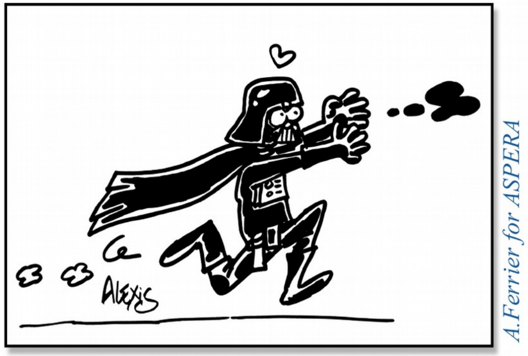
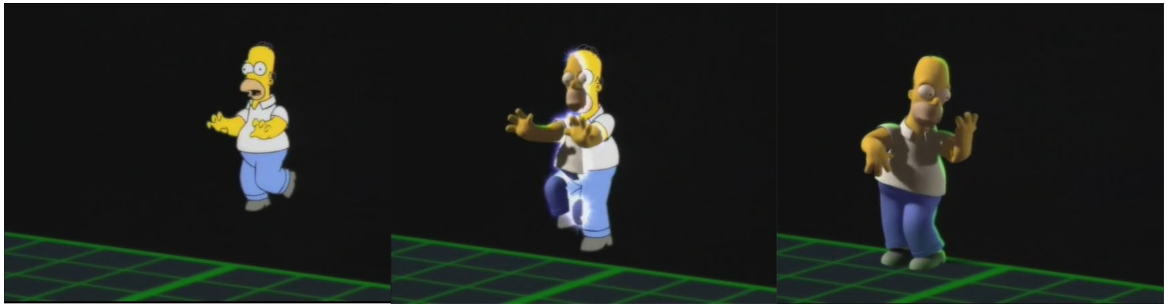




Searches for dark matter and extra dimensions at the LHC

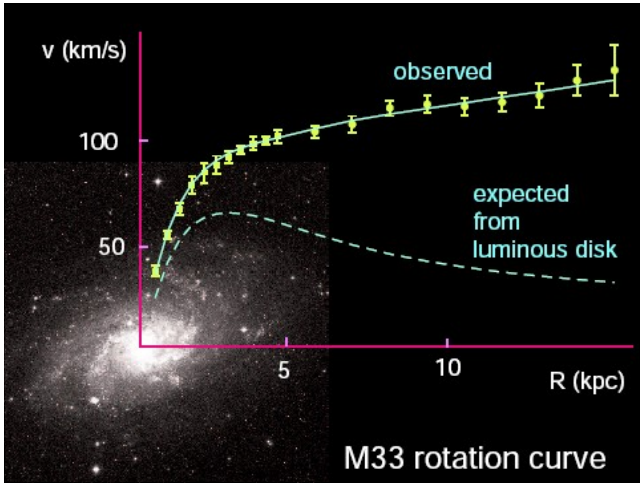
A review of the latest results

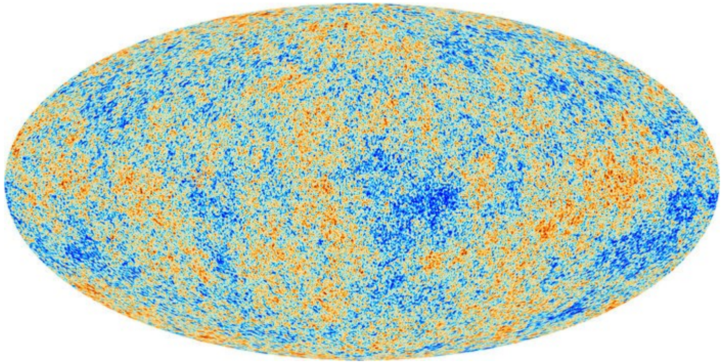
Marie-Hélène Genest

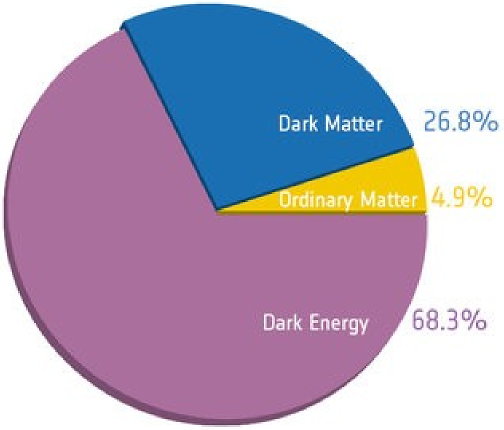
On behalf of the ATLAS and CMS Collaborations

Dark Matter

- Multiple evidences for the existence of dark matter





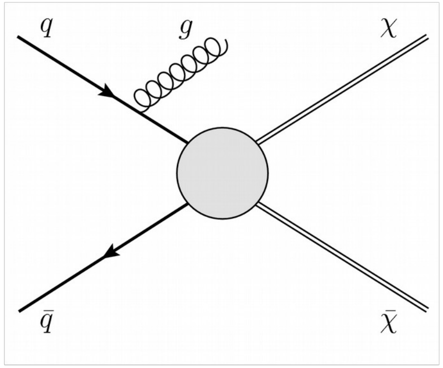


- A stable neutral weakly interacting massive particle (WIMP) is a good candidate : need to go beyond the SM
- No unambiguous direct detection so far
- The LHC can complement direct detection limits

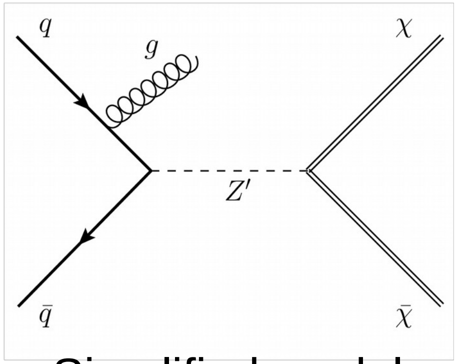
arXiv:1502.01518
submitted to EPJC

Jet+ E_T^{miss}

- Invisible DM particles escape detection:
  - Tag events using recoiling object(s)
  - Measure the missing transverse momentum (E_T^{miss})

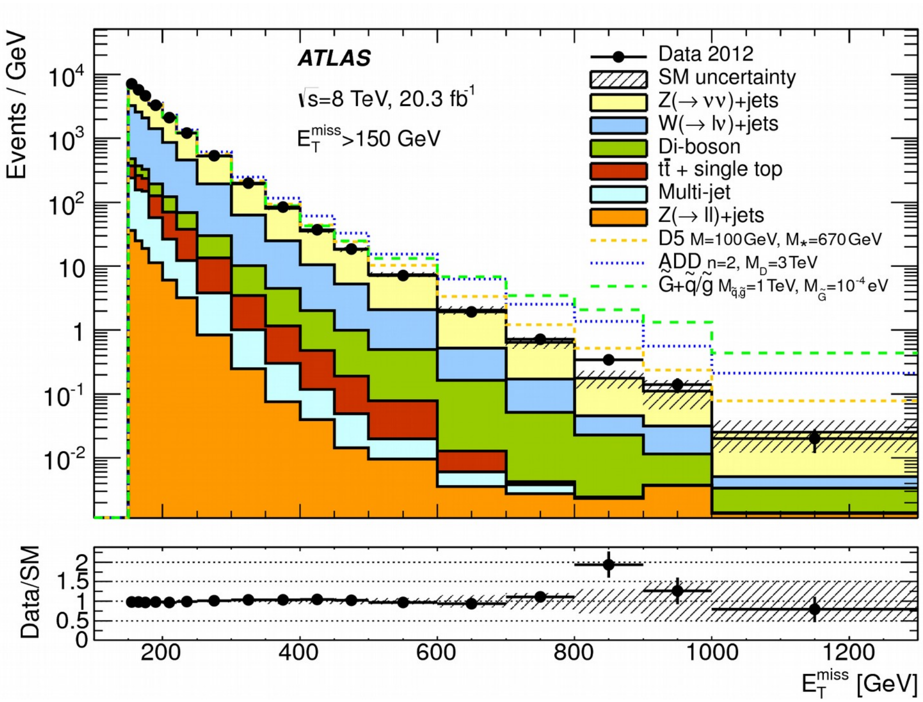


EFT

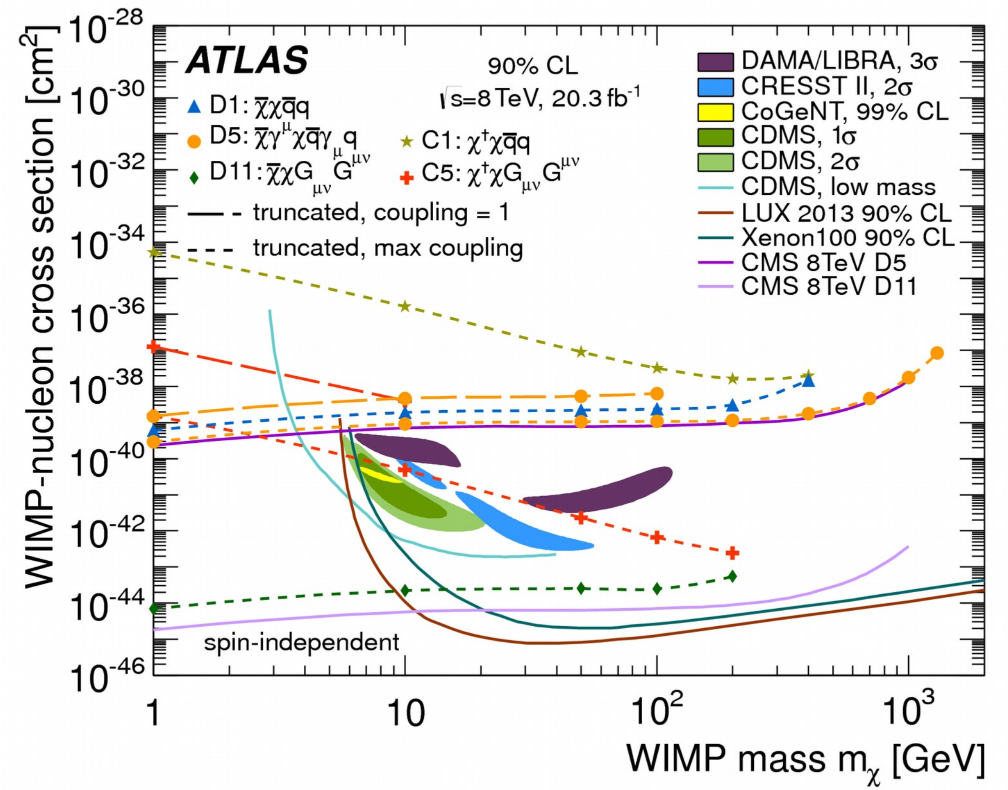


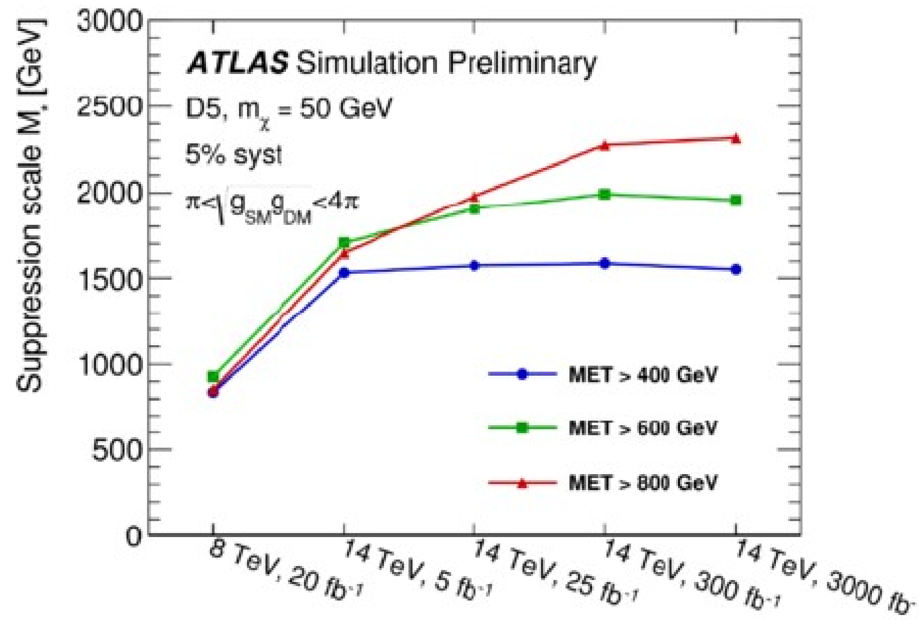
Simplified model

- Event selection:
  - Leading jet within |η| < 2.0 and with p_T > min(120 GeV, 0.5*E_T^{miss})
  - 9 signal regions with E_T^{miss} thresholds from 150 to 700 GeV
  - $\Delta\varphi$(sel. jets, E_T^{miss})>1.0
  - Lepton and isolated track veto
- Z(νν)+jets BG constrained using W(lν) and Z(ll) control regions



Jet+ E_T^{miss}



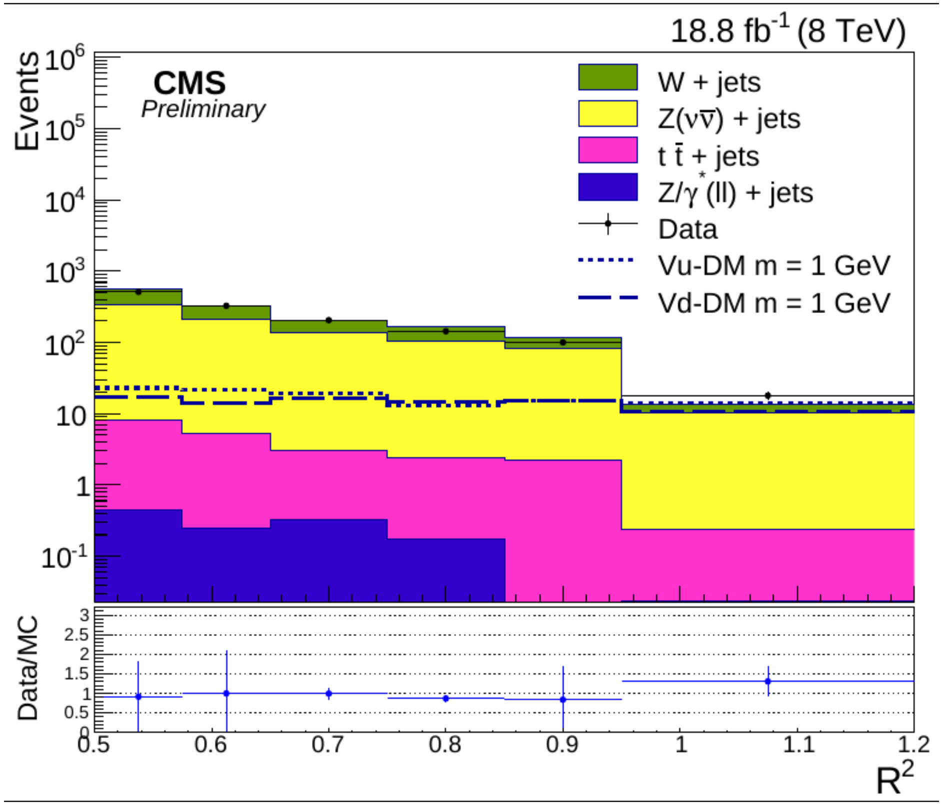


- **Model-dependent comparison !**
  - Complementarity: outlines strengths of each of the experiments
- Truncation procedure applied to ensure EFT validity
- Simplified model results also available
- Improved sensitivity expected within the first months of run-2

Using the razor instead

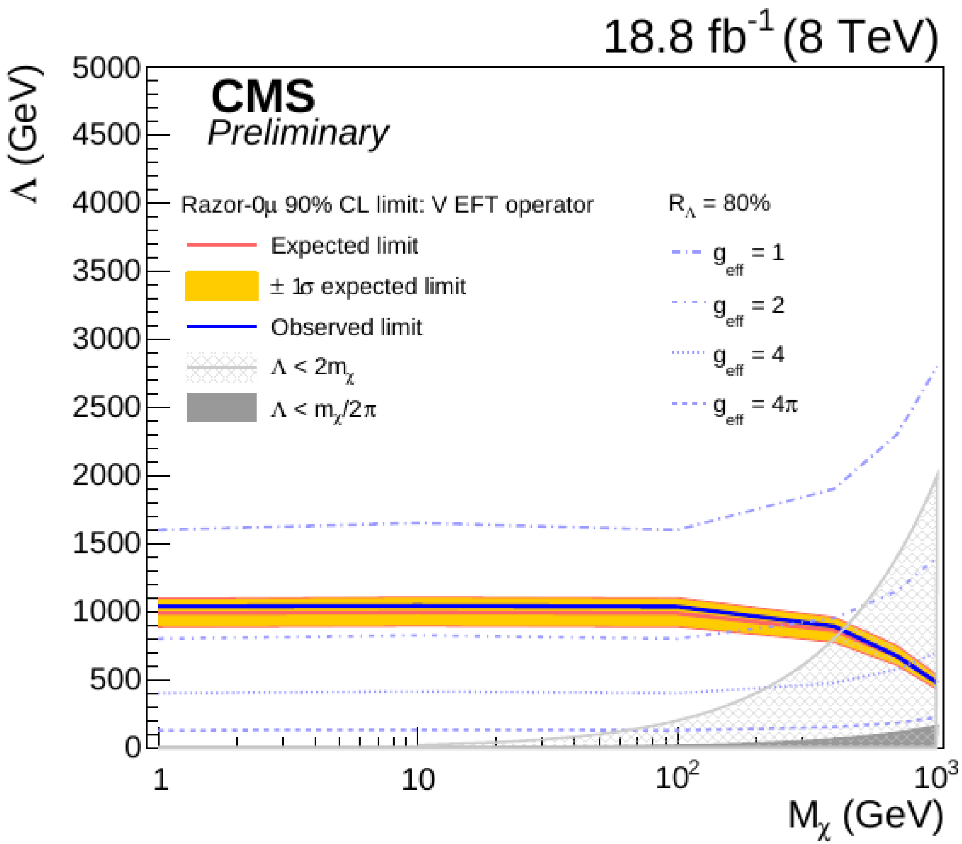
Idea first proposed in Phys. Rev. D 86 (2012) 015010

- ≥2 jets with p_T > 80 GeV and $|\eta| < 2.4$
- Form two megajets (all presel. jets) with $|\Delta\varphi(J_1,J_2)| < 2.5$
- Compute the razor variables :
  - $$M_R \equiv \sqrt{(|\vec{p}_{J_1}| + |\vec{p}_{J_2}|)^2 - (p_z^{J_1} + p_z^{J_2})^2}$$
  - $$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{J_1} + p_T^{J_2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{J_1} + \vec{p}_T^{J_2})}{2}}$$
  - $$R \equiv \frac{M_T^R}{M_R}$$
- M_R > 200 GeV and $R^2 > 0.5$
  - Background highly peaked at low R^2 (back-to-back megajets)
  - Signal evenly distributed in R^2
- BG estimated from muon CRs



Using the razor instead

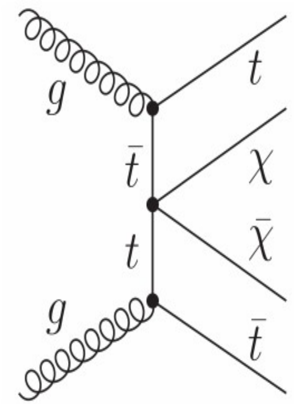
- Limits on the EFT suppression scale comparable to the jet+E_T^{miss}search
  - The looser selection compensates the lower cross section due to the 2-jet requirement
- Both analyses are mostly independent

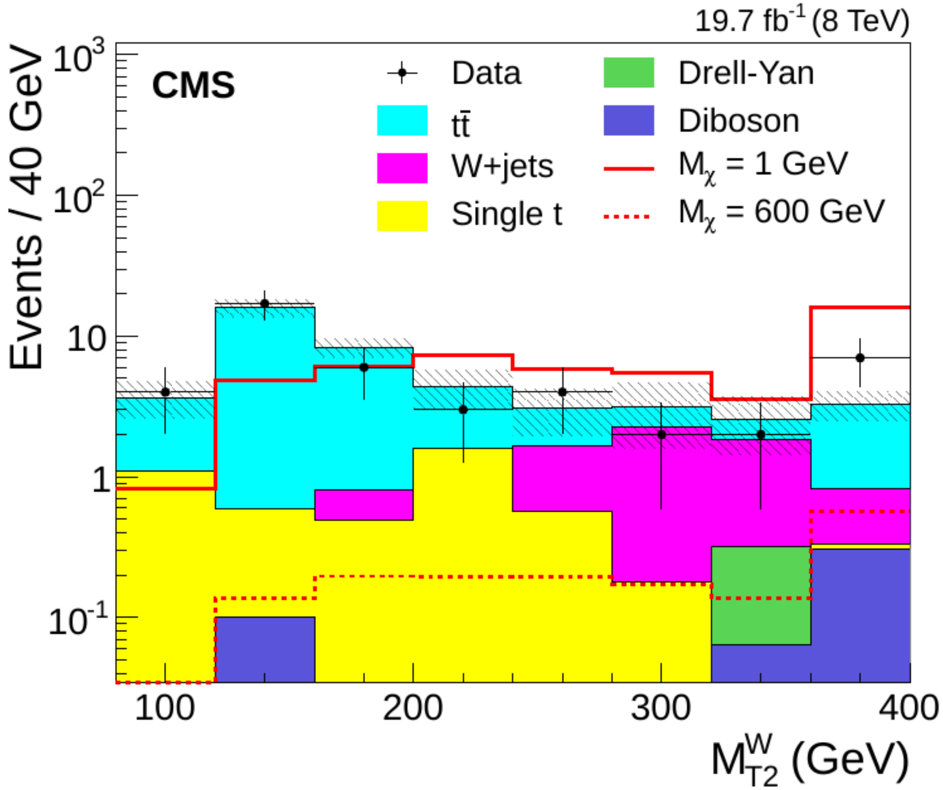


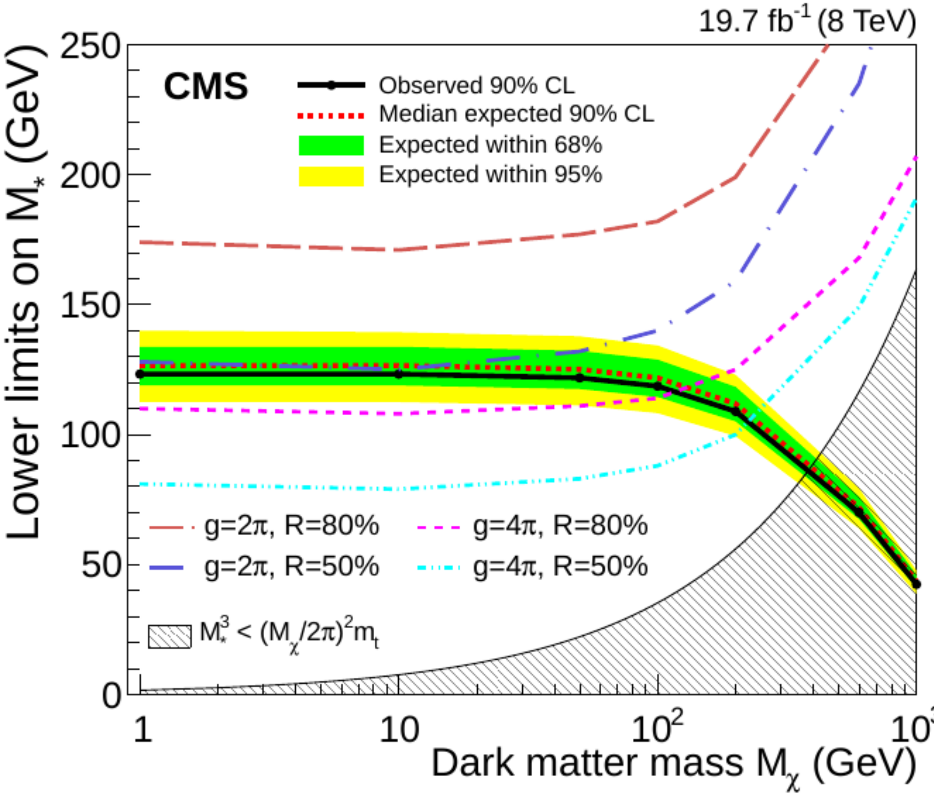
arxiv:1504.03198
submitted to JHEP

Search for DM + $t\bar{t}$

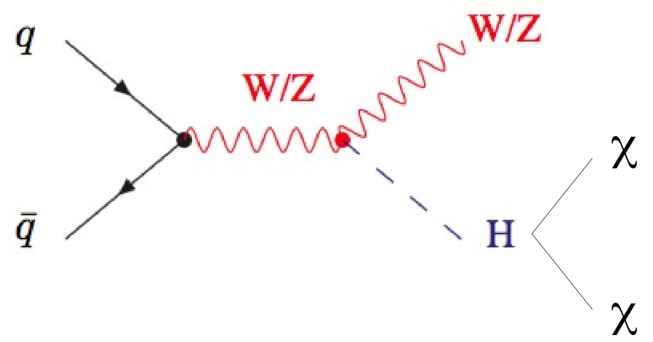
- EFT with scalar interaction : proportional to quark mass
  - Better constraints when DM couples to heavy quarks
- Semileptonic $t\bar{t}$ considered:
  - 1 lepton, ≥ 3 jets, ≥ 1 b-tagged
  - E_T^{miss} > 320 GeV, m_T > 160 GeV, $\Delta\varphi(j_{1,2}, E_T^{miss})$>1.2
  - m_{T2}^W > 200 GeV
    - Minimal "parent" mass using p_T and mass constraints, assuming two identical parents decaying to bW



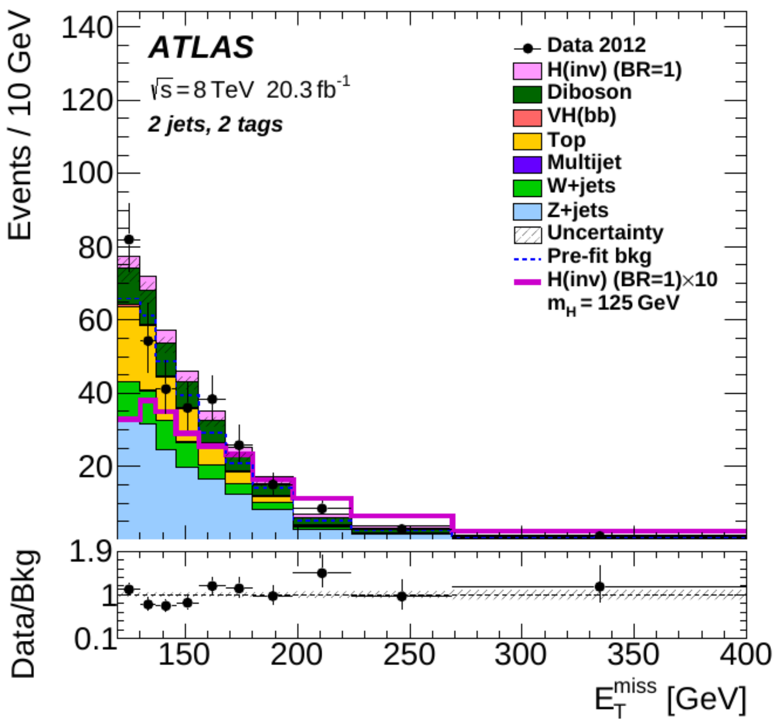




V(jj) + H(invisible)

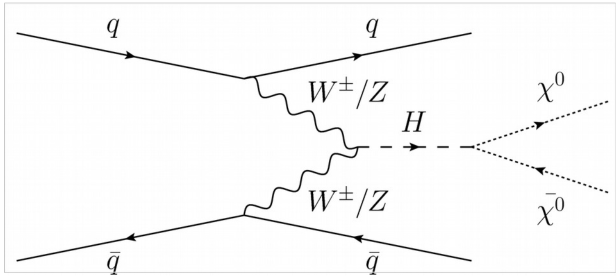


- Higgs boson portal model :
  - The Higgs can decay into a pair of DM particles if kinematically allowed
- Look for BR(Higgs → invisible)
- Hadronic W/Z + large E_T^{miss} :
  - 6 categories (2/3 jets, 0/1/2 b-tags)
  - m_{jj} and ΔR_{jj} cuts depending on E_T^{miss}
- BR(Higgs → invisible) < 78%

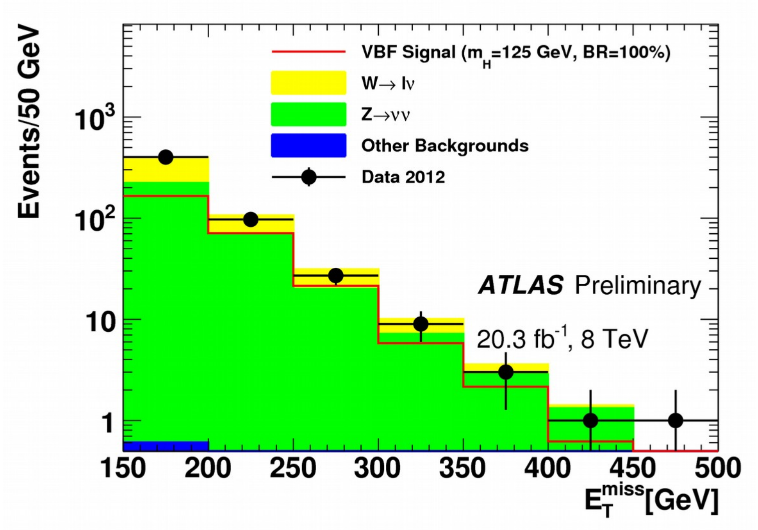


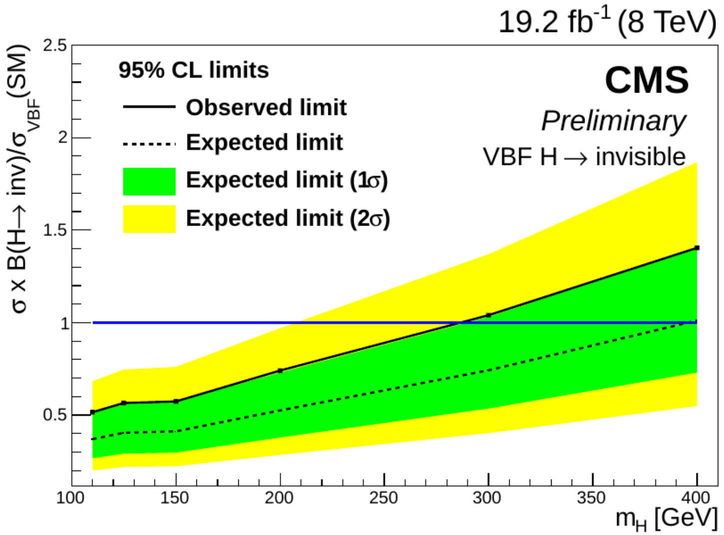
ATLAS-CONF-2015-004
CMS-PAS-HIG-14-038

VBF H(invisible)



- One can also look in the more sensitive VBF mode
- ATLAS:
  - Only m_H = 125 GeV probed; simultaneous fit to the signal region and several control regions
- CMS :
  - Update to a previous analysis, using parked triggers with looser thresholds





BR(Higgs→invisible) < 35% (29%)
To be combined with ZH(inv)

BR(Higgs→invisible) < 47% (35%)
after combination with ZH(inv)

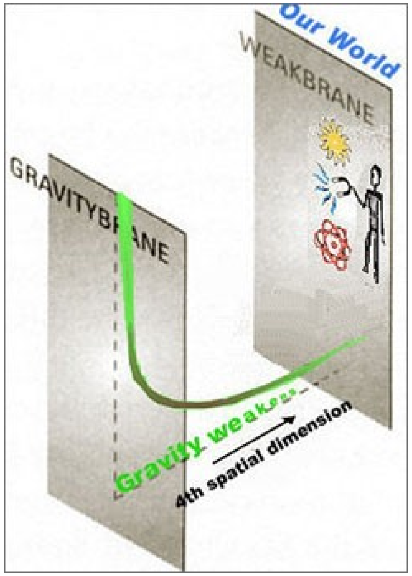
Extra dimensions

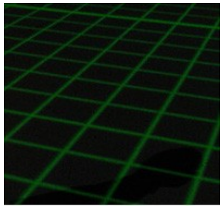
- Proposed solution the hierarchy problem
  - The gravity can propagate in the extra dimensions
  - Quantum black holes (QBH) can also be produced as the effective Planck scale is significantly smaller than the nominal one
- Arkani-Hamed, Dimopoulos, Dvali (ADD) model :
  - New fundamental Planck scale M_D for n extra dimensions
  - Extra dimensions compactified
    - Kaluza-Klein towers of massive graviton modes

Compactified dimensions

$$M_{Pl}^2 = M_D^{2+n} R^n$$

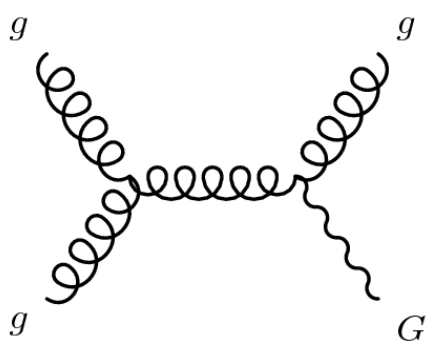
- Randall-Sundrum (RS) model :
  - 5-dimensional space-time bounded by (3+1) branes
    - SM localised on one of them
    - Gravity on the other but propagate in all dimensions
    - Extra dimension warped with curvature scale *k*
  - Series of Kaluza-Klein excitations G* of the graviton
    - the lightest is narrow, could be produced at the LHC

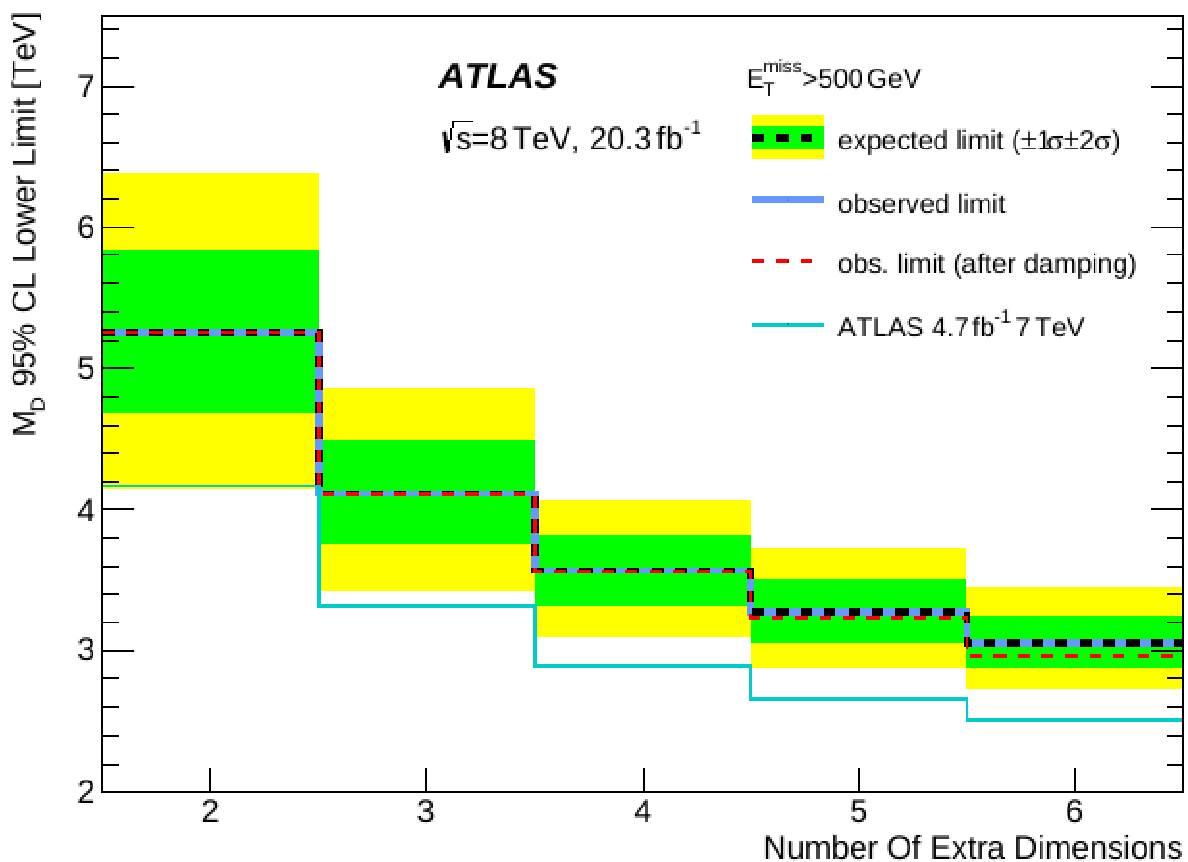




Jet+ E_T^{miss}

- The results of the search introduced before can also be interpreted in terms of limits on M_D in an ADD model :

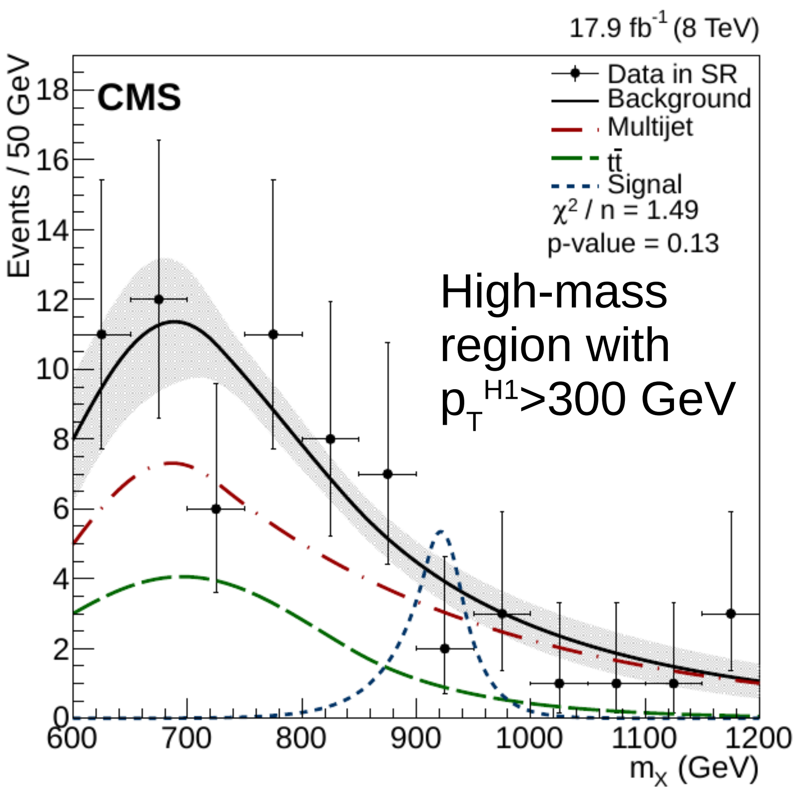




arxiv:1503.04114
submitted to PLB

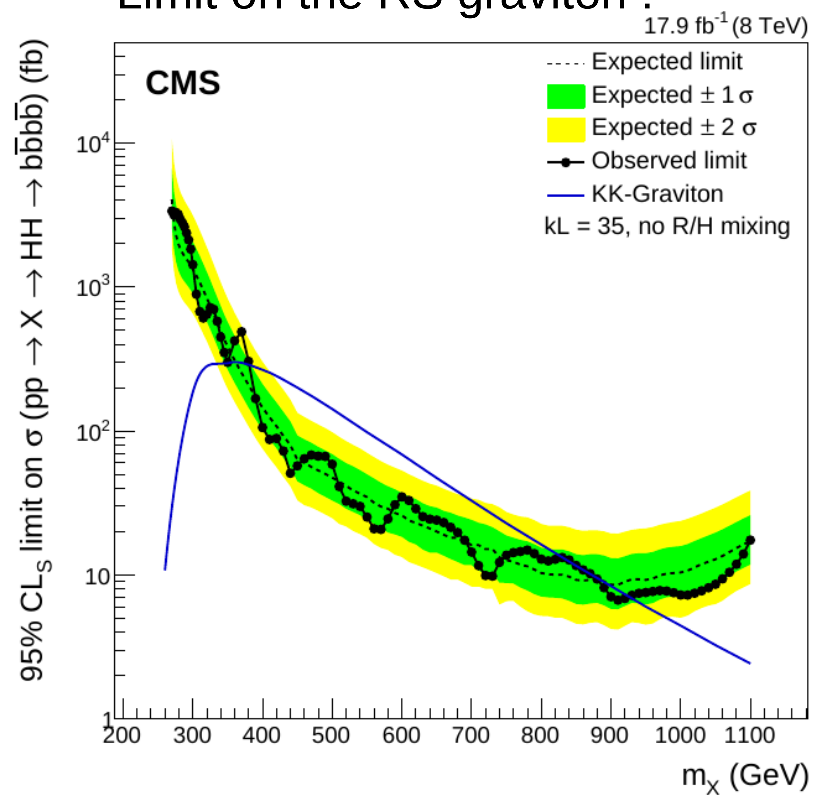
HH($b\bar{b}b\bar{b}$) resonance

- The RS graviton can decay in HH
- 4 b-jet forming two Higgs candidates + $\Delta m_{H1}^2 + \Delta m_{H2}^2 < (17.5\ \mathrm{GeV})^2$
  - Low-mass region (270 to 450 GeV)
  - High-mass region (450 to 1100 GeV) : $\Delta R(jj)<1.5$ for each Higgs candidate
    - 740 to 1100 GeV : p_T^{H1}>300 GeV



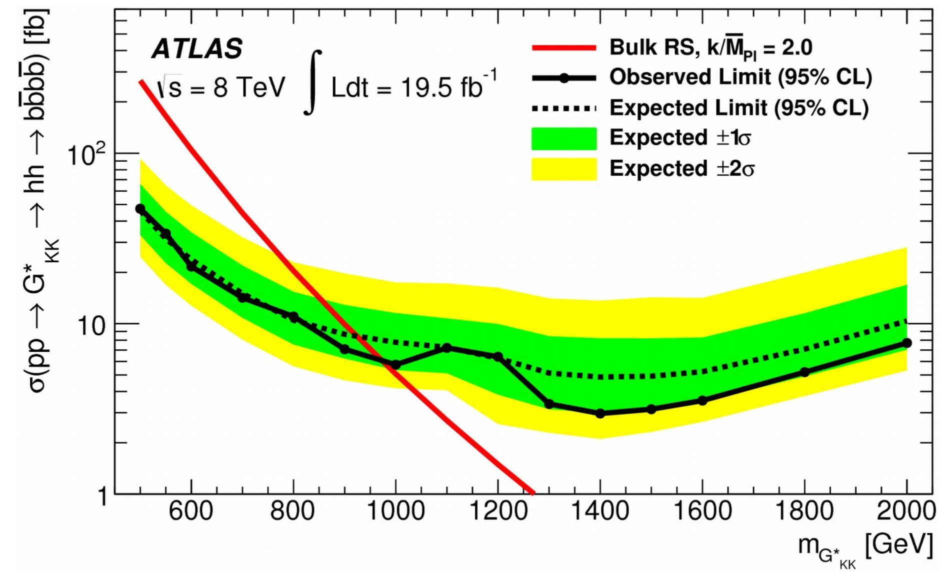
High-mass region with p_T^{H1}>300 GeV

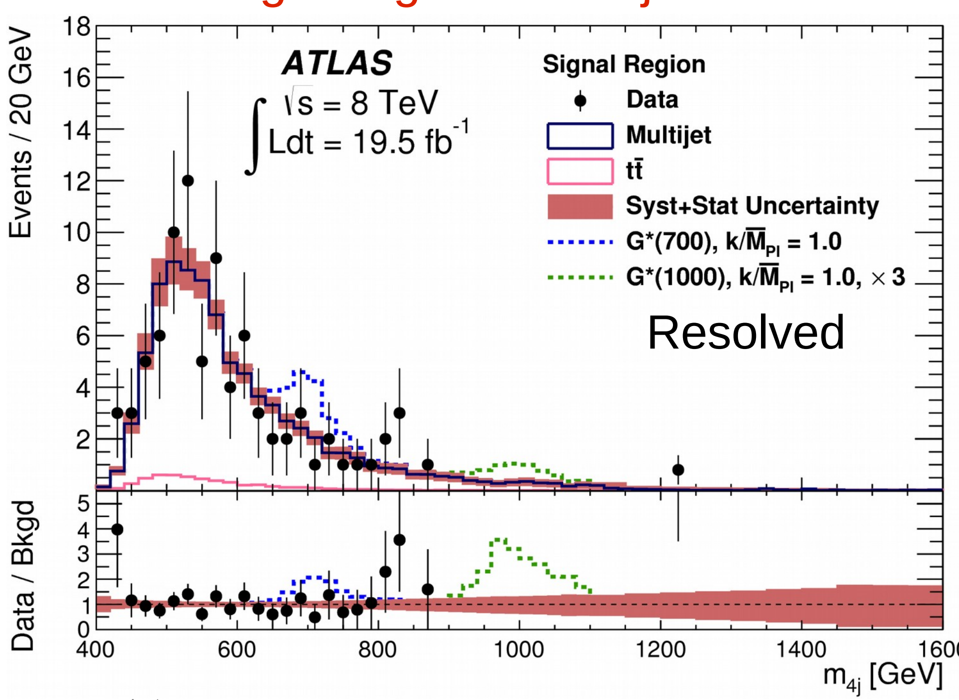
Limit on the RS graviton :

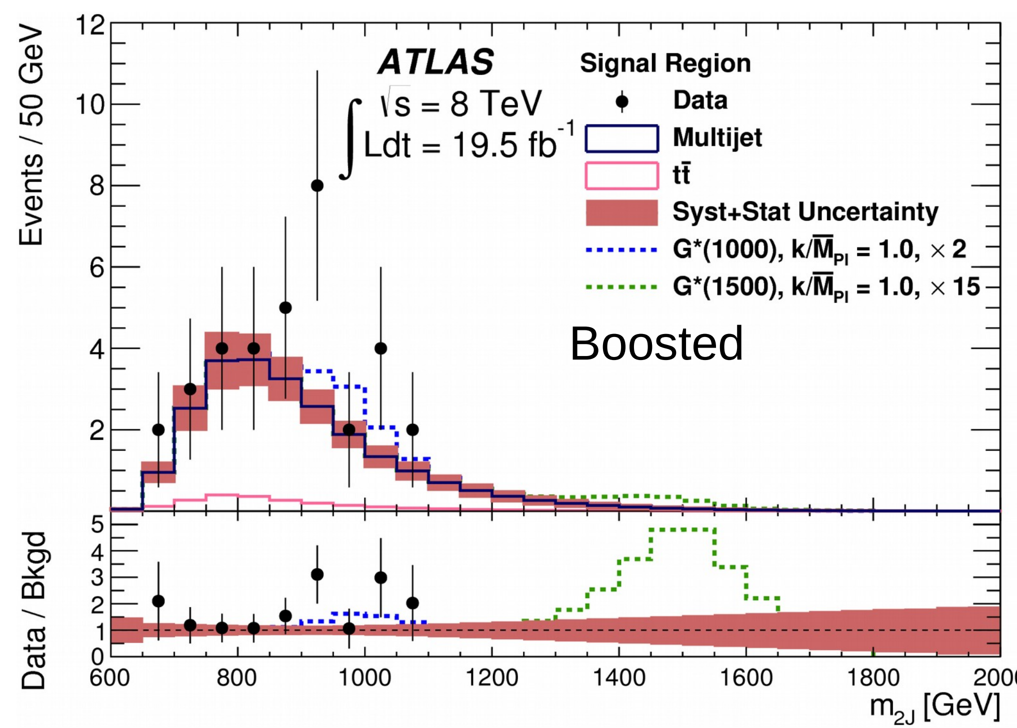


HH($b\bar{b}b\bar{b}$) resonance

- Resolved Regime:
  - At least 4 b-tagged jets
  - Form dijets with highest p_T jets
  - Mass-dependent cuts
- Merged Regime (boosted H):
  - Two trimmed large-R jets
  - b-tag using track-subjets



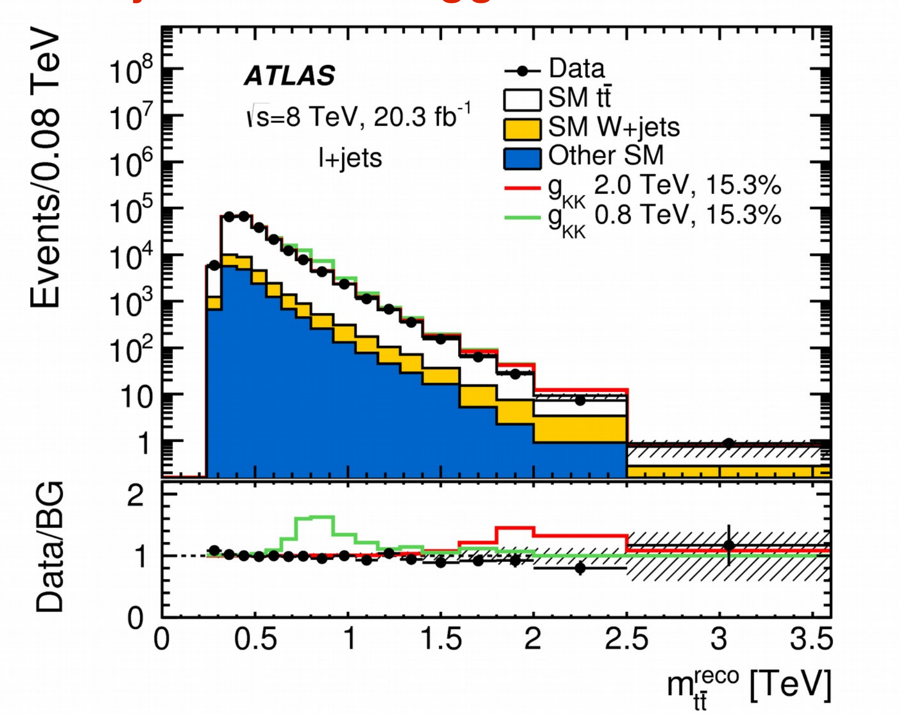




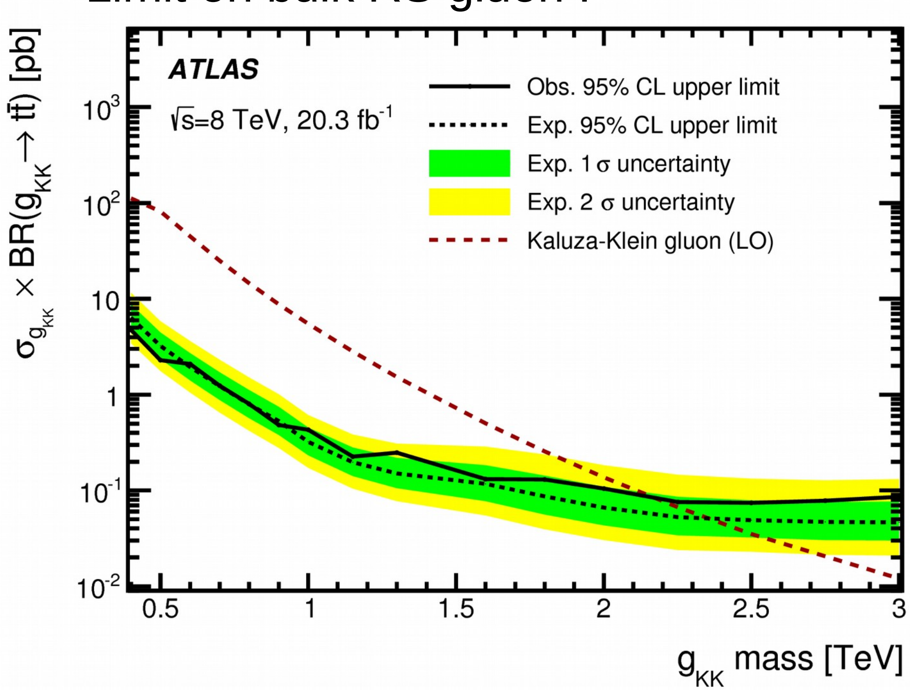
arXiv:1505.07018
submitted to JHEP

$t\bar{t}$ resonance

- Lepton + jets channel : 1 lepton, E_T^{miss} > 20 GeV, E_T^{miss} + m_T > 60 GeV
- Merged Regime (boosted tops) :
  - Trimmed ΔR<1.0 jet with m > 100 GeV + k_T-splitting scale $\sqrt{d_{12}} > 40$ GeV
  - Lepton mini-isolation, at least one b-jet
- If not boosted, then check the resolved regime :
  - ≥4 jets, one b-tagged

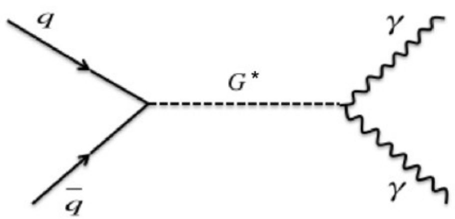


Limit on bulk RS gluon :

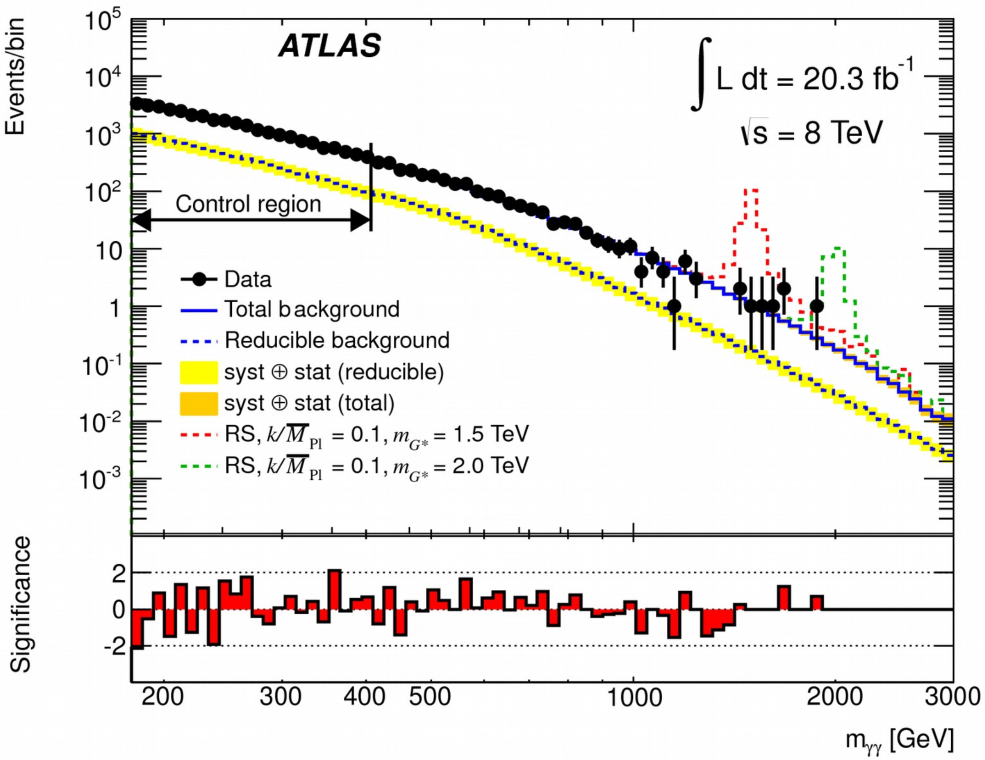


arxiv:1504.05511
submitted to PRD
PAS EXO21045

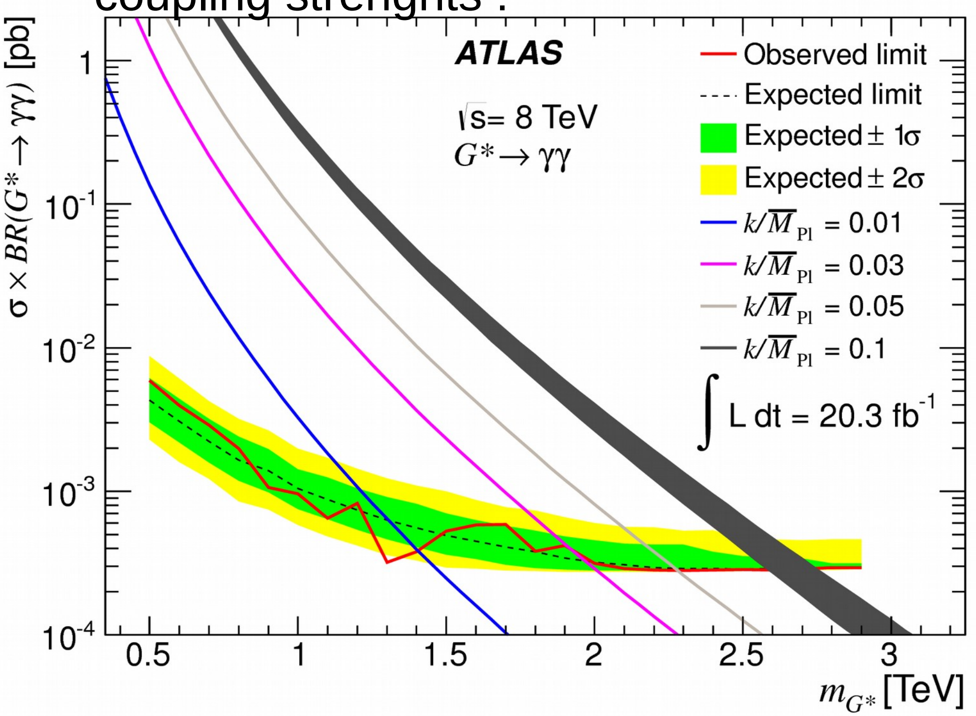
$\gamma\gamma$ resonances



- At least two tight photons with E_T>50 GeV
- The two leading photons are used to construct the diphoton mass spectrum
- Main background is SM diphoton, estimated by MC (Pythia+Diphox) normalized to data in the low-mass region



Limits on the RS graviton for different coupling strenghts :

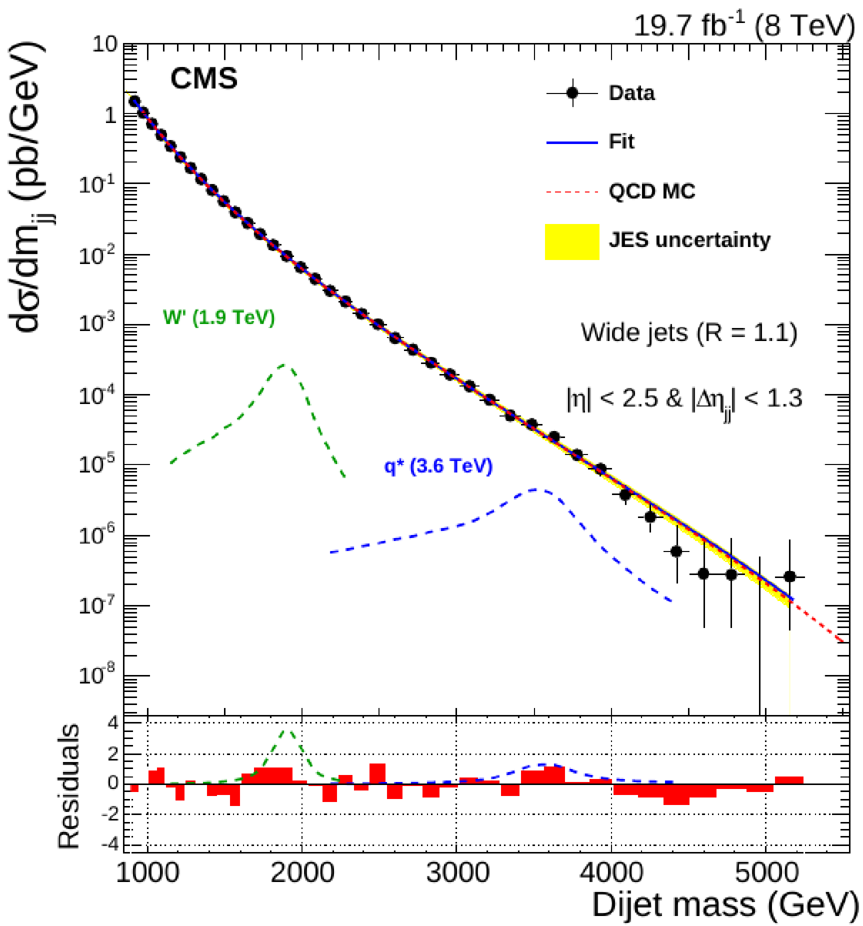


Similar limit in CMS

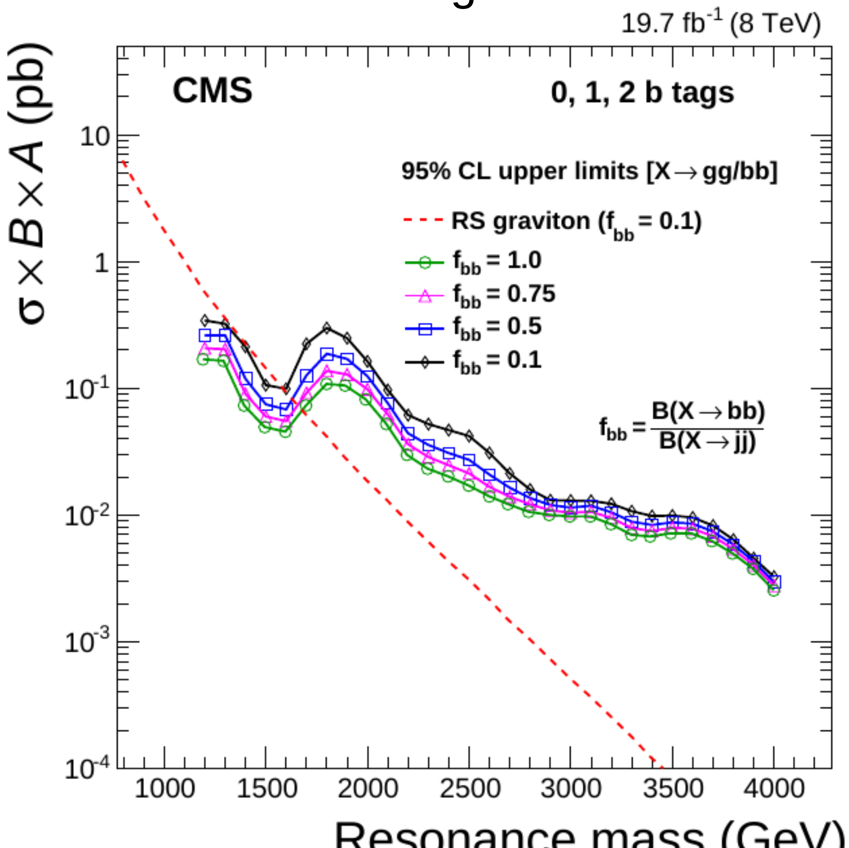
Phys. Rev. D 91, 052009 (2015)

Dijet resonances

- $\Delta R<1.1$ jets to build the m_{jj} spectrum, $|\Delta\eta_{jj}|<1.3$ to suppress the multijet background
- 3 categories : 0, 1, 2 b-tagged
- Multijet background fitted with a 4-parameter functional form $\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$ $x = m_{jj}/\sqrt{s}$
- Search for narrow resonances



Limits on the RS graviton :



Phys. Rev. D 91, 052009 (2015)

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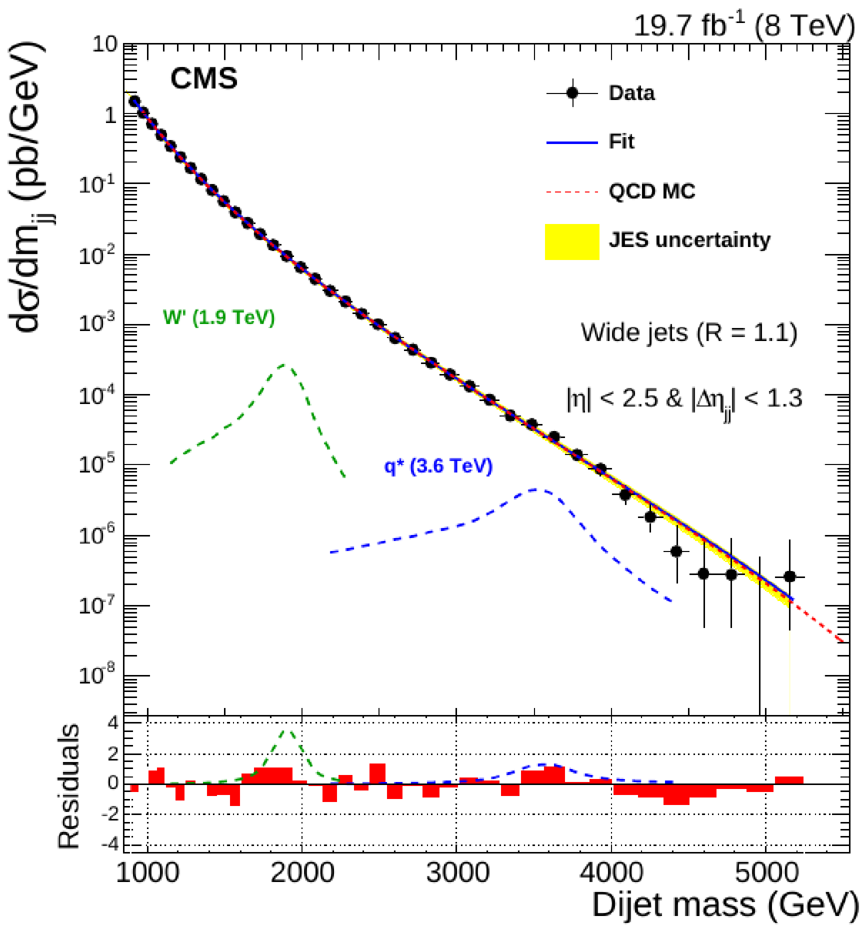
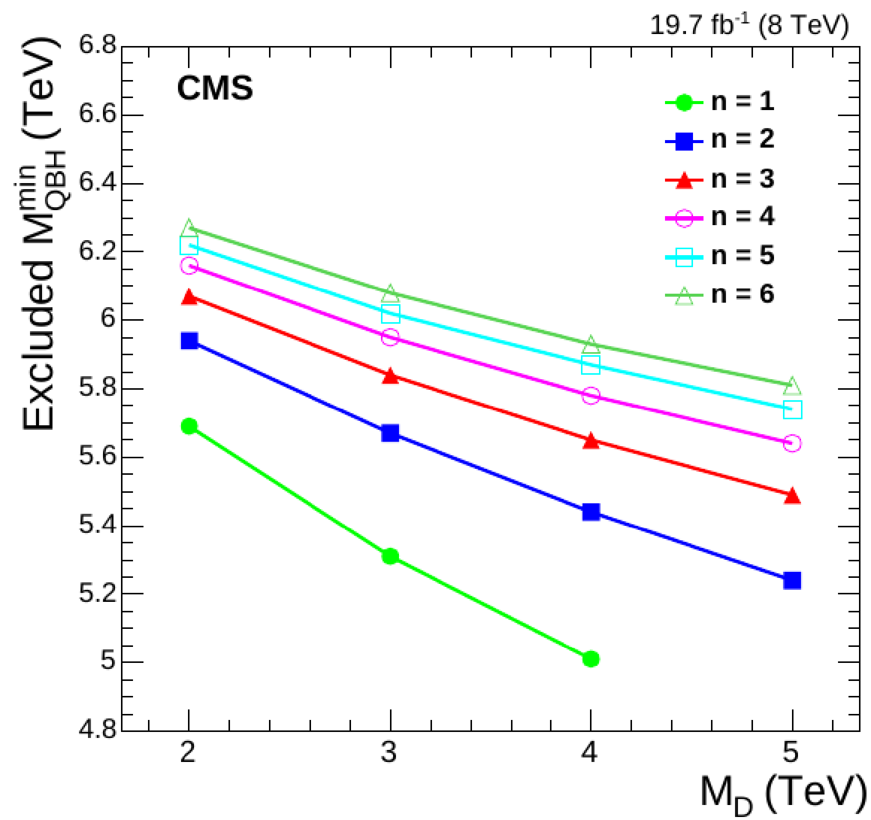
- Search for wide resonances (relative widths up to 30% of the mass)



Limits on QBHs :

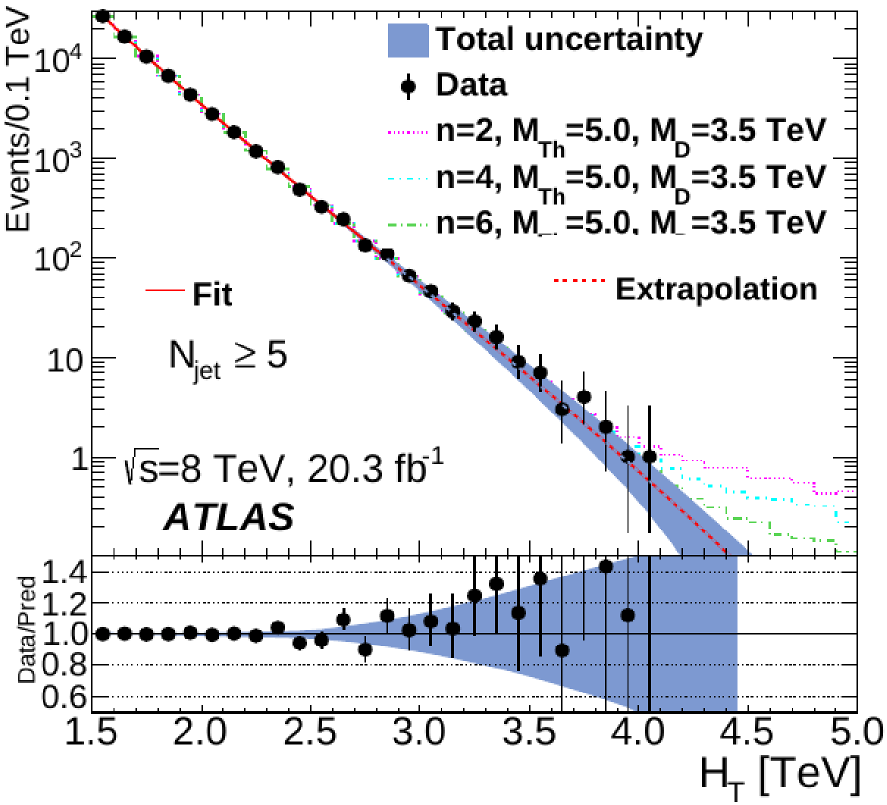


arxiv:1503.08988
submitted to JHEP

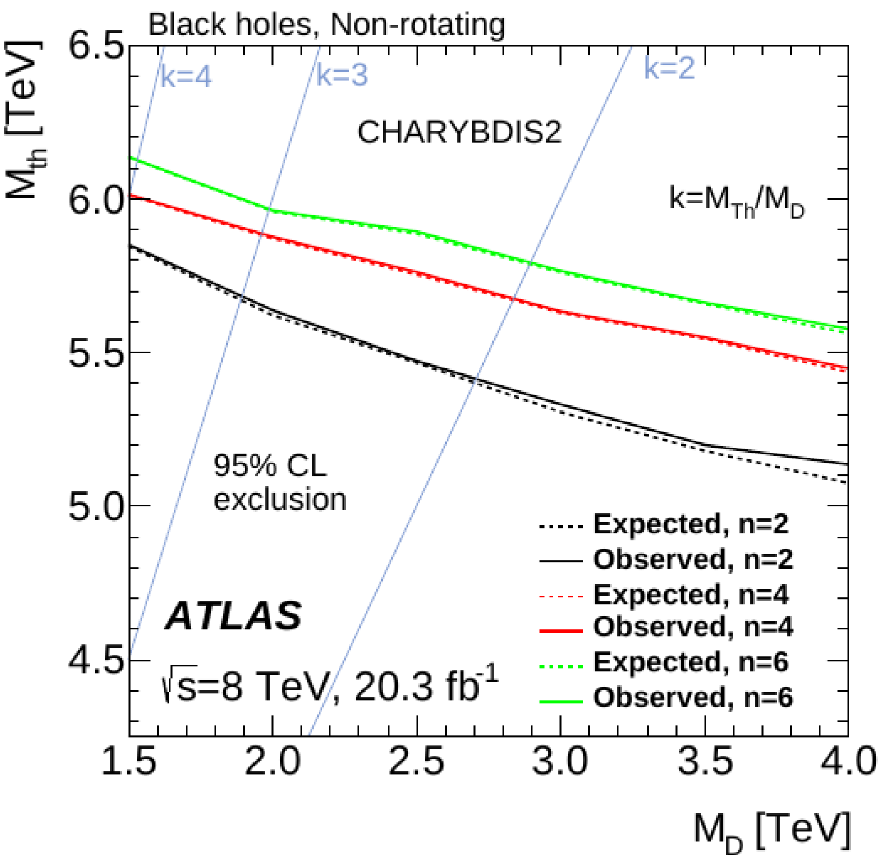
Multi-jet, using H_T

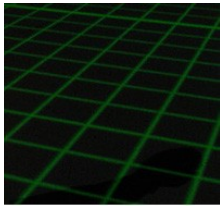
$$H_T = \sum_{N_{Jet}} p_T^{Jet}$$

- 6 bins of inclusive jet (p_T > 50 GeV) multiplicity (from 3 to 8)
- Fit and extrapolate the H_T distribution for each N_{jet} bin using a functional form $dN/dH_T = p_0(1-x)^{p_1}/x^{p_2}$, $x = H_T/\sqrt{s}$.



Interpretation in a variety of BH models, eg :





Conclusions and outlook

- ATLAS and CMS have searched for dark matter and extra dimensions in many final states using the run-1 data
  - No sign of them… yet.
- … but Run-2 is starting this year at 13 TeV!
  - With only ~1 fb^{-1} of data, dijet resonance searches could discover 7 TeV QBH
  - The sensitivity to DM will also be improved with respect to the run-1 results within the first year of data taking

Extra slides

More analyses...

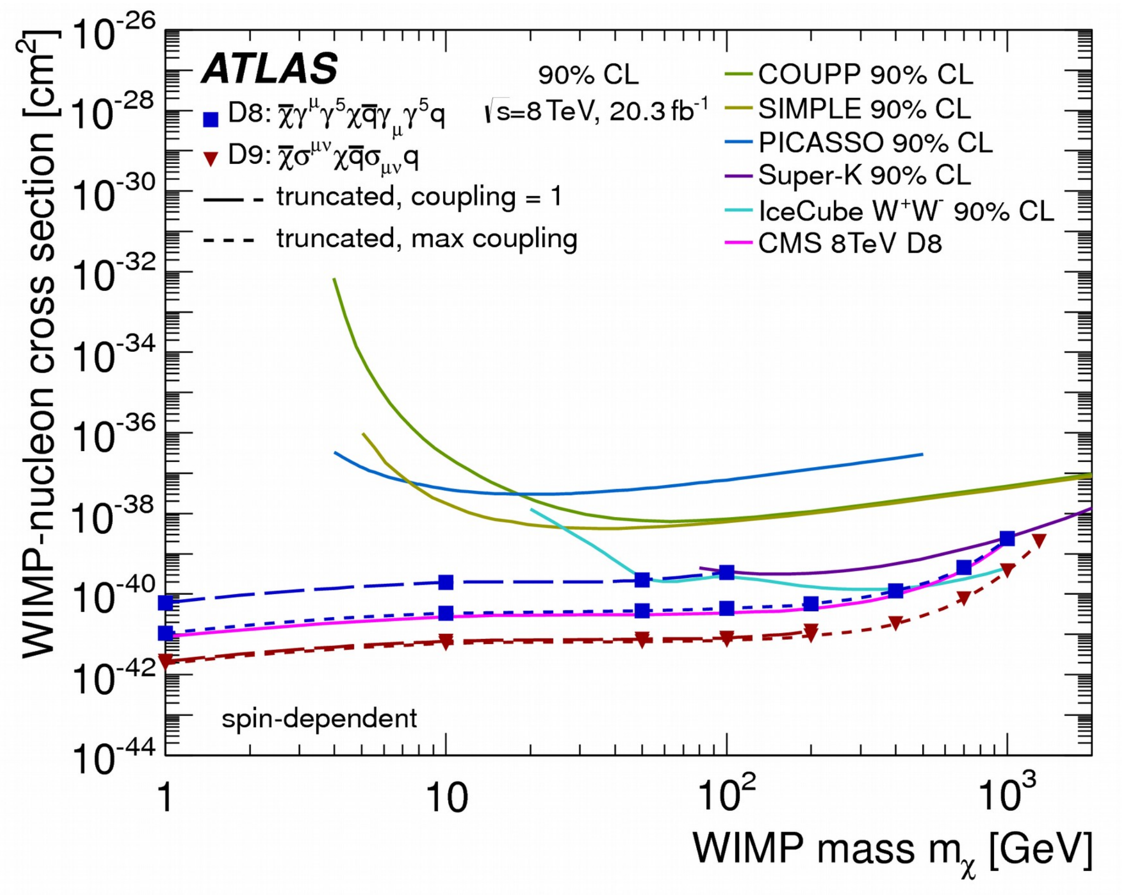
- **CMS :**
  - Mono-photon : arXiv:1410.8812, submitted to PLB
  - Dark Matter and extra-dimensions in lepton+MET : arXiv:1408.2745, submitted to Phys. Rev. D
  - Mono-jet : arXiv:1408.3583, 10.1140/epjc/s10052-015-3451-4
  - Dilepton Mass Distribution : arXiv:1412.6302, 10.1007/JHEP04(2015)025
  - Extra dimensions in dijet angular distributions : arXiv:1411.2646, 10.1016/j.physletb.2015.04.042
  - Search for black holes   arXiv:1303.5338, 10.1007/JHEP07(2013)178
  - Search for high-mass diphoton resonances PAS EXO12045
  - Large extra dimensions with tau-lepton pairs PAS EXO12046
  - Mono-top : Phys. Rev. Lett. 114 (2015) 101801
  - ttbar resonance in all final states : B2G-13-008
  - Dark Matter in Association with Top Quark Pairs (Di-lepton Final State) : B2G-13-004

More analyses...

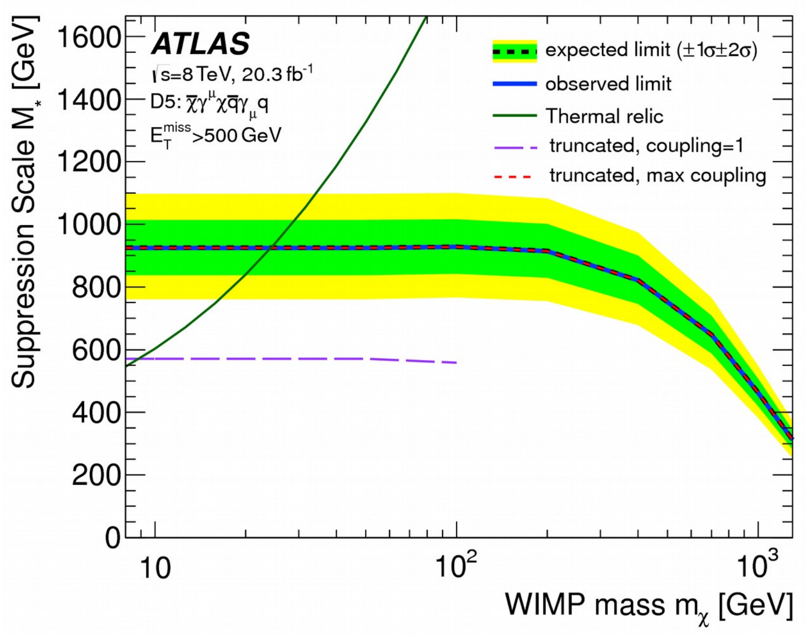
ATLAS :

- Mono-photon : PRD 91, 012008 (2015)
- Invisible + single-top-quarks : EPJC 75 (2015) 79
- Heavy quarks and missing transverse momentum : EPJC 75 (2015) 92
- One lepton and missing transverse momentum : JHEP 09 (2014) 037
- Large extra dimensions in the dilepton channel : EPJC 74 (2014) 3134
- Dijet resonance : PRD 91, 052007 (2015)
- Microscopic black holes and string balls in final states with leptons and jets : JHEP 08 (2014) 103
- Dark matter in events with a Z boson and missing transverse momentum : PRD 90, 012004 (2014)
- Quantum black-hole in high-invariant-mass lepton+jet final states : PRL 112, 091804 (2014)
- Dark matter with hadronic W/Z boson and missing transverse momentum : PRL 112, 041802 (2014)
- Microscopic black holes in like-sign dimuon (large track multiplicity) : PRD 88, 072001 (2013)

More on jet+E_T^{miss} EFT



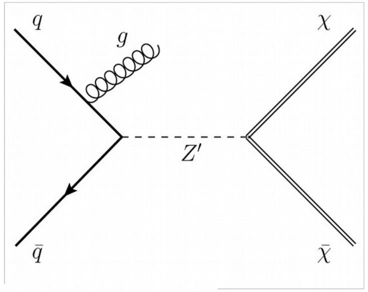
More on jet+E_T^{miss} EFT

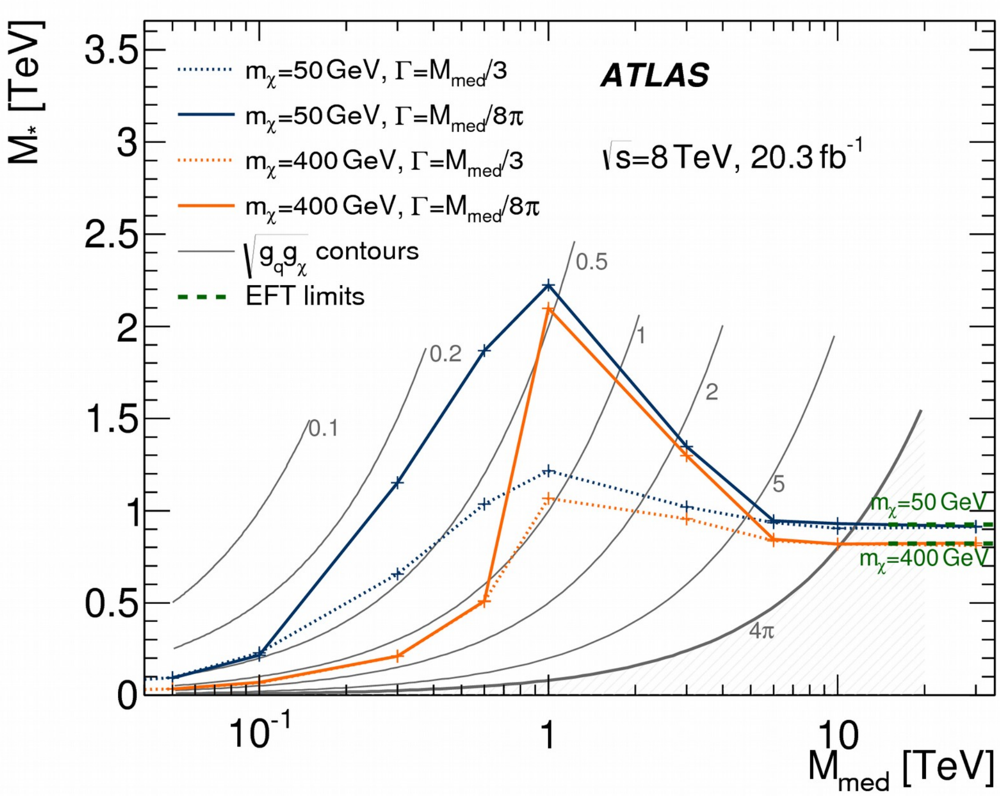


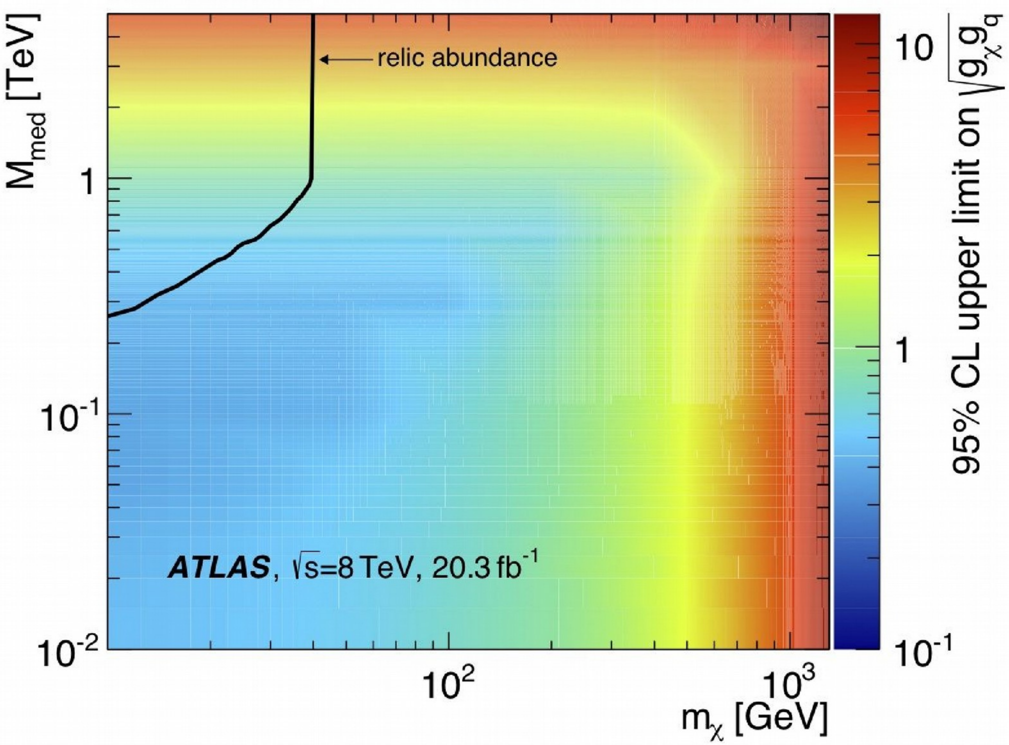
Name	Initial state	Type	Operator
C1	qq	scalar	$\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$
C5	gg	scalar	$\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

- Limit on suppression scale of EFT M*
- EFT validity addressed explicitly : $Q^2_{\rm tr} < \Lambda^2$
  - coupling/operator-dependent statement)
- Under discussion in literature and in the ATLAS/CMS DM Forum (recommendations to be issued shortly)

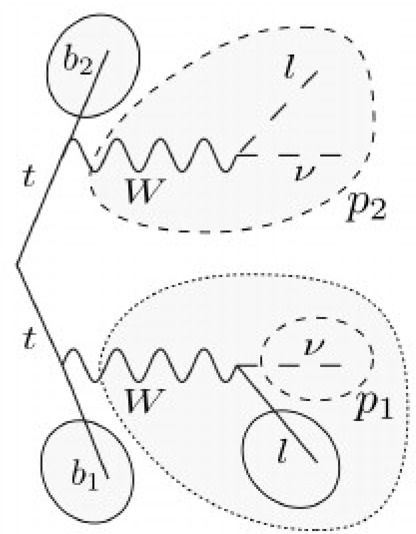
Simplified model jet+E_T^{miss}







M_{T2}^{W}



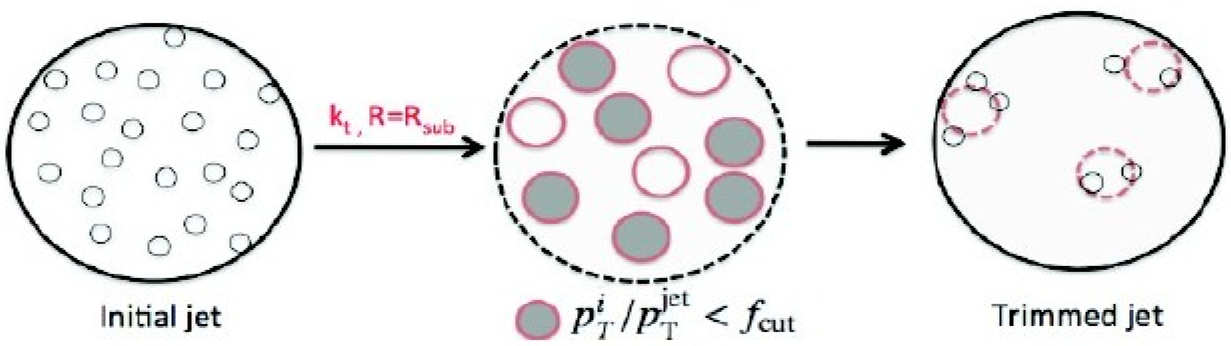
Discriminant against the main background:
dileptonic top pair production, where one lepton is missed

$$M_{T2}^{W} = \min\left(m_y \text{ consistent with: } \left\{ \begin{array}{l} \vec{p}_1^{\,T} + \vec{p}_2^{\,T} = \vec{p}_T^{\,\text{miss}}, p_1^2 = 0, (p_1 + p_\ell)^2 = p_2^2 = M_W^2, \\ (p_1 + p_\ell + p_{b1})^2 = (p_2 + p_{b2})^2 = m_y^2 \end{array} \right\} \right)$$

More on jet+$\mathrm{E_T^{miss}}$(ADD)

- The analysis partially probes the region $\hat{s} > M_D^2$
- Challenges the validity of the lower bounds on M_D
  - dependence on the unknown UV behaviour of the theory.
- Limits recomputed with suppression factor $M_D^4/\hat{s}^2$ for events with $\hat{s} > M_D^2$
  - Decrease of the 95% CL on M_D :
    - Negligible for n = 2
    - About 3% for n = 6

Fat jets



$$\sqrt{d_{ij}} \equiv \min(p_{T,i}, p_{T,j})\, \Delta R_{ij}$$

The k_T algorithm clusters high p_T objects late, so that the scale of the last merging, (ij=12) is sensitive to the hard structure of the jet : for top quark decay, the k_T splitting scale is peaked near half the top quark mass.

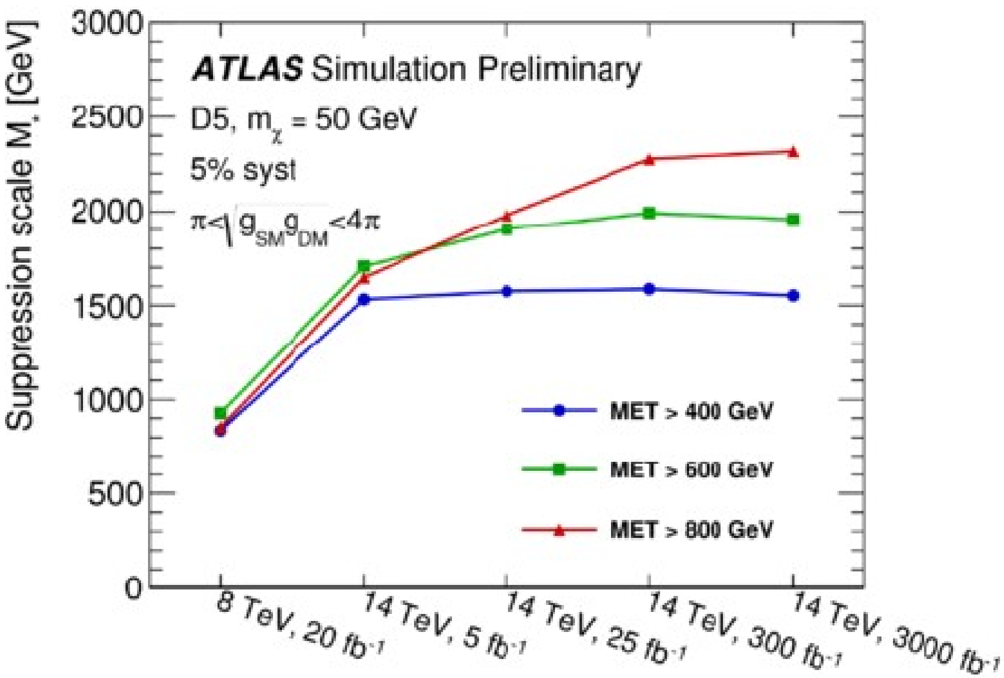
The use of mini-isolation improves the lepton signal efficiency and background rejection with respect to the fixed-cone algorithm. For the $t\bar{t}$ resonance analysis, the mini-isolation is defined as :

$$\sum_{\text{tracks}} p_T^{\text{track}}$$ for all good tracks with p_T>1 GeV with ΔR < 10 GeV / E_T

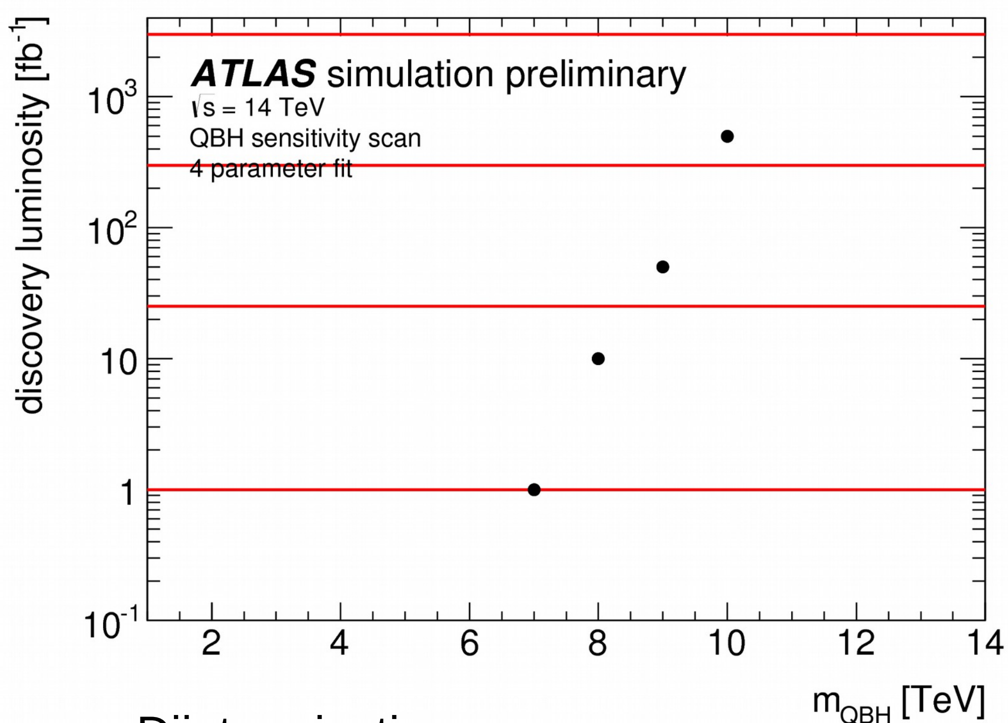
$MI_{10}/E_T < 0.05$ is requested

ATLAS-PHYS-PUB-2015-004
ATLAS-PHYS-PUB-2014-007
ATL-PHYS-PUB-2013-014

Prospects



Monojet projection



Dijet projection

The 95% CL upper limit on BR(H$\rightarrow$invisible) expected with 300 fb^{-1} is 0.25 and decreases to 0.12 with 3000 fb^{-1}.