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

19 months

16th Feb.

2013 2014 2015


LHC

SPS

PS

PS Booster

beam to beam

available for works

Physics
Beam commissioning
Shutdown
Powering tests

from F. Bordry
8th October 2014
The LHC timeline

L~7x10^{33}  
Pile-up~20-35

L=1.6x10^{34}  
Pile-up~30-45

L=2-3x10^{34}  
Pile-up~50-80

L=5x10^{34}  
Pile-up~130-200
### Higgs

**ATLAS Prelim.**  
$m_H = 125.36 \text{ GeV}$

### Signal Strength ($\mu$)

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\mu$</th>
<th>Total Uncertainty</th>
<th>$\sigma$(stat.)</th>
<th>$\sigma$(sys inc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$1.17^{+0.27}_{-0.27}$</td>
<td>$1.17^{+0.23}_{-0.33}$</td>
<td>$+0.16$</td>
<td>$-0.11$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4l$</td>
<td>$1.44^{+0.40}_{-0.33}$</td>
<td>$1.44^{+0.21}_{-0.11}$</td>
<td>$+0.34$</td>
<td>$-0.31$</td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow l\ell\nu\nu$</td>
<td>$1.08^{+0.22}_{-0.20}$</td>
<td>$1.08^{+0.16}_{-0.13}$</td>
<td>$+0.16$</td>
<td>$-0.15$</td>
</tr>
<tr>
<td>$W,Z H \rightarrow b\bar{b}$</td>
<td>$0.5^{+0.4}_{-0.4}$</td>
<td>$0.5^{+0.2}_{-0.2}$</td>
<td>$+0.3$</td>
<td>$-0.3$</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>$1.4^{+0.4}_{-0.4}$</td>
<td>$1.4^{+0.3}_{-0.3}$</td>
<td>$+0.3$</td>
<td>$-0.3$</td>
</tr>
</tbody>
</table>

- $\sqrt{s} = 7 \text{ TeV}$, $L dt = 4.5-4.7 \text{ fb}^{-1}$
- $\sqrt{s} = 8 \text{ TeV}$, $L dt = 20.3 \text{ fb}^{-1}$
Higgs couplings at HL-LHC

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 $1/2$
  ✓ $\gamma\gamma$ 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

<table>
<thead>
<tr>
<th>Model</th>
<th>(e, \mu, \tau, \gamma, ) Jets</th>
<th>(E_{\text{miss}}^T)</th>
<th>(\sqrt{s})</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inclusive Searches</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSUGRA/CMSSM</td>
<td>1 2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.27 TeV</td>
</tr>
<tr>
<td>MSUGRA/CMSSM</td>
<td>1 3-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.1 TeV</td>
</tr>
<tr>
<td>MSUGRA/CMSSM</td>
<td>0 7-10 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.1 TeV</td>
</tr>
<tr>
<td>GMSB (NLS)</td>
<td>1 2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.33 TeV</td>
</tr>
<tr>
<td>GMSB (NLS)</td>
<td>0 3-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.18 TeV</td>
</tr>
<tr>
<td>GGM (NLO)</td>
<td>1 2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.12 TeV</td>
</tr>
<tr>
<td>GGM (NLO)</td>
<td>2 0-3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.12 TeV</td>
</tr>
<tr>
<td>GGM (NLO)</td>
<td>0 5-9 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.28 TeV</td>
</tr>
<tr>
<td>GGM (NLO)</td>
<td>1 (e, \mu, \tau)</td>
<td>Yes</td>
<td>20.3</td>
<td>1.28 TeV</td>
</tr>
<tr>
<td>GGM (NLO)</td>
<td>0 mono-jet</td>
<td>Yes</td>
<td>20.3</td>
<td>1.3 TeV</td>
</tr>
</tbody>
</table>

| **Other** | | | | |
| Scalar gluon pair, \(g_{\gamma} + g_{\gamma}\) | 4 jets | - | 10-1 | 100-287 GeV |
| Scalar gluon pair, \(g_{\gamma} + h\) | 2 jets | - | 10-1 | 285-620 GeV |
| WIMP interaction (D, Dirac) | 0 mono-jet | Yes | 10.5 | 850 GeV |

**Reference**

- ATLAS-CONF-2013-062
- ATLAS-CONF-2013-089
- ATLAS-CONF-2014-001
- ATLAS-CONF-2014-144
- ATLAS-CONF-2014-152
- ATLAS-CONF-2012-147
- ATLAS-CONF-2013-069
- ATLAS-CONF-2013-058
- ATLAS-CONF-2013-091
- ATLAS-CONF-2013-092
- ATLAS-CONF-2012-069
- ATLAS-CONF-2013-051
- ATLAS-CONF-2012-147

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

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**Supersymmetry?**

### ATLAS Preliminary

\[ \sqrt{s} = 7, 8 \text{ TeV} \]

<table>
<thead>
<tr>
<th>Mass scale [TeV]</th>
<th>(\sqrt{s} = 7 \text{ TeV} ) full data</th>
<th>(\sqrt{s} = 8 \text{ TeV} ) full data</th>
<th>(\sqrt{s} = 8 \text{ TeV} ) partial data</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

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Supersymmetry?

Squark-gluino-neutralino model

\[
\begin{align*}
\text{Gluino mass [GeV]} & \quad 800 & 1000 & 1200 & 1400 & 1600 & 1800 & 2000 & 2200 & 2400 \\
\text{Squark mass [GeV]} & \quad 800 & 1000 & 1200 & 1400 & 1600 & 1800 & 2000 & 2200 & 2400 & 2600 & 2800 \\
\end{align*}
\]

\[
\int L \, dt = 20.3 \text{ fb}^{-1}, \quad \sqrt{s} = 8 \text{ TeV} \\
0\text{-lepton, 2-6jets}
\]

\[
\text{ATLAS 1405.7875} \\
N. Craig
\]
Supersymmetry?

**Diagram:**
- **Axes:** $m_q$ vs $m_{\chi_i}$
- **Legend:**
  - Observed limit ($\pm 1 \sigma_{\text{theo}}$)
  - Expected limit ($\pm 1 \sigma_{\text{exp}}$)
- **ATLAS**
- **Plot Details:**
  - $\sqrt{s} = 8$ TeV, $\int L dt = 20.3$ fb$^{-1}$
  - Numbers give 95% CL excluded cross section [fb]

**Equations and Notations:**
- $\chi \rightarrow \bar{q} \gamma$
- $\bar{q}$
- $q$
- $\bar{\chi}$
- $\gamma$

**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
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
  \[ H_{\text{inf}} \gtrsim V_{\text{max}}^{1/4} \sim 10^9 \text{ GeV} \]
- Observation of (prim.) $r$ would imply some kind of beyond-SM (unless top mass $2 - 3\sigma$ below best fit)

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

*Fairbairn, Hogan 1403.6786, $H_{\text{inf}} = 10^{14}$ GeV*
SM vacuum instability and inflation

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- Observation of (prim.) $r$ would imply some kind of beyond-SM
  (unless top mass $2 - 3\sigma$ below best fit)
- Ways around: small non-minimal coupling, . . .

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

Fairbairn, Hogan 1403.6786, $H_{\text{inf}} = 10^{14} \text{ GeV}$
Herranen, Murkkanen, Nurmi, Rajantie 1407.3141
Baryogenesis and the LHC

Collider exp. + Baryon asymmetry
Baryon asymmetry

\[ Y_P = 4n_{\text{He}}/n_b \]

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

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

Consistent value BBN \((T \sim \text{keV})\) and CMB \((T \sim \text{eV})\)

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

Baryogenesis \((\sim 10^9 + 1 : 10^9 \text{ particles vs antiparticles})\)

- 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 $m_H \gtrsim 70\,\text{GeV}$

from T. Konstandin
EW baryogenesis

- MSSM: need very light RH stops, practically excluded

Direct stop search \( pp \rightarrow \tilde{t}\tilde{t} \)
EW baryogenesis

MSSM: need very light RH stops, practically excluded

Indirect from Higgs couplings to gluon/photon via stop loop

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

Atlas 1407.0608; 1406.1122

Curtin, Jaiswal, Meade 1203.2932
EW baryogenesis

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

Atlas 1407.0608; 1406.1122

Indirect from Higgs couplings to gluon/photon via stop loop

Atlas 1407.0608; 1406.1122

- SM+singlet, 2HDM, dim6

Curtin, Jaiswal, Meade 1203.2932

⇒ 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

\[ m_1 < 0.12 \text{ eV} \]

\[ M_1 \gtrsim 3 \times 10^9 \text{ GeV} \]

\[ T_{\text{reh}} \gtrsim 10^9 \text{ GeV} \]

*Di Bari 1206.3168 (unflavoured)*
Vanilla leptogenesis vs neutrino mass

$M_1 \gtrsim 3 \times 10^9 \text{ GeV}$

$\Rightarrow T_{\text{reh}} \gtrsim 10^8 \text{ GeV}$

$m_1 < 0.12 \text{ eV}$

$\Rightarrow \text{absolute neutrino mass scale is very important ingredient}$
Dark Matter and the LHC
Dark Matter

\[ \Omega_{\chi} h^2 = 0.1199 \pm 0.0027 \]

*Planck XVI 1303.5076*
Many dark matter candidates proposed, with very different characteristics...

The production mechanism of dark matter particles is very model dependent.
‘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, ...
‘The decade of the WIMP’

\[ \Omega \chi h^2 = 0.1199 \pm 0.0027 \simeq 0.1 \text{ pb} \cdot c / \langle \sigma v \rangle \]

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, …
Many experiments at edge of sensitivity for WIMP\textsubscript{y} cross sections

Large uncertainties: need input from simulations, halo profile, substructures, velocity distribution, . . . ; foregrounds, cosmic ray propagation, . . . ⇒ Collider/CMB bounds highly desirable
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

Counts, 2.12 - 3.32 GeV

0 14
0.1
Residuals (Counts - Model)
-3.84 3.84
Residuals, GCE templ. readded

Galactic center excess?

Calore, Cholis, Weniger 1409.0042

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

Galactic center excess?

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

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

\[ \mathcal{L}_S = \frac{\bar{\chi} \chi \alpha_s G_{\mu\nu} G^{\mu\nu}}{\Lambda^3} \]

\[ \ldots \]

\[ CMS \ 1408.3583 \]

\[ cf. \ also \ Goodman, \ Ibe, \ Rajamaran, \ Sheperd, \ Tait, \ Yu \ 10; \ Bai, \ Fox, \ Harnik \ 10 \]
DM and the LHC

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

\[ \mathcal{L}_S = \frac{\bar{\chi} \chi \alpha_s \, G_{\mu\nu} \, G^{\mu\nu}}{\Lambda^3} \]

\[ \mathcal{L}_A = \frac{\bar{\chi} \gamma_\mu \gamma_5 \chi \, \bar{q} \gamma^\mu \gamma_5 q}{\Lambda^2} \]

\[ \ldots \]

Axial-vector operator

\[ \frac{(\gamma_\mu \gamma_5 \chi)(\bar{q} \gamma^\mu \gamma_5 q)}{\Lambda^2} \]

\( \chi \)-Nucleon Cross Section [cm\(^2\)]

**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; \ldots

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

\[ CMS \ 1408.3583 \]
DM and the LHC

\[ \mathcal{L}_V = \frac{\bar{\chi} \gamma_\mu \chi \bar{q} \gamma^\mu q}{\Lambda^2} \]
\[ \mathcal{L}_S = \frac{\bar{\chi} \chi \alpha_s G_{\mu\nu} G^{\mu\nu}}{\Lambda^3} \]
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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

\[ \chi \quad \text{SM} \quad \chi \quad \text{SM} \]

t-channel

\[ \chi \quad \eta \quad \text{SM} \quad \chi \quad \bar{\text{SM}} \]
When is the mediator important?

- Collider searches (direct production of mediator for $m_\eta \lesssim 2 - 3$ TeV)
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- 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
When is the mediator important?

- Collider searches (direct production of mediator for $m_\eta \lesssim 2 - 3$ TeV)
  
  \begin{align*}
  \text{A1} & : g \bar{\eta} g \eta g s g s \\
  \text{A2} & : g \bar{\eta} g \eta g^2 s \\
  \text{A3} & : q \bar{\eta} \bar{q} \eta g s g s \\
  \text{A4} & : q q \eta \chi \eta f f
  \end{align*}

- Indirect detection (internal bremsstrahlung for $m_\eta \lesssim 5m_\chi$, Majorana)
  
  \begin{align*}
  \text{Bergstrom 89; Bergstrom, Bringmann, Edsjo 0710.3169} \\
  \text{A1} & : \chi \bar{q} \eta \chi q \\
  \text{A2} & : \chi \eta \chi q \gamma \\
  \text{A3} & : \chi \bar{q} \gamma \eta \chi
  \end{align*}

- Direct detection (EFT OK, except resonance for $m_\eta \simeq m_\chi$)
  
  \begin{align*}
  \text{Hisano, Ishiwata, Nagata 1110.3719; Gondolo, Scopel 1307.4481; Drees, Nojiri; \ldots} \\
  \text{A1} & : \chi \chi \eta \chi \eta \\
  \text{A2} & : g \chi \chi g \eta g g
  \end{align*}
Complementarity (for thermal production)

DM coupling to u–quark

$\Delta m \approx m_h - m_c$

$y = 0.33$

$\mathcal{M}_G, Ibarra, Rydbeck, Vogl$ 1403.4634
Complementarity (for thermal production)

DM coupling to u–quark

\[ \frac{m}{m_e} \]

\[ \Delta m \]

\[ h = \text{squark} \]

\[ y = 0.33 \]

\[ H.E.S.S. \]

\[ XENON100 \]

\[ LUX \]

\[ \text{ATLAS Monojet} \]

\[ \text{ATLAS jets + ETmiss} \]

\[ \text{overproduction/ non-pert.} \]

\[ \text{underproduction} \]

\[ \text{MG, Ibarra, Rydbeck, Vogl 1403.4634} \]
Complementarity (for thermal production)

DM coupling to u–quark (prospects)

\[ m_{\chi}/m_{\tilde{b}} \]

\[ m_\chi \text{ [GeV]} \]

ATLAS
jets + ETmiss

overproduction/
non-pert.

underproduction

XENON100
XENON1T
LUX

CMG, Ibarra, Rydbeck, Vogl 1403.4634
DM coupling to leptons
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

- 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), . . .
Massive neutrinos and leptogenesis

\[ m_{\nu_1}^2 - m_{\nu_2}^2 = 7.02\ldots8.09 \cdot 10^{-5} \text{eV}^2 \quad (3\sigma \text{ range}) \]
\[ |m_{\nu_1}^2 - m_{\nu_3}^2| = 2.31\ldots2.60 \cdot 10^{-3} \text{eV}^2 \]

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

\[ m_{\nu} = -v_{EW}^2 y \hat{M}_{\nu_R}^{-1} y^T \]
Massive neutrinos and leptogenesis

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Add right-handed neutrinos to SM, seesaw explains why \( m_\nu \) is so small

\[ m_\nu = -v_{EW}^2 y \hat{M}_{\nu R}^{-1} y^T \]

\[ \ldots \text{and baryon asymmetry} \]

- 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 \( \nu_R \leftrightarrow \ell^c \phi \)

\[ (\Gamma_i/H)|_{T=M_i} \simeq \frac{\tilde{m}_{\nu,i}/8\pi}{1.66g_v^2v_{EW}^2/M_{pl}} \simeq \tilde{m}_{\nu,i}/\text{meV} \]

\[ \sim \mathcal{O}(1-100) \leftrightarrow \text{leptogenesis works well for observed } \nu \text{ mass scale} \]
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 2-4 jets; matching for two ad. jets)