# The LHC and Cosmology

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4.12.2014 Ferrara

### Particle Physics and Cosmology



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



## The LHC timeline The LHC timeline





### Higgs





# Higgs couplings t at HL-LHC

	Coupling	Uncertainty (%)					
		$300 \text{ fb}^{-1}$		3000 fb <sup>-1</sup>			
		Scenario 1	Scenario 2	Scenario 1	Scenario 2		
CMS	K-	6.5	5.1	5.4	1.5		
	KY	5.7	2.7	4.5	1.0		
	$\kappa_a$	11	5.7	7.5	2.7		
	$\kappa_b$	15	6.9	11	2.7		
	RI	14	8.7	8.0	3.9		
	KT.	8.5	5.1	5.4	2.0		

#### **CMS** Projection

Assumption NO invisible/undetectable contribution to  $\Gamma_{H}$ :

- Scenario 1: system./Theory err. unchanged w.r.t. current analysis

- Scenario 2: systematics scaled by 1/sqrt(L), theory errors scaled by  $\frac{1}{2}$ 

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

#### ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: ICHEP 2014

	Model	$e, \mu, \tau, \gamma$	Jets	E <sup>miss</sup> <sub>T</sub>	∫£ dt[fb	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM MSUGRA/CMSSM MSUGRA/CMSSM 49, 7-49 <sup>4</sup> C <sup>2</sup> 82, 7-49 <sup>4</sup> C <sup>2</sup> 82, 7-49 <sup>4</sup> C <sup>2</sup> 82, 7-49 <sup>4</sup> C <sup>2</sup> 64, 7-49 <sup>4</sup> C <sup>4</sup> 64, 7-49 <sup>4</sup> C <sup>4</sup> 7-49	$\begin{matrix} 0 \\ 1  e, \mu \\ 0 \\ 0 \\ 1  e, \mu \\ 2  e, \mu \\ 2  e, \mu \\ 1 \cdot 2  \tau + 0 \cdot 1  \ell \\ 2  \gamma \\ 1  e, \mu + \gamma \\ \gamma \\ 2  e, \mu  (Z) \\ 0 \end{matrix}$	2-6 jets 3-6 jets 2-6 jets 2-6 jets 2-6 jets 0-3 jets - - - - - - - - - - - - -	Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 4.7 20.3 20.3 4.7 20.3 20.3 4.8 4.8 5.8 10.5	4.1 1.2 V.1 4.1 1.2 V.1 4.1 1.5 V.1 4.1 1	m(g)=m(g) any m(g) m(g)=0, (m(g)=m(g)=m(g)=m(g)=m(g)=m(g)=m(g)=m(g)	1405.7875 ATLAS-CONF-2013-082 1308.1841 1405.7875 1405.7875 ATLAS-CONF-2013-089 1407.0803 ATLAS-CONF-2013-09 ATLAS-CONF-2013-09 ATLAS-CONF-2012-147 ATLAS-CONF-2012-147 ATLAS-CONF-2012-147
3 <sup>rd</sup> gen. <u>§</u> med.	$\frac{\tilde{\sigma} \rightarrow b \tilde{b} \tilde{\chi}_{1}^{0}}{\tilde{\sigma} \rightarrow t \tilde{\chi}_{1}^{0}}$ $\frac{\tilde{\sigma} \rightarrow t \tilde{\chi}_{1}^{0}}{\tilde{\sigma} \rightarrow b t \tilde{\ell}_{1}^{+}}$	0 0 0-1 e, µ 0-1 e, µ	3 b 7-10 jets 3 b 3 b	Yes Yes Yes Yes	20.1 20.3 20.1 20.1	ž 1.25 TeV ž 1.1 TeV ž 1.34 TeV ž 1.34 TeV	m( <sup>20</sup> )<400 GeV m( <sup>20</sup> )<350 GeV m( <sup>20</sup> )<400 GeV m( <sup>20</sup> )<300 GeV	1407.0600 1308.1841 1407.0600 1407.0600
3 <sup>rd</sup> gen. squarks direct production	$ \begin{array}{l} b_1 \bar b_1 \cdot b_1 \rightarrow b \bar t_1^0 \\ \bar b_1 \bar b_1 \cdot b_1 \rightarrow b \bar t_1^0 \\ \bar b_1 \bar b_1 \cdot b_1 \rightarrow b \bar t_1^0 \\ \bar i_1 \bar i_1 (light), \bar i_1 \rightarrow b \bar b \bar t_1^0 \\ \bar i_1 \bar i_1 (light), \bar i_1 \rightarrow b \bar b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1^0 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \\ \bar i_1 (medlum), \bar i_1 \rightarrow b \bar t_1 \end{pmatrix} $	$\begin{array}{c} 0 \\ 2  e, \mu  (SS) \\ 1 \cdot 2  e, \mu \\ 2  e, \mu \\ 2  e, \mu \\ 0 \\ 1  e, \mu \\ 0 \\ 1  e, \mu \\ 0 \\ 3  e, \mu  (Z) \end{array}$	2 b 0-3 b 1-2 b 0-2 jets 2 jets 2 b 1 b 2 b 1 ono-jet(-t 1 b 1 b 1 b	Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.1 20.3 4.7 20.3 20.3 20.1 20 20.1 20.3 20.3 20.3 20.3	5. 104-50 GeV 110580-001 / 275-426 GeV 1. 105210 GeV 1. 105210 GeV 1159-60 GeV 1159-60 GeV 1159-60 GeV 105-60 GeV 105-60 GeV 105-60 GeV	m(?)-30 GeV m(?)-22 m(?) m(?)-55 GeV m(?)-m(V)-60(W)-50 GeV, m(?,)<-m(?) m(?)-1 GeV m(?)-5 GeV m(?)-5 GeV m(?)-5 GeV m(?)-5 GeV m(?)-55 GeV m(?)-55 GeV	1308.2631 1404.2500 1208.8405,1209.2102 1403.4853 1308.2631 1407.0583 1407.0583 1406.1122 1407.0608 1403.5222
EV/ direct	$ \begin{array}{c} l_{1,R} t_{1,R}, l \rightarrow l \tilde{k}_1^0 \\ \tilde{k}_1^* \tilde{k}_1, \tilde{k}_1^+ \rightarrow l \nu(l \tilde{v}) \\ \tilde{k}_1^* \tilde{k}_1, \tilde{k}_1^+ \rightarrow l \nu(l \tilde{v}), l \tilde{v}_L^* l \tilde{k}_1 \\ \tilde{k}_1^* \tilde{k}_2^+ \rightarrow \tilde{k}_1 \nu l_L (l (\tilde{v}), l \tilde{v}_L^* l (\tilde{v})) \\ \tilde{k}_1^* \tilde{k}_2^+ \rightarrow W \tilde{k}_1^* L \tilde{k}_1^0 \\ \tilde{k}_2^+ \tilde{k}_2^+ \rightarrow W \tilde{k}_1^* L \tilde{k}_1^0 \\ \tilde{k}_2^+ \tilde{k}_2^+ \gamma \tilde{k}_{2,2}^- \rightarrow \tilde{k}_R \ell \end{array} $	2 e, µ 2 e, µ 2 τ 3 e, µ 2 · 3 e, µ 1 e, µ 4 e, µ	0 0 0 2 <i>b</i> 0	Yes Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 20.3	2 99-325 GeV 1 100-350 GeV 2 10	$\begin{array}{l} m(\tilde{r}_{1}^{0})\!=\!0 \; \text{GeV} \\ m(\tilde{r}_{1}^{0})\!=\!0 \; \text{GeV} \; m(\tilde{r},\tilde{r}_{1}\!=\!0.5(m(\tilde{r}_{1}^{0})\!+\!m(\tilde{r}_{1}^{0}))) \\ m(\tilde{r}_{1}^{0})\!=\!0 \; \text{GeV} \; m(\tilde{r},\tilde{r})\!=\!0.5(m(\tilde{r}_{1}^{0})\!+\!m(\tilde{r}_{1}^{0})) \\ m(\tilde{r}_{1}^{0})\!=\!m(\tilde{r}_{2}^{0})\!=\!0.5(m(\tilde{r}_{1}^{0})\!+\!m(\tilde{r}_{1}^{0})) \\ m(\tilde{r}_{1}^{0})\!=\!m(\tilde{r}_{2}^{0})\!=\!0. \; \text{deposes decoupled} \\ m(\tilde{r}_{1}^{0})\!=\!m(\tilde{r}_{2}^{0})\!=\!0.\; \text{stepsons decoupled} \\ m(\tilde{r}_{1}^{0})\!=\!m(\tilde{r}_{2}^{0})\!=\!0.\; \text{stepsons decoupled} \\ m(\tilde{r}_{1}^{0})\!=\!0.\; m(\tilde{r}_{2}^{0})\!=\!0.\; \text{stepsons decoupled} \\ m(\tilde{r}_{1}^{0})\!=\!0.\; m(\tilde{r}_{2}^{0})\!=\!0.\; \text{stepsons decoupled} \\ m(\tilde{r}_{1}^{0})\!=\!m(\tilde{r}_{2}^{0})\!=\!0.\; \text{m}(\tilde{r}_{2}^{0})\!=\!m(\tilde{r}_{1}^{0}) \\ m(\tilde{r}_{1}^{0})\!=\!0.\; m(\tilde{r}_{2}^{0})\!=\!0.\; \text{stepsons decoupled} \\ m(\tilde{r}_{1}^{0})\!=\!m(\tilde{r}_{1}^{0})\!=\!0.\; m(\tilde{r}_{2}^{0})\!=\!m(\tilde{r}_{1}^{0}) \\ m(\tilde{r}_{1}^{0})\!=\!m(\tilde{r}_{1}^{0})\!=\!0.\; m(\tilde{r}_{1}^{0})\!=\!m(\tilde{r}_{1}^{0}) \\ m(\tilde{r}_{1}^{0})\!=\!m(\tilde{r}_{1}^{0})\!=\!0.\; m(\tilde{r}_{1}^{0})\!=\!m(\tilde{r}_{1}^{0}) \\ m(\tilde{r}_{1}^{0}) \\ m(\tilde{r}$	1403.5294 1403.5294 1407.0350 1402.7029 1403.5294,1402.7029 ATLAS-CONF-2013.093 1405.5086
Long-lived particles	$\begin{array}{l} \text{Direct} \tilde{\mathcal{K}}_{1}^{+} \tilde{\mathcal{K}}_{1}^{-} \text{prod.}, \log - \text{lived} \tilde{\mathcal{K}}_{1}^{+} \\ \text{Stable, stopped } \tilde{g} \text{ R-hadron} \\ \text{GMSB, stable } \tilde{r}, \tilde{\mathcal{K}}_{1}^{0} {\rightarrow} \tilde{r}(\tilde{c}, \tilde{\mu}) {+} \tilde{r}(c, \tilde{\mu}) {+} \tilde{r}(c, \tilde{\mu}) {+} \tilde{r}(\tilde{c}, \tilde{\mu}) {+} \tilde{r}(\tilde{c},$	Disapp. trk 0 ,µ) 1-2 µ 2 γ 1 µ, displ. vtx	1 jet 1-5 jets	Yes Yes Yes	20.3 27.9 15.9 4.7 20.3	X <sup>1</sup> 270 GeV         832 GeV           2         832 GeV         832 GeV           X <sup>1</sup> / <sub>4</sub> 230 GeV         1.0 TeV	$\begin{split} m(\tilde{t}_1^2) = & m(\tilde{t}_2^2) = & 160 \ \text{MeV}, \ \tau(\tilde{t}_1^2) = & 0.2 \ \text{ns} \\ m(\tilde{t}_1^2) = & 100 \ \text{GeV}, \ 10 \ \mu\text{s} < \tau(\tilde{g}) < & 1000 \ \text{s} \\ & 10 \ \text{stan} < & 50 \ \text{ct} \\ & 0.4 < \tau(\tilde{t}_1^2) < & 2 \ \text{ns} \\ & 1.5 \ < & \tau < & 156 \ \text{mm}, \ \text{BR}(\mu) = & 1, \ m(\tilde{t}_1^0) = & 108 \ \text{GeV} \end{split}$	ATLAS-CONF-2013-069 1310.6584 ATLAS-CONF-2013-058 1304.6310 ATLAS-CONF-2013-092
RPV	$\begin{array}{l} LFV pp {\rightarrow} \tilde{v}_{\tau} + X, \tilde{v}_{\tau} {\rightarrow} e + \mu \\ LFV pp {\rightarrow} \tilde{v}_{\tau} + X, \tilde{v}_{\tau} {\rightarrow} e(\mu) + \tau \\ Bilinear RPV CMSSM \\ \tilde{k}_{1}^{+} \tilde{k}_{1}^{-}, \tilde{k}_{1}^{+} {\rightarrow} W \tilde{k}_{1}^{0}, \tilde{k}_{1}^{0} {\rightarrow} e \tilde{v}_{\mu}, e \mu \tilde{v}_{e} \\ \tilde{k}_{1}^{+} \tilde{k}_{1}^{-}, \tilde{k}_{1}^{+} {\rightarrow} W \tilde{k}_{1}^{0}, \tilde{k}_{1}^{0} {\rightarrow} \tau \tau \tilde{v}_{e}, e \tau \tilde{v}_{\tau} \\ \tilde{\delta}^{-} \frac{e q \rho q}{\delta {\rightarrow} \tilde{t}_{1} t, \tilde{t}_{1} {\rightarrow} b s} \end{array}$	$\begin{array}{c} 2 \ e, \mu \\ 1 \ e, \mu + \tau \\ 2 \ e, \mu  (SS) \\ 4 \ e, \mu \\ 3 \ e, \mu + \tau \\ 0 \\ 2 \ e, \mu  (SS) \end{array}$	0-3 b 6-7 jets 0-3 b	· Yes Yes Yes Yes	4.6 4.6 20.3 20.3 20.3 20.3 20.3 20.3	5. 5.5 TeV 5. 1.1.TeV 4.2 750.GeV 5. 750.GeV 6. 916 GeV 8. 916 GeV 8. 916 GeV	$\begin{split} & k_{111}^{i}=0.10,  \lambda_{12}=0.06 \\ & \lambda_{121}^{i}=0.10,  \lambda_{123}=0.06 \\ & m(q)=m(q),  c_{122}=<1mn \\ & m(q_{1}^{21})=0.2 xm(q_{1}^{21}),  \lambda_{221}=0 \\ & m(q_{1}^{21})=0.2 xm(q_{1}^{21}),  \lambda_{221}=0 \\ & m(q_{1}^{21})=0.2 xm(q_{1}^{21}),  \lambda_{221}=0 \\ & BR(q)=BR(q)=BR(q)=0.6 \end{split}$	1212.1272 1212.1272 1404.2500 1405.5086 1405.5086 ATLAS-CONF-2013-091 1404.250
Other	Scalar gluon pair, sgluon $\rightarrow q\bar{q}$ Scalar gluon pair, sgluon $\rightarrow t\bar{t}$ WIMP interaction (D5, Dirac $\chi$ )	0 2 e, µ (SS) 0	4 jets 2 b mono-jet	Yes Yes	4.6 14.3 10.5	sgluon 100-287 GeV sgluon 350-800 GeV M* scale 704 GeV	incl. limit from 1110.2693 $m(\chi){<}80{\rm GeV}, limit of {<}887{\rm GeV}  {\rm for}  {\rm D8}$	1210.4826 ATLAS-CONF-2013-051 ATLAS-CONF-2012-147
	$\sqrt{s} = 7 \text{ TeV}$ full data	$\sqrt{s} = 8$ TeV partial data	$\sqrt{s} = full$	8 TeV data		10-1 1	Mass scale [TeV]	

\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 or theoretical signal cross section uncertainty.

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



N. Craig

ATLAS 1405.7875



ATLAS 1405.7875

N. Craig



ATLAS 1405.7875

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

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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

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

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



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$$H_{inf}\gtrsim V_{max}^{1/4}\sim 10^9~{
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- Observation of (prim.) r would imply some kind of beyond-SM (unless top mass 2 – 3σ below best fit)
- Ways around: small non-minimal coupling, ...



Herranen, Murkkanen, Nurmi, Rajantie 1407.3141

### Baryogenesis and the LHC





### Baryon asymmetry



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  $m_H\gtrsim 70 {\rm GeV}$



from T. Konstandin

### EW baryogenesis

#### MSSM: need very light RH stops, practically excluded



Direct stop search  $pp 
ightarrow { ilde t} { ilde t}$ 

### EW baryogenesis

#### MSSM: need very light RH stops, practically excluded



### EW baryogenesis

#### MSSM: need very light RH stops, practically excluded



- SM+singlet, 2HDM, dim6 Curtin, Meade, Yu 1409.0005; Craig et al 1412.0258;...
- ⇒ Precision Higgs coupling, invisible decay, triple-Higgs measurements crucial (sometimes challenging, HL-LHC)

### Baryogenesis and neutrinos



### Vanilla leptogenesis vs neutrino mass



Di Bari 1206.3168 (unflavoured)

### Vanilla leptogenesis vs neutrino mass



BOSS 1403.4599

Di Bari 1206.3168 (unflavoured)

 $\Rightarrow$  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'

$$\Omega_\chi h^2 = 0.1199 \pm 0.0027 \simeq 0.1\, {
m pb} \cdot c \,/\langle \sigma 
u 
angle$$

Planck XVI 1303.5076



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

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

Planck XVI 1303.5076

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

e.g. 1305.5597 1310.0828, 1410.2242; 1301.1173



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, ... ⇒ 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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Calore, Cholis, Weniger 1409.0042

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

B. Andersson, Fermi LAT dwarf Pass 8

### 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

### 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
- Most model-independent: effective operator description
  - Straightforward and systematic
  - Limited reach of validity @ LHC energies

### DM and the LHC



CMS 1408.3583

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

### DM and the LHC



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### DM and the LHC



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



### 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  $m_\eta \lesssim 5 m_\chi$ , Majorana)



Bergstrom 89; Bergstrom, Bringmann, Edsjo 0710.3169

### When is the mediator important?

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



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



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)

DM coupling to u-quark



MG, Ibarra, Rydbeck, Vogl 1403.4634

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DM coupling to u-quark



MG, Ibarra, Rydbeck, Vogl 1403.4634

### Complementarity (for thermal production)

DM coupling to u-quark (prospects)



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), ...



### Conclusion

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- Also many other interesting connections: neutrino mass, models/scale of inflation, DM self-interactions, topological defects reheating vs heavy ion (QFT in extreme environments), ...



thank you!

image from T. Kamon

### Massive neutrinos and leptogenesis

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

Add right-handed neutrinos to SM, seesaw explains why  $m_{\nu}$  is so small

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



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... and baryon asymmetry

Fukugita, Yanagida 86

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

$$\begin{split} (\Gamma_i/H)|_{\mathcal{T}=M_i} &\simeq \quad \frac{\tilde{m}_{\nu,i}/8\pi}{1.66g_*v_{EW}^2/M_{pl}} \simeq \tilde{m}_{\nu,i}/\text{meV} \\ &\sim \quad \mathcal{O}(1-100) \iff \frac{\text{leptogenesis works well}}{\text{for observed }\nu \text{ mass scale}} \end{split}$$

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

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  $\mathcal{L} = 20.3 \text{ fb}^{-1}$  (signal regions with 2-4jets; matching for two ad. jets) ATLAS 1405.7875; ATLAS-CONF-2013-047