# Non-SUSY searches including Dark Matter at the LHC

Cristina Biino - INFN Torino

# Outline

## Exotic searches by ATLAS and CMS at LHC(*)

- Resonance searches
  - Di-jets
  - Di-leptons
  - Di-photons
  - Di-bosons
- X+MET and Dark Matter searches
  - Mono X (where X is a single jet, photon, W, Z, …)
- ….

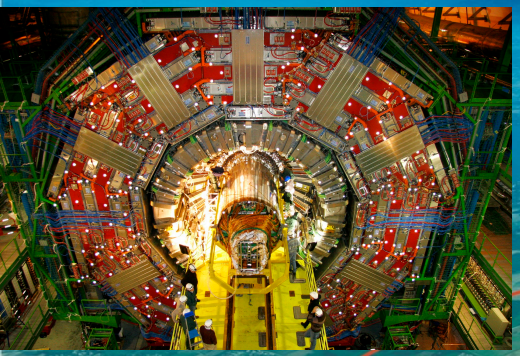
*(*) This talk covers only a selection of results*

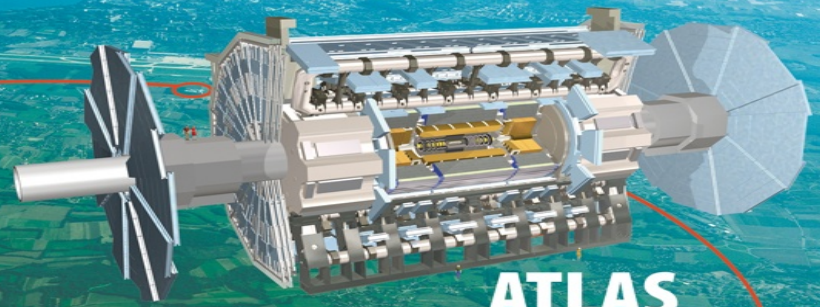
# ATLAS and CMS detectors at the LHC

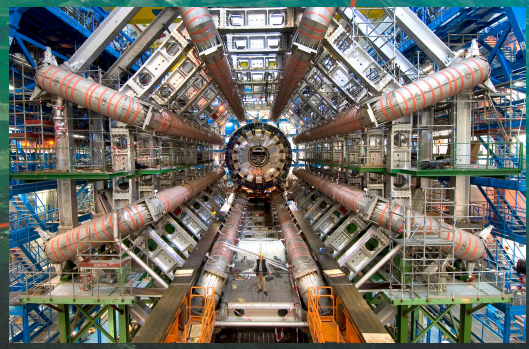
**Two general purpose detectors, designed to search for the Higgs Boson**

The Large Hadron Collider (LHC), one of the largest and truly global scientific projects ever

- pp collisions at a centre of mass energy of 7, 8 and 13 TeV
- PbPb collisions at a centre of mass energy of 2.76 TeV/nucleon



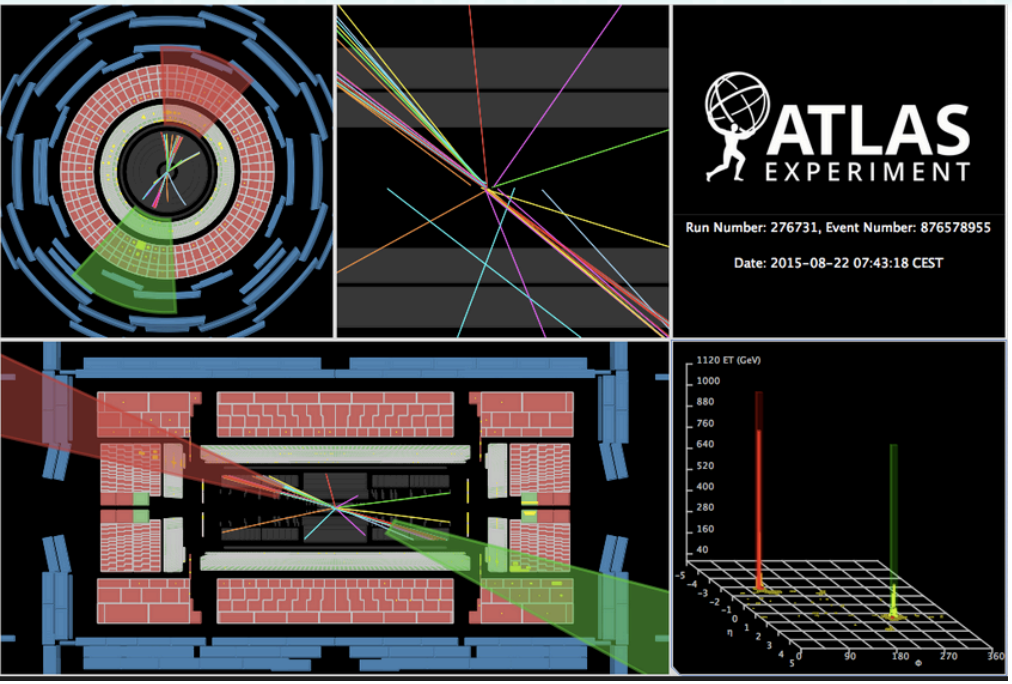


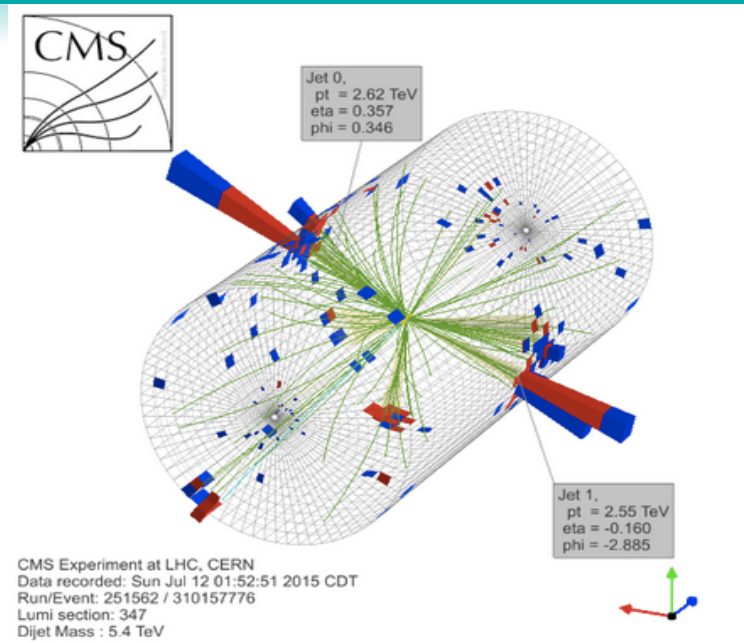


http://cms.web.cern.ch/

http://atlas.web.cern.ch/

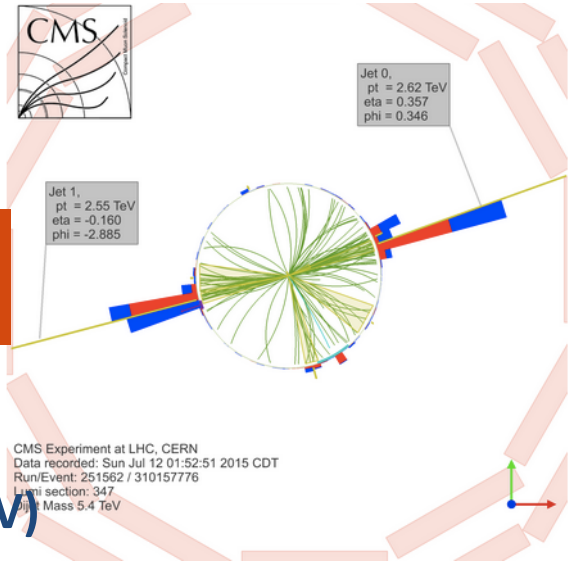
# Di-jets events at 13 TeV




***ATLAS-CONF-2015-042***

**The highest-mass, central dijet event. The invariant mass is 6.9 TeV**




***CMS-PhysicsResults EXO15001***

**Display of the event with the highest di-wide-jet mass (5.4 TeV)**

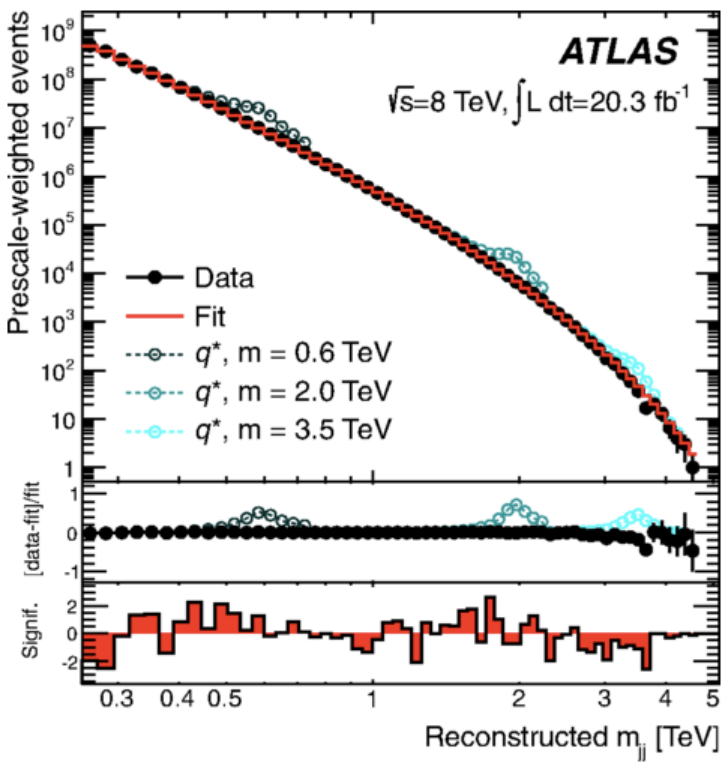
# Di-jets

Signature → classical bump search in dijet mass spectrum, sensitive to any resonance coupling to quarks/gluons

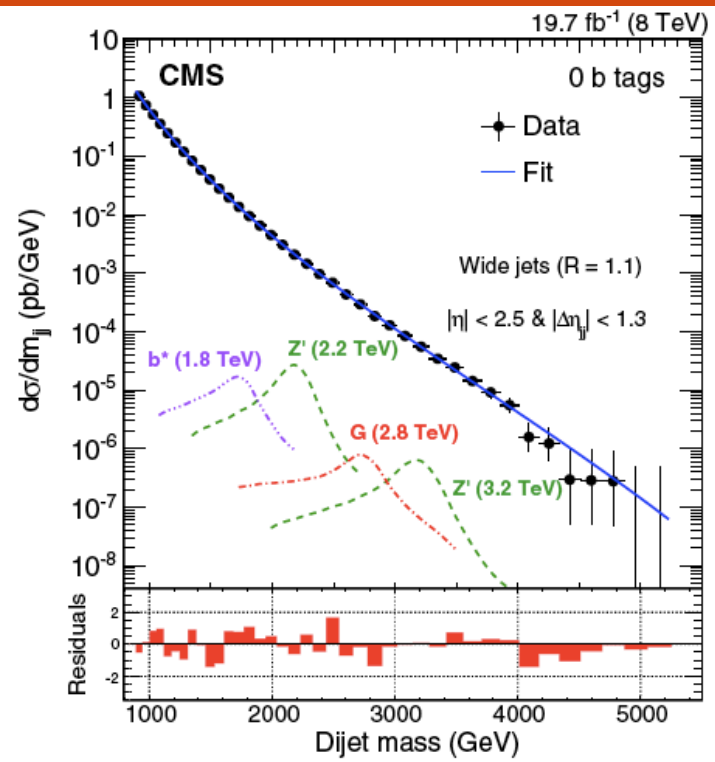
Simple → data driven, background parametrised by smooth function

Powerful → generic search, many interpretations, high mass reach

***ATLAS: Phys. Rev. D 91, 052007 (2015)***

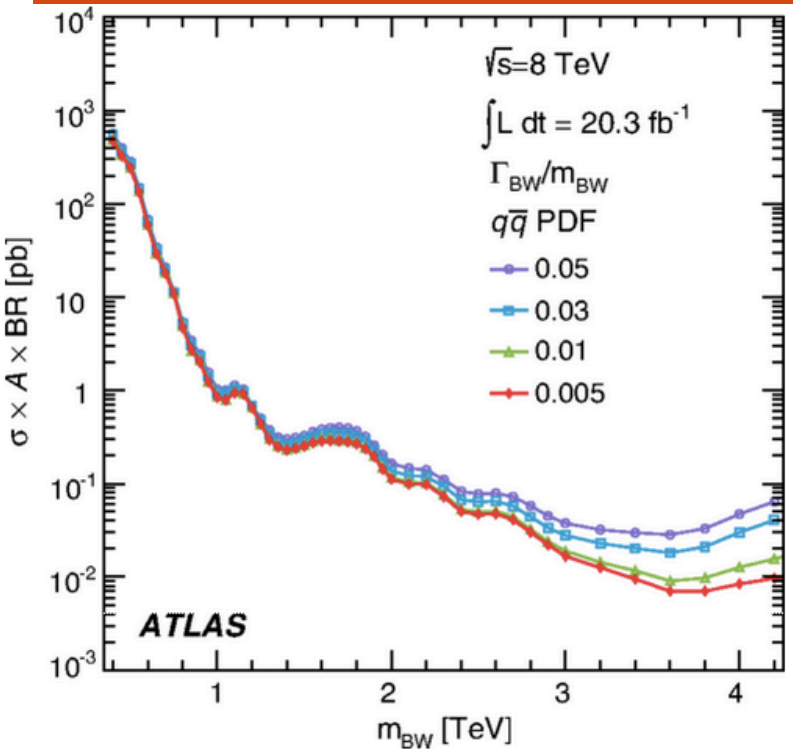



***CMS: Phys. Rev. D 91, 052009 (2015)***

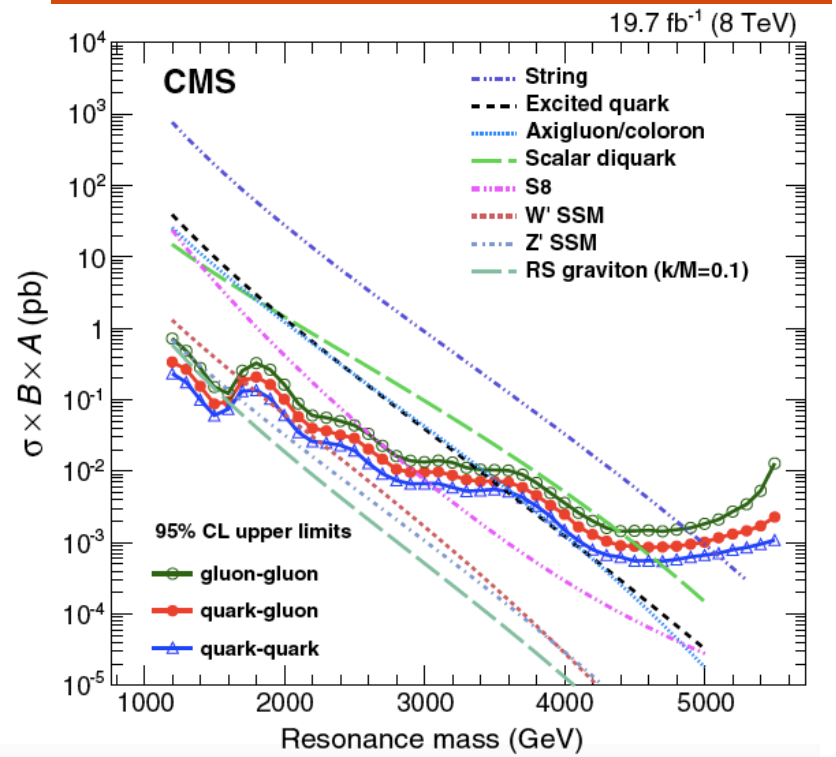


# Di-jets results

**ATLAS: Phys. Rev. D 91, 052007 (2015)**

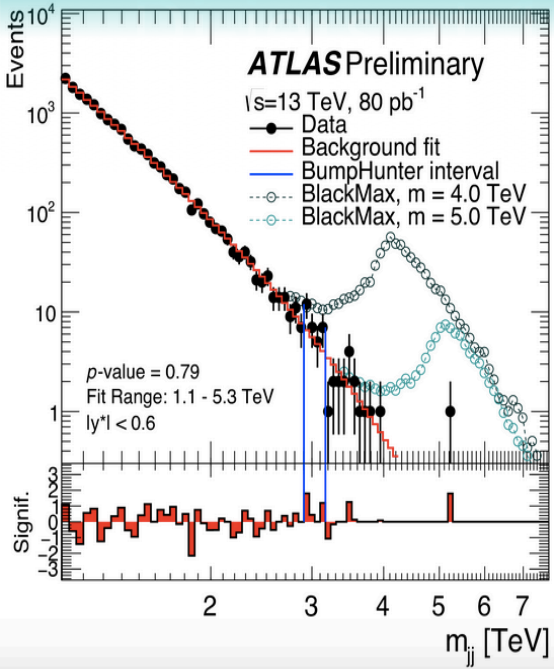



**CMS: Phys. Rev. D 91, 052009 (2015)**

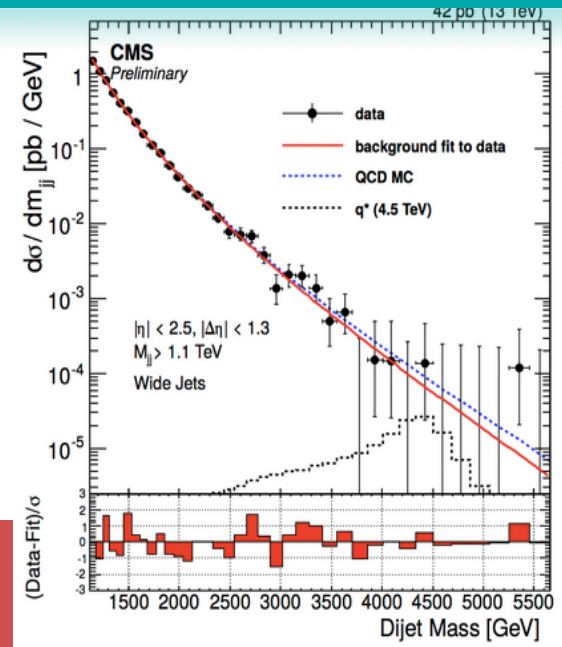



Limits are interpreted as resonances (string, excited quarks, scalar diquarks, W', Z', RS graviton) and quantum black holes.
Resonances with masses 2-5 TeV excluded depending on model.

# Di-jets at 13 TeV

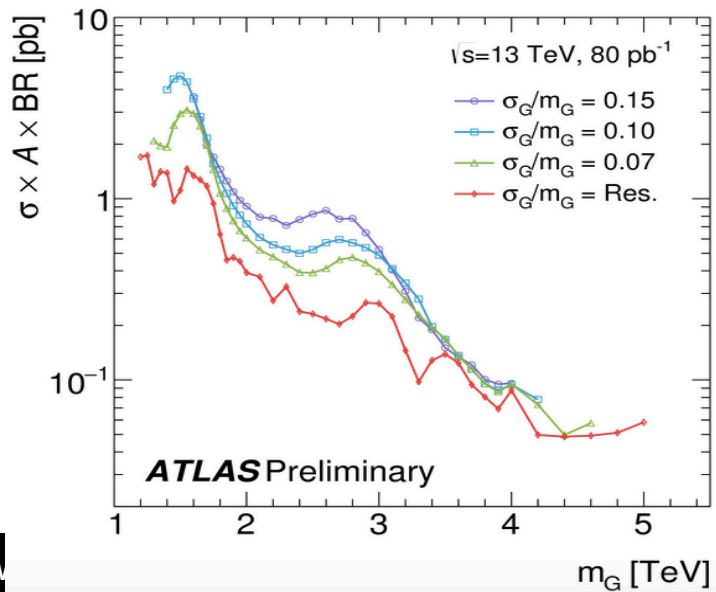


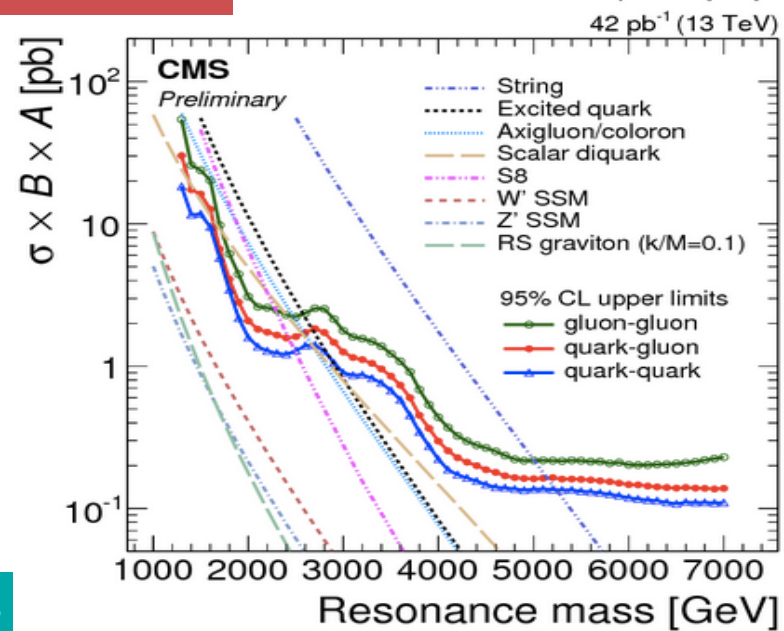

The parton luminosity ratio increases rapidly at high masses. At 13 TeV, with a much smaller integrated luminosity, we have the same sensitivity as at 8 TeV



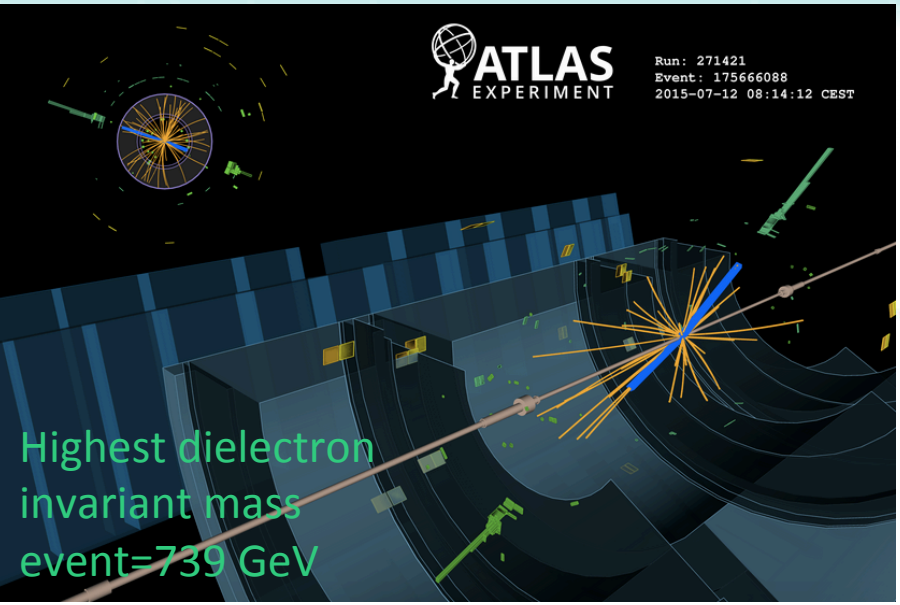

***ATLAS-CONF-2015-042***

***CMS-PhysicsResults EXO15001***

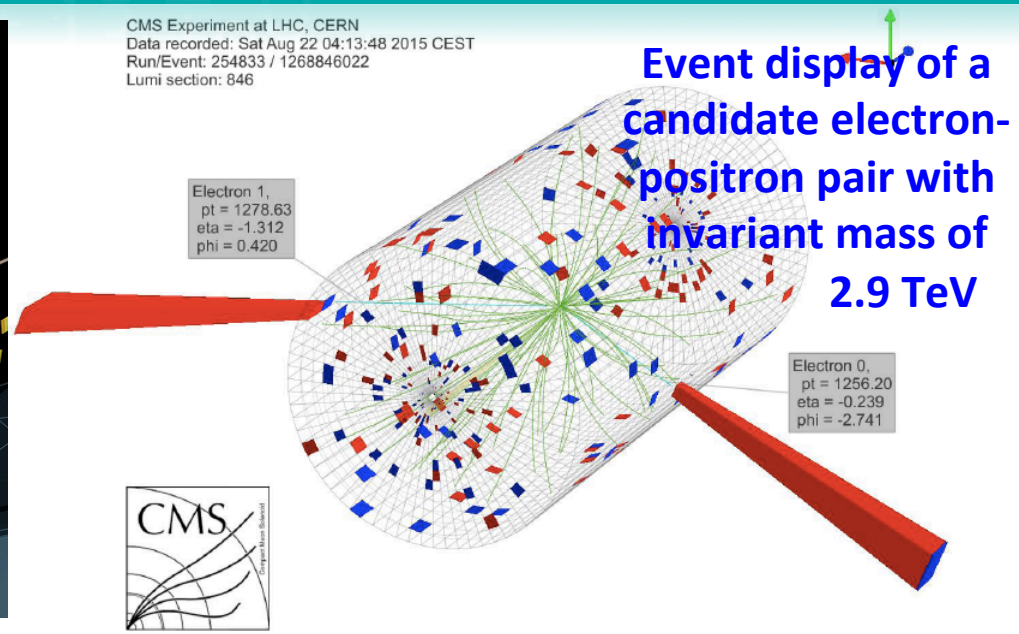


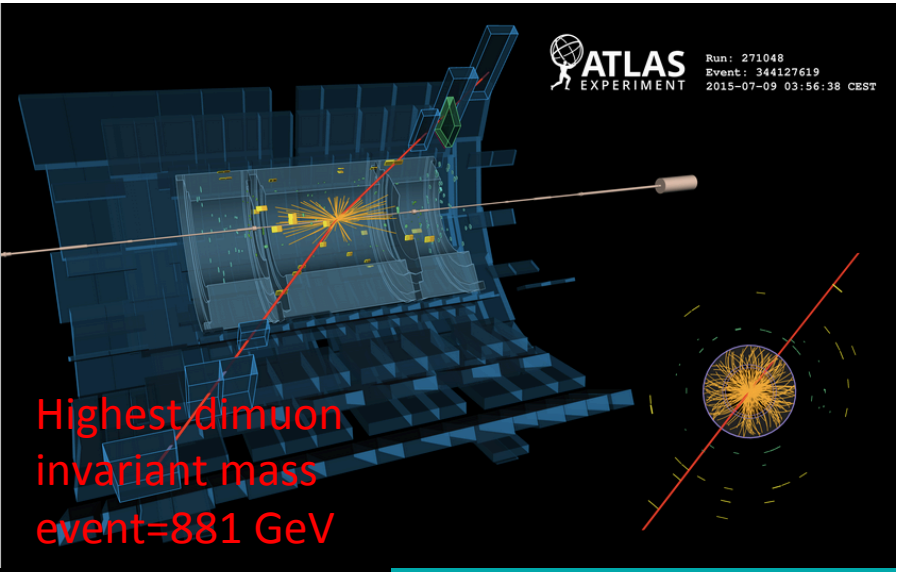
# Di-leptons events at 13 TeV



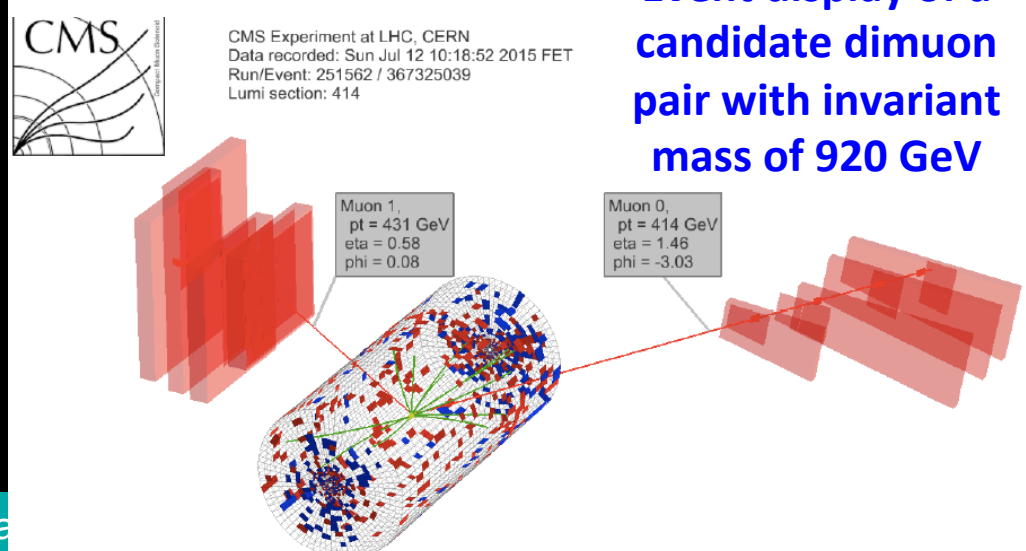

Highest dielectron invariant mass event=739 GeV




**Event display of a candidate electron-positron pair with invariant mass of 2.9 TeV**



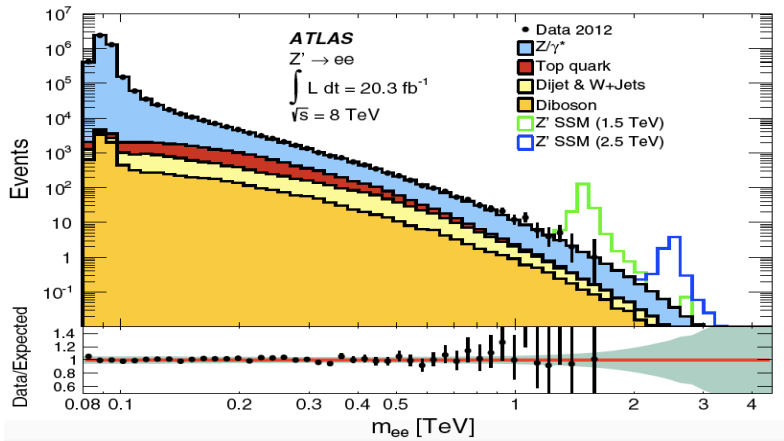

Highest dimuon invariant mass event=881 GeV

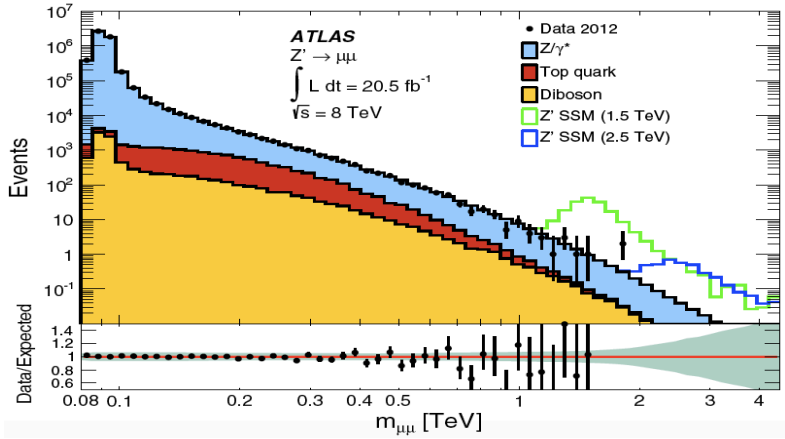


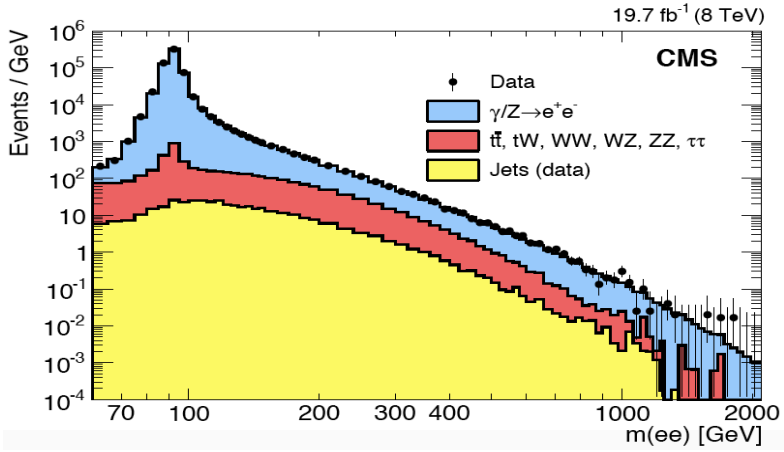

**Event display of a candidate dimuon pair with invariant mass of 920 GeV**

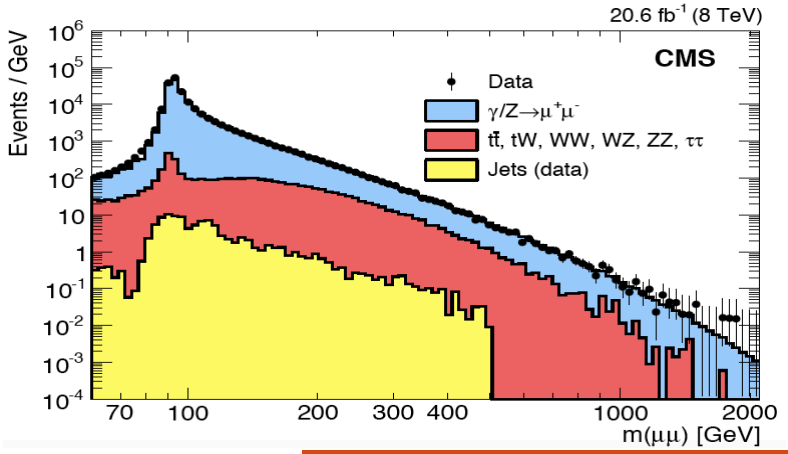
# Di-leptons

- Traditional tool to search for narrow resonances using leptons (mainly e, μ but also τ)
- Low background (DY) and good mass resolution



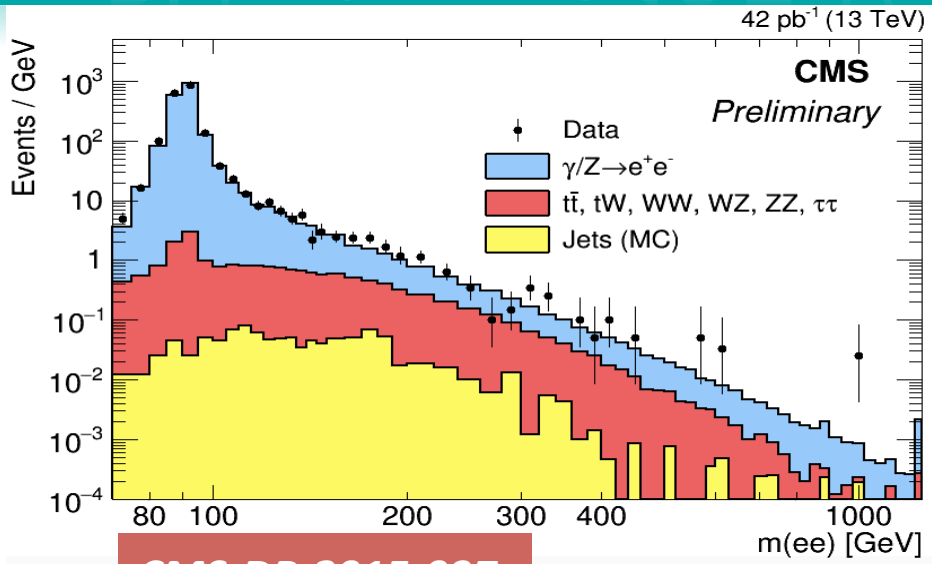



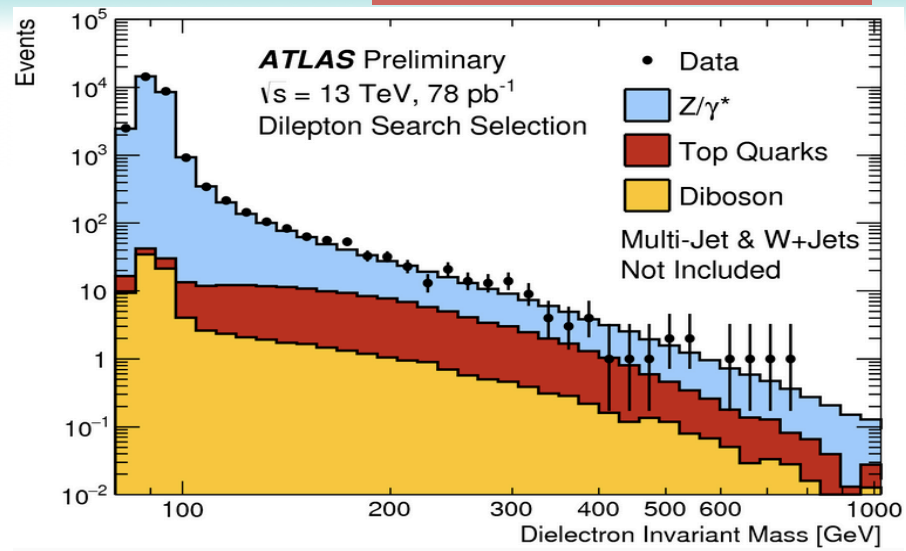

***ATLAS: Phys. Rev. D 90, 052005 (2015)***

***CMS: JHEP 04 025 (2015)***

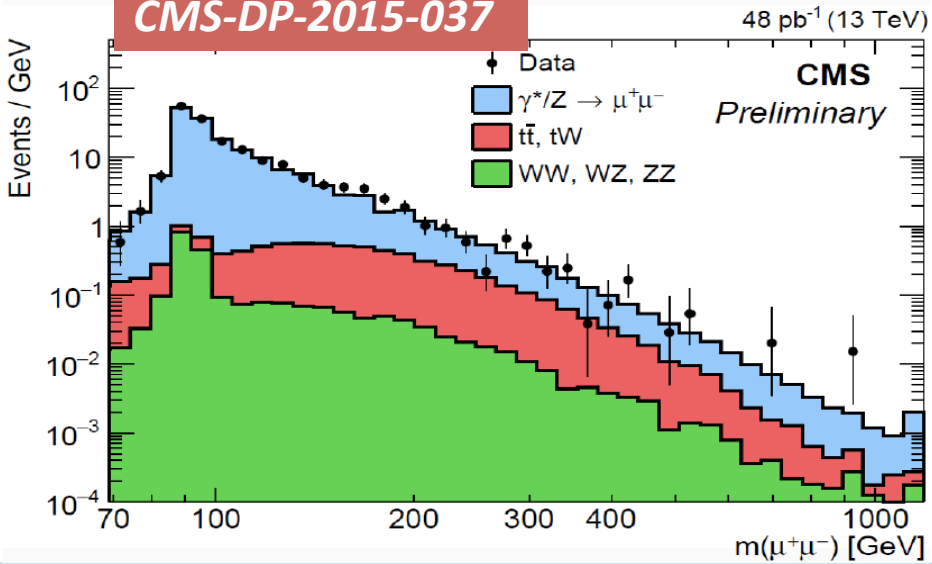
# Di-leptons at 13 TeV

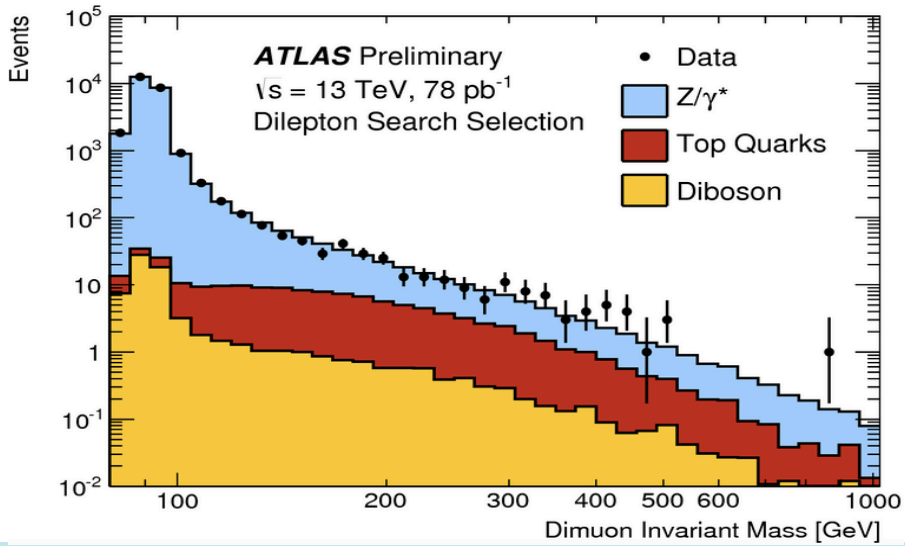
ATLAS-EXOT-2015-001



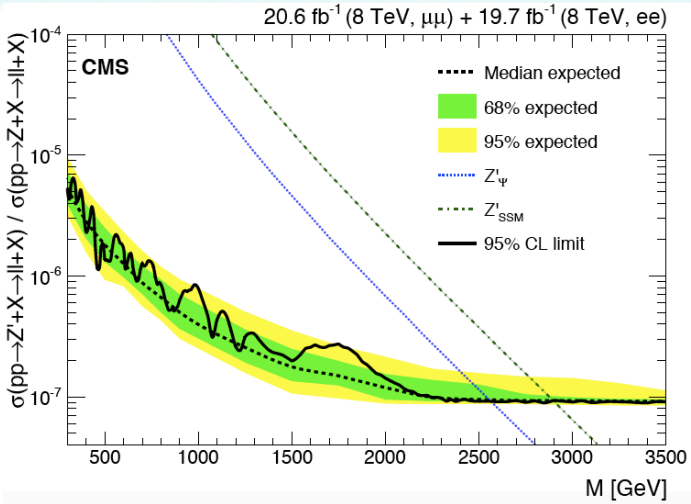

CMS-DP-2015-037

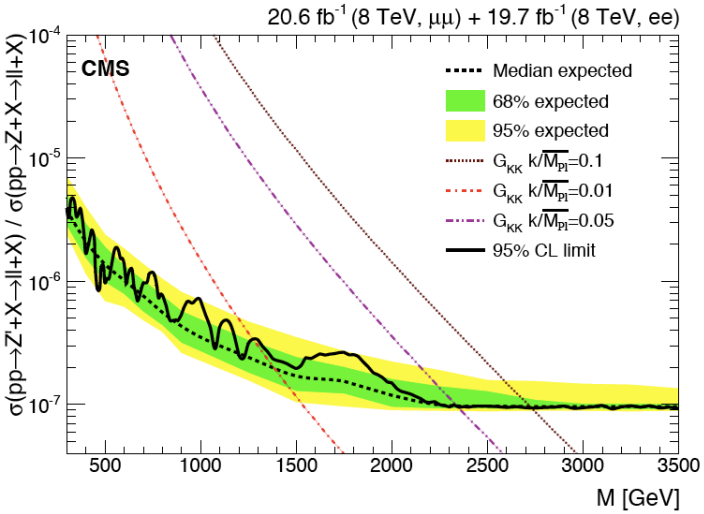



Good agreement between data and total background expectation in whole mass range

# Di-leptons

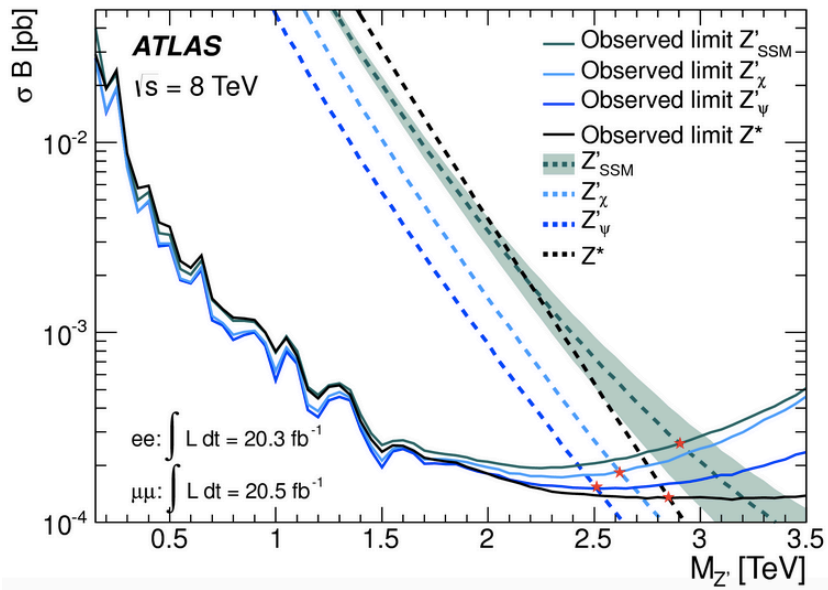



Limits can be interpreted in various models as :

- Z' resonance,
- spin-2 graviton…

- Best sensitivity to Z', RS graviton

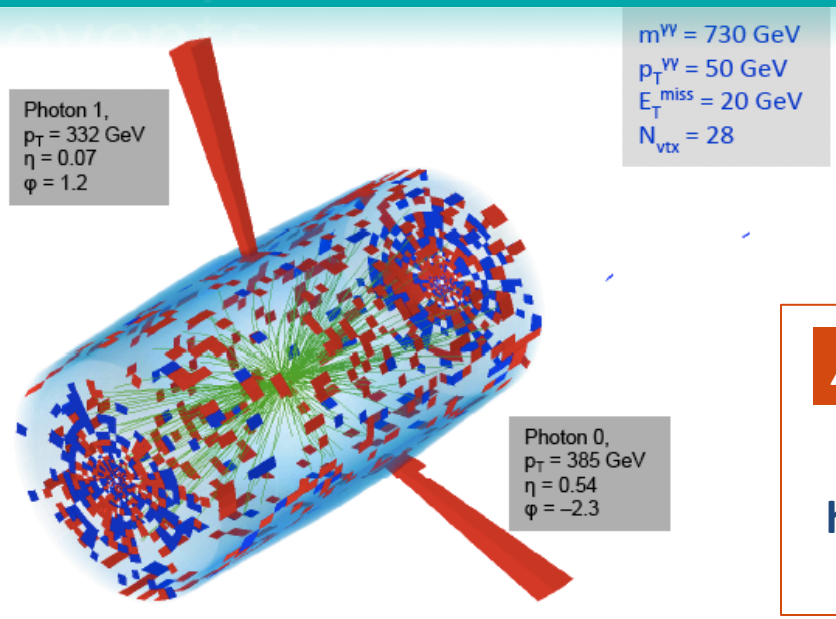



***ATLAS: Phys. Rev. D 90, 052005 (2015)***

***CMS: JHEP 04 025 (2015)***

Typical mass limits 2.5-3 TeV depending on model.

# Di-photons events

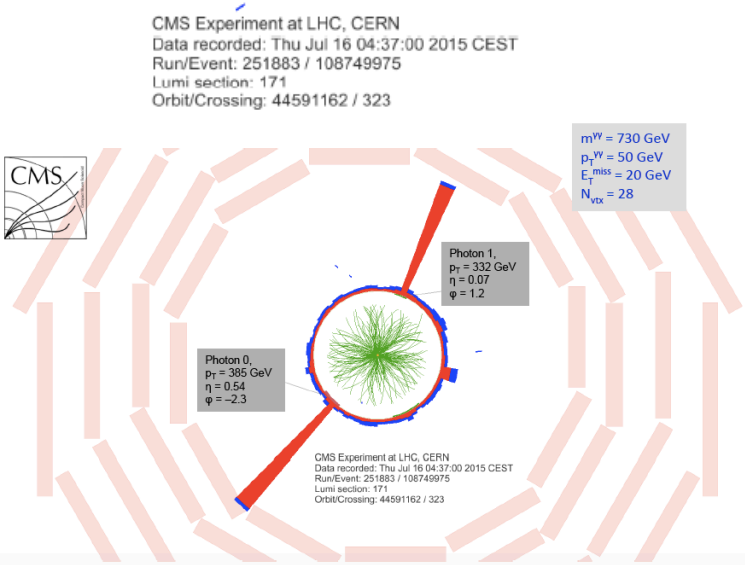


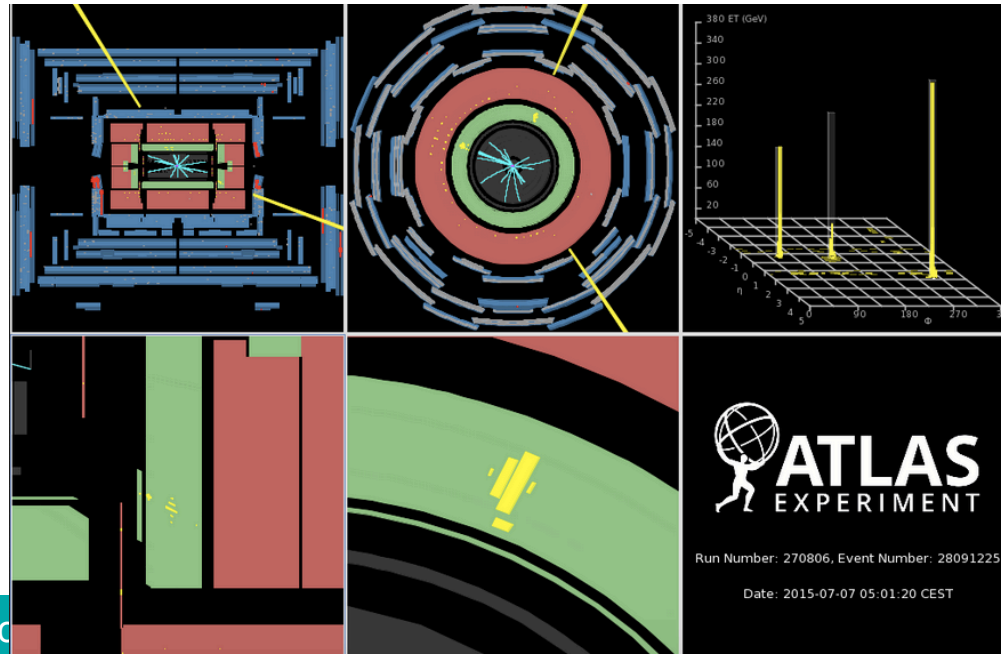

**CMS DP2015_037**

**Event display of the highest-mass diphoton candidate event. $M_{\gamma\gamma}$ = 730 GeV**

**ATLAS EXOT-2015-003**

**Event display of the highest-mass diphoton event. $M_{\gamma\gamma}$ = 940 GeV**

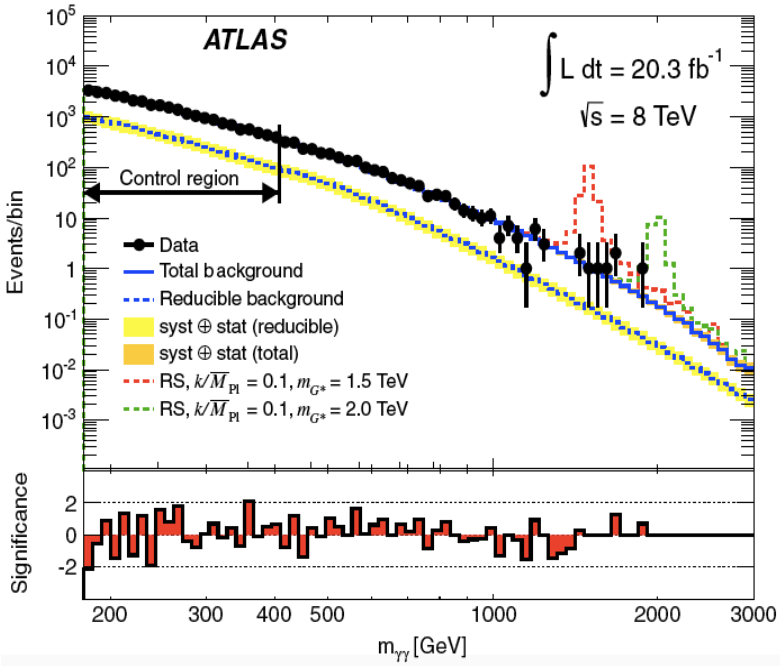


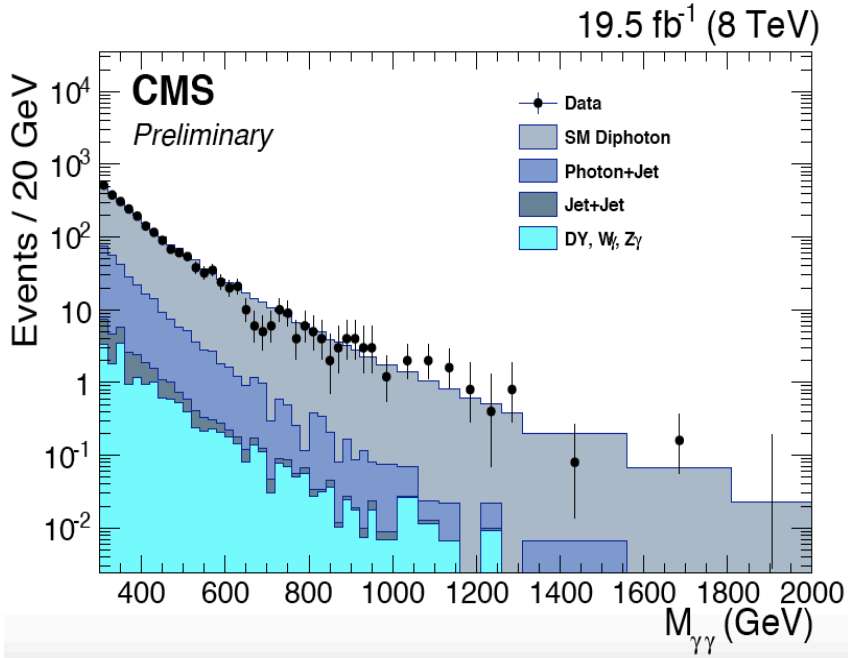
# Di-photons

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

***ATLAS: Phys. Rev. D 92, 032004***



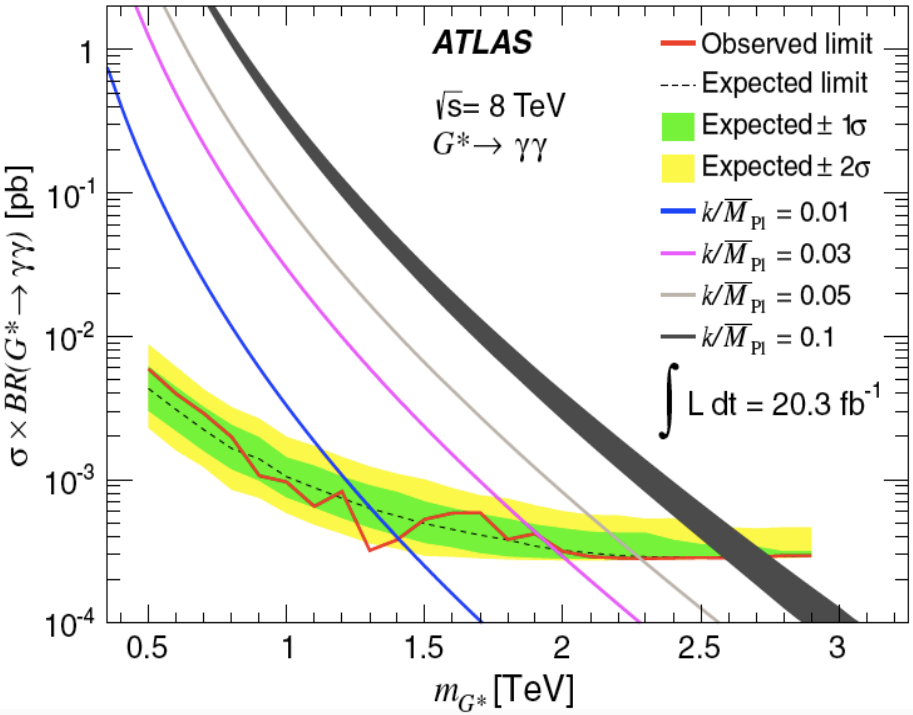

***CMS: PAS EXO-12-045 and 048***

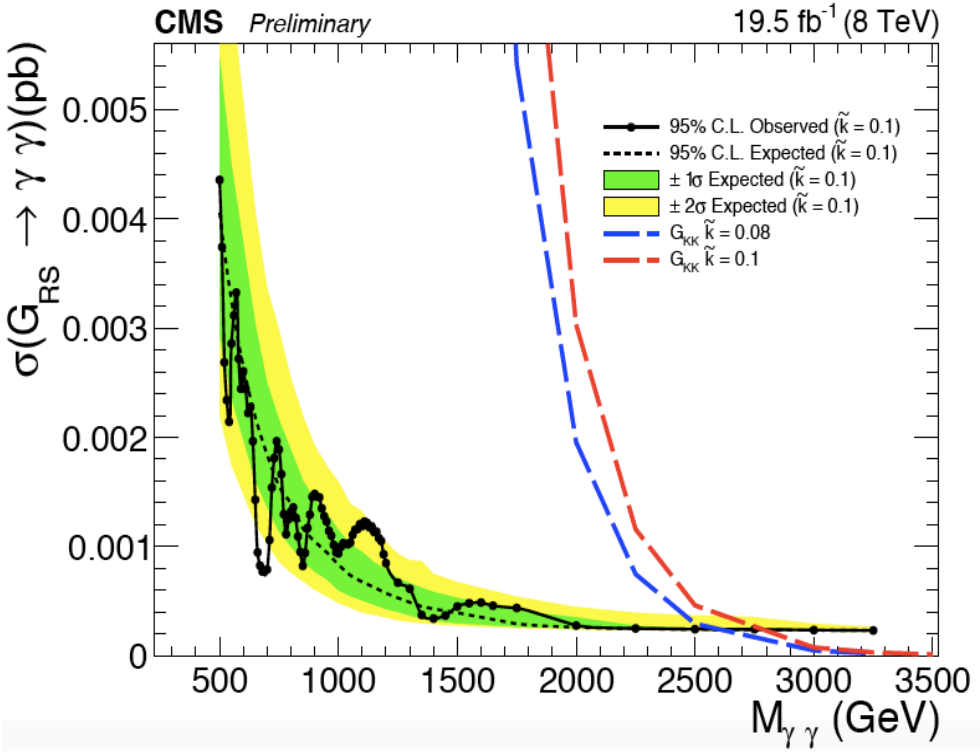


# Di-photons

**ATLAS: Phys. Rev. D 92, 032004**

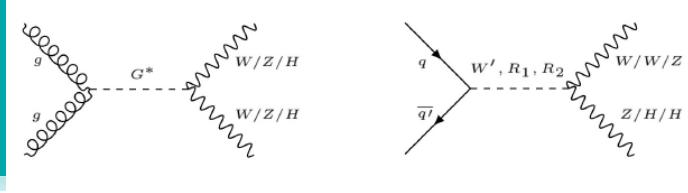
**CMS: Pas EXO-12-045 and 048**



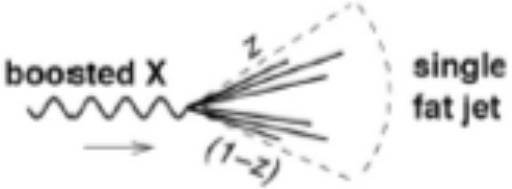

Observed limits (TeV) Limits on RS graviton mass 1-2.7 TeV (sensitivity similar to di-lepton)

# Di-bosons

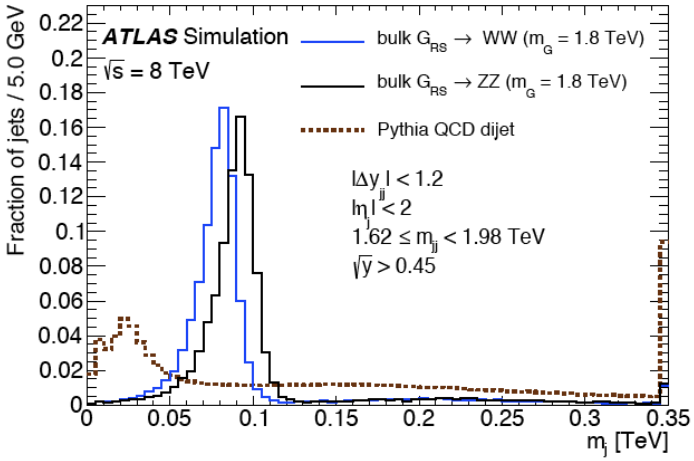



Search for resonance decaying to pairs of W, Z, H

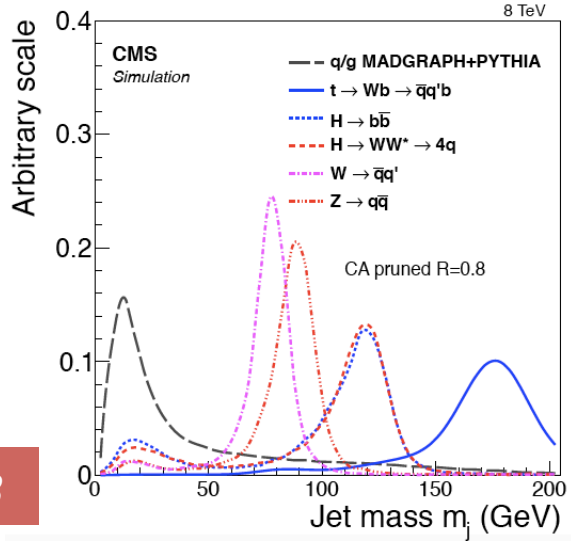
- Challenging topology: at resonance masses above 1 TeV the decay products of bosons overlap due to strong boost → needs dedicated techniques to handle boosted topologies of final states
- Main models used as benchmark in Run1 analysis: Extended Gauge Model, bulk Randall-Sundrum model , Minimal Walking Technicolor, Heavy Vector Triplet (HVT)



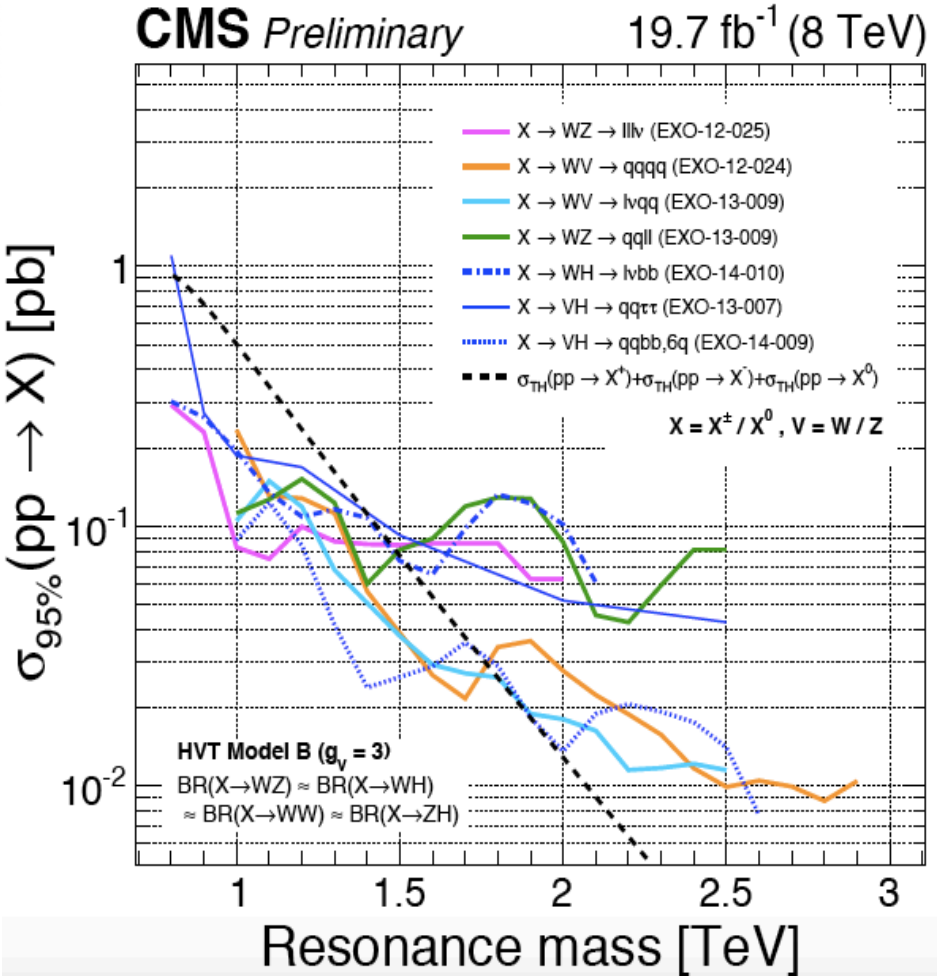

**ATLAS arXiv: 1506.00962**



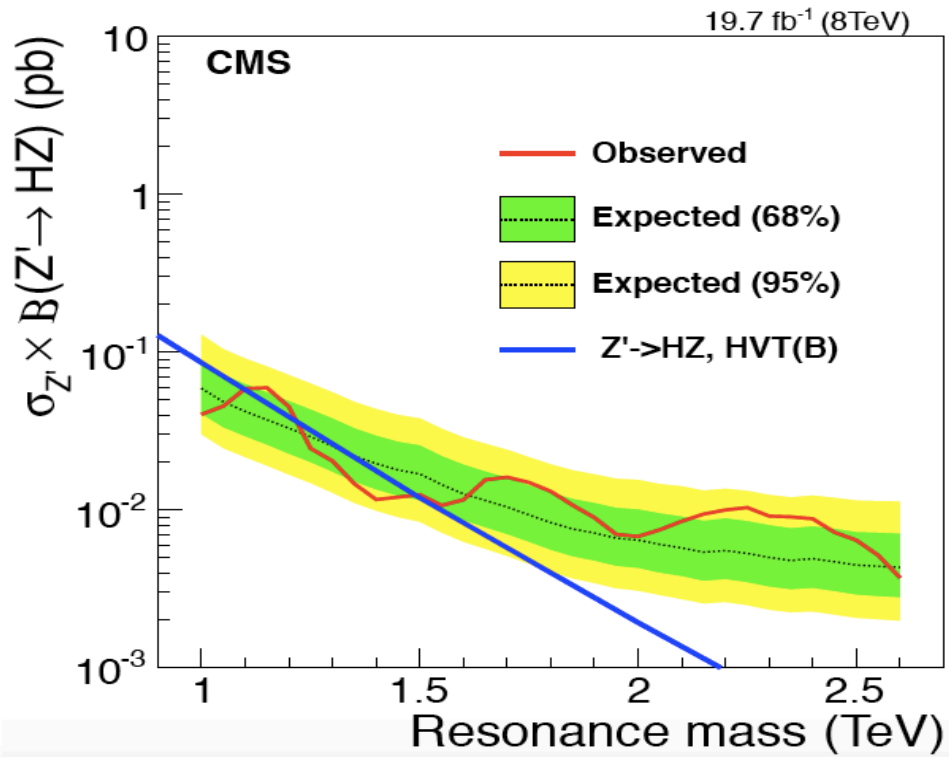

**CMS arXiv: 1506.01443**



# Di-bosons

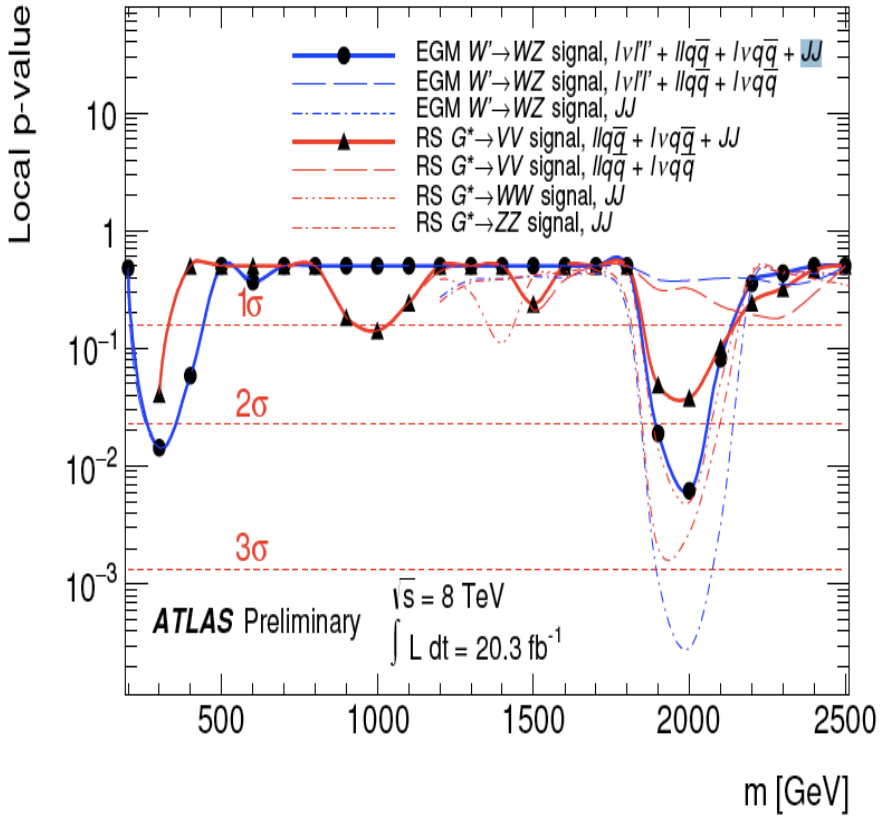


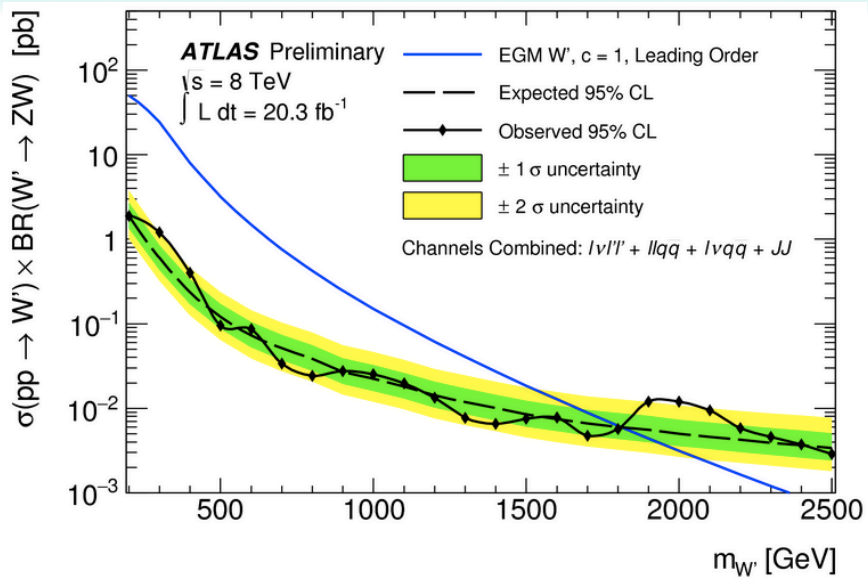

**CMS: arXiv 1506.01443**

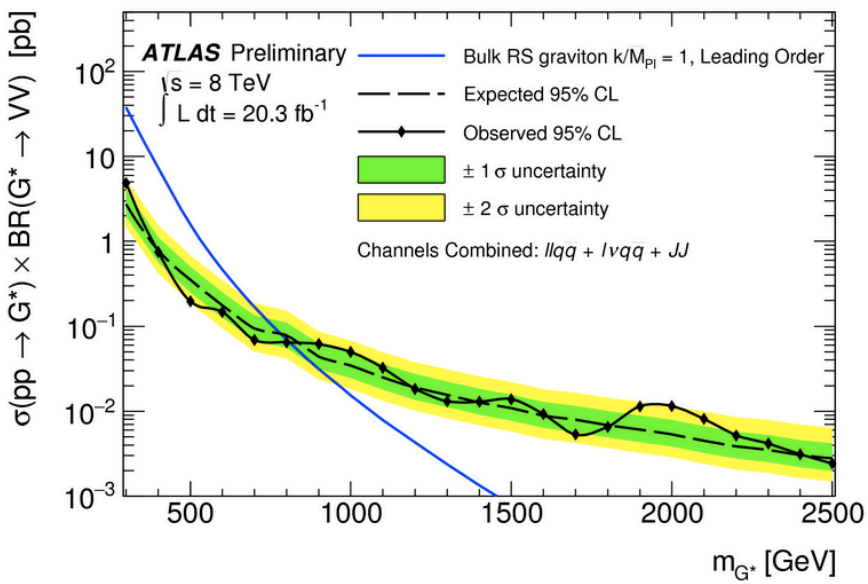



***CMSPublic/PhysicsResultsEXO14010***

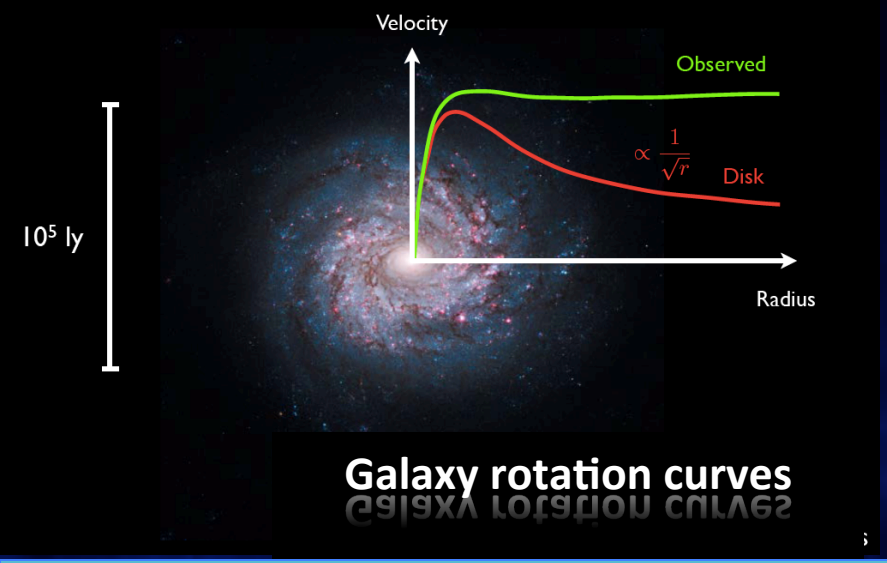
# Di-bosons

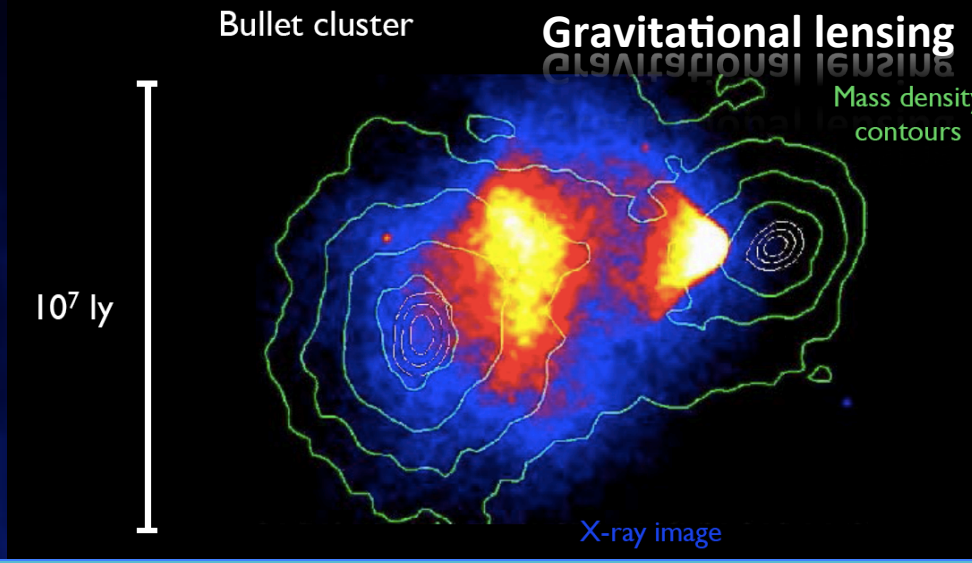


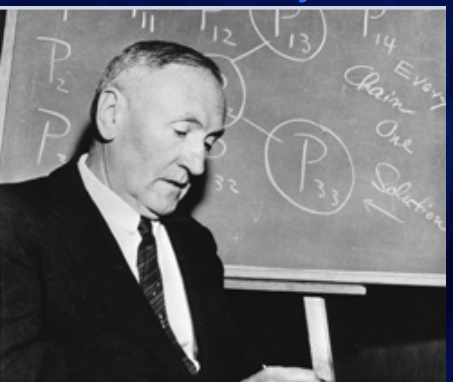

*ATLAS-CONF-2015-045*



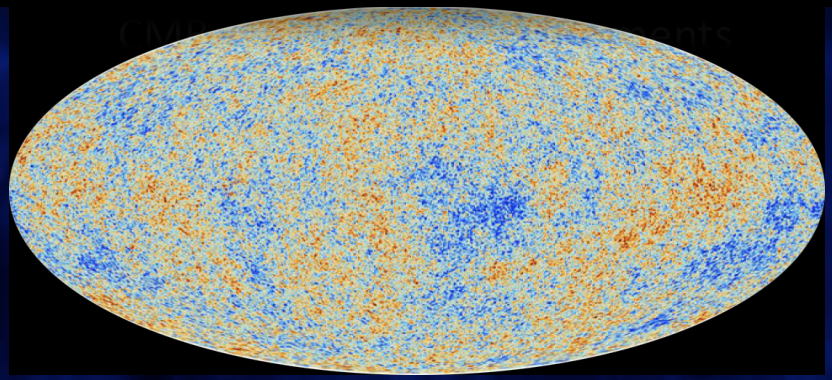




# Evidence for Dark Matter

Fritz Zwicky



**Planck 2013:** DM vs luminous matter from CMB anisotropy measurements



Vera Cooper Rubin and Kent Ford

# Content of Universe

4%

73%

23%

The only properties that have been gathered from the cosmological data are that it is abundant, stable, cold, neutral and interacts very weakly with ordinary baryonic matter.

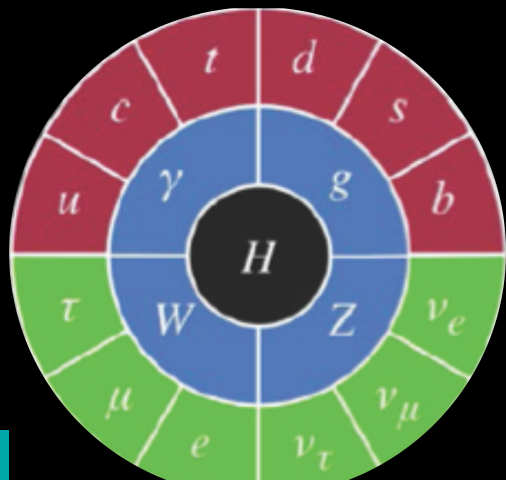
So far no non-gravitational interactions of dark matter have been found.

Ordinary Matter

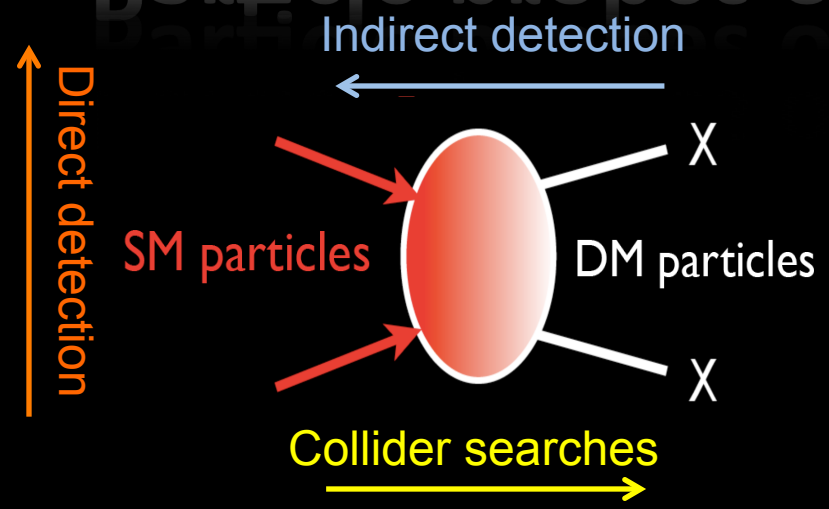
Dark Matter

Dark Energy

Nothing in the SM of elementary particle physics fits the profile.



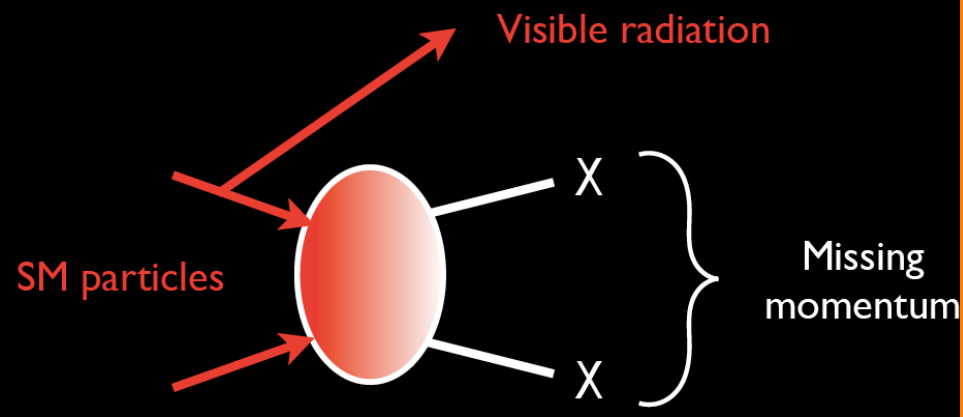
# Particle probes of Dark Matter (DM)




The common theme of searches for DM is that all methods are determined by how the DM particles interact with the SM.

- The DM particles interact so weakly that they are expected to pass through the detector components without any significant interaction, making them effectly invisible
- One way to see DM particles nonetherless is to look for *"missing momentum"* and additional SM radiation

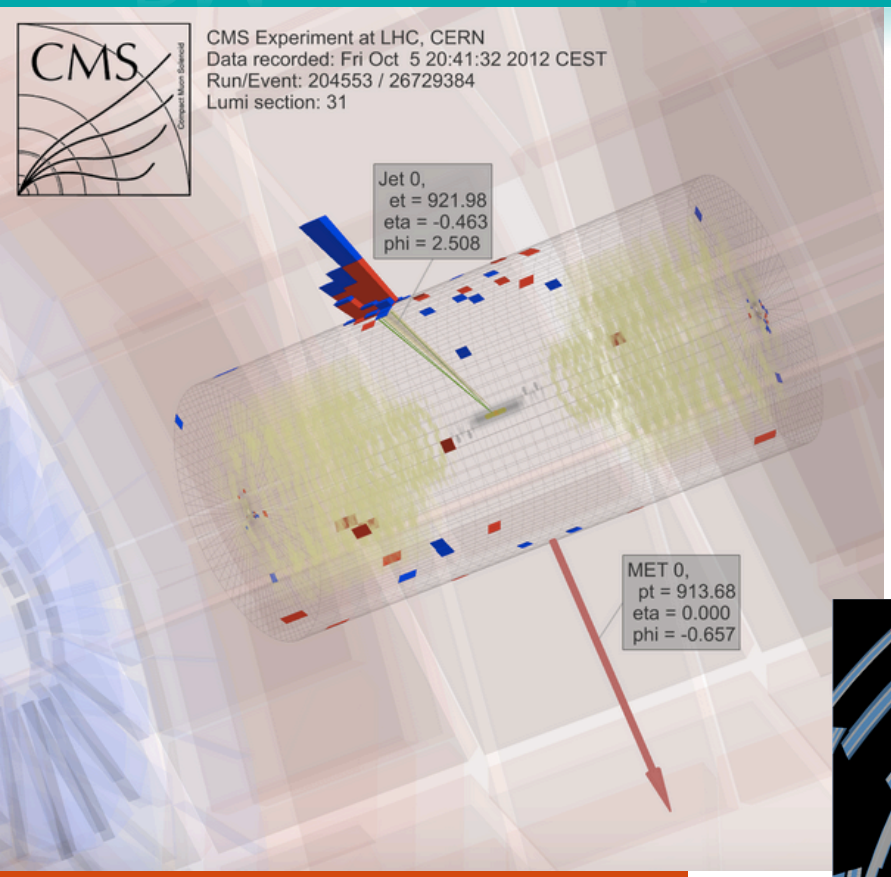
## Search for DM at the LHC




**Search for a particle recoiling against DM**

- **MET and a photon, jet, W, Z, Higgs,…**

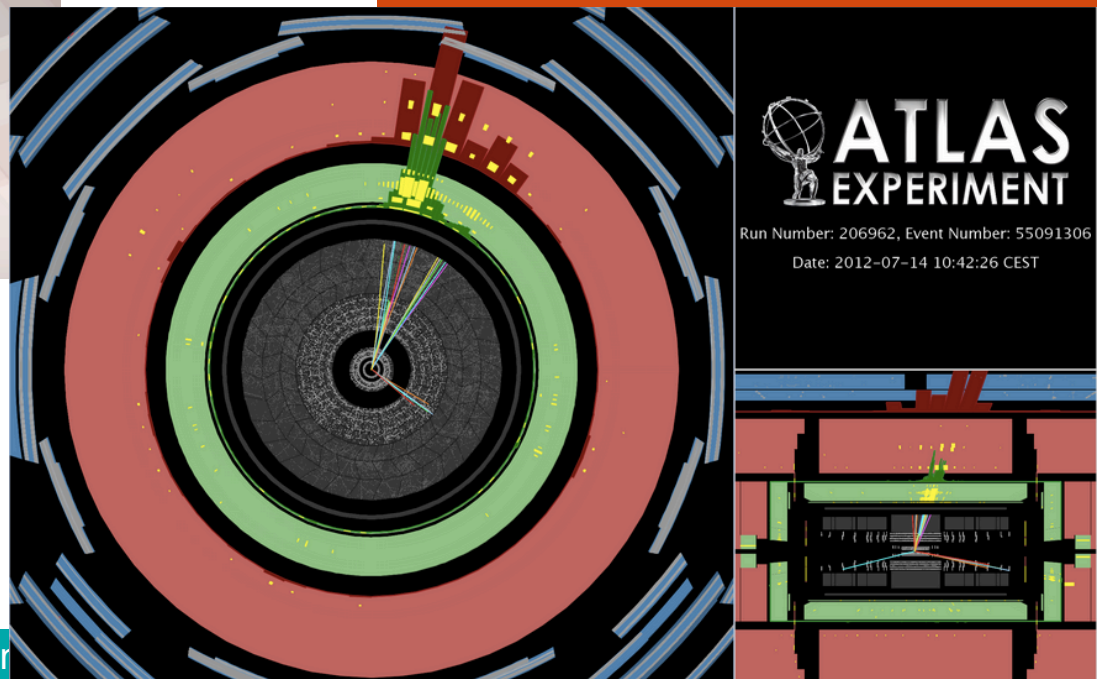
# DM – mono-jet events



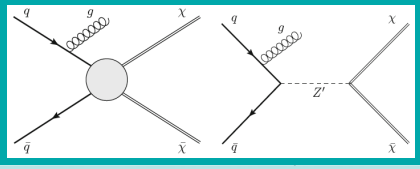

**CMS-PAS-EXO-12-048**

## Event displays for monojet candidate events

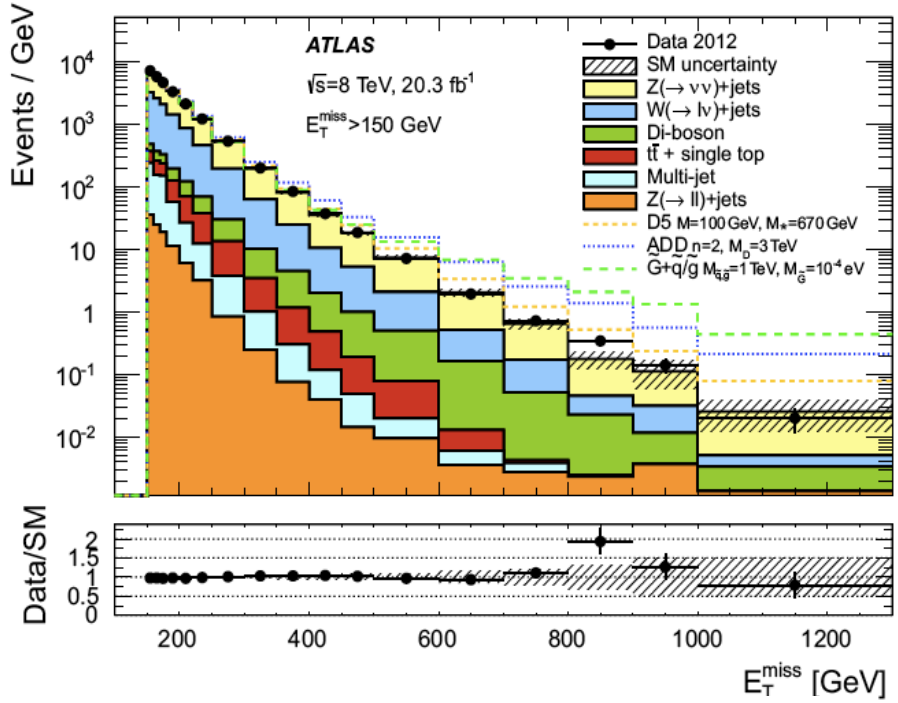
**ATLAS-CONF-2012-147**

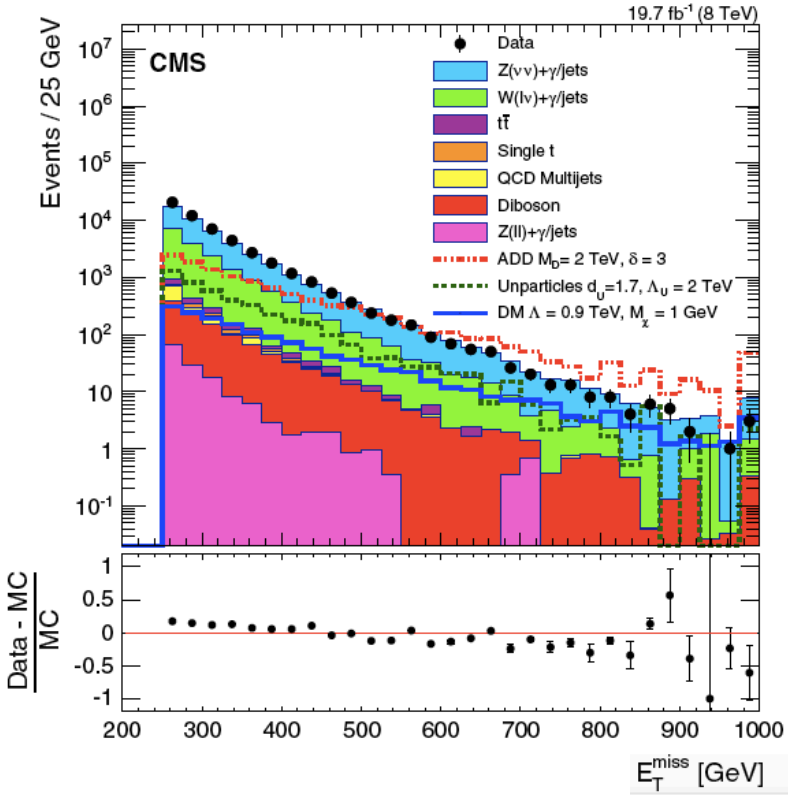


# DM – mono-jet searches



- Large $E_T^{miss}$ with one central high-$p_T$ jet well separated from $E_T^{miss}$
- Lepton veto
- Main background: $Z \longrightarrow \nu\nu$




SR9 selection:

126 observed for 97 ± 14 expected

MET > 550GeV:

519 observed for 509 ± 66 expected

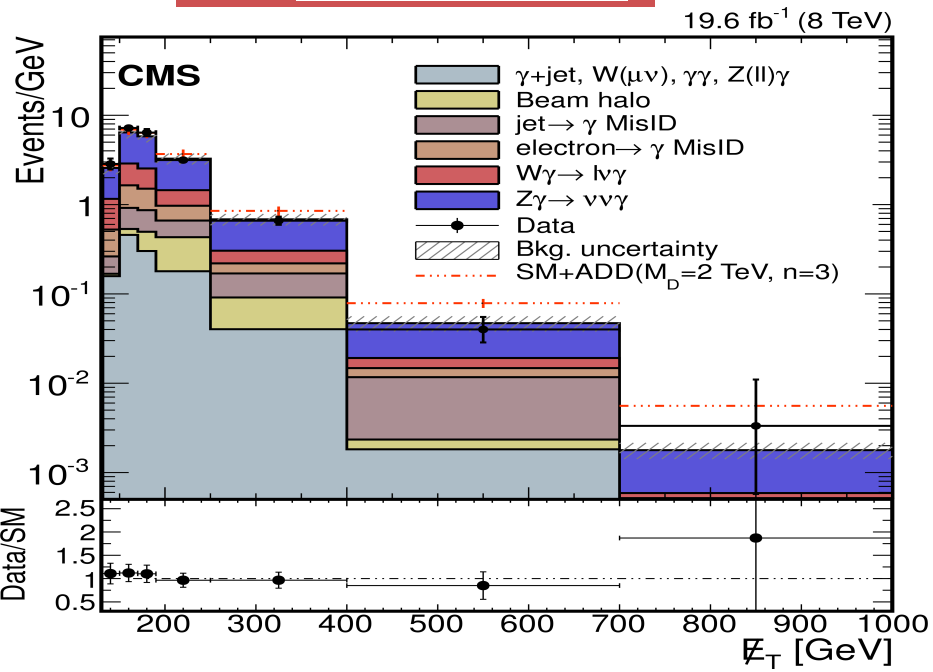
***ATLAS: Eur. Phys. J. C75 (2015) 299***

***CMS: Eur. Phys. J. C75 (2015) 235***

# DM – mono-photon search

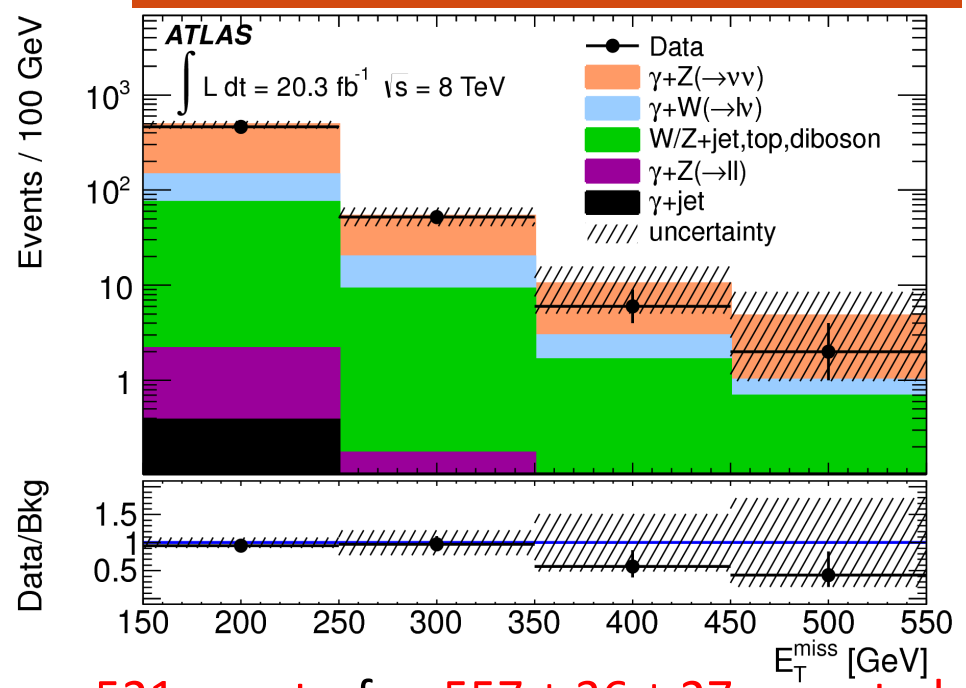
- Large $E_T^{miss}$ with one central high-$p_T$ photon well separated from $E_T^{miss}$
- Lepton veto
- Main background: Z ($\nu\nu$) + $\gamma$ and $W\gamma/Z\gamma$ with lost leptons

*CMS arXiv:1410.8812*




630 events for 614 ± 63 expected

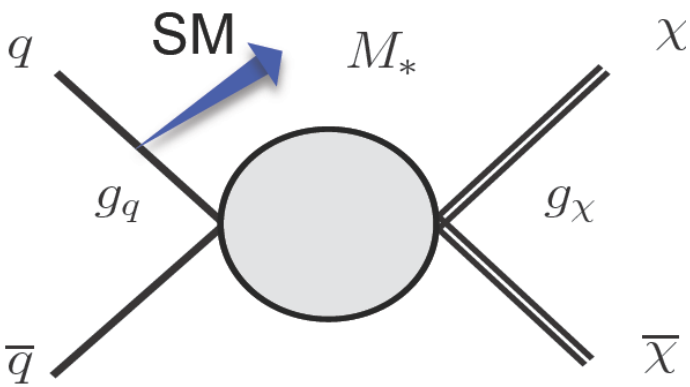
*ATLAS: Phys. Rev. D 91, 012008 (2015), Phys. Rev. D 92, 059903 (2015)*




521 events for 557 ± 36 ± 27 expected

# DM – General EFT & Simplified model

**Effective Field Theory**




Hypothesis, for a given effective operator:

- $Q_{tr} << M_{med} = M_*(g_q g_\chi)^{1/2}$

Less free parameters:

- $M_*$ effective energy scale
- $M_\chi$ Dark Matter mass

Compute the excluded $M_*$:

- $M_*^{exclude} = M_*^{generated} (\sigma^{theo}/\sigma^{excluded})^{1/2p}$ where p is the power of $(1/M_*)$ in the EFT Lagrangian

Explicit mediator such as a Z'-like vector

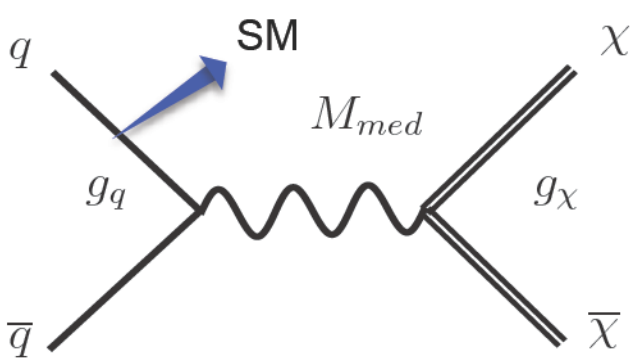
More free parameters:

- $M_\chi$ and $g_q g_\chi$
- Mediator type $M_{med}$ and width $\Gamma_{med}$ $(g_q g_\chi)$

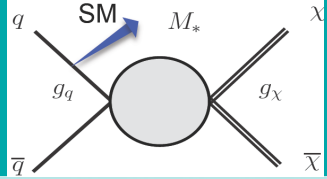
Compute excluded $M_*$ as a function of $M_{med}$ :

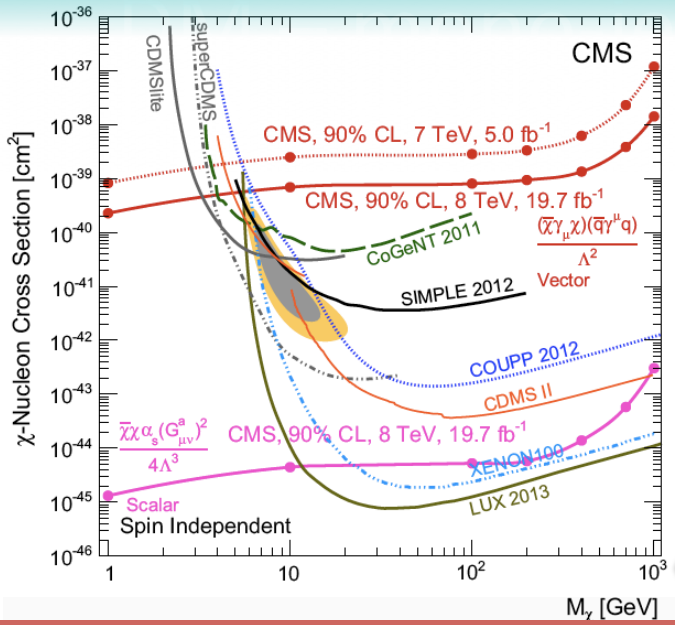
- for given $M_\chi$ and $\Gamma$ : $M_* = M_{med} (g_q g_\chi)^{1/2}$
- EFT region starts from $M_{med} > 5$TeV

**Simplified Model**



# DM – mono-jets search results

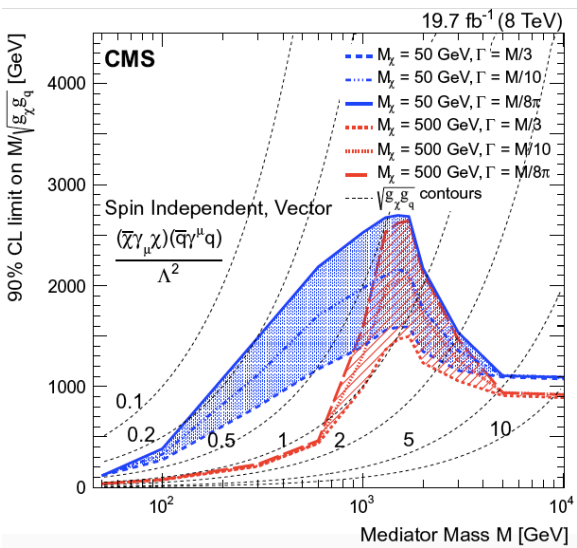


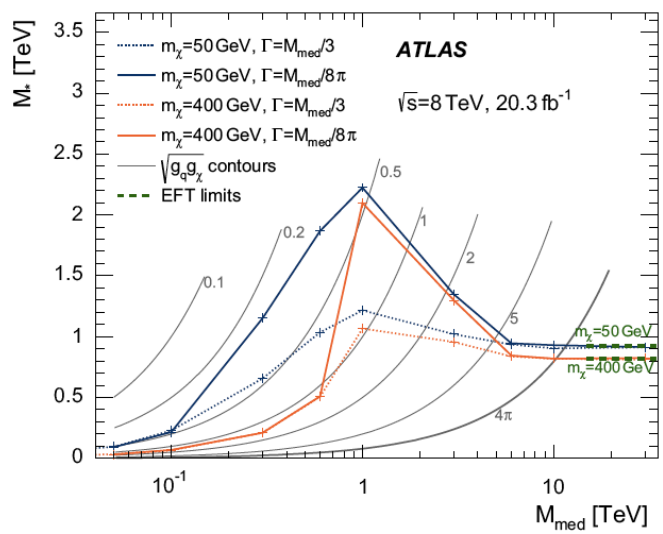




- No excess is found. All measurements are consistent with SM
- Extract limits for different EFT operators using most sensitive signal region in each case
- EFT validity truncation

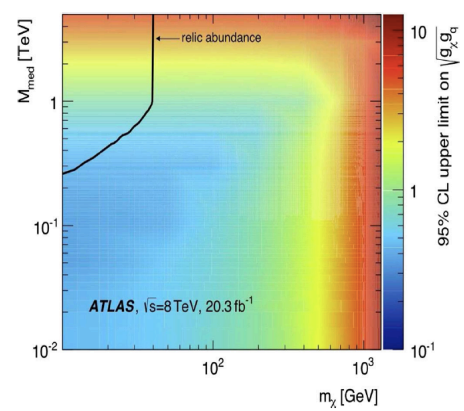
**Limit on DM-Nucleon scattering cross section**

*CMS: Eur.Phys.J. C75 (2015) 235*



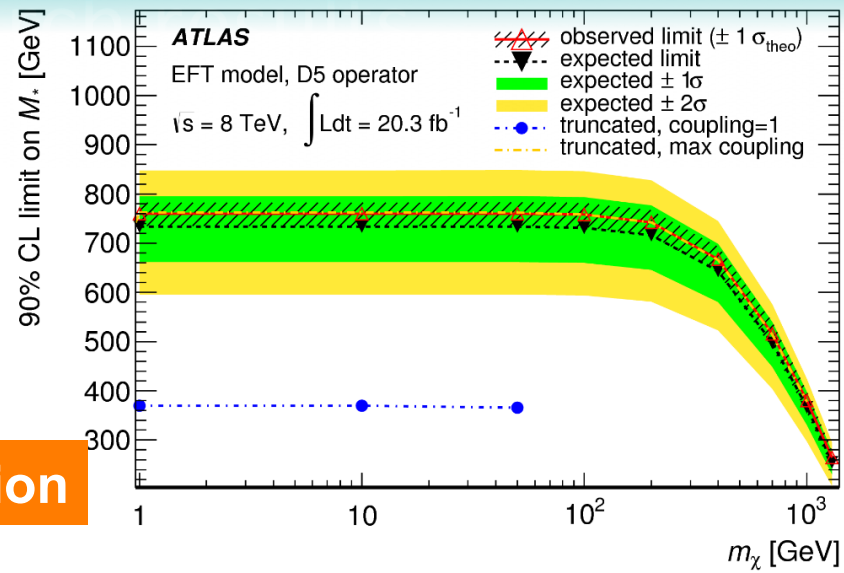

**Simplified Model: Z'**



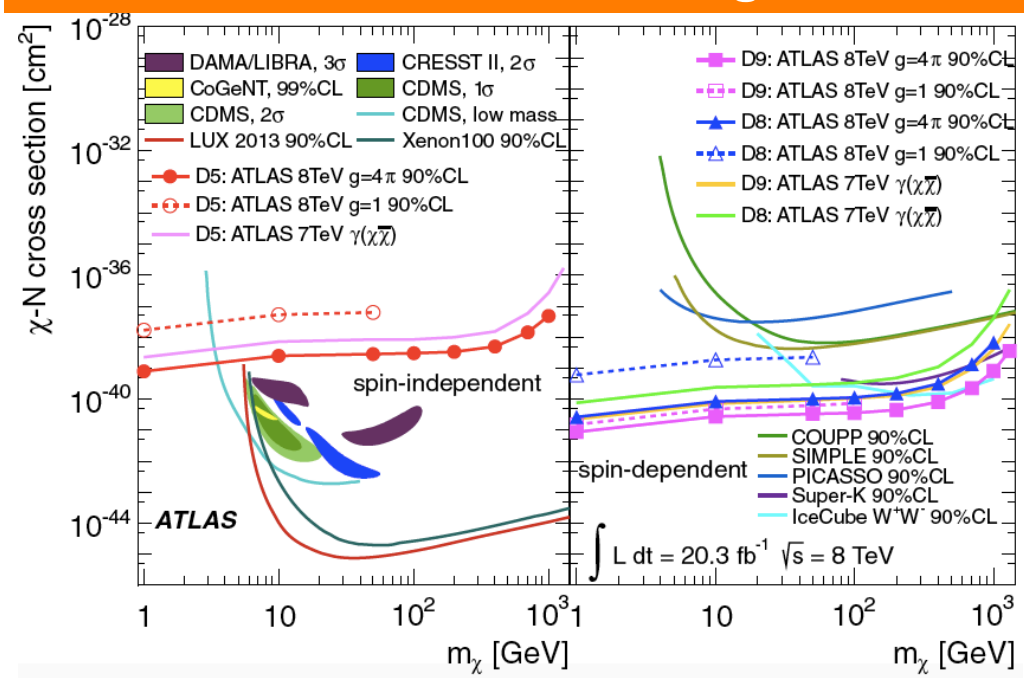

*ATLAS: Eur. Phys. J. C75 (2015) 299*

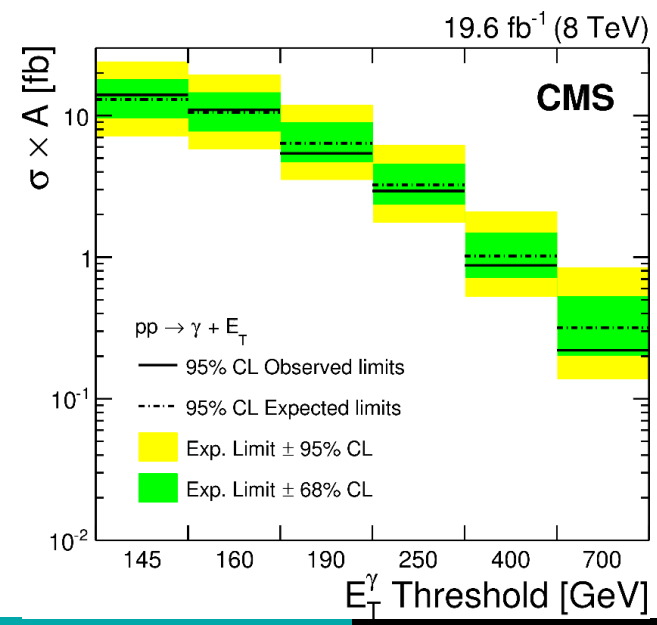
# DM – mono-photon search results

- No excess is found
- All measurements are consistent with SM
- Limits on cross section*accep-tance order of fb (or less)

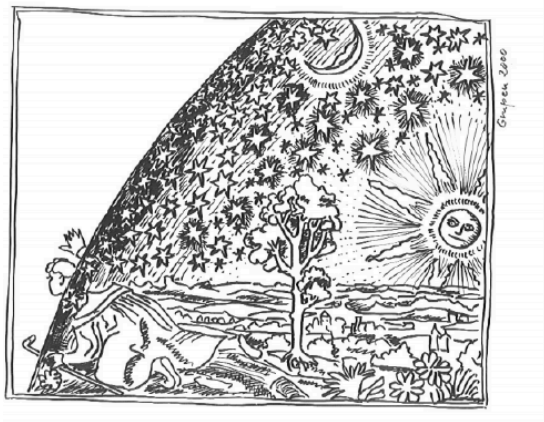



**Limit on DM-Nucleon scattering cross section**



# Conclusions



- Search for new physics beyond the SM, SUSY and non-SUSY is one of the motivations for the LHC experiments
- In Run1 ATLAS and CMS collected 20 $fb^{-1}$ of data at 8 TeV
- Many exotic searches have been performed by ATLAS and CMS
- A large phase space covered searching for possible new final states and testing many models
- No evidence for new exotic physics
- Many mass limits above TeV
- A few anomalies observed to be followed…

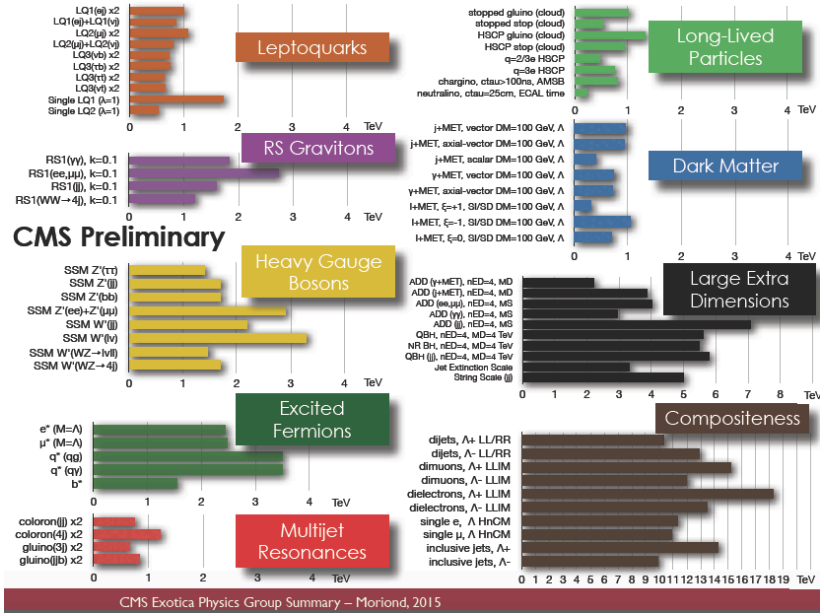
- Run2 in on going, expect to collect ~100 $fb^{-1}$ of data at 13 TeV
- With the increase in energy of Run2 new physics can be just around the corner.
- Will surpass soon the Run1 sensitivity in most exotic searches

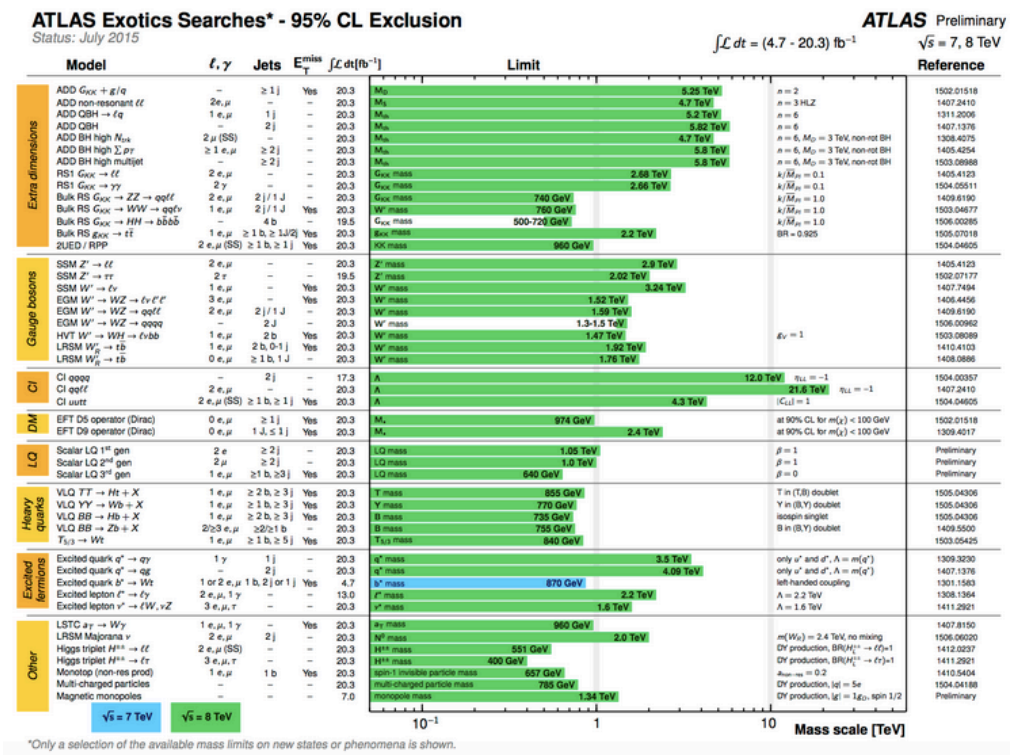
Hope something exotic may pop up soon (instead of upper limits)!

# Thank you

**For a list of ATLAS & CMS exotic results:**

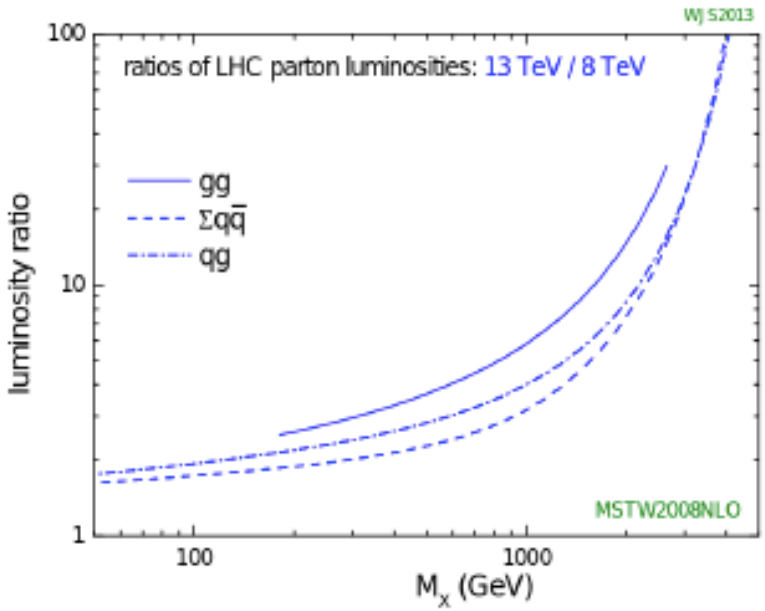
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G



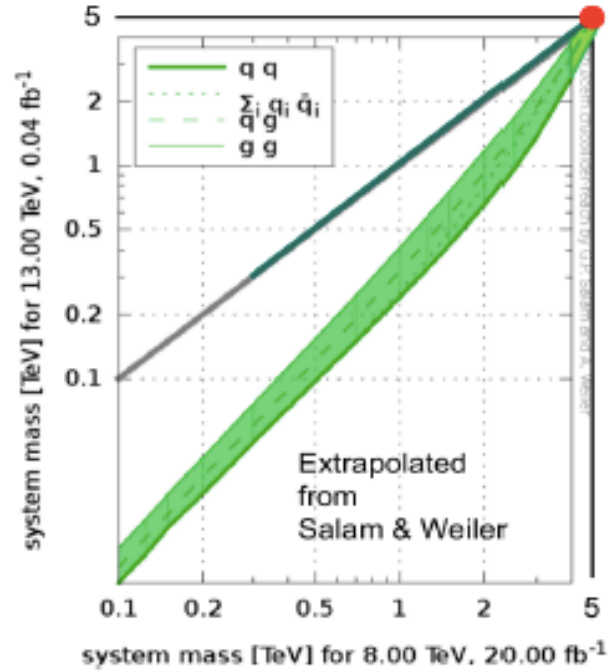



# Run1 vs Run2 sensitivity

- Parton luminosity ratio increase rapidly at high masses
- With much smaller integrated luminosity than Run1 → 13 TeV data same sensitivity as 8 TeV




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




http://collider-reach.web.cern.ch/collider-reach/

- From parton luminosity ratio → **present dataset @13 TeV more sensitive than Run 1 for masses > 5 TeV**

# Outline

## Exotic searches by ATLAS and CMS at LHC(*)

- **Resonance searches**
  - **Di-jets**
  - **Di-leptons**
  - **Di-photons**
  - **Di-bosons**
- **X+MET and Dark Matter searches**
  - **Mono X (where X is a single jet, photon, W, Z, …)**
- **Long-lived searches**
  - **Displaced photon/lepton/jets ; Delayed photons; Stopped particles; Disappearing tracks ; Heavy stable charged particles; ……..**
- **….**

***(*) This talk covers only a selection of results***