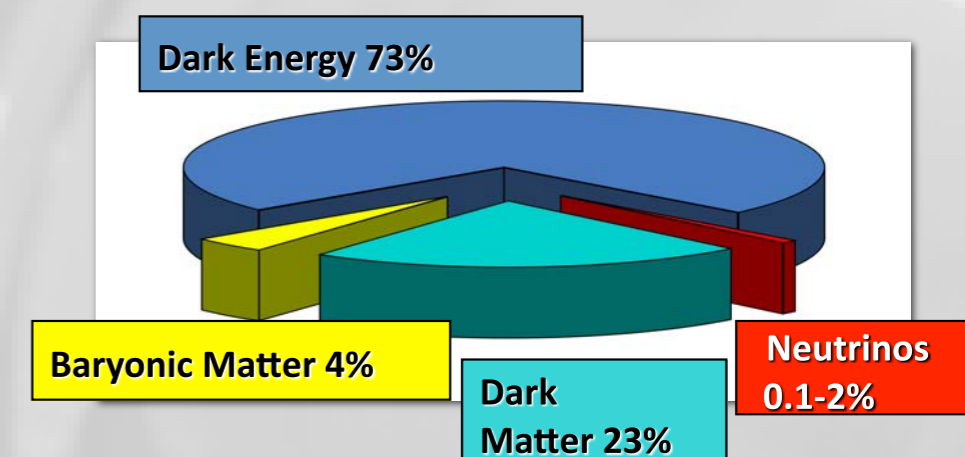


# Search for BSM Physics: Exotics and Future of LHC

- models / ideas for physics BSM
- some examples of LHC searches for physics BSM
- results of the 2015/16 LHC run-II ( $\sqrt{s} = 13$  TeV)
- LHC future plans
  - LHC
  - hl-LHC
  - FCC

today, there are few but significant signals  
for BSM physics:

- neutrinos are not massless
- 95% of the mass/energy budget of the universe cannot be explained by SM particles and forces:
  - Dark Matter (23%)
  - Dark Energy (73%)

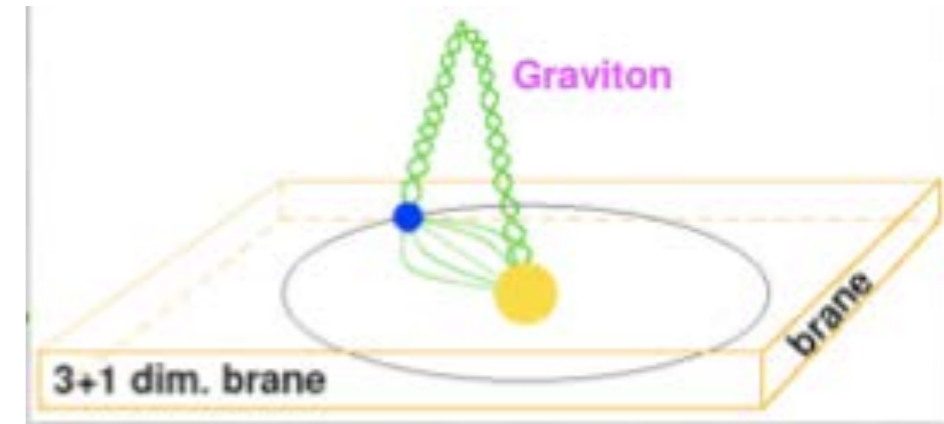


## some en vogue models of BSM:

- Supersymmetry (SUSY) (see previous lecture)
- composite models (excited quarks & leptons)
- new symmetries (new heavy gauge bosons)
- large extra dimensions (micro black holes,...)
- technicolor models (new gauge interactions)
- leptoquarks (GUT)
- ...

# ADD model of large extra dimensions:

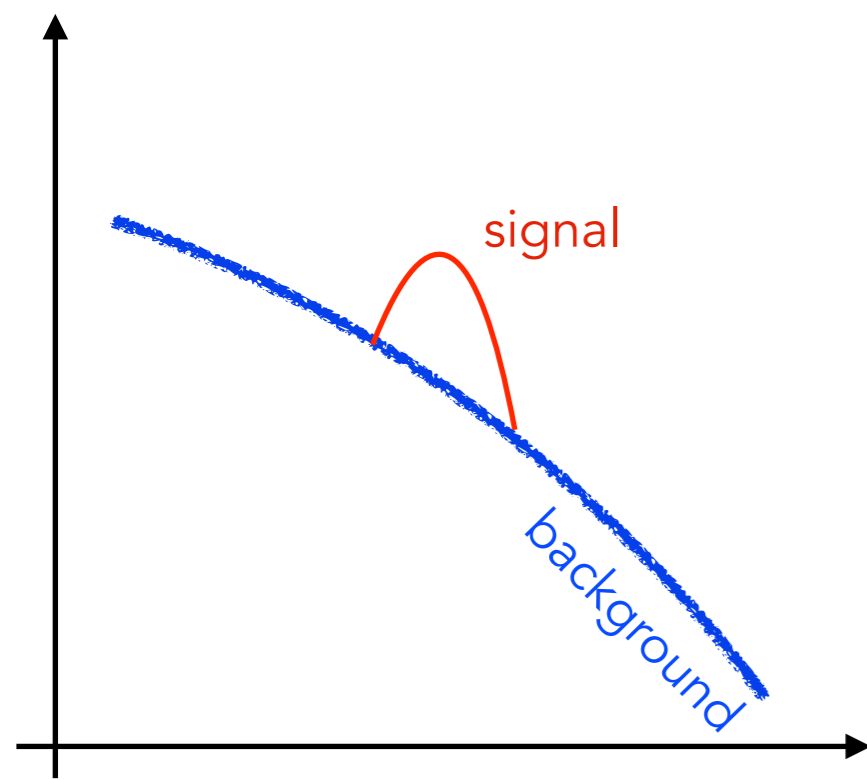
- fields of SM are confined to 3+1-dimensional membrane
- gravity propagates to  $n$  additional spatial extra dimensions
- extra dimensions are compactified on an  $n$ -dimensional torus / sphere of radius  $R$
- Planck-mass in  $4+n$  dimensions :  $M_D^{n+2} \sim M_{\text{Pl}}^2 R^{-n}$  may approach TeV scale for large  $n \rightarrow$  micro black holes?



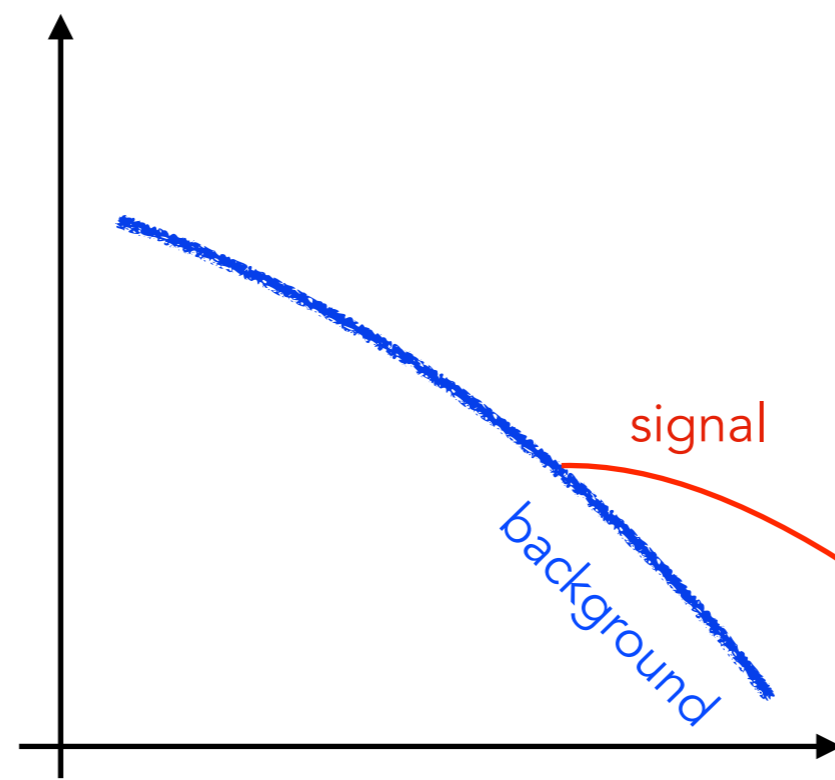
- 1 N. Arkani-Hamed, S. Dimopoulos, G. Dvali (1998). "The Hierarchy problem and new dimensions at a millimeter". *Physics Letters* **B429** (3–4): 263–272. [arXiv:hep-ph/9803315](https://arxiv.org/abs/hep-ph/9803315).
- 2 N. Arkani-Hamed, S. Dimopoulos, G. Dvali (1999). "Phenomenology, astrophysics and cosmology of theories with submillimeter dimensions and TeV scale quantum gravity". *Physical Review* **D59** (8): 086004. [arXiv:hep-ph/9807344](https://arxiv.org/abs/hep-ph/9807344).

# exp. signatures of exotic BSM models:

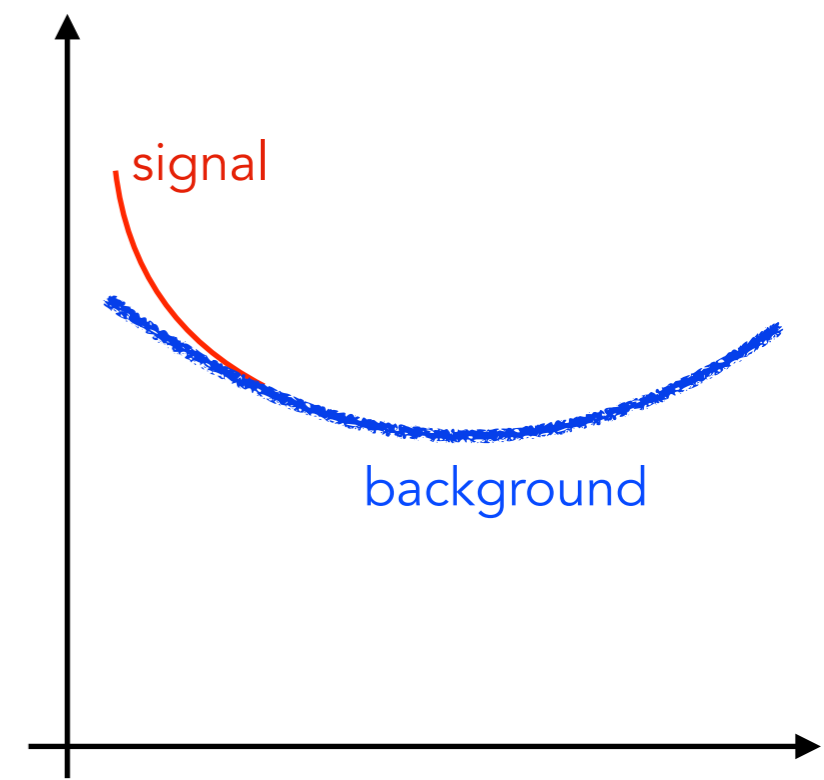
- high-mass resonances decaying into jets, leptons, bosons
- high system energies involving visible and invisible objects
- specific event properties (angular distributions,...)



pair mass  
(jets, leptons, bosons)



energy of system  
(visible, invisible)



internal property  
(e.g. angular distribution)

## exp. signatures of exotic BSM models:

- high-mass resonances decaying into jets, leptons, bosons
- high system energies involving visible and invisible objects
- specific event properties (angular distributions,...)

extensive searches have not shown any significant deviations from SM and thus, no compelling signature of any physics  
BSM

# summary of (model dependent) exclusion limits:

## ATLAS Exotics Searches\* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 20.3) \text{ fb}^{-1}$$

$$\sqrt{s} = 8, 13 \text{ TeV}$$

Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
Extra dimensions	ADD $G_{KK} + g/q$	-	$\geq 1 j$	Yes	3.2	$M_D$ 6.58 TeV	$n = 2$ 1604.07773
	ADD non-resonant $\ell\ell$	$2 e, \mu$	-	-	20.3	$M_S$ 4.7 TeV	$n = 3 \text{ HLZ}$ 1407.2410
	ADD QBH $\rightarrow \ell q$	$1 e, \mu$	$1 j$	-	20.3	$M_{\text{th}}$ 5.2 TeV	$n = 6$ 1311.2006
	ADD QBH	-	$2 j$	-	15.7	$M_{\text{th}}$ 8.7 TeV	$n = 6$ ATLAS-CONF-2016-069
	ADD BH high $\sum p_T$	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	$M_{\text{th}}$ 8.2 TeV	$n = 6, M_D = 3 \text{ TeV, rot BH}$ 1606.02265
	ADD BH multijet	-	$\geq 3 j$	-	3.6	$M_{\text{th}}$ 9.55 TeV	$n = 6, M_D = 3 \text{ TeV, rot BH}$ 1512.02586
	RS1 $G_{KK} \rightarrow \ell\ell$	$2 e, \mu$	-	-	20.3	$G_{KK} \text{ mass}$ 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$ 1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2 \gamma$	-	-	3.2	$G_{KK} \text{ mass}$ 3.2 TeV	$k/\overline{M}_{Pl} = 0.1$ 1606.03833
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	$1 e, \mu$	$1 J$	Yes	13.2	$G_{KK} \text{ mass}$ 1.24 TeV	$k/\overline{M}_{Pl} = 1.0$ ATLAS-CONF-2016-062
	Bulk RS $G_{KK} \rightarrow HH \rightarrow bbbb$	-	$4 b$	-	13.3	$G_{KK} \text{ mass}$ 360-860 GeV	$k/\overline{M}_{Pl} = 1.0$ ATLAS-CONF-2016-049
	Bulk RS $g_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2j$	Yes	20.3	$g_{KK} \text{ mass}$ 2.2 TeV	$BR = 0.925$ 1505.07018
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 4 j$	Yes	3.2	$KK \text{ mass}$ 1.46 TeV	Tier (1,1), $BR(A^{(1,1)} \rightarrow tt) = 1$ ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	13.3	$Z' \text{ mass}$ 4.05 TeV	ATLAS-CONF-2016-045
	SSM $Z' \rightarrow \tau\tau$	$2 \tau$	-	-	19.5	$Z' \text{ mass}$ 2.02 TeV	1502.07177
	Leptophobic $Z' \rightarrow bb$	-	$2 b$	-	3.2	$Z' \text{ mass}$ 1.5 TeV	1603.08791
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	13.3	$W' \text{ mass}$ 4.74 TeV	ATLAS-CONF-2016-061
	HVT $W' \rightarrow WZ \rightarrow qq\nu\nu$ model A	$0 e, \mu$	$1 J$	Yes	13.2	$W' \text{ mass}$ 2.4 TeV	$g_V = 1$ ATLAS-CONF-2016-082
	HVT $W' \rightarrow WZ \rightarrow qqqq$ model B	-	$2 J$	-	15.5	$W' \text{ mass}$ 3.0 TeV	$g_V = 3$ ATLAS-CONF-2016-055
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	3.2	$V' \text{ mass}$ 2.31 TeV	$g_V = 3$ 1607.05621
	LRSM $W'_R \rightarrow tb$	$1 e, \mu$	$2 b, 0-1 j$	Yes	20.3	$W' \text{ mass}$ 1.92 TeV	1410.4103
LRSM $W'_R \rightarrow tb$	$0 e, \mu$	$\geq 1 b, 1 J$	-	20.3	$W' \text{ mass}$ 1.76 TeV	1408.0886	
CI	CI $qqqq$	-	$2 j$	-	15.7	$\Lambda$ 19.9 TeV $\eta_{LL} = -1$	ATLAS-CONF-2016-069
	CI $\ell\ell qq$	$2 e, \mu$	-	-	3.2	$\Lambda$ 25.2 TeV $\eta_{LL} = -1$	1607.03669
	CI $uutt$	$2(SS) \geq 3 e, \mu \geq 1 b, \geq 1 j$	Yes	20.3	$\Lambda$ 4.9 TeV	$ C_{RR}  = 1$ 1504.04605	
DM	Axial-vector mediator (Dirac DM)	$0 e, \mu$	$\geq 1 j$	Yes	3.2	$m_A$ 1.0 TeV	$g_q=0.25, g_\chi=1.0, m(\chi) < 250 \text{ GeV}$ 1604.07773
	Axial-vector mediator (Dirac DM)	$0 e, \mu, 1 \gamma$	$1 j$	Yes	3.2	$m_A$ 710 GeV	$g_q=0.25, g_\chi=1.0, m(\chi) < 150 \text{ GeV}$ 1604.01306
	$ZZ\chi\chi$ EFT (Dirac DM)	$0 e, \mu$	$1 J, \leq 1 j$	Yes	3.2	$M_*$ 550 GeV	$m(\chi) < 150 \text{ GeV}$ ATLAS-CONF-2015-080
LQ	Scalar LQ 1 <sup>st</sup> gen	$2 e$	$\geq 2 j$	-	3.2	LQ mass 1.1 TeV	$\beta = 1$ 1605.06035
	Scalar LQ 2 <sup>nd</sup> gen	$2 \mu$	$\geq 2 j$	-	3.2	LQ mass 1.05 TeV	$\beta = 1$ 1605.06035
	Scalar LQ 3 <sup>rd</sup> gen	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	20.3	LQ mass 640 GeV	$\beta = 0$ 1508.04735
Heavy quarks	VLQ $TT \rightarrow Ht + X$	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	20.3	T mass 855 GeV	T in (T,B) doublet 1505.04306
	VLQ $YY \rightarrow Wb + X$	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet 1505.04306
	VLQ $BB \rightarrow Hb + X$	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	20.3	B mass 735 GeV	isospin singlet 1505.04306
	VLQ $BB \rightarrow Zb + X$	$2/\geq 3 e, \mu$	$\geq 2/\geq 1 b$	-	20.3	B mass 755 GeV	B in (B,Y) doublet 1409.5500
	VLQ $QQ \rightarrow WqWq$	$1 e, \mu$	$\geq 4 j$	Yes	20.3	Q mass 690 GeV	1509.04261
	VLQ $T_{5/3} T_{5/3} \rightarrow WtWt$	$2(SS) \geq 3 e, \mu \geq 1 b, \geq 1 j$	Yes	3.2	$T_{5/3} \text{ mass}$ 990 GeV	ATLAS-CONF-2016-032	
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	$1 \gamma$	$1 j$	-	3.2	$q^* \text{ mass}$ 4.4 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ 1512.05910
	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	15.7	$q^* \text{ mass}$ 5.6 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ ATLAS-CONF-2016-069
	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	8.8	$b^* \text{ mass}$ 2.3 TeV	ATLAS-CONF-2016-060
	Excited quark $b^* \rightarrow Wt$	$1 \text{ or } 2 e, \mu$	$1 b, 2-0 j$	Yes	20.3	$b^* \text{ mass}$ 1.5 TeV	$f_g = f_L = f_R = 1$ 1510.02664
	Excited lepton $\ell^*$	$3 e, \mu$	-	-	20.3	$\ell^* \text{ mass}$ 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$ 1411.2921
	Excited lepton $\nu^*$	$3 e, \mu, \tau$	-	-	20.3	$\nu^* \text{ mass}$ 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$ 1411.2921
Other	LSTC $a_T \rightarrow W\gamma$	$1 e, \mu, 1 \gamma$	-	Yes	20.3	$a_T \text{ mass}$ 960 GeV	1407.8150
	LRSM Majorana $\nu$	$2 e, \mu$	$2 j$	-	20.3	$N^0 \text{ mass}$ 2.0 TeV	$m(W_R) = 2.4 \text{ TeV, no mixing}$ 1506.06020
	Higgs triplet $H^{\pm\pm} \rightarrow ee$	$2 e (SS)$	-	-	13.9	$H^{\pm\pm} \text{ mass}$ 570 GeV	DY production, $BR(H_L^{\pm\pm} \rightarrow ee)=1$ ATLAS-CONF-2016-051
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	-	-	20.3	$H^{\pm\pm} \text{ mass}$ 400 GeV	DY production, $BR(H_L^{\pm\pm} \rightarrow \ell\tau)=1$ 1411.2921
	Monotop (non-res prod)	$1 e, \mu$	$1 b$	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$ 1410.5404
	Multi-charged particles	-	-	-	20.3	multi-charged particle mass 785 GeV	DY production, $ q  = 5e$ 1504.04188
	Magnetic monopoles	-	-	-	7.0	monopole mass 1.34 TeV	DY production, $ g  = 1g_D, \text{spin } 1/2$ 1509.08059

$\sqrt{s} = 8 \text{ TeV}$   $\sqrt{s} = 13 \text{ TeV}$

\*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).

so far: no positive signals → mass range exclusions

“Absence of evidence is not evidence of absence”

meaning:

no sign of physics BSM from Run-I / Run-II data,  
but unexplored phase space still large!



# ATLAS highest mass central dijet event

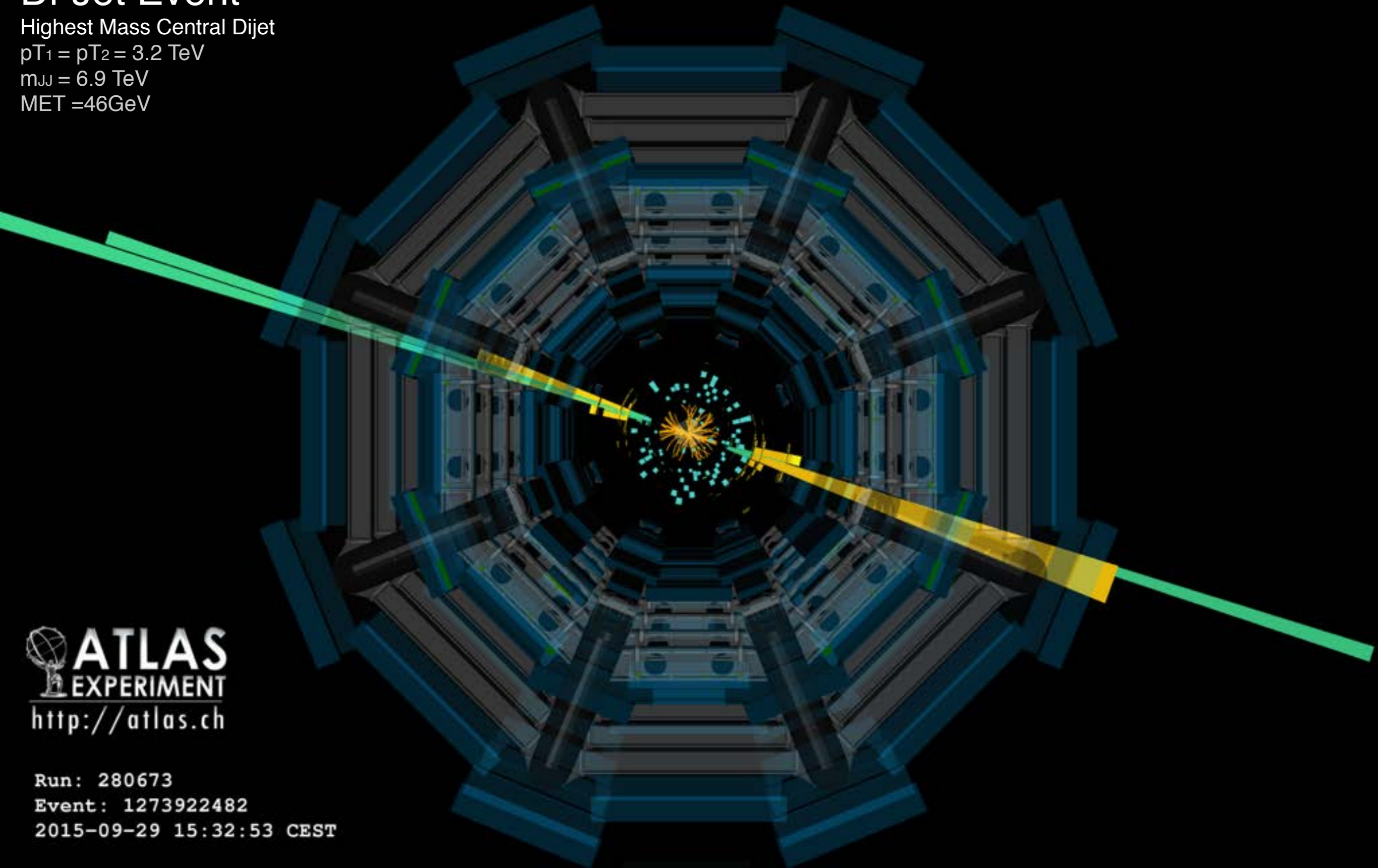
## Di-Jet Event

Highest Mass Central Dijet

$p_{T1} = p_{T2} = 3.2 \text{ TeV}$

$m_{JJ} = 6.9 \text{ TeV}$

$\text{MET} = 46 \text{ GeV}$



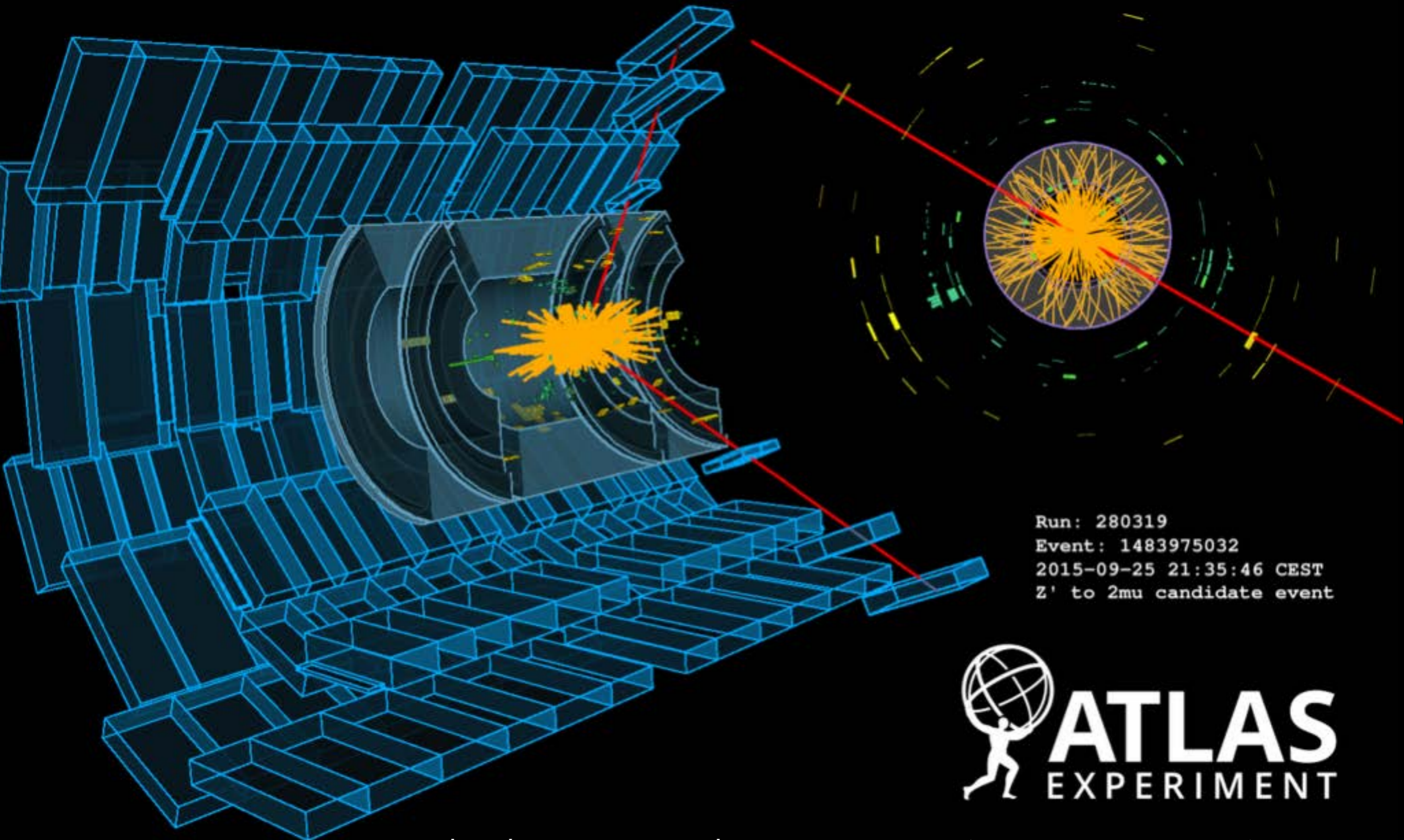
 **ATLAS**  
EXPERIMENT  
<http://atlas.ch>

Run: 280673

Event: 1273922482

2015-09-29 15:32:53 CEST

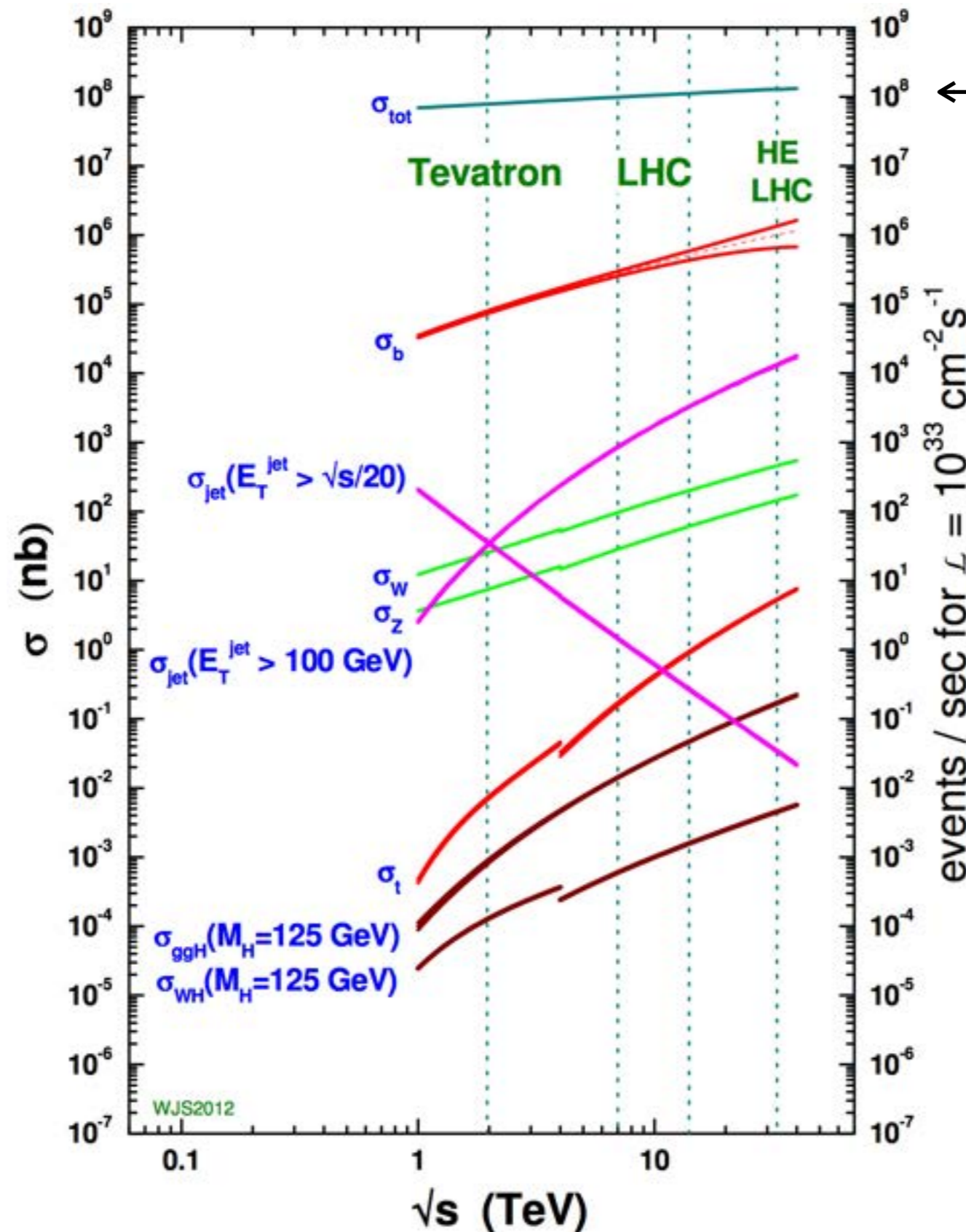
# high mass dimuon event



highest mass dimuon event ( $m_{\mu\mu} = 1.46 \text{ TeV}$ )

# production cross sections at the LHC

proton - (anti-)proton cross sections



↔ total cross section:  
 $10^8$  evts/s (dominated  
 by strong interaction)

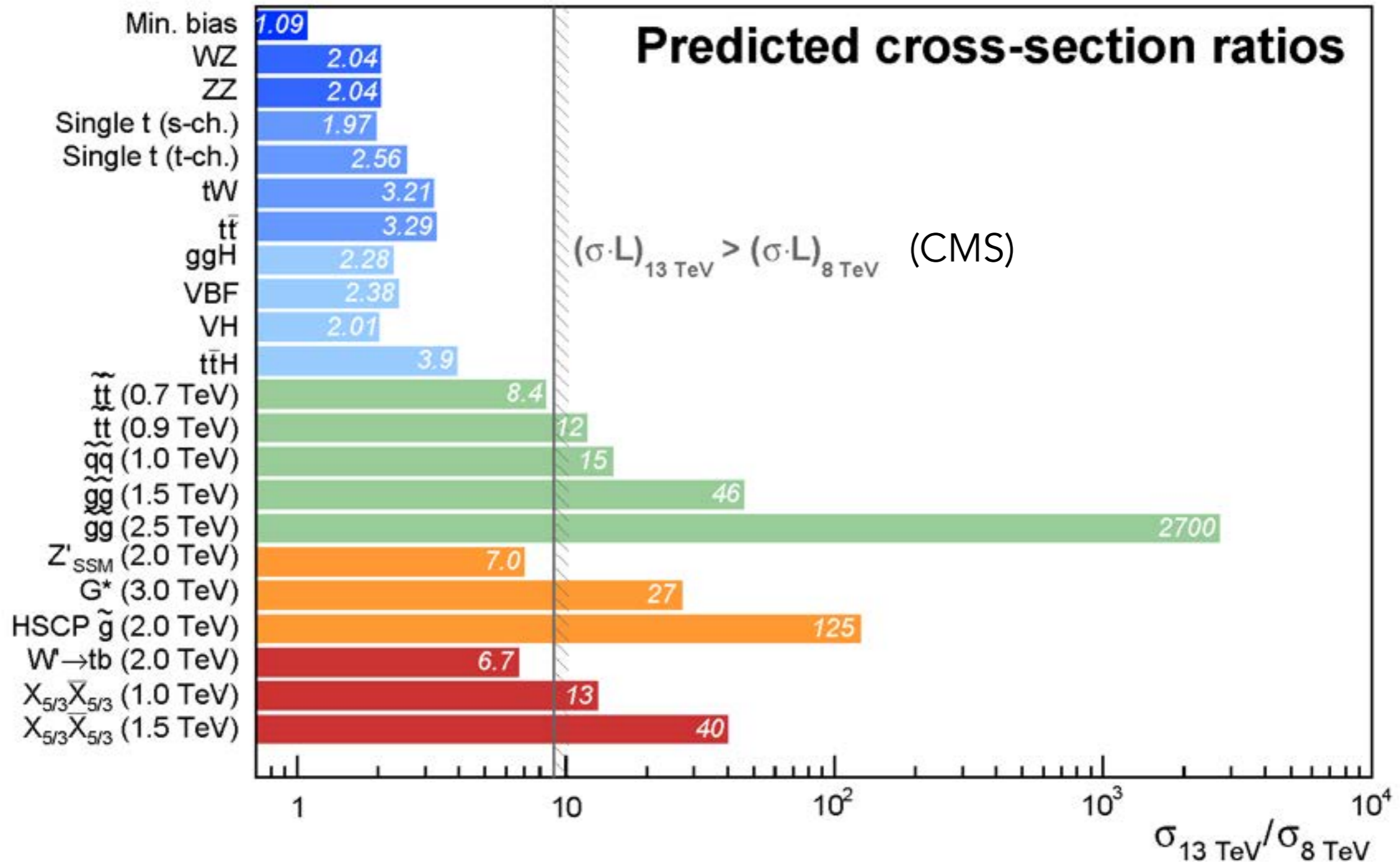
↔ max. read-out:  
 $\sim 10^3$  evts/sec

↔ O(1) top-event/sec

↔ O(1) Higgs/min

# production cross sections at the LHC

cross section ratios 13 TeV / 8 TeV

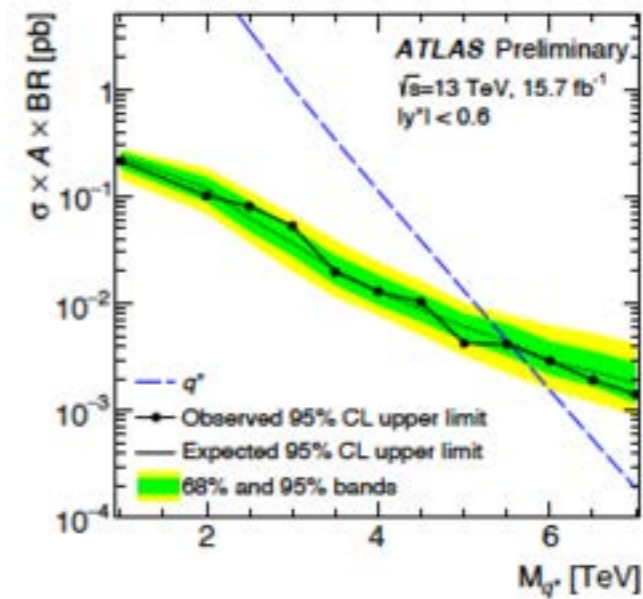
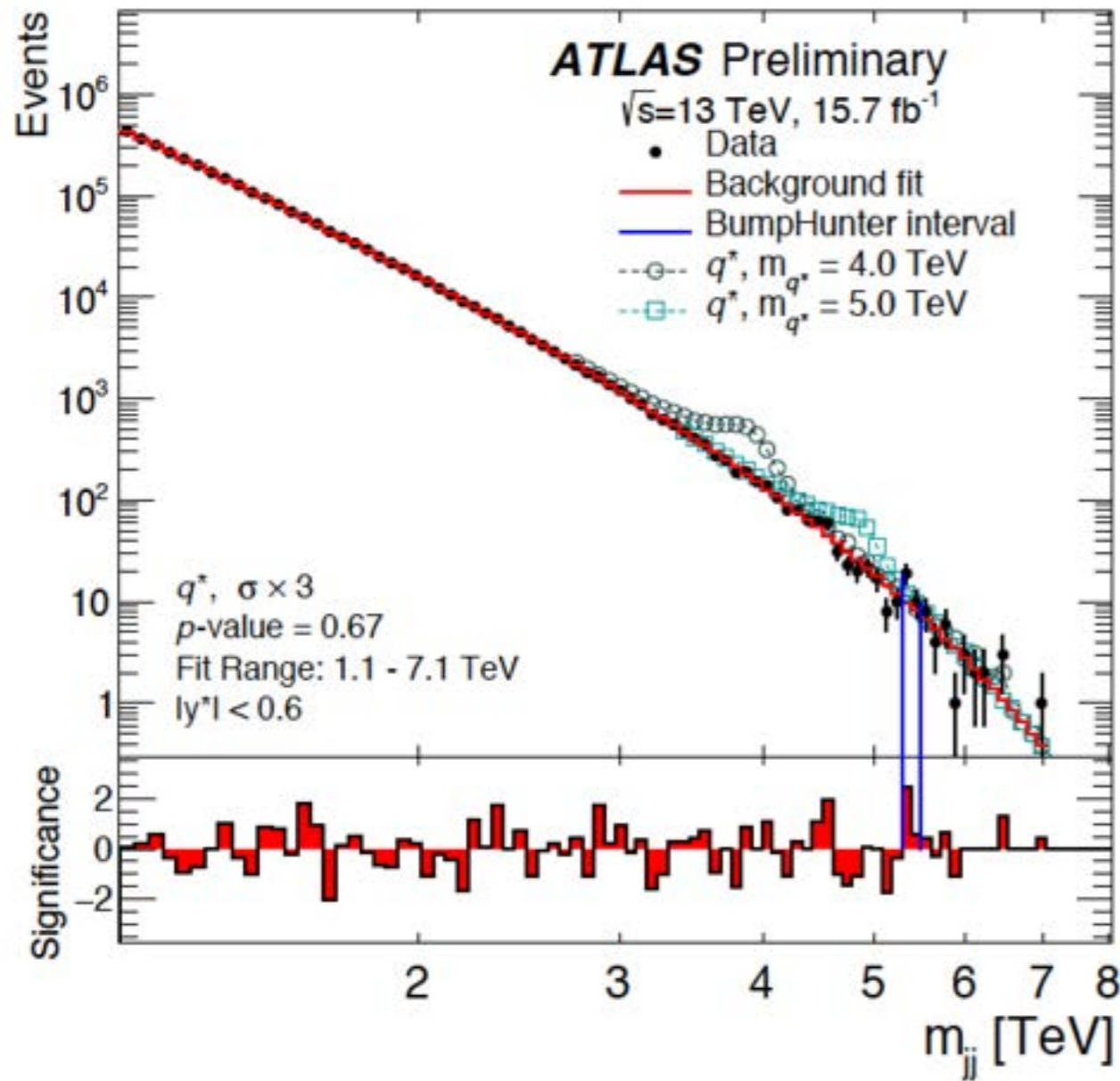


- for SM processes (top-quark; Higgs): x-sections increase by  $\sim 2 \dots 3$  at 13 TeV
- for new phenomena and masses of  $O(\text{TeV})$ , increase of  $\sim 10$  to 100s
- therefor, many results from run-II already surpass those from run-I

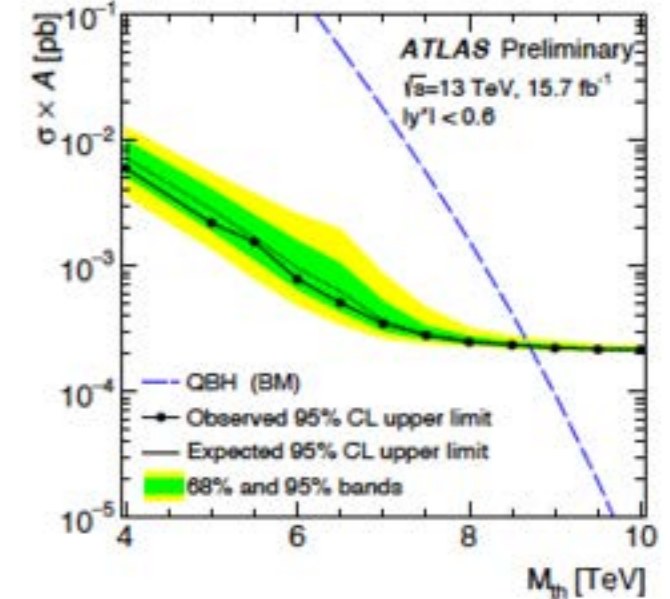
# Searches for composite / excited quarks

13 TeV data: Dijet Resonant Searches

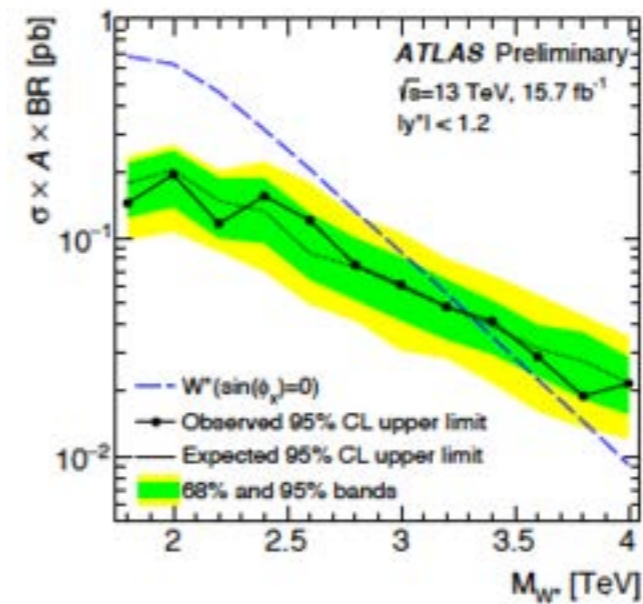
ATLAS-CONF-2016-069



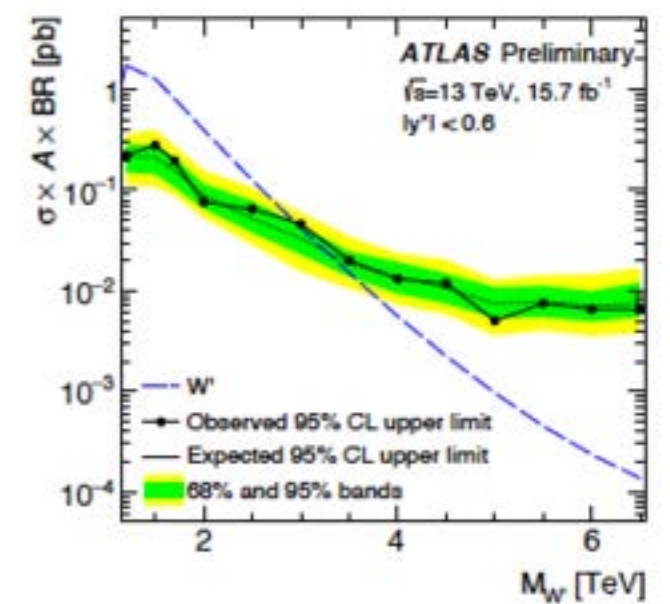
(a)  $q^*$



(b) BLACKMAX



(c)  $W^*$



(d)  $W'$

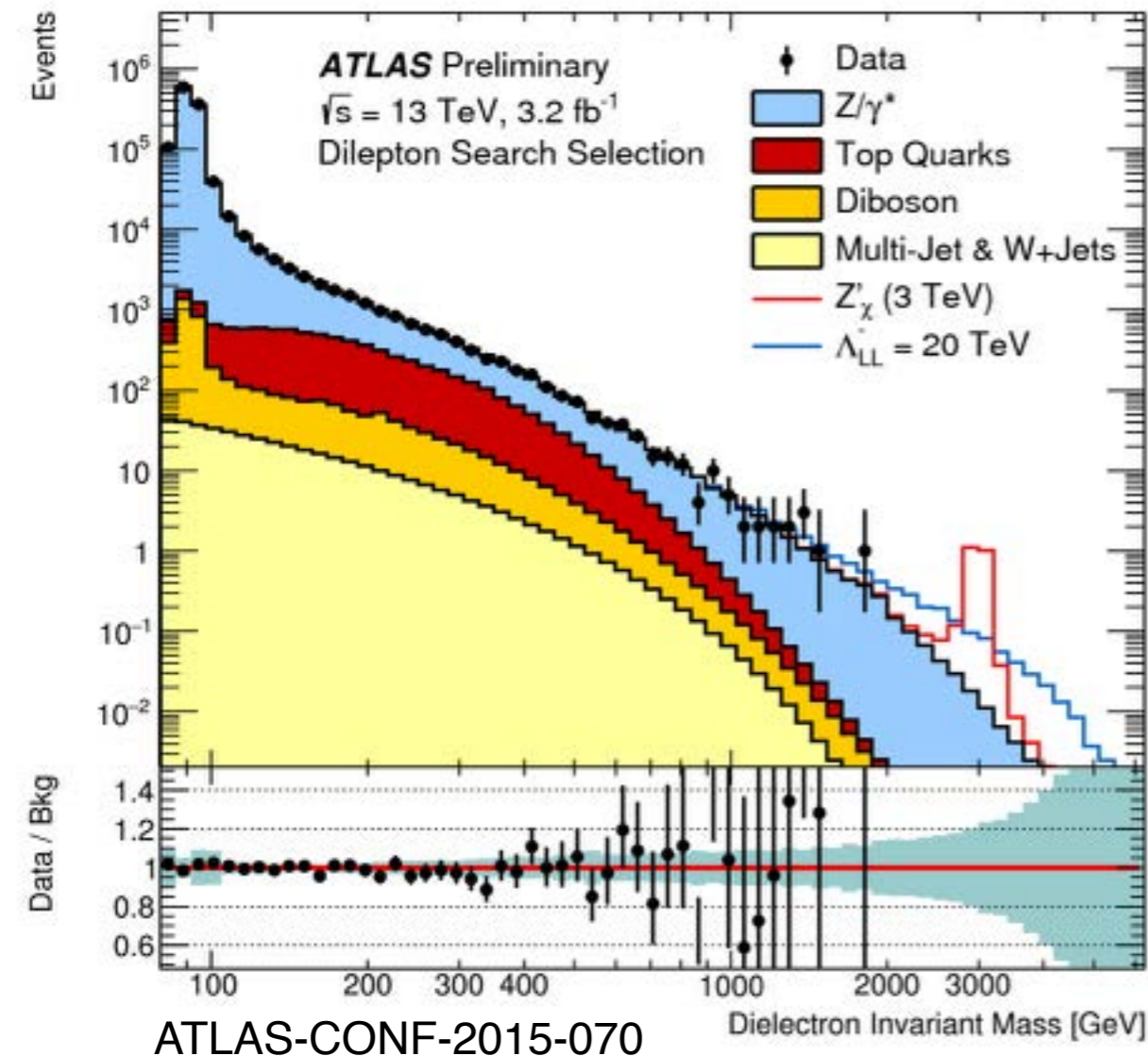
excludes e.g. excited quarks with masses  $< 5.6$  TeV, and quantum BHs with masses  $< 8.7$  TeV ( $n=6$ )

Figure 3: The 95% credibility-level upper limits obtained from the  $m_{jj}$  distribution on cross-section,  $\sigma$ , times acceptance,  $A$ , for the models described in the text. Clockwise from top left:  $q^*$ , quantum black holes with  $n = 6$  generated with BLACKMAX,  $W'$  and  $W^*$  where the first three use the nominal selection and the last uses the widened  $|y^*| < 1.2$  selection. The numerical values of the observed and expected limits are summarised in Table 1.

# Searches for additional U(1)' Symmetry

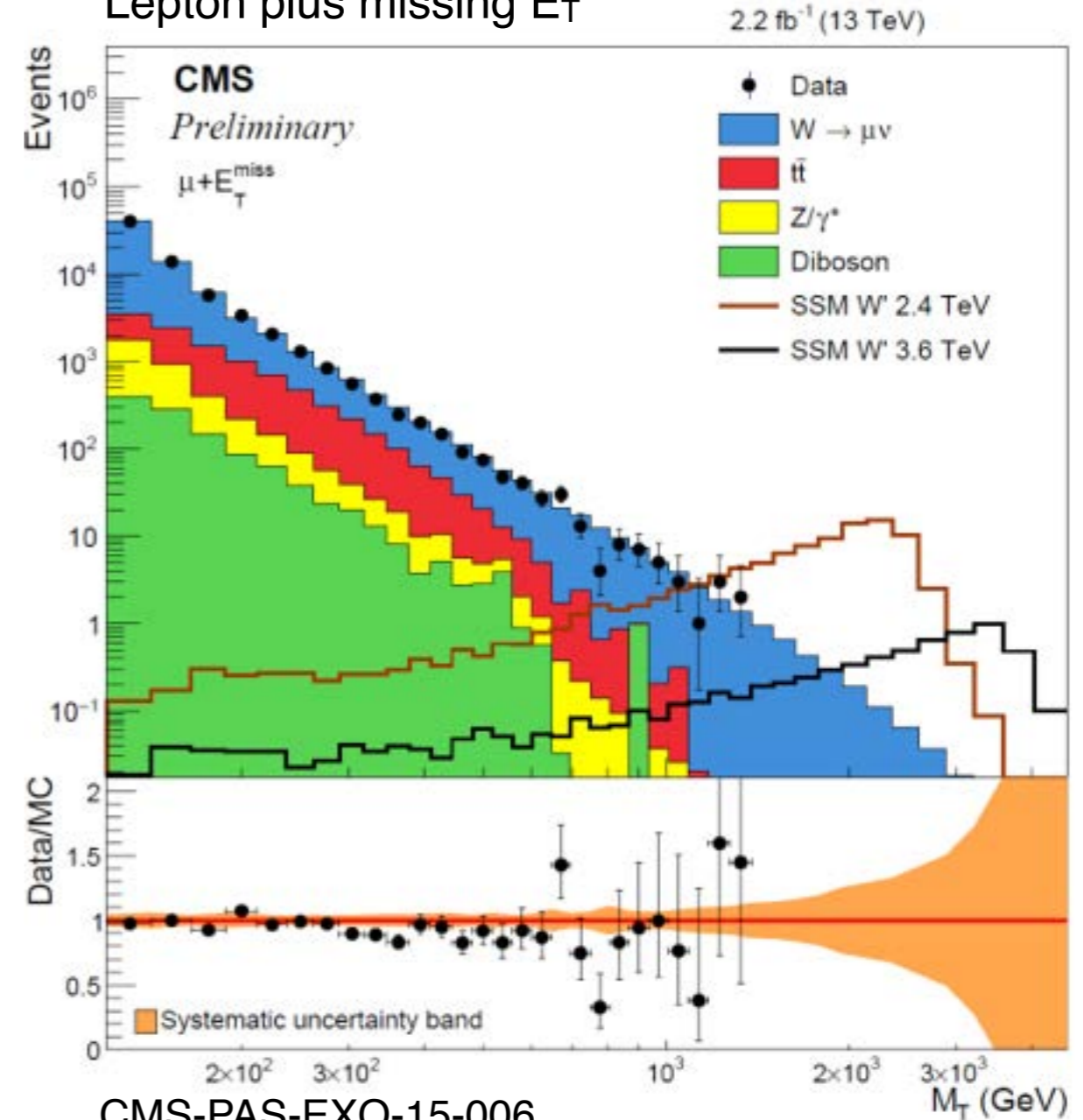
13 TeV data: Search for Heavy Gauge Bosons (Z' and W')

Dilepton Resonance Search



excludes e.g.  $Z'$  with  $m_{Z'} < 3.4 \text{ TeV}$ ,  
 and  $llqq$  contact interactions with  
 scales  $\Lambda_{llqq} < 20 \text{ TeV}$

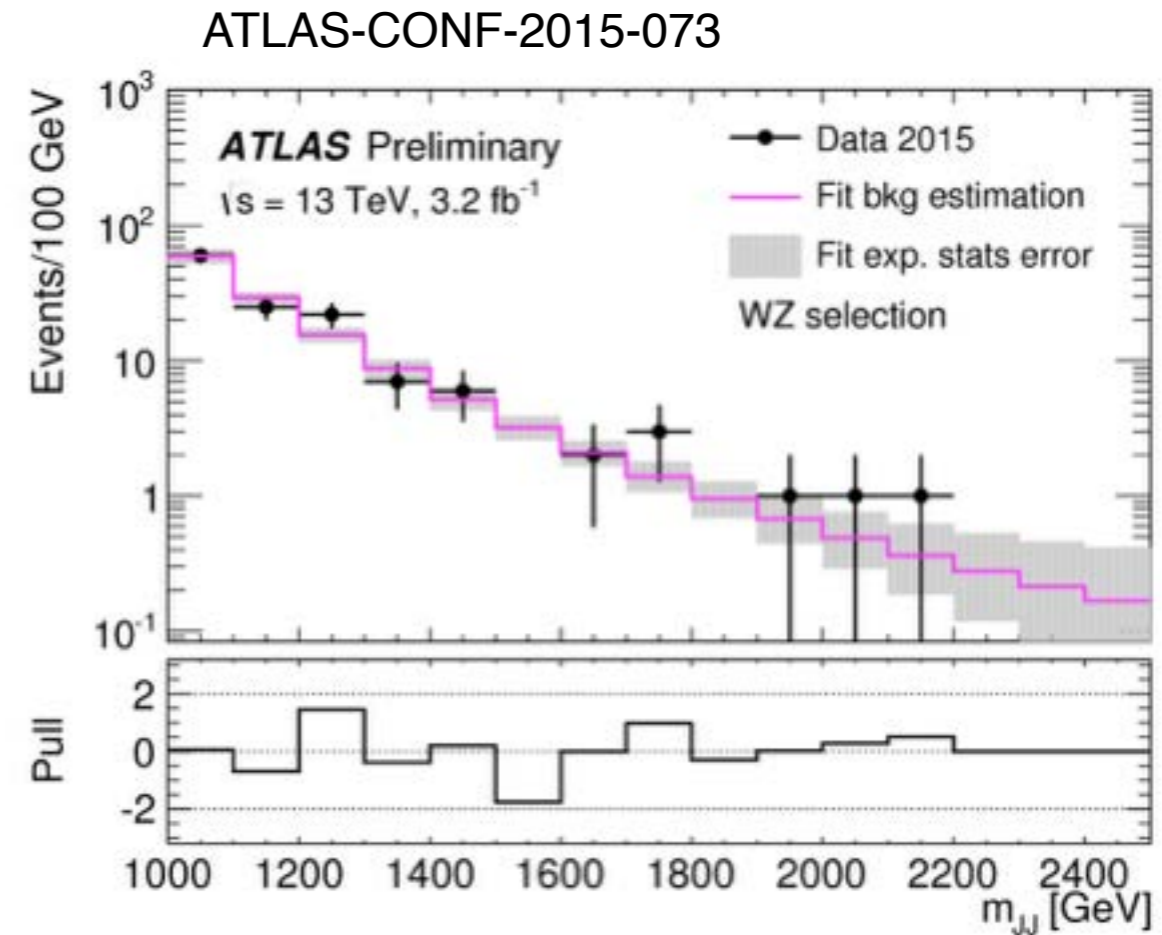
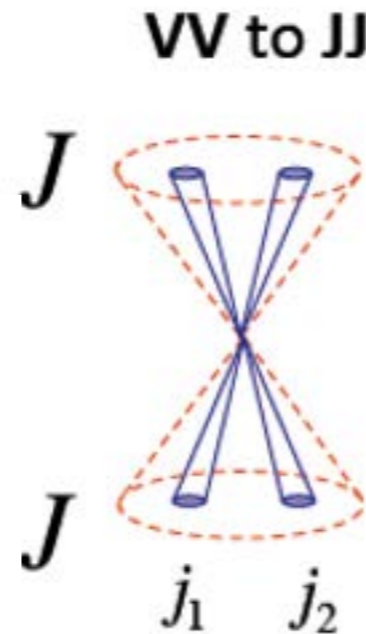
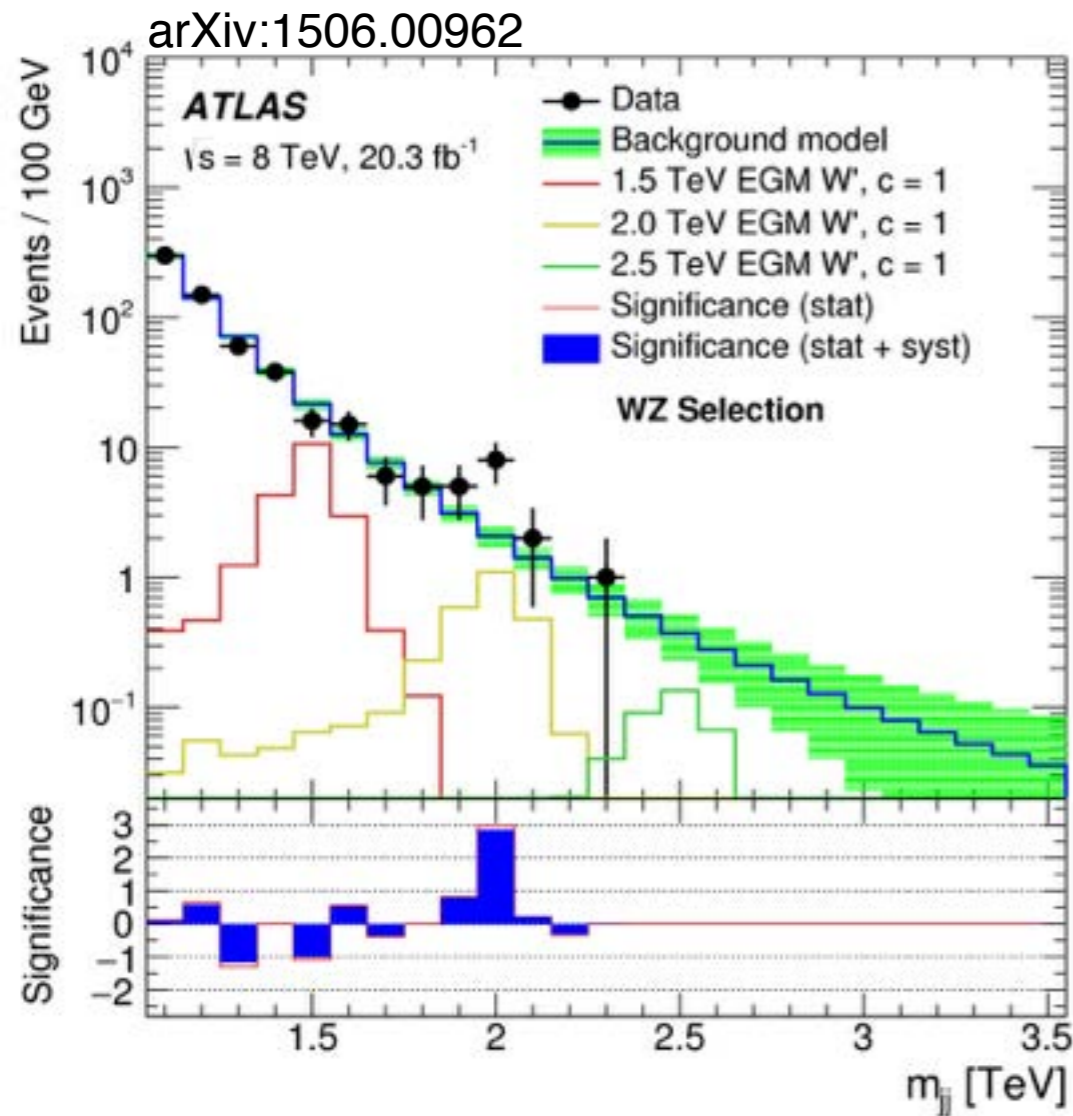
Lepton plus missing  $E_T$



excludes  $W' \rightarrow l\nu$  with  $m_{W'} < 4.4 \text{ TeV}$

# Searches for Diboson Resonances

(new heavy gauge bosons; Kaluza-Klein excitations of the graviton,...)



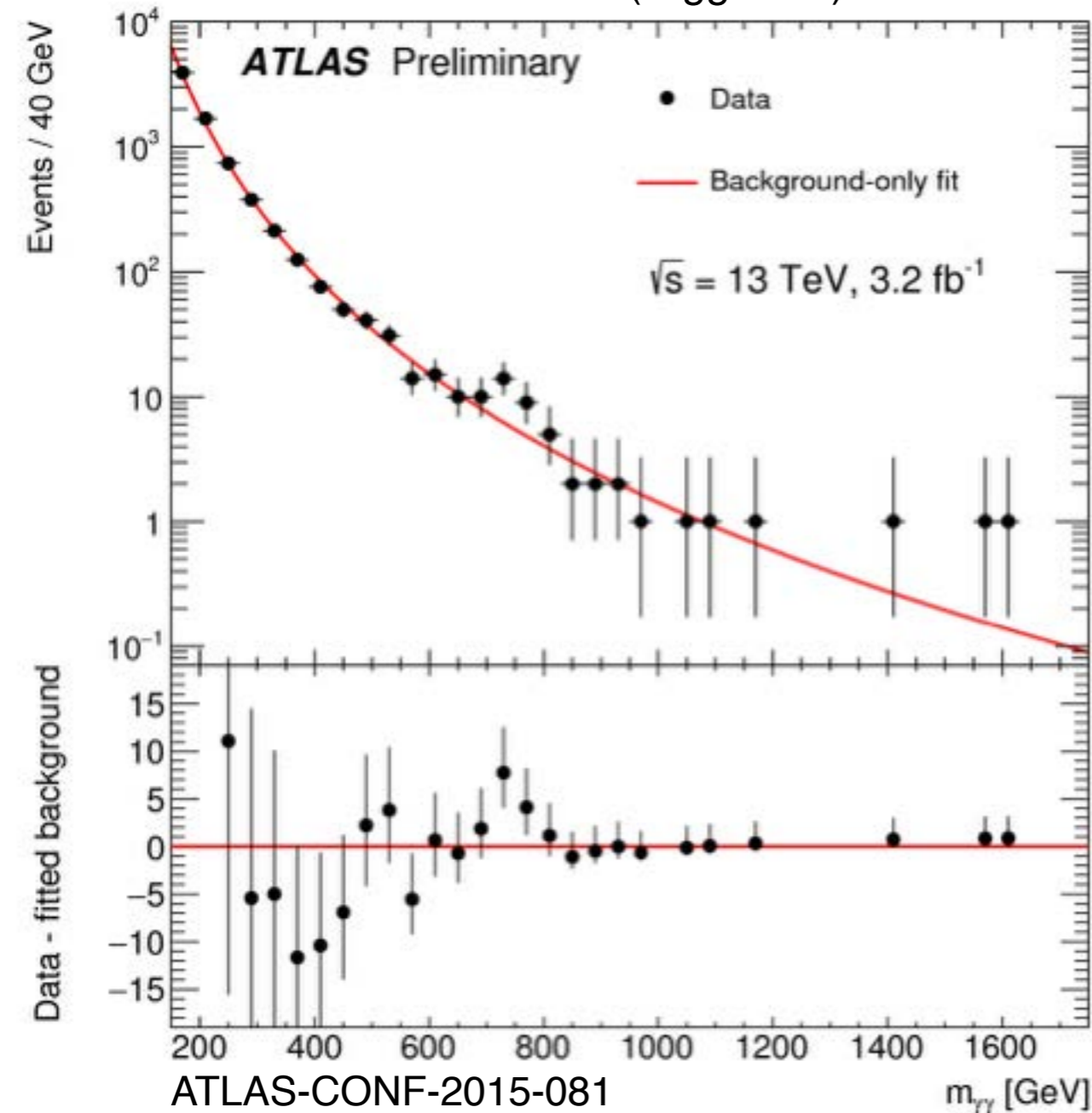
modest excess observed in run-I:  
 $3.4 \sigma$  local,  $2.5 \sigma$  global significance

no excess observed in run II yet,  
 but sensitivity still too low for  
 conclusive probe

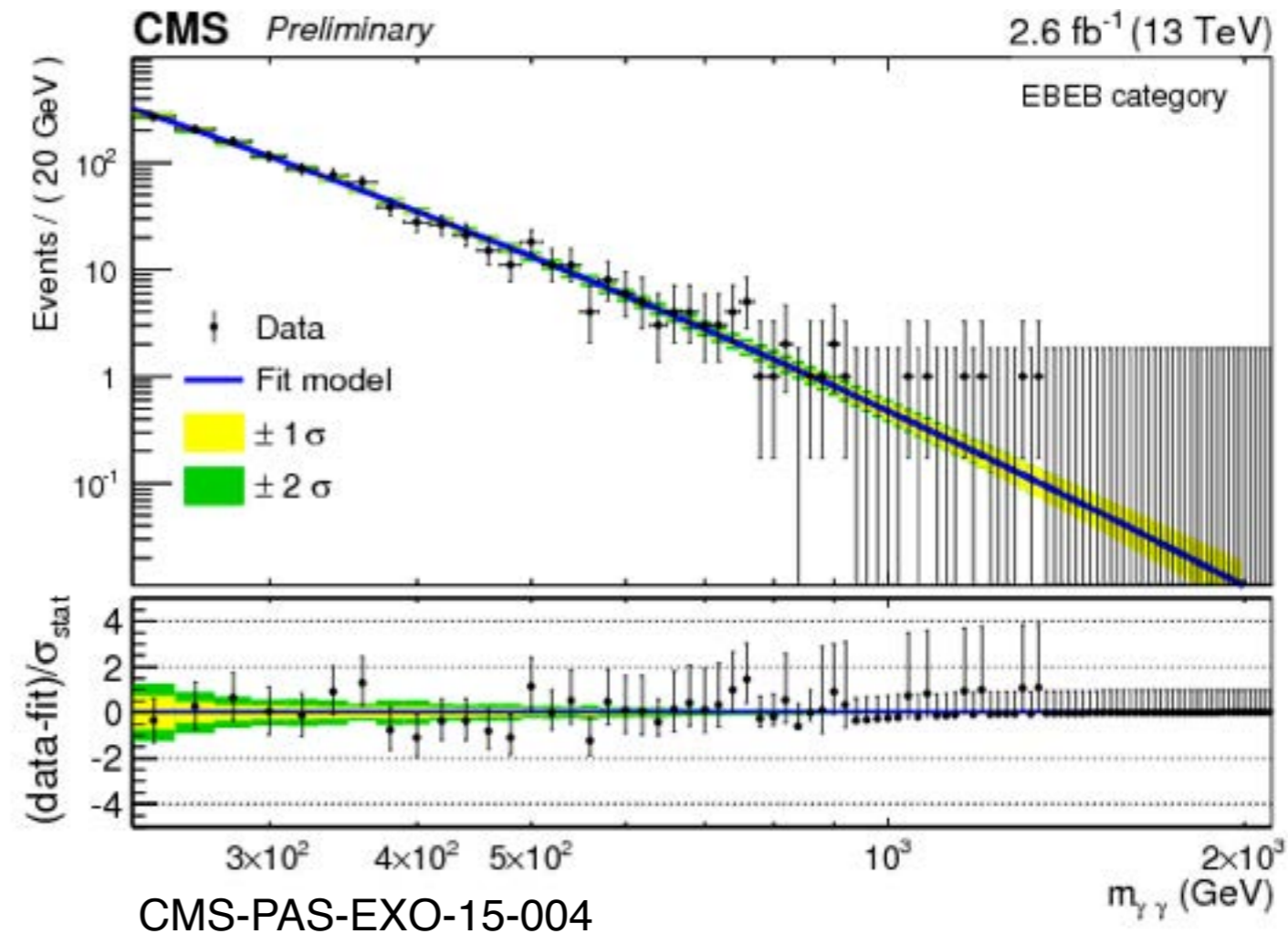
# Searches for Diphoton Resonances

Higgs-like (spin 0) or Graviton-like (spin 2) objects

search for narrow width (Higgs-like) resonance



search for narrow to wide width (graviton-like) resonance

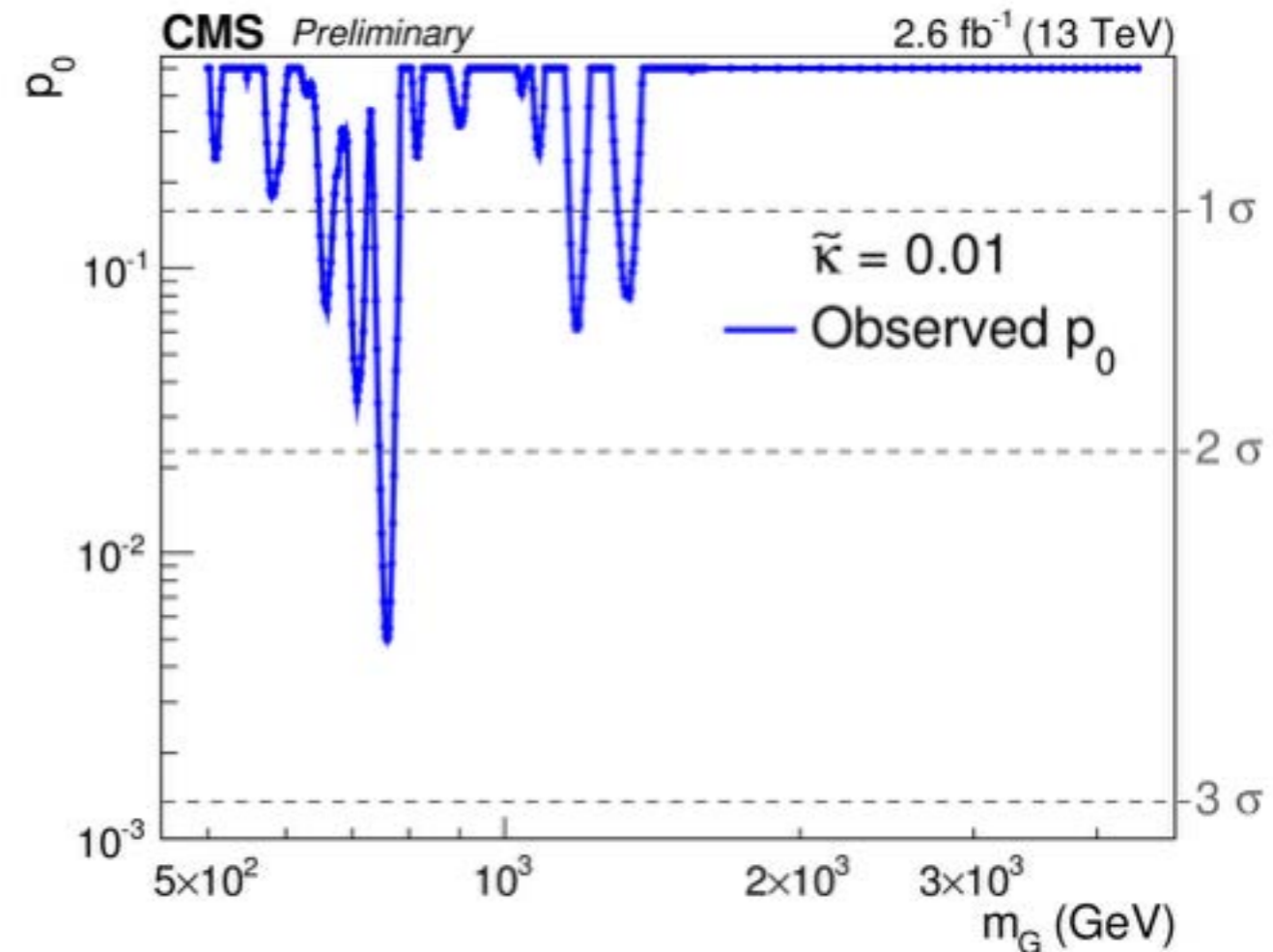
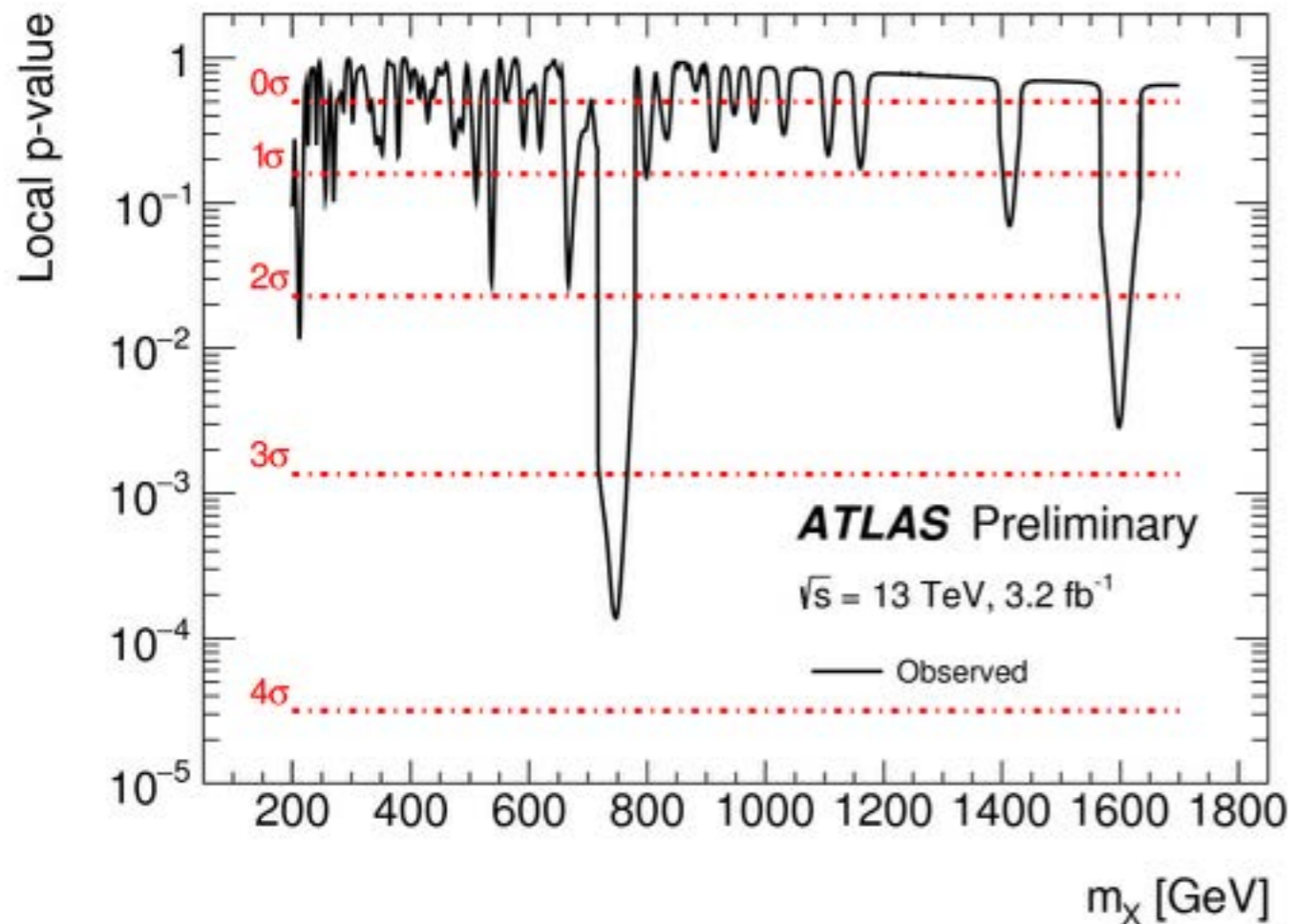


- $m_{\gamma\gamma}$  resolution:  $\sim 1\%$  (ATLAS)  $\sim 1.1 / 1.8 \%$  (CMS)
- different bin sizes: 40 GeV (ATLAS) 20 GeV (CMS)



# Searches for New Phenomena

13 TeV data: Diphoton Resonant Searches  
(2015 data)



local p-value:  $3.6 \sigma$  at 750 GeV

global p-value:  $2.0 \sigma$  (200-2000 GeV)  
[for narrow width assumption ( $\Gamma \sim 0.004 \text{ GeV}$ )]

best fit (largest p-value):

$\Gamma \sim 45 \text{ GeV}$ , p-value  $3.9 (2.3) \sigma$

local p-value:  $2.6 \sigma$  at 760 GeV

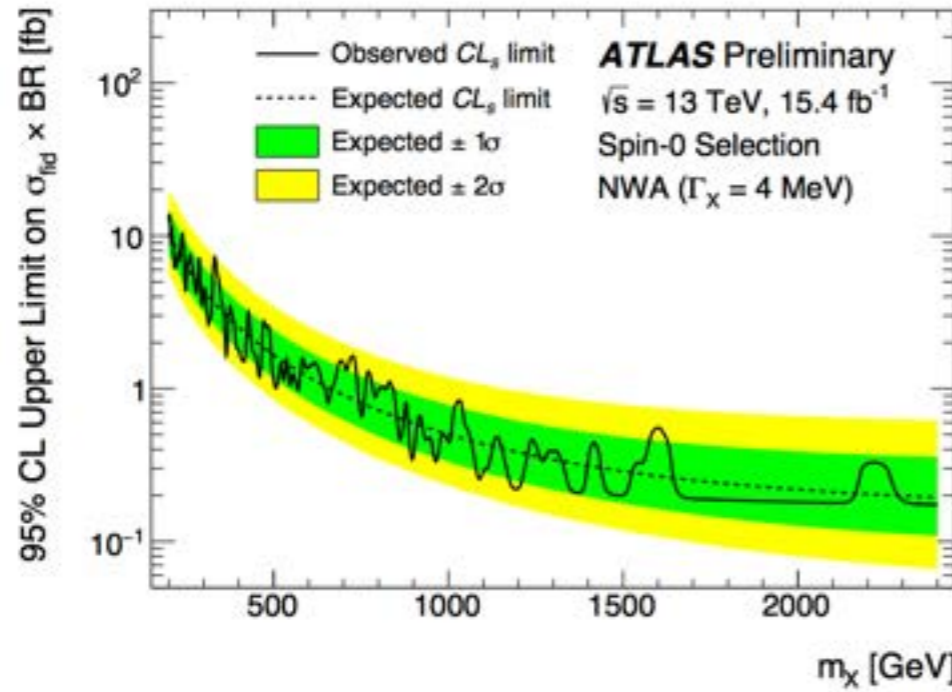
global p-value:  $< 1.2 \sigma$  (500-4500 GeV)  
[for narrow width assumption ( $\Gamma \sim 0.1 \text{ GeV}$ )]

for large width ( $\Gamma \sim 42 \text{ GeV}$ ):

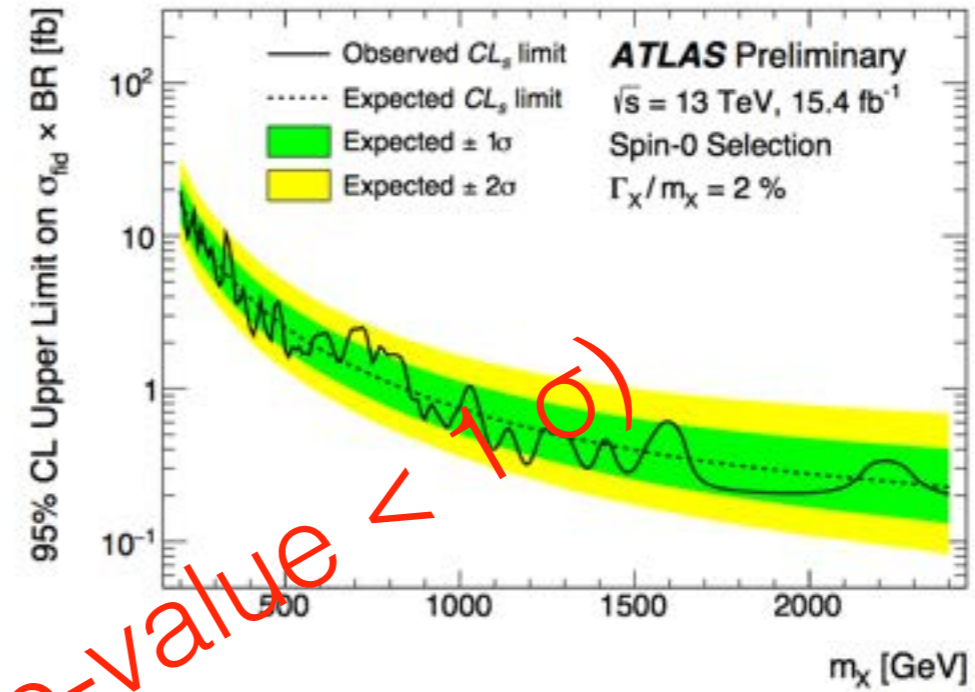
p-value  $2.0 (< 1) \sigma$

# Searches for New Phenomena

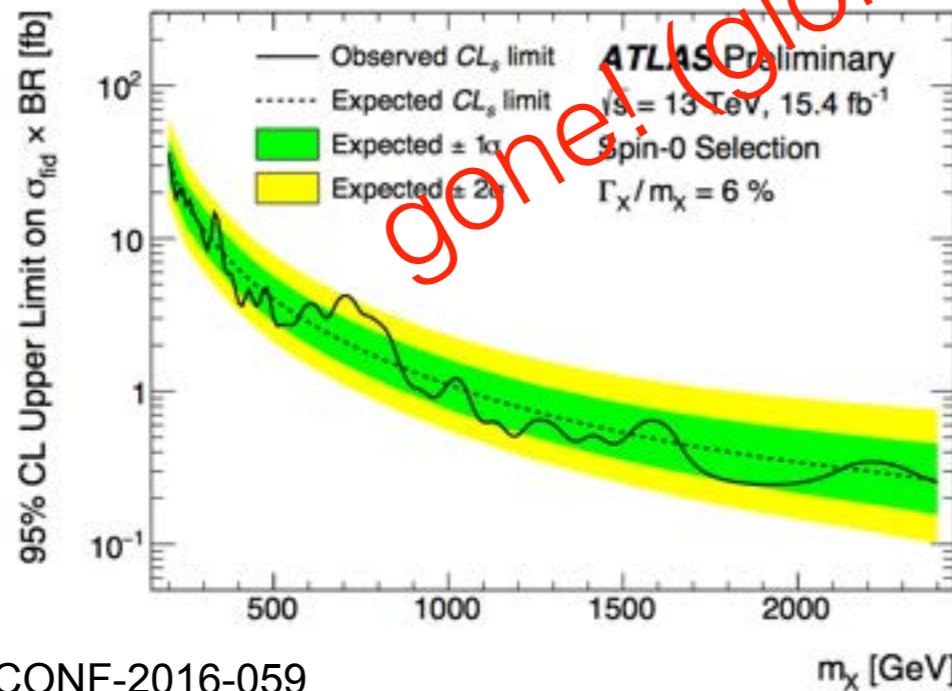
13 TeV data: Diphoton Resonant Searches  
(2015+2016 data)



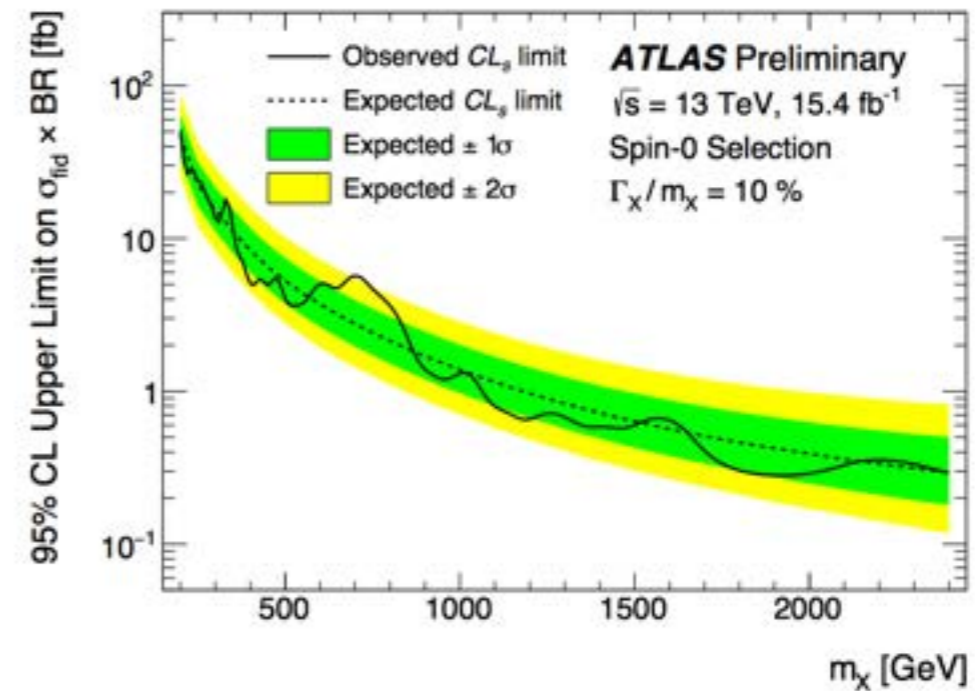
(a)



(b)



(c)



(d)

ATLAS-CONF-2016-059

# LHC - future planning:

2015 - 2022: (run-II, run-III)

- full energy (13-14 TeV) and luminosity ( $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ )

————— expect ~4 times more data than available today —————

from ~2025 - 2035:

- upgraded LHC and detectors (hl-LHC; luminosity x 5)

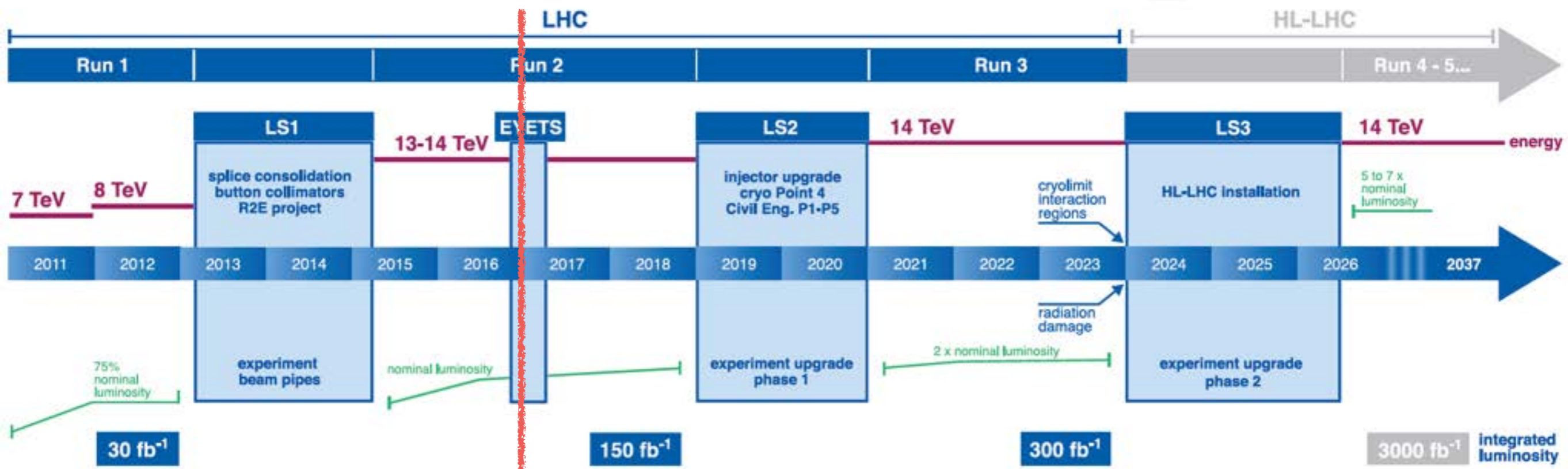
————— expect ~10 times more data than before —————

> ~ 2035:

- Future Circular Collider (FCC)? 100 km circumf., 100 TeV

# LHC — future plans

## LHC / HL-LHC Plan



we are here:  
~70 fb<sup>-1</sup>

(<3% of total planned)

→  
hl-LHC with  
~5-7 times  
luminosity

Run 1:	E = 7 / 8 TeV;	intL ~ 25 fb <sup>-1</sup>	(2009 - 2013)
Run 2 / 3:	E = 13/14 TeV;	intL ~ 300 fb <sup>-1</sup>	(2015 - 2023)
Run 4 - 6:	E = 14 TeV;	intL ~ 3000 fb <sup>-1</sup>	(2026 - 2035)

# hl-LHC : challenges (detector upgrades)

- pile up (up to  $\sim 200$ )
- radiation damage (exchange Si-tracker)
- occupation (dead time of detector channels)
- read-out electronics (old; slow; aging)
- triggering
- data handling (storage, calibration, analysis, costs!)
- expert's knowledge preservation
- motivation ...

# after LHC — a next-generation proton collider?



Image © 2013 DigitalGlobe

Image © 2013 IGN-France

LHC  
27 km, 8.33 T  
14 TeV (c.o.m.)

HE-LHC  
27 km, **20 T**  
**33 TeV (c.o.m.)**

FCC-hh  
80 km, **20 T**  
100 TeV (c.o.m.)

FCC-hh  
100 km, **16 T**  
100 TeV (c.o.m.)

## Summary of this lecture:

- similar as in case of SUSY searches, so far no significant signal for physics BSM found
- exclusion limits for excited leptons and quarks, for new heavy gauge bosons, for the effects of extra spacial dimensions and other effects range up to mass scales of many 100 GeV to TeV
- The discovery potential of LHC so far explored is only at the percent level of the planned overall LHC program
- extended program of (luminosity-) upgraded LHC until 2035, with integrated luminosities of up to  $3000 \text{ fb}^{-1}$ , approved and started
- studies and development of future hadron collider started (FCC)

See e.g.: Tobias Golling: LHC searches for exotic new particles, Progress in Particle and Nuclear Physics 90 (2016) 156–200

# Summary of this lecture series:

- the LHC successfully completed its first run period (2010-2012) at energies of 7 and 8 TeV c.m., with  $\sim 25 \text{ pb}^{-1}$  of data collected per experiment in p-p collider mode
- the validity of the Standard Model was scrutinized to the per-cent level, for many processes and signatures, for mass scales up to and exceeding 1 TeV
- a new Boson with a mass of 125 GeV was discovered; its properties (spin, couplings) are compatible with those expected for the SM Higgs boson
- intense searches for signals of physics beyond the SM did not uncover new significant effects, but posed exclusion limits up to mass scales of many TeV
- after 2 years of intense refurbishments and repairs, LHC continued to run in 2015/16, at 13 TeV c.m. energy and (slightly) above design luminosity of  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , and collected  $\sim 40 \text{ pb}^{-1}$
- modest excesses of potential New Physics signals seen in  $\gamma\gamma$  final states at  $\sim 750 \text{ GeV}$ , and in diboson final states around 2 TeV were statistical artifacts and finally disappeared
- the LHC program is planned to commence, incl. lumi upgrades, until about 2035, with the ultimate goal to collect  $3000 \text{ pb}^{-1}$  of data