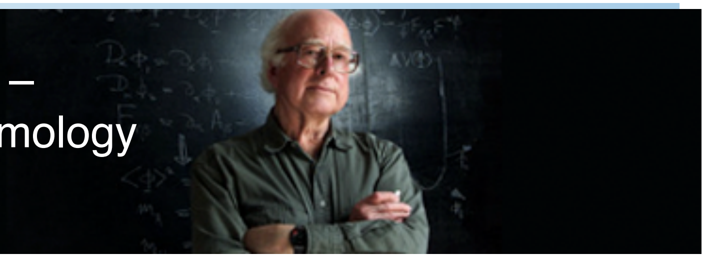
Imperial College London

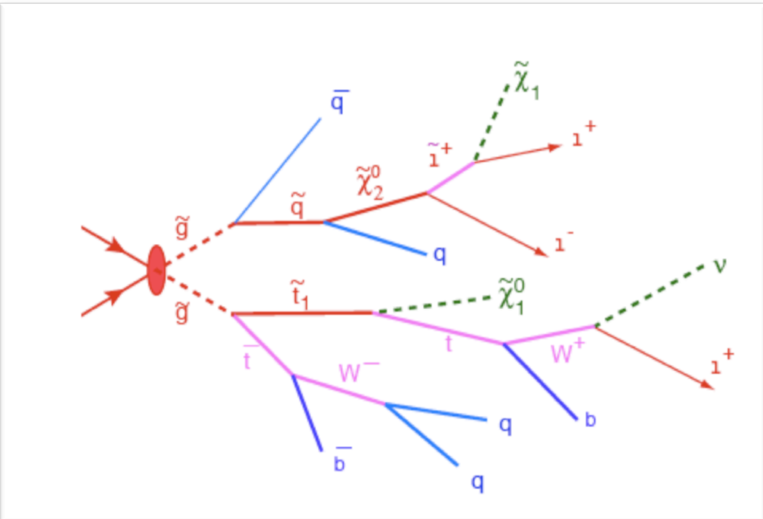
The Higgs Centre for Theoretical Physics

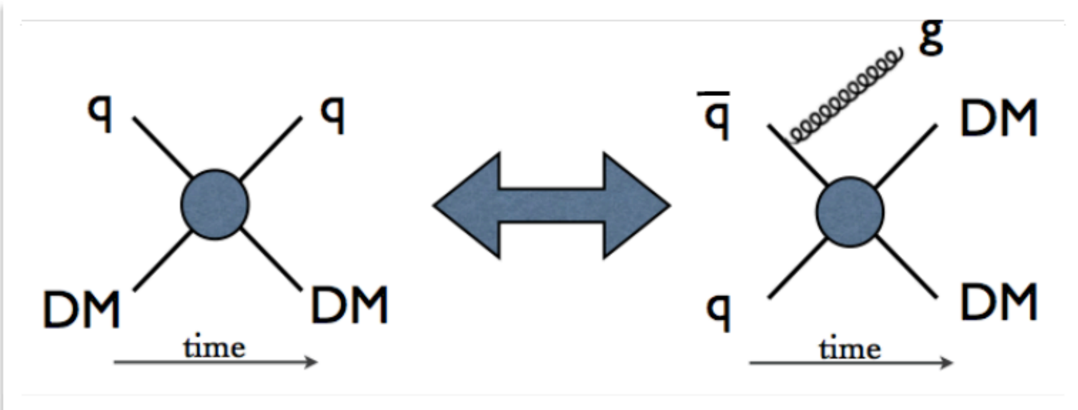
2014 Higgs Symposium –
New Horizons in Particle Cosmology
30 June to 2 July



Oliver Buchmueller, Imperial College London

SEARCHES FOR DARK MATTER PRODUCTION AT COLLIDER & DIRECT DETECTION EXPERIMENTS

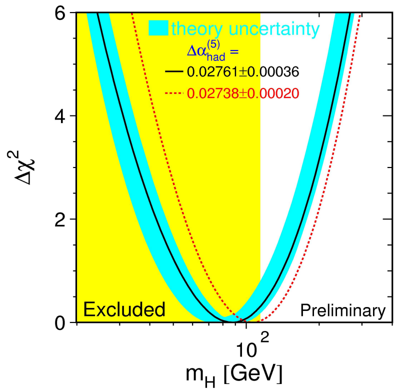


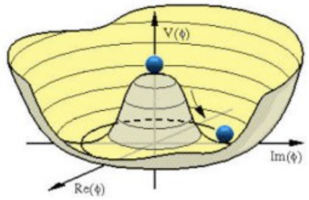


Fundamental Open Questions in Particle Physics

I. What is the origin of mass?

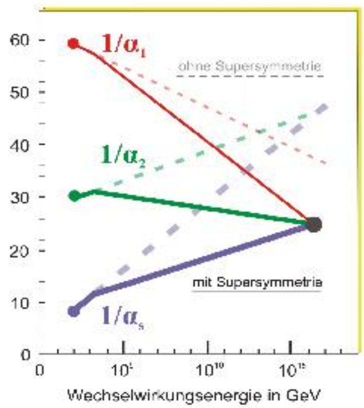
- *Why are the vector bosons Z and W are massive whereas the photon is massless?*
- *Is there a Higgs boson - or even more of them ?*

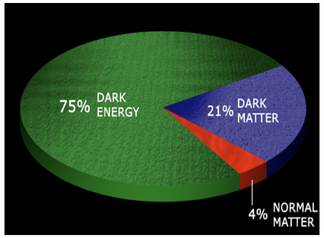




I. What is the origin of Dark matter in our Universe ?

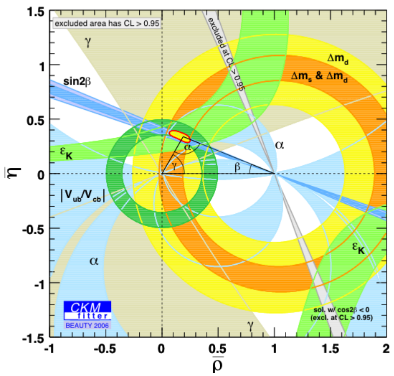
- *Is a fundamental particle responsible for it?*
- *Is there a new symmetry in nature?*
  - *=> Does Supersymmetry exist and can it explain DM?*

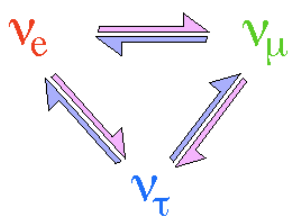




III. What is the origin of the matter-anti-matter asymmetry in our Universe?

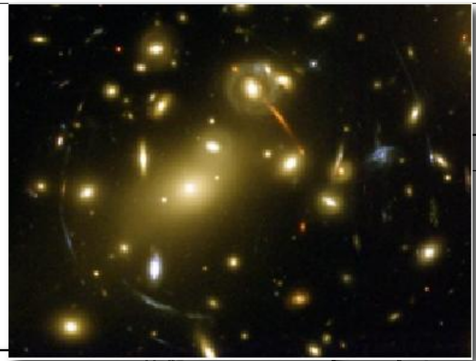
- *Does the answer lie in in CP violation?*
- *Neutrino masses and mixing - how do they fit in the picture?*

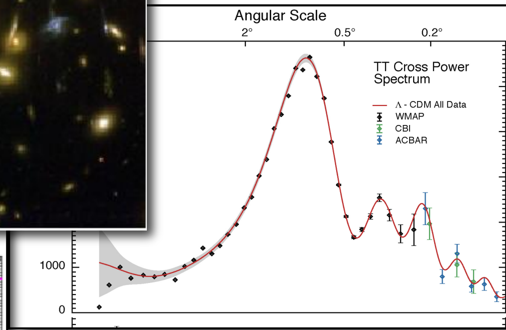


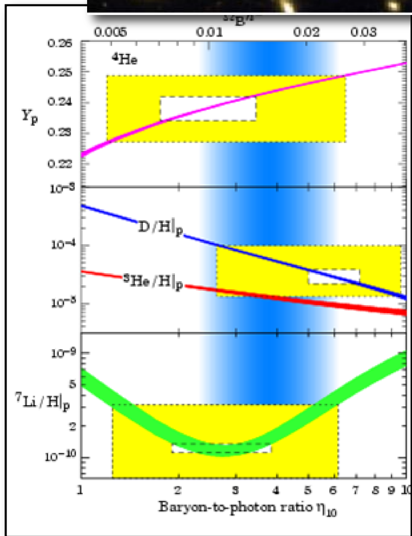


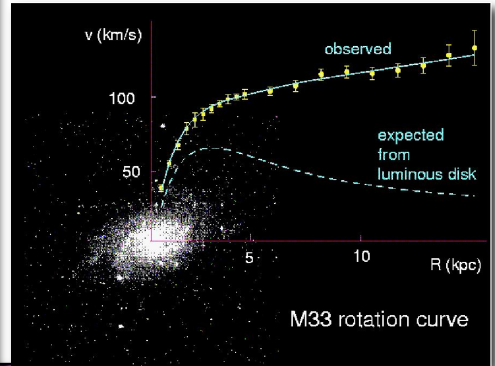
Very Strong Evidence for Dark Matter Today!

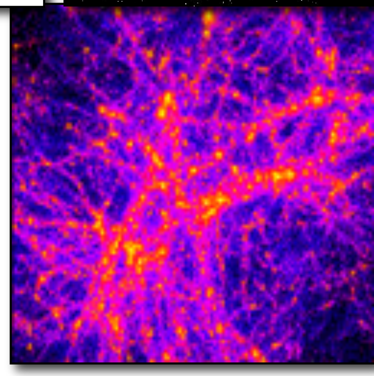
- Galactic rotation curves
- Gravitational lensing
- Light element abundances
- CMB anisotropies
- Large scale structure
- Etc…



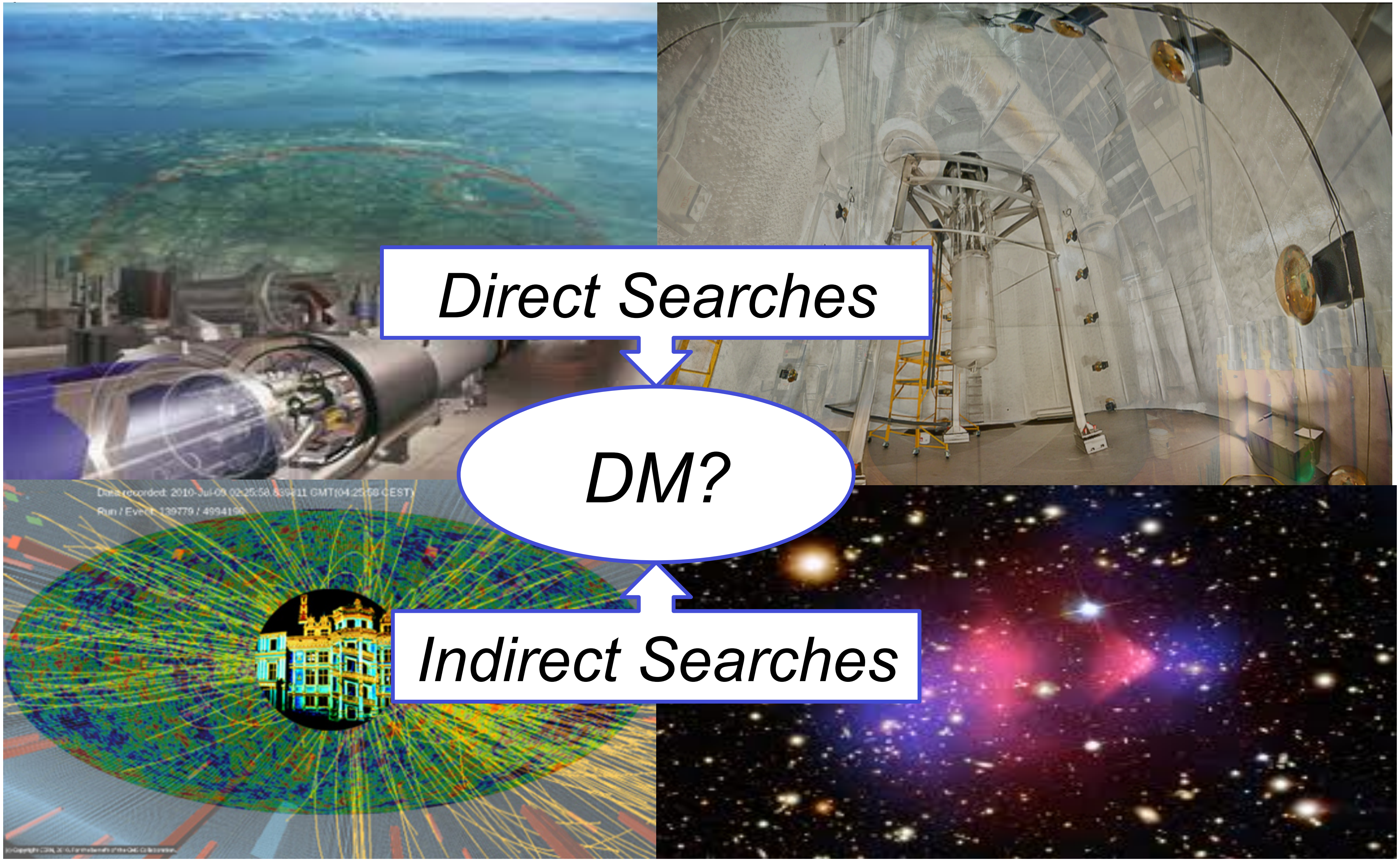






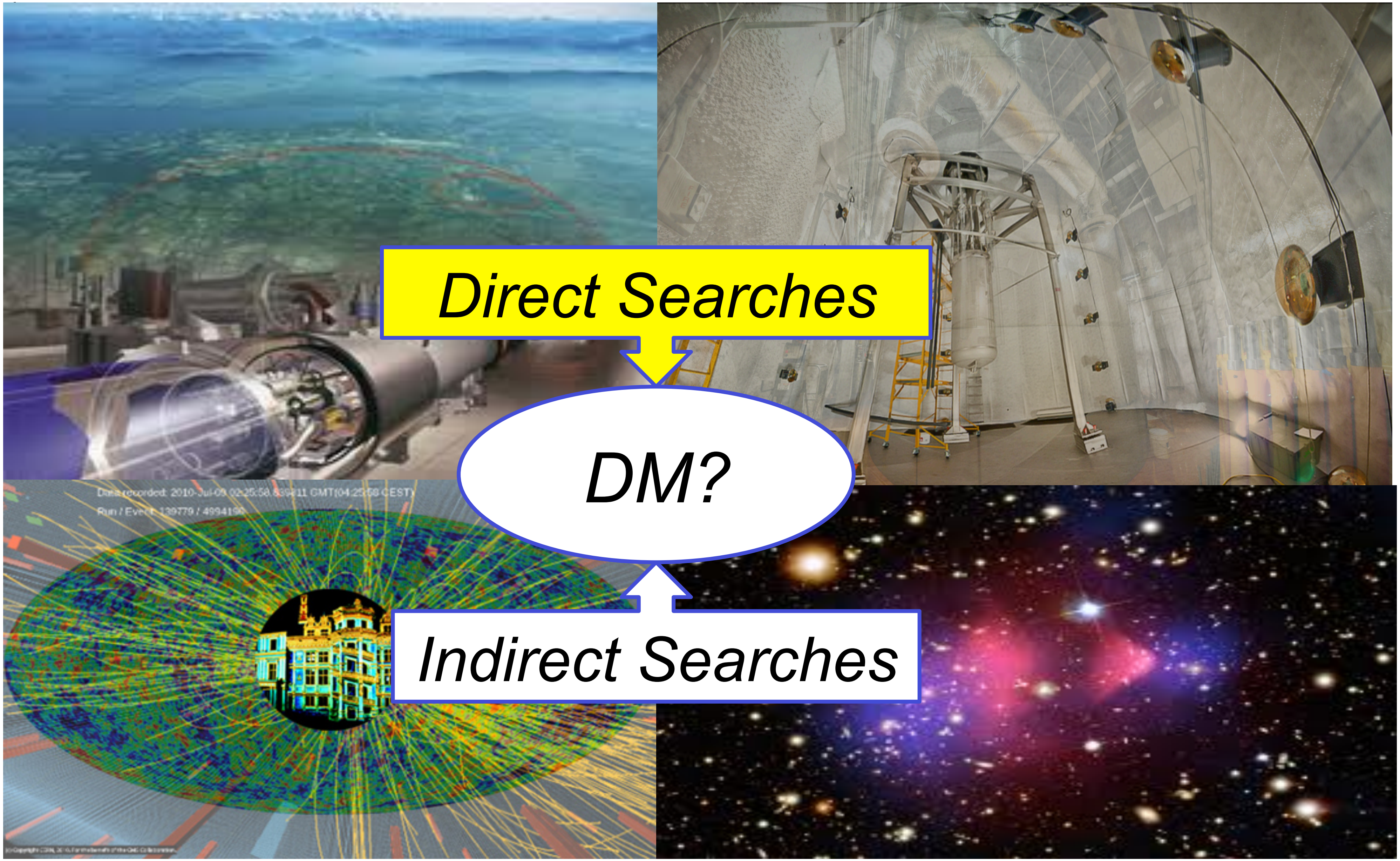


Dark Matter Searches

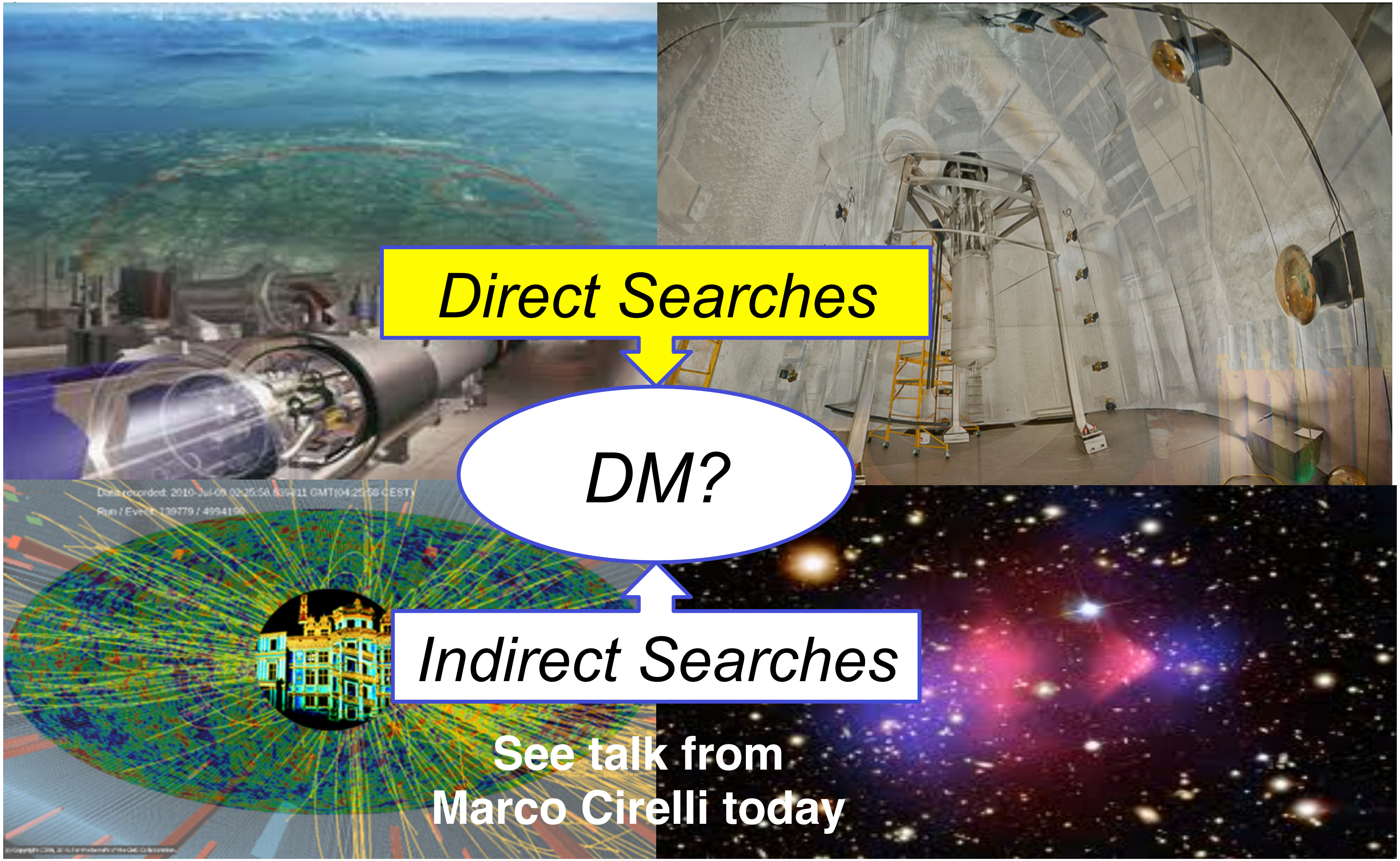


Imperial College London

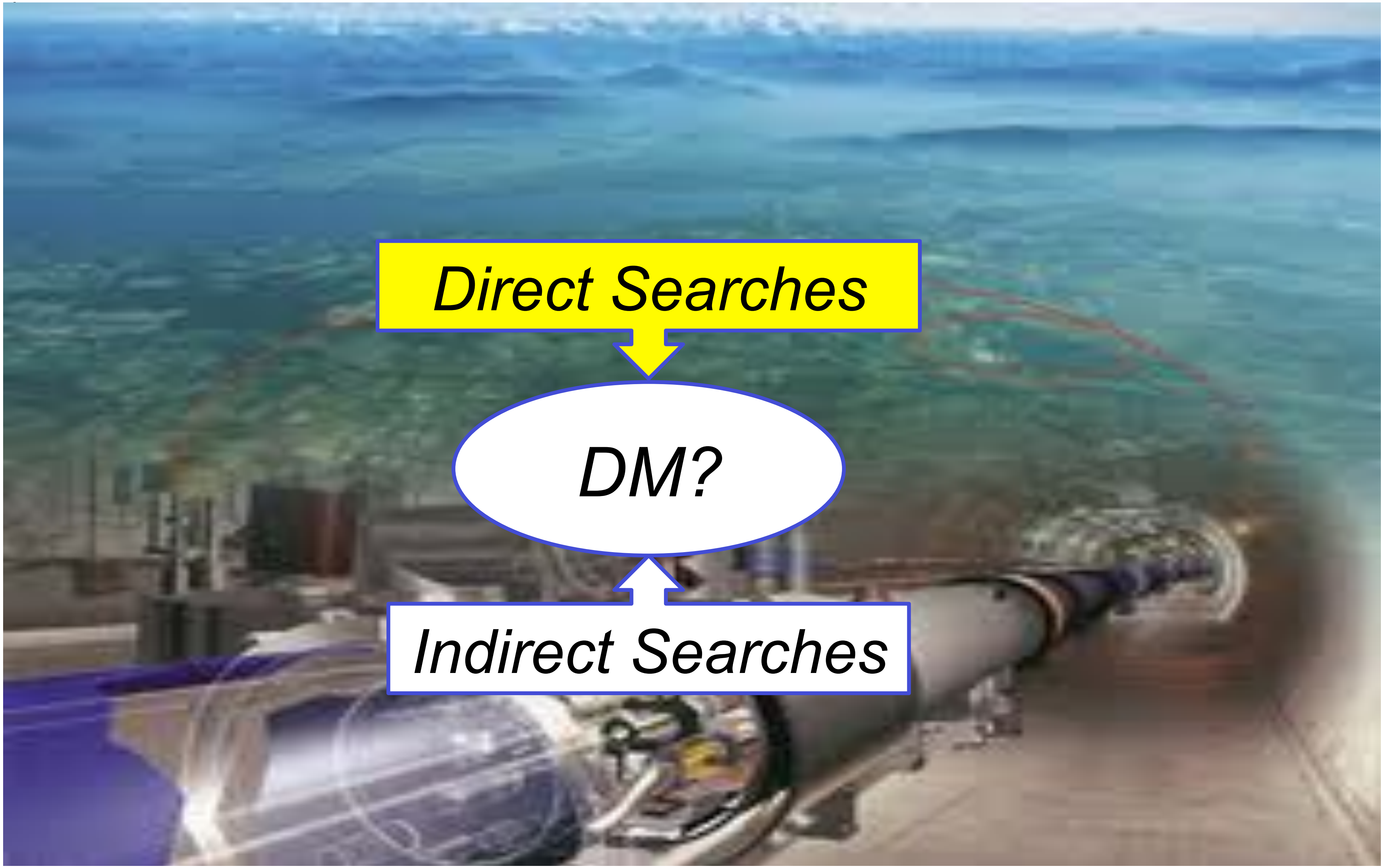
Dark Matter Searches



Dark Matter Searches



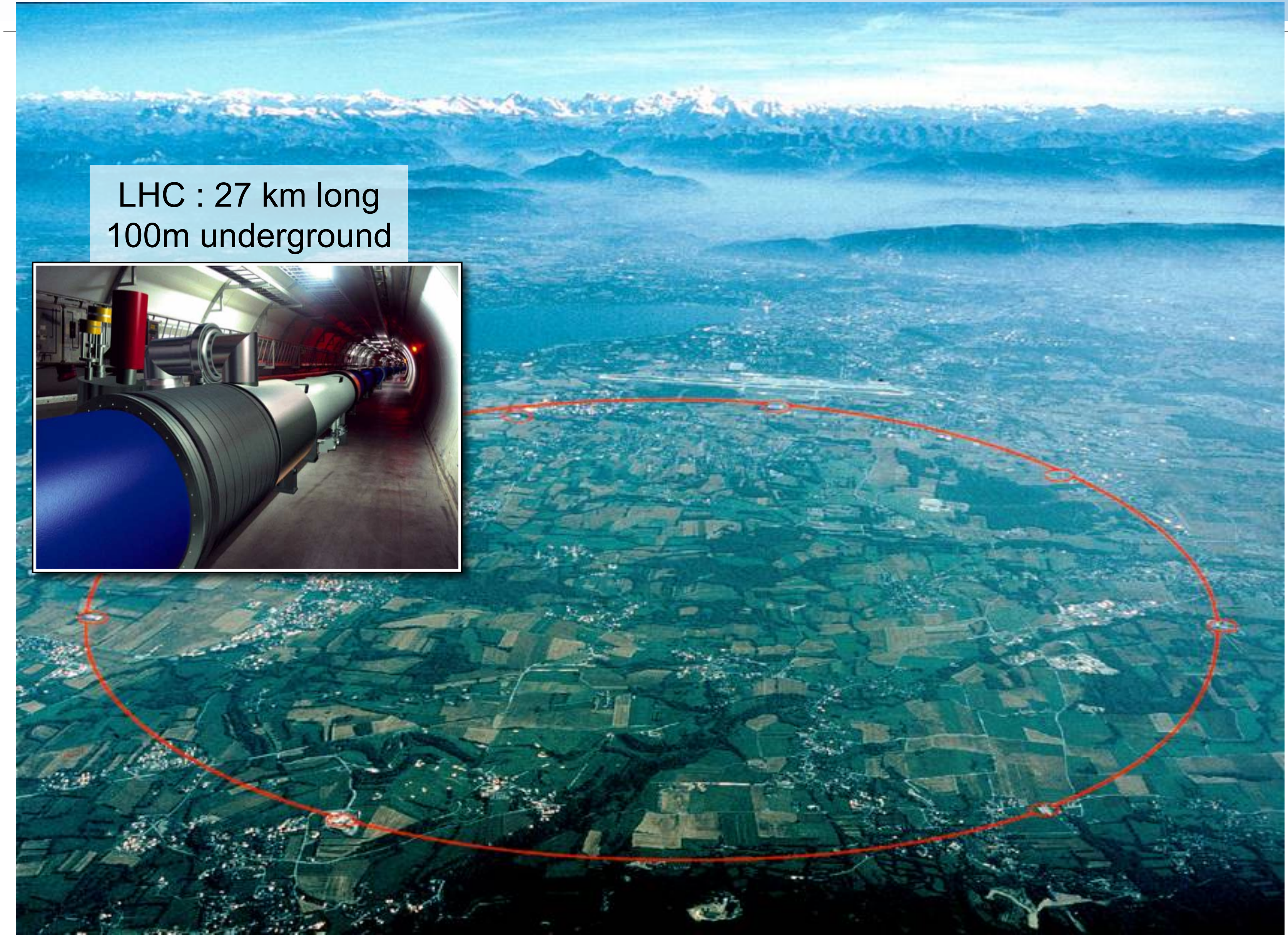
Dark Matter Searches at Colliders



The Large Hadron Collider at CERN

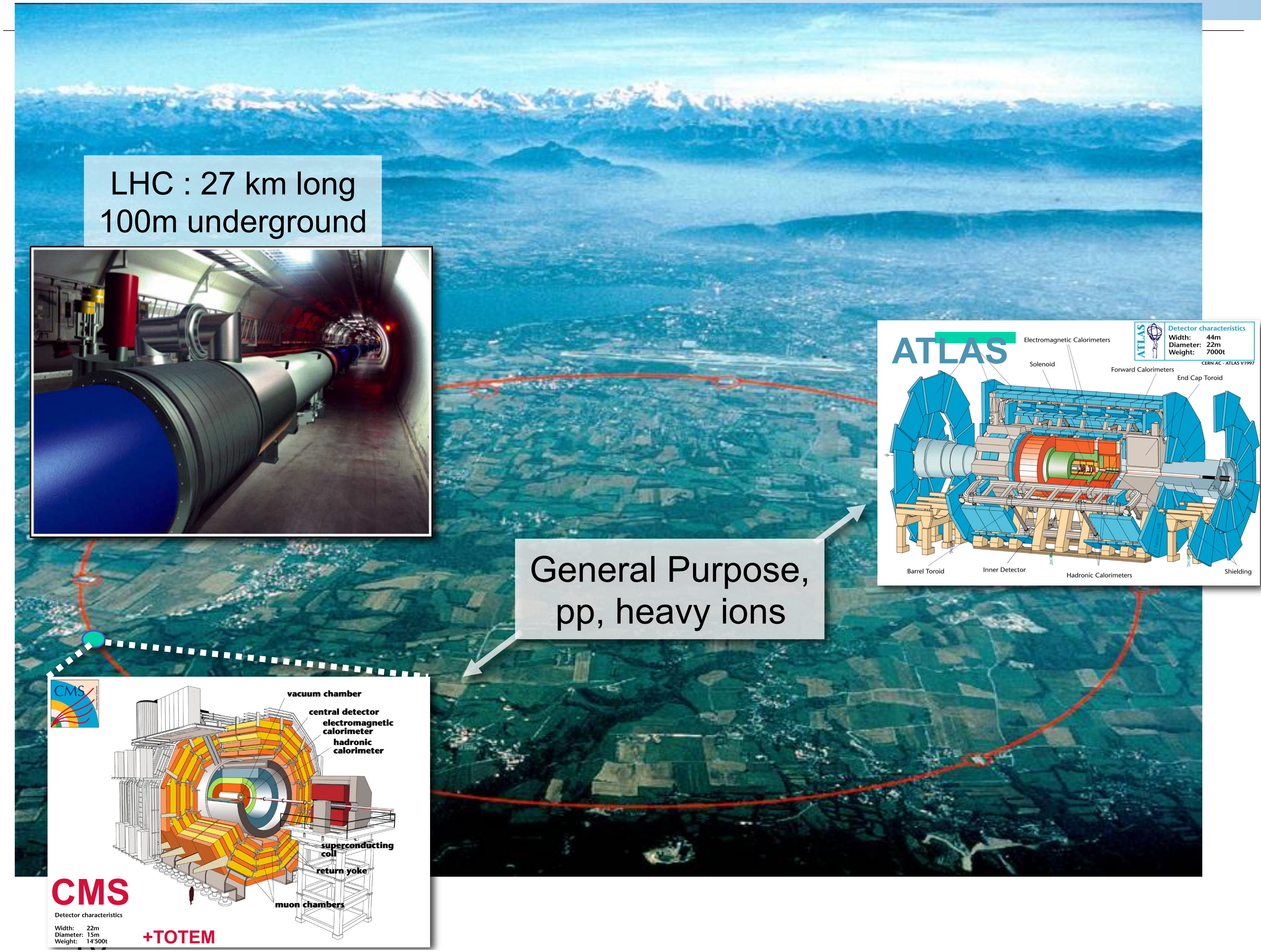
The Large Hadron Collider at CERN

LHC : 27 km long
100m underground

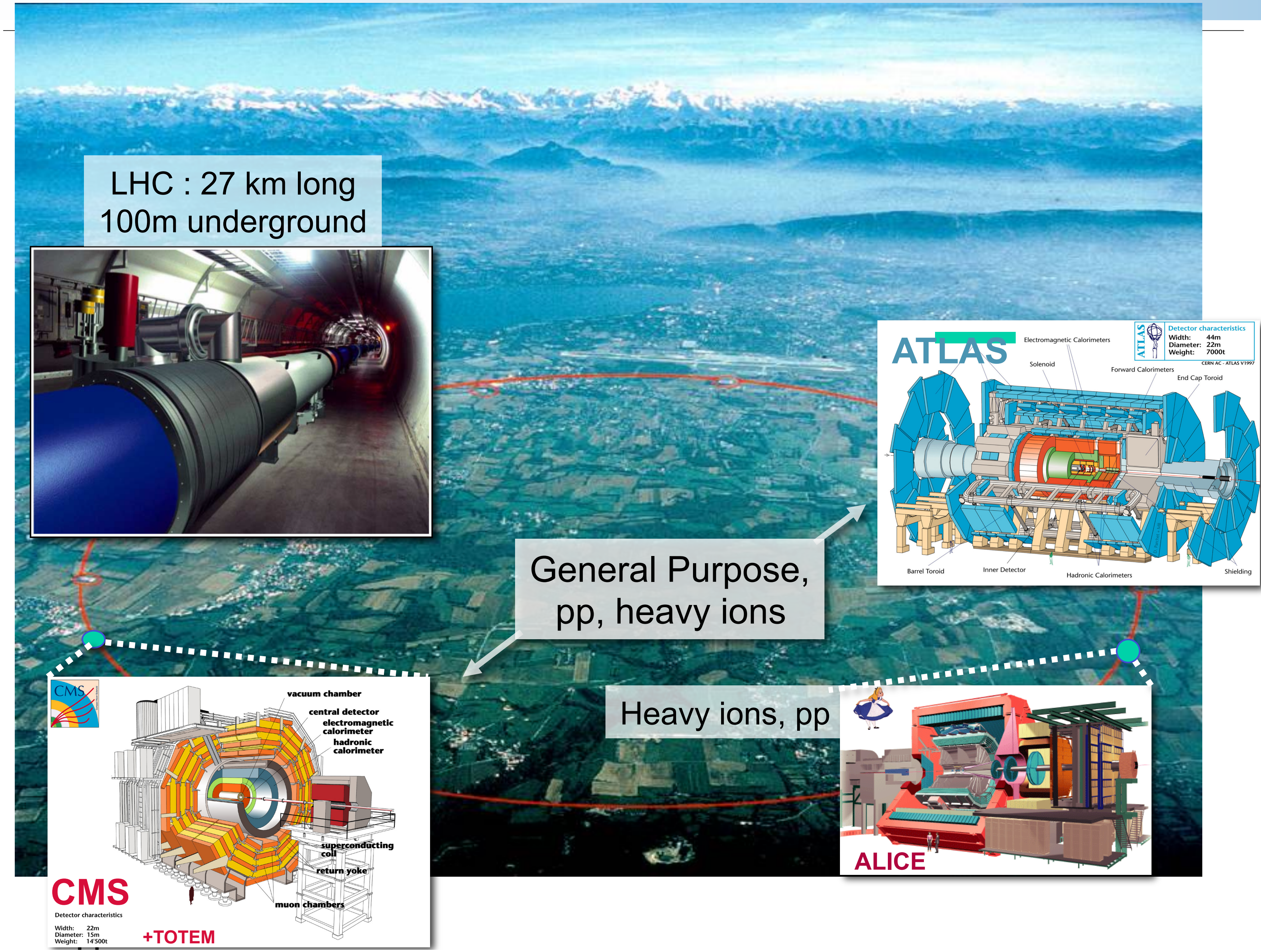


Imperial College
London

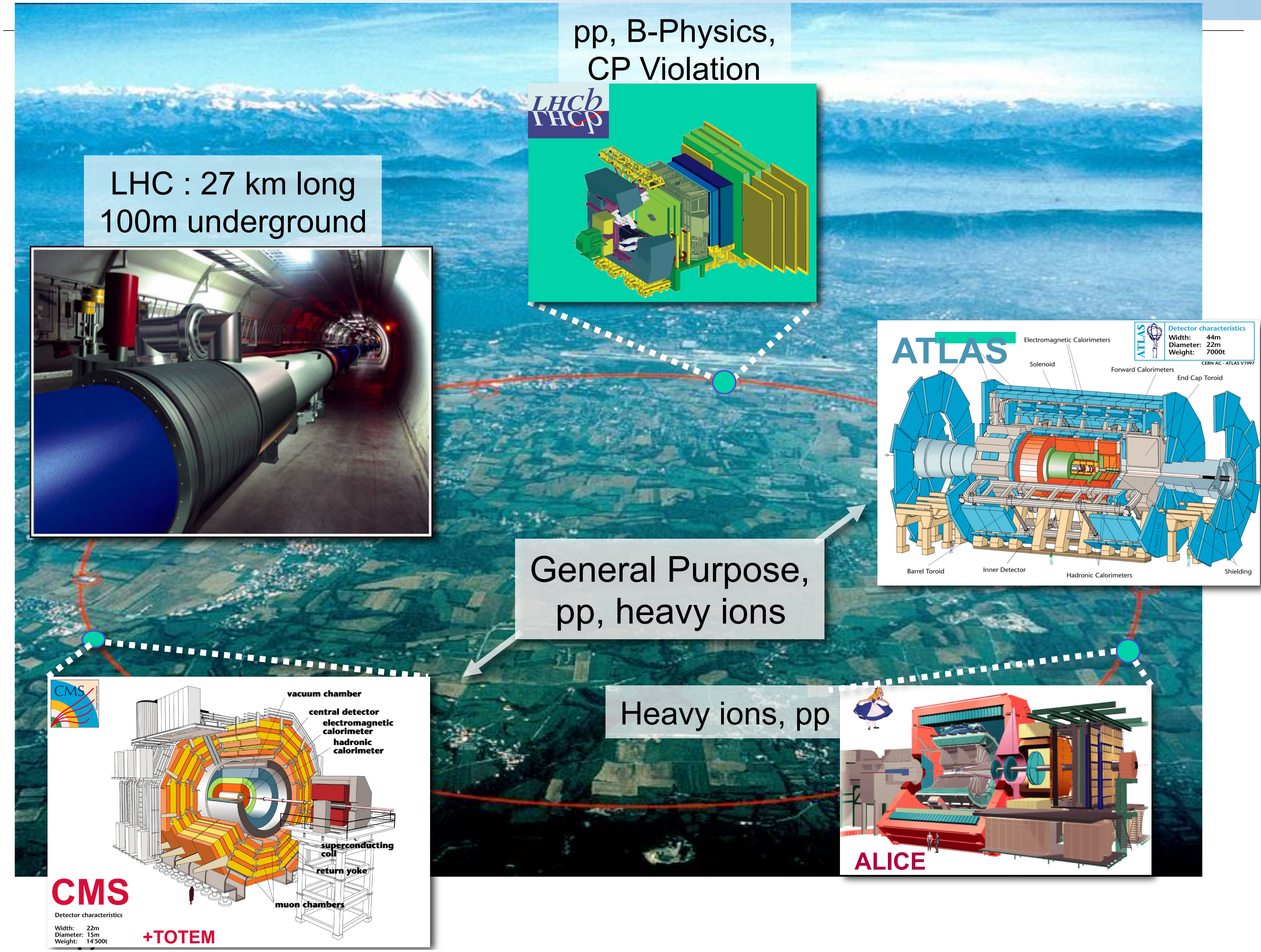
The Large Hadron Collider at CERN

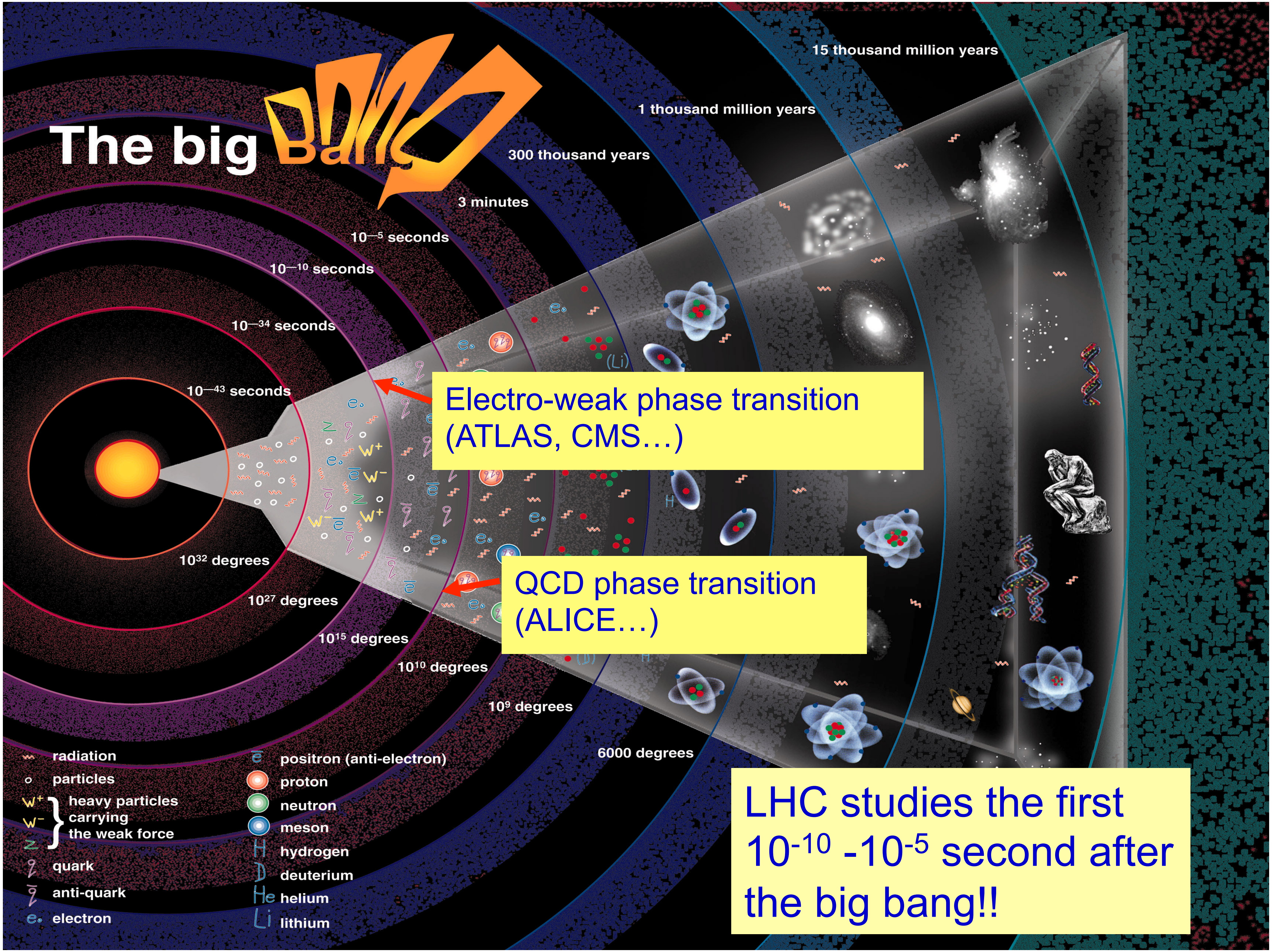


The Large Hadron Collider at CERN



The Large Hadron Collider at CERN





Electro-weak phase transition (ATLAS, CMS…)

QCD phase transition (ALICE…)

LHC studies the first 10^{-10} -10^{-5} second after the big bang!!

In Supersymmetry at colliders

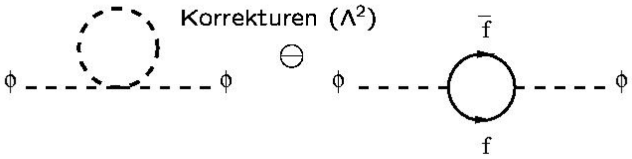
(i.e. a famous model ...but only one model)

Why is SUSY so attractive?

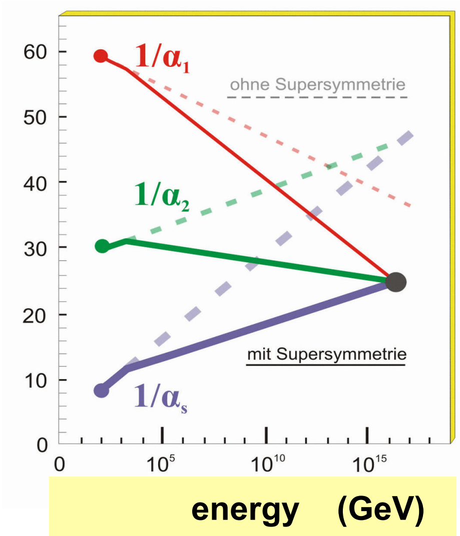
1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided

$m_{SUSY} \sim 1$ TeV

$$\Delta m_H = f(m_B^2 - m_f^2)$$



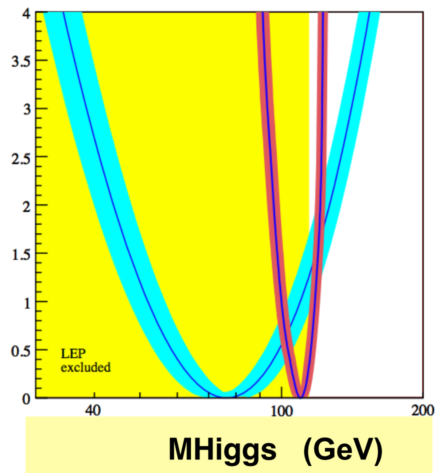
(Hierarchy or naturalness problem)



2. Unification of coupling constants of the three interactions seems possible

3. SUSY provides a candidate for dark matter,

The lightest SUSY particle (LSP)

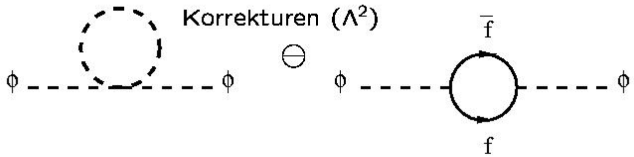


4. A SUSY extension is a small perturbation, consistent with the electroweak precision data

Why is SUSY so attractive?

1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided

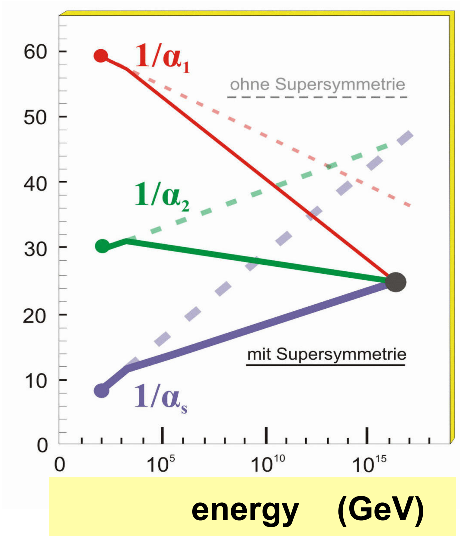
$$\Delta m_H = f(m_B^2 - m_f^2)$$



(Hierarchy or naturalness problem)

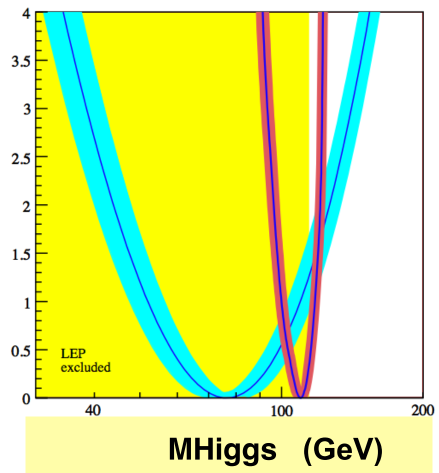
2. Unification of coupling constants of the three interactions seems possible

m_{SUSY} ~ 1 TeV



3. SUSY provides a candidate for dark matter,

The lightest SUSY particle (LSP)



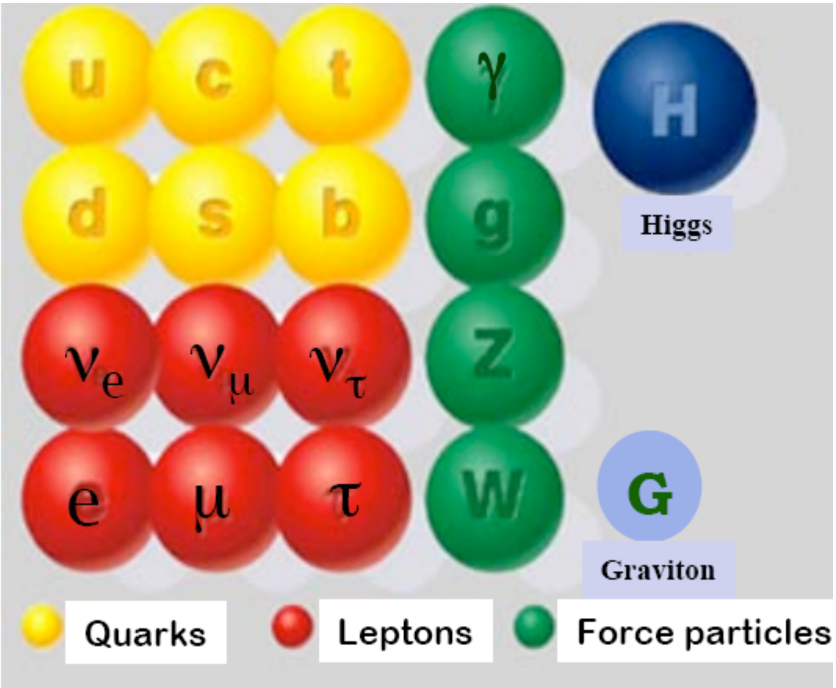
4. A SUSY extension is a small perturbation, consistent with the electroweak precision data

Supersymmetry

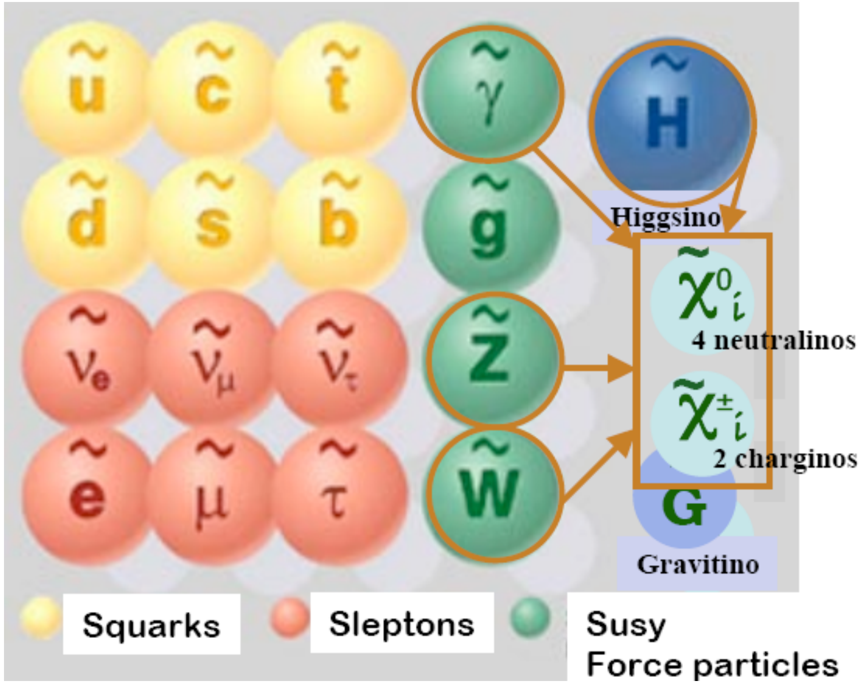
Extension of the Standard Model: Introduce a new symmetry

Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

Standard Model particles



SUSY particles



New Quantum number: R-parity: $R_p = (-1)^{B+L+2s}$ = +1 SM particles

- 1 SUSY particles

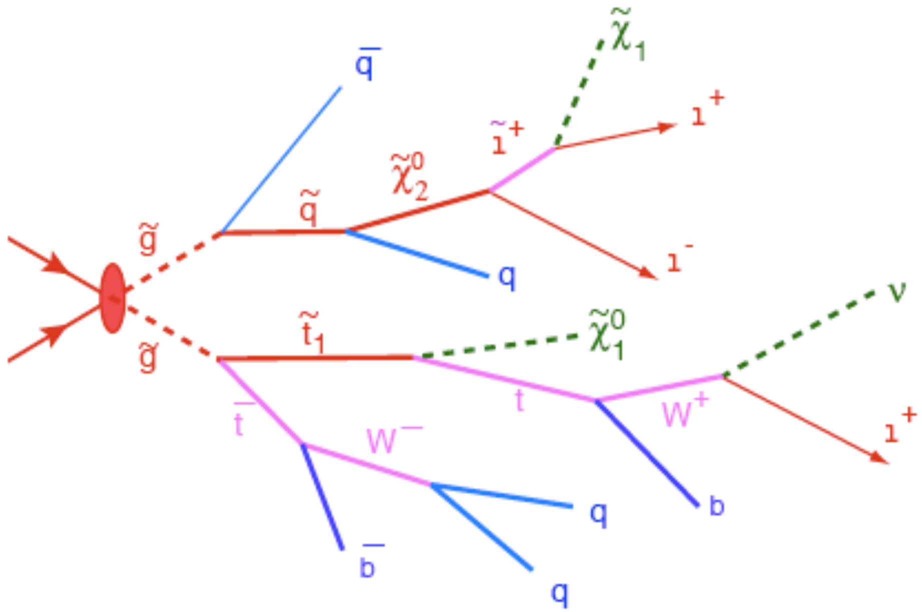
R-parity conservation:

- SUSY particles are produced in pairs
- The lightest SUSY particle (LSP) is stable

What do we call a "SUSY search"?

The definition is purely derived from the experimental signature.
Therefore, a "SUSY search signature" is characterized by

Lots of missing energy, many jets, and possibly leptons in the final state



Missing Energy:
- *from LSP*

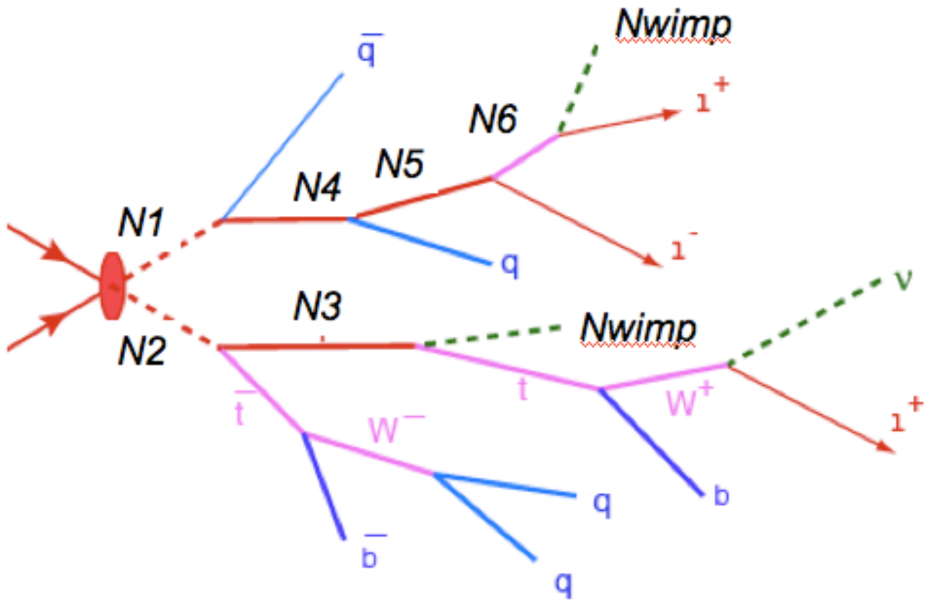
Multi-Jet:
- *from cascade decay (gaugino)*

Multi-Leptons:
- *from decay of charginos/neutralios*

RP-Conserving SUSY is a very prominent example predicting this famous signature but …

What is its experimental signature?

… by no means is it the only New Physics model predicting this experimental pattern. Many other NP models predict this genuine signature



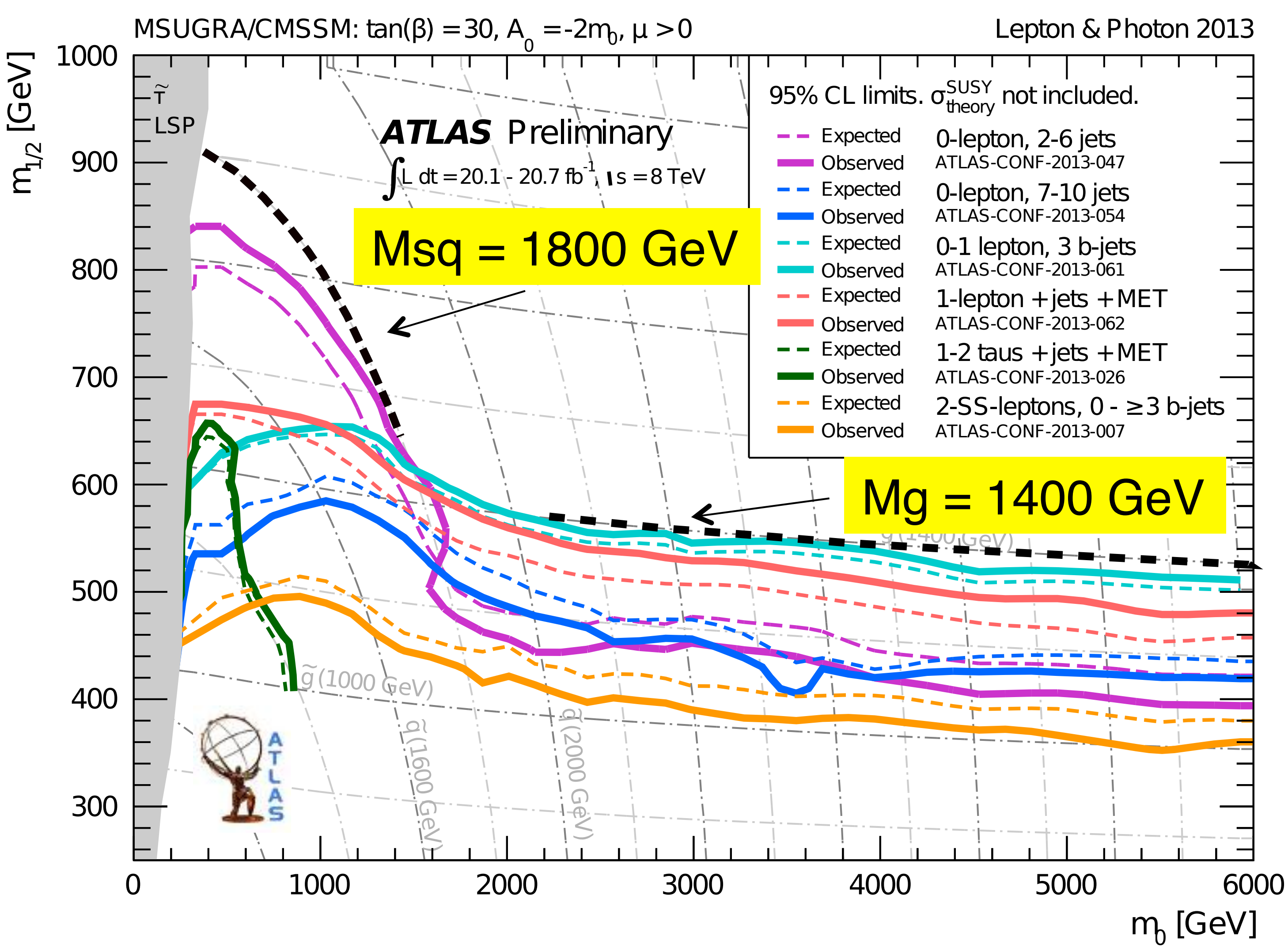
Missing Energy:
- *Nwimp - end of the cascade*

Multi-Jet:
- *from decay of the Ns (possibly via heavy SM particles like top, W/Z)*

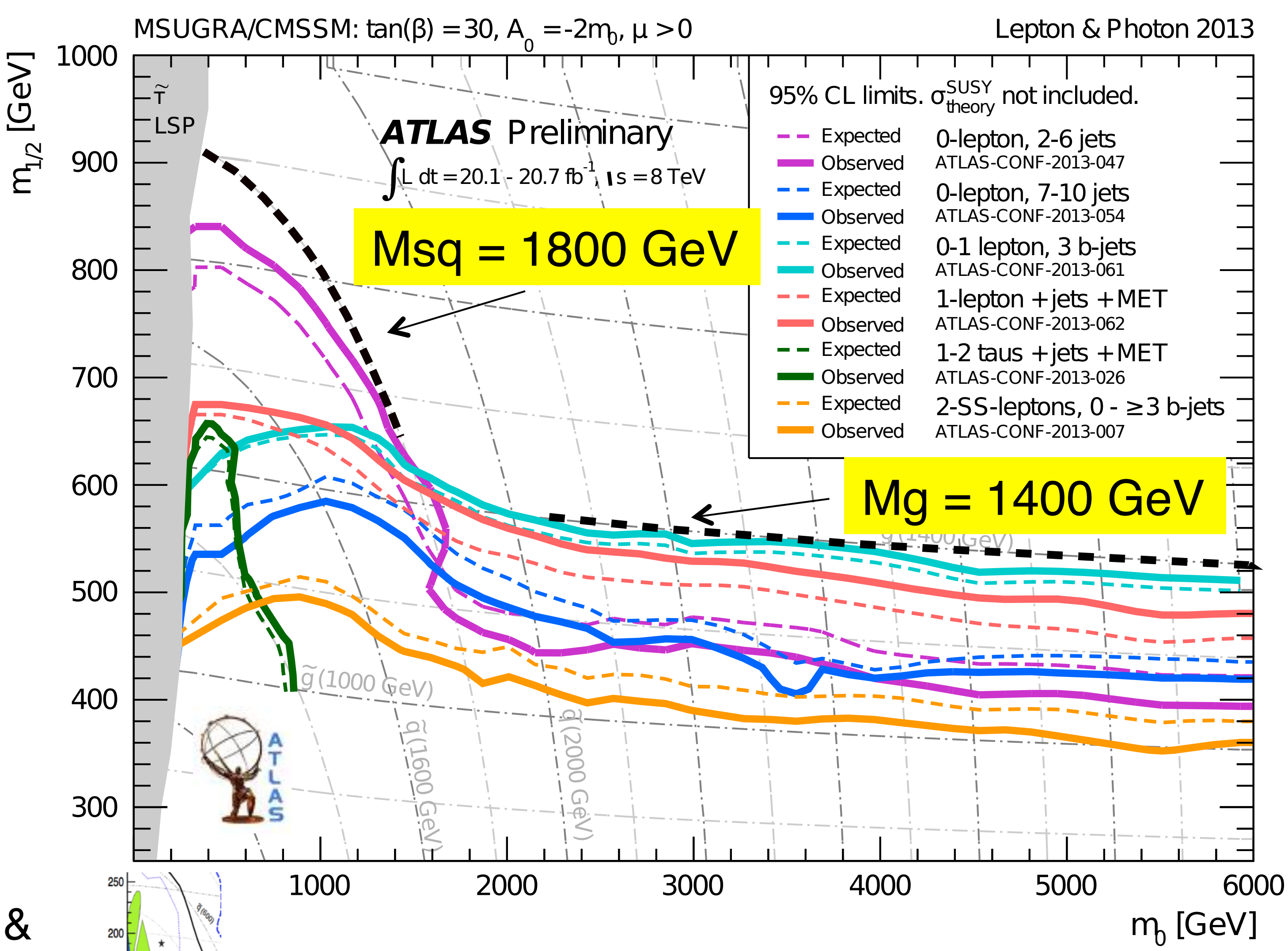
Multi-Leptons:
- *from decay of the N's*

Model examples are Extra dimensions, Little Higgs, Technicolour, etc but a more generic definition for this signature is as follows.

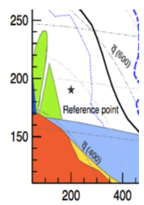
Inclusive SUSY Searches in 2013



Inclusive SUSY Searches in 2013

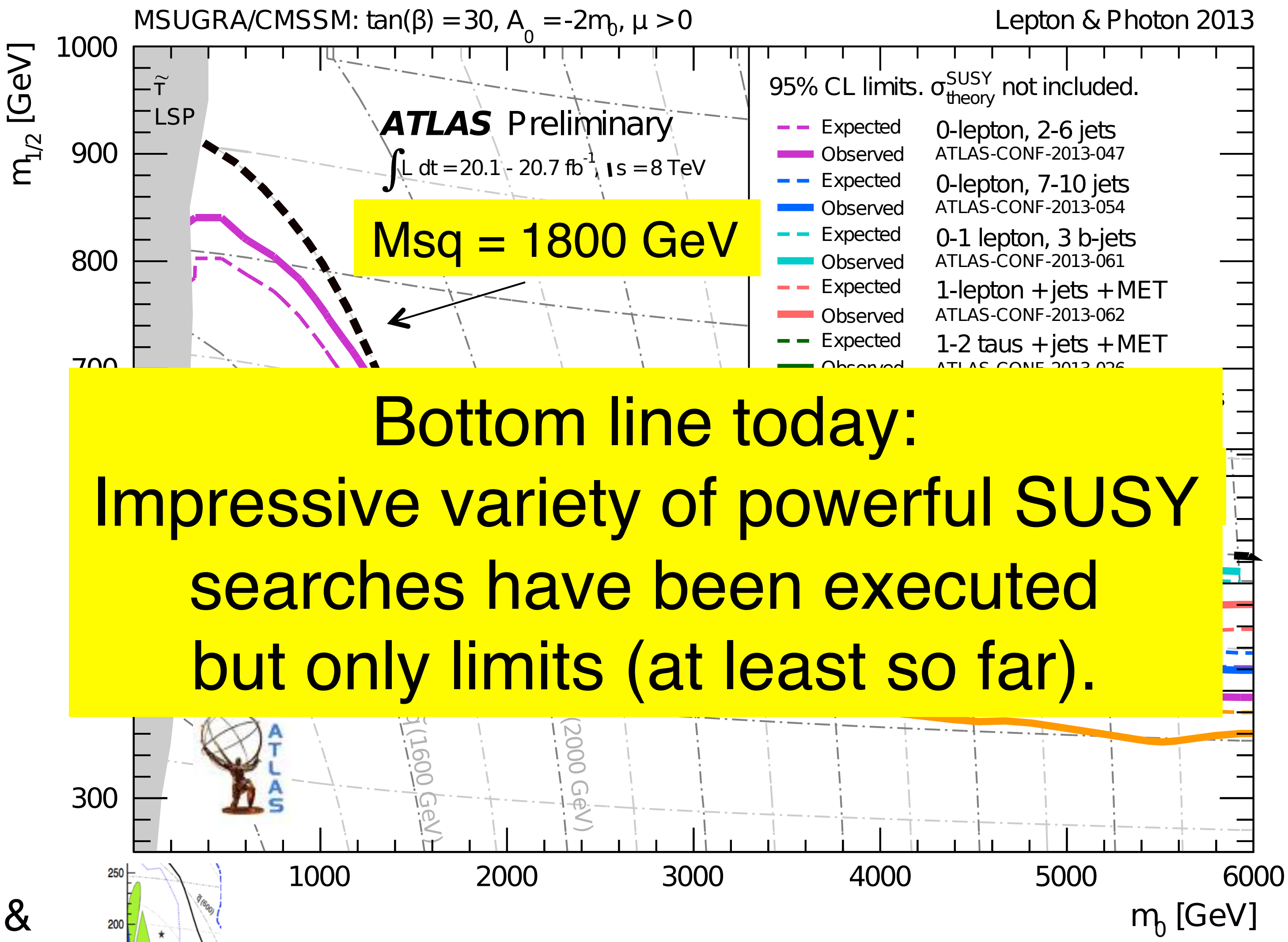


LEP &
Tevatron



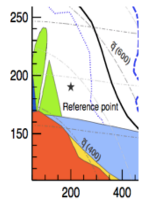
The LHC has pushed the mass scale in constraint SUSY models to a new level!

Inclusive SUSY Searches in 2013



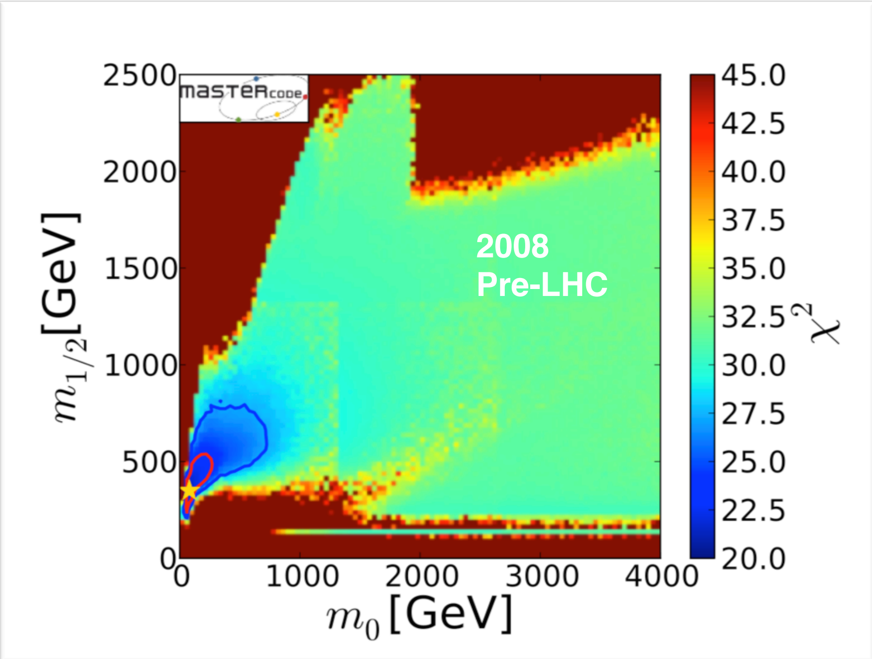
Bottom line today:
Impressive variety of powerful SUSY searches have been executed but only limits (at least so far).

LEP & Tevatron



The LHC has pushed the mass scale in constraint SUSY models to a new level!

CMSSM: Evolution with time



X^2 increase from bluish to reddish

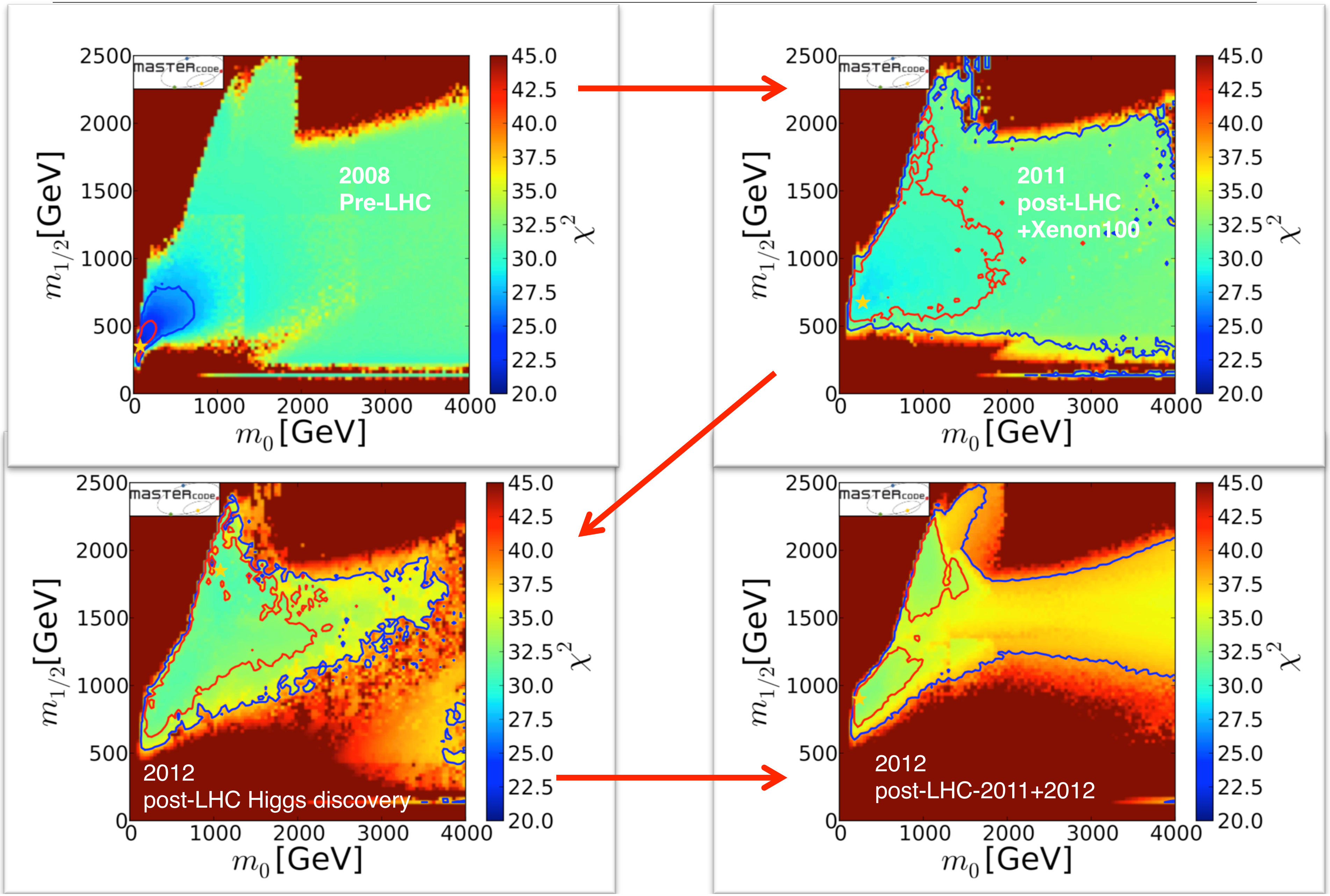
Source:
http://mastercode.web.cern.ch/mastercode/

Observable	Source Th./Ex.	Constraint	$\Delta\chi^2$ (CMSSM)	$\Delta\chi^2$ (NUHM1)	$\Delta\chi^2$ ("SM")
m_t [GeV]	[43]	173.2 ± 0.90	0.05	0.06	-
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	[42]	0.02749 ± 0.00010	0.009	0.004	-
M_Z [GeV]	[44]	91.1875 ± 0.0021	2.7×10^{-5}	0.26	-
Γ_Z [GeV]	[26] / [44]	$2.4952 \pm 0.0023 \pm 0.001_{\rm SUSY}$	0.078	0.047	0.14
$\sigma^0_{\rm had}$ [nb]	[26] / [44]	41.540 ± 0.037	2.50	2.57	2.54
R_l	[26] / [44]	20.767 ± 0.025	1.05	1.08	1.08
$A_{\rm fb}(\ell)$	[26] / [44]	0.01714 ± 0.00095	0.72	0.69	0.81
$A_\ell(P_\tau)$	[26] / [44]	0.1465 ± 0.0032	0.11	0.13	0.07
R_b	[26] / [44]	0.21629 ± 0.00066	0.26	0.29	0.27
R_c	[26] / [44]	0.1721 ± 0.0030	0.002	0.002	0.002
$A_{\rm fb}(b)$	[26] / [44]	0.0992 ± 0.0016	7.17	7.37	6.63
$A_{\rm fb}(c)$	[26] / [44]	0.0707 ± 0.0035	0.86	0.88	0.80
A_b	[26] / [44]	0.923 ± 0.020	0.36	0.36	0.35
A_c	[26] / [44]	0.670 ± 0.027	0.005	0.005	0.005
A_ℓ(SLD)	[26] / [44]	0.1513 ± 0.0021	3.16	3.03	3.51
$\sin^2\theta^\ell_w(Q_{\rm fb})$	[26] / [44]	0.2324 ± 0.0012	0.63	0.64	0.59
M_W [GeV]	[26] / [44]	$80.399 \pm 0.023 \pm 0.010_{\rm SUSY}$	1.77	1.39	2.08
$a_\mu^{\rm EXP} - a_\mu^{\rm SM}$	[53] / [42,54]	$(30.2 \pm 8.8 \pm 2.0_{\rm SUSY}) \times 10^{-10}$	4.35	1.82	11.19 (N/A)
M_h [GeV]	[28] / [55,56]	$> 114.4[\pm 1.5_{\rm SUSY}]$	0.0	0.0	0.0
$\rm BR^{EXP/SM}_{b\to s\gamma}$	[45] / [46]	$1.117 \pm 0.076_{\rm EXP}$ $\pm 0.082_{\rm SM} \pm 0.050_{\rm SUSY}$	1.83	1.09	0.94
${\rm BR}(B_s \to \mu^+\mu^-)$	[29] / [41]	CMS & LHCb	0.04	0.44	0.01
$\rm BR^{EXP/SM}_{B\to\tau\nu}$	[29] / [46]	$1.43 \pm 0.43_{\rm EXP+TH}$	1.43	1.59	1.00
${\rm BR}(B_d \to \mu^+\mu^-)$	[29] / [46]	$< 4.6[\pm 0.01_{\rm SUSY}] \times 10^{-9}$	0.0	0.0	0.0
$\rm BR^{EXP/SM}_{B\to X_s\ell\ell}$	[47] / [46]	0.99 ± 0.32	0.02	$\ll 0.01$	$\ll 0.01$
$\rm BR^{EXP/SM}_{K\to\mu\nu}$	[29] / [48]	$1.008 \pm 0.014_{\rm EXP+TH}$	0.39	0.42	0.33
$\rm BR^{EXP/SM}_{K\to\pi\nu\bar\nu}$	[49] / [50]	< 4.5	0.0	0.0	0.0
$\Delta M^{\rm EXP/SM}_{B_s}$	[49] / [51,52]	$0.97 \pm 0.01_{\rm EXP} \pm 0.27_{\rm SM}$	0.02	0.02	0.01
$\frac{\Delta M^{\rm EXP/SM}_{B_s}}{\Delta M^{\rm EXP/SM}_{B_d}}$	[29] / [46,51,52]	$1.00 \pm 0.01_{\rm EXP} \pm 0.13_{\rm SM}$	$\ll 0.01$	0.33	$\ll 0.01$
$\Delta\epsilon^{\rm EXP/SM}_K$	[49] / [51,52]	$1.08 \pm 0.14_{\rm EXP+TH}$	0.27	0.37	0.33
$\Omega_{\rm CDM}h^2$	[31] / [13]	$0.1120 \pm 0.0056 \pm 0.012_{\rm SUSY}$	8.4×10^{-4}	0.1	N/A
$\sigma_p^{\rm SI}$	[25]	$(m_{\chi^0_1}, \sigma_p^{\rm SI})$ plane	0.13	0.13	N/A
jets + $\not{E}_T$	[18,20]	$(m_0, m_{1/2})$ plane	1.55	2.20	N/A
$H/A, H^\pm$	[21]	$(M_A, \tan\beta)$ plane	0.0	0.0	N/A
Total χ^2/d.o.f. p-values	All	All	28.8/22 15%	27.3/21 16%	32.7/23 (21.5/22) 9% (49%)

Global Fit to indirect and direct constraints on SUSY!

Other "fitter" groups find very similar results: e.g.
SuperBayeS: **arXiv:1212.2636**
Fittino group: **arXiv:1204.4199**

CMSSM: Evolution with time



SUSY Status – post 7 TeV LHC data

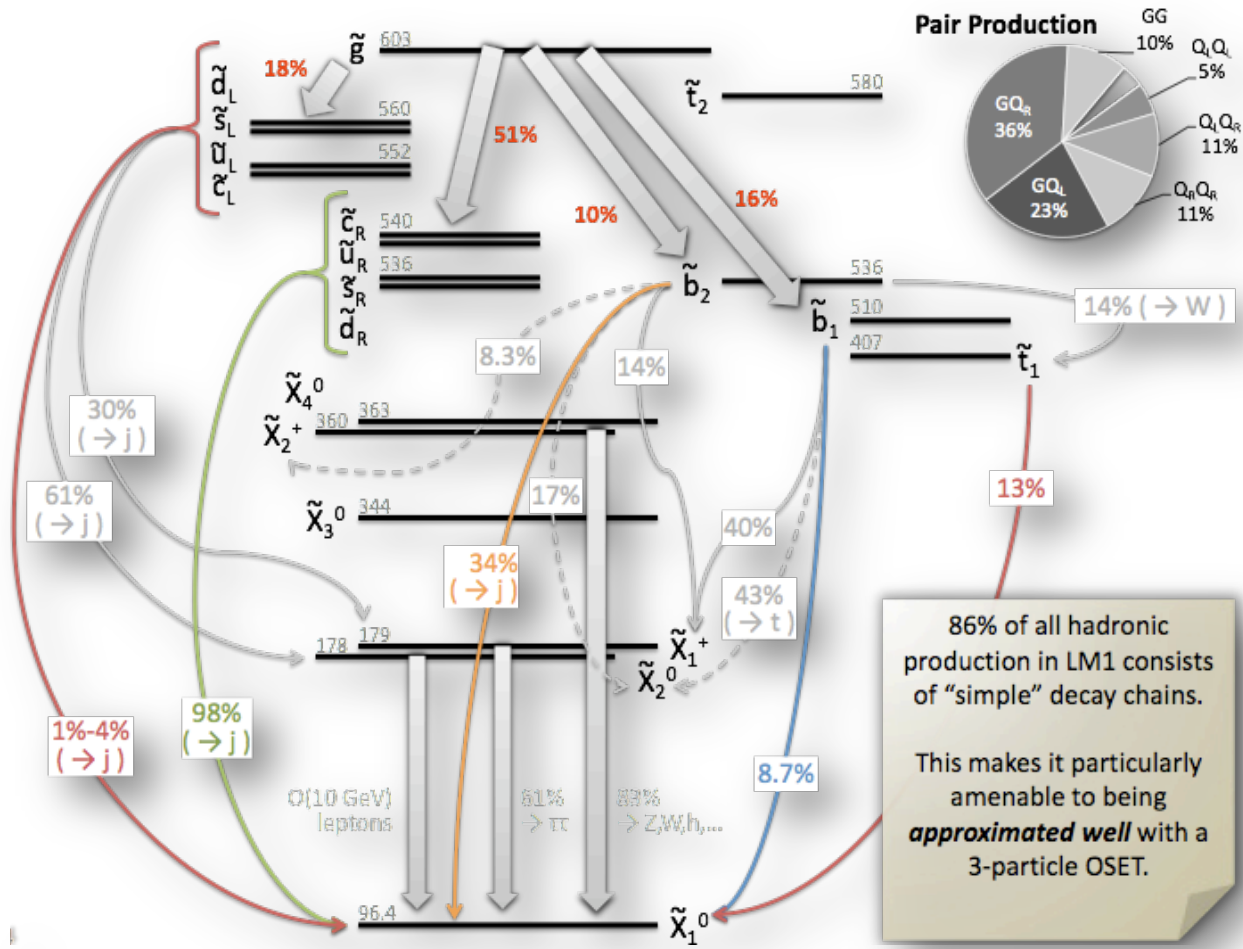
- Constrained SUSY models like the CMSSM are severely put under pressure by the LHC limits!

- Experiments define new benchmarks and less complex SUSY models in order to present the interpretation of their searches.

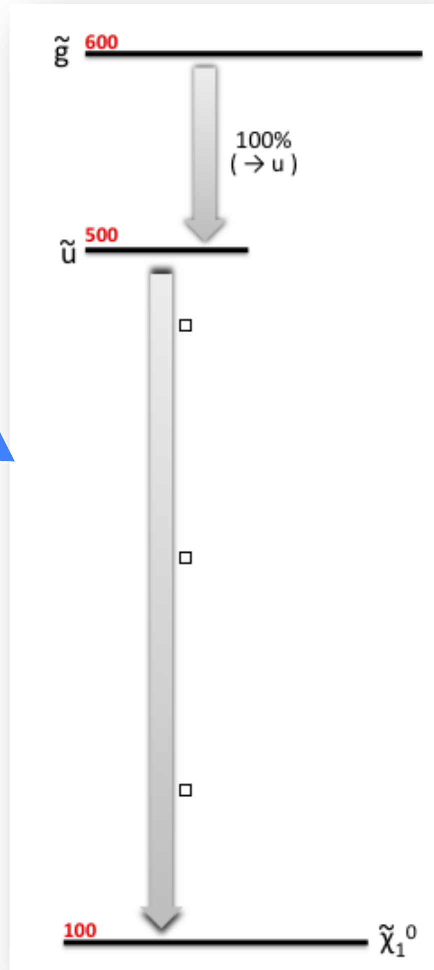
- Aided by the discovery of a Higgs boson, the focus of the experimental search strategy and corresponding interpretation shifts towards other scenarios like "Natural SUSY" (i.e. 3rd generation squark searches).

Interpretation in Simplified Models

CMSSM



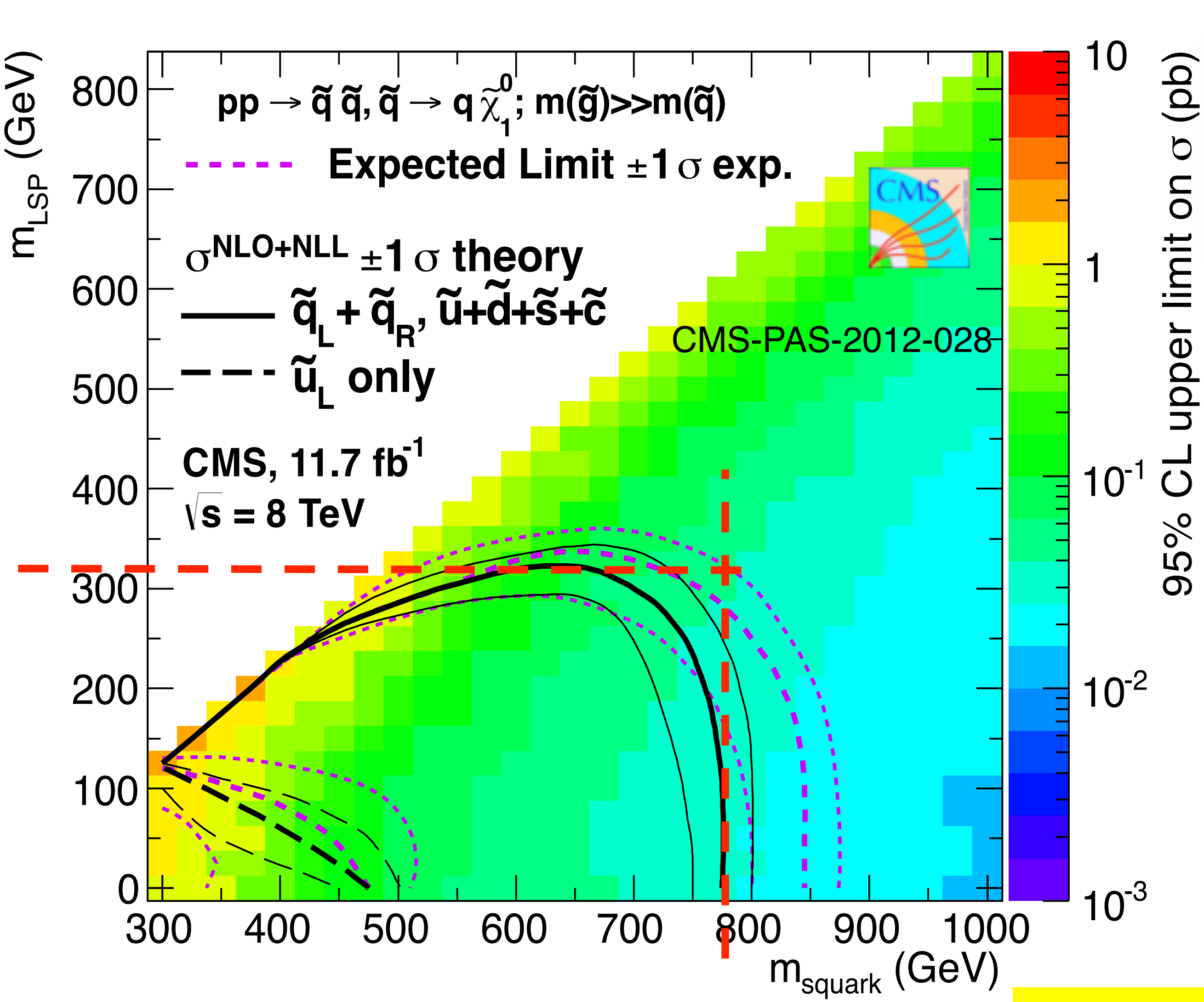
What the individual searches are sensitive to is much more simple…

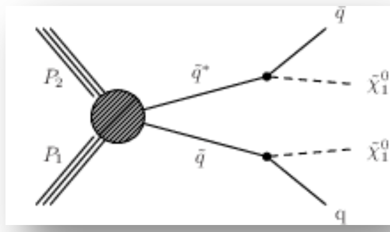


Simplified model spectrum (SMS)
with 3 particles, 2 decay modes

SMS: a few interesting features

$m_{LSP}^{max} \approx 0.3$ TeV : LSP mass above which there is NO limit anymore





$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}^0\bar{q}\tilde{\chi}^0$

$m_G^{max} \approx 0.8$ TeV : Best limit in plane

Assumes 100% BR for decay chain considered.

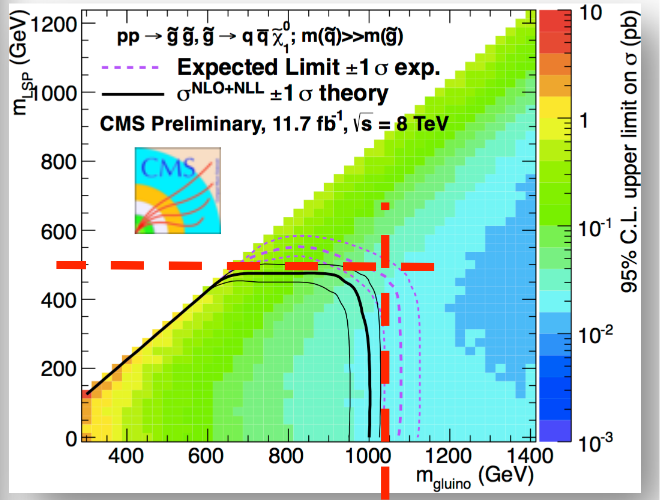
Imperial College London

How to summarize SMS limits?

Approach taken in the 2012 and 2013 Experimental SUSY PDG reviews [OB & Paul De Jong]:

http://pdg.lbl.gov/2012/reviews/rpp2012-rev-susy-2-experiment.pdf
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf

Model	Assumption	$m_{\tilde{q}}$	$m_{\tilde{g}}$
CMSSM	$m_{\tilde{q}} \approx m_{\tilde{g}}$	1400	1400
	all $m_{\tilde{q}}$	-	800
	all $m_{\tilde{g}}$	1300	-
Simplified model $\tilde{g}\tilde{g}$	$m_{\tilde{\chi}_1^0} = 0$	-	900
	$m_{\tilde{\chi}_1^0} > 300$	-	no limit
Simplified model $\tilde{q}\tilde{q}$	$m_{\tilde{\chi}_1^0} = 0$	750	-
	$m_{\tilde{\chi}_1^0} > 250$	no limit	-
Simplified model $\tilde{g}\tilde{q}, \tilde{g}\bar{\tilde{q}}$	$m_{\tilde{\chi}_1^0} = 0$, $m_{\tilde{q}} \approx m_{\tilde{g}}$	1500	1500
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{g}}$	1400	-
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{q}}$	-	900



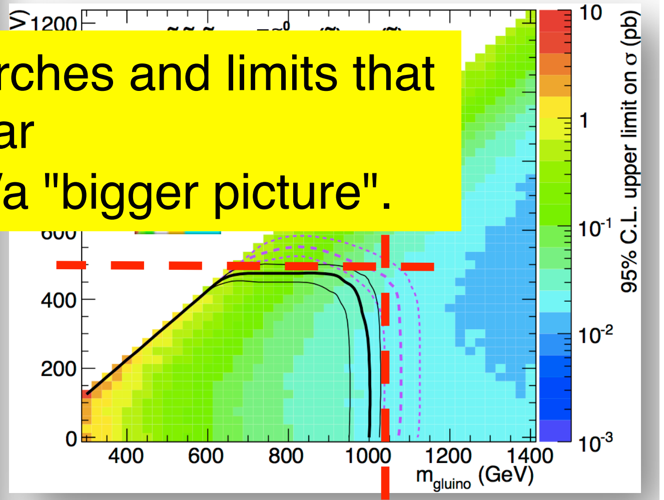
This was an appropriate approach for the rather limited amount of inclusive searches and corresponding SMS interpretations available in 2011 (7 TeV).

How to summarize SMS limits?

Approach taken in the 2012 and 2013 Experimental SUSY PDG reviews [OB & Paul De Jong]:

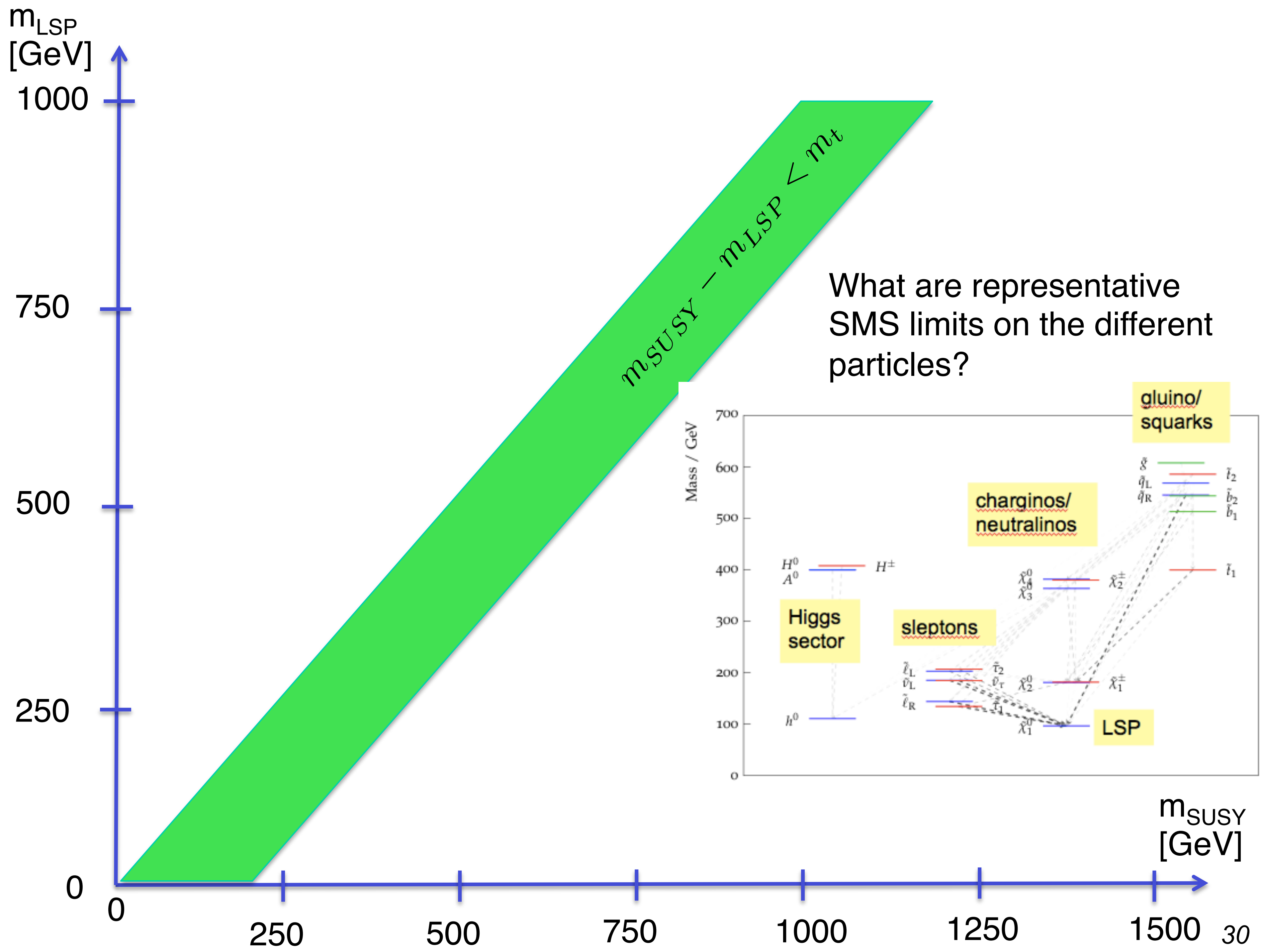
http://pdg.lbl.gov/2012/reviews/rpp2012-rev-susy-2-experiment.pdf
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf

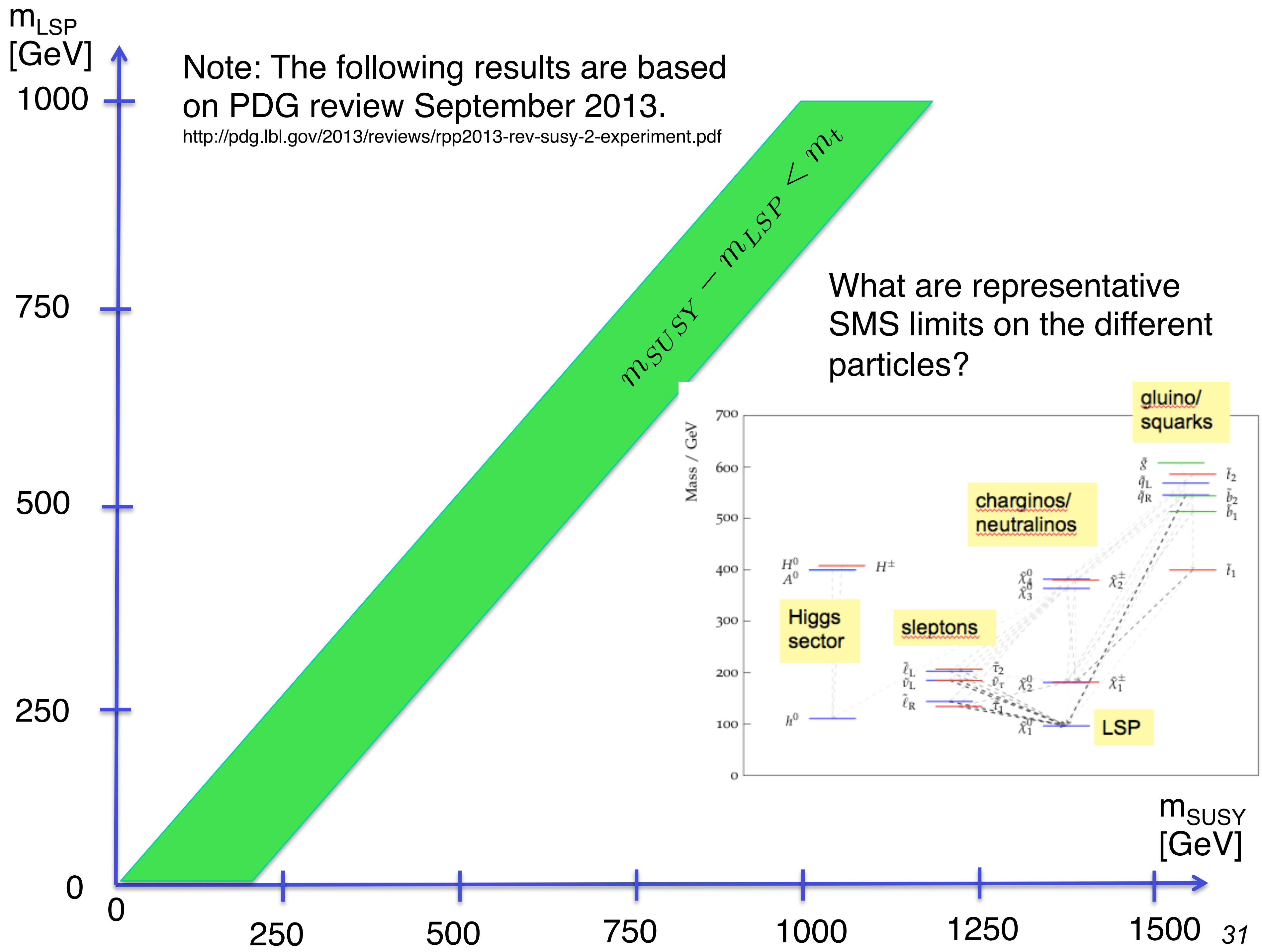
Model	Assumption	$m_{\tilde{q}}$	$m_{\tilde{g}}$
CMSSM	$m_{\tilde{q}} \approx m_{\tilde{g}}$	1400	1400
	all $m_{\tilde{q}}$		800
Simpli			
Simplified model $\tilde{q}\bar{\tilde{q}}$	$m_{\tilde{\chi}_1^0} = 0$	750	-
	$m_{\tilde{\chi}_1^0} > 250$	no limit	-
Simplified model $\tilde{g}\tilde{q}, \tilde{g}\bar{\tilde{q}}$	$m_{\tilde{\chi}_1^0} = 0$, $m_{\tilde{q}} \approx m_{\tilde{g}}$	1500	1500
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{g}}$	1400	-
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{q}}$	-	900



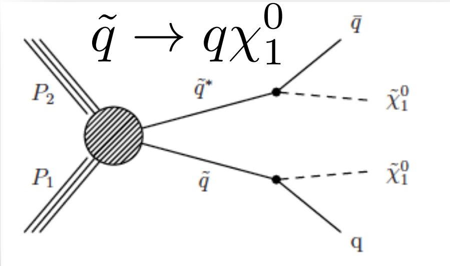
It is a challenge to do justice to the many searches and limits that have been established so far
- even more so to put it all together into the/a "bigger picture".

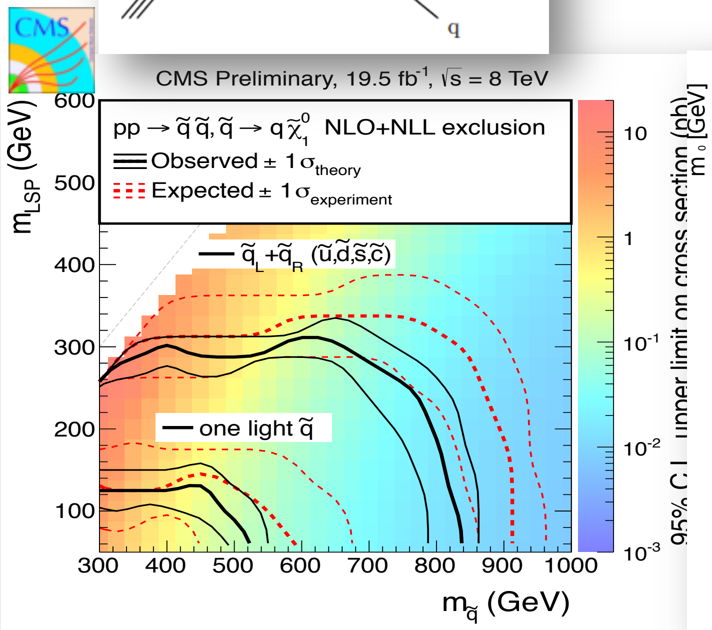
This was an appropriate approach for the rather limited amount of inclusive searches and corresponding SMS interpretations available in 2011 (7 TeV).

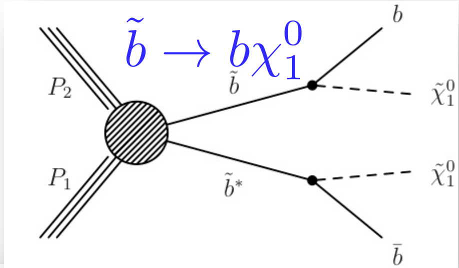

m$_{LSP}$ [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500
m$_{SUSY}$ [GeV]
$m_{SUSY} - m_{LSP} < m_t$
What are representative SMS limits on the different particles?
gluino/ squarks
charginos/ neutralinos
Higgs sector
sleptons
LSP
Mass / GeV
700
600
500
400
300
200
100
0

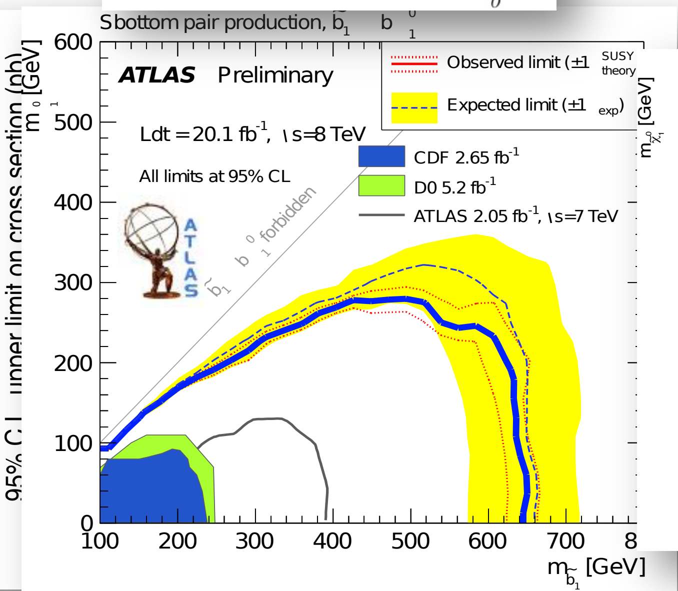

Note: The following results are based on PDG review September 2013.
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf
m_{LSP} [GeV]
1000
750
500
250
0
$m_{SUSY} - m_{LSP} < m_t$
What are representative SMS limits on the different particles?
Mass / GeV
gluino/ squarks
charginos/ neutralinos
Higgs sector
sleptons
LSP
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500

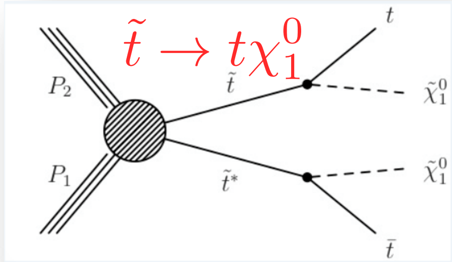
Direct squark production – chosen limits

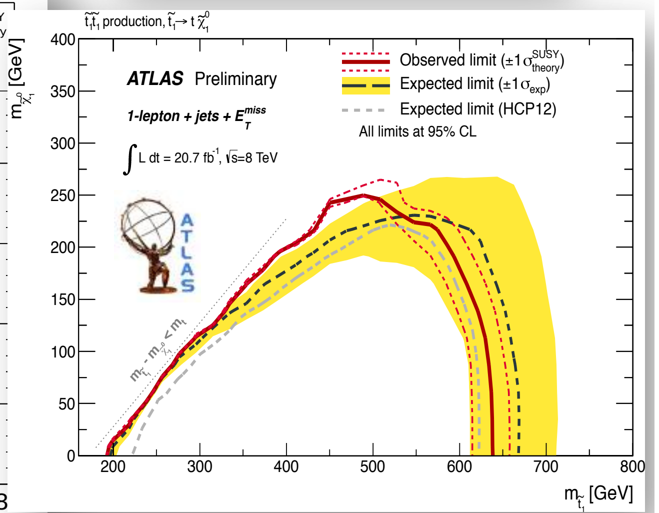










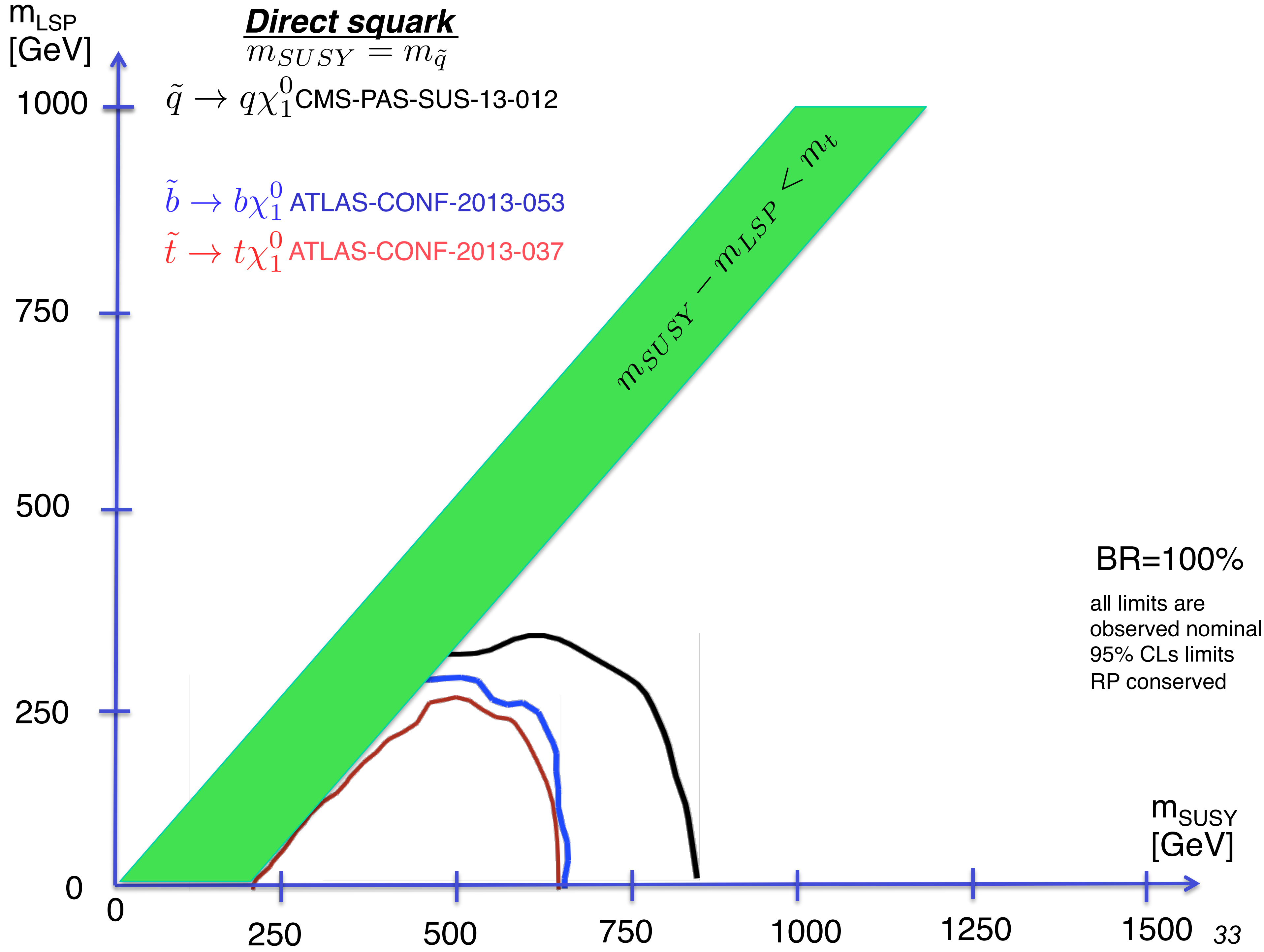


CMS-SUS-PAS-13-012
Signature: Jets + E_t^{miss} + H_T
Limit assumes all 1st & 2nd gen squarks to be mass degenerate or only one light squark!

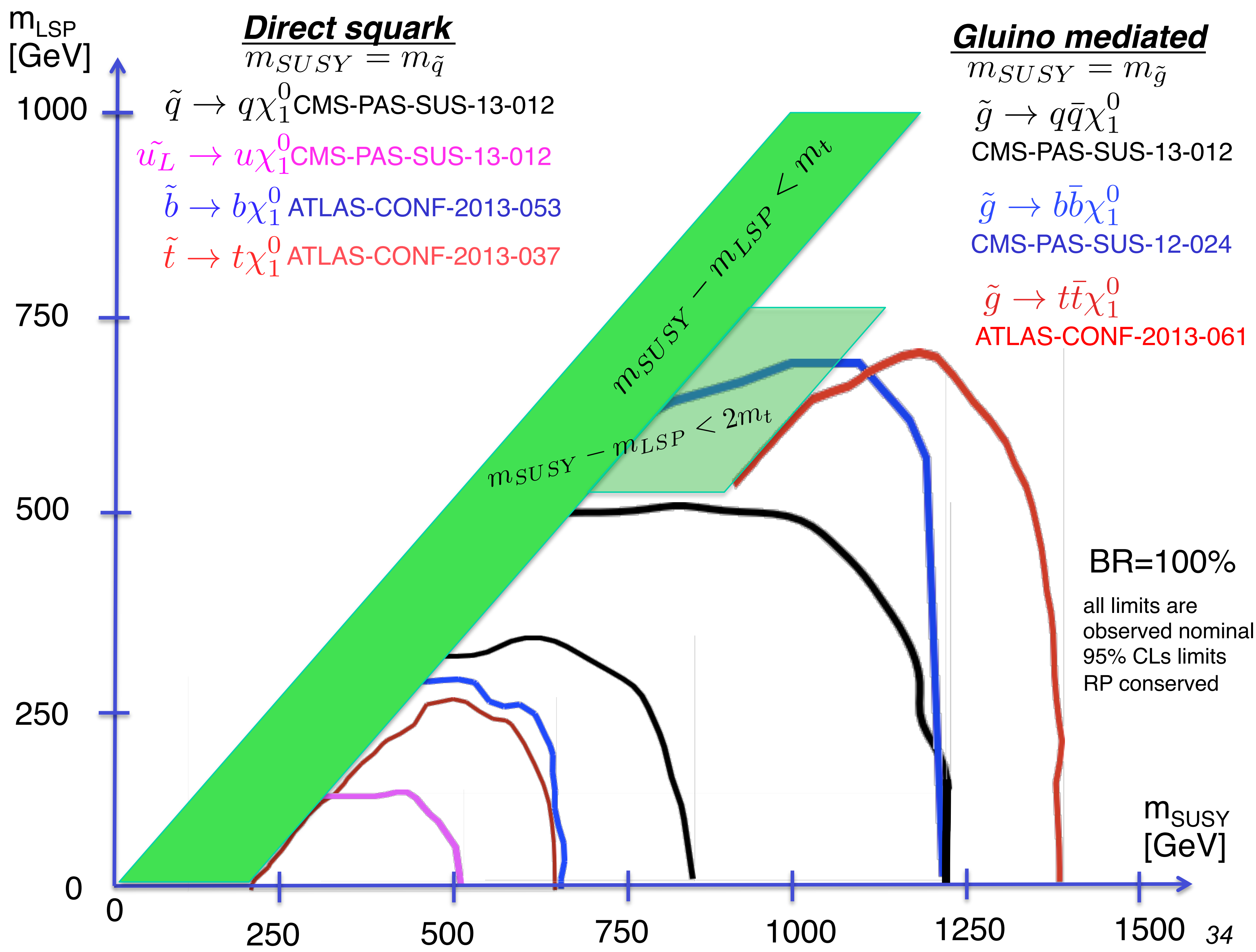
ATLAS-CONF-2013-053
Signature: 2 b-jets + E_T^{mis}

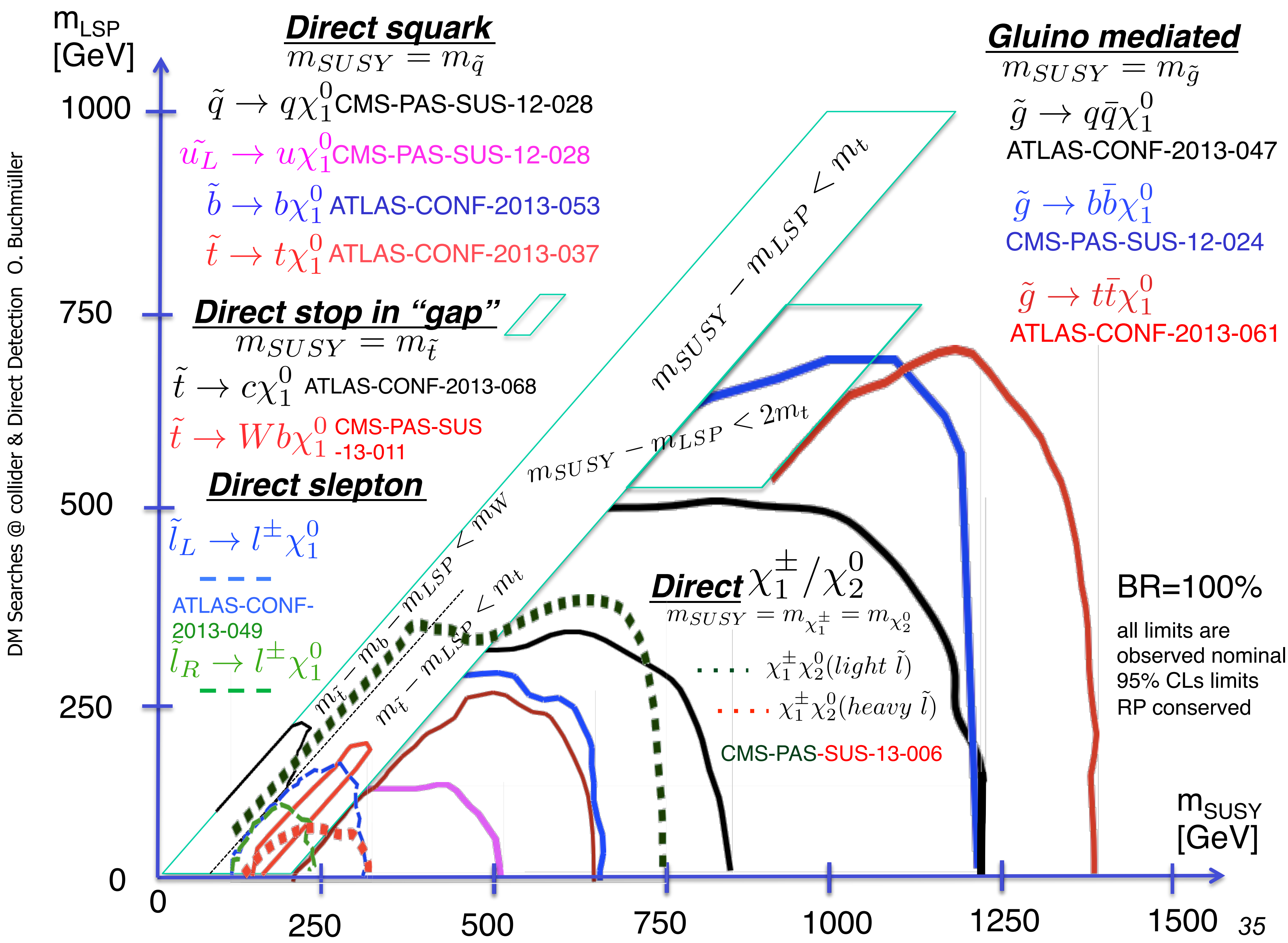
ATLAS-CONF-2013-037
Signature: 1Lepton + jets + E_T^{mis}

DM Searches @ collider & Direct Detection O. Buchmüller

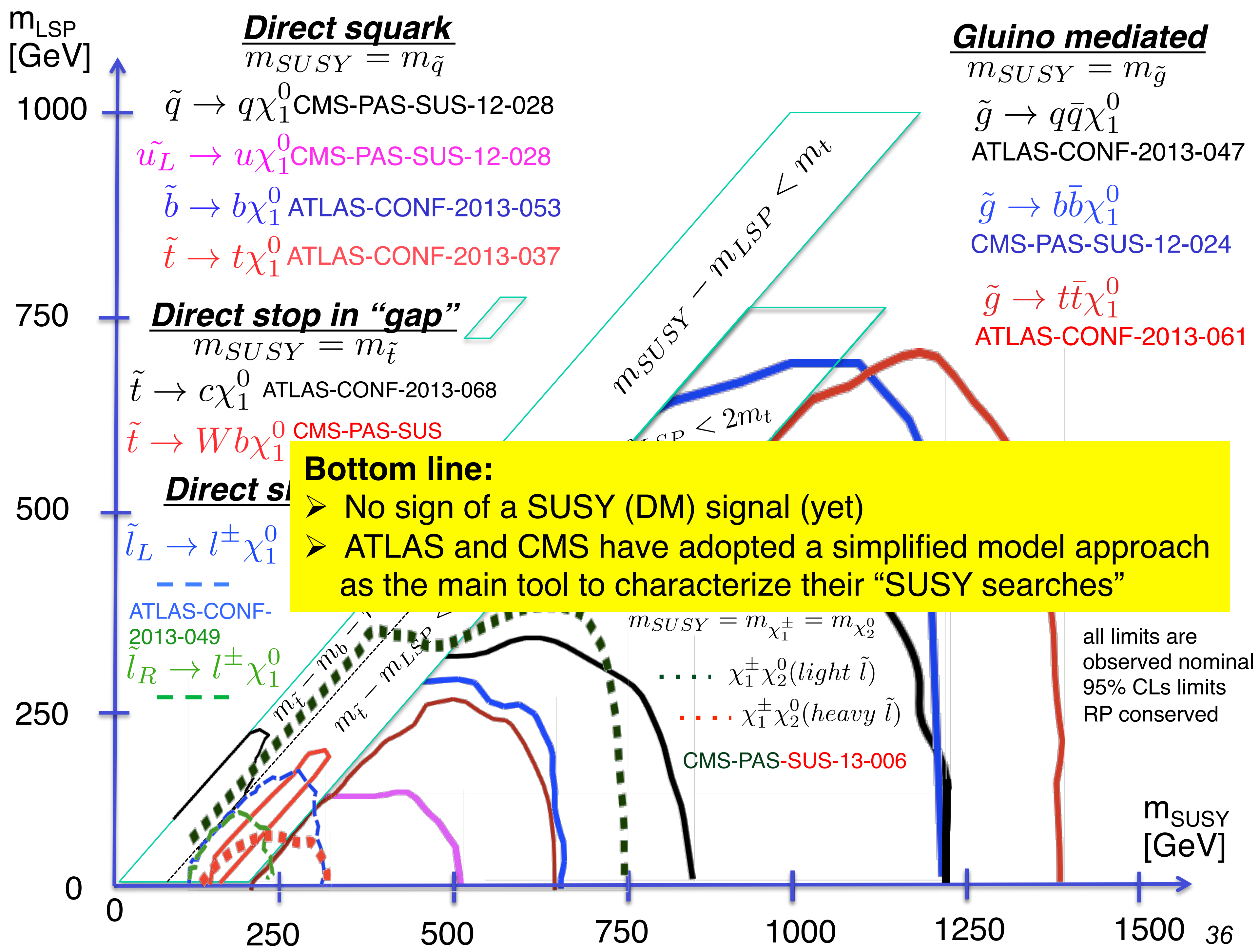


DM Searches @ collider & Direct Detection O. Buchmüller





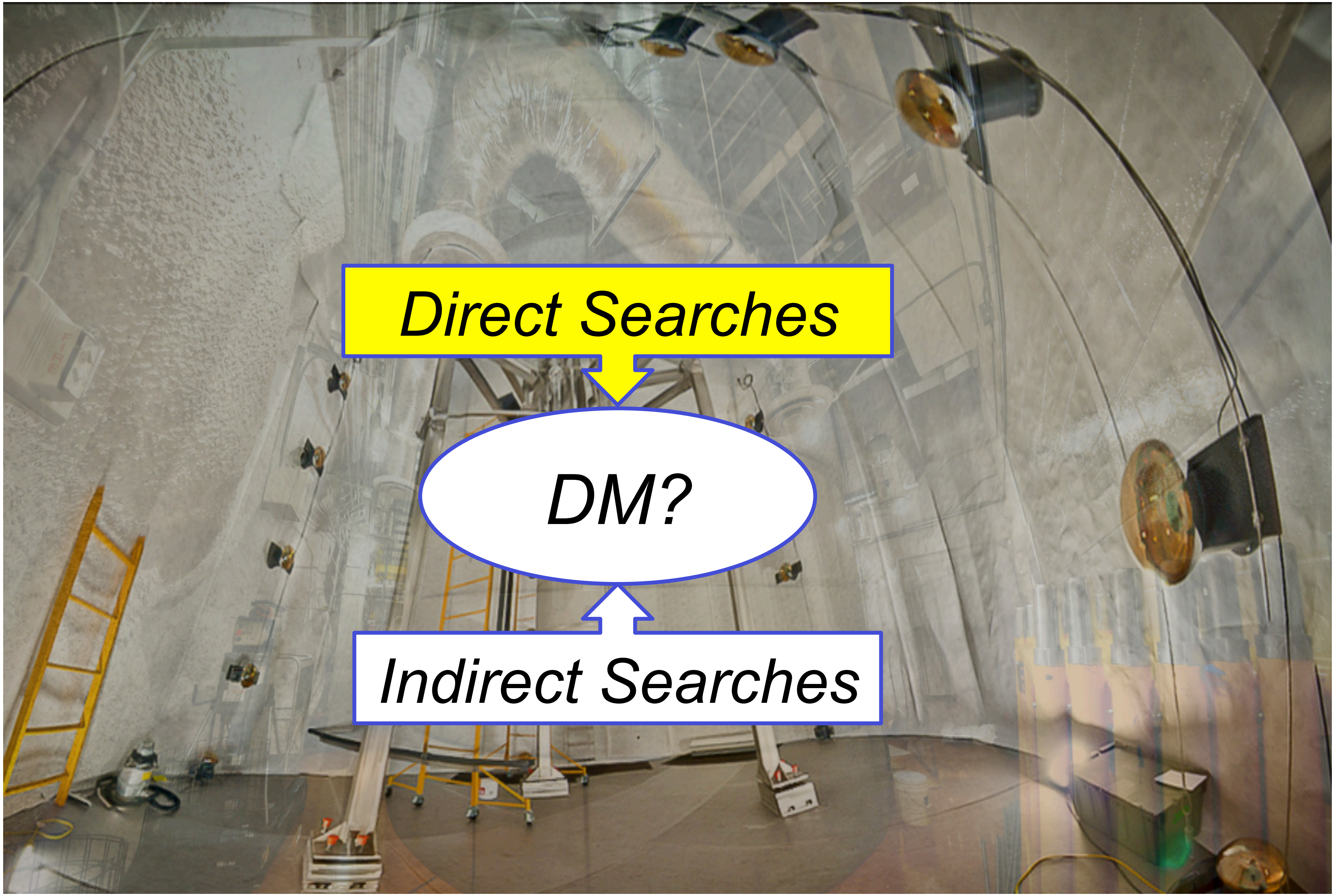
m_LSP [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$ CMS-PAS-SUS-12-028
$\tilde{u_L} \to u\chi_1^0$ CMS-PAS-SUS-12-028
$\tilde{b} \to b\chi_1^0$ ATLAS-CONF-2013-053
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$ ATLAS-CONF-2013-068
$\tilde{t} \to Wb\chi_1^0$ CMS-PAS-SUS -13-011
Direct slepton
$\tilde{l}_L \to l^\pm\chi_1^0$
ATLAS-CONF-2013-049
$\tilde{l}_R \to l^\pm\chi_1^0$
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS-CONF-2013-047
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-PAS-SUS-12-024
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF-2013-061
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
Direct $\chi_1^\pm/\chi_2^0$
$m_{SUSY} = m_{\chi_1^\pm} = m_{\chi_2^0}$
$\chi_1^\pm\chi_2^0(light\ \tilde{l})$
$\chi_1^\pm\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
m_SUSY [GeV]
0
250
500
750
1000
1250
1500
DM Searches @ collider & Direct Detection O. Buchmüller



Bottom line:

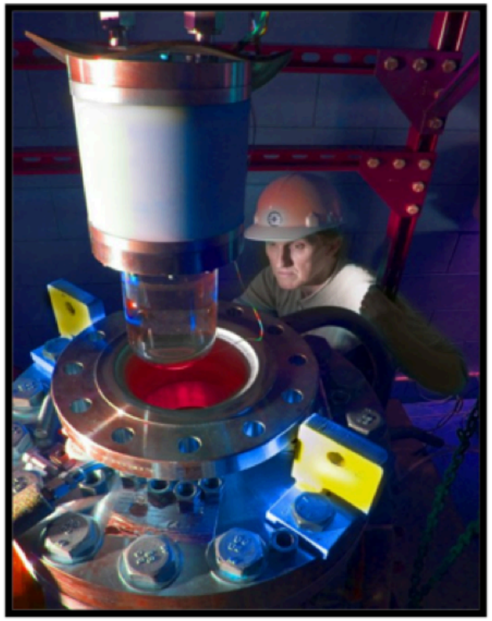
- No sign of a SUSY (DM) signal (yet)
- ATLAS and CMS have adopted a simplified model approach as the main tool to characterize their “SUSY searches”

Dark Matter Searches at Direct Detection Experiments

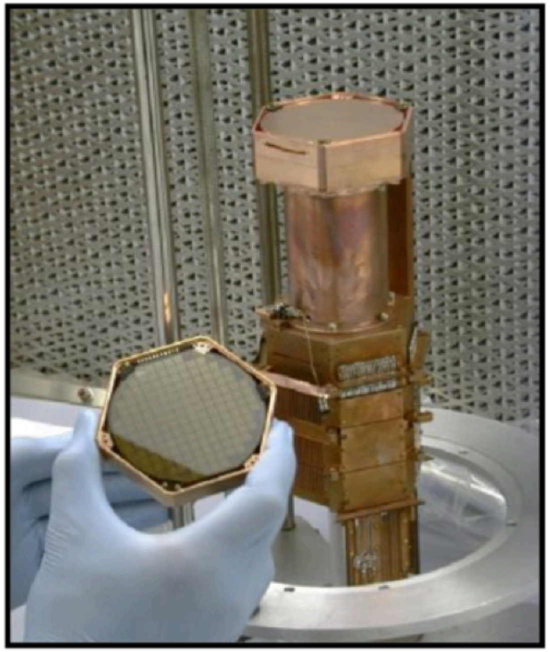


Direct Detection Experimets: Examples

COUPP

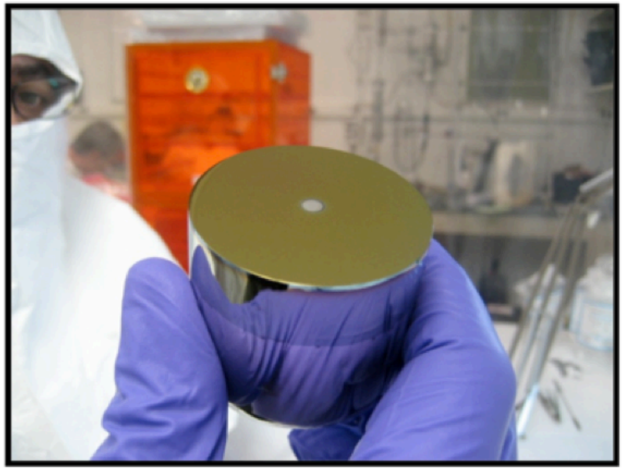


CDMS



CRESST

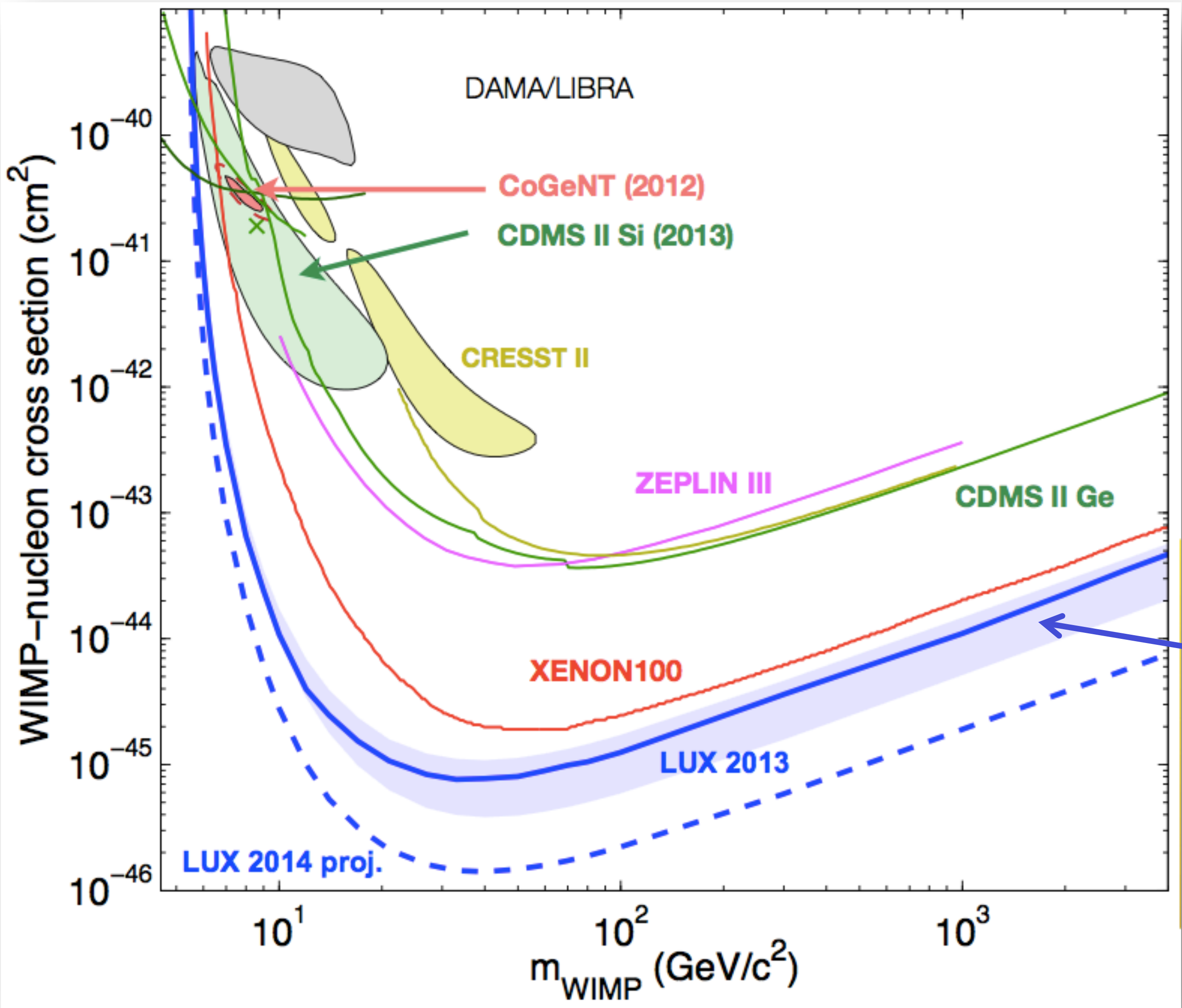
CoGeNT



(+ EDELWEISS, DAMA, EURECA, ZEPLIN, DEAP, ArDM, WARP, LUX, SIMPLE, PICASSO, DMTPC, DRIFT, KIMS, ...)

Xenon

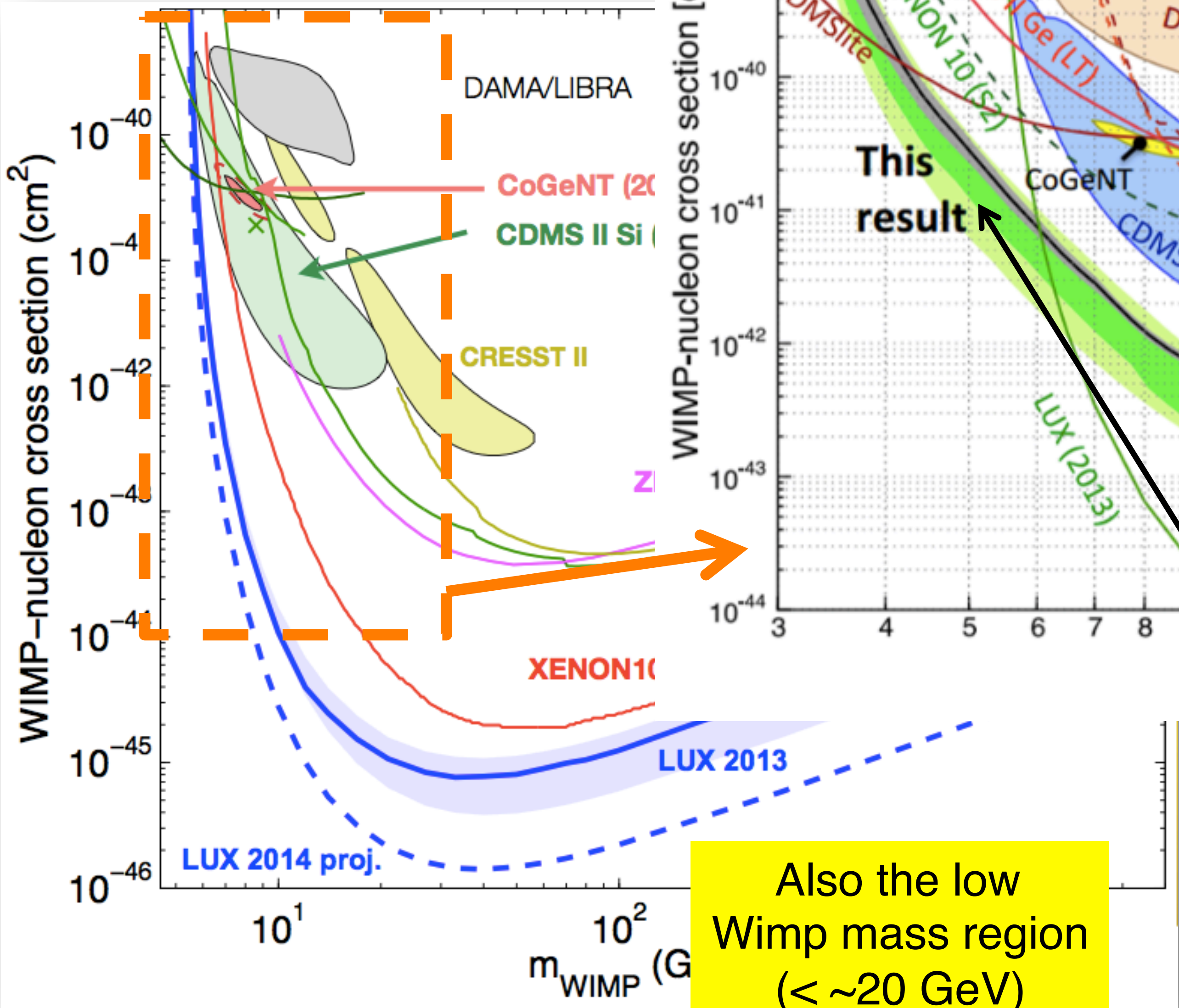
Dark Matter Searches: Direct Detection Experiments

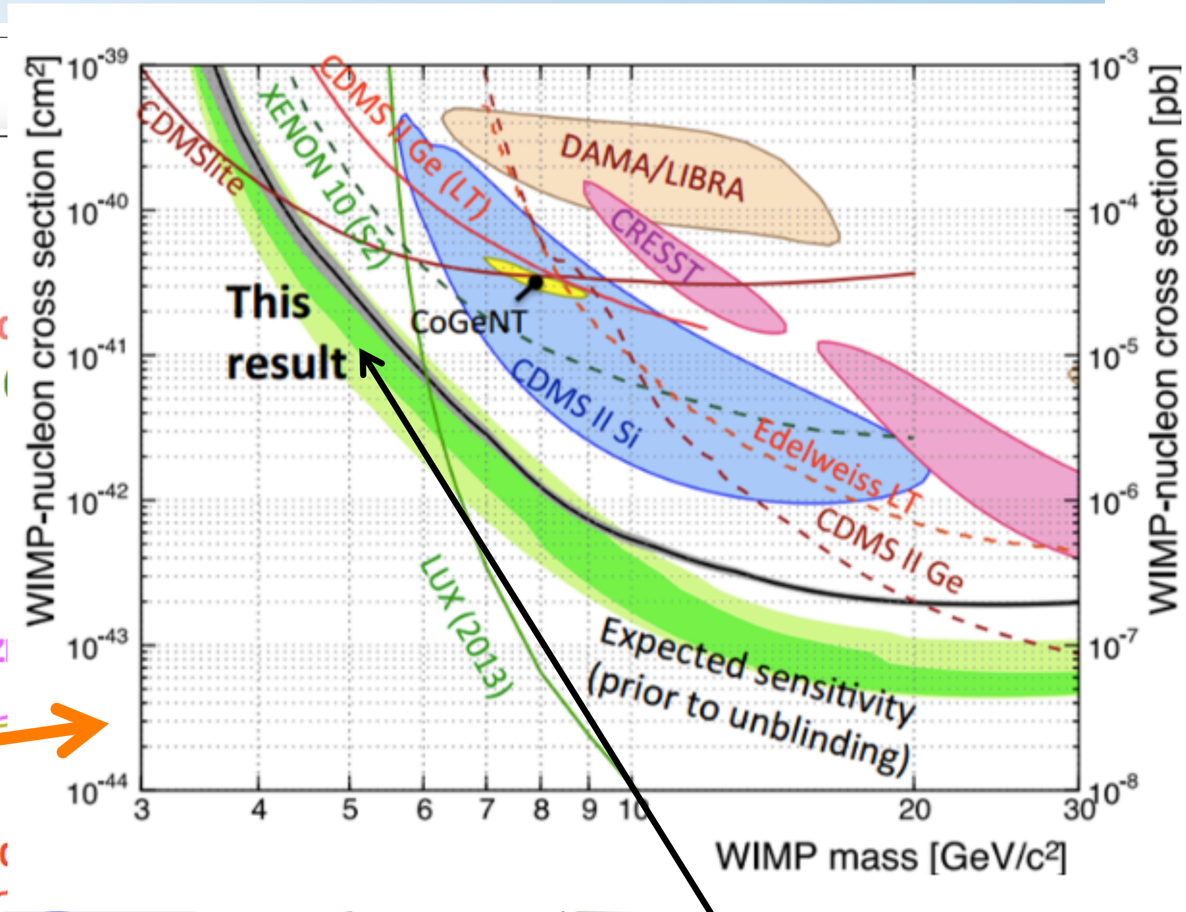


LUX

New 2013 Lux
85.3 live-days of data with a fiducial volume of 118 kg. Conservative assumptions!
Improved results expected soon!

Dark Matter Searches: Direct Detection Experiments



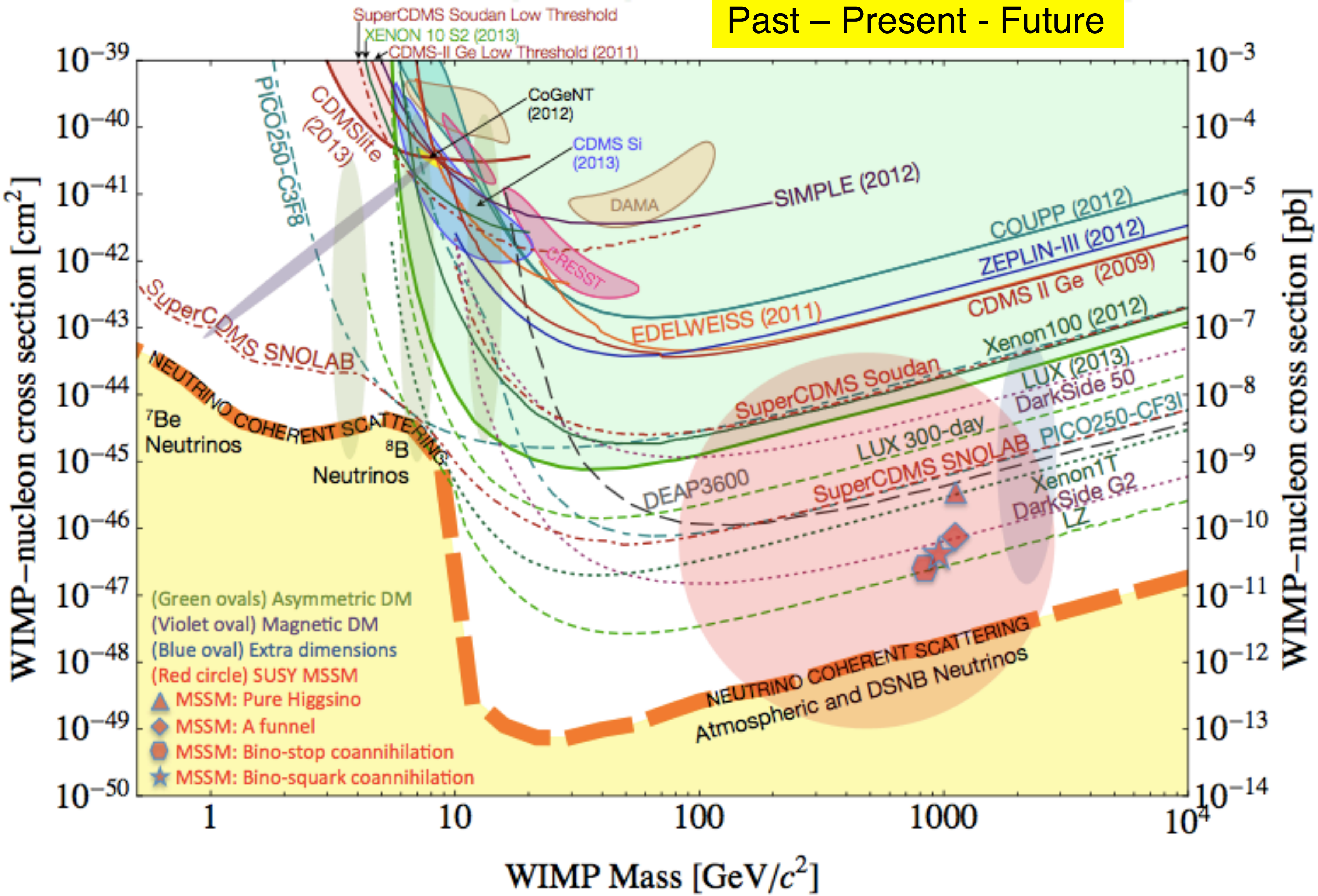


Also the low Wimp mass region (< ~20 GeV) is very interesting!

New SuperCDMS result with 577 days exposure pushes the CDMSlite limit down at 4-6 GeV DM mass range

Direct Detection Landscape in a nutshell!

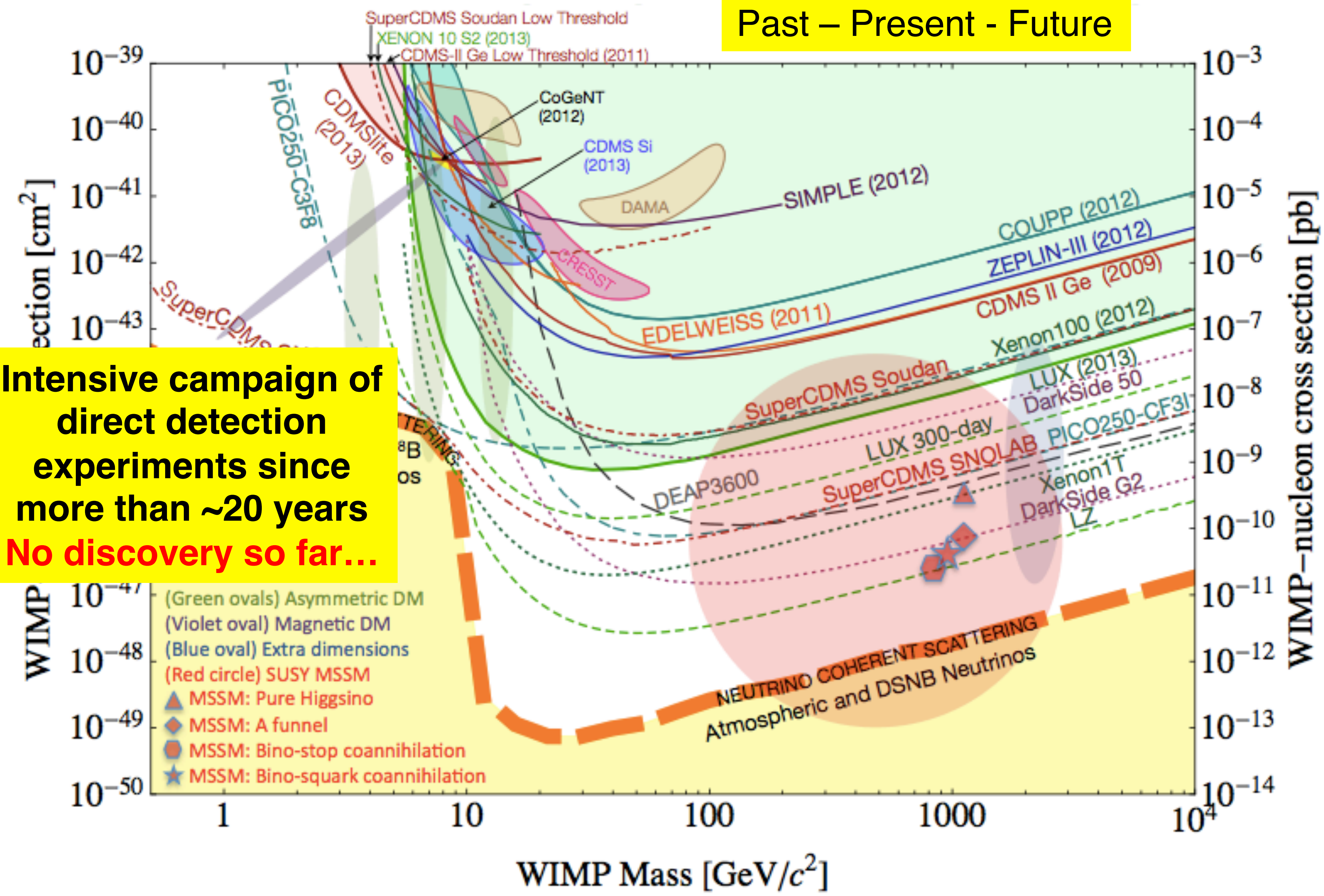
Past – Present - Future



DM Searches @ collider & Direct Detection O. Buchmüller

Direct Detection Landscape in a nutshell!

Past – Present - Future

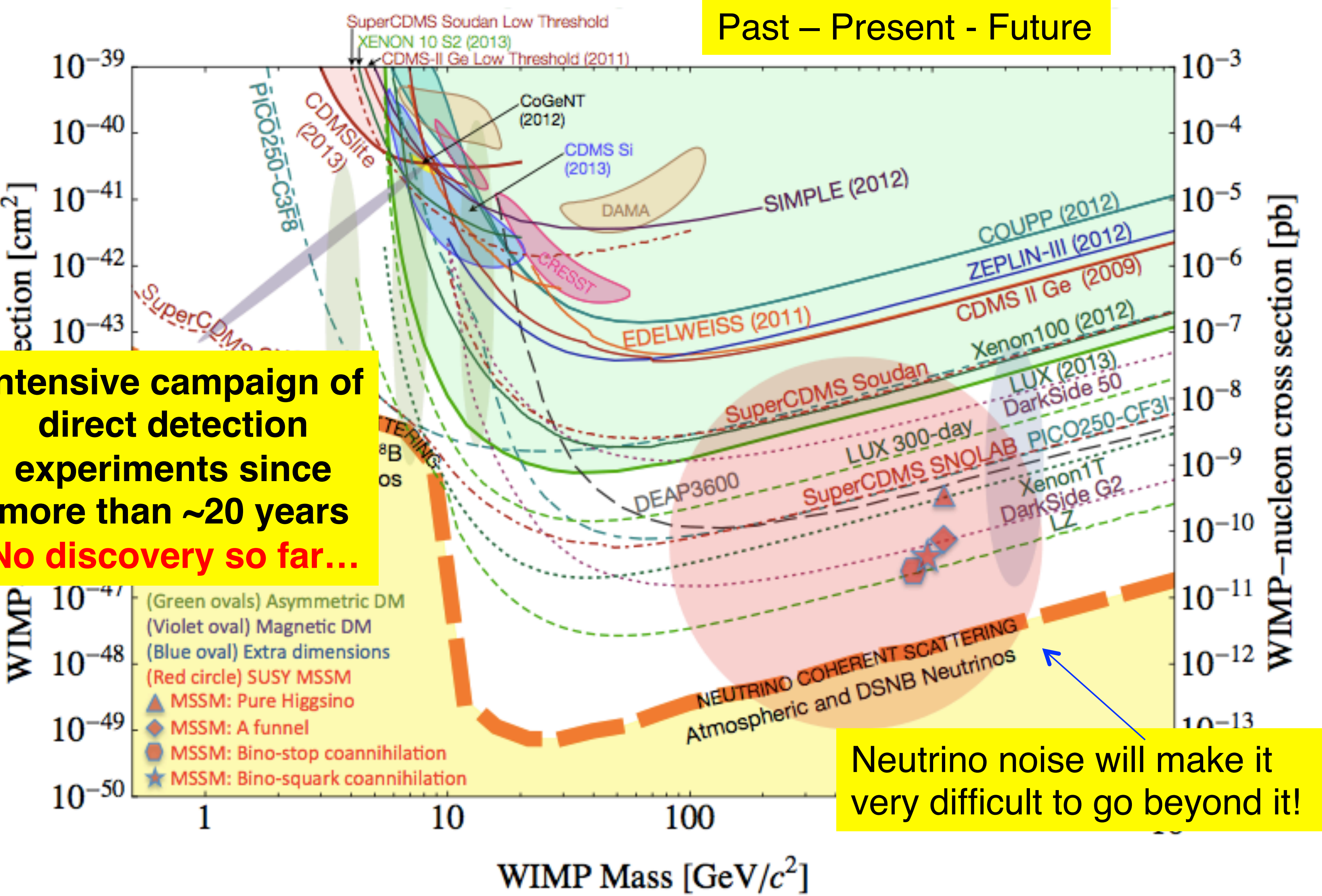


Intensive campaign of direct detection experiments since more than ~20 years

No discovery so far…

Direct Detection Landscape in a nutshell!

Past – Present - Future

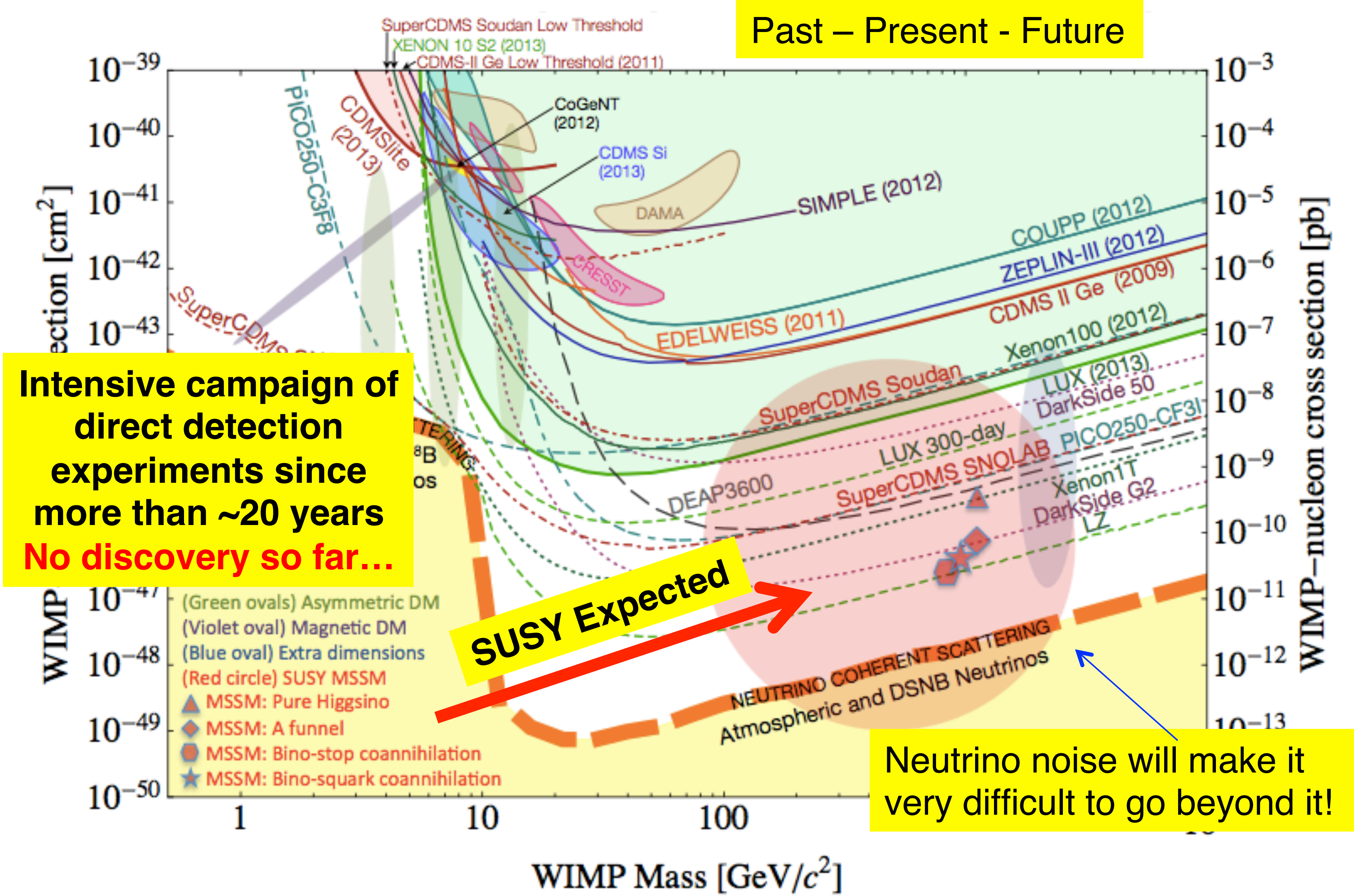


Intensive campaign of direct detection experiments since more than ~20 years
No discovery so far…

Neutrino noise will make it very difficult to go beyond it!

Imperial College London

Direct Detection Landscape in a nutshell!

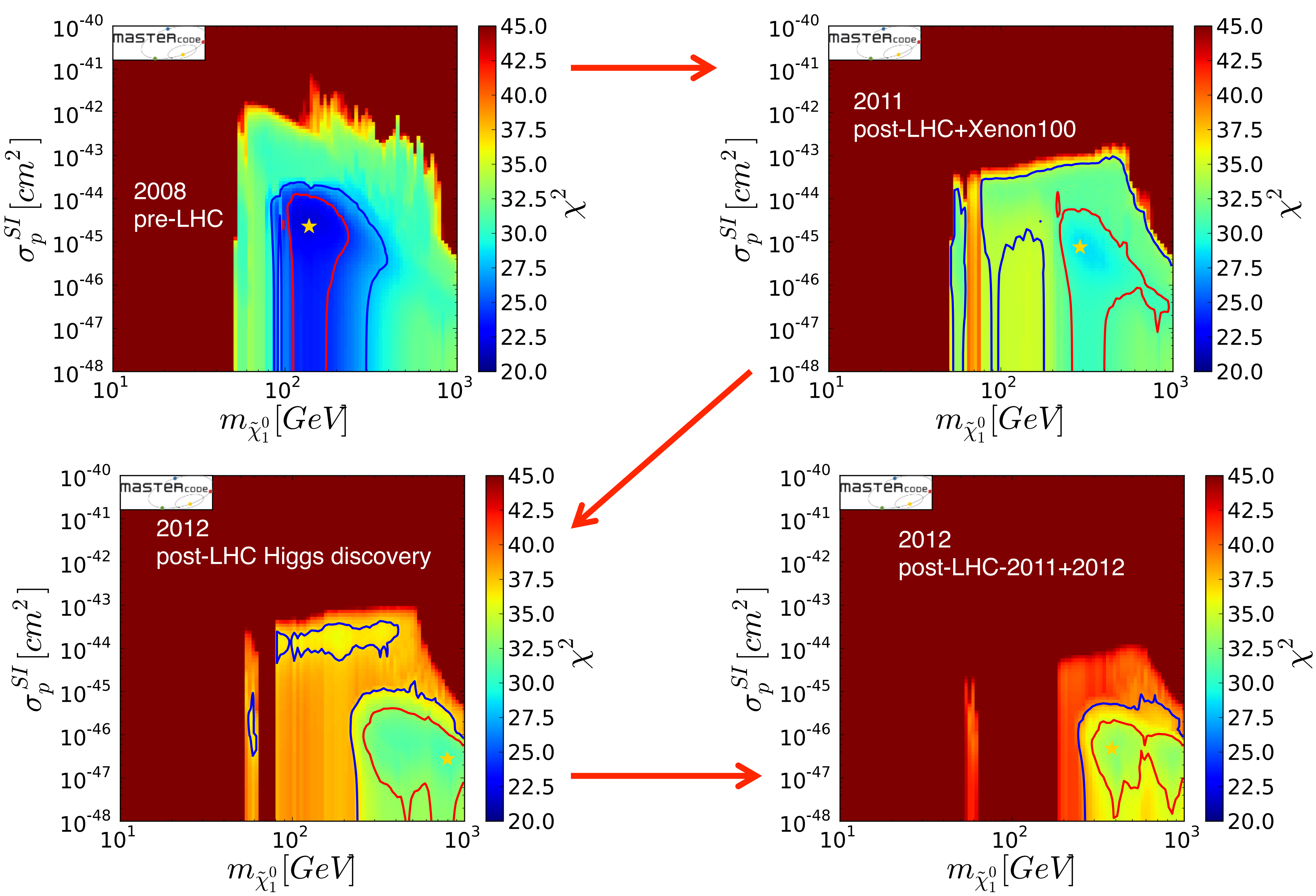


In Supersymmetry at Colliders and Direct Detection

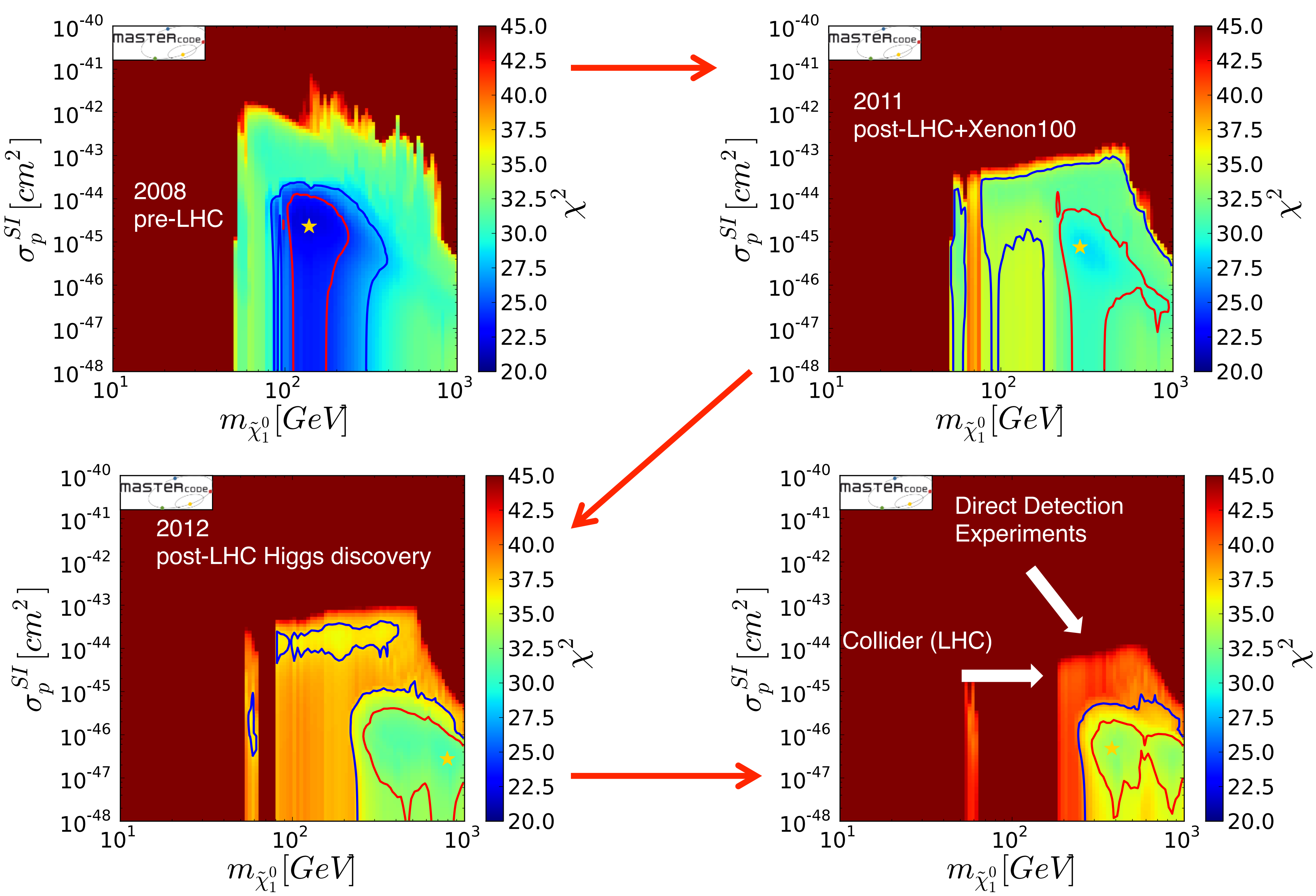
(i.e. a famous model …but only one model)

Imperial College London

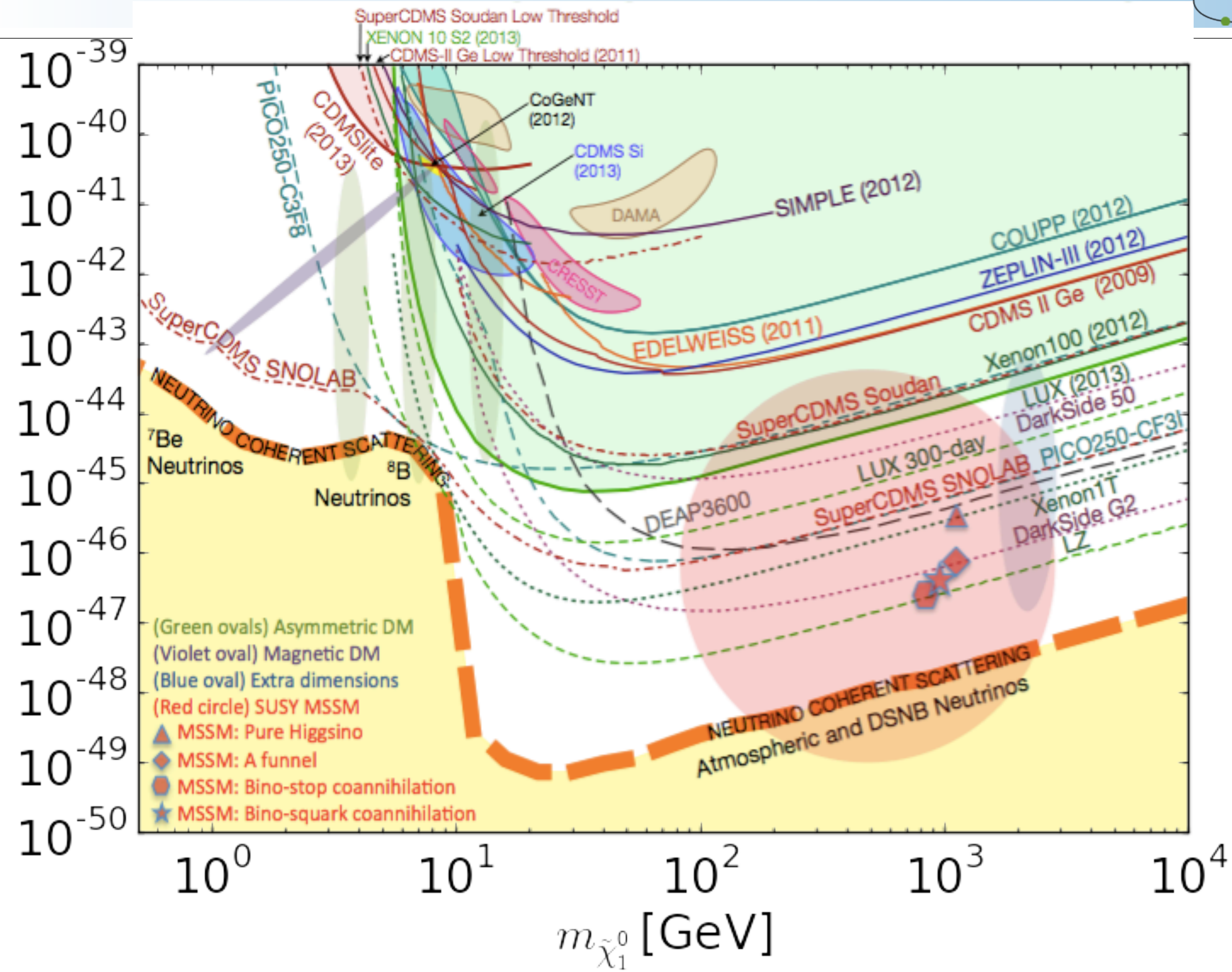
SUSY & Dark Matter: Evolution with time



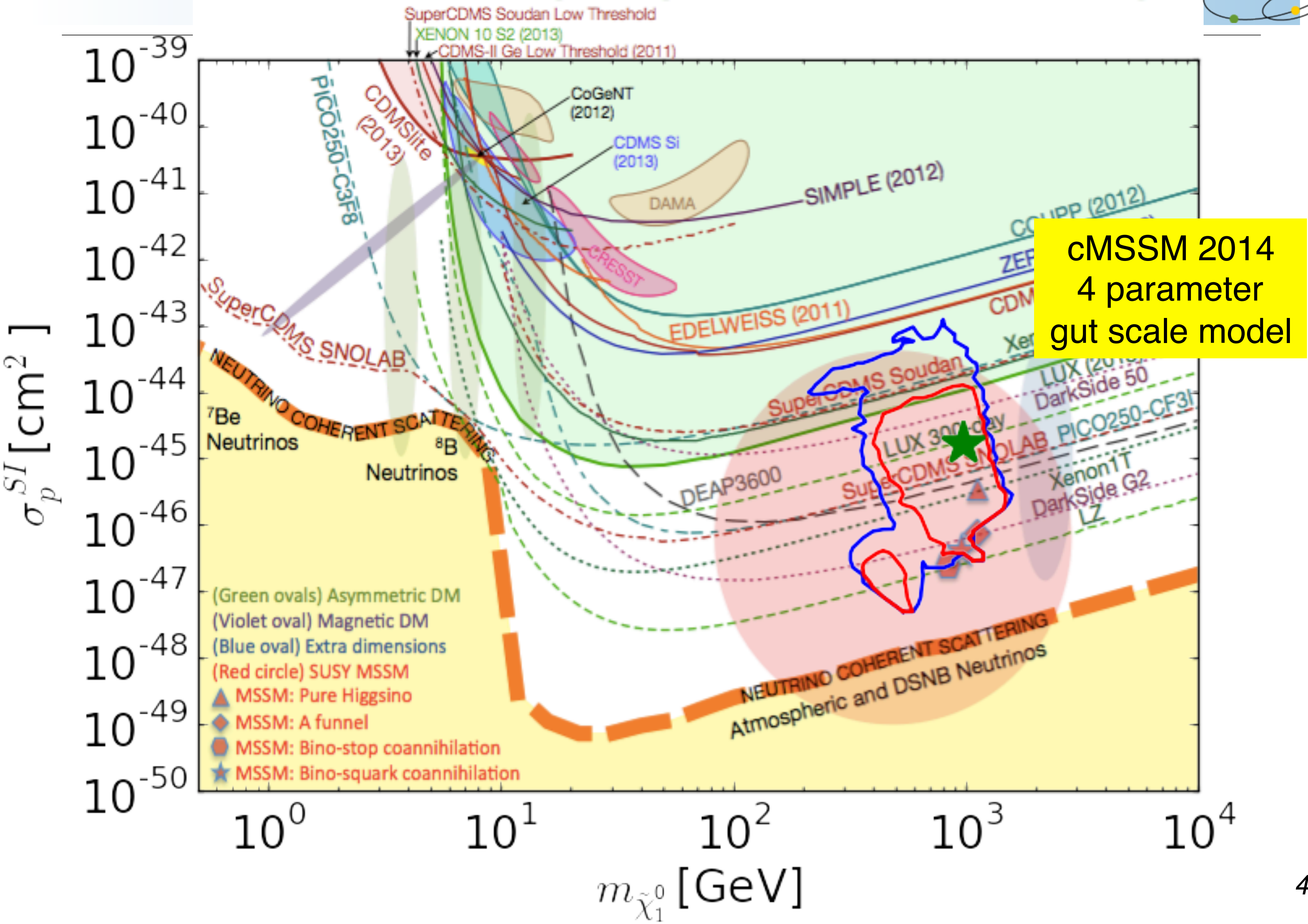
SUSY & Dark Matter: Evolution with time



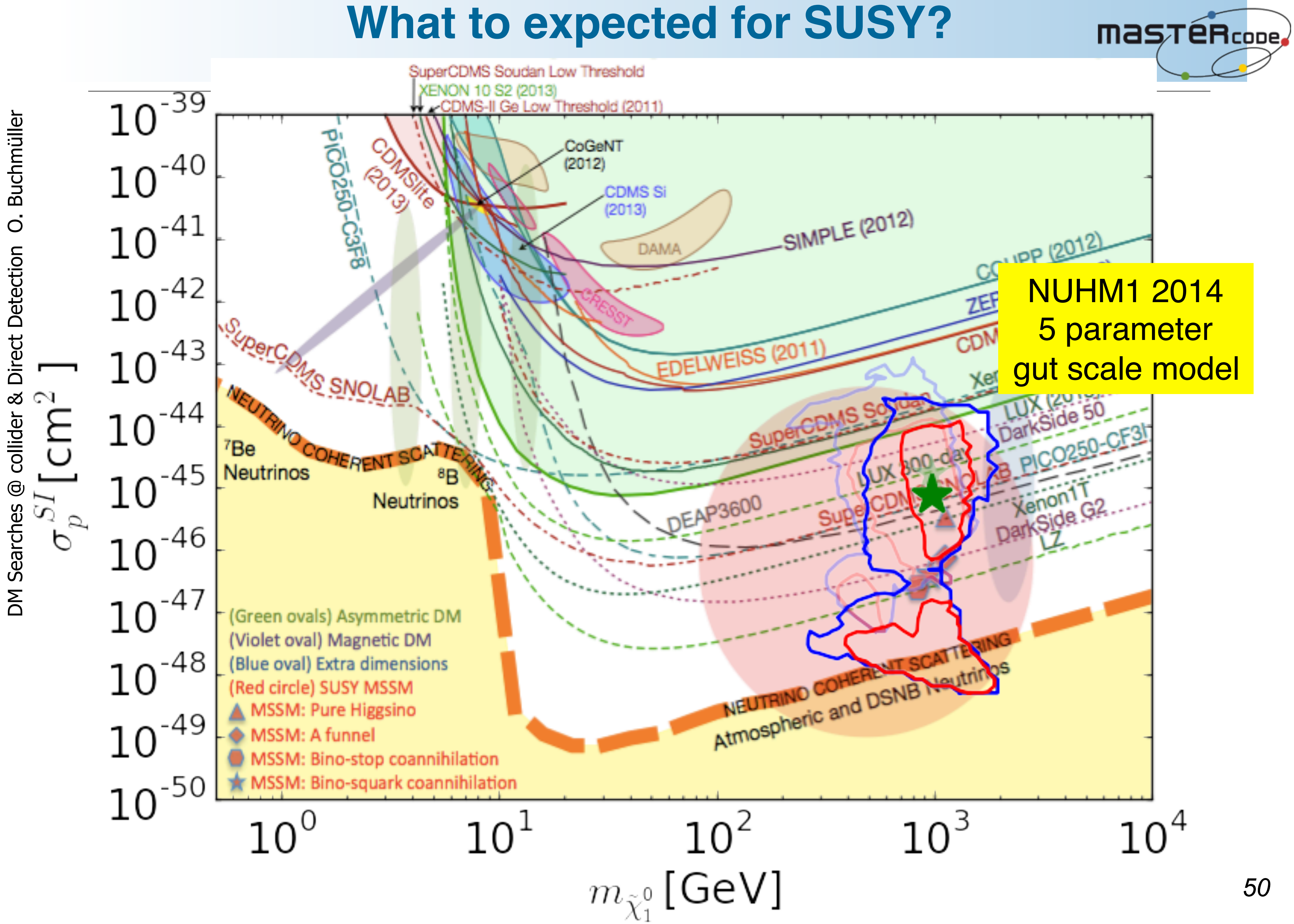
What to expected for SUSY?



What to expected for SUSY?



What to expected for SUSY?

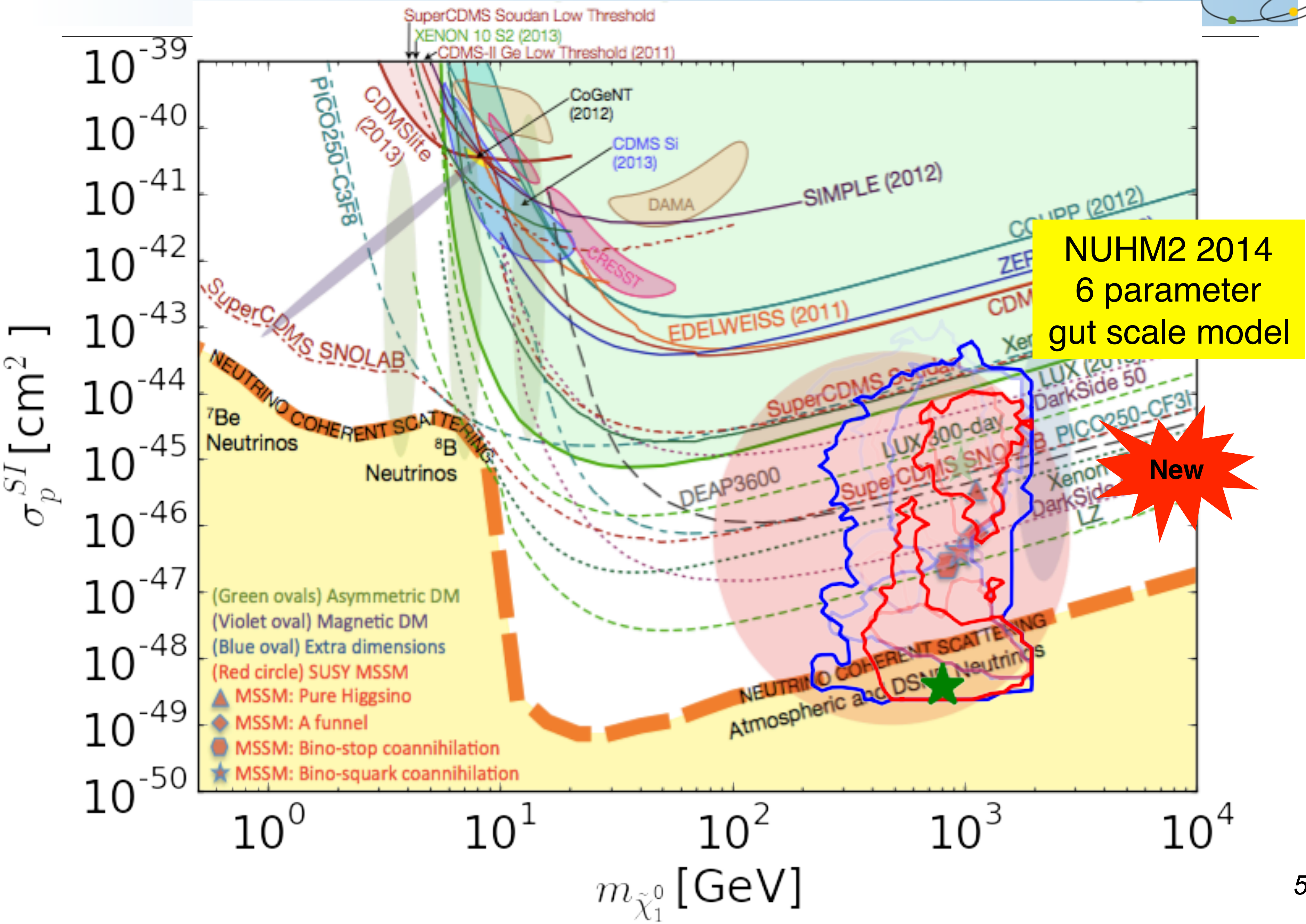


Imperial College London

What to expected for SUSY?

MasterCode

DM Searches @ collider & Direct Detection O. Buchmüller

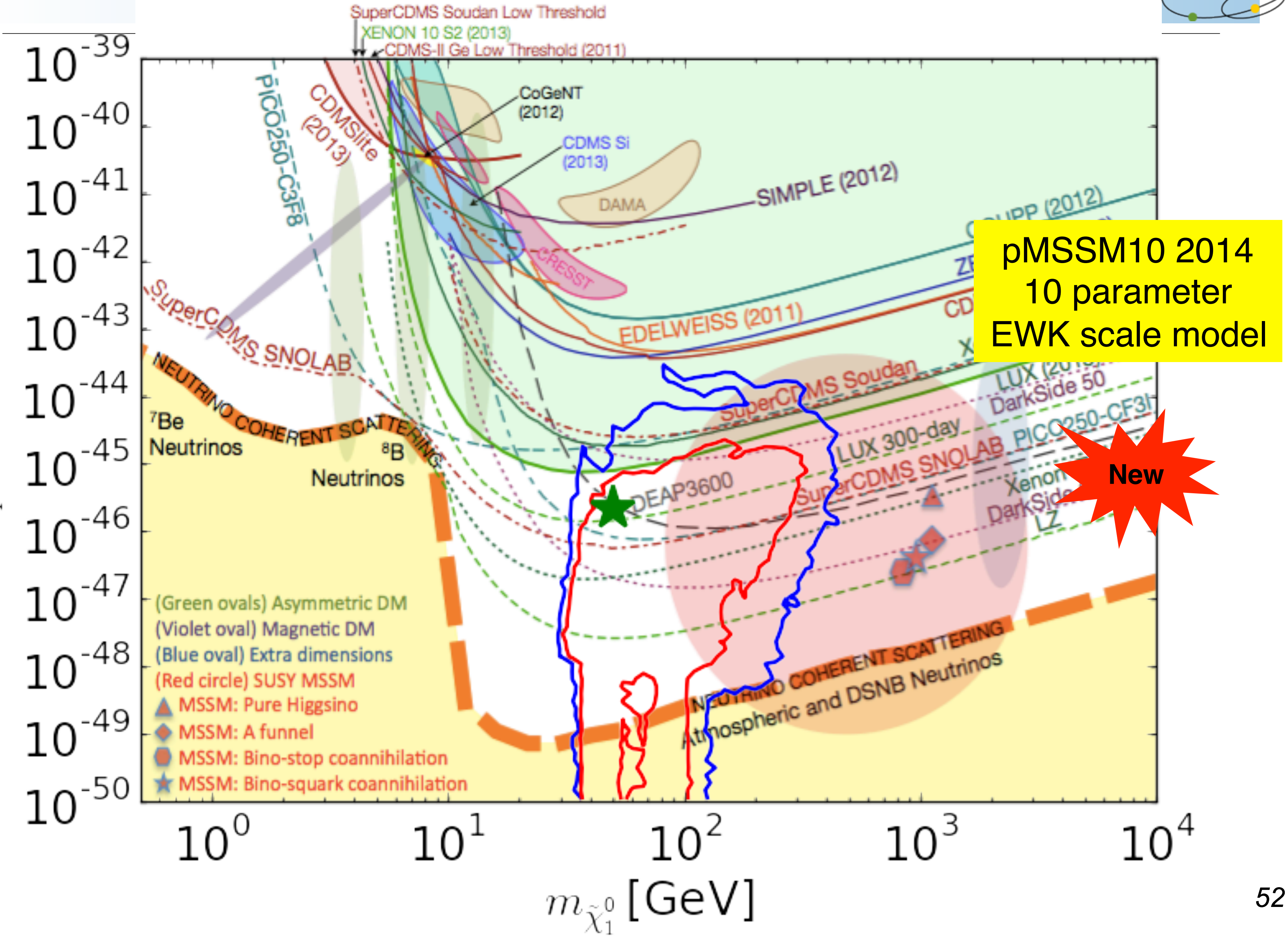


Imperial College London

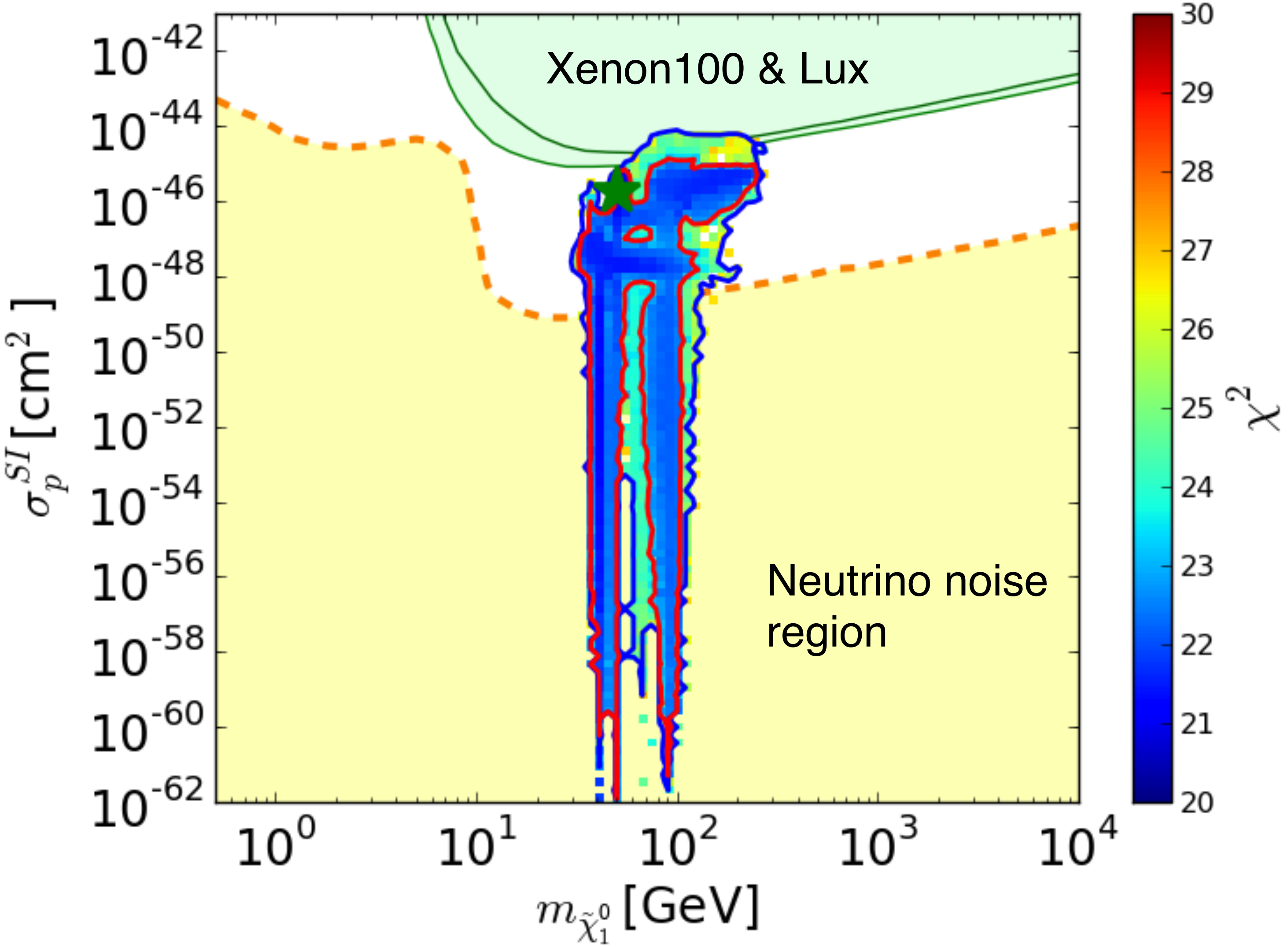
What to expected for SUSY?

MasterCode

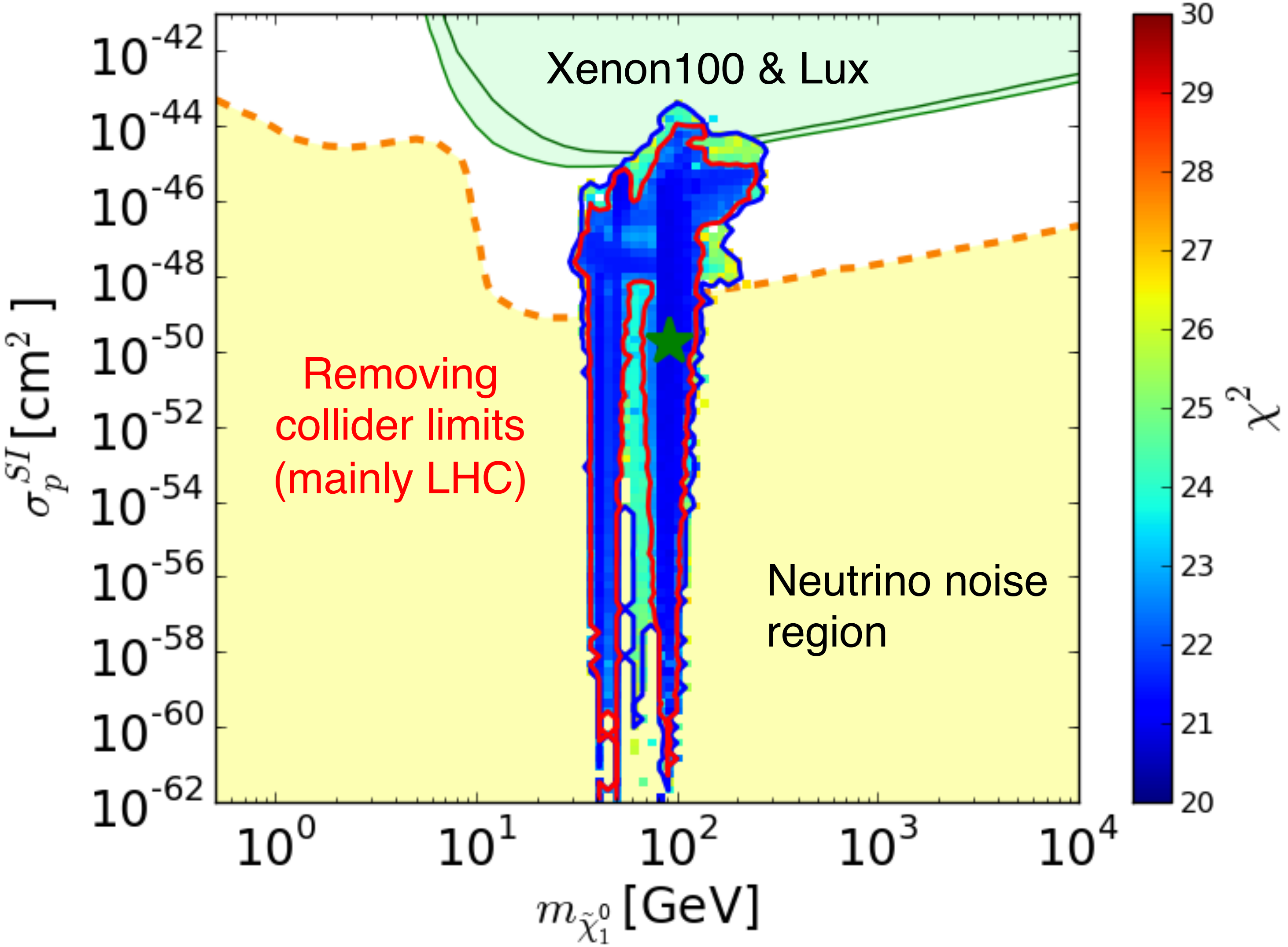
DM Searches @ collider & Direct Detection O. Buchmüller



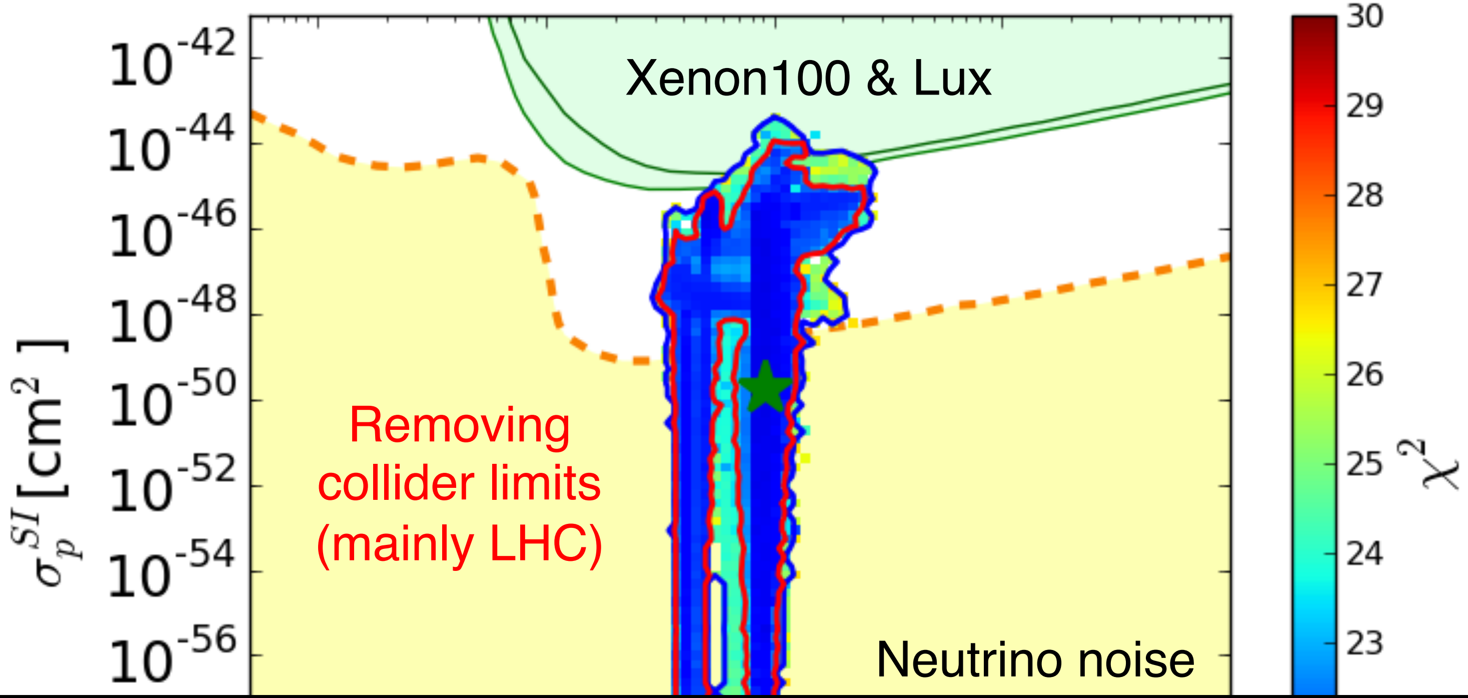
What to expect for SUSY (pMSSM)



What to expect for SUSY (pMSSM)



What to expect for SUSY (pMSSM)



SUSY summary:

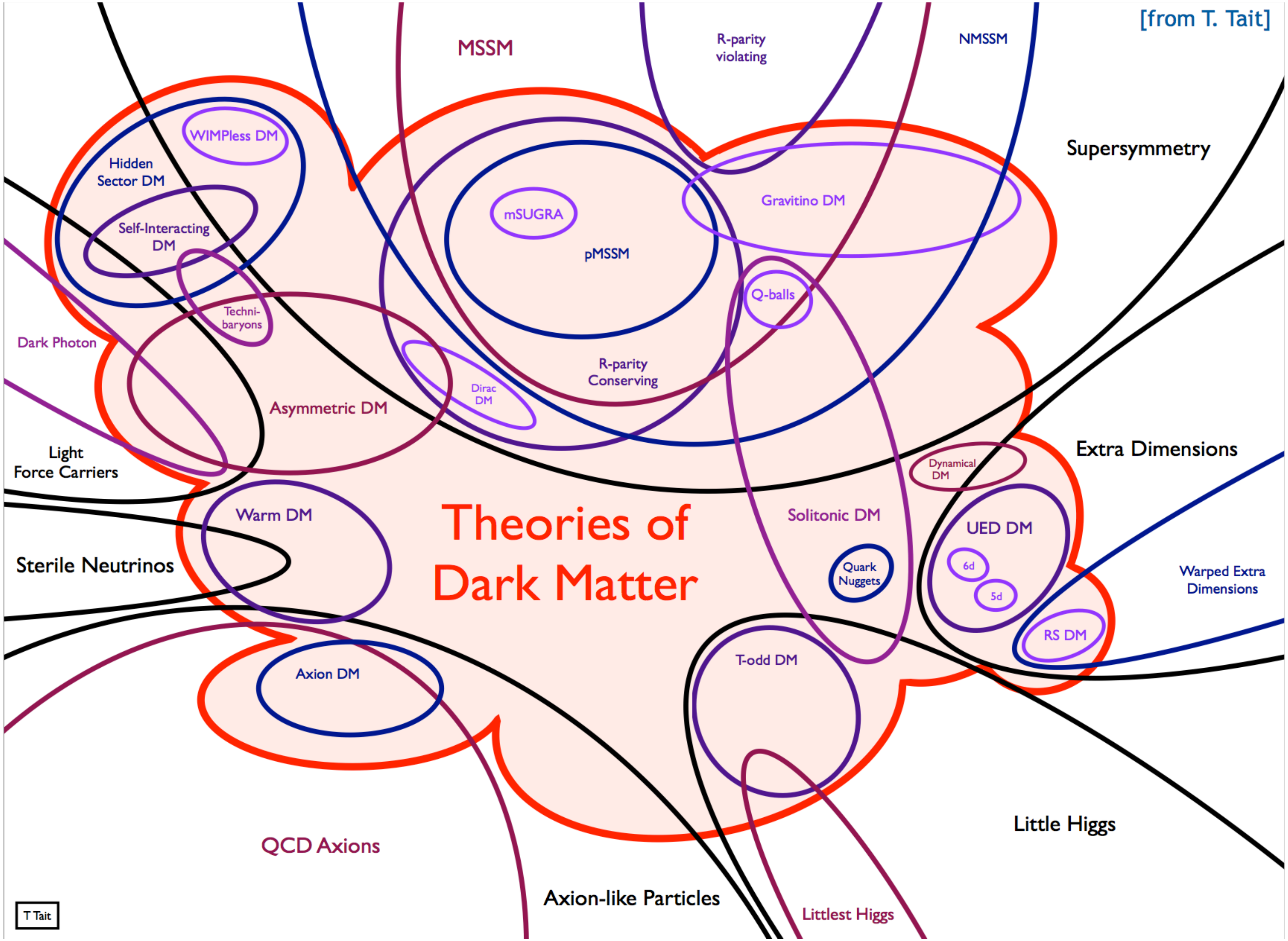
- There remains still a lot of unexplored parameter space in SUSY
- Large regions are within the neutrino noise region
- LHC searches are can probe regions not accesible to DM Direct detection experiments

➢ **Need to better work out complementarity between collider and DD**

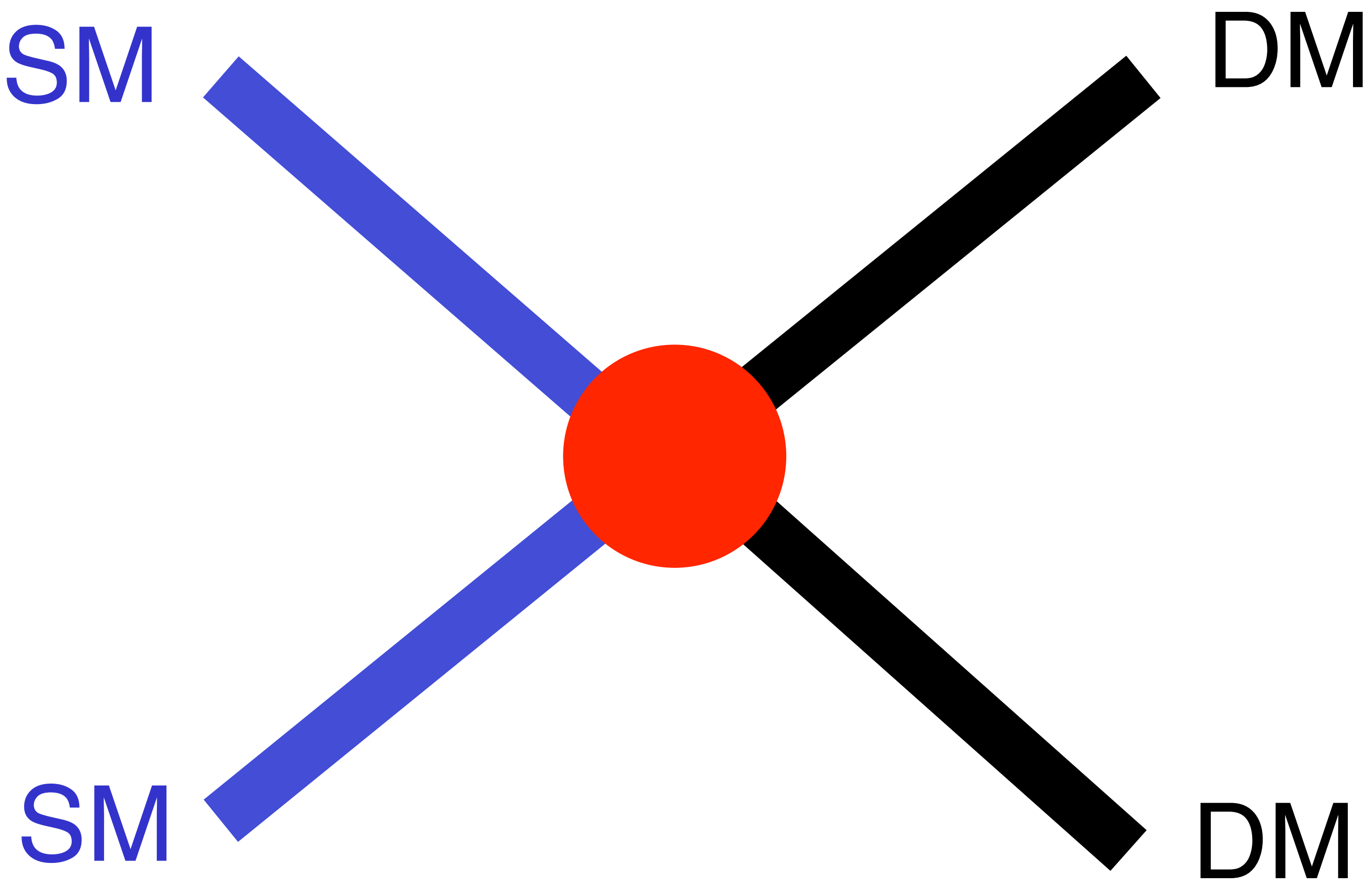
Beyond Models!

Generic Direct Searches for Dark Matter

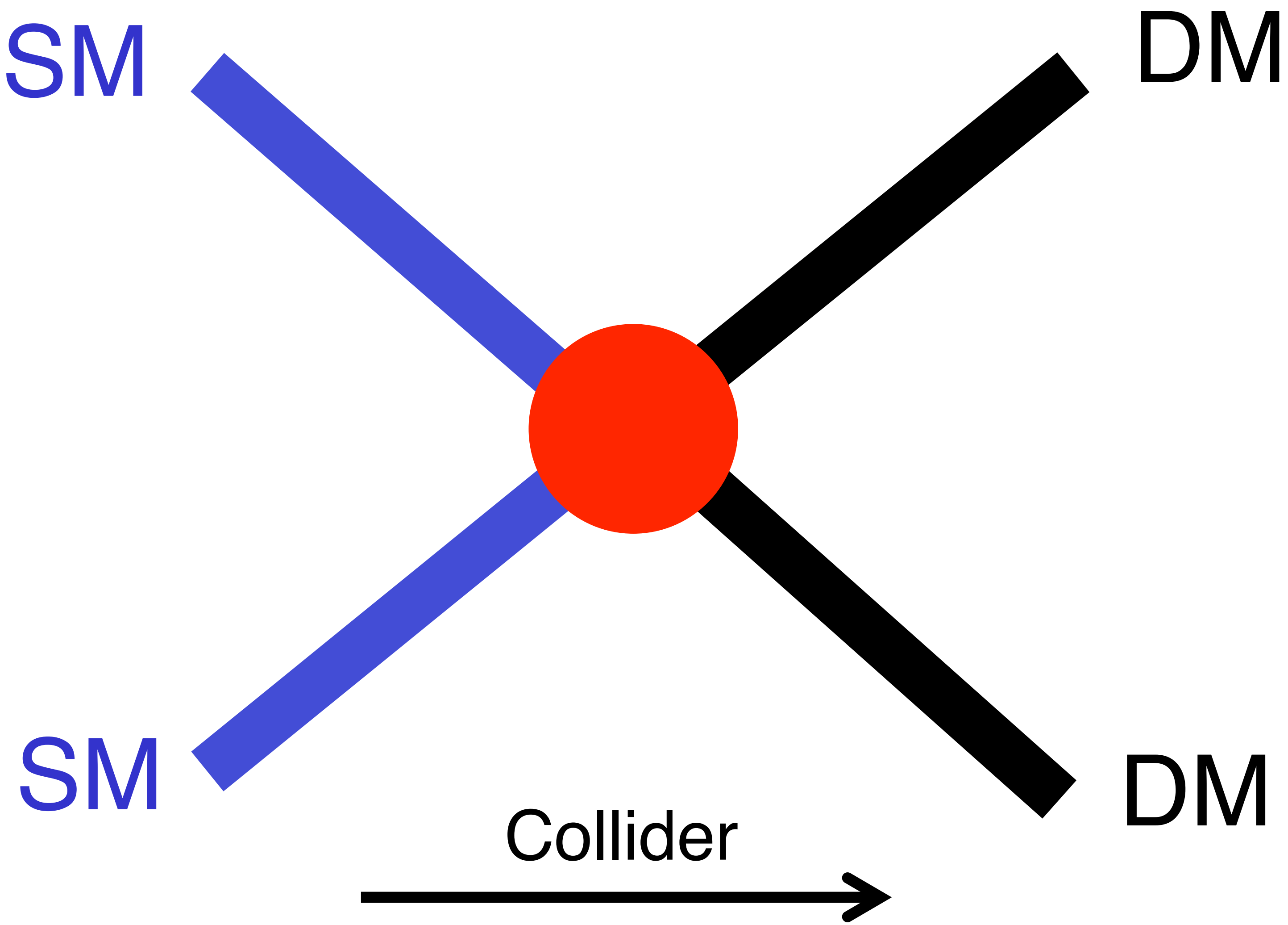
The Theoretical Landscape of DM Theories



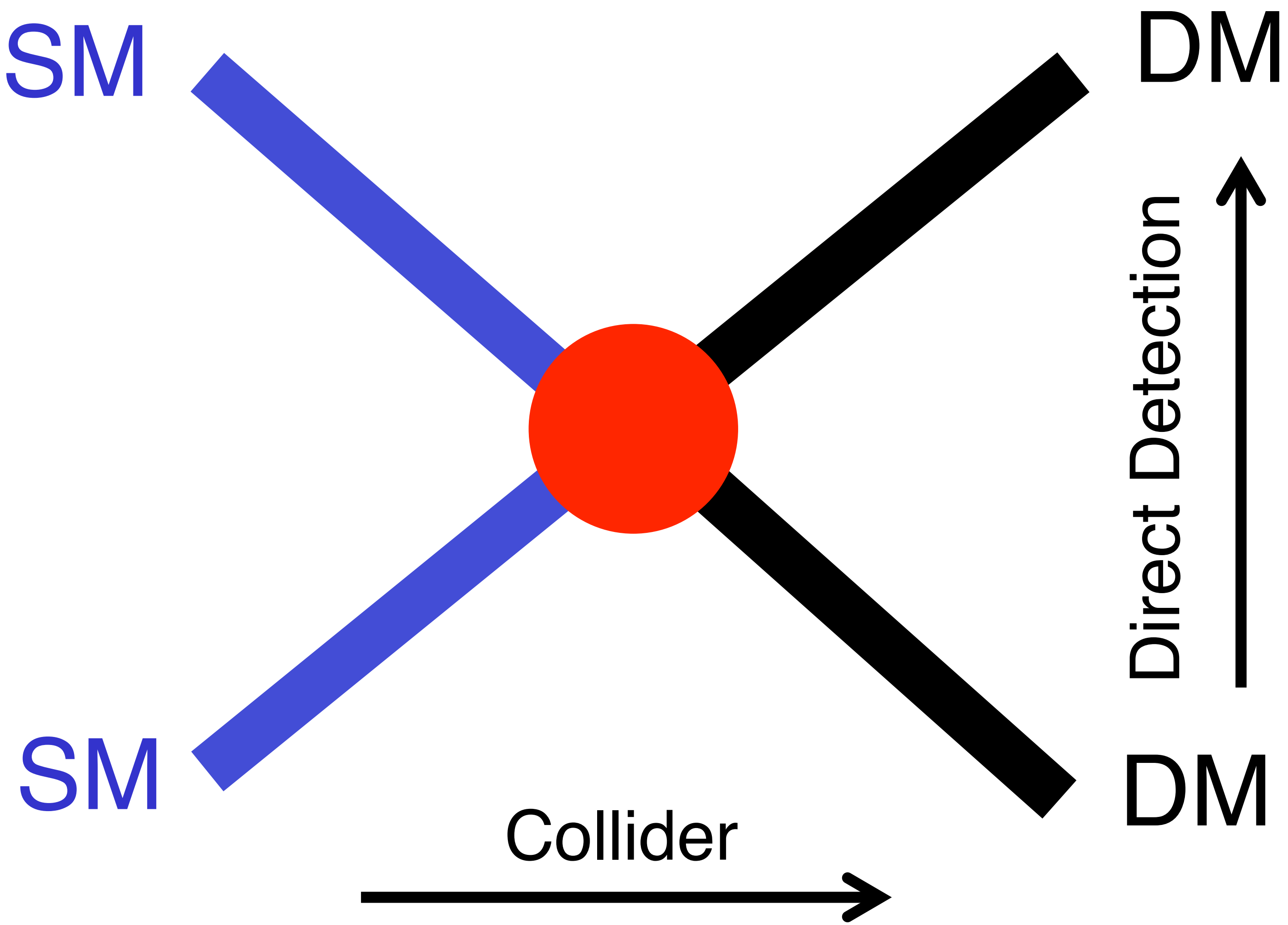
Dark Matter Searches



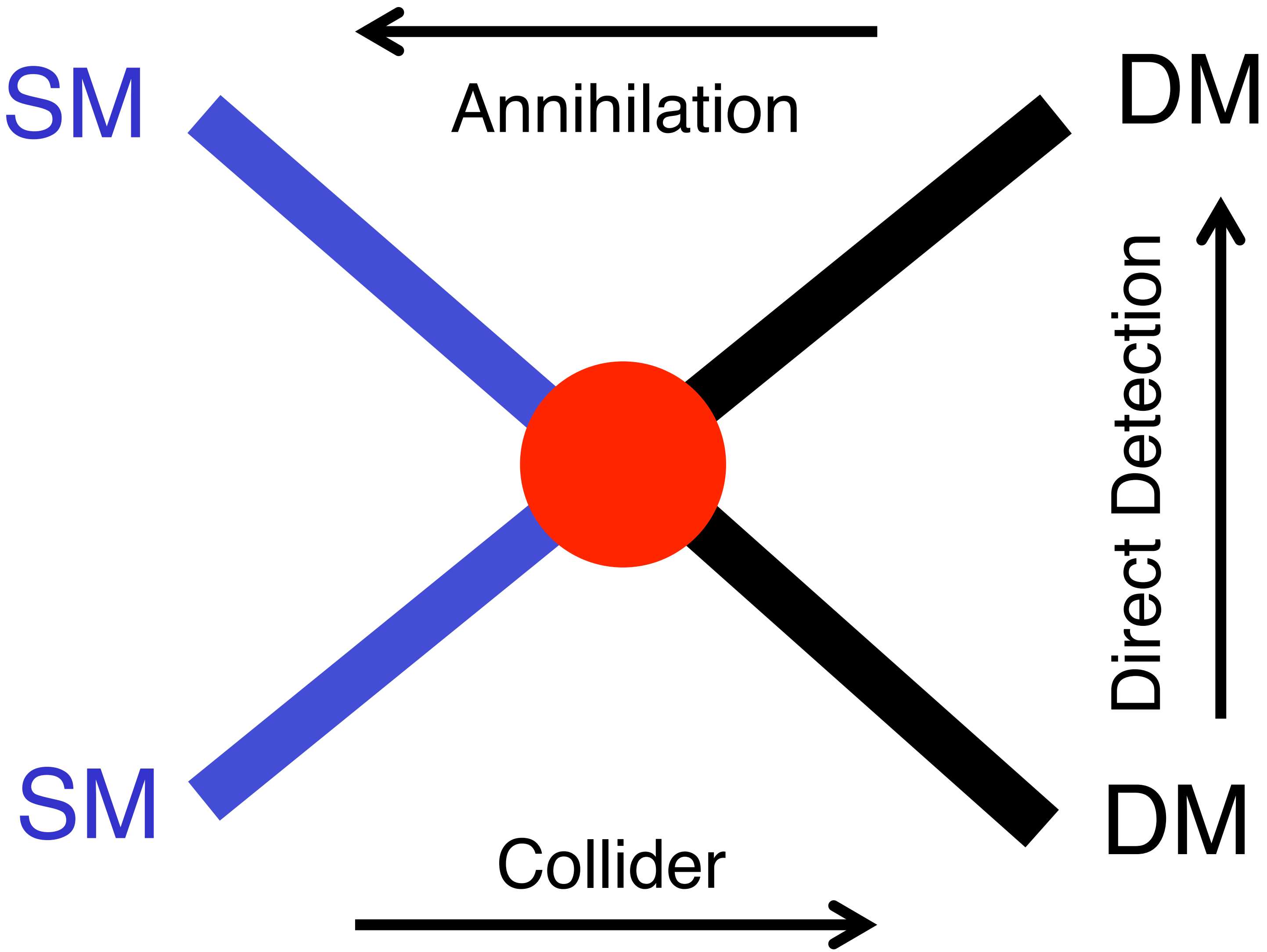
Dark Matter Searches



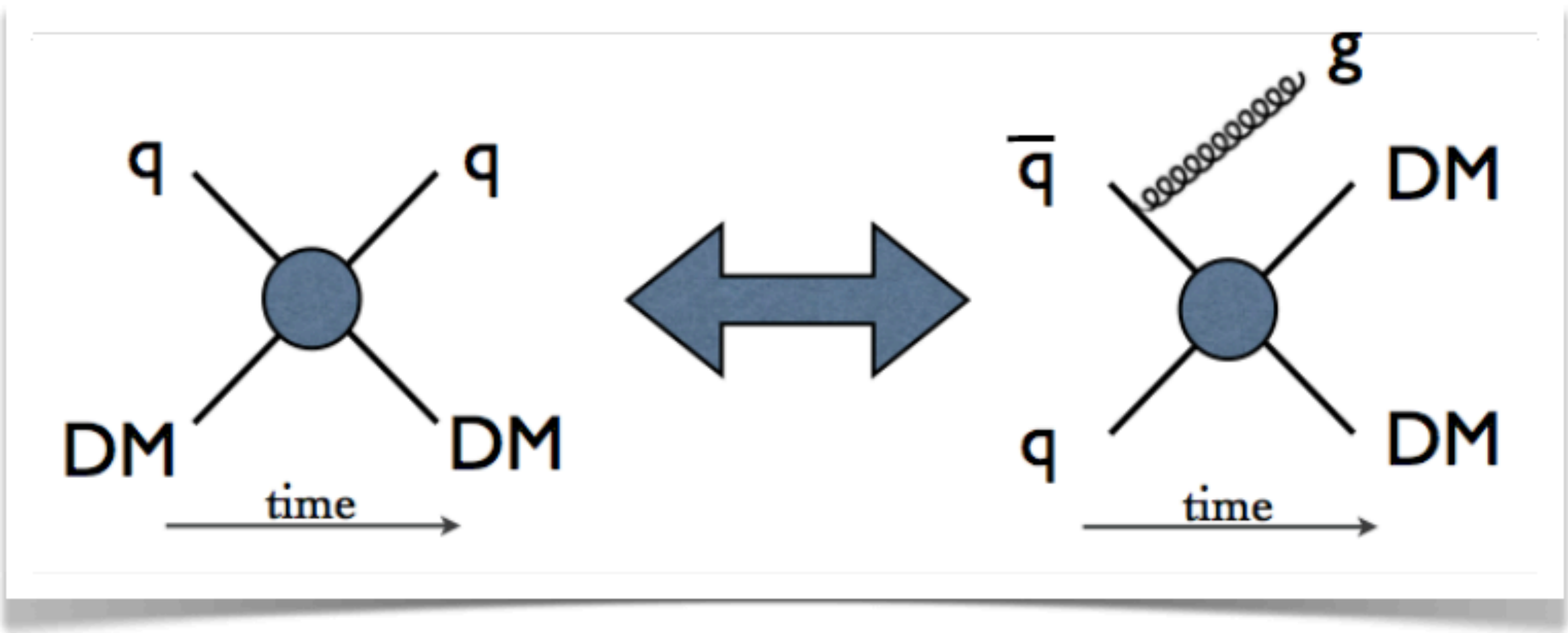
Dark Matter Searches



Dark Matter Searches

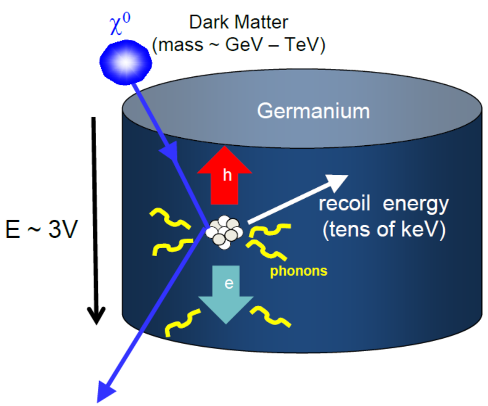


Dark Matter Searches: Direct Detection vs Colliders



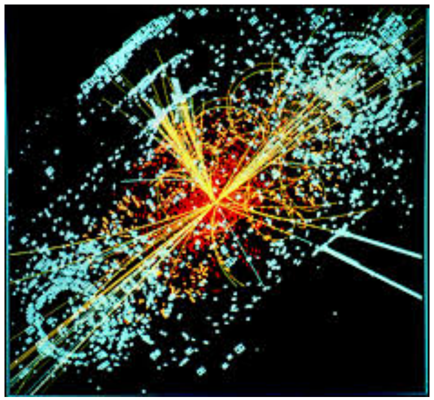
Direct Detection Experiments

- DM-nucleus scattering



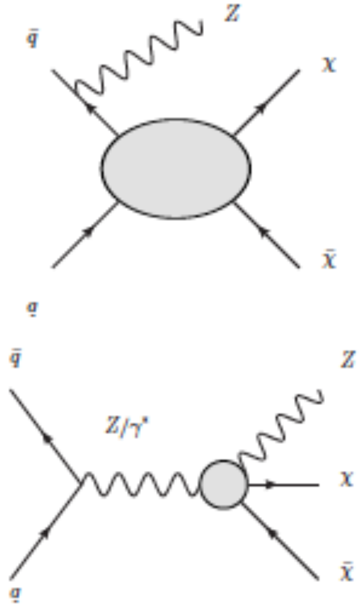
Collider Experiments

- Pair-production of DM
- missing energy signature



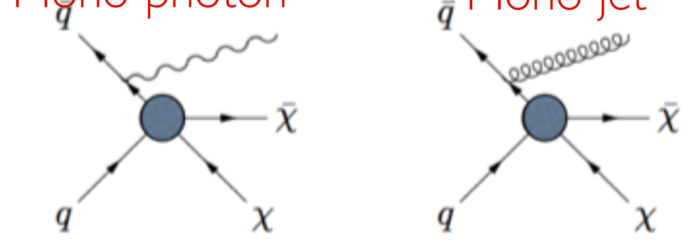
Mono-Mania (at the LHC)

Mono-Z

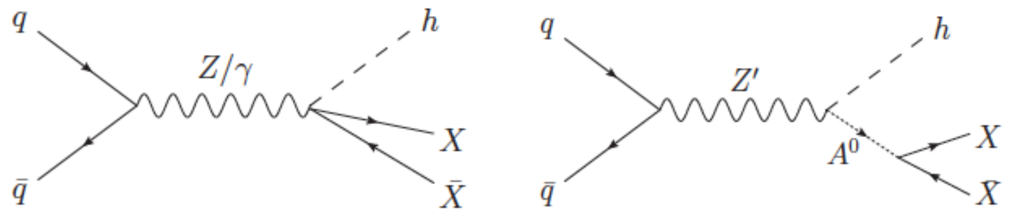


Mono-photon

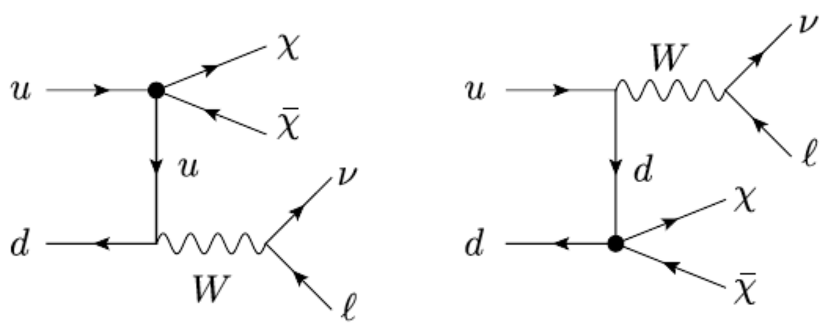
Mono-jet



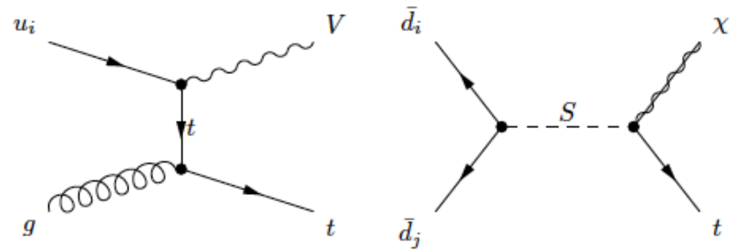
Mono-Higgs



Mono-W

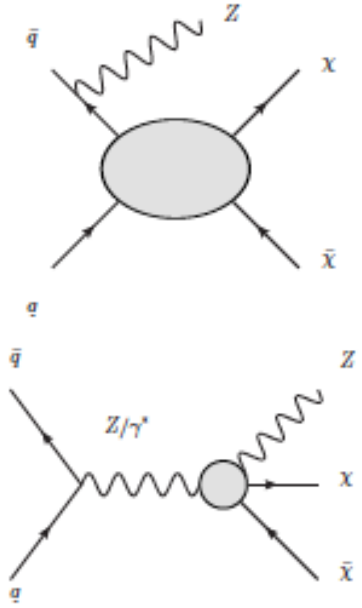


Mono-top

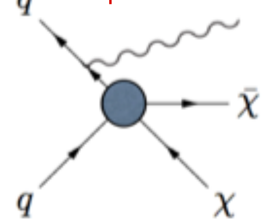


Mono-Mania (at the LHC)

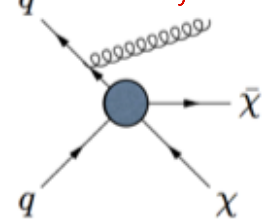
Mono-Z



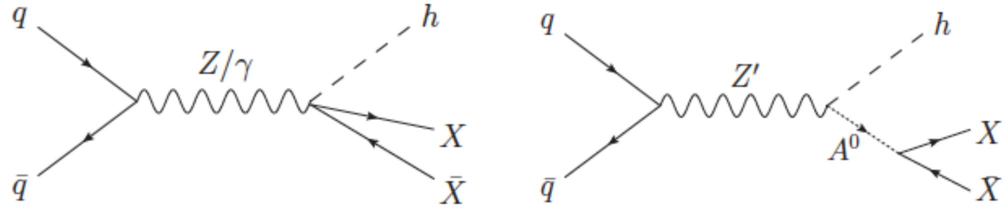
Mono-photon



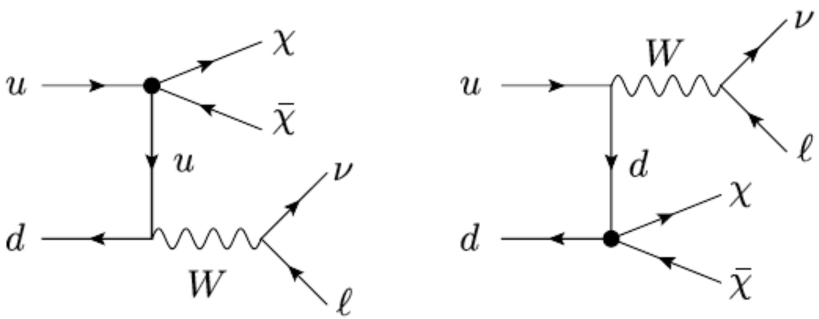
Mono-jet



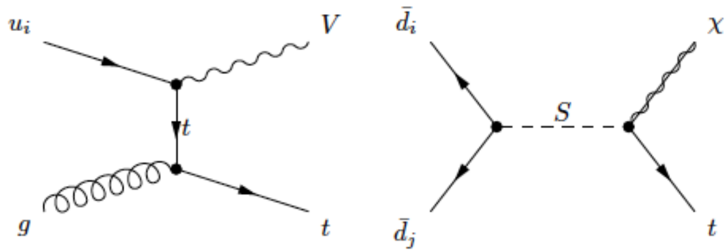
Mono-Higgs



Mono-W

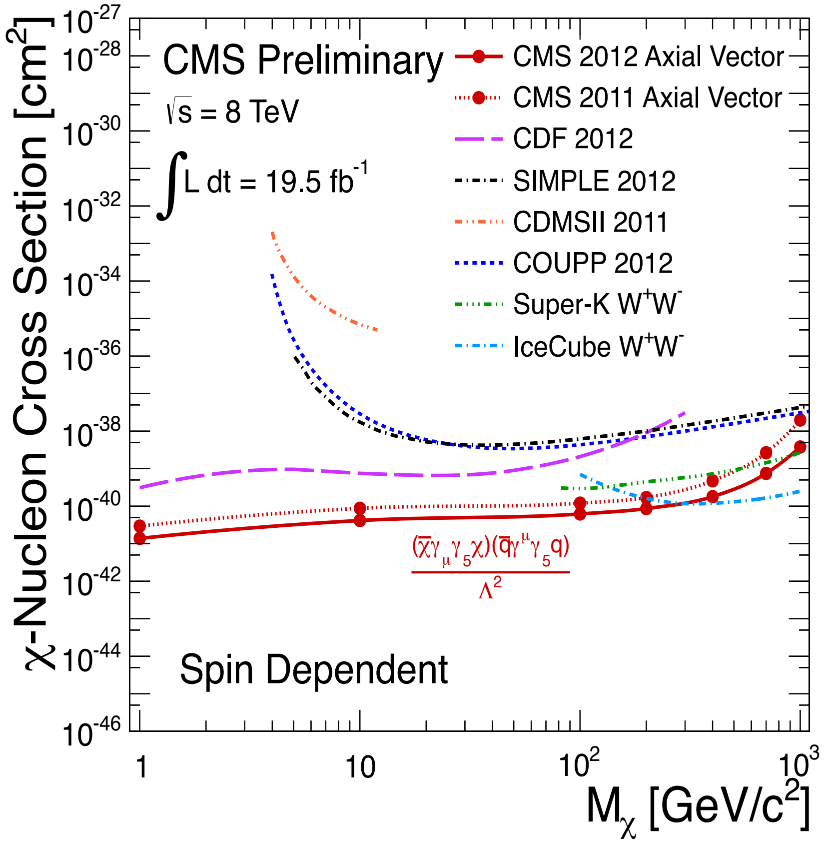


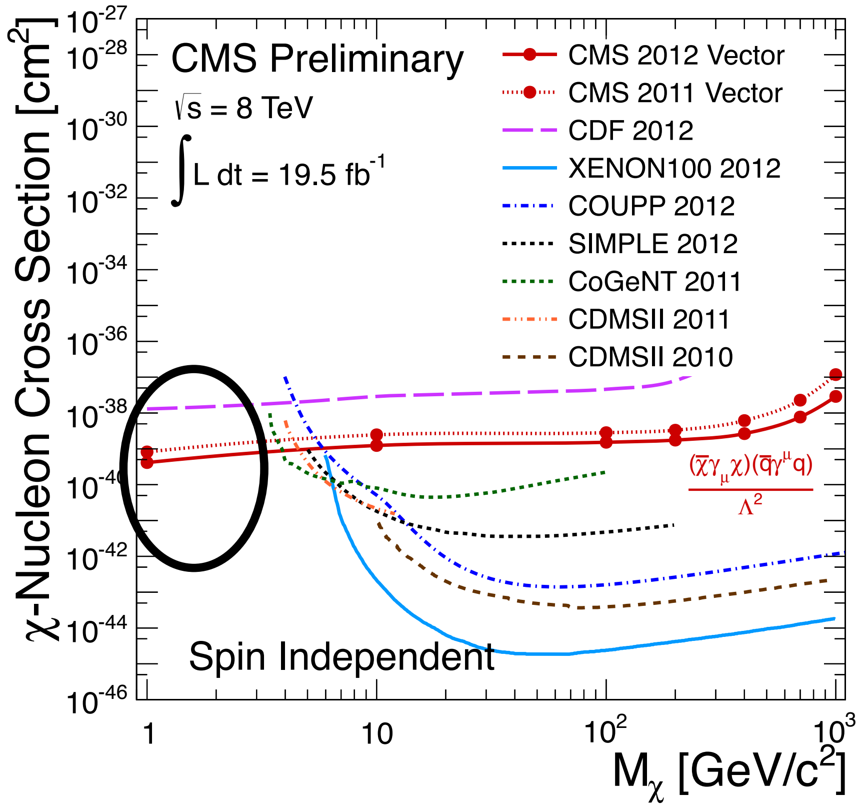
Mono-top



Imperial College London

Monojet analyses better than direct detection?!





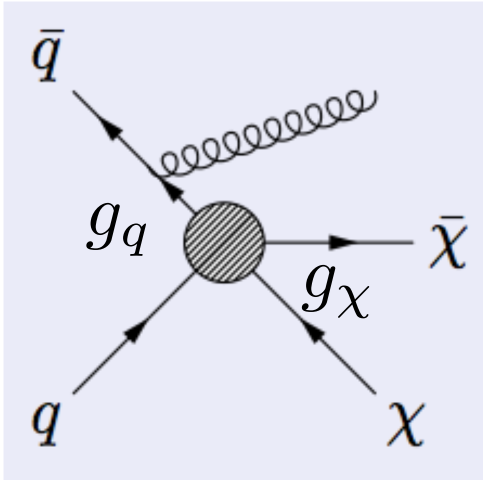
Claim [often made]:

For low mass and the entire spin-dependent case monojet limits are stronger than direct detection limits!

Effective Field Theory (EFT) Interpretation

Example of considered operators:

$$O_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma_\mu q)}{\Lambda^2}$$ Vector operator, s-channel



$$O_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)}{\Lambda^2}$$ Axial vector operator, s-channel

Assumption of EFT

If the operator (e.g. V or AV) mediator is suitably(!!) heavy it can be integrated out to obtain the effective V or AV contact operator. In this case (and only this case), the contact interaction scale Λ is related to the parameters entering the Lagrangian:

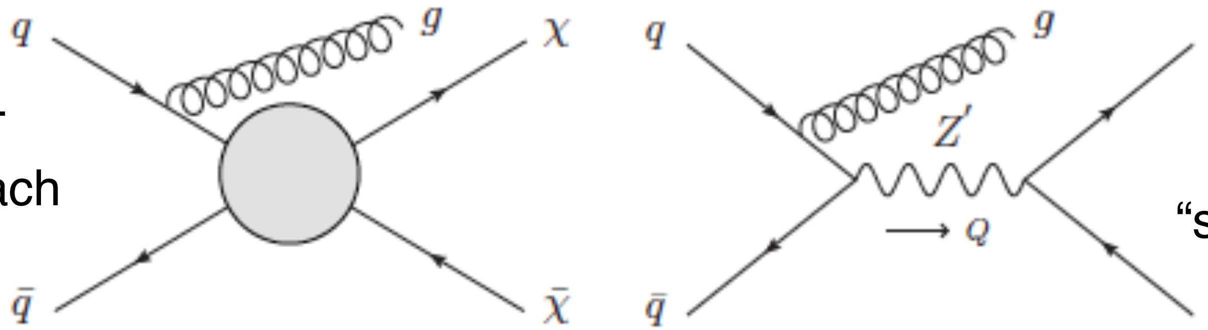
$$\Lambda = \frac{M_{mediator}}{\sqrt{g_q g_\chi}}$$ (relation in the full theory)

Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

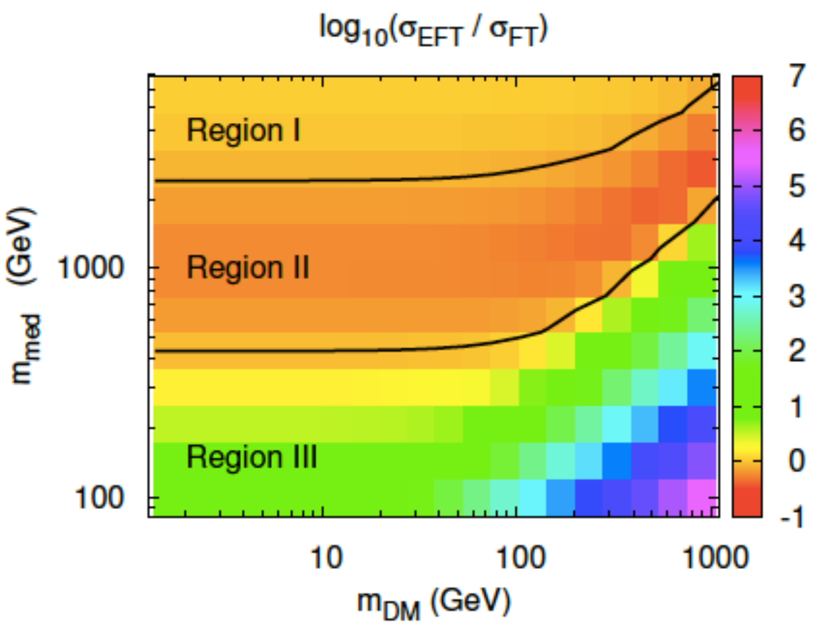
- Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT
approach



FT
one diagram
"simplified model"

Use vector and axial-vector mediators (e.g. Z') as example - scalar are similar in conclusion!



Compare prediction of FT with EFT in m_{med} – m_{DM} plane.
Three regions become visible:

Region I: EFT and FT agree better then 20%
- EFT is valid!

Region II: EFT yields significant weaker limits then FT
- EFT limits are too conservative!

Region III: EFT yields significant stronger limits then FT
- EFT limits are too aggressive!

Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

➢ Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT approac

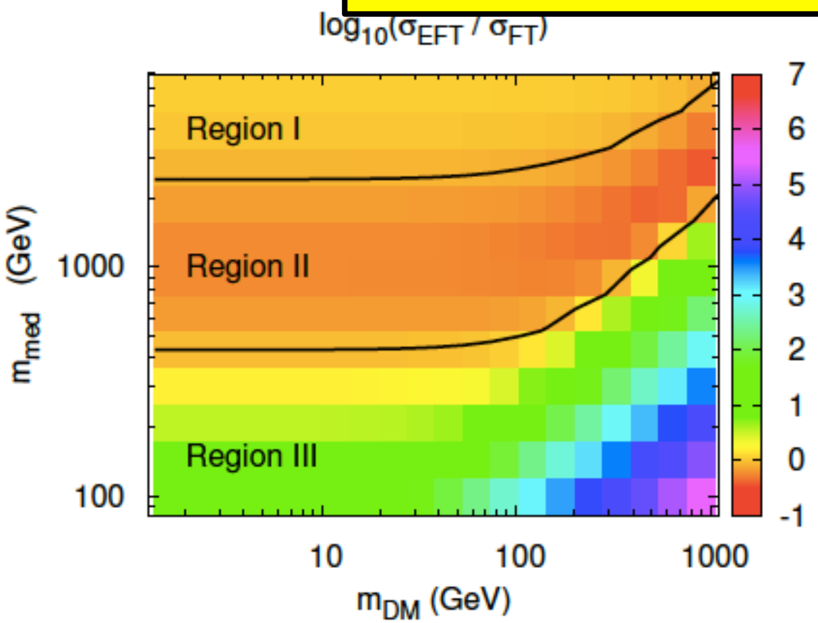
FT one diagram mplified model”

Use vector ar ilar in conclusion!

Bottom line:

The EFT is an inappropriate tool to describe collider searches and thus MUST NO BE USED to compare Direct Detection and colliders.

We need to find new ways to do this!



Compare prediction of FT with EFT in $m_{med} - m_{DM}$ plane. Three regions become visible:

Region I: EFT and FT agree better then 20%

➢ EFT is valid!

Region II: EFT yields significant weaker limits then FT

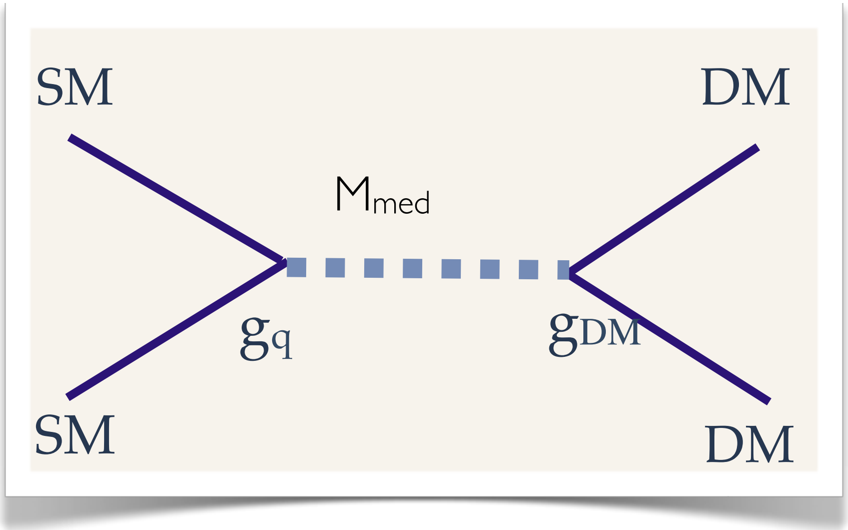
➢ EFT limits are too conservative!

Region III: EFT yields significant stronger limits then FT

➢ EFT limits are too aggressive!

Minimal Simplified Dark Matter Model

Based on work from :
OB, S. Malik,
M.Dolan,C.McCabe



s-channel

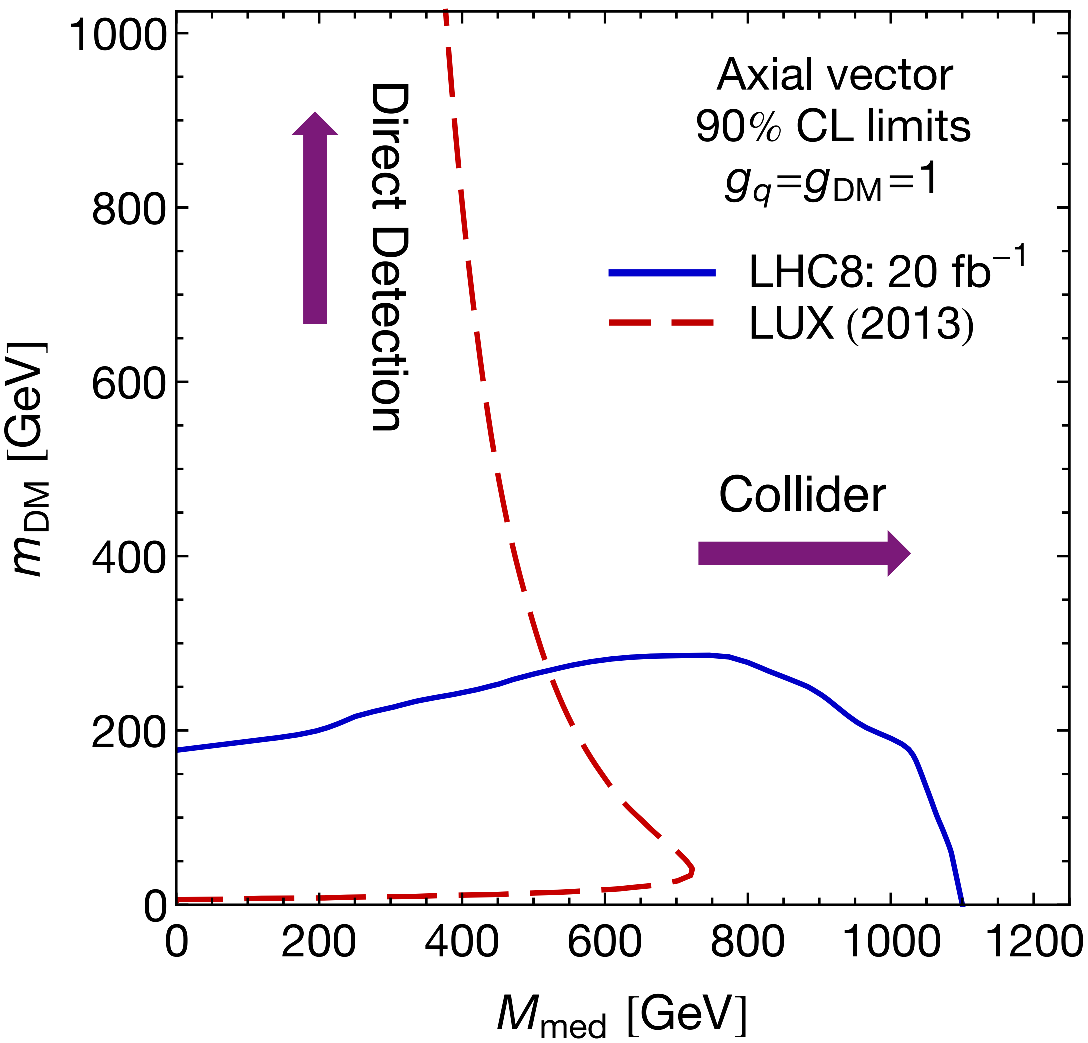
Define simplified model with (minimum) 4 parameters	
Mediator mass (M_{med})	DM mass (M_{DM})
g_q	g_{DM}

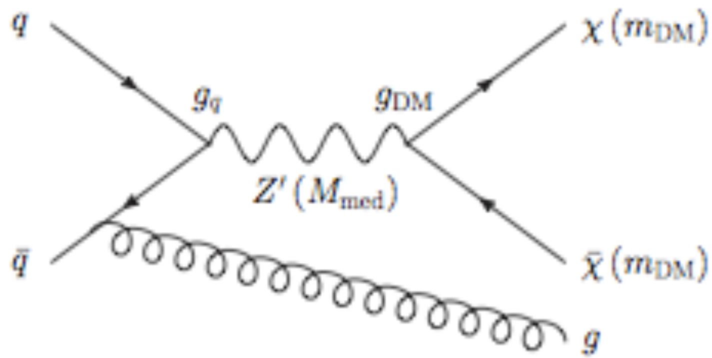
DM	
Dirac fermion	Scalar - real
Majorana fermion	Scalar - complex

Consider comprehensive set of diagrams for mediator	
Vector	Axial-vector
Scalar	Pseudoscalar

Dark Matter Limits from Direct Searches: Today

Examples: CMS monojet search and recent LUX result: interpretation in simplified models

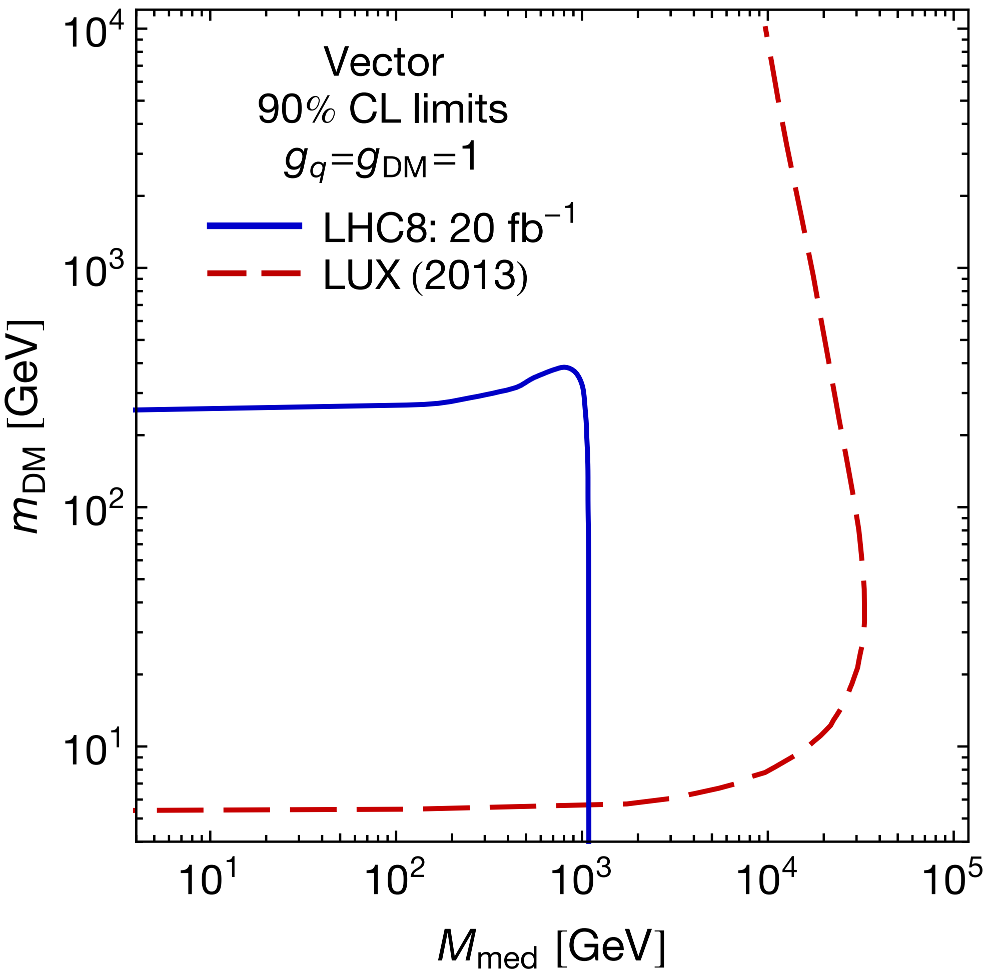




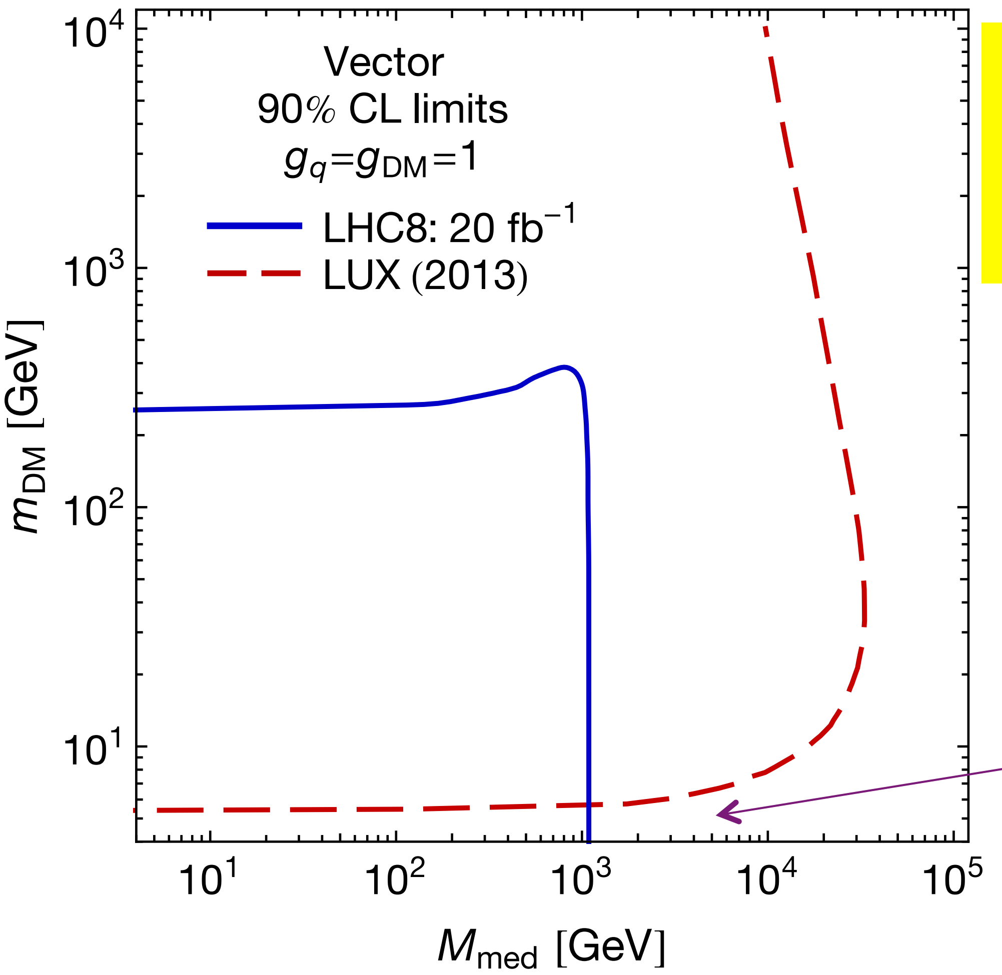
Assumes:
- couplings to all quarks
- $g_q=g_{DM}=1$
- width calculated from g

Direct Detection experiments and collider are complementary probing different regions of the relevant parameter space!

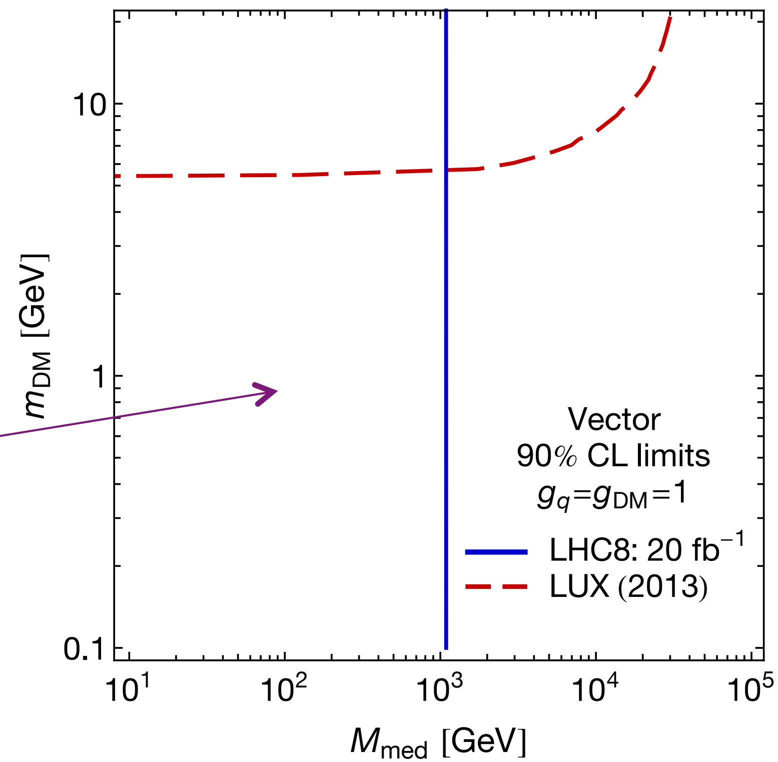
The Vector Case



The Vector Case



While for Axial-Vector collider and DD are complementary in the full parameter space, for the pure Vector case, DD limits are strong EXCEPT for low DM masses!

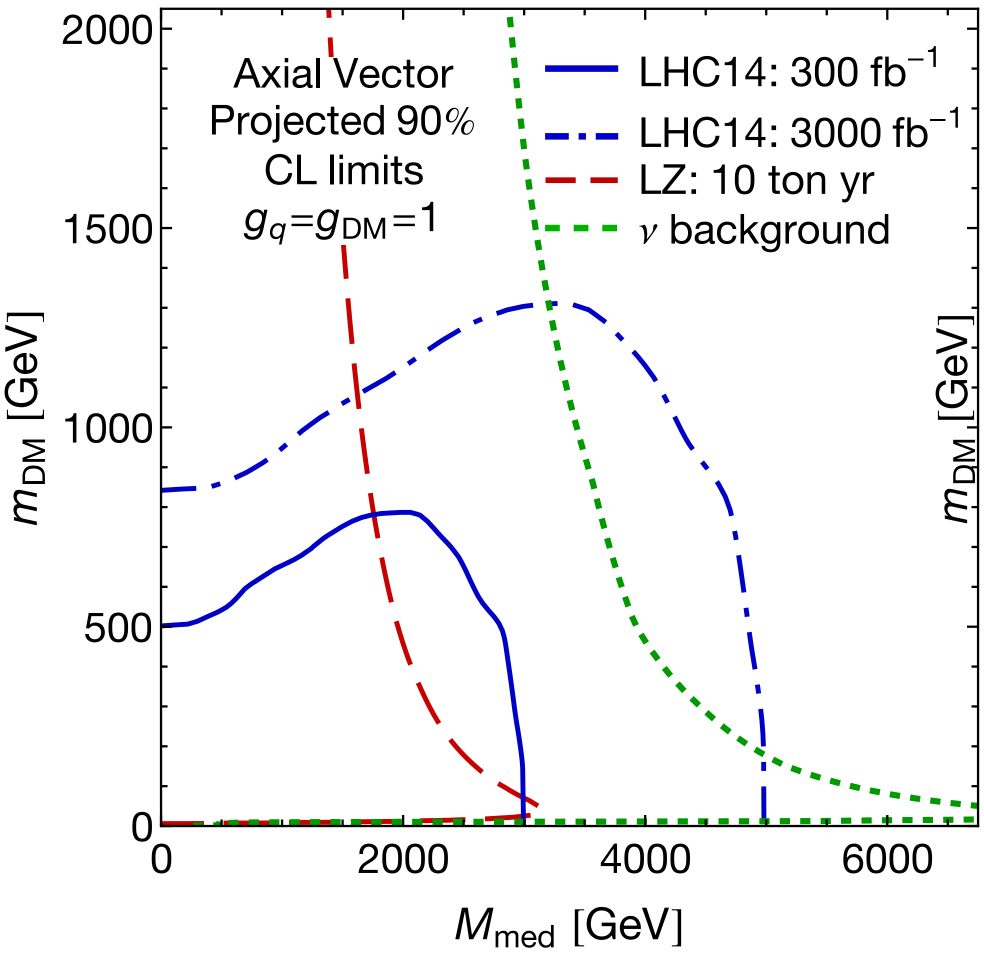


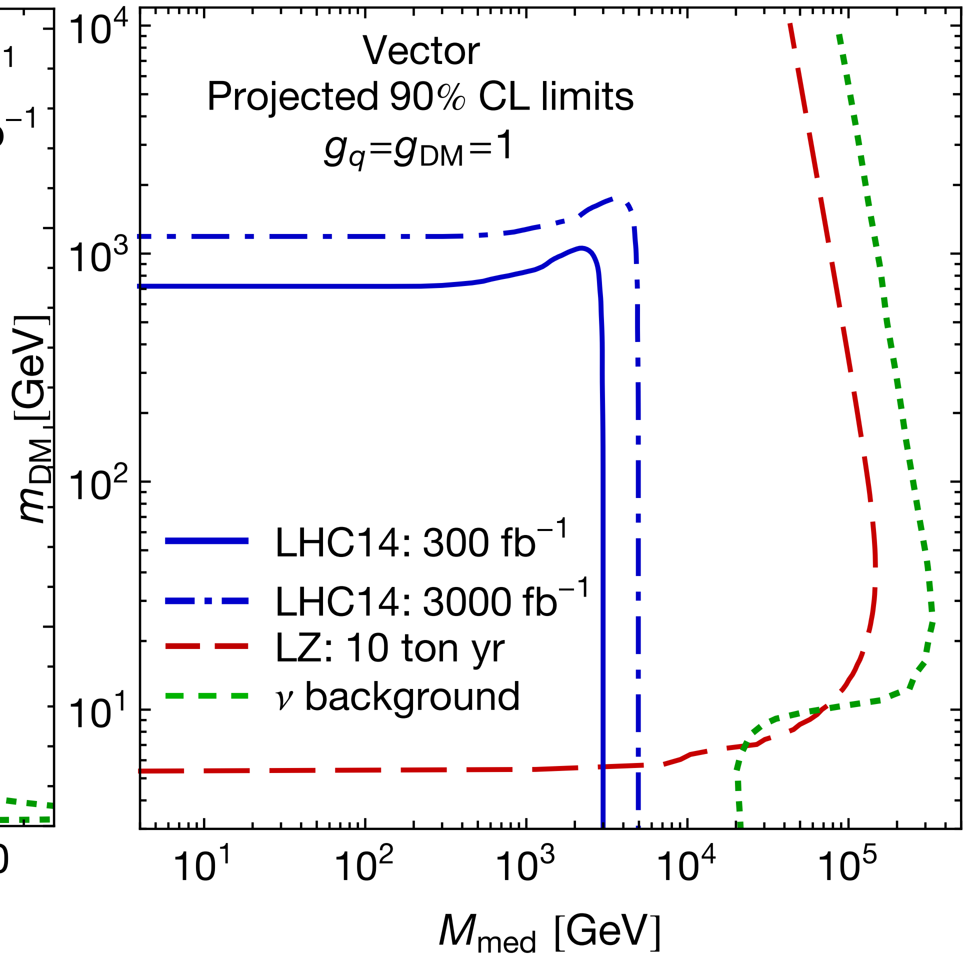
Note: Vector scales like Atomic number squared (~130^2)
while AV scales like the spin (~1).

Imperial College London

Future Projections

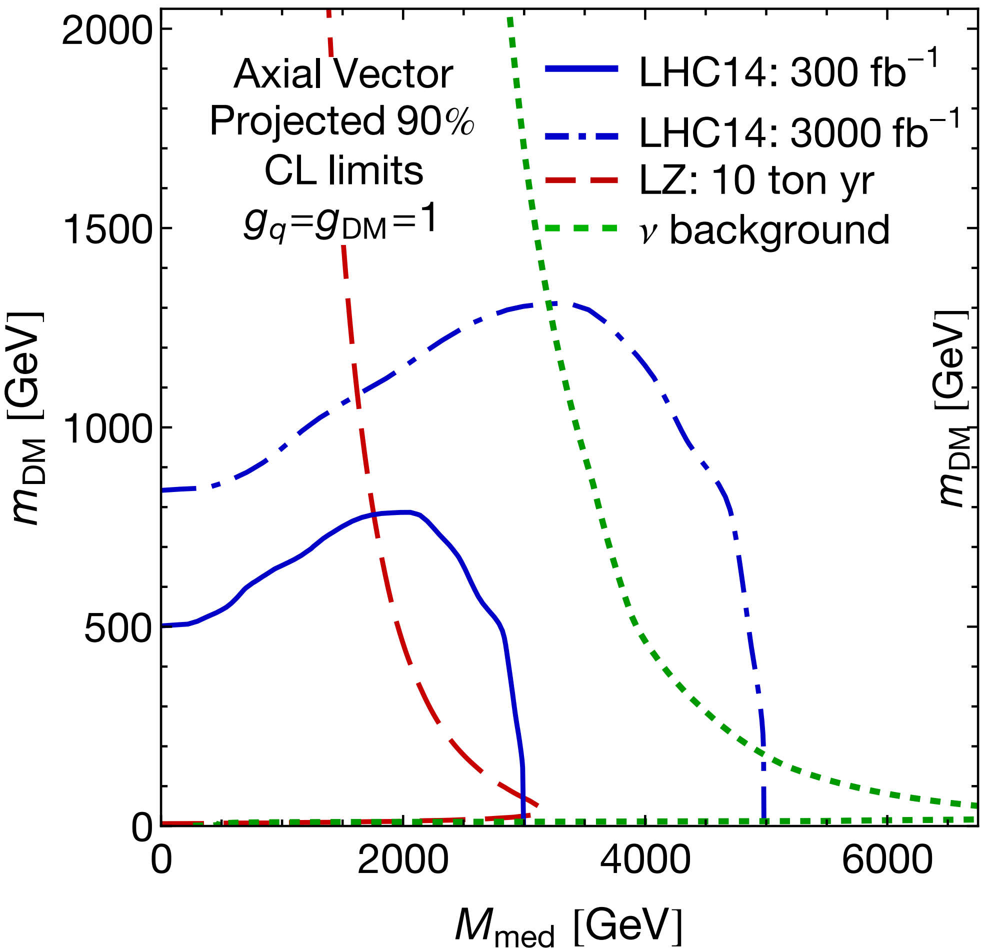
DM Searches @ collider & Direct Detection O. Buchmüller

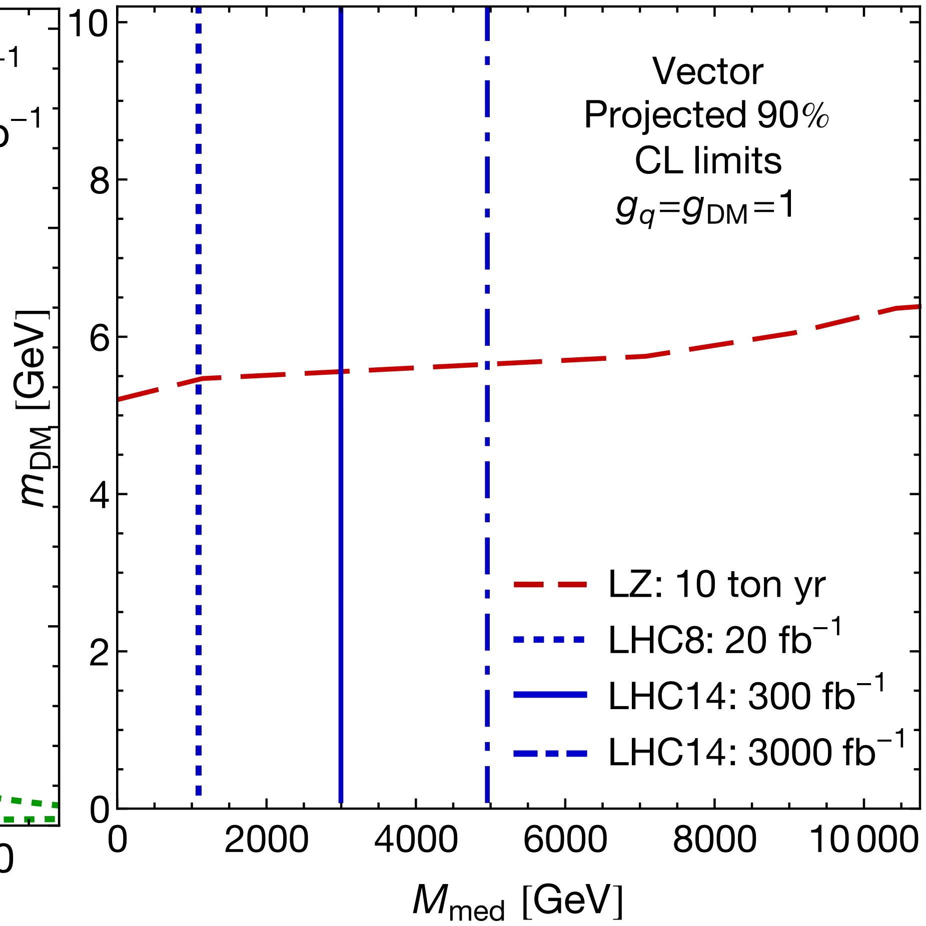




Compare:
LHC @ 300/fb and HL-LHC@/3000/fb
with Direct Detection:
Lux-Zeppline (~2025) and Neutrino noise border

Future Projections





Important complementarity of the two experimental approaches will allow good coverage of the relevant parameter space!

Big discovery potential!

Summary

- So far the origin Dark Matter has not revealed itself!
- Both the LHC as well as Direct Detection experiments are probing very interesting regions in the parameter space!
- WE need to better work out the complementarity between collider and DD
  - Effective Field Theory is not the answer!
  - Simplified models might be helpful!
- The forthcoming data taking campaign of DD experiments as well as the high energy running of the LHC starting 2015 will be our next very (as in very) real chance for discovery!

The story continues … stay tuned!

Imperial College London

Outlook: 8 TeV vs 14 TeV

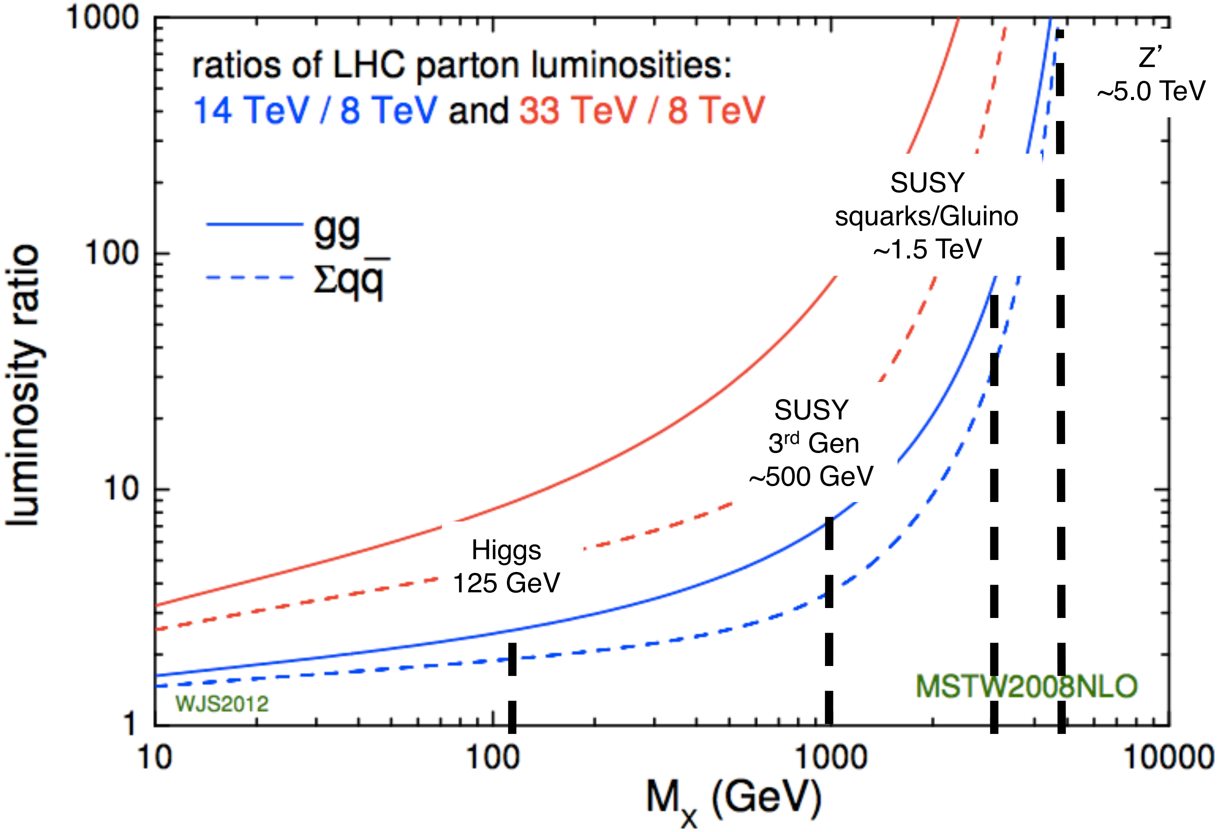
Use parton luminosities to illustrate the gain of 14 vs 8 TeV

Higgs:
pp → H, H→WW, ZZ and γγ
mainly gg: factor ~2

SUSY – 3rd Generation:
Mass scale ~ 500 GeV
qq and gg: factor ~3 to 6

SUSY – Squarks/Gluino:
Mass scale ~ 1.5 TeV
qq,gg,qg: factor ~40 to 80

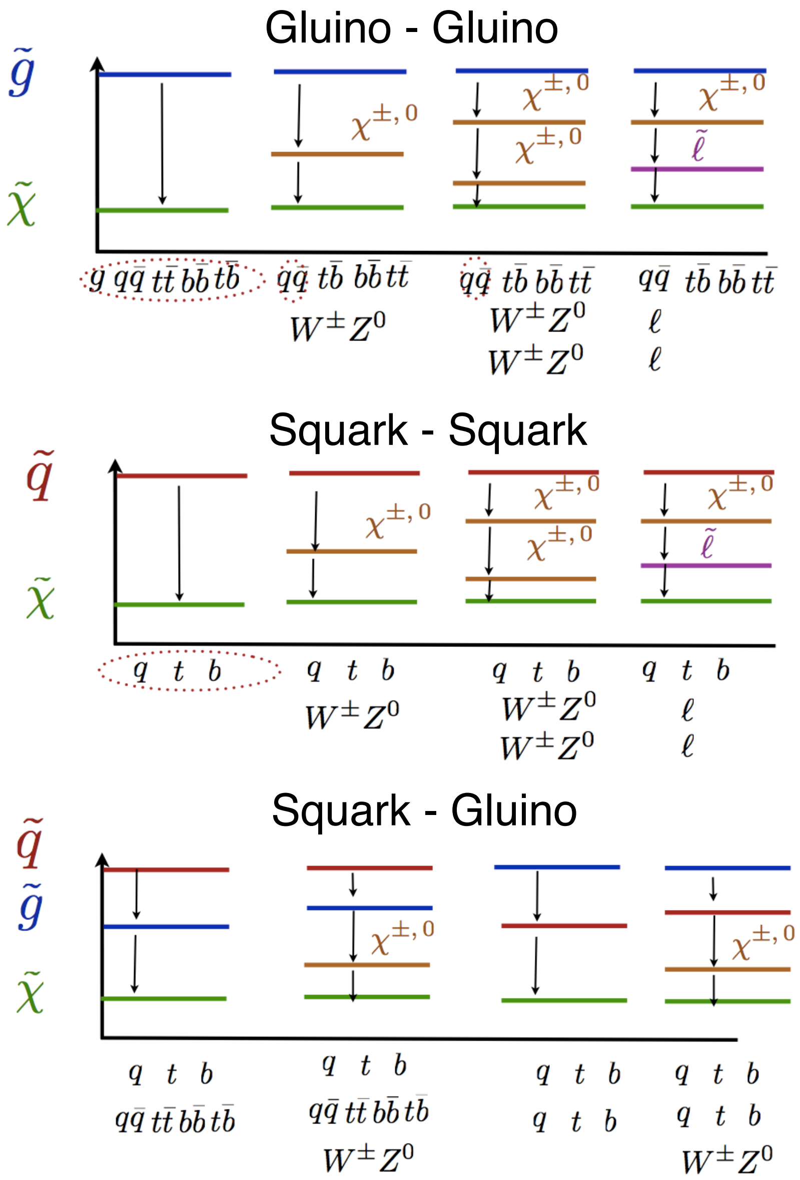
Z' :
Mass scale ~ 5 TeV
qq: factor ~1000



Increase in energy will help a lot!
Not just for SUSY...

BACKUP

Early SUSY Search Strategy at the LHC



Search Signatures

- SUSY-like decay chains range from short to long and simple to very complicated.
- All physics objects, MET, jets, leptons, photons, b's taus, tops, W, Z, etc are involved
- Comprehensive coverage of all possible signature requires a topology oriented search strategy:

References Analyses

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

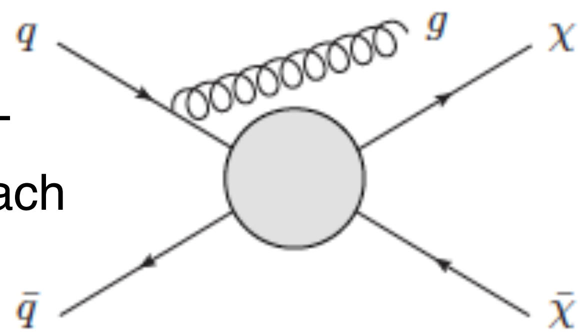
Already in less then two years of operation ATLAS & CMS managed to carry out the full list of these core "SUSY References Analyses"!

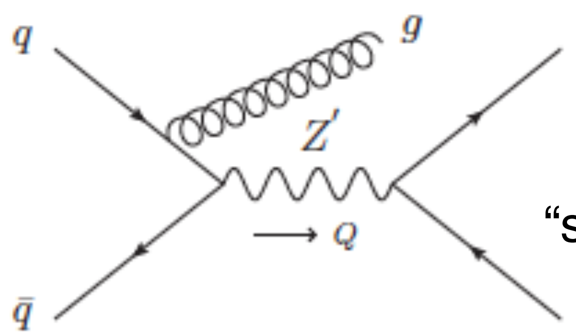
Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

- Compare Effective Field Theory (EFT) with Full Theory (FT)

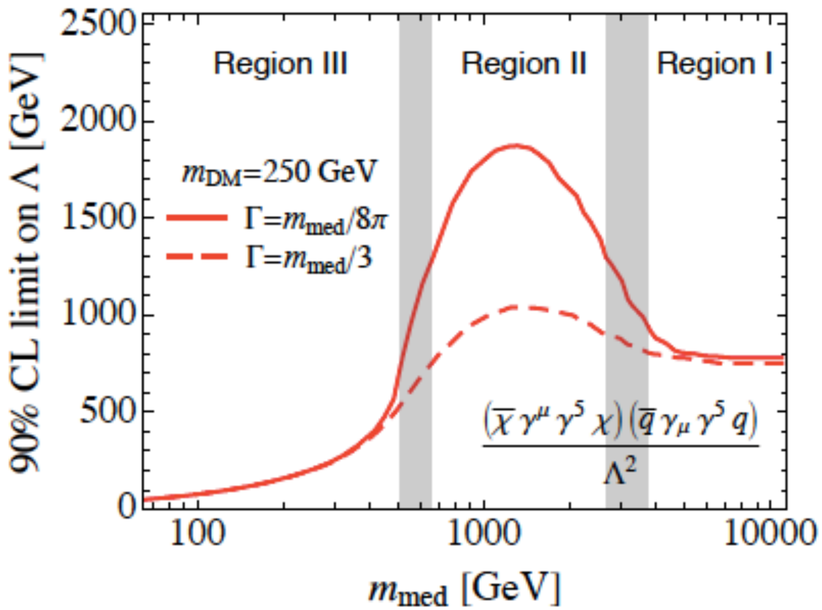
EFT
approach





FT
one diagram
"simplified model"

Use vector and axial-vector mediators (e.g. Z') as example - scalar are similar in conclusion!



Three Regions as function of mediator mass:

Region I: Heavy m_{med}

- EFT is valid!

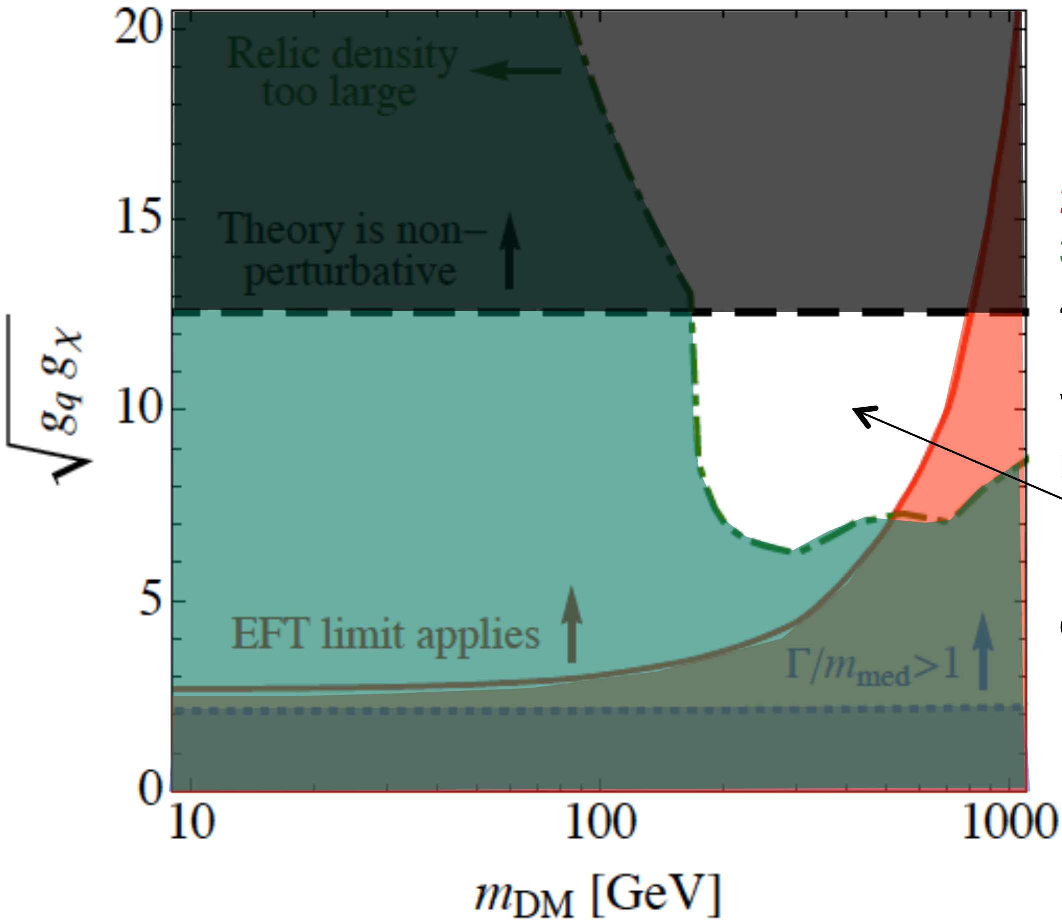
Region II: Medium m_{med} – Resonant enhancement

- EFT limits are too conservative!

Region III: Low m_{med}

- EFT limits are too aggressive!

What those this imply on model-dependences of EFT limits?



Look at EFT validity in m_{DM} – coupling* plane!

1. Must require $m_{med} < \Gamma_{med}$
2. Region in which EFT is valid (20%)
3. Require compatibility with relic density
4. Require theory to be perturbative (<4π)

When we also require that the region/theory must be perturbative:

$$\sqrt{g_q g_\chi} < 4\pi$$

only a very small region is left!

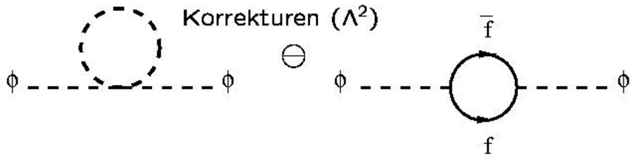
This together with the observation that all DM theories for which the EFT is valid must have $m_{med} < \Gamma_{med}$ leads to the conclusion the the EFT only applies to a very (as in VERY) small class of DM models.

EFT limits of monojet searches are therefore highly model-depended!

Why is SUSY so attractive?

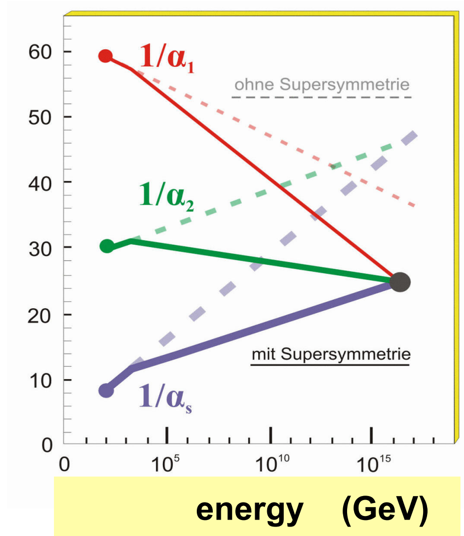
1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided

$$\Delta m_H = f(m_B^2 - m_f^2)$$



(Hierarchy or naturalness problem)

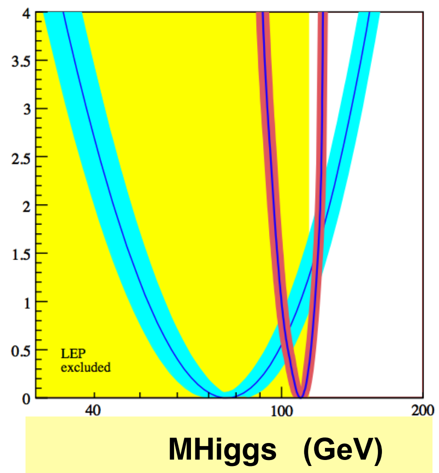
m_{SUSY} ~ 1 TeV



2. Unification of coupling constants of the three interactions seems possible

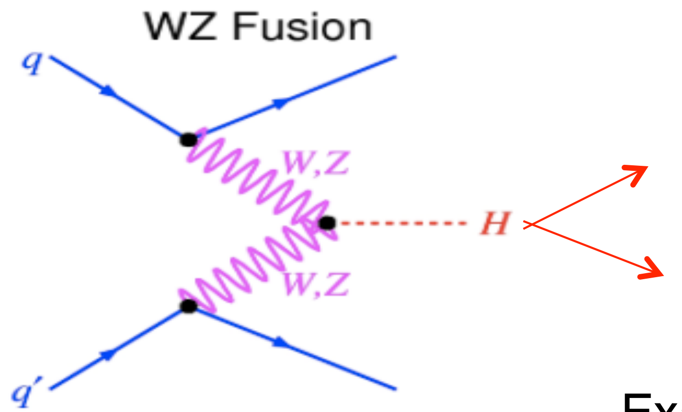
3. SUSY provides a candidate for dark matter,

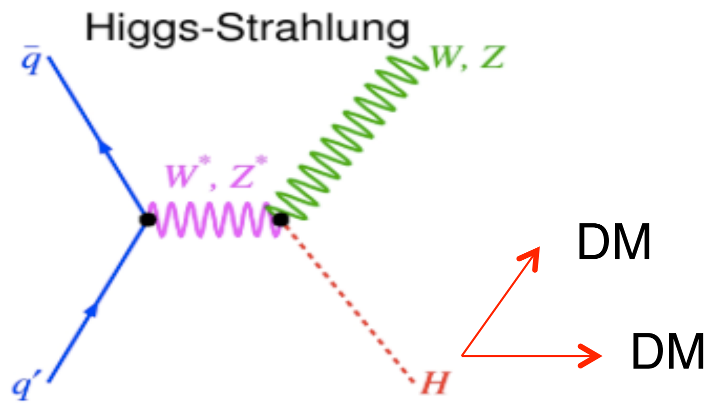
The lightest SUSY particle (LSP)



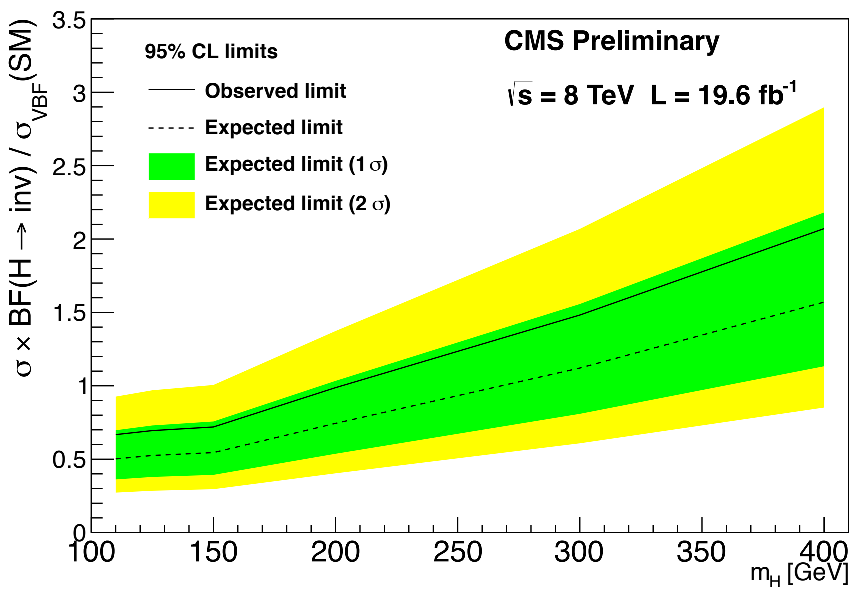
4. A SUSY extension is a small perturbation, consistent with the electroweak precision data

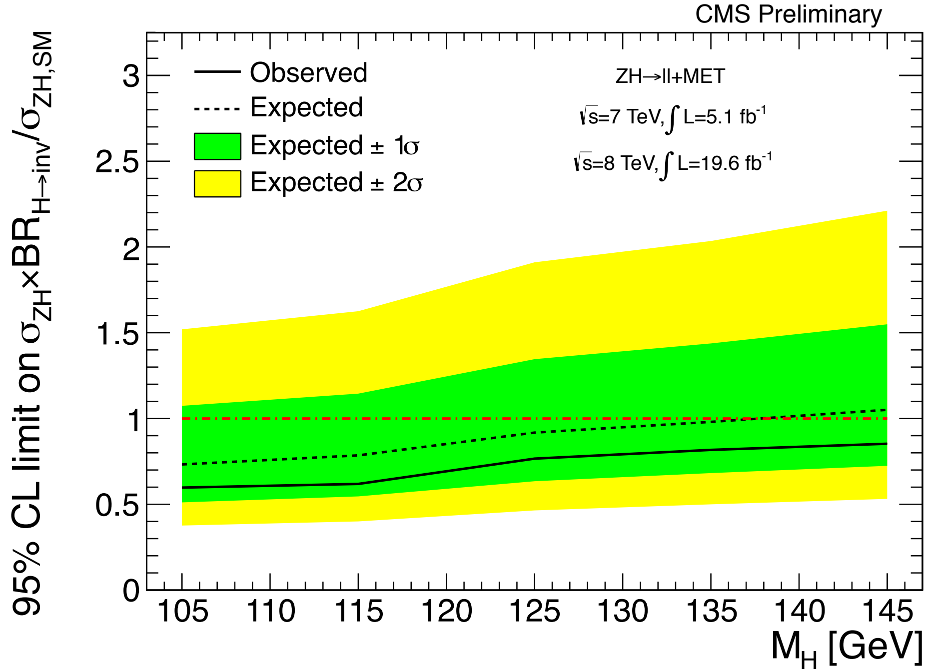
Dark Matter from invisible Higgs searches





Example CMS





BR(H->invisible) < 68% @ 95%CL

BR(H->invisible) < 75% @ 95%CL

Dark Matter from invisible Higgs searches

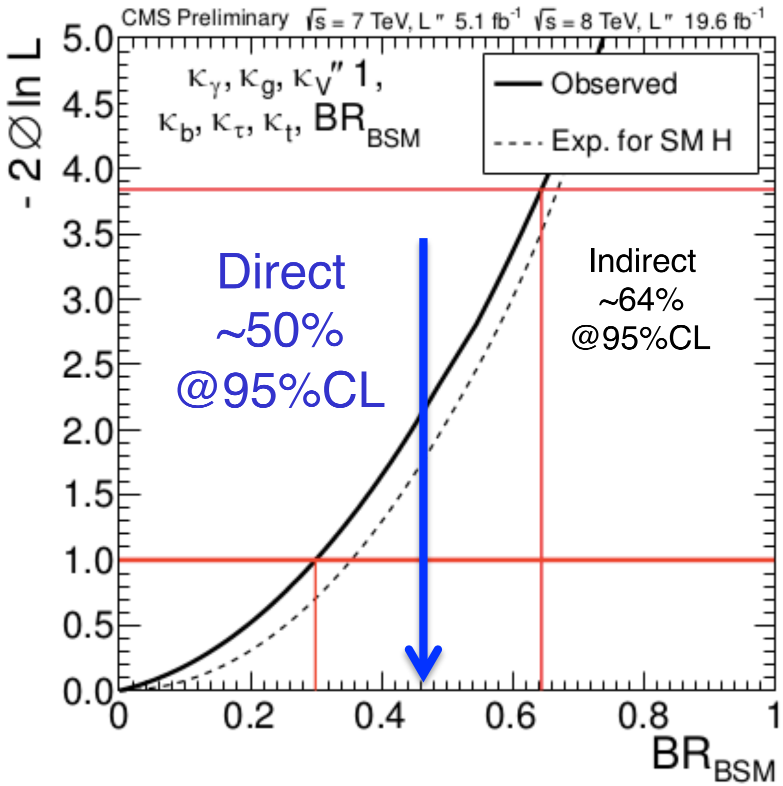
Status 2012 CMS only:

VBF: $BR_{H\text{->}invisible}$ < 68% @ 95%CL

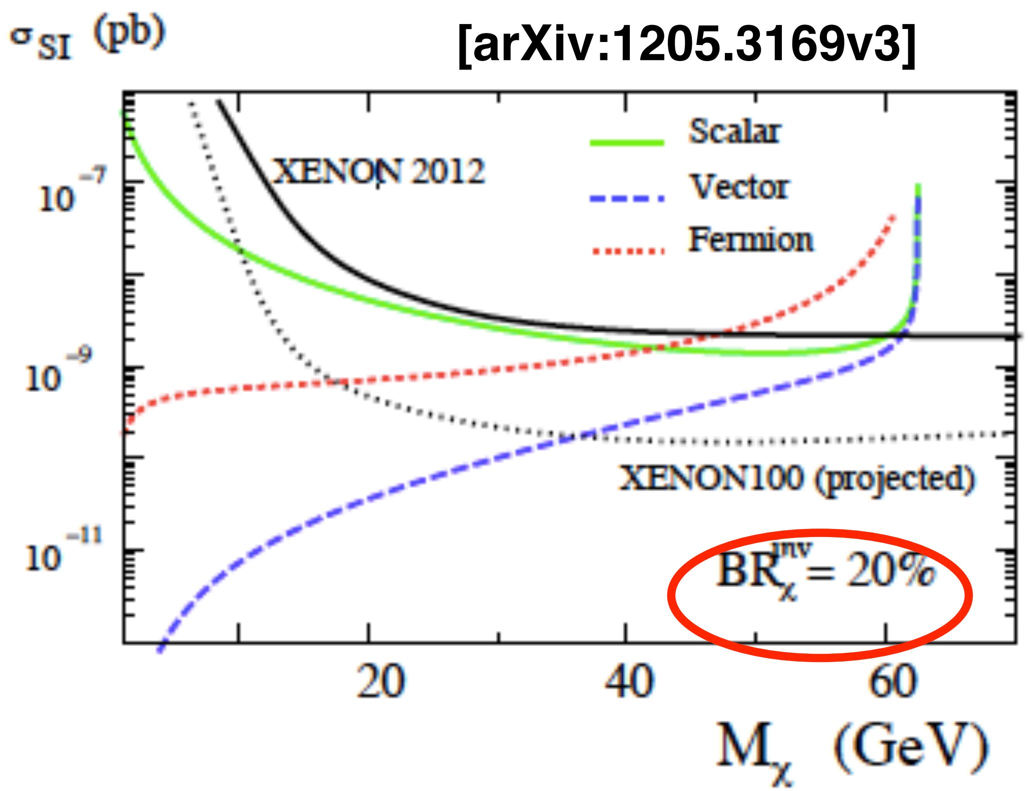
VH: $BR_{H\text{->}invisible}$ < 75% @ 95%CL

Naïve combination: ~ 50% @ 95% CL

$BR_{H\text{->}invisible}$ Direct vs Indirect

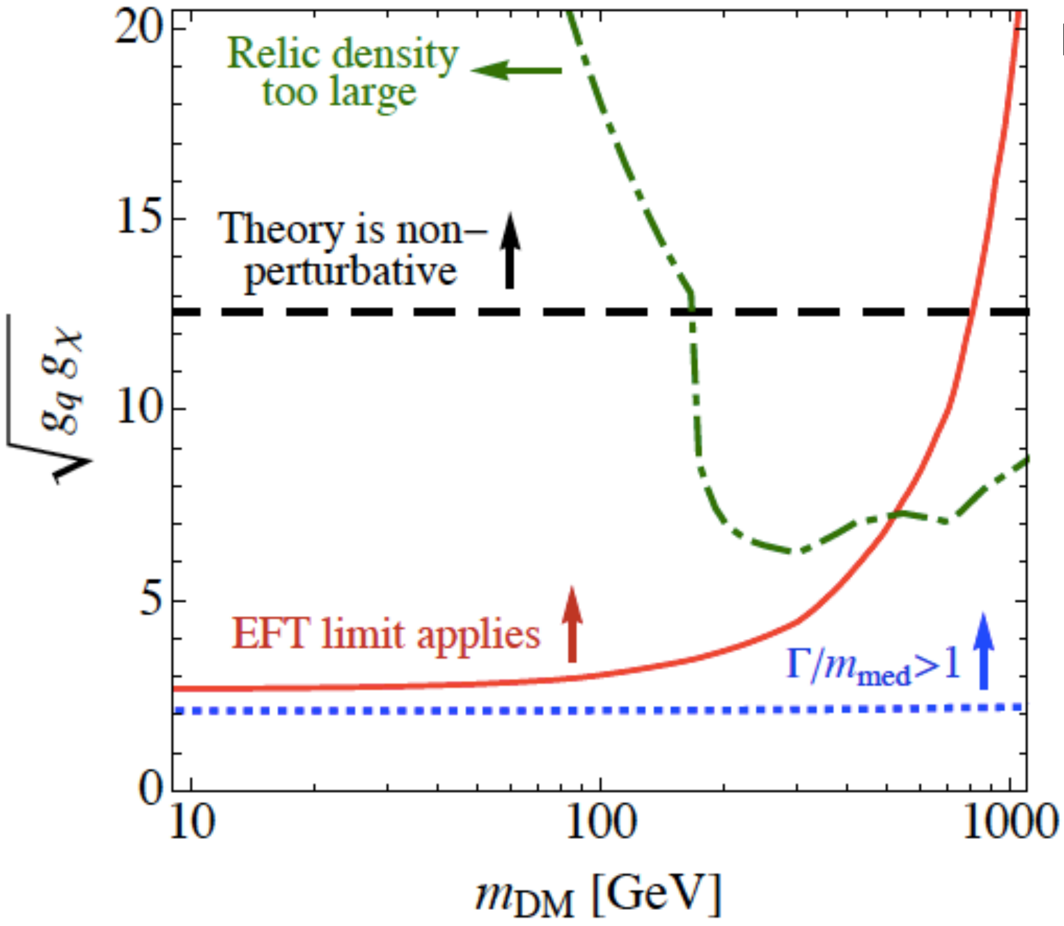


[arXiv:1205.3169v3]



Assuming the experiments are able to maintain trigger and analysis acceptances, the LHC will provide a VERY powerful comparison of indirect & direct measurement of $\Gamma_{H\text{->}invisible}$.
In the (near) future this might provide a stringent constraint for $M_{DM} < M_H/2$

What those this imply on model-dependences of EFT limits?

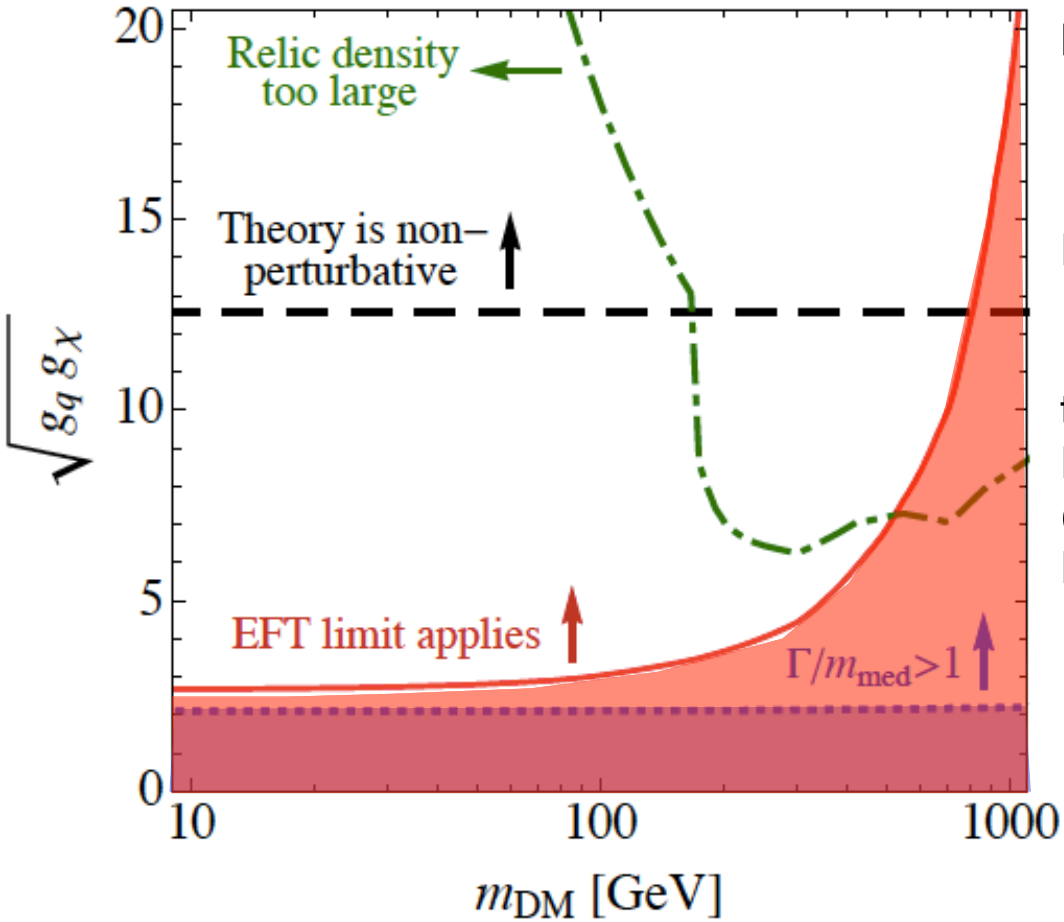


Look at EFT validity in m_{DM} – coupling* plane!

* Coupling chose such that CMS EFT limit on Λ applies to FT

Imperial College London

Model-dependences of EFT limits



Look at EFT validity in m_{DM} – coupling* plane!

1. Region in which EFT is valid

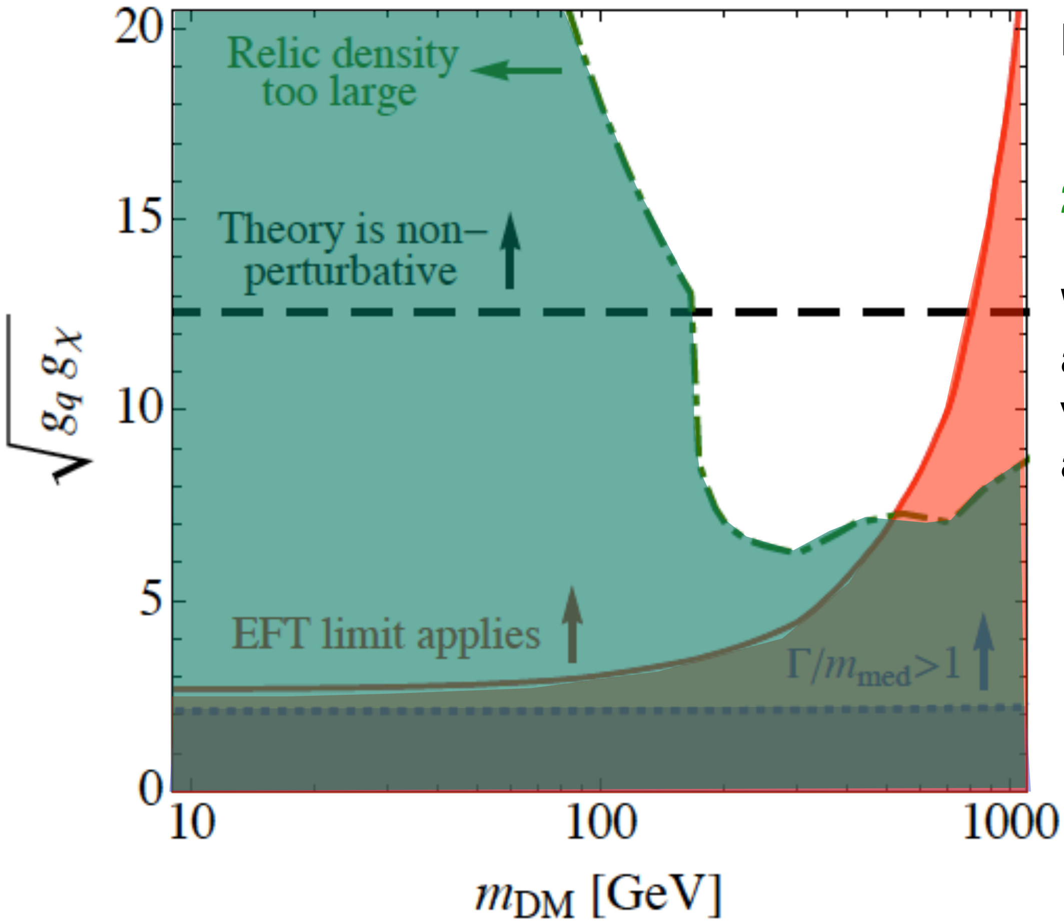
For this we calculate the minimum coupling

$$\sqrt{g_q g_\chi} = m_{med}/\Lambda_{CMS}$$

that the simplified model must have for the EFT limits to apply. This is defined by region I (i.e. better then 20% agreement of FT and EFT).

* Coupling chose such that CMS EFT limit on Λ applies to FT

Model-dependences of EFT limits



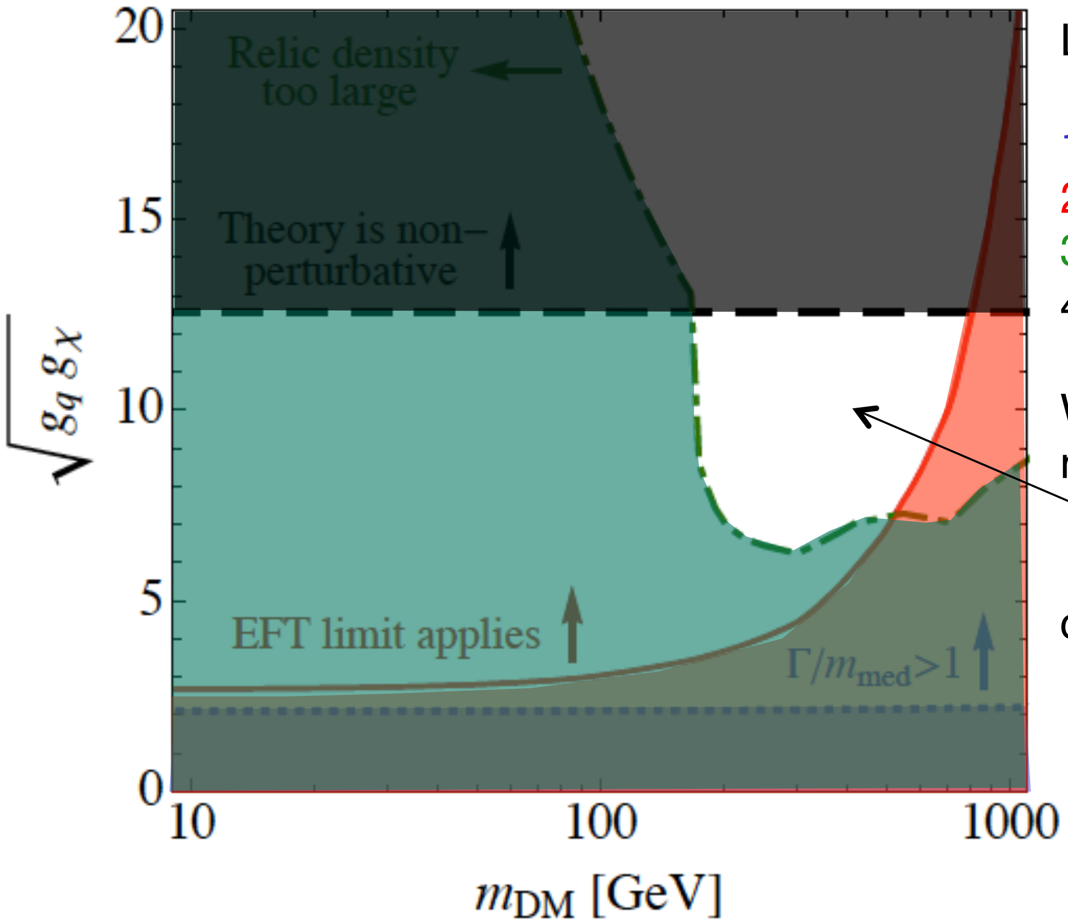
Look at EFT validity in m_{DM} – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density

When exclude the region in which relic abundance is larger then the observed value of $\Omega_{XX}h^2 = 0.119$ only mediator masses above a few hundred GeV fulfill this.

* Coupling chose such that CMS EFT limit on Λ applies to FT

Model-dependences of EFT limits



Look at EFT validity in m_{DM} – coupling* plane!

1. Must require $m_{med} < \Gamma_{med}$
2. Region in which EFT is valid (20%)
3. Require compatibility with relic density
4. Require theory to be perturbative (<4π)

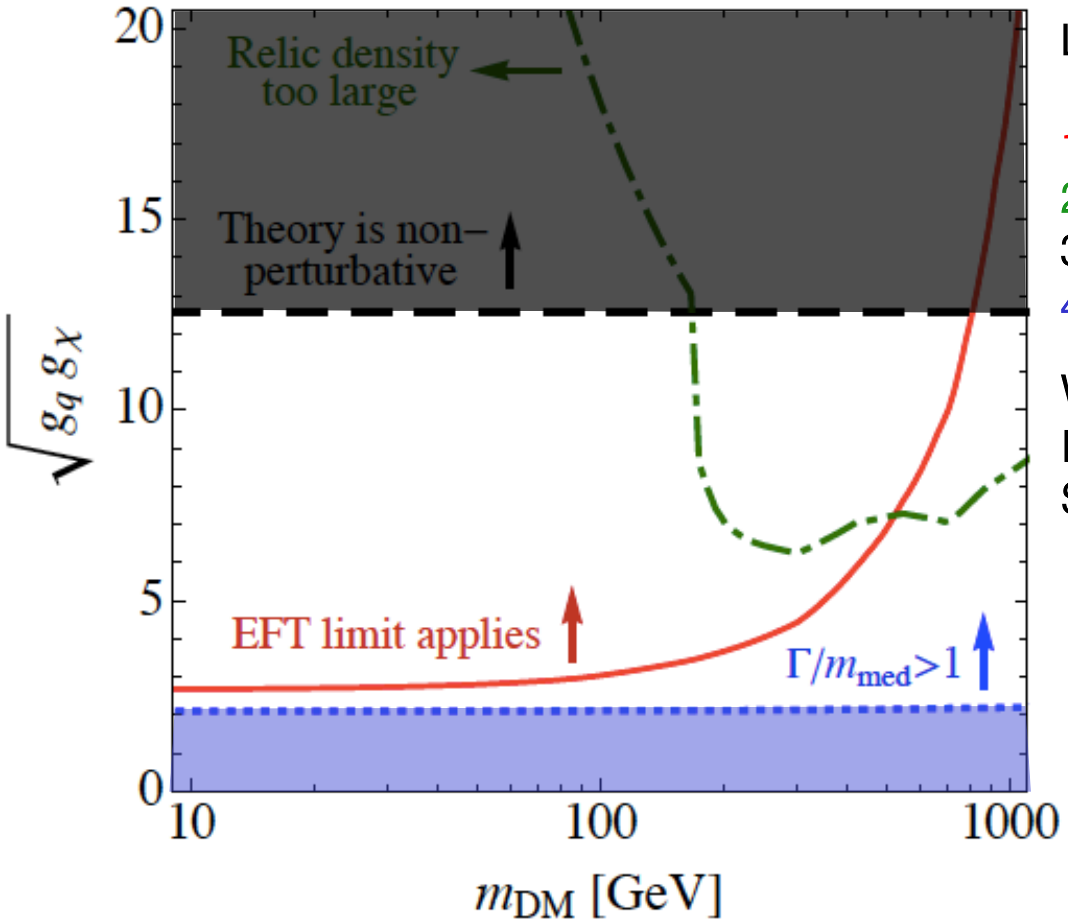
When we also require that the region/theory must be perturbative:

$$\sqrt{g_q g_\chi} < 4\pi$$

only a very small region is left!

EFT limits of monojet searches only apply to a very (as in VERY) small class of DM models!

Model-dependences of EFT limits



Look at EFT validity in m_{DM} – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density
3. Require theory to be perturbative (<4π)
4. $m_{med} < \Gamma_{med}$ ALWAYS!

We also find that for all DM models the EFT
Is valid the mass of the mediator must be
Smaller than its width!

In the reaming part of the plot:

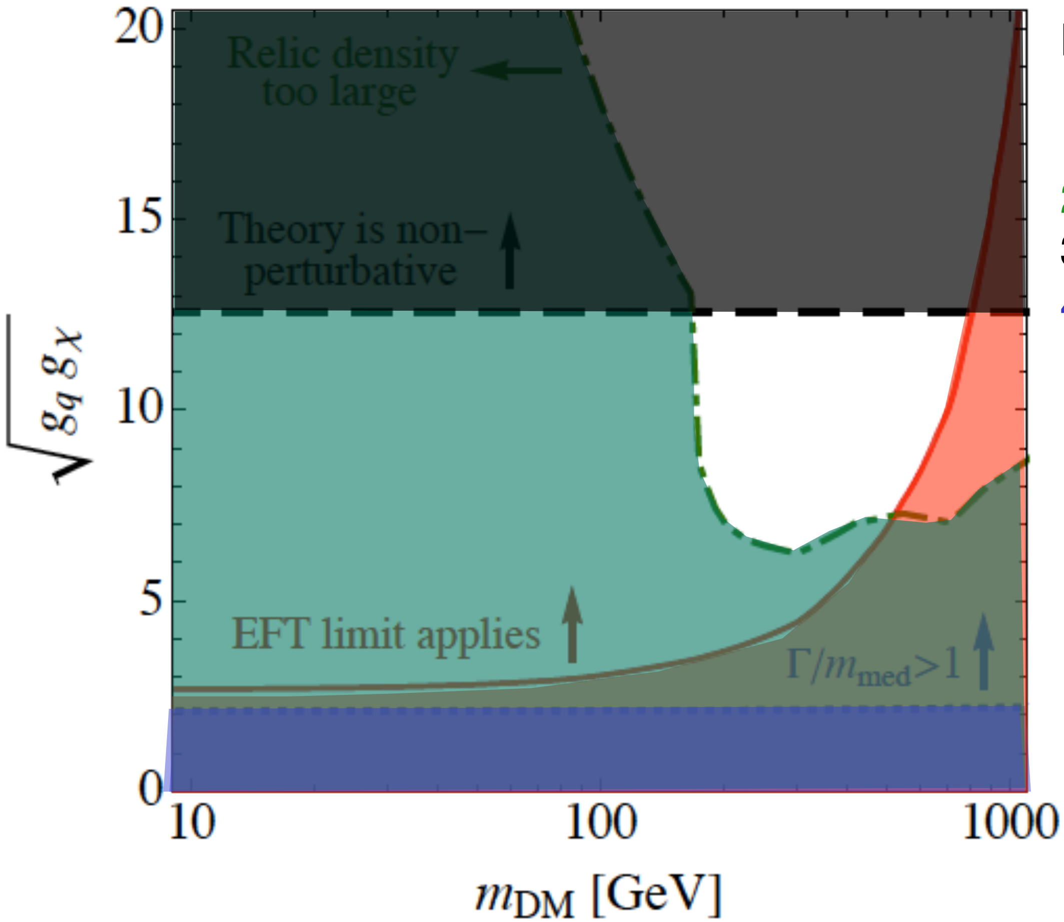
$$\sqrt{g_q g_\chi} > 2$$

a particle-like interpretation of the mediator is doubtful because of $m_{med} < \Gamma_{med}$!

See discussion about equation 3.5 in arXiv:1308.6799 for further details.

Imperial College London

What those this imply on model-dependences of EFT limits?



Look at EFT validity in m_{DM} – coupling* plane!

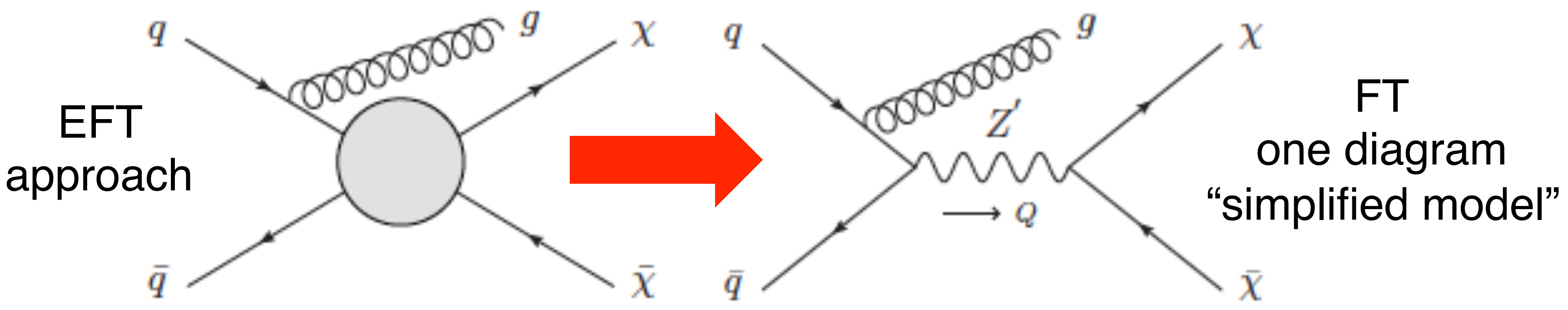
1. Region in which EFT is valid (20%)
2. Require compatibility with relic density
3. Require theory to be perturbative (<4π)
4. $m_{med} < \Gamma_{med}$ ALWAYS!

The observation that all DM theories for which the EFT is valid must have $m_{med} < \Gamma_{med}$ and the small class to models it applies in any case leads to the conclusion the EFT only applies to a very small class of DM models.

EFT limits of monojet searches are therefore highly model-depended!

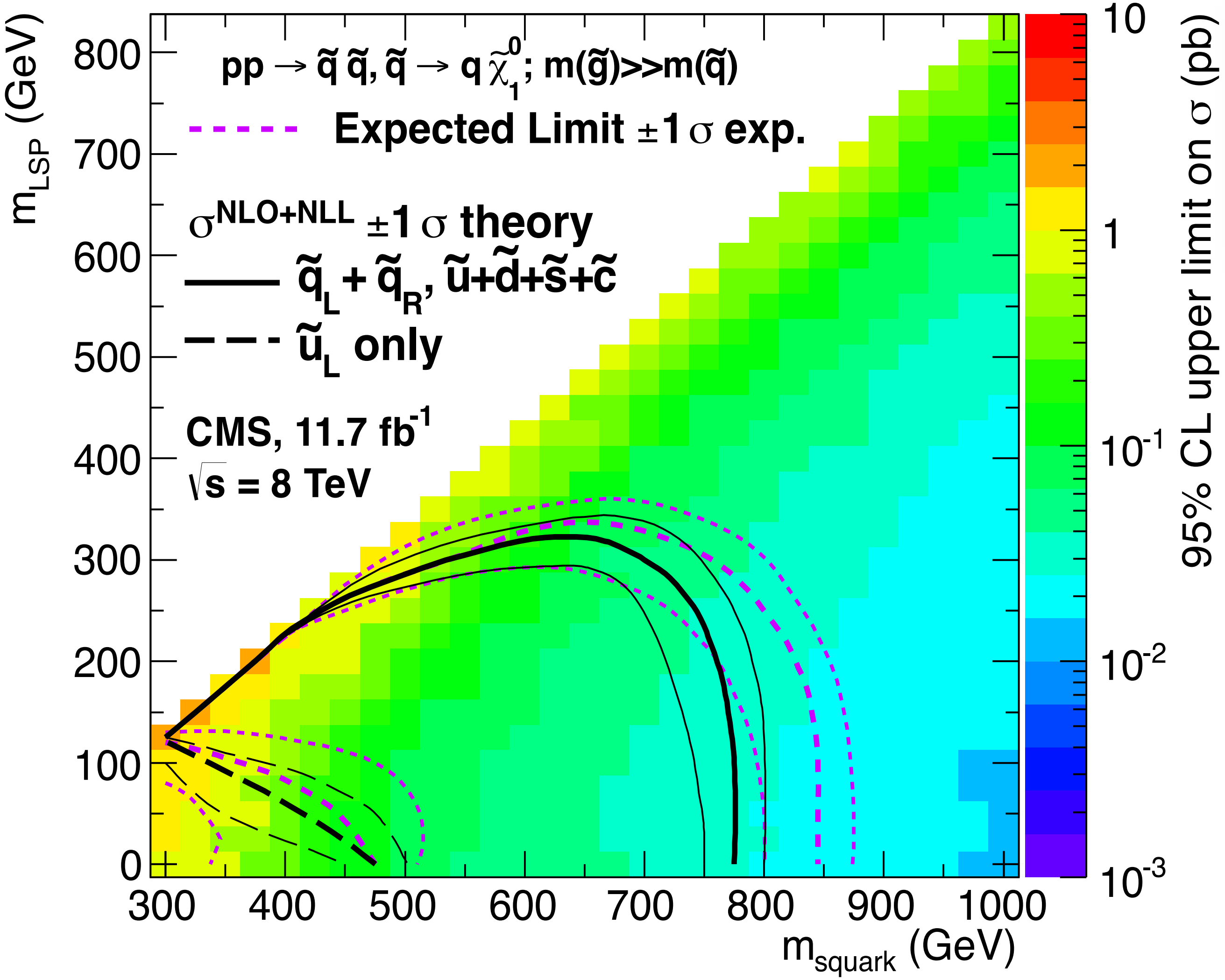
Alternative Interpretation Ansatz: Simplified models

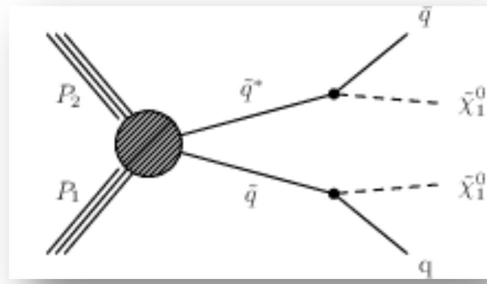
Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799
- Compare Effective Field Theory (EFT) with Full Theory (FT)



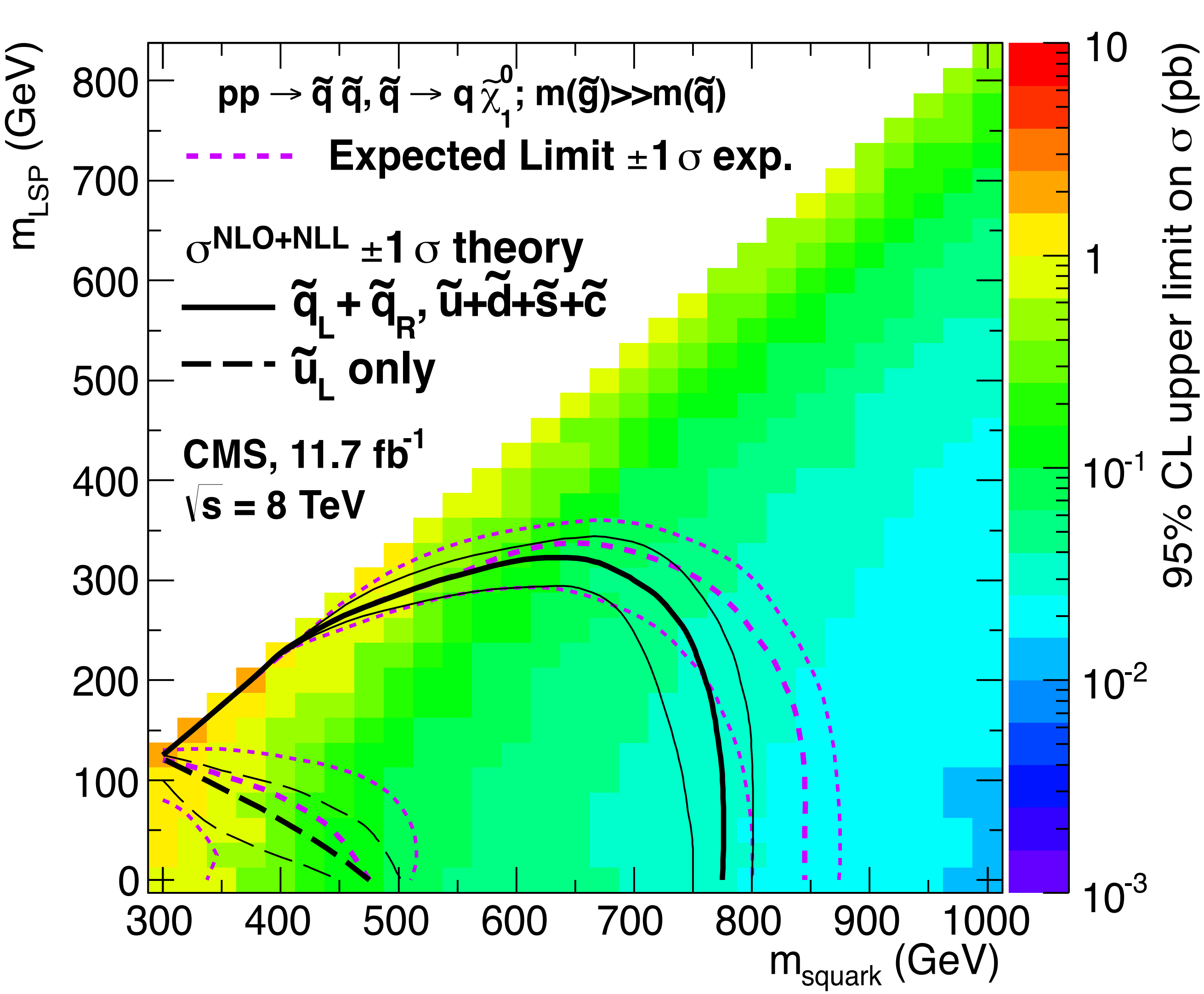
After three years of operation at the LHC the landscape for interpretation of searches has changed dramatically – new superior & modern approaches have replaced in many areas longstanding traditional ones (e.g. SUSY searches)

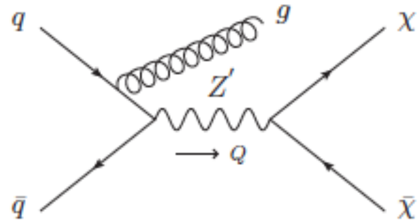
The proposal



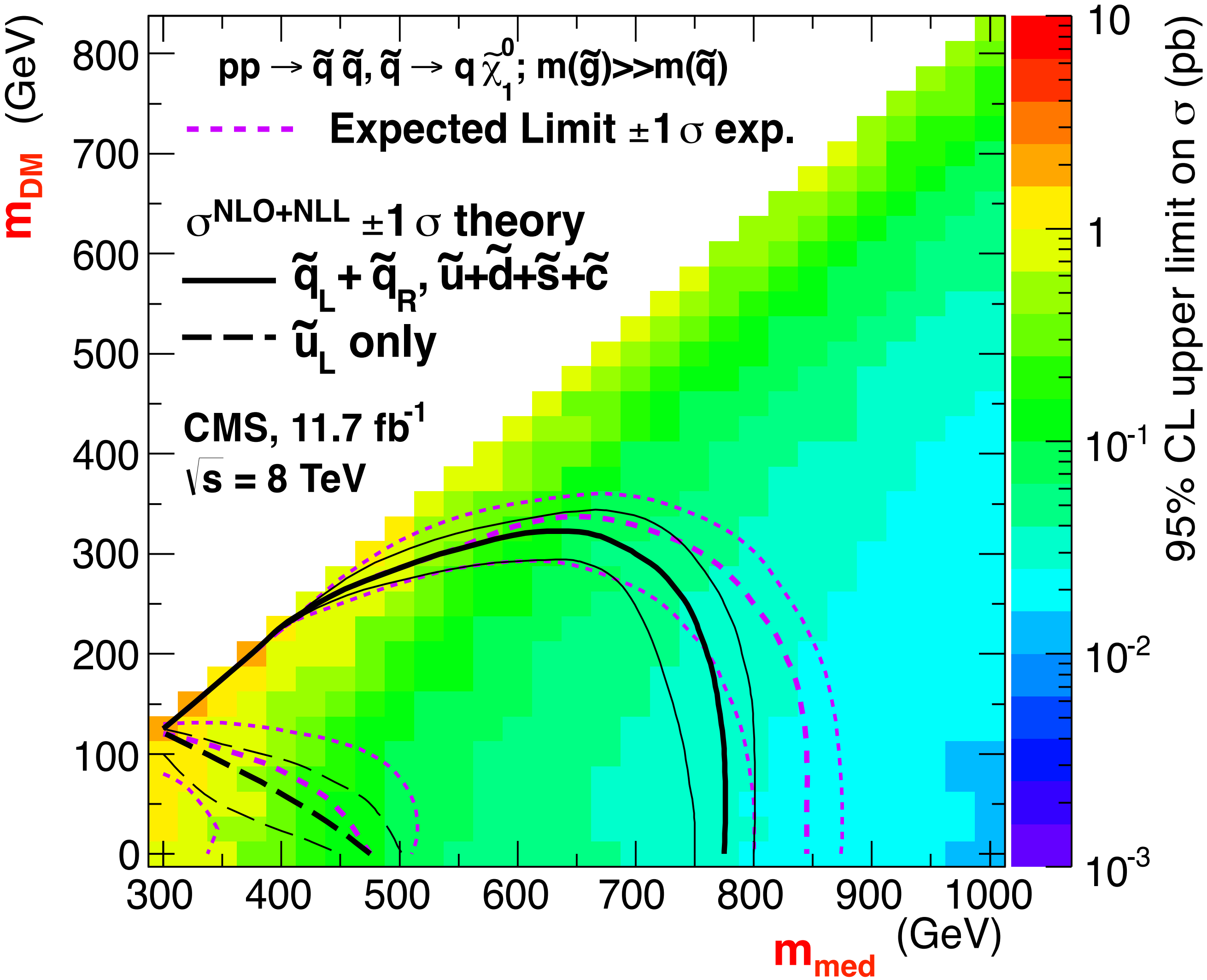


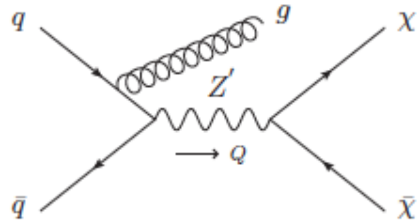
The proposal



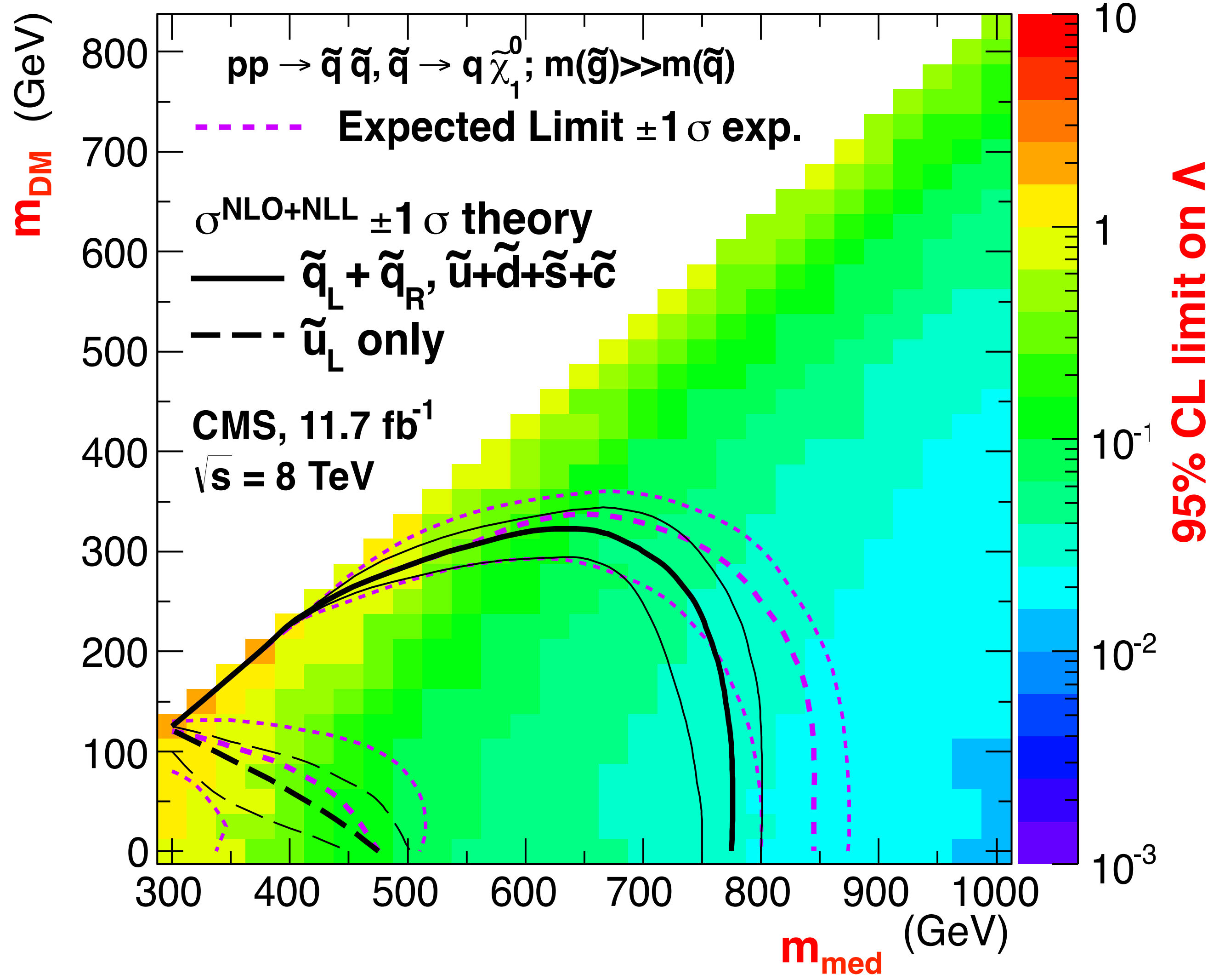


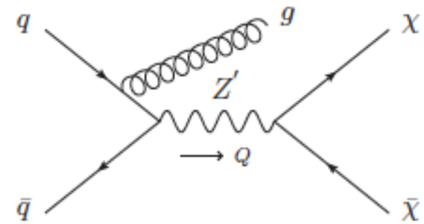
The proposal





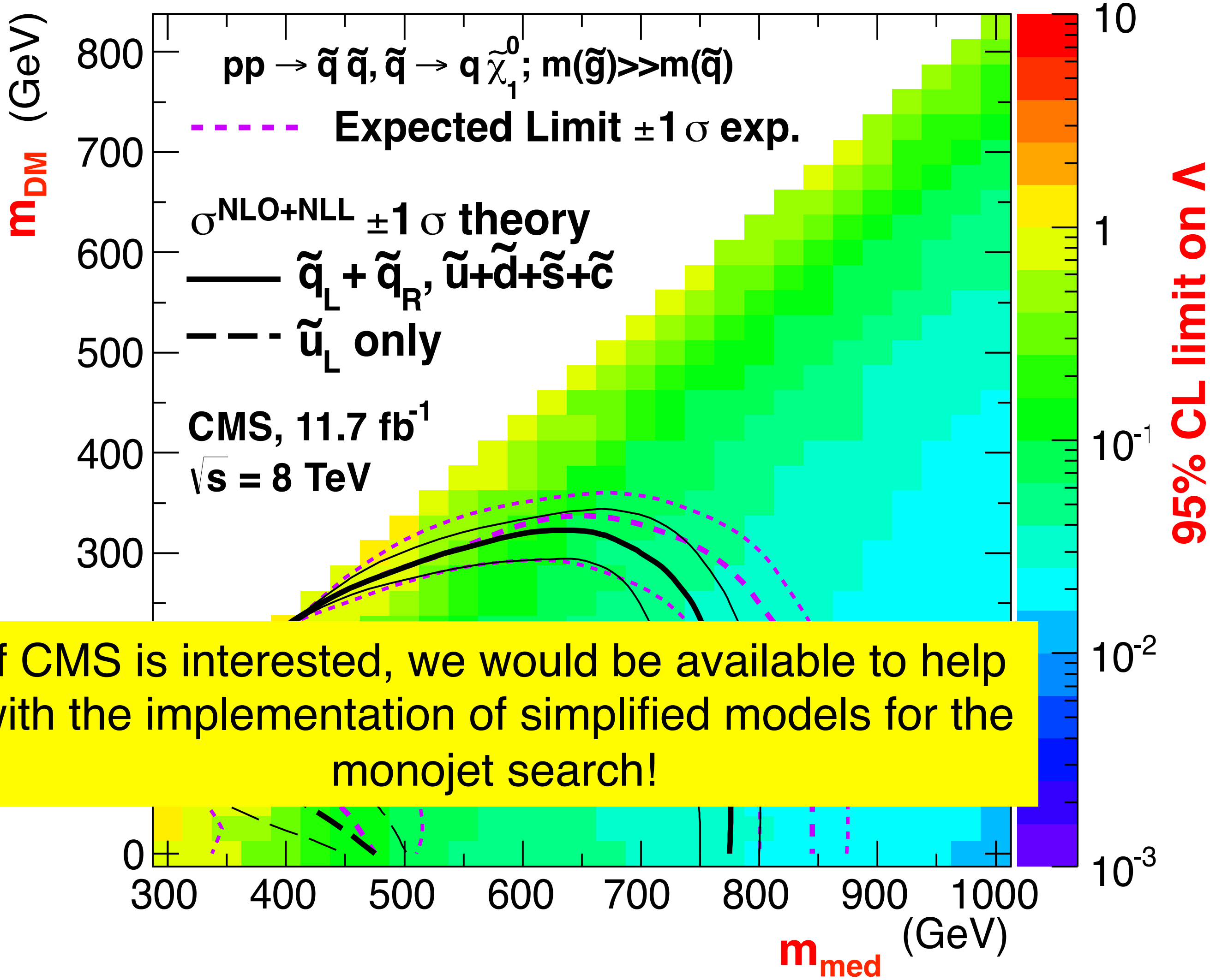
The proposal



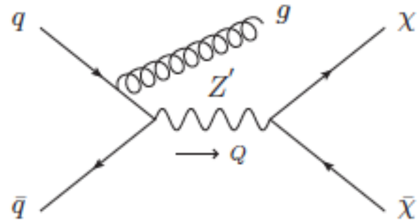


Very similar to limits in SUSY simplified models – m_{med}, m_{DM}, Λ and possibly some variation of Γ_{med} will cover the full problem!

The proposal



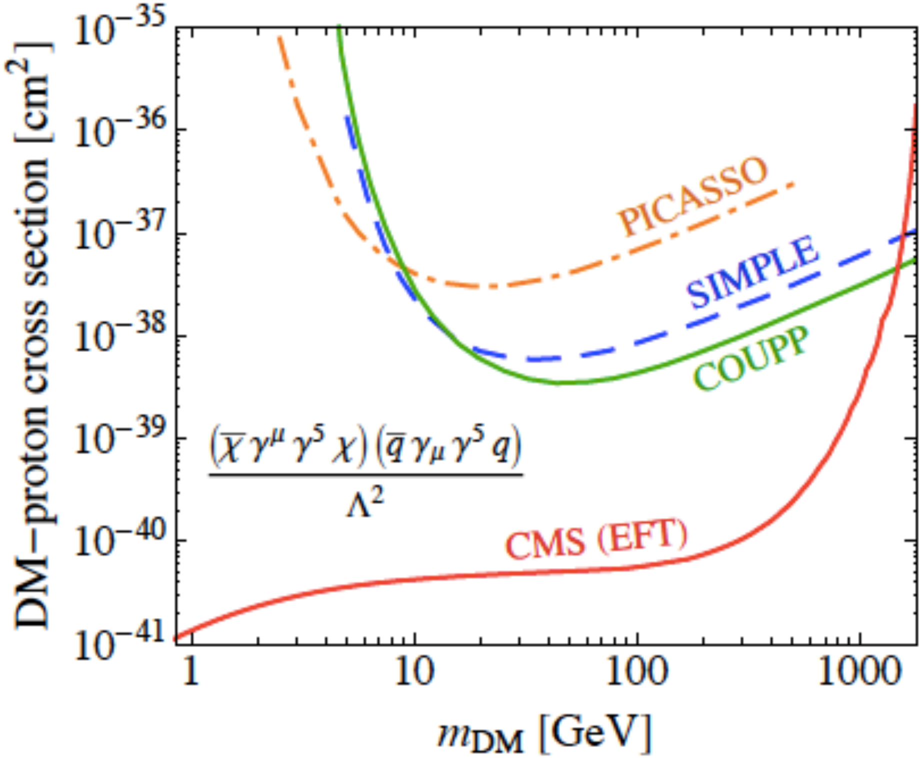
If CMS is interested, we would be available to help with the implementation of simplified models for the monojet search!

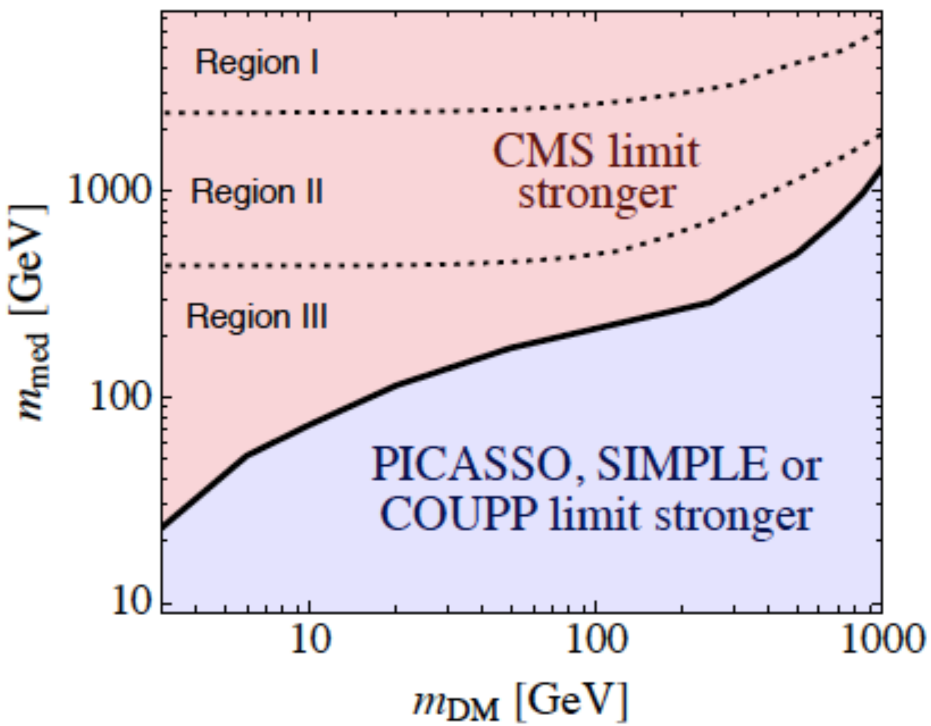


Very similar to limits in SUSY simplified models – m_{med}, m_{DM}, Λ and possibly some variation of Γ_{med} will cover the full problem!

Beyond EFT limits: Simplified models

Working out the complementarity between direct DM detection experiments and collider based DM searches!





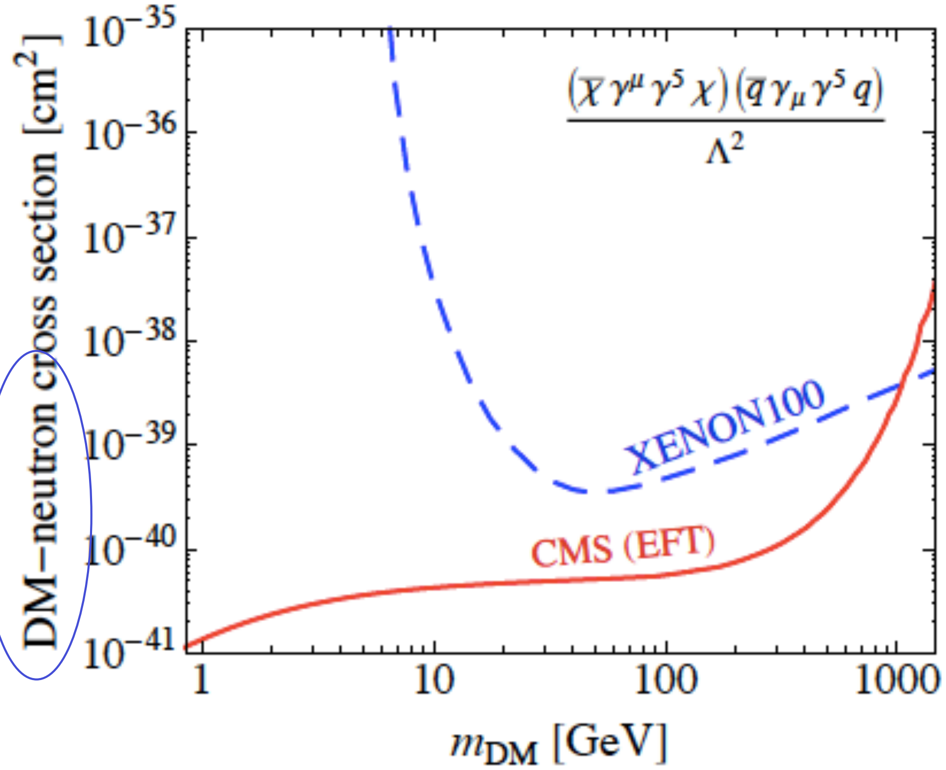
EFT limits give the impression that monsjet searches outperform direct detection BUT EFT only applies a VERY small class of DM models.

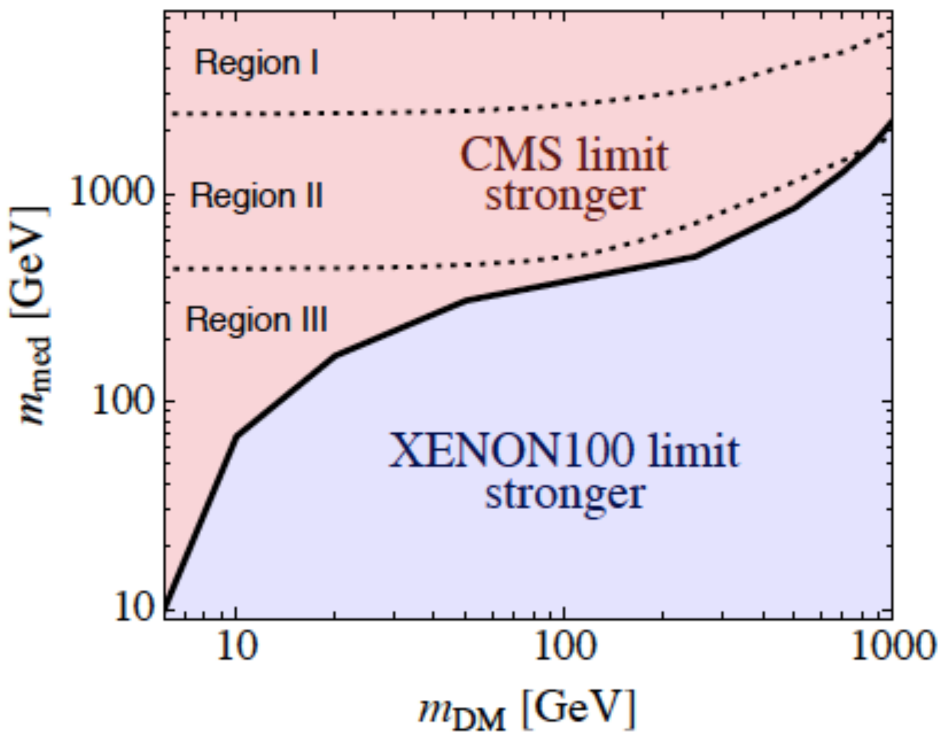
Simplified model limits give a much better Account of the REAL complementarity and thus seem superior for a comparison.

Beyond EFT limits: Simplified models

Buchmüller

Working out the complementarity between direct DM detection experiments and collider based DM searches!



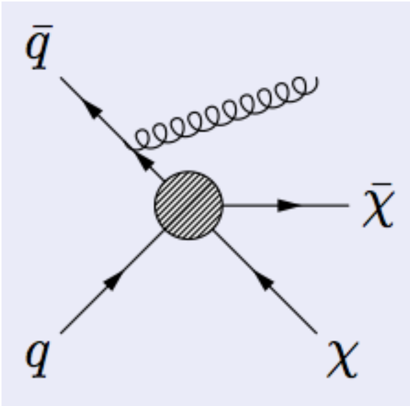


EFT limits give the impression that monsjet searches outperform direct detection BUT EFT only applies a VERY small class of DM models.

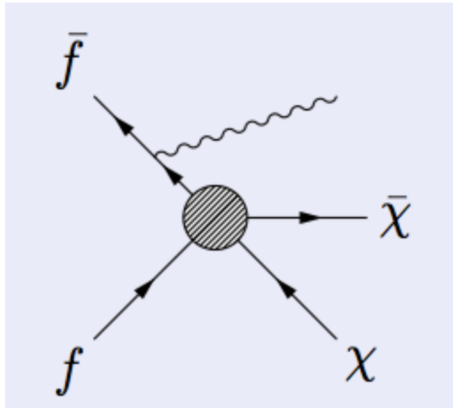
Simplified model limits give a much better Account of the REAL complementarity and thus seem superior for a comparison.

Monojet and Monophoto (plus E_T^{miss})

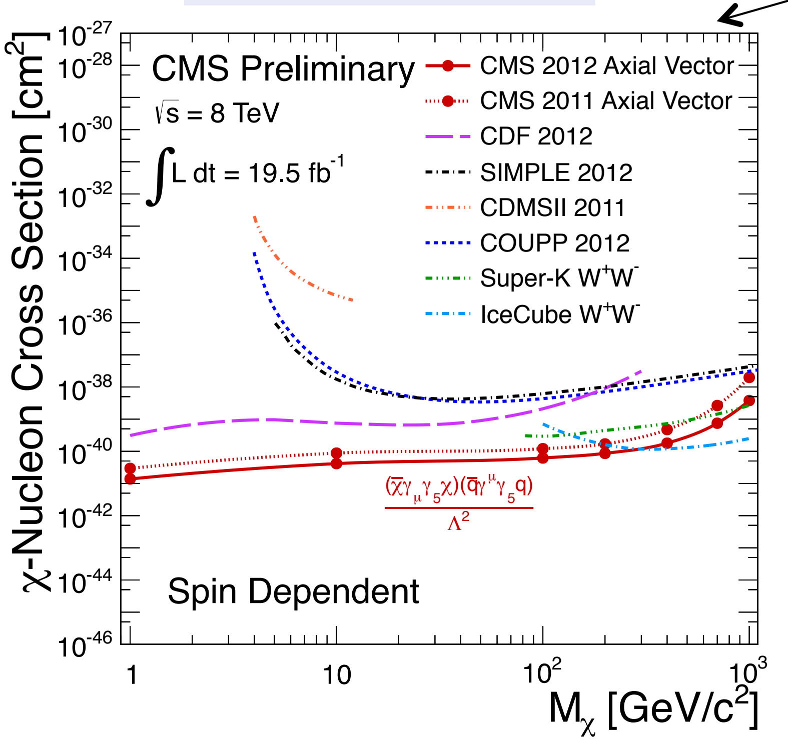
Monojet: hard jet + E_T^{miss}

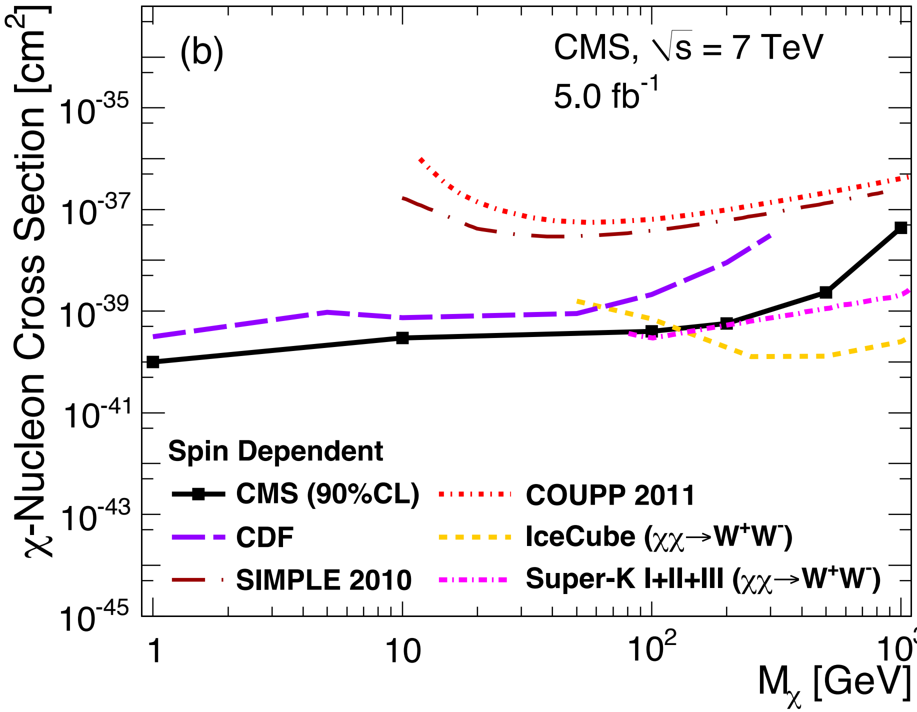


Monphoton: hard photon + E_T^{miss}



Note different y scale

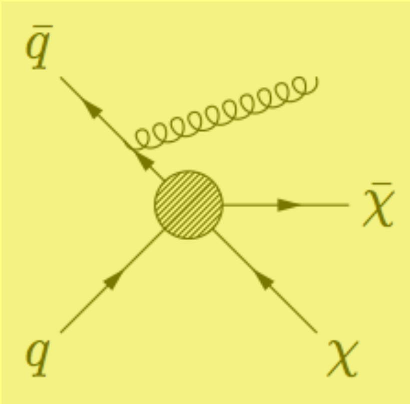


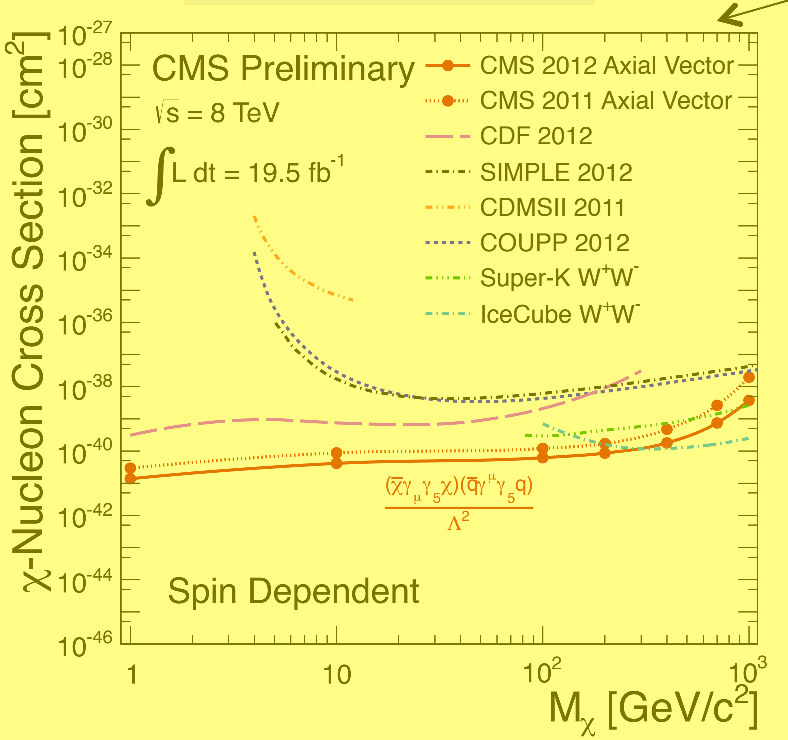


Imperial College London

Monojet and Monophoto (plus E_T^{miss})

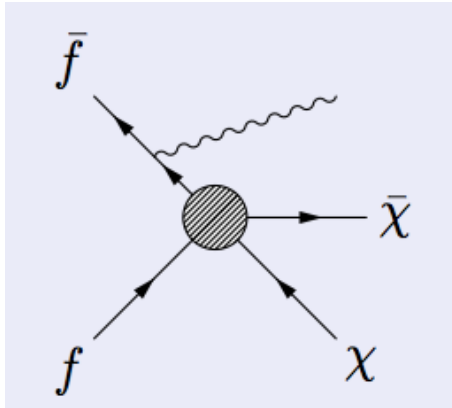
Monojet: hard jet + E_T^{miss}

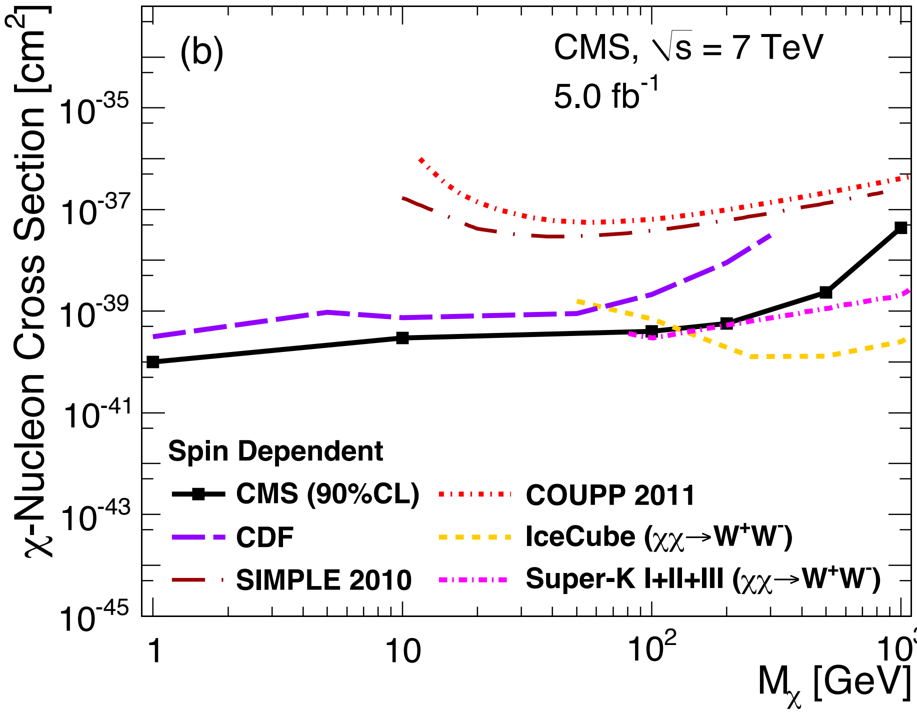




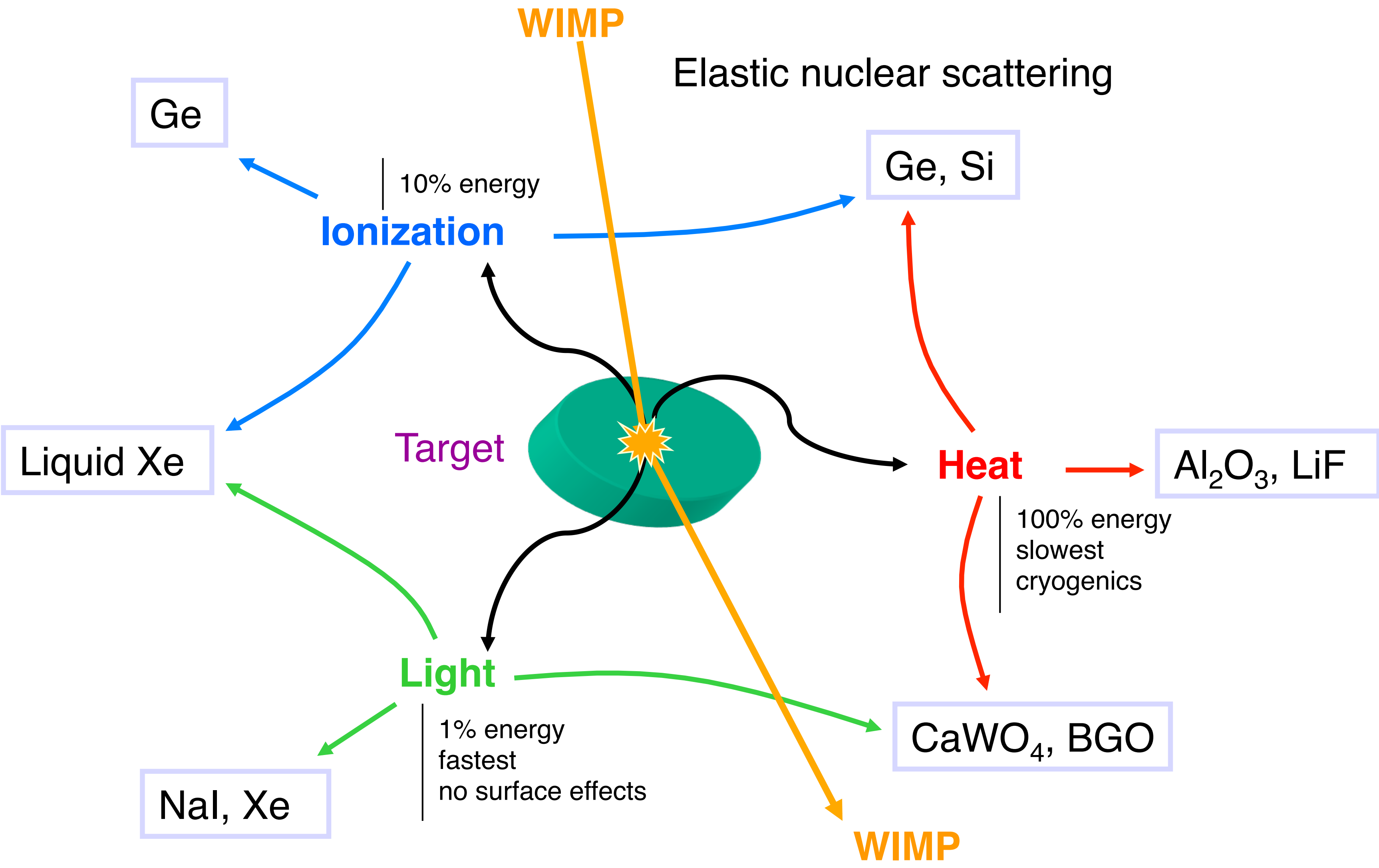
Note different y scale

Monphoton: hard photon + E_T^{miss}





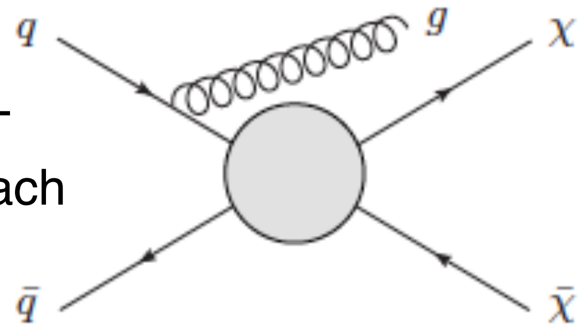
Direct Detection Techniques

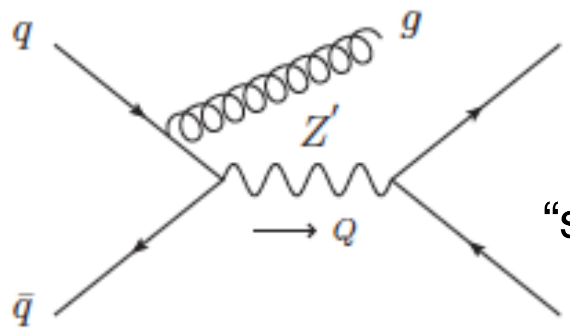


Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799
➢ Compare Effective Field Theory (EFT) with Full Theory (FT)

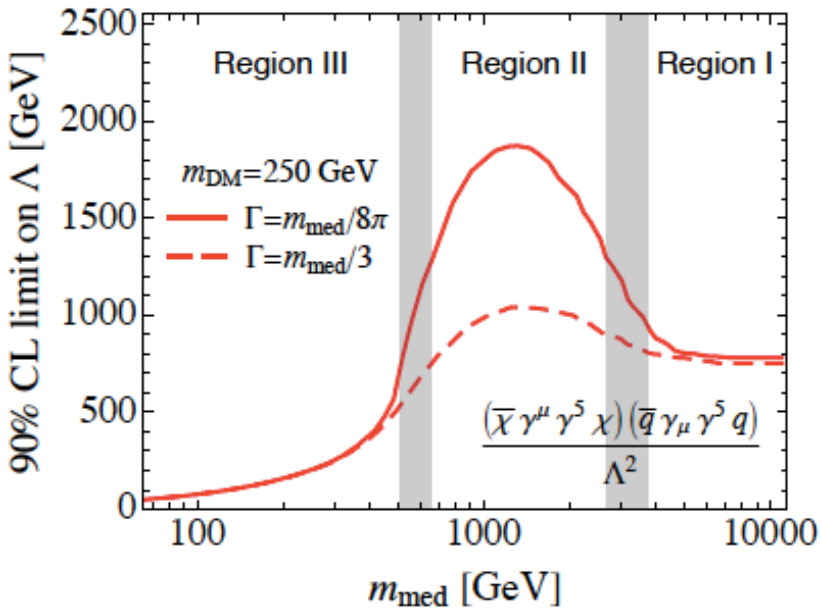
EFT
approach





FT
one diagram
“simplified model”

Use vector and axial-vector mediators (e.g. Z’) as example - scalar are similar in conclusion!



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!