Dark Matter Searches at the LHC

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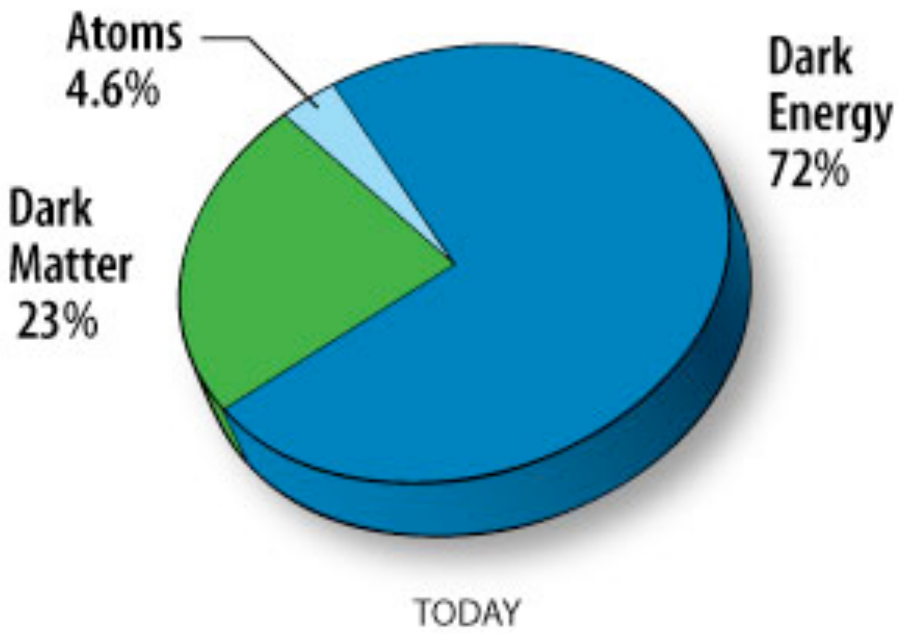
Banff DM-Statistics Workshop 2018

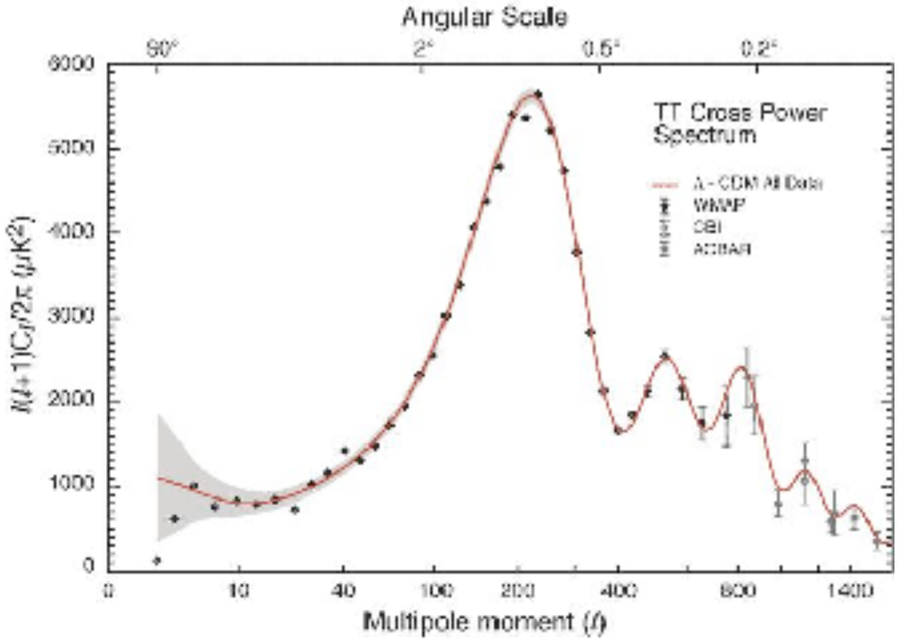
Dark Matter Motivation

Abundance of astrophysical evidence for the existence of cold, dark matter (DM).

Galaxy Rotation Curves

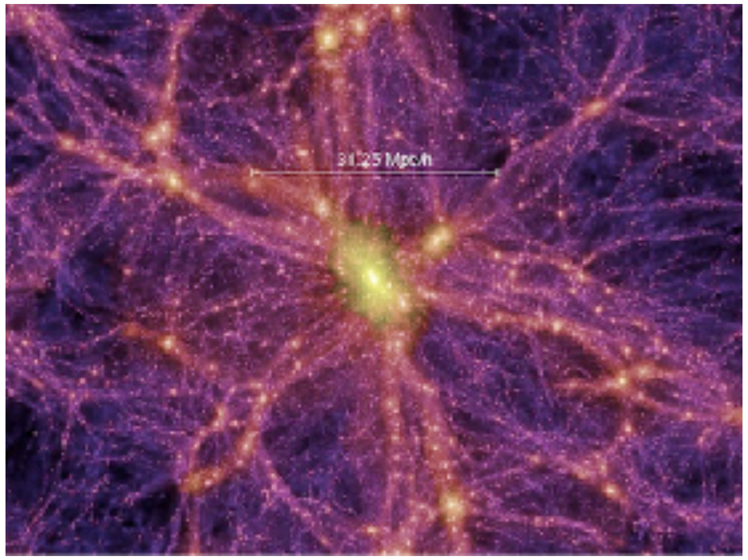


CMB



Gravitational Lensing

Structure Formation

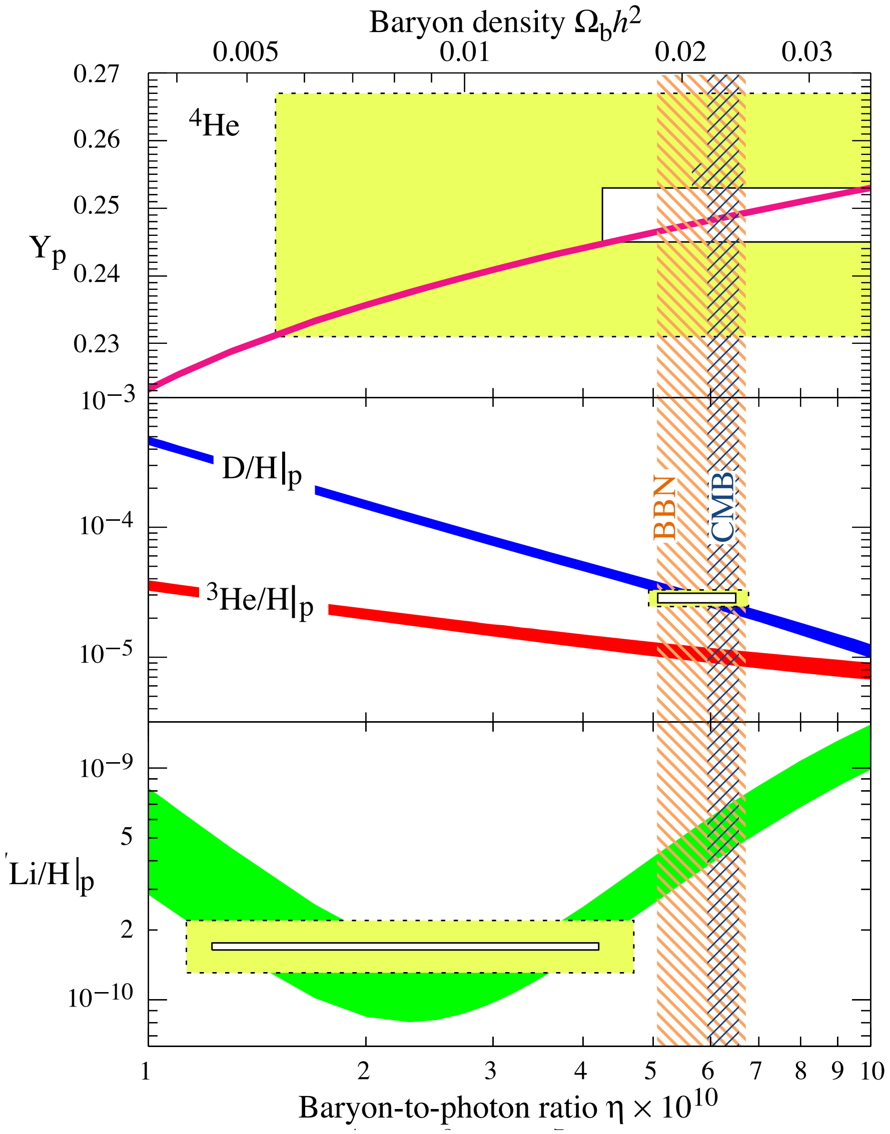


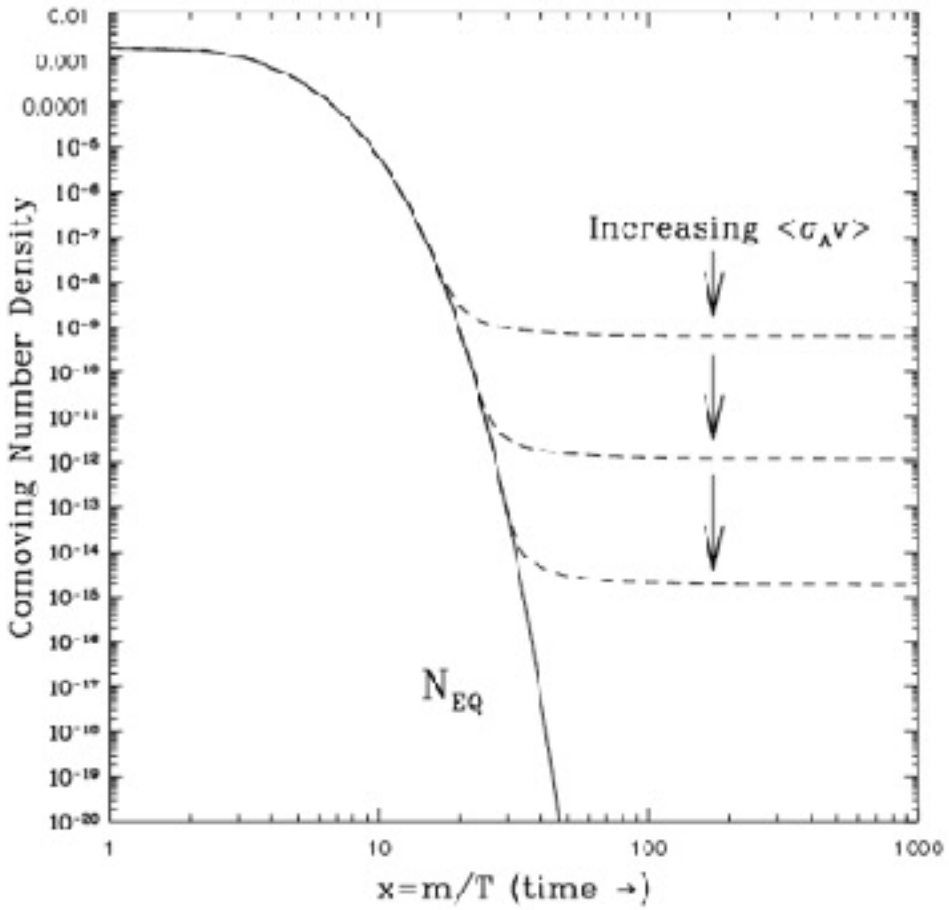
Particle Dark Matter

Dark matter cannot be explained by Standard Model (SM) particles.

- CMB and Big Bang Nucleosynthesis measure the baryon fraction and rule out ordinary dark baryons.

- Supporting a new, Beyond the Standard Model (BSM) particle, WIMP miracle predicts a weakly interacting particle will freeze out with correct relic abundance to account for current dark matter density.

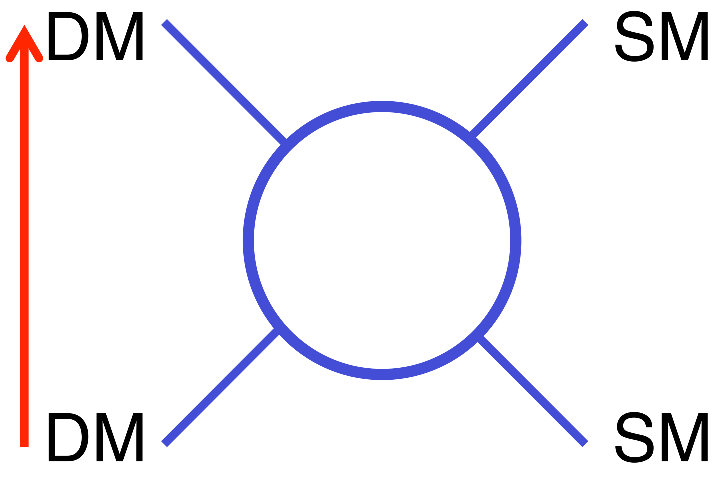




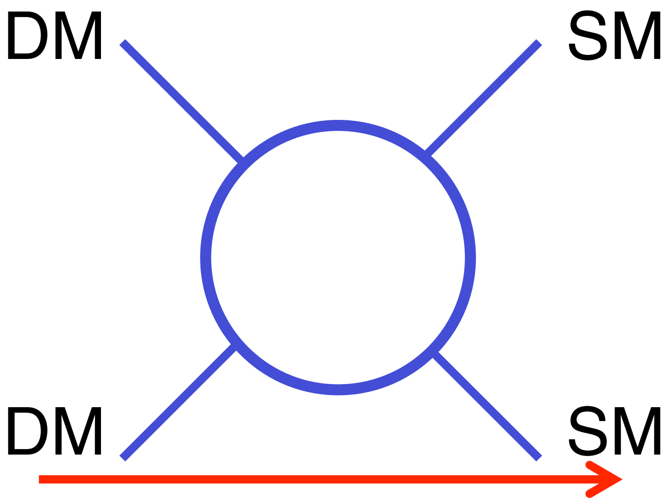
$$< \sigma v > \simeq 3 \cdot 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

Detection Methods

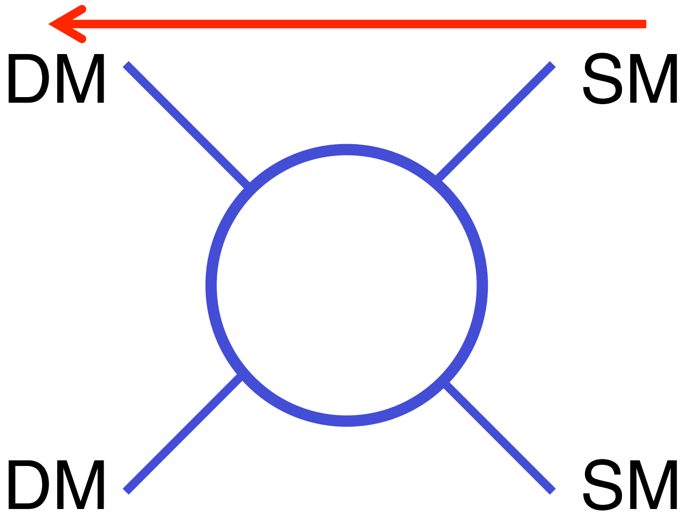
Direct Detection



Indirect Detection



Collider Production

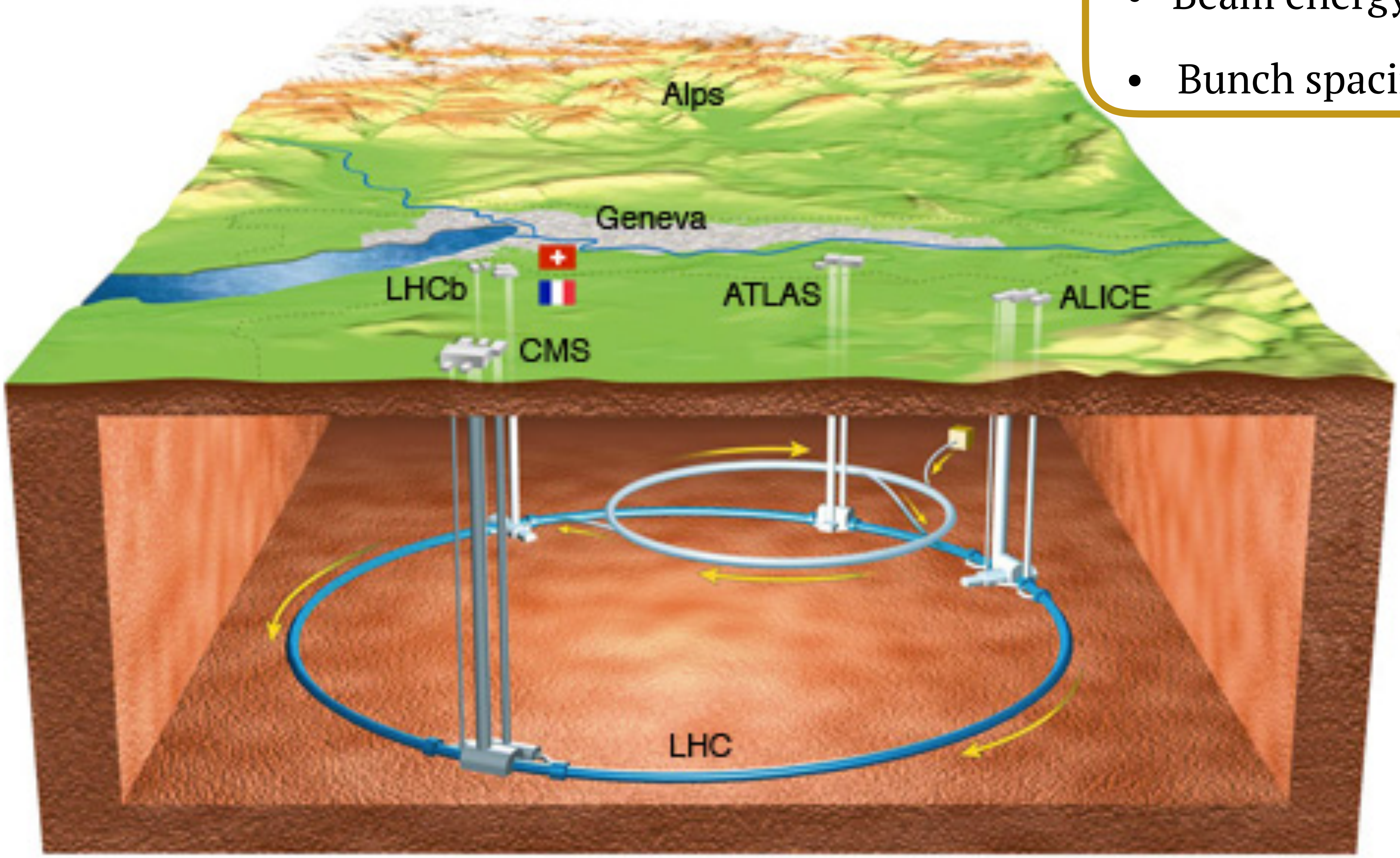


LHC

Located along the French-Swiss border, the Large Hadron Collider is a proton-proton accelerator. Collisions occur at center of mass energies of 13 TeV.

Since 2015

- Beam energy: 6.5 TeV
- Bunch spacing: 25 ns



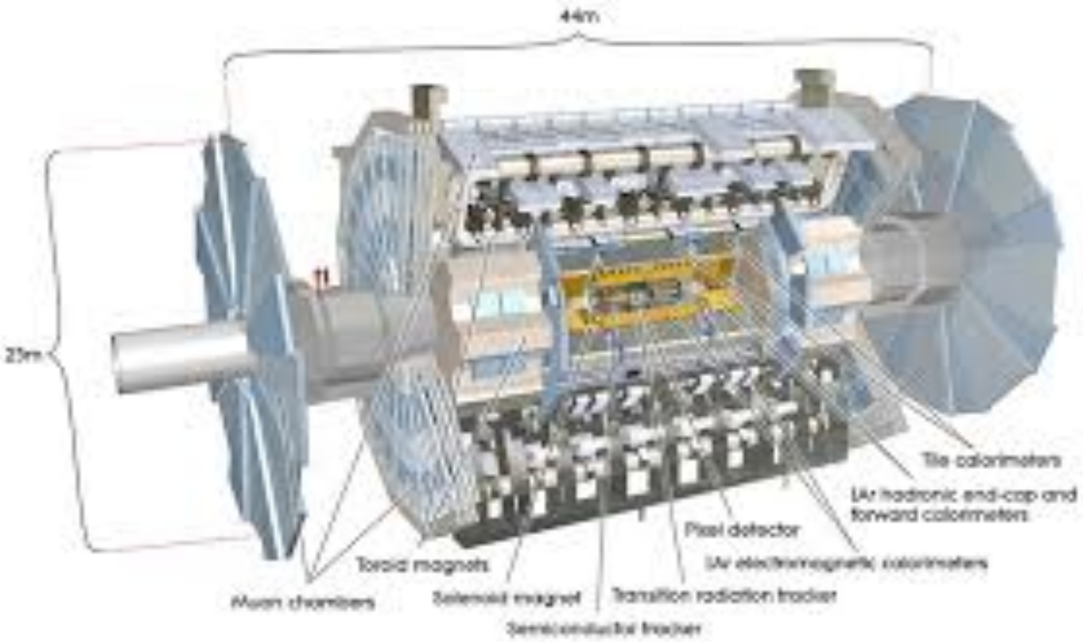
LHC

Experiments

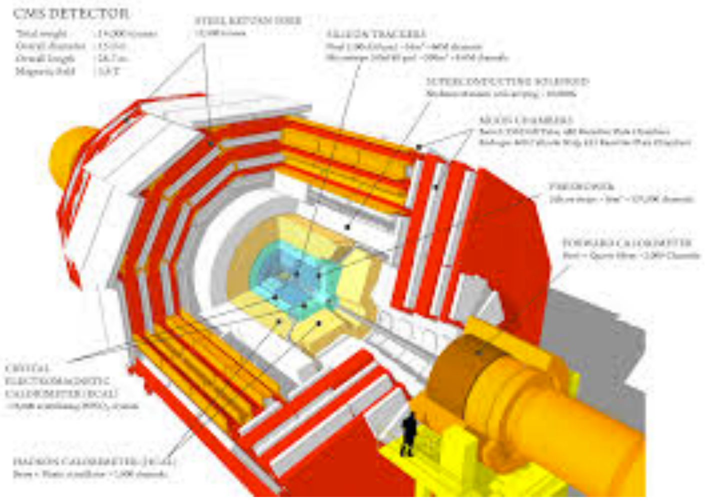
There are four main detectors located along the LHC ring:

General Discovery

ATLAS

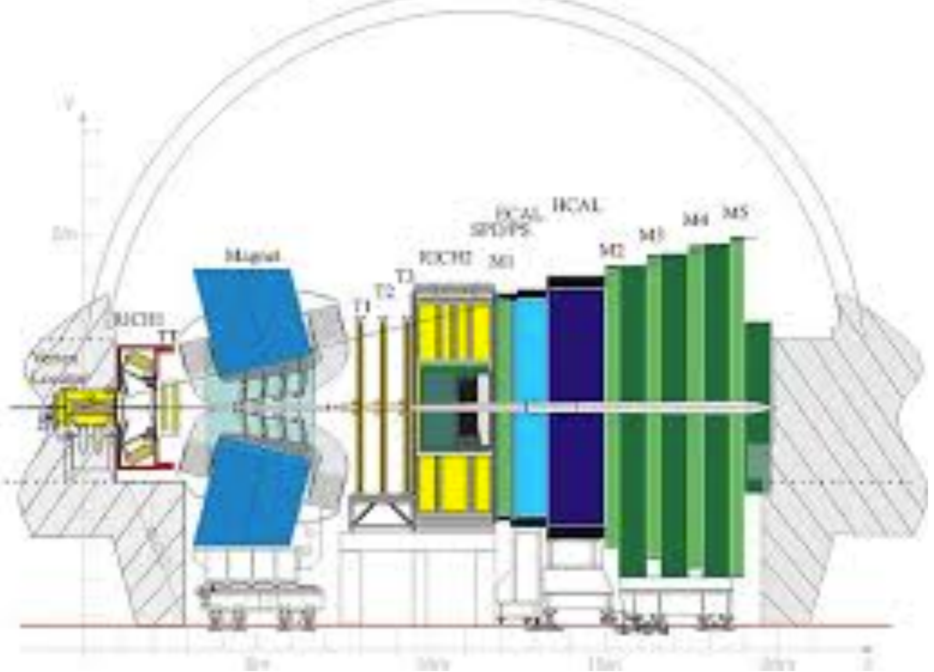


CMS

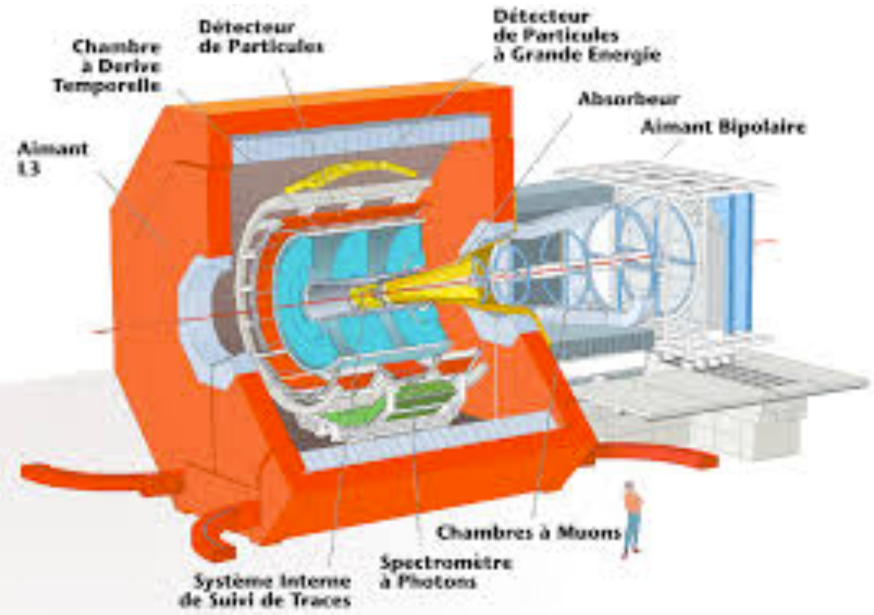


Specialized

LHCb

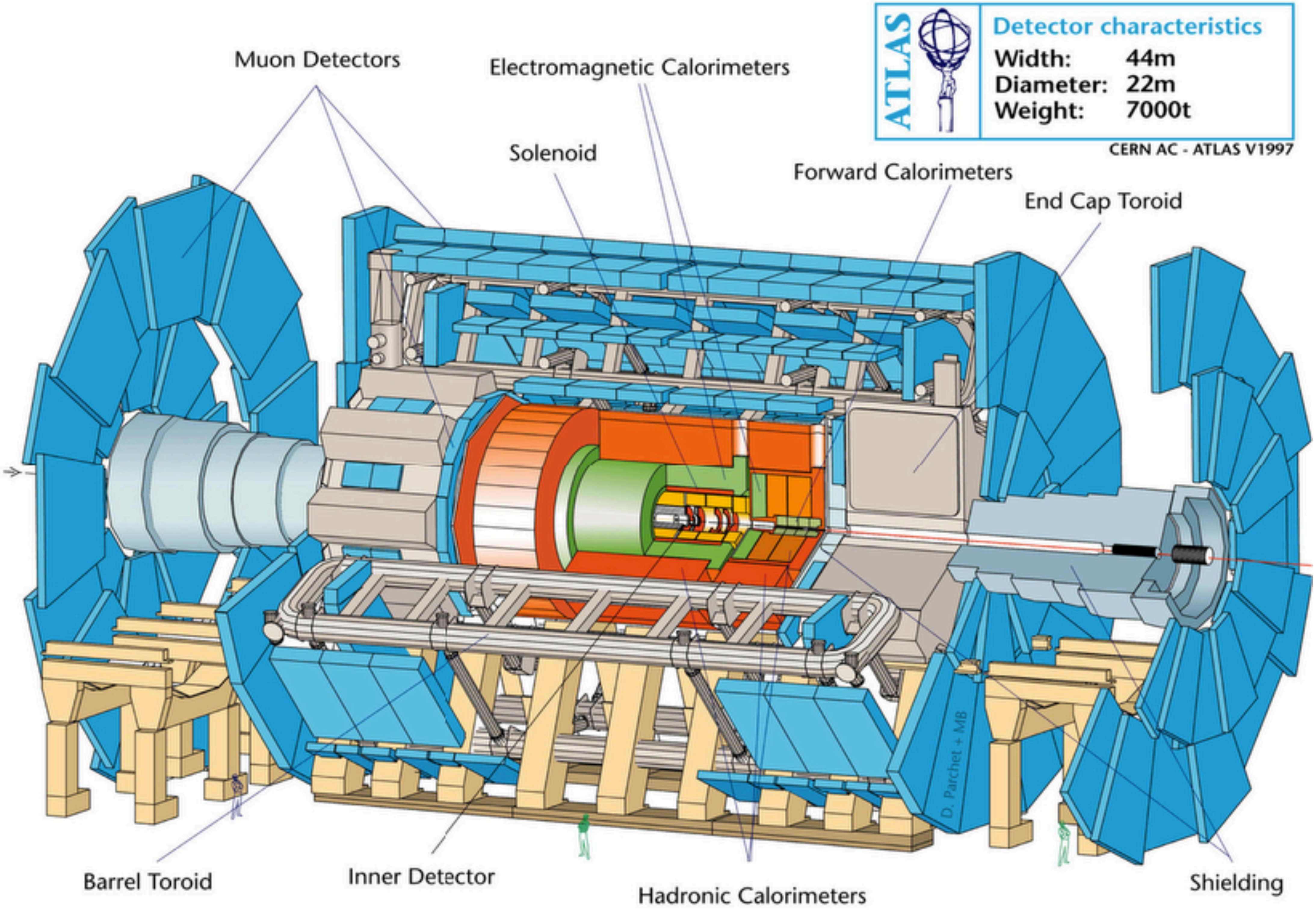


ALICE

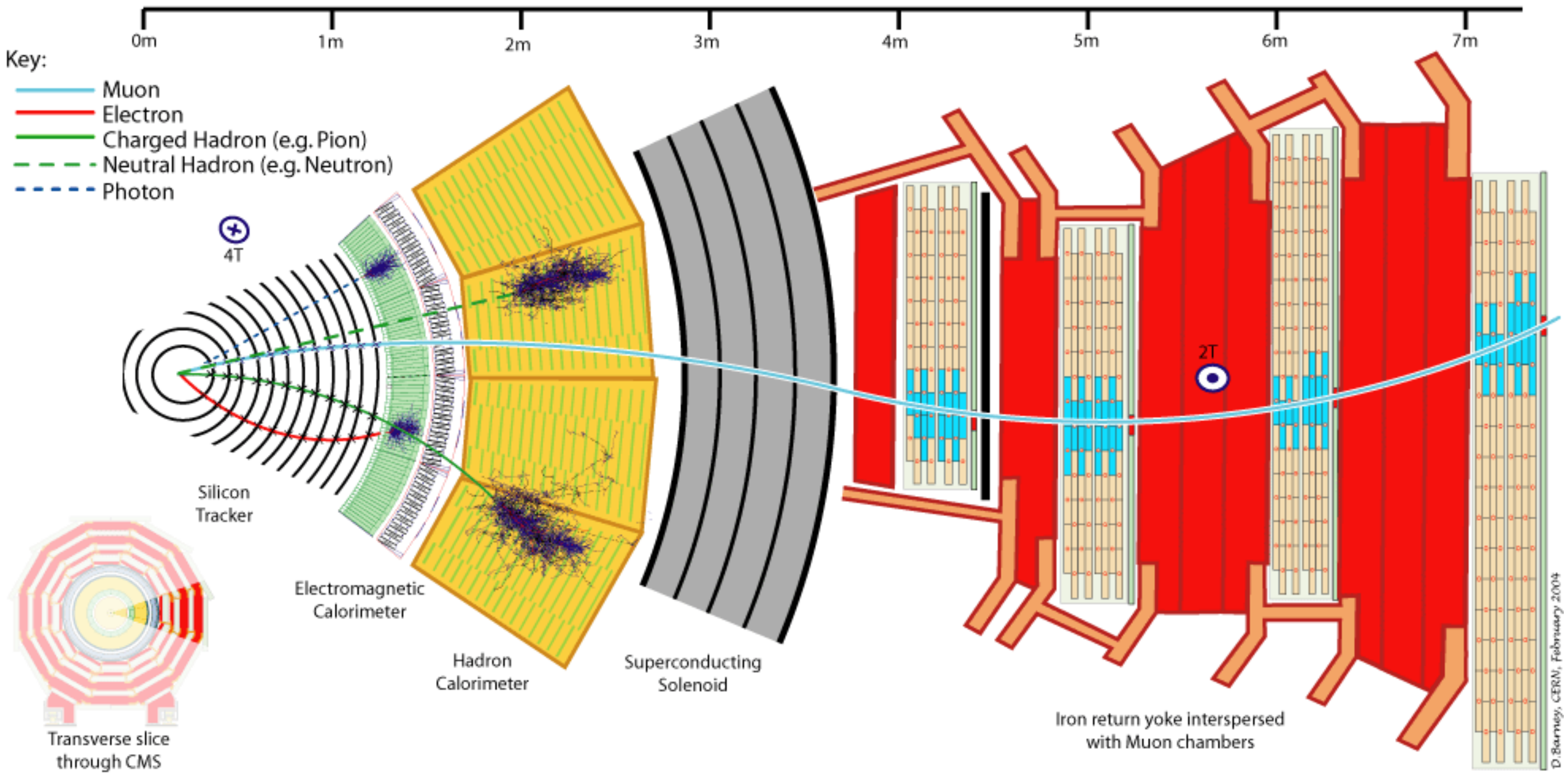


Experiments

ATLAS and CMS detectors consist of an Inner Tracker, Electromagnetic Calorimeter (ECAL), Hadronic Calorimeter (HCAL) , Muon System, and Magnetic Field.



Particle Reconstruction



- Basic reconstruction elements: **charged tracks** in the Inner Tracker, **energy clusters** in the ECAL and HCAL, and **muon tracks** in the Muon System.

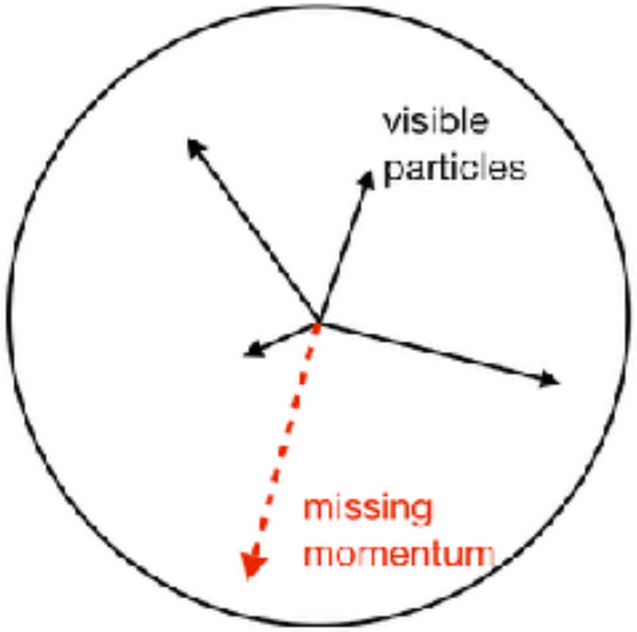
- Elements are grouped together to identify **muons**, **electrons**, **photons**, **charged hadrons**, and **neutral hadrons**.

Mono-X + MET

Look for DM through the presence of missing transverse energy (MET) in the detector:

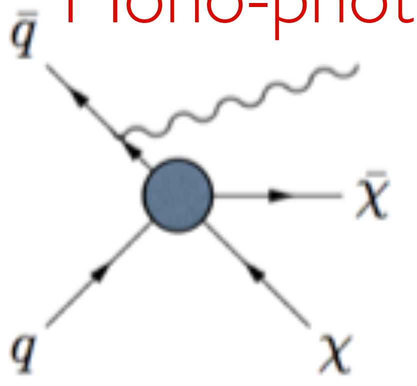
$\mathbf{E_T^{miss}} = -\Sigma\, \overrightarrow{p_T}$ All Reconstructed Objects

Neutrinos also produce $\mathbf{E_T^{miss}}$,and are one of the main source of background.

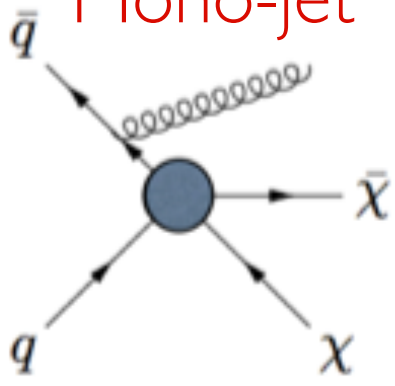


P_T imbalance requires the DM production to be recoiled against something. For recoil off of Initial State Radiation (ISR), there are the Mono-Jet, Mono-Photon, and Mono-Z signatures.

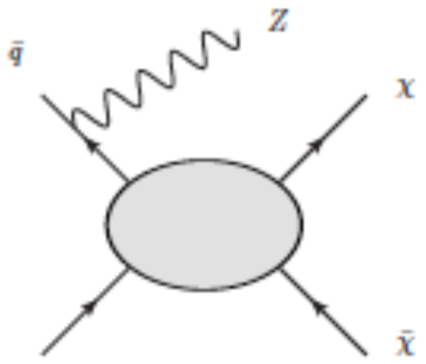
Mono-photon



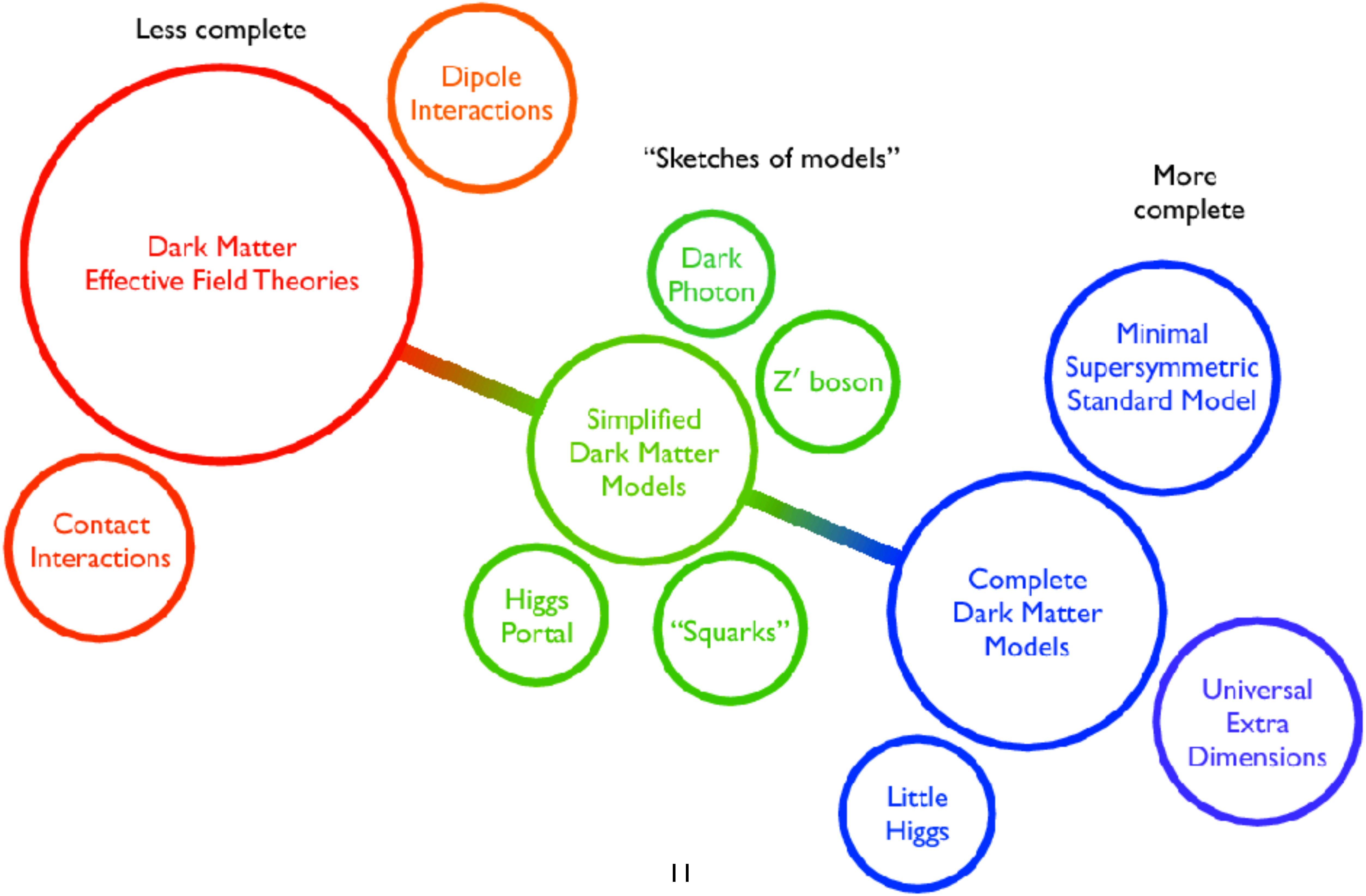
Mono-jet



Mono-Z



Dark Matter Models

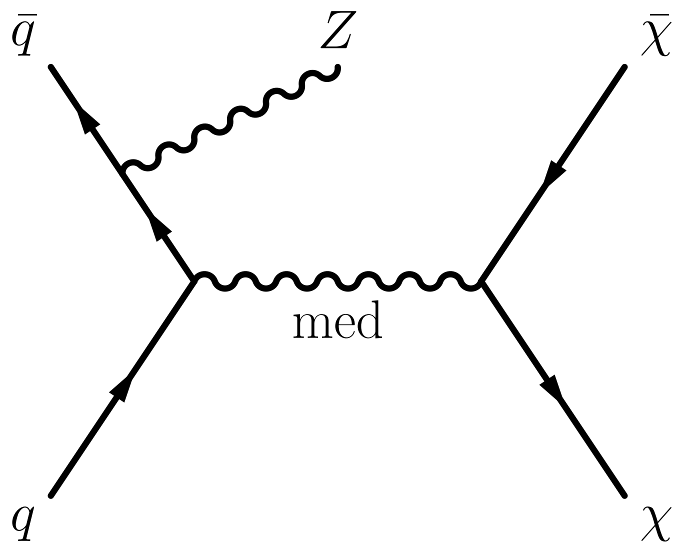


Simplified Models

Collider searches use simplified models of DM.

Mediator types:

- **Vector**
- **Axial-vector**
- Scalar
- Pseudoscalar



DM simplified models have 6 free parameters:

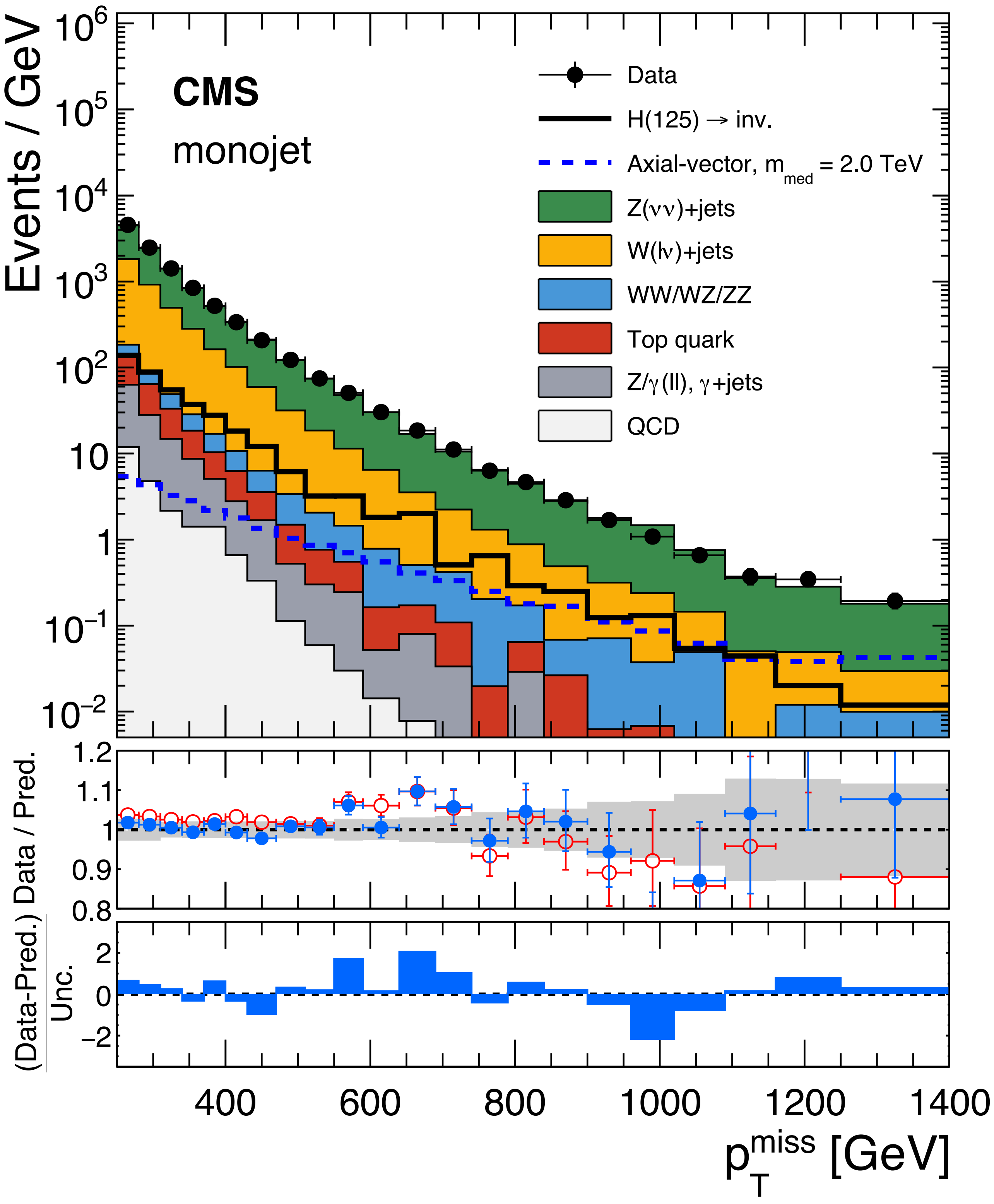
- g_q - mediator coupling to quarks
- g_ℓ - mediator coupling to leptons
- g_χ - mediator coupling to DM
- M_{DM} - DM mass
- M_{med} - Mediator mass
- Γ_{med} - Mediator width

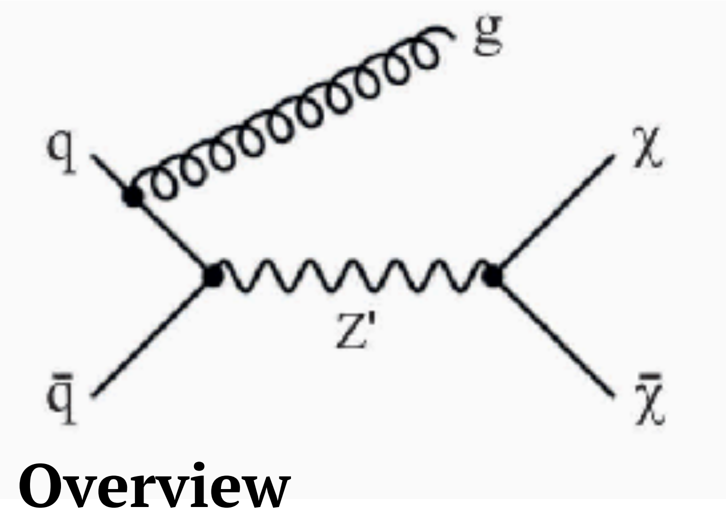
Following the recommendations of the DM Working Group, ATLAS and CMS have agreed to study a common set of couplings values:

- For Vector and Axial-vector models $g_q=0.25$, $g_\ell=0$, $g_\chi=1$
- Γ_{med} is set using the minimal width formula.
- Results are shown as 2D exclusion plots in M_{med} : M_{DM}.

Analysis Strategy (Mono-Jet)

arXiv:1712.02345





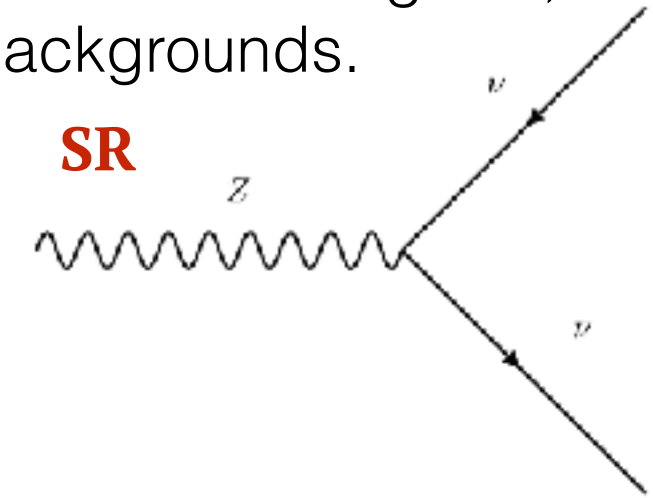
Analysis Overview

- Estimate signal through Monte Carlo simulation. (including detector response)
- Estimate Background through Monte Carlo and Data Driven Estimates.
- Optimize Selection Cuts for maximum Signal over Background
- Bin Events by Discriminating Variable
- Unblind Data
- Calculate Likelihoods for discovery significances and 95% CL exclusion limits.

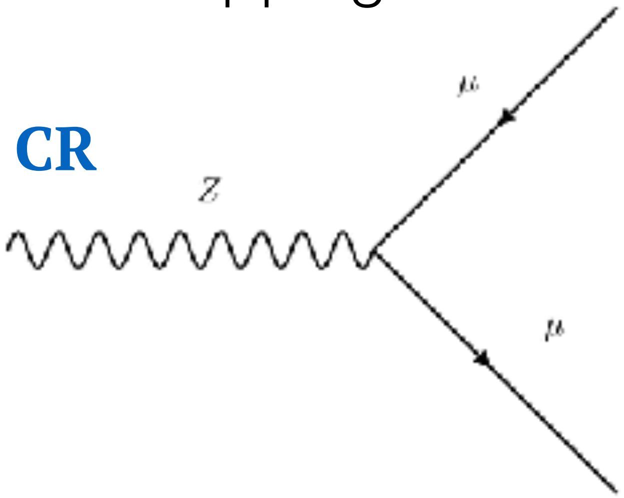
Data Driven Estimates

Data control regions, non-overlapping with the signal region, are leveraged to estimate backgrounds.

SR

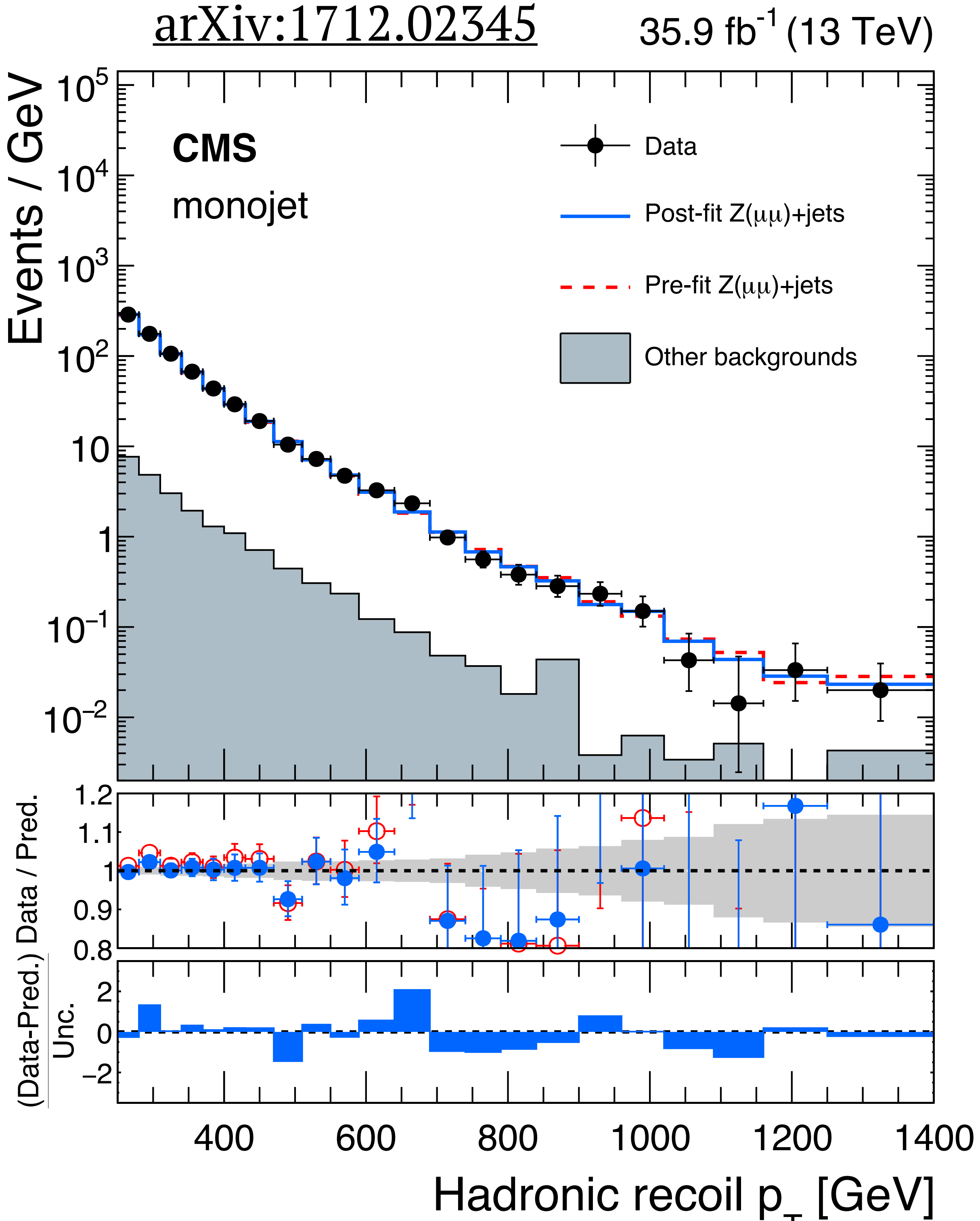


CR



- One of the main backgrounds for Mono-Jet is Z(νν) + jets.
- Dimuon control region is same as signal region, but with inverted lepton veto and requirement of muon pair consistent with Z-boson decay.
- Simulated transfer factors account for branching fractions and different selection efficiencies, multiply control region Z(μμ) to estimate Z(νν) background in the signal region.
- Five control regions used for final estimate of Z(νν) + jets and W(ℓν) + jets backgrounds, fit to maximum likelihood.

arXiv:1712.02345



Control regions also used to validate simulated background estimates.

Likelihood Profile

Likelihood for observed number of events following a Poisson distribution. Product over nbins.

Signal **Estimated Background**

$$\mathcal{L}(\mu) = \prod_{i=1}^{nbins} \mathrm{Pois}(x_i|\mu \cdot s_i(\theta) + b_i(\theta)) \times P_n(\theta)$$

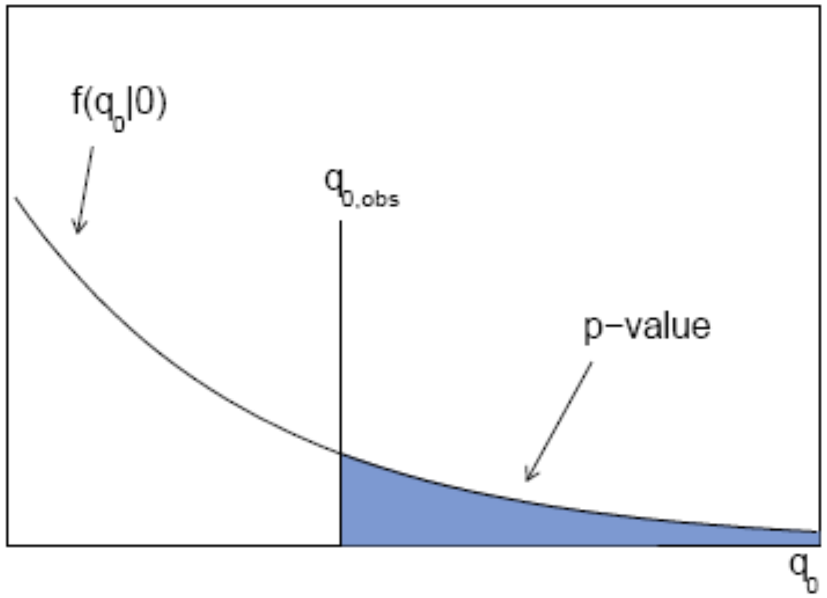
Observed Events **Strength Parameter** **Nuisance Parameters**

Significances and limits are calculated using a likelihood profile test statistic, q_μ. From Wilk's theorem, test statistic behaves asymptotically as a $\chi 2$ distribution.

$$q_\mu = -2\ln \frac{\mathcal{L}(\mu, \hat{\hat{\theta}})}{\mathcal{L}(\hat{\mu}, \hat{\theta})}$$

← maximizes likelihood for specific μ

← global maximum likelihood



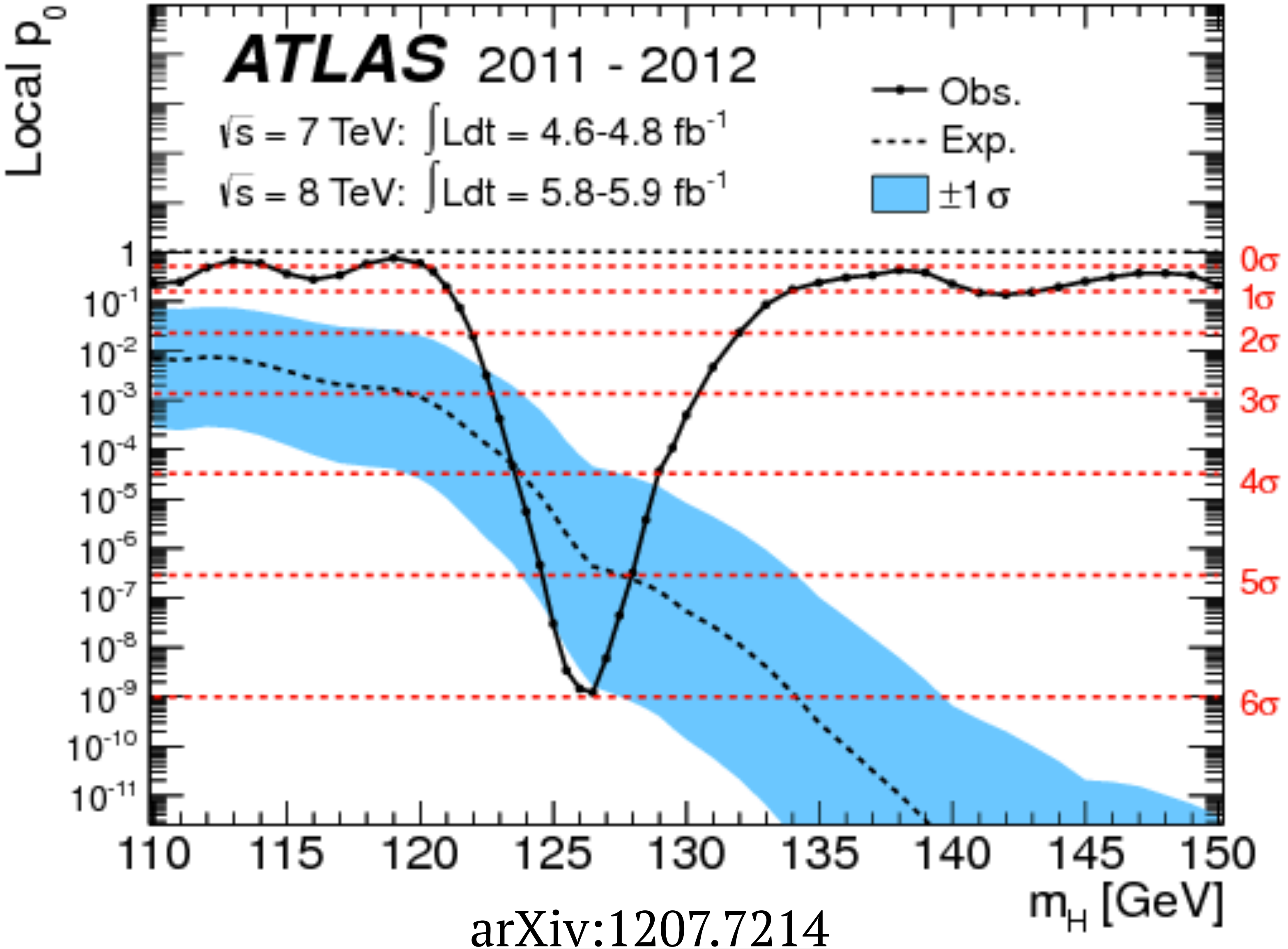
From the distribution, $\chi 2$, get p-value for specific q. Can convert p-value into equivalent significance.

$$Z = \Phi^{-1}(1-p)$$

Inverse Gaussian CDF

Discovery

For discovery significance is calculated over the background only hypothesis, μ = 0.



arXiv:1207.7214

Definition of test-statistic:

$$q_0 = \begin{cases} -2\ln\lambda(0) & \hat{\mu} \geq 0 \\ 0 & \hat{\mu} < 0 \end{cases}$$

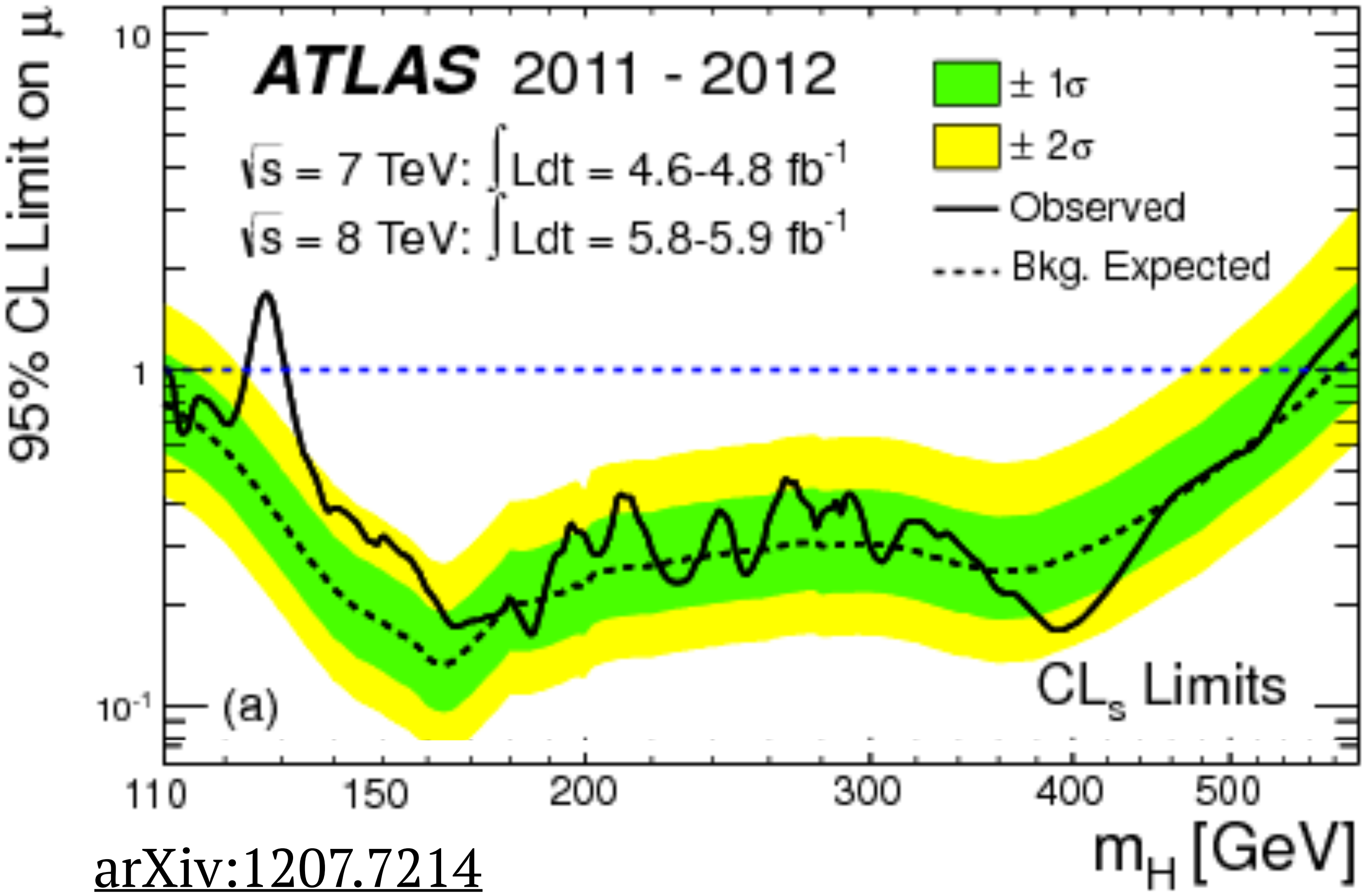
(One sided profile likelihood) with:

$$\lambda(0) = \frac{\mathcal{L}(0, \hat{\hat{\theta}})}{\mathcal{L}(\hat{\mu}, \hat{\theta})}$$

Dashed line shows expected significance for the μ = 1 (SM Higgs boson) case.

Exclusion Limits

For exclusion limits, scan signal models and hypothesis test to find 95% confidence level.



arXiv:1207.7214

Definition of test-statistic:

$$\tilde{q}_\mu = \begin{cases} -2\ln\tilde{\lambda}(\mu) & \hat{\mu} \le \mu \\ 0 & \hat{\mu} > \mu \end{cases}$$

Again one-sided profile likelihood:

$$\tilde{\lambda}(\mu) = \begin{cases} \frac{L(\mu,\hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(\hat{\mu},\hat{\boldsymbol{\theta}})} & \hat{\mu} \ge 0 \\ \frac{L(\mu,\hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(0,\hat{\hat{\boldsymbol{\theta}}}(0))} & \hat{\mu} < 0 \end{cases}$$

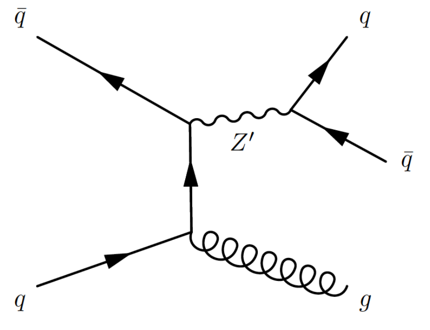
For small expected signal compared to background, use CLs method.

$$\mathrm{CL}_s \equiv \frac{p_{s+b}}{1-p_b} \qquad \begin{aligned} p_{s+b} &= P(q \ge q_{\mathrm{obs}}|s+b) \\ p_b &= P(q \le q_{\mathrm{obs}}|b) \end{aligned}$$

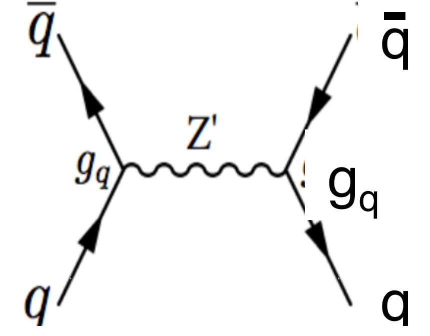
For 2D exclusion plots (Simplified Model), at each point (M_{med}, M_{DM}) calculate CLs values for nominal signal, q_1. Draw contour along CLs = 0.05.

Simplified Model Results

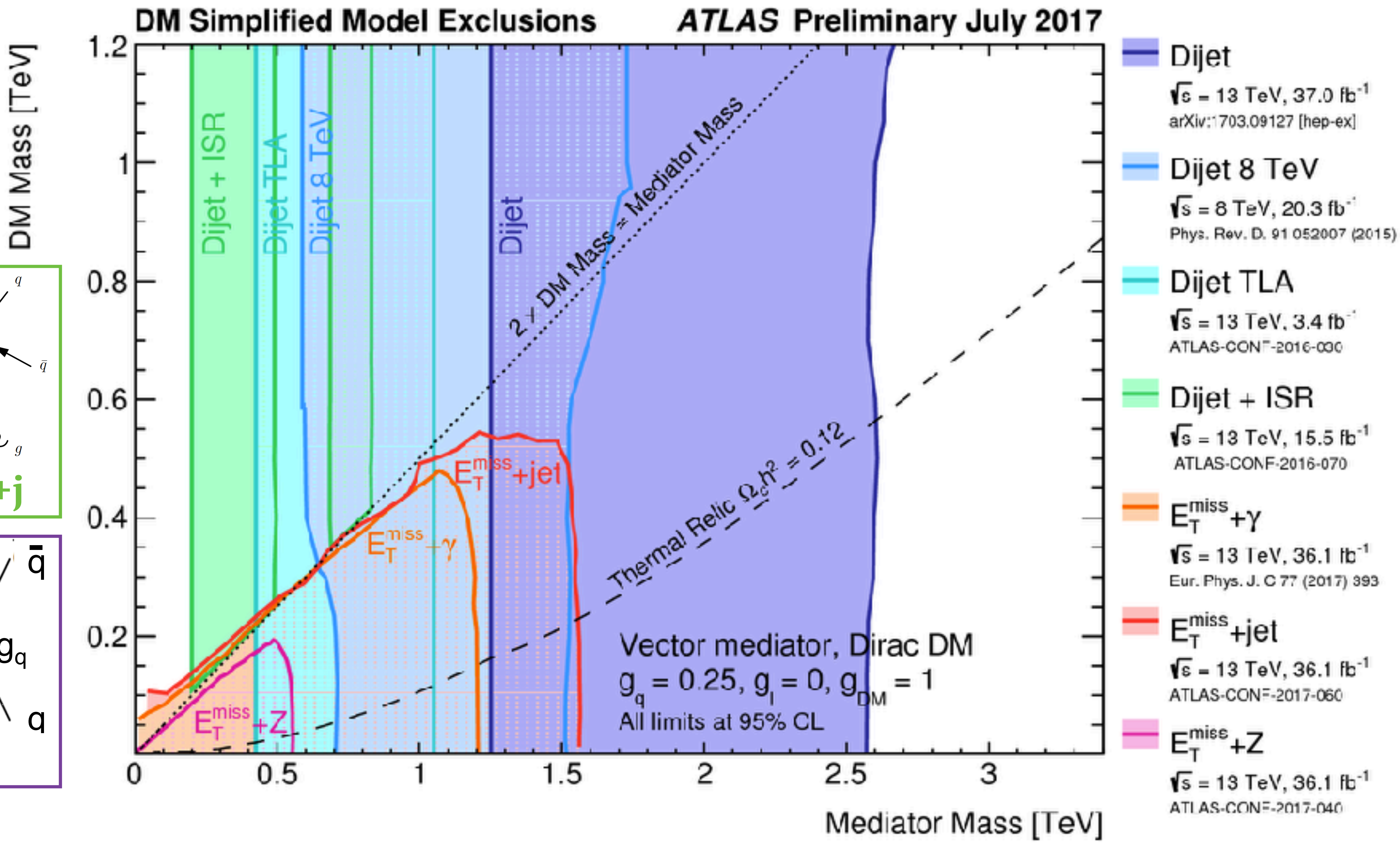
Vector model:



Z' → (jj) +j



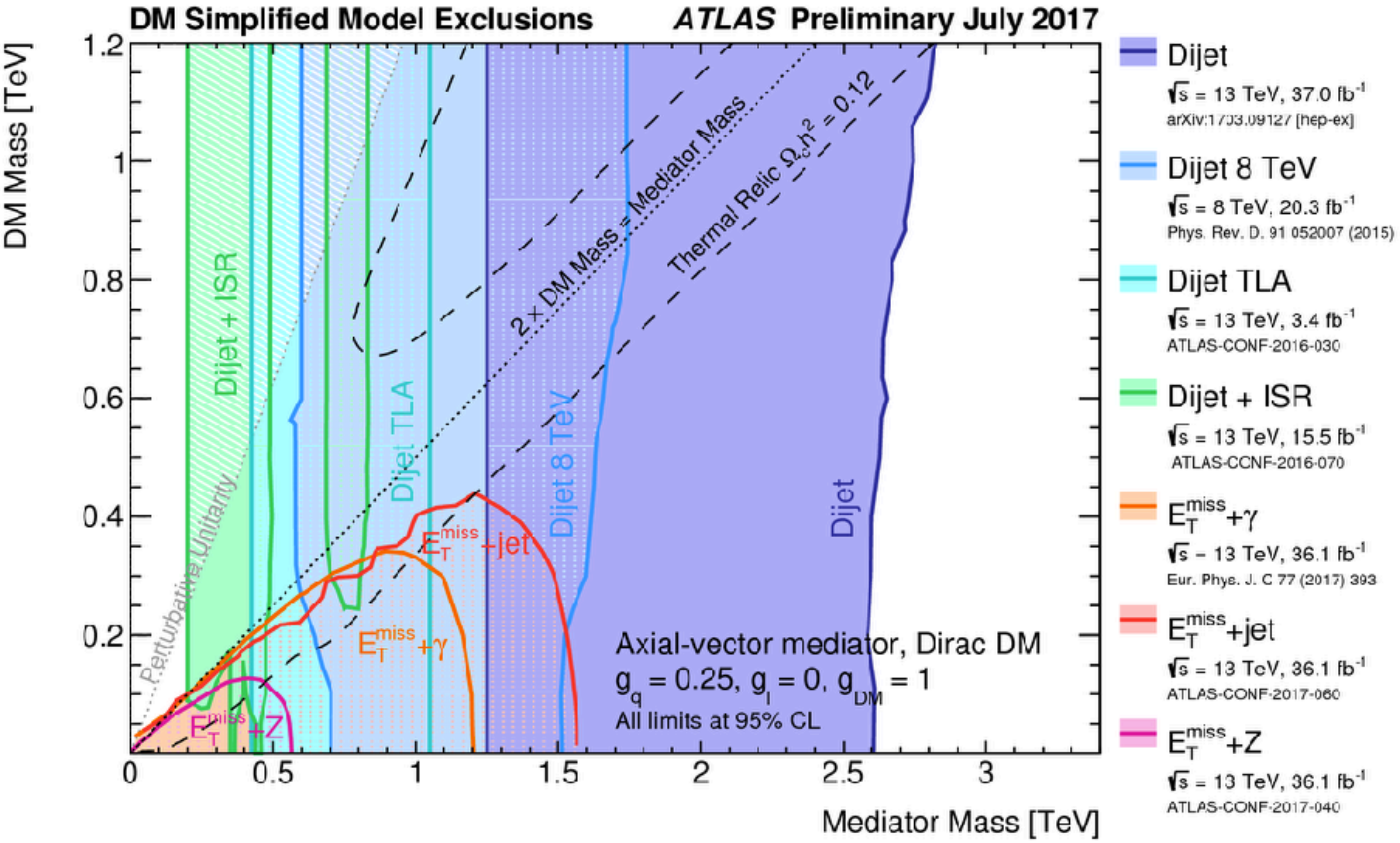
Z' → j+j



Because mediators couple to quarks, they can also decay to dijet final states.

Simplified Model Results

Axial-vector model:

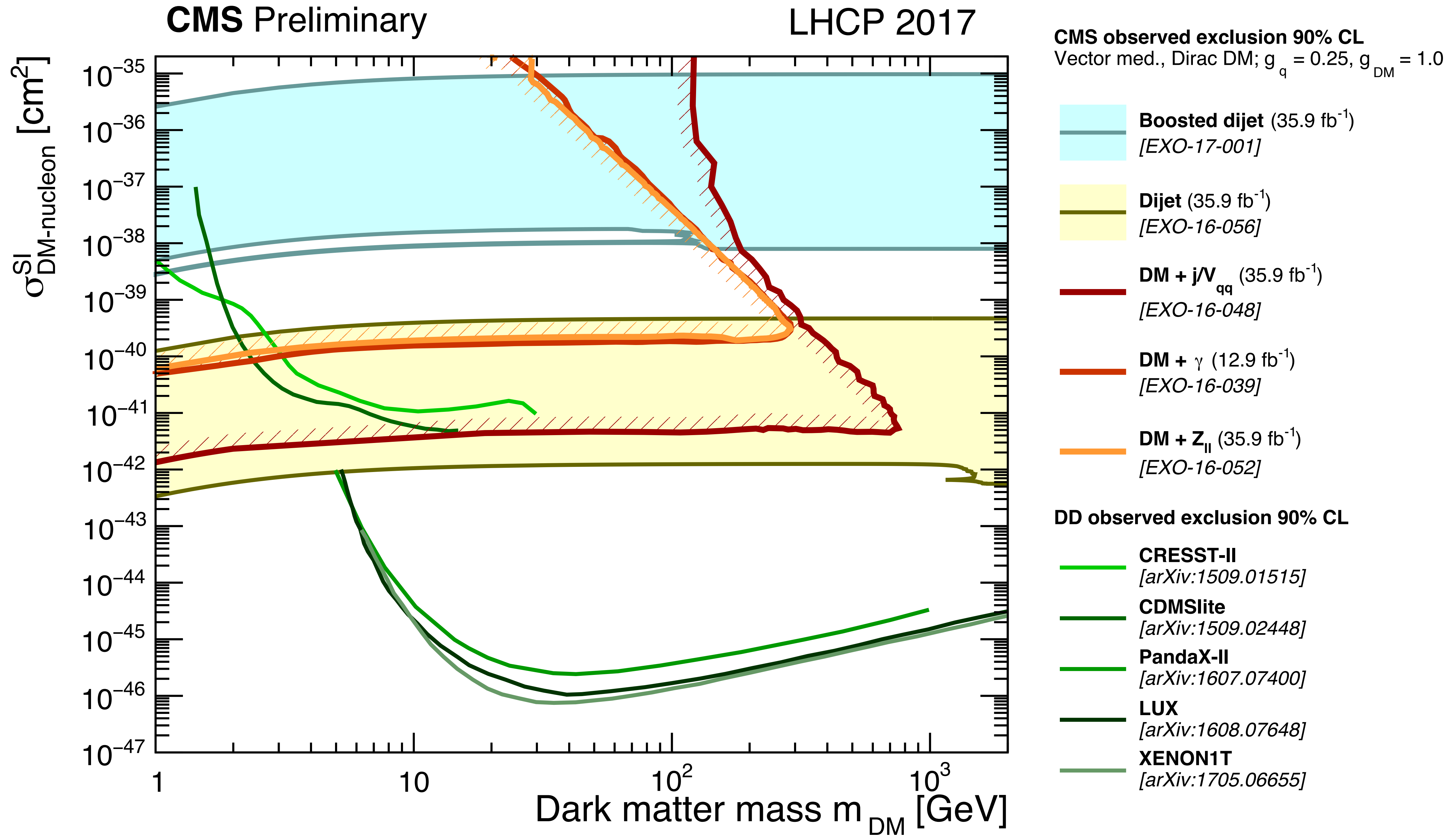


Comparing to Direct Detection

Simplified models allow for comparison between direct detection and collider results:

Vector model:

$$\sigma^{0}_{\mathrm{SI}} \approx 1.1 \times 10^{-39}\ \mathrm{cm}^2 \cdot \left(\frac{g_{\mathrm{DM}}\, g_q}{1}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$$

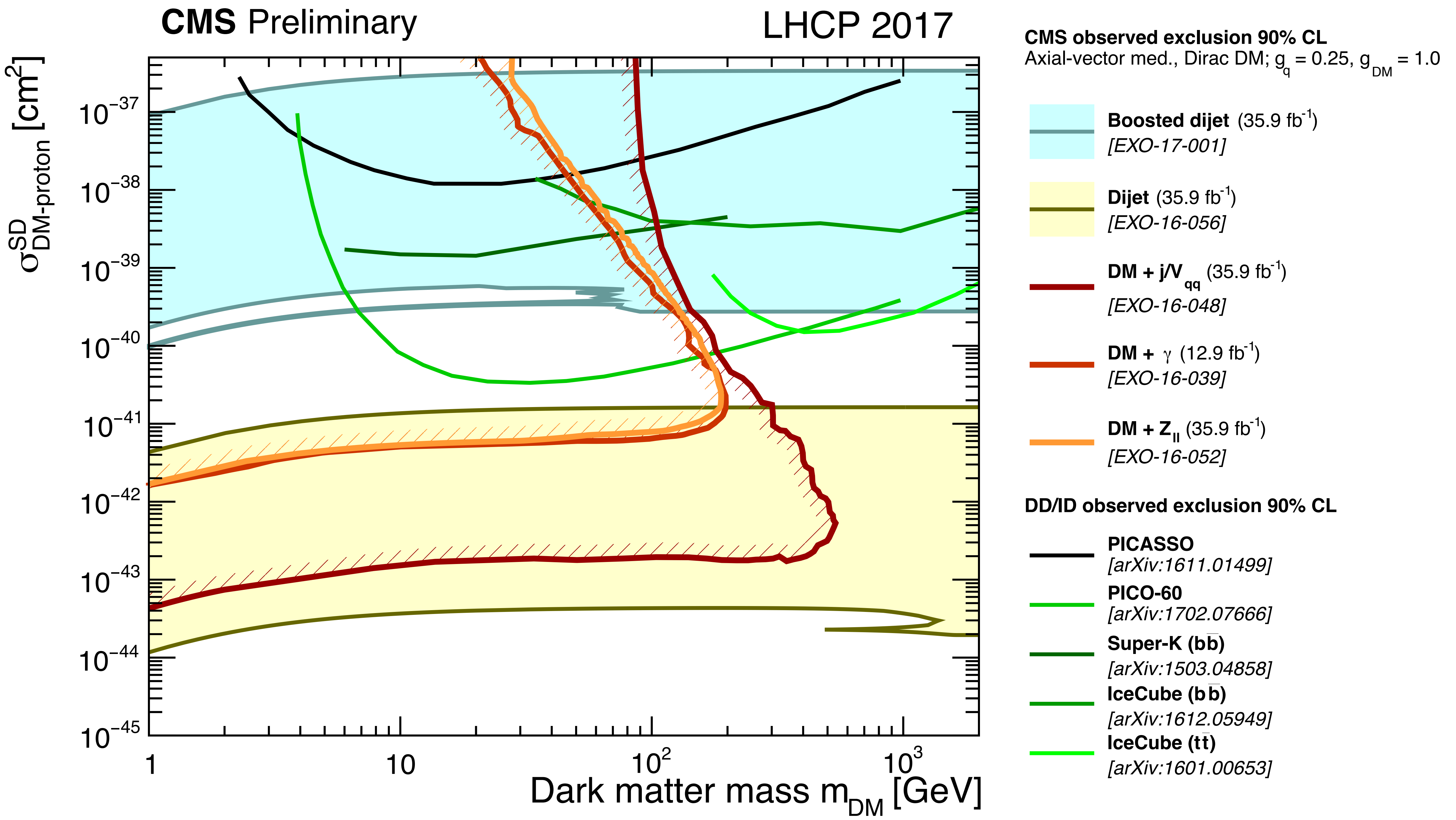


Comparing to Direct Detection

Simplified models allow for comparison between direct detection and collider results:

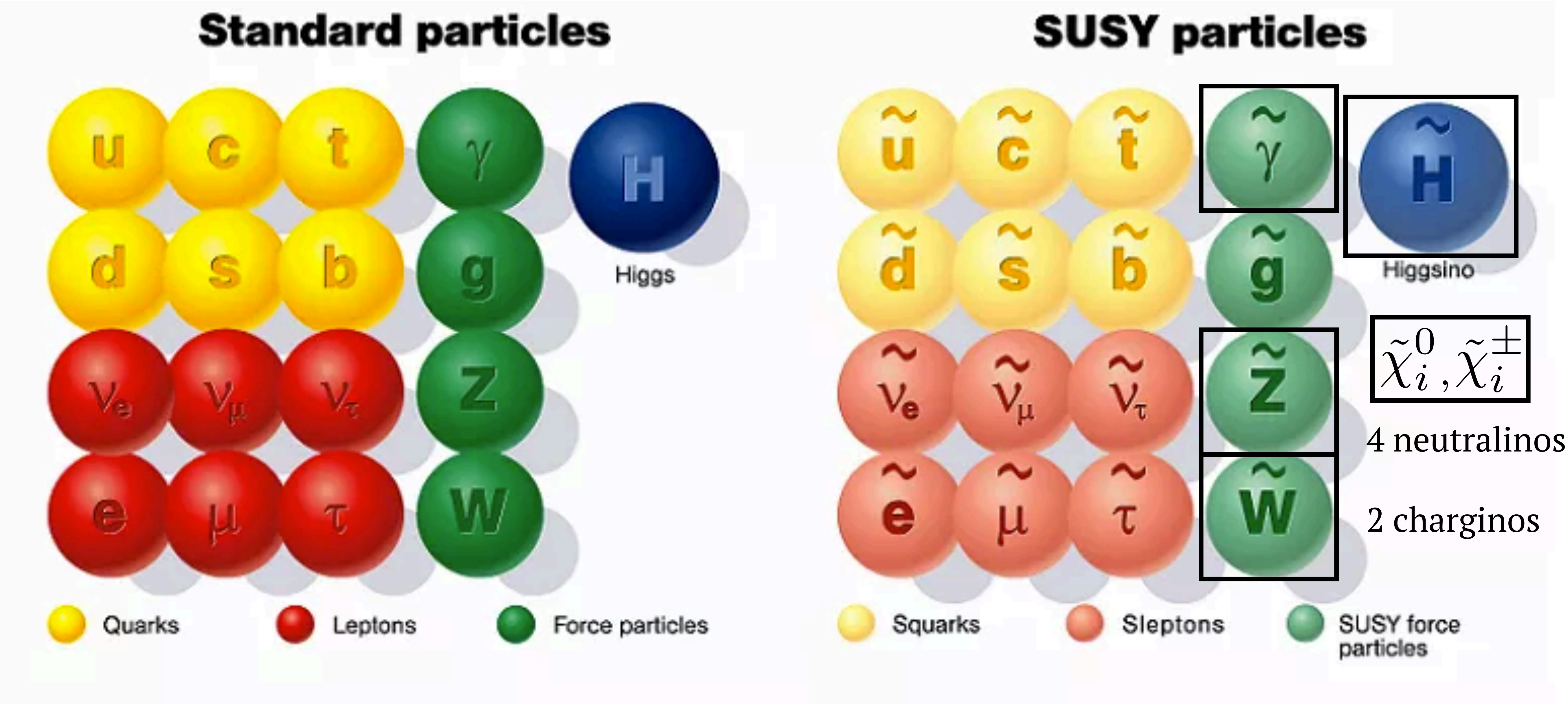
Axial-vector model:

$$\sigma^0_{\mathrm{SD}} \approx 4.6 \times 10^{-41}\ \mathrm{cm}^2 \cdot \left(\frac{g_{\mathrm{DM}}\, g_q}{1}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$$



Supersymmetry

Supersymmetry (SUSY) is a well developed theory for solving the hierarchy problem in the SM. Each SM particle has a supersymmetric pair.



$\tilde{\chi}_i^0, \tilde{\chi}_i^\pm$

4 neutralinos

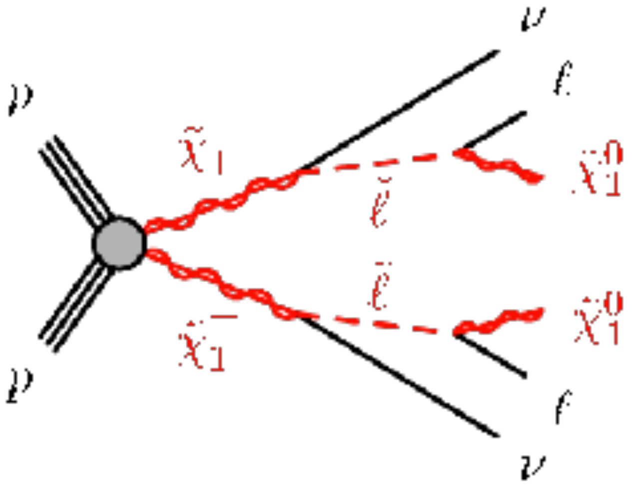
2 charginos

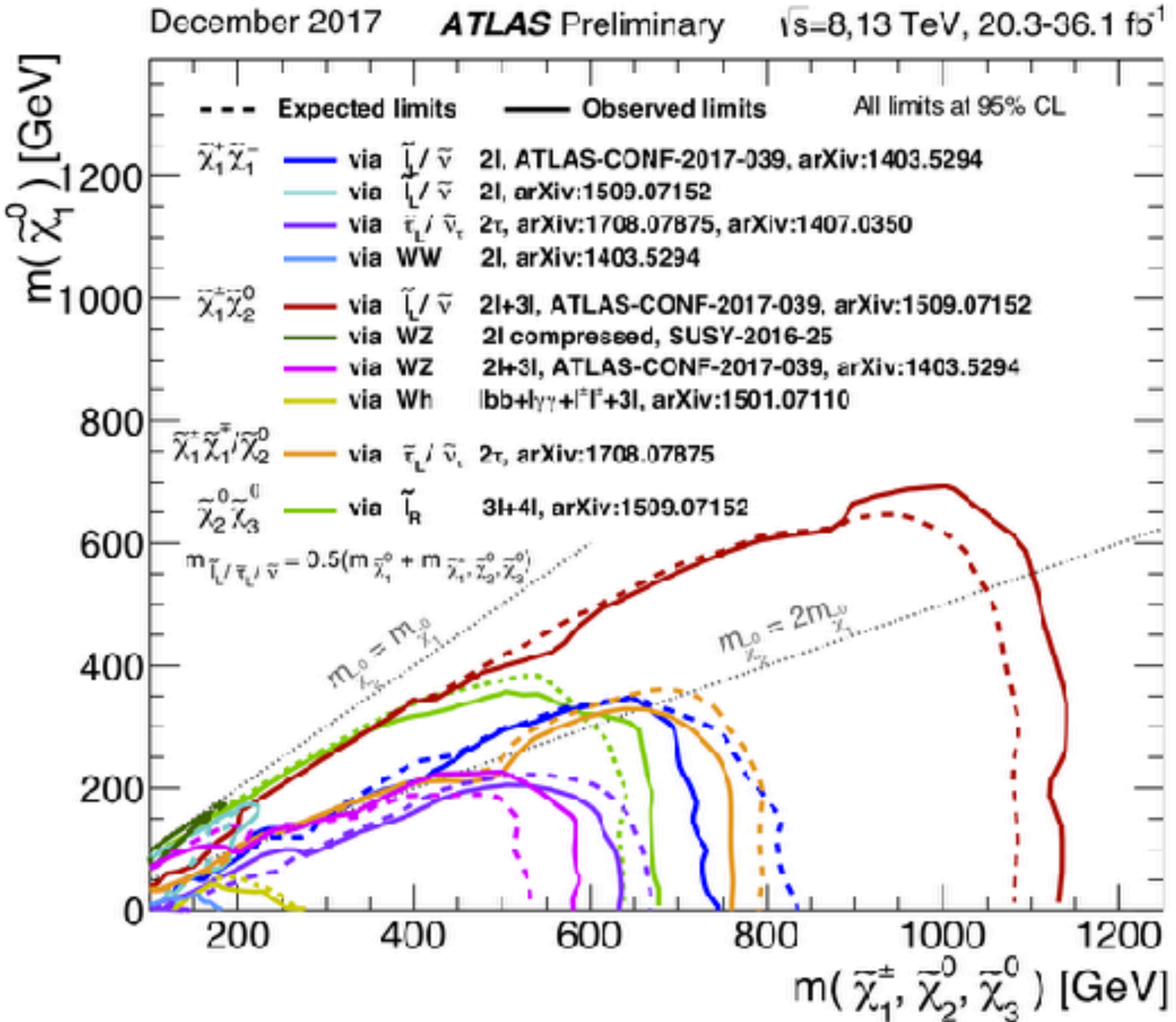
In many SUSY models, the lightest neutralino is stable and provides a natural DM particle candidate.

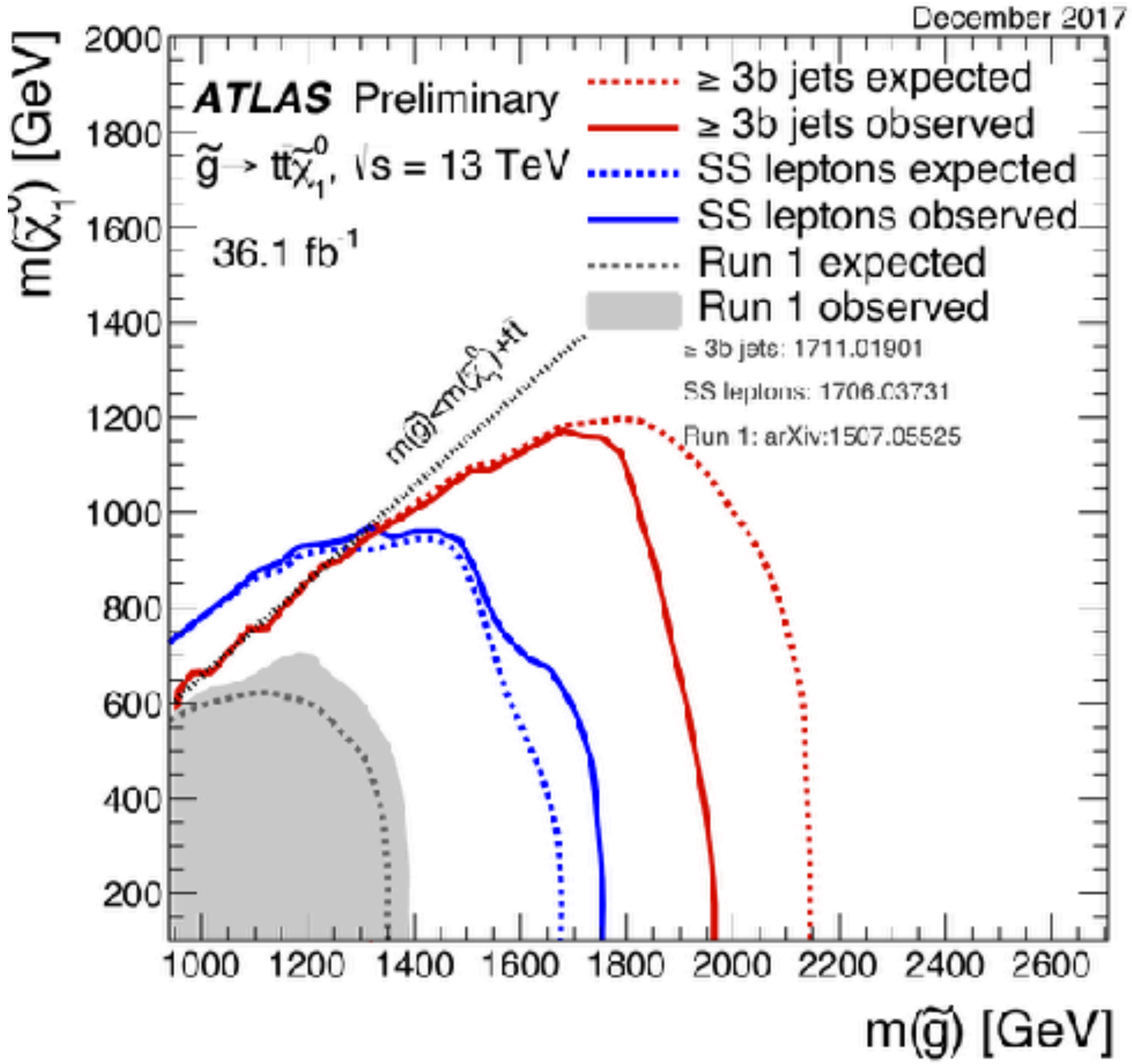
SUSY Limits

Left figure shows the limits for the lightest neutralino mass versus one of the heavier neutralino or charging masses.

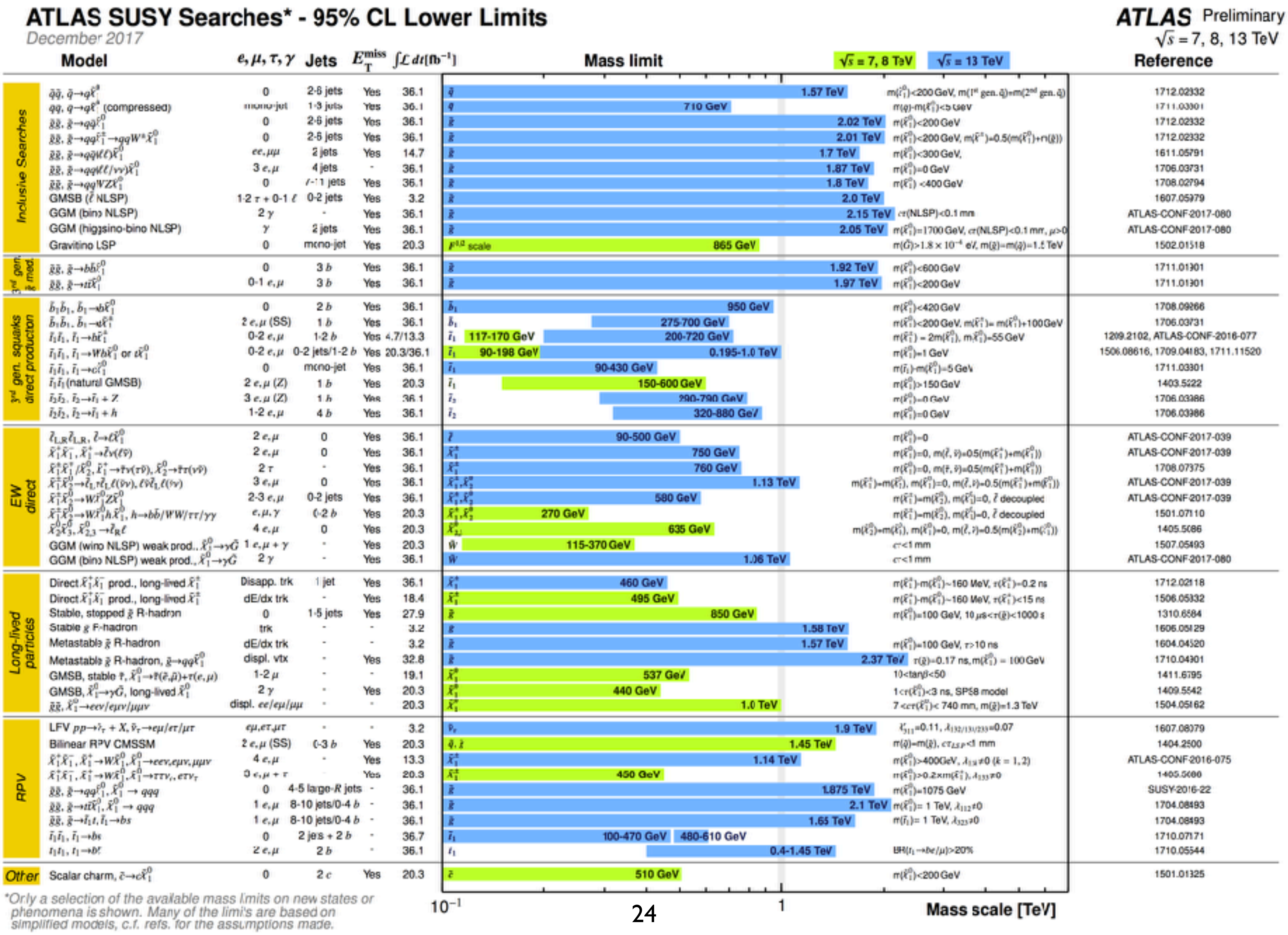
Right figure similarly shows limits for the lightest neutralino mass versus gluino mass.







SUSY Searches



ATLAS SUSY Searches* - 95% CL Lower Limits
December 2017

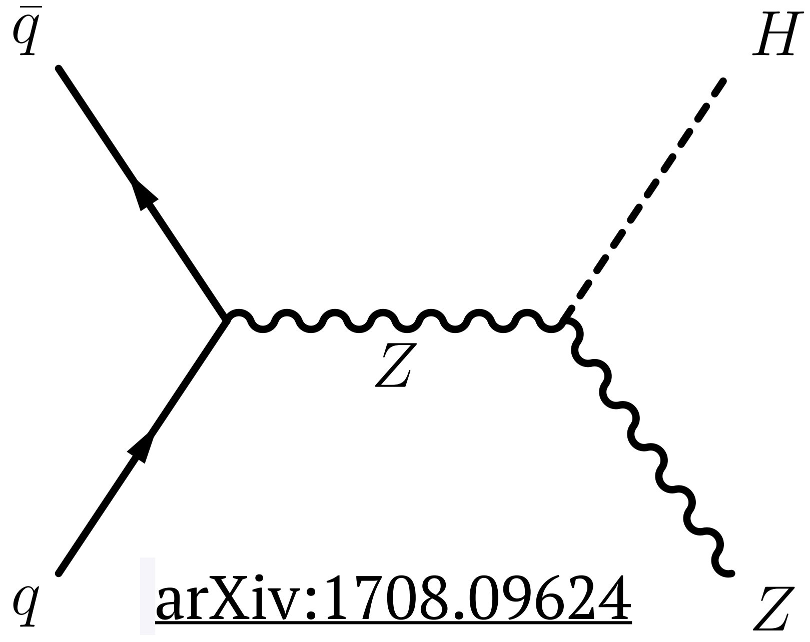
ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV

🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$		Mass limit		Reference
Inclusive Searches	$\tilde q\tilde q$, $\tilde q\to q\tilde\chi_1^0$	0	2-6 jets	Yes	36.1	$\tilde q$	🟦 1.57 TeV	$m(\tilde\chi_1^0)$<200 GeV, $m(1^{st}$ gen. $\tilde q)=m(2^{nd}$ gen. $\tilde q)$	1712.02332
	$\tilde q\tilde q$, $\tilde q\to q\tilde\chi_1^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	$\tilde q$	🟦 710 GeV	$m(\tilde q)-m(\tilde\chi_1^0)$<5 GeV	1711.03301
	$\tilde g\tilde g$, $\tilde g\to q\bar q\tilde\chi_1^0$	0	2-6 jets	Yes	36.1	$\tilde g$	🟦 2.02 TeV	$m(\tilde\chi_1^0)$<200 GeV	1712.02332
	$\tilde g\tilde g$, $\tilde g\to qq\tilde\chi_1^\pm\to qqW^\pm\tilde\chi_1^0$	0	2-6 jets	Yes	36.1	$\tilde g$	🟦 2.01 TeV	$m(\tilde\chi_1^0)$<200 GeV, $m(\tilde\chi^\pm)=0.5(m(\tilde\chi_1^0)+m(\tilde g))$	1712.02332
	$\tilde g\tilde g$, $\tilde g\to q\bar q(\ell\ell)\tilde\chi_1^0$	$ee,\mu\mu$	2 jets	Yes	14.7	$\tilde g$	🟦 1.7 TeV	$m(\tilde\chi_1^0)$<300 GeV,	1611.05791
	$\tilde g\tilde g$, $\tilde g\to qq(\ell\ell/\nu\nu)\tilde\chi_1^0$	3 e,μ	4 jets	-	36.1	$\tilde g$	🟦 1.87 TeV	$m(\tilde\chi_1^0)$=0 GeV	1706.03731
	$\tilde g\tilde g$, $\tilde g\to qqWZ\tilde\chi_1^0$	0	7-11 jets	Yes	36.1	$\tilde g$	🟦 1.8 TeV	$m(\tilde\chi_1^0)$ <400 GeV	1708.02794
	GMSB ($\tilde\ell$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde g$	🟦 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	36.1	$\tilde g$	🟦 2.15 TeV	$c\tau$(NLSP)<0.1 mm	ATLAS-CONF-2017-080
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1	$\tilde g$	🟦 2.05 TeV	$m(\tilde\chi_1^0)$=1700 GeV, $c\tau$(NLSP)<0.1 mm, $\mu>0$	ATLAS-CONF-2017-080
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	🟩 865 GeV	$m(\tilde G)>1.8\times10^{-4}$ eV, $m(\tilde g)=m(\tilde q)=1.5$ TeV	1502.01518
3rd gen. $\tilde g$ med.	$\tilde g\tilde g$, $\tilde g\to b\bar b\tilde\chi_1^0$	0	3 b	Yes	36.1	$\tilde g$	🟦 1.92 TeV	$m(\tilde\chi_1^0)$<600 GeV	1711.01901
	$\tilde g\tilde g$, $\tilde g\to t\bar t\tilde\chi_1^0$	0-1 e,μ	3 b	Yes	36.1	$\tilde g$	🟦 1.97 TeV	$m(\tilde\chi_1^0)$<200 GeV	1711.01901
3rd gen. squarks direct production	$\tilde b_1\tilde b_1$, $\tilde b_1\to b\tilde\chi_1^0$	0	2 b	Yes	36.1	$\tilde b_1$	🟦 950 GeV	$m(\tilde\chi_1^0)$<420 GeV	1708.09266
	$\tilde b_1\tilde b_1$, $\tilde b_1\to t\tilde\chi_1^\pm$	2 e,μ (SS)	1 b	Yes	36.1	$\tilde b_1$	🟦 275-700 GeV	$m(\tilde\chi_1^0)$<200 GeV, $m(\tilde\chi_1^\pm)=m(\tilde\chi_1^0)$+100 GeV	1706.03731
	$\tilde t_1\tilde t_1$, $\tilde t_1\to b\tilde\chi_1^\pm$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde t_1$	🟩 117-170 GeV 🟦 200-720 GeV	$m(\tilde\chi_1^\pm)=2m(\tilde\chi_1^0)$, $m(\tilde\chi_1^0)$=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde t_1\tilde t_1$, $\tilde t_1\to Wb\tilde\chi_1^0$ or $t\tilde\chi_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde t_1$	🟩 90-198 GeV 🟦 0.195-1.0 TeV	$m(\tilde\chi_1^0)$=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde t_1\tilde t_1$, $\tilde t_1\to c\tilde\chi_1^0$	0	mono-jet	Yes	36.1	$\tilde t_1$	🟦 90-430 GeV	$m(\tilde t_1)-m(\tilde\chi_1^0)$=5 GeV	1711.03301
	$\tilde t_1\tilde t_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde t_1$	🟩 150-600 GeV	$m(\tilde\chi_1^0)$>150 GeV	1403.5222
	$\tilde t_2\tilde t_2$, $\tilde t_2\to\tilde t_1+Z$	3 e,μ (Z)	1 b	Yes	36.1	$\tilde t_2$	🟦 290-790 GeV	$m(\tilde\chi_1^0)$=0 GeV	1706.03986
	$\tilde t_2\tilde t_2$, $\tilde t_2\to\tilde t_1+h$	1-2 e,μ	4 b	Yes	36.1	$\tilde t_2$	🟦 320-880 GeV	$m(\tilde\chi_1^0)$=0 GeV	1706.03986
EW direct	$\tilde\ell_{L,R}\tilde\ell_{L,R}$, $\tilde\ell\to\ell\tilde\chi_1^0$	2 e,μ	0	Yes	36.1	$\tilde\ell$	🟦 90-500 GeV	$m(\tilde\chi_1^0)$=0	ATLAS-CONF-2017-039
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+\to\tilde\ell\nu(\ell\tilde\nu)$	2 e,μ	0	Yes	36.1	$\tilde\chi_1^\pm$	🟦 750 GeV	$m(\tilde\chi_1^0)$=0, $m(\tilde\ell,\tilde\nu)=0.5(m(\tilde\chi_1^\pm)+m(\tilde\chi_1^0))$	ATLAS-CONF-2017-039
	$\tilde\chi_1^\pm\tilde\chi_1^\mp/\tilde\chi_2^0$, $\tilde\chi_1^+\to\tilde\tau\nu(\tau\tilde\nu)$, $\tilde\chi_2^0\to\tilde\tau\tau(\nu\tilde\nu)$	2 τ	-	Yes	36.1	$\tilde\chi_1^\pm$	🟦 760 GeV	$m(\tilde\chi_1^0)$=0, $m(\tilde\tau,\tilde\nu)=0.5(m(\tilde\chi_1^\pm)+m(\tilde\chi_1^0))$	1708.07875
	$\tilde\chi_1^\pm\tilde\chi_2^0\to\tilde\ell_L\nu\tilde\ell_L\ell(\tilde\nu\nu)$, $\ell\tilde\nu\tilde\ell_L\ell(\tilde\nu\nu)$	3 e,μ	0	Yes	36.1	$\tilde\chi_1^\pm,\tilde\chi_2^0$	🟦 1.13 TeV	$m(\tilde\chi_1^\pm)=m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)$=0, $m(\tilde\ell,\tilde\nu)=0.5(m(\tilde\chi_1^\pm)+m(\tilde\chi_1^0))$	ATLAS-CONF-2017-039
	$\tilde\chi_1^\pm\tilde\chi_2^0\to W\tilde\chi_1^0 Z\tilde\chi_1^0$	2-3 e,μ	0-2 jets	Yes	36.1	$\tilde\chi_1^\pm,\tilde\chi_2^0$	🟦 580 GeV	$m(\tilde\chi_1^\pm)=m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)$=0, $\tilde\ell$ decoupled	ATLAS-CONF-2017-039
	$\tilde\chi_1^\pm\tilde\chi_2^0\to W\tilde\chi_1^0 h\tilde\chi_1^0$, $h\to b\bar b/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde\chi_1^\pm,\tilde\chi_2^0$	🟩 270 GeV	$m(\tilde\chi_1^\pm)=m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)$=0, $\tilde\ell$ decoupled	1501.07110
	$\tilde\chi_2^0\tilde\chi_3^0$, $\tilde\chi_{2,3}^0\to\tilde\ell_R\ell$	4 e,μ	0	Yes	20.3	$\tilde\chi_{2,3}^0$	🟩 635 GeV	$m(\tilde\chi_2^0)=m(\tilde\chi_3^0)$, $m(\tilde\chi_1^0)$=0, $m(\tilde\ell,\tilde\nu)=0.5(m(\tilde\chi_2^0)+m(\tilde\chi_1^0))$	1405.5086
	GGM (wino NLSP) weak prod., $\tilde\chi_1^0\to\gamma\tilde G$	1 e,μ + γ	-	Yes	20.3	$\tilde W$	🟩 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde\chi_1^0\to\gamma\tilde G$	2 γ	-	Yes	36.1	$\tilde W$	🟦 1.06 TeV	$c\tau$<1 mm	ATLAS-CONF-2017-080
Long-lived particles	Direct $\tilde\chi_1^+\tilde\chi_1^-$ prod., long-lived $\tilde\chi_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde\chi_1^\pm$	🟦 460 GeV	$m(\tilde\chi_1^\pm)-m(\tilde\chi_1^0)$~160 MeV, $\tau(\tilde\chi_1^\pm)$=0.2 ns	1712.02118
	Direct $\tilde\chi_1^+\tilde\chi_1^-$ prod., long-lived $\tilde\chi_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde\chi_1^\pm$	🟩 495 GeV	$m(\tilde\chi_1^\pm)-m(\tilde\chi_1^0)$~160 MeV, $\tau(\tilde\chi_1^\pm)$<15 ns	1506.05332
	Stable, stopped $\tilde g$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde g$	🟩 850 GeV	$m(\tilde\chi_1^0)$=100 GeV, 10 μs<$\tau(\tilde g)$<1000 s	1310.6584
	Stable $\tilde g$ R-hadron	trk	-	-	3.2	$\tilde g$	🟦 1.58 TeV		1606.05129
	Metastable $\tilde g$ R-hadron	dE/dx trk	-	-	3.2	$\tilde g$	🟦 1.57 TeV	$m(\tilde\chi_1^0)$=100 GeV, τ>10 ns	1604.04520
	Metastable $\tilde g$ R-hadron, $\tilde g\to qq\tilde\chi_1^0$	displ. vtx	-	Yes	32.8	$\tilde g$	🟦 2.37 TeV	$\tau(\tilde g)$=0.17 ns, $m(\tilde\chi_1^0)$ = 100 GeV	1710.04901
	GMSB, stable $\tilde\tau$, $\tilde\chi_1^0\to\tilde\tau(\tilde e,\tilde\mu)+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde\chi_1^0$	🟩 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde\chi_1^0\to\gamma\tilde G$, long-lived $\tilde\chi_1^0$	2 γ	-	Yes	20.3	$\tilde\chi_1^0$	🟩 440 GeV	1<$\tau(\tilde\chi_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde g\tilde g$, $\tilde\chi_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde\chi_1^0$	🟩 1.0 TeV	7 <$c\tau(\tilde\chi_1^0)$< 740 mm, $m(\tilde g)$=1.3 TeV	1504.05162
RPV	LFV $pp\to\tilde\nu_\tau+X$, $\tilde\nu_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	$\tilde\nu_\tau$	🟦 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde q,\tilde g$	🟩 1.45 TeV	$m(\tilde q)=m(\tilde g)$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+\to W\tilde\chi_1^0$, $\tilde\chi_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	$\tilde\chi_1^\pm$	🟦 1.14 TeV	$m(\tilde\chi_1^0)$>400GeV, $\lambda_{12k}\neq0$ (k = 1, 2)	ATLAS-CONF-2016-075
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+\to W\tilde\chi_1^0$, $\tilde\chi_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde\chi_1^\pm$	🟩 450 GeV	$m(\tilde\chi_1^0)>0.2\times m(\tilde\chi_1^\pm)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde g\tilde g$, $\tilde g\to qq\tilde\chi_1^0$, $\tilde\chi_1^0\to qqq$	0	4-5 large-R jets	-	36.1	$\tilde g$	🟦 1.875 TeV	$m(\tilde\chi_1^0)$=1075 GeV	SUSY-2016-22
	$\tilde g\tilde g$, $\tilde g\to t\bar t\tilde\chi_1^0$, $\tilde\chi_1^0\to qqq$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde g$	🟦 2.1 TeV	$m(\tilde\chi_1^0)$= 1 TeV, $\lambda_{112}\neq0$	1704.08493
	$\tilde g\tilde g$, $\tilde g\to\tilde t_1 t$, $\tilde t_1\to bs$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde g$	🟦 1.65 TeV	$m(\tilde t_1)$= 1 TeV, $\lambda_{323}\neq0$	1704.08493
	$\tilde t_1\tilde t_1$, $\tilde t_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde t_1$	🟦 100-470 GeV 🟦 480-610 GeV		1710.07171
	$\tilde t_1\tilde t_1$, $\tilde t_1\to b\ell$	2 e,μ	2 b	-	36.1	$\tilde t_1$	🟦 0.4-1.45 TeV	BR($\tilde t_1\to be/\mu$)>20%	1710.05544
Other	Scalar charm, $\tilde c\to c\tilde\chi_1^0$	0	2 c	Yes	20.3	$\tilde c$	🟩 510 GeV	$m(\tilde\chi_1^0)$<200 GeV	1501.01325

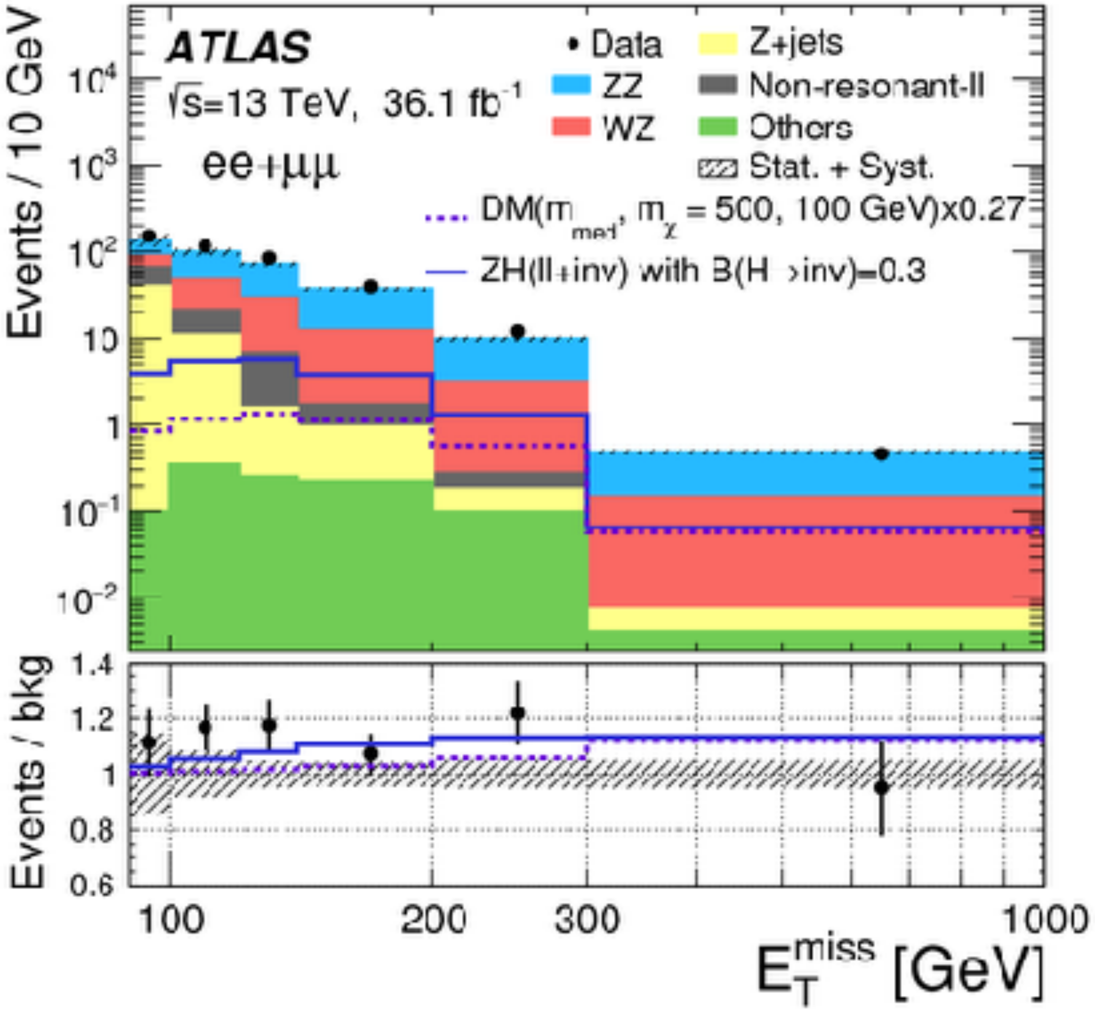
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

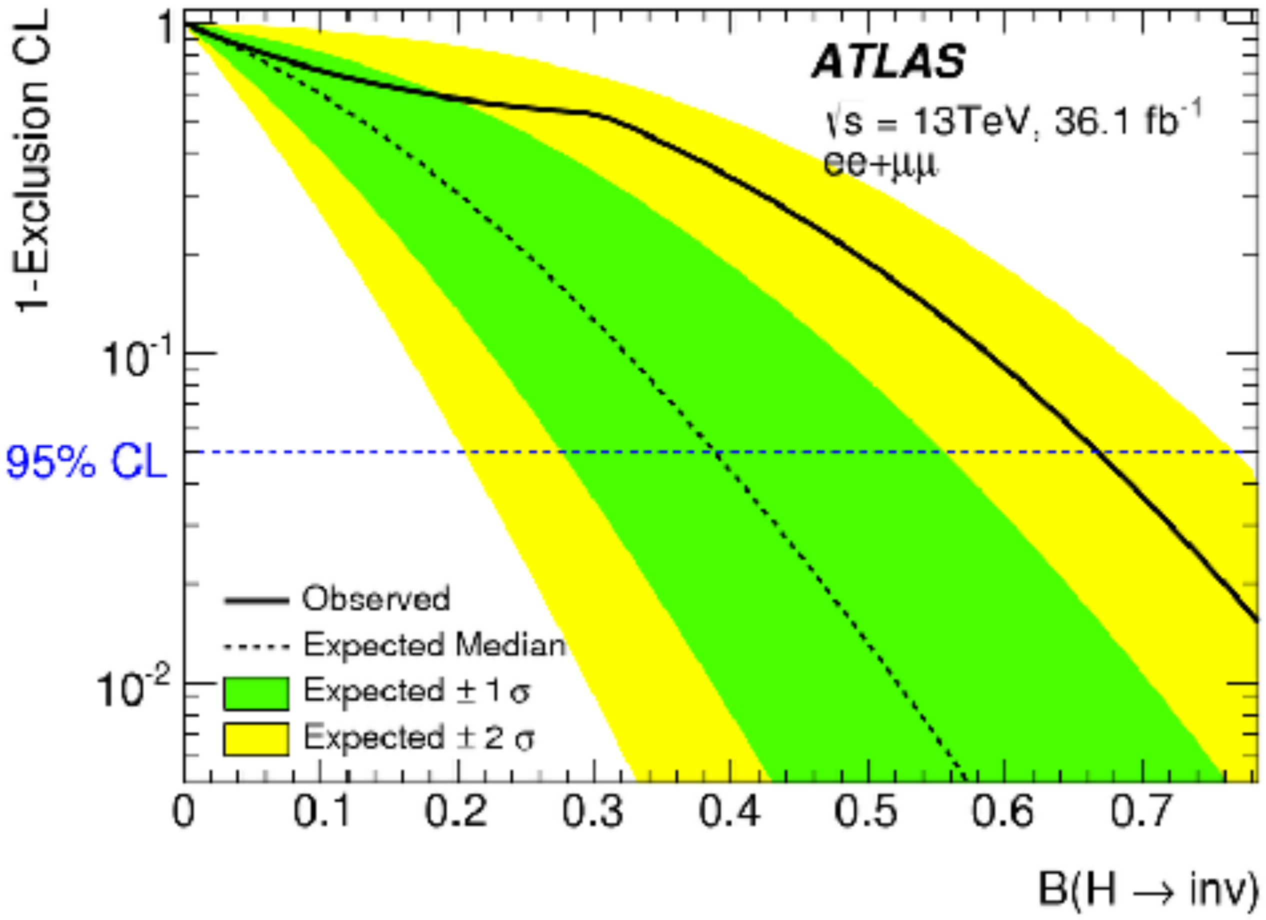
Invisible Higgs Decay



arXiv:1708.09624

If DM couples to the Higgs boson, and $m_\chi < 0.5\, m_H$, it should manifest as an invisible Branching Fraction for the Higgs.



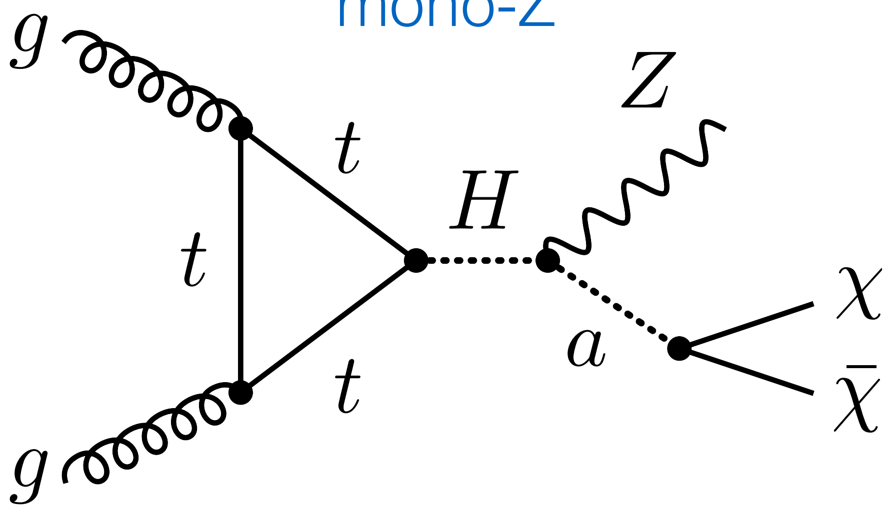


Two Higgs Doublet with Pseudoscalar Mediator

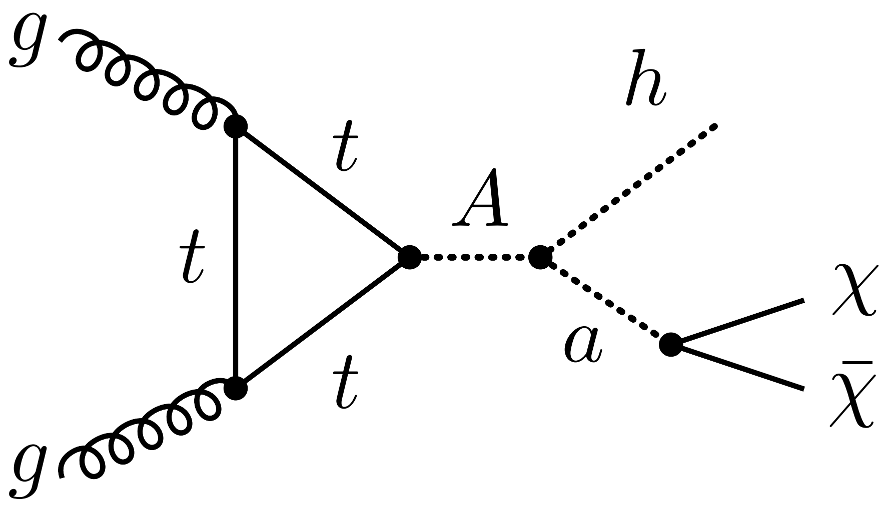
Two Higgs Doublet models with a light pseudoscalar (a) mediator to dark matter can produce enhanced signals in the mono-Z and mono-Higgs channels compared to Mono-Jet.

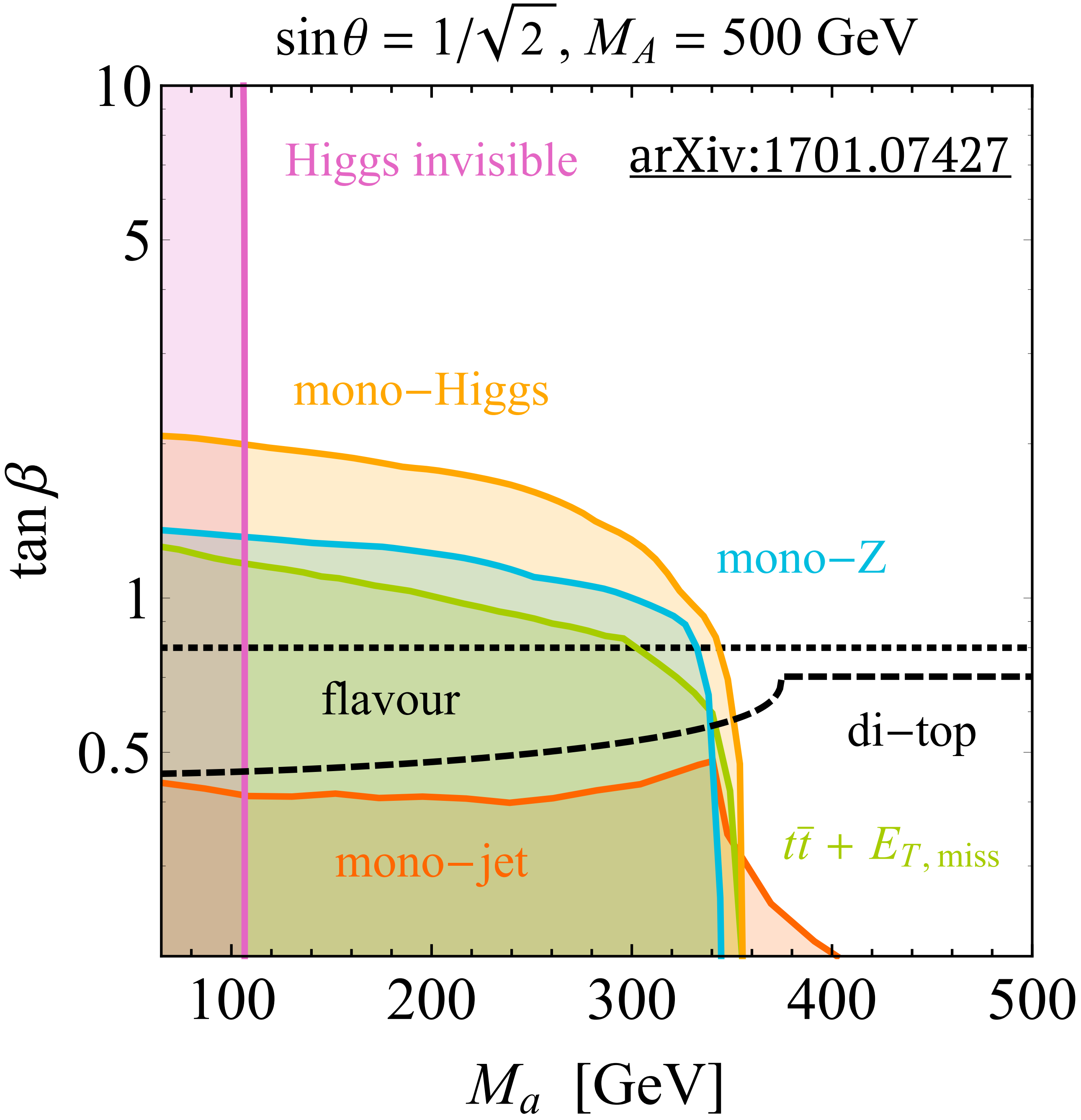
Enhancement due to resonant production of two higgs doublet's heavy scalar (H) or heavy pseudoscalar (A) particles.

mono-Z



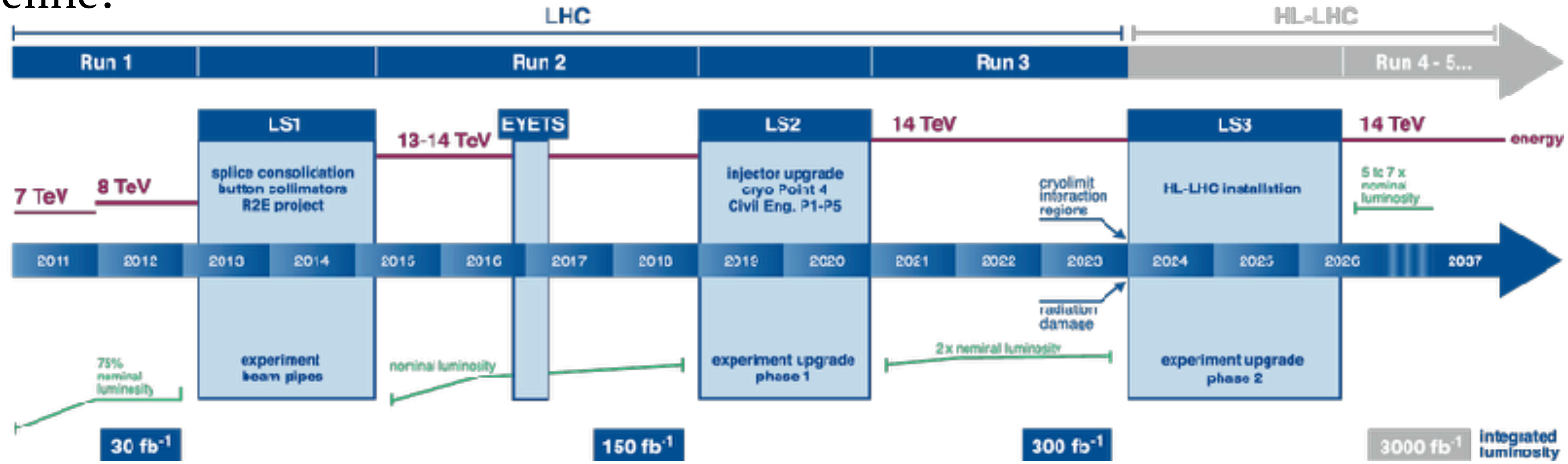
mono-Higgs

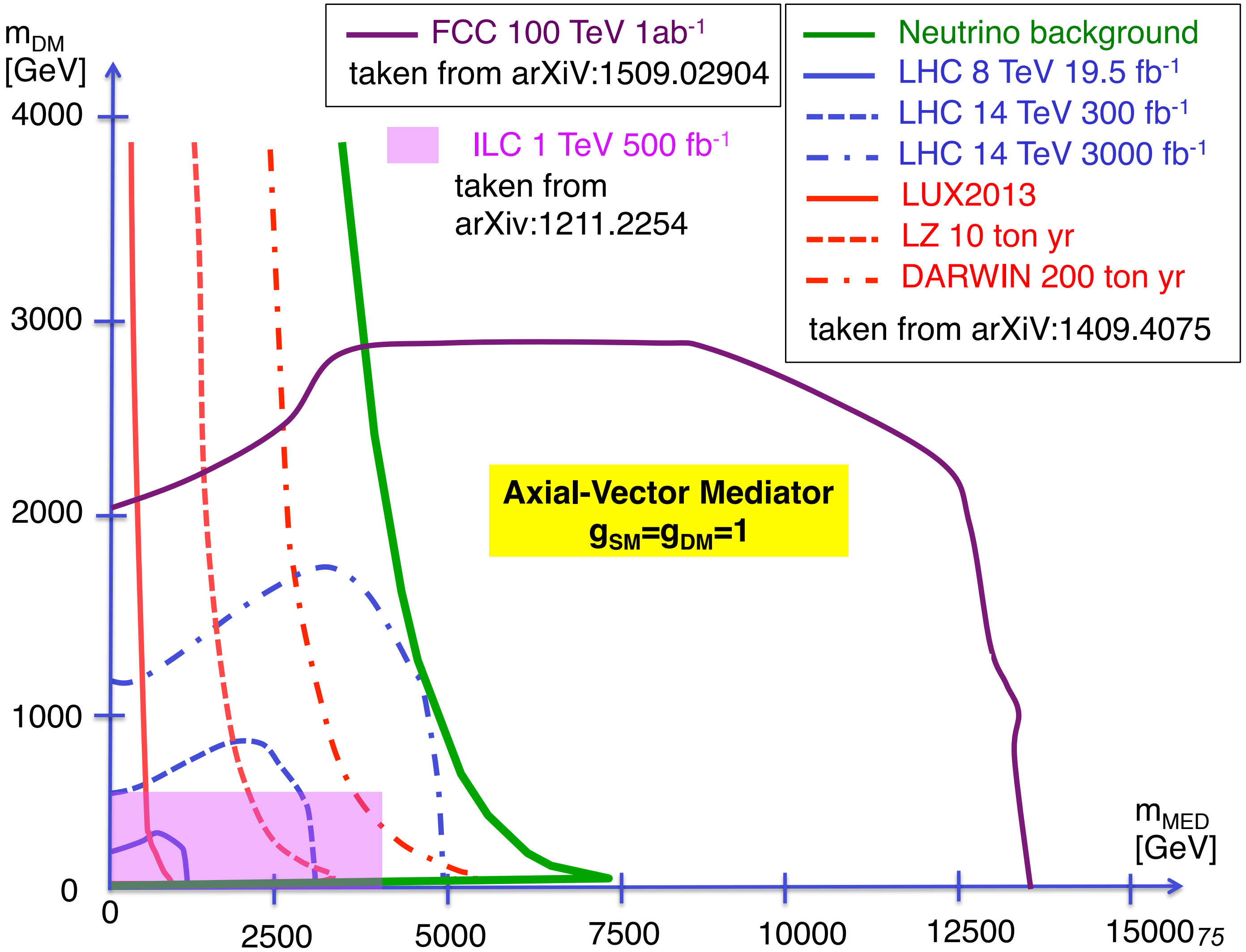



$\sin\theta = 1/\sqrt{2}$, M_A = 500 GeV

Future of Collider Searches

LHC Timeline:





taken from arXiV:1509.02904

taken from arXiv:1211.2254

taken from arXiV:1409.4075

Conclusion

- Searches for DM at the LHC are ongoing and complement current direct and indirect searches.

- Collider searches look for Mono-X + MET signatures.

- Results are interpreted as limits on generic, simplified models of Dark Matter with minimal number of free parameters.

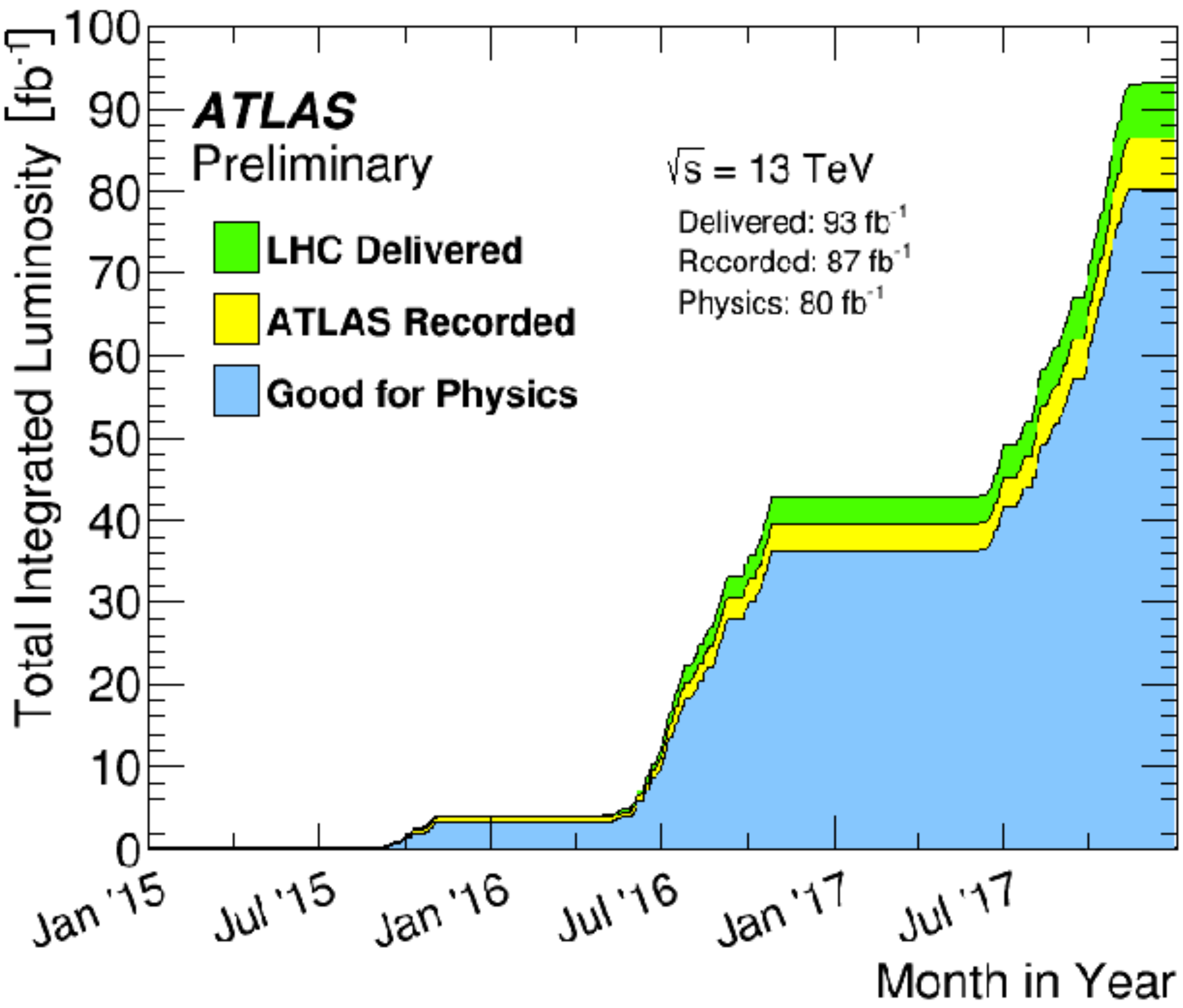
- In addition, optimized searches for specific, developed theories such as SUSY are also carried out.

- The DM hunt continues, with the completion of LHC Run-2 scheduled in 2018, and over the LHC lifetime a total of 3000 fb^{-1} of data to be collected.

Backup Slides

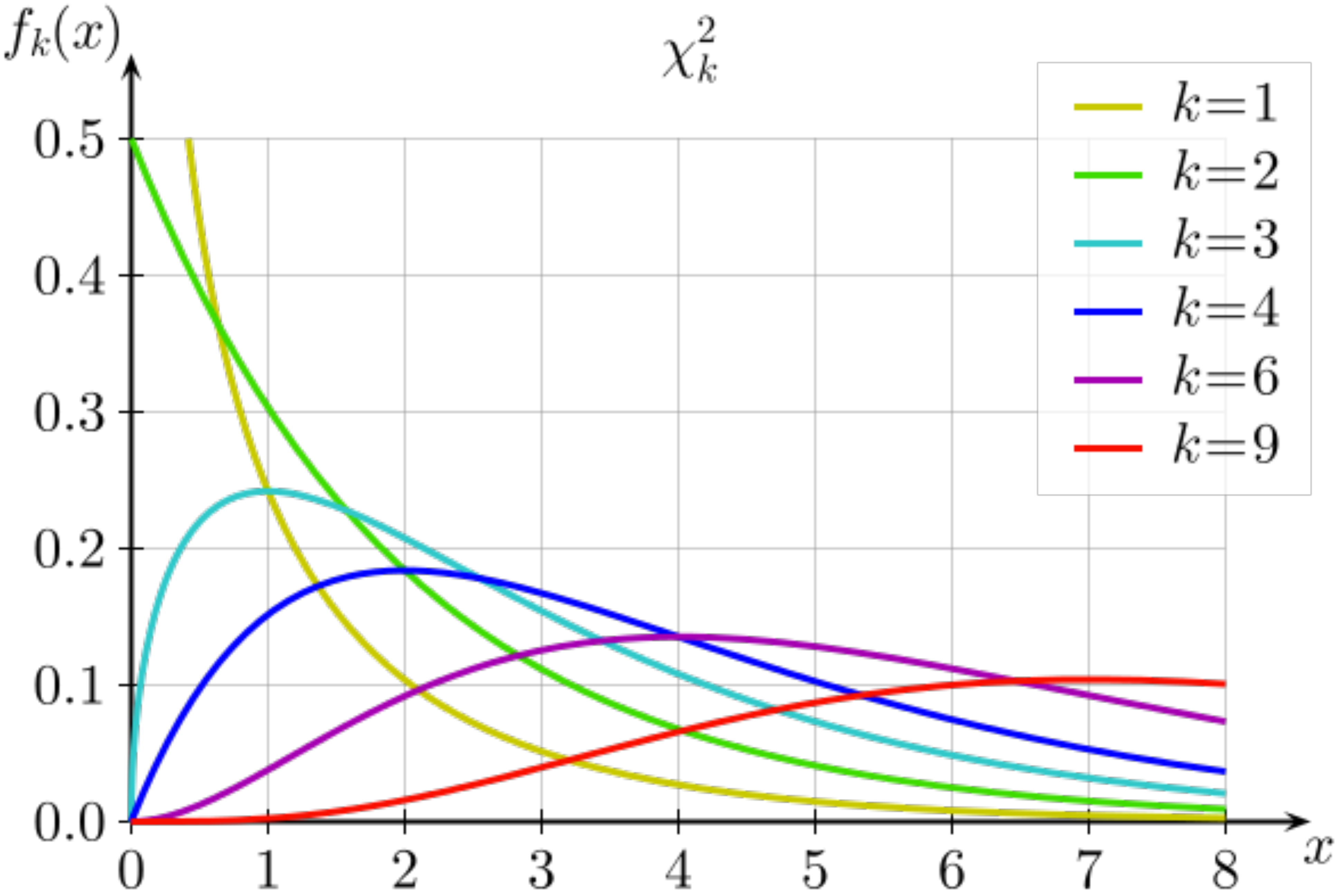
Integrated Luminosity

$$L_{int} = \frac{N}{\sigma}$$



χ2 Distribution

χ2 distribution for k degrees of freedom:



CLs Method

Distribution of q under the signal + background and signal only hypotheses.

$$\mathrm{CL}_s \equiv \frac{p_{s+b}}{1-p_b}$$

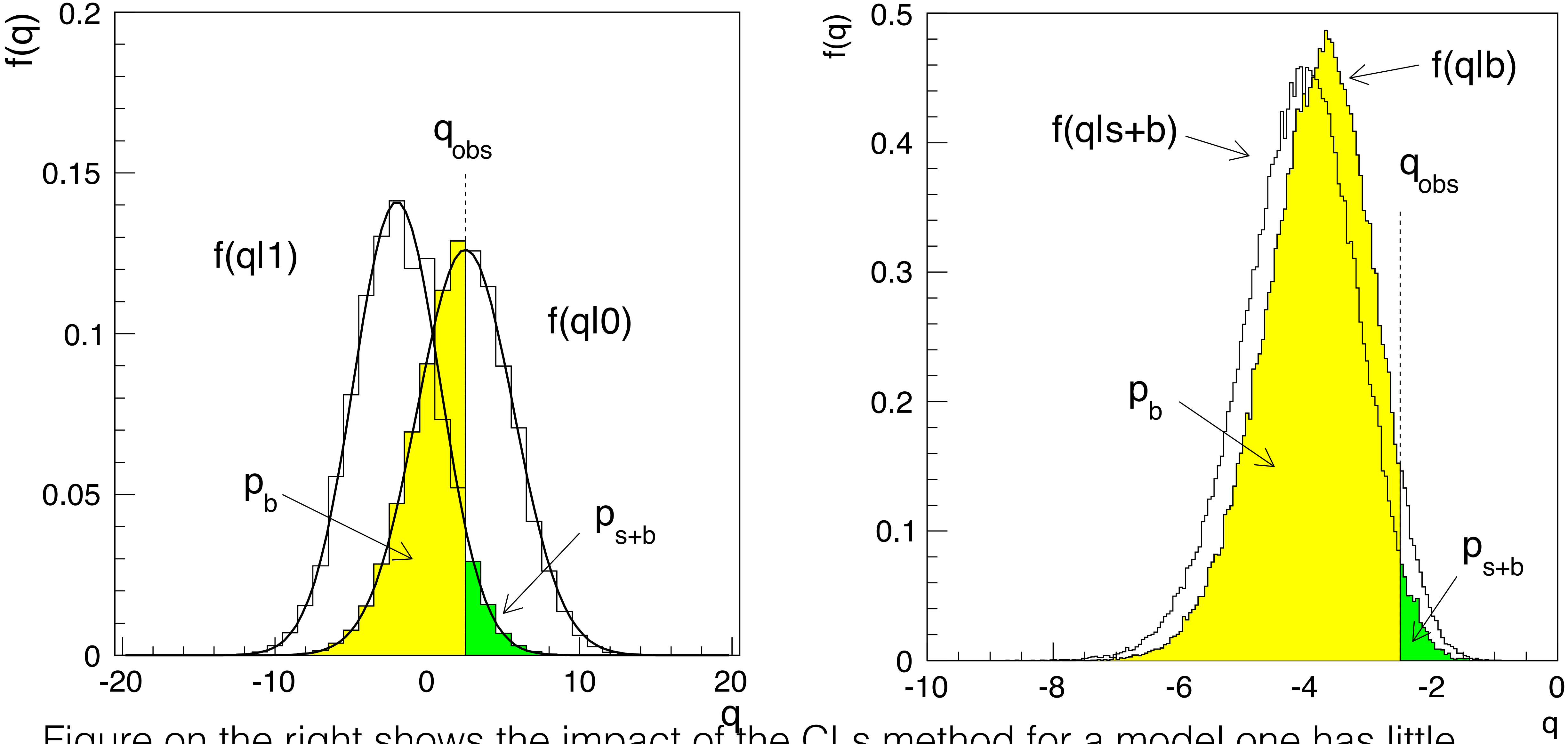


Figure on the right shows the impact of the CLs method for a model one has little sensitivity to.

DM in Association with tt~

Dark matter produced in association with top and and bottom quarks.

arXiv 1710.11412