EUROPEAN PHYSICAL SOCIETY HEP2015

Searches for eXotic phenomena

beyond the Standard Model

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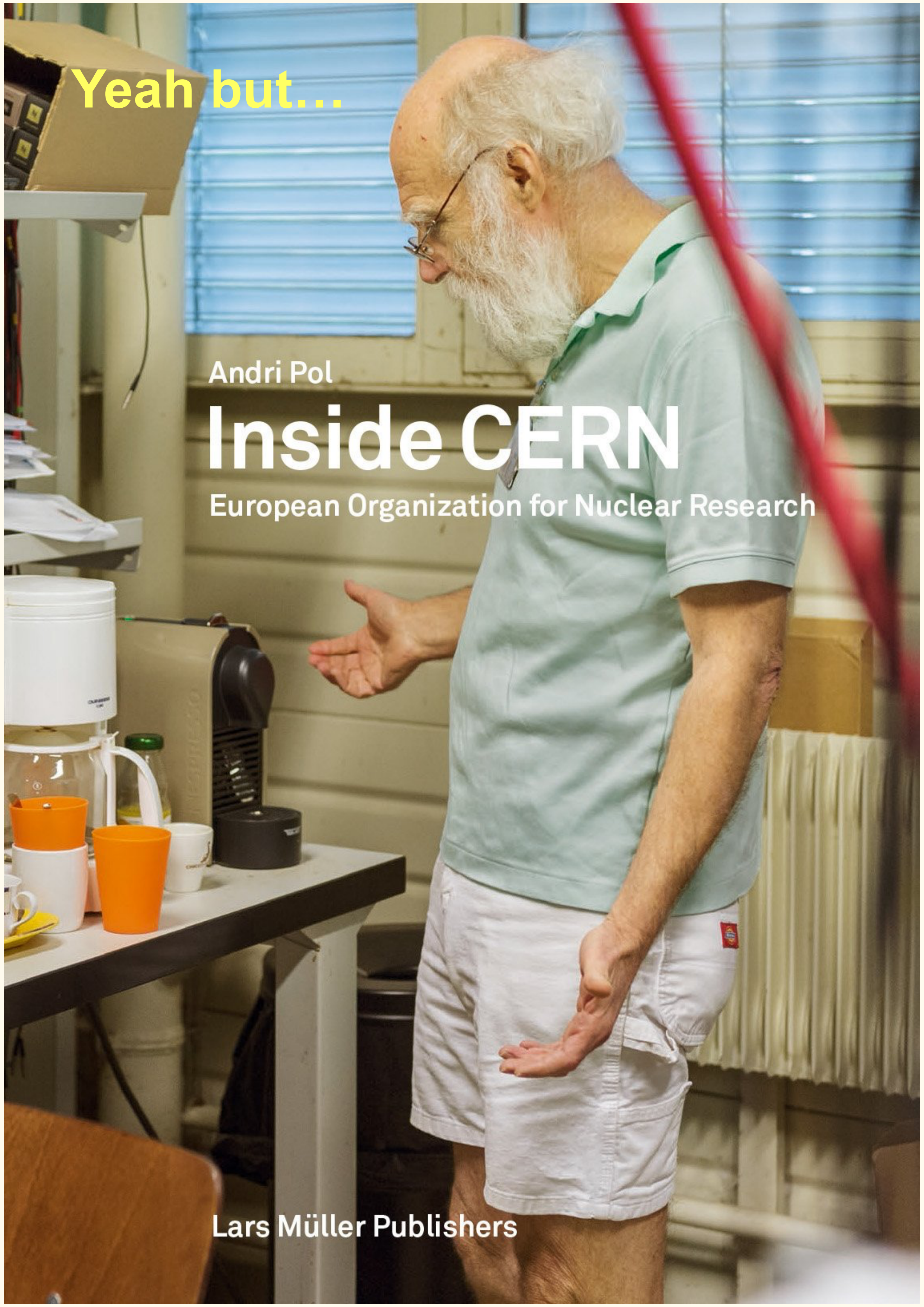
ATLAS CMS Compact Muon Solenoid LHCb

Introduction

- Yes we discovered the Higgs boson but we did not discover New Physics beyond SM
- However, the Higgs boson discovery not only confirmed the anticipated answers but also the anticipated questions!
- On the naturalness grounds we have even more reasons to believe that the physics beyond SM may well be in the reach of LHC
- Many theoretical models propose solutions to SM puzzles
- They serve as a very useful guidance and benchmarks for experimentalists but our main focus is on experimental signatures



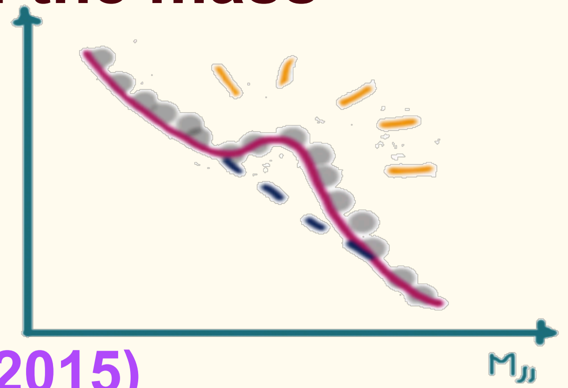
Overview

- **Scope of the talk:**
  - Where are we after Run 1?
  - Where do we go in Run 2?
- **Structured by experimental signatures:**
  - Di-objects
  - "Mono"-objects + missing energy
  - Multi-objects
  - Displaced/delayed objects

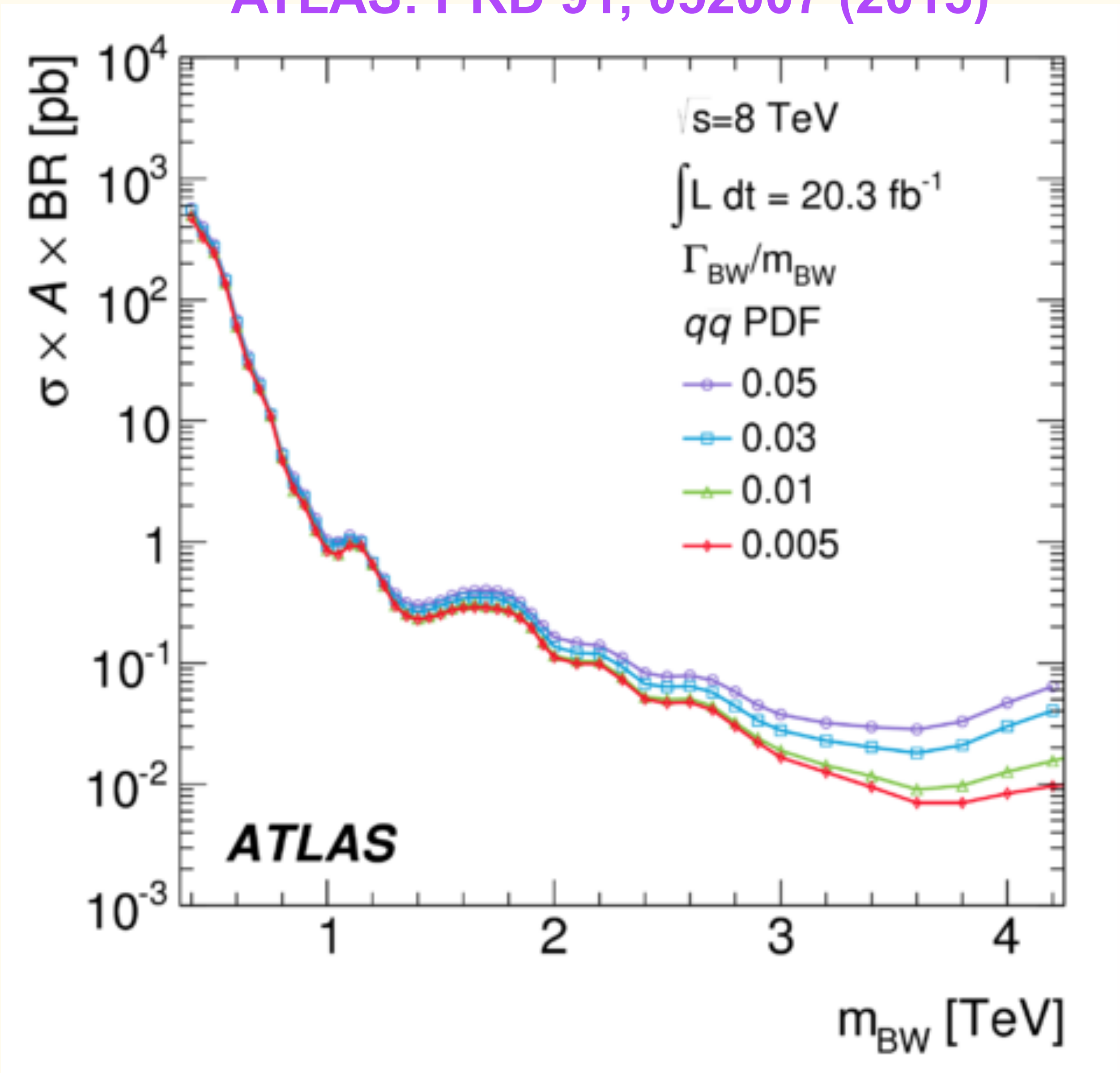
- **Impossible to give an exhaustive review - complementary information in parallel talks:**
  - B. Clerbaux: Searches for resonant and non-resonant new phenomena in CMS
  - W. Fedorko: Searches for resonant and non-resonant new phenomena in ATLAS
  - V. Cavaliere: Search for new phenomena in diboson final states in ATLAS and CMS
  - D. Zerwas: Searches for Dark Matter in ATLAS and CMS
  - S. Jain: Searches for new phenomena in multilepton final states in ATLAS and CMS
  - I. Marchesini: Searches for top/bottom partners and new phenomena in top/bottom quark pair signatures in ATLAS and CMS
  - A. E. Hart: Searches for long-lived, weakly interacting particles in ATLAS and CMS
  - A. Policicchio: Searches for highly ionizing particles in ATLAS and CMS
  - A. Tricomi: Prospects of the high luminosity LHC from CMS and ATLAS
  - N. Arnaud: Search for long-lived particles at BABAR, Belle and LHCb
  - V. Mitsou: MoEDAL: Seeking magnetic monopoles and more at the LHC
  - E. Graverini: SHiP: a new facility with a dedicated detector to search for new long-lived neutral particles

Di-jets

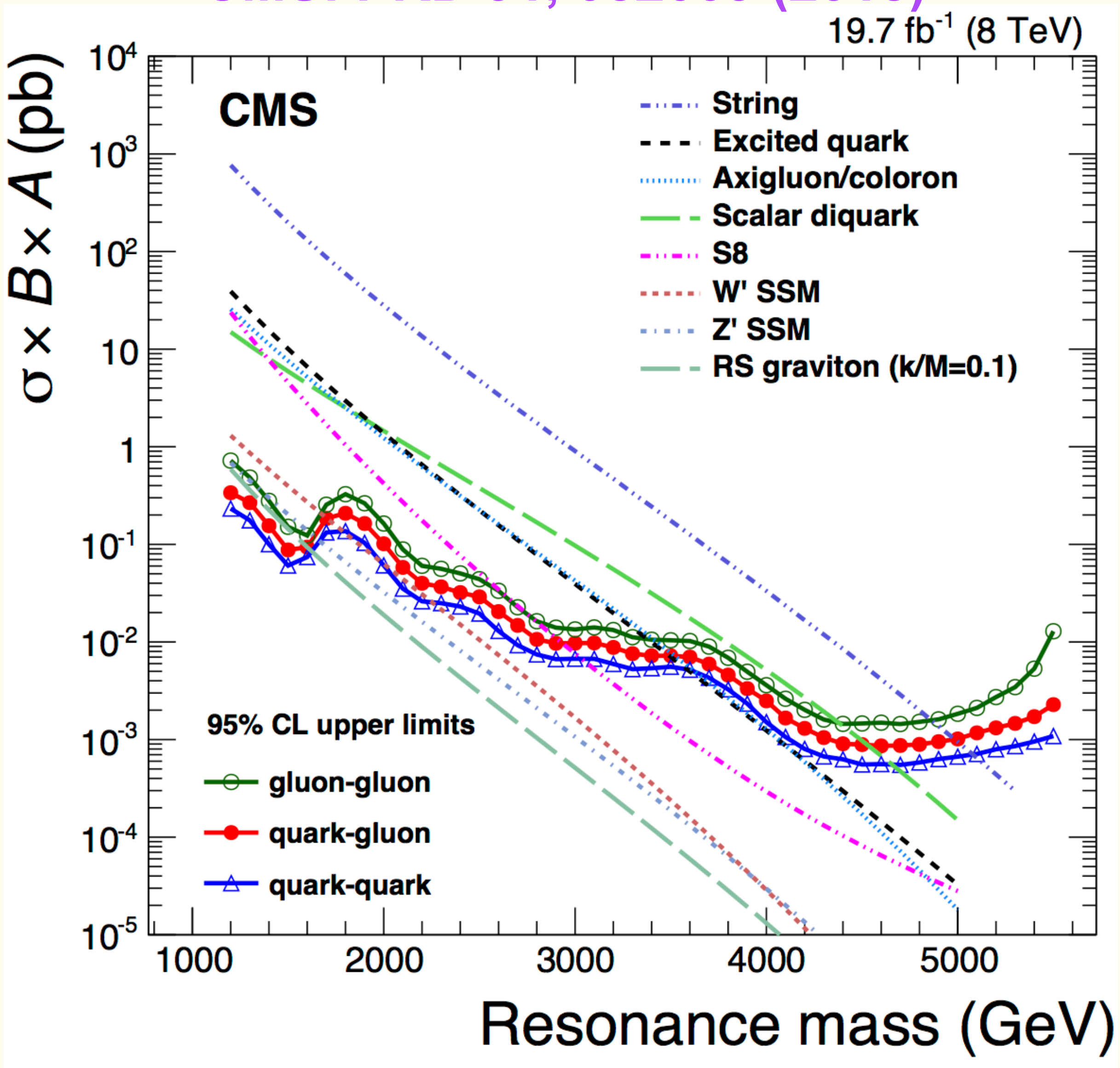
- **Classical bump search** – narrow resonance: up to widths 20-30% of the mass
- **Simple** – Data-driven, background parameterized by smooth function
- **Powerful** – generic search, many interpretations, high mass reach



ATLAS: PRD 91, 052007 (2015)



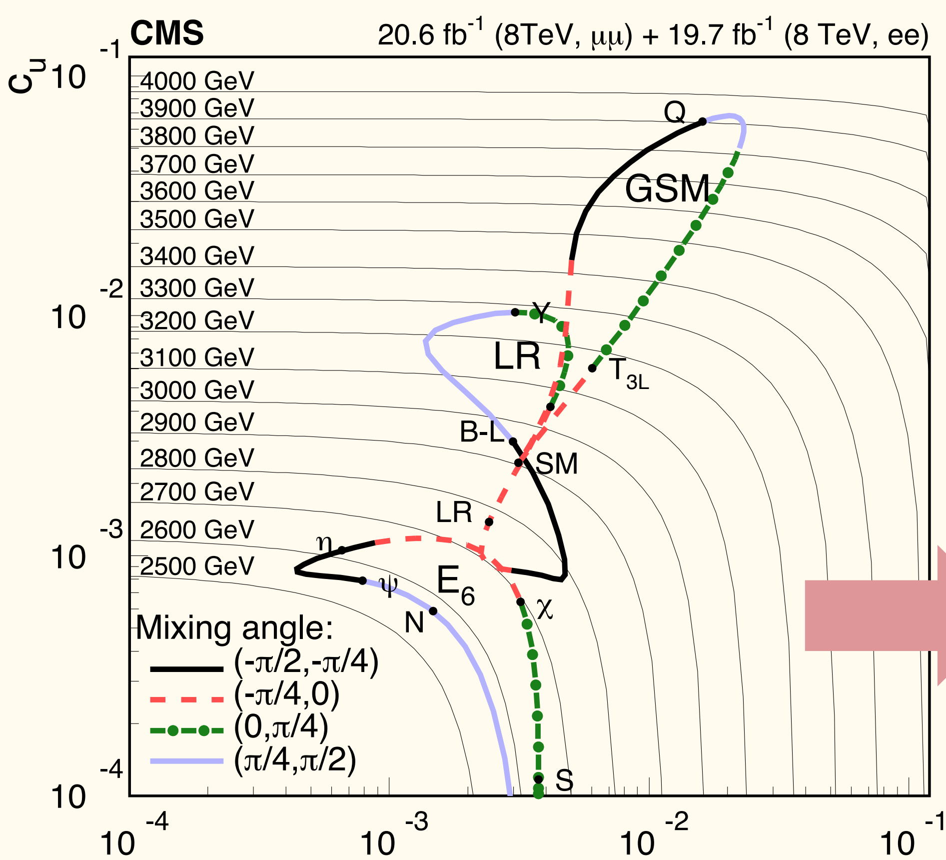
CMS: PRD 91, 052009 (2015)



- **Excluded resonances with masses of 2 – 5 TeV depending on model**

Di-leptons

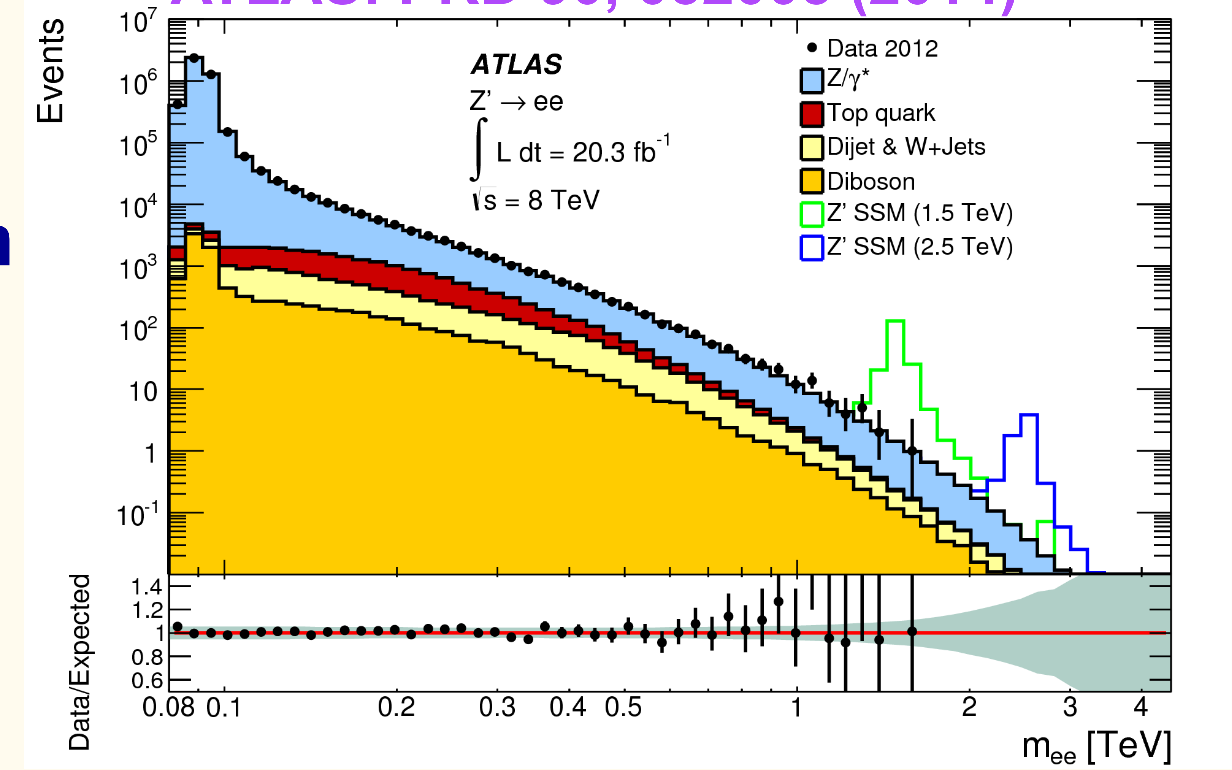
- Traditional tool to probe narrow resonances
  - Leptons: mainly e, μ but also τ
- Low background (DY), good mass resolution



CMS: JHEP 04 (2015) 025

- Best sensitivity to Z', RS graviton and many others

ATLAS: PRD 90, 052005 (2014)

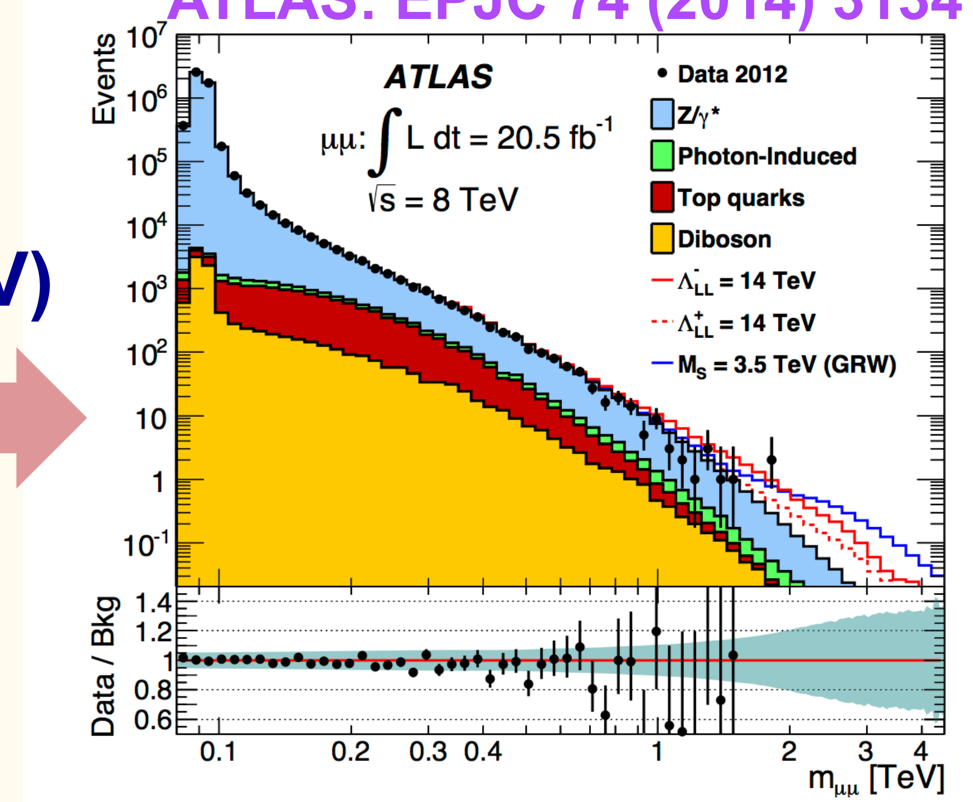


- Limits represented as a function of couplings and mixing angle for various benchmark models

PRD 83 (2011) 075012

- Typical mass limits 2.5 – 3 TeV

ATLAS: EPJC 74 (2014) 3134

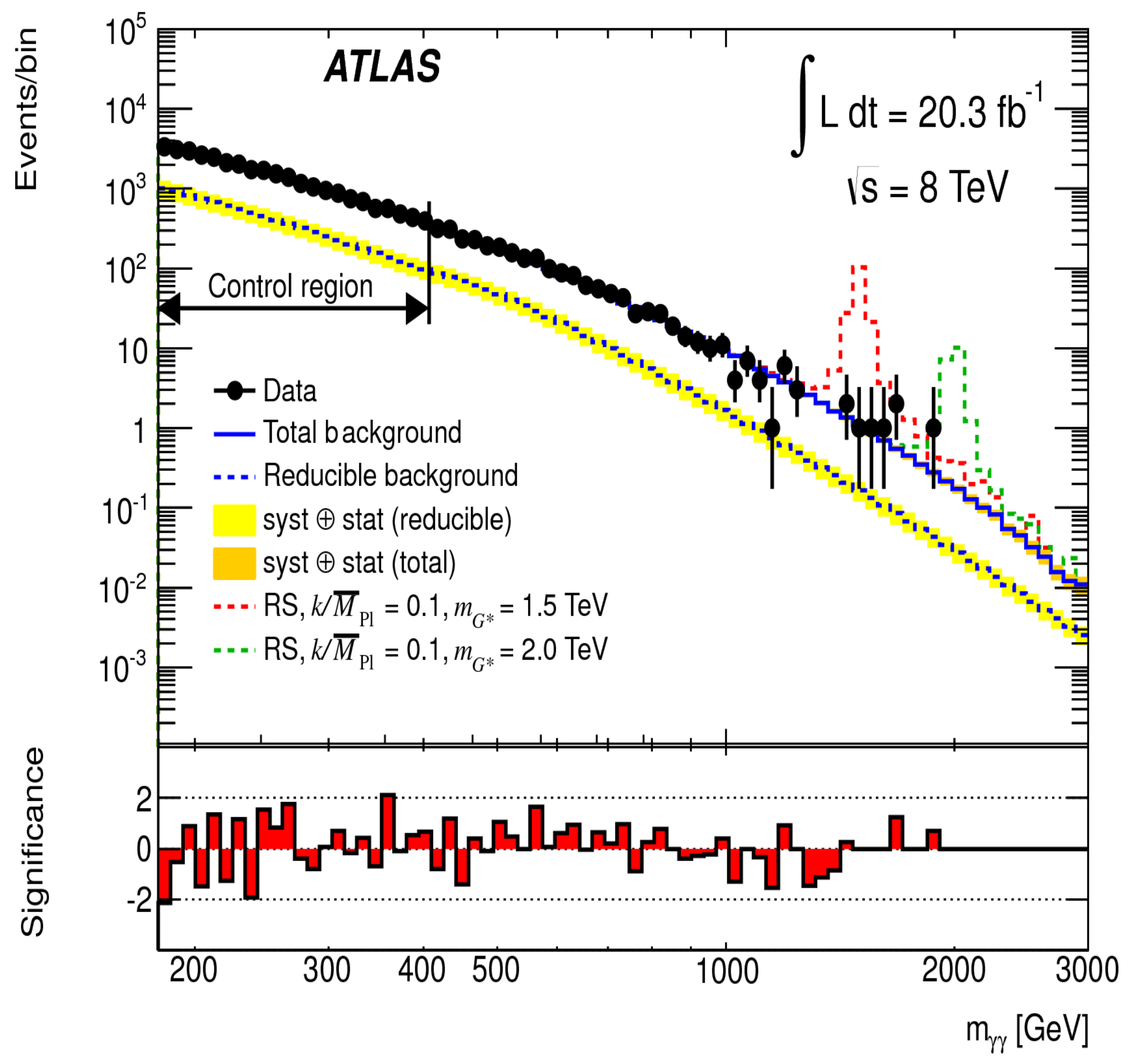


- W' searched in l + MET channel (limit above 3 TeV)
- Sensitive also to non-resonant processes:
  - ADD model of extra dimensions: dense KK states
  - Contact Interaction: low energy manifestation of high energy effects

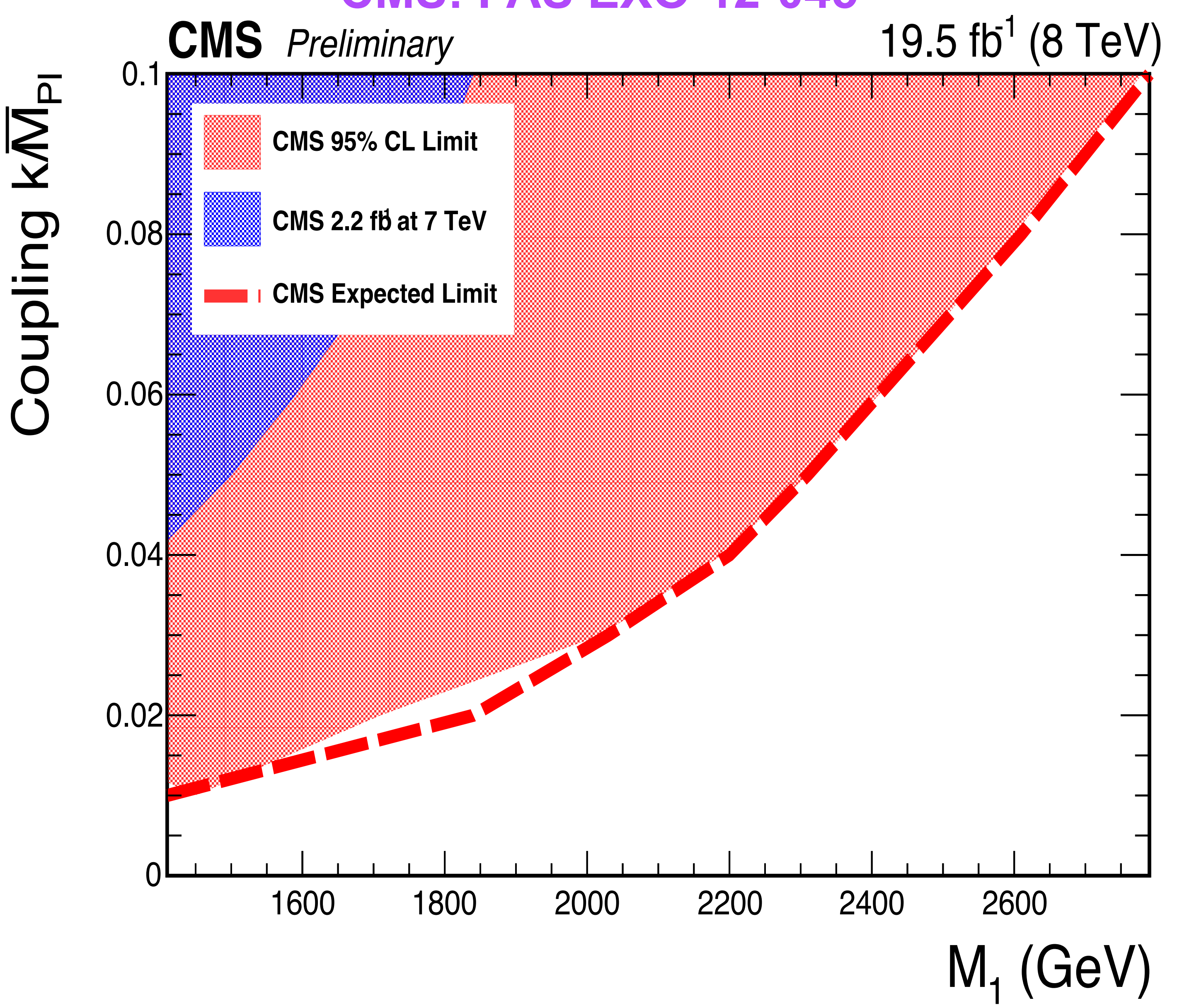
Di-photons

- Sensitive to spin 2 (RS graviton) or spin 0 (heavy Higgs) resonances
- Clean topology with well understood SM γγ background (Higgs searches)
- Challenge is the photon reconstruction and ID at high energies

ATLAS: arXiv 1504.05511



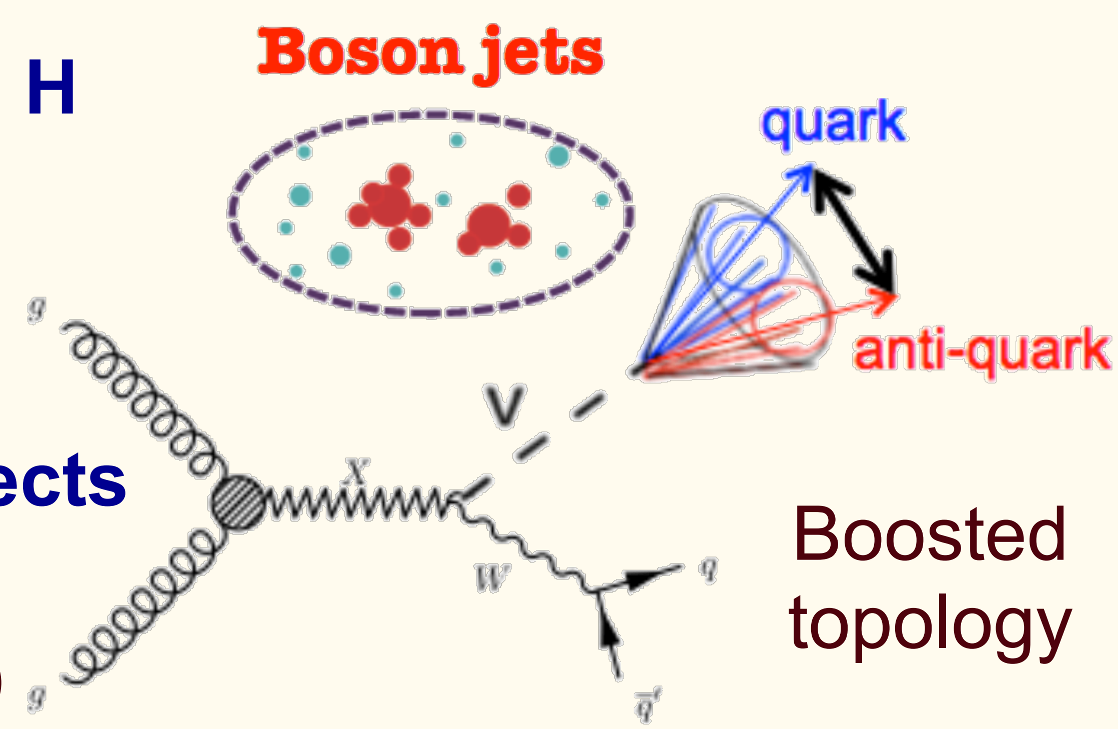
CMS: PAS EXO-12-045



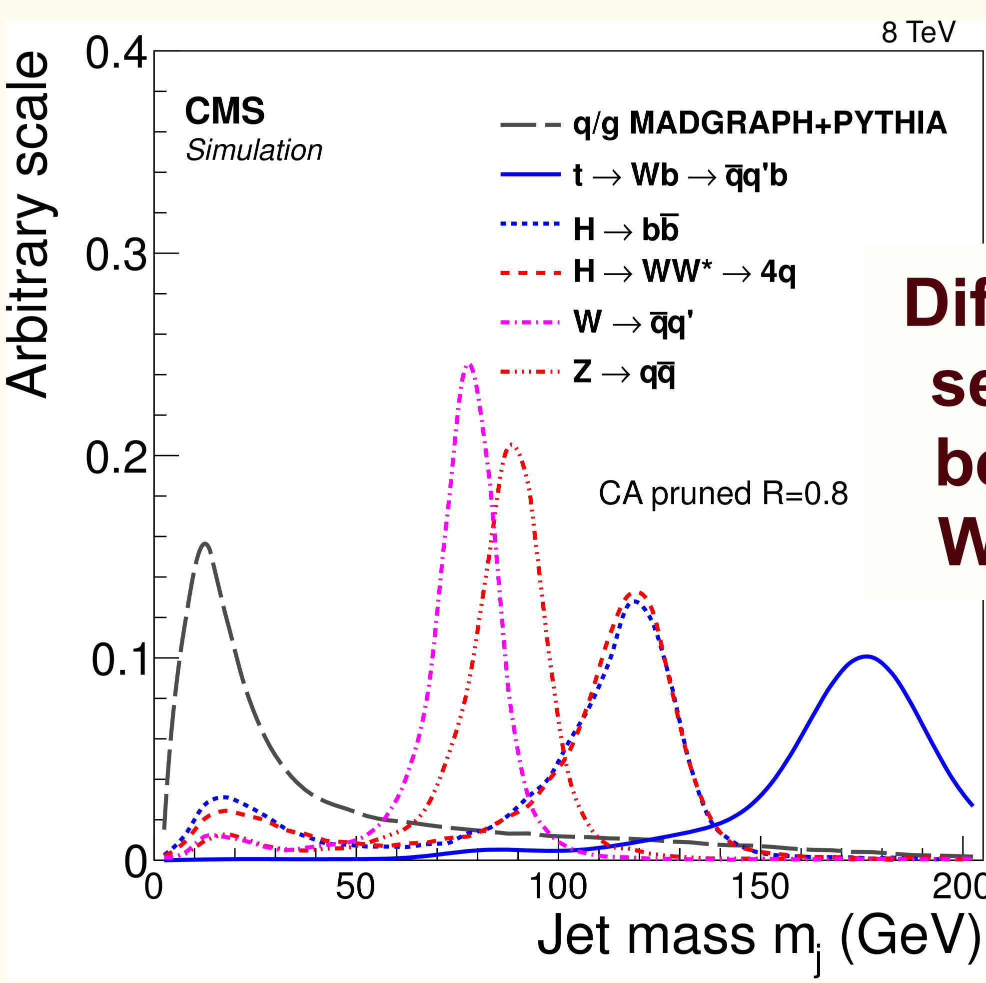
- Limits on RS graviton mass 1- 2.7 TeV (sensitivity similar to di-lepton)

Di-bosons

- **Search for resonance decaying to pairs of W, Z, H**
- **Challenging topology:**
  - **At resonance masses above 1 TeV the decay products of bosons overlap due to strong boost**
- **Needs dedicated techniques to reconstruct objects**
  - **Specific lepton isolation**
  - **Grooming techniques (cleaning pileup and noise)**
  - **Boson tagging (jet substructure, jet mass)**

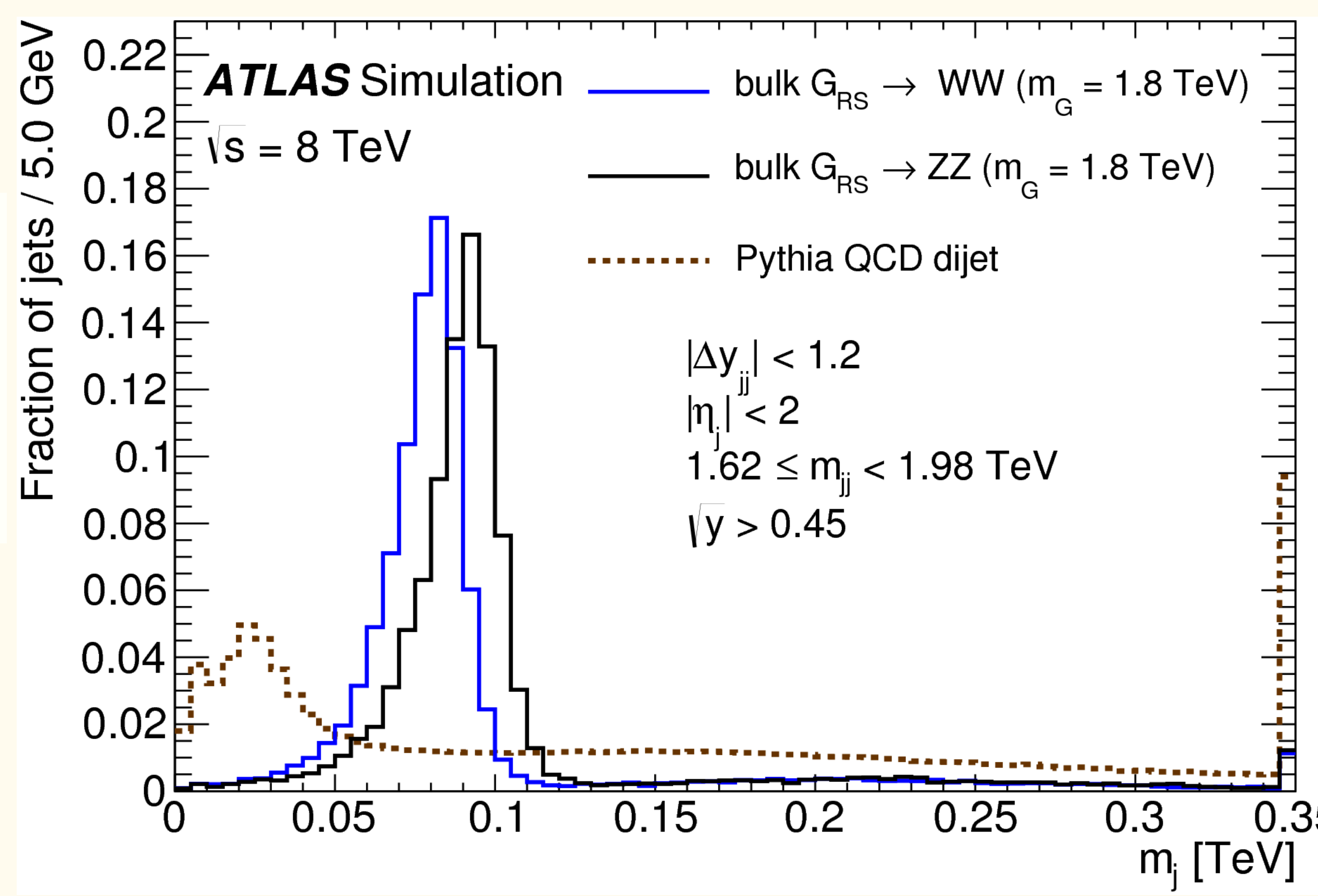


CMS: arXiv: 1506.01443



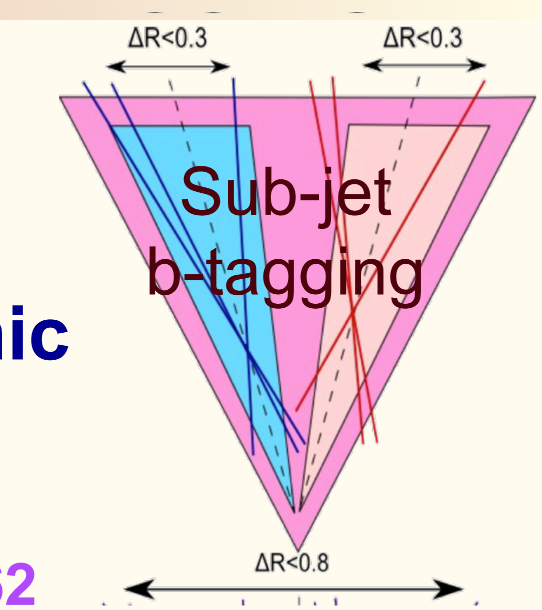
Difficult to separate between W and Z

ATLAS: arXiv 1506.00962

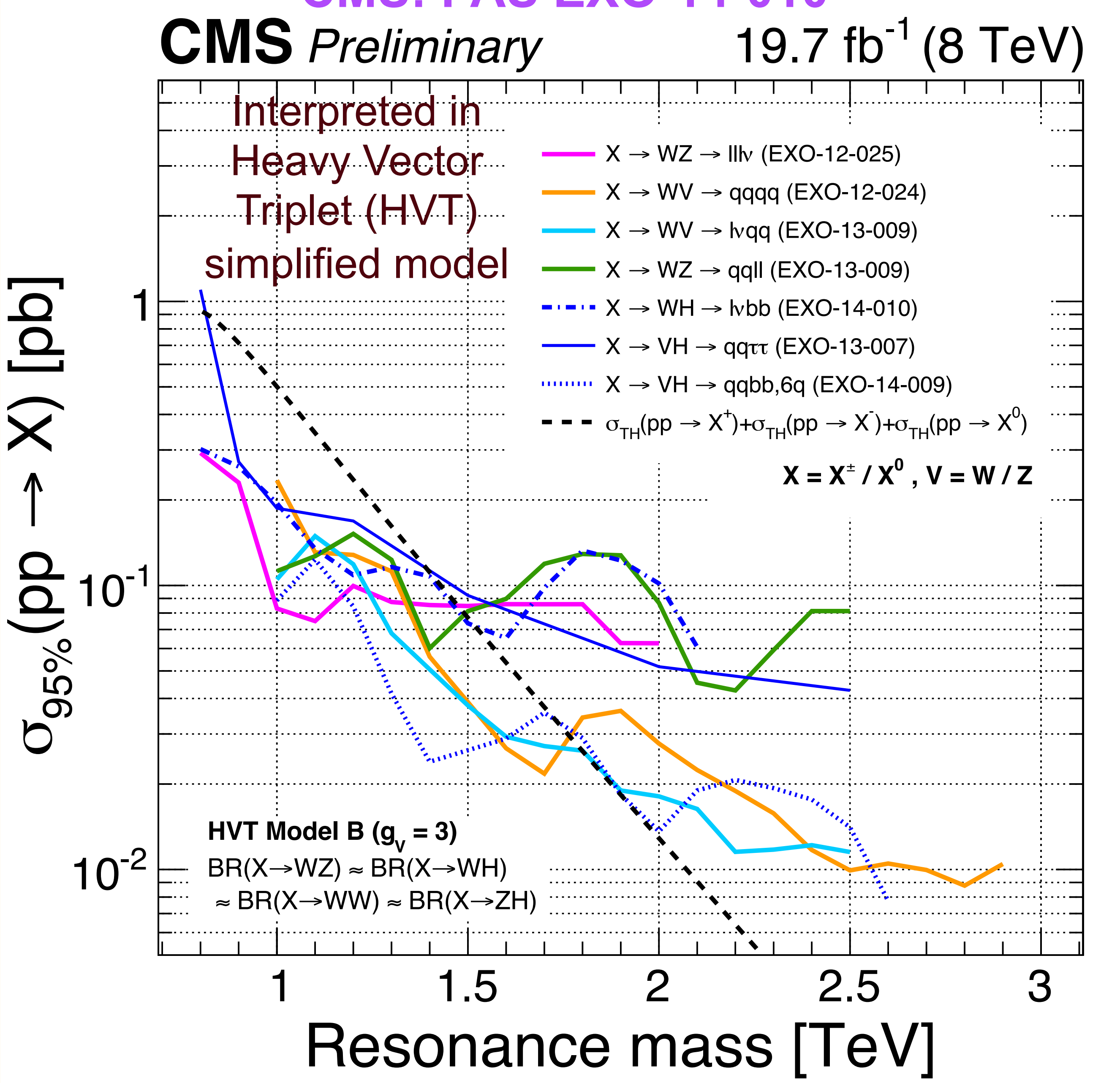


Di-bosons

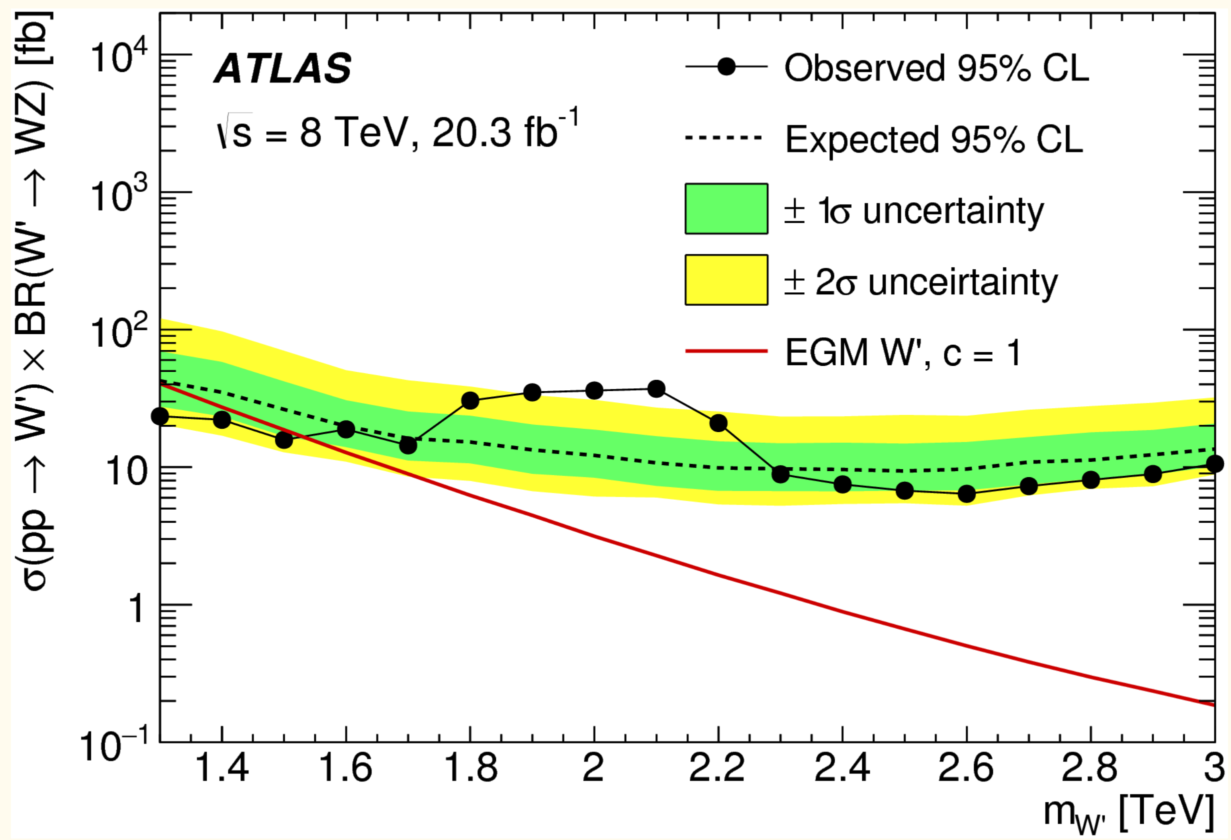
- **Sensitive to many models e.g. to spin-1 (Z', W') and spin-2 (RS graviton) resonances**
- **Large variety of final states: leptonic, semi-leptonic, all hadronic**
- **Channels with H became part of the suite (VH as well as HH)**



CMS: PAS EXO-14-010



ATLAS: arXiv 1506.00962

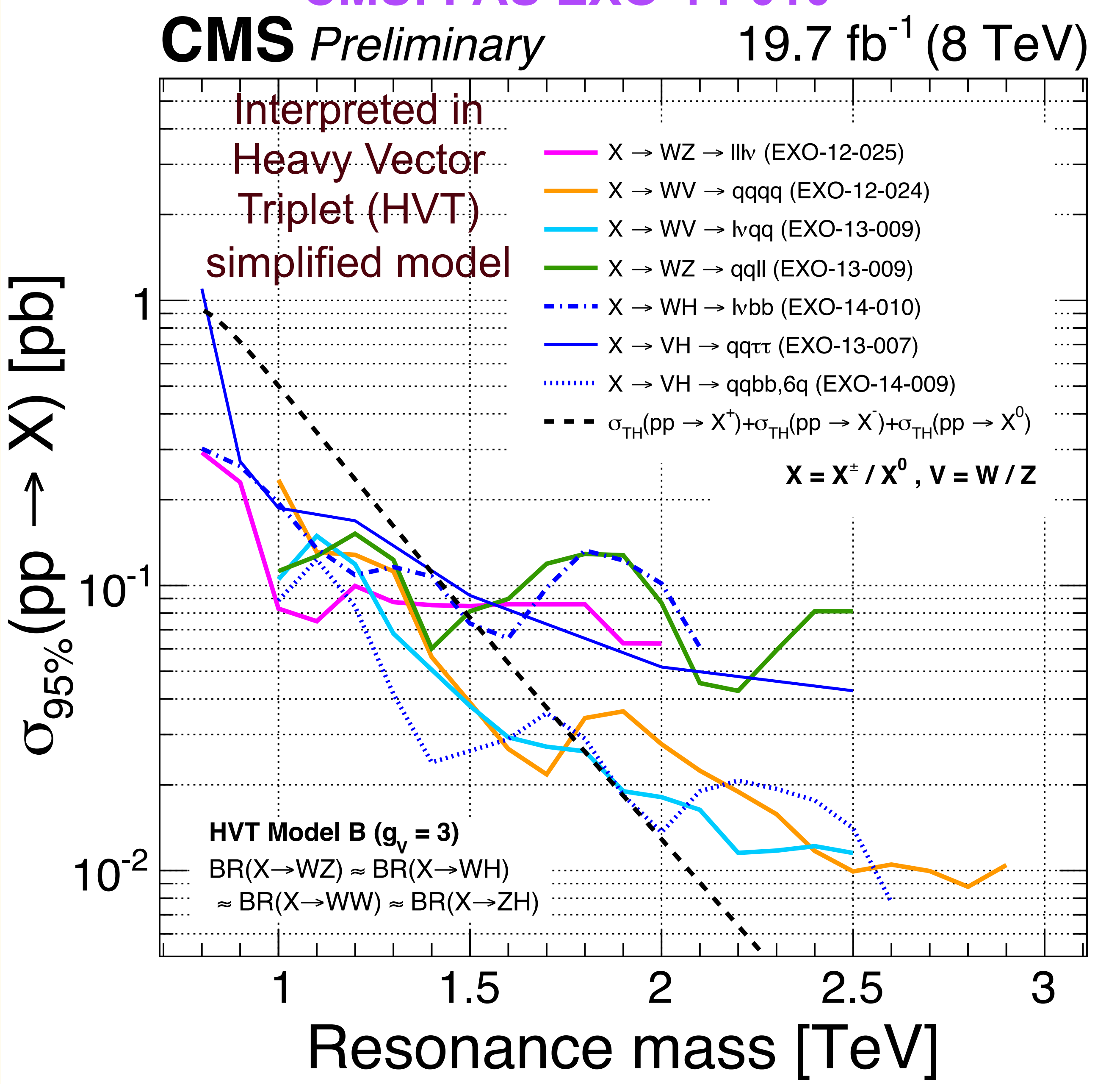


- **Current limits around 1.5 - 2 TeV**

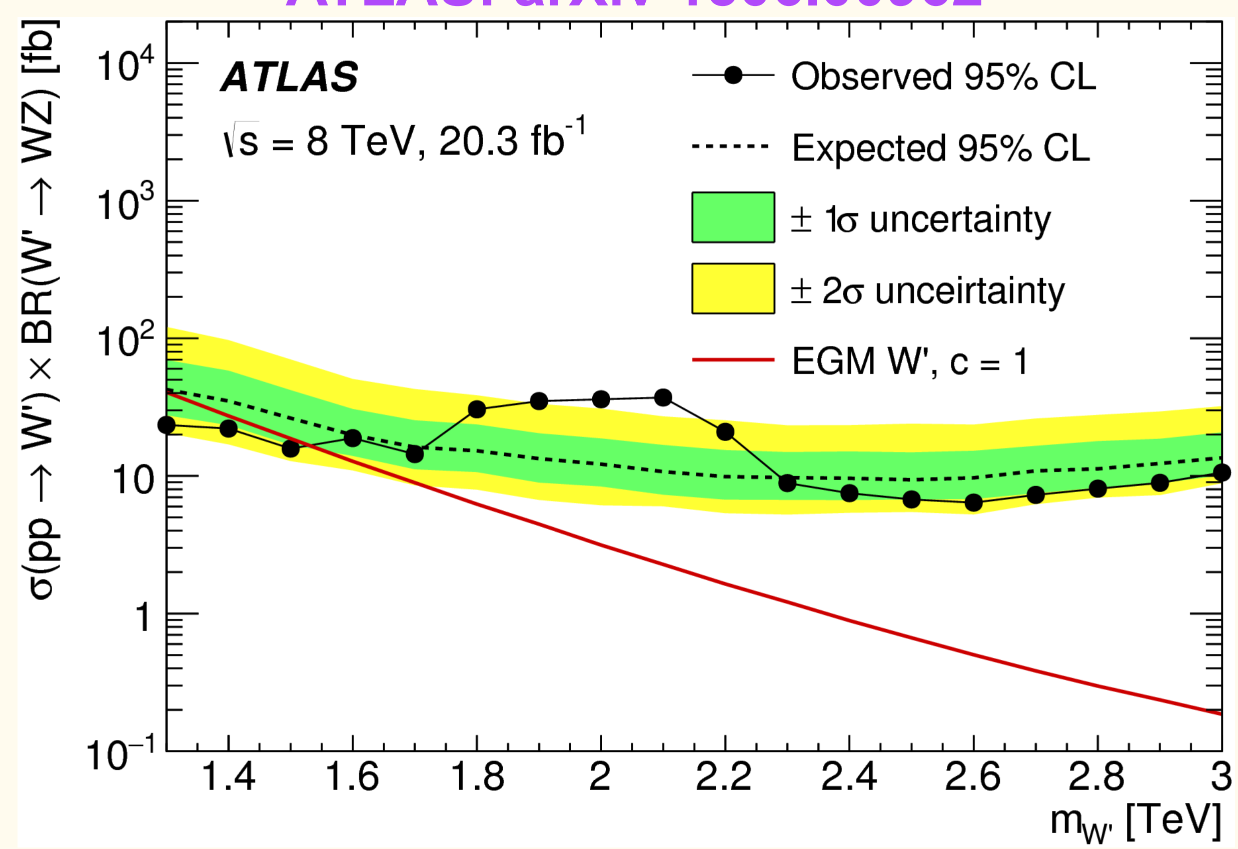
Di-bosons – excesses

- **Moderate excesses observed in some channels around 1.8 – 2 TeV**
  - **Global significance 1.5 – 2.5 σ**
- **Excesses of 2σ not unusual, but ATLAS + CMS at similar place = excitement**

CMS: PAS EXO-14-010



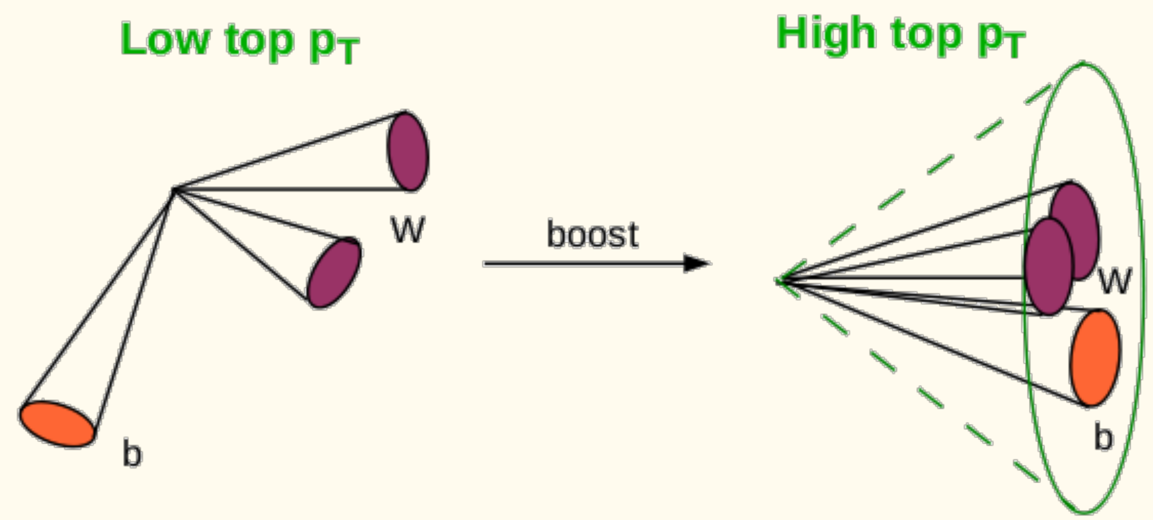
ATLAS: arXiv 1506.00962



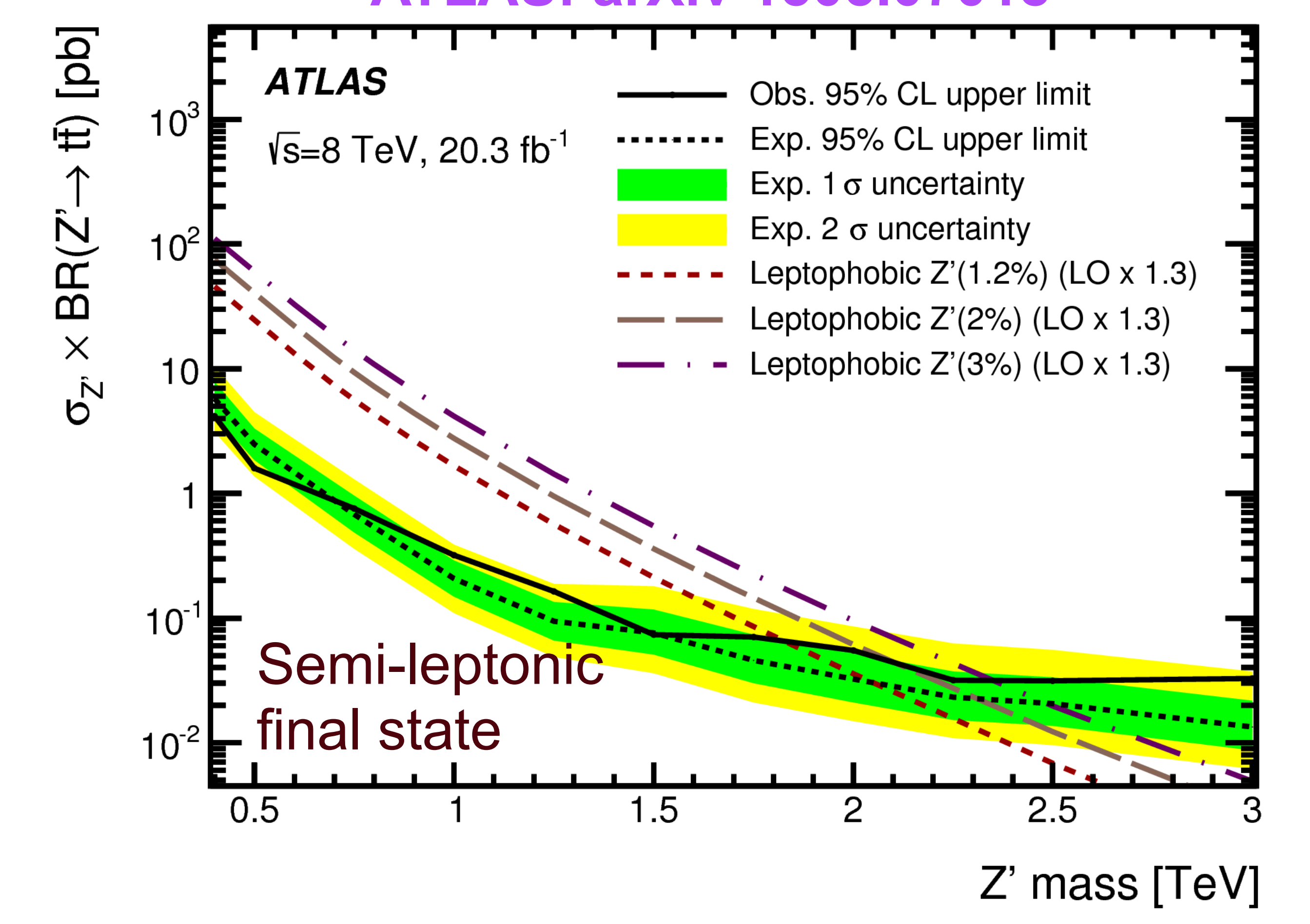
- **Not in all channels…**
- **Will know more after a few first fb^{-1} of Run 2 data**

Di-tops

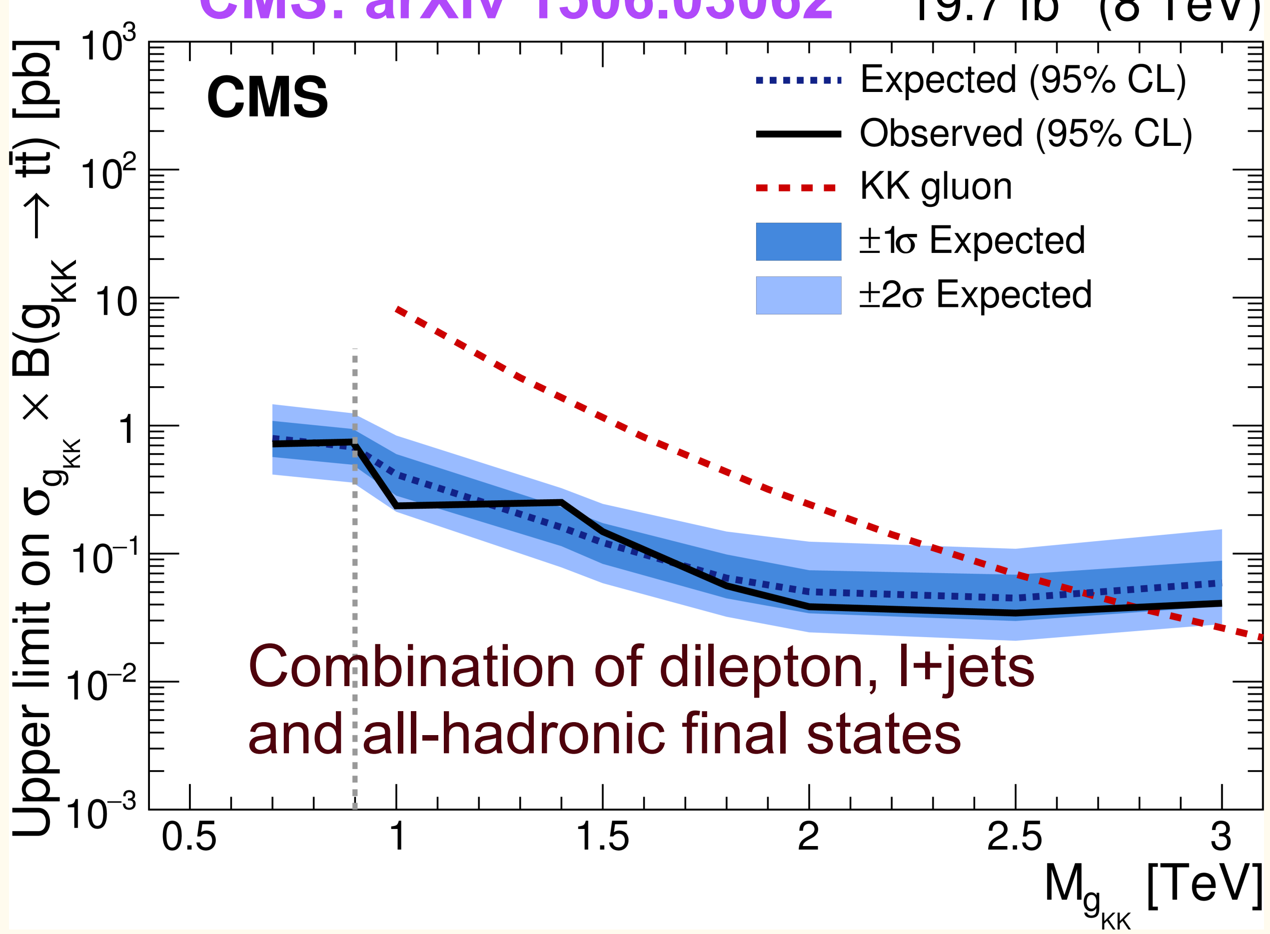
- **Sensitive to leptophobic Z', RS gluon and graviton, pseudoscalar Higgs, etc. with enhanced couplings to tt**
  - **Resonances with widths up to 40% of mass**
- **Heavily relying on boosted topology techniques – top-tagging**



ATLAS: arXiv 1505.07018



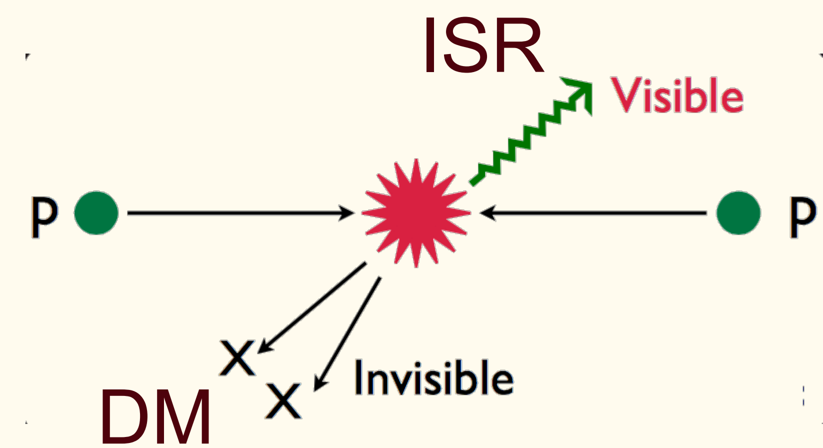
CMS: arXiv 1506.03062



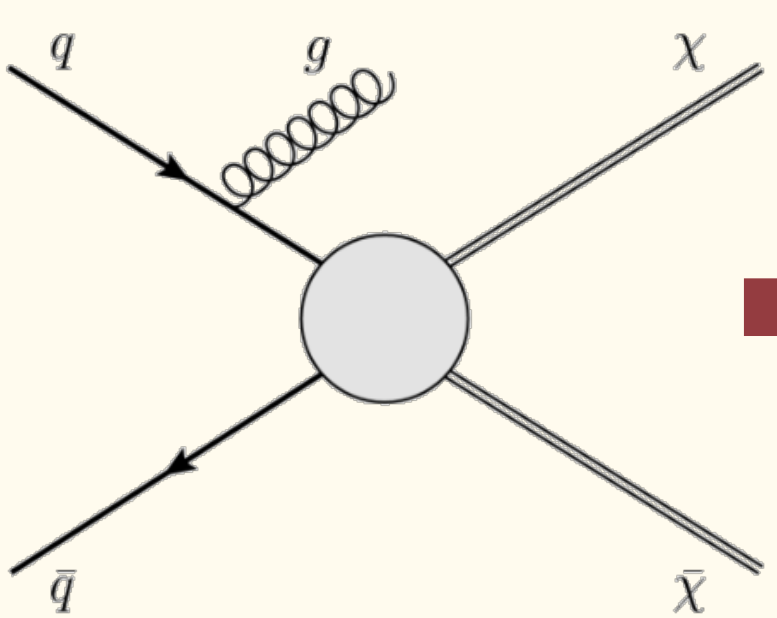
- **All studied types of resonances are excluded up to 2.5 – 3 TeV**

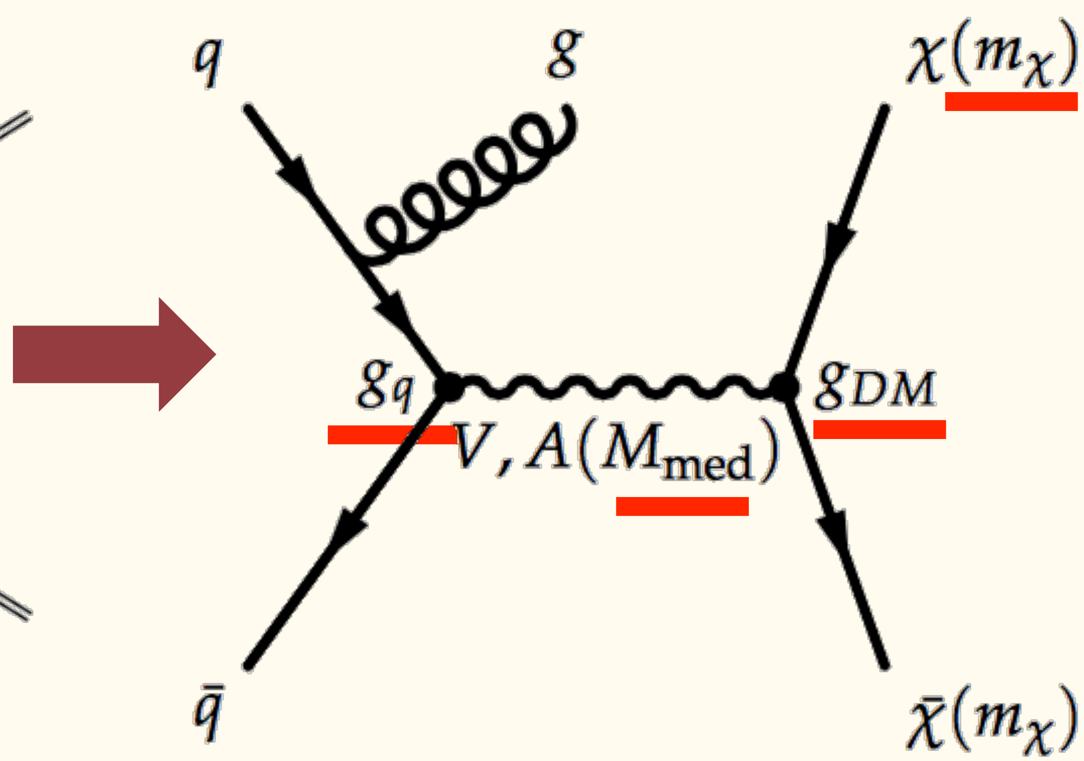
Mono-object + missing energy

- **Mono-jet/γ: main tool of collider Dark Matter search**
  - **Initial state radiation recoil is the only visible energy**
  - **Sensitive also to ED and compressed SUSY**
- **Early DM searches were interpreted in terms of effective field theories (EFT) as a contact interaction**
  - **Measure production rate as a function of DM mass**
  - **Assume large mediator mass**
    ⇒ restricts the validity range of the results too much



- **Need to extend to larger parameter space: two couplings and two masses: ATLAS-CMS Dark Matter Forum [arXiv: 1507.00966]**



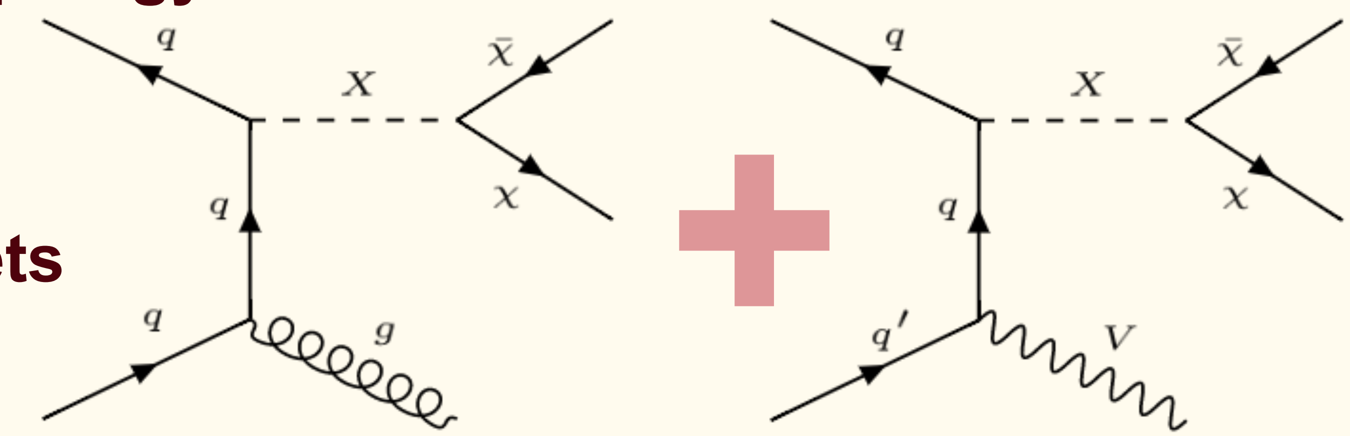


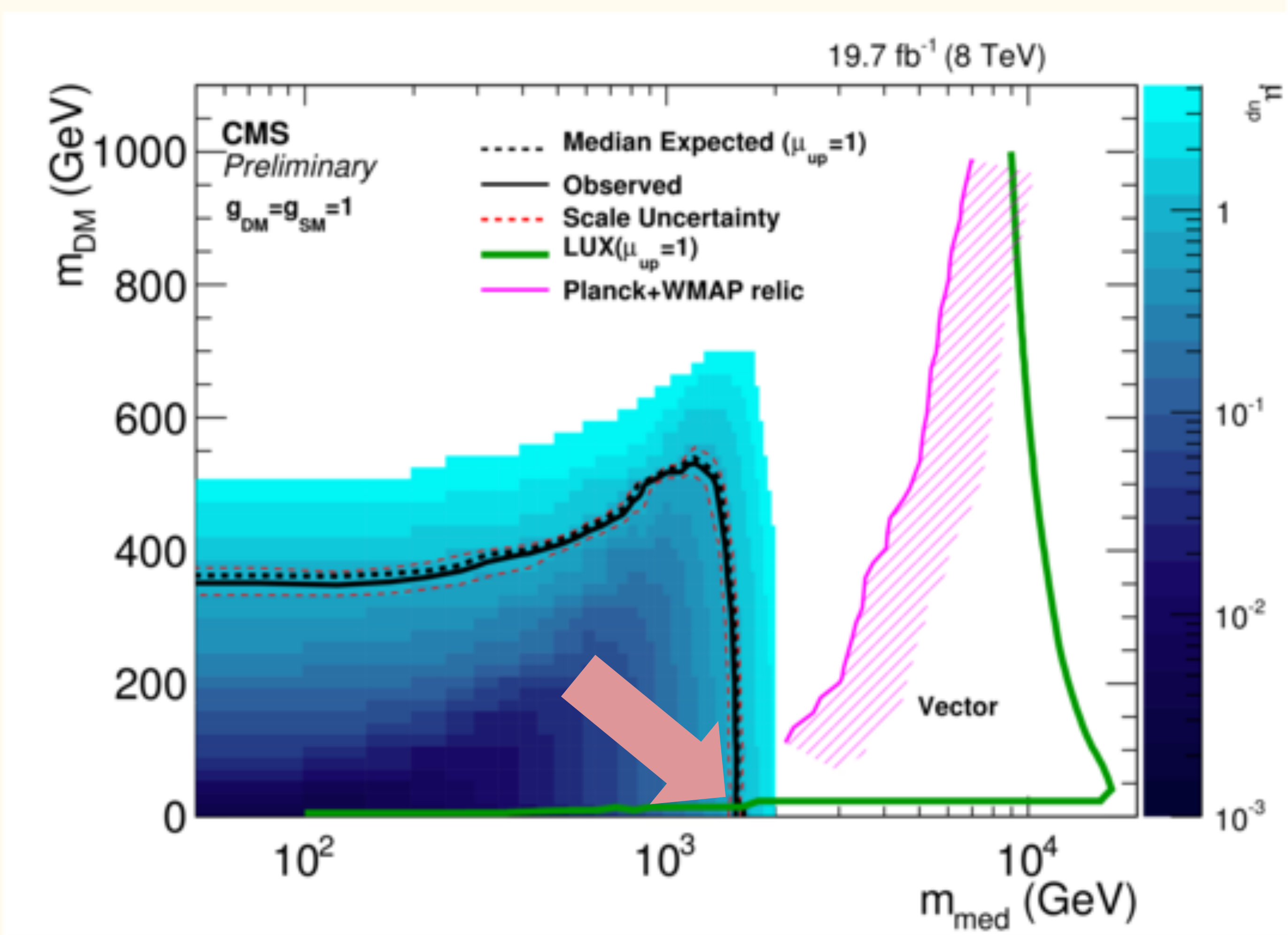
- **Common ATLAS-CMS parameter scan strategy**
- **Interesting connection to di-object resonance searches:**
  mediator = resonance

DM beyond mono-jet and mono-photon:

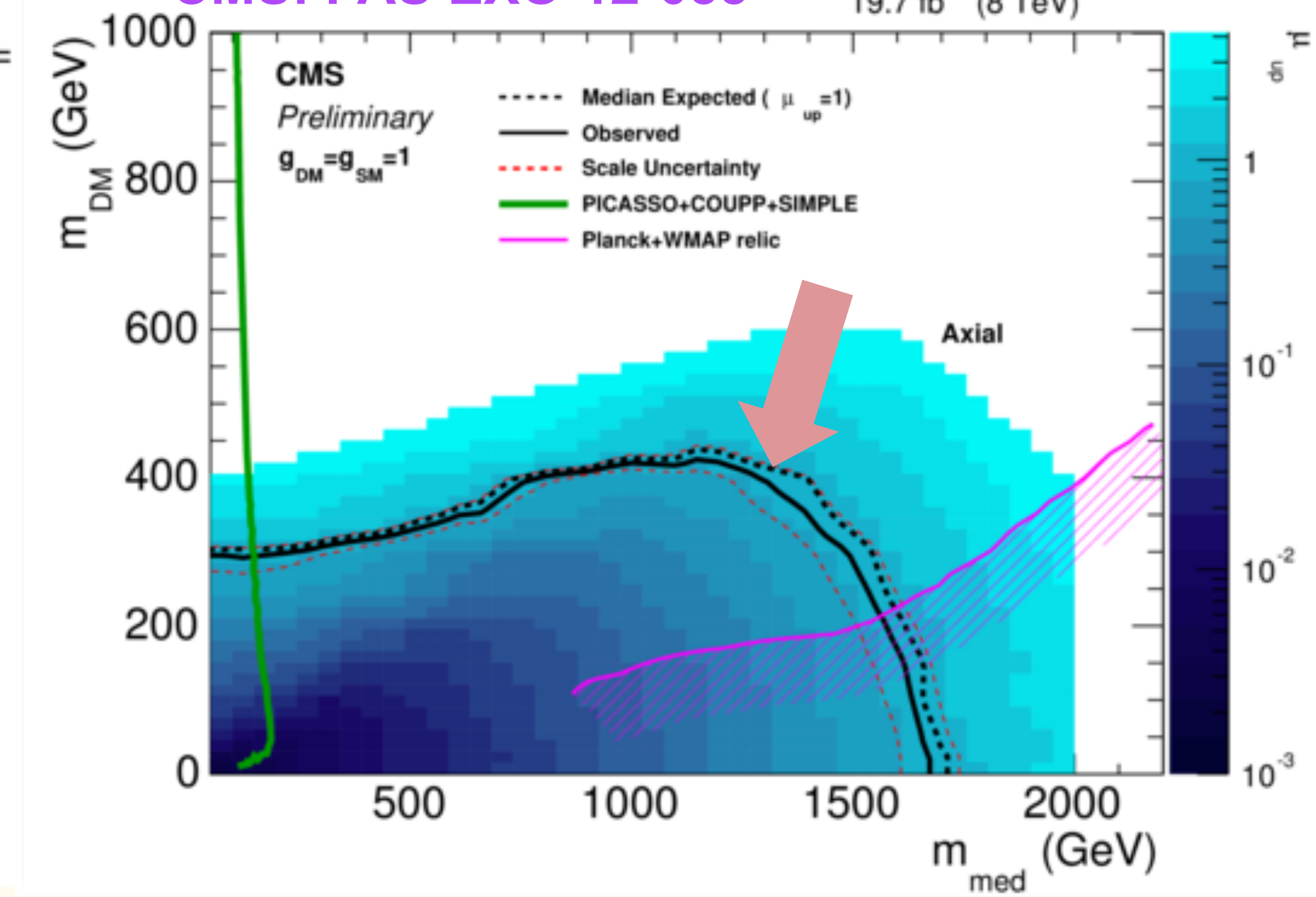
Mono-jet/W/Z + missing energy

- **Hadronic mono-W/Z search combined with mono-jet search**
  - **In resolved and unresolved (boosted) topology**
    - Jet substructure, q/g-tagging, etc.
- **Challenge: Z(vv) + jets backgrounds**
  - **Use multiple control samples: Z(μμ),γ+jets**
  - **Multiple control regions, MET shape**





CMS: PAS EXO-12-055

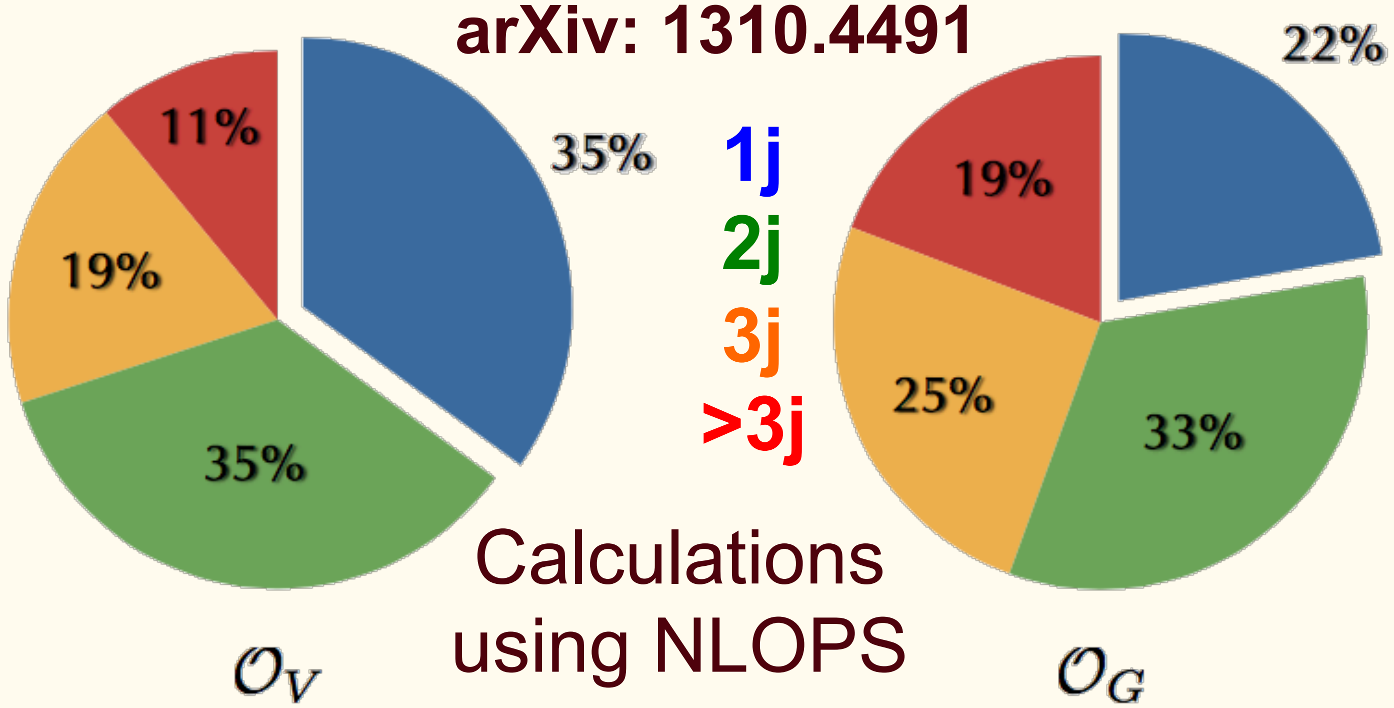


- **Other options: mono-W/Z with leptonic decays** (e.g. recent CMS: PAS EXO-12-054)

Multi-jet + missing energy

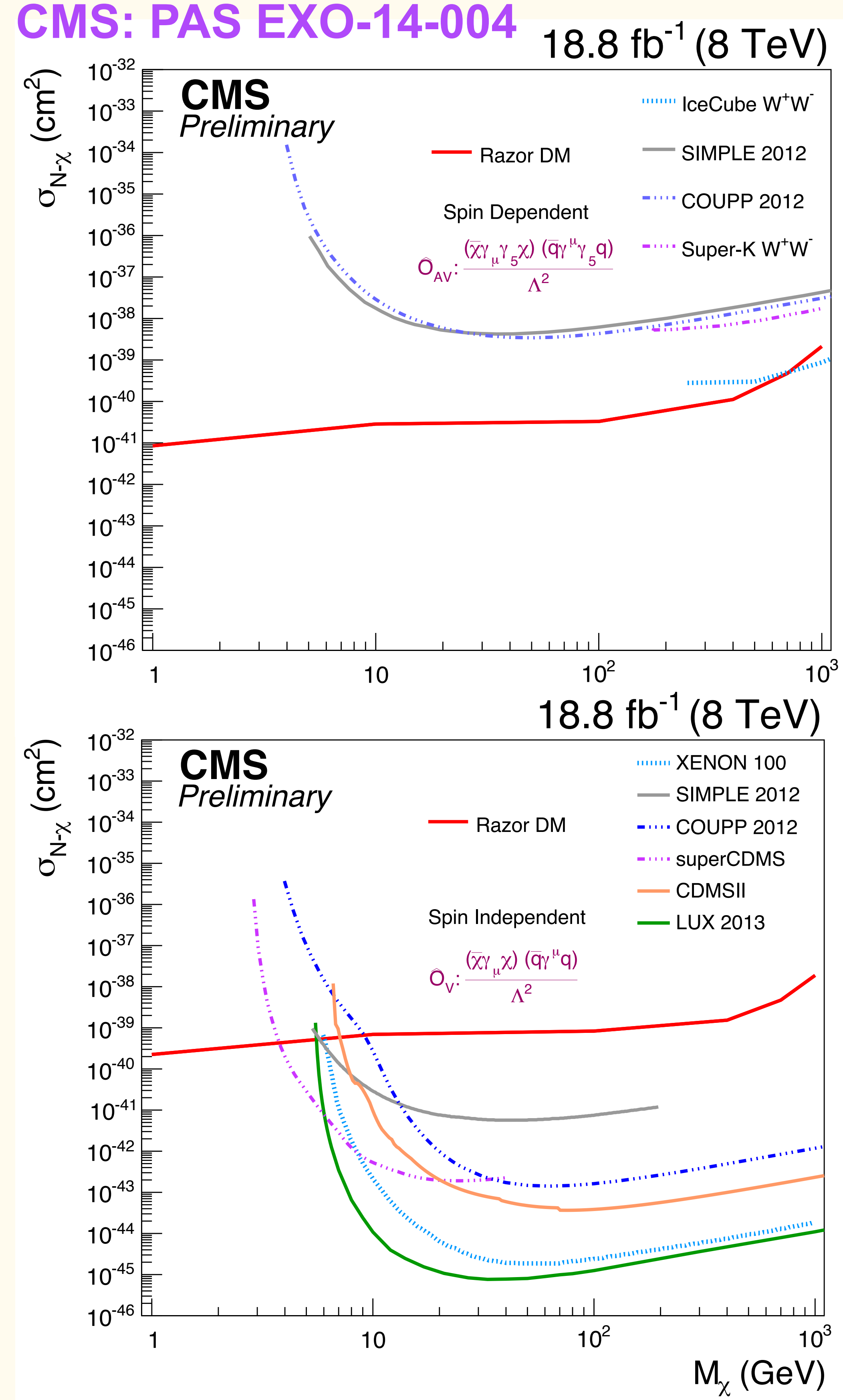
- **Large part of QCD initial state radiation consists of multiple jets**

arXiv: 1310.4491



Calculations using NLOPS

CMS: PAS EXO-14-004

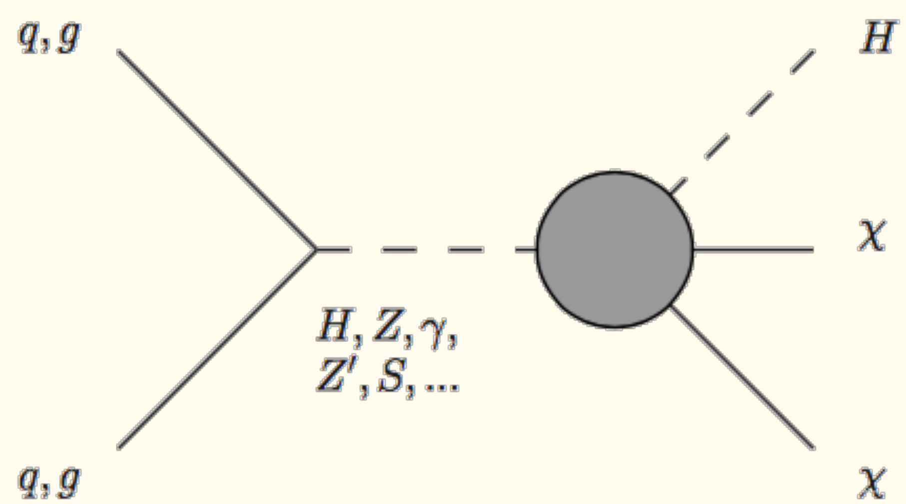


- **SUSY all-hadronic analyses also well suitable for this search**
- **Sensitivity similar to mono-jet searches**
  - **Lower background, looser selection**

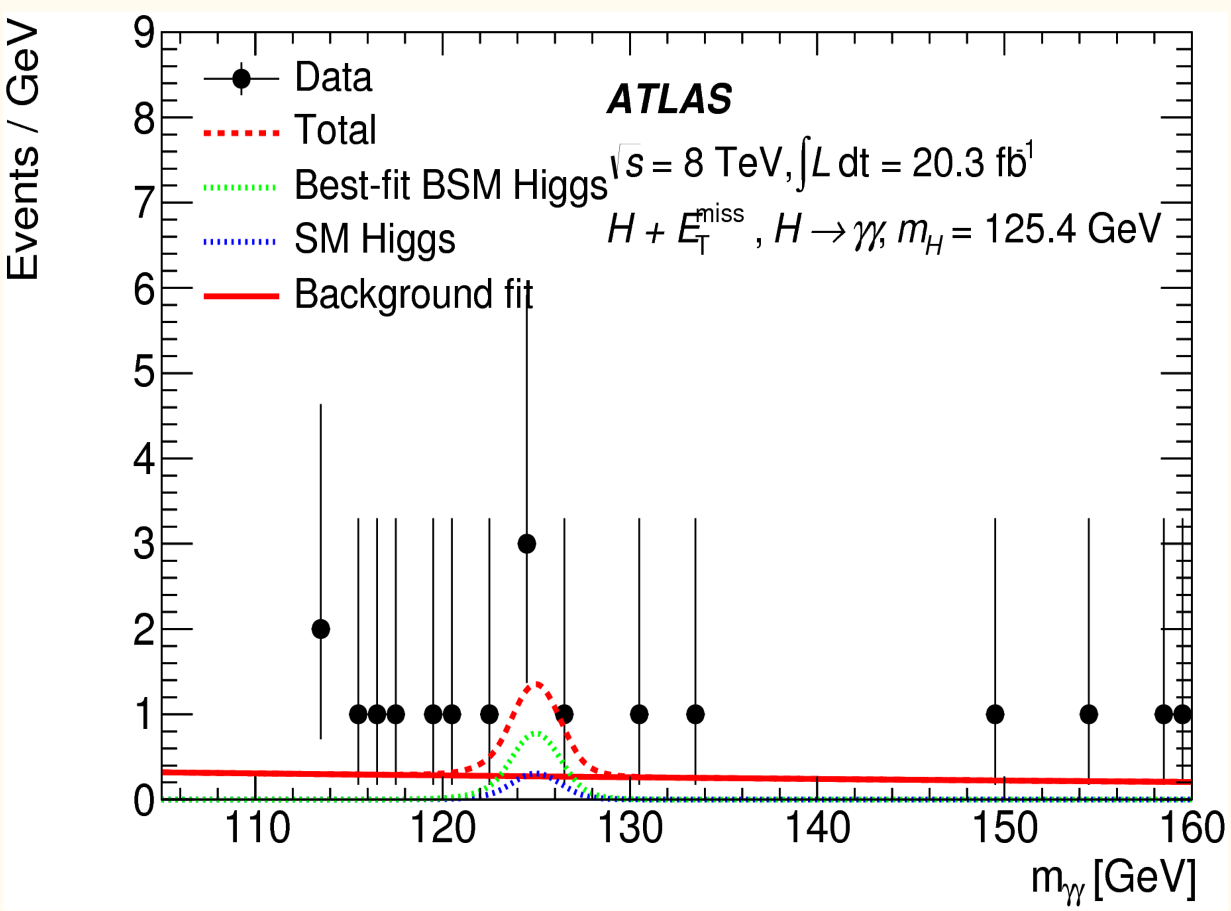
DM beyond mono-jet and mono-photon:

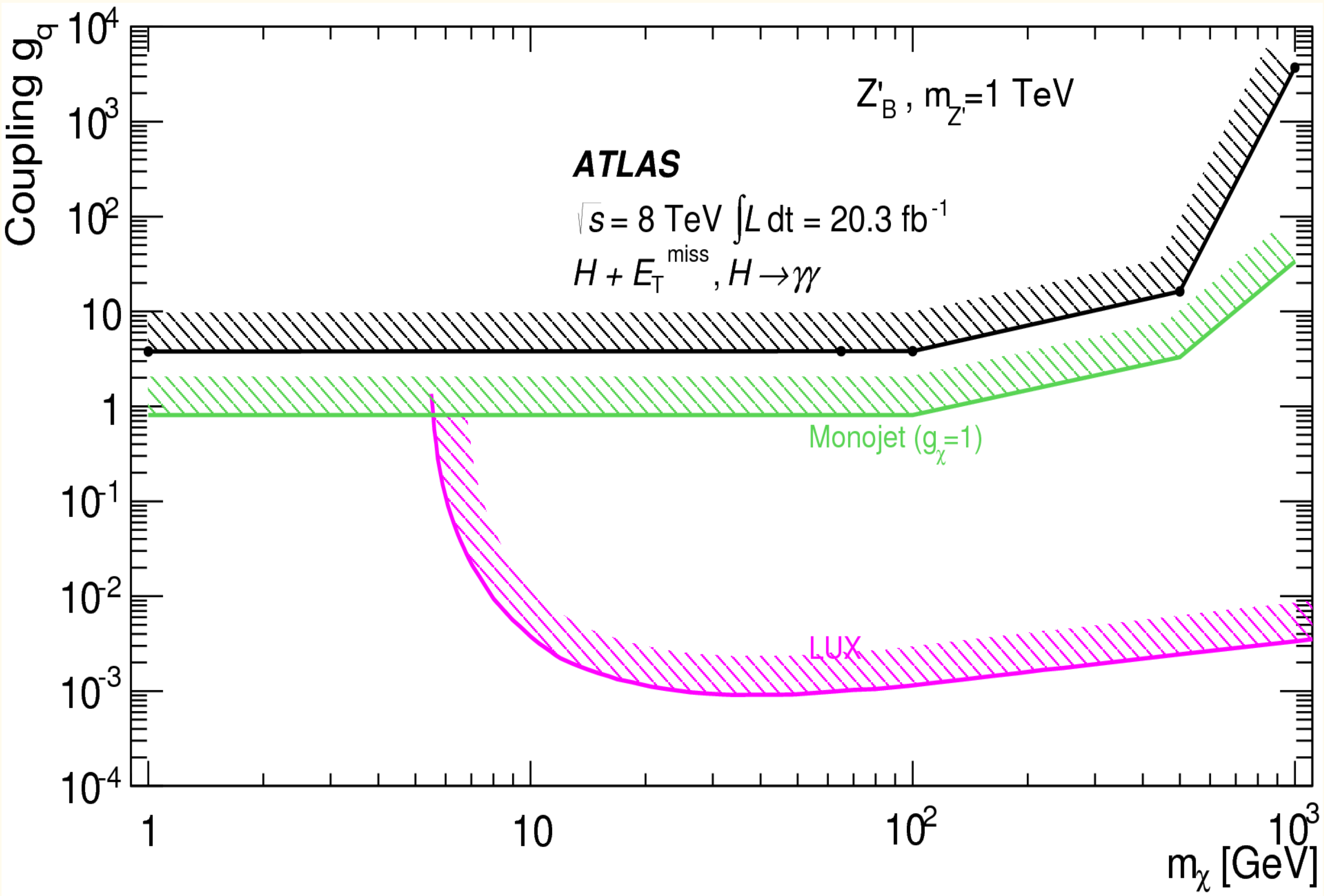
Mono-Higgs + missing energy

- **Recent result by ATLAS with mono-Higgs final state (H➡γγ)**
- **Explores additional models with different kinematics**
  - **No initial state radiation**



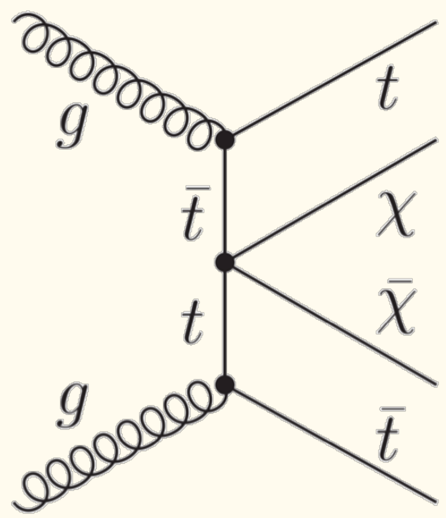
ATLAS: arXiv 1506.01081



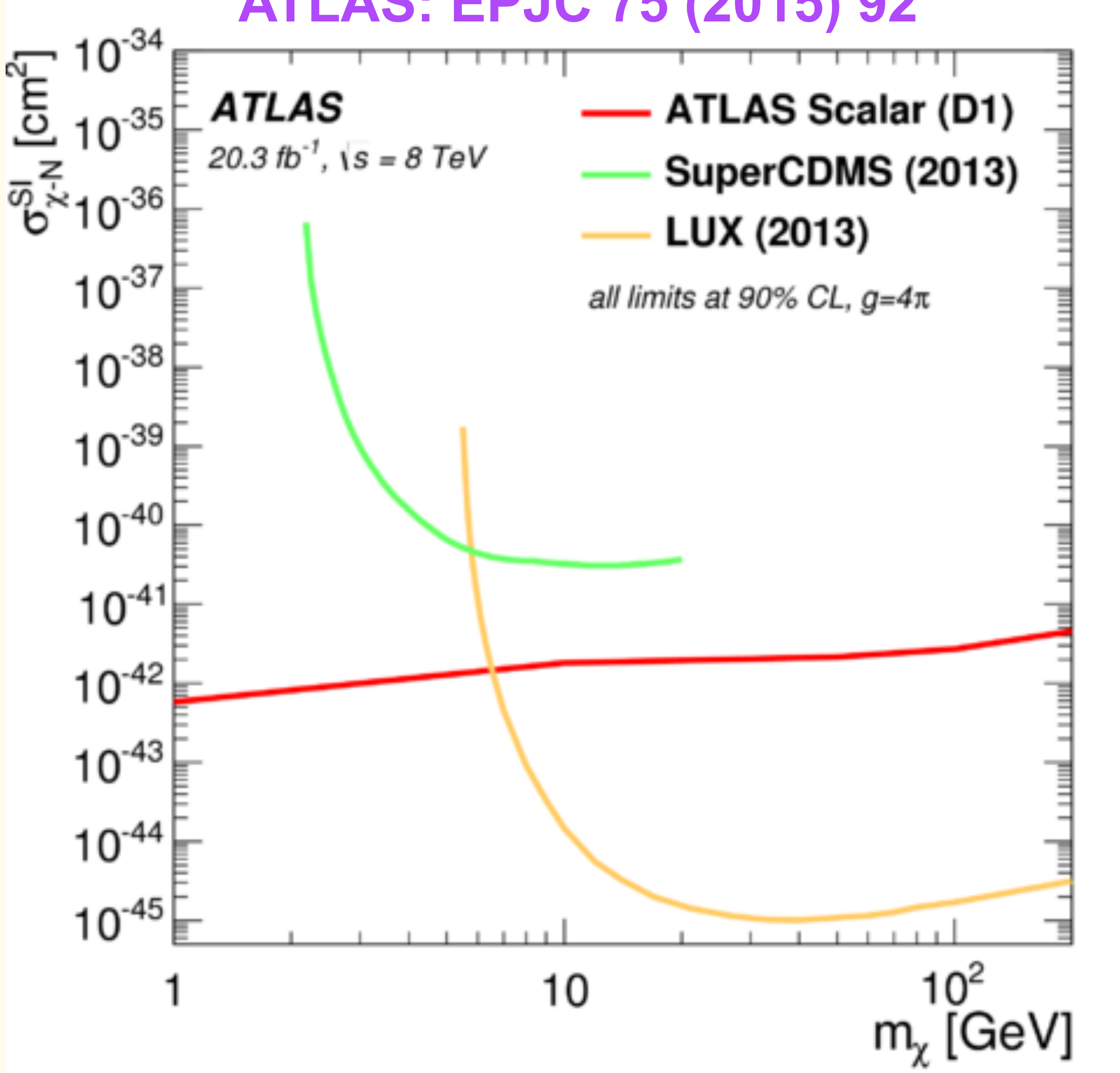


Heavy quarks + missing energy

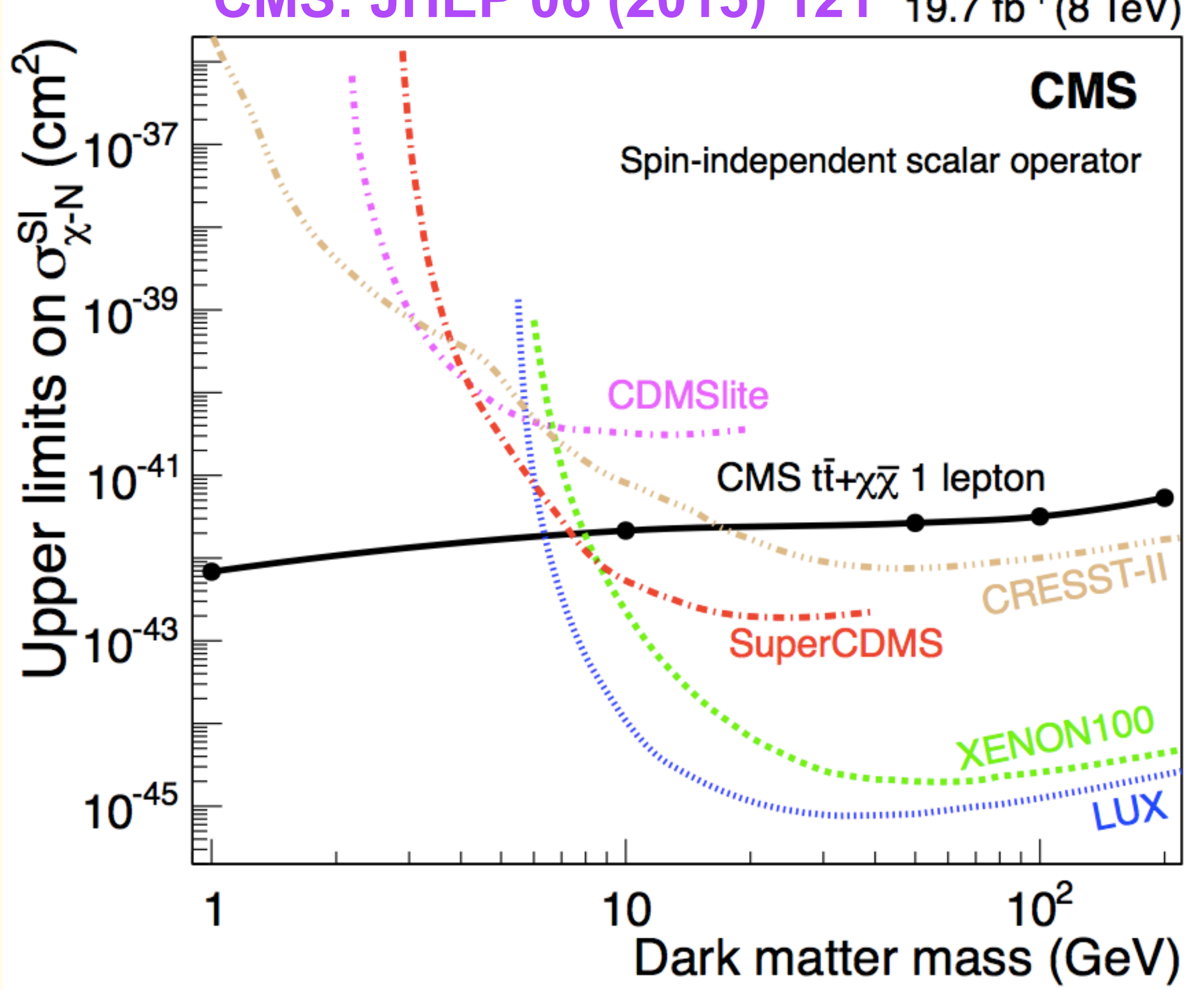
- **Heavy quarks associated with missing energy are particularly suited for searches for DM which couples to SM through effective scalar coupling**
- **Provides most stringent limits on this type of DM**



ATLAS: EPJC 75 (2015) 92

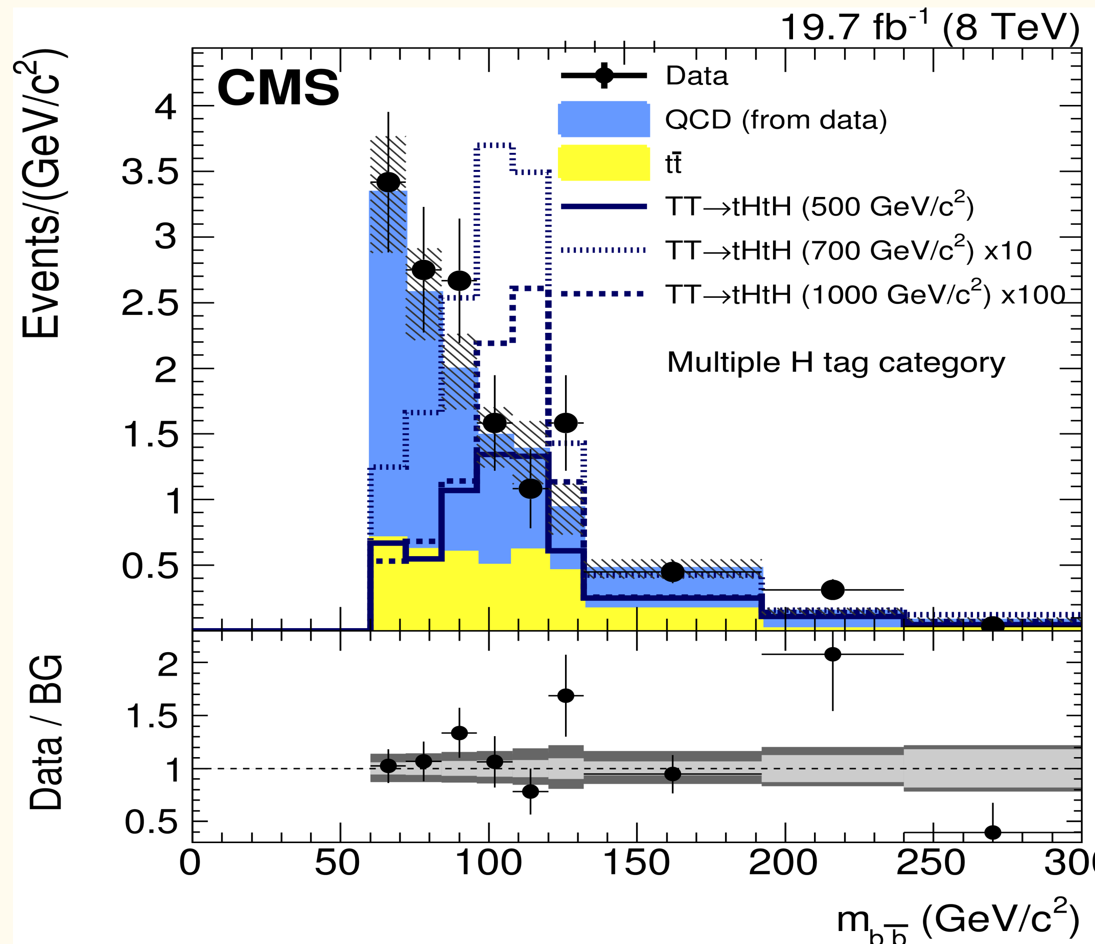


CMS: JHEP 06 (2015) 121

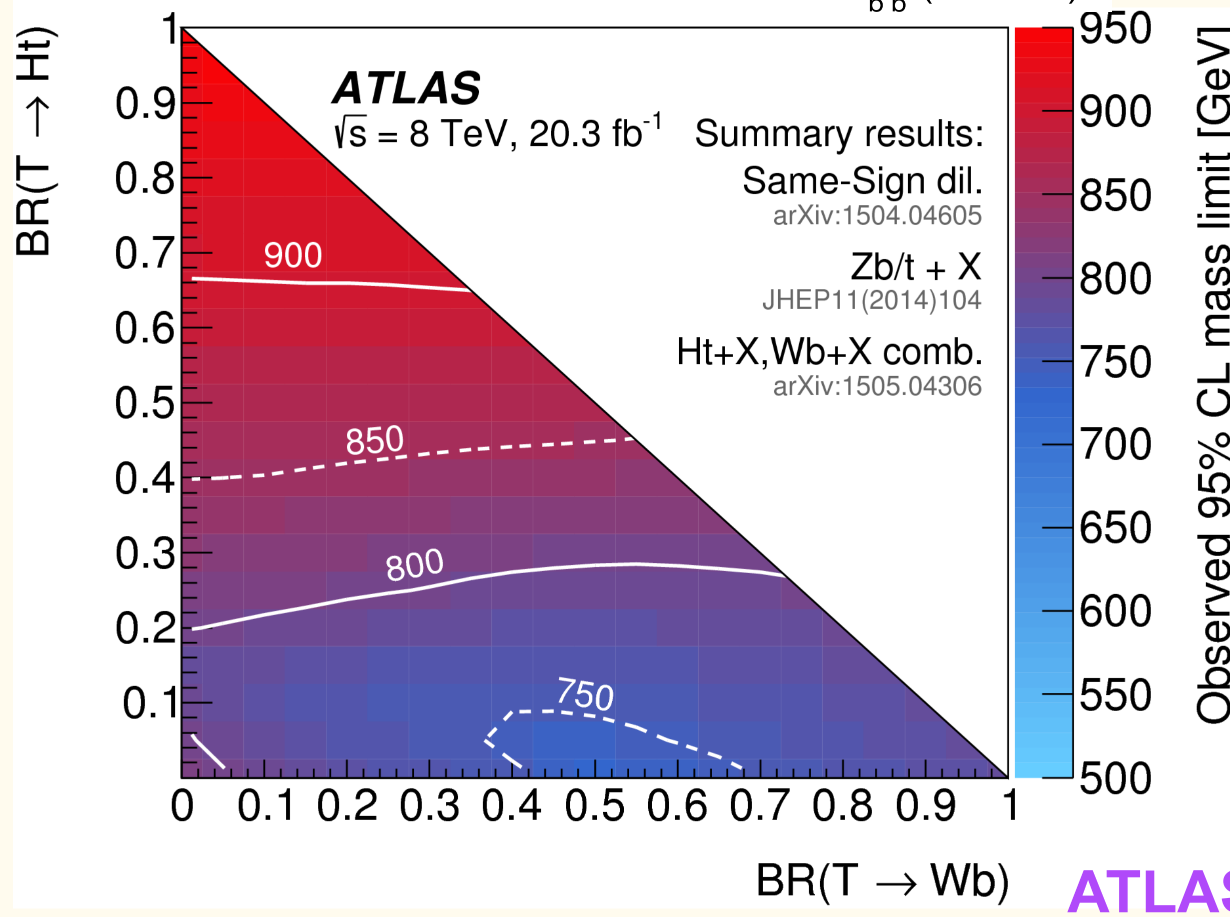


Multi-object topologies: VLQ

- **Vector-like quarks (VLQ) emerge in many BSM models. Based on naturalness, t and b partners are predicted at TeV scale**
  - **In Run 1 conditions produced mainly in pairs and decay into a combination of heavy quark and boson (W,Z,H)**
- **Searches deploy boosted signature techniques with sub-jet b-tagging and top-tagging**
  - **Exploring various final states: all-hadronic, l+jets, SS di-leptons, multi-lepton**
- **Run 1 limits on vector-like B and T: between 600 – 900 GeV**
- **In Run 2, also a single T,B production becomes important**



CMS: JHEP 06 (2015) 080



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html

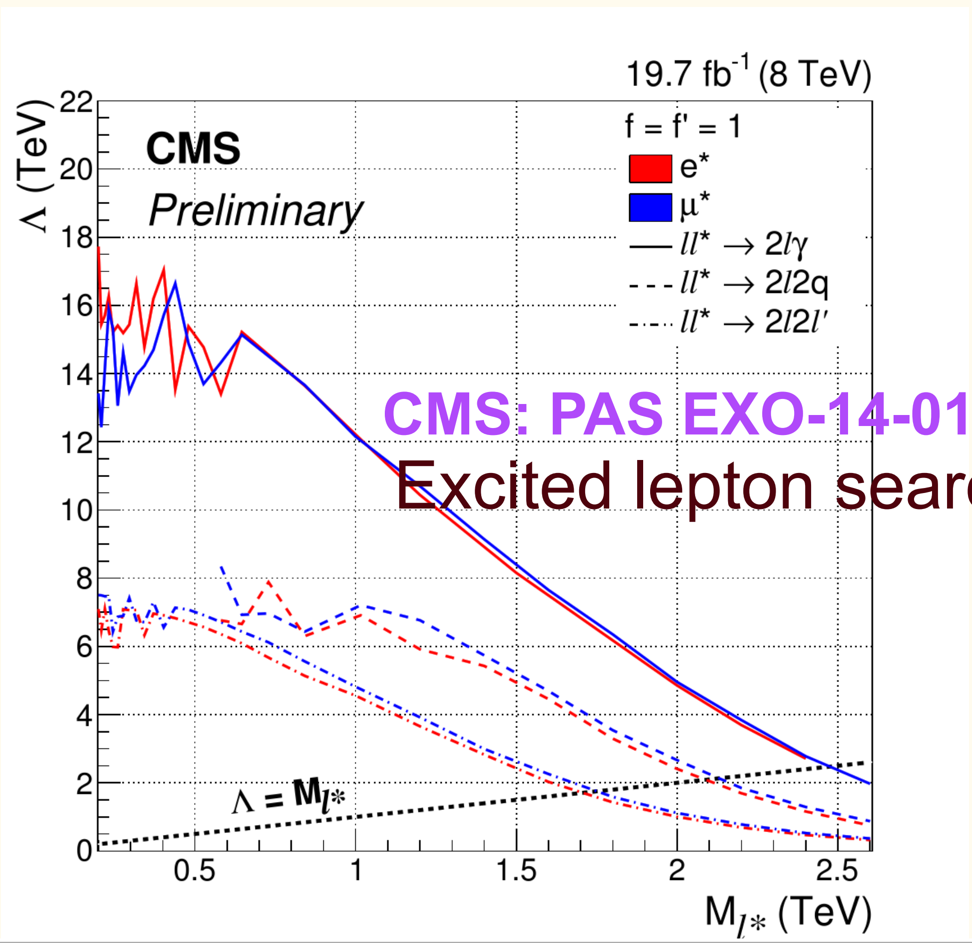
ATLAS

Multi-object topologies: excited leptons

- **To explain the family structure of SM, compositeness models predict excited fermion states**
  - **Excited leptons searched in llγ and llZ final states**
  - **Probe different couplings to SM gauge bosons**

ATLAS: PRD 91, 052007 (2015)

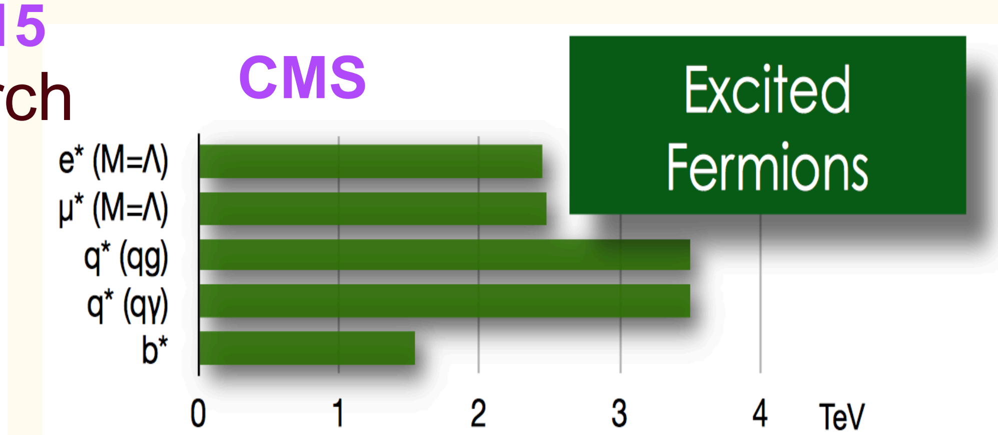
Excited quark search in di-jets

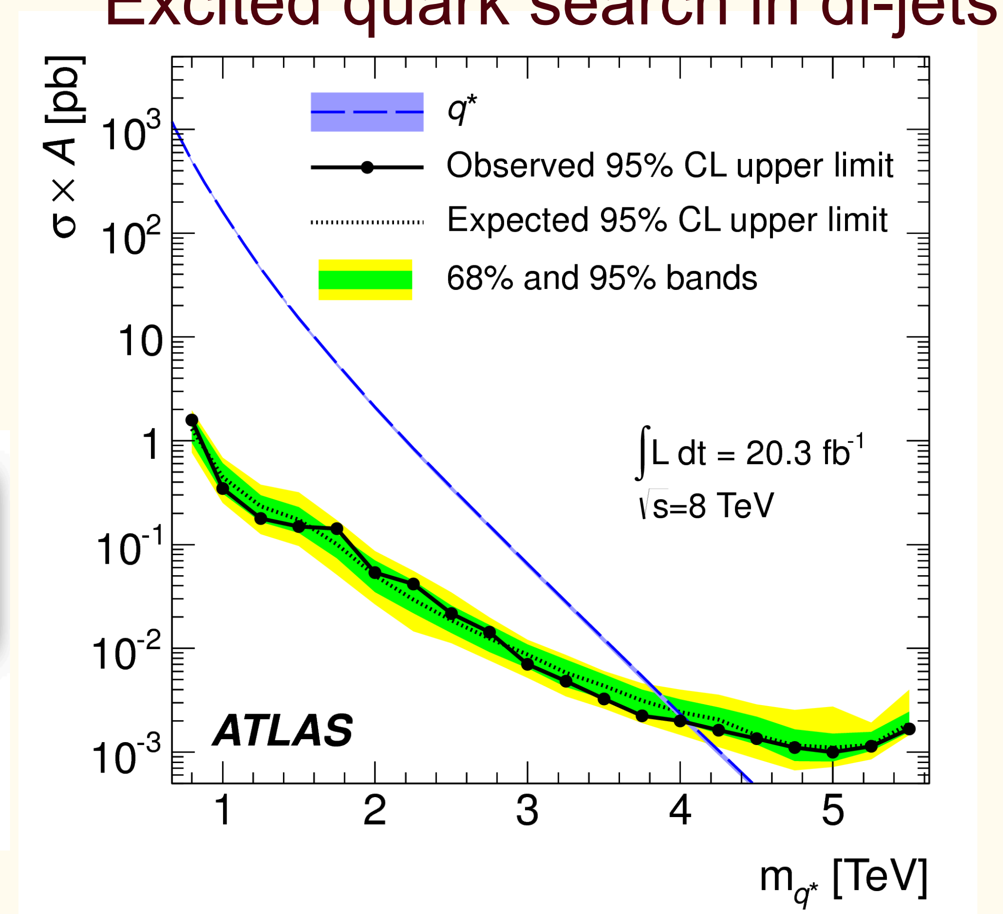


CMS: PAS EXO-14-015

Excited lepton search

- **Cf. excited quarks are searched in di-jet and photon+jet final states:**





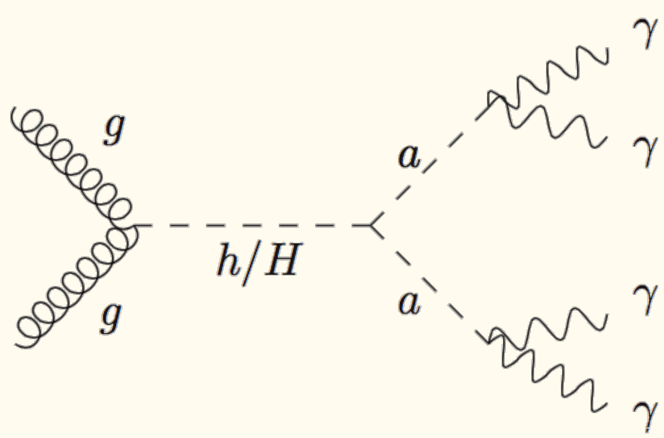
ATLAS

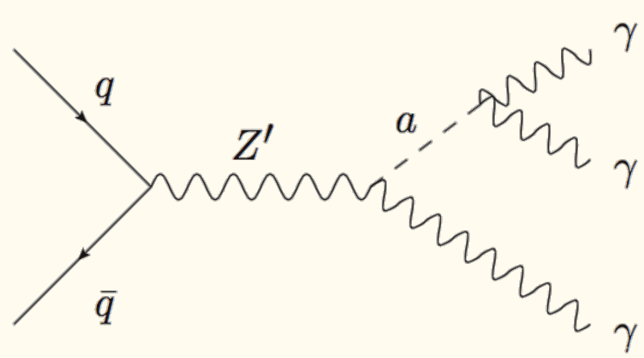
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q^* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1407.1376
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	2 e, μ, 1 γ	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
	Excited lepton $\nu^* \to \ell W, \nu Z$	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921

- **Excited leptons excluded up to 2 - 2.5 TeV and excited quarks up to 4 TeV**

Multi-object topologies: Multi-photons

- … and there are always new corners to look into
- New result at this conference in the talk of Theodota Lagouri:





ATLAS: EXOT-2013-24

Decays to light pseudoscalar neutral Higgs boson (α) $H \to \alpha\alpha \to 4\gamma$ (ATLAS)

Brand New

ATLAS (8 TeV)
EXOT-2013-24
To be submitted to Eur. Phys. J. C

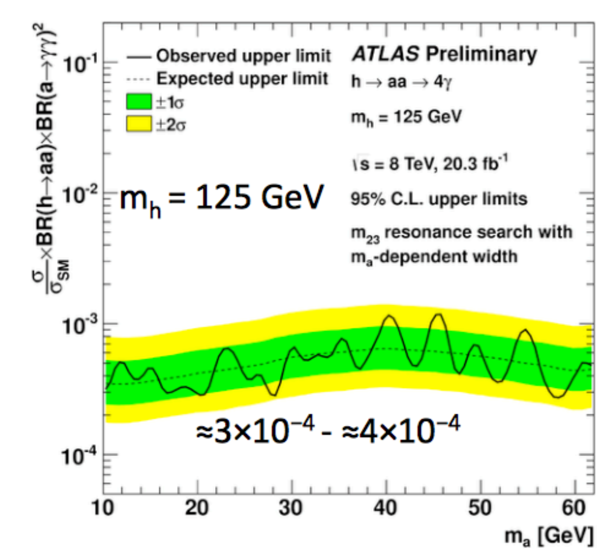
Many extensions of SM Higgs sector include CP-odd particles (α) with couplings to Higgs and branching ratios to photons visible at LHC

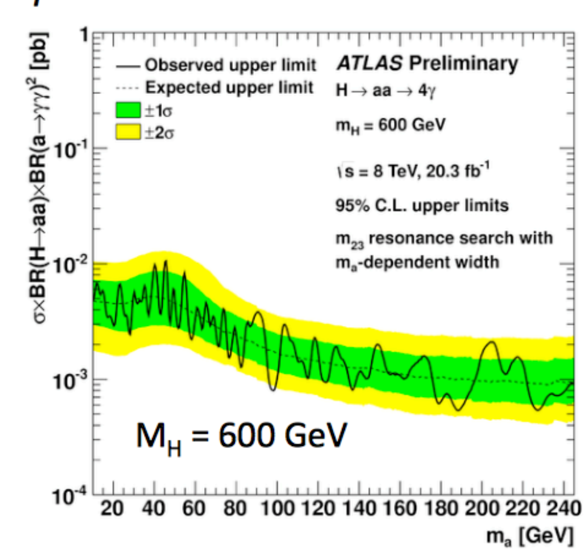
Signature: ≥ 3 isolated photons

- Signal: "tight" $\gamma_{1,2}$: $p_T > 22$ GeV, $\gamma_{3,(4)}$: $p_T > 17$ GeV
- Isolation: E_T(cone40) < 4 GeV
- Backgrounds: irr. (2,3,4) prompt photons, photon(s)+jet(s)
- Combination of data-driven (for jets) and MC

No significant excess of data over SM BGs
Consistent with SM expected limits

Resonance search in m_{23} spectrum





$300 < M_H < 900$ GeV
$10 \text{ GeV} < m_\alpha < m_H/2$

M_H: 600 GeV

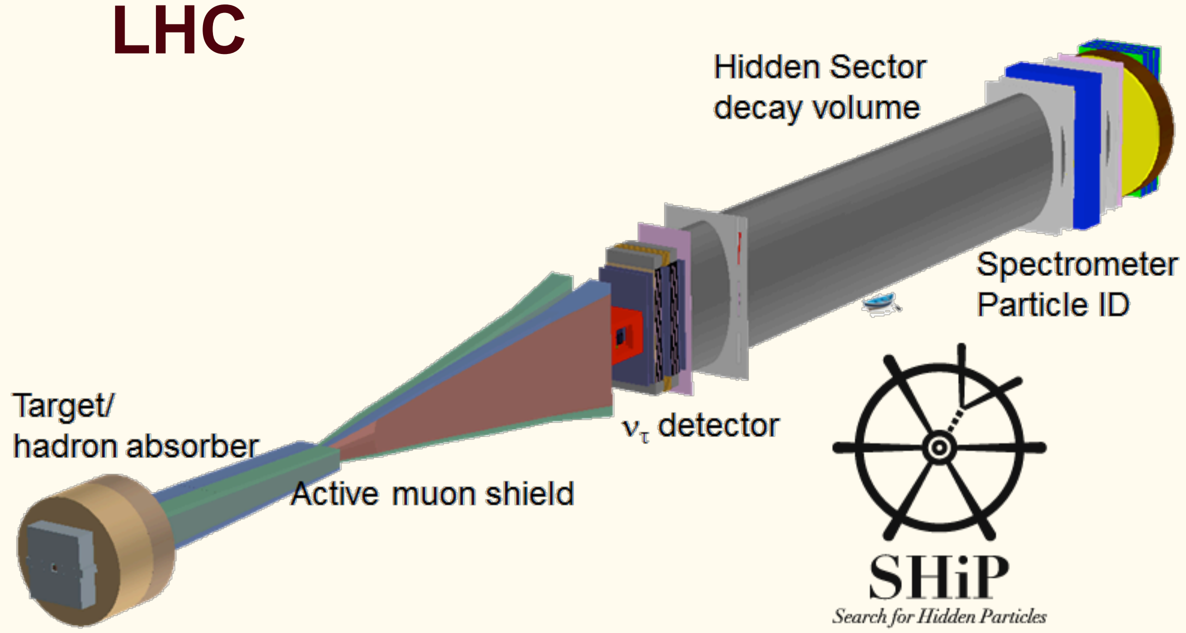
$\sigma/\sigma_{SM} \times BR(h \to \alpha\alpha) \times BR(\alpha \to \gamma\gamma)^2 < 10^{-3}$
$m_h = 125$ GeV, $10 \text{ GeV} < m_\alpha < 62$ GeV

$\sigma_H \times BR(h \to \alpha\alpha) \times BR(\alpha \to \gamma\gamma)^2 < 0.02$ pb $10 < m_\alpha < 90$ GeV
< 0.001 pb m_α up to 245 GeV

Th. Lagouri, Yale Univ. EPS HEP (22-29 Jul 2015) 14

Displaced/delayed objects

- **Displaced/delayed objects: tool to search for long-lived particles (LLP)**
  - **LLPs are predicted by a variety of BSM models with weak couplings (Hidden Valley, GMSB), small mass gaps (Stealth SUSY, AMSB), weakly broken symmetries (RPV SUSY), high mass mediator (Split SUSY)…**
- **Searches at ATLAS and CMS are complemented by LHCb and BaBar/Belle**
- **Future fixed target facility at SPS: SHiP (Search for Hidden Particles) [arXiv: 1504.04855]**
  - **Low energy scale and very weak couplings ⇒ complementary to LHC**

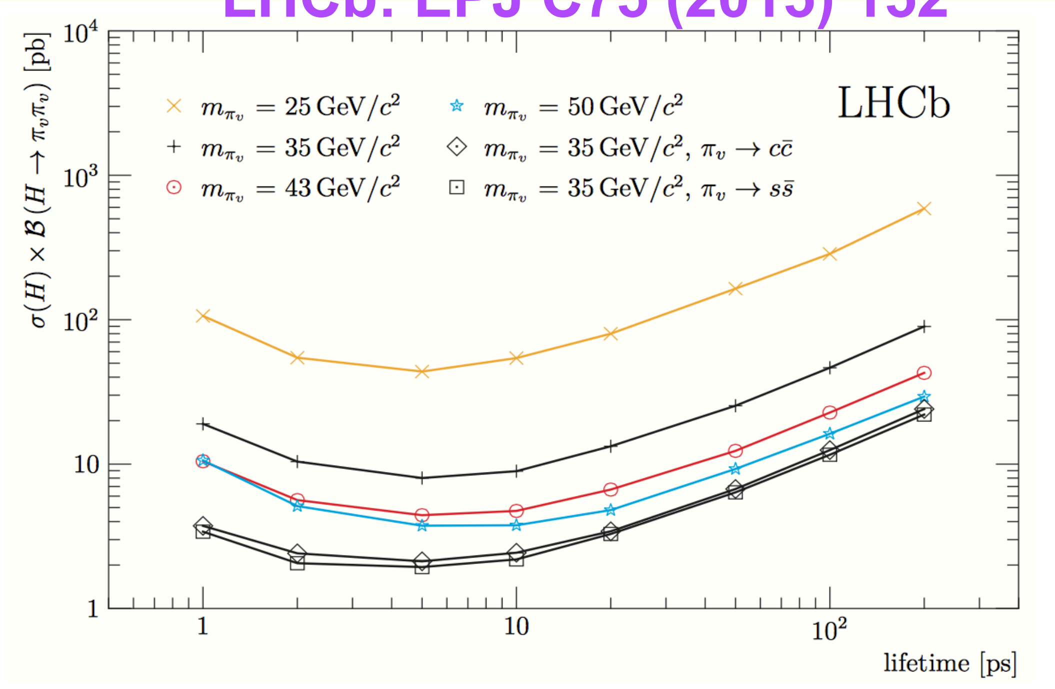


Q of LLP	Exp. signature
Neutral	Displaced jets
	Displaced leptons
	Displaced/delayed photons
	Displace vertex
	Lepton jets
Charged	dE/dx, TOF, ~~RICH~~ (Heavy stable charged particles)
	Disappearing/kinked tracks
Both	Delayed signal (stopped particles)

Displaced jets/leptons

- Usual benchmark $H/\Phi \rightarrow \Phi_{HS} \rightarrow \pi_v \pi_v$ with $\pi_v \rightarrow$ jj/ll (Hidden valley) but also Stealth or RPV SUSY
- New techniques using only muon detector signals and triggers to extend the probed lifetime range
  - MS jets in ATLAS and RSA muons in CMS

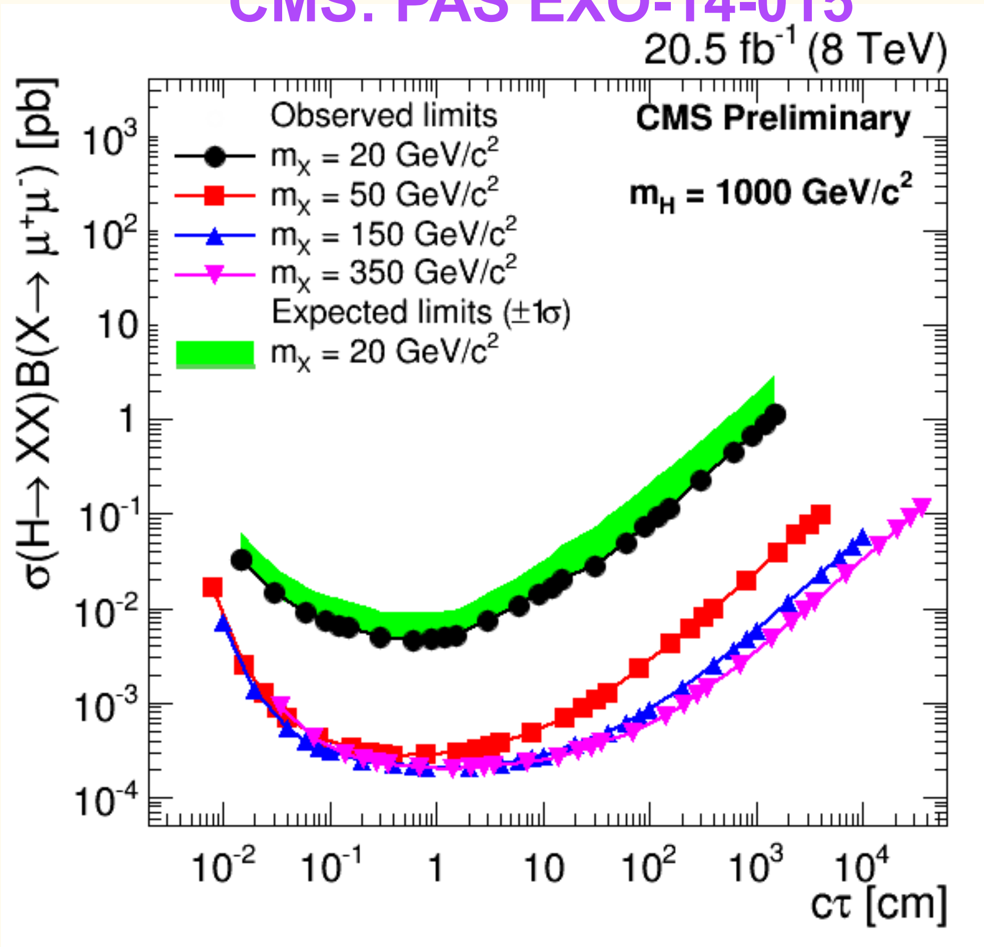
LHCb: EPJ C75 (2015) 152



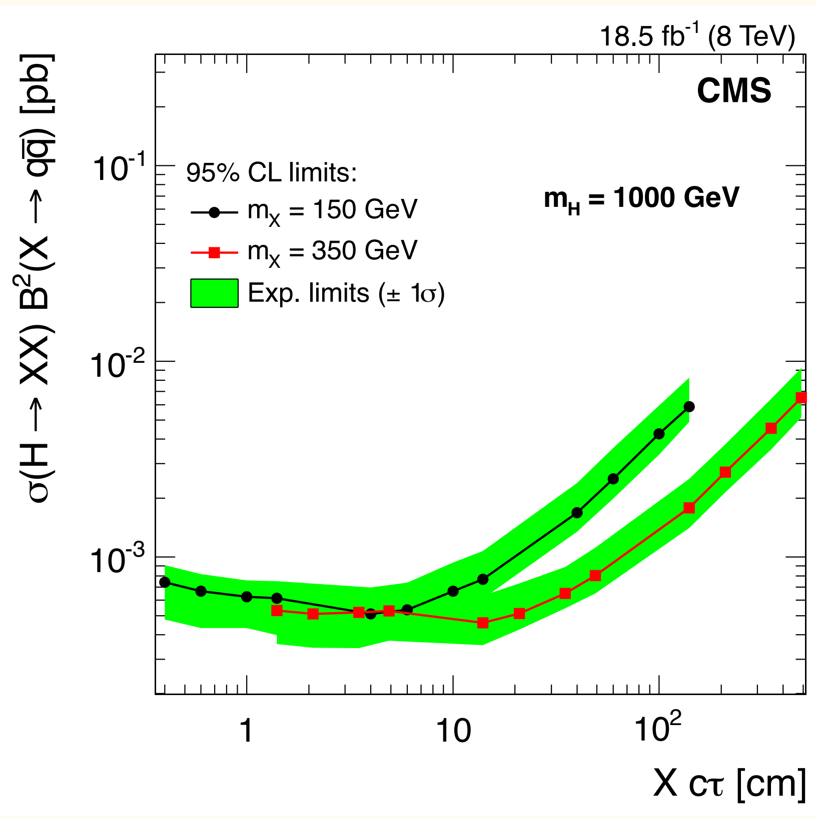
leptons

jets

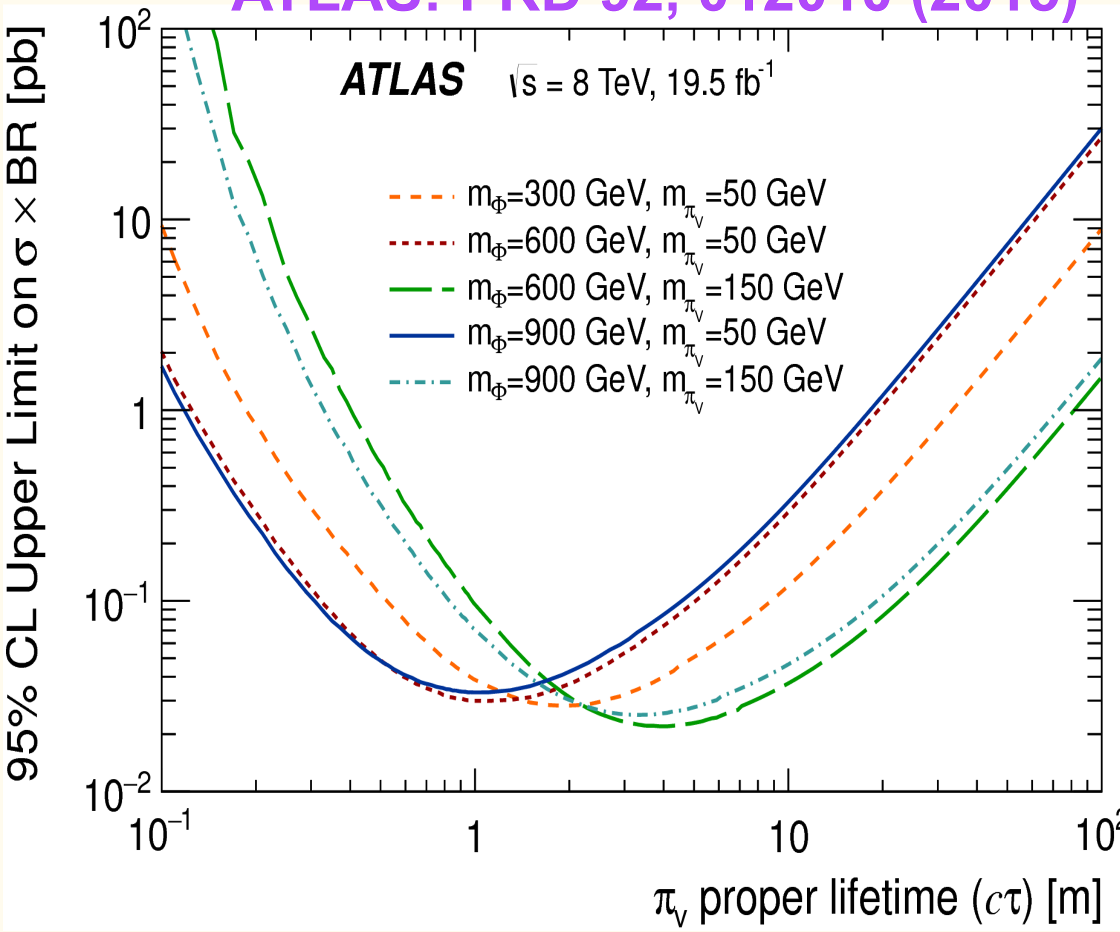
CMS: PAS EXO-14-015



CMS: PRD 91, 012007 (2015)



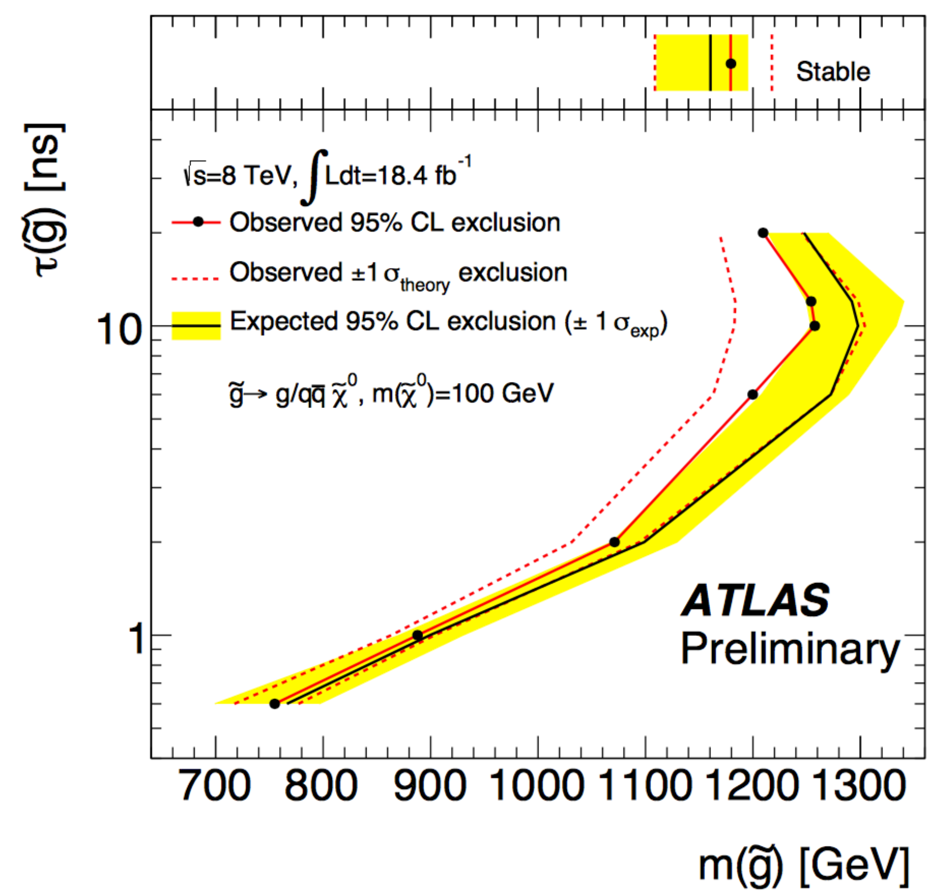
ATLAS: PRD 92, 012010 (2015)



Heavy stable charged particles

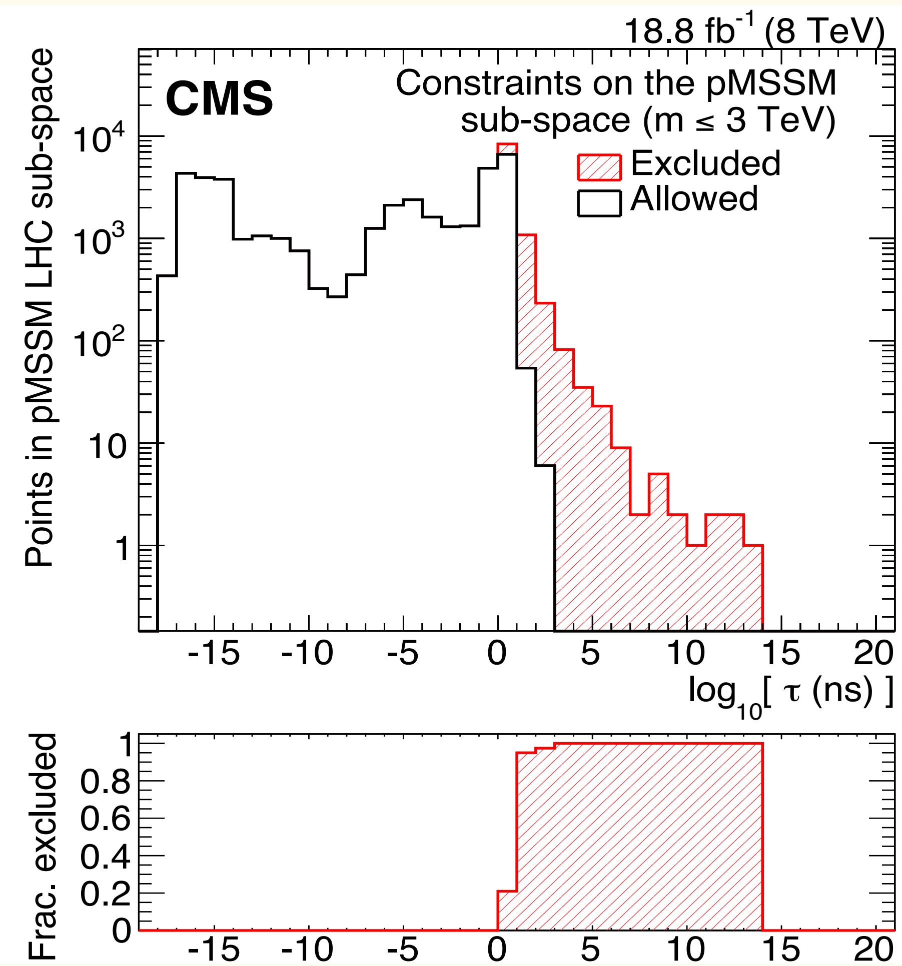
- **Benchmarks: R-hadrons, stable chargino, stau,…**
- **HSCP predicted to be slow – detection techniques:**
  - **dE/dx, TOF; LHCb: absence of RICH signal**

ATLAS: CONF-2015-013



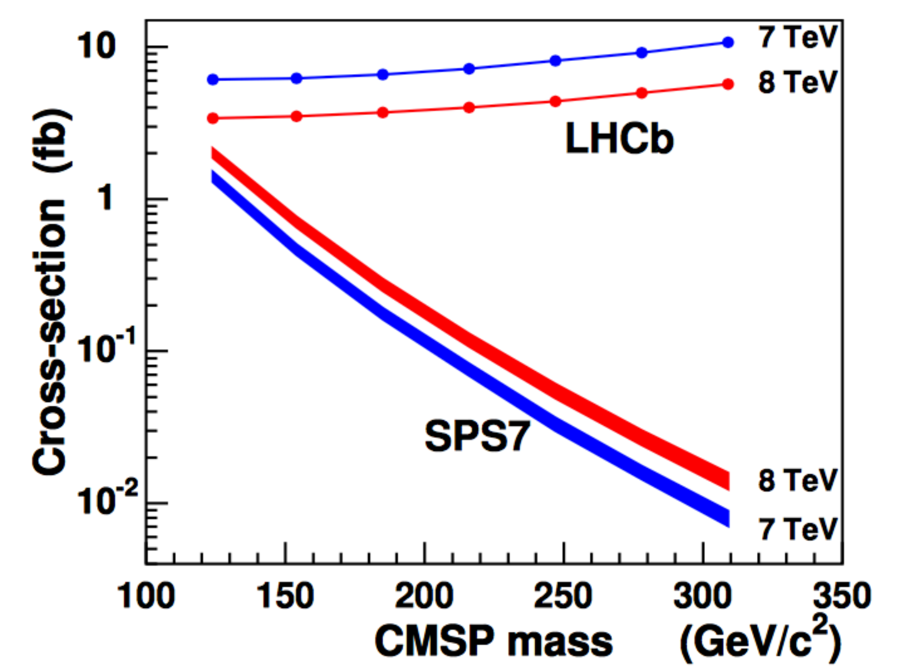
- **Stable and meta-stable R-hadron exclusion**
- **Sampling detector effects from control samples**

CMS: arXiv: 1502.02522

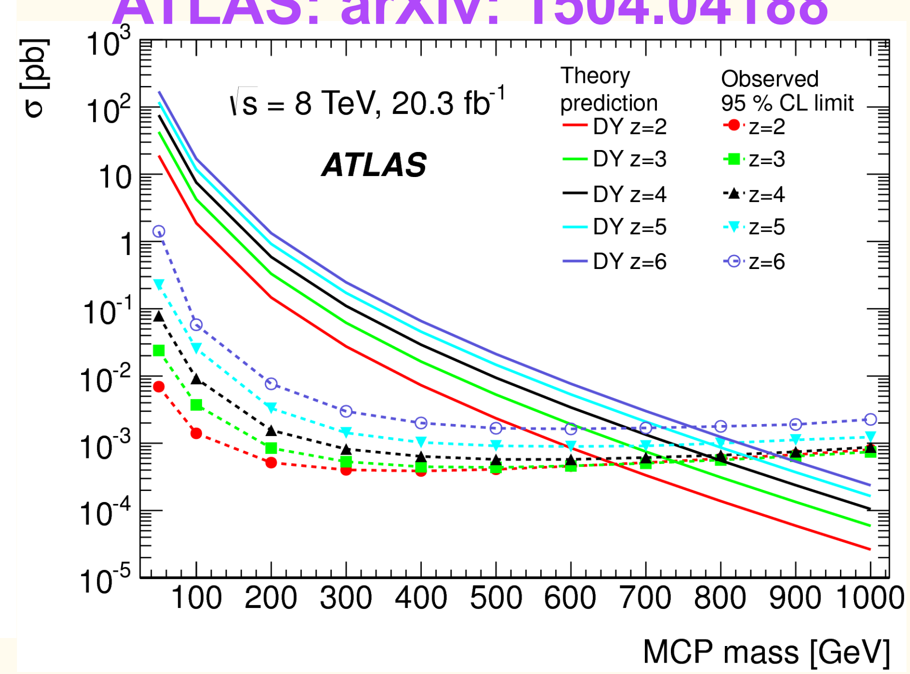


- **Similar techniques in CMS**
- **Reinterpreted now also in pMSSM and AMSB parameter space**

LHCb: arXiv: 1506.09173



ATLAS: arXiv: 1504.04188

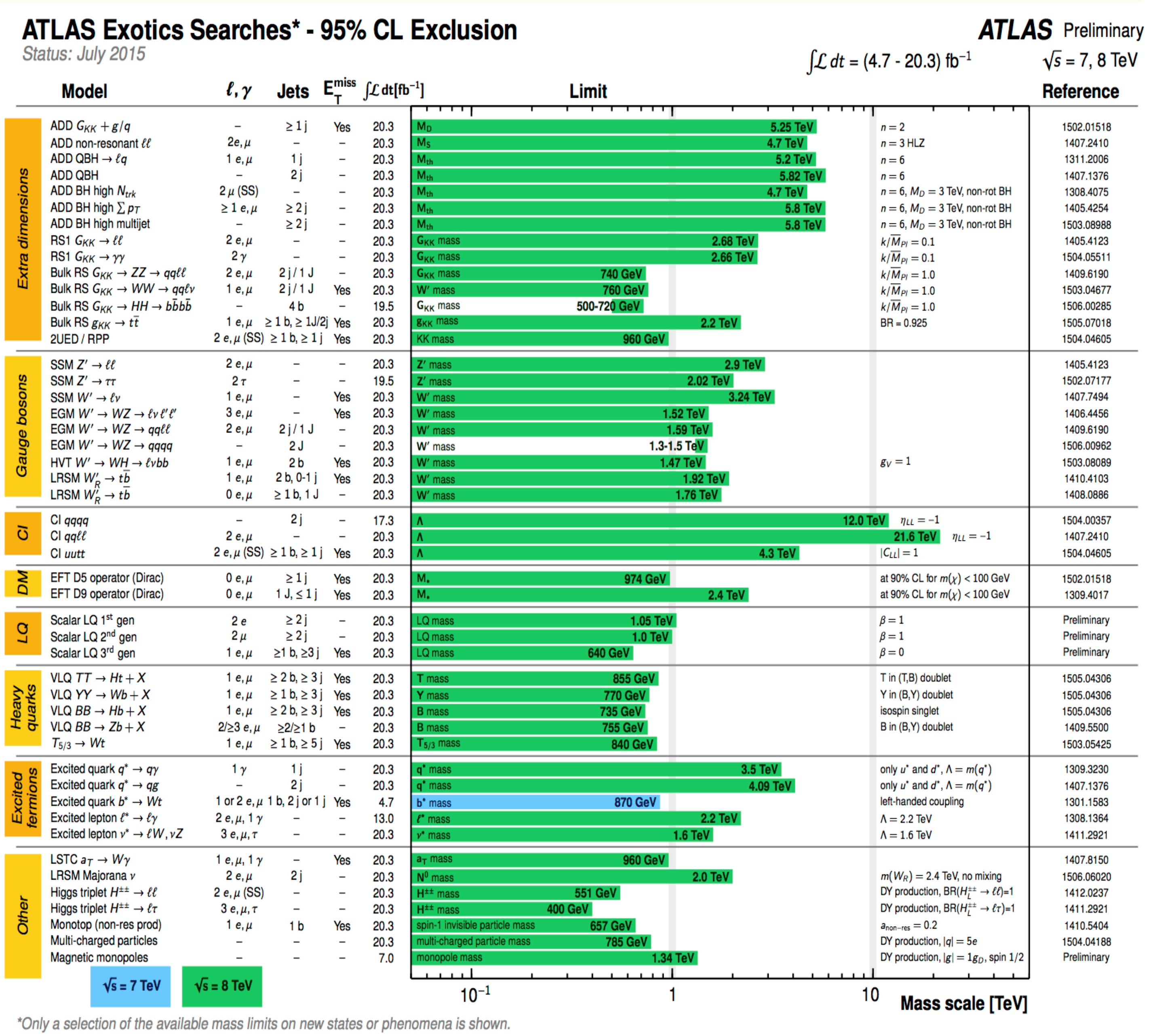


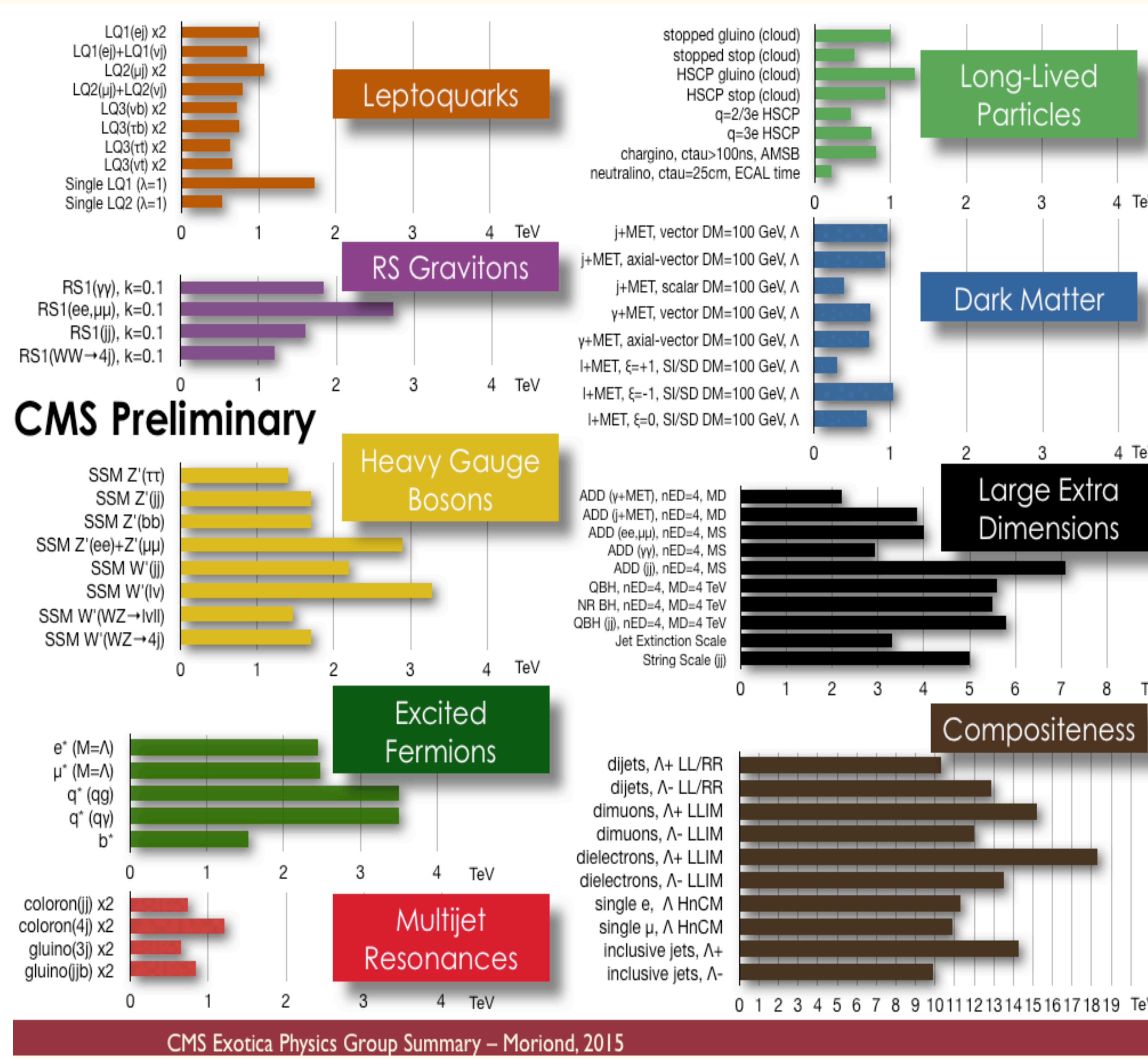
Limits on singly (LHCb) and multiply (ATLAS, CMS) charged HSCP produced in DY-like process

Run 1 legacy

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G



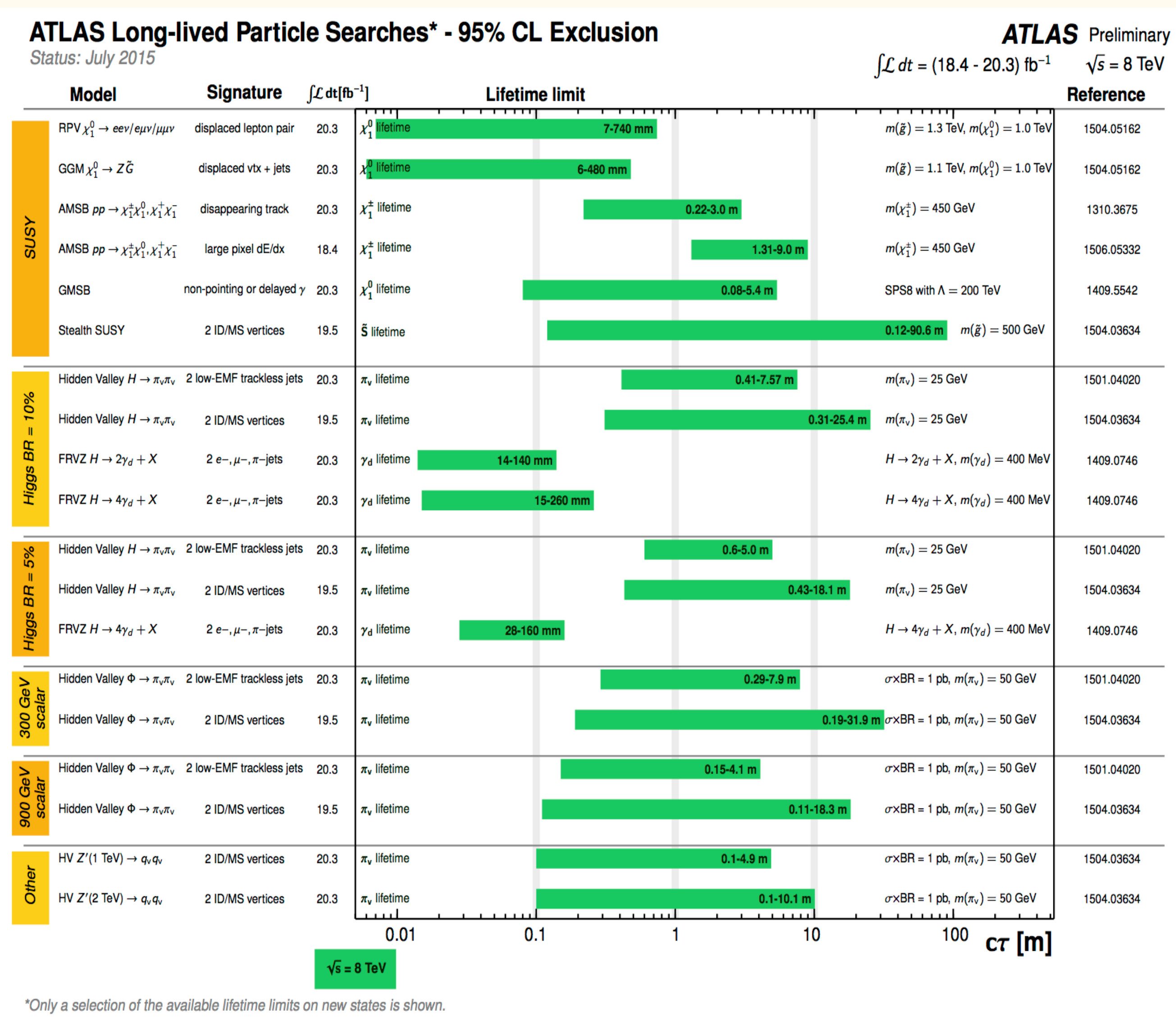


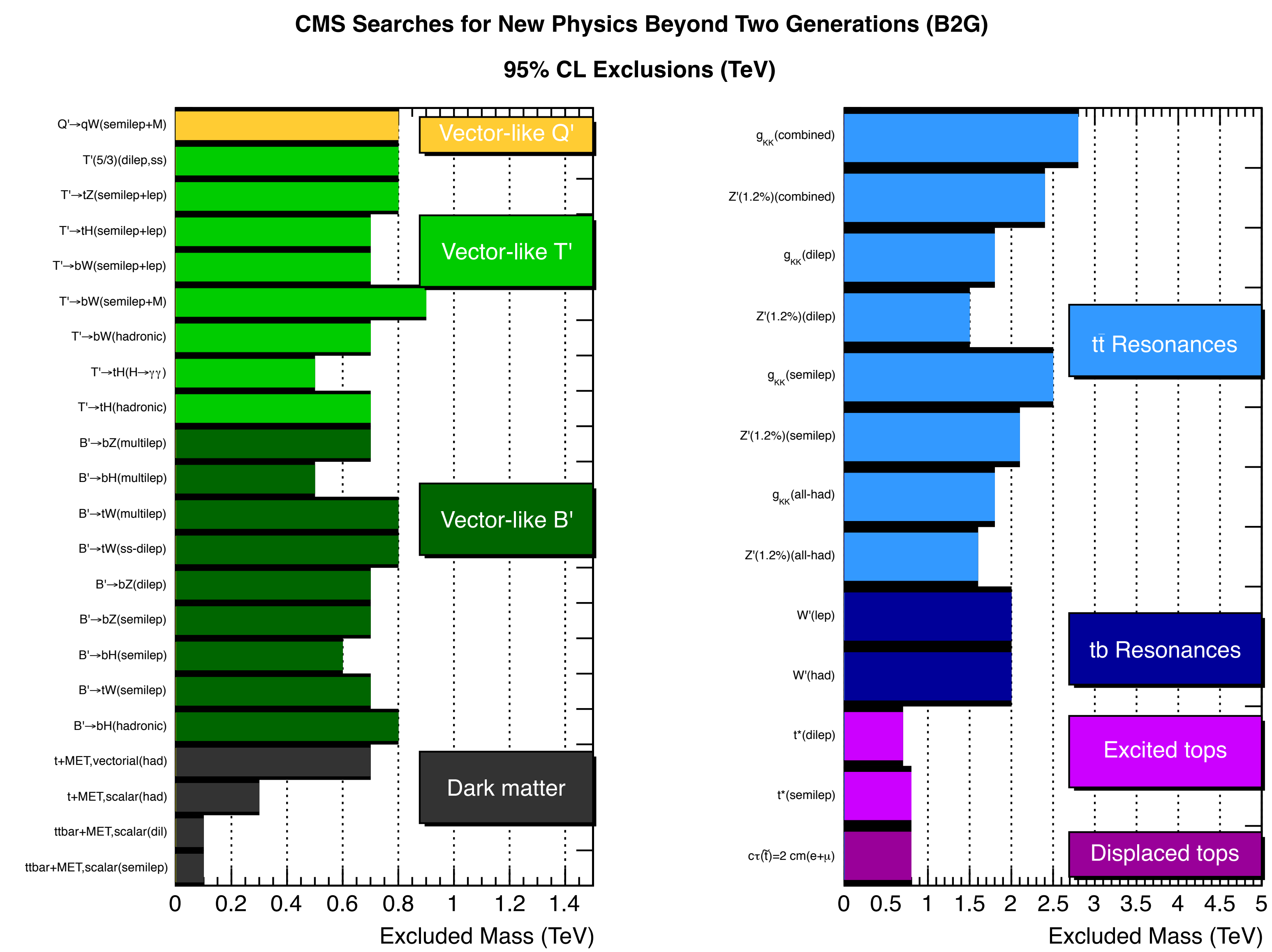
- **Large territory covered with 7 and 8 TeV data**
- **Many models excluded up to mass scales of several TeV**

Run 1 legacy

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G





- **Large territory covered with 7 and 8 TeV data**
- **Many models excluded up to mass scales of several TeV**

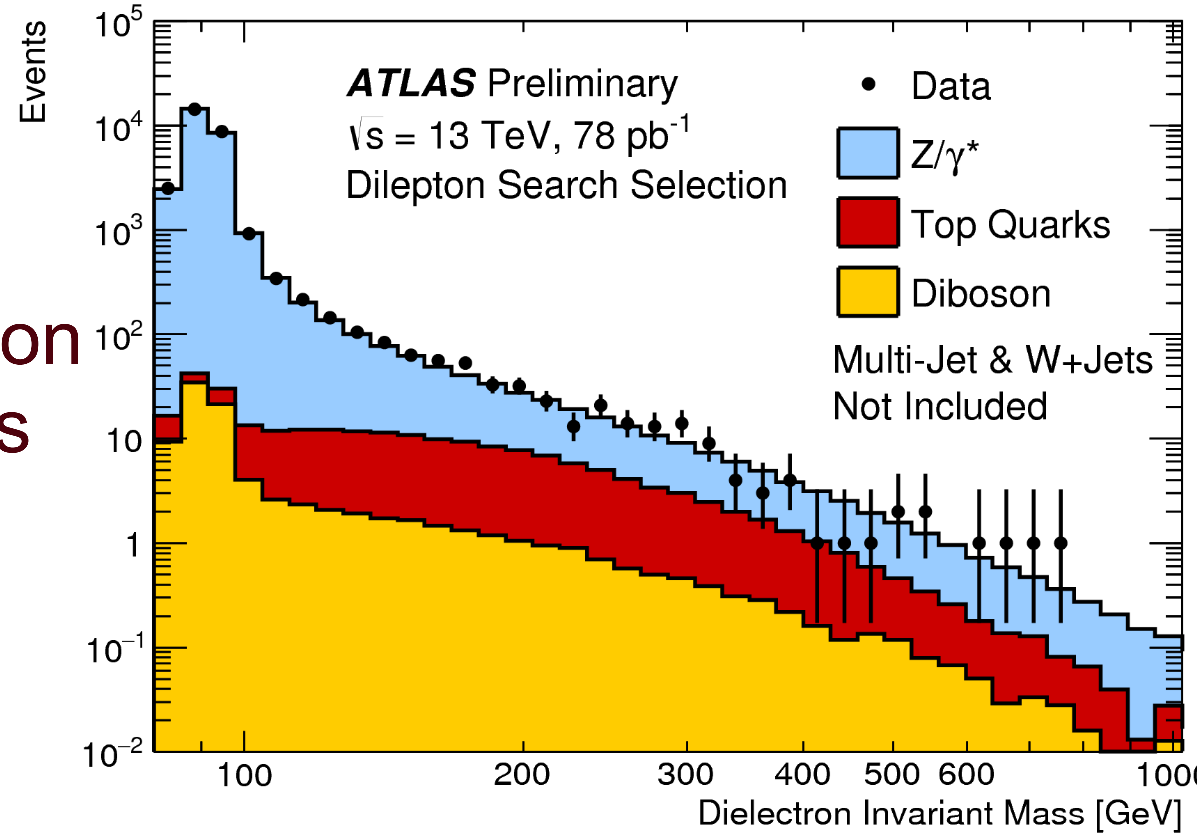
What more did we learn from Run 1?

- **Experimental tools:**
  - Tuned object reconstruction and triggering tools
  - Improved pile up handling
  - Techniques to explore boosted objects:
    - Close leptons, jet substructure, V,H,t-tagging
  - Combination tools for different samples and final states
    - Higgs search legacy
- **Collaboration between experiments**
  - ATLAS-CMS DM forum
  - Procedures to combine results between experiments
    - Higgs, $B \to \mu\mu$
  - Agreement in statistical procedures
- **Collaboration with theorists**
  - Improved signal and background generators
    - Higher order corrections, PDF uncertainties, radiative effects, additional processes
  - Simplified models (SUSY, DM, HVT) and bridging with full models
    - SModelS, …
  - Data presentation and simplified detector simulation
    - Resolution and efficiency matrices, HepData, Delphes, …

Run 2 appetizers

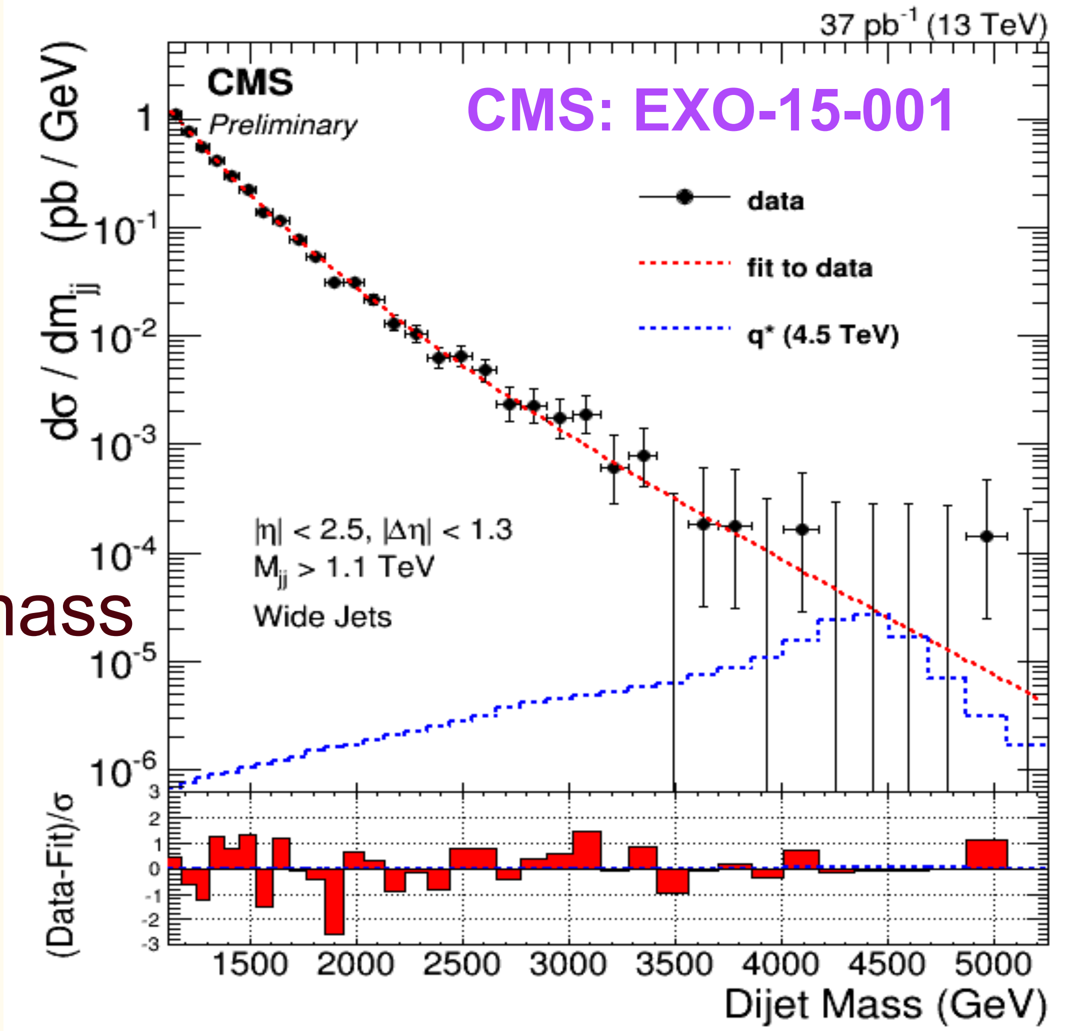
Di-electron inv. mass

ATLAS: EXOT-2015-001



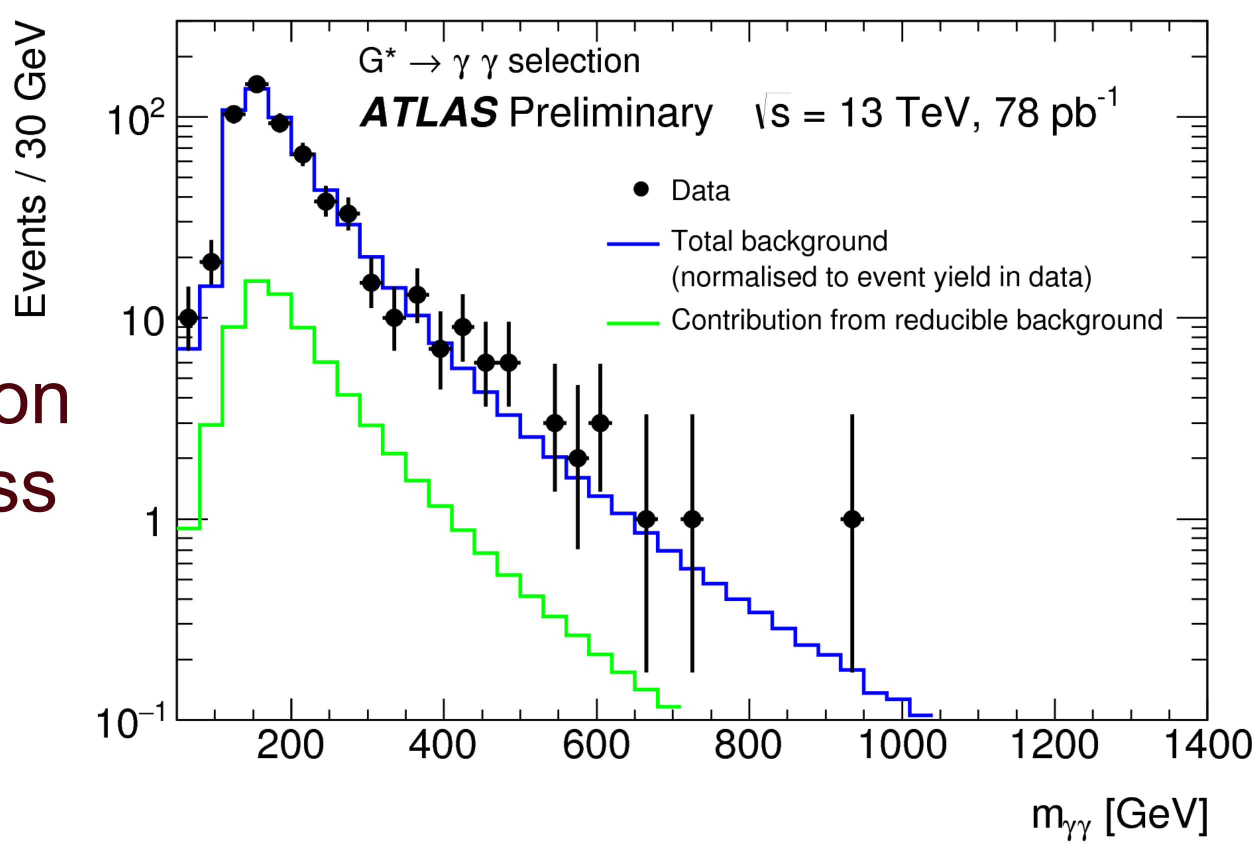
Di-jet inv. mass

CMS: EXO-15-001



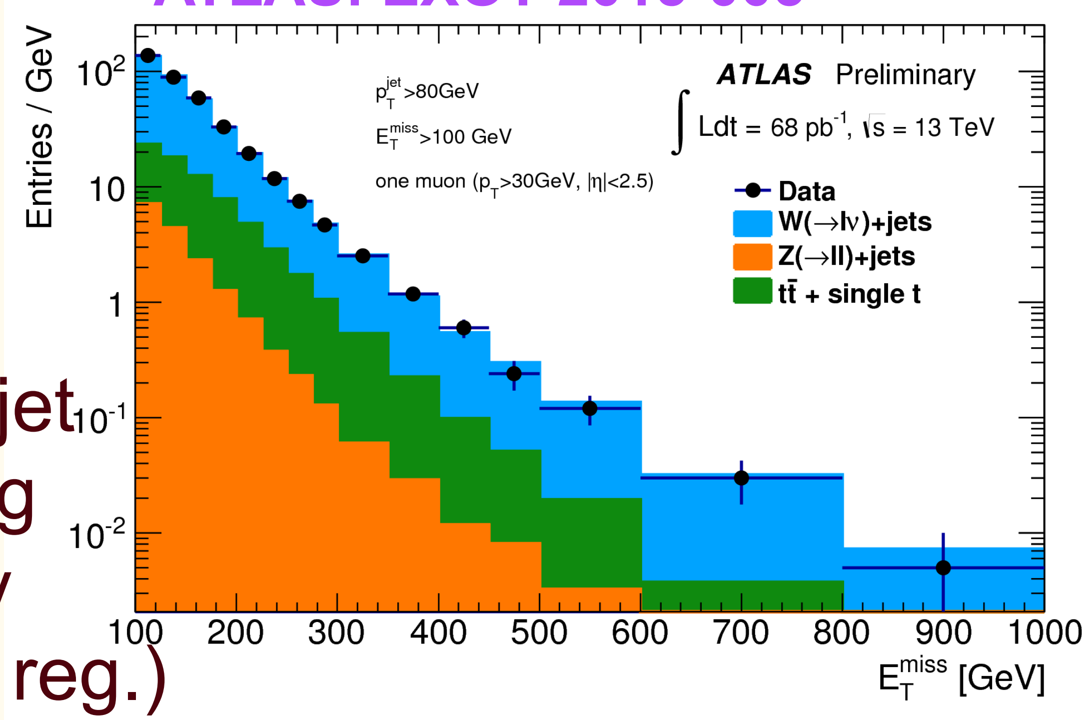
Di-photon inv. mass

ATLAS: EXOT-2015-003



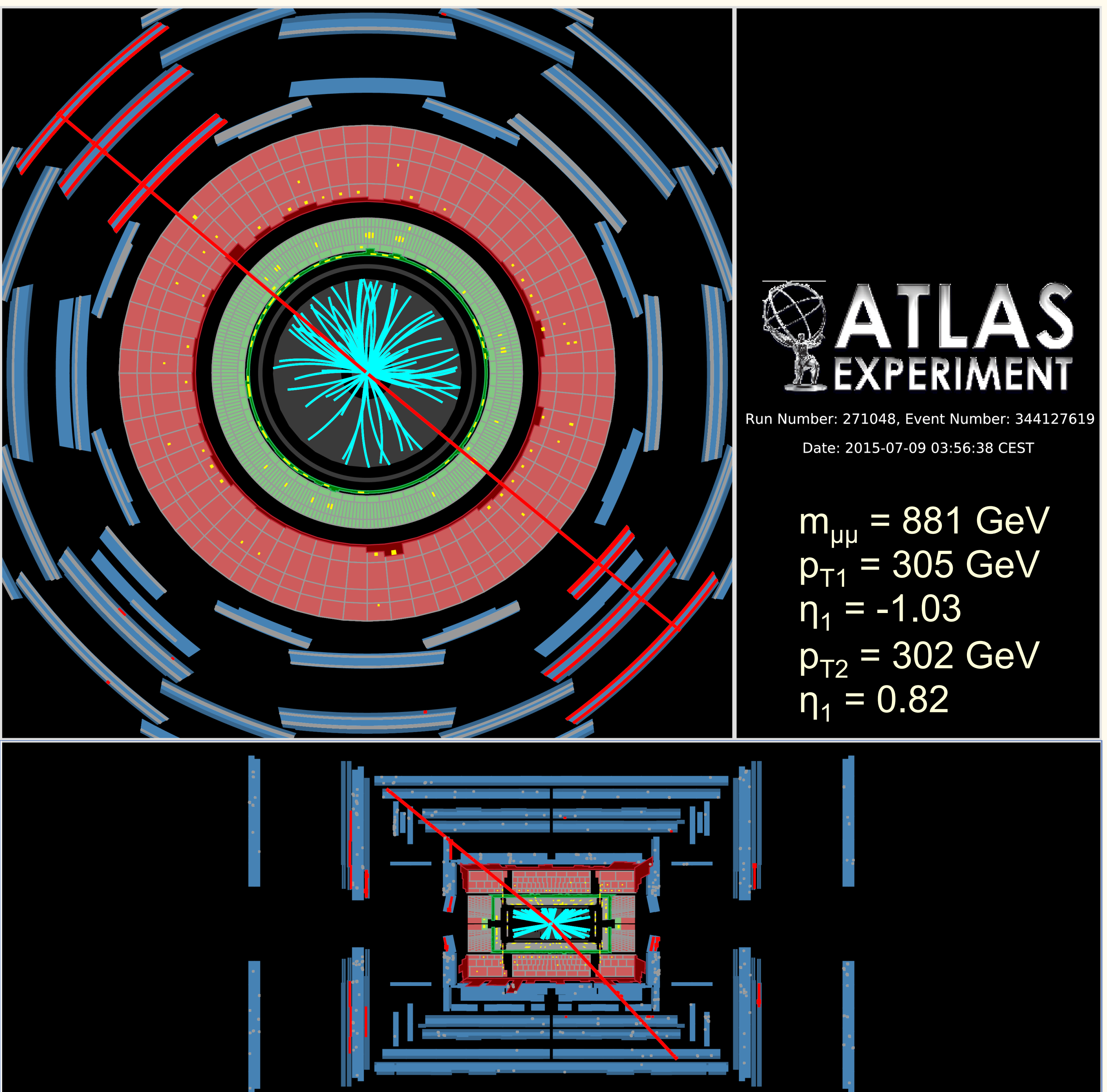
Mono-jet missing energy (contr. reg.)

ATLAS: EXOT-2015-005

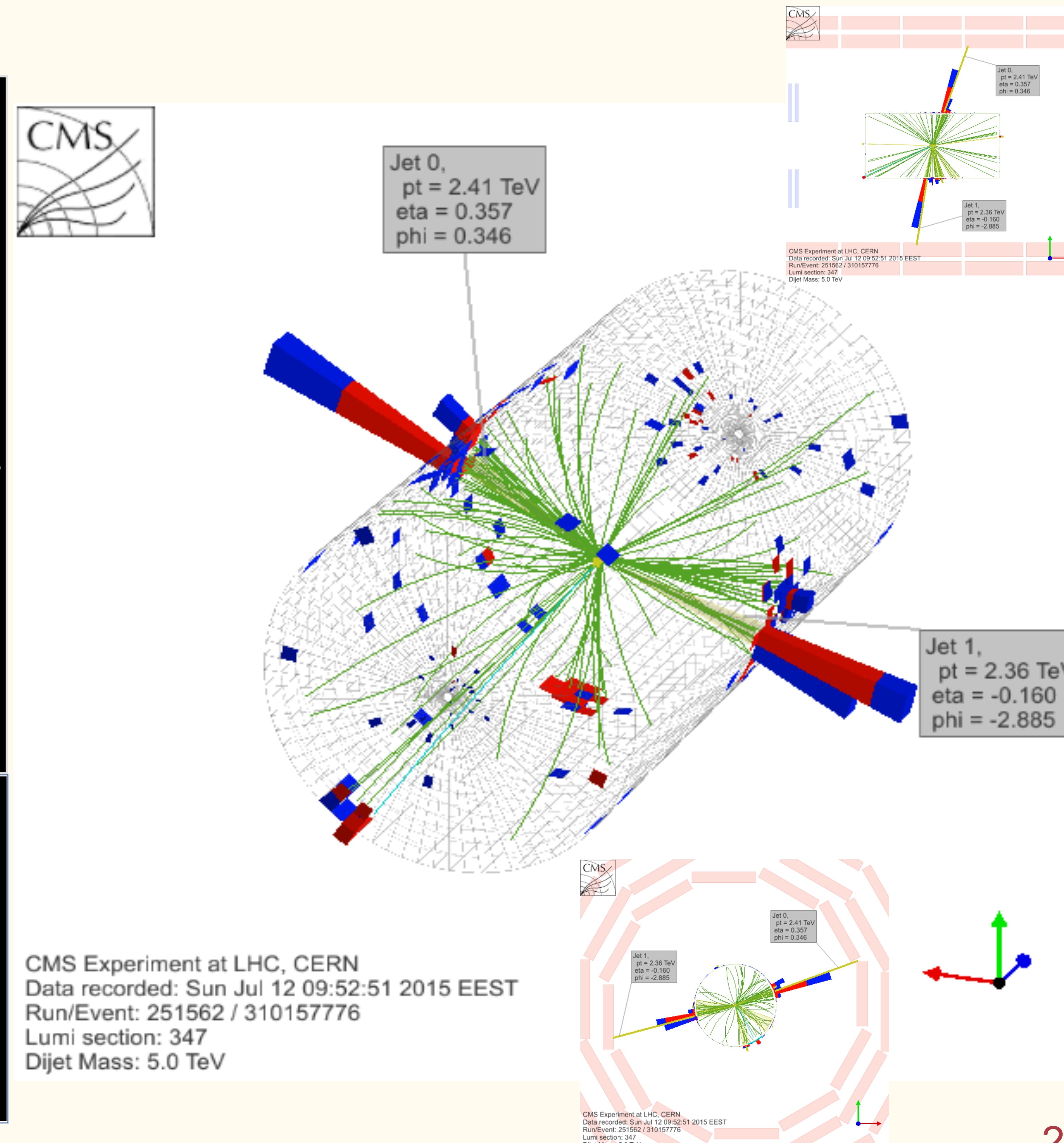


Run 2 appetizers

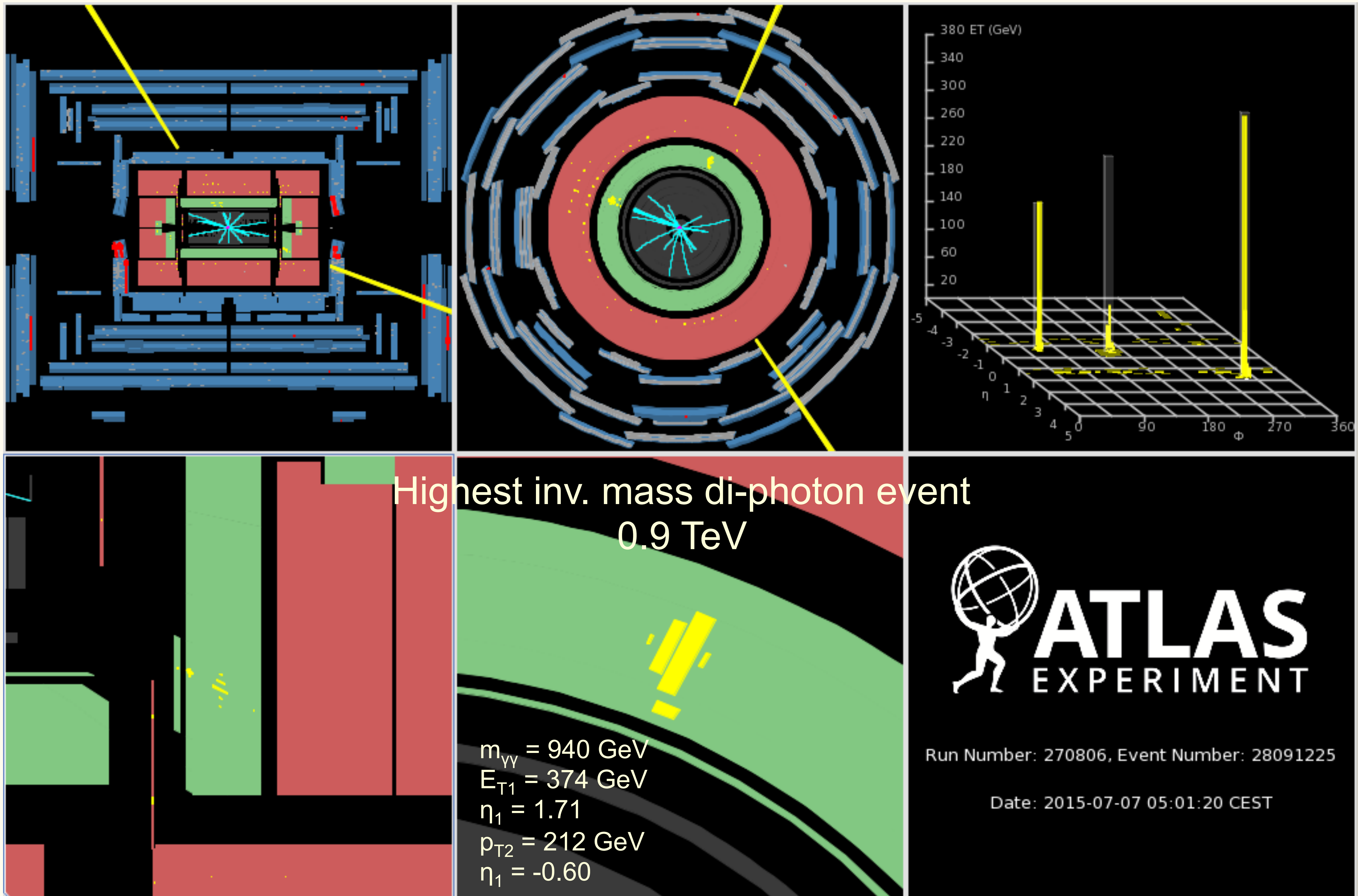
Highest inv. mass di-muon event
0.9 TeV



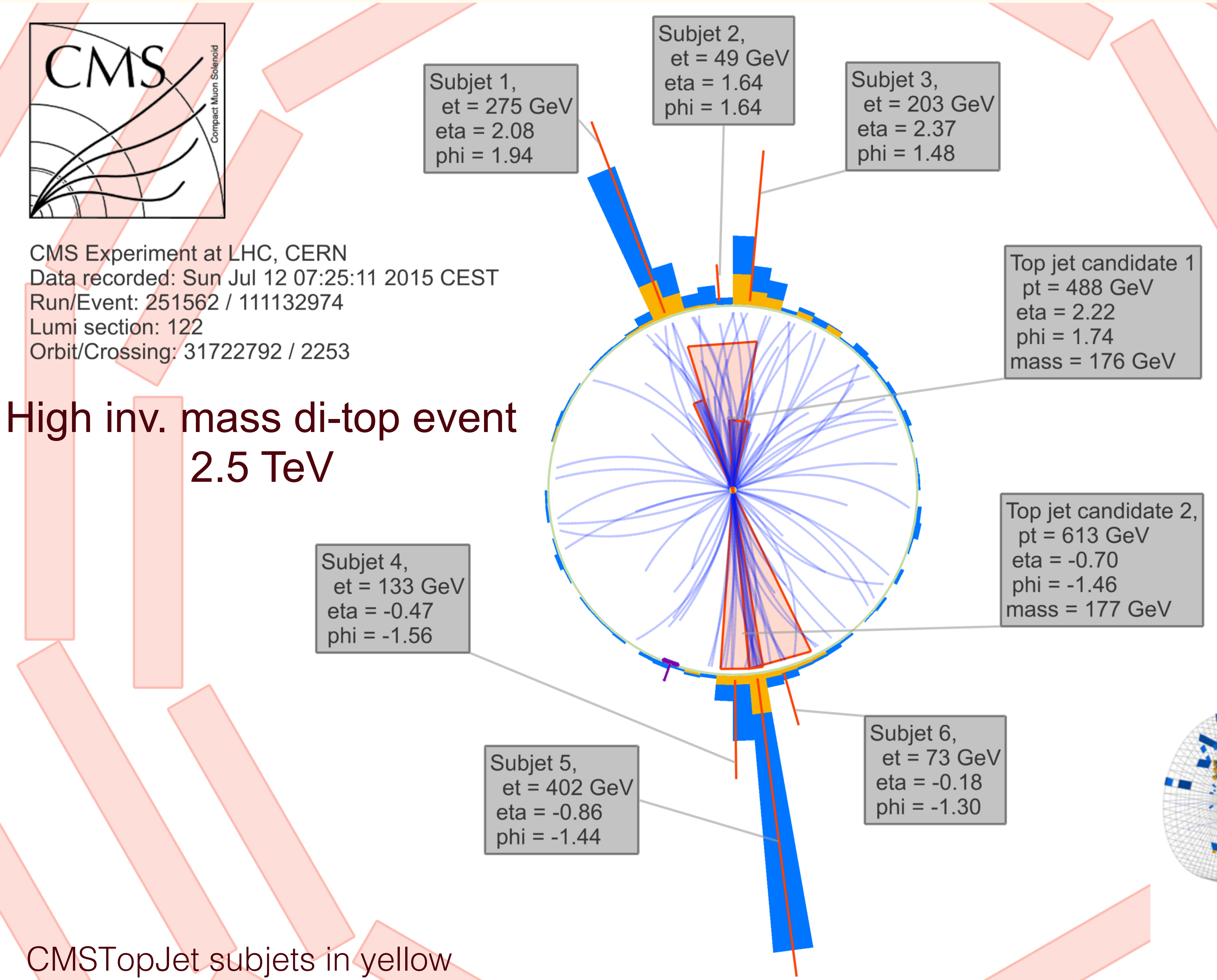
Highest inv. mass di-jet event
5 TeV



Run 2 appetizers



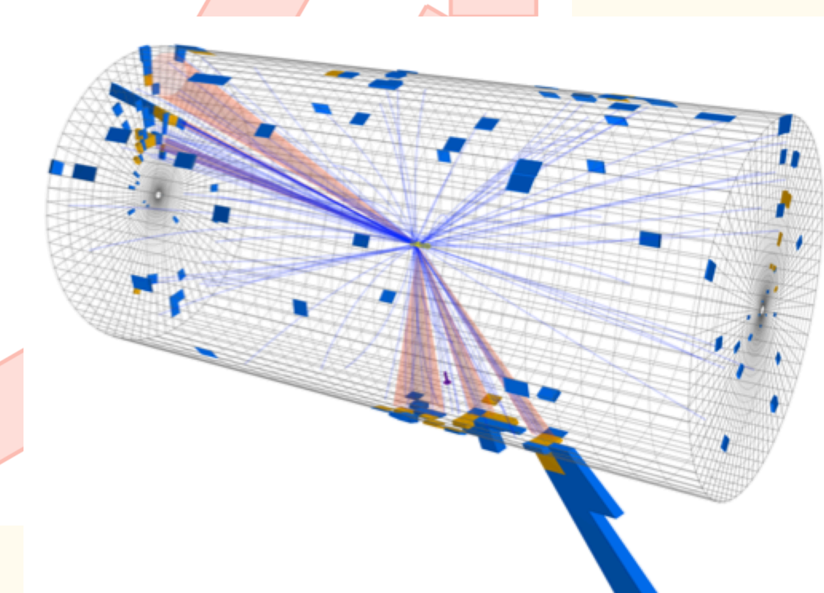
Run 2 appetizers



High inv. mass di-top event
2.5 TeV

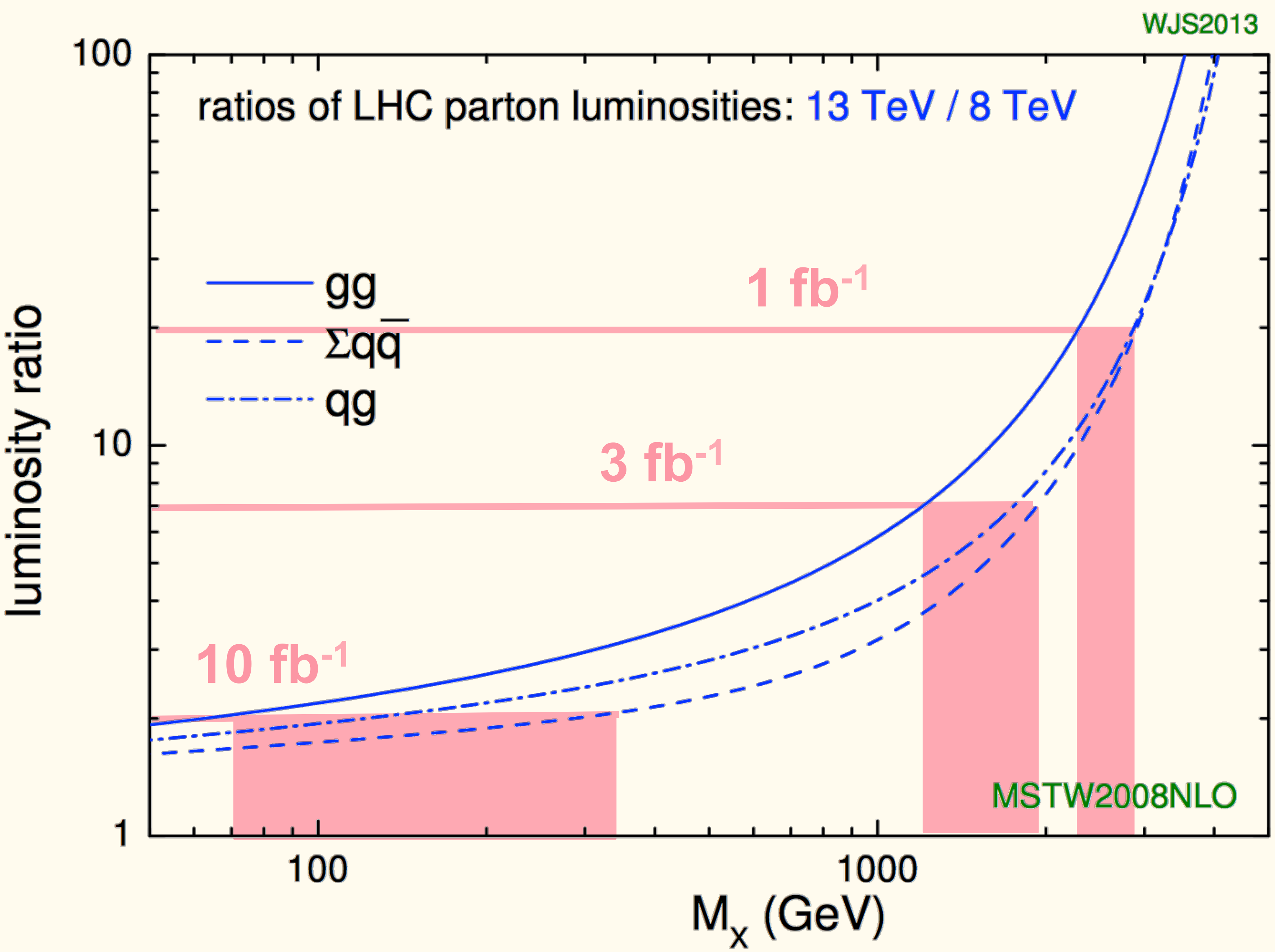
CMSTopJet subjets in yellow

m(topjet1)=177 GeV,
p_T(topjet1)=613 GeV,
m(topjet2)=176 GeV,
p_T(topjet2)=488 GeV,
ditopjet mass = 2491 GeV,
1 b-tagged subjet
(CSVIVFv2 medium OP)



We break into new territory now!

- **Increase of LHC energy boosts the production rate of objects with mass of > 2 TeV by about an order of magnitude**
- **Already the first 1 fb^{-1} provides access to mass scales unreached by Run 1**



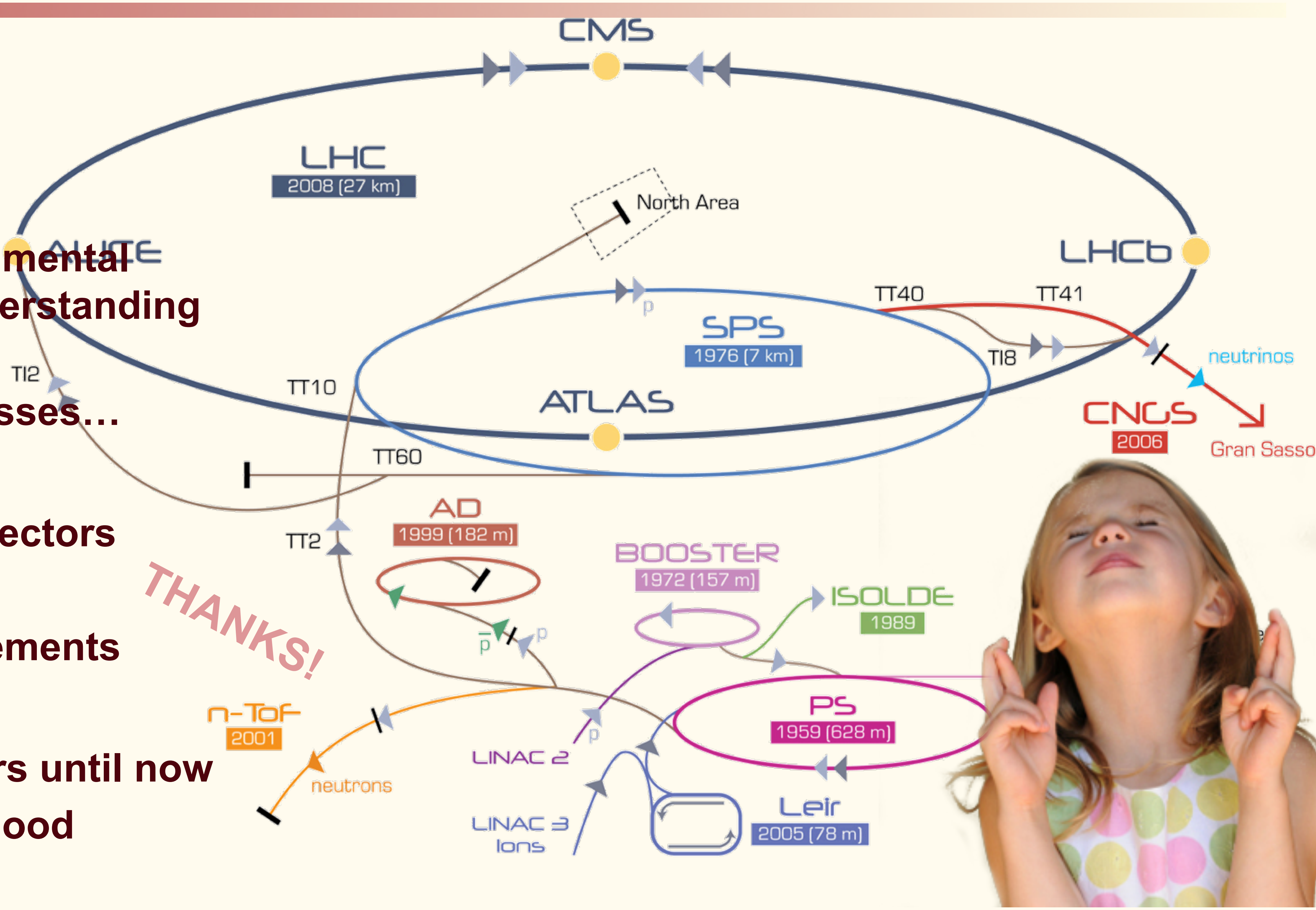
http://www.hep.ph.ic.ac.uk/~wstirlin/plots/lhclumi7813_2013_v1.pdf

Very rough examples of Run 2 integrated luminosities at which the Run 1 sensitivity to a given mass scale M_X will be surpassed:

M_X	gg	qq
4 TeV	0.1 fb^{-1}	0.2 fb^{-1}
2 TeV	1.5 fb^{-1}	2.5 fb^{-1}
1 TeV	3.5 fb^{-1}	7 fb^{-1}
.5 TeV	5 fb^{-1}	9 fb^{-1}

Wrap up

- **Run 1:**
  - **Higgs**
  - **Exclusions**
  - **Improved experimental techniques, understanding of backgrounds**
  - **A few mild excesses…**
- **LS1:**
  - **Refurbished detectors**
  - **13 TeV LHC**
  - **Injector improvements**
- **Run 2:**
  - **No showstoppers until now**
  - **First data look good**



⇒ We have all reasons to have high expectations and be excited!

Conclusion

Be prepared for surprises:

Conclusion

Be prepared for surprises:

The new physics

will

Rise like a Phoenix

from the ashes of Run 1

Conclusion

Be prepared for surprises:

The new physics
will
Rise like a Phoenix
from the ashes of Run 1

and it can be really

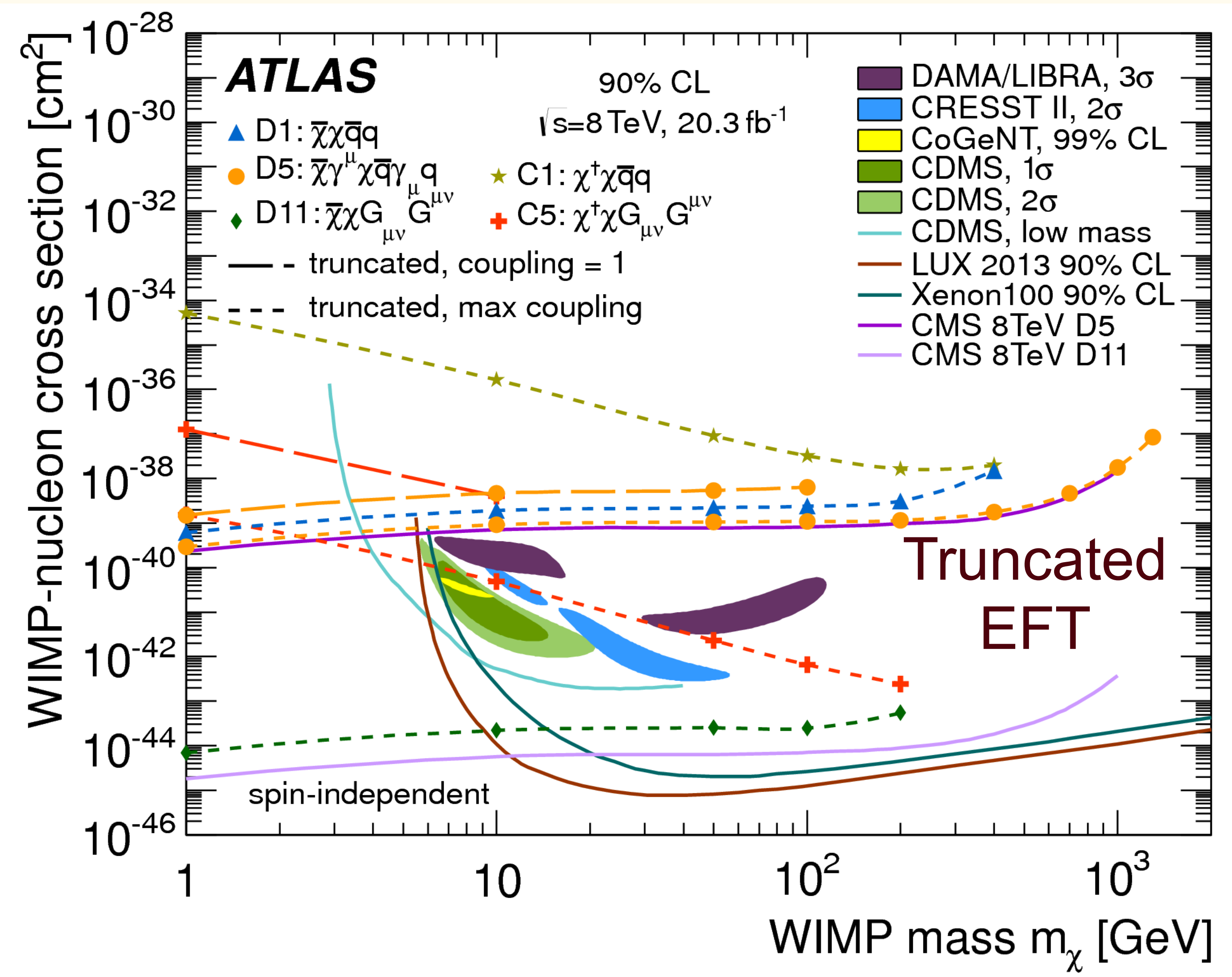
exotic

Austrian Winner of the
European Song Contest 2014
Conchita Wurst:
“Rise like a Phoenix”

Additional material

Mono-jet + missing energy (DM)

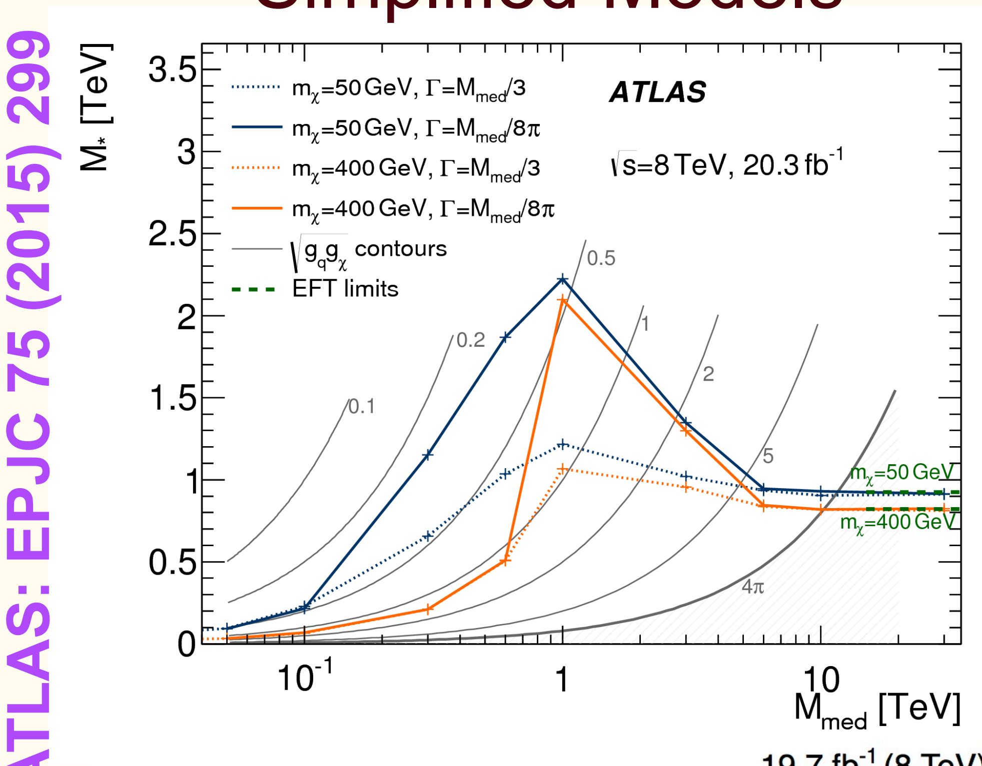
- **Classical channel for DM searches**
- **Main background Z➡vv est. in data-driven way**



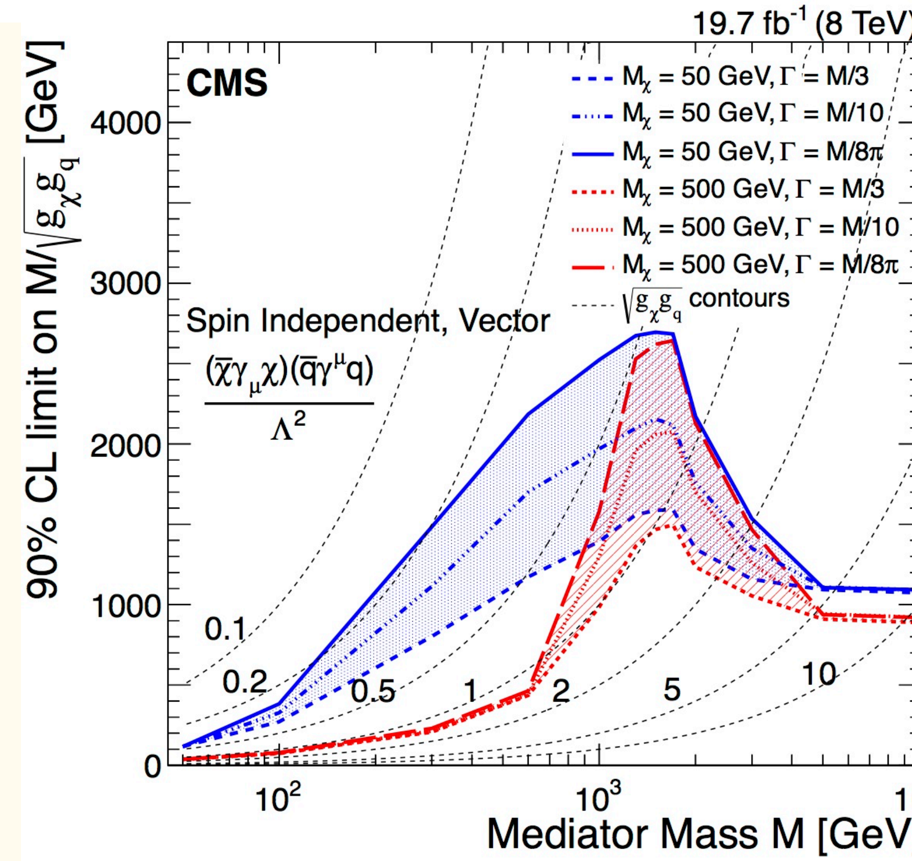
- **Collider searches complementary to direct detection searches esp. at low DM mass and for spin-dependent couplings**

Simplified Models

ATLAS: EPJC 75 (2015) 299



CMS: EPJC 75 (2015) 235

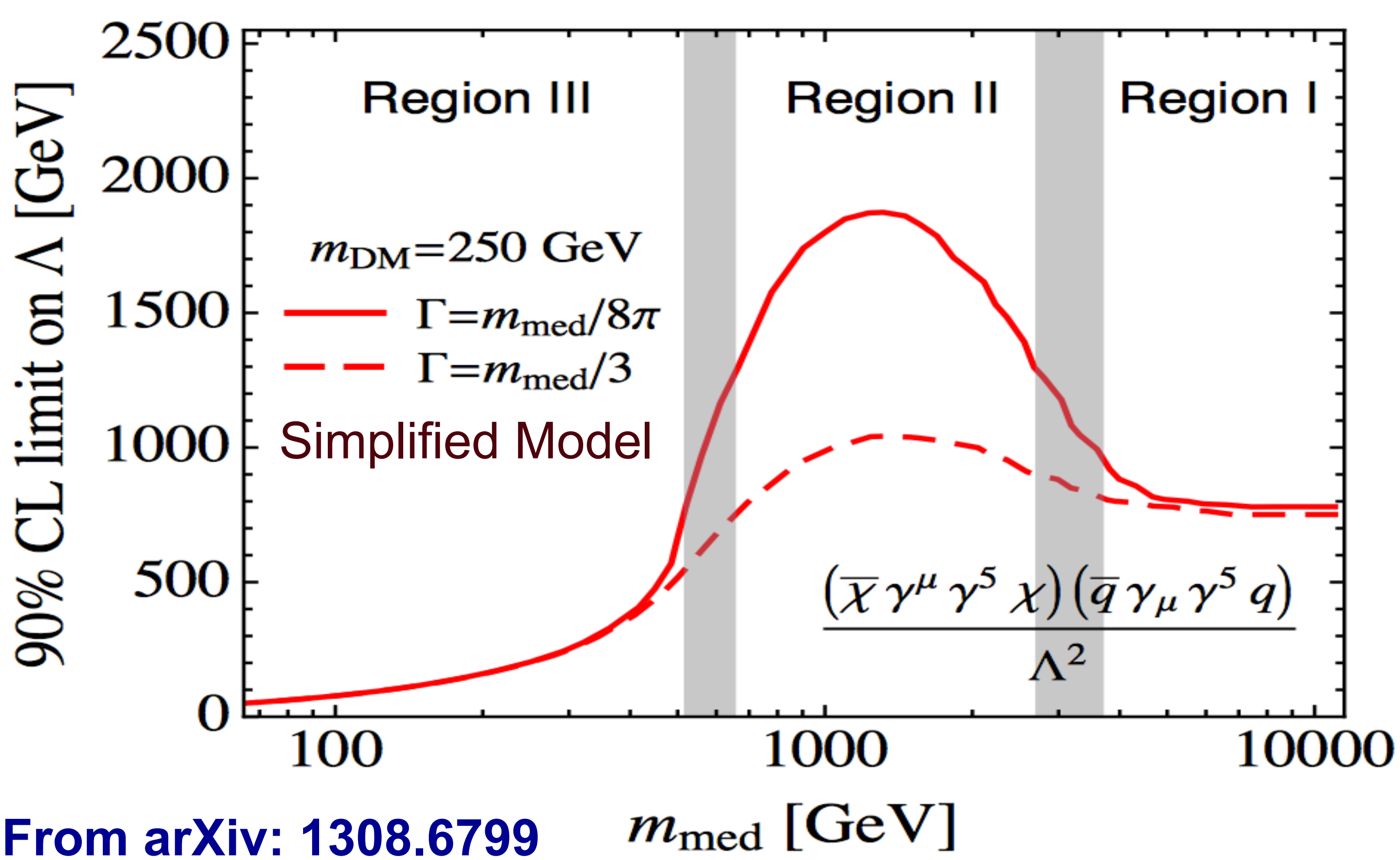


Mono-jet + missing energy

- **Classical channel for DM searches**
- **Main background Z➡vv est. in data-driven way**
- **New interpretation in simplified models:**

$$\Lambda \equiv \frac{m_{\rm med}}{\sqrt{g_q\, g_\chi}}$$

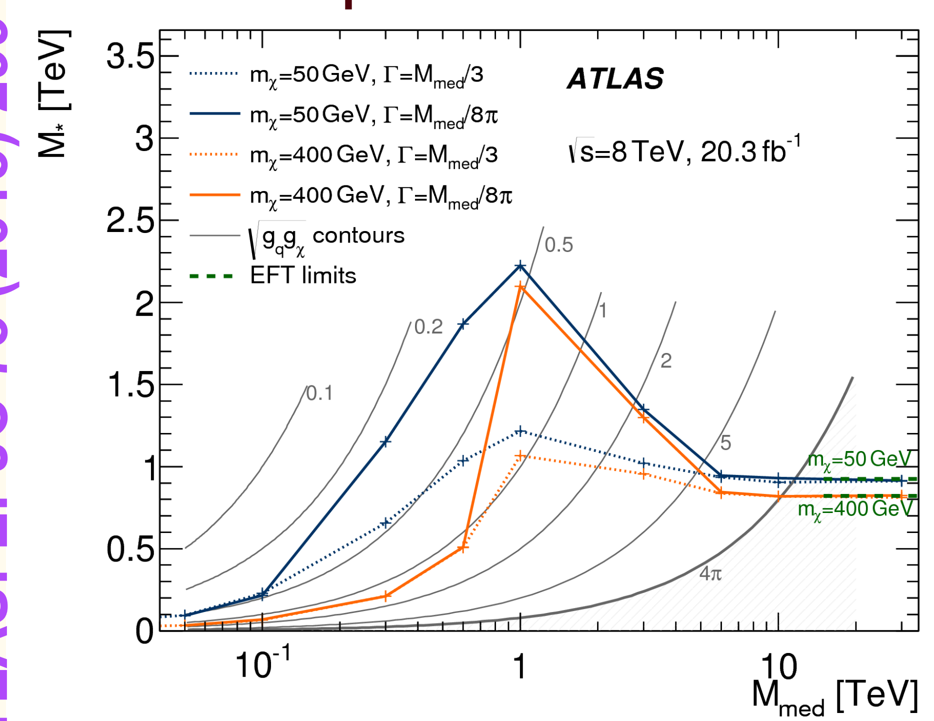
EFT too optimistic (σ too large)	EFT too pessimistic (lacking resonant enhancement)	EFT ~ok



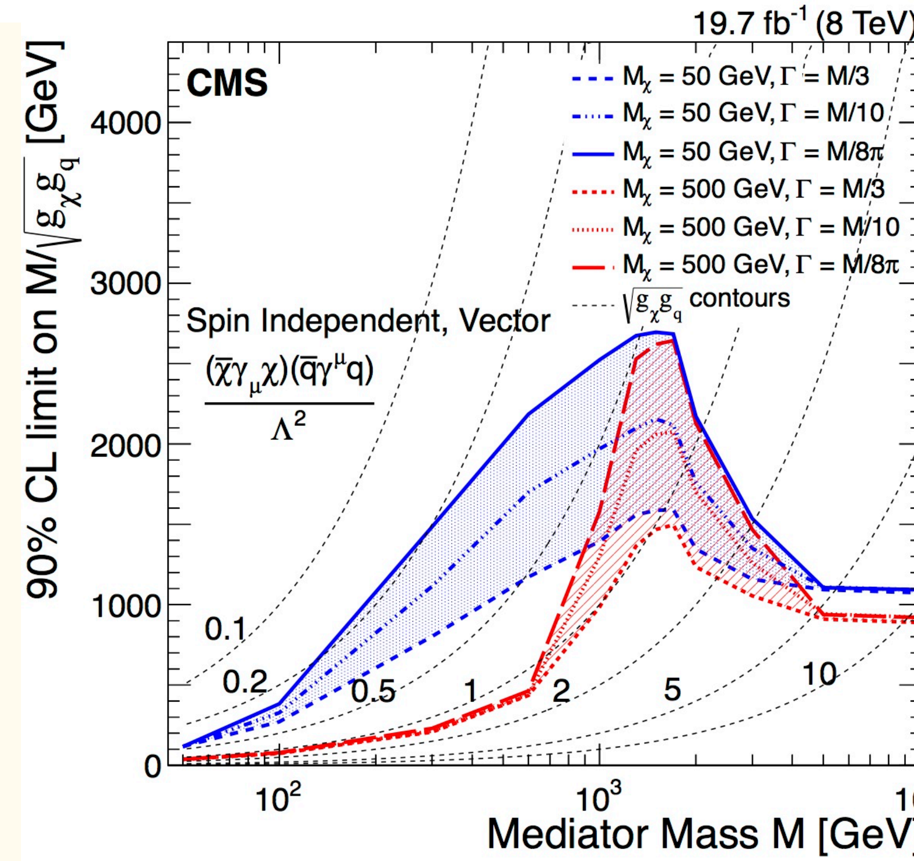
From arXiv: 1308.6799

Simplified Models

ATLAS: EPJC 75 (2015) 299



CMS: EPJC 75 (2015) 235

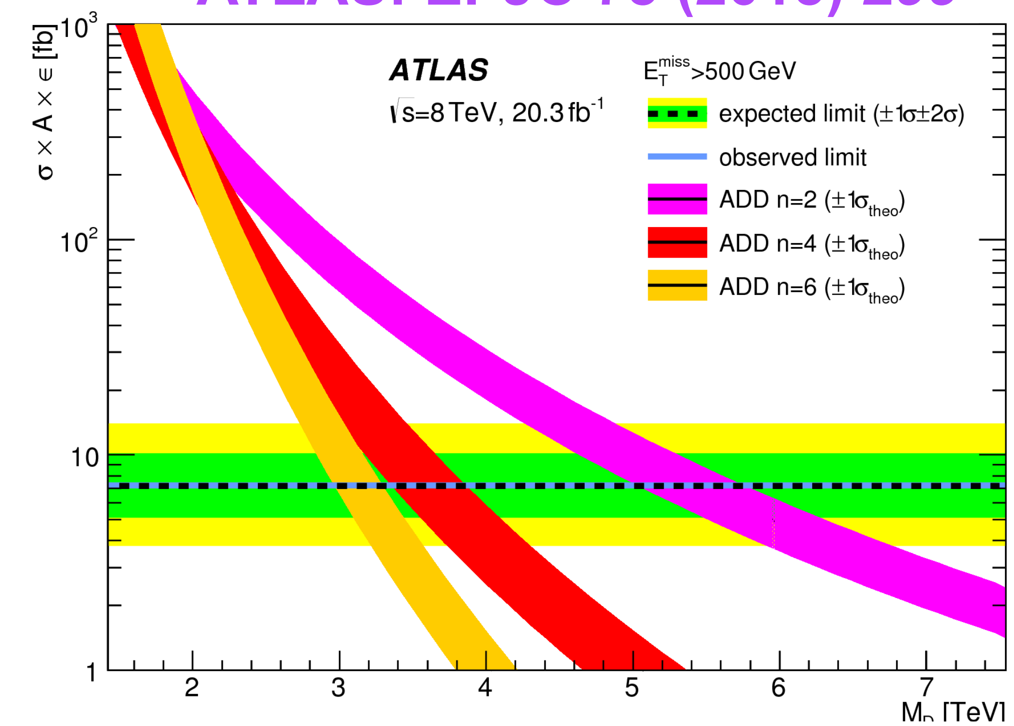


Mono-jet + missing energy (ED)

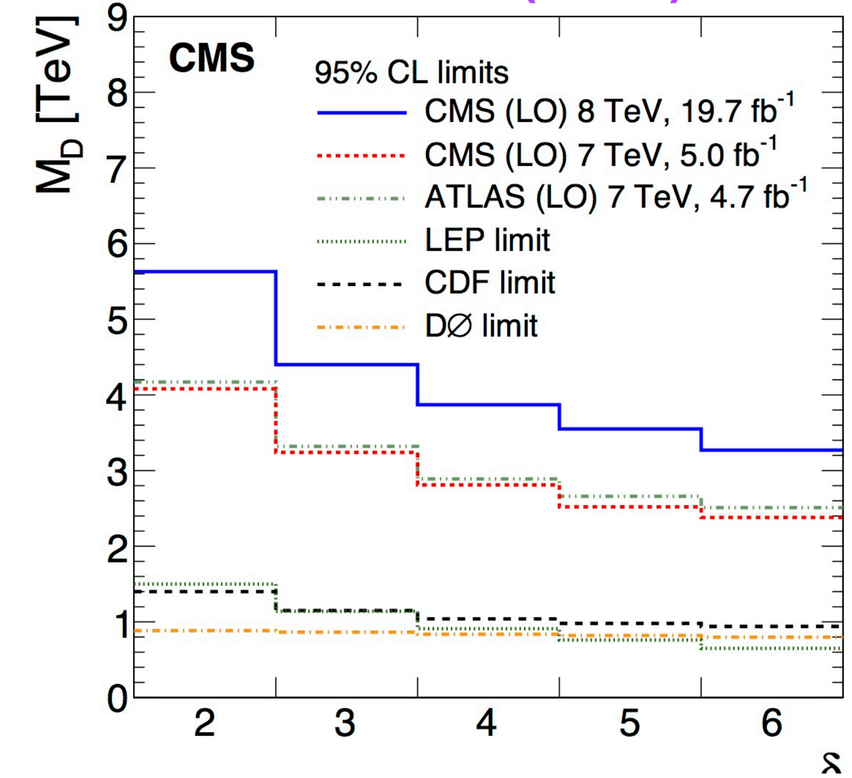
- **Also the most sensitive channel for Arkani-Dimopoulos-Dvali (ADD) model of extra dimensions**

Mono-jet results

ATLAS: EPJC 75 (2015) 299

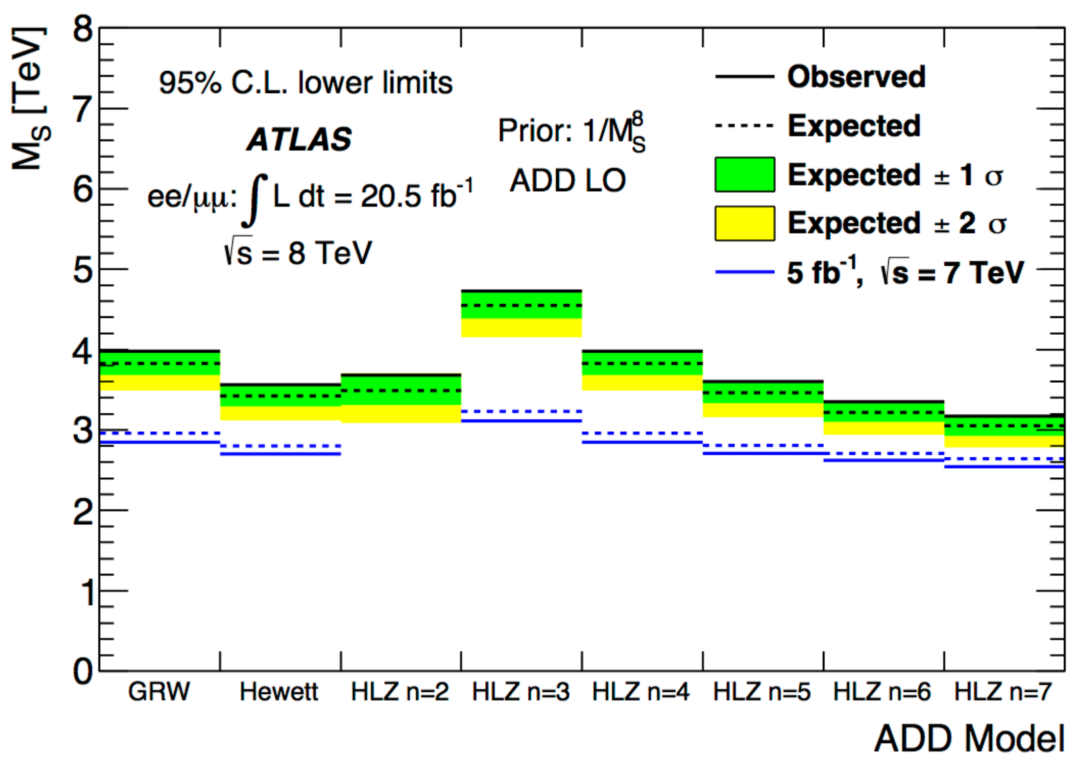


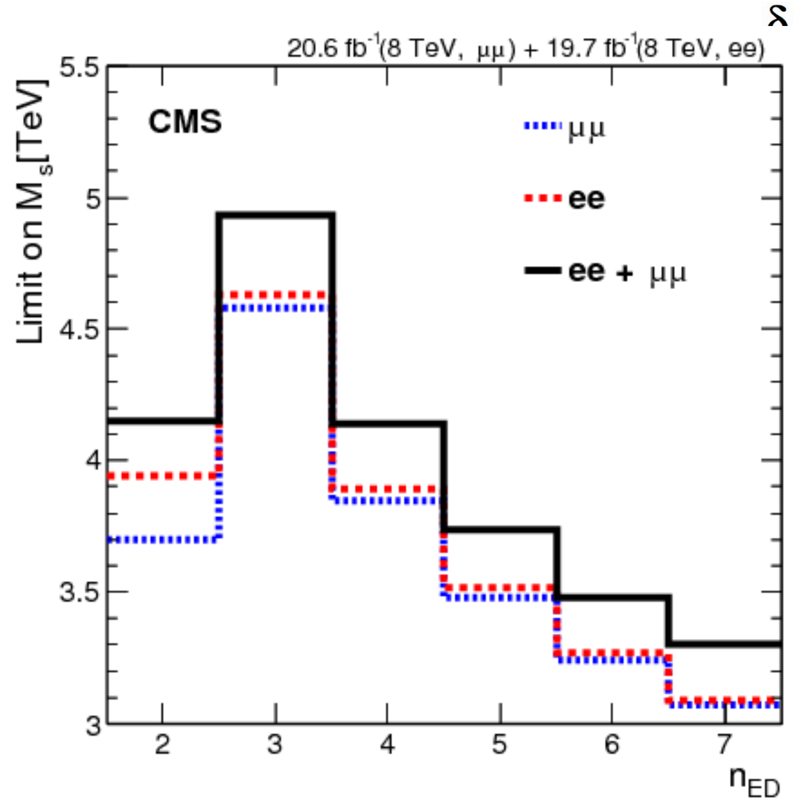
CMS: EPJC 75 (2015) 235



compared to

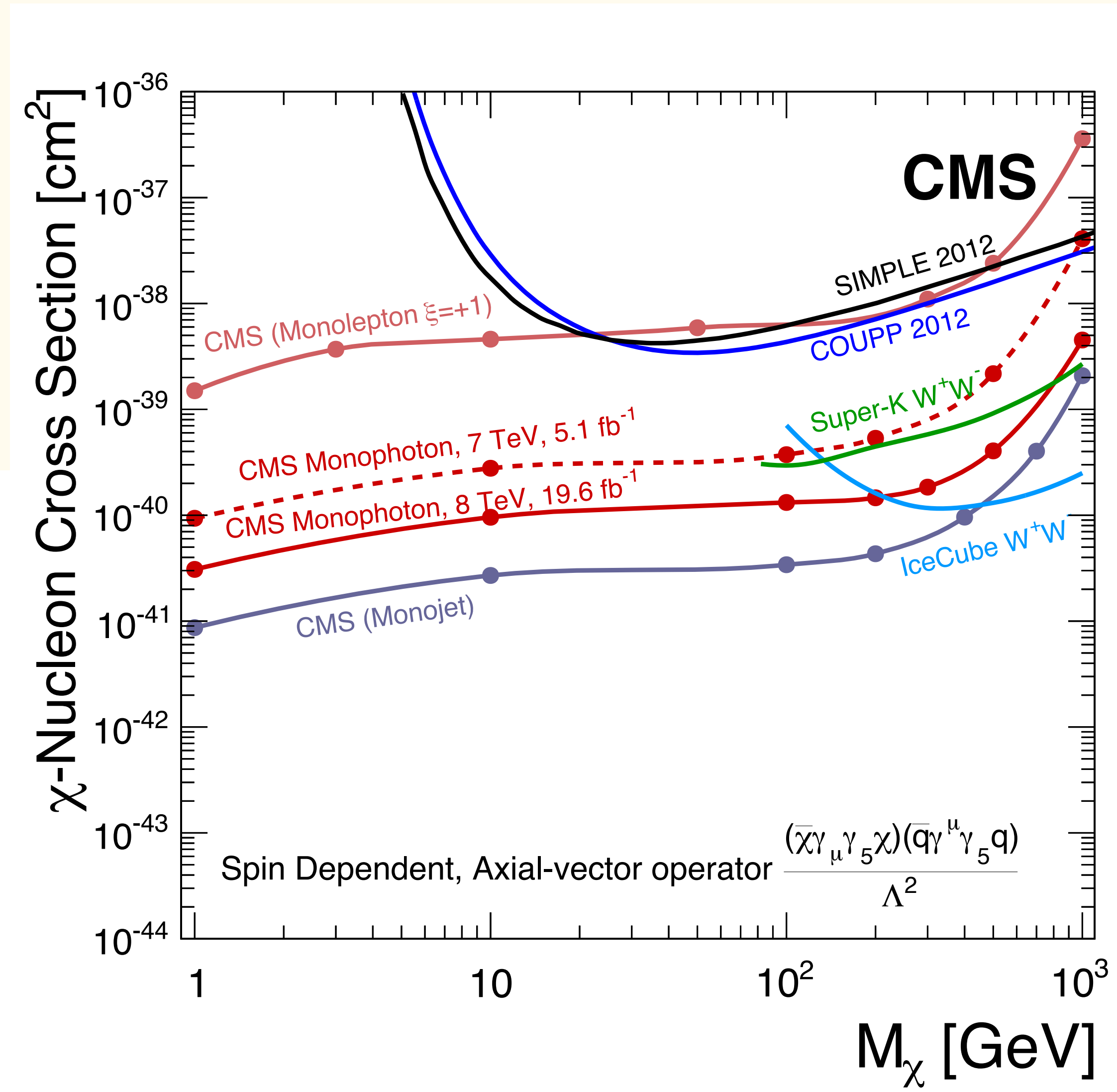
Di-lepton (ee+μμ) results



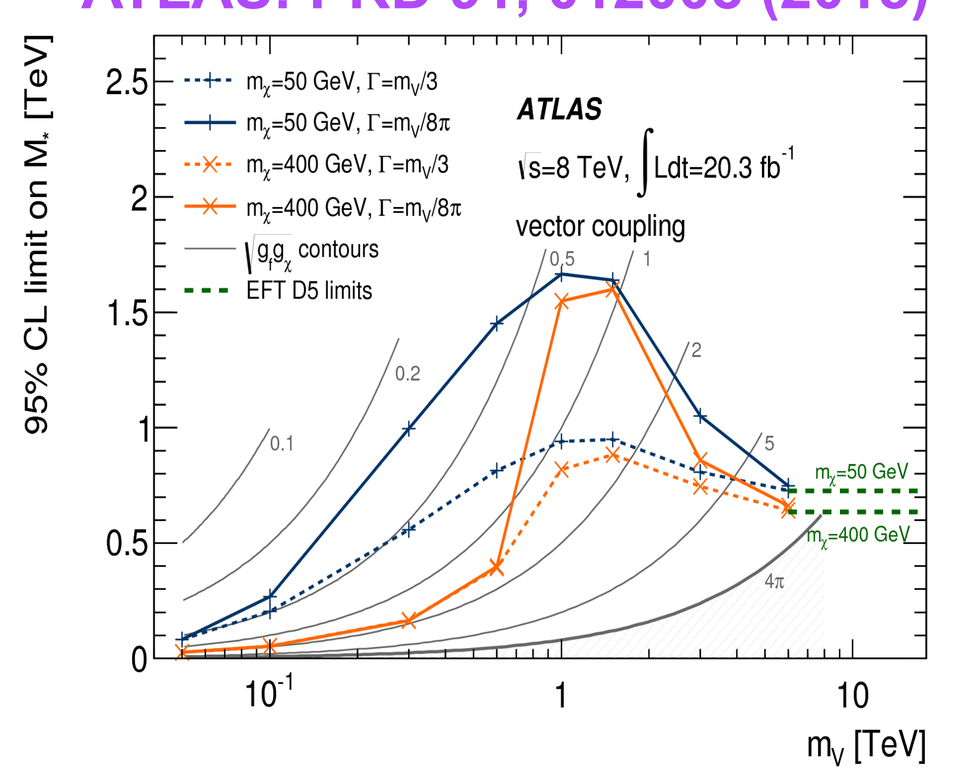


Mono-photon + missing energy

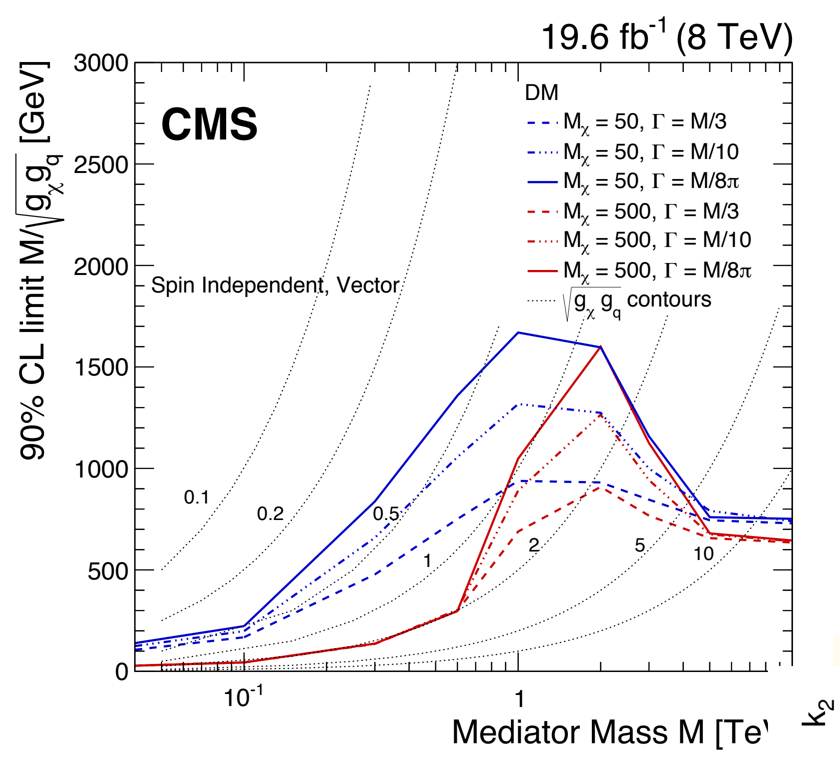
- **Slightly less sensitive to DM and ADD than mono-jet**
- **Main backgrounds Z(W)γ + jets**

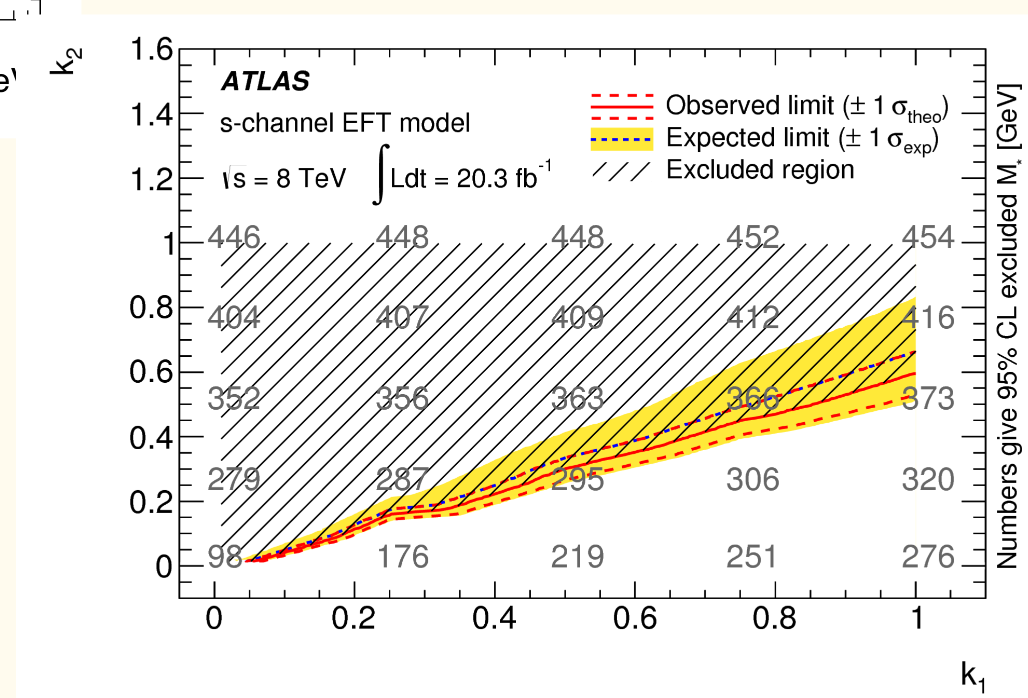


ATLAS: PRD 91, 012008 (2015)



CMS: arXiv: 1410.8812



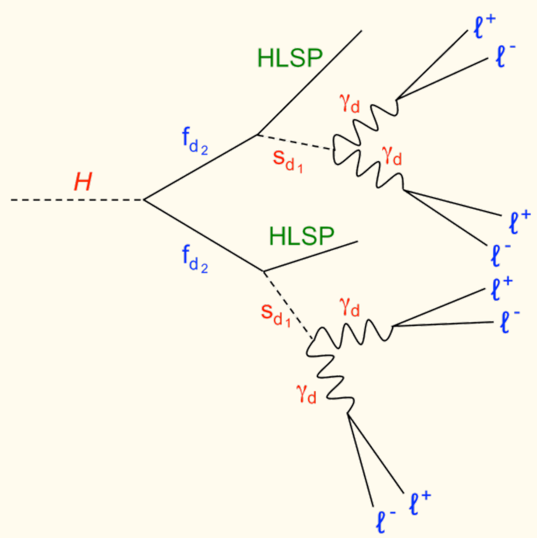


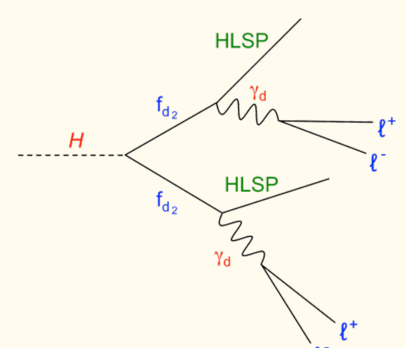
Specific application:

- **ATLAS publication addresses also the Fermi-LAT gamma-ray excess at 130 GeV**
  - **Comparing γ → γχχ production to χχ → γγ annihilation**

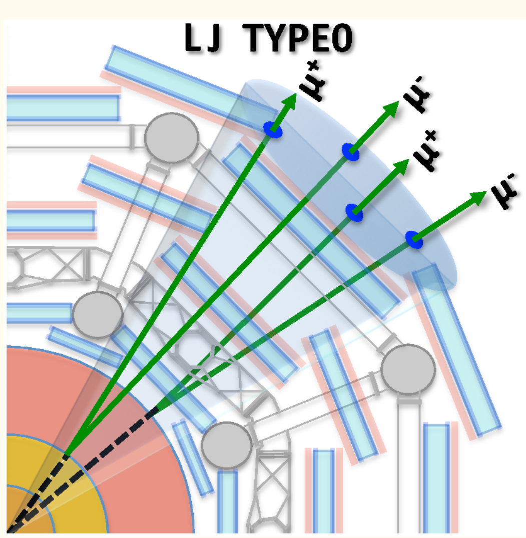
Lepton jets

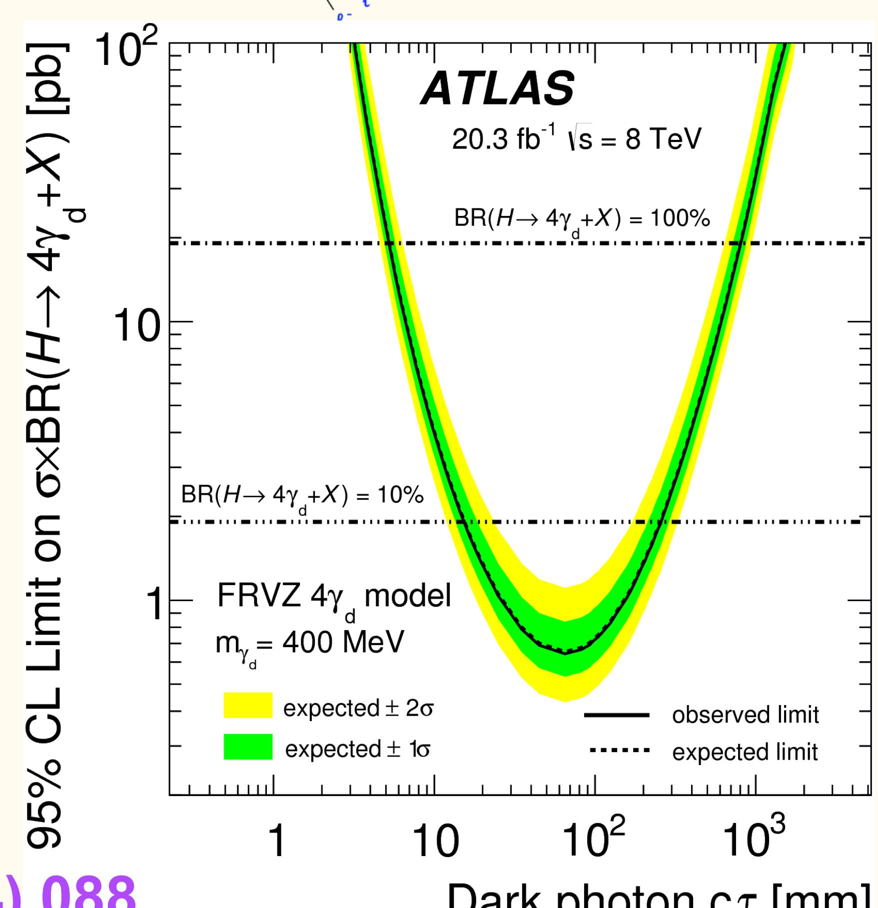
- **Window to a hidden sector communicating with SM via mixing of photons with massive dark photons γ_D which can be long-lived**
  - **Complementary way to detect dark matter**
  - **If $2m_\mu < m_{\gamma D} < 2m_\tau$, the dark photon decays predominantly to μ or e**
- **Parameter space constrained by large variety of experiments**





Also NA48/2:
arXiv: 1412.8053





ATLAS: JHEP 11 (2014) 088

CMS: arXiv 1506.00424