Institute for
Theoretical
Particle Physics
and Cosmology

RWTH AACHEN UNIVERSITY

CTEQ-MCnet school 2016

Model-independent new physics searches at the LHC?

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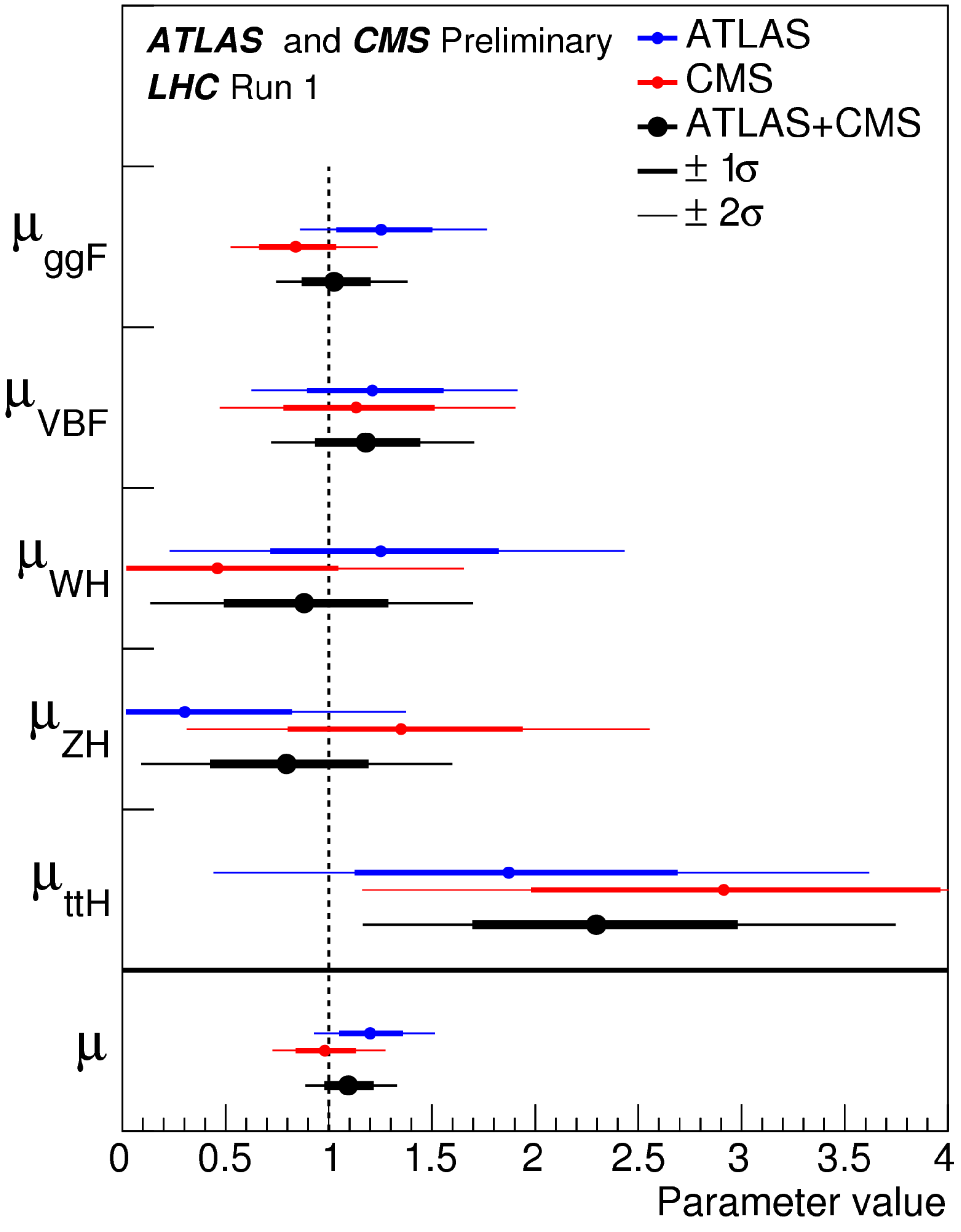
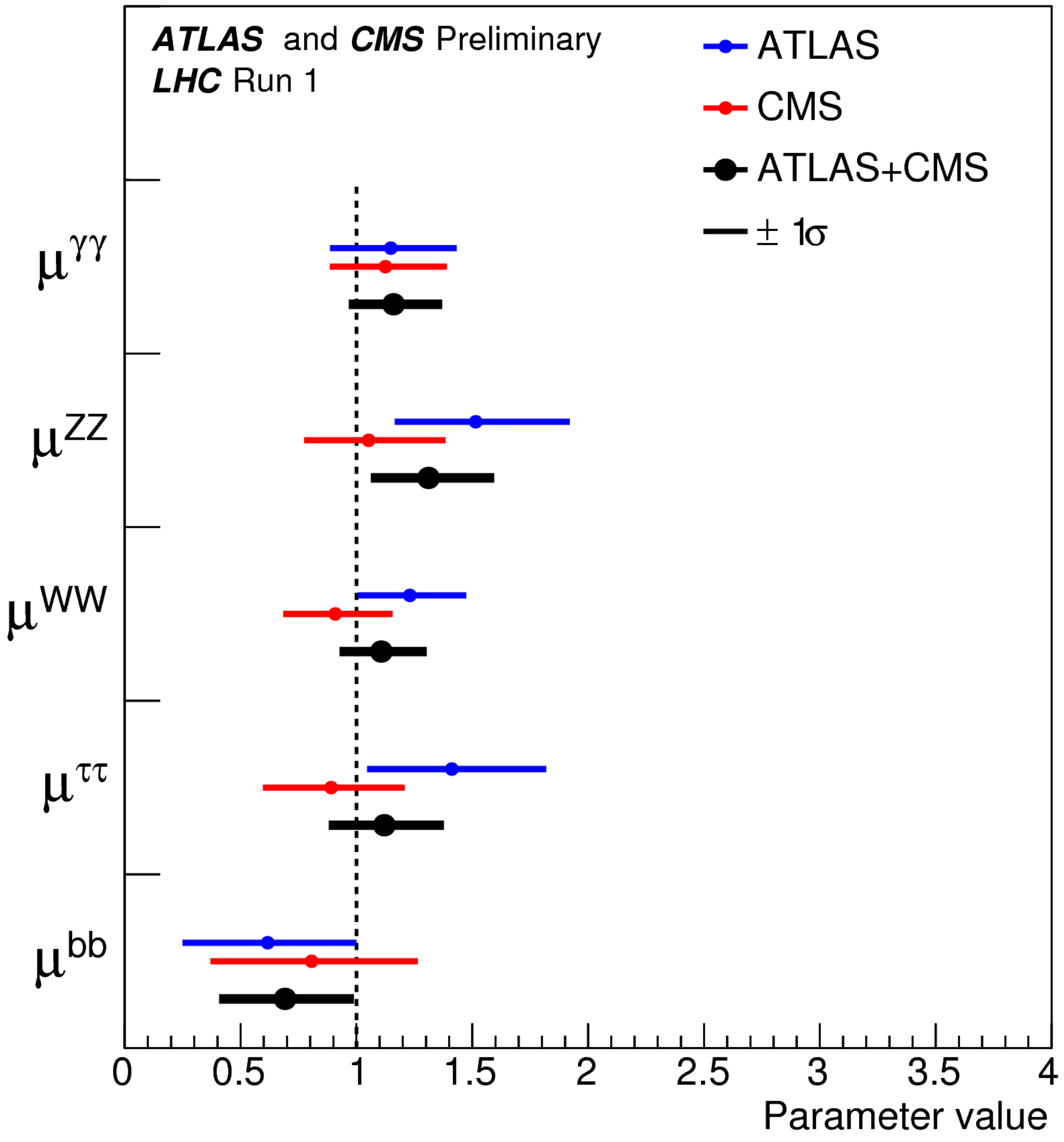
DFG Deutsche Forschungsgemeinschaft

Lessons from the LHC: a Higgs boson has been found

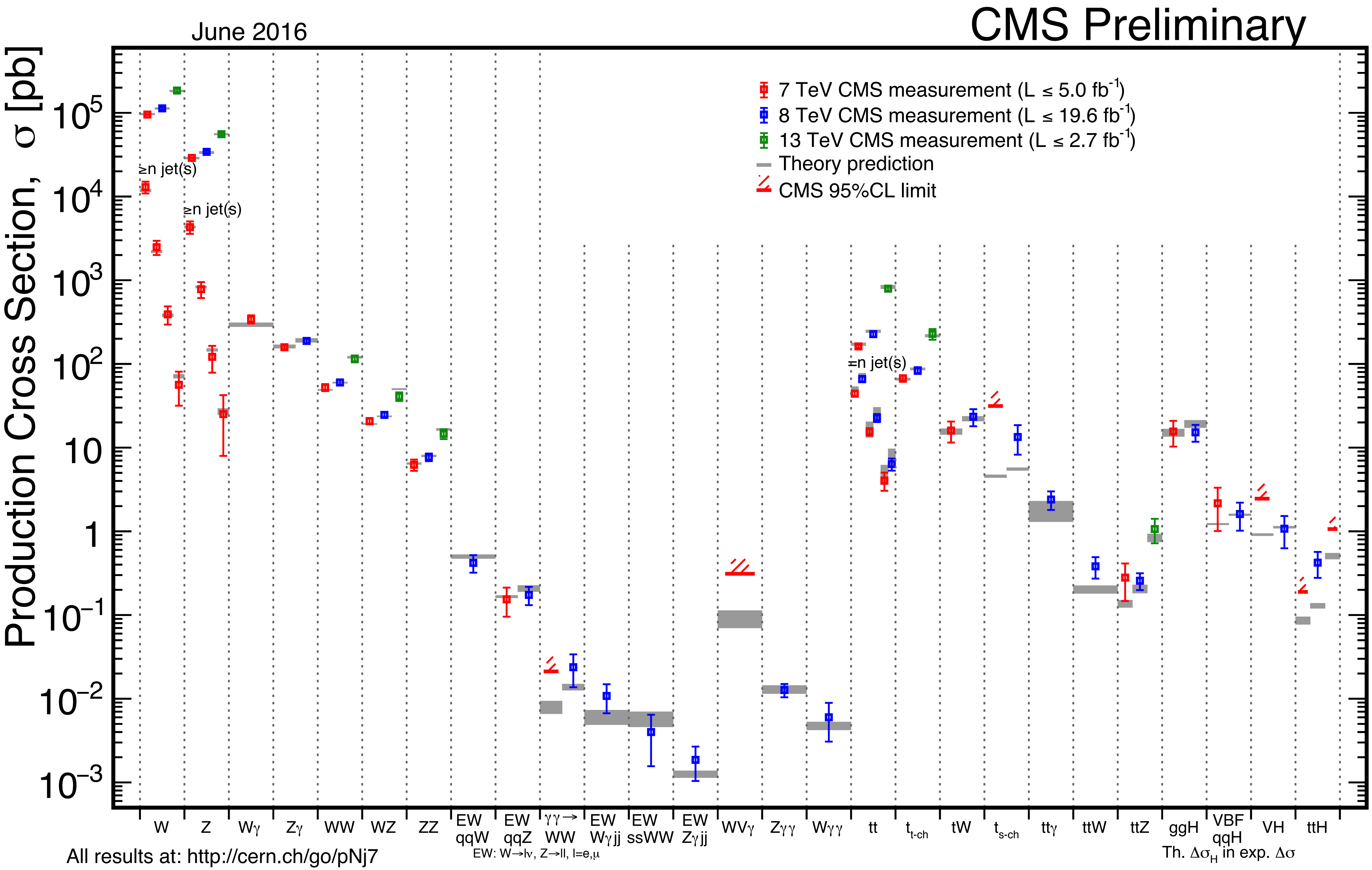
…and it looks like the Standard Model Higgs





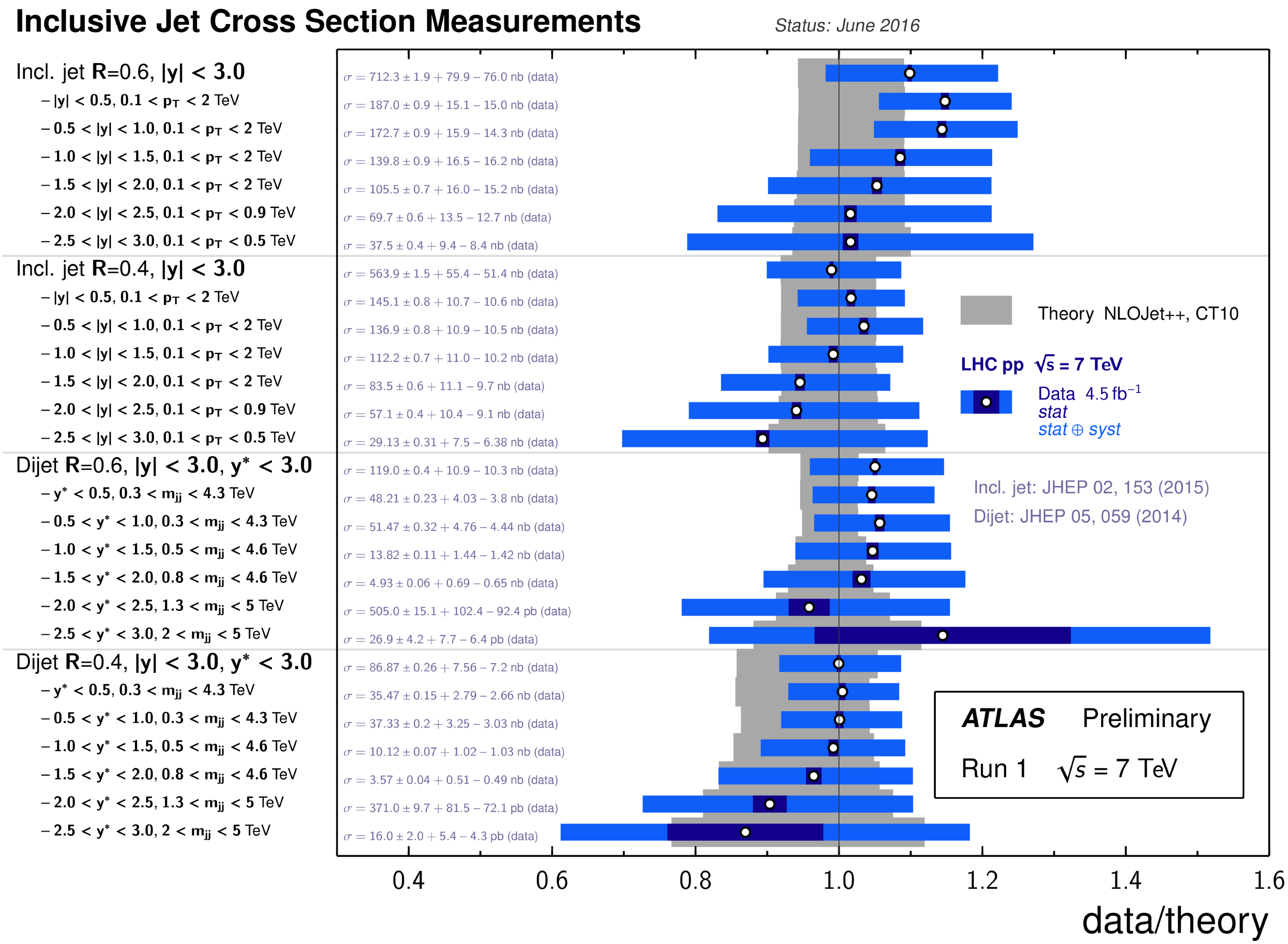
Lessons from the LHC:

the SM has passed all tests with flying colours



Lessons from the LHC:

the SM has passed all tests with flying colours



Physics beyond the Standard Model?

The problem of mass

What stabilises the Higgs mass?
What sets the scale of the fermion masses?

The problem of unification

Is there a grand unified theory?

The problem of flavour

Why are there so many types of quarks and leptons?
What is the origin of CP-violation?

Cosmological problems

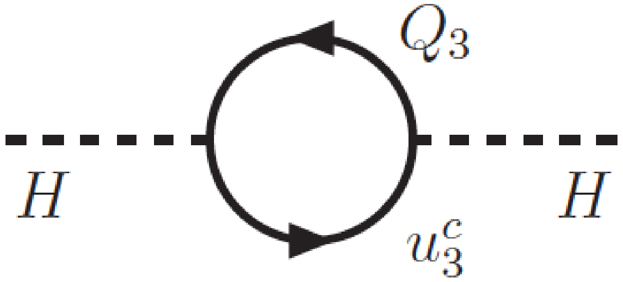
What is the origin of the matter-antimatter asymmetry?
What is the nature of dark matter and dark energy?

The holy grail

What is the theory of quantum gravity?

BSM physics at the LHC?

The naturalness problem: why is $M_{\text{Higgs}} \ll M_{\text{Planck}}$?



$$\delta M_{\mathrm{H}}^2 \sim \frac{3\lambda_t^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 \sim (0.3\,\Lambda_{\mathrm{UV}})^2$$

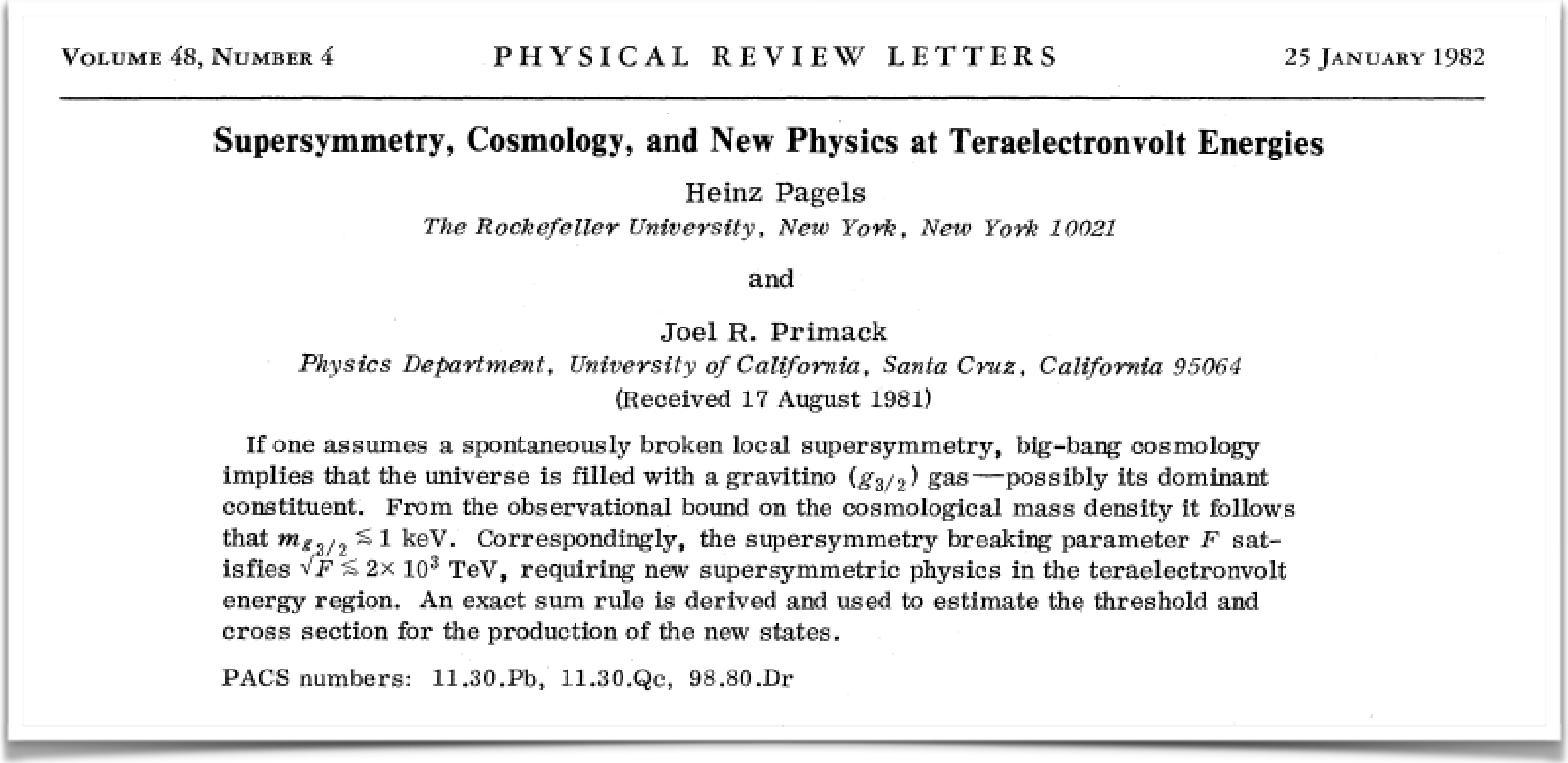
→ new coloured (top-)partners with mass ≲ 500 GeV?

Dark matter

Weakly interacting massive particle(s) with mass ≲ 1 TeV?

WIMP dark matter: from SUSY to simplified models

WIMP dark matter: from SUSY to simplified models



VOLUME 48, NUMBER 4 PHYSICAL REVIEW LETTERS 25 JANUARY 1982

Supersymmetry, Cosmology, and New Physics at Teraelectronvolt Energies

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and

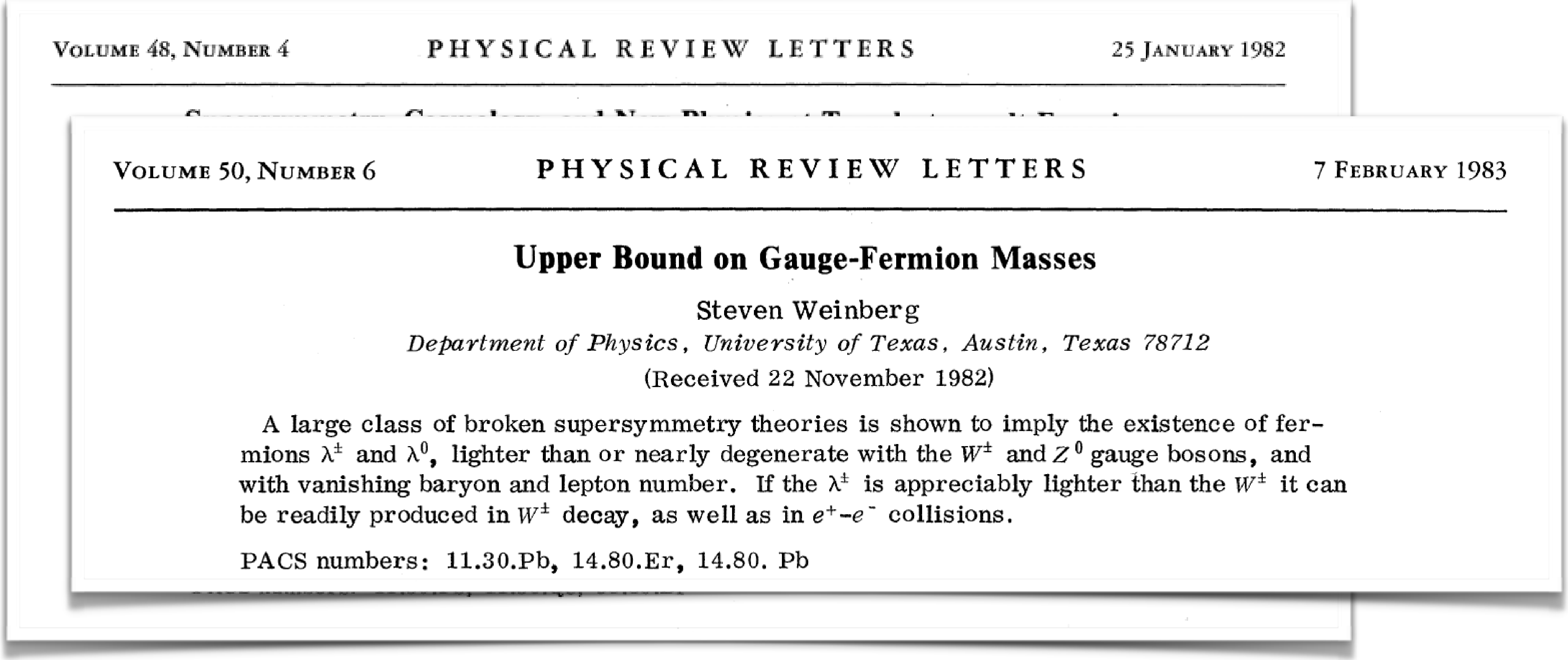
Joel R. Primack
Physics Department, University of California, Santa Cruz, California 95064

(Received 17 August 1981)

If one assumes a spontaneously broken local supersymmetry, big-bang cosmology implies that the universe is filled with a gravitino ($g_{3/2}$) gas—possibly its dominant constituent. From the observational bound on the cosmological mass density it follows that $m_{g_{3/2}} \lesssim 1$ keV. Correspondingly, the supersymmetry breaking parameter F satisfies $\sqrt{F} \lesssim 2\times 10^3$ TeV, requiring new supersymmetric physics in the teraelectronvolt energy region. An exact sum rule is derived and used to estimate the threshold and cross section for the production of the new states.

PACS numbers: 11.30.Pb, 11.30.Qc, 98.80.Dr

WIMP dark matter: from SUSY to simplified models



VOLUME 48, NUMBER 4 PHYSICAL REVIEW LETTERS 25 JANUARY 1982

VOLUME 50, NUMBER 6 PHYSICAL REVIEW LETTERS 7 FEBRUARY 1983

Upper Bound on Gauge-Fermion Masses

Steven Weinberg
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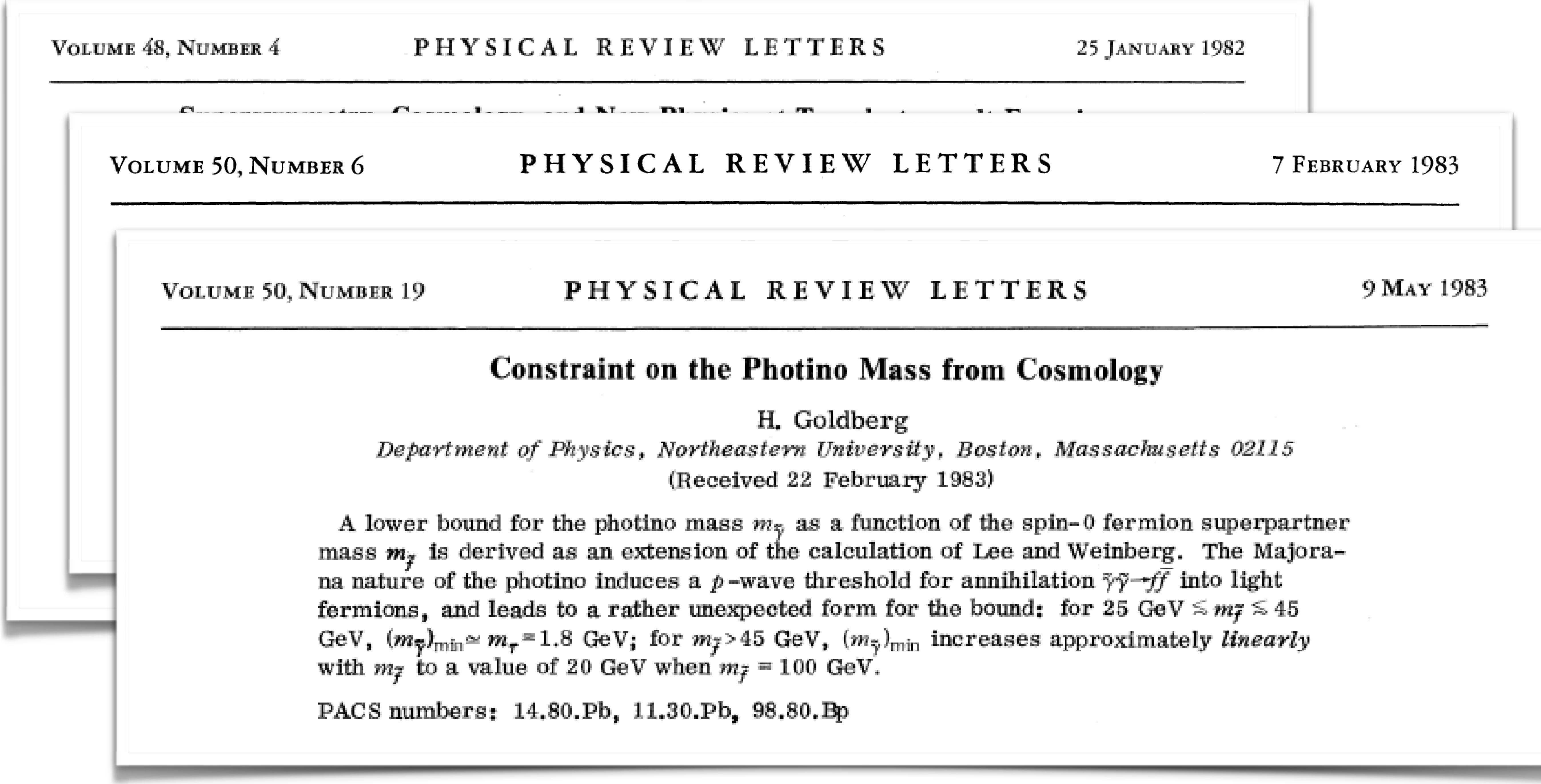
(Received 22 November 1982)

A large class of broken supersymmetry theories is shown to imply the existence of fermions $\lambda^\pm$ and λ^0, lighter than or nearly degenerate with the $W^\pm$ and Z^0 gauge bosons, and with vanishing baryon and lepton number. If the $\lambda^\pm$ is appreciably lighter than the $W^\pm$ it can be readily produced in $W^\pm$ decay, as well as in e^+-e^- collisions.

PACS numbers: 11.30.Pb, 14.80.Er, 14.80. Pb

WIMP dark matter: from SUSY to simplified models



VOLUME 48, NUMBER 4 PHYSICAL REVIEW LETTERS 25 JANUARY 1982

VOLUME 50, NUMBER 6 PHYSICAL REVIEW LETTERS 7 FEBRUARY 1983

VOLUME 50, NUMBER 19 PHYSICAL REVIEW LETTERS 9 MAY 1983

Constraint on the Photino Mass from Cosmology

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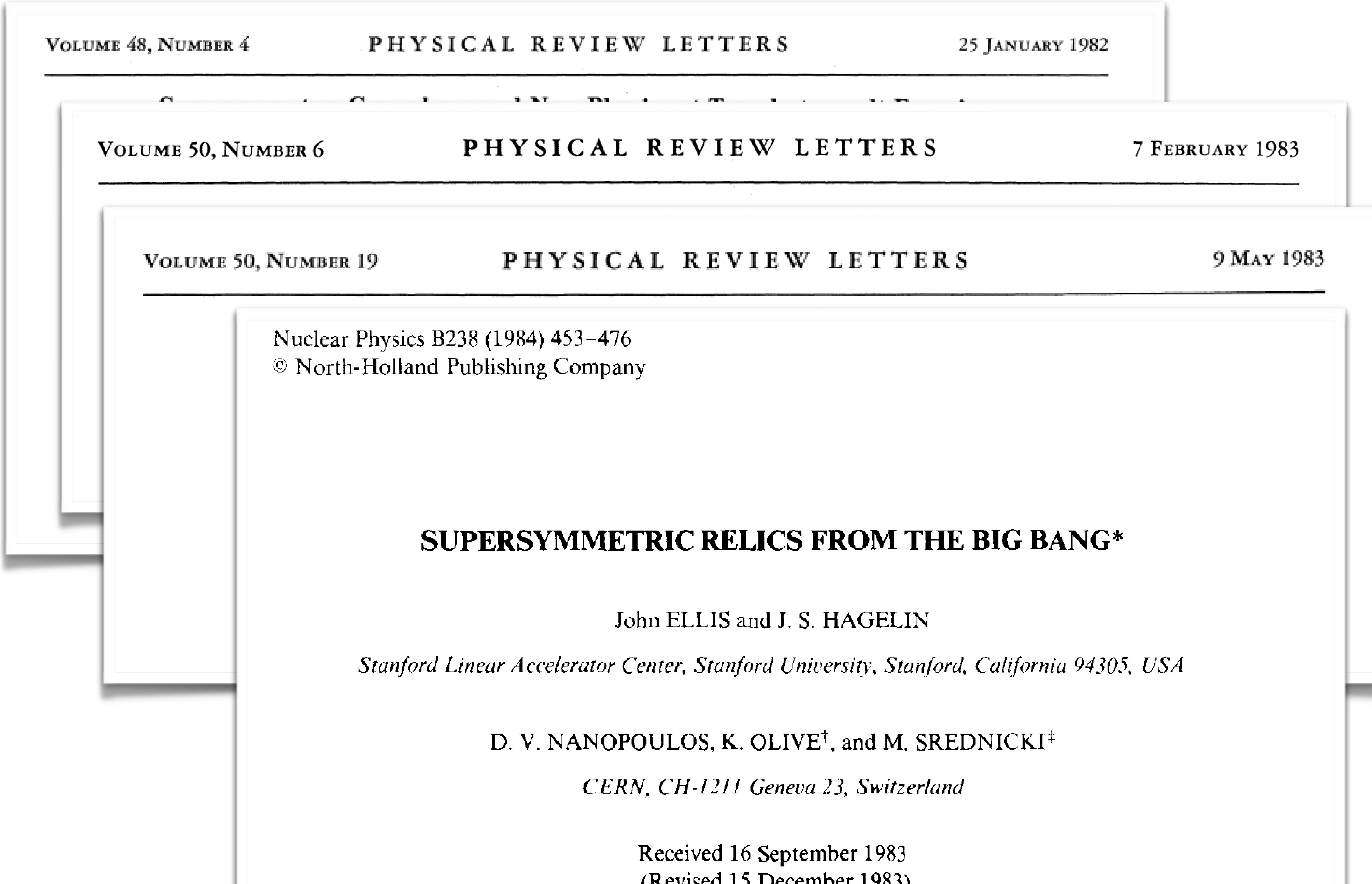
(Received 22 February 1983)

A lower bound for the photino mass $m_{\tilde{\gamma}}$ as a function of the spin-0 fermion superpartner mass $m_{\tilde{f}}$ is derived as an extension of the calculation of Lee and Weinberg. The Majorana nature of the photino induces a p-wave threshold for annihilation $\tilde{\gamma}\tilde{\gamma}\to f\bar{f}$ into light fermions, and leads to a rather unexpected form for the bound: for 25 GeV $\lesssim m_{\tilde{f}} \lesssim$ 45 GeV, $(m_{\tilde{\gamma}})_{\min} \simeq m_{\tau} = 1.8$ GeV; for $m_{\tilde{f}} > 45$ GeV, $(m_{\tilde{\gamma}})_{\min}$ increases approximately *linearly* with $m_{\tilde{f}}$ to a value of 20 GeV when $m_{\tilde{f}} = 100$ GeV.

PACS numbers: 14.80.Pb, 11.30.Pb, 98.80.Bp

WIMP dark matter: from SUSY to simplified models



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SUPERSYMMETRIC RELICS FROM THE BIG BANG*

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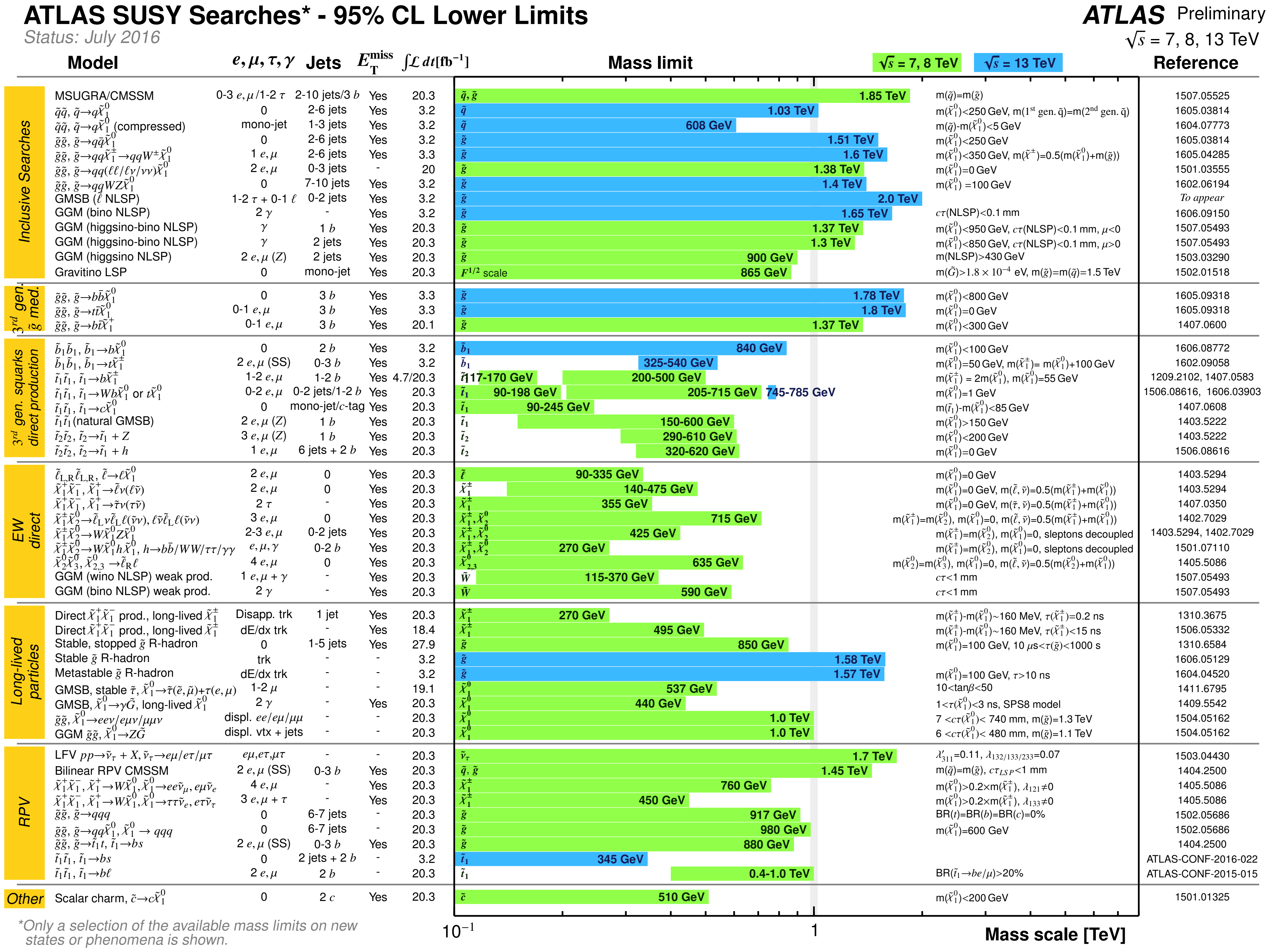
Received 16 September 1983
(Revised 15 December 1983)

Lessons from the LHC: no sign of SUSY



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2016

ATLAS Preliminary

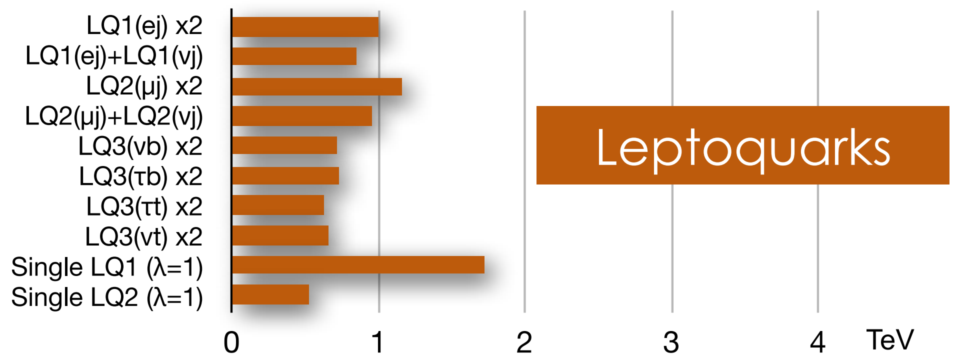
$\sqrt{s}$ = 7, 8, 13 TeV

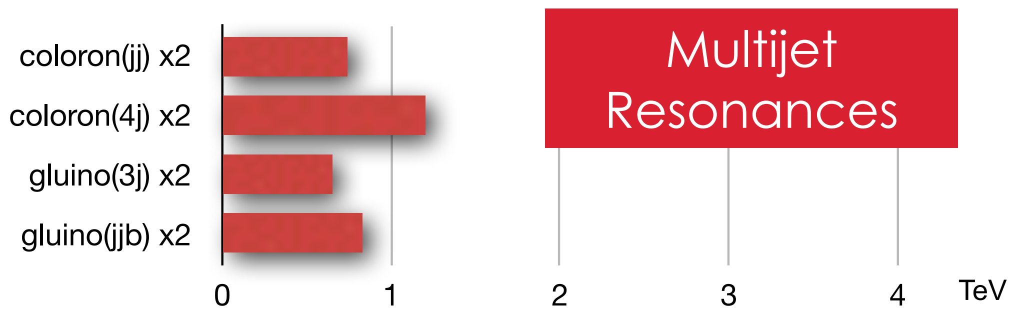
🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

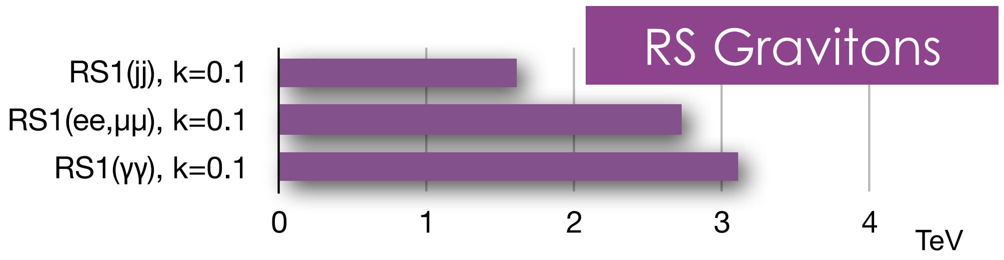
	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$	🟩 1.85 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	3.2	$\tilde{q}$	🟦 1.03 TeV	m($\tilde{\chi}_1^0$)<250 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1605.03814
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$	🟦 608 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	3.2	$\tilde{g}$	🟦 1.51 TeV	m($\tilde{\chi}_1^0$)<250 GeV	1605.03814
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	2-6 jets	Yes	3.3	$\tilde{g}$	🟦 1.6 TeV	m($\tilde{\chi}_1^0$)<350 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	1605.04285
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$	🟩 1.38 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1501.03555
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-10 jets	Yes	3.2	$\tilde{g}$	🟦 1.4 TeV	m($\tilde{\chi}_1^0$) =100 GeV	1602.06194
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$	🟦 2.0 TeV		*To appear*
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{g}$	🟦 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$	🟩 1.37 TeV	m($\tilde{\chi}_1^0$)<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	$\tilde{g}$	🟩 1.3 TeV	m($\tilde{\chi}_1^0$)<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$	🟩 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	🟩 865 GeV	m($\tilde{G}$)>1.8 × 10^{-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	3.3	$\tilde{g}$	🟦 1.78 TeV	m($\tilde{\chi}_1^0$)<800 GeV	1605.09318
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	3.3	$\tilde{g}$	🟦 1.8 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1605.09318
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	🟩 1.37 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	3.2	$\tilde{b}_1$	🟦 840 GeV	m($\tilde{\chi}_1^0$)<100 GeV	1606.08772
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	3.2	$\tilde{b}_1$	🟦 325-540 GeV	m($\tilde{\chi}_1^0$)=50 GeV, m($\tilde{\chi}_1^\pm$)= m($\tilde{\chi}_1^0$)+100 GeV	1602.09058
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7/20.3	$\tilde{t}_1$	🟩 117-170 GeV 🟩 200-500 GeV	m($\tilde{\chi}_1^\pm$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$	🟩 90-198 GeV 🟩 205-715 GeV 🟦 745-785 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1606.03903
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	🟩 90-245 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(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	20.3	$\tilde{t}_2$	🟩 290-610 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1 e,μ	6 jets + 2 b	Yes	20.3	$\tilde{t}_2$	🟩 320-620 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1506.08616
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	🟩 90-335 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	🟩 140-475 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$	🟩 355 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$	🟩 715 GeV	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($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$	🟩 425 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	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, sleptons 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.	1 e,μ + γ	-	Yes	20.3	$\tilde{W}$	🟩 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod.	2 γ	-	Yes	20.3	$\tilde{W}$	🟩 590 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	🟩 270 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^\pm$)=0.2 ns	1310.3675
	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, τ($\tilde{\chi}_1^\pm$)<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<τ($\tilde{g}$)<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
	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<τ($\tilde{\chi}_1^0$)<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
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$	🟩 1.0 TeV	6 <$c\tau$($\tilde{\chi}_1^0$)< 480 mm, m($\tilde{g}$)=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	20.3	$\tilde{\nu}_\tau$	🟩 1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	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
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu$, $e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^\pm$	🟩 760 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e$, $e\tau\tilde{\nu}_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$	🟩 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	🟩 917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	🟩 980 GeV	m($\tilde{\chi}_1^0$)=600 GeV	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$	🟩 880 GeV		1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	3.2	$\tilde{t}_1$	🟦 345 GeV		ATLAS-CONF-2016-022
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$	🟩 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
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.*

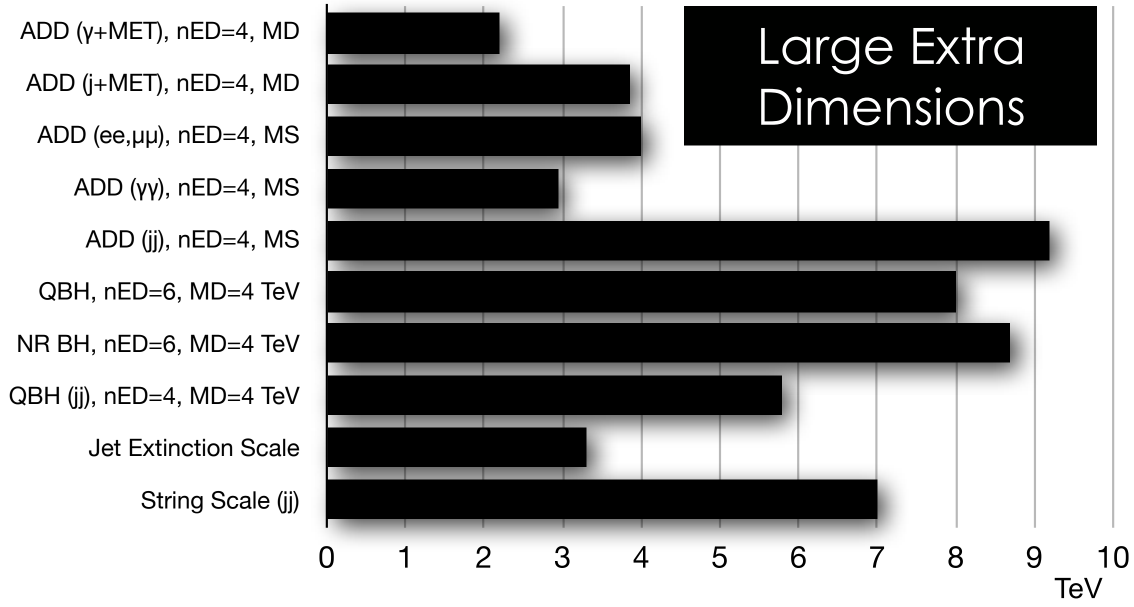
Lessons from the LHC: no sign of new physics

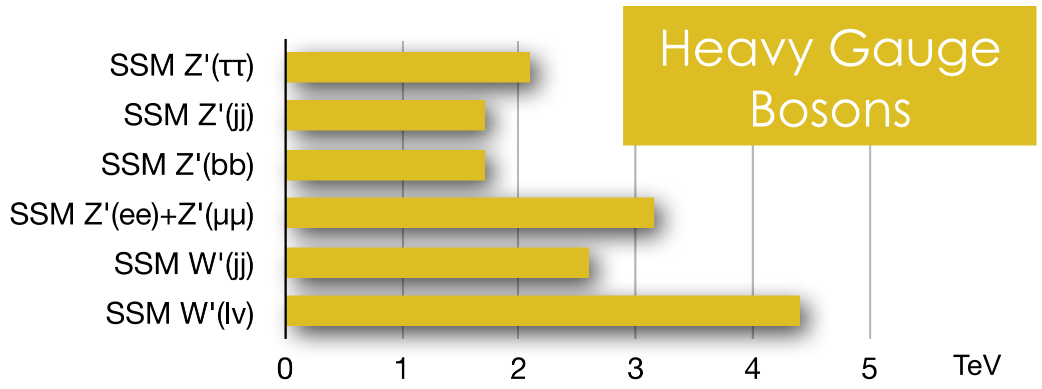


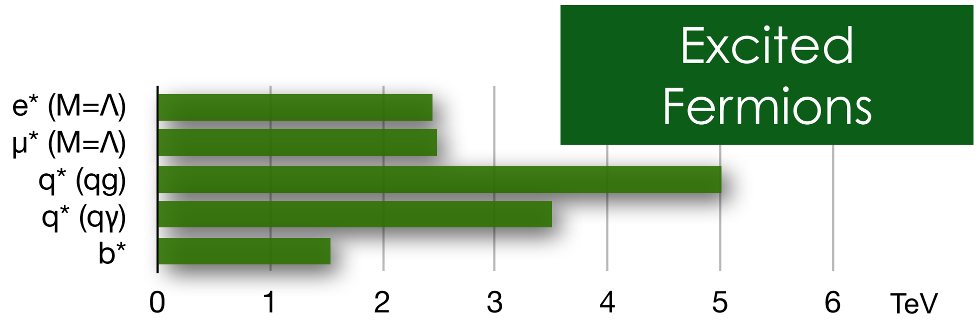


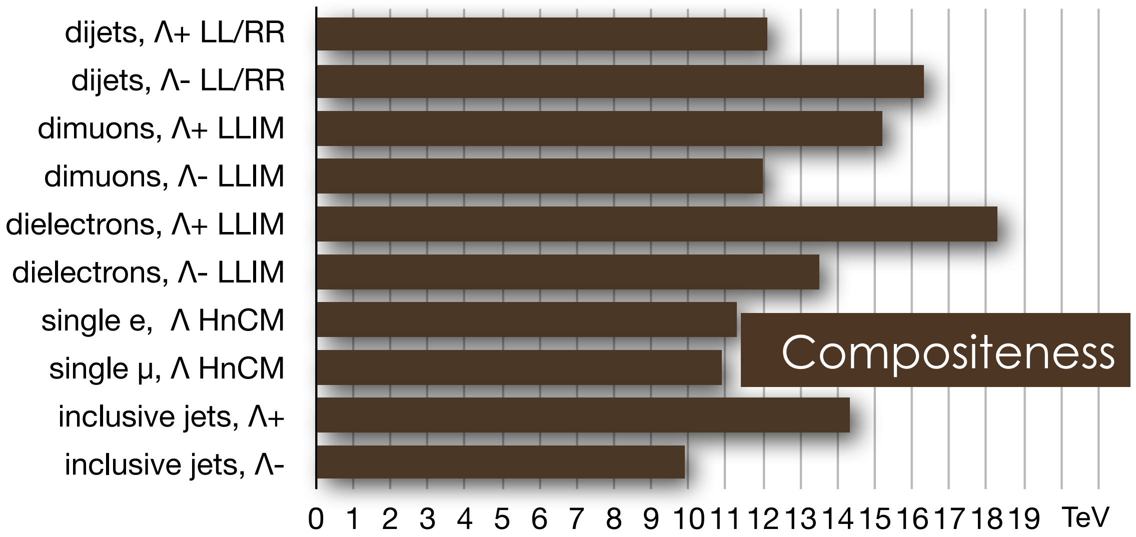


CMS Preliminary

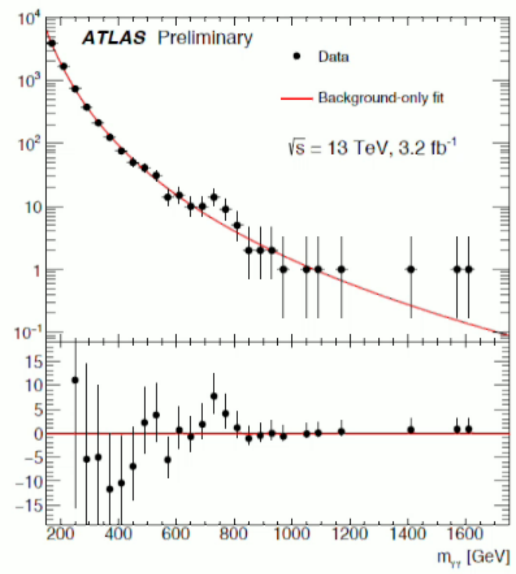




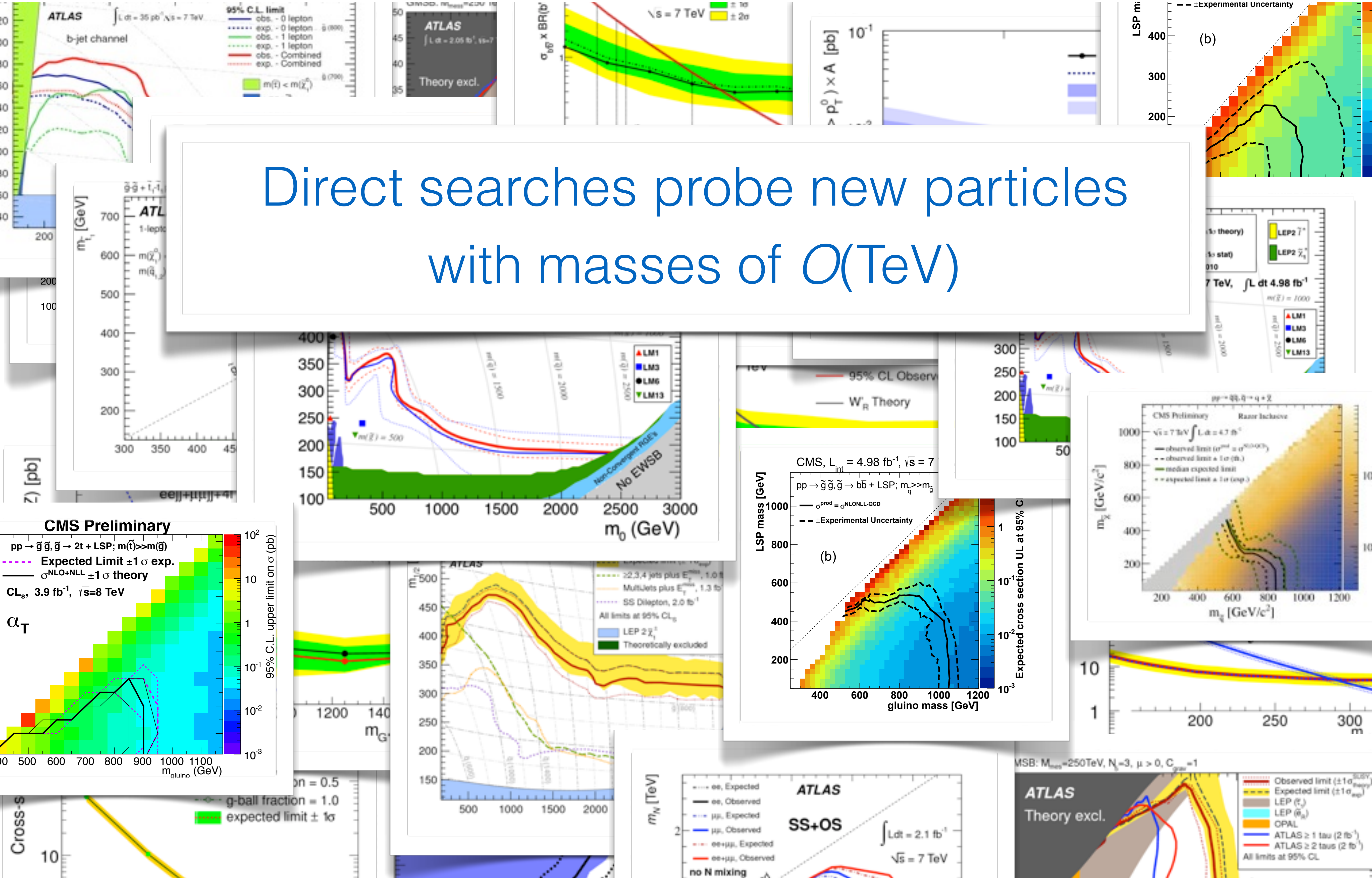




(750 GeV) **Light at the end of the tunnel?**

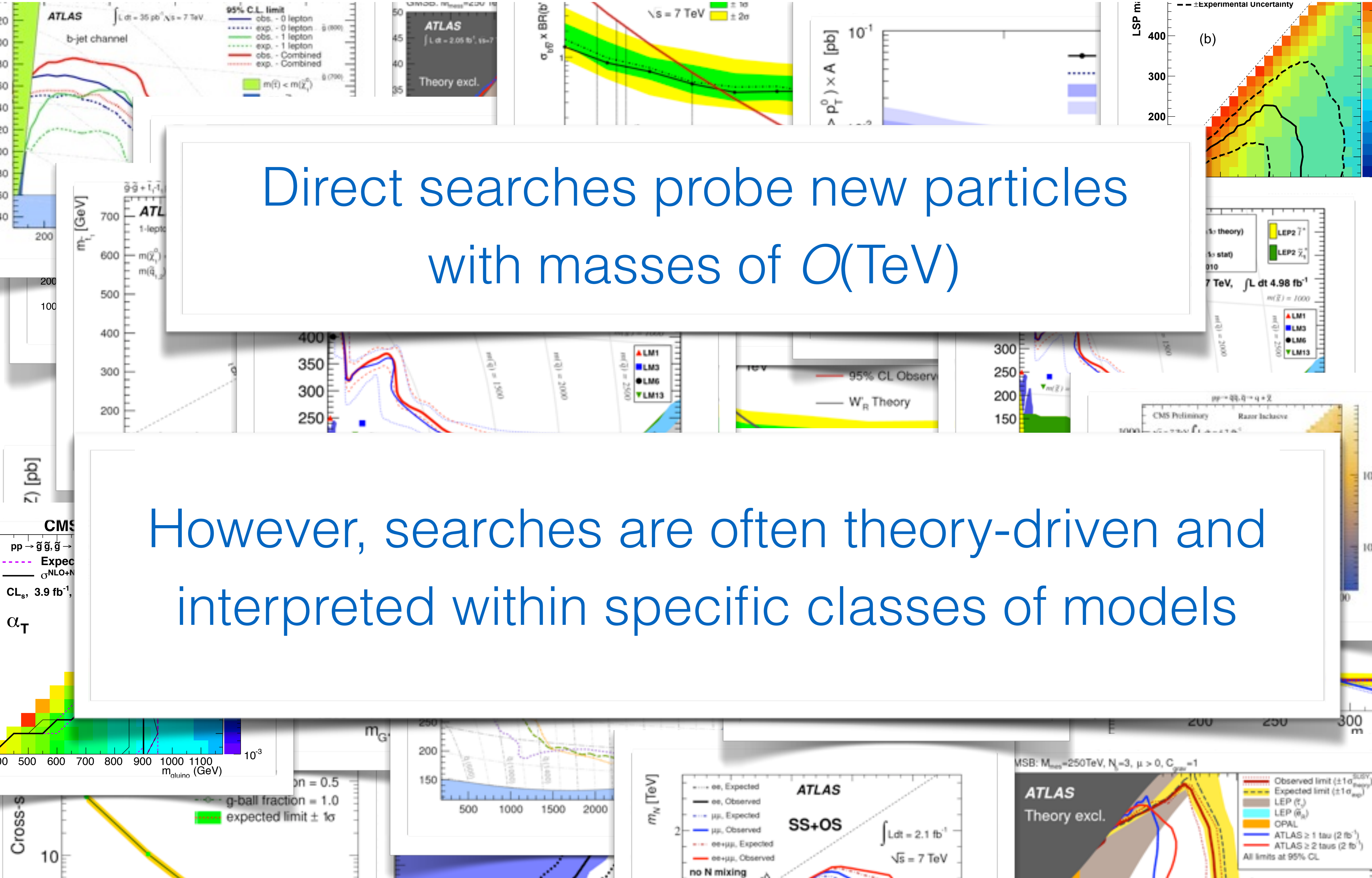


Lessons from the LHC: no sign of new physics



Direct searches probe new particles with masses of O(TeV)

Lessons from the LHC: no sign of new physics



Direct searches probe new particles with masses of *O*(TeV)

However, searches are often theory-driven and interpreted within specific classes of models

- Do we search in all the right places?
- Can we interpret the results in a wider class of models?
- If new physics is seen, can we characterise it in terms of observed properties, with minimal reliance on untested assumptions?

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For the LHC-13 we need to

- Explore a wider range of BSM models
- and move towards more model-independent searches: effective field theories and simplified models.

Model-independent searches for dark matter

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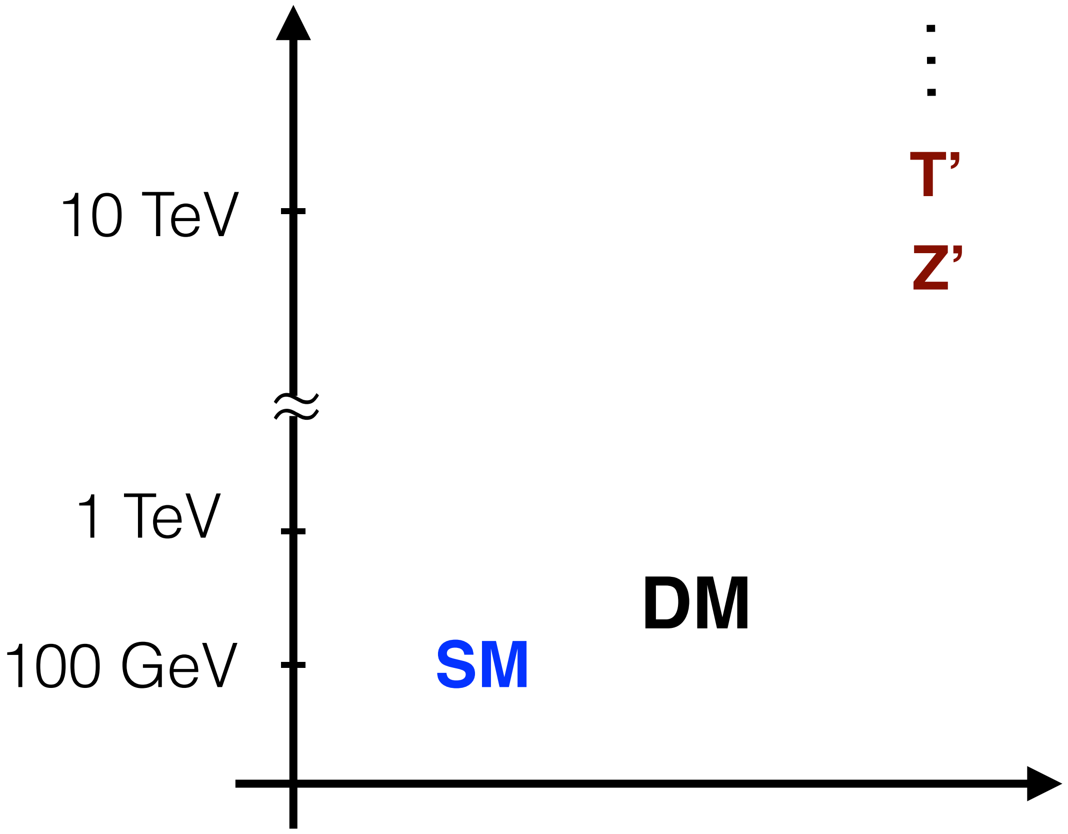
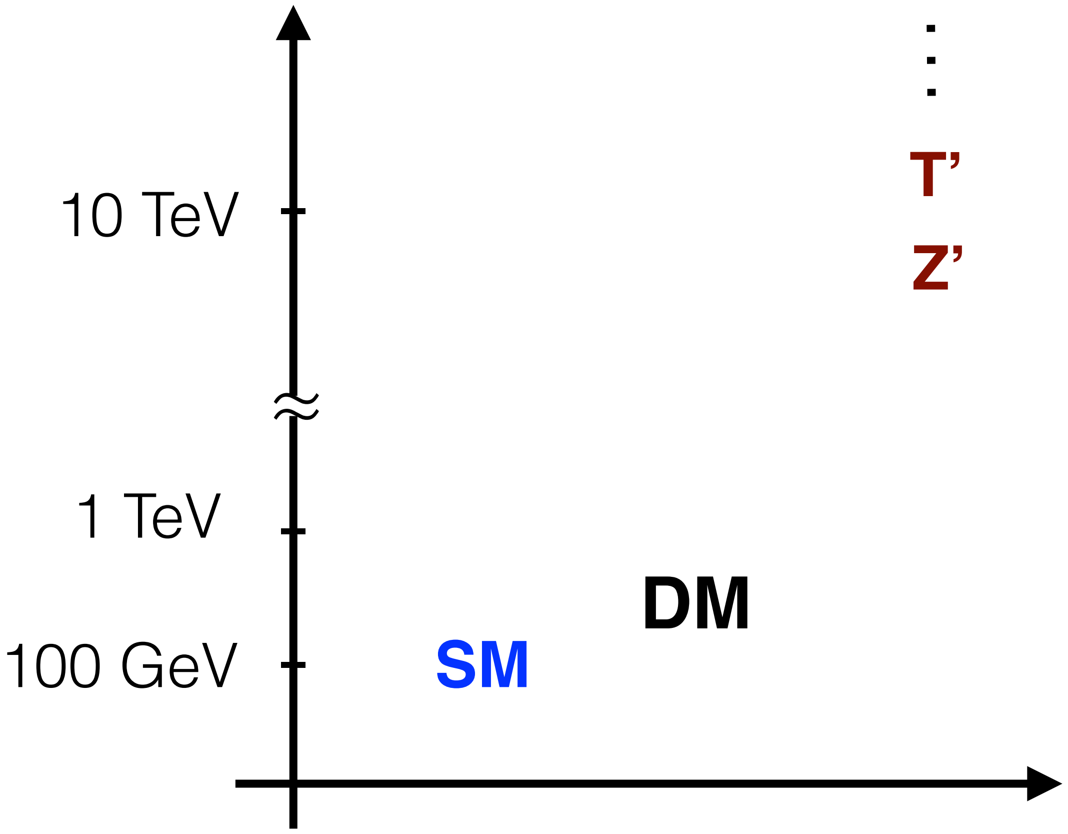
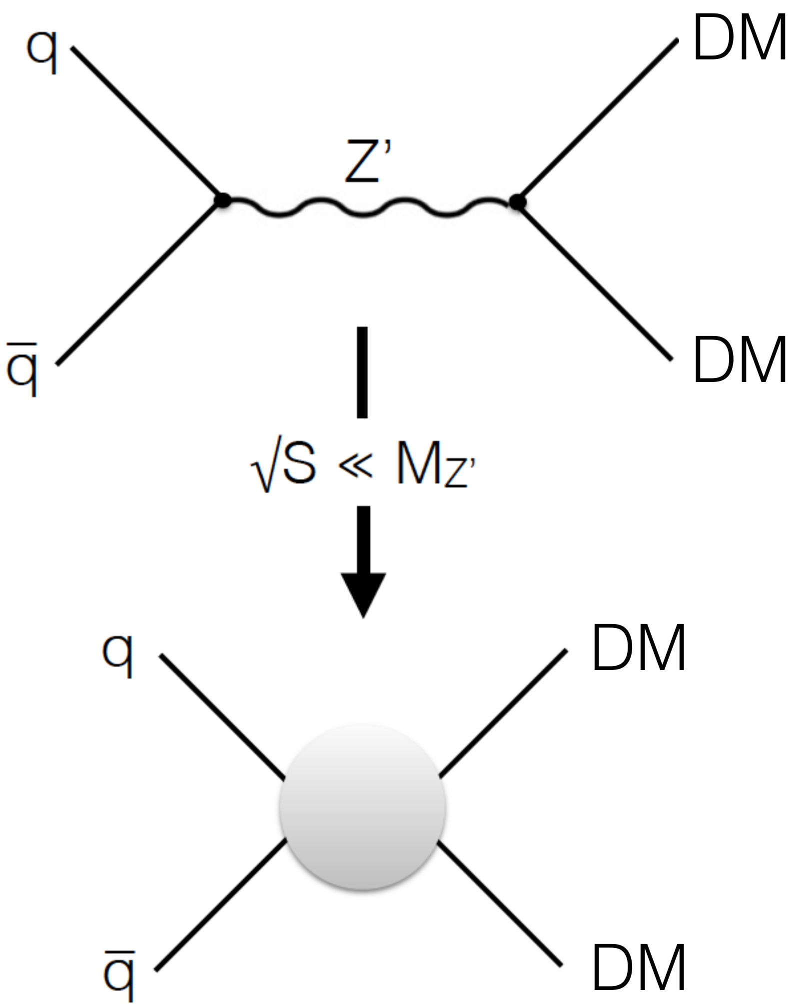


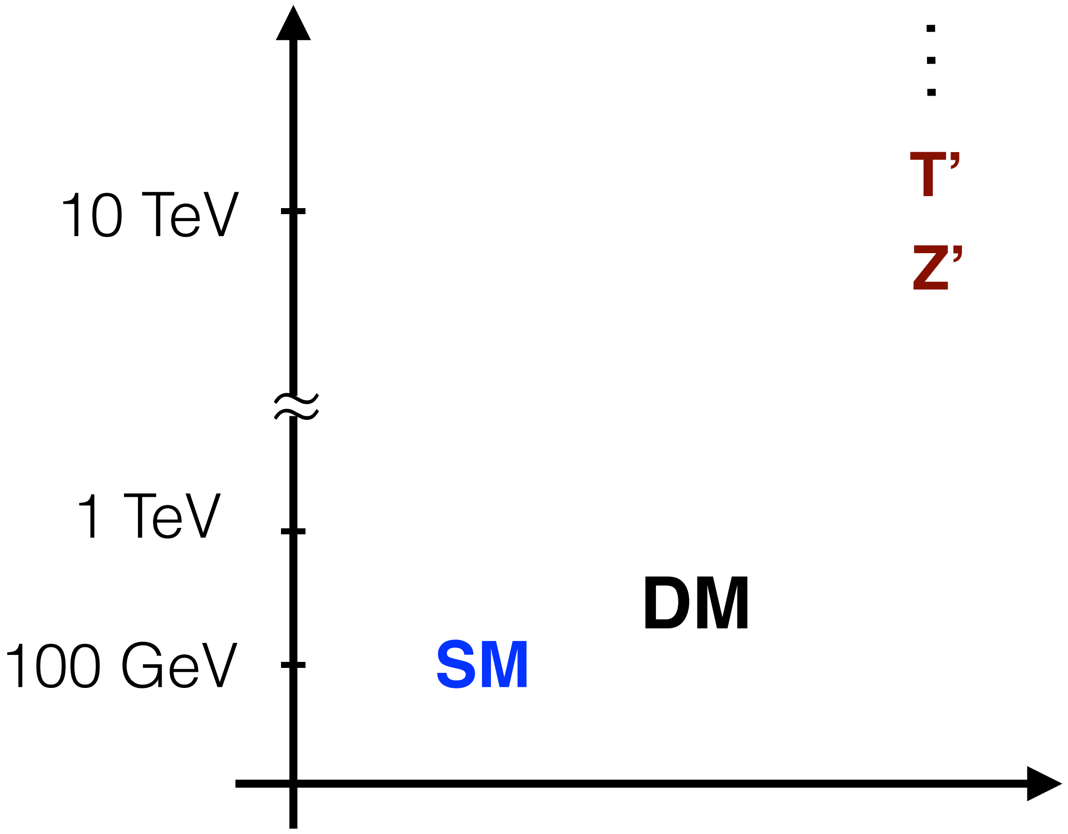
Model-independent searches for dark matter

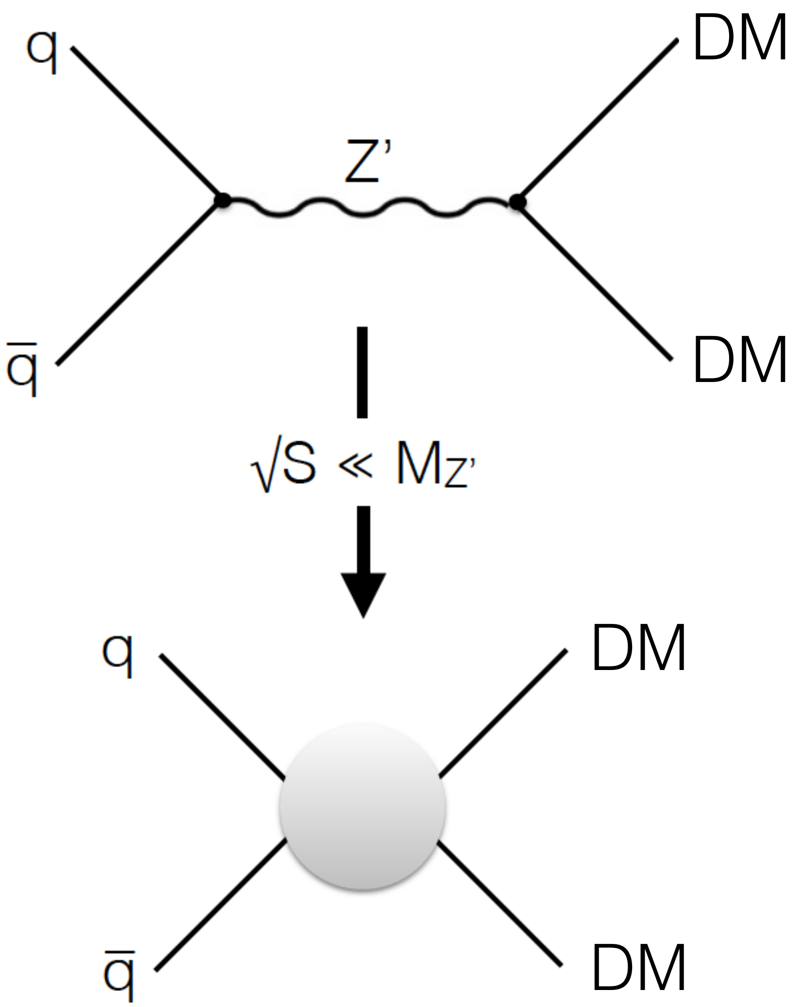




Model-independent searches for dark matter

effective field theories





$$M(q\bar{q} \to \psi_{\rm DM}\overline{\psi}_{\rm DM}) = \frac{1}{M_*^2}(\bar{q}\Gamma q)(\overline{\psi}_{\rm DM}\Gamma\psi_{\rm DM})$$

However, if M$_{Z'}$ ≫ √S, the dark matter signal is weak:

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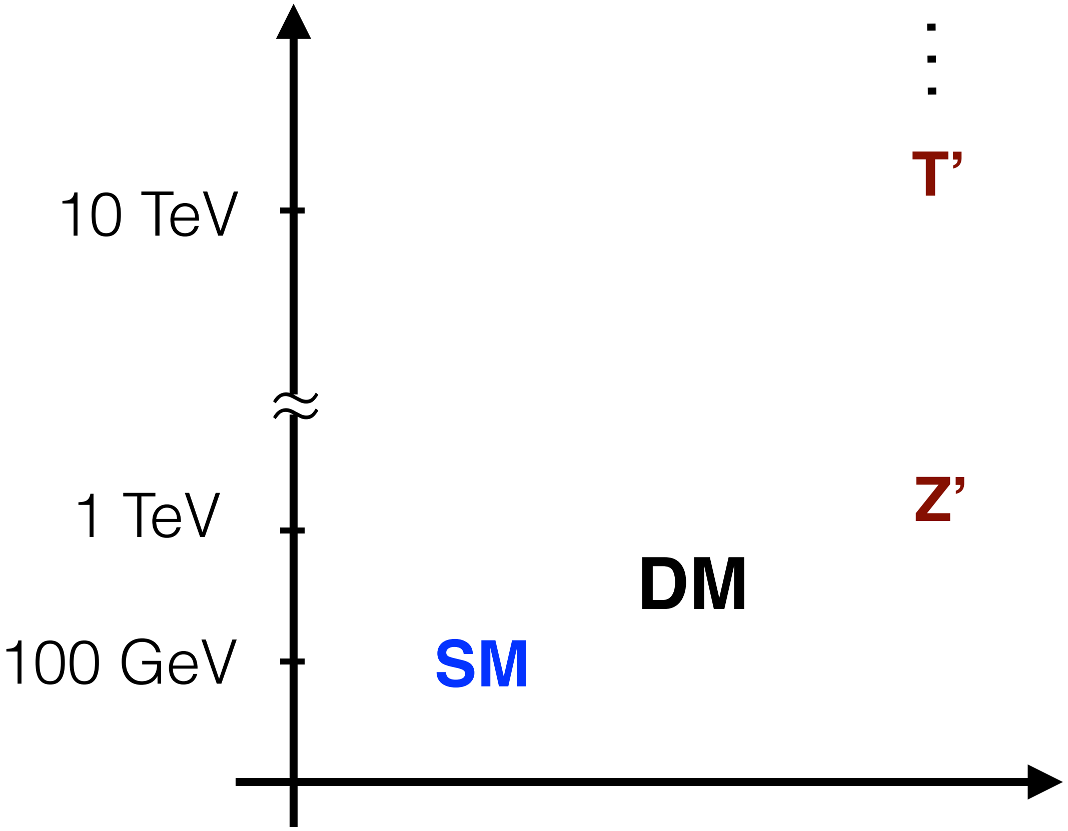
It is thus more interesting to consider simplified models, where at least one mediator is at the TeV scale:



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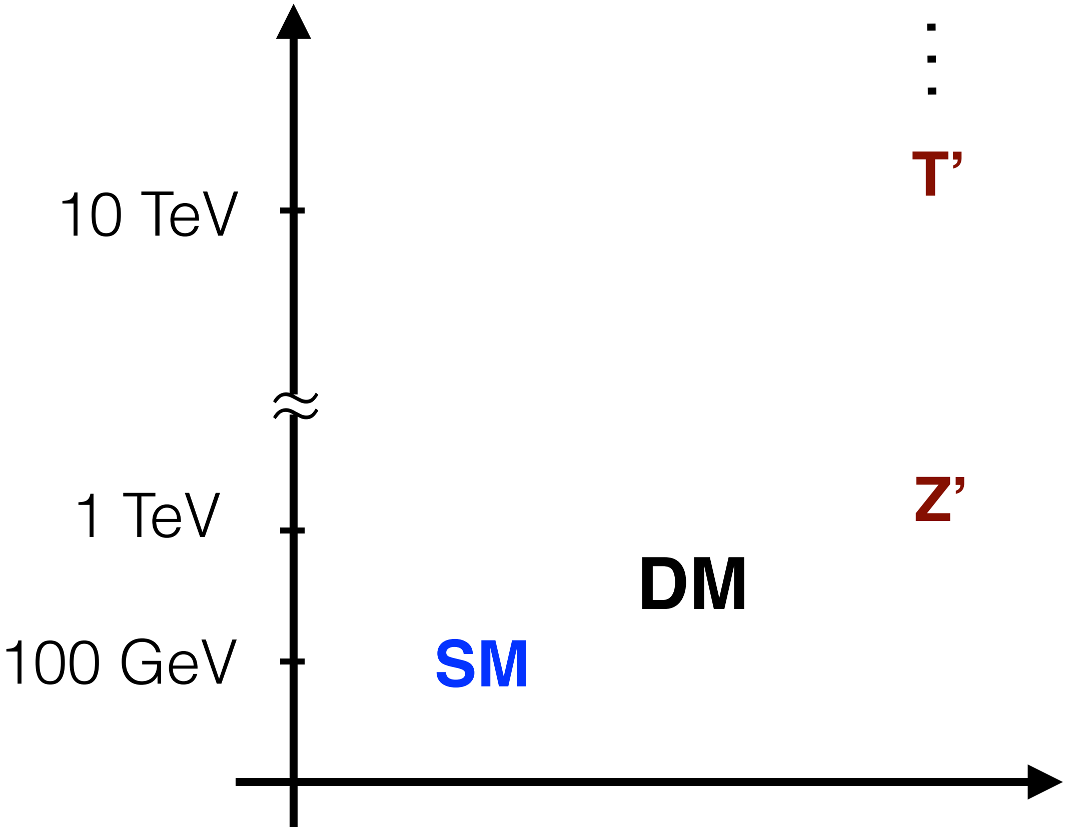
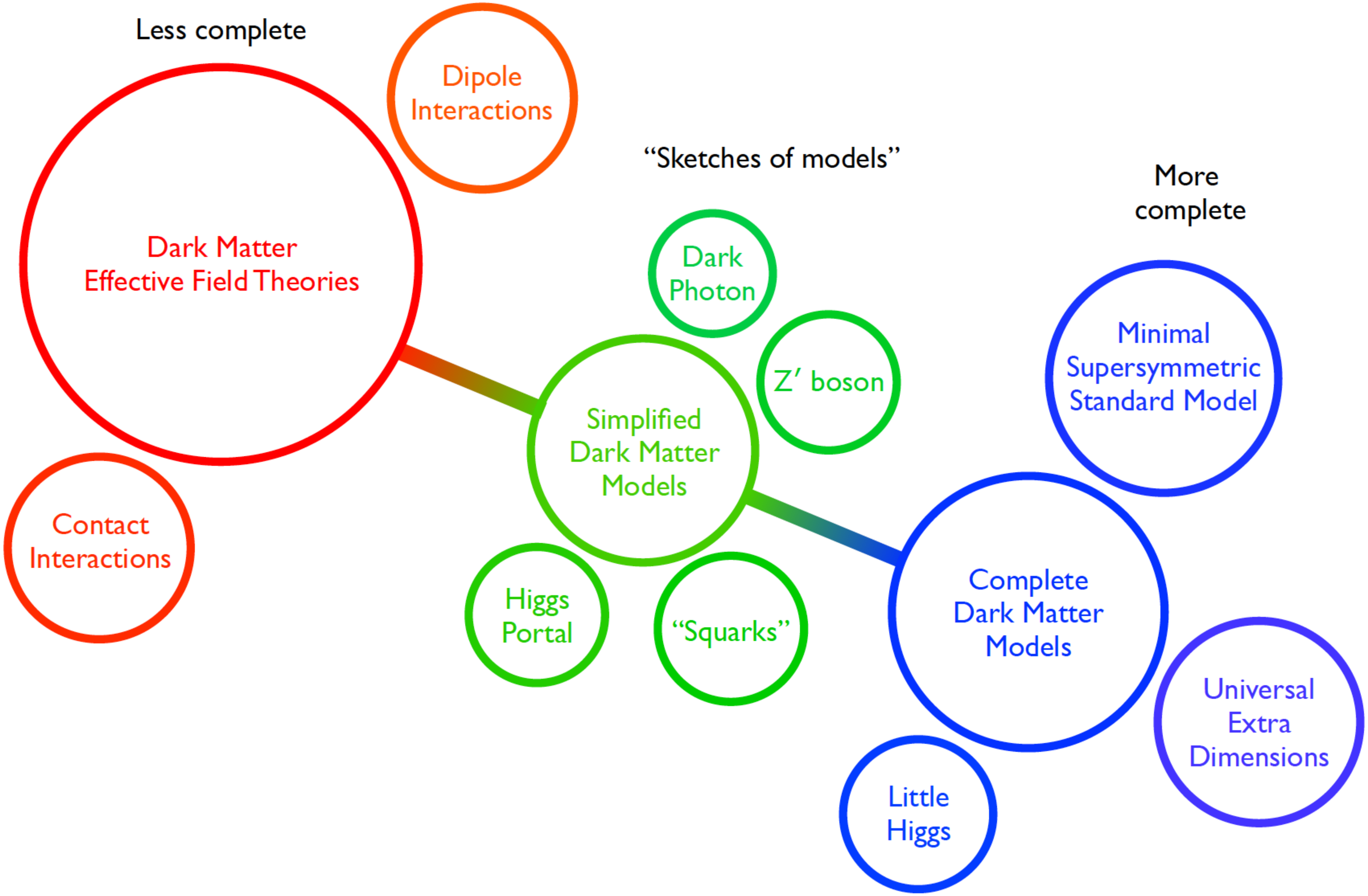


Such simplified models

- provide a reliable framework for LHC analyses;
- allow to explore constraints from mediator searches;
- allow to connect LHC analyses with direct and indirect dark matter searches.

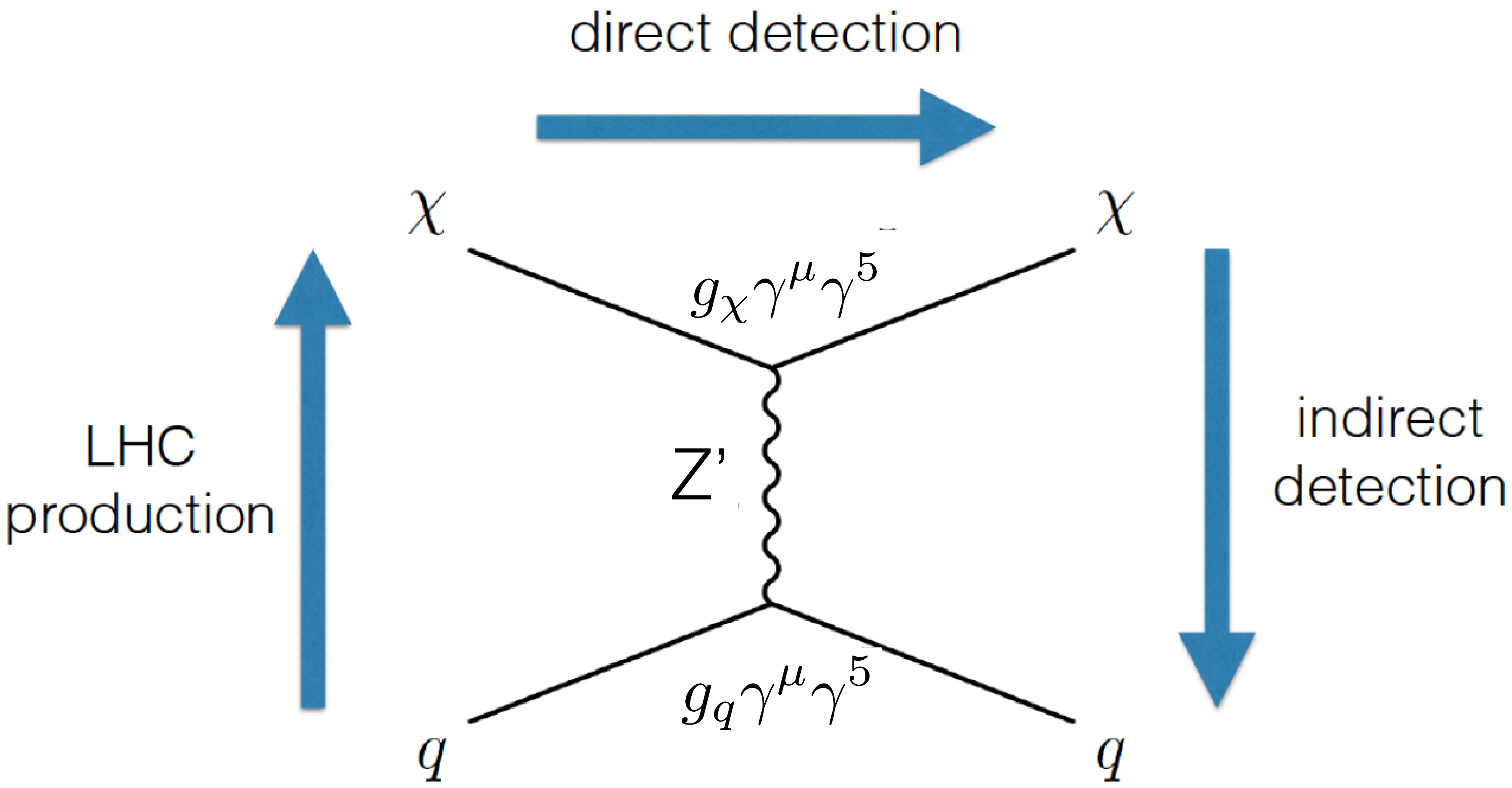
WIMP dark matter: from SUSY to simplified models

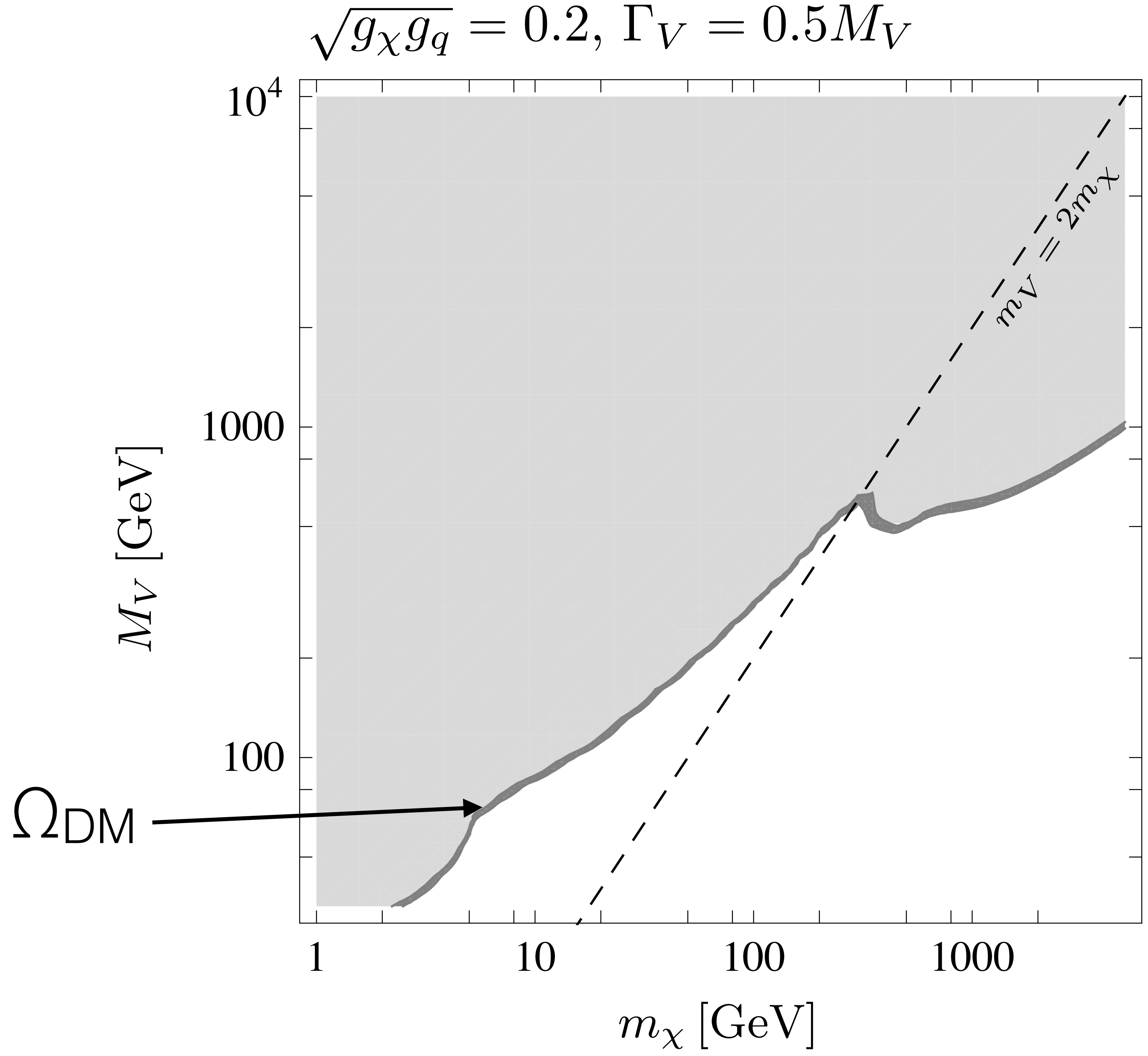


arXiv:1506.03116 [hep-ph]

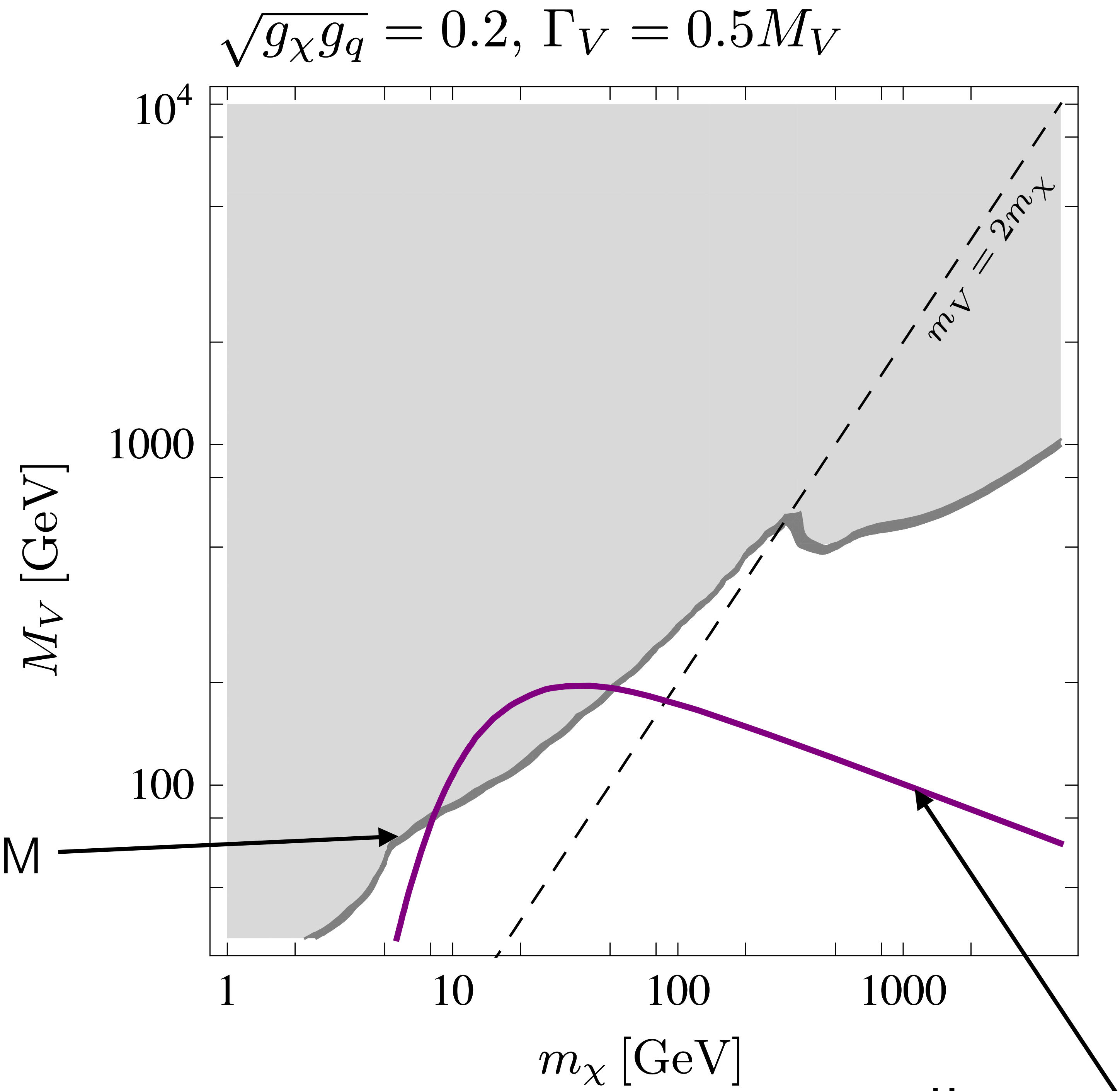
Consider a simplified dark matter model with an axial-vector mediator Z' which couples to a Majorana dark matter fermion χ and SM quarks.

The model has only four parameters (M_χ, $M_{Z'}$, $\sqrt{g_\chi g_q}$, $\Gamma_{Z'}$), and it can be tested in direct and indirect detection, and at the LHC.





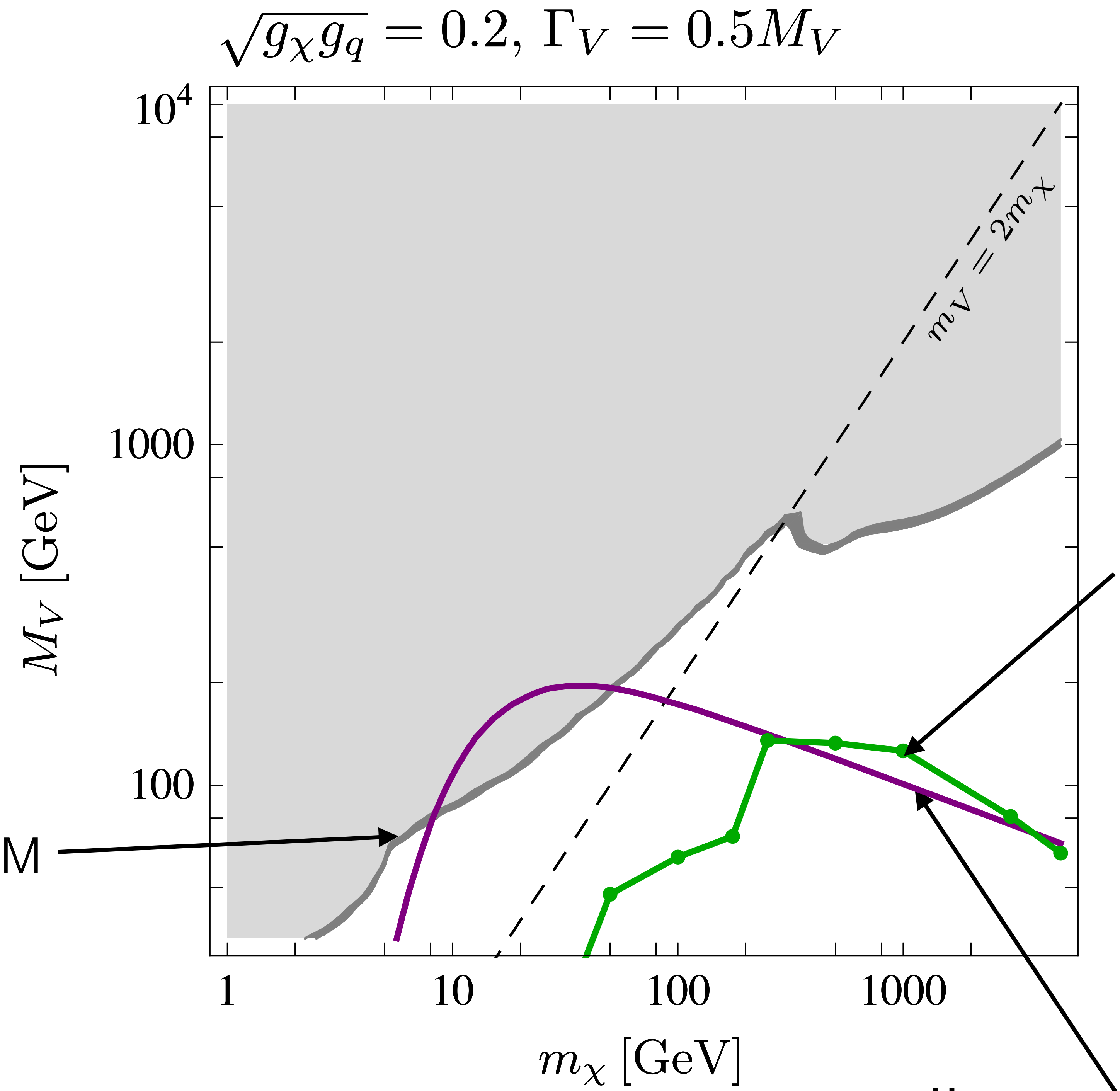
Heisig et al., arXiv:1509.07867 [hep-ph]



Ω_{DM}

direct detection

Heisig et al., arXiv:1509.07867 [hep-ph]



indirect detection

ICECUBE

SOUTH POLE NEUTRINO OBSERVATORY

Ω_{DM}

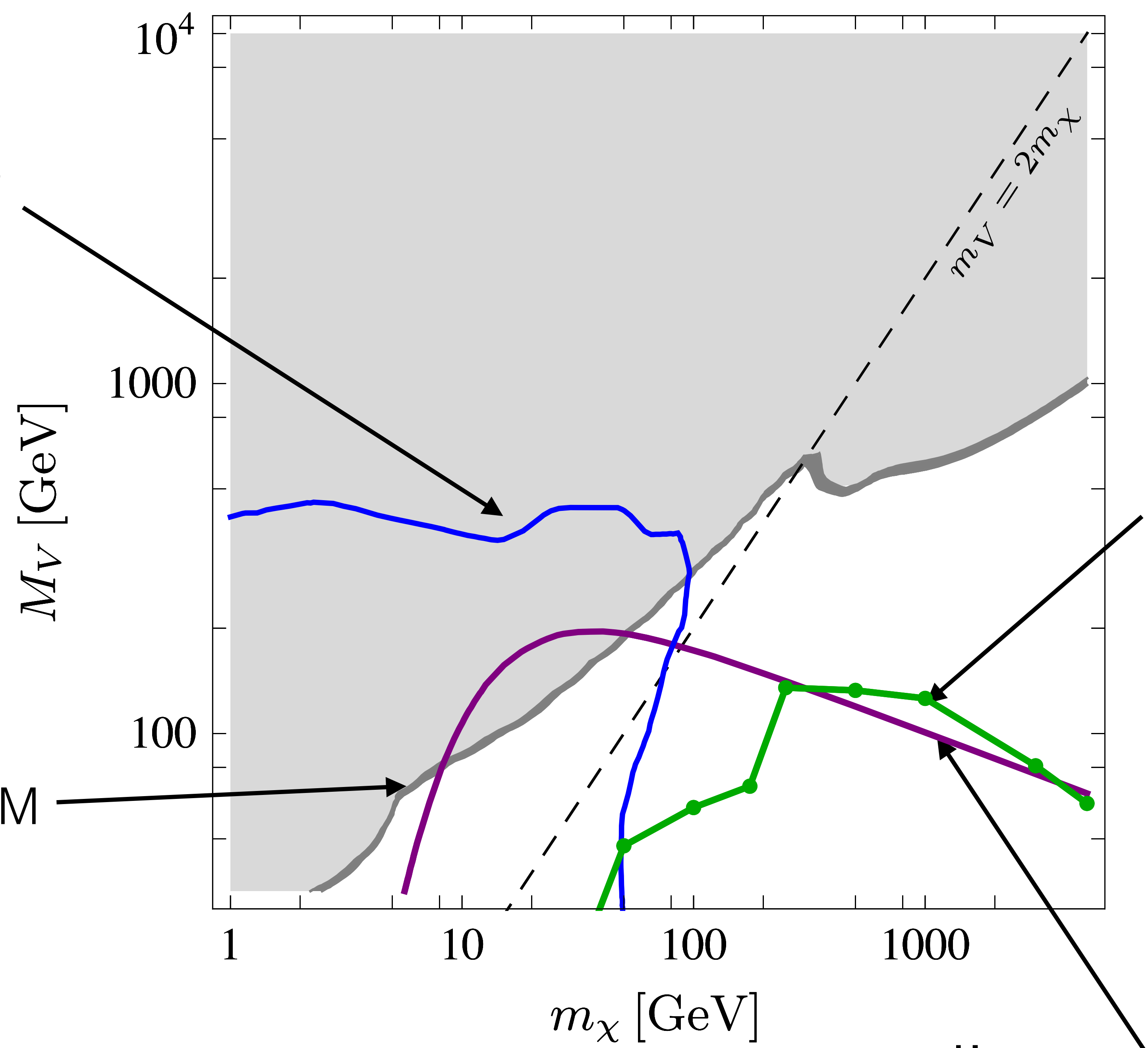
direct detection

LUX

Heisig et al., arXiv:1509.07867 [hep-ph]

mono-jet searches

$\sqrt{g_\chi g_q} = 0.2,\ \Gamma_V = 0.5 M_V$



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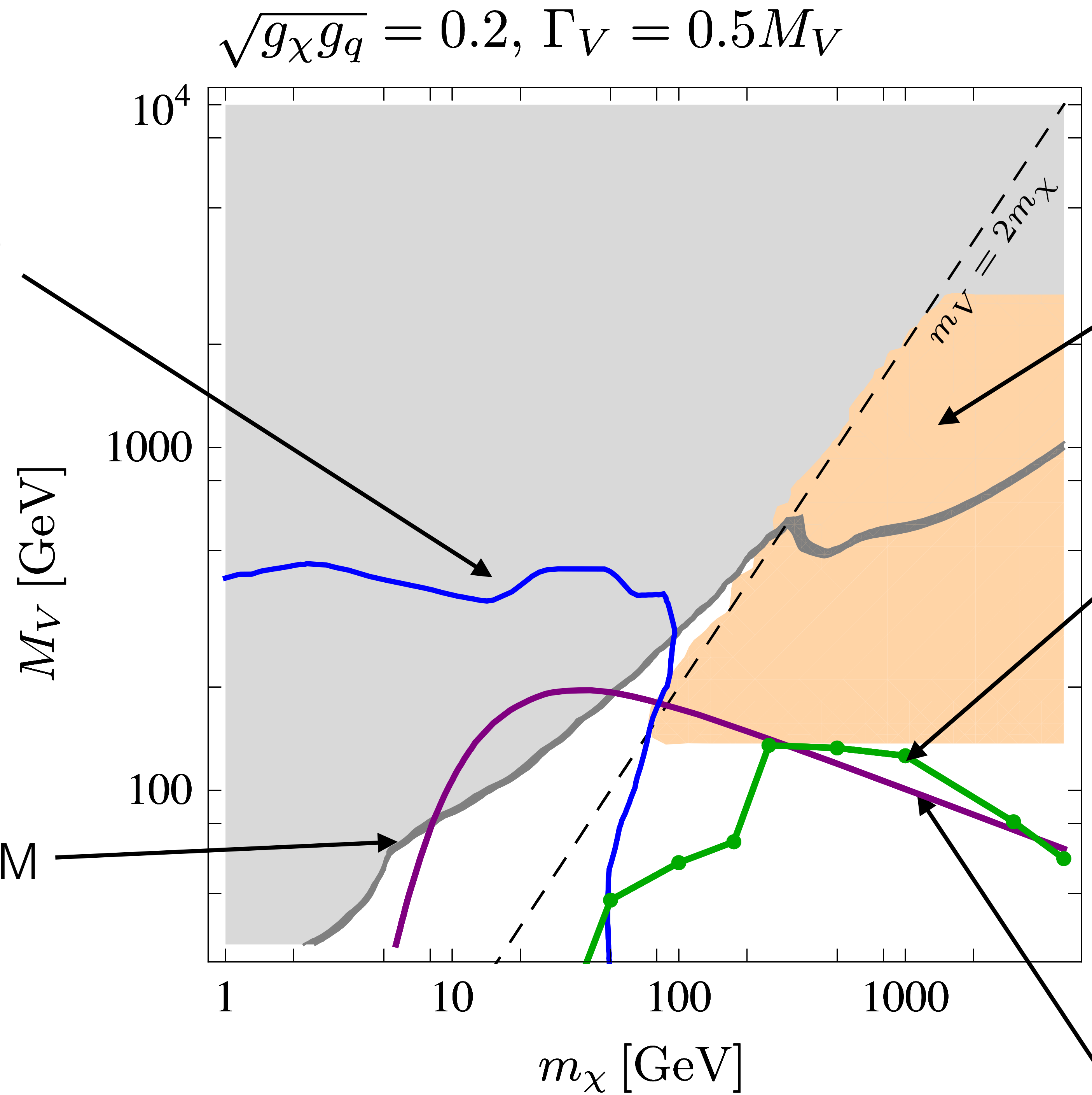

mono-jet searches

direct mediator searches

Chala et al., arXiv:1503.05916 [hep-ph]

indirect detection

Ω_{DM}

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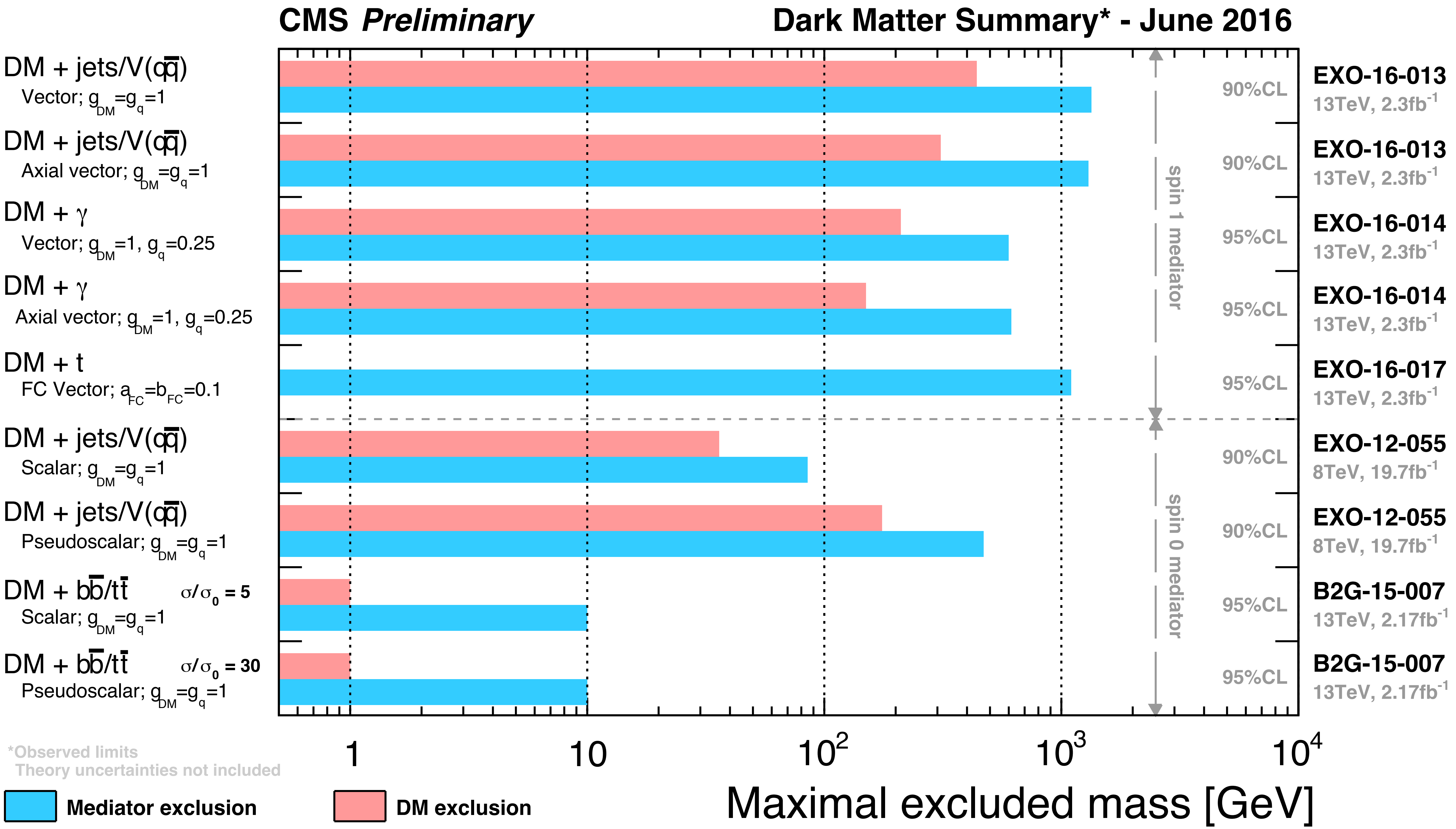
Heisig et al., arXiv:1509.07867 [hep-ph]

Lessons from the LHC: no sign of dark matter



Science may be described as the art of systematic oversimplification (Karl Popper)

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Consider a simplified dark matter model with a Z’:

$$\mathcal{L} = Z'_\mu \bar{\chi}[g^V_{\rm DM}\gamma^\mu + g^A_{\rm DM}\gamma^\mu\gamma_5]\chi + \sum_{f=q,l,\nu} Z'_\mu \bar{f}[g^V_f\gamma^\mu + g^A_f\gamma^\mu\gamma_5]f$$

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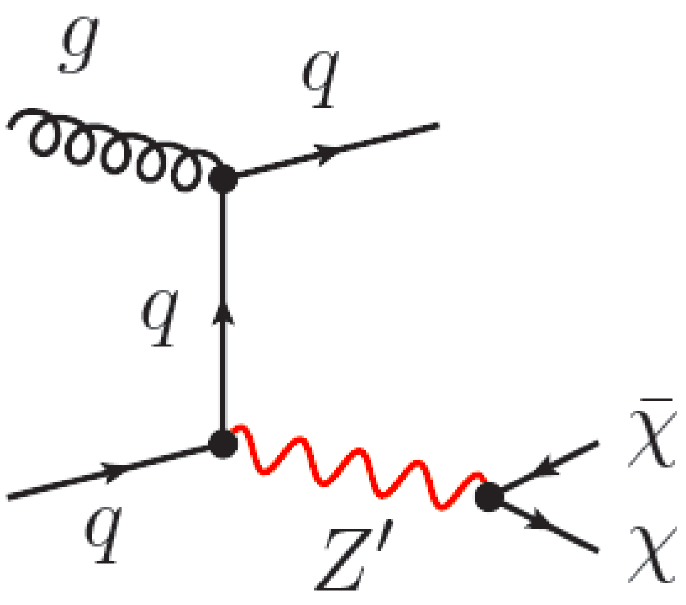

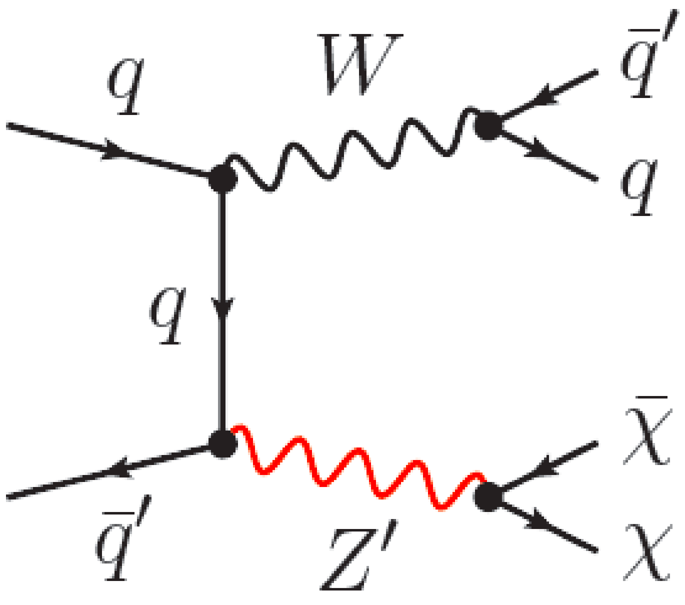

Bell et al., arXiv:1503.07874 [hep-ph]; Haisch et al., arXiv:1603.01267 [hep-ph]

Let us set $g^A_{\rm DM} = g^A_q = 0$ and $g^V_{\rm DM} = 1$:

$$\mathcal{L} = Z'_\mu \bar{\chi}\gamma^\mu\chi + Z'_\mu[g^V_u\,\bar{u}\gamma^\mu u + g^V_d\,\bar{d}\gamma^\mu d]$$

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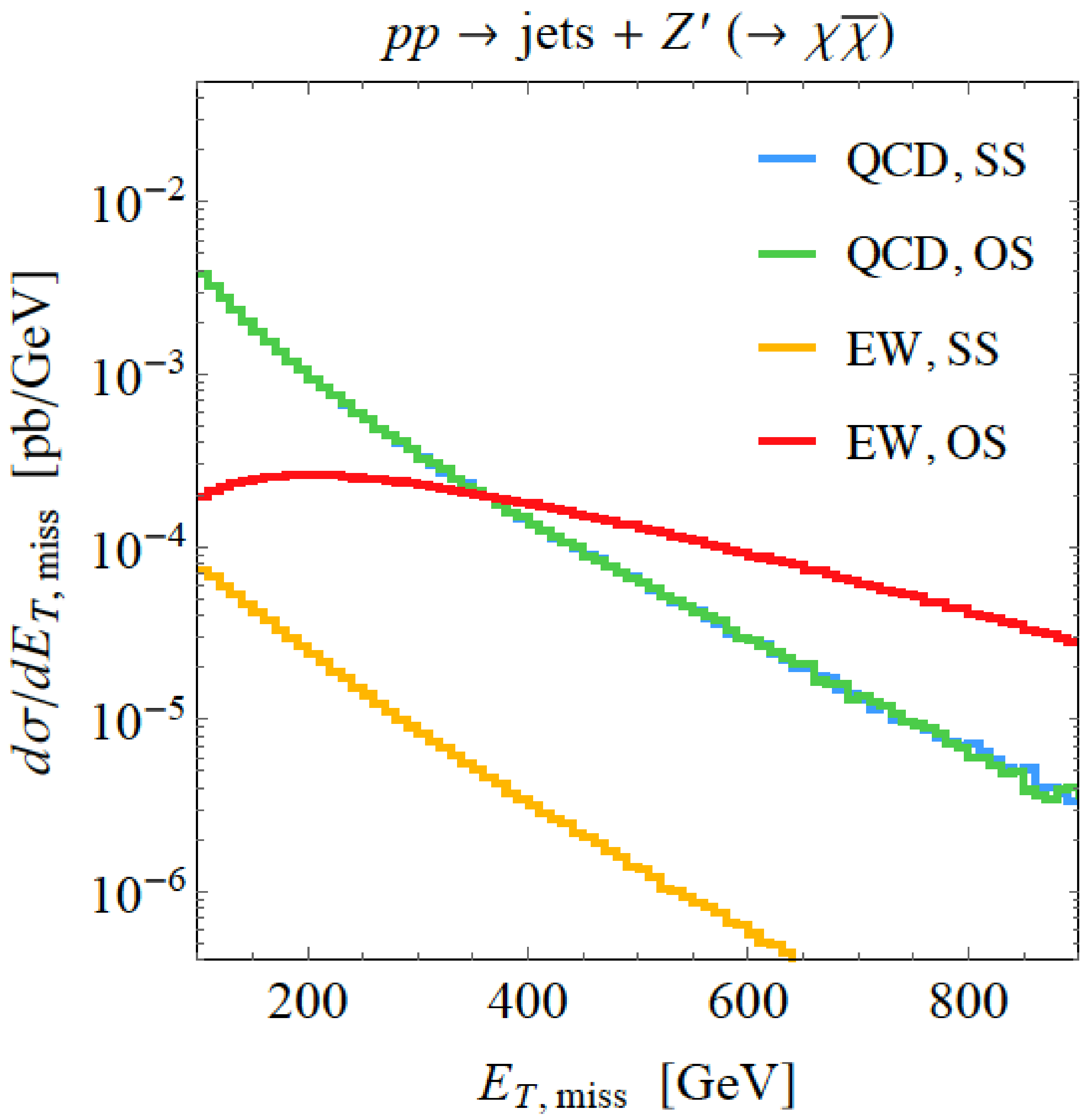

$$g^V_u = g^V_d = 0.25 \quad \text{(SS)}$$

$$g^V_u = -g^V_d = -0.25 \quad \text{(OS)}$$

Unitarity violation and the choice of couplings

A partial wave analysis of $u + \bar{d} \to W^+ + Z'$ yields:

$$\mathcal{M}(\text{p-wave}) = \frac{g}{96\pi M_W M_{Z'}} \, s \, \left(g_u^A - g_d^A - g_u^V + g_d^V\right)$$

and thus the scattering amplitude may violate unitarity.

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Impose $g_u^A - g_d^A - g_u^V + g_d^V = 0$

or equivalently $g_u^L = g_u^V - g_u^A = g_d^V - g_d^A = g_d^L$

i.e. left-chiral u and d-quarks should have the same coupling to the Z’

Compare to the Standard Model

$$\mathcal{L}_{\rm SM} = \sum_q Z_\mu \bar{q}\,[g^V_{Z,q}\gamma^\mu + g^A_{Z,q}\gamma^\mu\gamma_5]q$$

$$g^V_{Z,q} = \frac{g}{2c_W}\left(T_{3,q} - 2Q_q s_W^2\right) \quad \text{and} \quad g^A_{Z,q} = -\frac{g}{2c_W}T_{3,q}$$

Thus $g^L_{Z,u} - g^L_{Z,d} = g c_W \neq 0$

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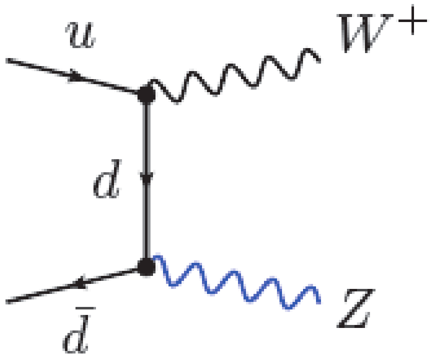
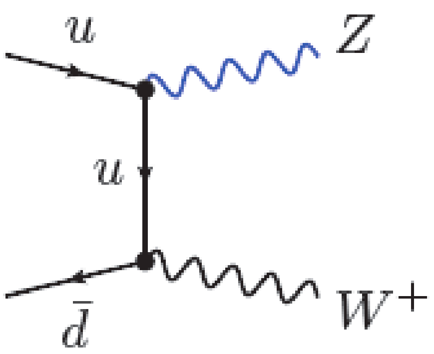
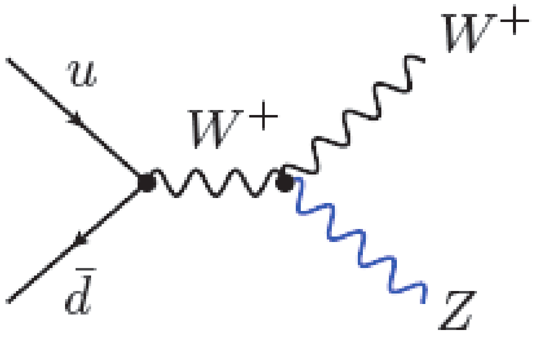
Triple gauge boson couplings come to rescue







$$|M|^2 \to \frac{3g^4 c_W^4 |V_{ud}|^2}{32 M_W^2}\left(d_1 + d_2 - 2d_3\right)^2 s^2 \sin^2\theta$$

(Over-)simplified models may violate unitarity

- restrict the choice of couplings
- add more particles/interactions

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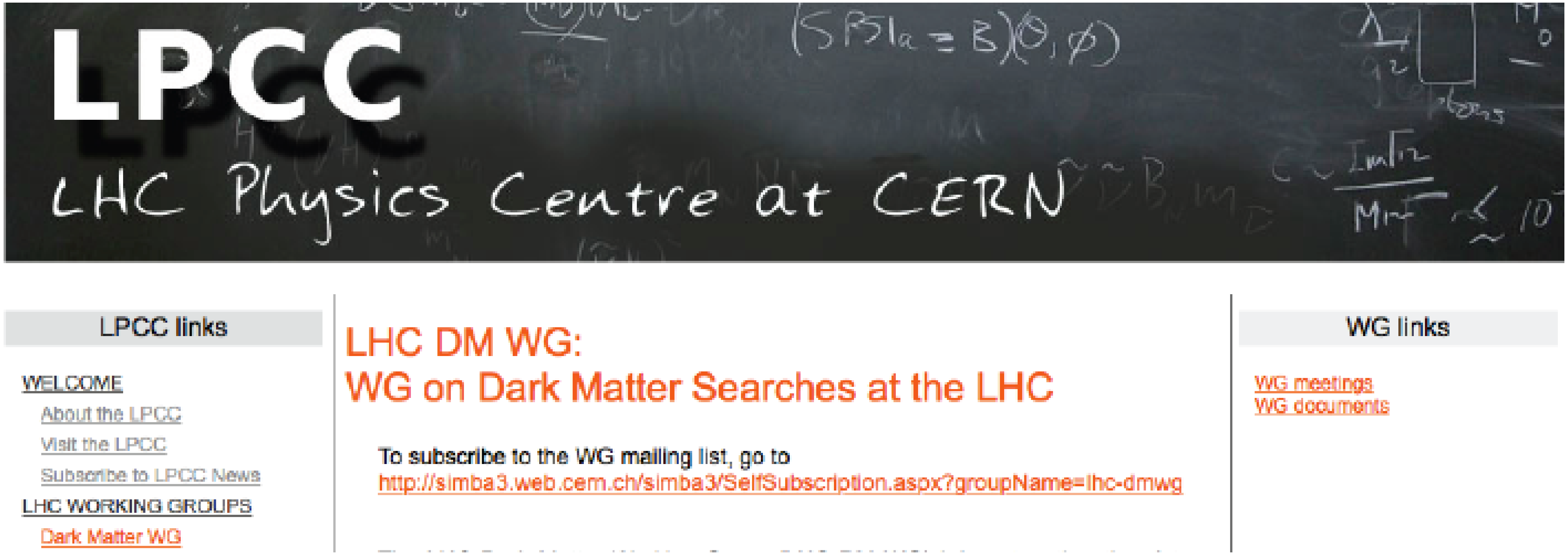
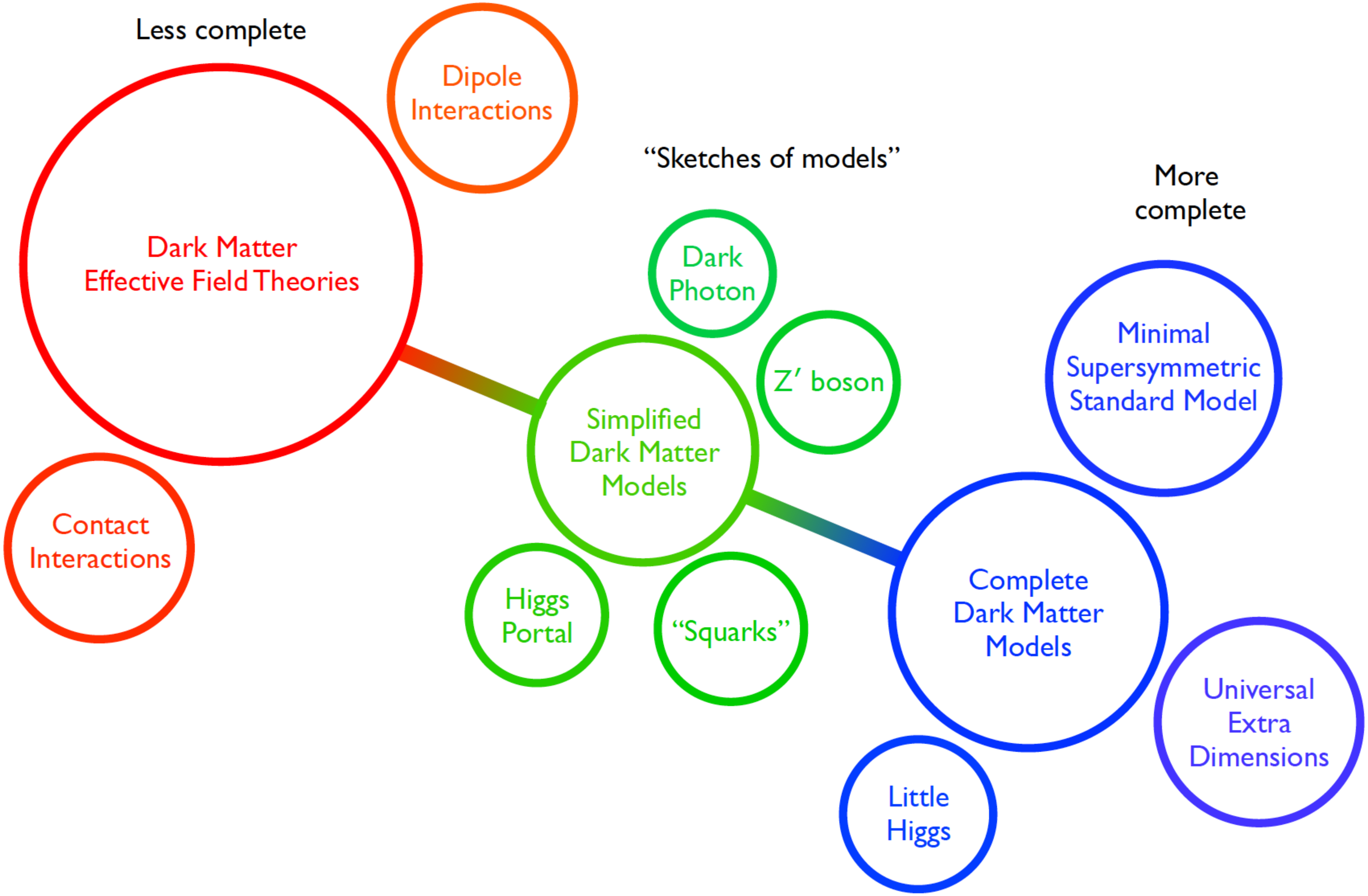


LHC DM WG:
WG on Dark Matter Searches at the LHC

To subscribe to the WG mailing list, go to
http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg

WIMP dark matter: from SUSY to simplified models



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

arXiv:1506.03116 [hep-ph]

Summary

Searches for new physics are increasingly designed and interpreted in terms of simplified models rather than specific top-down models

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- mediate between theory and data
- allow to explore the space of theories and signatures
- connect direct and indirect searches for new physics

However

- How do we choose the right simplified models?
- How do simplified models connect to theory?

Conclusions

The limits from direct searches, and the Higgs boson mass and profile, tend to push the new physics scale beyond TeV.

New physics is either natural and somewhat elaborate, or simple and unnatural.

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For the LHC-13 we need to

- explore a wider range of BSM models
- move towards more model-independent searches: effective field theories, simplified models.

Should new physics be natural, simple, beautiful, perturbative,…?

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Don’t expect too much guidance from theory…

Should new physics be natural, simple, beautiful, perturbative,…?

Experiment has to tell!

Thank you!