar	$\frac{1}{4M_\star^3}\bar\chi\chi\alpha_s(G^a_{\mu\nu})^2$

Initially done only for
CONTACT INTERACTIONS
(EFT couplings)

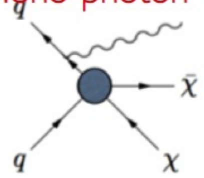


“MONO”-Searches at the LHC

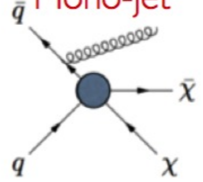
Mono-Z



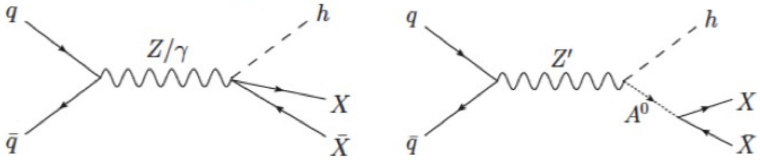
Mono-photon



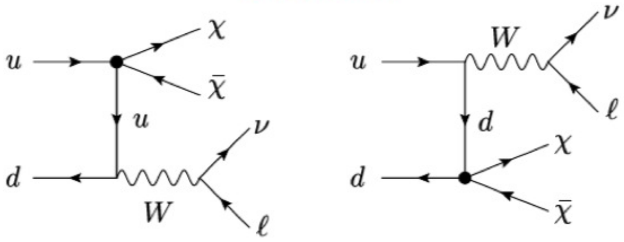
Mono-jet



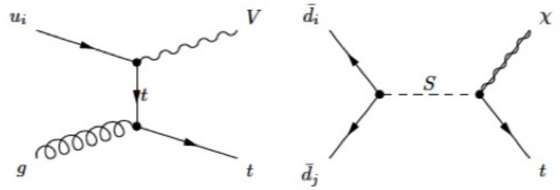
Mono-Higgs



Mono-W

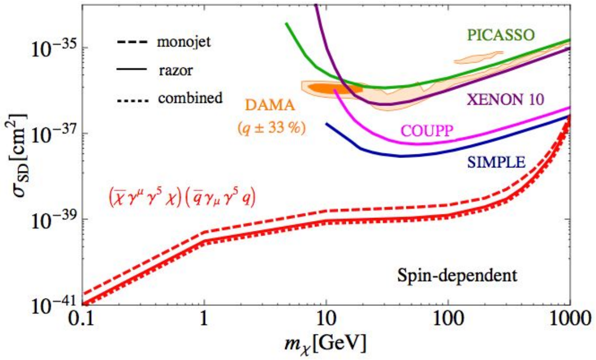


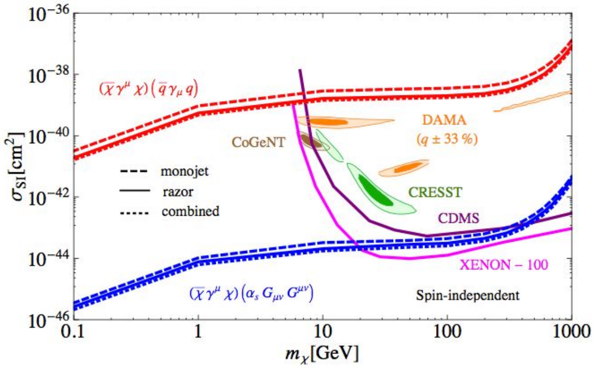
Mono-top

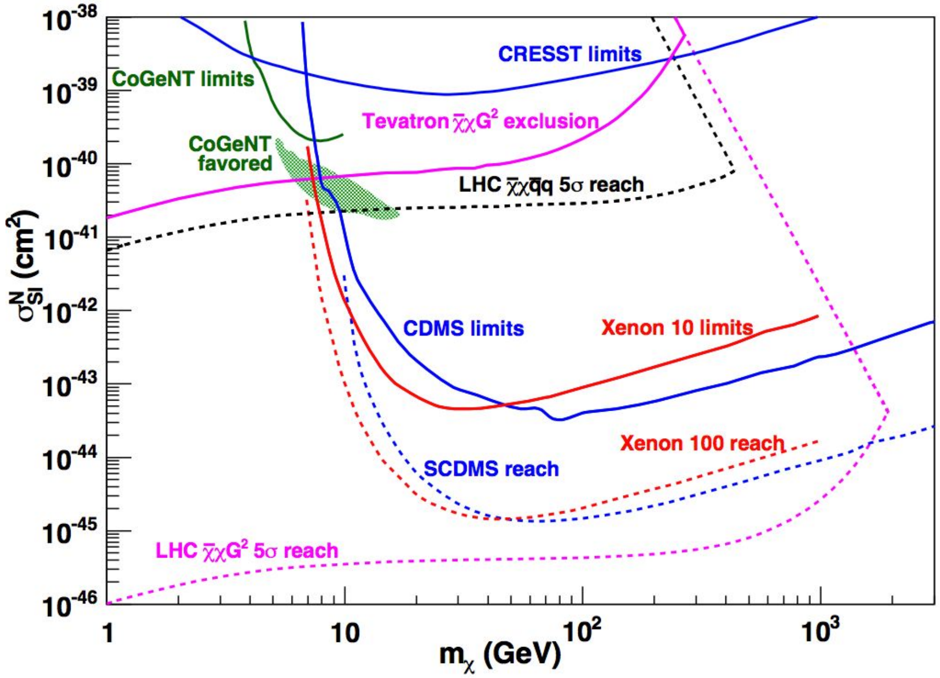


EFT “Mono”- searches at the LHC

direct production plus a photon or gluon (monophoton monojet signal) for CONTACT interactions Beltran et al 1002.4137; Fox et al 1203.1662







CAVEAT: in direct DM detection “contact interaction” if mediator M> q > MeV’s but at LHC q much larger,M> 100’s GeV- Compare with care!

“Mono”- searches at the LHC - direct detection limits must be compared with care.

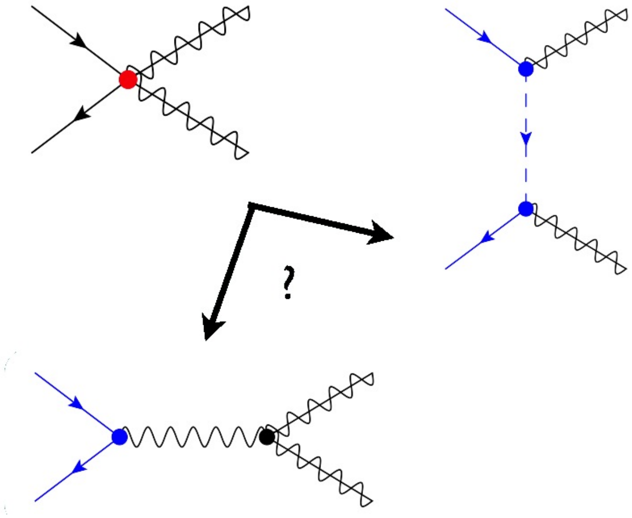
The approach using single effective operators with contact interactions, is limited because of absence of possible interference between different operators, effect of lighter mediators than those necessary to have a contact interaction at the LHC...

A mediator heavy at the partonic LHC energies is also heavy in direct detection BUT THE OPPOSITE IS NOT TRUE. If the mediator is light for the LHC, could itself be produced (and at LEP etc) so limits change.

Now trying to use **“simplified models”** and classify classes of mediators in the s-channel and the t-channel, or by the way the DM relic density could occur (e.g. proposed “Benchmarks for DM detection at the LHC” De Simone, Giudice & Strumia 1402.6287)
. **Lots of work to do in this direction...**
“LHC Dark Matter Working Group” recommendations: 1603.04156

EFT vs “simplified model”

- Many different FT couplings have the same EFT limit! Many, many models to study. How to classify them?

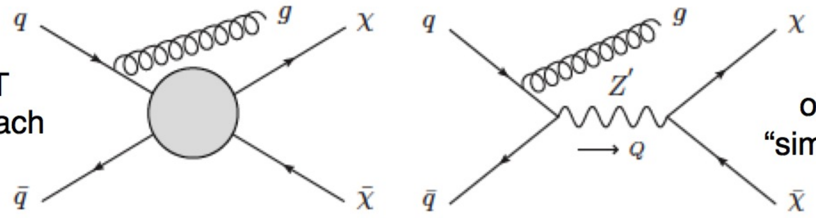


- For light enough mediators, limits on them are important. The mediators themselves can be created at the LHC and other accelerators.

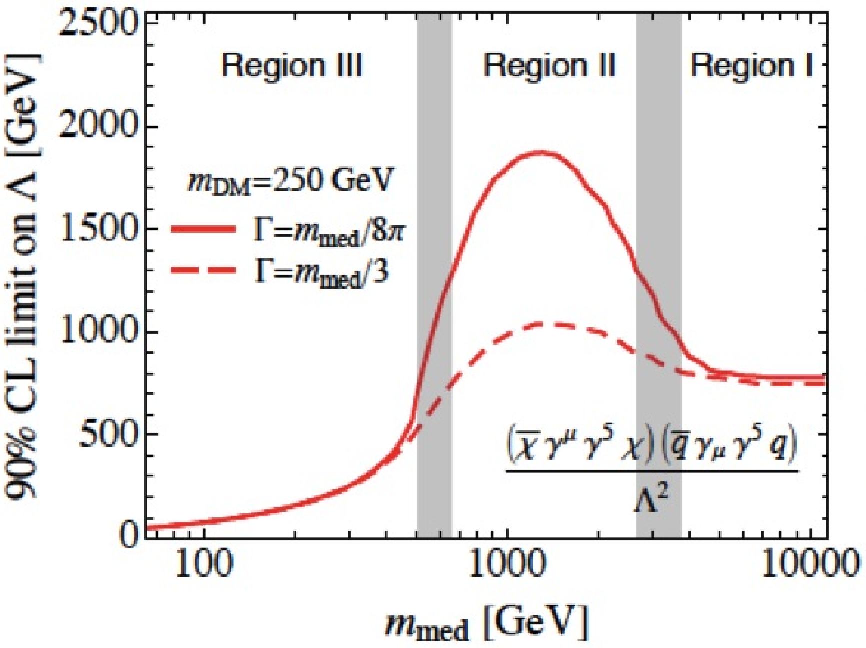
Example: EFT vs a “simplified model”

Buchmueller, Dolan, Mc Cabe 1308.6799

EFT
approach



FT
one diagram
“simplified model”



Three Regions as function of mediator mass:

Region I: Heavy m_{med}
- ➢ EFT is valid!

Region II: Medium m_{med} – Resonant enhancement
- ➢ EFT limits are too conservative!

Region III: Low m_{med}
- ➢ EFT limits are too aggressive!

How to present “simplified models”

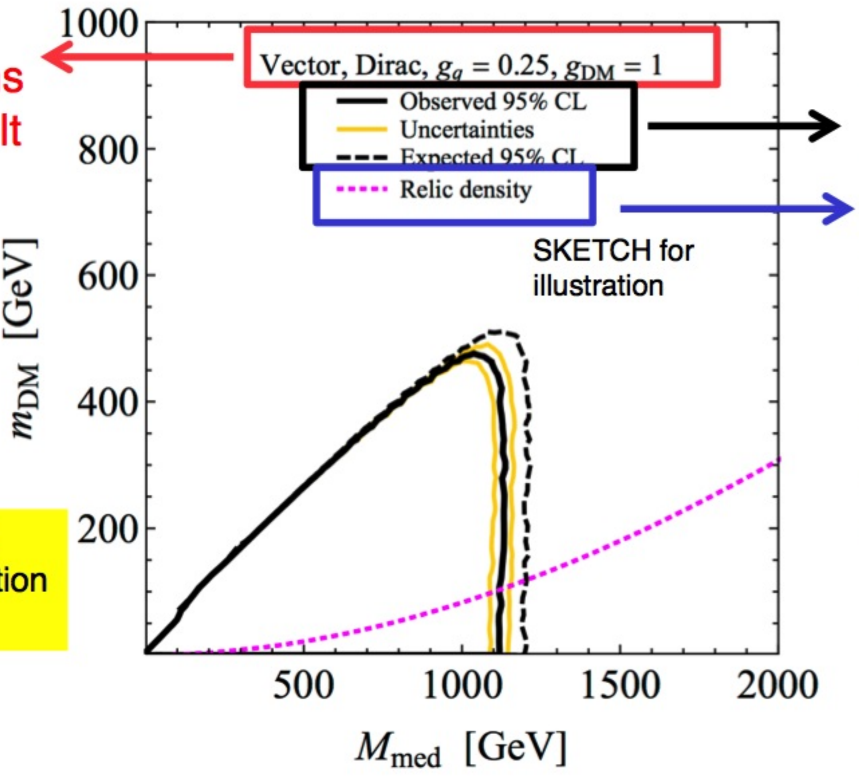
“LHC Dark Matter Working Group” recommendations, 1603.04156

Main result of the interpretation of collider search in simplified model

Clearly state
Main assumptions
entering the result

- Mediator
- DM type
- Couplings

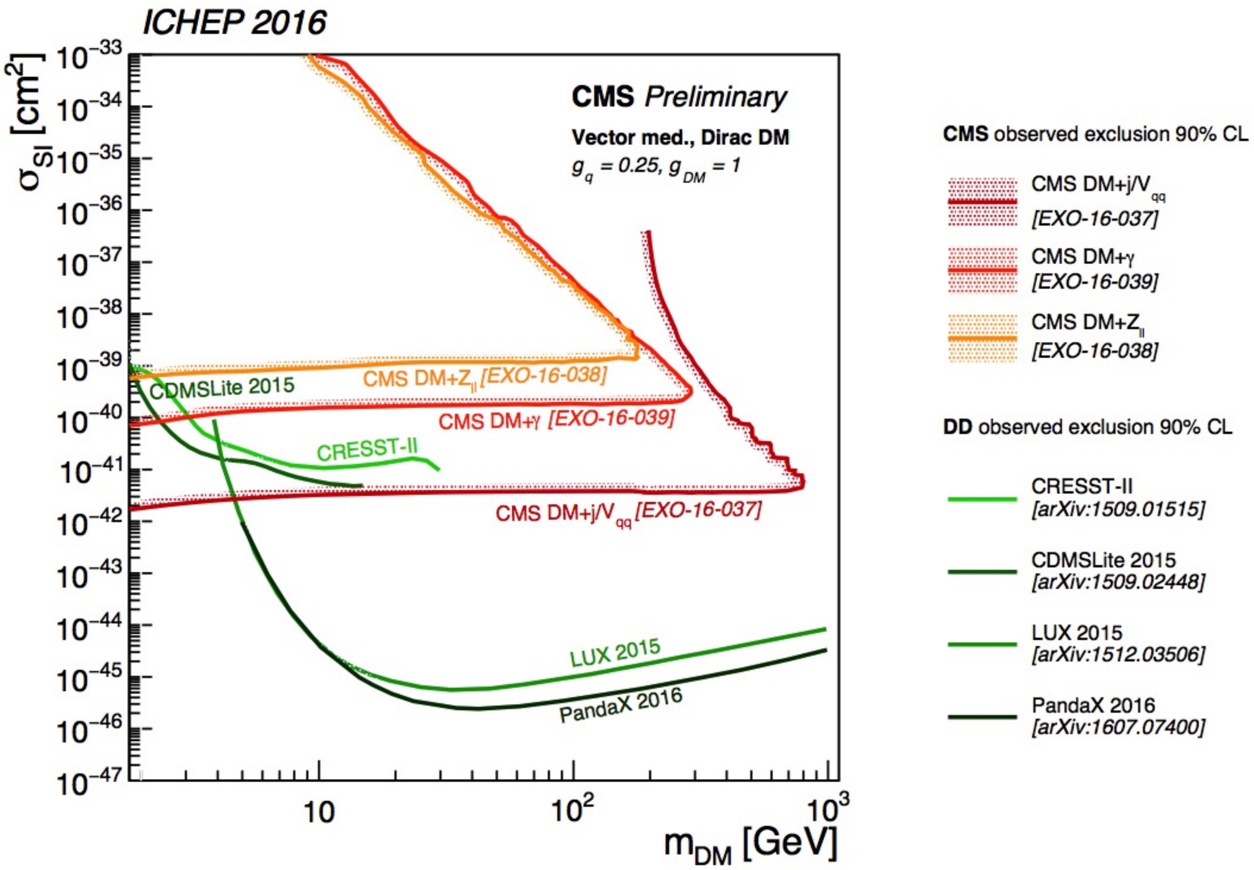
All based on LHC
DM WG recommendation
1603.04156



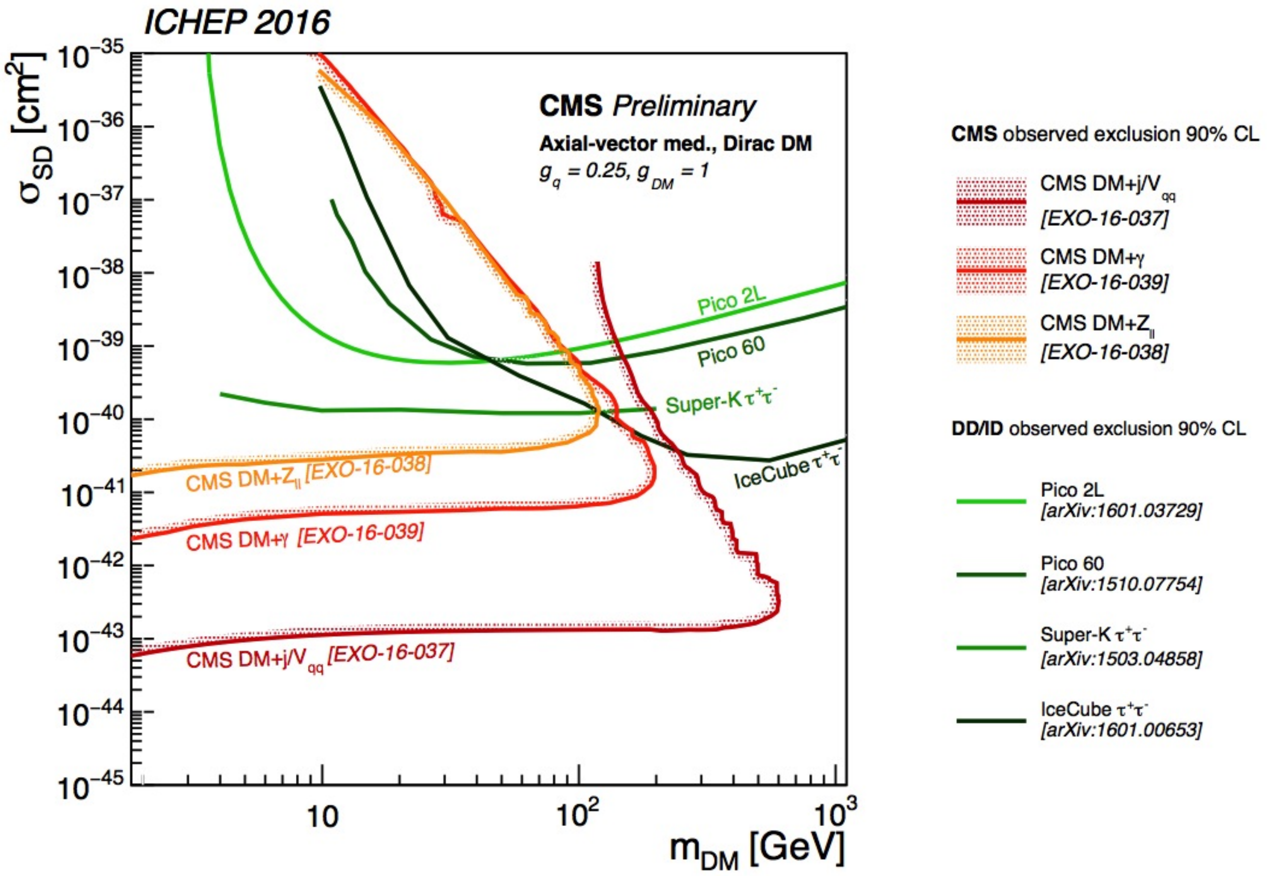
Usual “LHC limits”
For 95% CL [not 90%]

Indicate Relic density line but do not use it as “validity” requirement. Its FI only.
[more caveats and discussion are provided in the report]

“Mono” searches - Simplified Model - Vector mediator-SI



“Mono”searches - Simplified Model Axial-Vect. mediator - SD



How would these results compared if for this particle $\Omega/\Omega_{DM} = f = 0.01$?

Example of complementarity of DM searches

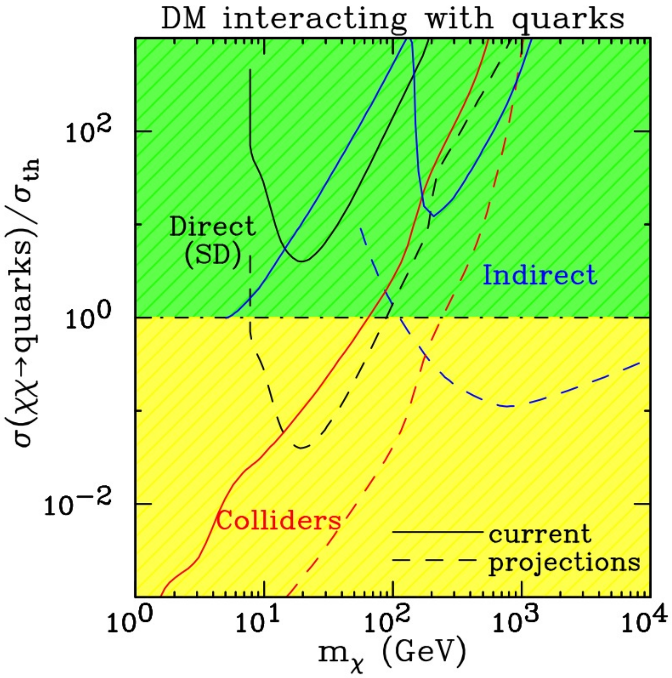
Simple contact interaction model considered for the Snowmass 2013 study (Bauer et al. 2013)

$$\mathscr{L} = \frac{1}{M_q^2}\,\bar{\chi}\gamma^\mu\gamma_5\chi\sum_q \bar{q}\gamma_\mu\gamma_5 q + \frac{\alpha_S}{M_g^3}\,\bar{\chi}\chi G^{a\mu\nu}G^a_{\mu\nu} + \frac{1}{M_\ell^2}\,\bar{\chi}\gamma^\mu\chi\sum_\ell \bar{\ell}\gamma_\mu\ell\ ,$$

The interactions with quarks mediate SD direct signals (*), and those with gluons mediate SI direct signals. M_q, M_g, and M_ℓ are chosen so that the relic density is exactly that of the DM though thermal production.

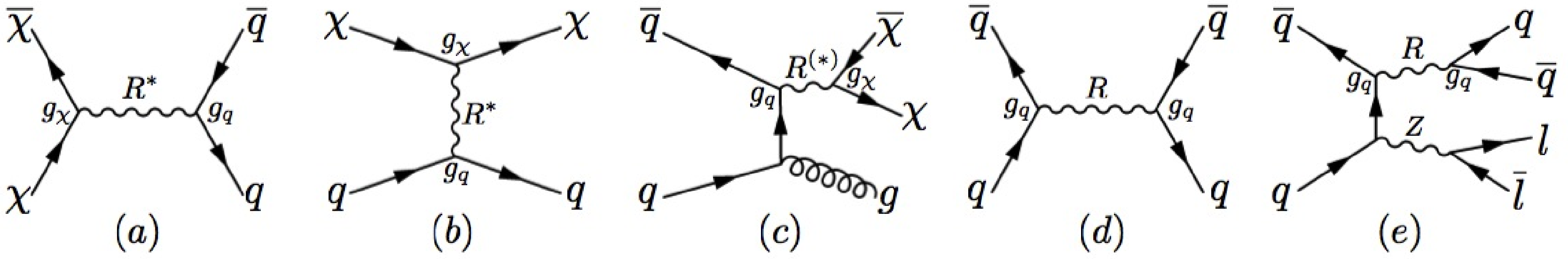
(* You will prove that $\gamma^\mu\gamma_5$ leads to SD scattering).

Notice that: the limits would be very different if the DM candidate accounted for only a fraction $\Omega/\Omega_{DM} = f < 1$ of the DM (*)



(* In exercise 10 you will explore this - assuming the indirect limits come from DM annihilation).

Important complementarity of dark sector particles and mediators searches More complete Simplified Model Chala et al. 1503.0591



Dark Sector Particle (DSP) χ and mediator R in all channels:

(a) DM annihilation which sets the relic abundance,

(b) DM scattering in direct detection experiments,

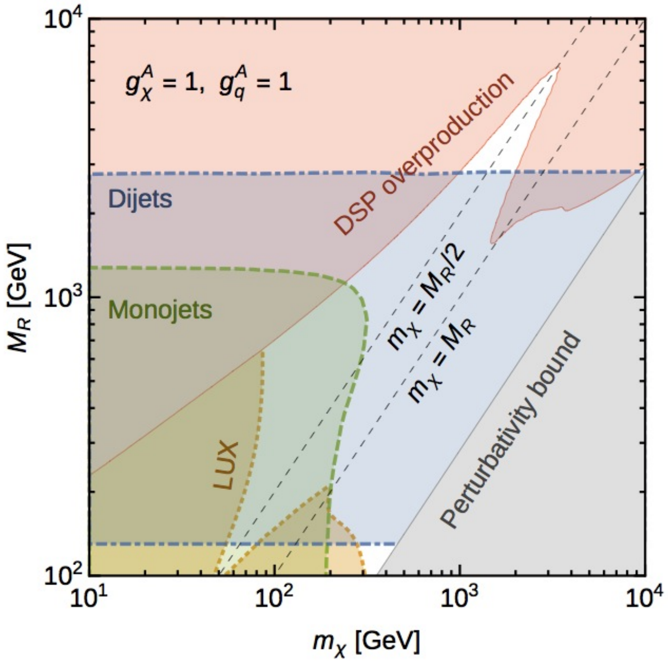
(c) monojet signatures, in this case due to initial state radiation of a gluon,

(d) LHC Dijet resonance signatures purely through mediator-quark couplings and

(e) dijet associated production (at UA2, CDF, CMS, and ATLAS)

Example of combined constraints (at 95% CL): everything excluded!

Chala et al. 1503.0591

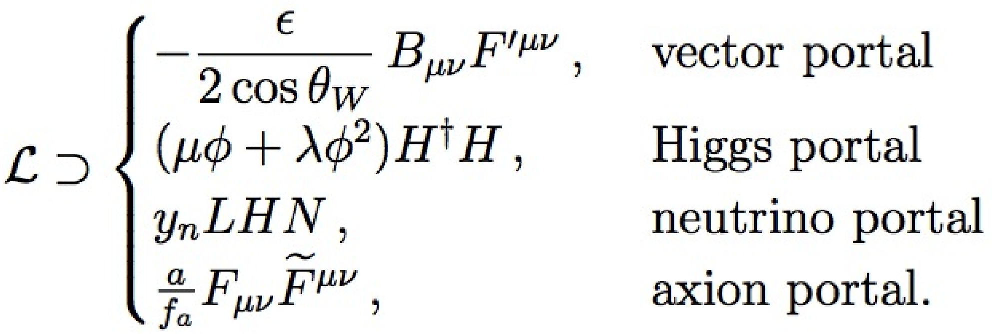


This shows that for each LHC DM Simplified Models there should be a complete study of the mediator particles in all experiments too.

A lot of work remains to do at the LHC!

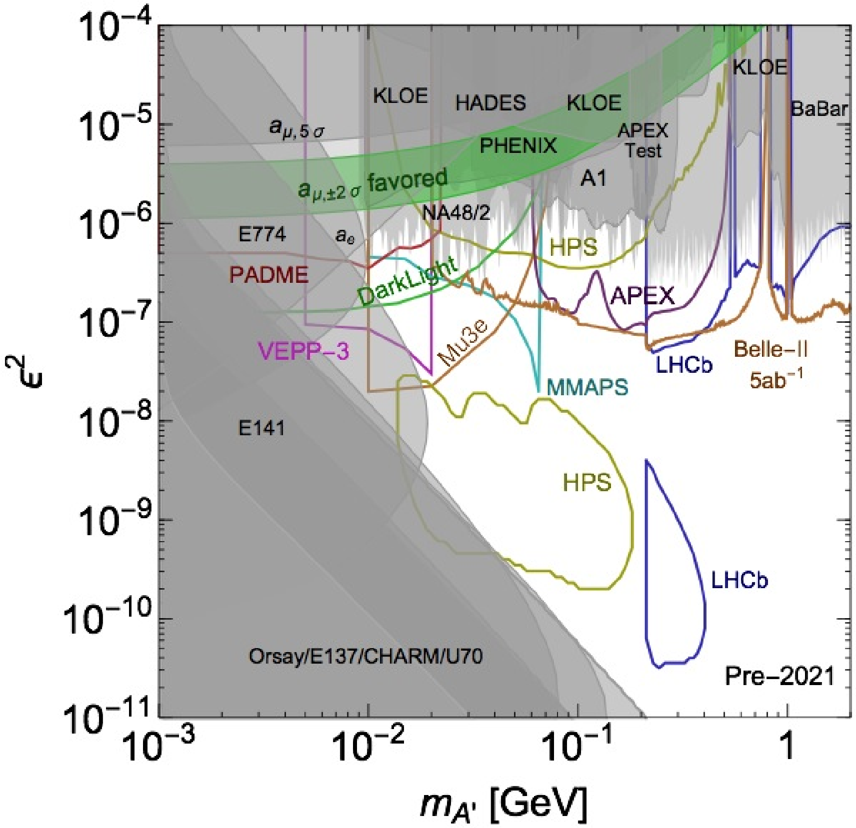
Brief comment on accelerator dark sector searches Dark Sectors Workshop 1608.08683

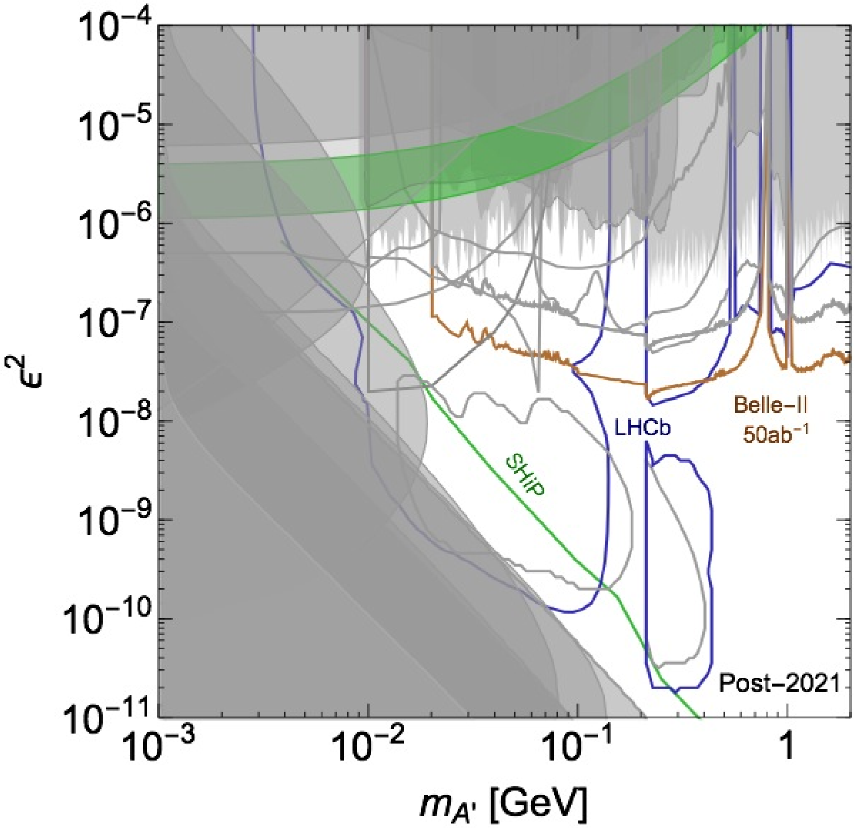
Dark sectors include one or more mediator particles coupled to the SM via a portal. The portal relevant for dark sector-SM interactions depends on the mediator spin and parity: it can be a scalar φ, a pseudoscalar a, a fermion N, or a vector $A^{'}$ (dark or hidden photon).



$$\mathcal{L} \supset \begin{cases} -\dfrac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu} \,, & \text{vector portal} \\ (\mu\phi + \lambda\phi^2) H^\dagger H \,, & \text{Higgs portal} \\ y_n L H N \,, & \text{neutrino portal} \\ \frac{a}{f_a} F_{\mu\nu} \widetilde{F}^{\mu\nu} \,, & \text{axion portal.} \end{cases}$$

Many proposals to detect dark sector particles in all types of accelerators (fixed target, lepton colliders, B factories).
e.g. Dark Photons $A^{'}$ search at LHCb via rare heavy quark decay modes producing a $A^{'}$ which could either produce MET or a visible decay, $A^{'} \rightarrow \mu^+\mu^-$ with or without a displaced vertex.


10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
ϵ^2
10^{-3}
10^{-2}
10^{-1}
1
$m_{A'}$ [GeV]
KLOE
HADES
KLOE
KLOE
BaBar
$a_{\mu,5\sigma}$
PHENIX
APEX
Test
$a_{\mu,\pm2\sigma}$ favored
A1
NA48/2
E774
a_e
HPS
PADME
DarkLight
APEX
Mu3e
VEPP−3
LHCb
Belle−II
$5ab^{-1}$
MMAPS
E141
HPS
LHCb
Orsay/E137/CHARM/U70
Pre−2021


10^{-4}
10^{-5}
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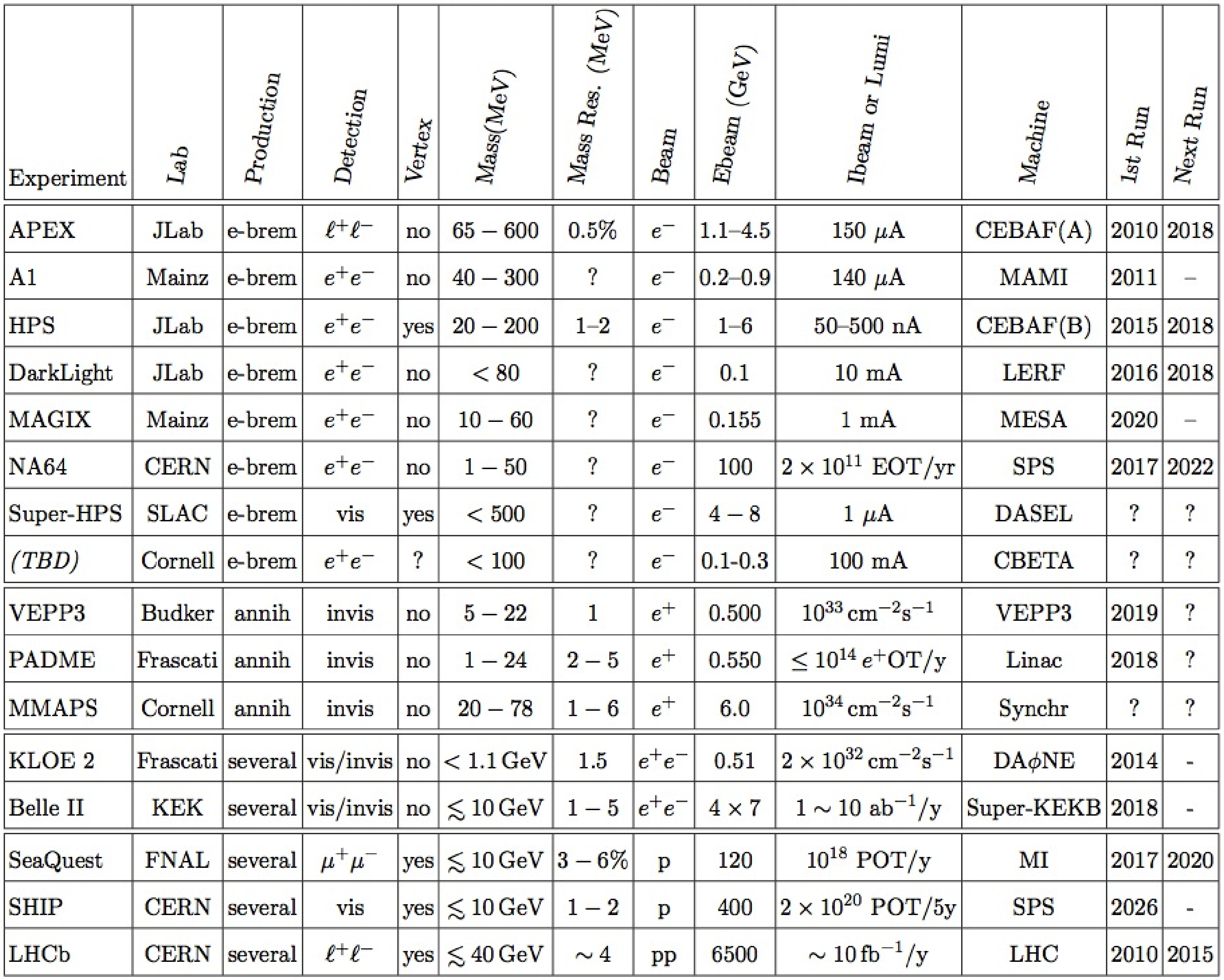
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
ϵ^2
10^{-3}
10^{-2}
10^{-1}
1
$m_{A'}$ [GeV]
Belle−II
$50ab^{-1}$
LHCb
SHiP
Post−2021

TABLE I: Summary of dark photon experiments.



Experiment	Lab	Production	Detection	Vertex	Mass(MeV)	Mass Res. (MeV)	Beam	Ebeam (GeV)	Ibeam or Lumi	Machine	1st Run	Next Run
APEX	JLab	e-brem	$\ell^+\ell^-$	no	$65-600$	0.5%	e^-	1.1–4.5	150 μA	CEBAF(A)	2010	2018
A1	Mainz	e-brem	e^+e^-	no	$40-300$	?	e^-	0.2–0.9	140 μA	MAMI	2011	–
HPS	JLab	e-brem	e^+e^-	yes	$20-200$	1–2	e^-	1–6	50–500 nA	CEBAF(B)	2015	2018
DarkLight	JLab	e-brem	e^+e^-	no	< 80	?	e^-	0.1	10 mA	LERF	2016	2018
MAGIX	Mainz	e-brem	e^+e^-	no	$10-60$	?	e^-	0.155	1 mA	MESA	2020	–
NA64	CERN	e-brem	e^+e^-	no	$1-50$	?	e^-	100	2×10^{11} EOT/yr	SPS	2017	2022
Super-HPS	SLAC	e-brem	vis	yes	< 500	?	e^-	$4-8$	1 μA	DASEL	?	?
(TBD)	Cornell	e-brem	e^+e^-	?	< 100	?	e^-	0.1-0.3	100 mA	CBETA	?	?
VEPP3	Budker	annih	invis	no	$5-22$	1	e^+	0.500	$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	VEPP3	2019	?
PADME	Frascati	annih	invis	no	$1-24$	$2-5$	e^+	0.550	$\leq 10^{14}\,e^+$OT/y	Linac	2018	?
MMAPS	Cornell	annih	invis	no	$20-78$	$1-6$	e^+	6.0	$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	Synchr	?	?
KLOE 2	Frascati	several	vis/invis	no	< 1.1 GeV	1.5	e^+e^-	0.51	$2\times10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	DAϕNE	2014	-
Belle II	KEK	several	vis/invis	no	$\lesssim 10$ GeV	$1-5$	e^+e^-	4×7	$1\sim10\ \mathrm{ab}^{-1}$/y	Super-KEKB	2018	-
SeaQuest	FNAL	several	$\mu^+\mu^-$	yes	$\lesssim 10$ GeV	$3-6\%$	p	120	10^{18} POT/y	MI	2017	2020
SHIP	CERN	several	vis	yes	$\lesssim 10$ GeV	$1-2$	p	400	2×10^{20} POT/5y	SPS	2026	-
LHCb	CERN	several	$\ell^+\ell^-$	yes	$\lesssim 40$ GeV	~ 4	pp	6500	$\sim 10\,\mathrm{fb}^{-1}$/y	LHC	2010	2015