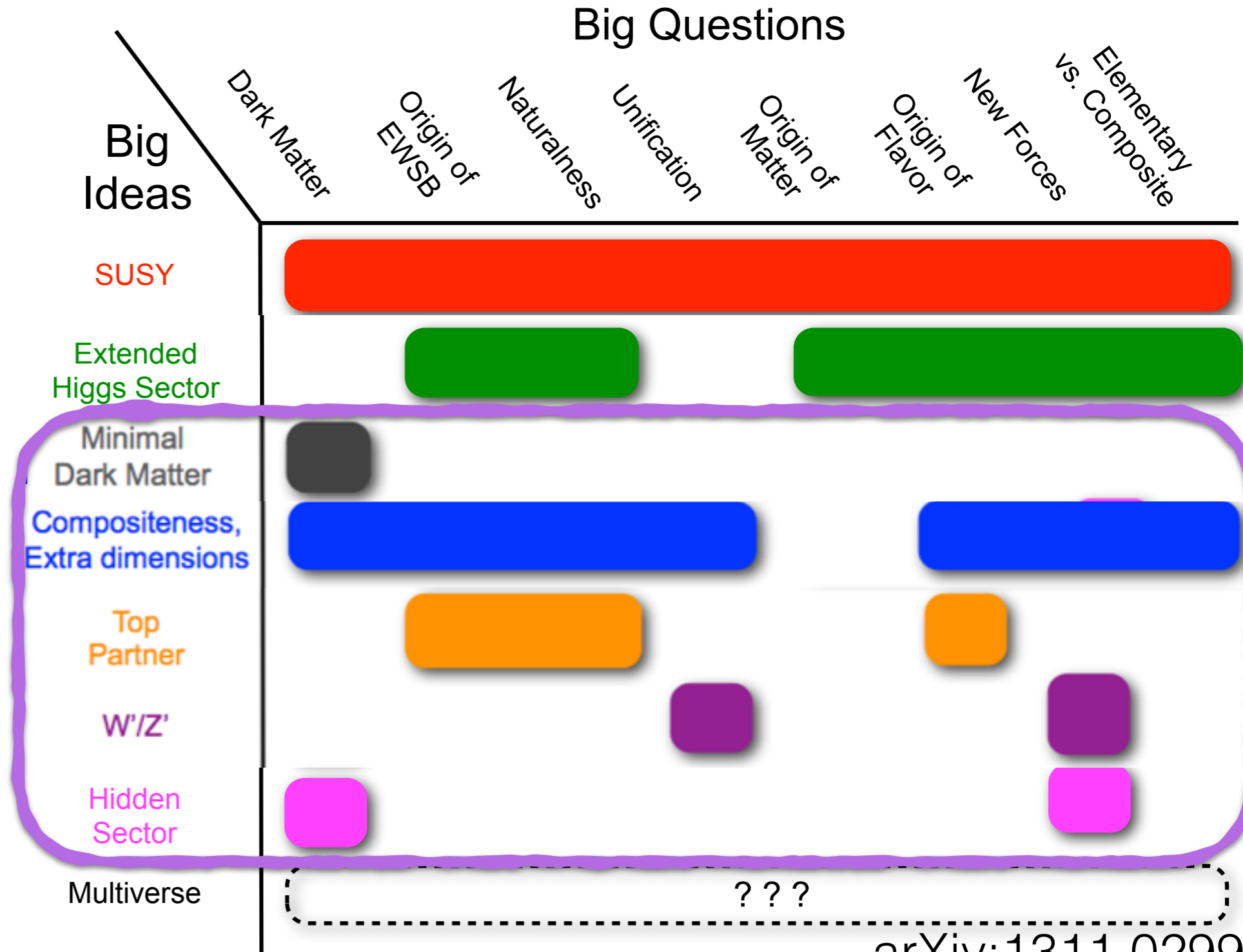


Exotic Summary

Shih-Chieh Hsu
University of Washington
Aug 9 2016



- Many Big Questions beyond the SM to be answered at TeV scale
- Big Ideas highly constrained from theory and observed phenomena



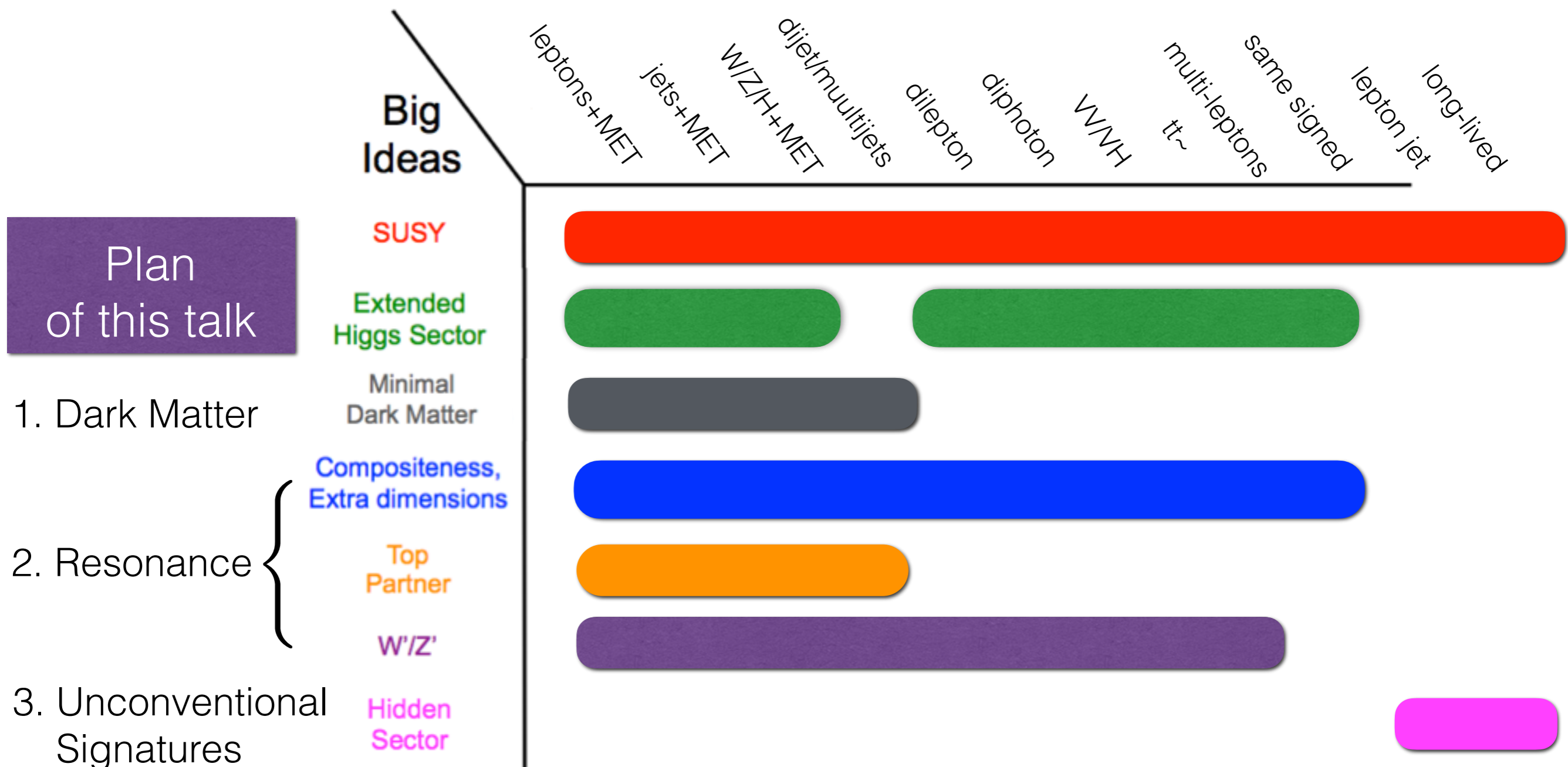
Wolfgang Adam's talk

Florencia Canelli's talk

Scope of this talk

Search Signatures for Big Ideas

- Quite often the same big idea probed by different signatures
 - It's crucial to search all complementary signatures



- A large number of contributions to this talk:
 - 6 parallel sessions, 22 talks and 16 posters
 - 2 submitted papers, 45 new conf. notes
- **Selected (2016 or First) results** as examples to illustrate key points
 - More results are linked below and in the backup slides

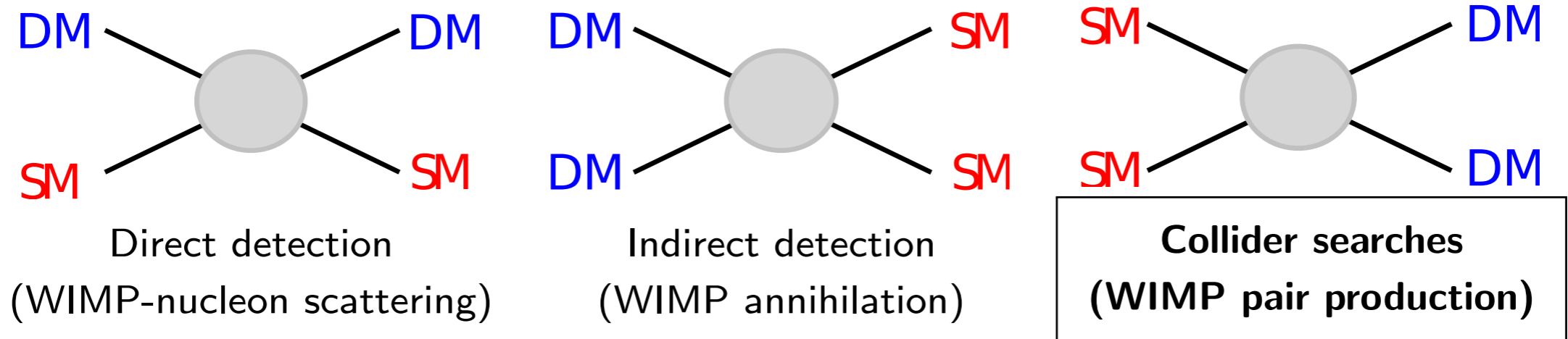
ICHEP Preliminary
[\[ATLAS Summer\]](#)
[\[CMS EXO\]](#)
[\[CMS-B2G\]](#)

Parallel Talk	Speakers	Parallel Talk	Speakers	Poster	Speakers
DM in CMS	Shin-Shan Yu	3rd generation t,tt,tb ATLAS	Danilo Lima	DM in 4top ATLAS	Leonid Serkin
DM in ATLAS	Steven Schramm	3rd generation Quark CMS	Michael Anthony Buttignol	H+MET ATLAS	Andrew Hard
dijet/multijet ATLAS/CMS	Saptaparna Bhattacharya	vector-like quark CMS	Julie Hogan	ZH CMS	Cesar Bernardes
dilepton ATLAS	Heberth Jesus Torres Davila	VLQ ATLAS	Georges Azuelos	HH4b CMS	Angelo De Souza Santos
heavy/LFV dilepton CMS	Hwi Dong Yoo	leptoquark & compositeness CMS	Seth Cooper	HH4b ATLAS	John Alison
multilepton ATLAS/CMS	Christos Leonidopoulos	leptoquark/excited quark ATLAS	Simon Viel	Vector-like Top CMS	Anthony Barker
WW/WZ/ZZ ATLAS	Nikolaos Konstantinidis	Long-lived CMS	Jamie Antonelli	photon+jet resonance CMS	Varun Sharma
Heavy Wh/Zh CMS	Salvatore Rappoccio	displaced hadronic/lepton jet	Edward Moyse	dijet Trigger level ATLAS	Karol Krizka
Heavy Higgs ATLAS	Karsten Koeneke	Long-lived SUSY ATLAS	Lauren Jeanty	Exotic/Higgs LHCb	Donatella Lucchesi
Heavy Neutral Higgs CMS	Benedikt Vormwald	black holes & anomaly charged ATLAS	Christopher Lester	Z(II)gamma resonance CMS	Kyungwook Nam
heavy diphoton ATLAS	Bruno Lenzi	Exotica with LHCb	Pieter David	tt Resonance CMS	Christine Mc Lean
heavy diphoton CMS	Bruno Chiara Ilaria Rovelli			stable massive charged ATLAS	Sascha Mehlhase
				long-lived charged ionization ATLAS	Bradley Axen
				long-lived particle at ATLAS	Gordon Watts
				long-lived	Antonio Policicchio



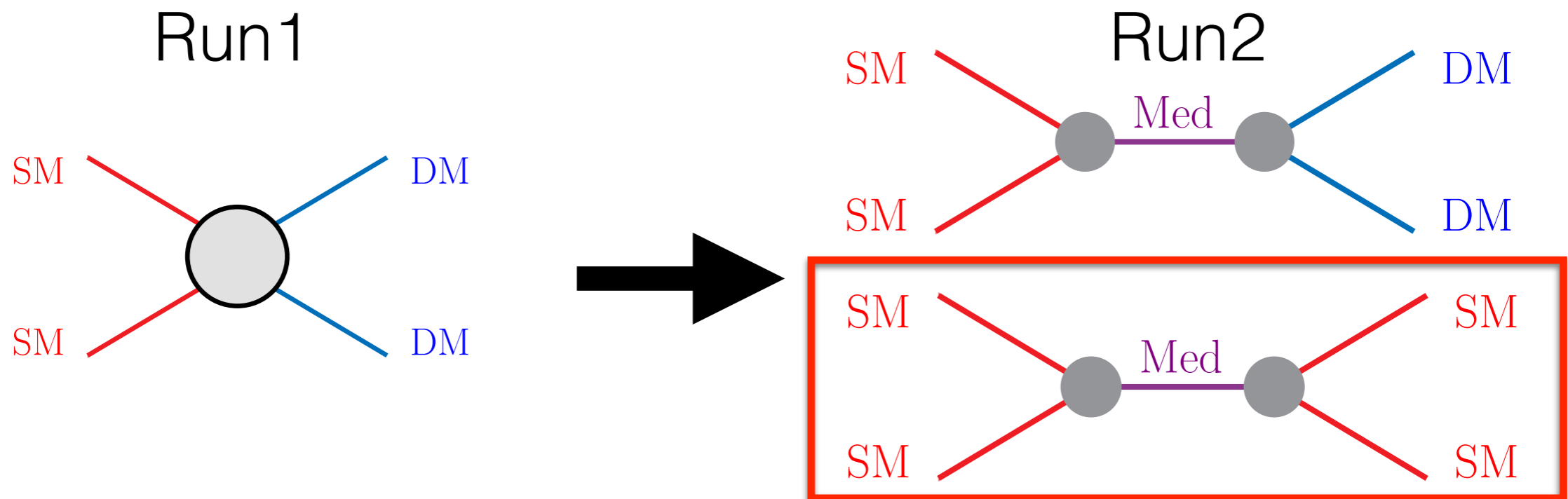
1. Dark Matter

- ATLAS/CMS searches assuming that DM is a WIMP



- DM interpretation using simplified model to avoid EFT validity concerns

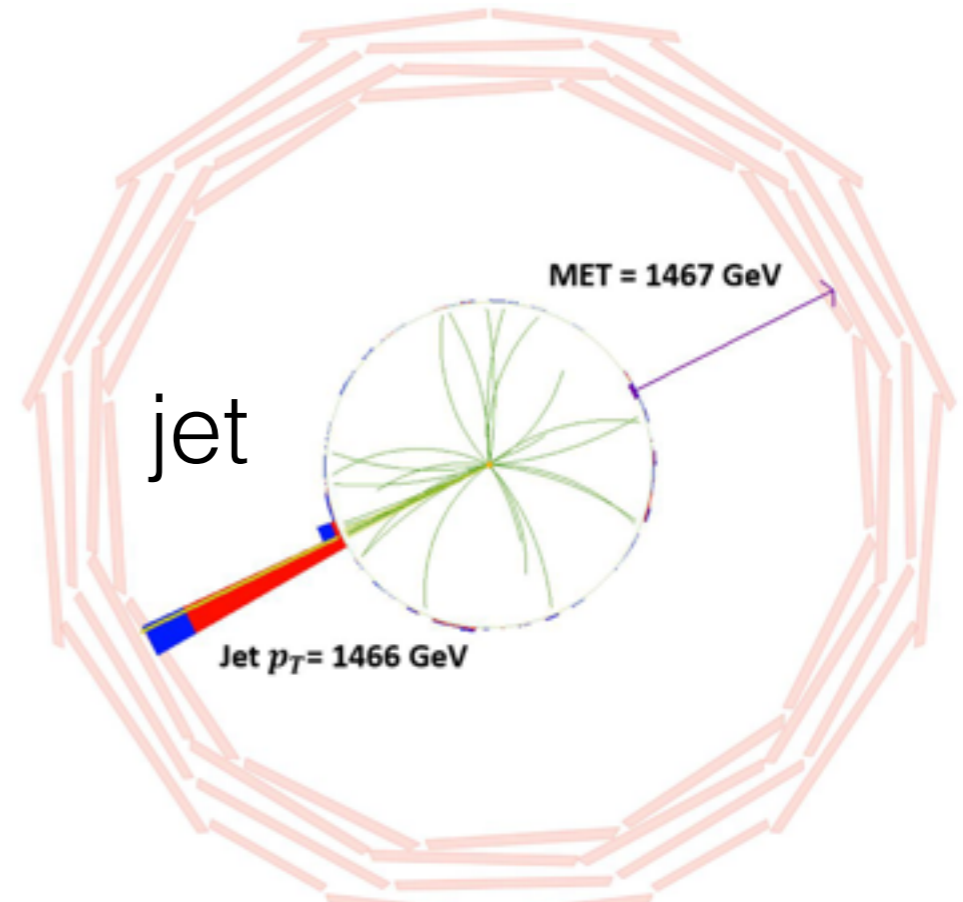
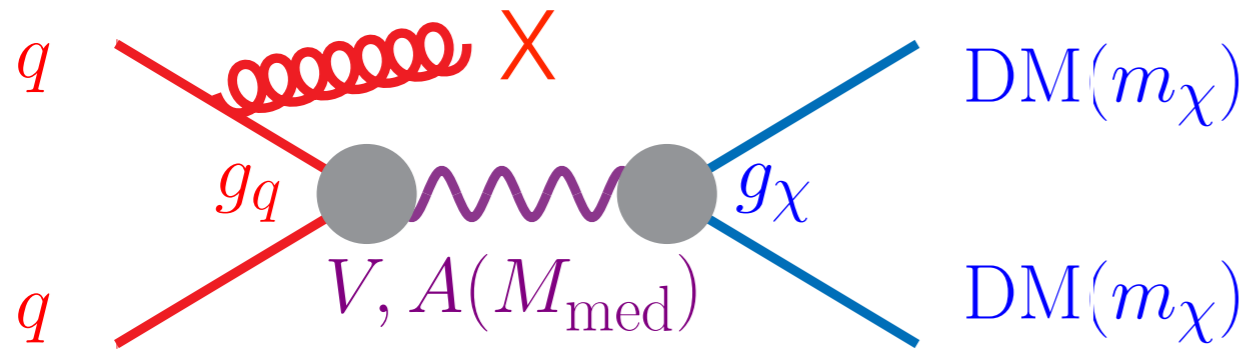
arXiv:1507.00966



Direct mediator searches contributing to DM interpretations

$ET^{\text{miss}} + X$ a.k.a. Mono-X

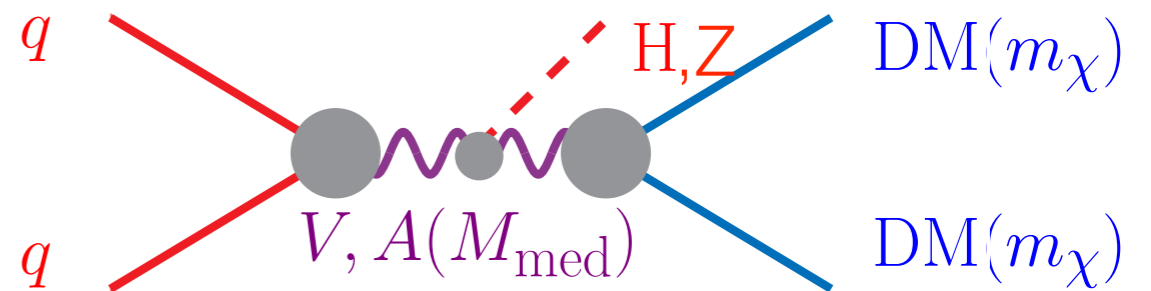
- X from ISR jet, b, t, γ , W, Z



CMS Experiment at LHC, CERN
 Data recorded: Sat Oct 3 06:58:12 2015 CEST
 Run/Event: 258159 / 550030997
 Lumi section: 434



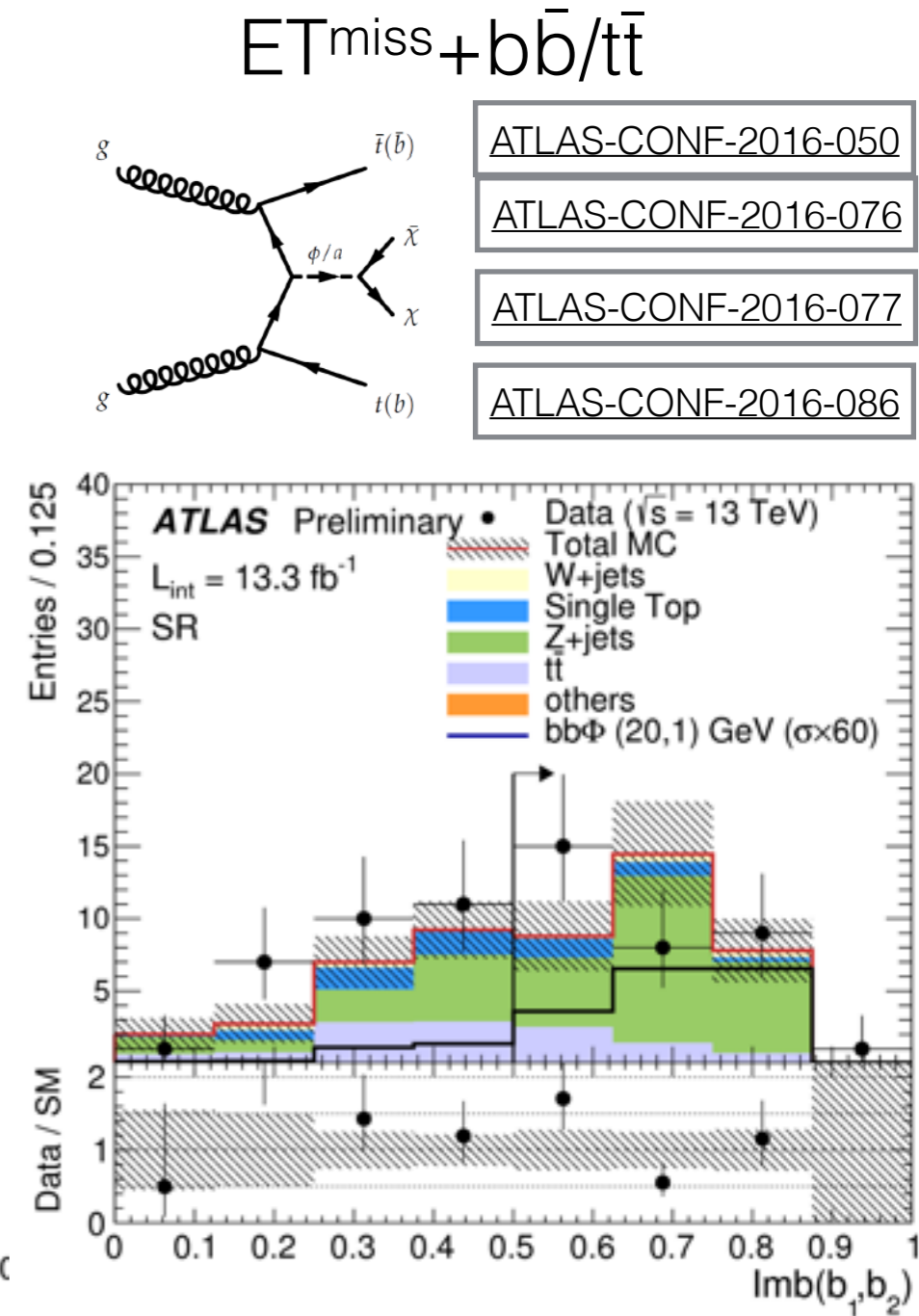
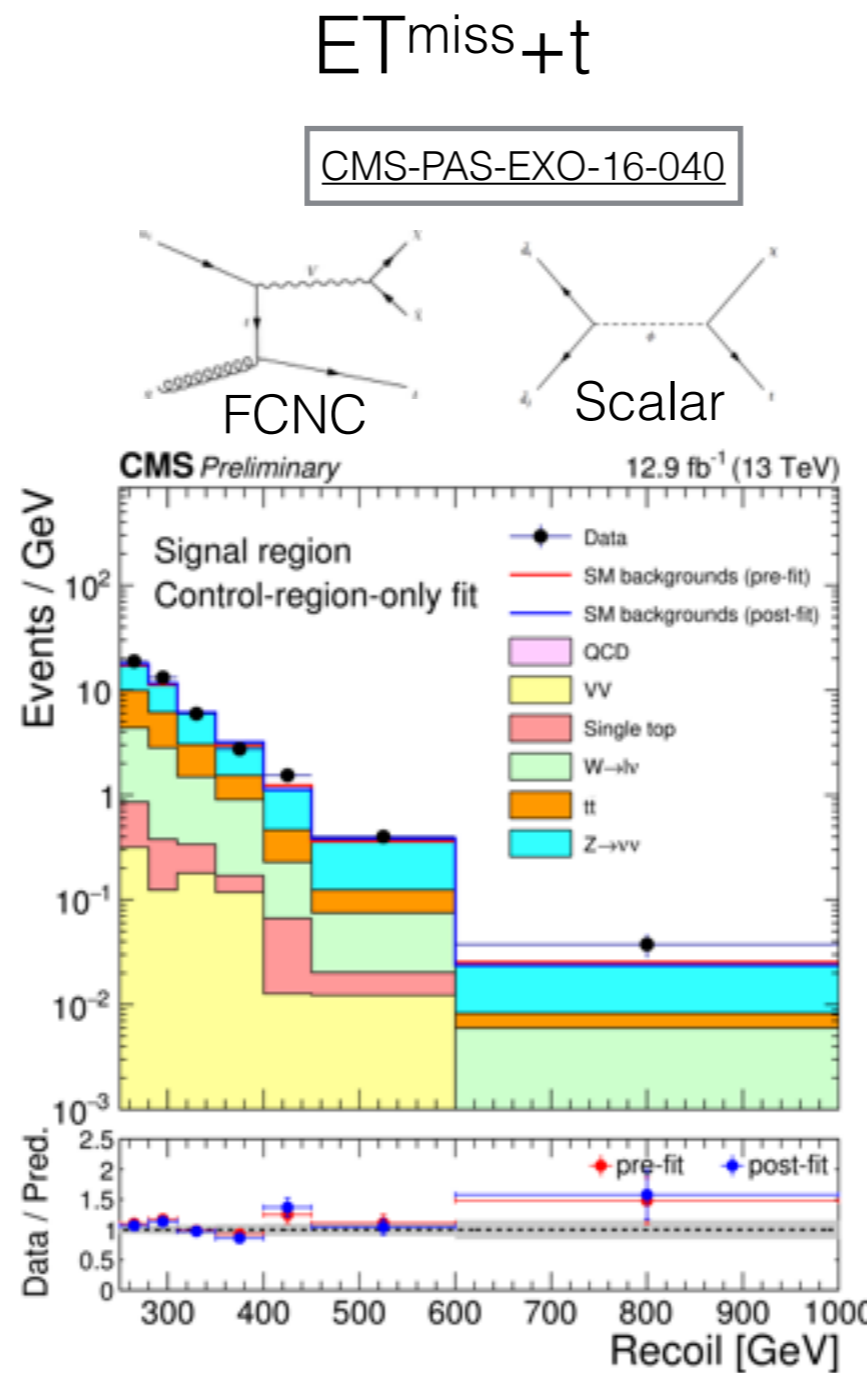
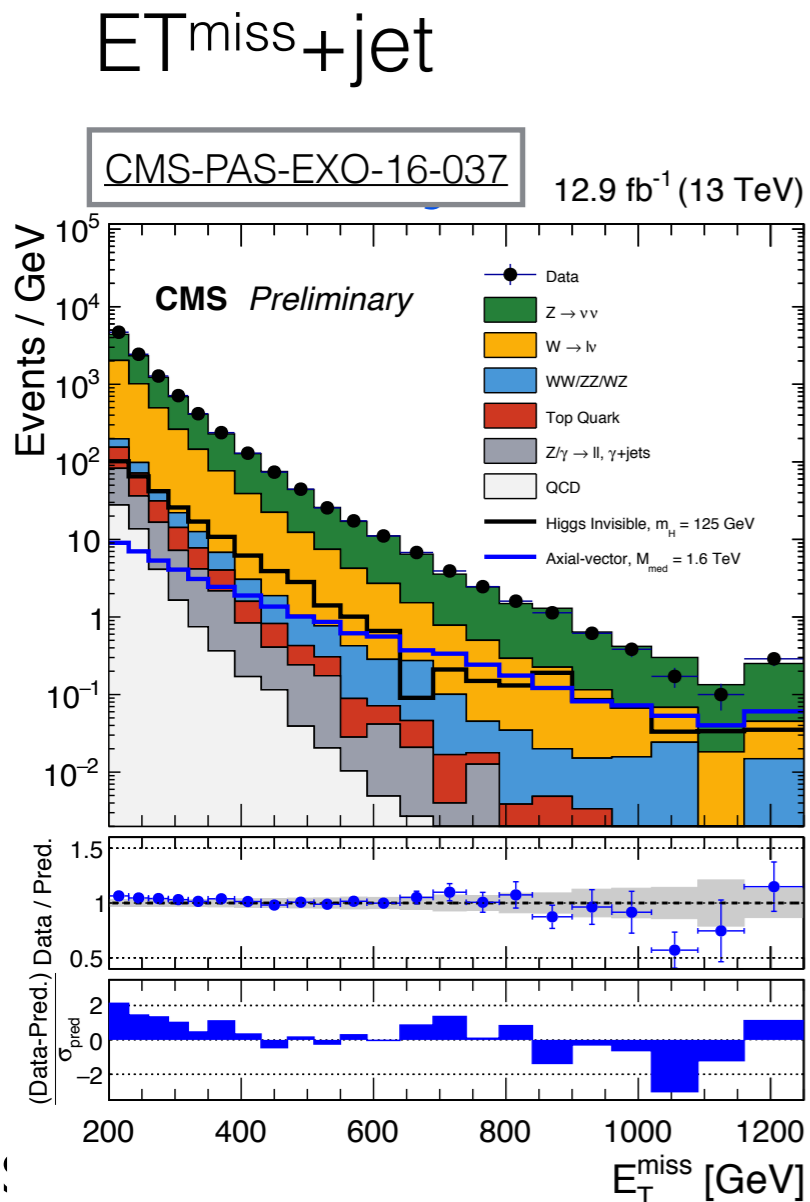
- X from mixing with mediator



- X from paired $t\bar{t}$, $b\bar{b}$

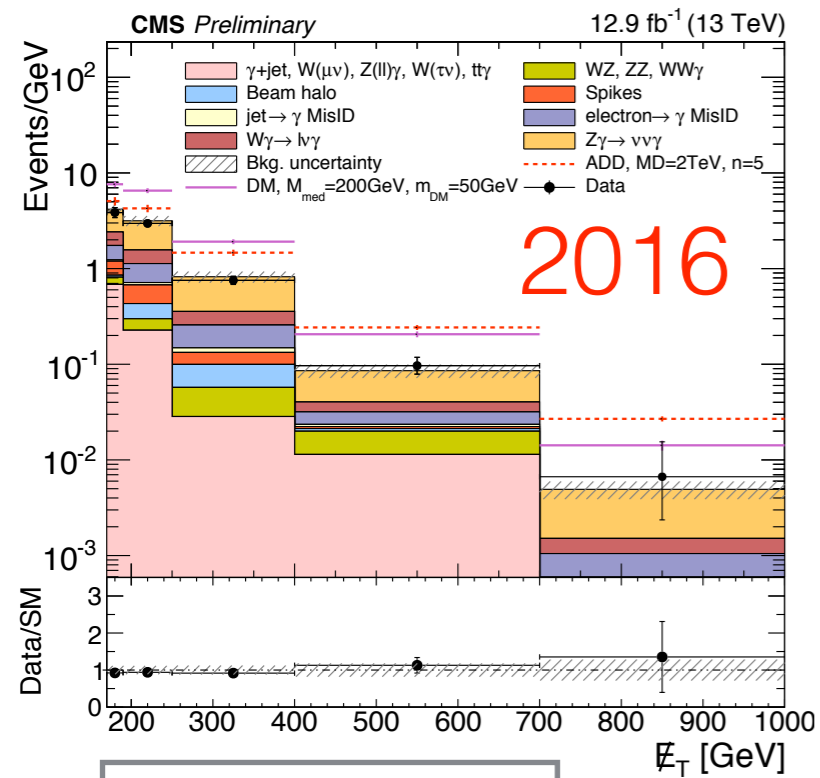
Mono-jet/b-jets/top analysis

- Key observables - imbalanced transverse momentum ET^{miss}
- Irreducible background: $Z(\nu\nu)+\text{jets}$
 - jets might be mis-reconstructed as b-jets, γ , W, Z

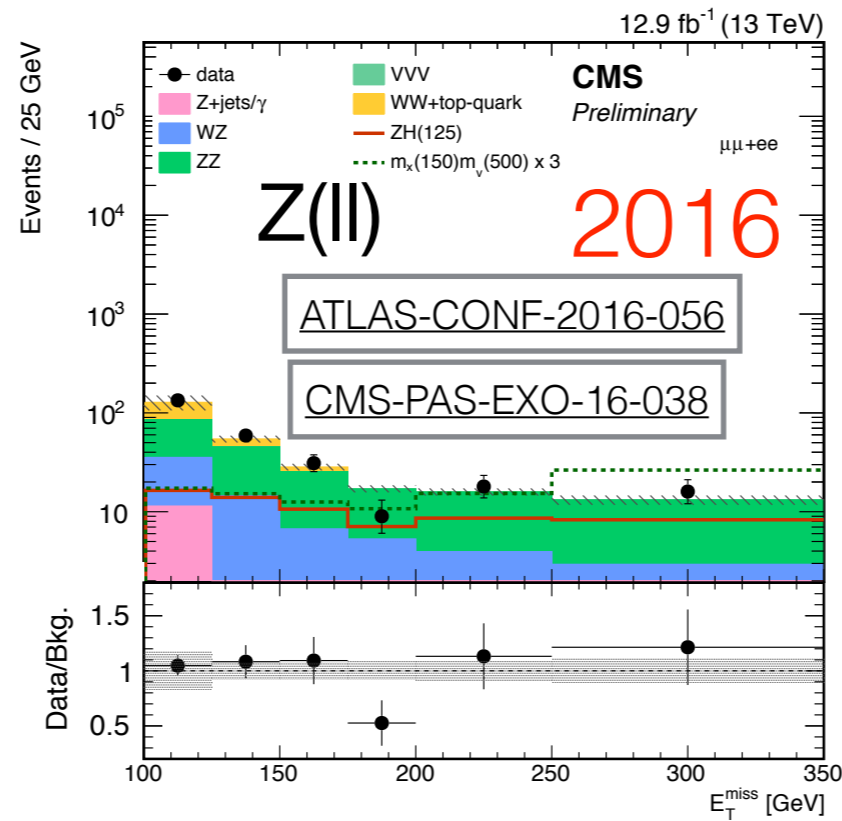


Mono- γ /W/Z/H

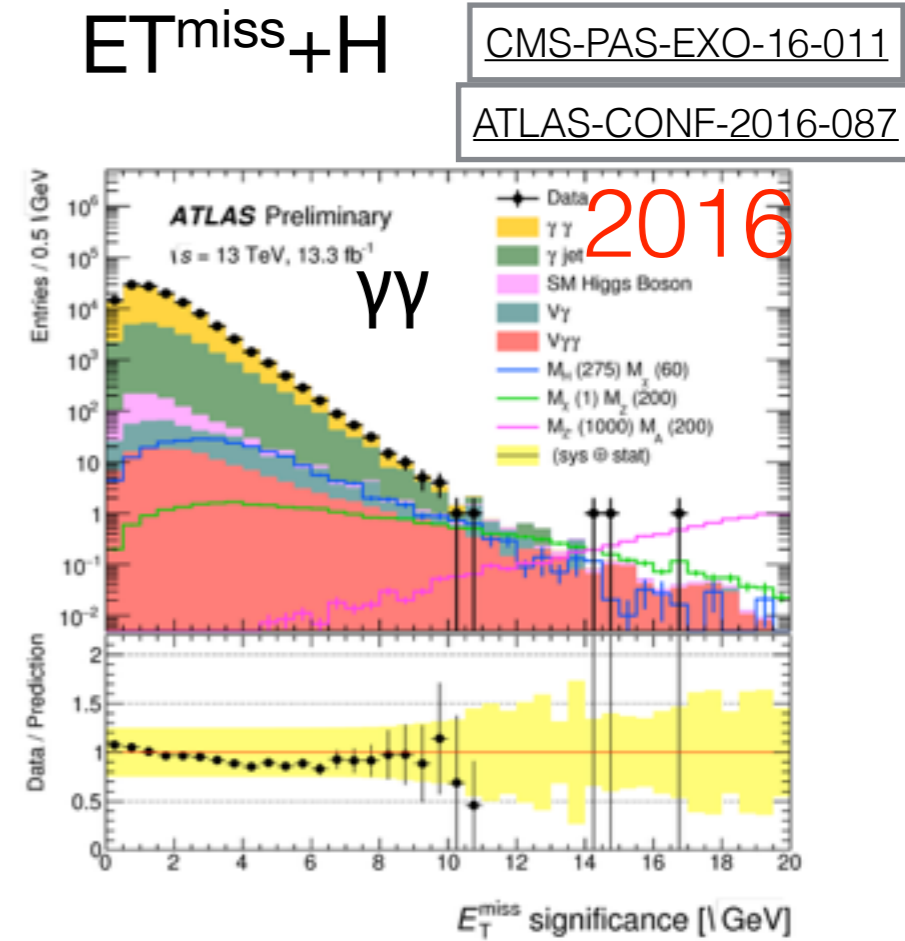
ET^{miss}+ γ



ET^{miss} + W/Z



ET^{miss}+H



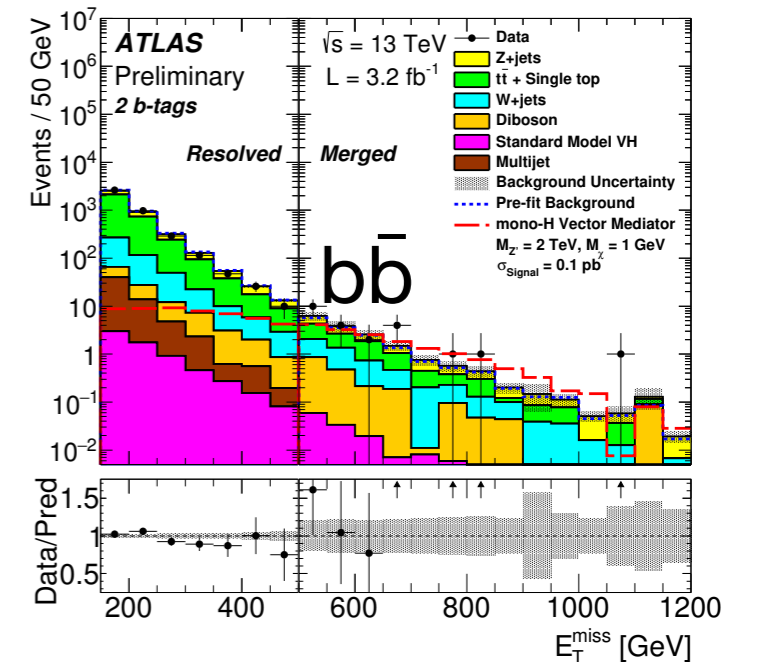
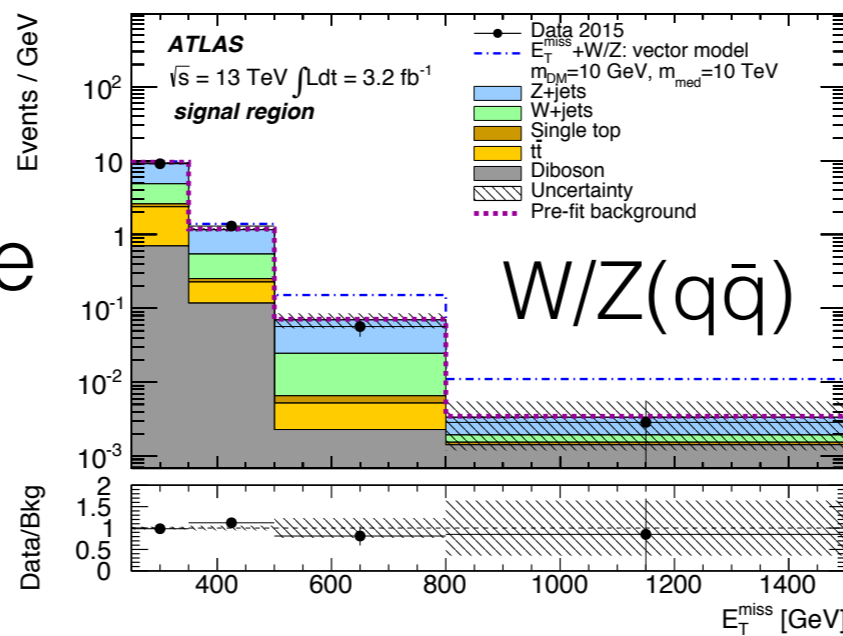
EXOT-2015-08

CMS-PAS-EXO-16-037 2015

ATLAS-CONF-2016-019

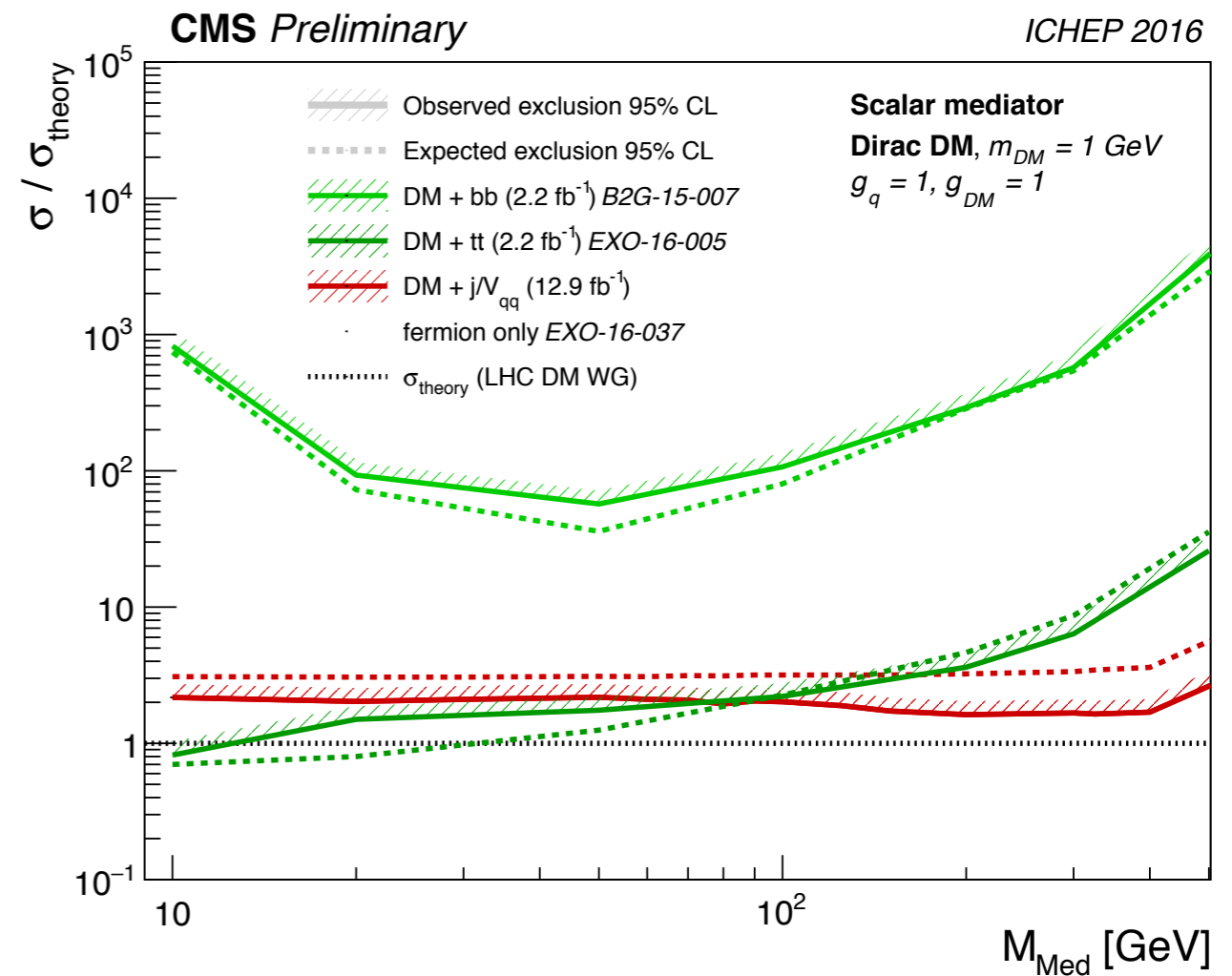
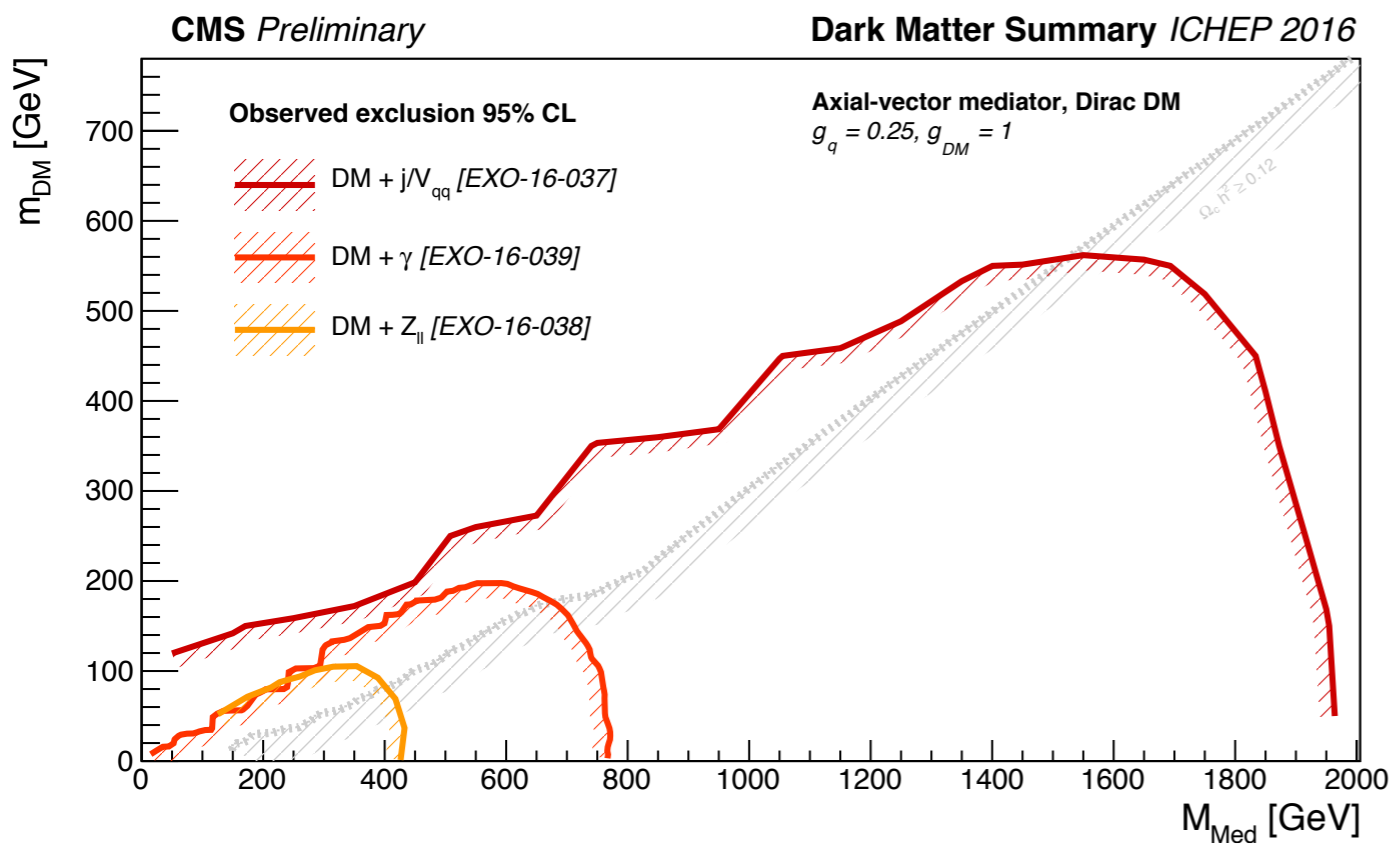
CMS-PAS-EXO-16-012 2015

Boosted jet substructure technique is used in hadronic W/Z/H



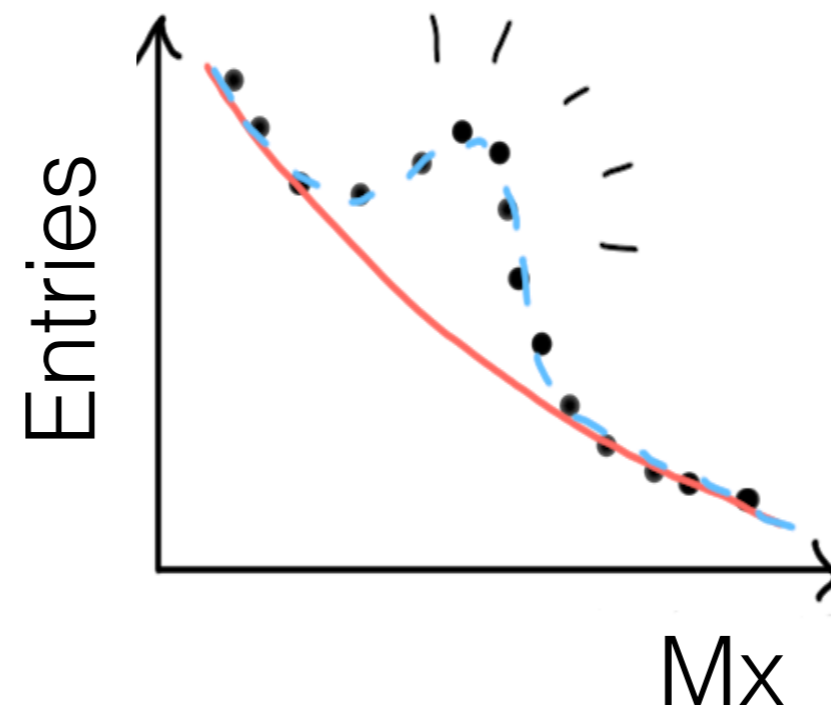
Dark Matter exclusion limit

- No significant excess observed so far
- DM mass exclusion up to ~ 550 GeV
- Vector Mediator mass exclusion up to 1.95 TeV





2. Resonance

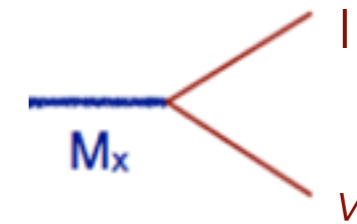
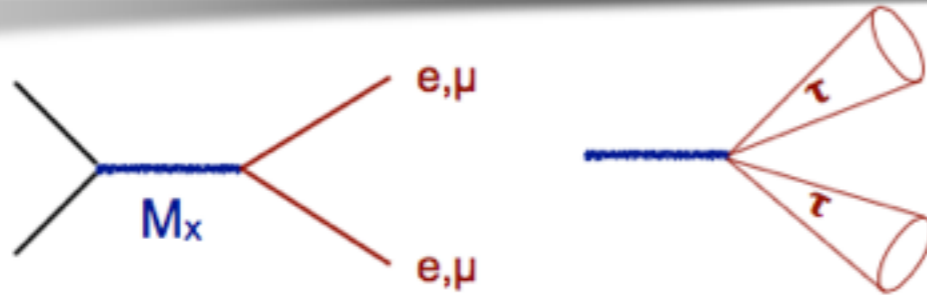


Heavy Resonances

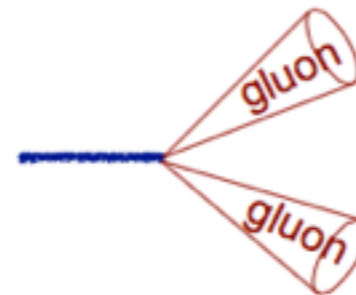
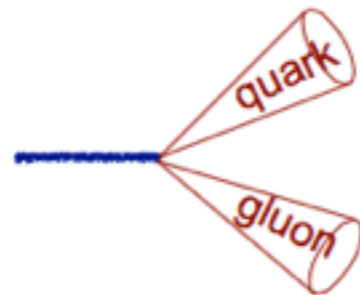
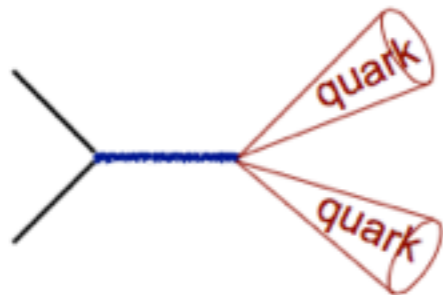
Neutral Charge

Charged

dilepton

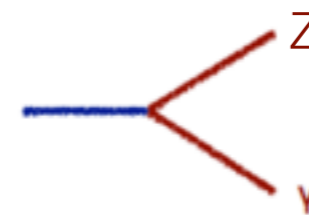
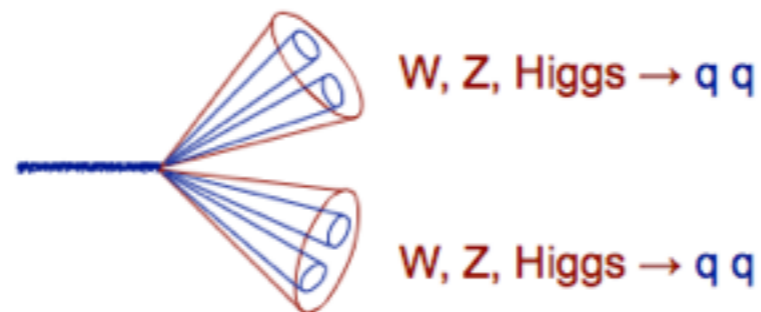
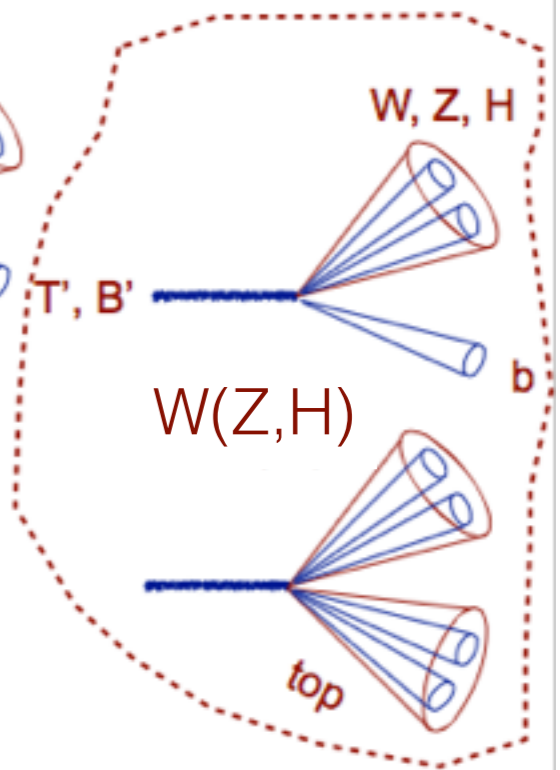
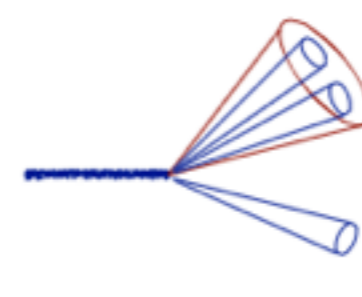
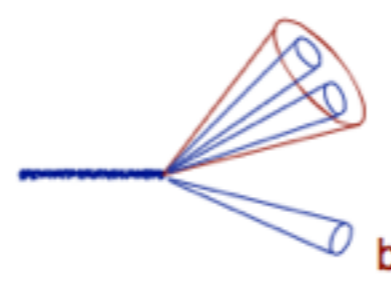
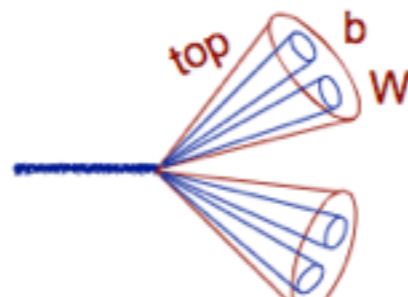
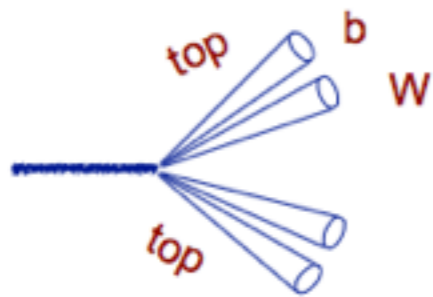


dijet



new fermions
top partners

top



diphoton

diboson

$Z\gamma$

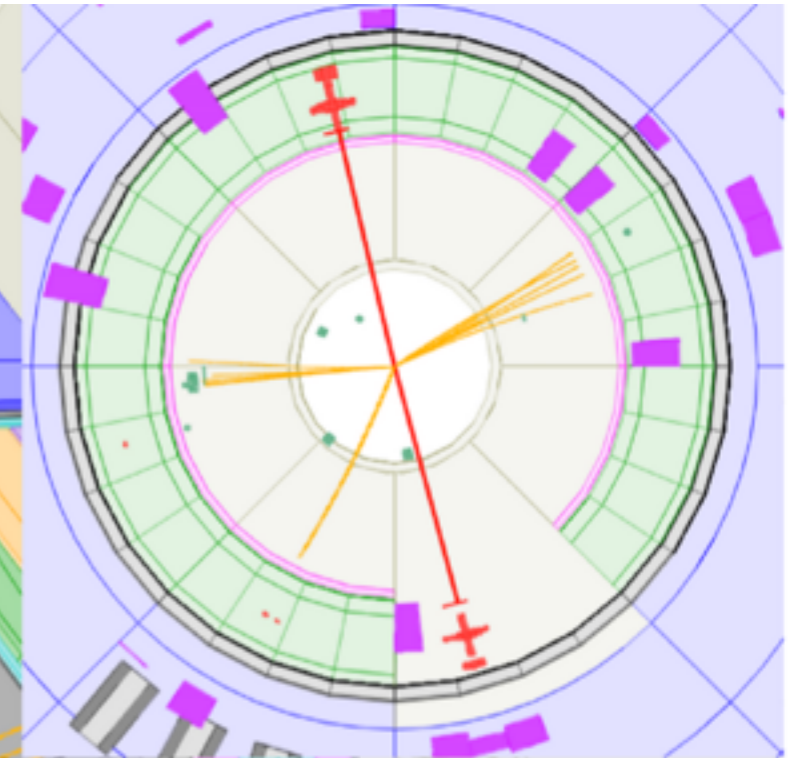
Courtesy S.Rahatlou

Z' dilepton

ATLAS Highest dielectron invariant mass
2.38 TeV

ET = 889 GeV

ET = 868 GeV

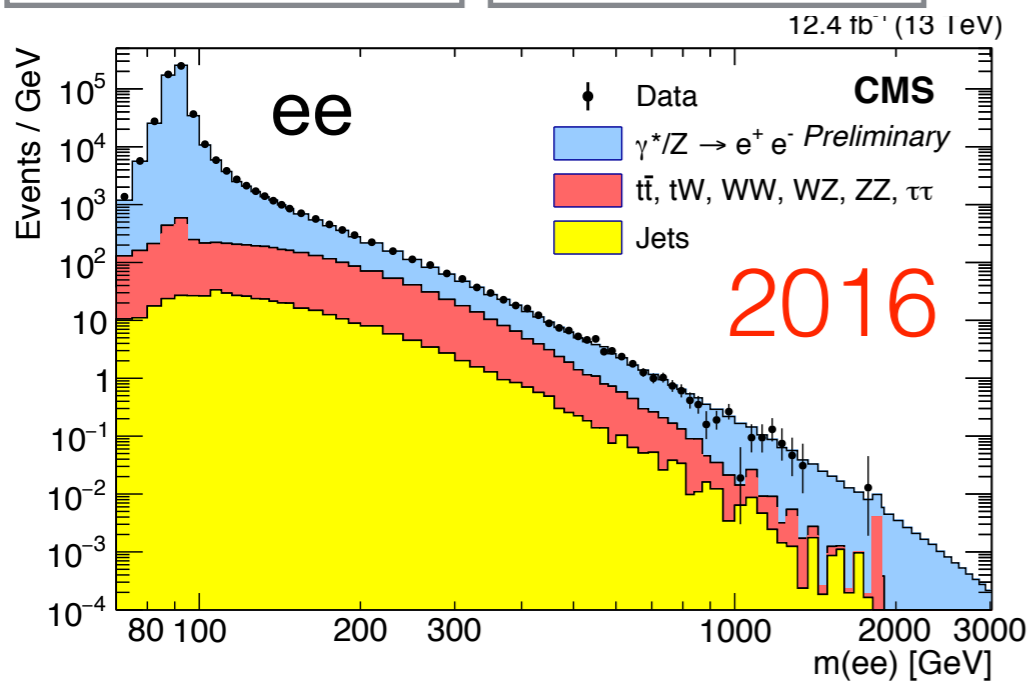


Run Number: 302393
Event Number: 3804660240
Date: 2016-06-20, 20:55:28 CET

Same Flavor Opposite Sign ($ee, \mu\mu, \tau\tau$)

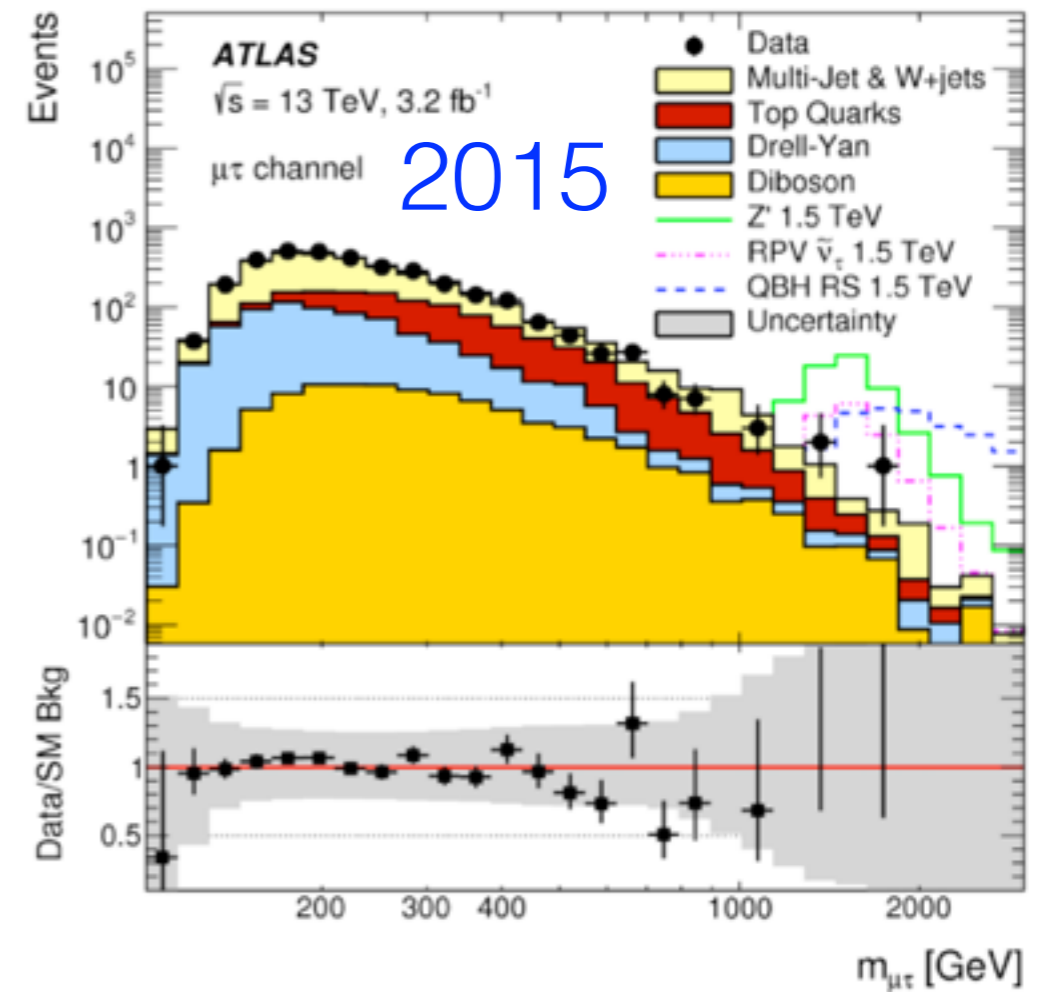
ATLAS-CONF-2016-045

CMS-PAS-EXO-16-031

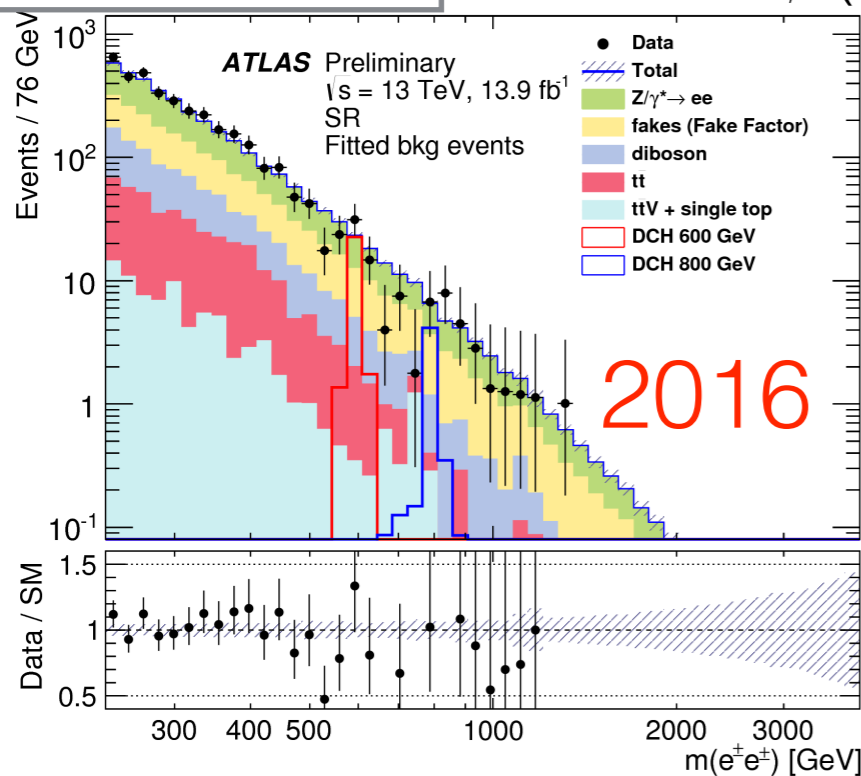
Lepton Flavor Violation ($e\mu, e\tau, \mu\tau$)

CMS-PAS-EXO-16-001

ATLAS-CONF-2016-045

Same Sign ($ee, \mu\mu$) Z'_{SSM} (3% width) > 4 TeV Z'_ψ (0.5% width) > 3.36 TeV

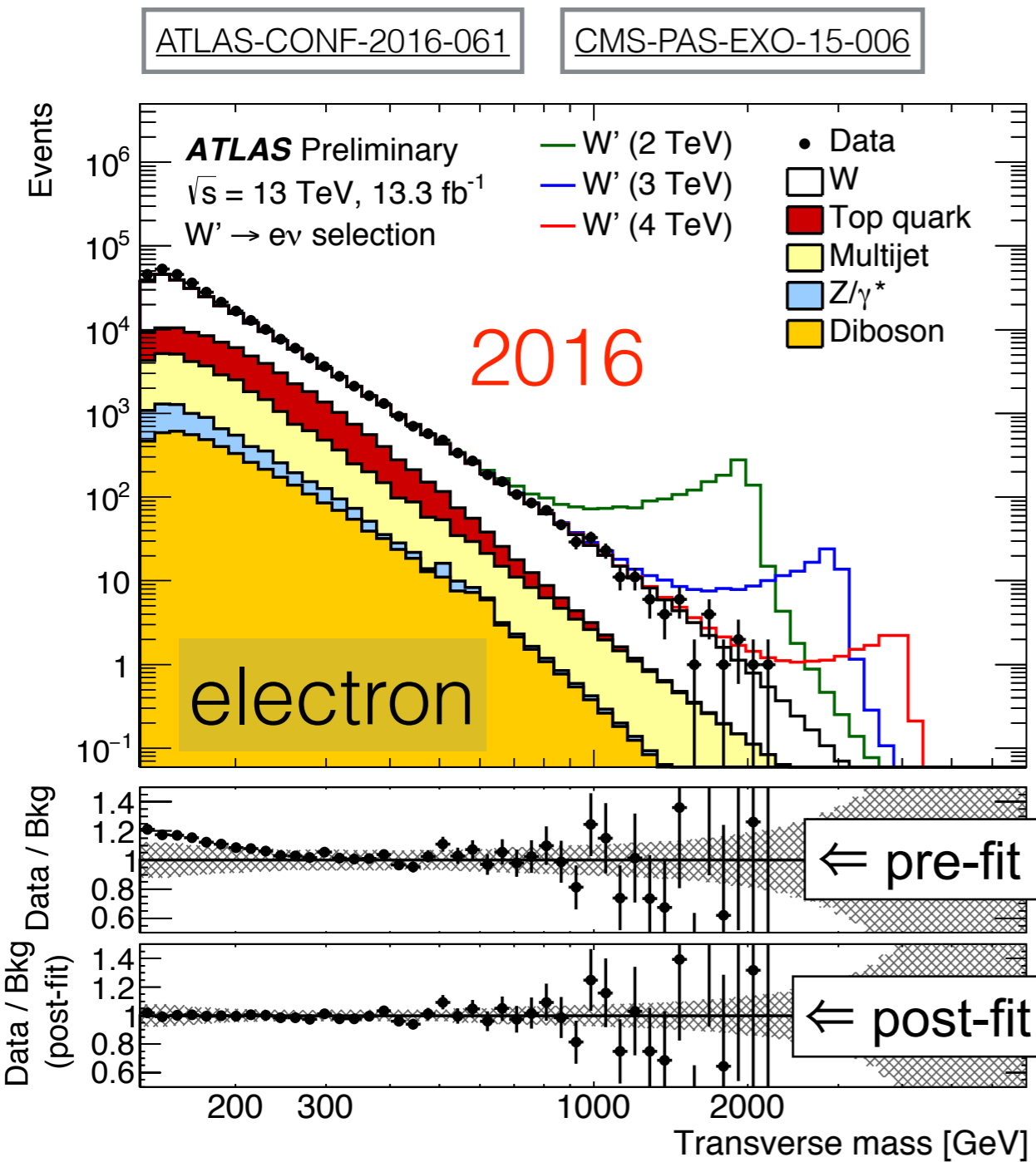
ATLAS-CONF-2016-051



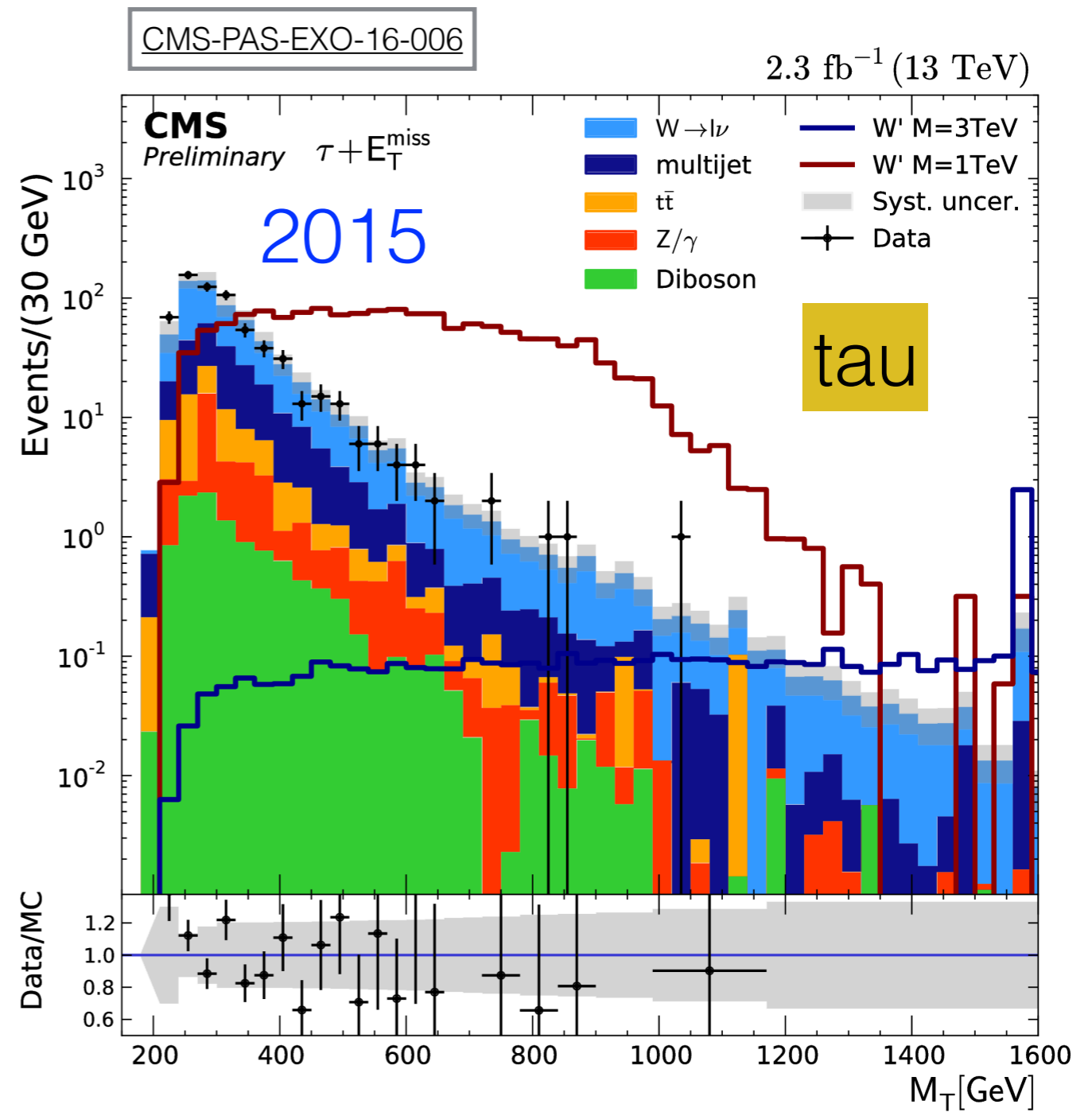
95% CL
exclusion limit

 $H_R^{\pm\pm} > 420 \text{ GeV}$ $H_L^{\pm\pm} > 570 \text{ GeV}$ RPV ($\lambda_{311}^1 = \lambda_{132} = \lambda_{231} = 0.2$) > 3.3 TeV

QBH (n=6) > 4.5 TeV



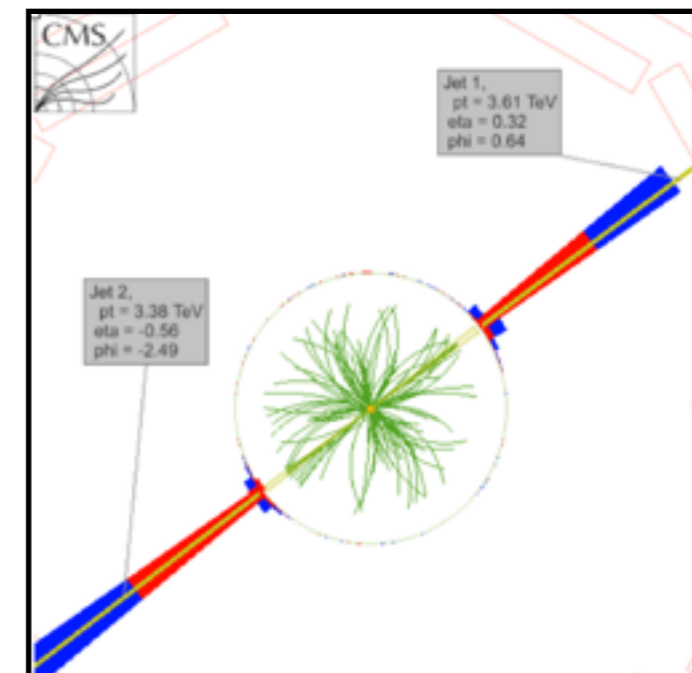
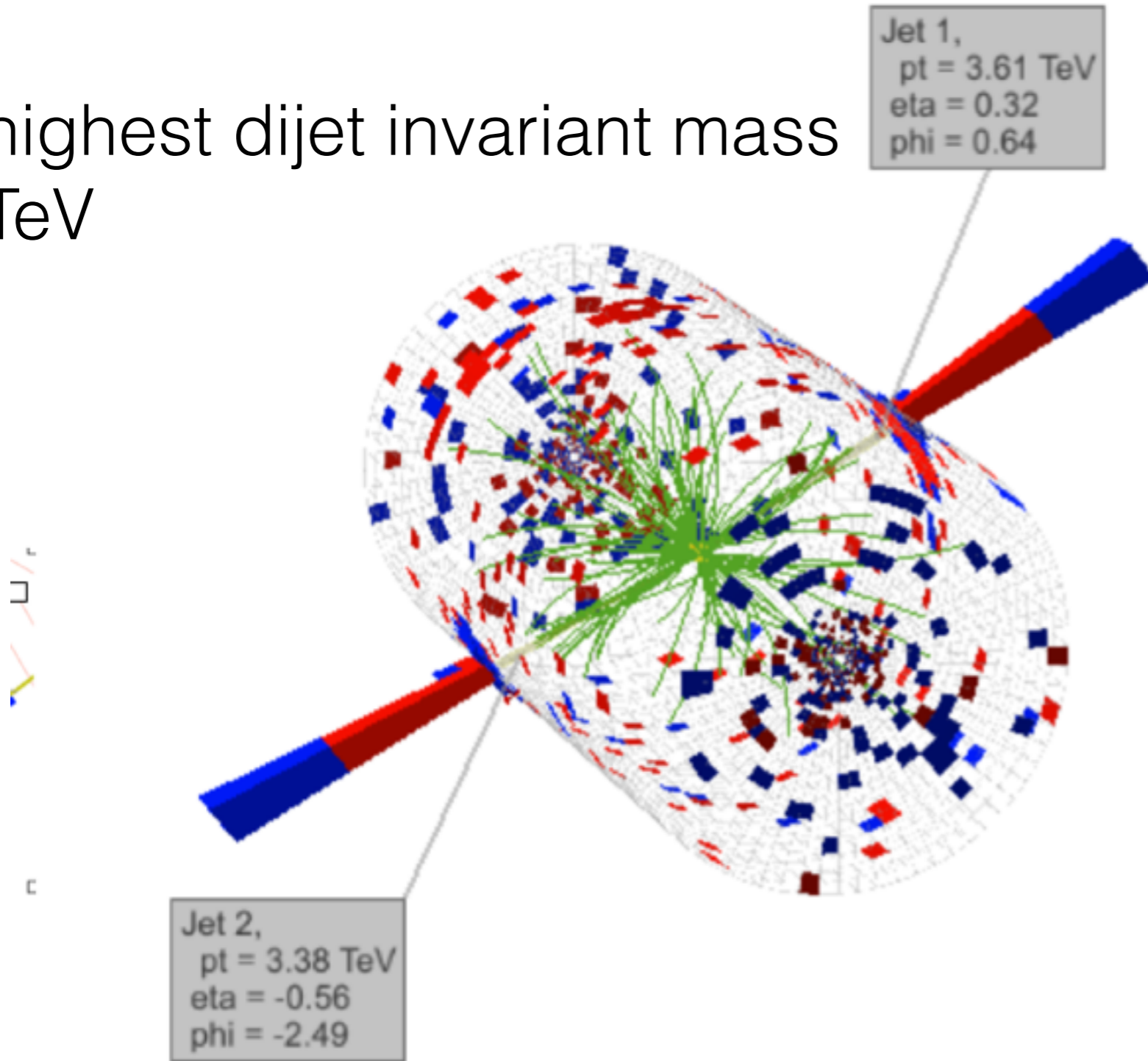
SSM $W' > 4.74 \text{ TeV}$



SSM $W' > 3.3 \text{ TeV}$

Dijet

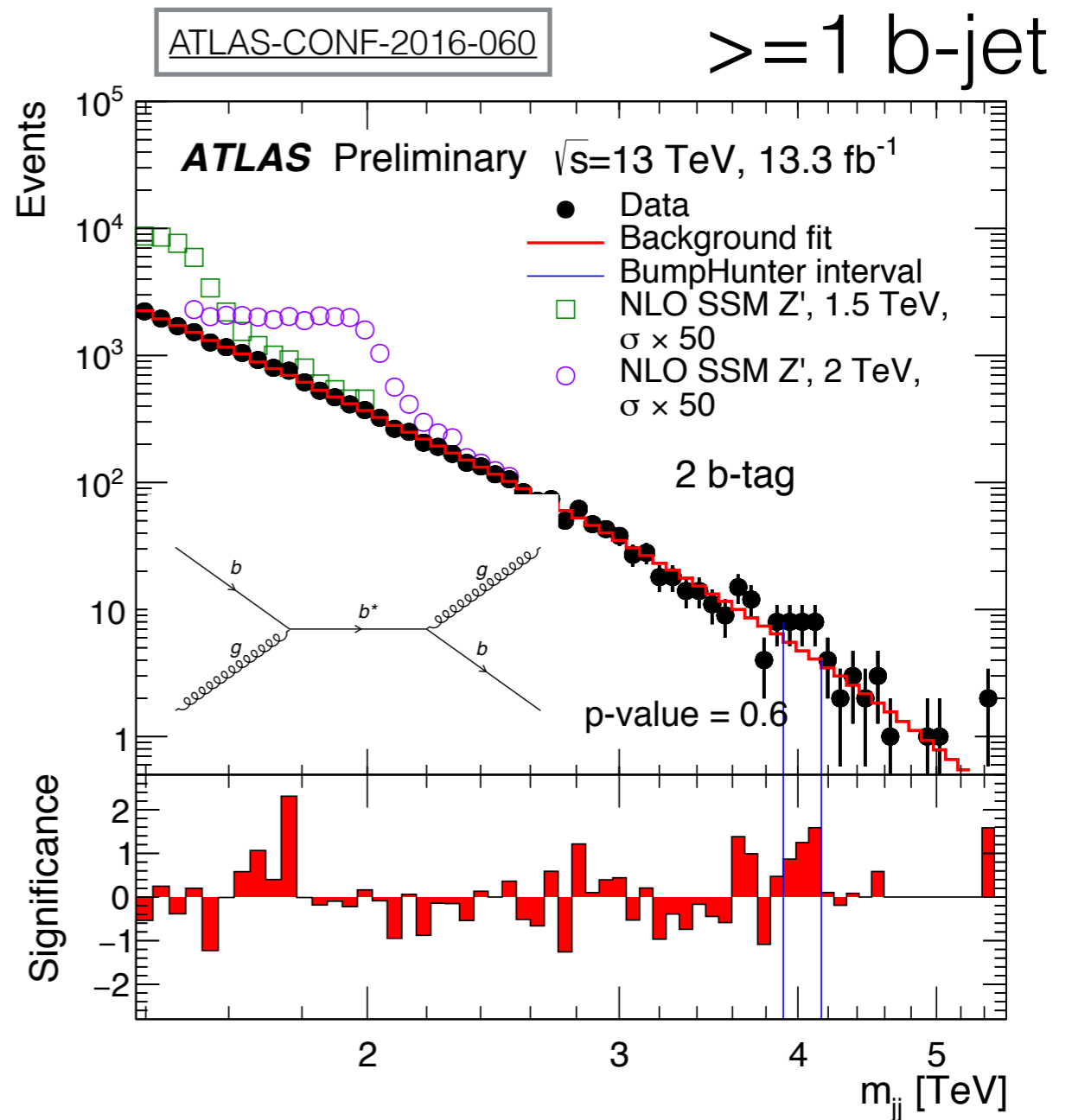
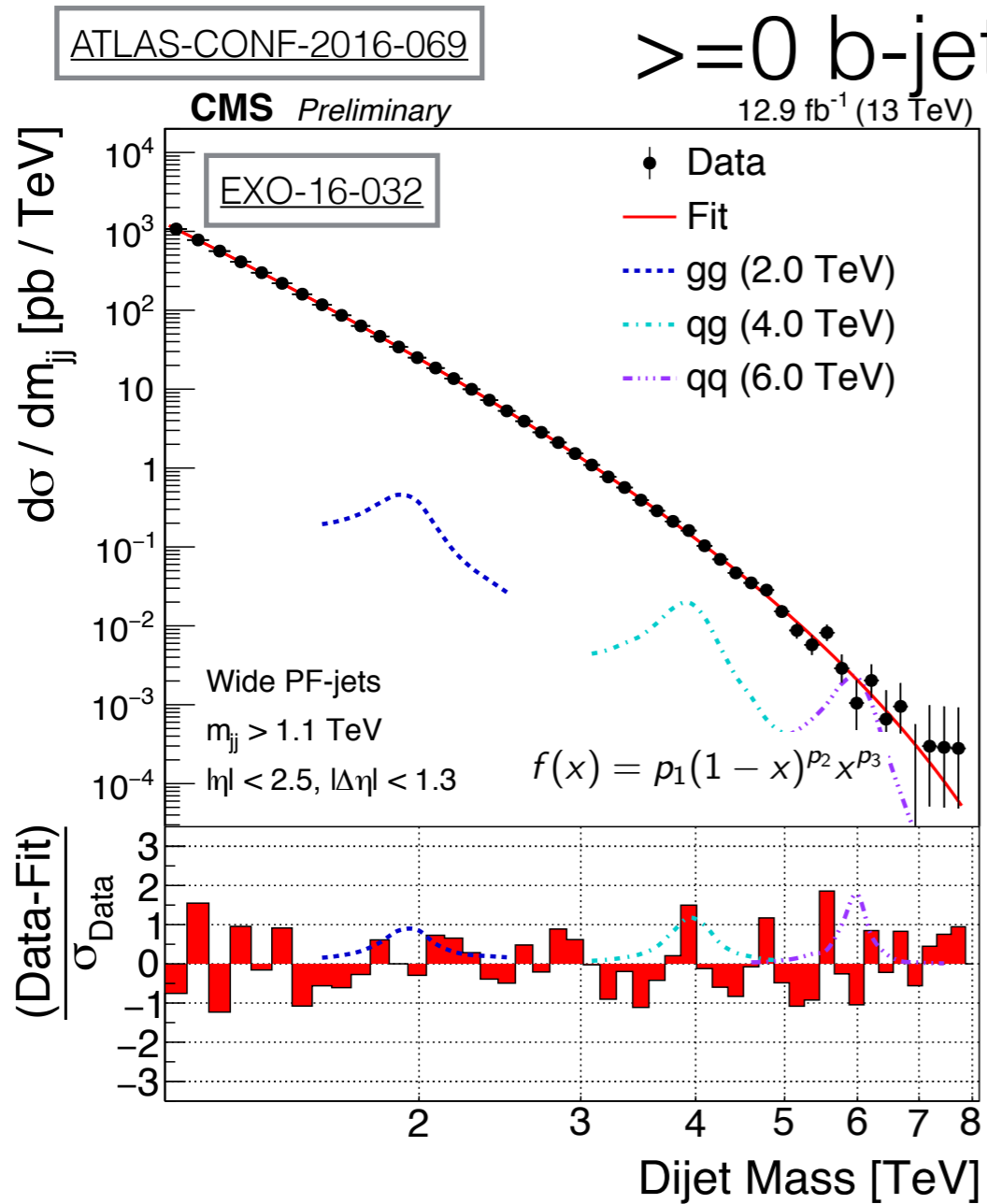
the highest dijet invariant mass
7.7 TeV



CMS Experiment at LHC, CERN
Data recorded: Thu May 12 00:40:47 2016 EEST
Run/Event: 273158 / 238962455
Lumi section: 150
Dijet Mass: 7.7 TeV



Background modeled by parametrized function for search



Model	95% CL Exclusion limit	
	Observed	Expected
Quantum black holes, ADD (BLACKMAX generator)	8.7 TeV	8.7 TeV
Excited quark	5.6 TeV	5.5 TeV
W'	2.9 TeV	3.3 TeV
W^*	3.3 TeV	3.3 TeV
Contact interactions ($\eta_{LL} = +1$)	12.6 TeV	13.7 TeV
Contact interactions ($\eta_{LL} = -1$)	19.9 TeV	23.7 TeV

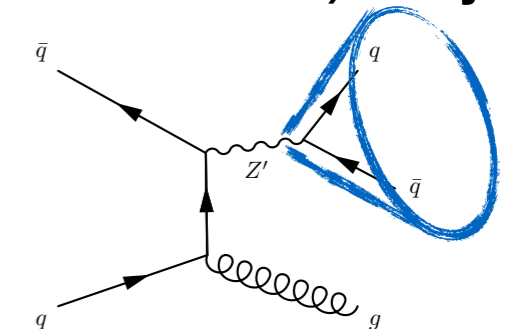
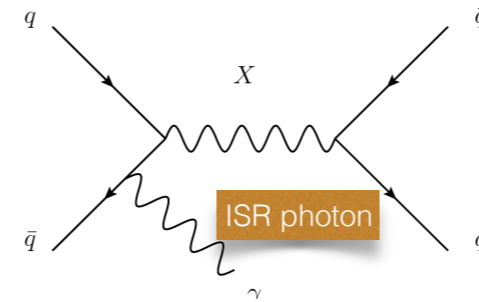
b^* (BR($b^* \rightarrow bg$)=0.85) > 2.3 TeV
 Z' > 1.5 TeV

Dijet: low mass search

Data scouting at trigger level

dijet+ISR photon

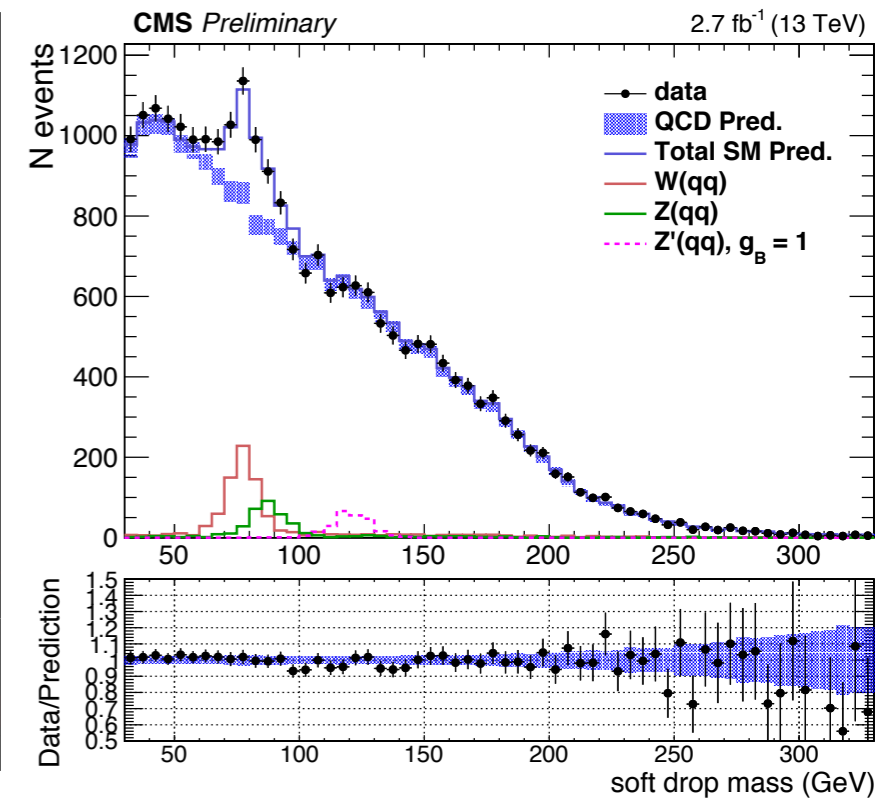
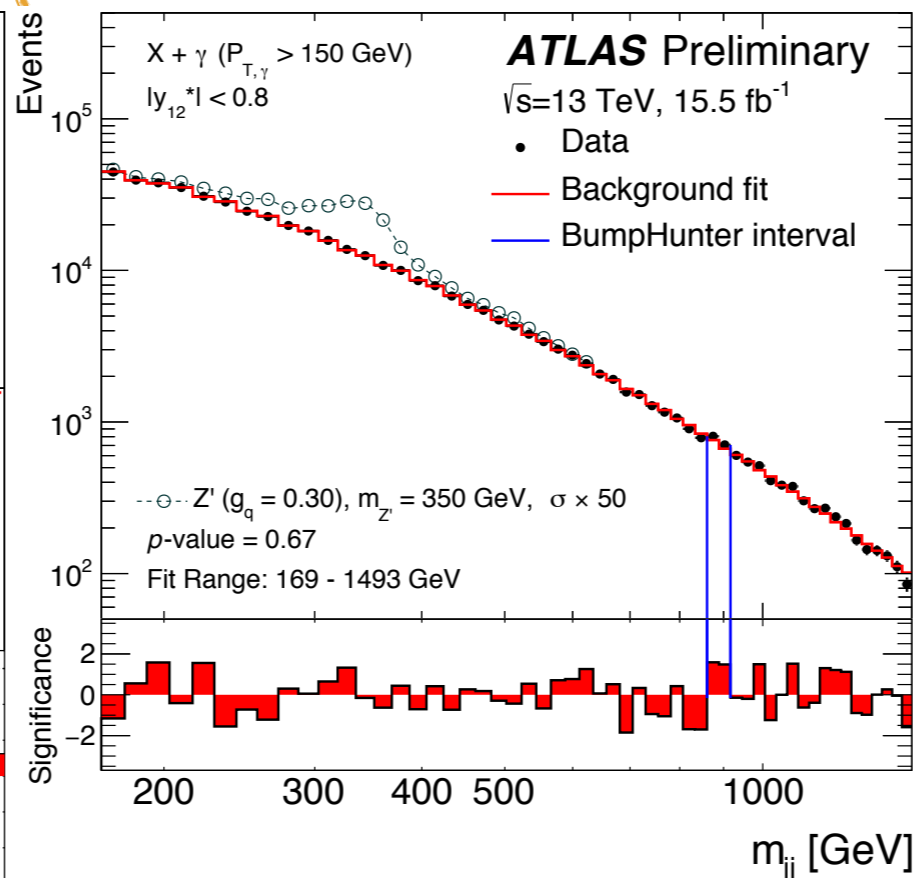
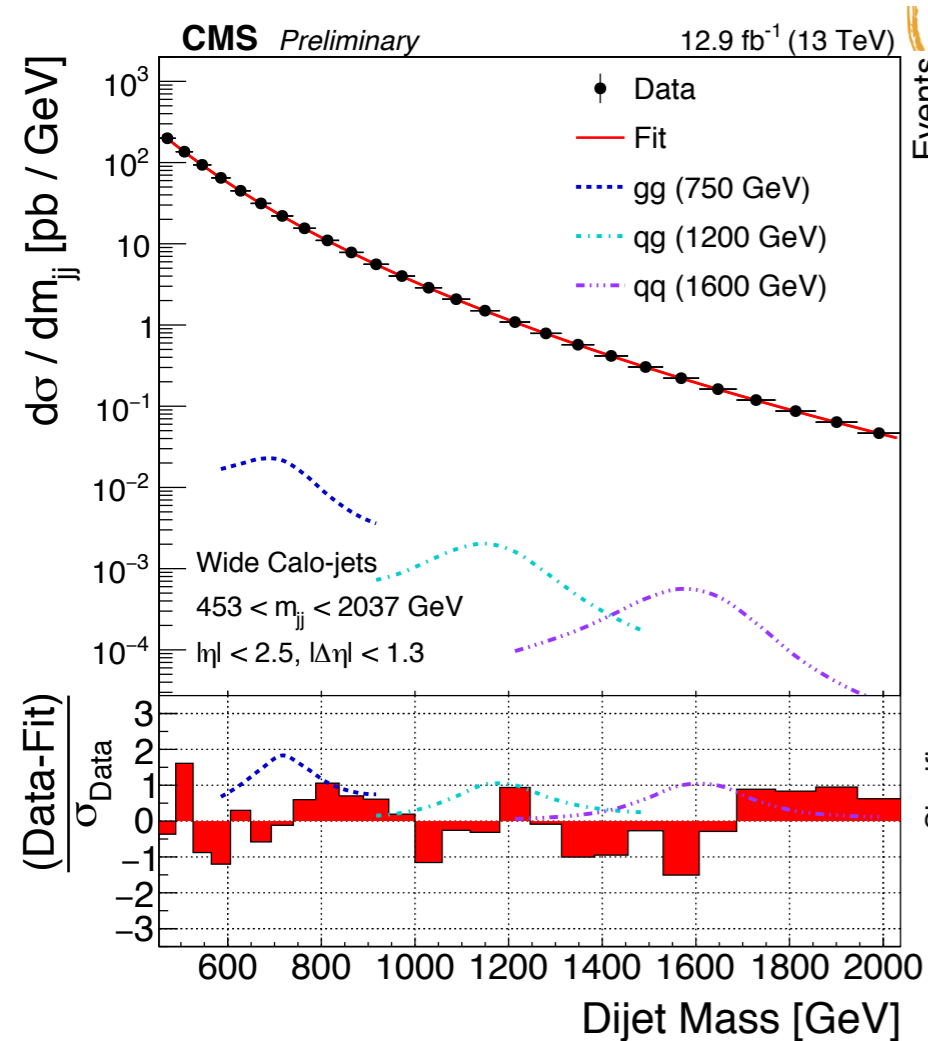
(boosted) dijet



EXO-2016-032

ATLAS-CONF-2016-029

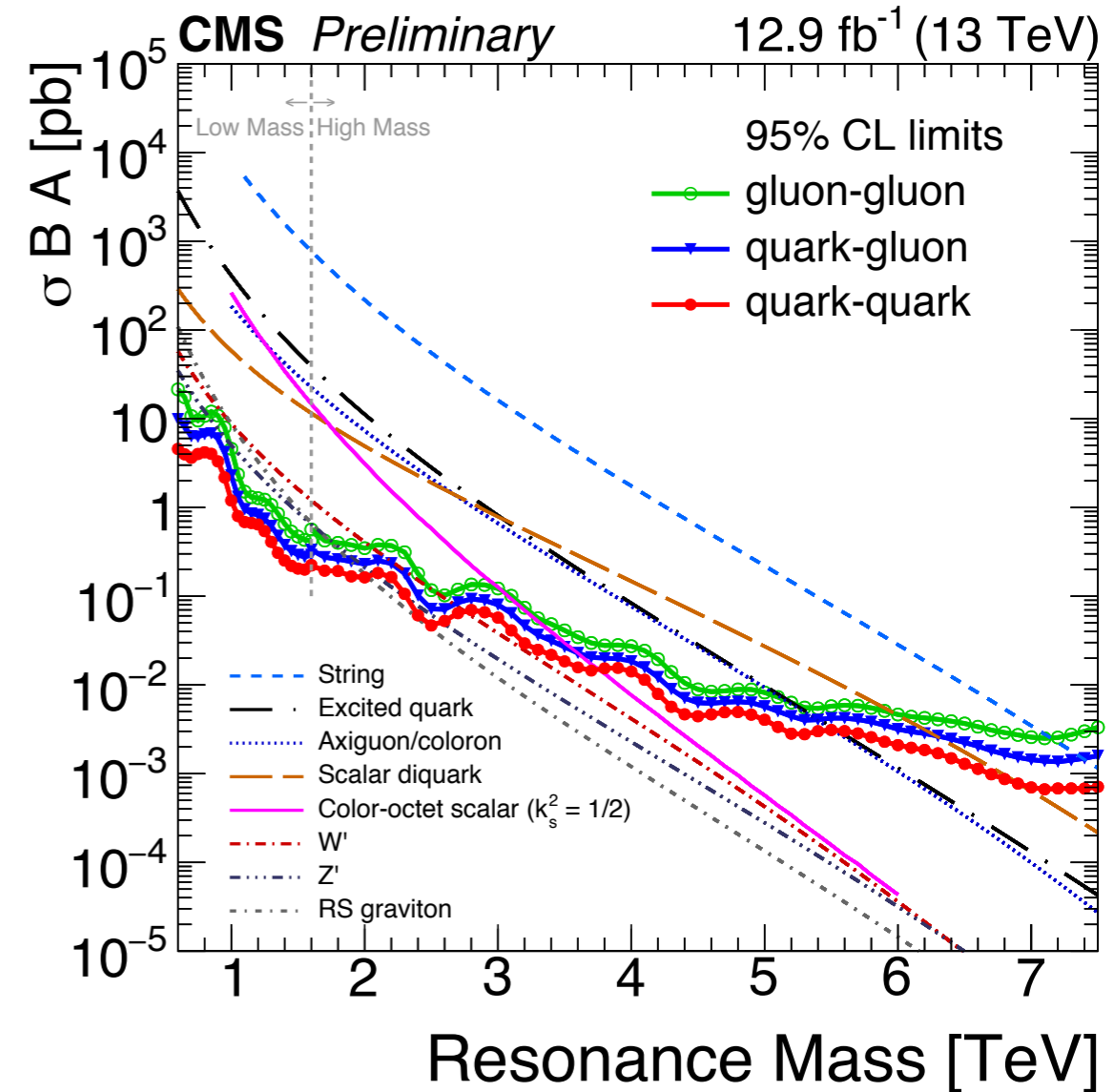
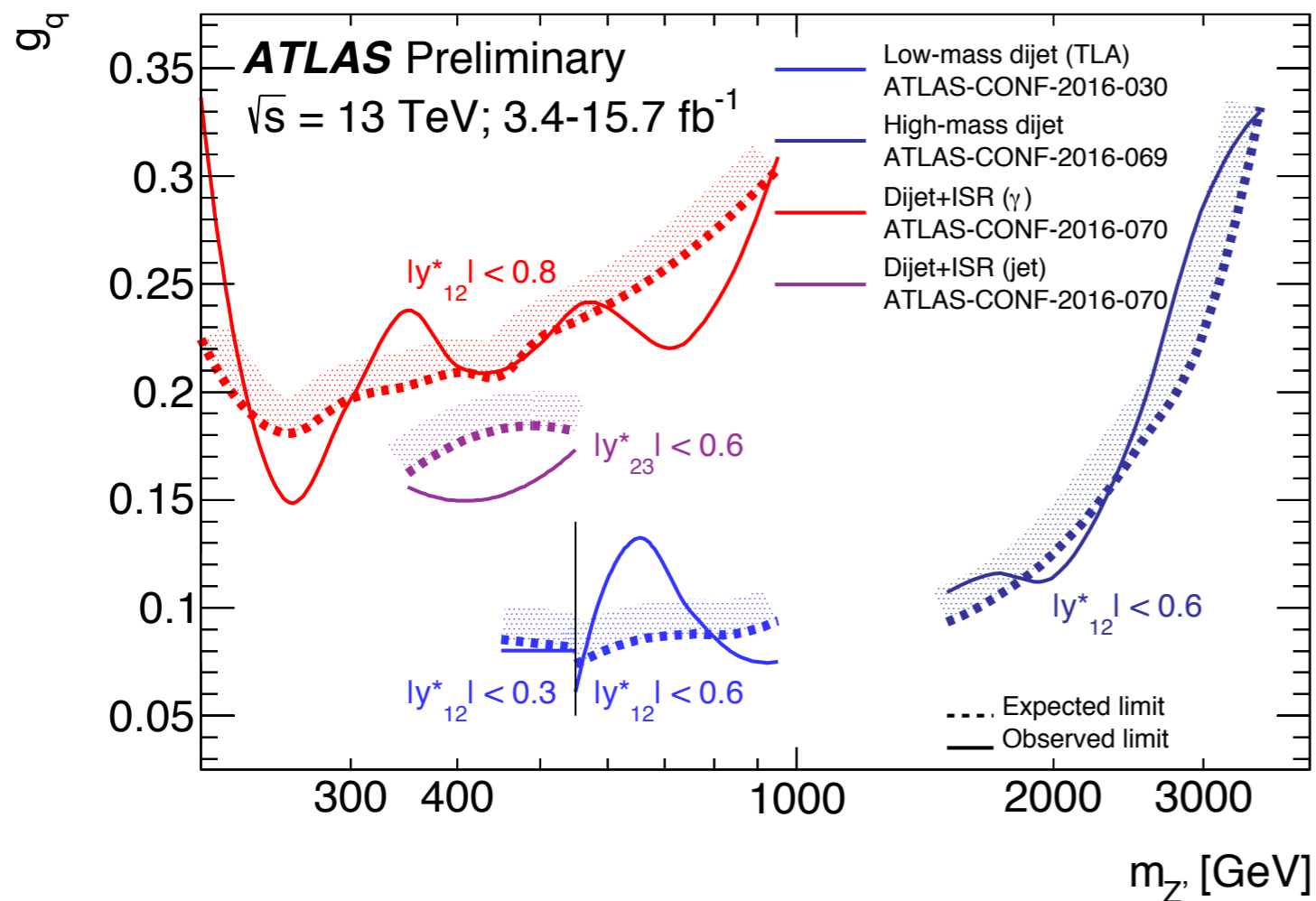
EXO-2016-030



The lowest mass (down to 100 GeV) probed by boosted dijet final state

Dijet search summary

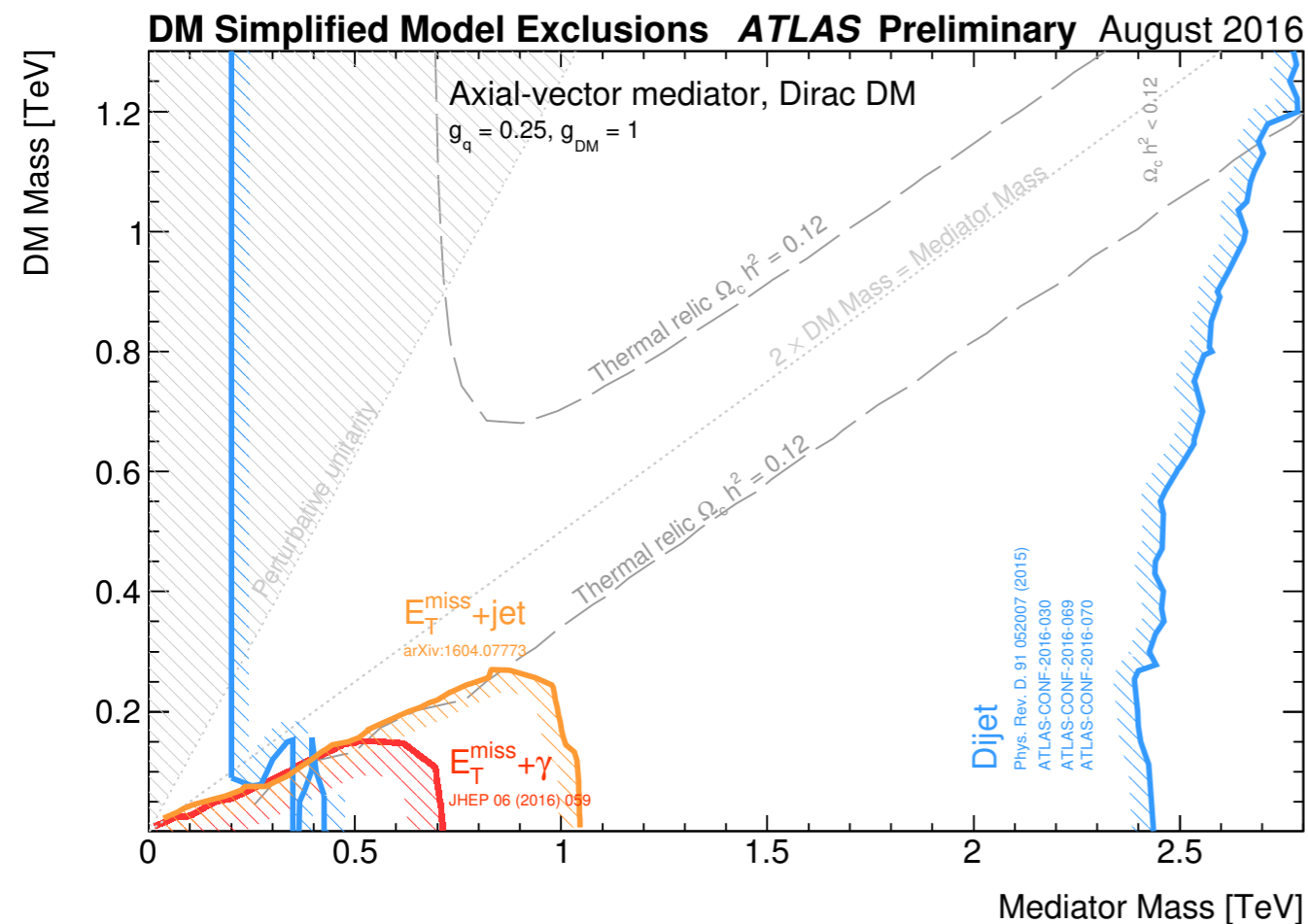
A broad mass - leptophobic Z' coupling parameter space constrained by combining various dijet channels.



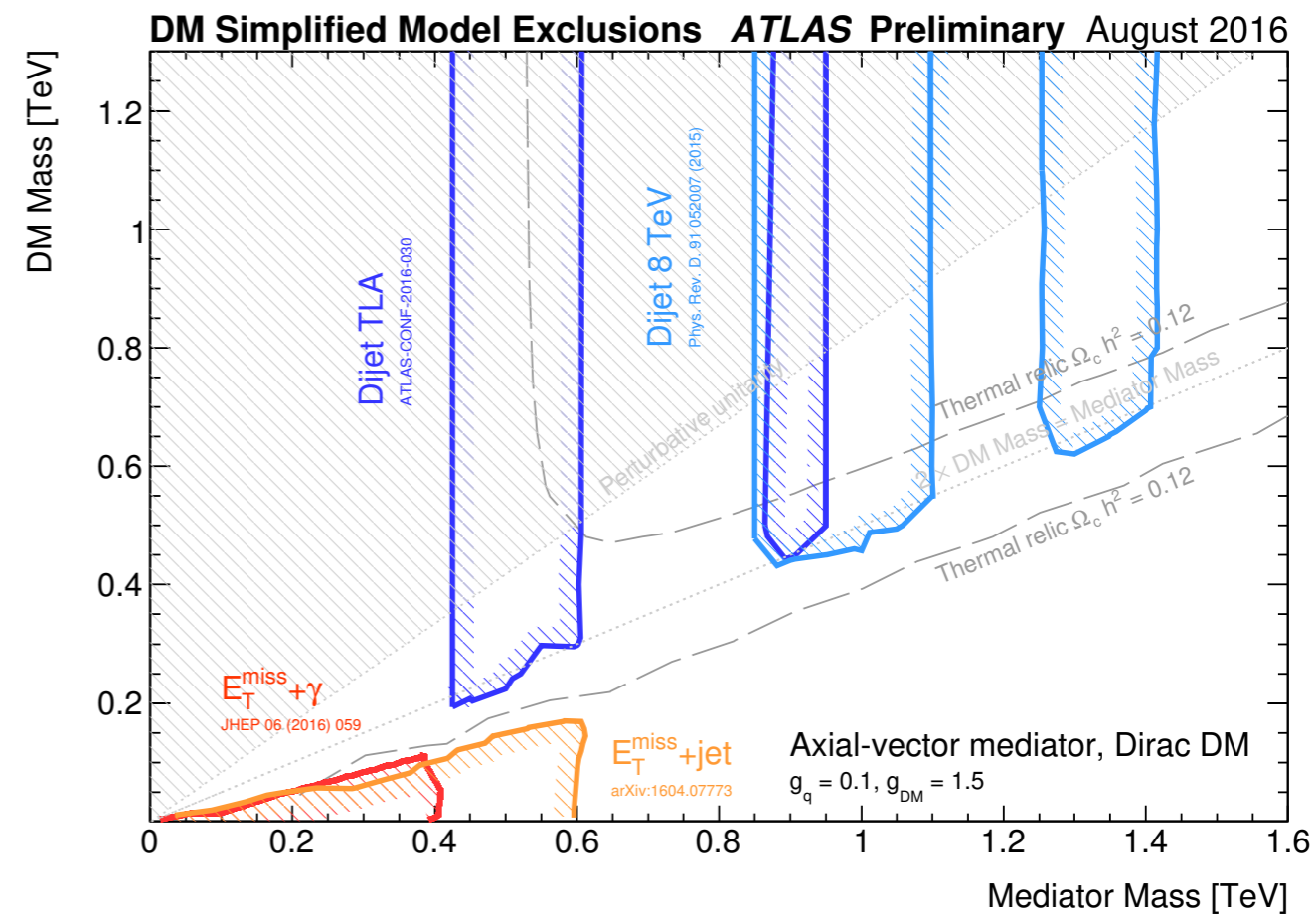
Combined with DM Interpretation

- Complementary searches by **mono-X** and **dijet**
 - Dijet searches cover a broad mediator mass range
 - Results highly depend on choice of coupling parameters

$$\mathcal{L} = g_q \bar{q} \gamma^\mu q Z'_\mu$$



$$g_q = 0.25 \quad g_{DM} = 1$$

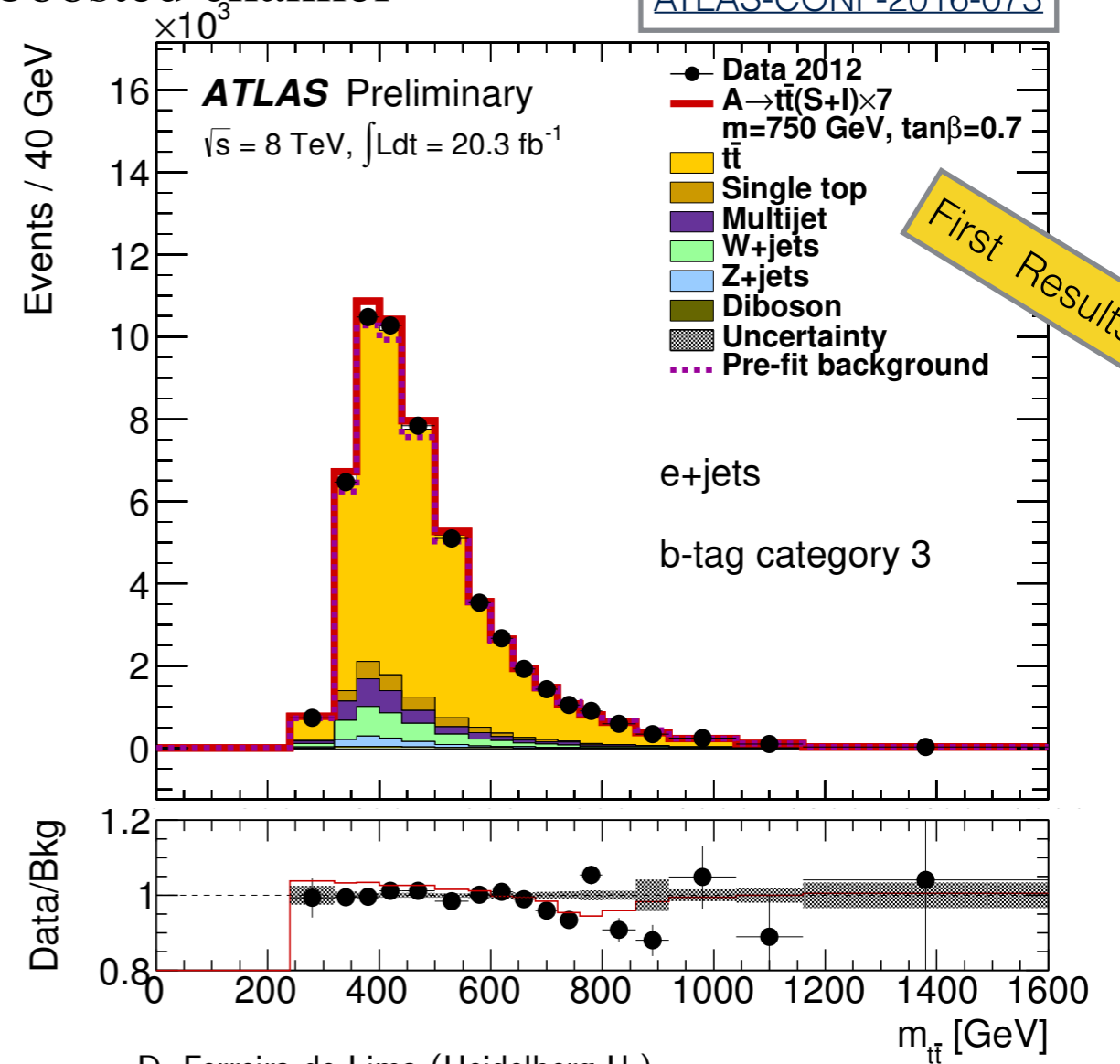
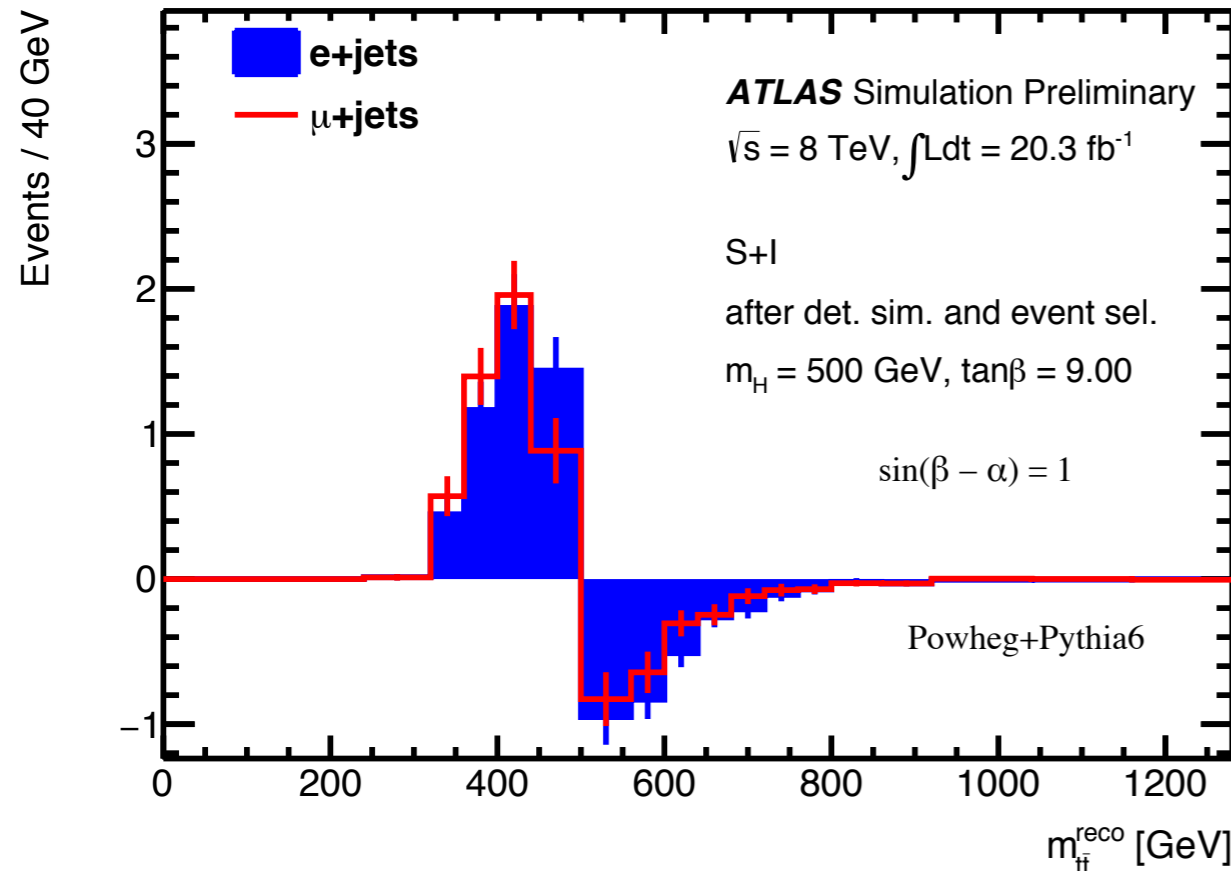
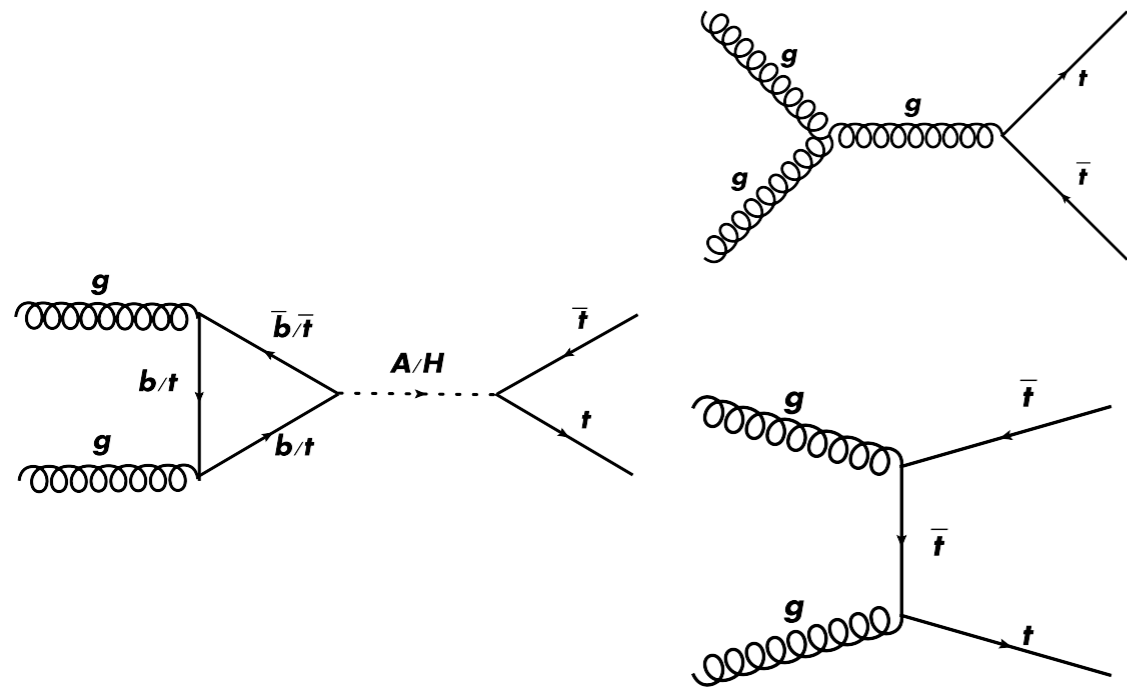


$$g_q = 0.1 \quad g_{DM} = 1.5$$

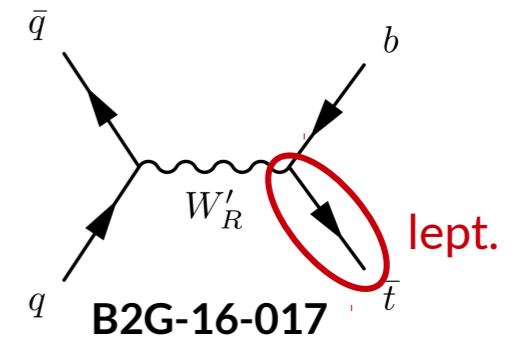
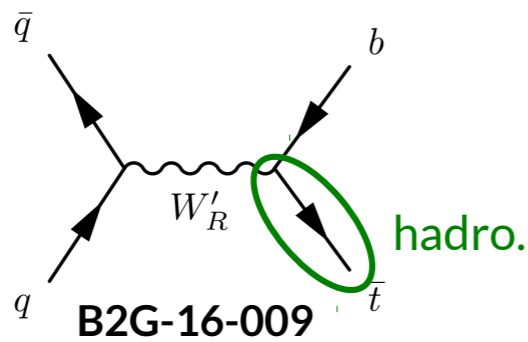
Non-trivial interference in gg to $t\bar{t}$ production between SM and type-II 2HDM

Reinterpretation of 8TeV analysis with addition of boosted channel

ATLAS-CONF-2016-073



$A(500\text{GeV}): \tan(\beta) > 0.8$
 $H(500\text{GeV}): \tan(\beta) > 0.5$

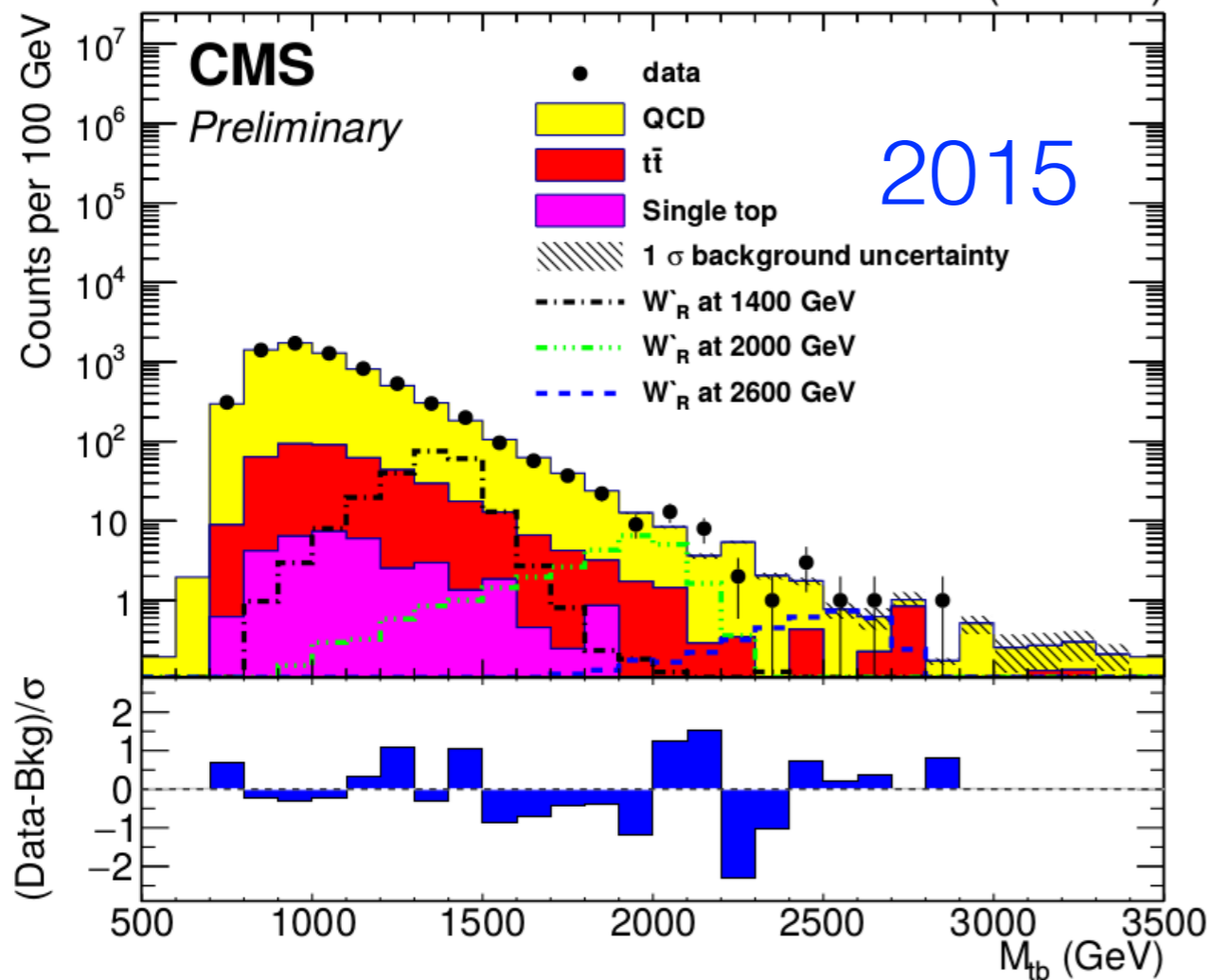
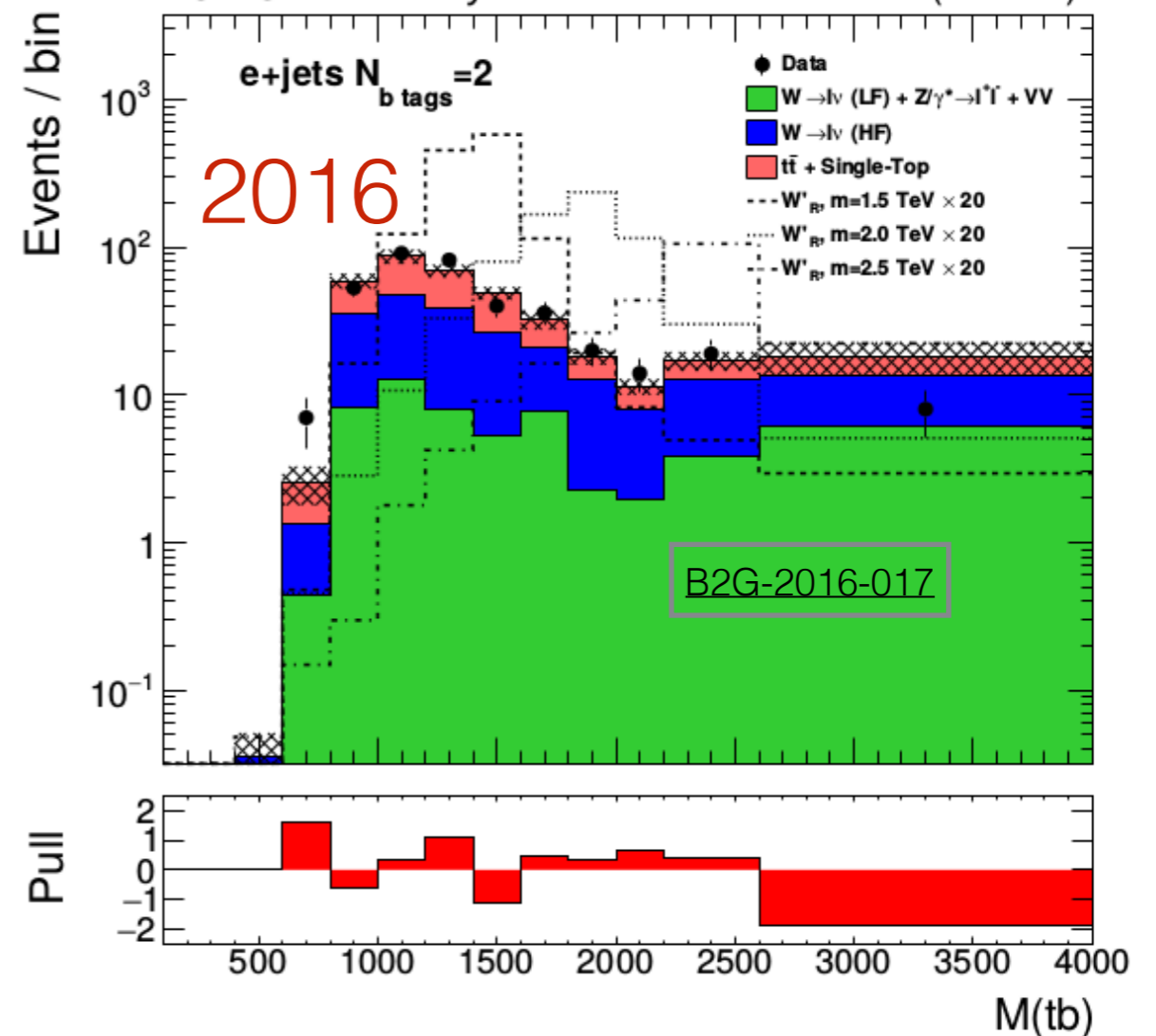


M_{tb} distribution (postfit)

 2.55 fb⁻¹ (13 TeV)

M_{tb} (e channel, 2 b-tags)

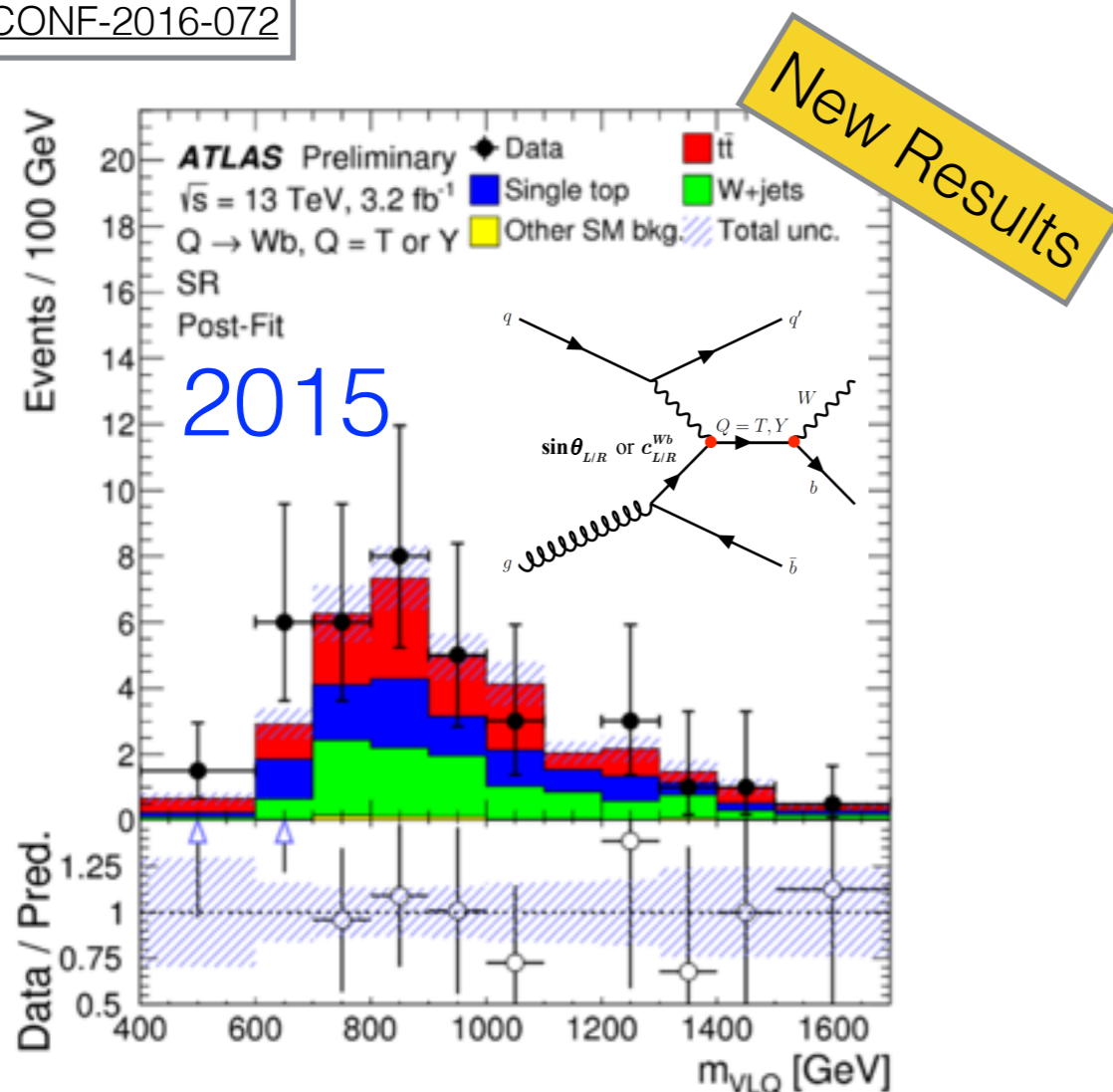
CMS Preliminary

 12.9 fb⁻¹ (13 TeV)

 $W'_R : [1 \sim 2] \text{ TeV}$

 $W'_R : [1 \sim 2.67] \text{ TeV}$

VLQ - Spin 1/2, colored, charged particles with both left- and right-handed coupling to charged currents.

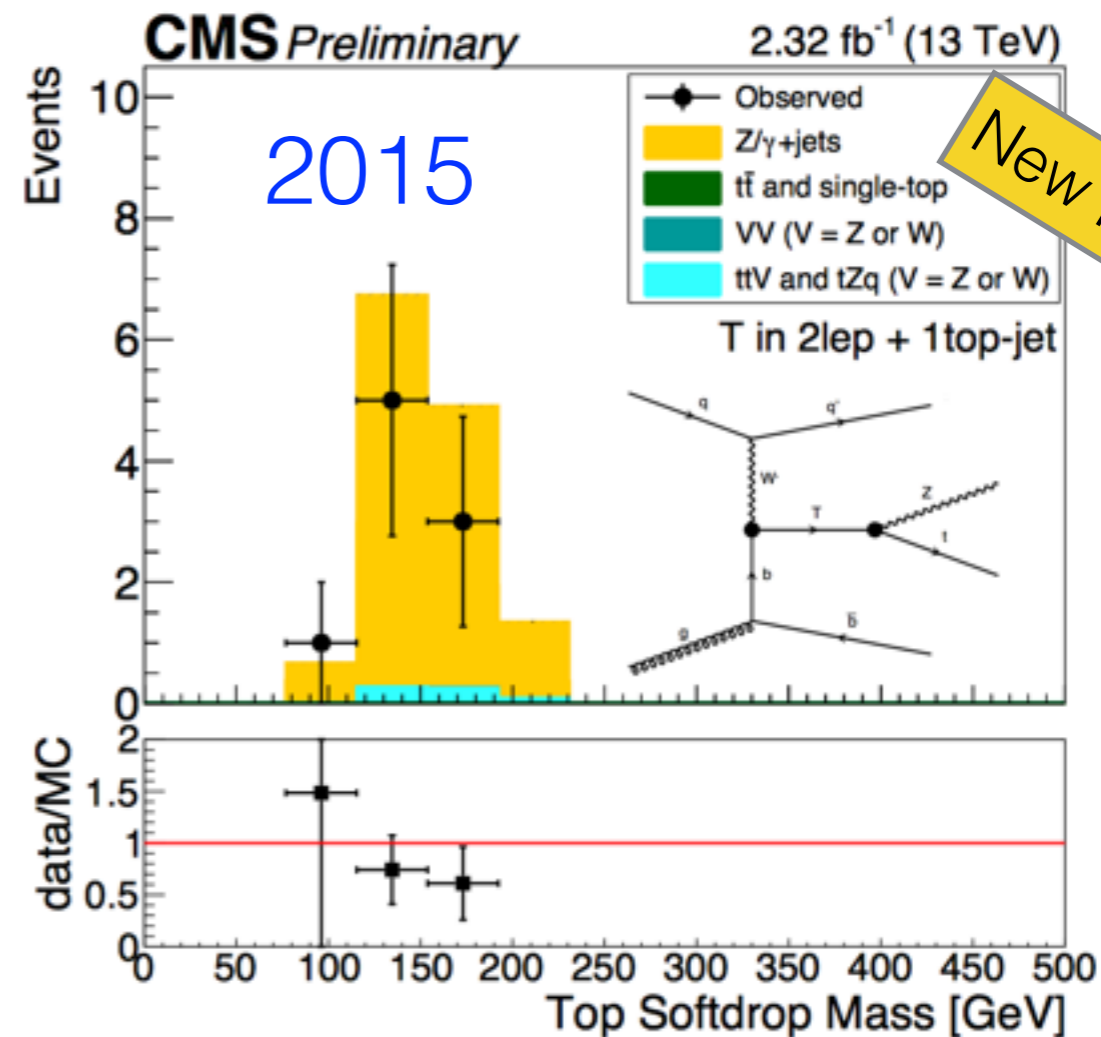
- **pair production** through QCD - dominant in low mass
Most channels have been updated with 2015 data
- **single production** through EWK coupling - dominant in high mass (model dependent)
New results shown below.

ATLAS-CONF-2016-072



New Results

CMS-PAS-B2G-16-001



New Results

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

$$mT(C(bW)=1, BR(tZ)=0.25) > 1.37 \text{ TeV}$$

VV/Vh/hh Resonance

Salvatore Rappoccio's talk

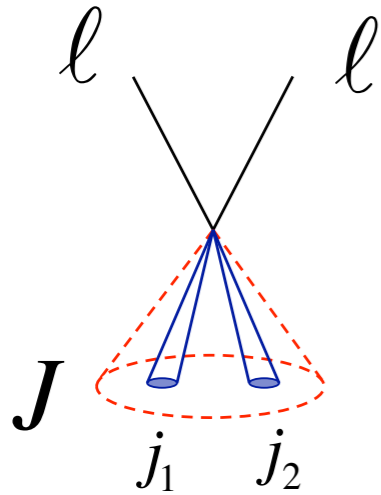
Nikolaos Konstantinidis's talk

Karsten Koeneke's talk

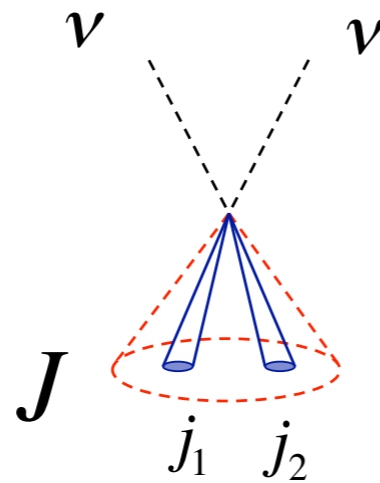
Benedikt Vormwald's talk

- Search for **VV/Vh/hh** resonance in **leptonic/hadronic** decay channels using **large-R jets with jet substructure techniques**

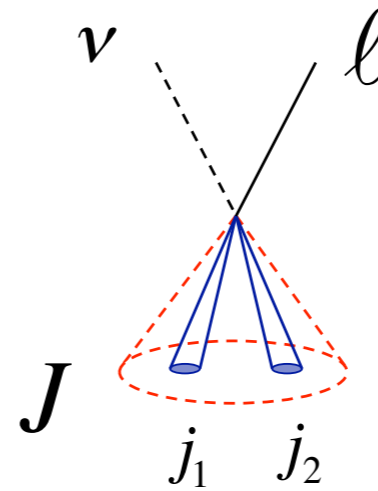
Z(l \bar{l})V



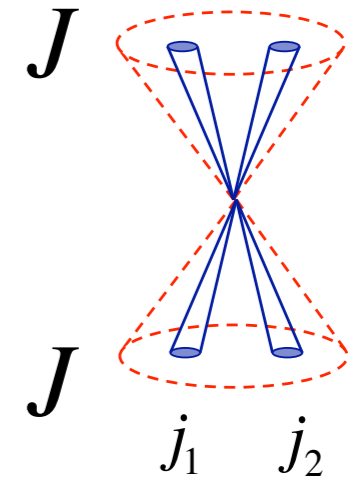
Z(\nu\bar{\nu})V



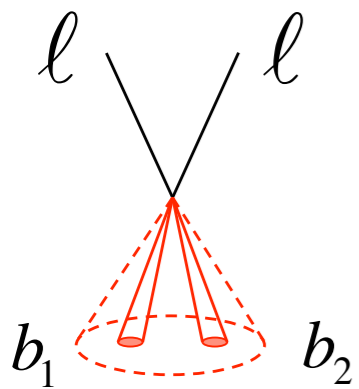
W(l\nu)V



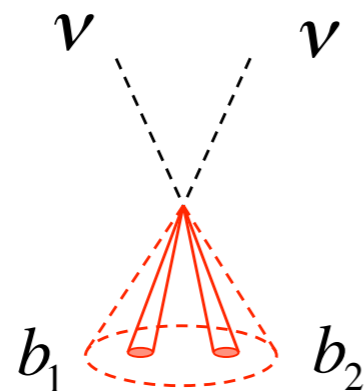
VV(JJ)



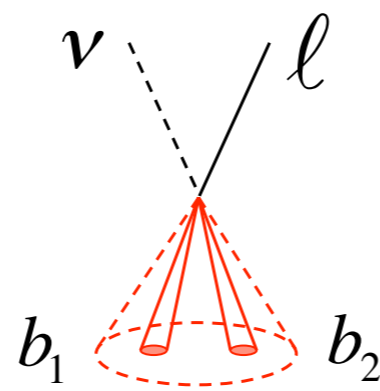
Z(l \bar{l})h



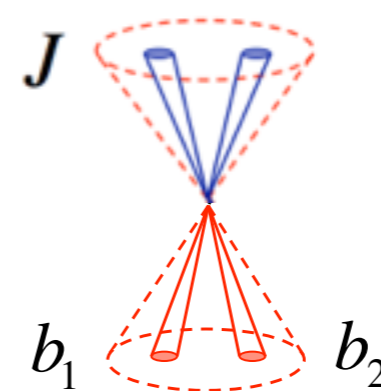
Z(\nu\bar{\nu})h



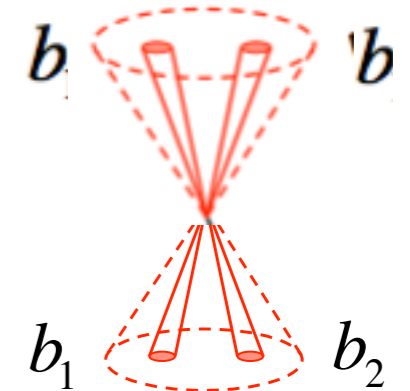
W(l\nu)h



V(J)h



hh

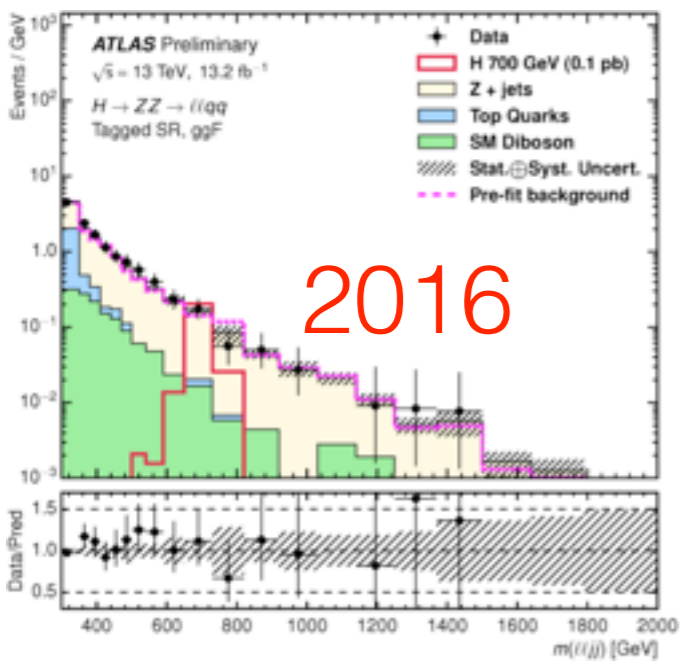


VV/Vh/hh Search Results

Z(l)lV

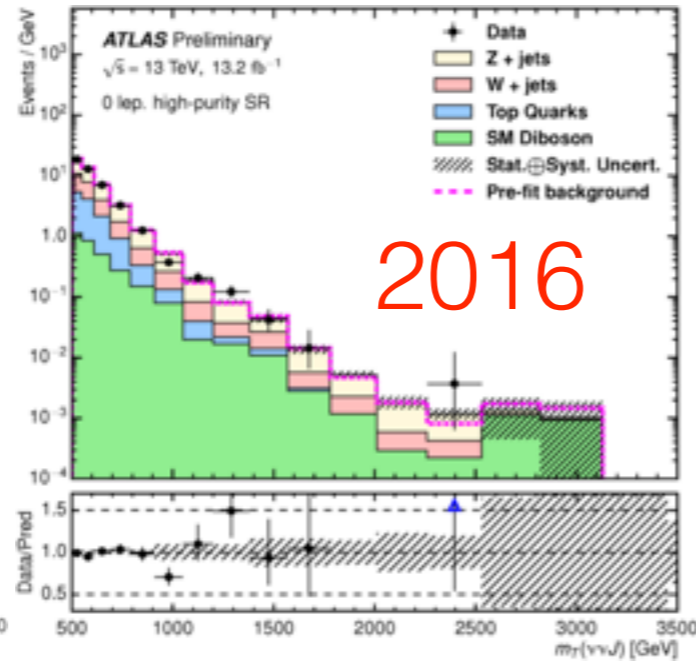
ATL-CONF-2016-082

B2G-16-010



Z(vv)V

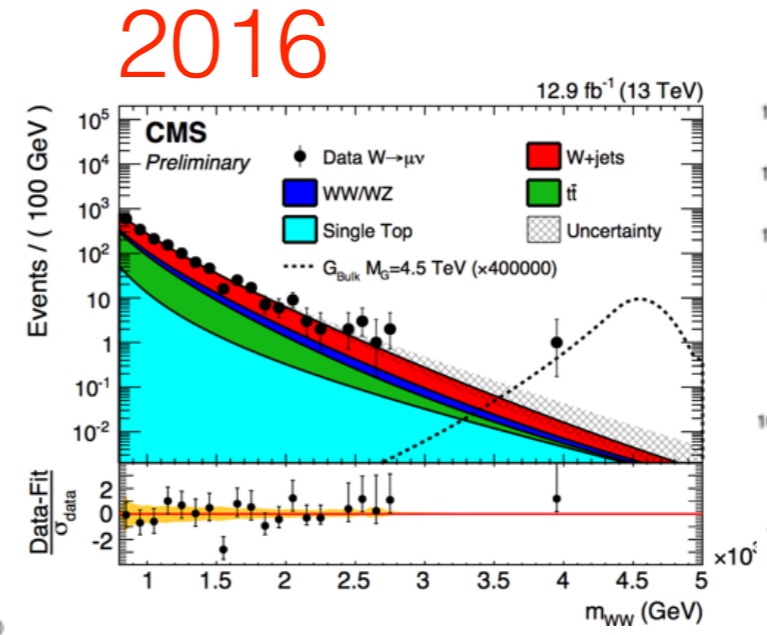
ATL-CONF-2016-082



W(lv)V

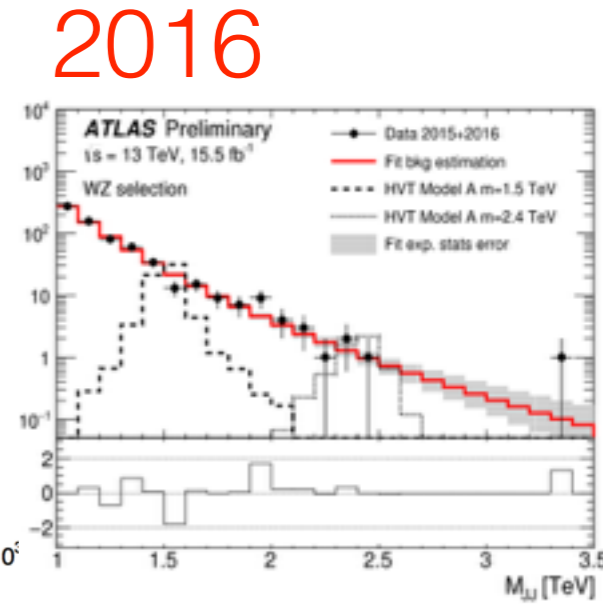
ATL-CONF-2016-062

B2G-16-020



VV(JJ)

ATL-CONF-2016-055



Z(l)lh

B2G-16-003

Z(vv)h

arXiv:1607.05621

W(lv)h

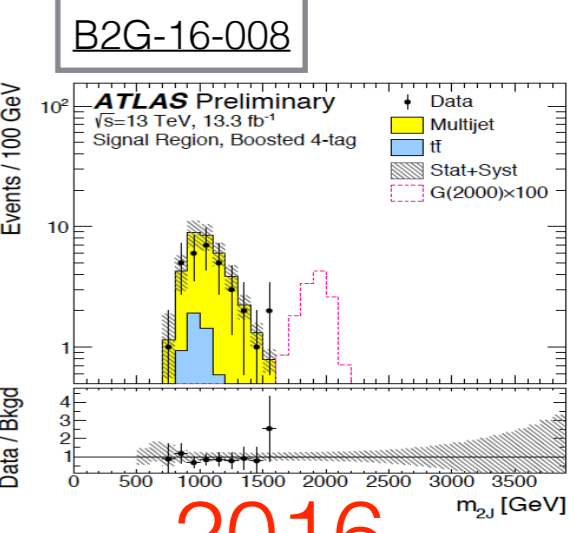
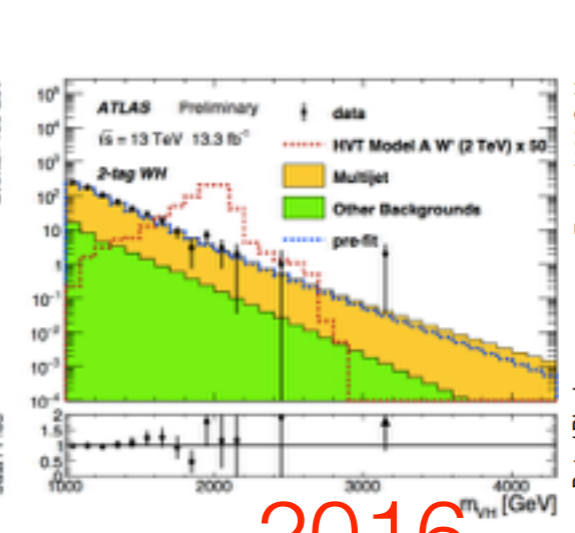
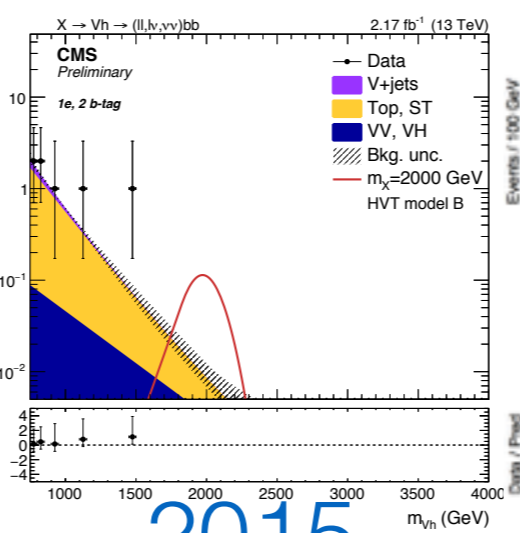
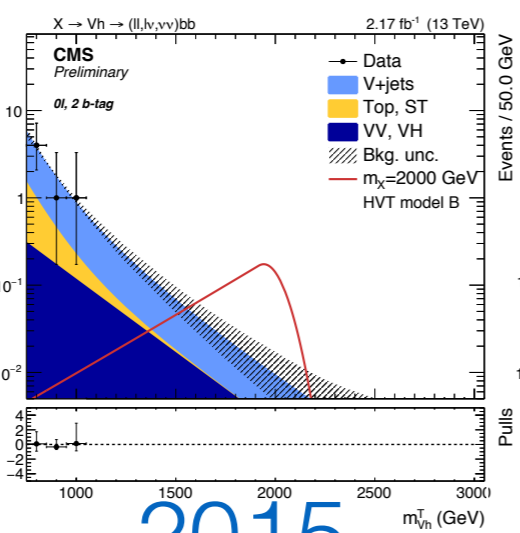
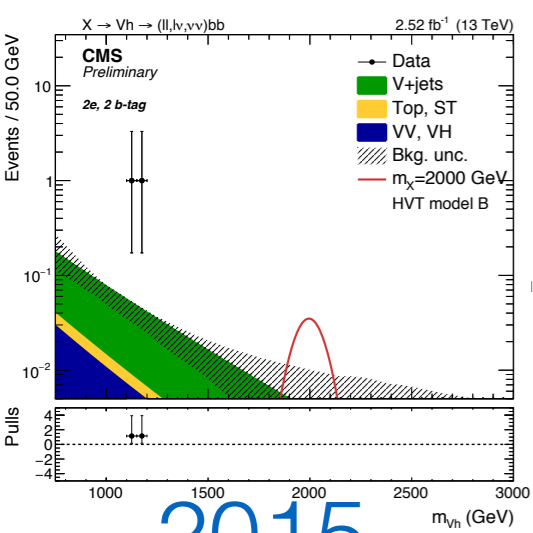
ATL-CONF-2016-083

V(J)h

ATL-CONF-2016-049

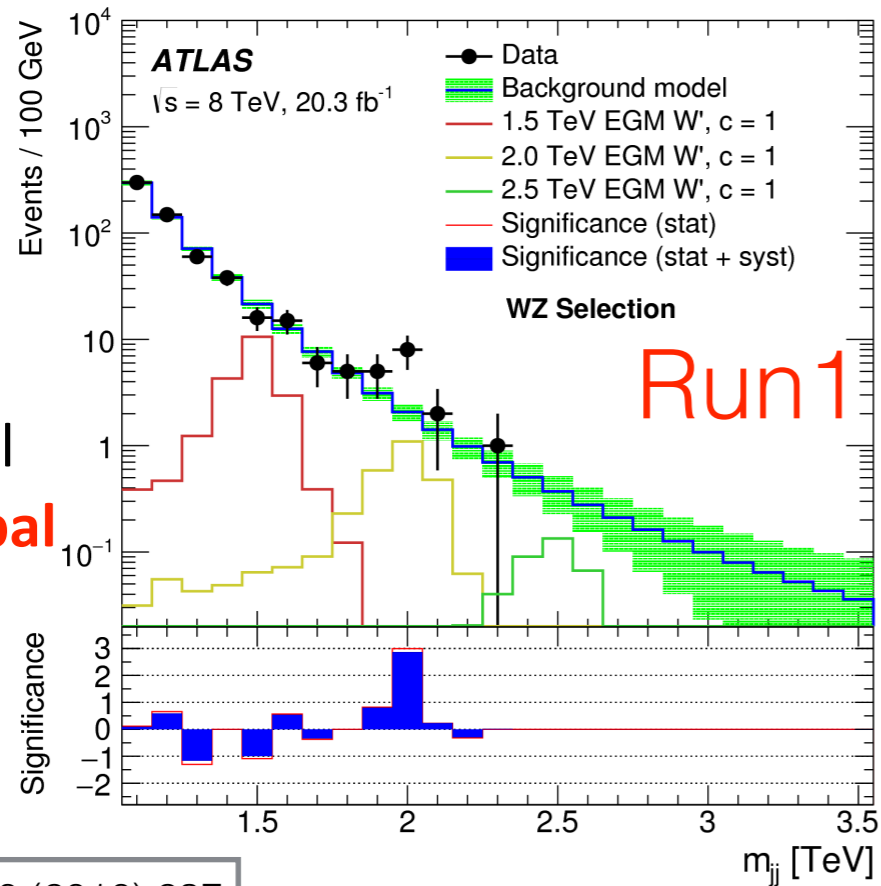
hh

B2G-16-008



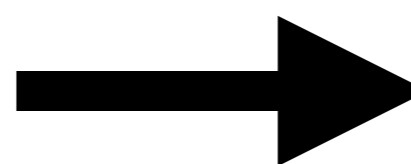
Revisit diboson excesses in Run1

JHEP12(2015)055

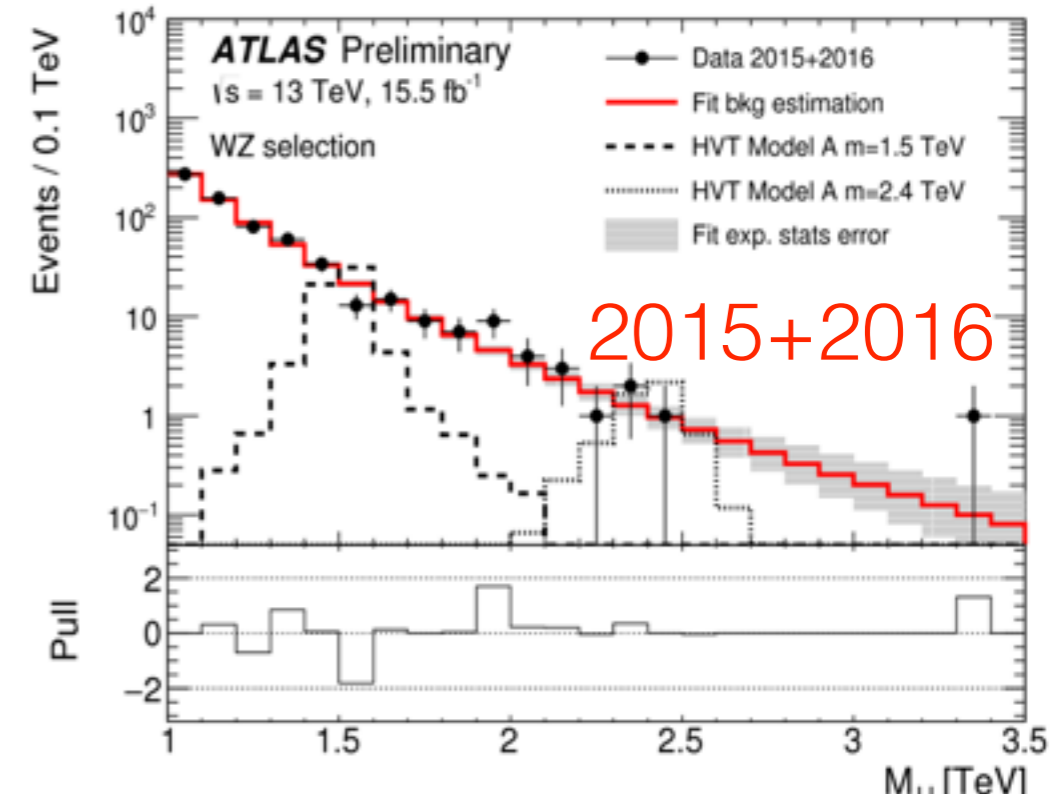


$m = 2 \text{ TeV}$
 3.4σ local
 2.5σ global

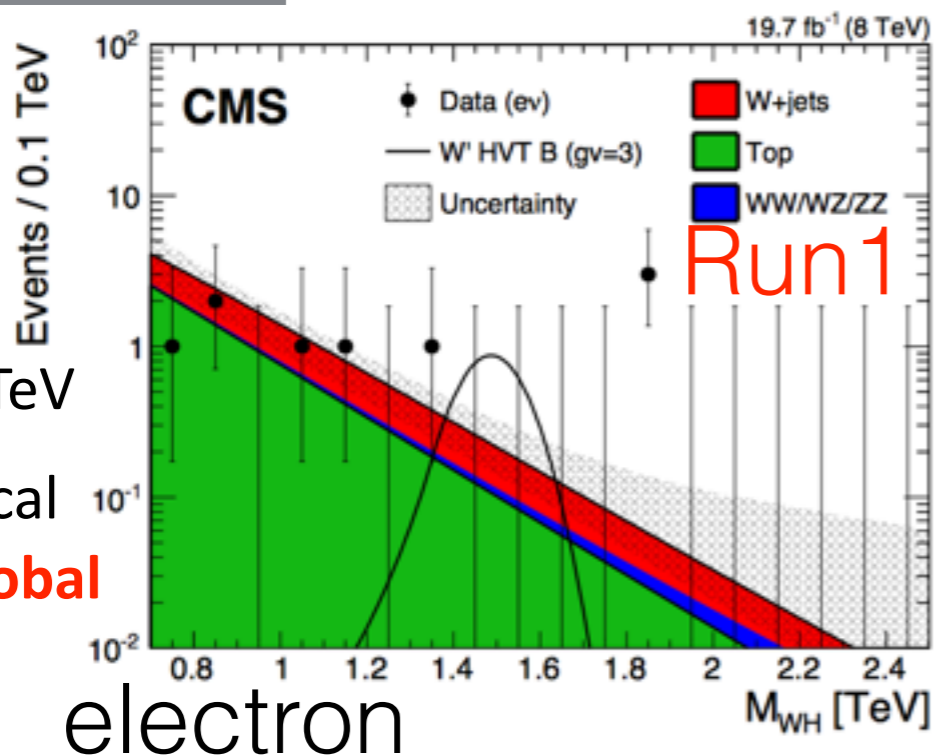
Excesses
not
confirmed
in Run2



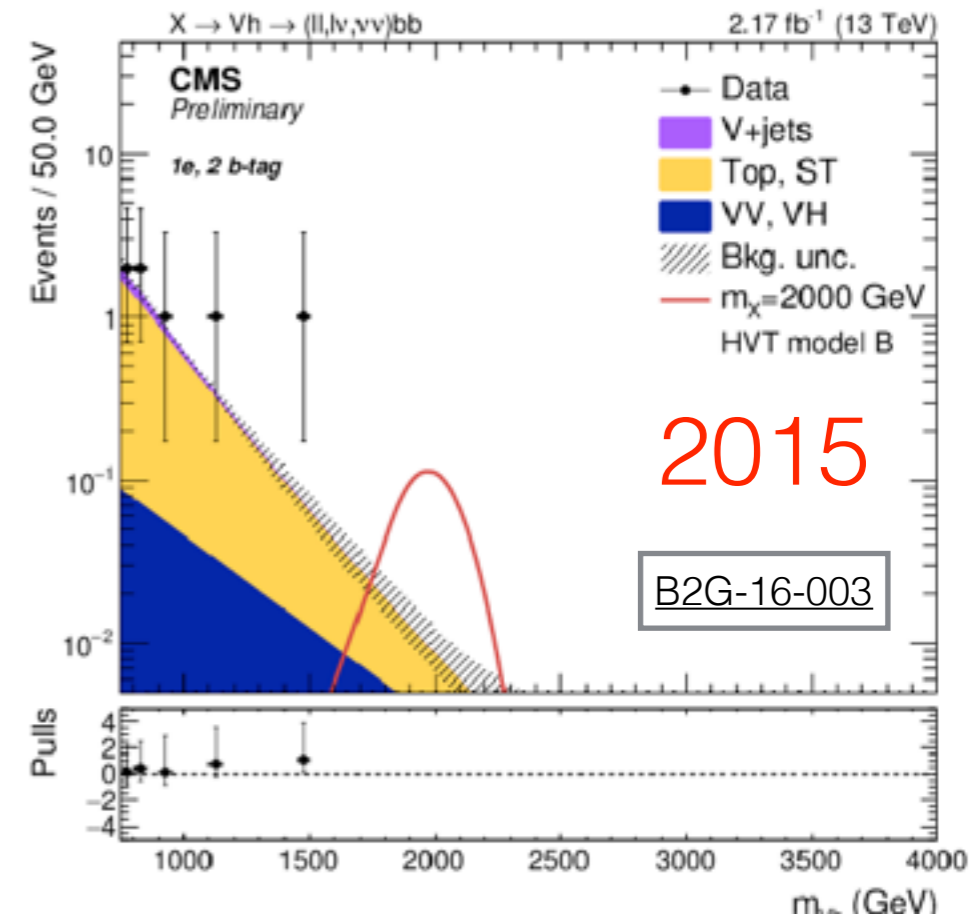
ATL-CONF-2016-055



EPJC 76 (2016) 237

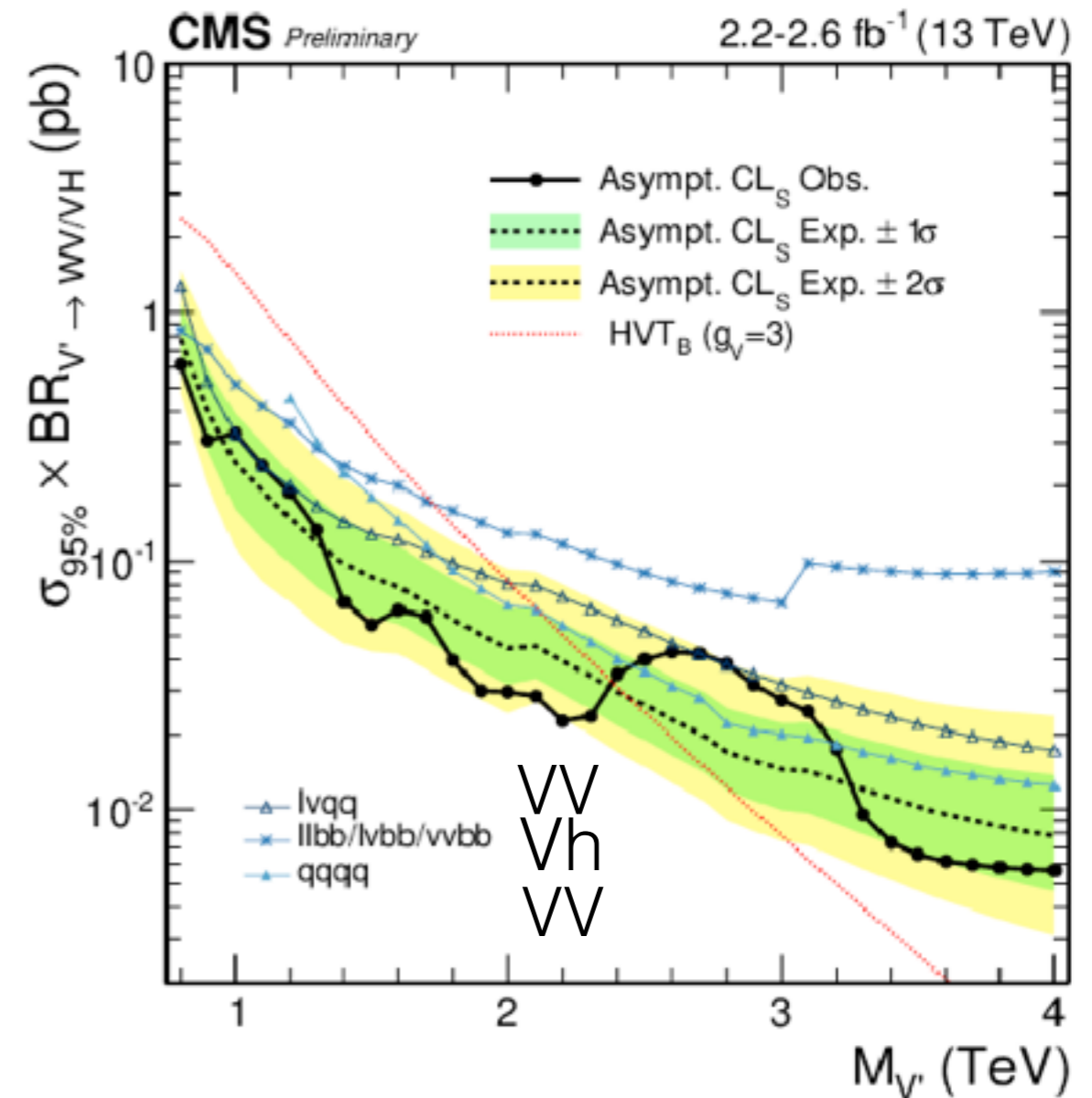
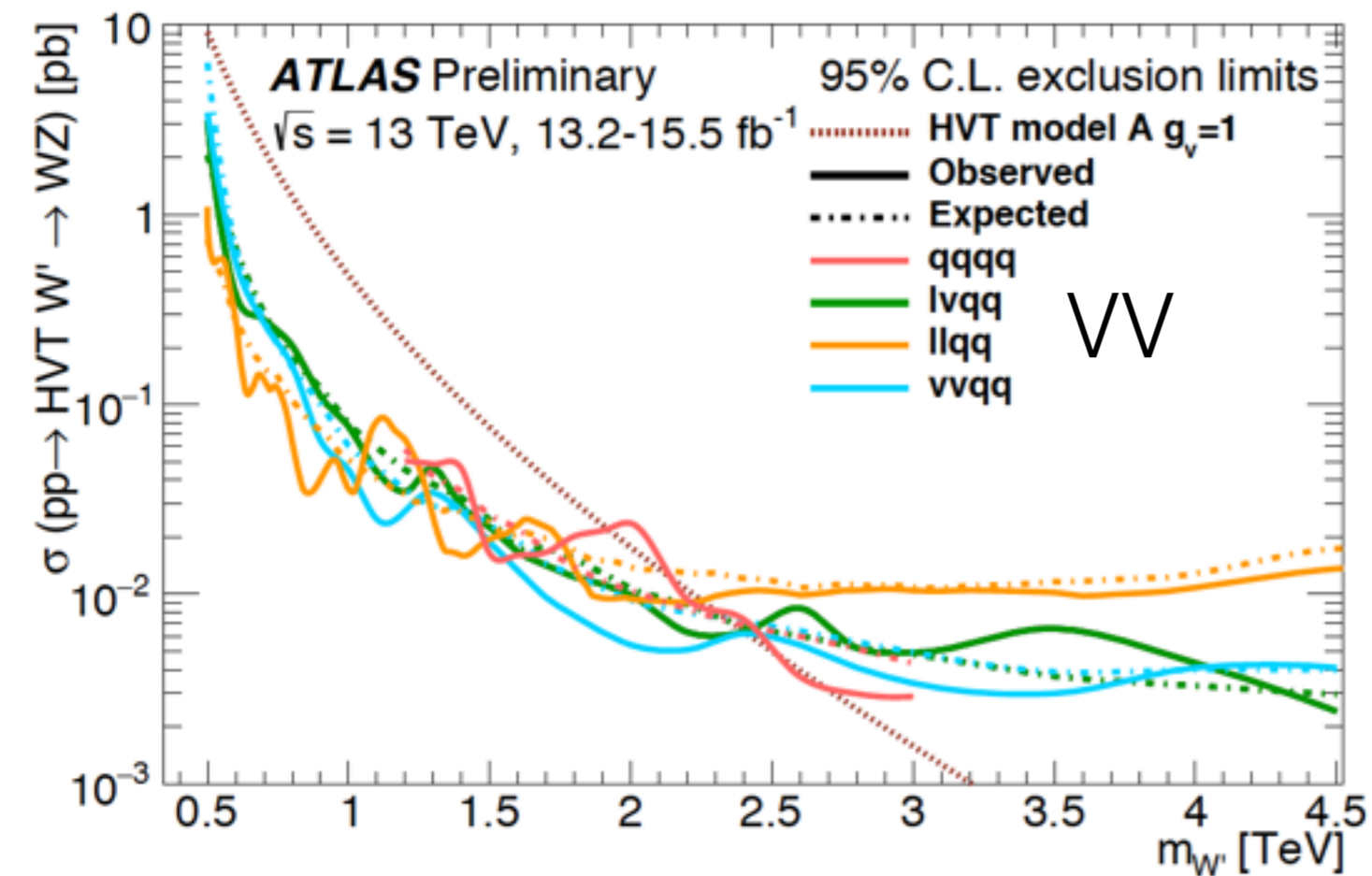


$m = 1.8 \text{ TeV}$
 2.9σ local
 1.9σ global

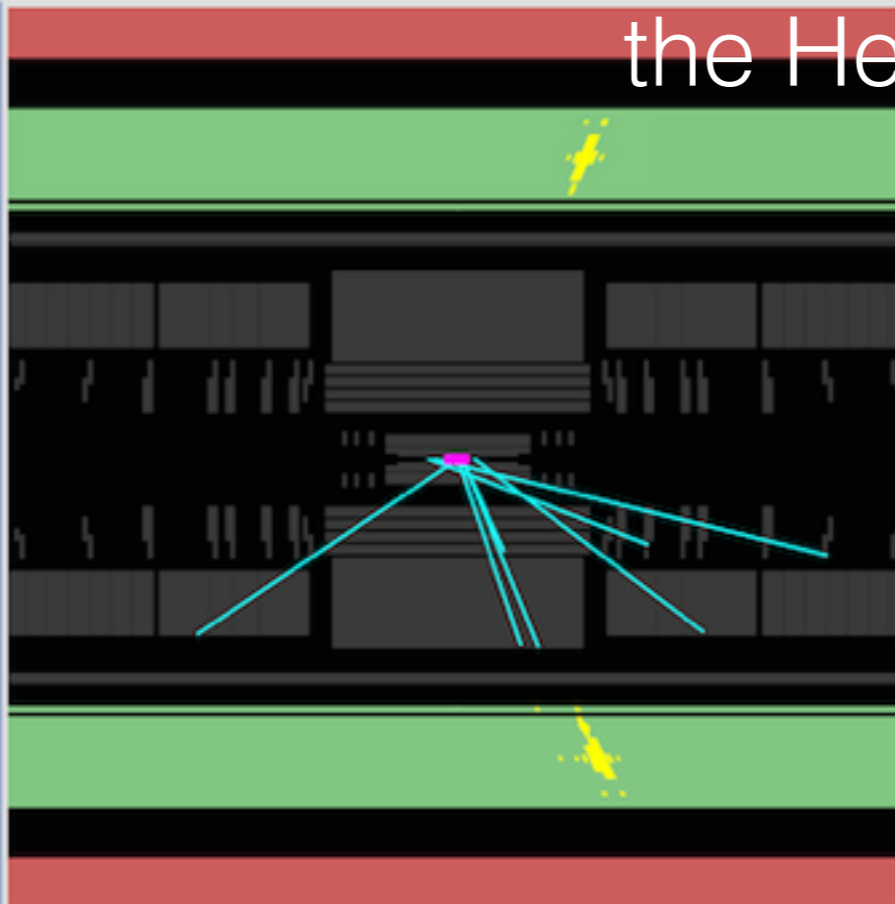
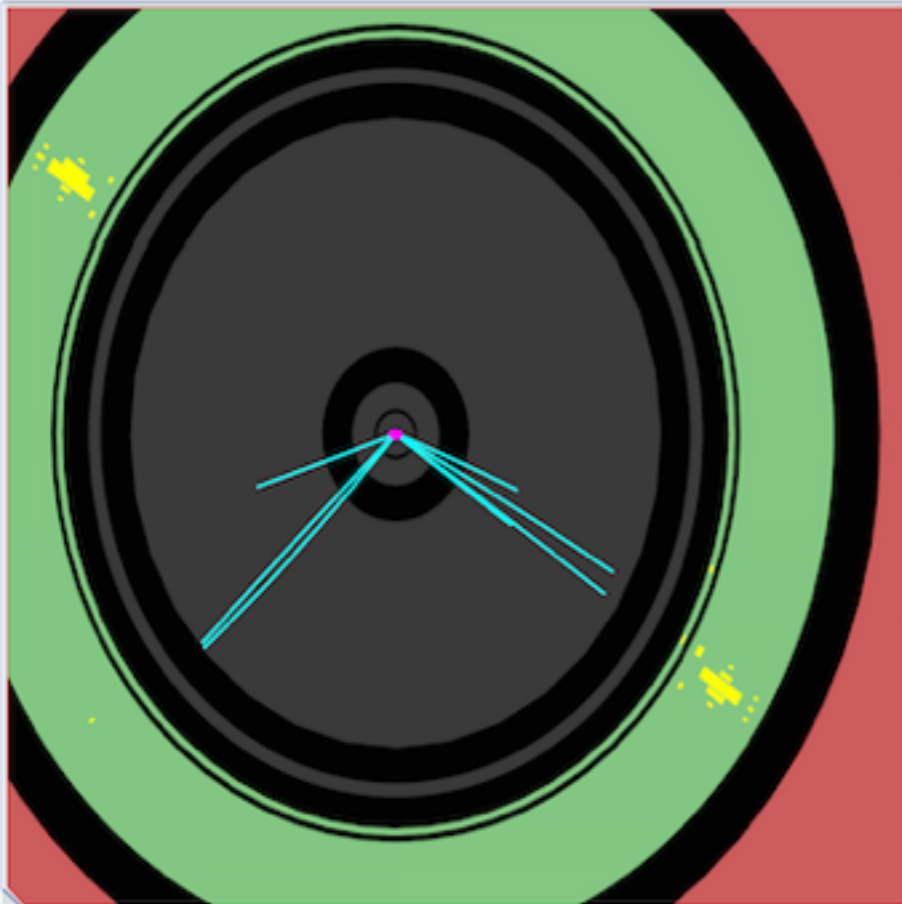
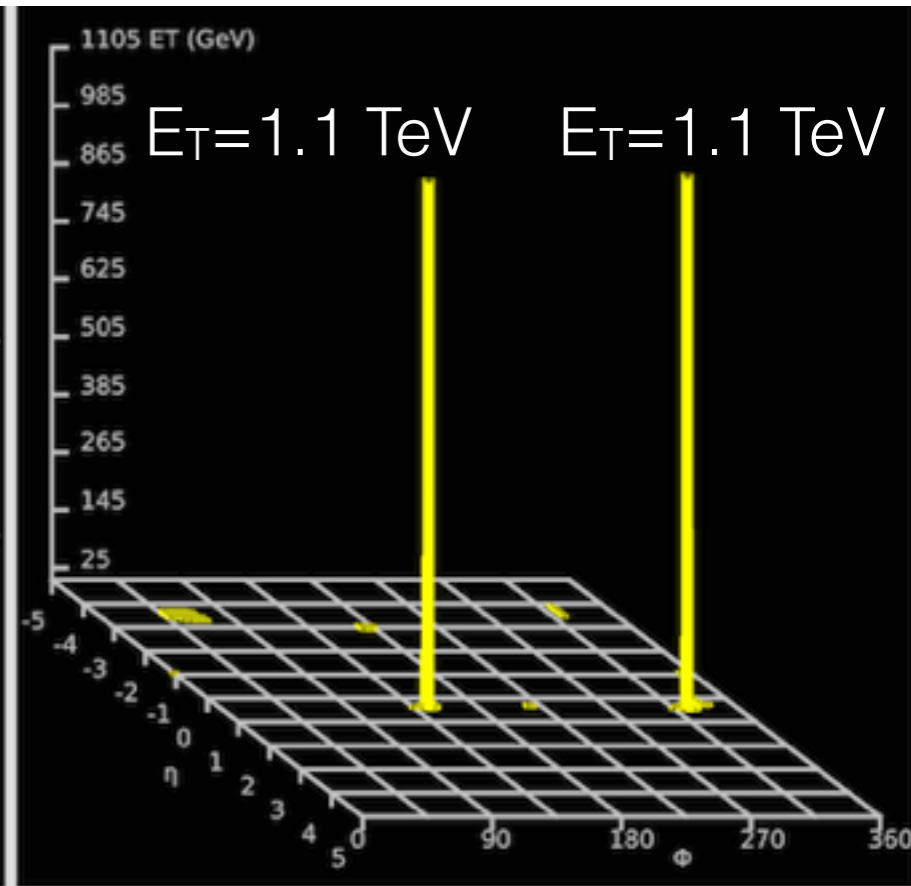
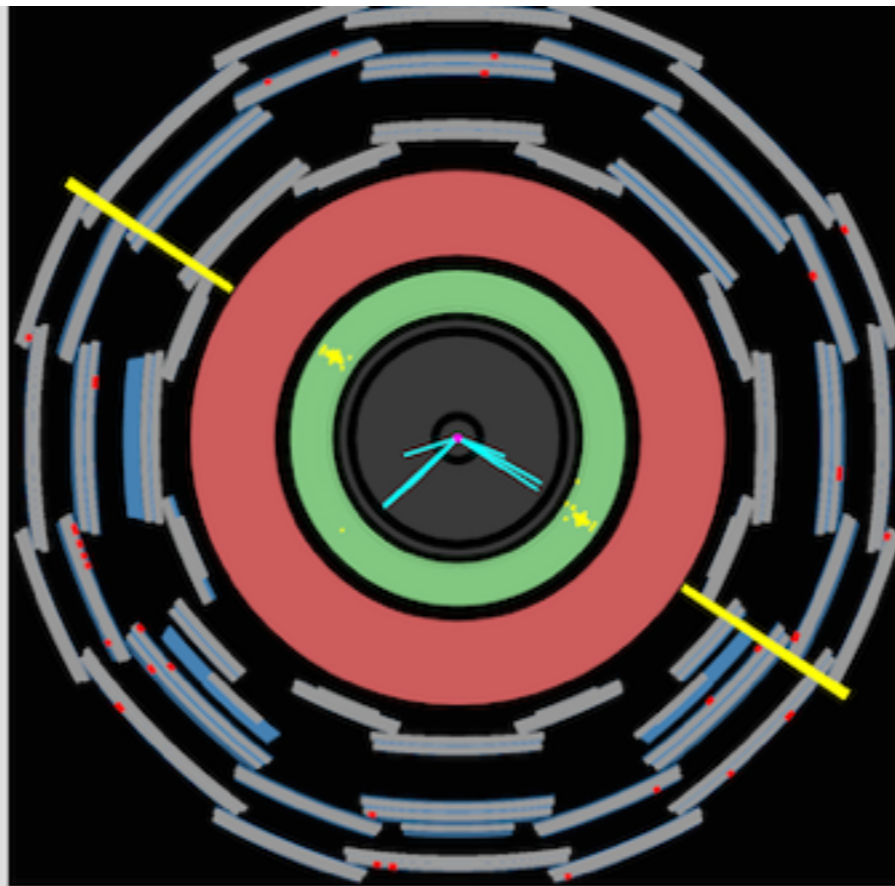
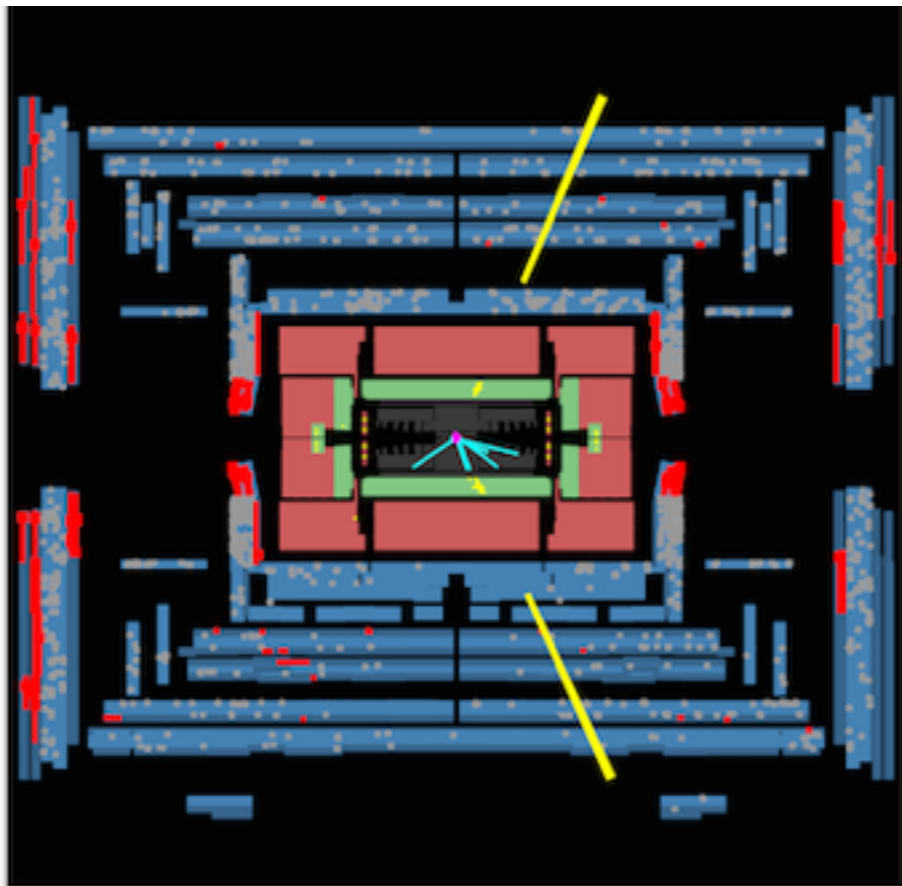


Diboson Resonance Limit

- RS Graviton mass limit up to 2 TeV
- HVT W' mass limit up to 2.4 TeV
- a joint interpretation of VV/Vh channel



Diphoton



the Heaviest invariant mass
2.2 TeV



ATLAS
EXPERIMENT

Run Number: 302956, Event Number: 2656107838

Date: 2016-06-29 14:32:52 CEST

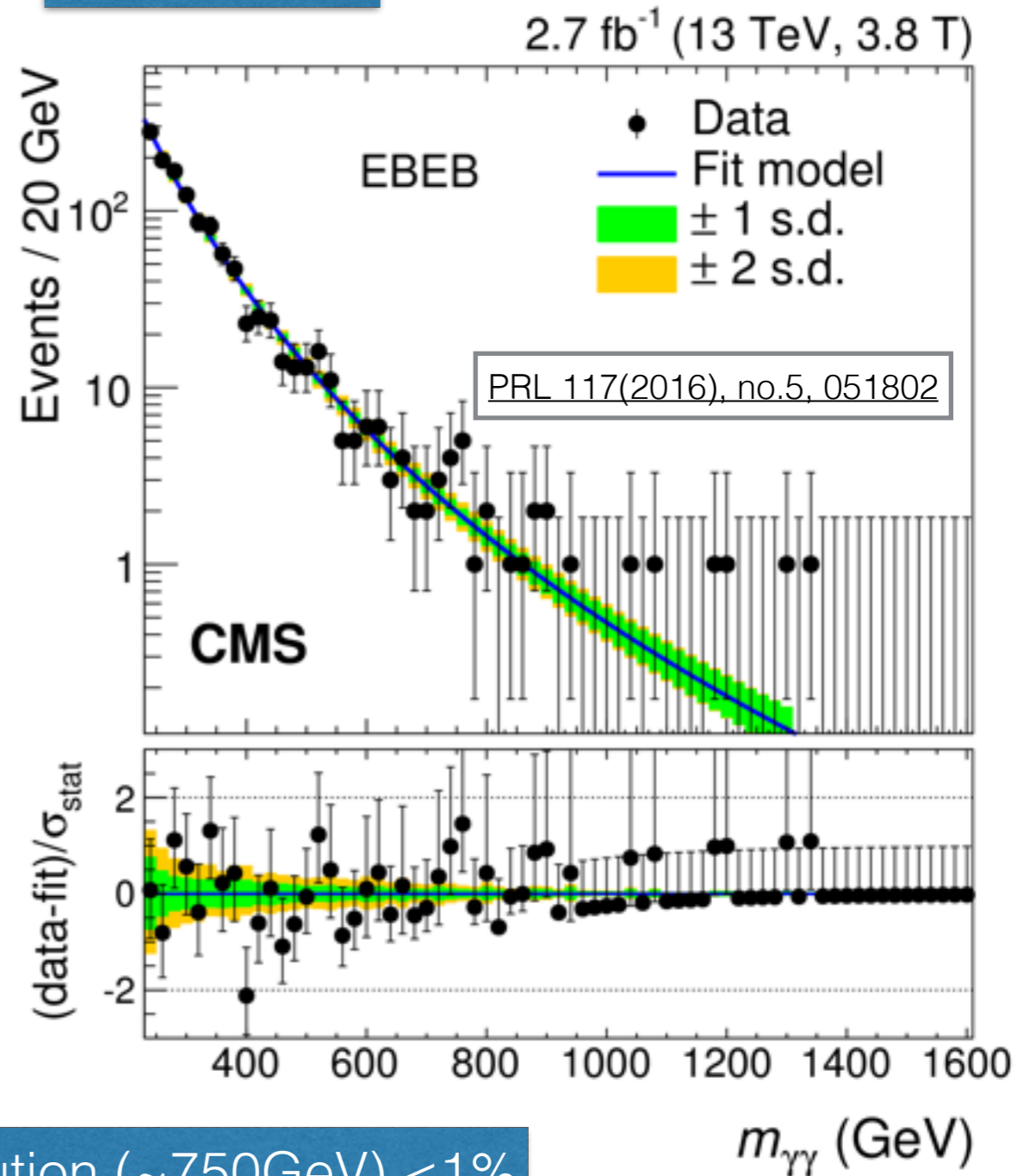
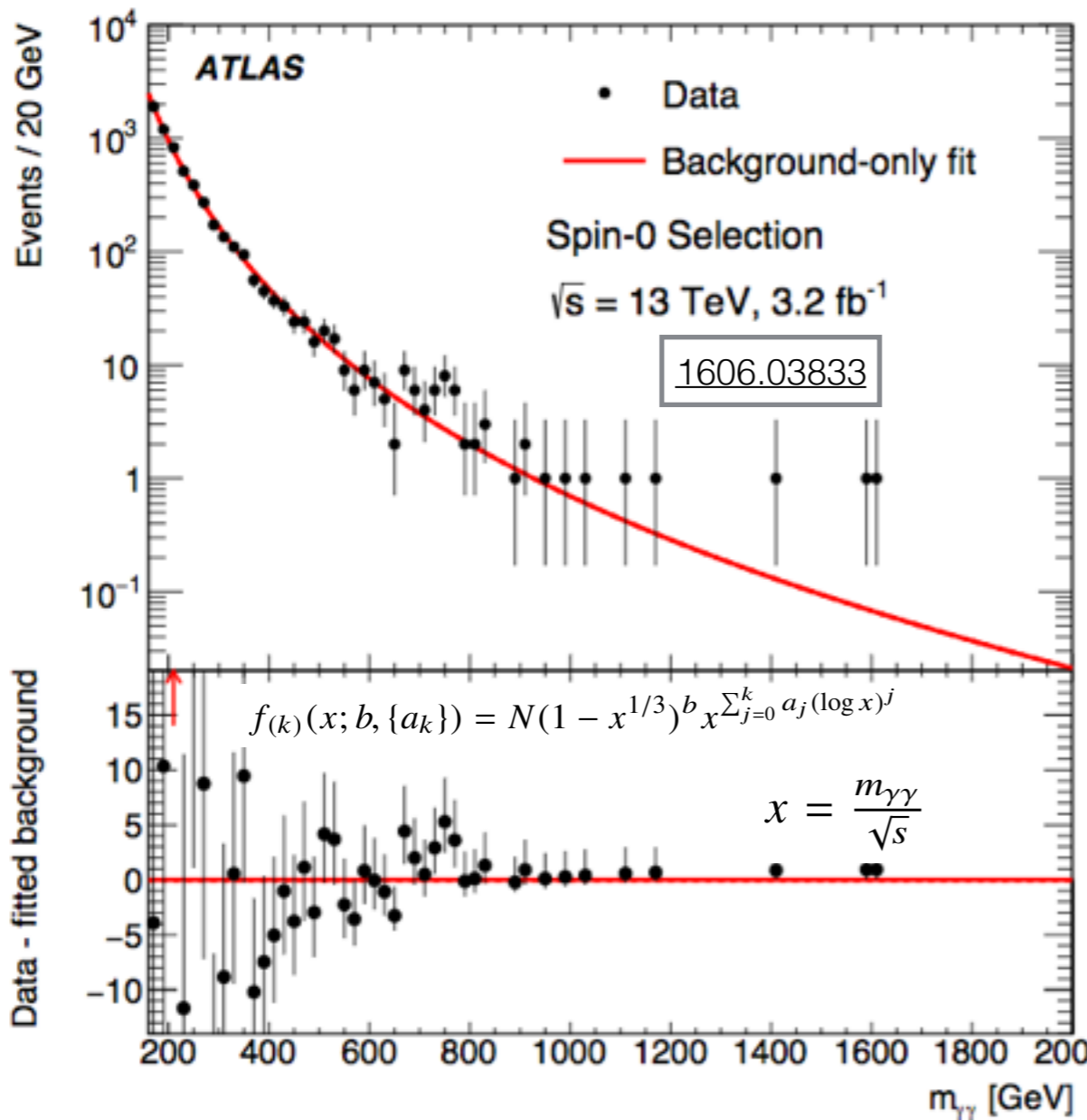
Diphoton in 2015

Bruno Lenzi's talk

Chiara Rovelli's talk

Significant excesses observed in 2015 data

purity ~90%



Significance in 2015

mass resolution (~750GeV) < 1%

$m = 750 \text{ GeV}$ ($\Gamma/M = 6\%$)

3.9σ (local) / 2.1σ (global)

→ 3.4σ (local) / $\sim 2\sigma$ (global) reprocessing

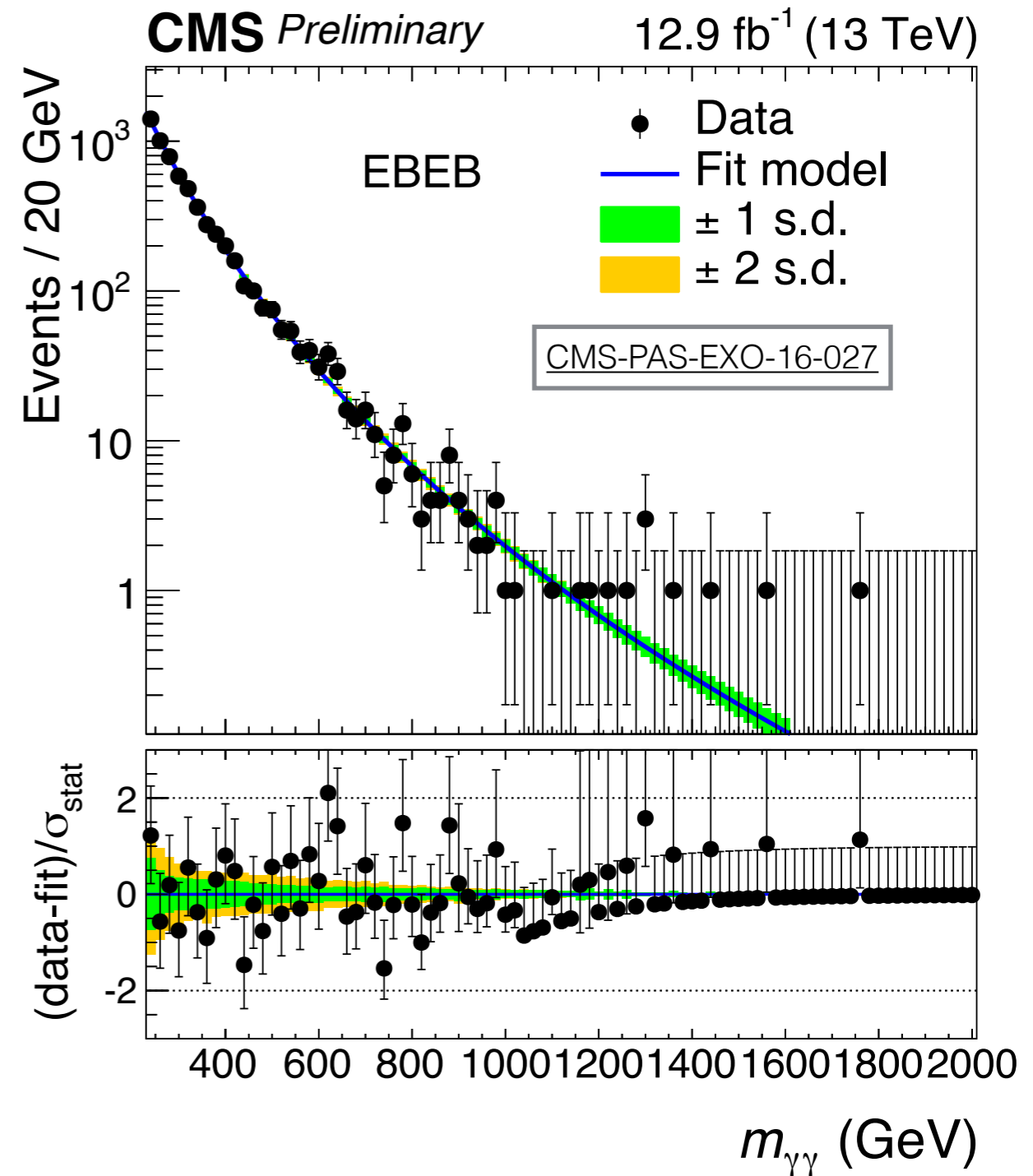
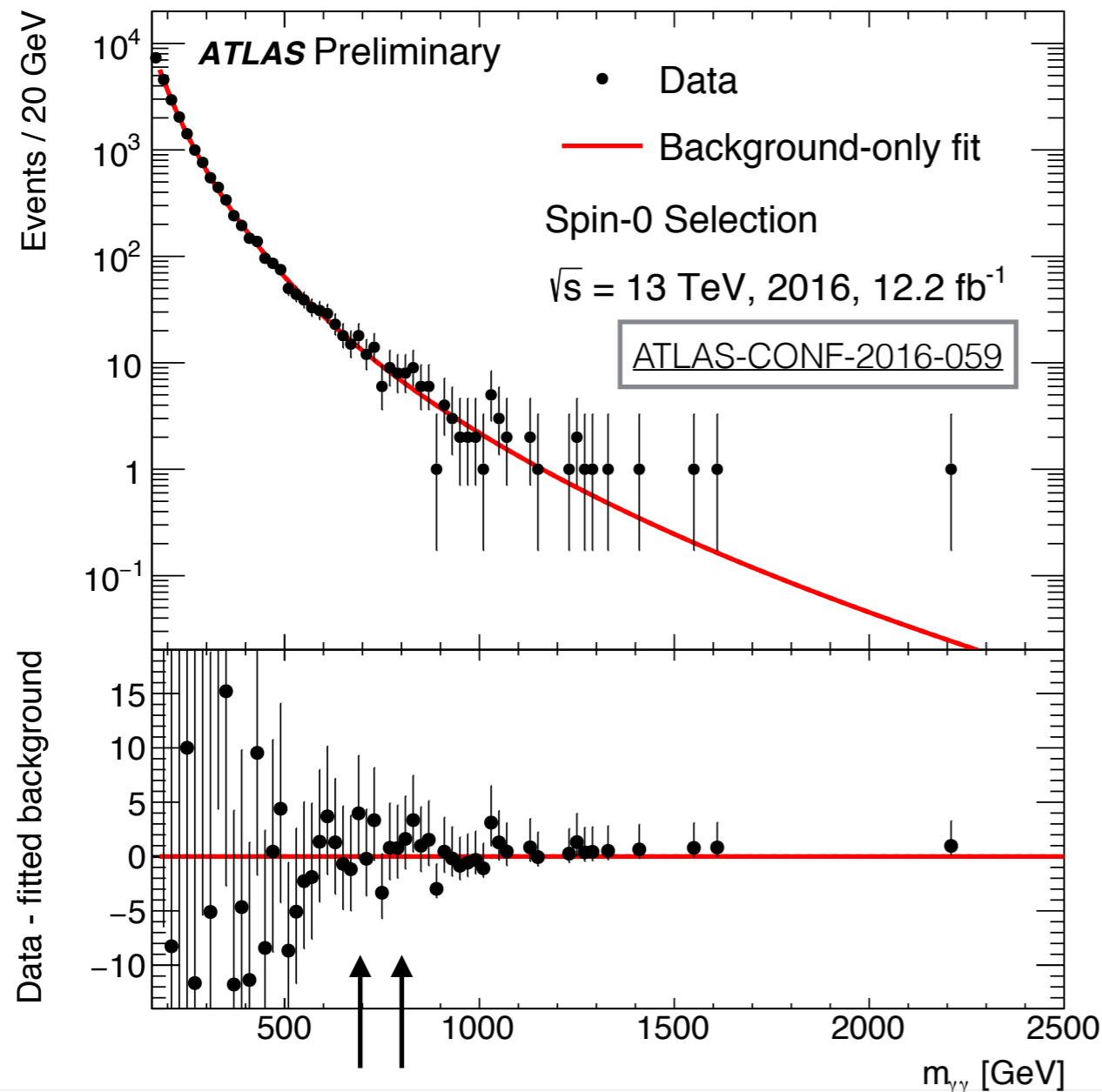
$m = 760 \text{ GeV}$ ($\Gamma/M = 1.4 \times 10^{-4}$)

2.9σ (local) / $< 1\sigma$ (global)

→ 3.4σ (local) / $< 1.6\sigma$ (global) 2015+8TeV

Diphoton in 2016

Excesses not confirmed in 2016 data



Significance in 2015+2016:

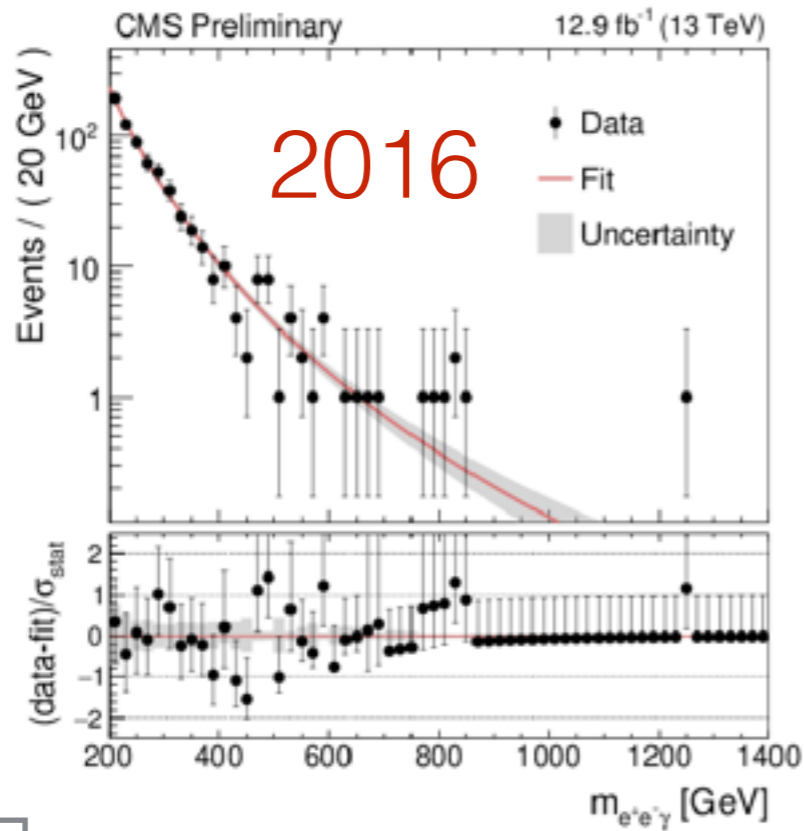
$m = 710 \text{ GeV}$ ($\Gamma/M = 10\%$)
 $2.3\sigma(\text{local}) / < 1\sigma(\text{global})$

$m = 760 \text{ GeV}$ ($\Gamma/M = 1.4 \times 10^{-4}$)
 $< 1\sigma(\text{local})$

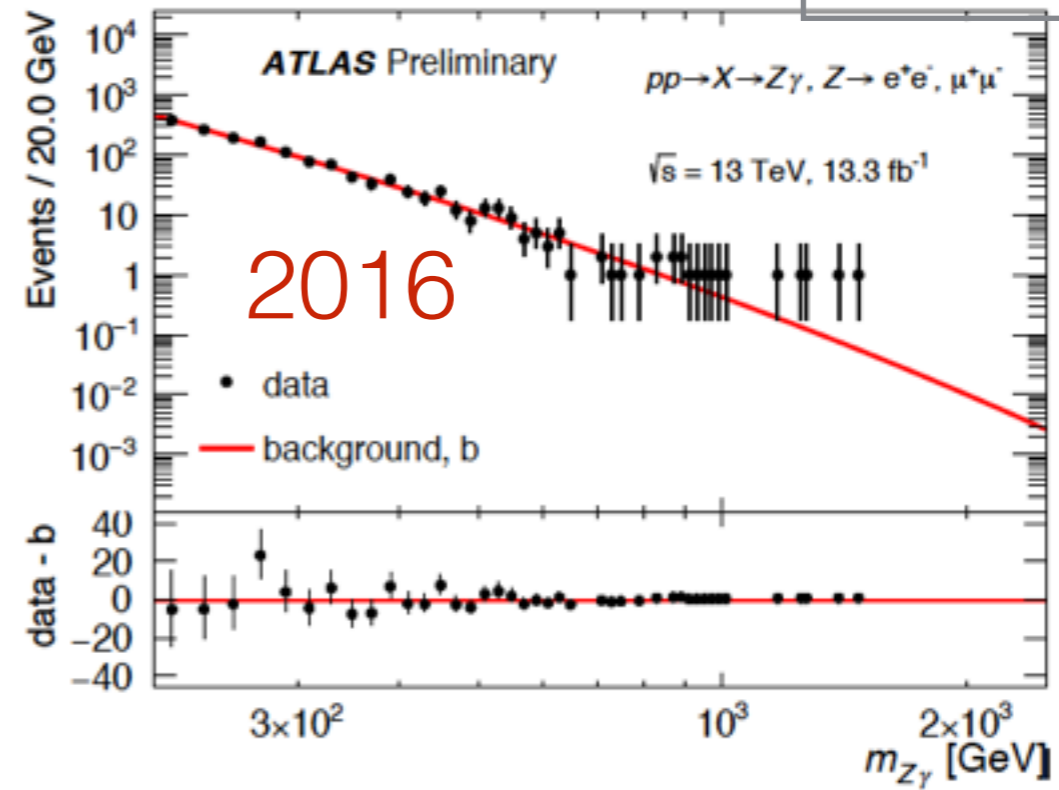
Zgamma in 2016

Giovanni Marchiori

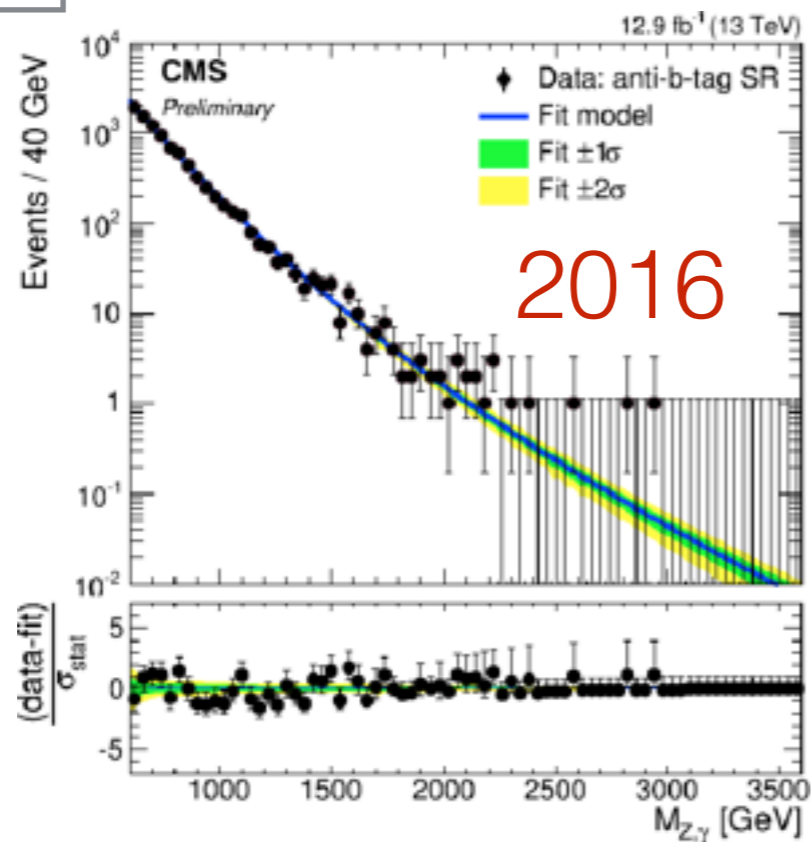
EXO-16-035



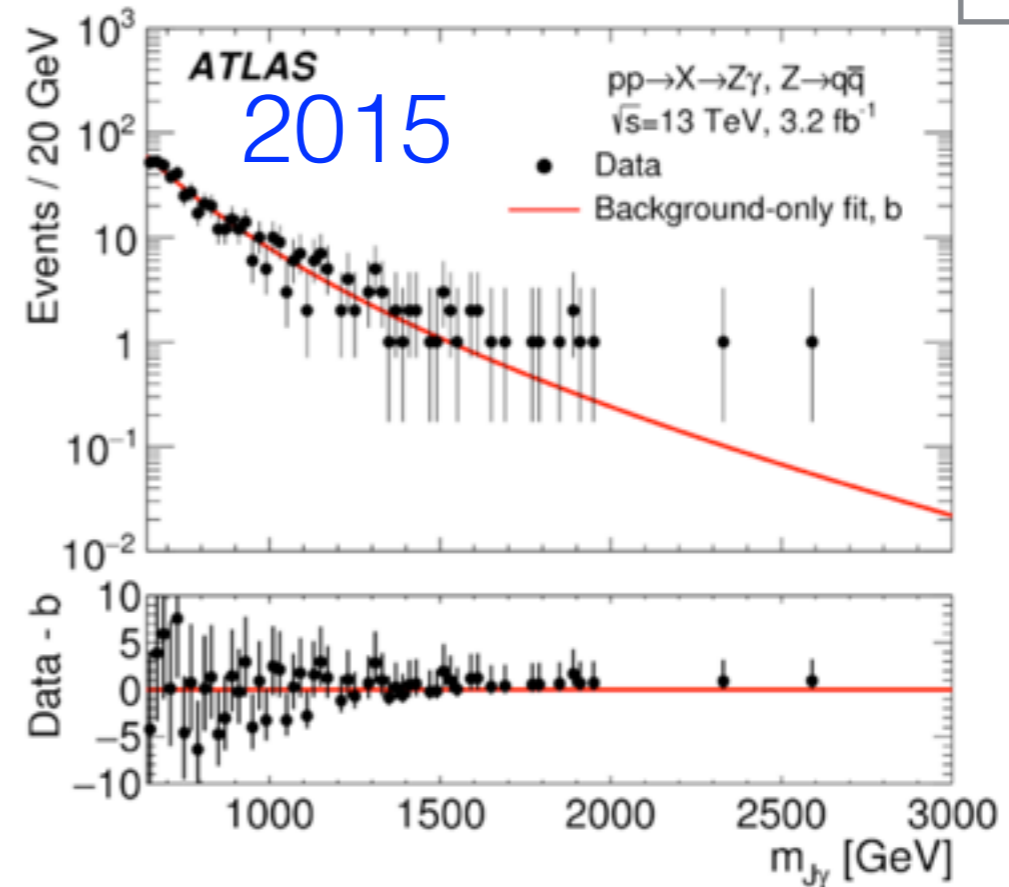
ATLAS-CONF-2016-044/



EXO-16-034

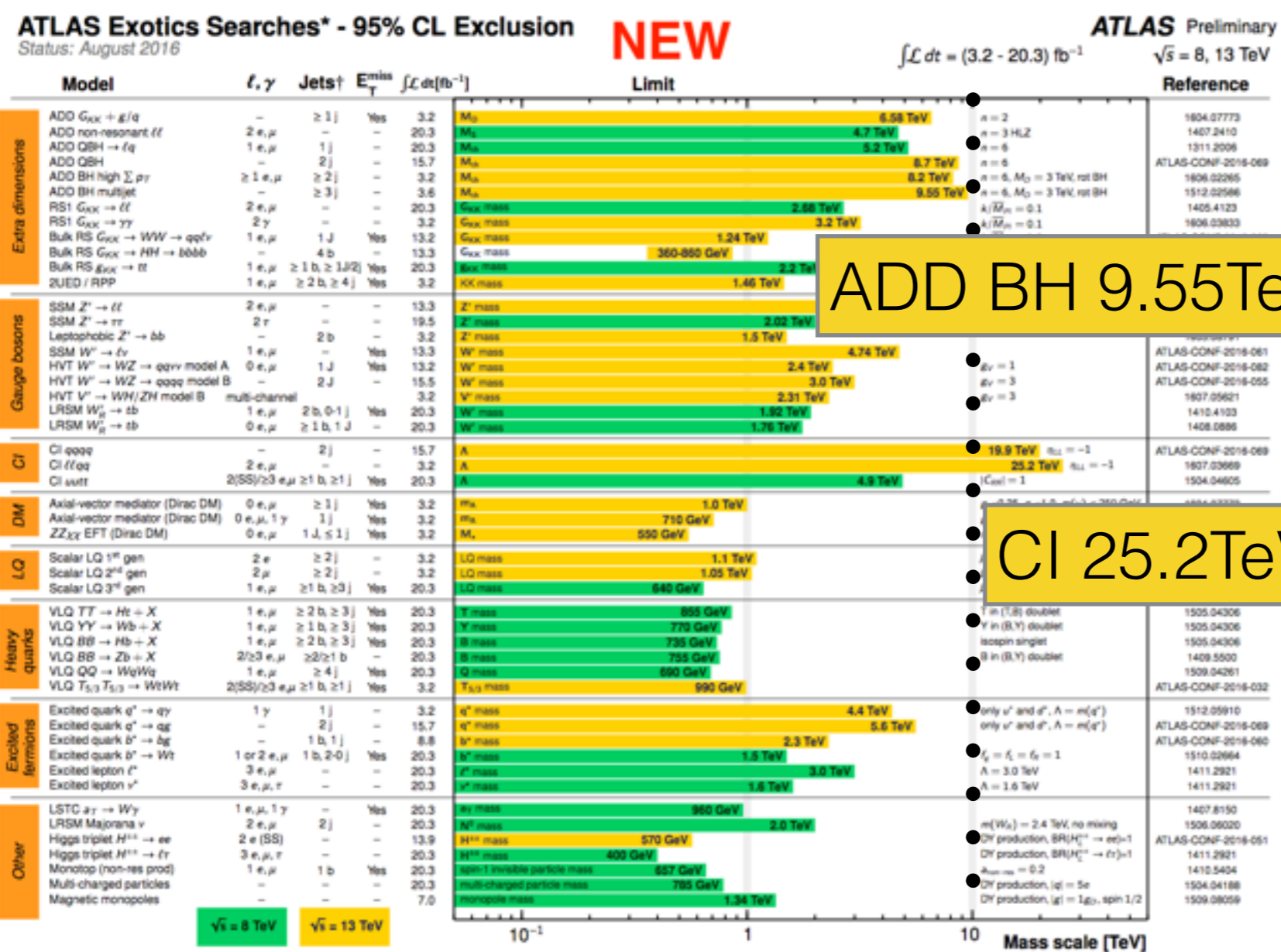


arXiv:1607.06363



Resonance search summary

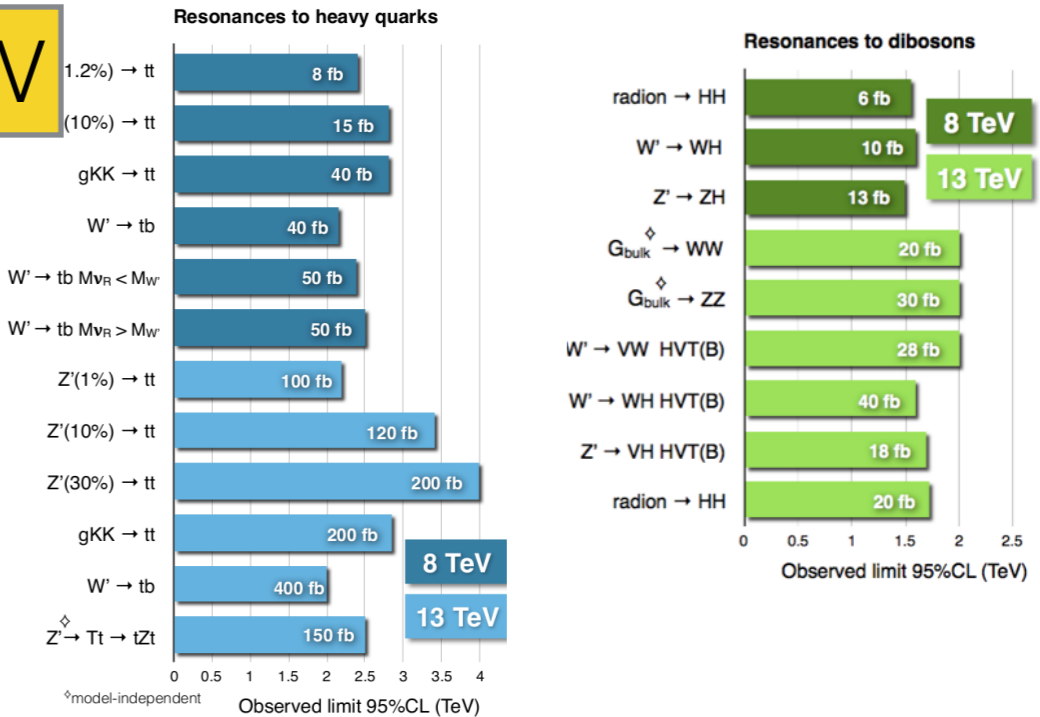
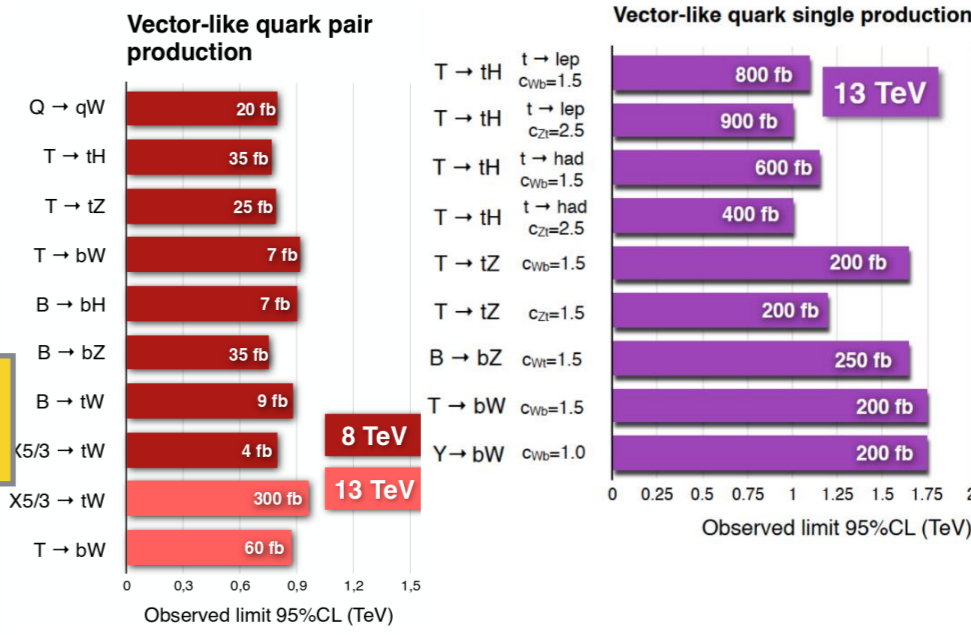
- Up to 25% mass limit increase by extending 2015 to 2016
- ~50% of the analyses updated to Run2



ADD BH 9.55 TeV

CI 25.2 TeV

10 TeV

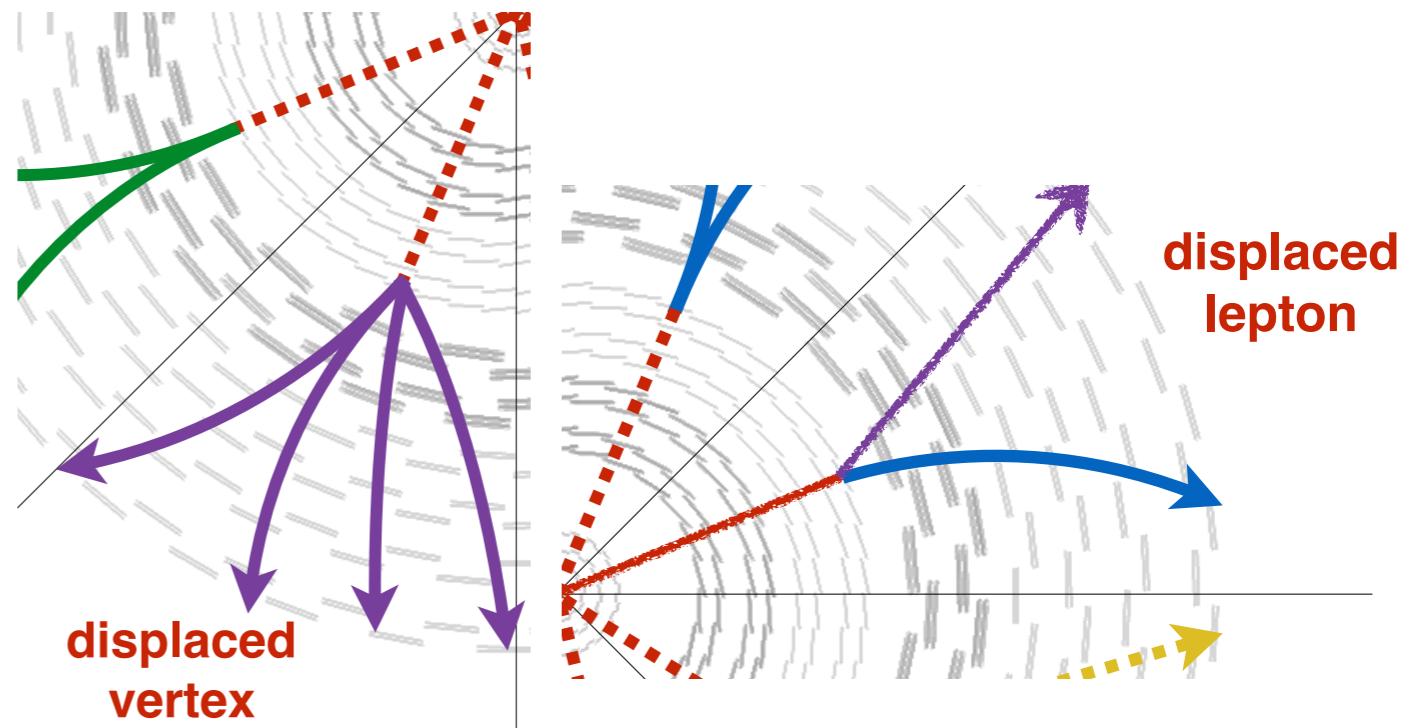
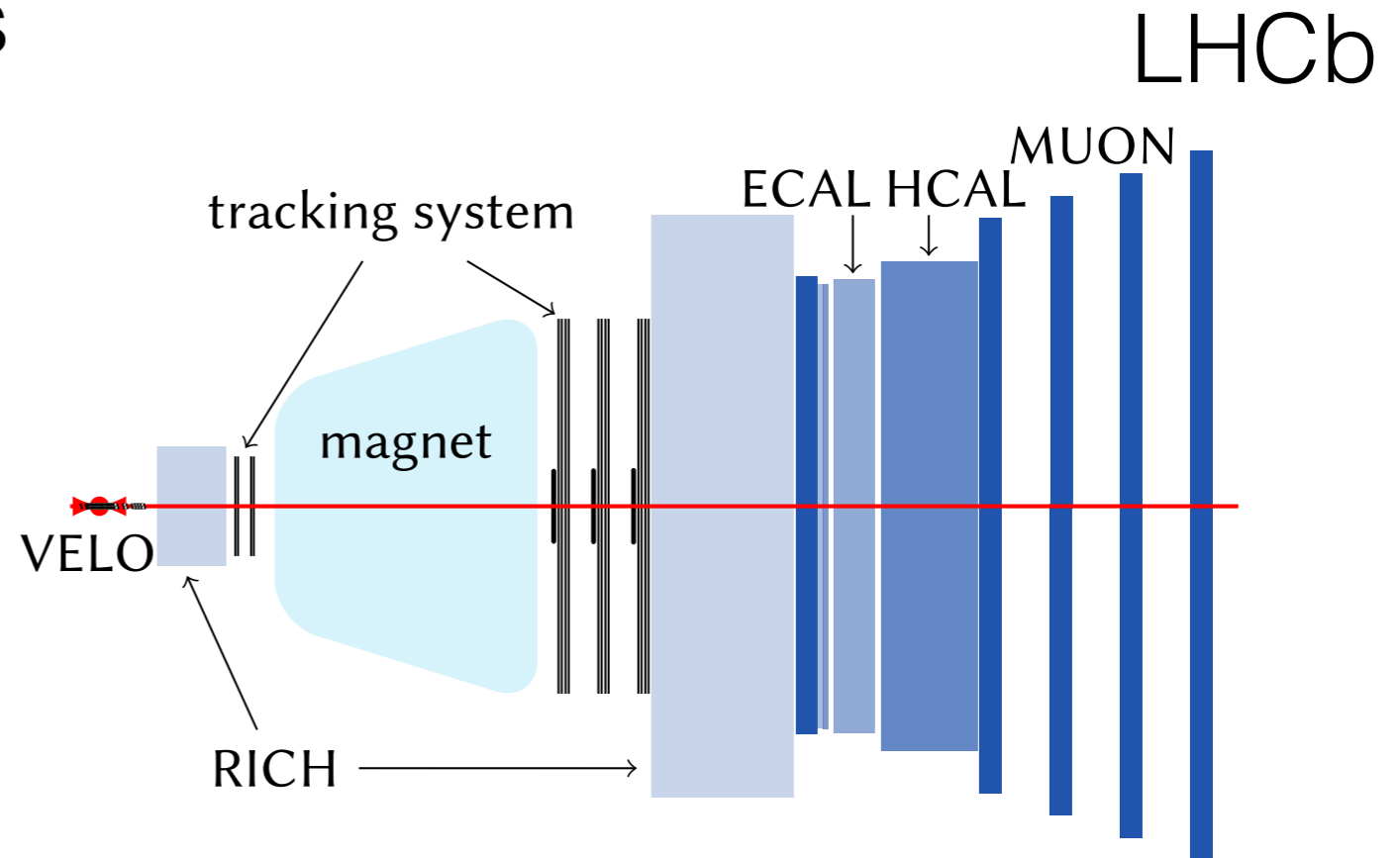
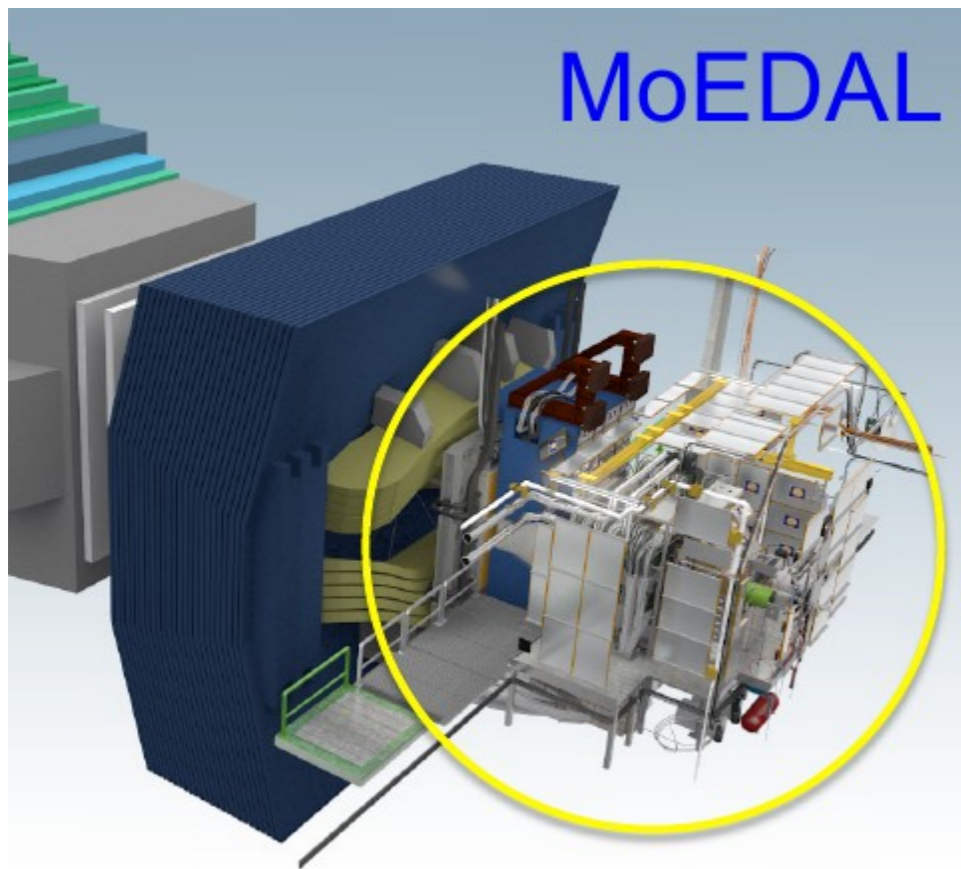




3. Unconventional Signatures

Unconventional Signatures

- Long-lived particles
- Multiple-charged particles

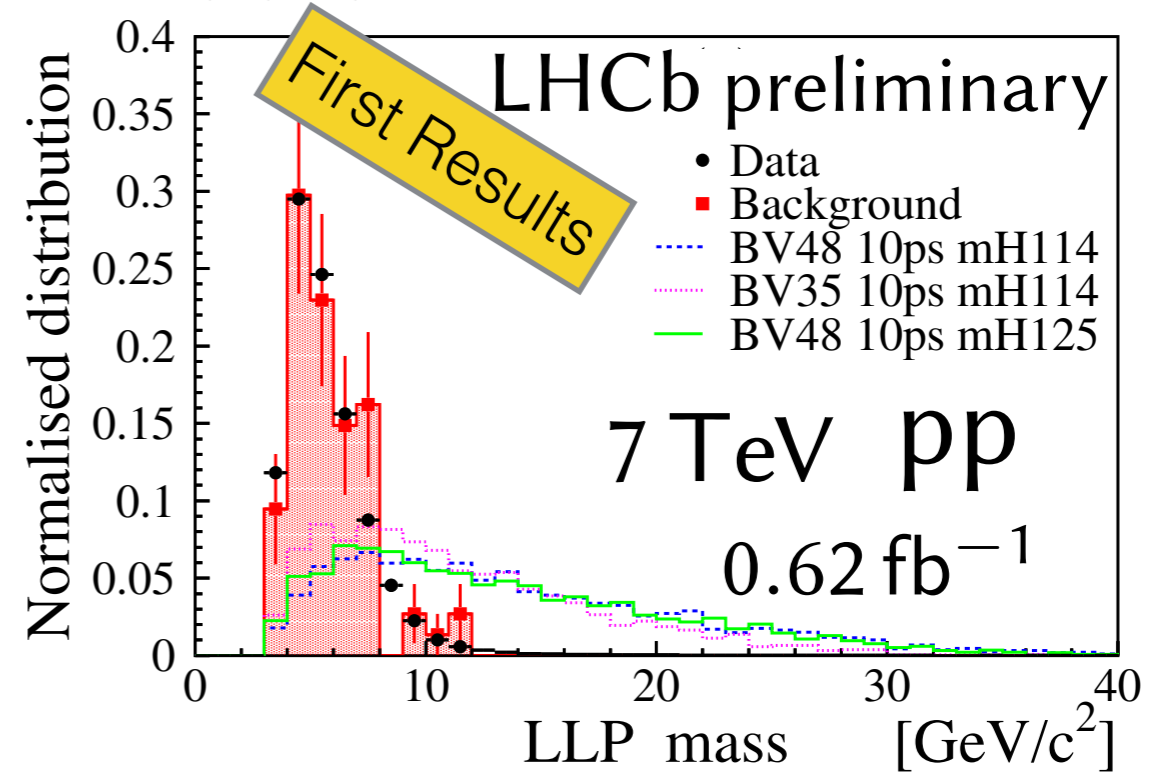


Complementary searches from **LHCb** and **ATLAS/CMS** to extend proper lifetime coverage

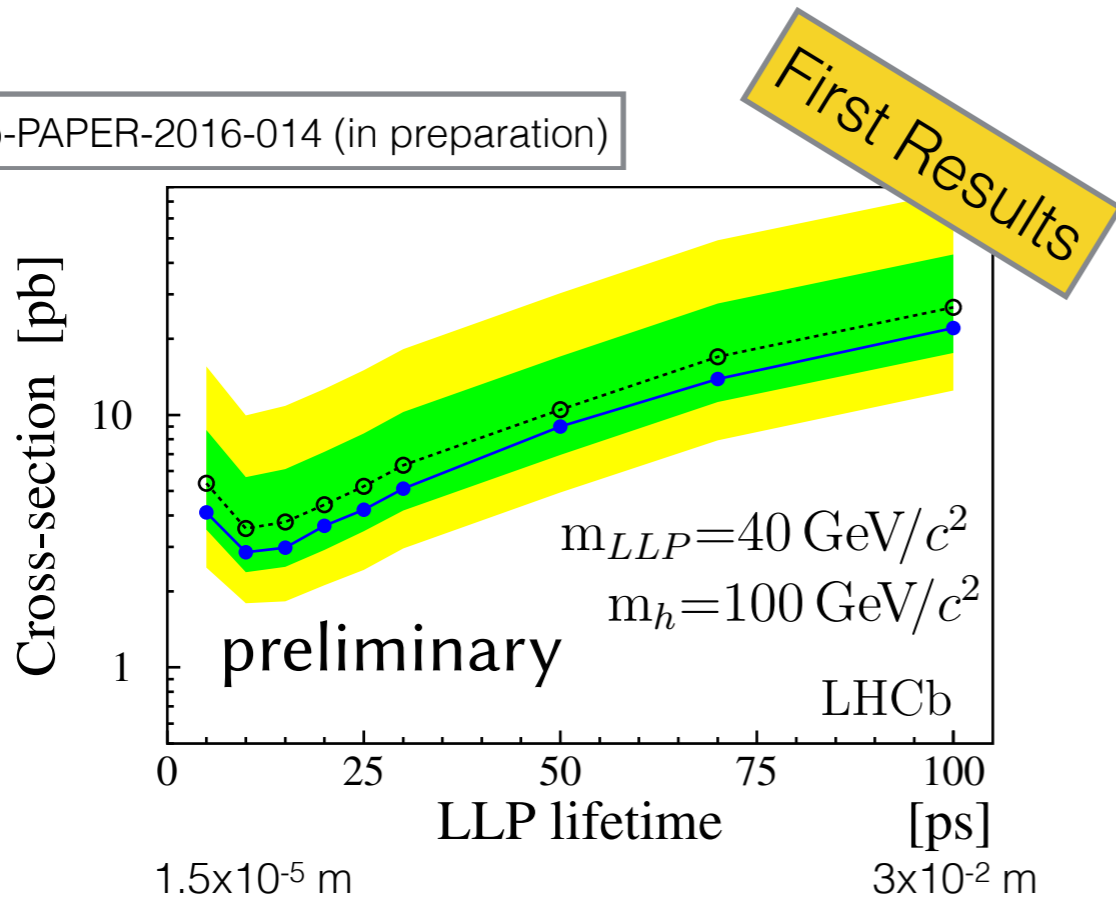
- LHCb: $O(10^{-5}) \sim O(10^{-2})$ m
- ATLAS: $O(0.1) \sim O(100)$ m

$$H \rightarrow \pi_\nu \pi_\nu, \pi_\nu \rightarrow b\bar{b} \text{ (HV)}$$

$$H \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow 3\text{jets} \text{ (BV)}$$

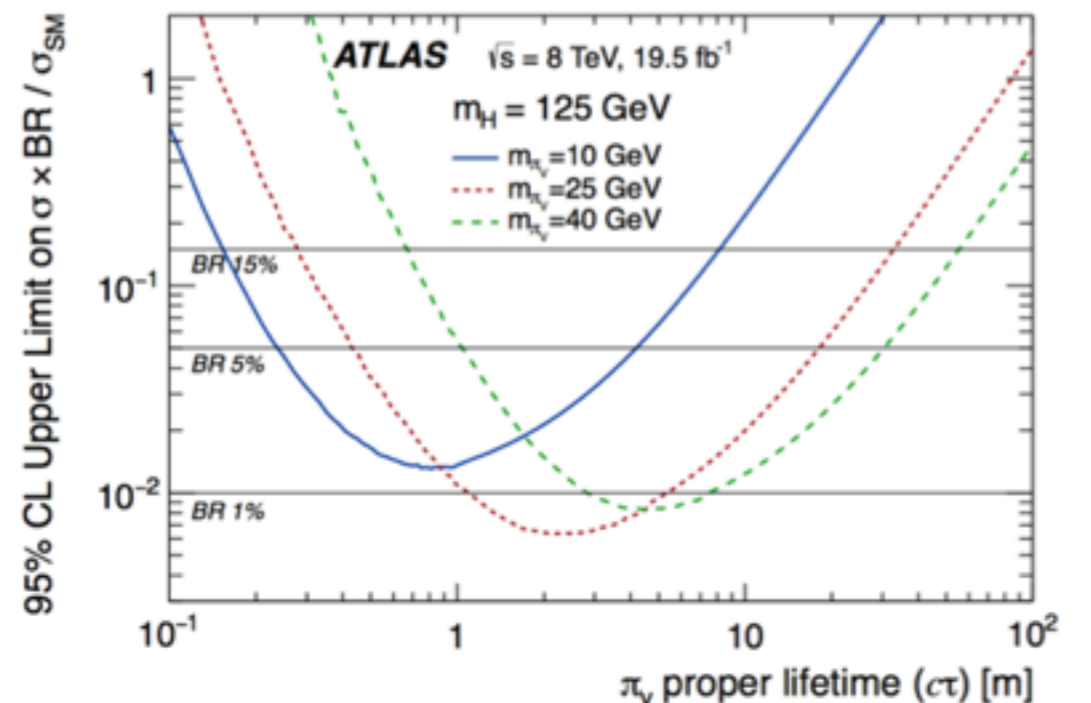


LHCb-PAPER-2016-014 (in preparation)



Phys. Rev. D 92, 012010 (2015)

Phys. Rev. D 92, 012010 (2015)



Lepton Jets and displaced tracks

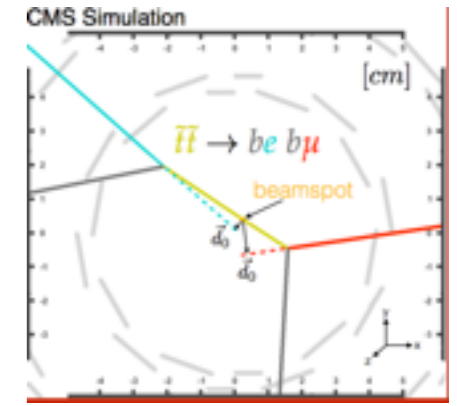
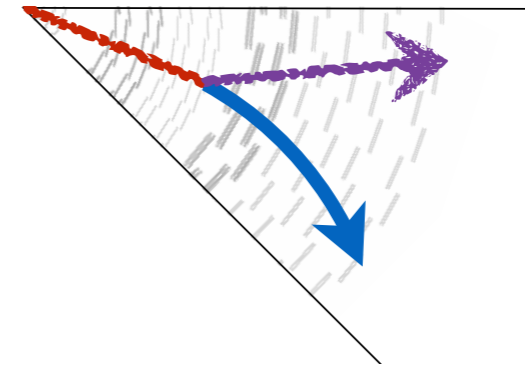
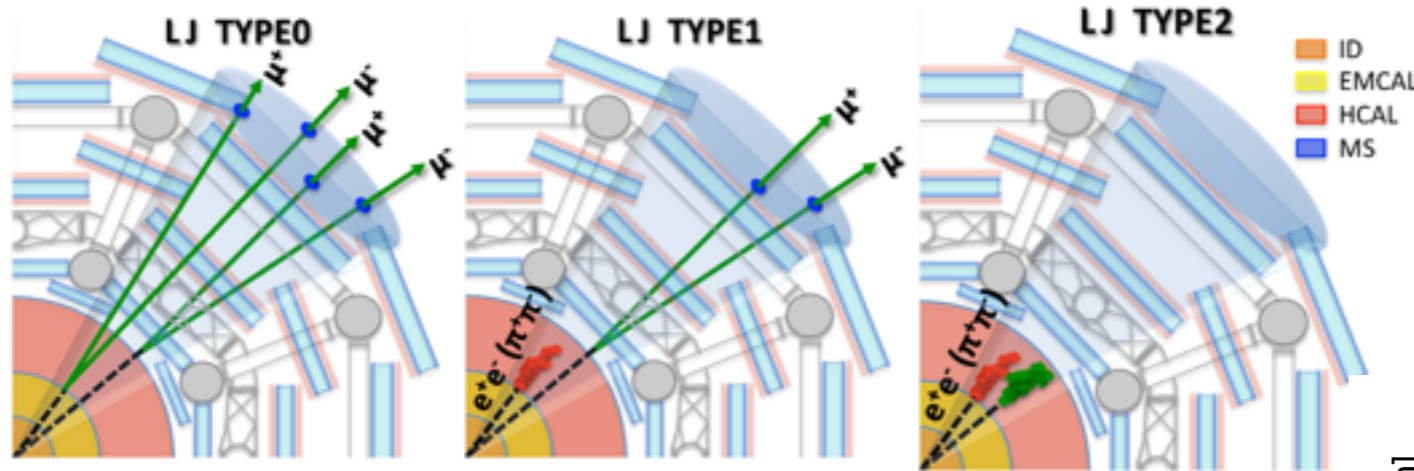
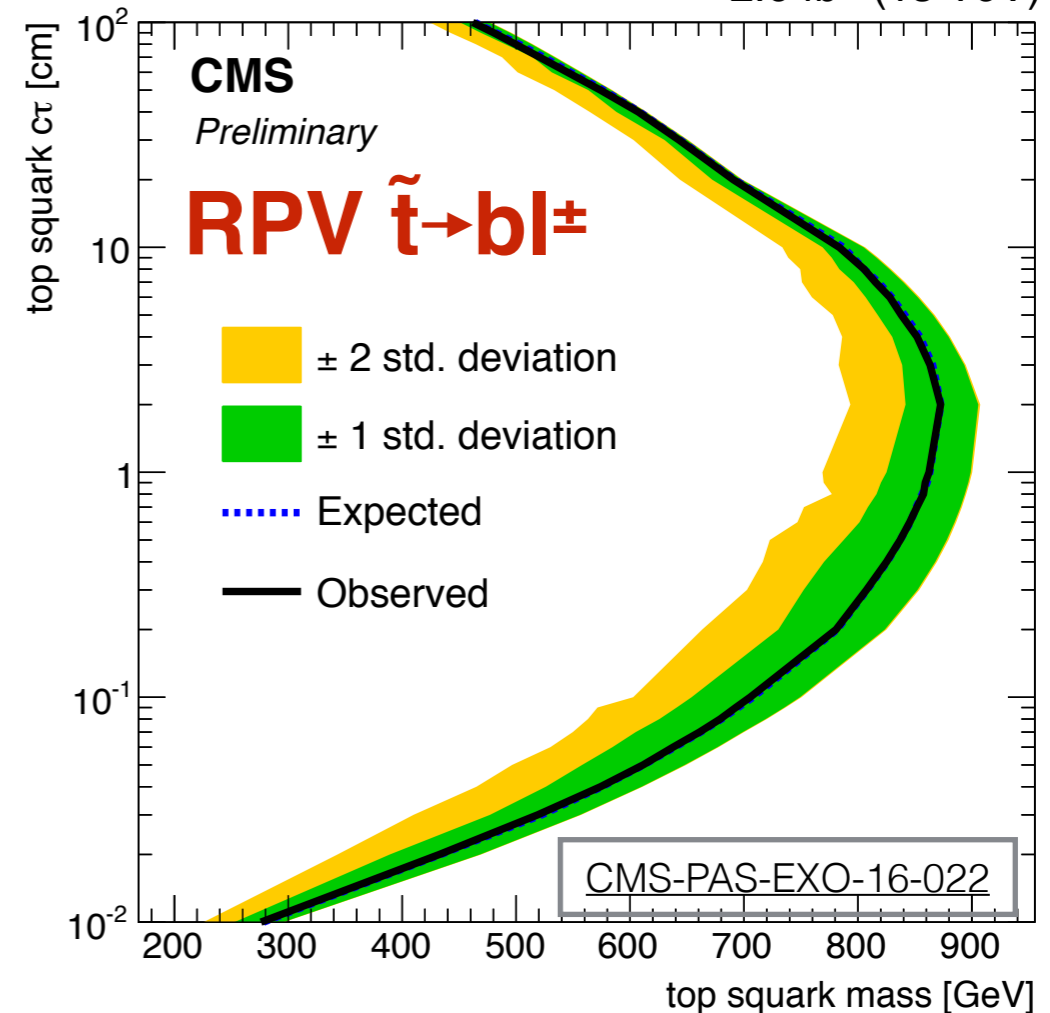
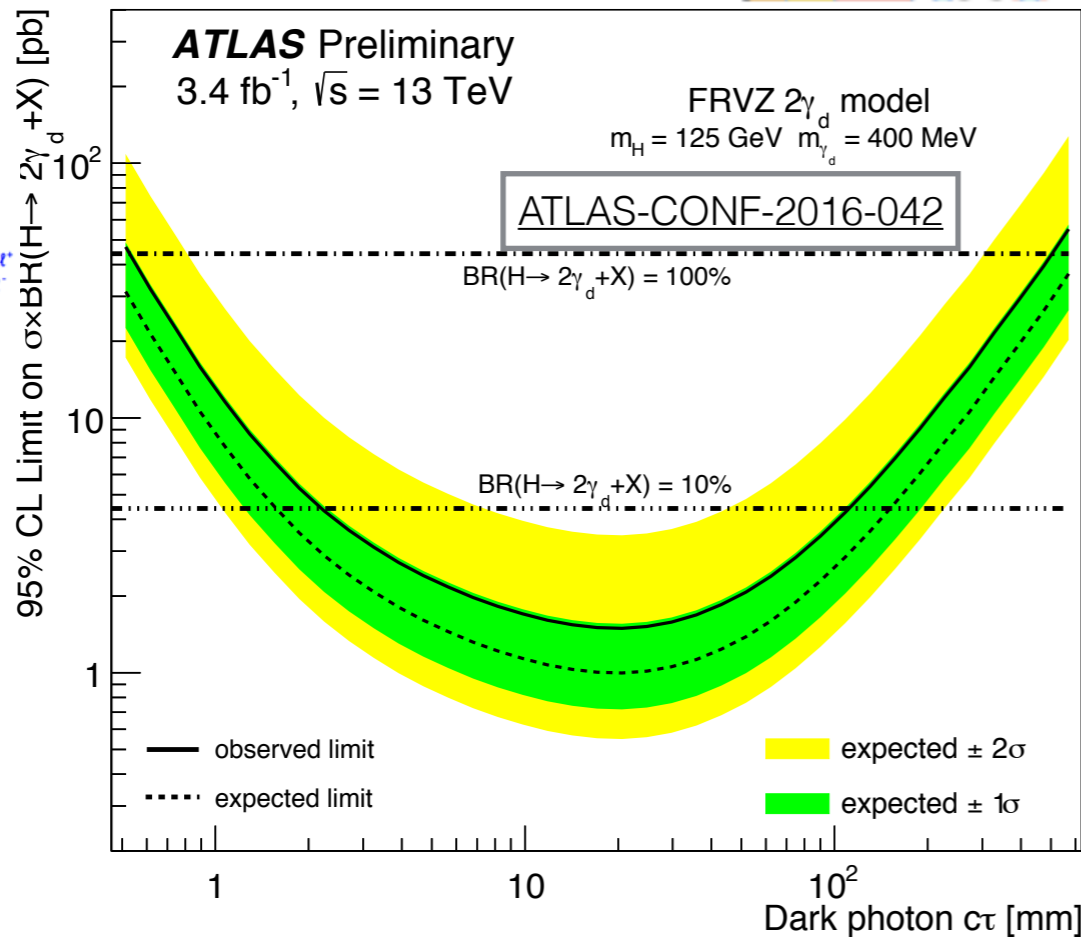
Edward Moyses's talk

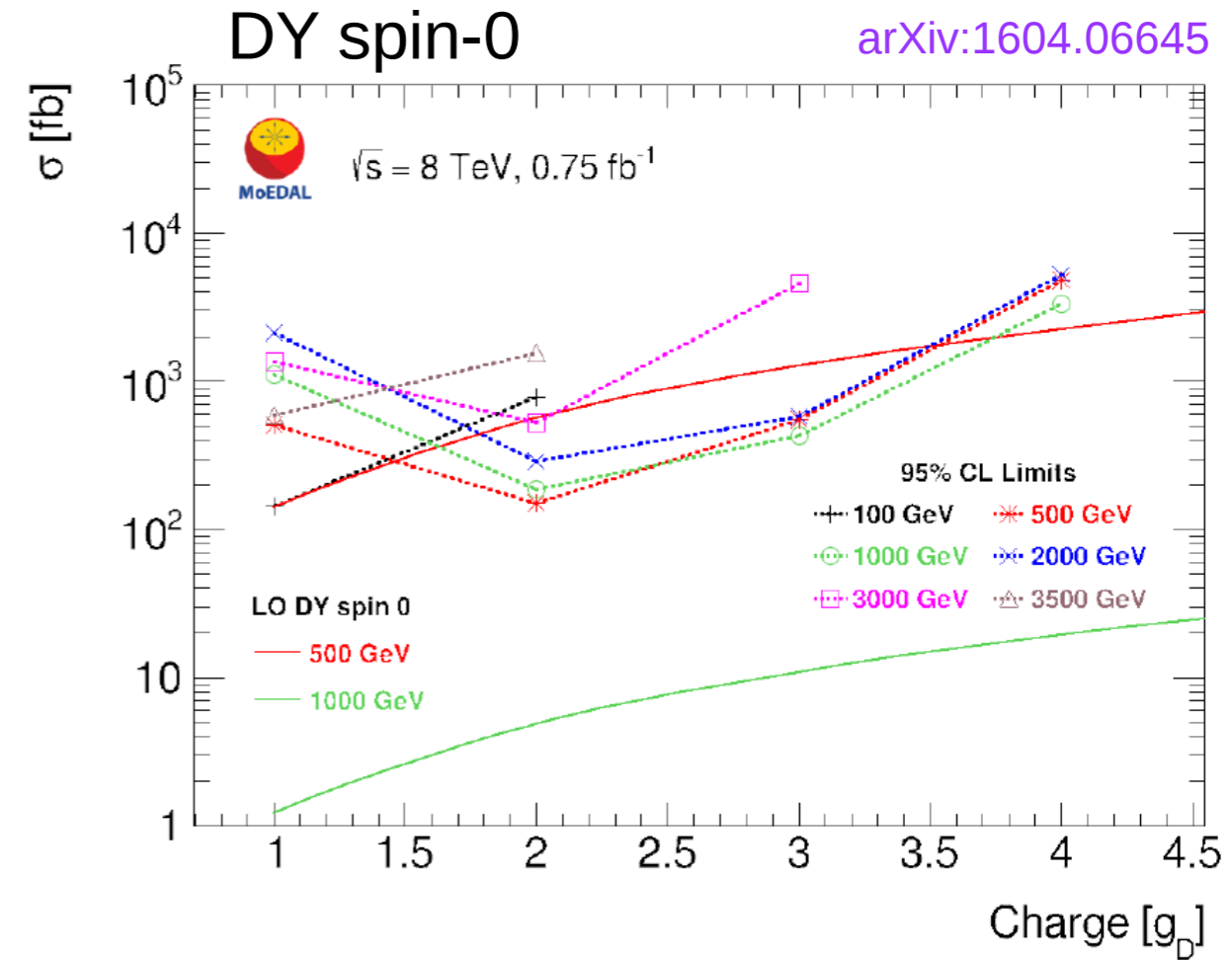
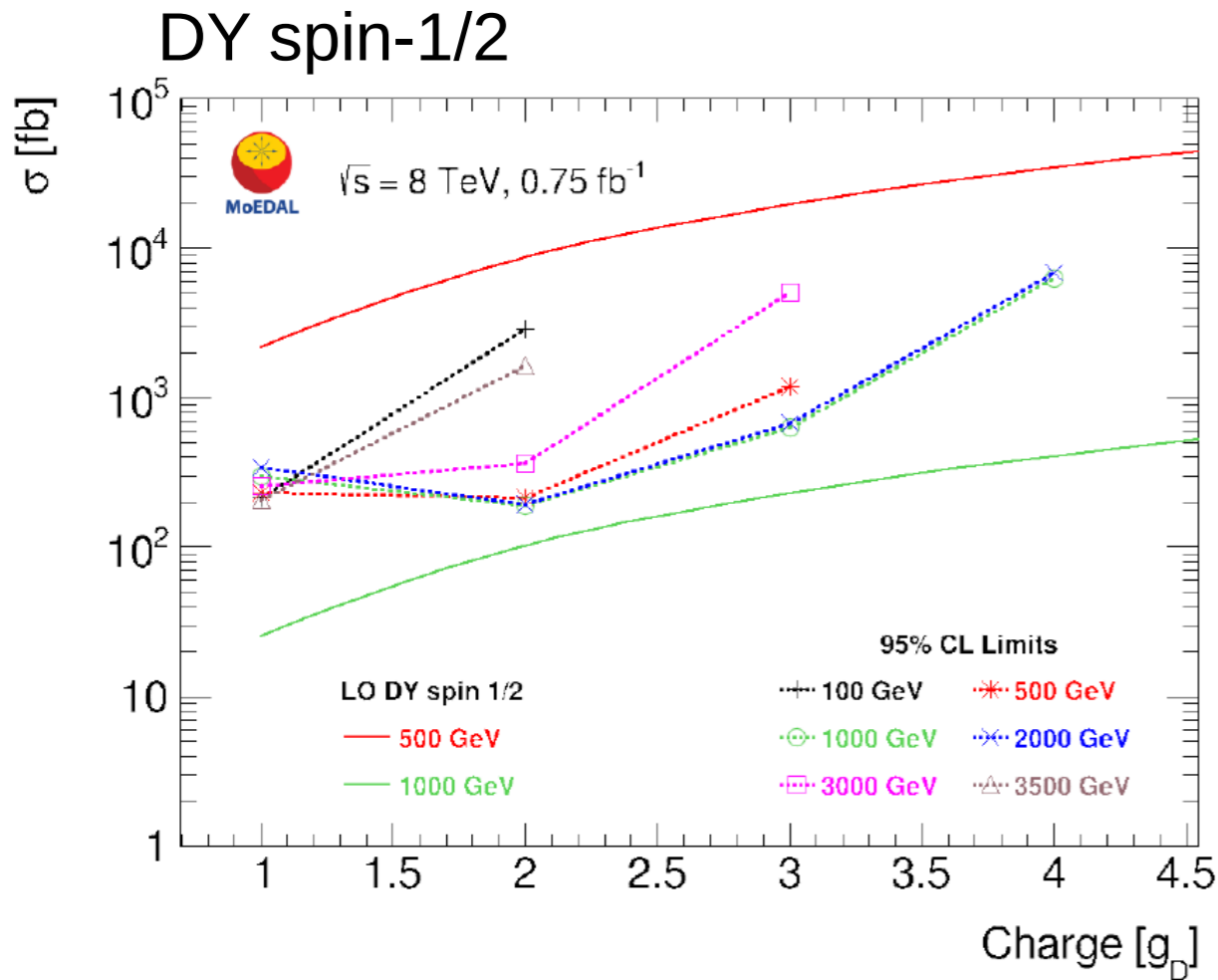
J. Antonelli's talk

- No excess found in the data

Lepton jet: collimated jet-like structures containing e/mu/pions

Displaced e- μ pair: large transverse impact parameter d_0 for analysis


 2.6 fb⁻¹ (13 TeV)




Magnetic monopole masses $> 2500 \text{ GeV}$

Magnetic monopole charge $|g| > 1.5g_D$ (up to $4 g_D$)

ATLAS magnetic monopole mass

arXiv:1509.08059

spin-1/2
spin-0

$ g = g_D$
1340
1050

Summary

- LHC experiments conducting BSM searches in broad and complementary signatures
- Known excesses (Diboson in Run1 and Diphoton in 2015) **not** confirmed using 2016 data
- **No new significant excesses observed.** Set new frontier scale:
 - Contact Interaction **energy**: 25.2 TeV
 - ADD BH **mass**: 9.55 TeV
 - W' **mass**: 4.74 TeV
 - Dark photon **lifetime**: 2.5~100 mm (dark photon 400 MeV)
 - **Magnetic charge**: $|g| > 1.5g_D$ (up to 4 g_D)
- More data to come - Stay tuned!

W

Backup

New Results for ICHEP

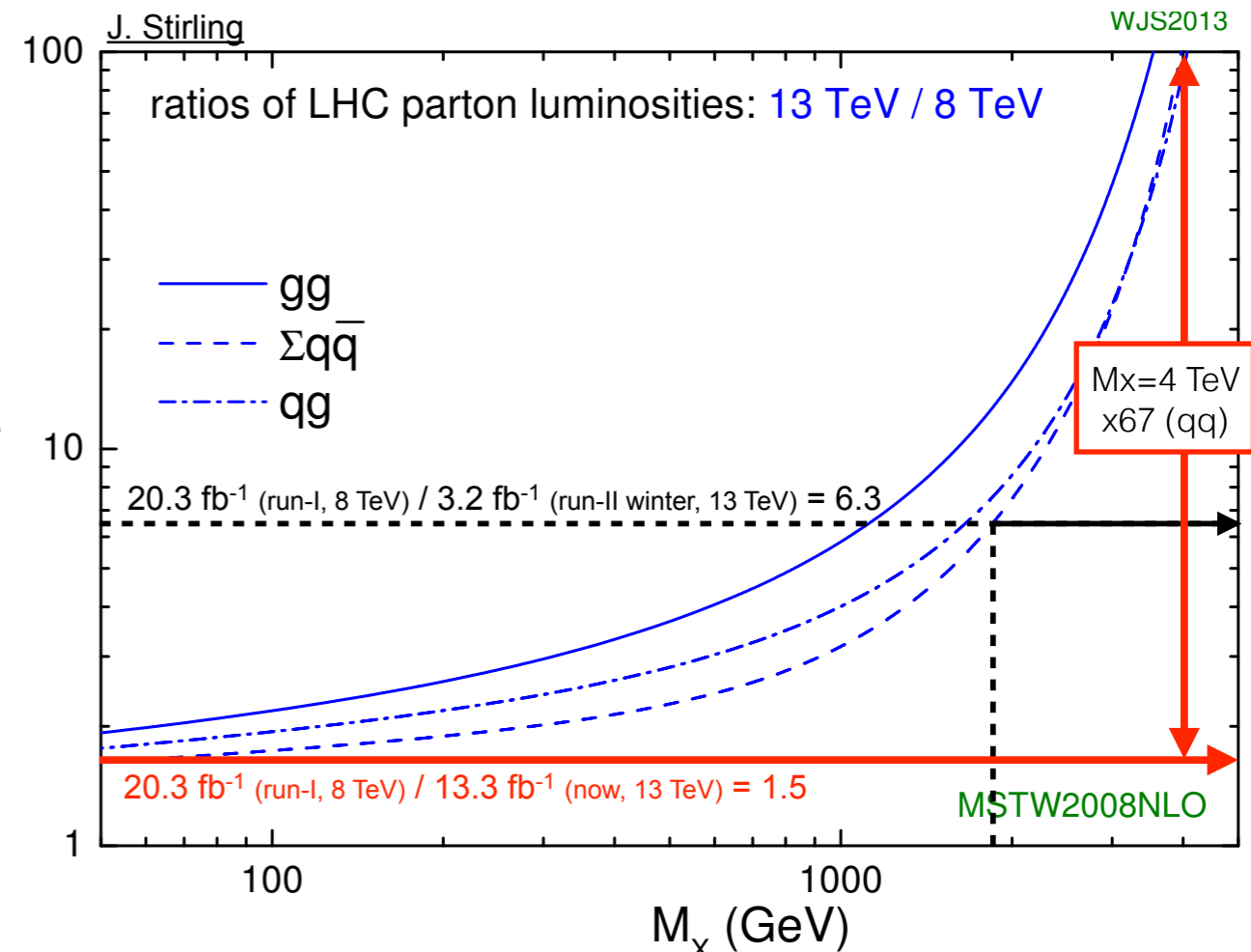
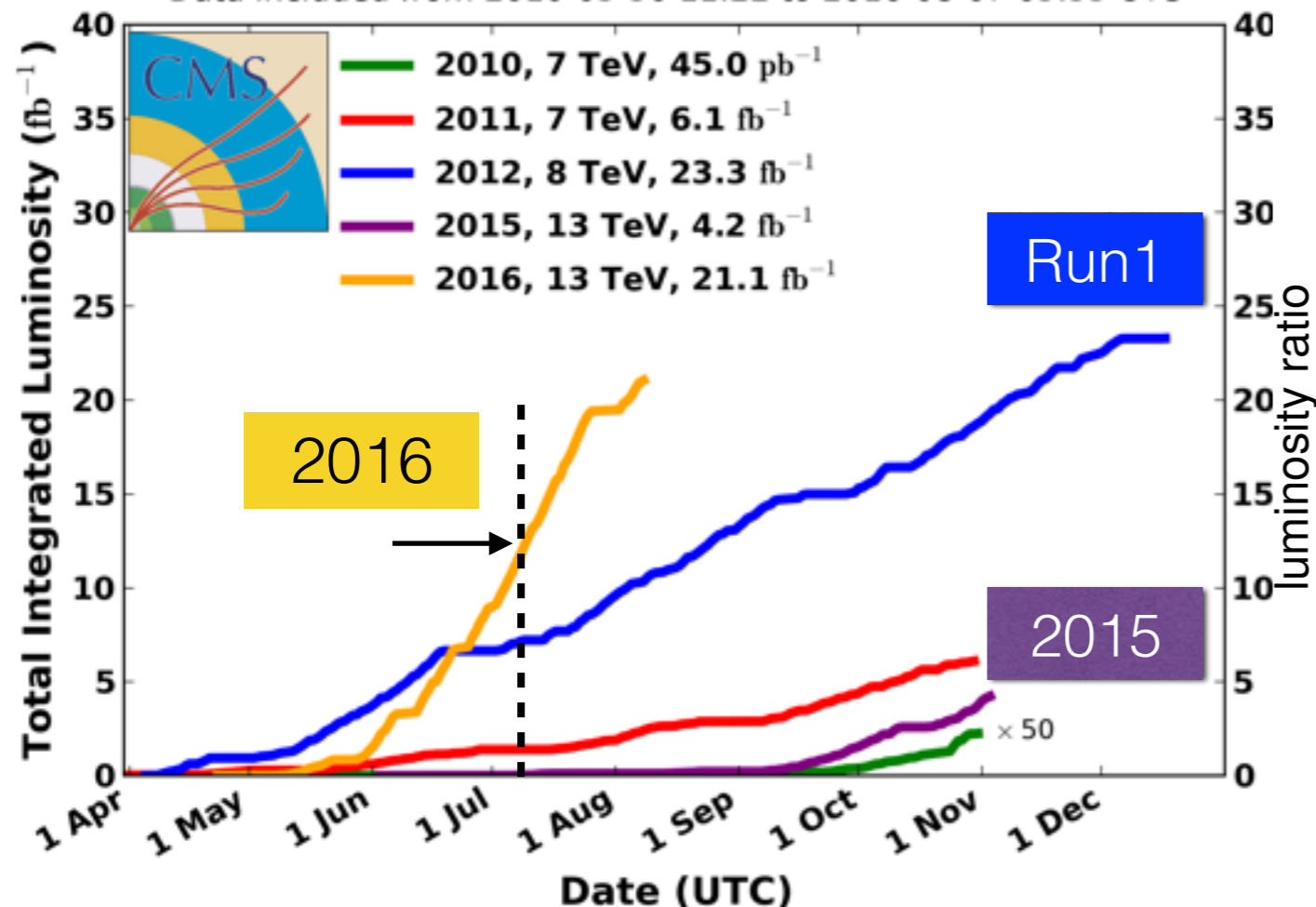
- ATLAS Exotics:
 - 18 conf notes; 1 submitted paper
 - <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults>
 - <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/Summer2016-13TeV>
- CMS Exotics:
 - 22 conf. notes; 1 submitted paper
 - <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>
 - <http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO/index.html>
- CMS Beyond 2 Generations:
 - 5 conf. notes submitted for ICHEP
 - <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G>
 - <http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G/index.html>
- LHCb Results
 - 1 conf. notes
 - <https://lhcb.web.cern.ch/lhcb/Physics-Results/LHCb-Physics-Results.html>

Amazing Performance from LHC

- Record breaking luminosity in 2016!
- Most selected results updated with 2015+2016 13TeV data
 - 2016 data ($\sim 13 \text{ fb}^{-1}$): comparable statistics w.r.t. Run1 in all system mass
 - Results expected to surpass all Run1 sensitivity

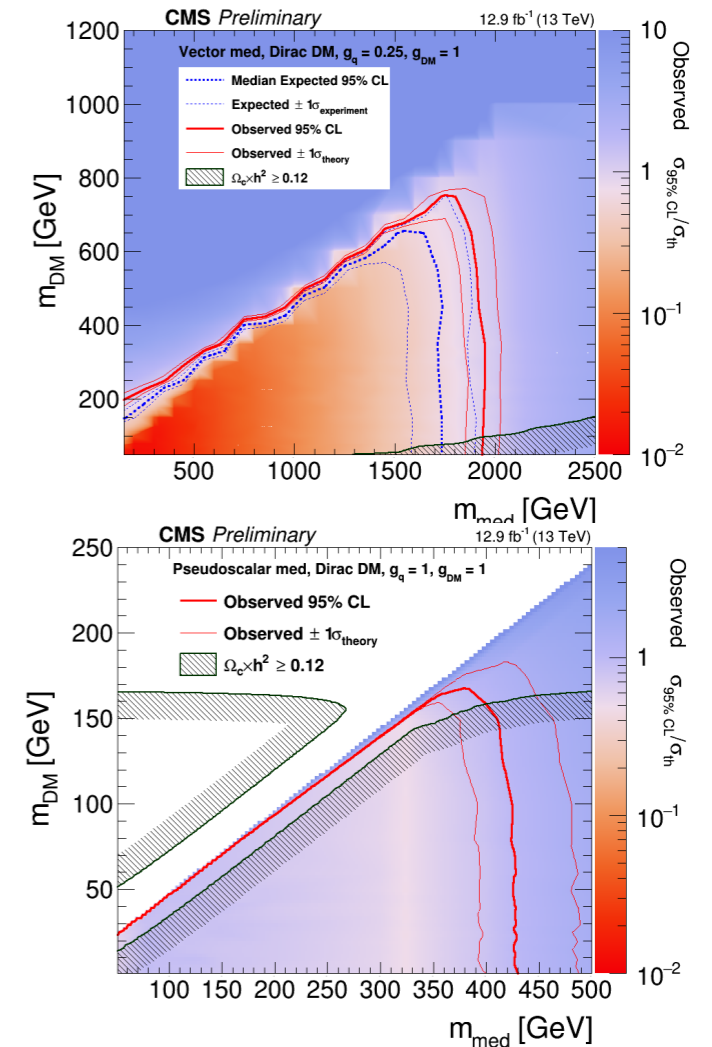
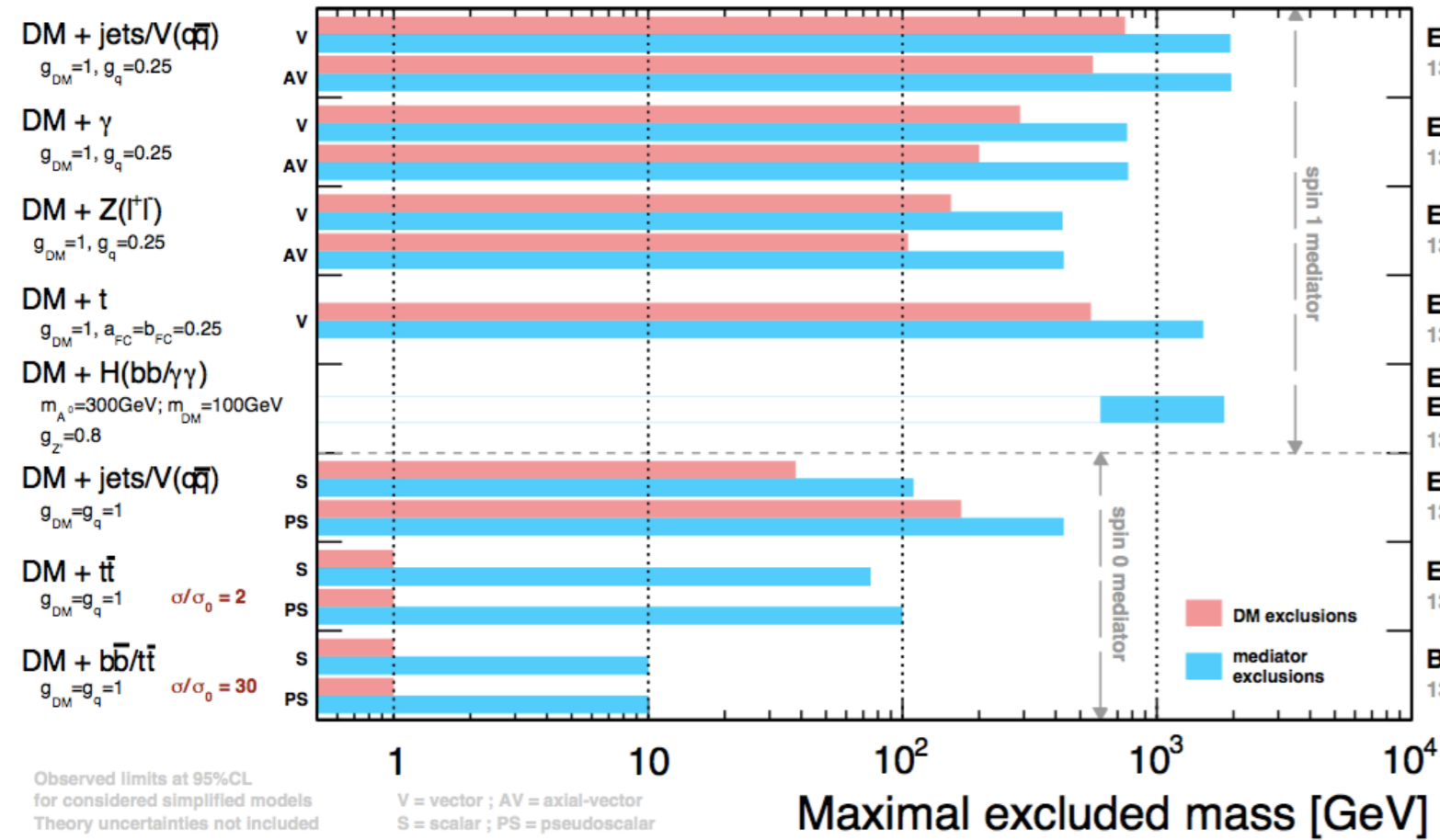
CMS Integrated Luminosity, pp

Data included from 2010-03-30 11:22 to 2016-08-07 05:35 UTC



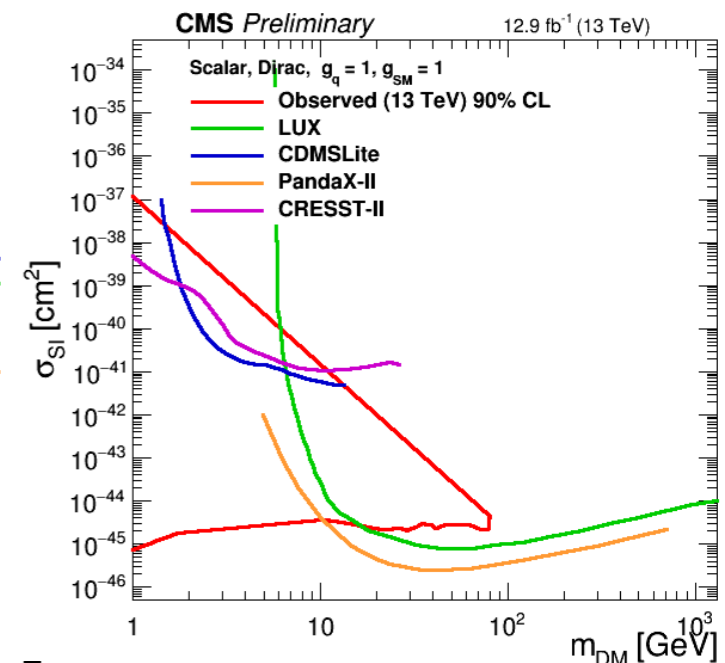
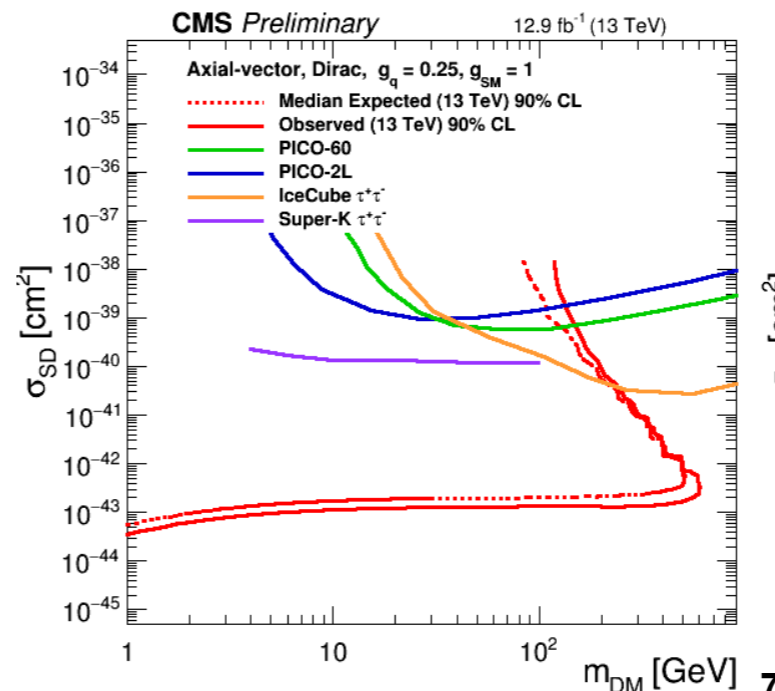
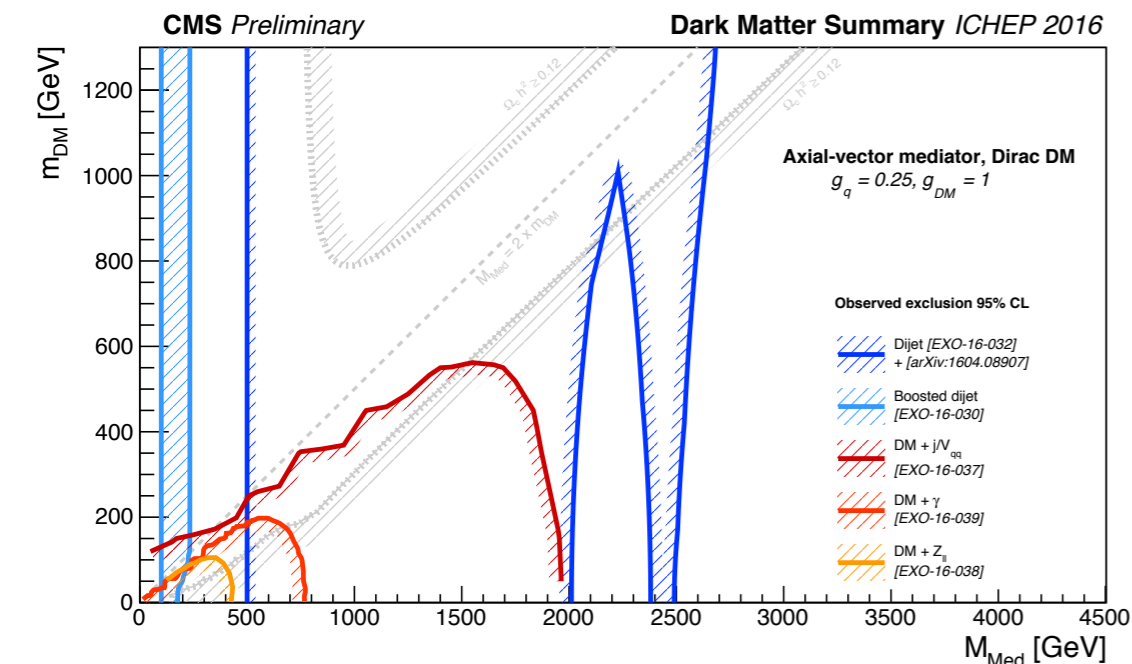
CMS DM Summary

CMS Preliminary Dark Matter Summary - ICHEP 2016



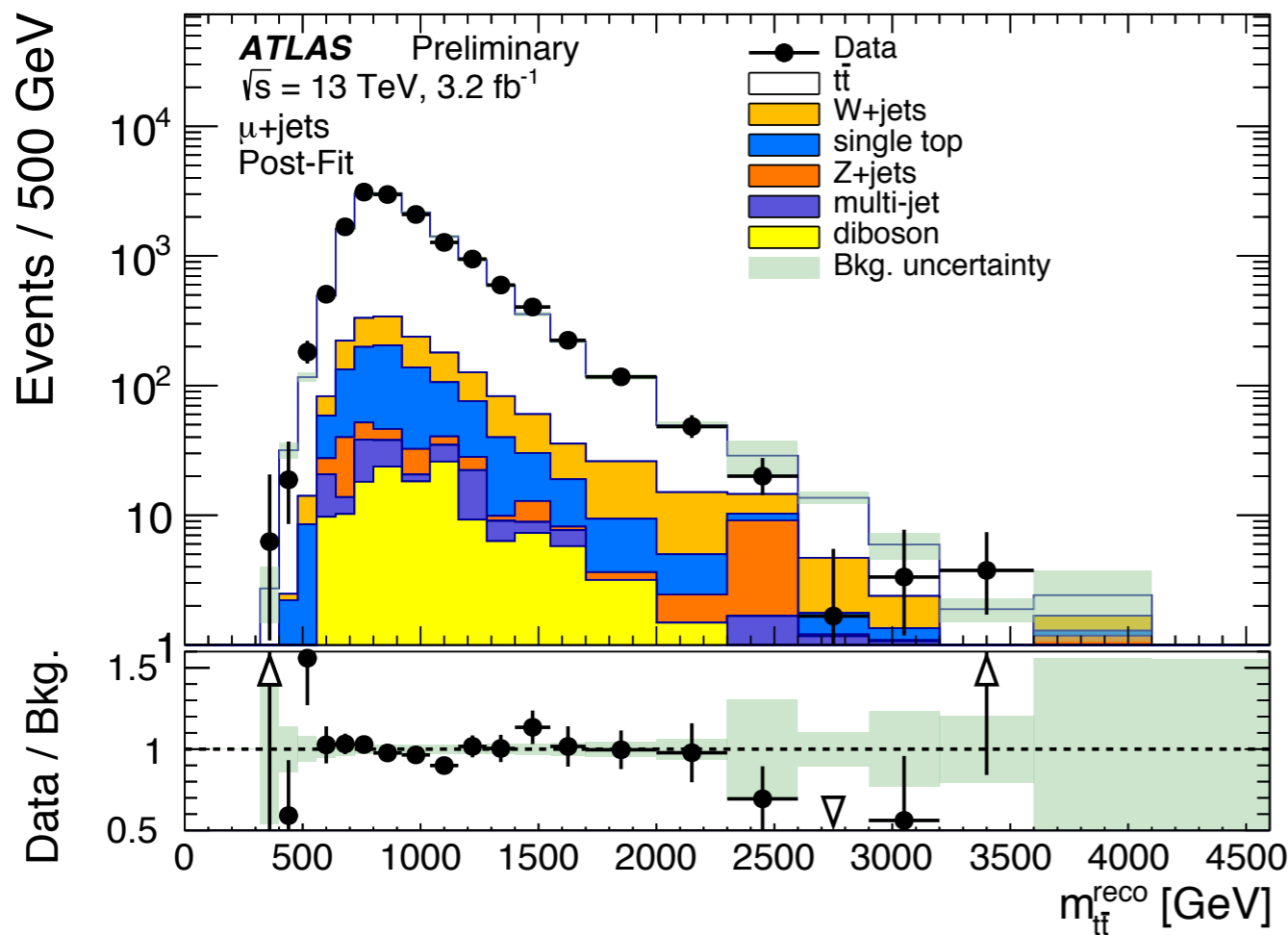
Axial-vector Mediator

Scalar Mediator

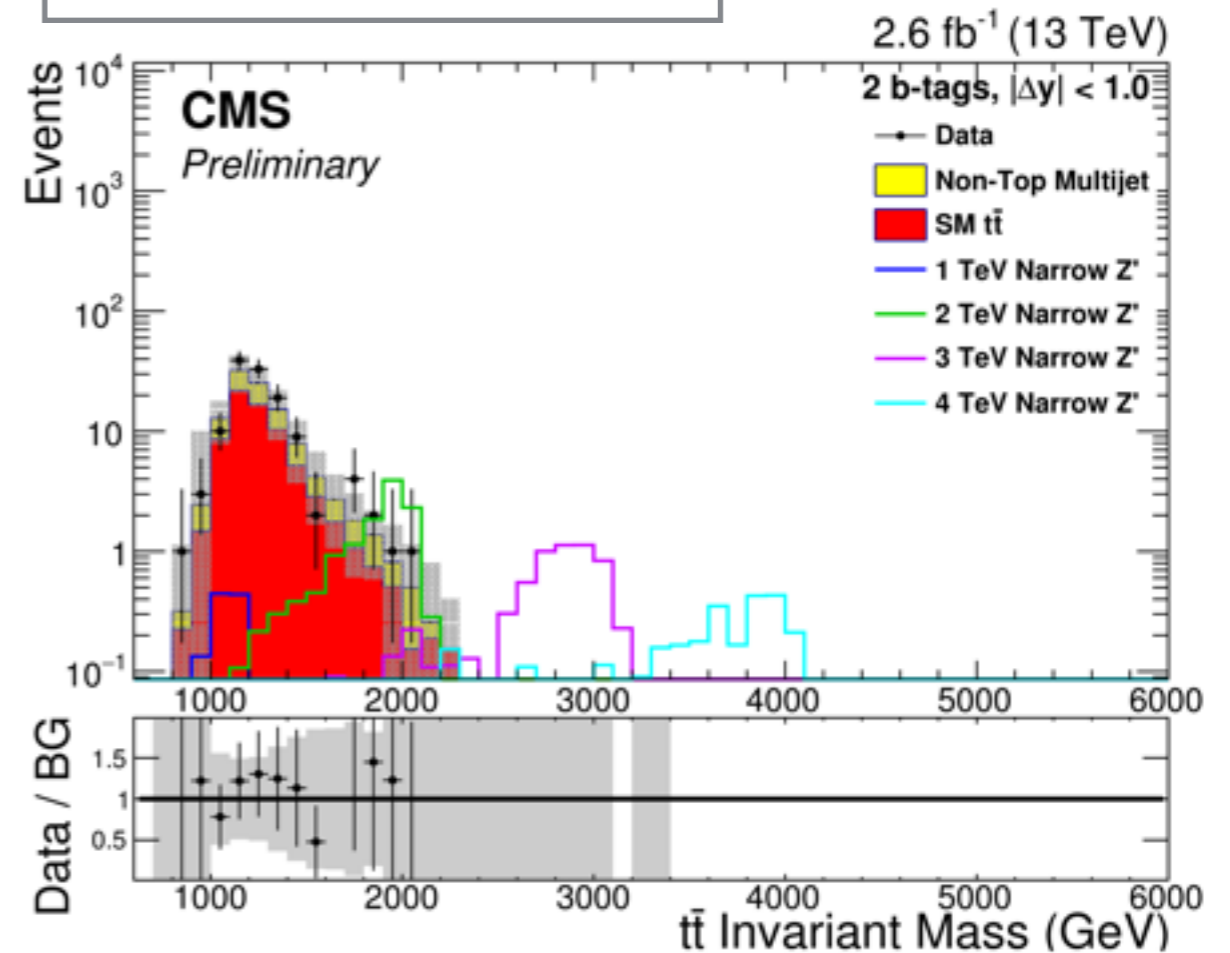


- Using jet substructure techniques to search in lepton+jet and full hadronic jet channels.

ATLAS-CONF-2016-014



CMS-PAS-B2G-15-003



Z'_{TC2} (1.2% width) $> 2.2 \text{ TeV}$
 Z'_{TC2} (3% width) $> 3.2 \text{ TeV}$

Signal Model	Exclusion Ranges (TeV)	
	Expected	Observed
Z' (1% Width)	1.2 – 1.6	1.4 – 1.6
Z' (10% Width)	1.0 – 3.1	1.0 – 3.3
Z' (30% Width)	1.0 – 3.7	1.0 – 3.8
RS Gluon	1.0 – 2.5	1 – 2.4

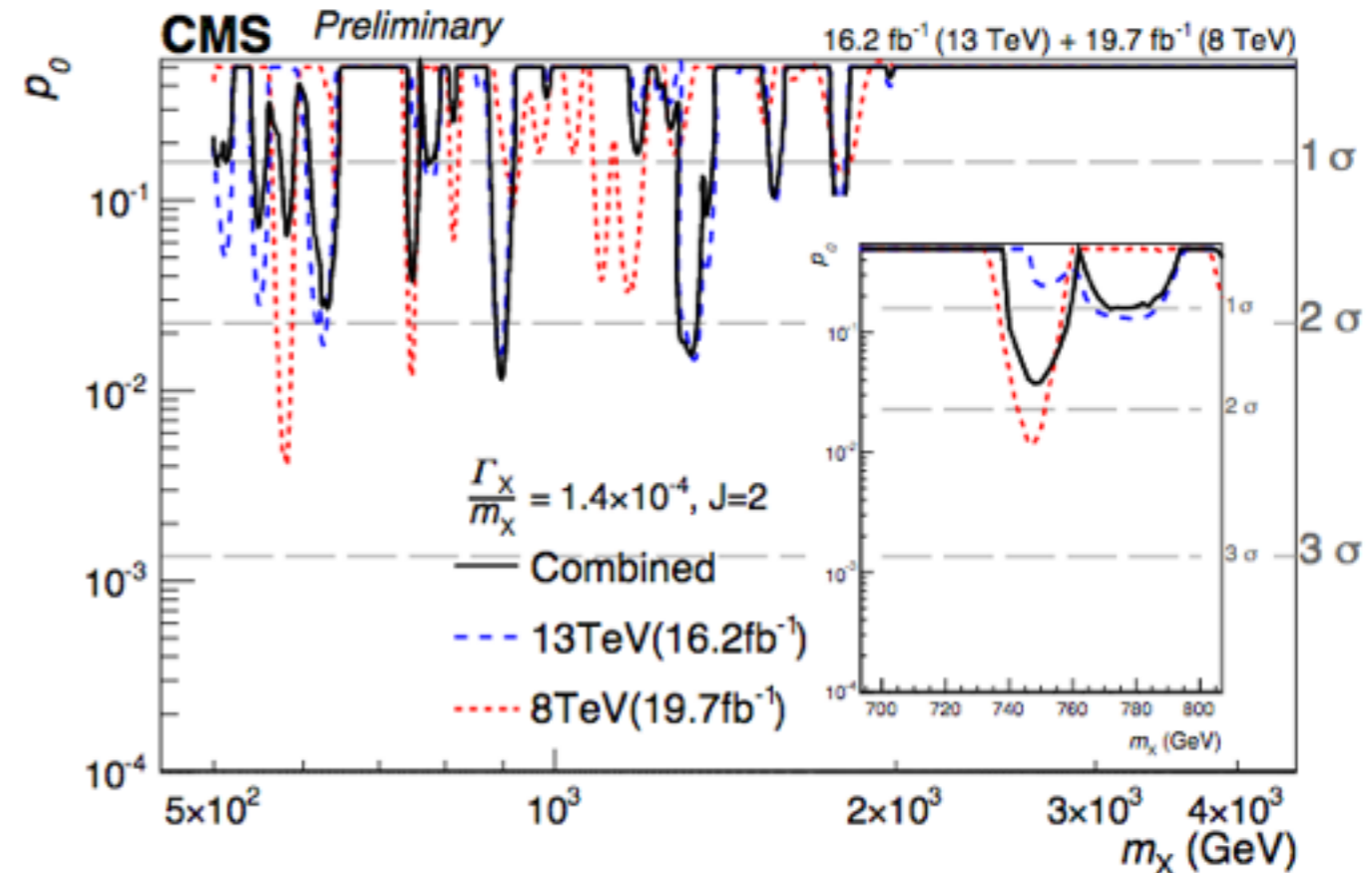
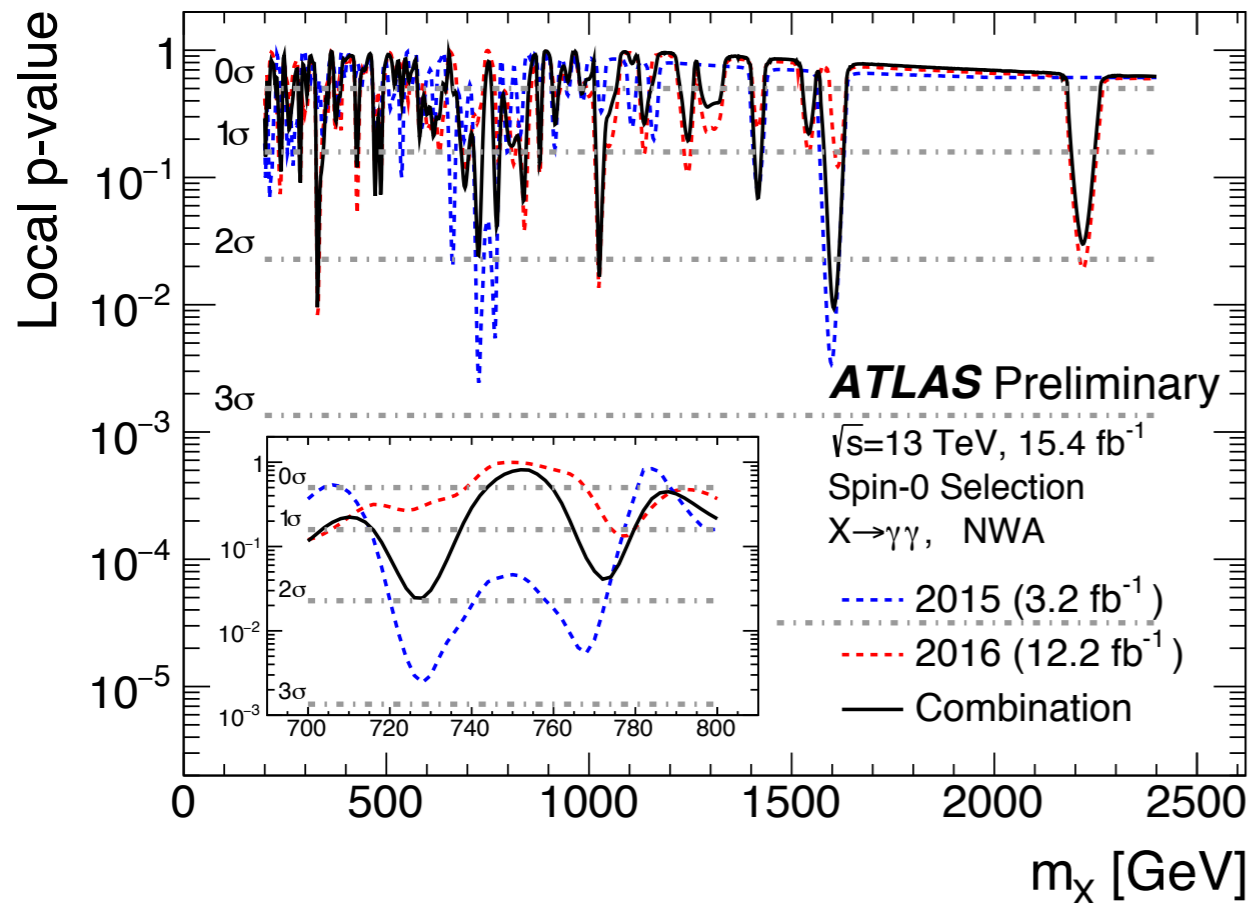
Diphoton Combination

2015+2016

Run1+2015+2016

ATLAS-CONF-2016-059

CMS-PAS-EXO-16-027



The largest combined significance

$m=1.6$ TeV (narrow width)
 2.4σ (local)/ $<1\sigma$ (global)

$m=0.9$ TeV (1.4×10^{-4} width)
 2.2σ (local)/ $<1\sigma$ (global)