The LHC and Cosmology

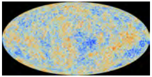
Mathias Garny (CERN)

4.12.2014 Ferrara

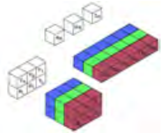
Particle Physics and Cosmology

Collider exp.

Baryon asymmetry



⋮



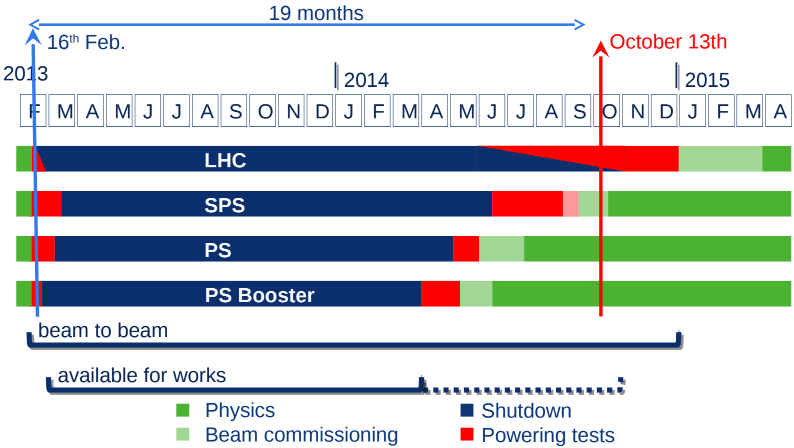
⋮

$+\ ?$

Neutrino exp.

Dark Matter

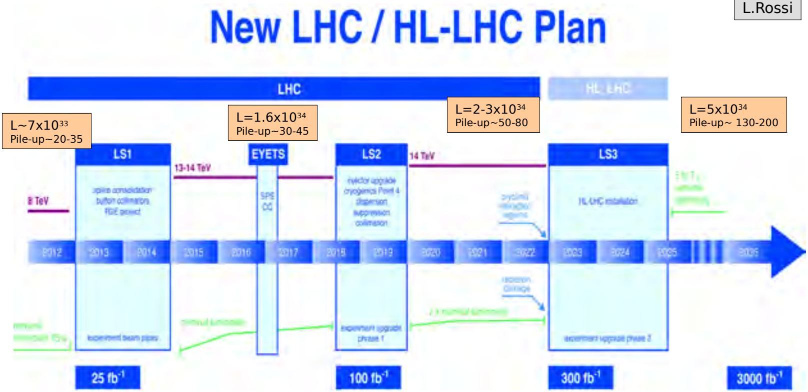
LS 1 from 16th Feb. 2013 to Dec. 2014



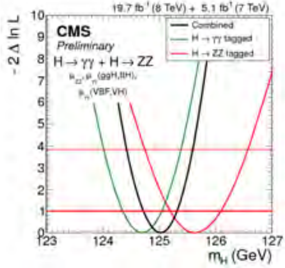
from F. Bordry

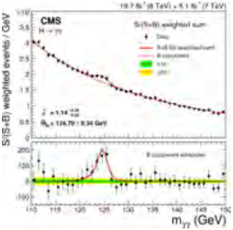
The LHC timeline

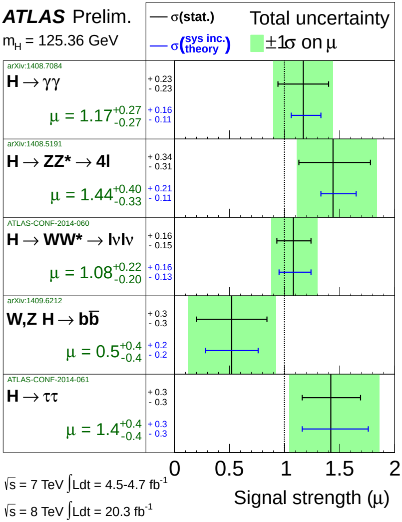
L.Rossi



Higgs


19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)
CMS
Preliminary
H → γγ + H → ZZ
Combined
H → γγ tagged
H → ZZ tagged
- 2 Δ ln L
m_H (GeV)
123
124
125
126
127


CMS
H → γγ
S/(S+B) weighted sum
S/(S+B) weighted events / GeV
m_γγ (GeV)


ATLAS Prelim.
m_H = 125.36 GeV
σ(stat.)
σ(sys inc. theory)
Total uncertainty
±1σ on μ
arXiv:1408.7084
H → γγ
μ = 1.17 +0.27 -0.27
+ 0.23
- 0.23
+ 0.16
- 0.11
arXiv:1408.5191
H → ZZ* → 4l
μ = 1.44 +0.40 -0.33
+ 0.34
- 0.31
+ 0.21
- 0.11
ATLAS-CONF-2014-060
H → WW* → lνlν
μ = 1.08 +0.22 -0.20
+ 0.16
- 0.15
+ 0.16
- 0.13
arXiv:1409.6212
W,Z H → bb̄
μ = 0.5 +0.4 -0.4
+ 0.3
- 0.3
+ 0.2
- 0.2
ATLAS-CONF-2014-061
H → ττ
μ = 1.4 +0.4 -0.4
+ 0.3
- 0.3
+ 0.3
- 0.3
0
0.5
1
1.5
2
Signal strength (μ)
√s = 7 TeV ∫Ldt = 4.5-4.7 fb⁻¹
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹

Higgs couplings t at HL-LHC

CMS

Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

CMS Projection

Assumption NO invisible/undetectable contribution to Γ_H:

- Scenario 1: system./Theory err. unchanged w.r.t. current analysis
- Scenario 2: systematics scaled by 1/sqrt(L), theory errors scaled by ½

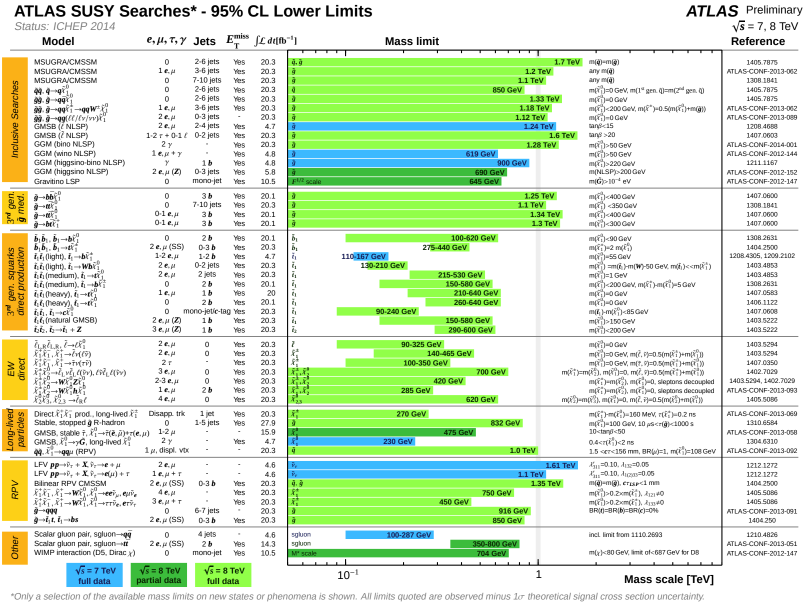
✓ γγ loop at 2-5% level

✓ down-type fermion couplings at 2-10% level

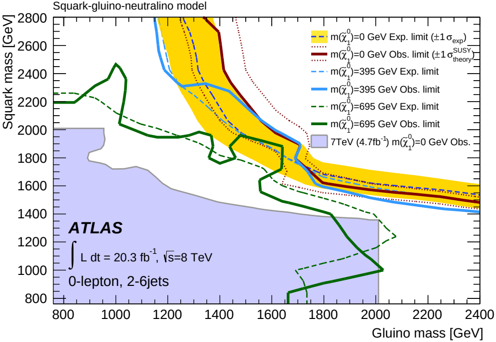
✓ direct top coupling at 4-8% level

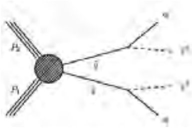
✓ gg loop at 3-8% level

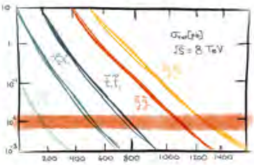
Supersymmetry?



Supersymmetry?



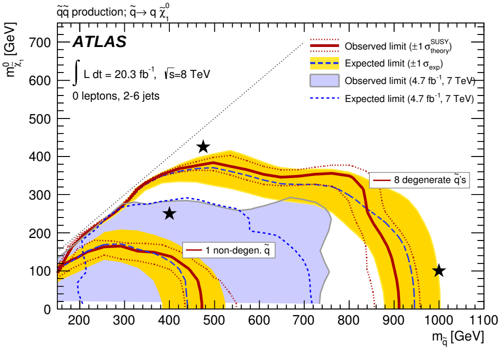


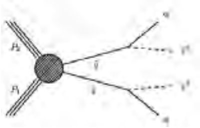


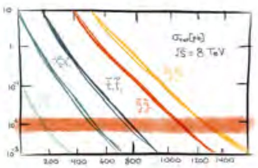
ATLAS 1405.7875

N. Craig

Supersymmetry?







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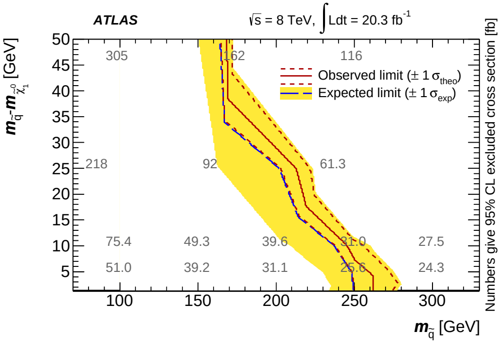

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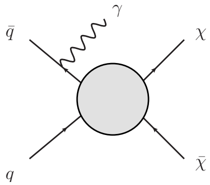
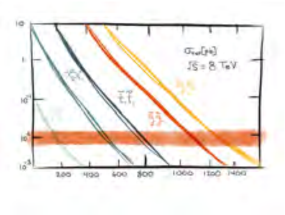
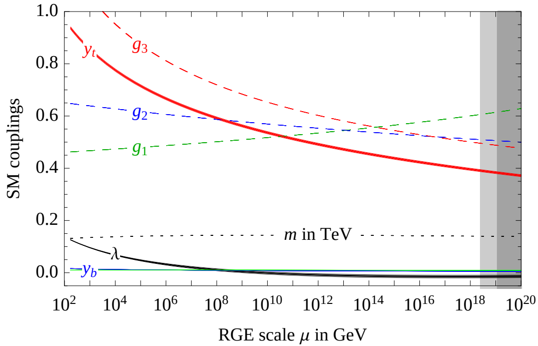
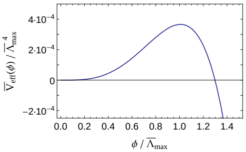




N. Craig

SM extrapolation



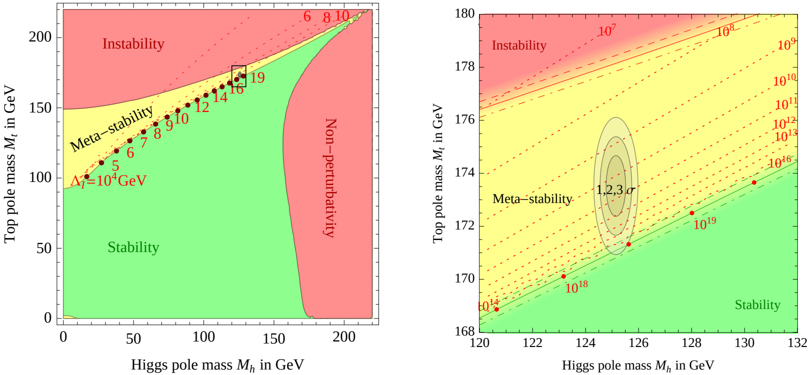


2-loop EW threshold, 3-loop running *Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia 1307.3536*

SM vacuum instability

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia 1307.3536

SM vacuum instability



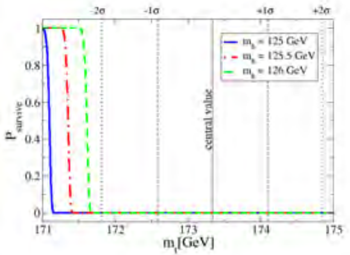
Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia 1307.3536

SM vacuum instability and inflation

- EW vacuum meta-stable (for best-fit m_t, m_h)
- Higgs could end up in unstable region in some Hubble patches if

$$H_{inf} \gtrsim V_{max}^{1/4} \sim 10^9 \text{ GeV}$$

- Observation of (prim.) r would imply some kind of beyond-SM (unless top mass $2-3\sigma$ below best fit)



$$P \sim \exp\left(-8\pi^2 V_{max}/3H^2\right)$$

Fairbairn, Hogan 1403.6786, $H_{inf} = 10^{14}$ GeV

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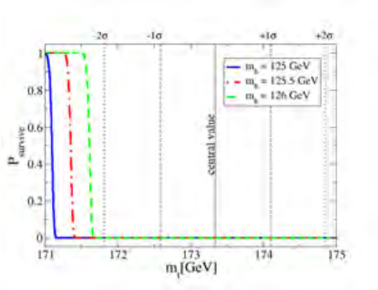
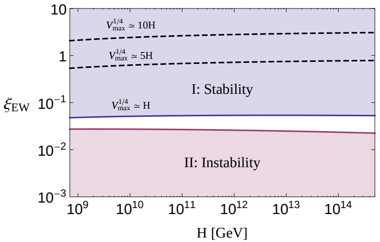
- Ways around: small non-minimal coupling, ...





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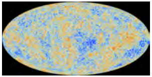
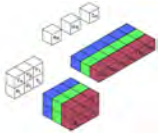
Fairbairn, Hogan 1403.6786, $H_{inf} = 10^{14}$ GeV   *Herranen, Murkkanen, Nurmi, Rajantie 1407.3141*

Baryogenesis and the LHC

Collider exp. ↘

Baryon asymmetry ↙



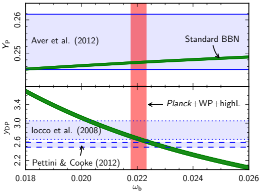


$+ \, ?$

Baryon asymmetry

$$Y_P = 4n_{He}/n_b$$

$$y_{DP} = n_D/n_H \cdot 10^5$$



$$\omega_b = \Omega_b h^2 = \eta/(2.74 \cdot 10^{-8})$$

Consistent value BBN ($T \sim$ keV) and CMB ($T \sim$ eV)

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} = \begin{cases} (6.15 \pm 0.15) \cdot 10^{-10} & \text{WMAP9} \\ (6.04 \pm 0.08) \cdot 10^{-10} & \text{Planck} \end{cases}$$

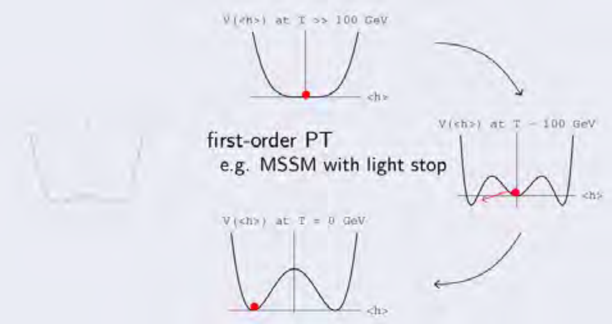
WMAP9 1212.5226, Planck 1303.5076

Baryogenesis ($\simeq 10^9 + 1 : 10^9$ particles vs antiparticles)

- CP violation, B violation, deviation from equilibrium

Electroweak baryogenesis

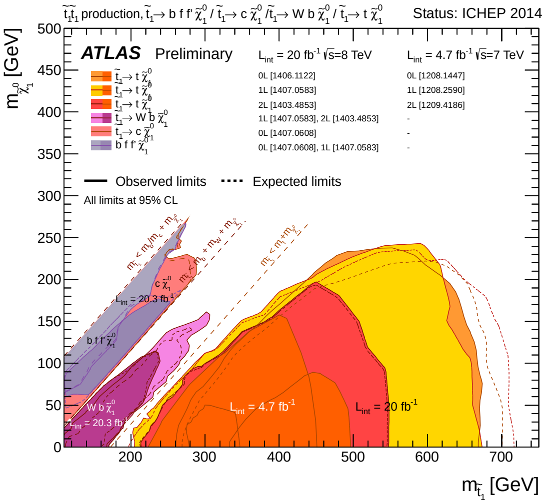
- The baryon asymmetry could be generated during a first order phase transition
- Electroweak phase transition in the SM is a crossover for $m_H \gtrsim 70$GeV



from T. Konstandin

EW baryogenesis

- MSSM: need very light RH stops, practically excluded



Direct stop search $pp \to \tilde{t}\tilde{t}$

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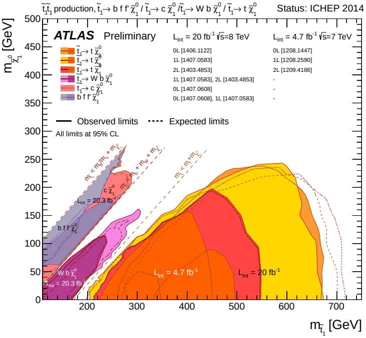
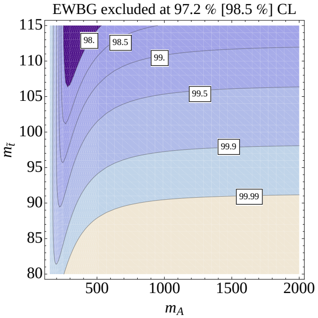


Direct stop search $pp \to \tilde{t}\tilde{t}$

Atlas 1407.0608; 1406.1122



Indirect from Higgs couplings to gluon/photon via stop loop

Curtin, Jaiswal, Meade 1203.2932

EW baryogenesis

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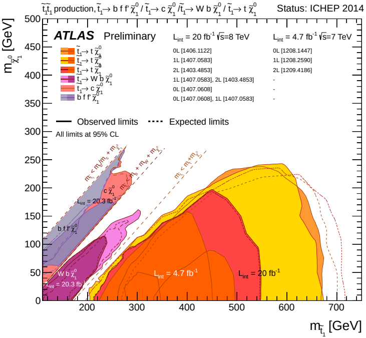

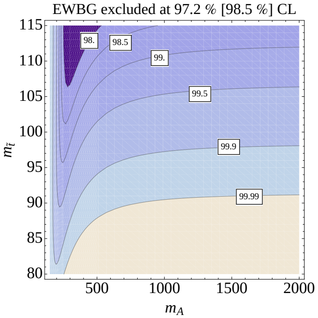

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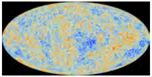
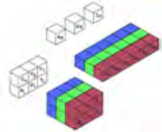
- SM+singlet, 2HDM, dim6 *Curtin, Meade, Yu 1409.0005; Craig et al 1412.0258;...*

$\Rightarrow$ Precision Higgs coupling, invisible decay, triple-Higgs measurements crucial (sometimes challenging, HL-LHC)

Baryogenesis and neutrinos

Baryon
asymmetry

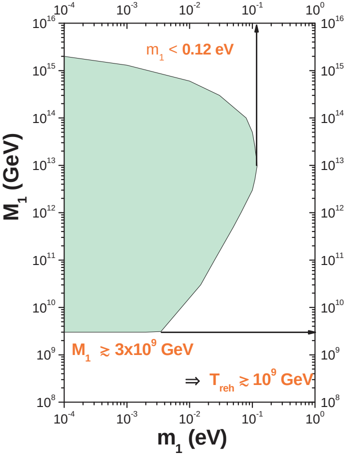




+ ?

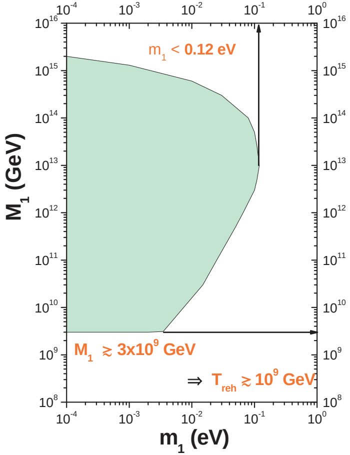
Neutrino
exp.

Vanilla leptogenesis vs neutrino mass



Di Bari 1206.3168 (unflavoured)

Vanilla leptogenesis vs neutrino mass



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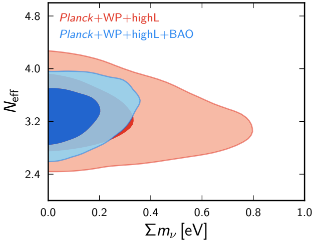
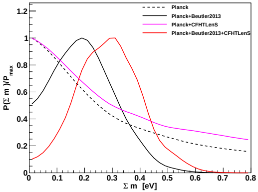


Planck 1303.5076

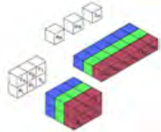


BOSS 1403.4599

$\Rightarrow$ absolute neutrino mass scale is very important ingredient

Dark Matter and the LHC

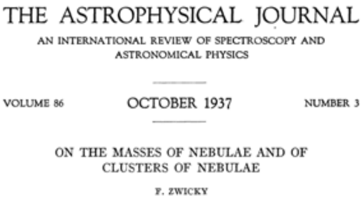
Collider exp.



$+\ ?$

Dark Matter

Dark Matter

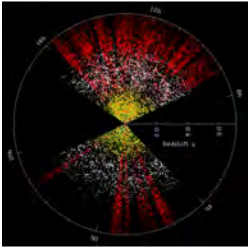

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

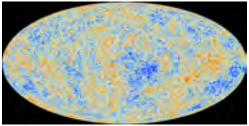
ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

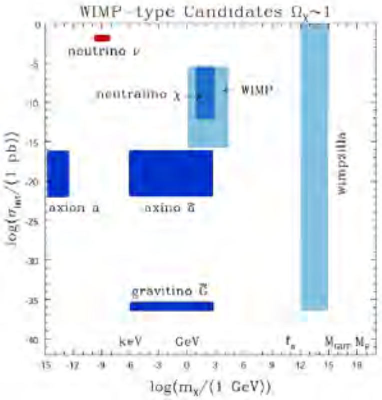


$$\Omega_\chi h^2 = 0.1199 \pm 0.0027$$

Planck XVI 1303.5076



Many dark matter candidates proposed,
with very different characteristics...



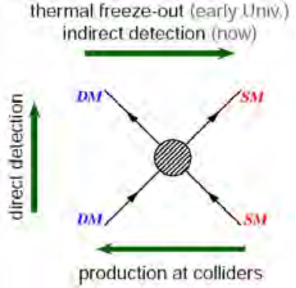
The production mechanism of dark matter particles is very model dependent

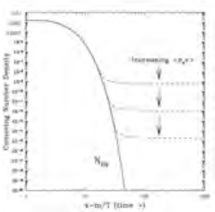
A. Ibarra; Kolb/Turner

‘The decade of the WIMP’

$$\Omega_\chi h^2 = 0.1199 \pm 0.0027 \simeq 0.1\,\text{pb} \cdot c\,/\langle \sigma v \rangle$$

Planck XVI 1303.5076





NB: other well-motivated possibilities: axions, ...

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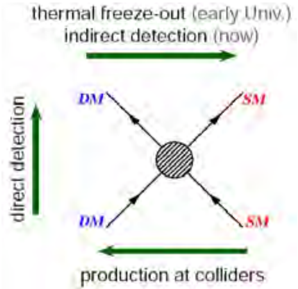
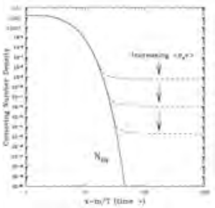
Planck XVI 1303.5076

Fermi, H.E.S.S., AMS02, Planck. . . , CTA, GAMMA-400

e.g. 1305.5597 1310.0828, 1410.2242; 1301.1173

XENON100 *1207.5988*
LUX *1310.8214*
. . .
XENON1T
LZ





LHC7+8, LHC13

e.g. CMS 1402.4770, ATLAS 1405.7875

NB: other well-motivated possibilities: axions, ...

WIMPology

- Many experiments at edge of sensitivity for WIMPy cross sections
- Large uncertainties: need input from simulations, halo profile, substructures, velocity distribution, . . . ; foregrounds, cosmic ray propagation, . . . $\Rightarrow$ Collider/CMB bounds highly desirable

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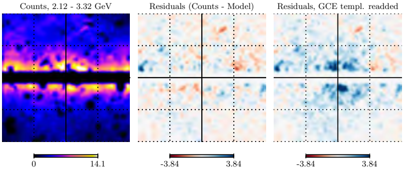

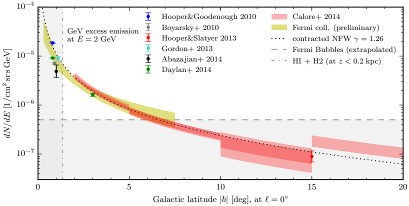

Galactic center excess?

Calore, Cholis, Weniger 1409.0042

Calore, Cholis, McCabe, Weniger 1411.4647; ...

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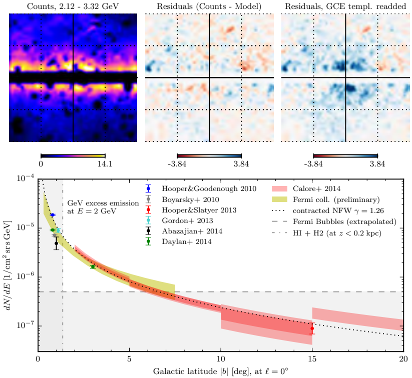
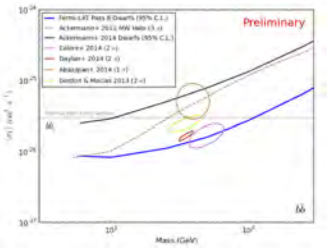


Galactic center excess?



B. Andersson, Fermi LAT dwarf Pass 8

Calore, Cholis, Weniger 1409.0042

Calore, Cholis, McCabe, Weniger 1411.4647; . . .

Interplay of ID, DD, LHC

- Combination of different probes is crucial to confirm/identify/'rule out' WIMPs
- How to compare different probes?
- Most complete: full models (MSSM)
  - Motivated from particle physics
  - Many free parameters

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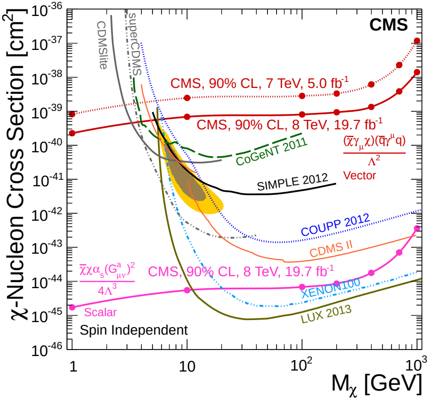
- How to compare different probes?
- Most complete: full models (MSSM)
  - Motivated from particle physics
  - Many free parameters
- Most model-independent: effective operator description
  - Straightforward and systematic
  - Limited reach of validity @ LHC energies

DM and the LHC



$$\mathcal{L}_V = \frac{\bar{\chi}\gamma_\mu\chi\,\bar{q}\gamma^\mu q}{\Lambda^2}$$

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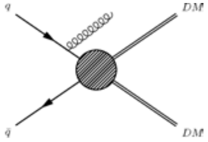

CMS 1408.3583

cf. also Goodman, Ibe, Rajamaran, Sheperd, Tait, Yu 10; Bai, Fox, Harnik 10

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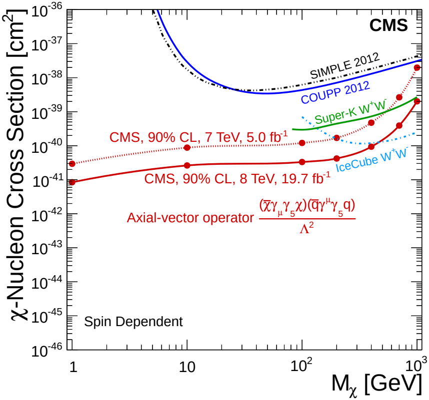

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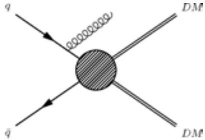

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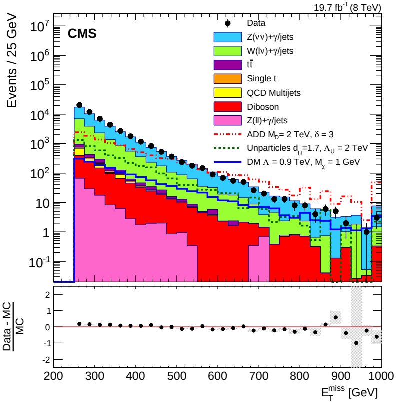

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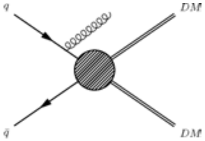


CMS 1408.3583

Validity of contact int. limit?

Momentum transfer $\sim$ TeV, limit on suppression scale $\Lambda \sim TeV$

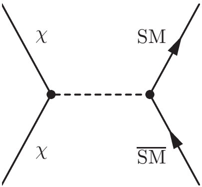
e.g. Busoni, De Simone, Morgante, Riotto 1402.1275; ...

cf. also Goodman, Ibe, Rajamaran, Sheperd, Tait, Yu 10; Bai, Fox, Harnik 10

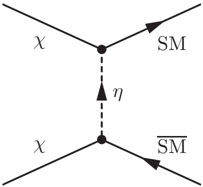
Interplay of ID, DD, LHC

- Bottom-up approach: DM + mediator

s-channel

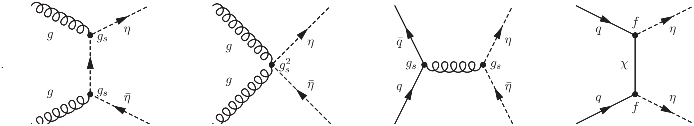


t-channel



When is the mediator important?

- Collider searches (direct production of mediator for $m_\eta \lesssim 2-3$ TeV)



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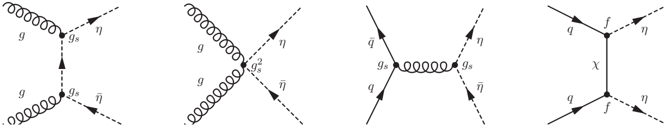
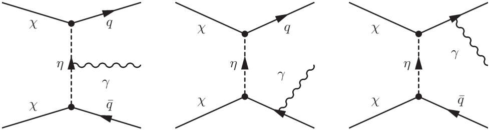


- Indirect detection (internal bremsstrahlung for $m_\eta \lesssim 5m_\chi$,Majorana)



Bergstrom 89; Bergstrom, Bringmann, Edsjo 0710.3169

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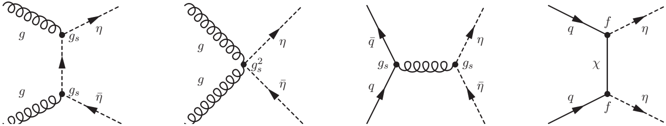

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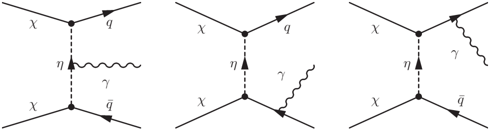
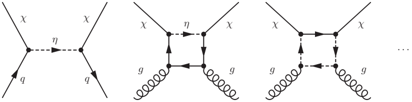


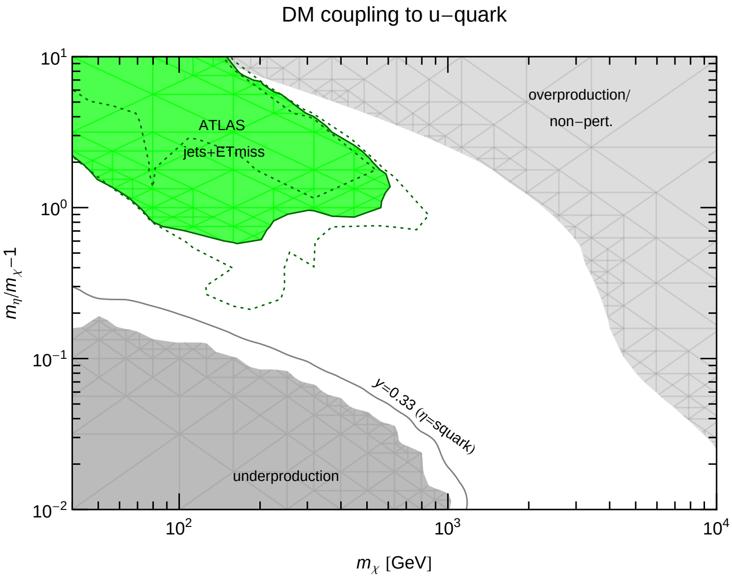
Bergstrom 89; Bergstrom, Bringmann, Edsjo 0710.3169

- Direct detection (EFT OK, except resonance for $m_\eta \simeq m_\chi$)



Hisano, Ishiwata, Nagata 1110.3719; Gondolo, Scopel 1307.4481; Drees, Nojiri; . . .

Complementarity (for thermal production)



MG, Ibarra, Rydbeck, Vogl 1403.4634

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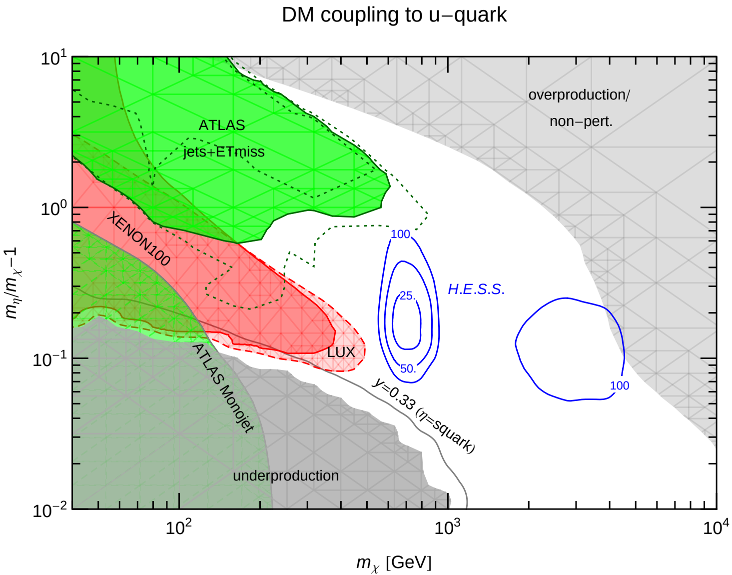

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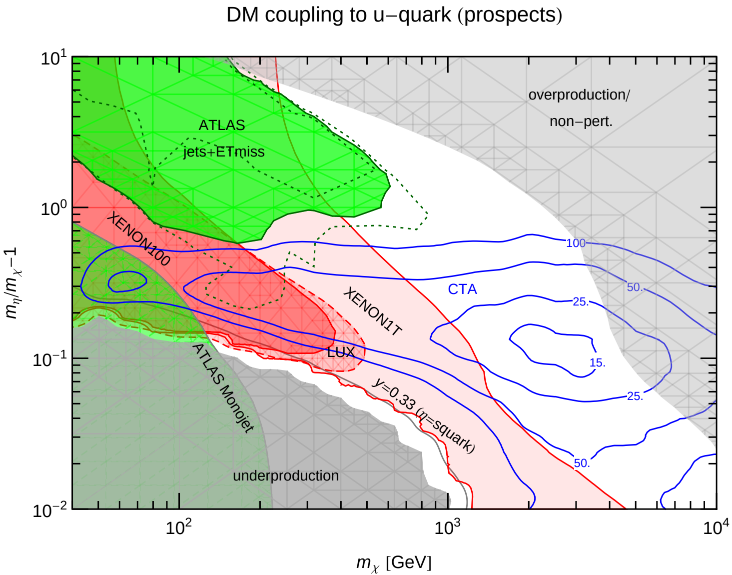

MG, Ibarra, Rydbeck, Vogl 1403.4634

DM coupling to leptons

MG, Ibarra, Pato, Vogl 1306.6342

Conclusion

- Most profound observational hints for physics beyond SM come from cosmology; way ahead of theory/laboratory
- Next LHC run(s) will have important consequences for many scenarios of WIMP dark matter, EW baryogenesis, ...
- Complementarity/combination with ID & DD will be crucial to identify/rule out WIMPs
- Also many other interesting connections: neutrino mass, models/scale of inflation, DM self-interactions, topological defects reheating vs heavy ion (QFT in extreme environments), ...

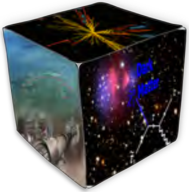

image from T. Kamon

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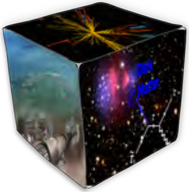

thank you!

image from T. Kamon

Massive neutrinos and leptogenesis

$$\begin{aligned} m^2_{\nu_1} - m^2_{\nu_2} &= 7.02...8.09 \cdot 10^{-5}\mathrm{eV}^2 \qquad (3\sigma \text{ range}) \\ |m^2_{\nu_1} - m^2_{\nu_3}| &= 2.31...2.60 \cdot 10^{-3}\mathrm{eV}^2 \end{aligned}$$

Add right-handed neutrinos to SM, seesaw explains why m_ν is so small

$$m_\nu = -v^2_{EW} y \hat{M}^{-1}_{\nu_R} y^T$$

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...and baryon asymmetry *Fukugita, Yanagida 86*

- B-L-violating Majorana masses M_{ν_R}
- CP-violation via Yukawa couplings y (like for quarks)
- Out-of-equilibrium (inverse) decay $\nu_R \leftrightarrow \ell\phi^\dagger$ and $\nu_R \leftrightarrow \ell^c\phi$

$$\begin{aligned} (\Gamma_i/H)|_{T=M_i} &\simeq \frac{\tilde{m}_{\nu,i}/8\pi}{1.66 g_* v_{EW}^2/M_{pl}} \simeq \tilde{m}_{\nu,i}/\mathrm{meV} \\ &\sim \mathcal{O}(1-100) \leftrightarrow \end{aligned}$$

leptogenesis works well for observed ν mass scale

Direct production of the mediator $gg, qq \to \eta\eta$, $\eta \to \chi q$

DM-SM-med.
coupling
strength

mass splitting

MG, Ibarra, Rydbeck, Vogl 1403.4634; cf. also Papucci, Vichi, Zurek 1402.2285 for Dirac DM

Reinterpretation of ATLAS search for jets + missing energy
$\mathcal{L} = 20.3$ fb^{-1} (signal regions with 2-4jets; matching for two ad. jets)

ATLAS 1405.7875; ATLAS-CONF-2013-047