Beyond the Standard Model

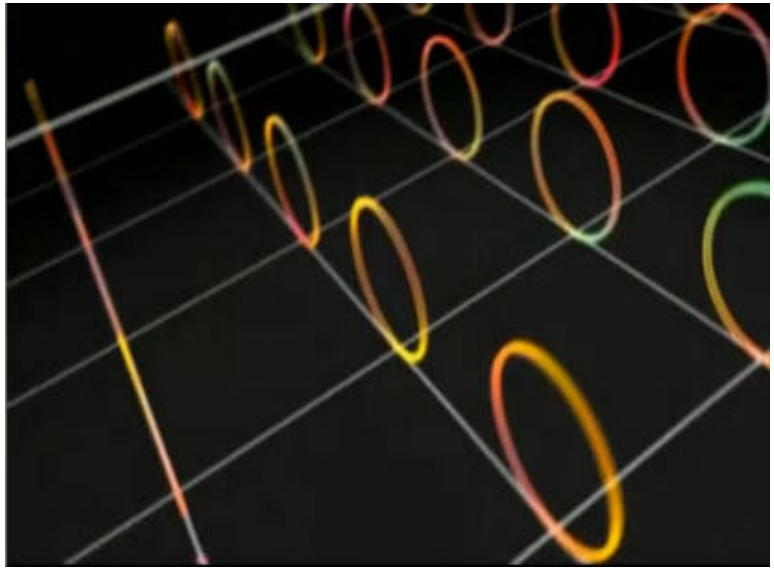
A selection of the latest LHC results

Theory LHC France, IPN Orsay, France
7-9 November 2016

Barbara Clerbaux (IIHE-Brussels, ULB)
on behalf of the ATLAS, CMS and LHCb experiments

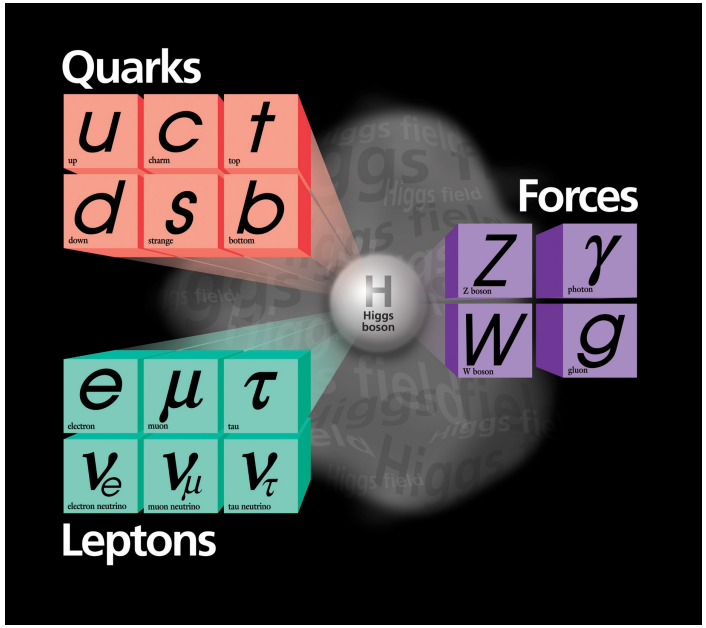
Plan of the talk

1. **Introduction :**
   - Exploring the unknown
   - The LHC Run2
2. **Di-photon story**
3. **Searches for resonances :**
   dileptons, lepton+MET, dijets



4. **Searches for diboson resonances**
5. **Searches for vector like quarks**
6. **Searches for long lived particles**
7. **BSM searches at LHCb**
8. **Conclusions**

Exploring the unknown



SM : Beautiful theory

Many "WHY" :

- Origin of EWSB ?
- Naturalness ?
- Unification ?
- More forces ? More dimensions ?
- Neutrinos nature and masses ?
- Matter/anti-matter asymmetry ?
- Nature of the dark matter
- Dark energy ?

At the LHC :

- Energy frontiers : 13 TeV runs
  → opening new phase space at high mass
- Collisions rates : above the design value
  Excellent LHC performance
  → exploring small cross sections

LHC now :
key period
for the search
For new physics
(at the energy frontier)

Exploring the unknown

New ideas
Model DRIVEN

- Grand Unified Theories
- Leptoquarks
- Compactified Extra Dimension
- Quantum Black Holes
- Little Higgs
- Hidden Valley
- Contact Interactions/Compositeness
- Exited Fermions
- Technicolor
- …

SUSY -> Loïc's talk
Extended scalar sector -> Suzanne's talk
DM -> Marie-Helene's talk

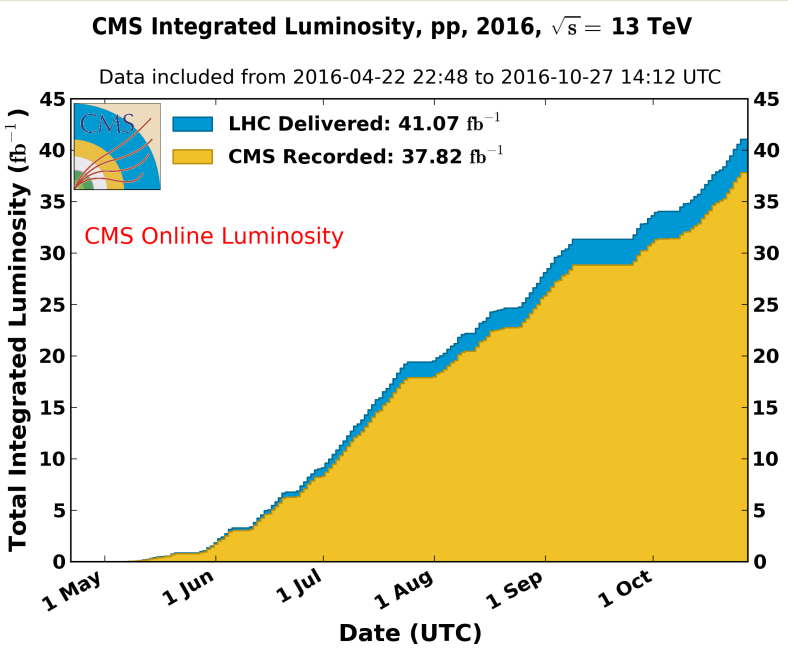
New ideas
Topology DRIVEN

- Resonances (bumps hunting)
- multi-boson resonances
- boosted topologies
- Large missing transverse momentum
- Heavy quarks
- Excesses in high mass tails
- Long lived particles
- Systemtatics scan / topologies
- ……

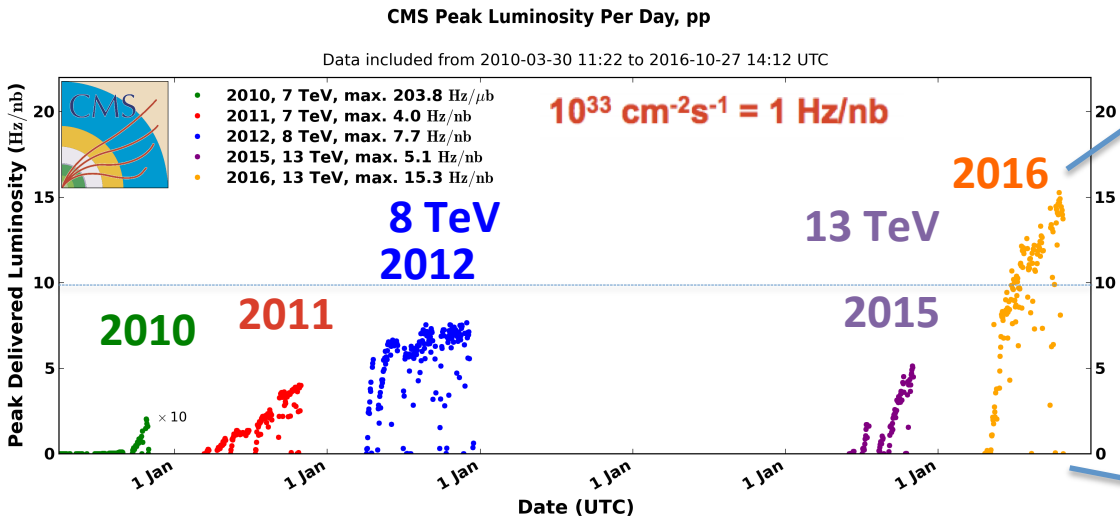
If signal is observed
→ Characterisation

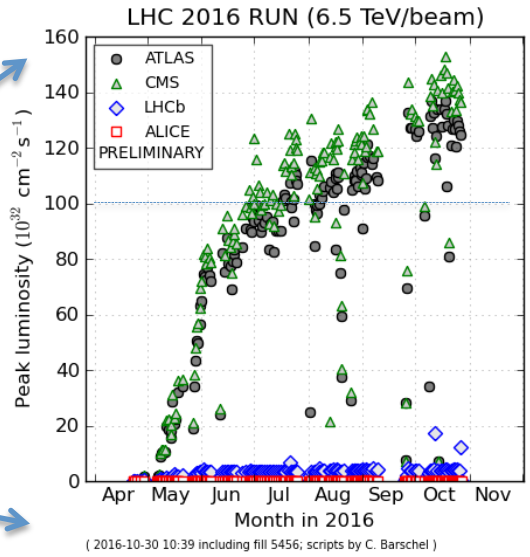
LHC performance

- **Run 2 Dataset**
  - 2015: ~3 /fb
  - 2016: ~40 /fb delivered to CMS and ATLAS
  - August 2016 : 13 /fb analyzed & presented at ICHEP



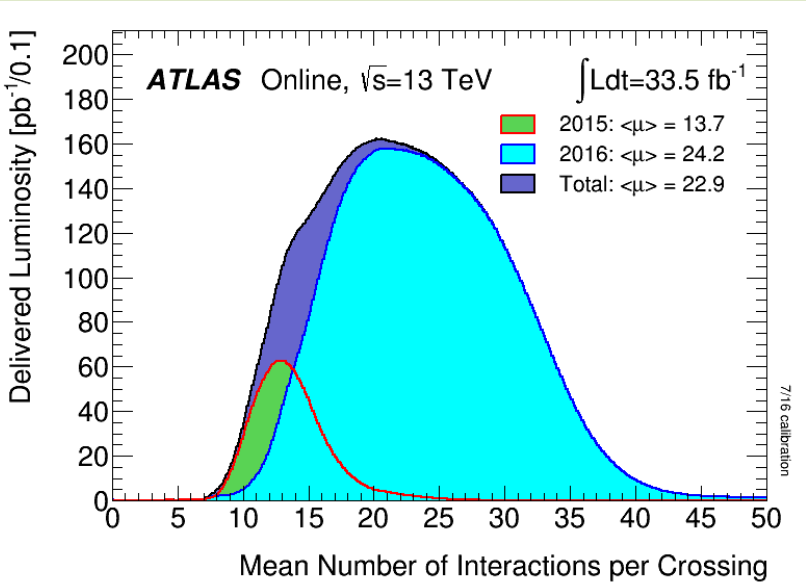
- **Instantaneous Luminosity** (Design Lumi = 10^{34} cm^{-2}s^{-1})



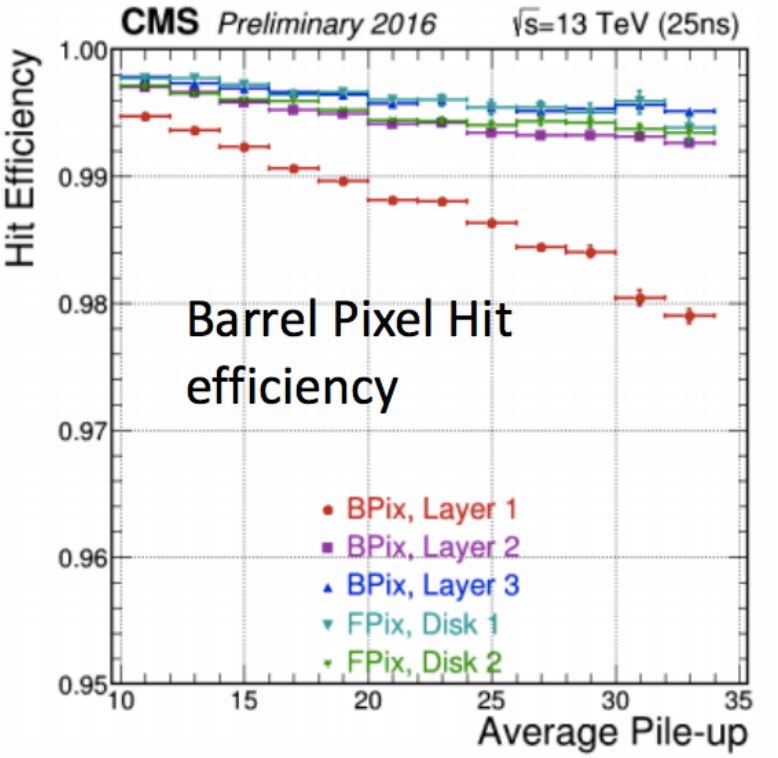


Pile-up events

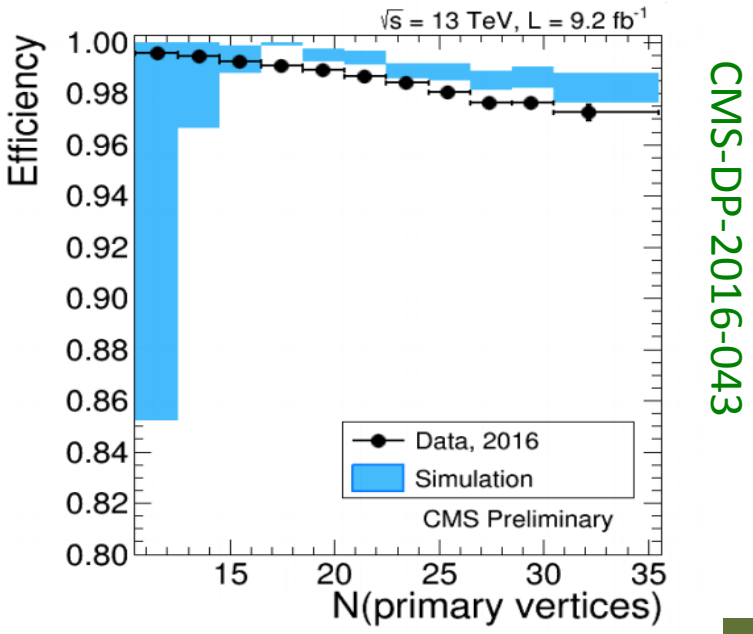
- **Challenge : high values for the mean number of pile-up events**



Pixel Hit Efficiency



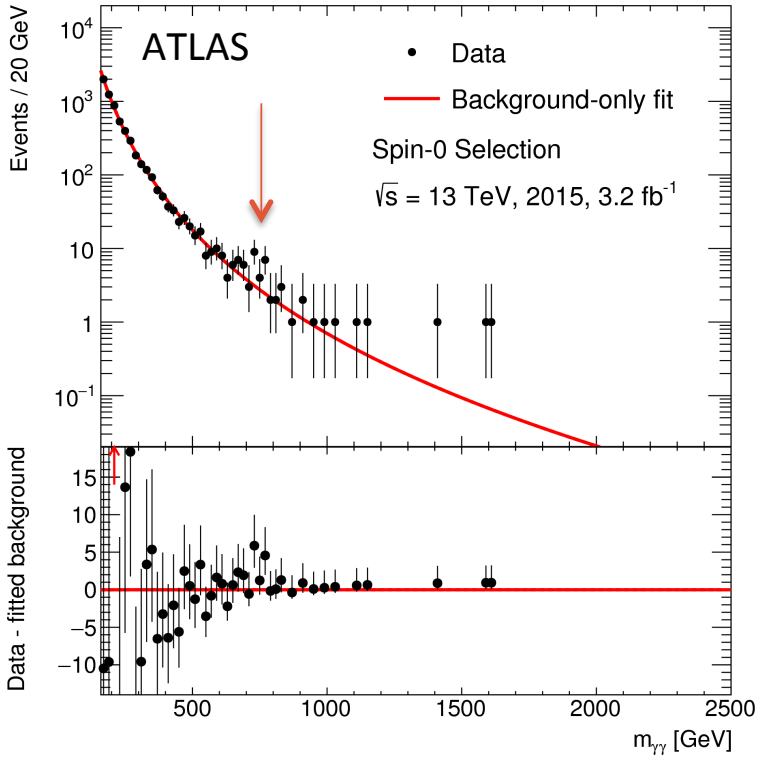
Muon reconstruction efficiency

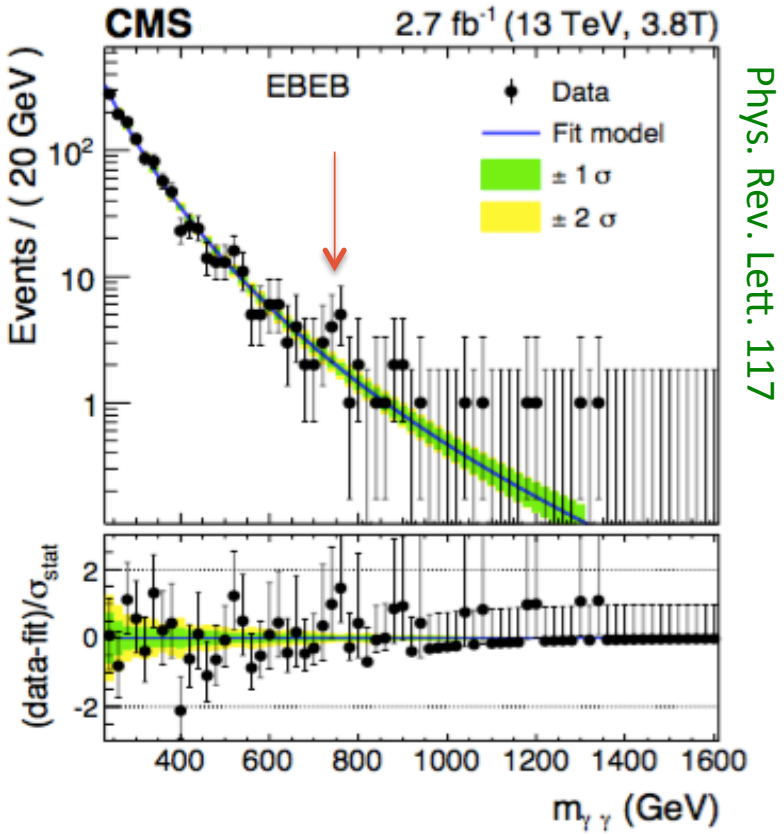


Di-photon story

- **γγ resonances at 750 GeV:** **2015 data** Mass resolution at 750 GeV < 1%

JHEP 09 (2016) 001





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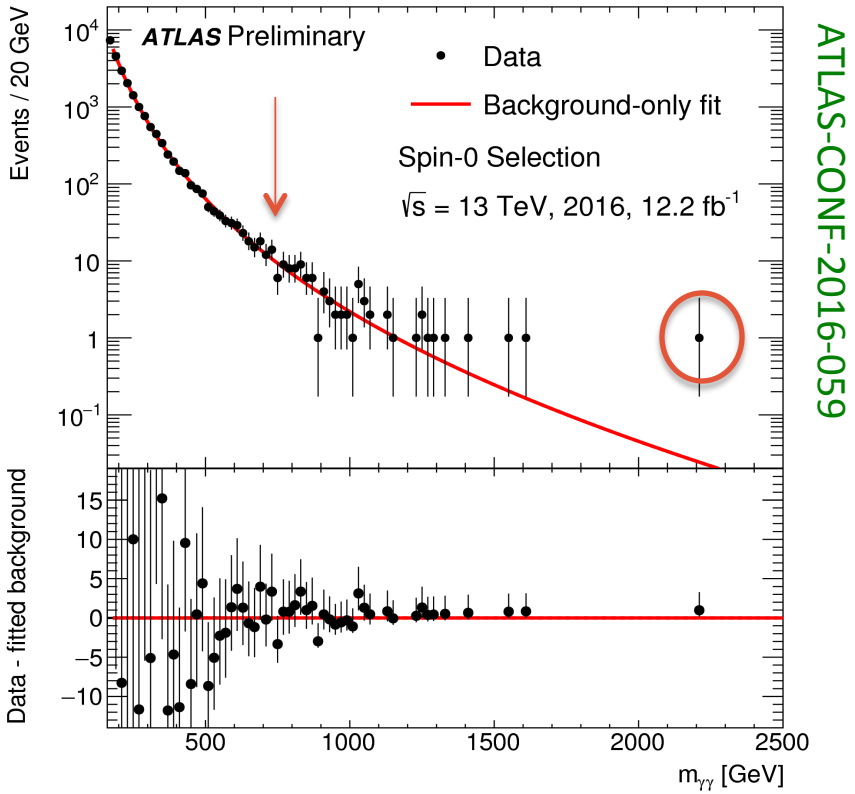
M= 750 GeV (Γ/M = 6%)
- 3.9σ (local); 2.1σ (global)
- 3.4σ (local); ~2σ (global) w/reprocessing

M= 760 GeV (Γ/M = 0.014)
- 2.9σ (local); 1σ (global)
- 3.4σ (local); >1.6σ (global) w/2015+8TeV

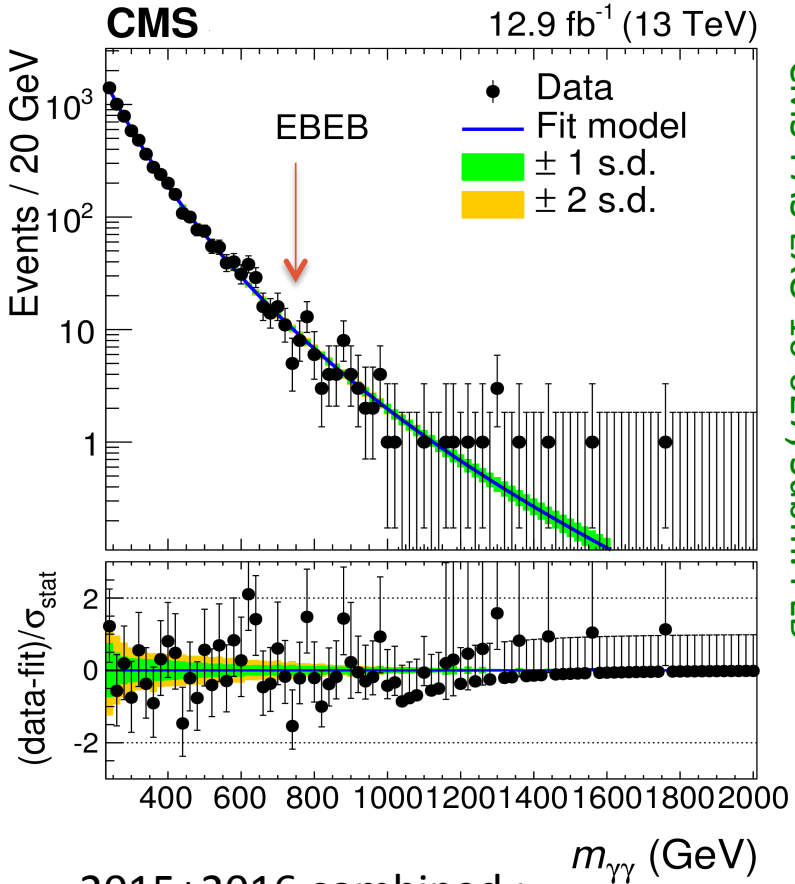
Di-photon story

- **γγ resonances at 750 GeV:** **2016 data**



ATLAS-CONF-2016-059

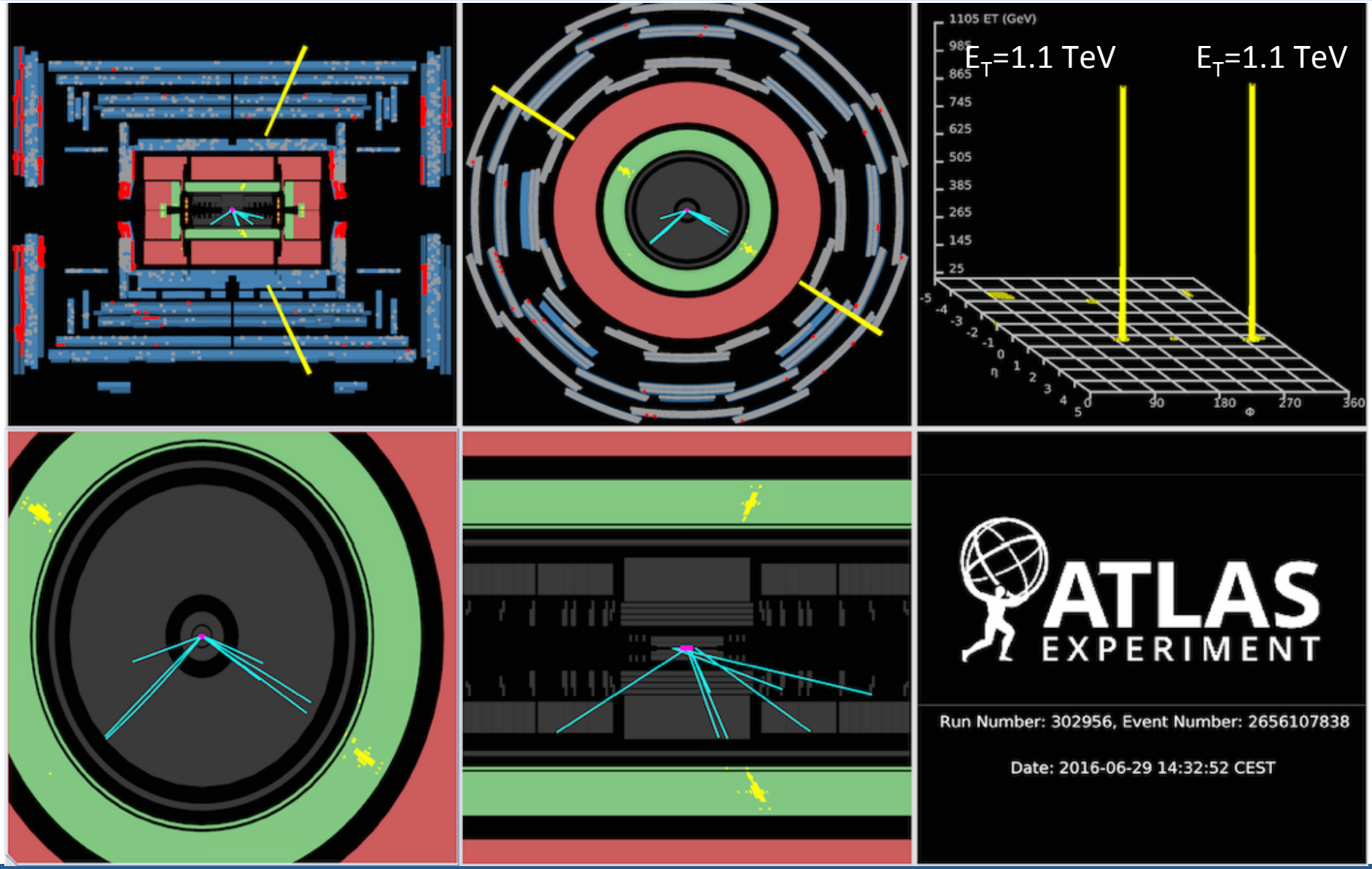
2015+2016 combined :
M= 710 GeV (Γ/M = 10%)
• 2.3σ (local); <1σ (global)



CMS-PAS-EXO-16-027, Subm. PLB

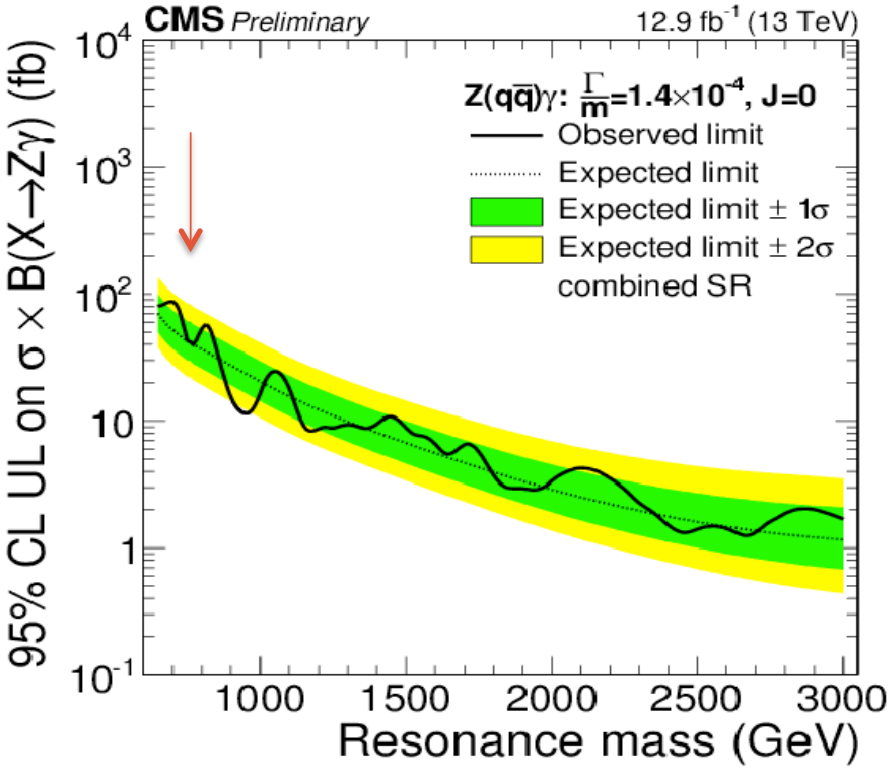
2015+2016 combined :
M= 760 GeV (Γ/M = 0.014)
• < 1σ (local)

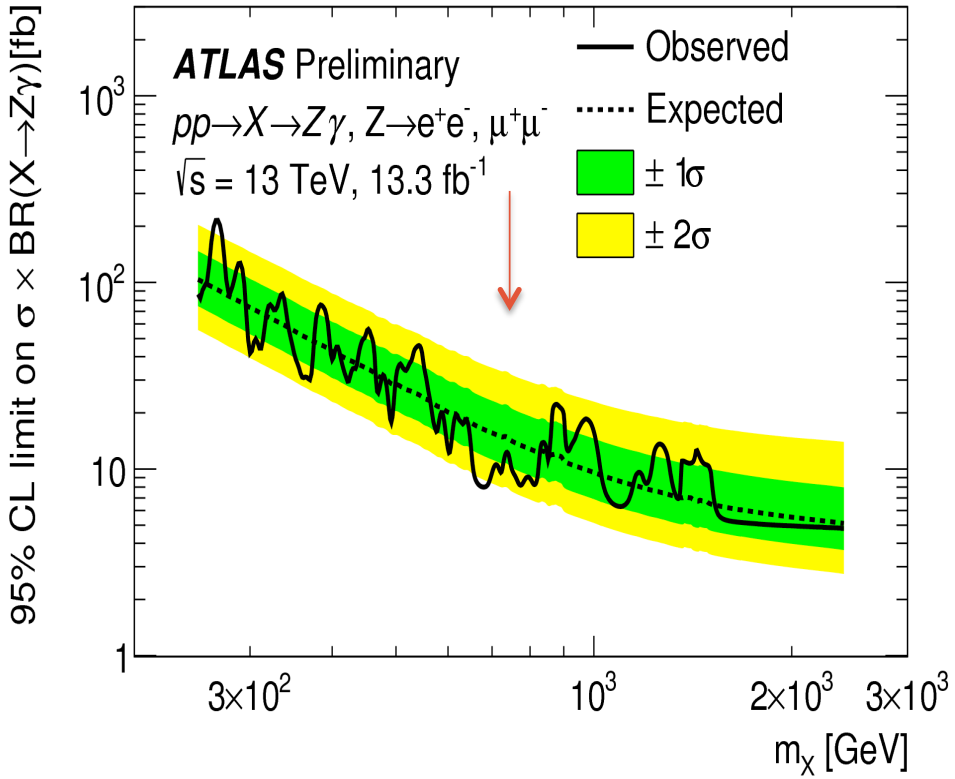
Heaviest diphoton mass event : 2.2 TeV



Zγ channel

- **Search for resonances in the Zγ channel : 2016 data**





→ No excess observed

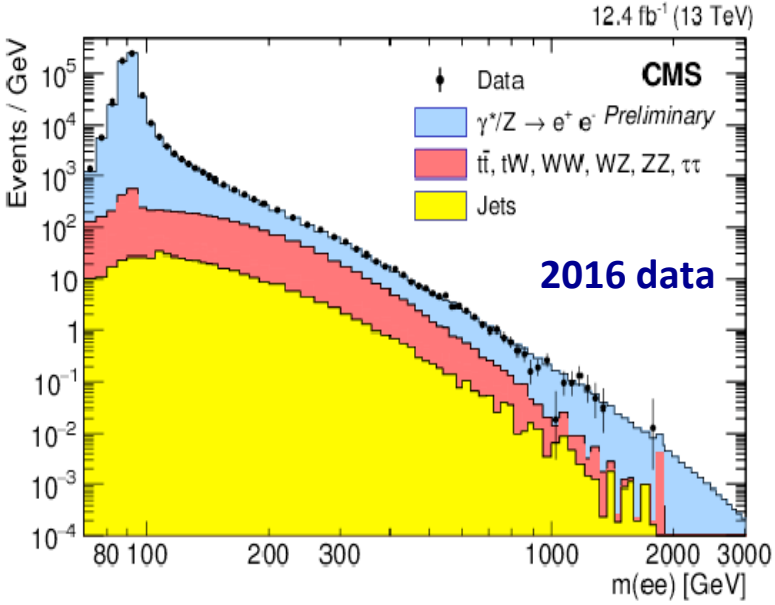
CMS-PAS-EXO-16-035
CMS-PAS-EXO-16-034

ATLAS-CONF-2016-044

Resonances : Dilepton

- **Same flavor opposite sign (ee, μμ, ττ)**

ATLAS-CONF-2016-045
CMS-PAS-EXO-16-031

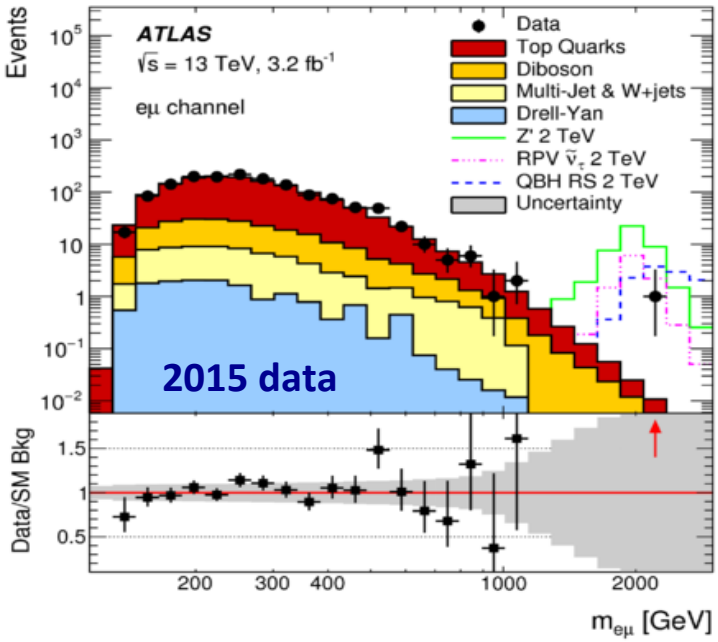


Z'_{ψ} (width = 0.5%) > 3.36 TeV
Z'_{SSM} (width = 3%) > 4.05 TeV

(2015 data only : Z'_{SSM} > 3.2 TeV)
(2012 data at 8 TeV : Z'_{SSM} > 2.9 TeV)

- **Lepton Flavor Violation (eμ, eτ, μτ)**

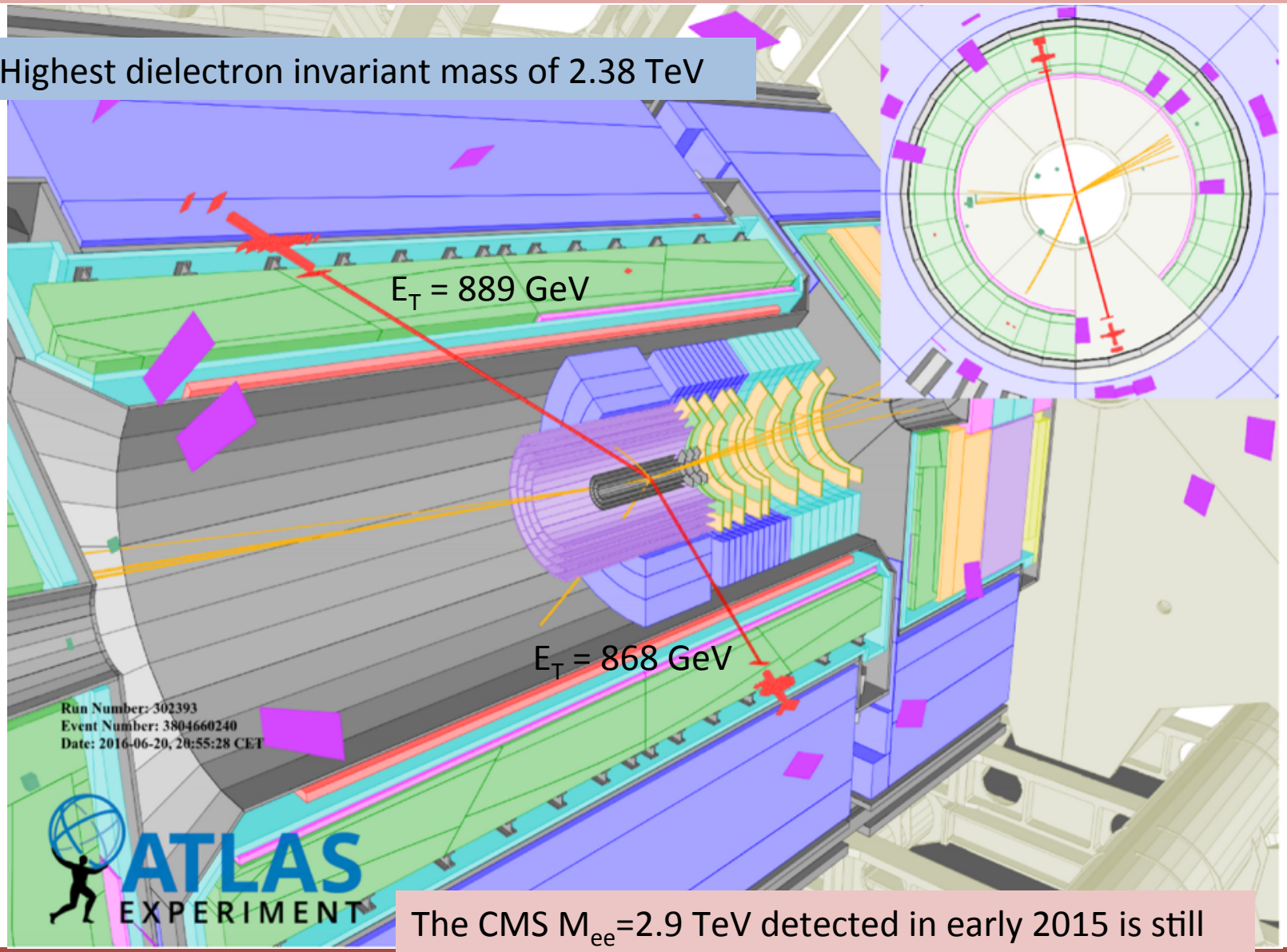
CMS-PAS-EXO-16-001
ATLAS : EPJC 76(2016)541



QBH(n=6)>4.5TeV
RPV($\lambda_{311}=\lambda_{132}=\lambda_{231}=0.2$)>3.3TeV

Resonances : Dilepton

ATLAS Highest dielectron invariant mass of 2.38 TeV

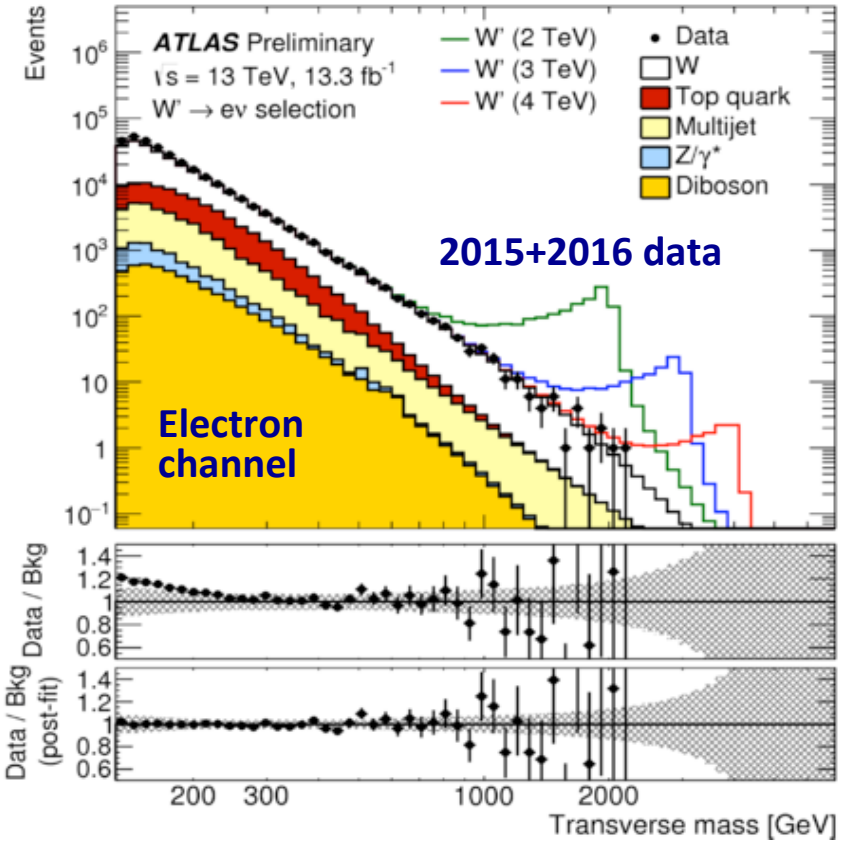


The CMS M_{ee}=2.9 TeV detected in early 2015 is still the highest dilepton mass event observed at 13 TeV

Resonances : lepton+MET

- **W' → e + MET, μ + MET**

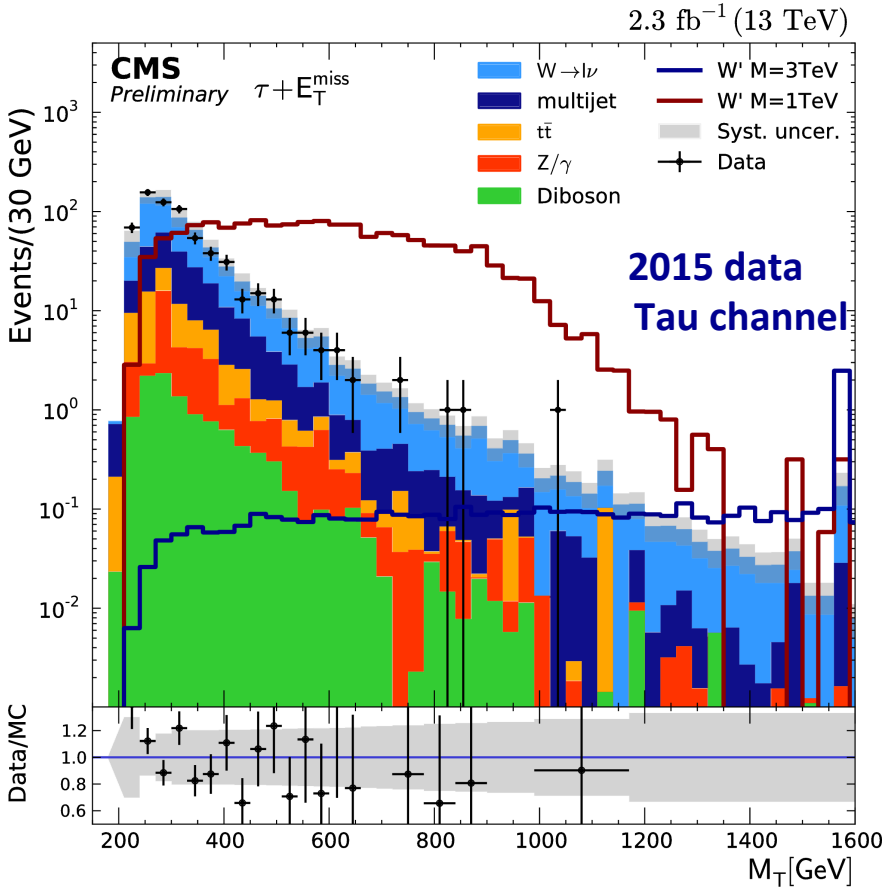
ATLAS-CONF-2016-061
CMS-PAS-EXO-15-006



W'_{SSM} > 4.74 TeV

- **W' → τ + MET**

CMS-PAS-EXO-16-006



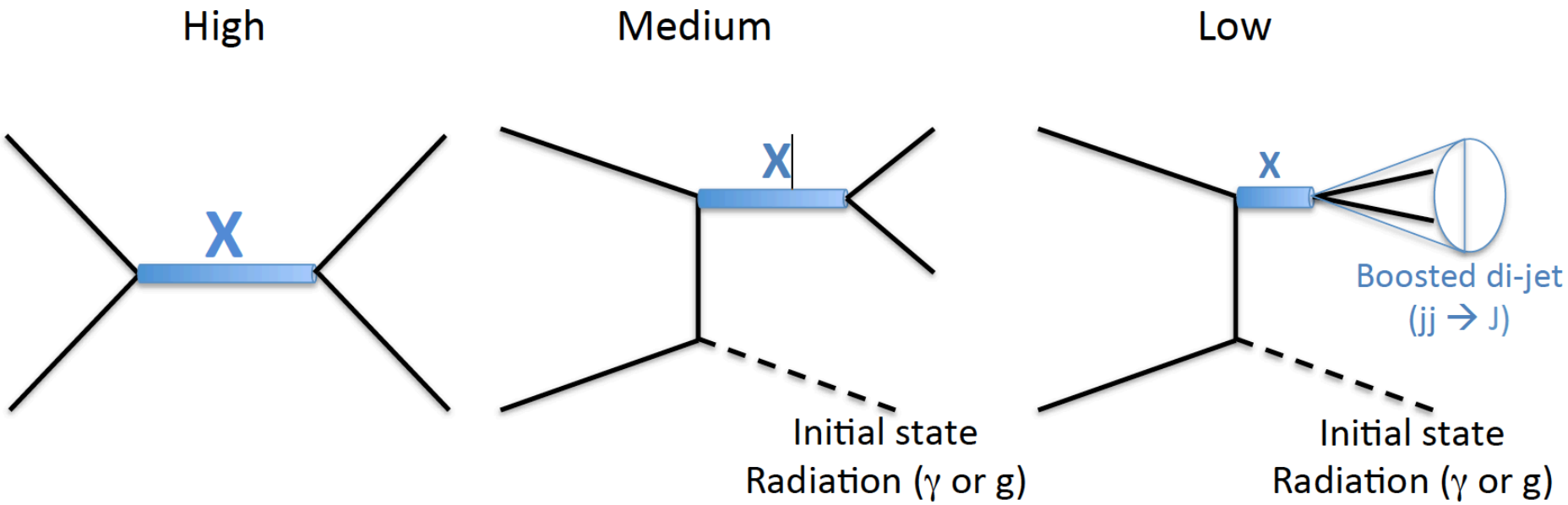
W'_{SSM} > 3.3 TeV

Resonances : di-jets

- **Develop techniques to optimise the searches :**

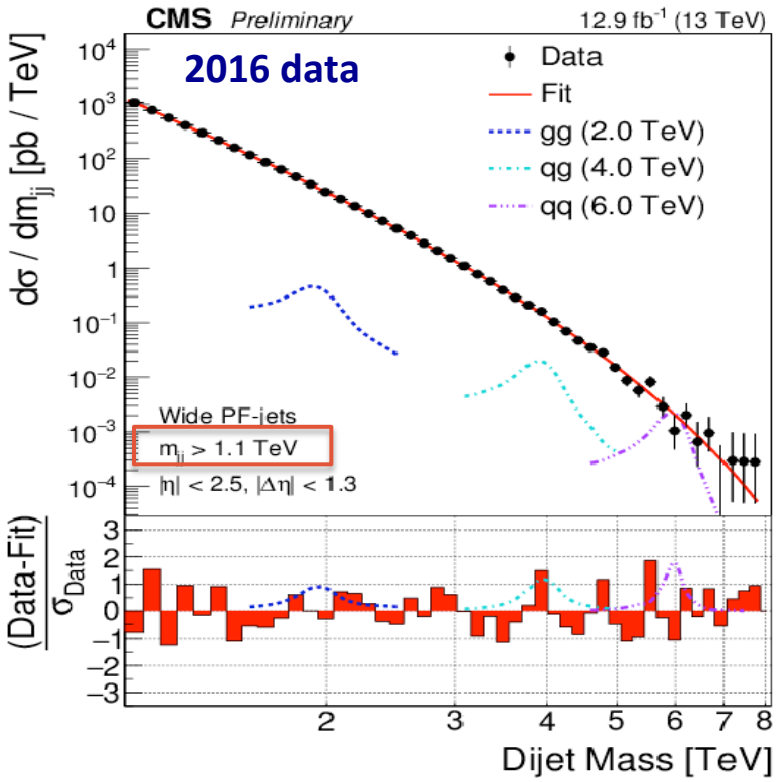
At high dijet mass :
use standard triggers

At medium/low dijet mass :
use data scouting at trigger level
or dijet + ISR (g or γ)



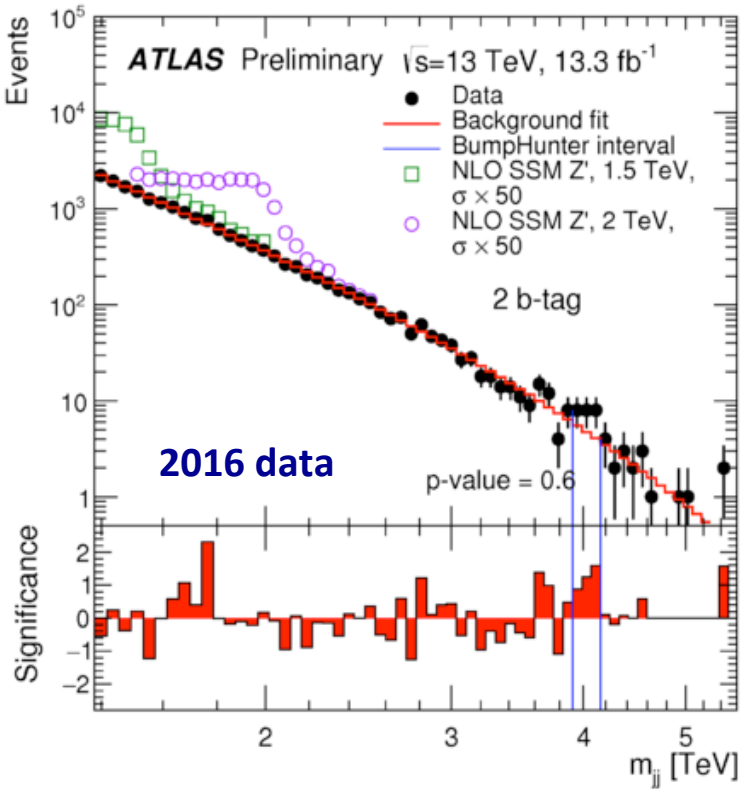
Di-jets at high mass

- **Dijet : qq, qg, gg**



CMS-PAS-EXO-16-032
ATLAS-CONF-2016-069

- **Dijet : bb**



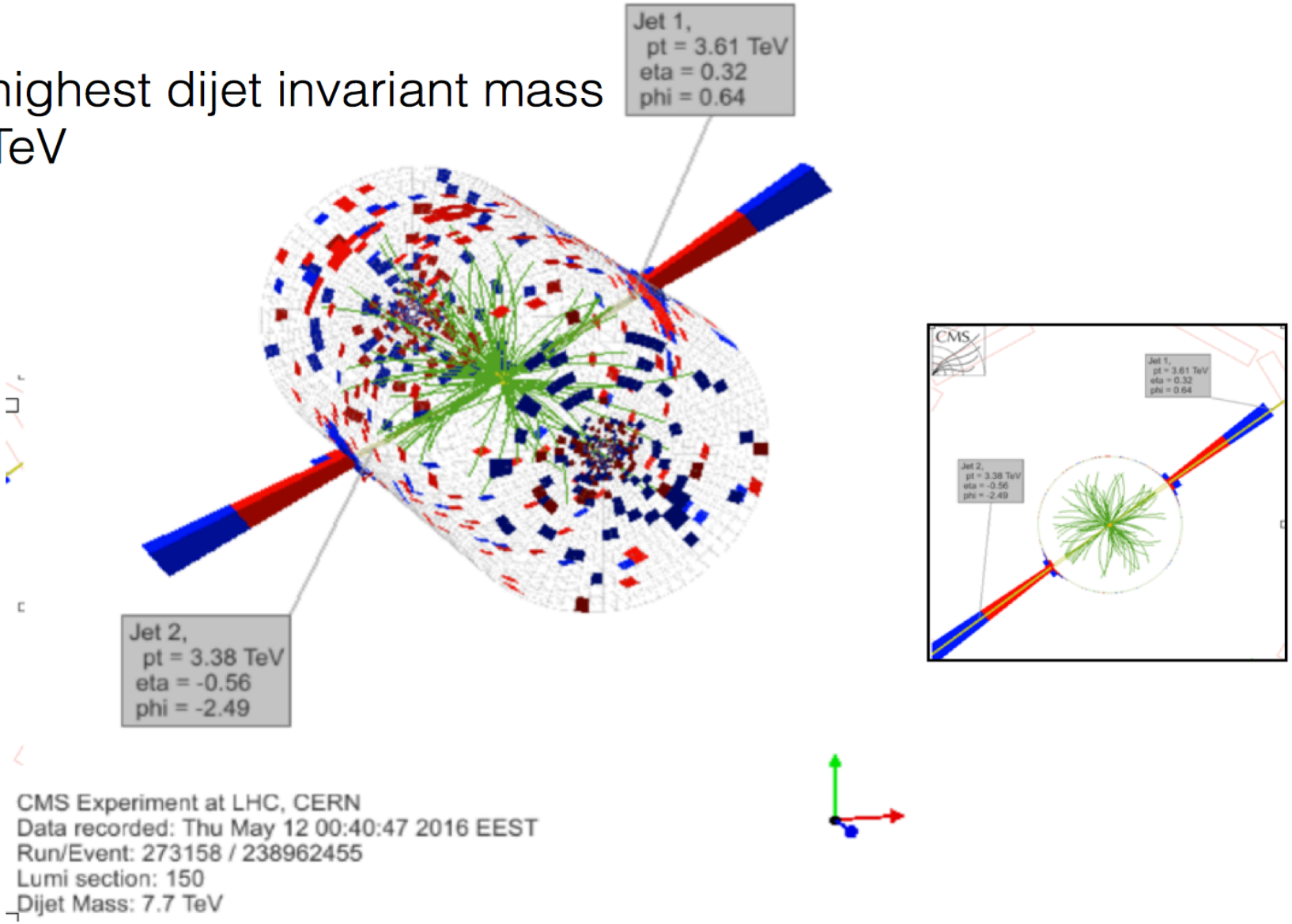
ATLAS-CONF-2016-060

Z' > 1.5 TeV

Model	Limit (TeV)	Model	Limit (TeV)
QBH	8.7	String	7.4
q*	5.6	Axigluon	5.5
W'	2.9	Z'	2.1
CI (η_{LL}=+1)	12.6	RS G	1.9

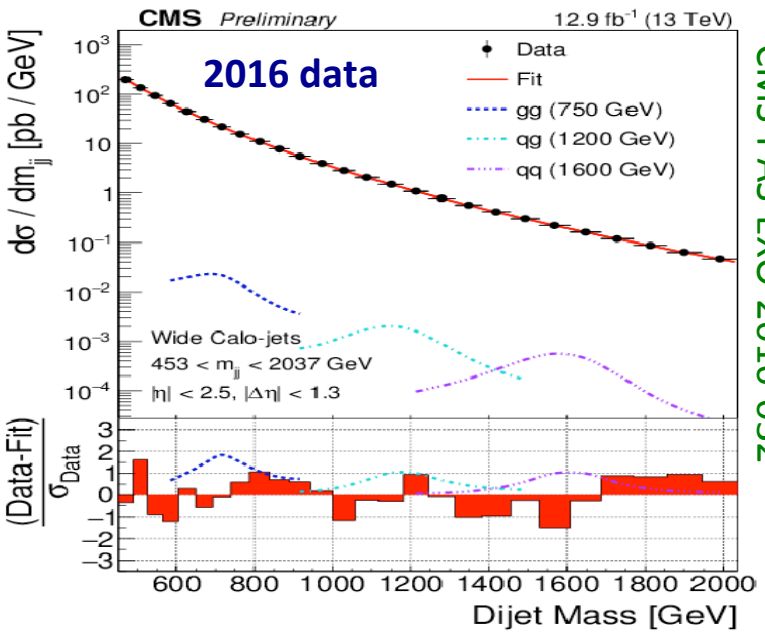
Di-jets

the highest dijet invariant mass
7.7 TeV



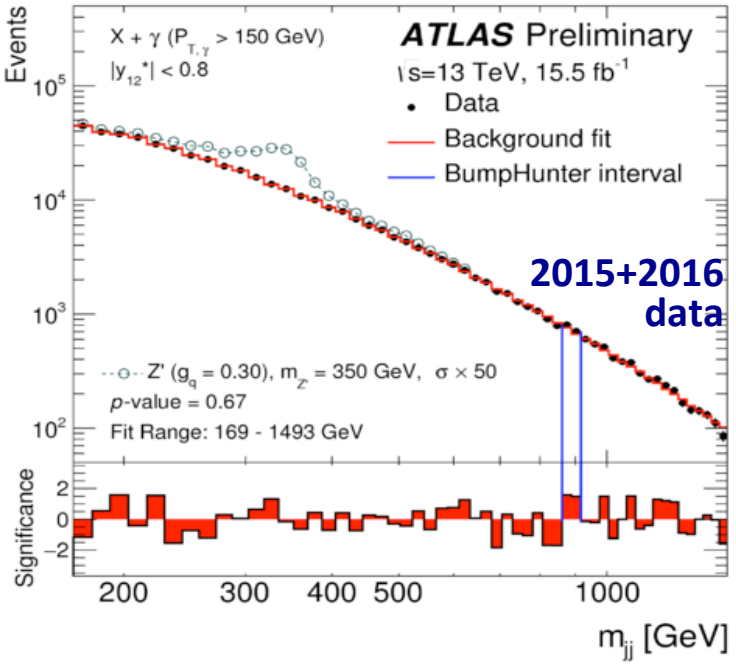
Di-jets at “low” mass

- **Data scouting**



ATLAS-CONF-2016-030
CMS-PAS-EXO-2016-032

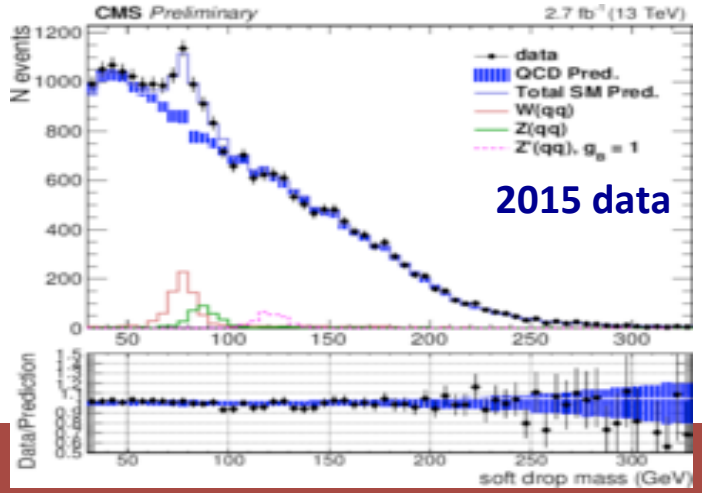
- **Dijet + ISR**



ATLAS-CONF-2016-070
ATLAS-CONF-2016-029

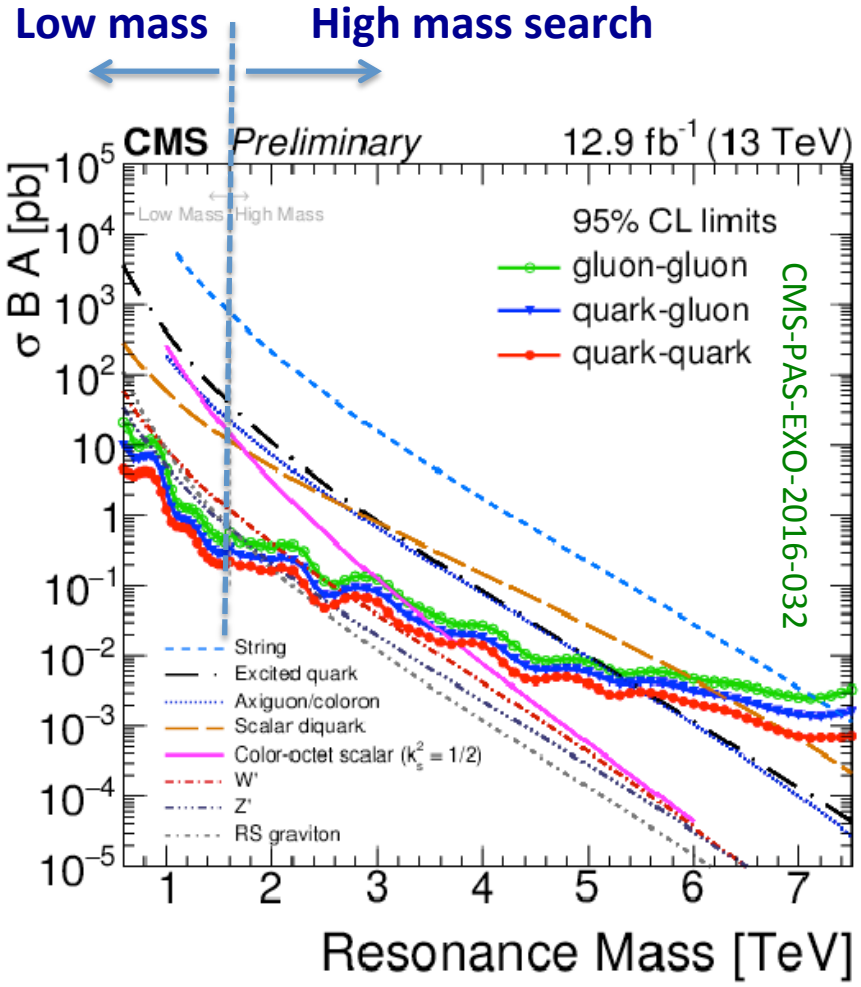
- **Dijet + ISR**
  boosted jet : jj->J

Probe mass as low as 100 GeV

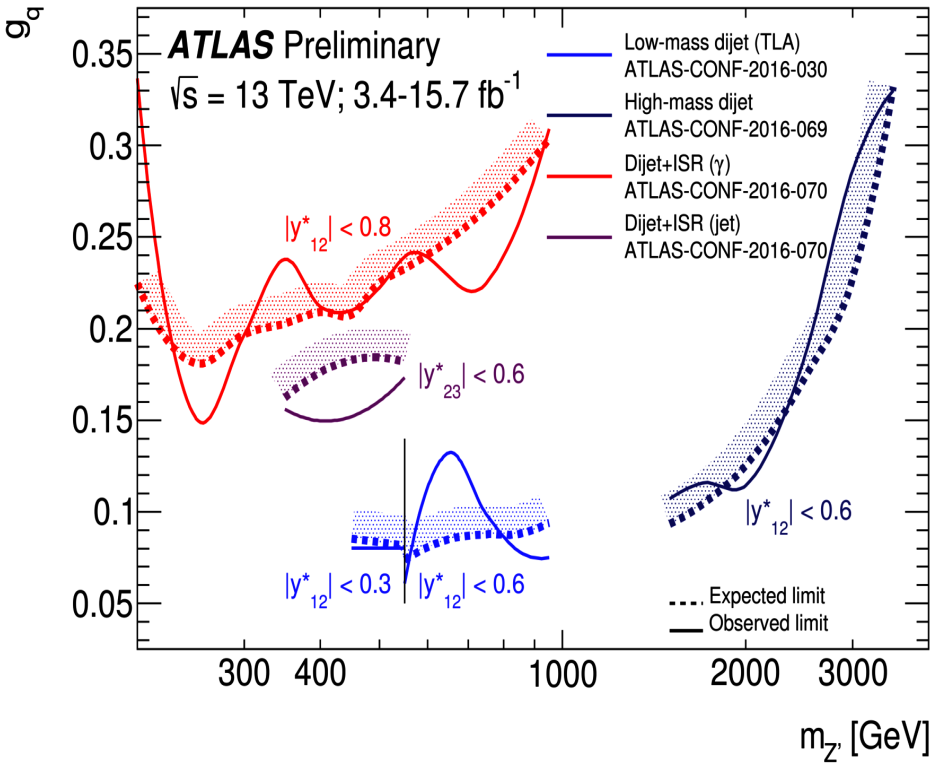


CMS-PAS-EXO-2016-030

Di-jets summary



- **Interpretation for the leptophobic Z' model**
  g_q : quark coupling



Diboson signatures

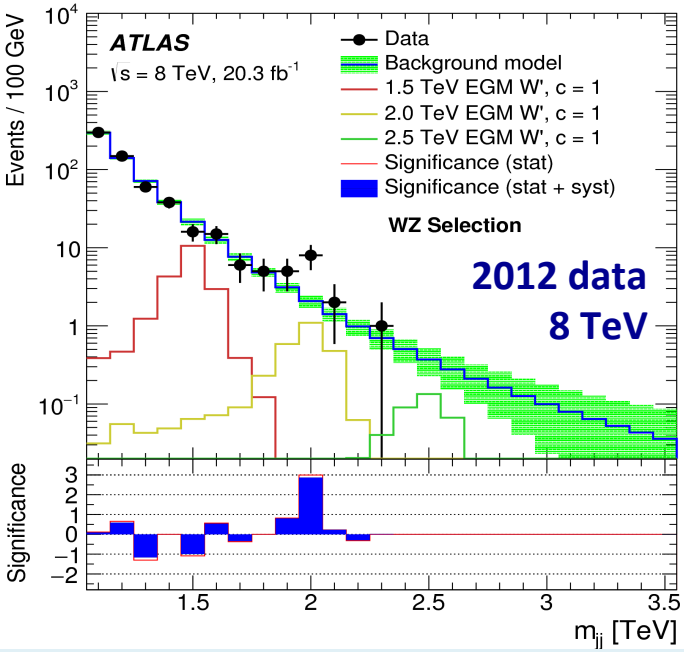
Search for VV, Vγ, (VH, HH) resonances (V=W,Z)

In leptonic/hadronic decay channels using large-R jets with jet substructure techniques

Example of models :
Spin 0 : Heavy scalars in the extended Higgs sector: H->WW, ZZ
Spin 1 : Heavy Vector Triplet (HVT): W' -> WZ, Z' ->WW
Spin 2 : "Bulk" Randall-Sundrum (RS) Graviton: G* ->WW,ZZ

- **Search for VV in the all hadronic channel :**

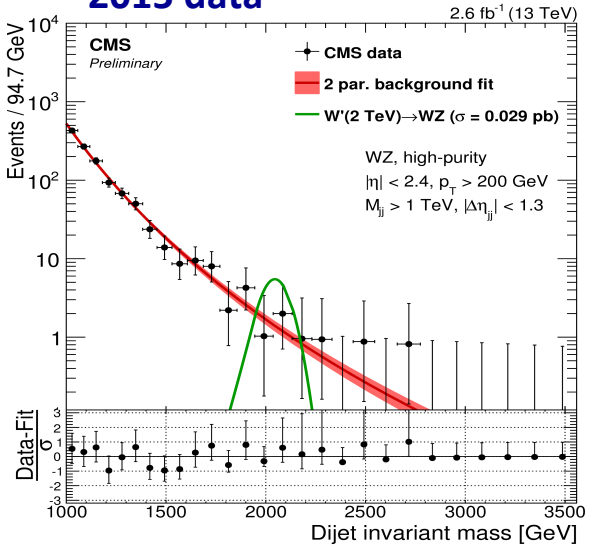
8 TeV excess :



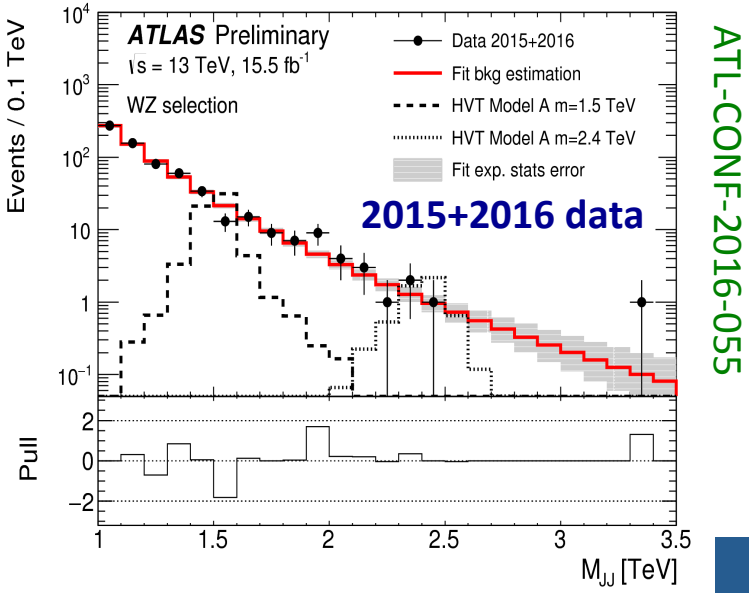
JHEP12(2015)055

M(jj)= 2 TeV : 3.4σ (local), 2.5σ (global)

2015 data



CMS-PAS-EXO-2015-002



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Diboson signatures

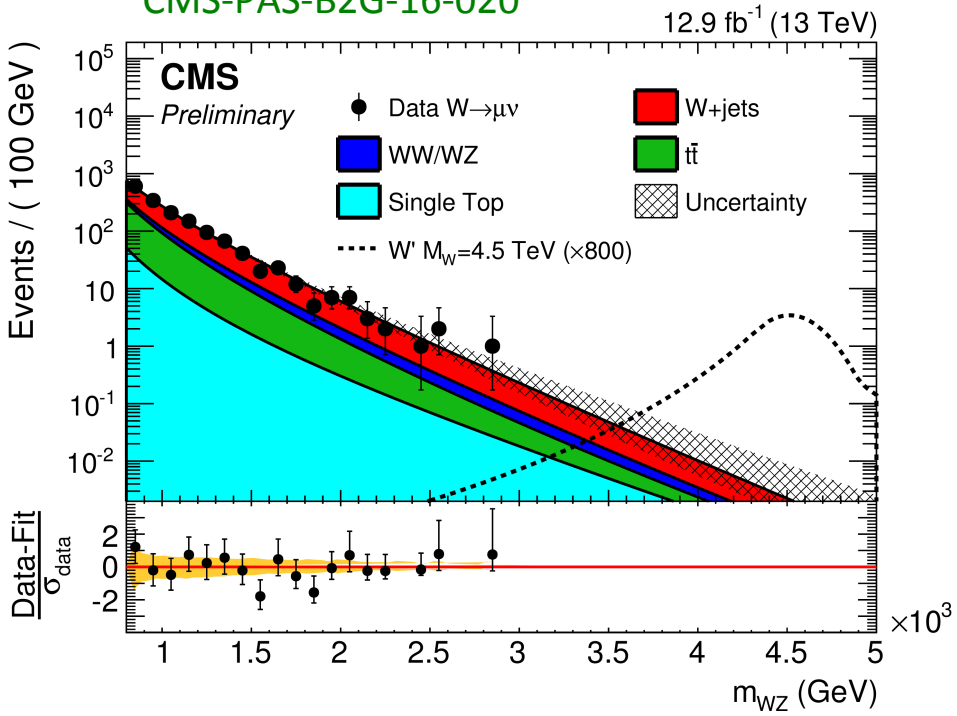
- **Search for VV in the semi-leptonic channels :**
  Boosted V-tagging used

ZV : Z⟶ ll + V⟶ qq

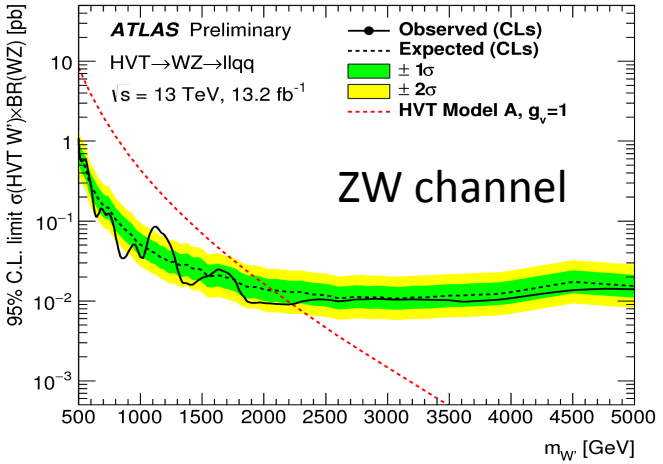
WV : W⟶ lν + V⟶ qq

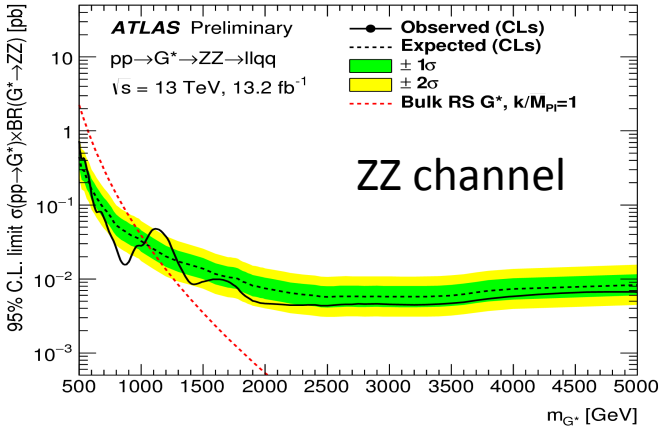
CMS-PAS-B2G-16-020

2016 data



2015+2016 data





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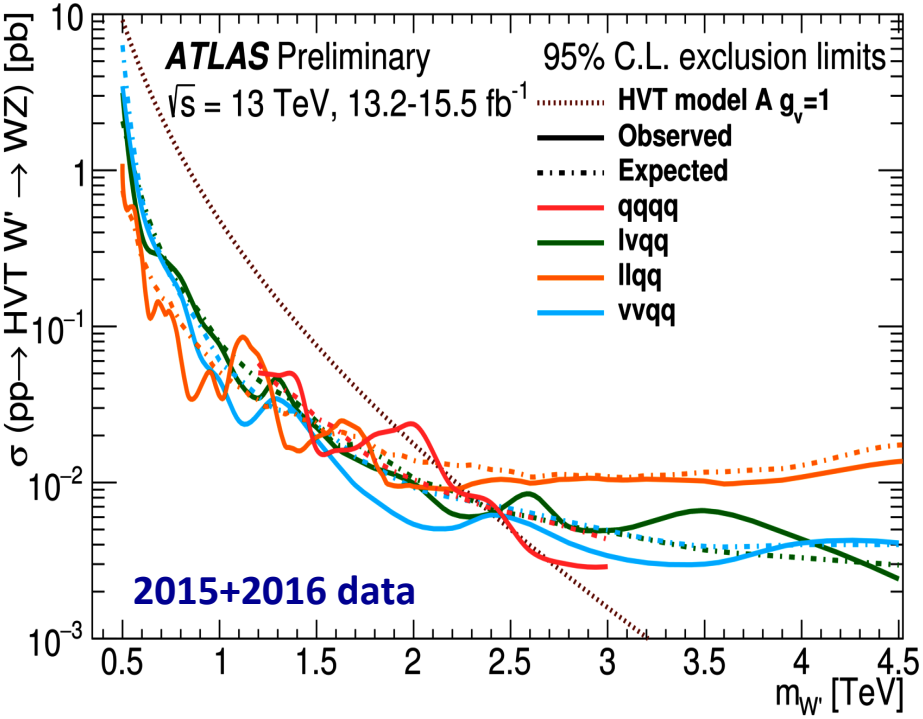
Interpretation: Bulk graviton ⟶ WW
HVT W' ⟶ WZ

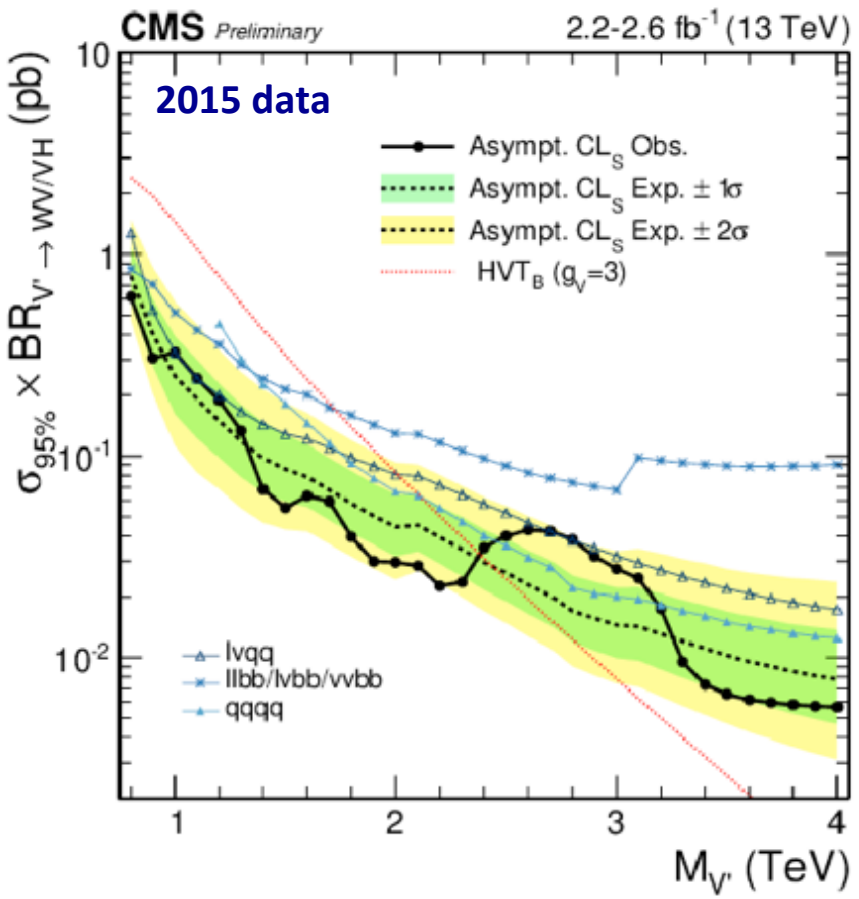
Diboson signatures

Overlaying limits from all WZ searches, no persistent excesses



Model	Limit (TeV)
RS Graviton	2.0
HVT W’	2.4

joint interpretation of VV/Vh channels



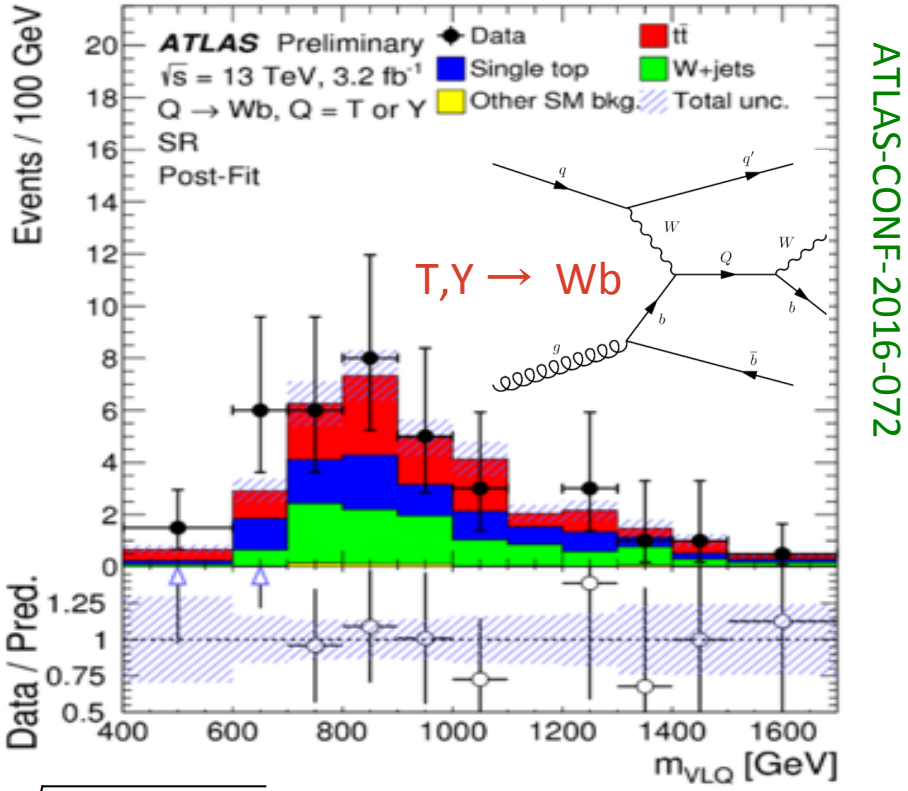
Vector Like Quark (VLQ)

VLQ in composite H theories: T → Ht, Zt, Wb, and B→ Hb, Zb, Wt

VLQ : spin 1/2, colored, charged particles with both LH & RH coupling to charged currents

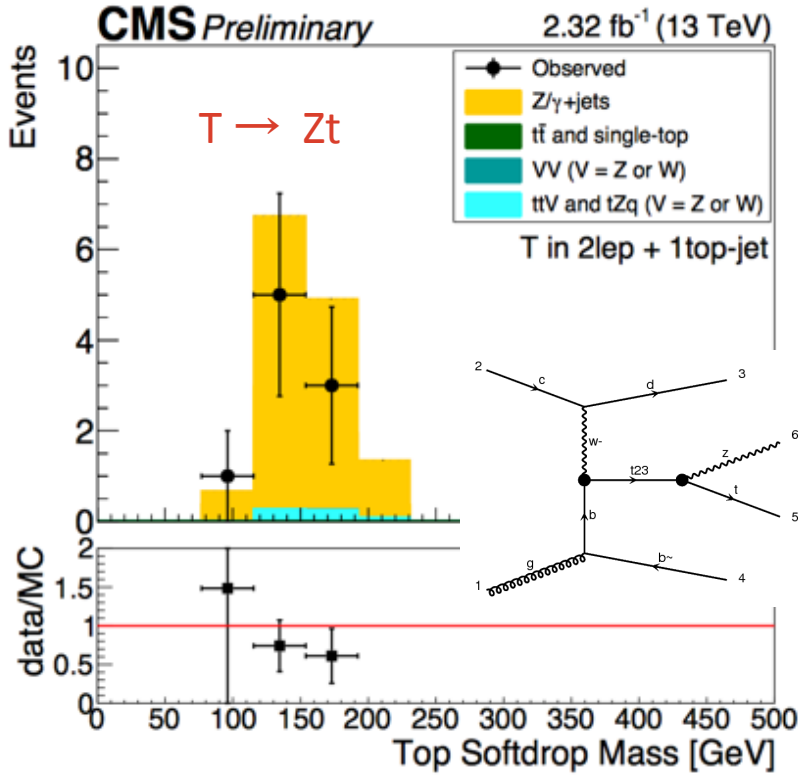
- **Single production through EWK coupling - dominant in high mass (model dependent) :**

T : |Q| =2/3 Y : |Q| =4/3



ATLAS-CONF-2016-072

$\sqrt{(c_L^{Wb})^2 + (c_R^{Wb})^2} = 1/\sqrt{2}$ → m(T/Y) >1.44 TeV



CMS-PAS-B2G-16-001

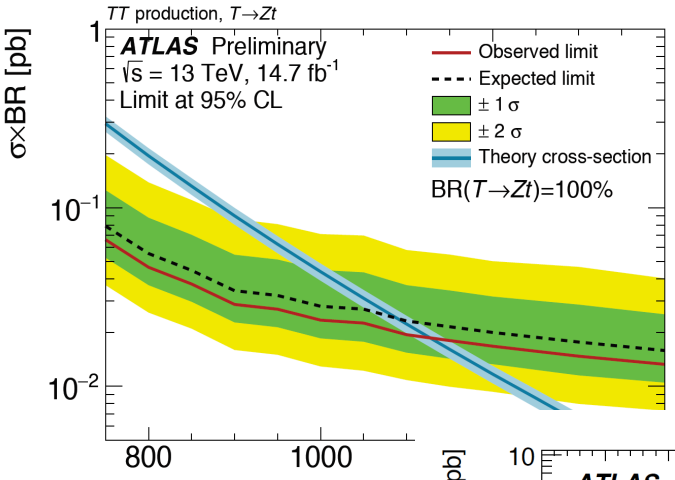
BR(Zt)=0.25, C(Wb)=1 → m(T)>1.37 TeV

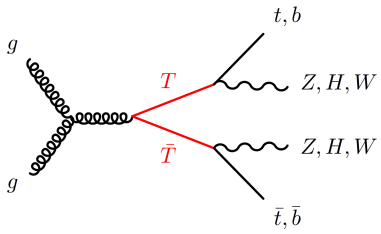
Vector Like Quark (VLQ)

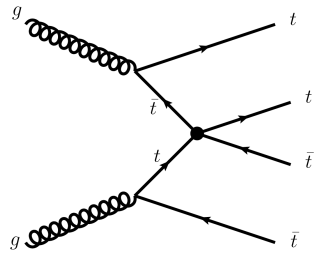
VLQ in composite H theories: T⟶ Ht,Zt,Wb, B⟶ Hb,Zb,Wt

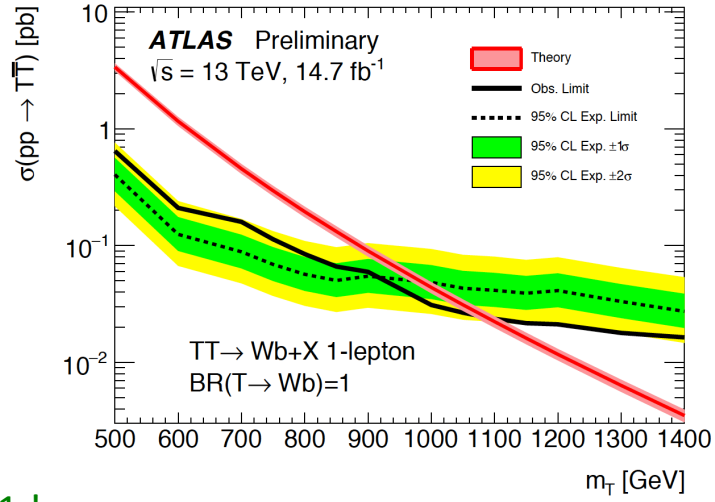
VLQ : spin 1/2, colored, charged particles with both LH & RH coupling to charged currents

- **Pair production through QCD - dominant in low mass :**

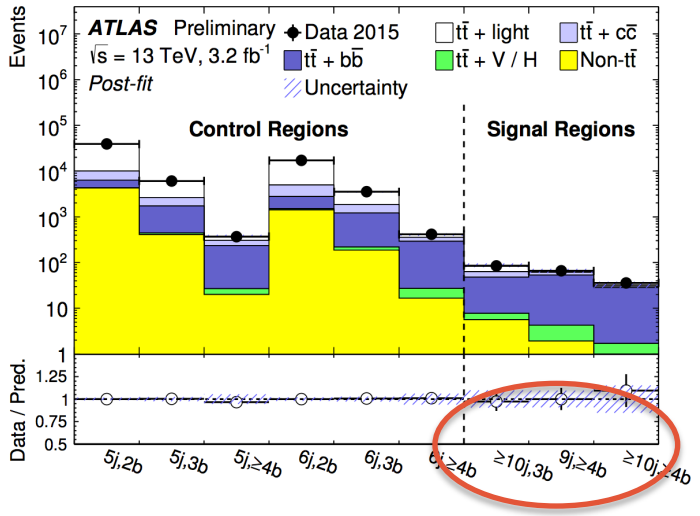








>9 jets and > 3b-jets, high H_T



ATLAS-CONF-2016-020

ATLAS-CONF-2016-101 !

ATLAS-CONF-2016-102 !

Search for long lived particles

Search for unconventional signatures :

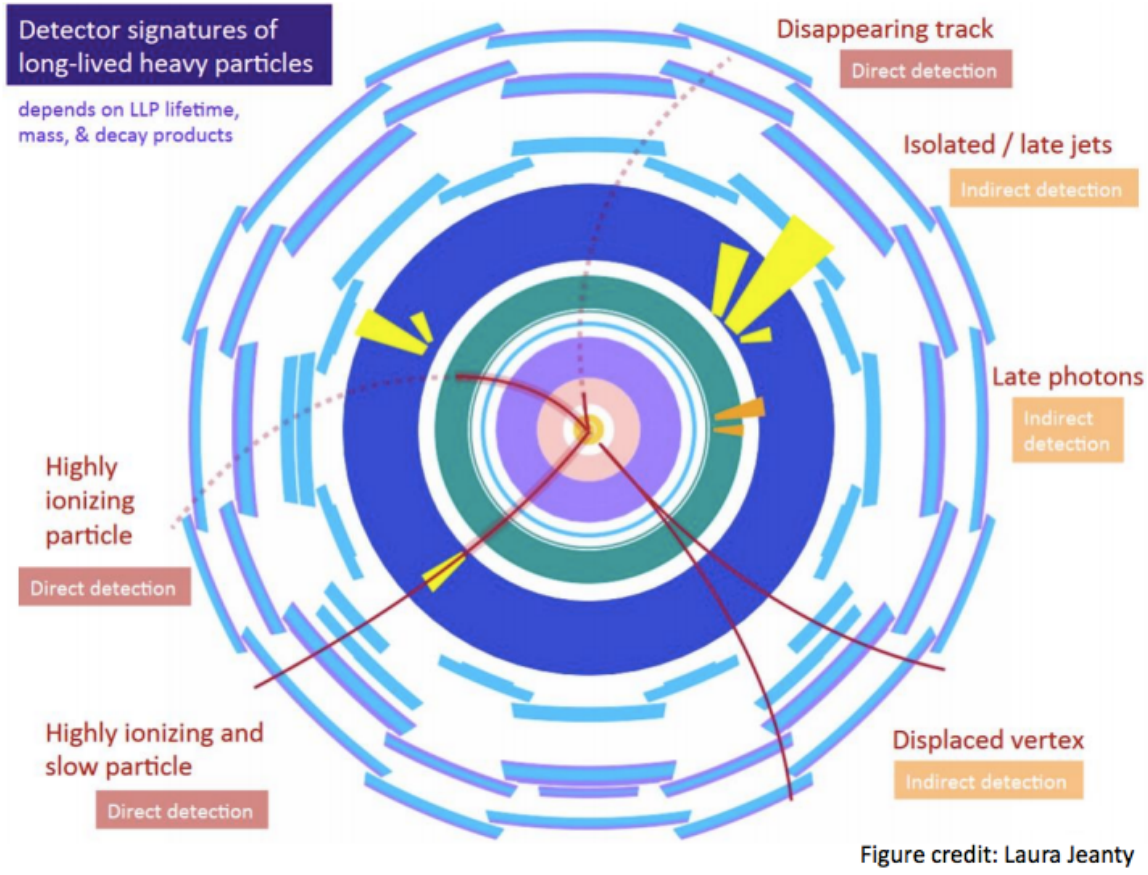


Figure credit: Laura Jeanty

- "Long-lived" = decays within or outside of the detector volume
- LLPs : in a variety of models:
  - Split/RPV/Stealth SUSY
  - Exotic Higgs
  - Hidden Valley, etc.
- LLP signatures tend to be unusual and require dedicated searches & reconstruction algorithms

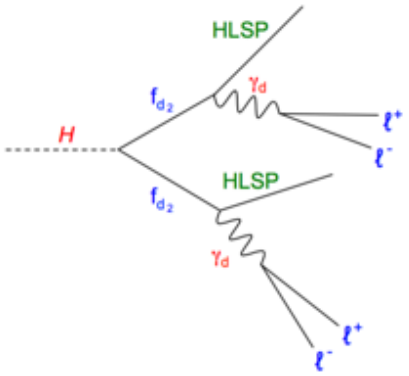
Results include :

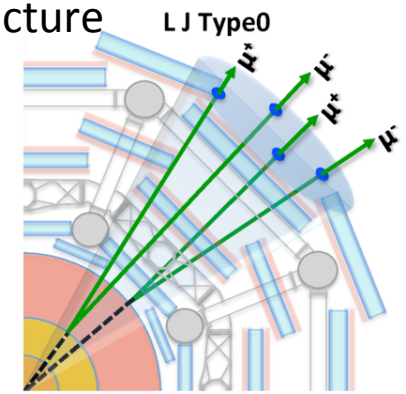
- Displaced photons
- Disappearing tracks
- Displaced leptons (eμ)
- Heavy stable charged particles

Long lived particles

- **Displaced "lepton-jet"**

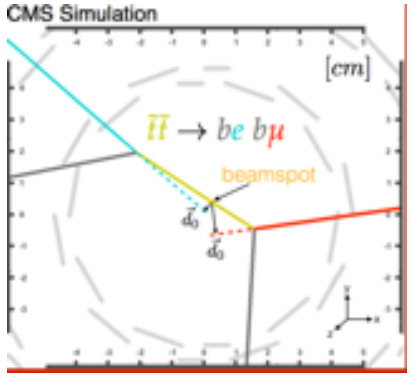
Collimated jet-like structure containing e/μ/π

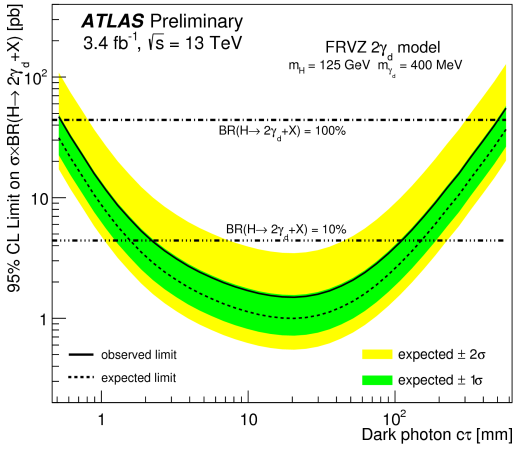




- **Displaced e-μ pair**

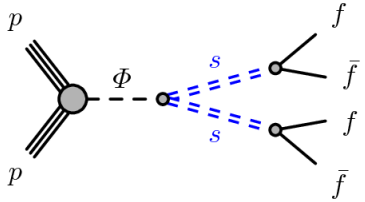
Large transverse Impact parameter

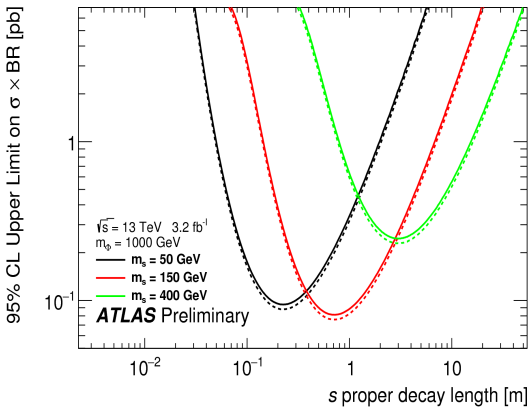




ATLAS-CONF-2016-042

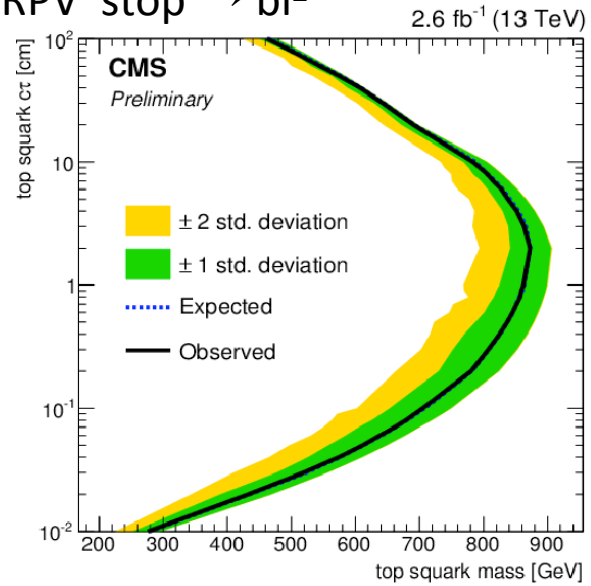
- **Displaced jet**





ATLAS-CONF-2016-103 !

RPV stop ⟶ bl±

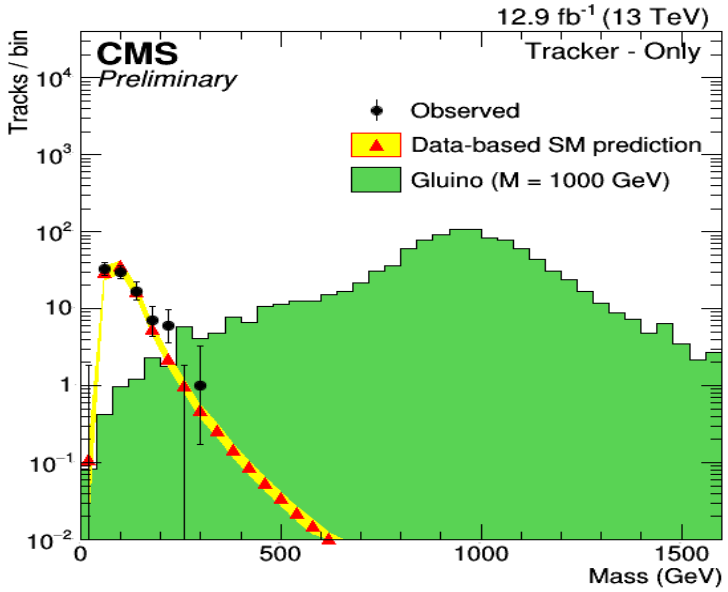


CMS-PAS-EXO-16-022

Heavy stable charged particles

Distinctive signatures of large dE/dx and long time-of flight
Two analyses : track reconstructed (i) tracker-only; (ii) tracker + muon chambers
Trigger : muon (pt>50 GeV) or MET>170 GeV

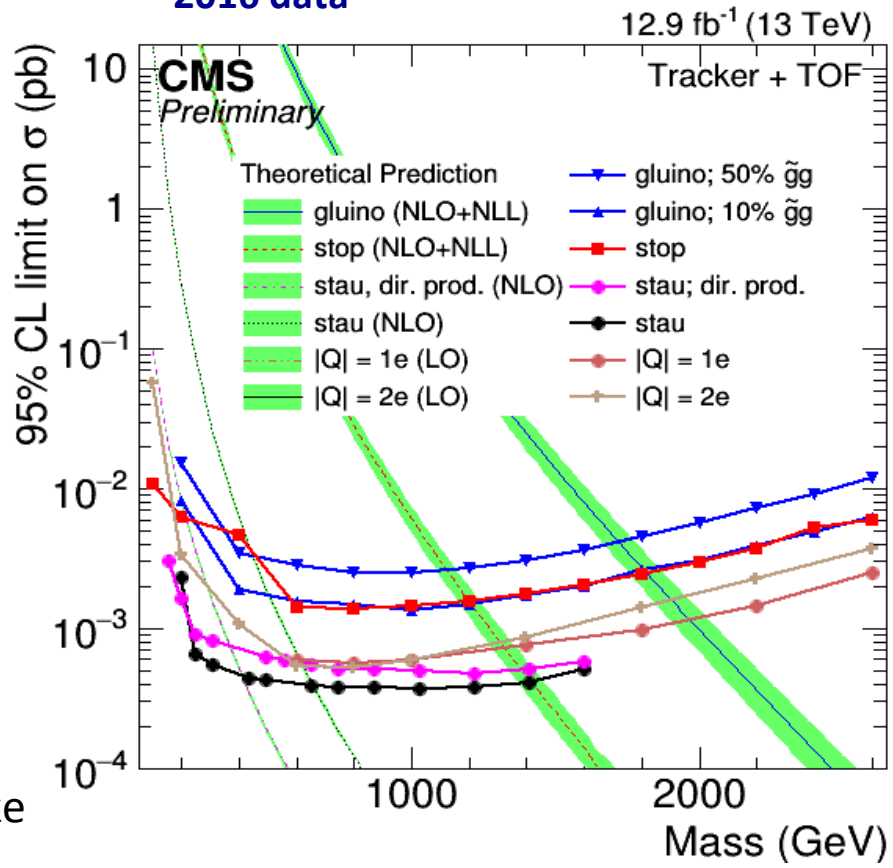
CMS-PAS-EXO-16-036



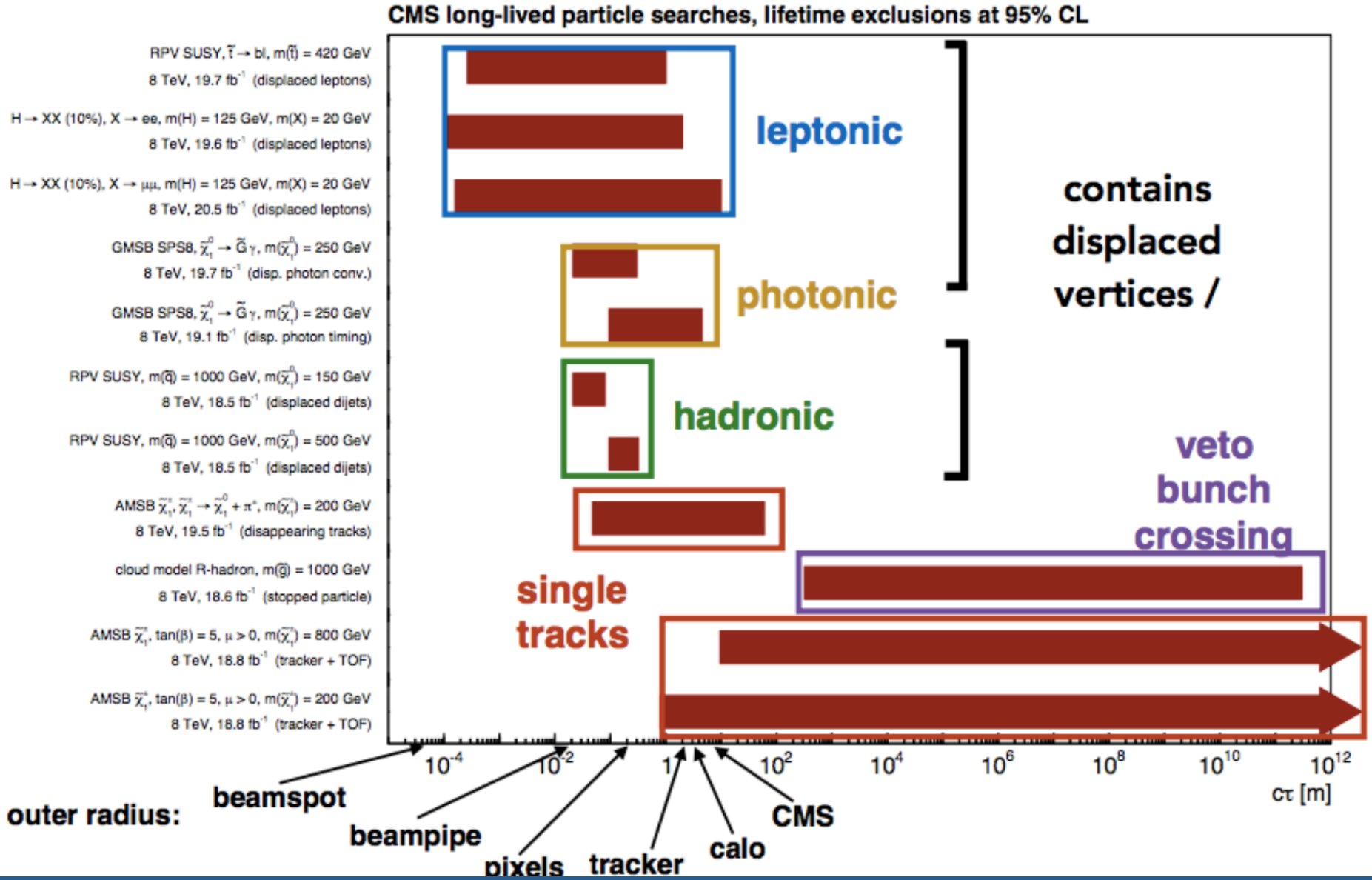
Constraints on HSCP benchmark models :

- gluino and stop1 pair production from split SUSY (R-hadrons)
- stau1 from mGMSB model
- Drell-Yan production of long-lived lepton-like fermions |Q|=1 and |Q|=2

2016 data



Long lived particles



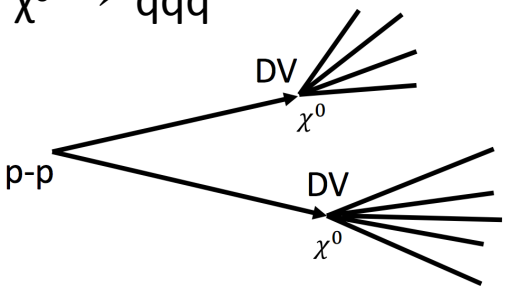
BSM searches at LHCb

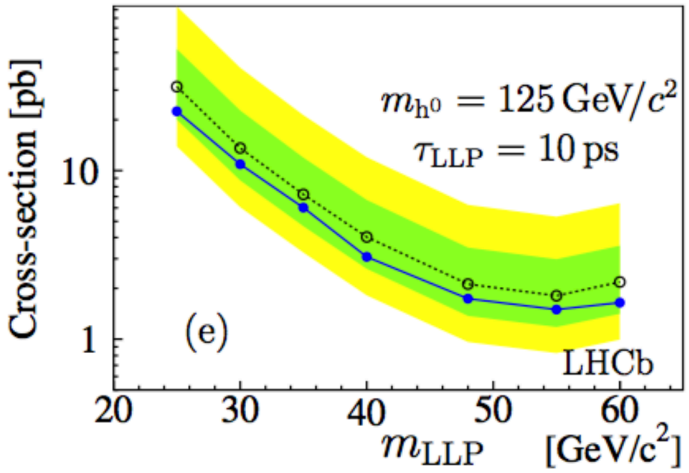
LHCb active in BSM searches :
- Complementary region with respect to ATLAS and CMS
- Very good displaced vertex reconstruction
- Good particle identification
- Powerful heavy jet tagging

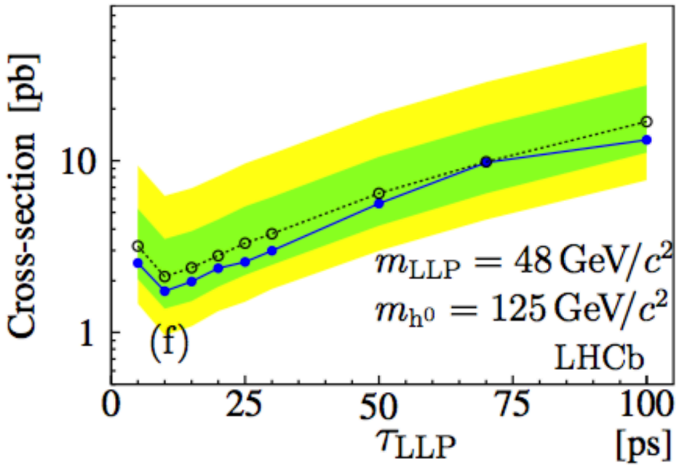
- **Search for higgs-like bosons decaying into long-lived particles (LLP)**

  Channel considered : $h^0 \rightarrow \chi^0\chi^0$ with χ^0 being the LLP $\chi^0 \rightarrow qqq$

  Benchmark model : MSSM mSUGRA with baryon number violation
  - H mass particle from 80 GeV to 140 GeV
  - $\tau(LLP)$ = 5−100 ps (up to 30 cm flight distance)
  - $M(LLP)$ = 20 − 60 GeV





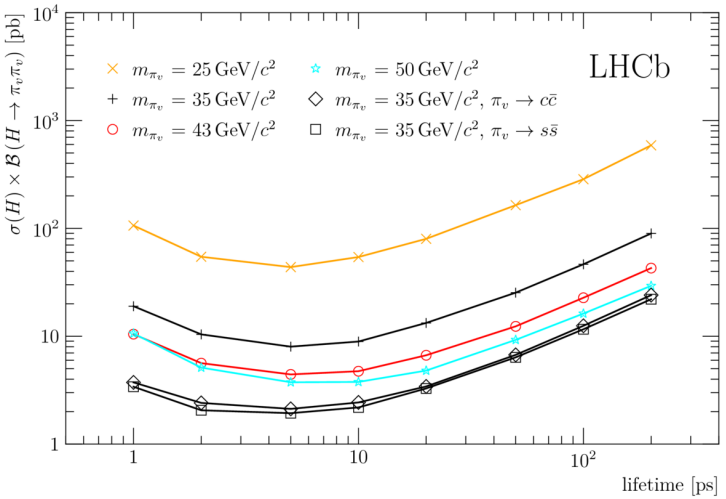


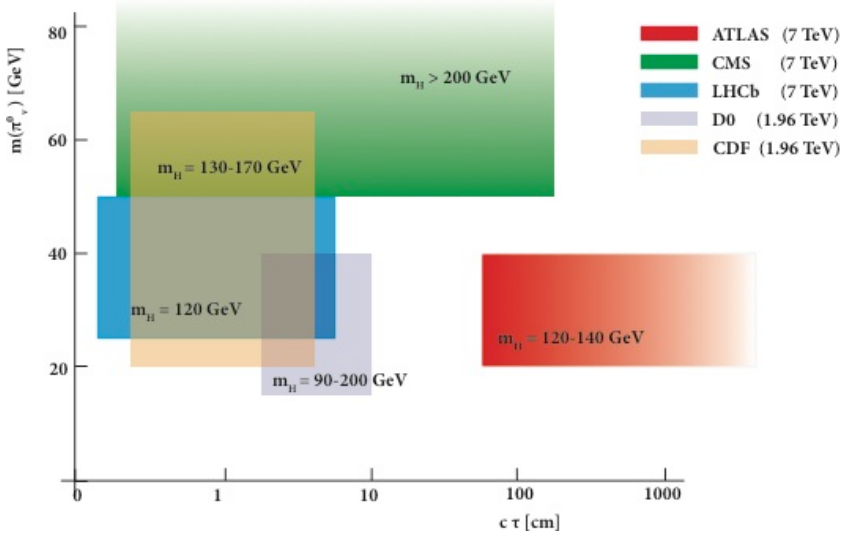
arXiv:1609.03124, subm. to EPJC

BSM searches at LHCb

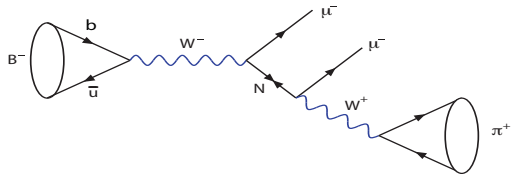
- **Search for long lived particles decaying to jet pairs**

EPJC 75 (2015) 152





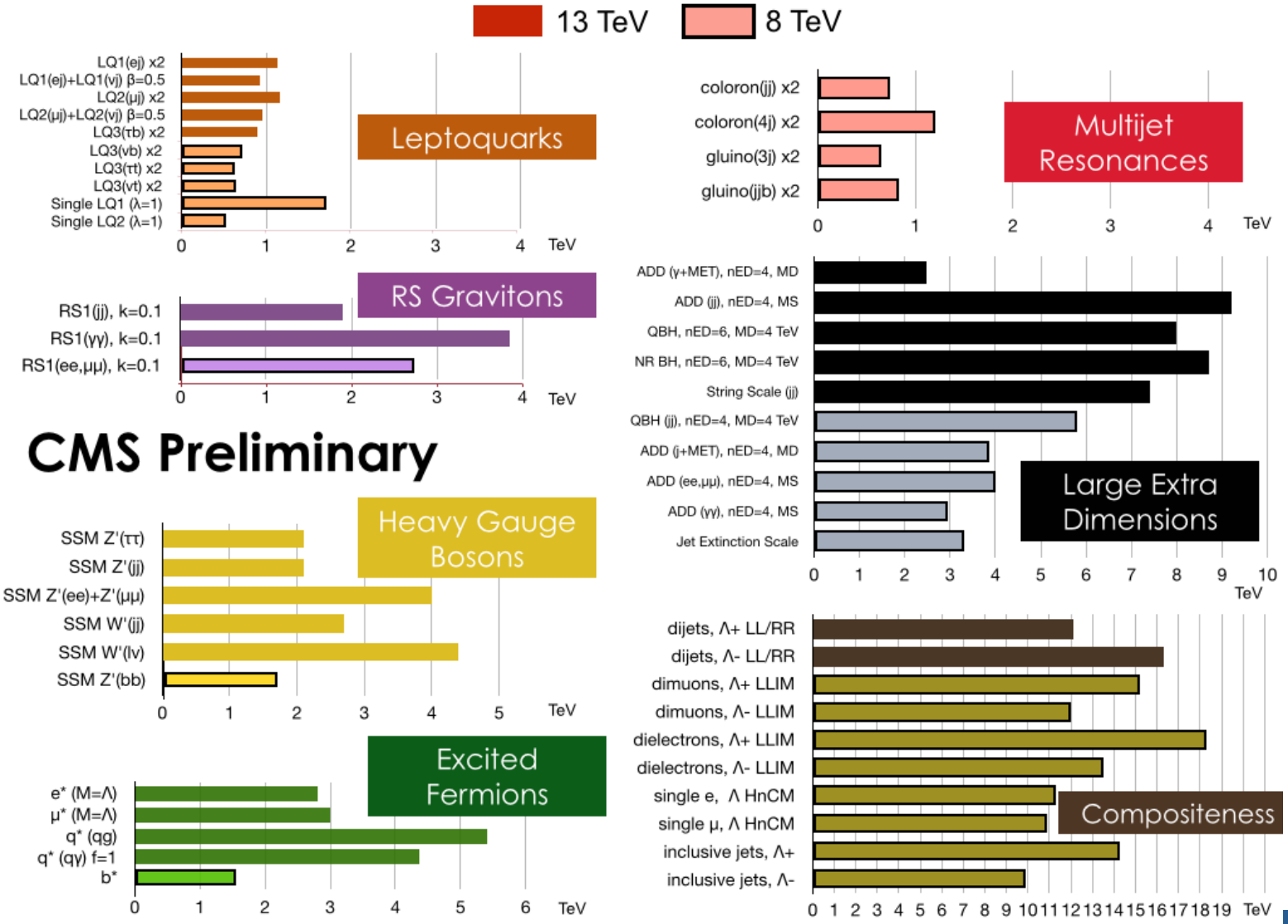
- Search for exotic massive particles decaying semileptonically
  LHCb-PAPER-2016-047
- Search for the SM Higgs boson decaying in bb or cc in association with W or Z
  LHCb-CONF-2016-006
- Search for hidden-sector bosons in $B^0 \to K^{*0}\mu^+\mu^-$ decays
  PRL 115 (2015) 161802
- Search for heavy charged long-lived particles using RICH
  EPJC 75 (2015) 595
- Search for Majorana neutrinos in $B^- \to \pi^+\mu^-\mu^-$
  PRL 112 (2014) 131802



- Search violation of lepton flavour and baryon number in tau lepton decays at LHCb PLB 724 (2013) 36

Exotic searches : CMS summary

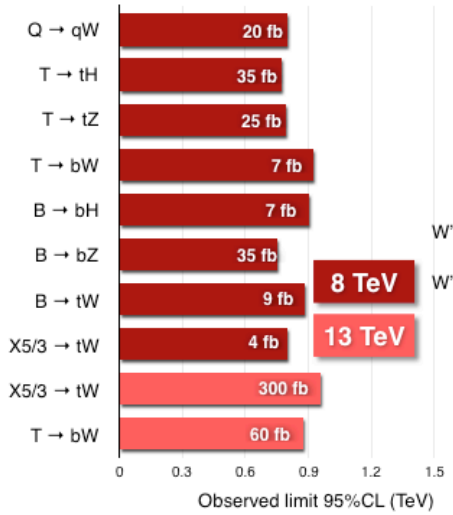
About 50% of the run 1 searches are updated at 13 TeV



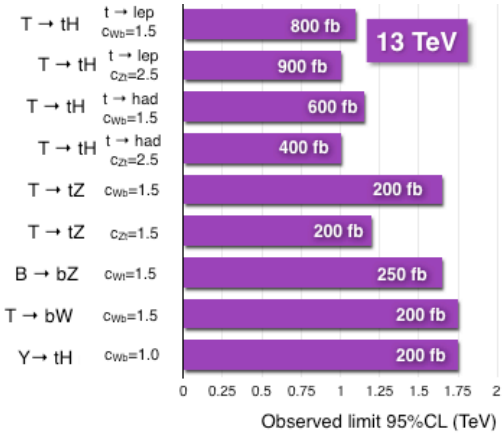
Exotic searches : CMS summary

About 50% of the run 1 searches are updated at 13 TeV

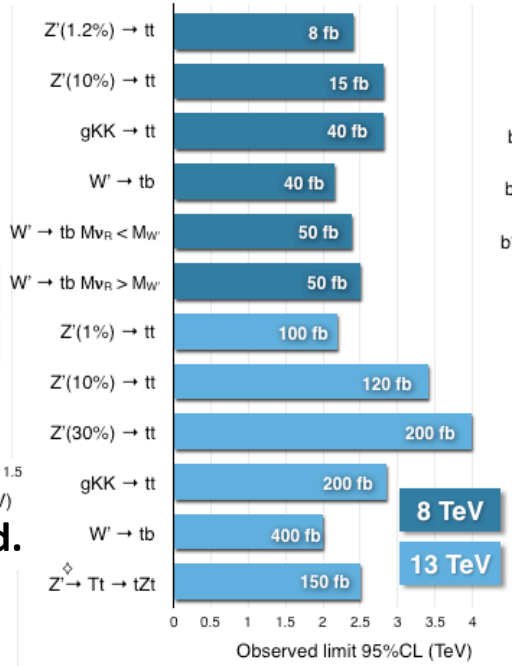
Vector Like Quarks pair prod.



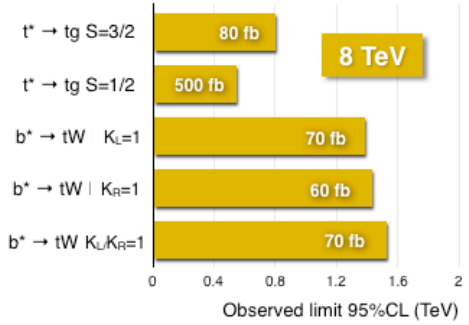
Vector Like Quarks single prod.



Resonances to heavy quarks

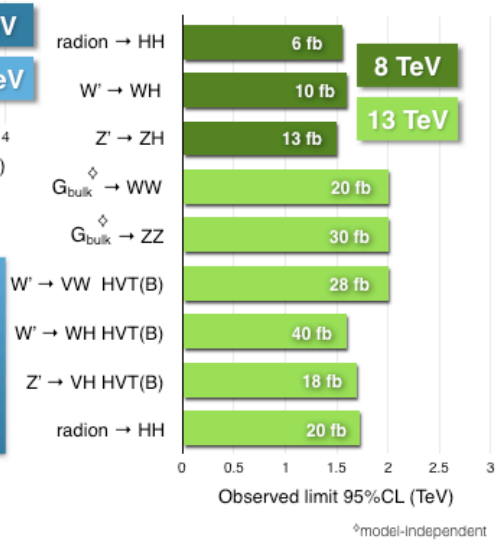


Excited quarks



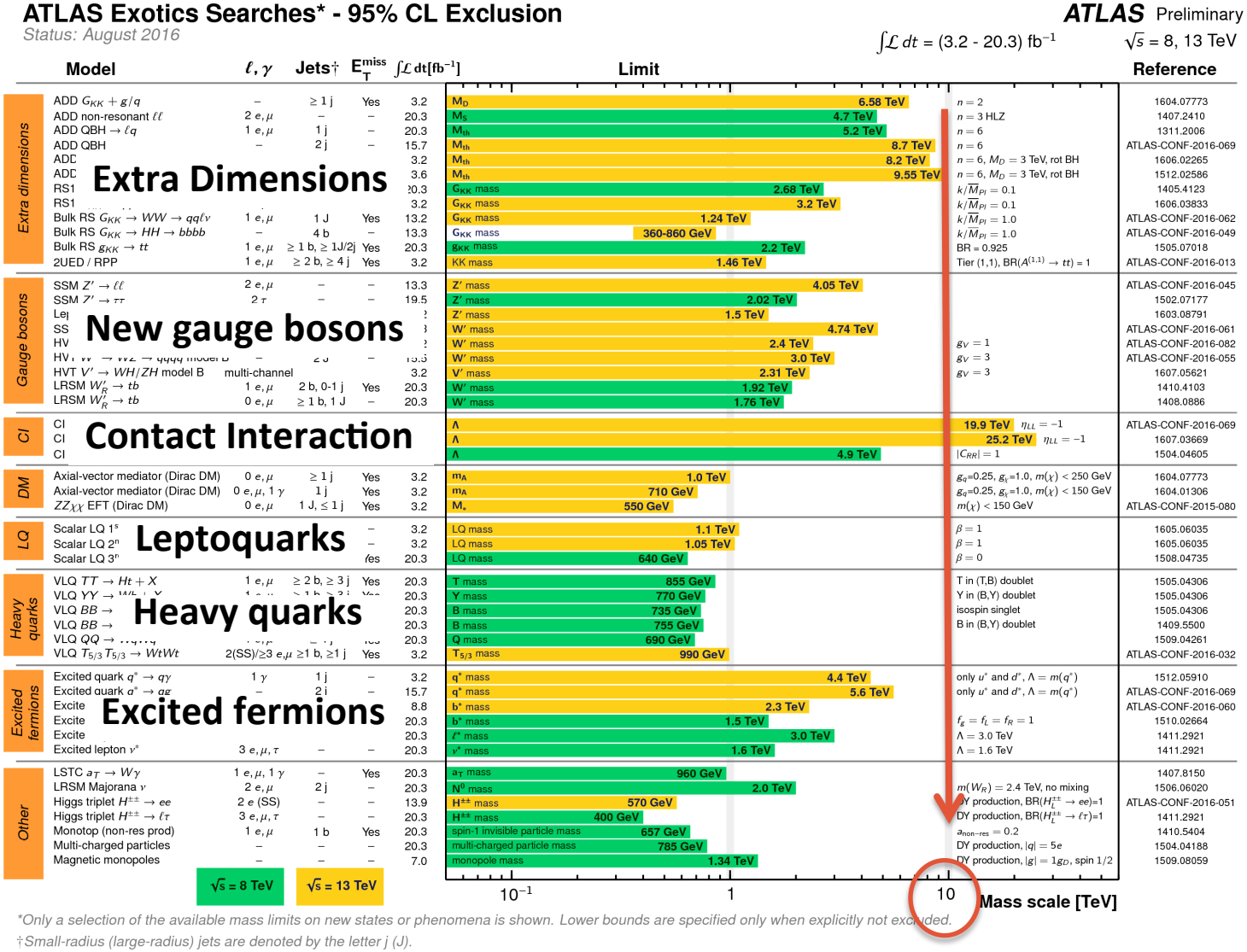
B2G
new physics searches with heavy SM particles

Resonances to dibosons



Exotic searches : ATLAS summary

About 50% of the run 1 searches are updated at 13 TeV



13 TeV

8 TeV

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Conclusions

- SM not complete - Need for BSM
  New physics to discover at the TeV scale ?

- LHC experiments conducting BSM searches in broad and complementary signatures

- Unfortunately the observed small excesses :
  - Diboson in Run1
  - Diphoton in 2015

  are not confirmed using 2016 data

- No new significant excesses observed

- However set new frontier scale – Major extension of reach compared to run 1
  Further constraints BSM model parameter space
  The results probe well into the TeV, even multi-TeV, mass scale range

- More data to come – Many more searches will come with the full 2016 data now available - Stay tuned!