Vorlesung 13:

Search for BSM Physics: Exotics

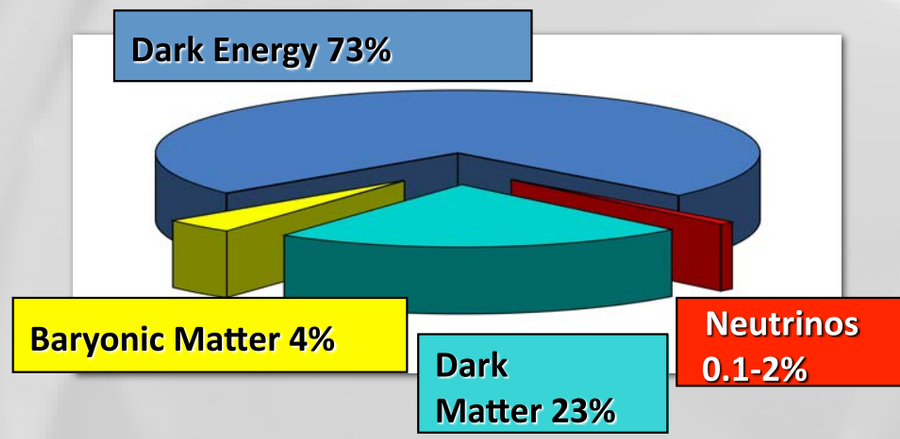
and

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%)

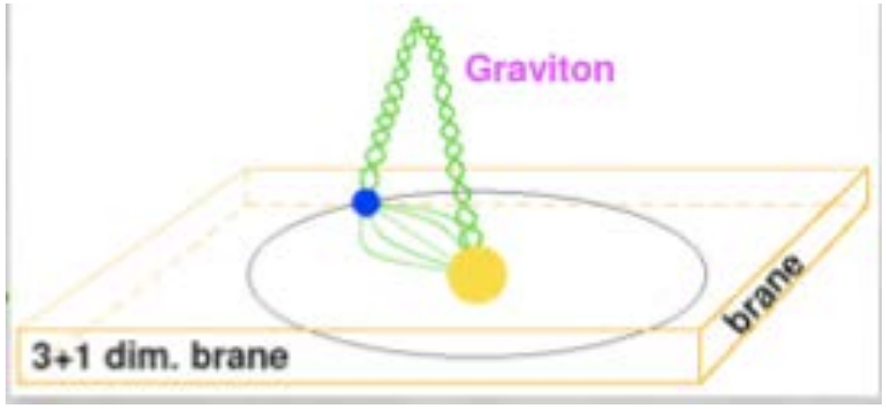


some en vogue models of BSM:

- 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



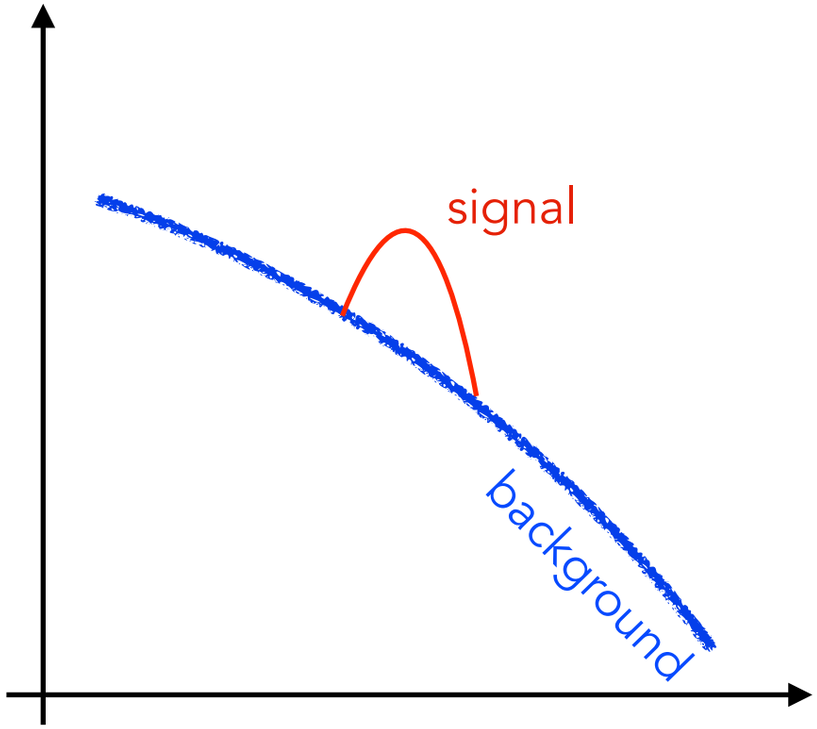
- extra dimensions are compactified on an *n*-dimensional torus / sphere of radius *R*
- Planck-mass in 4+*n* dimensions : $M_D^{n+2} \sim M_{Pl}^2 R^{-n}$ may approach TeV scale for large n → micro black holes?

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.

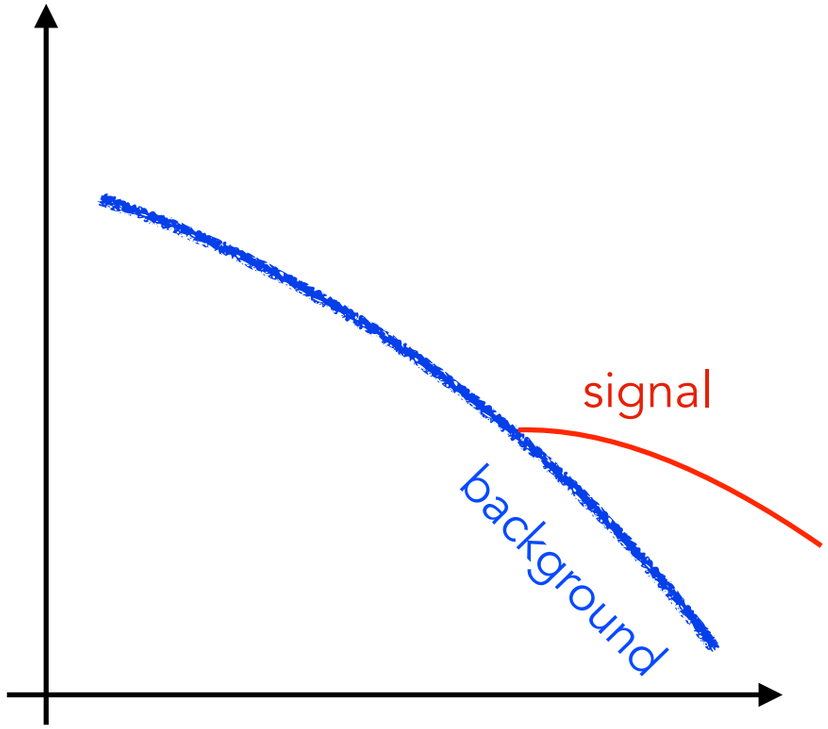
2 N. Arkani-Hamed, S. Dimopoulos, G. Dvali (1999). "Phenomenology, astrophysics and cosmology of theories with submillimeter dimensions and TeV scale quantum gravity". *Physical Review* **D59** (8): 086004. arXiv:hep-ph/9807344.

exp. signatures of exotic BSM models:

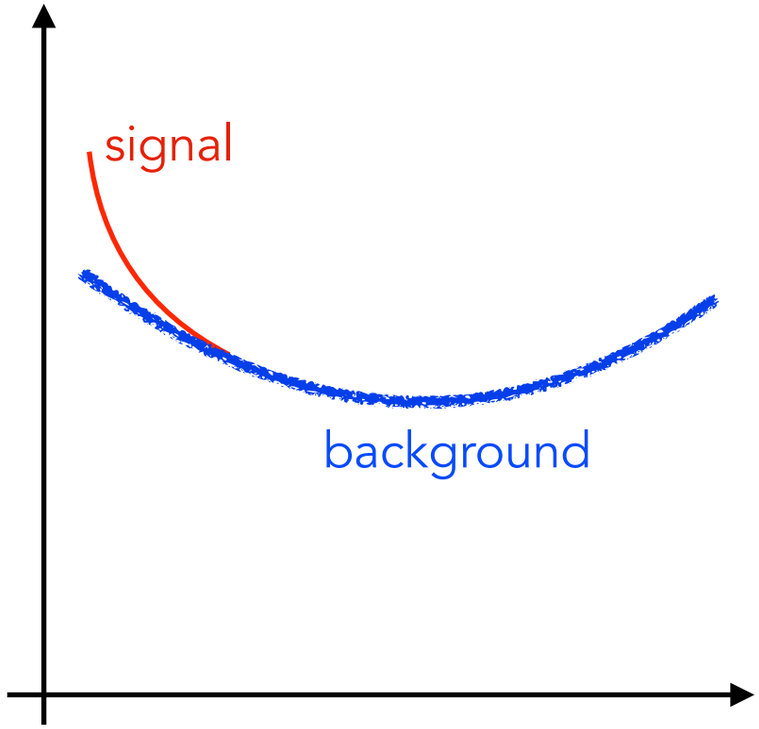
- high-mass resonances decaying into jets, leptons, bosons
- high system energies involving visible and invisible objects
- specific event properties (angular distributions,…)



pair mass
(jets, leptons, bosons)



energy of system
(visible, invisible)



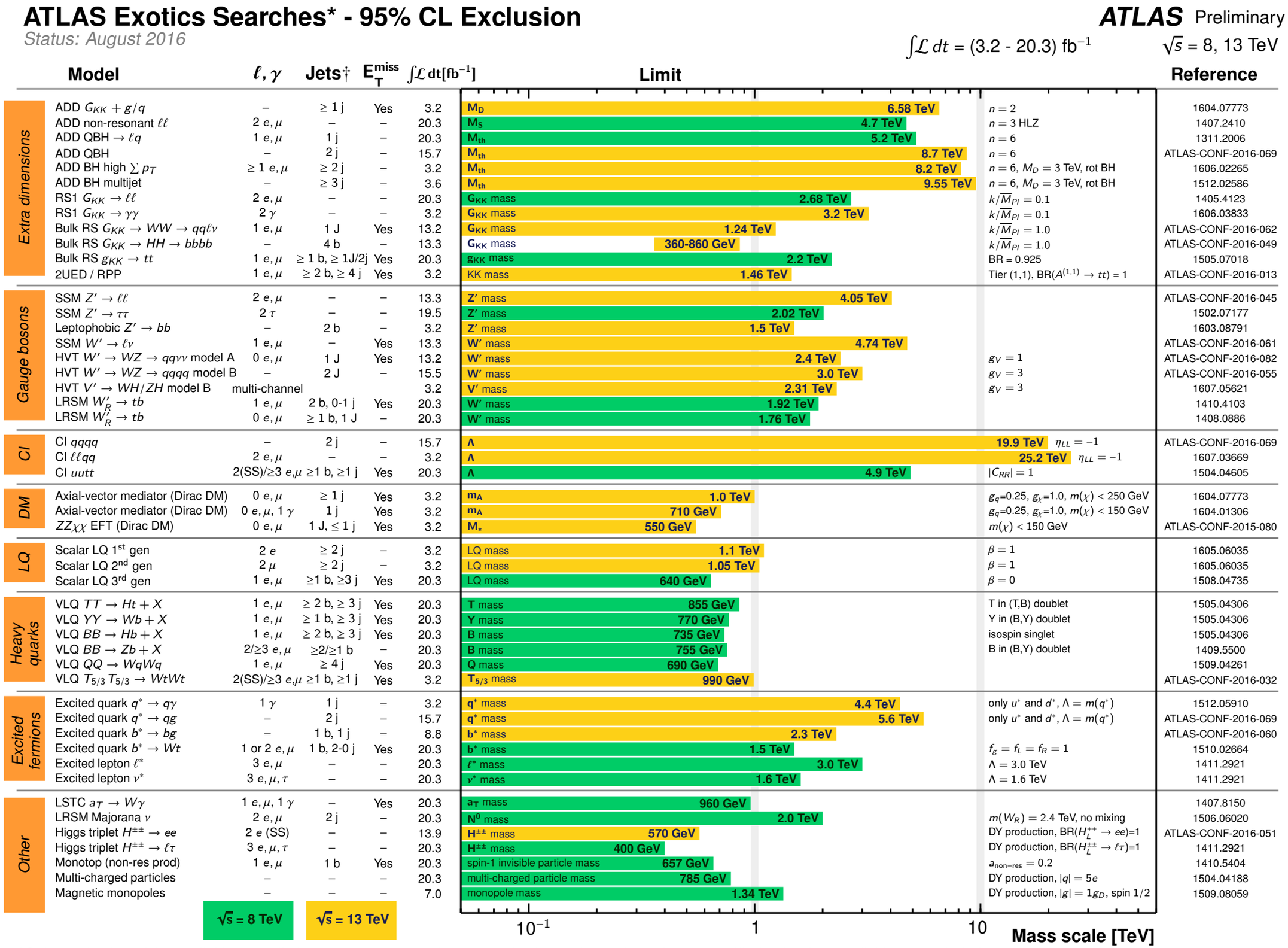
internal property
(e.g. angular distribution)

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:



*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

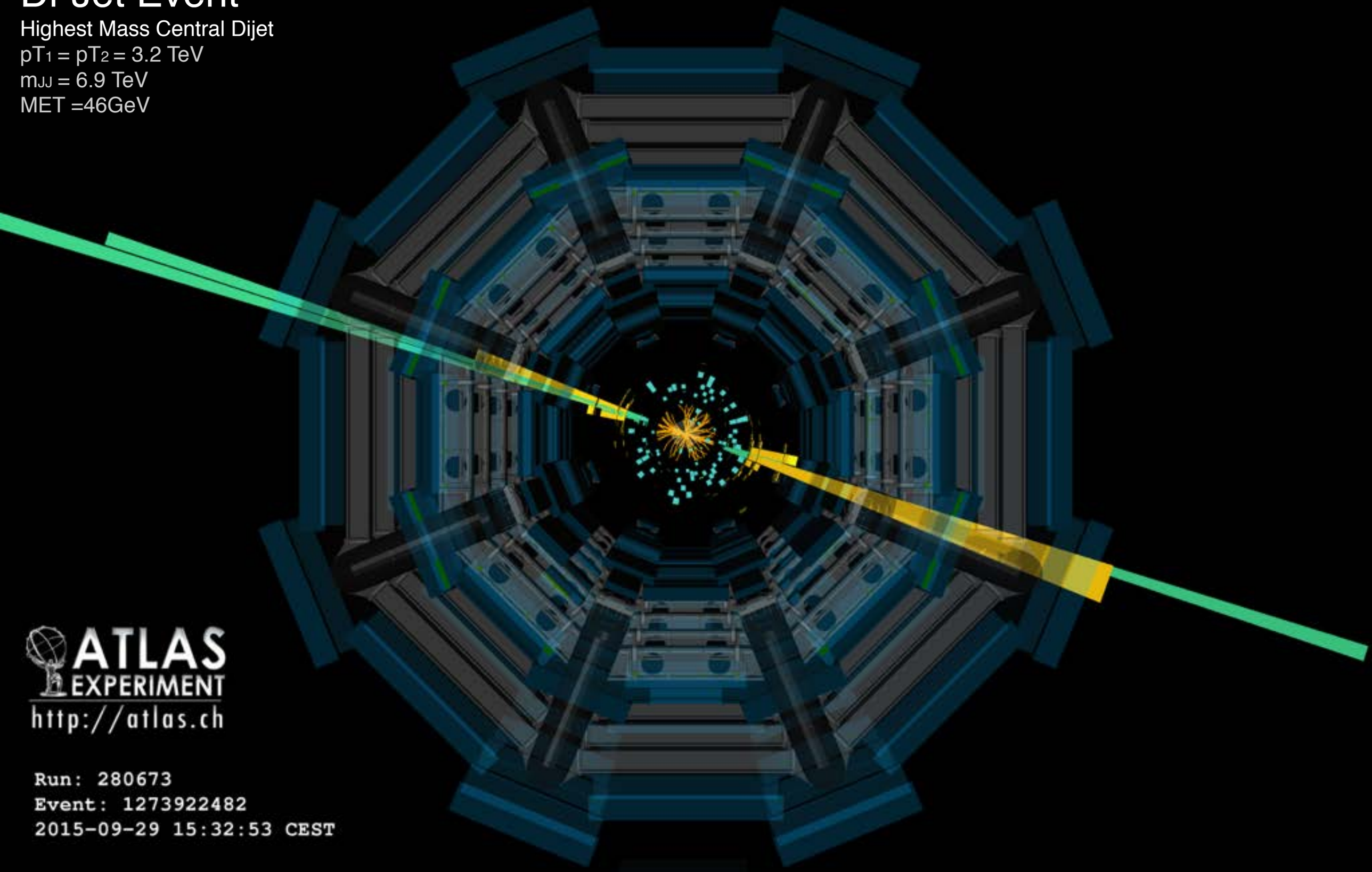
Di-Jet Event

Highest Mass Central Dijet

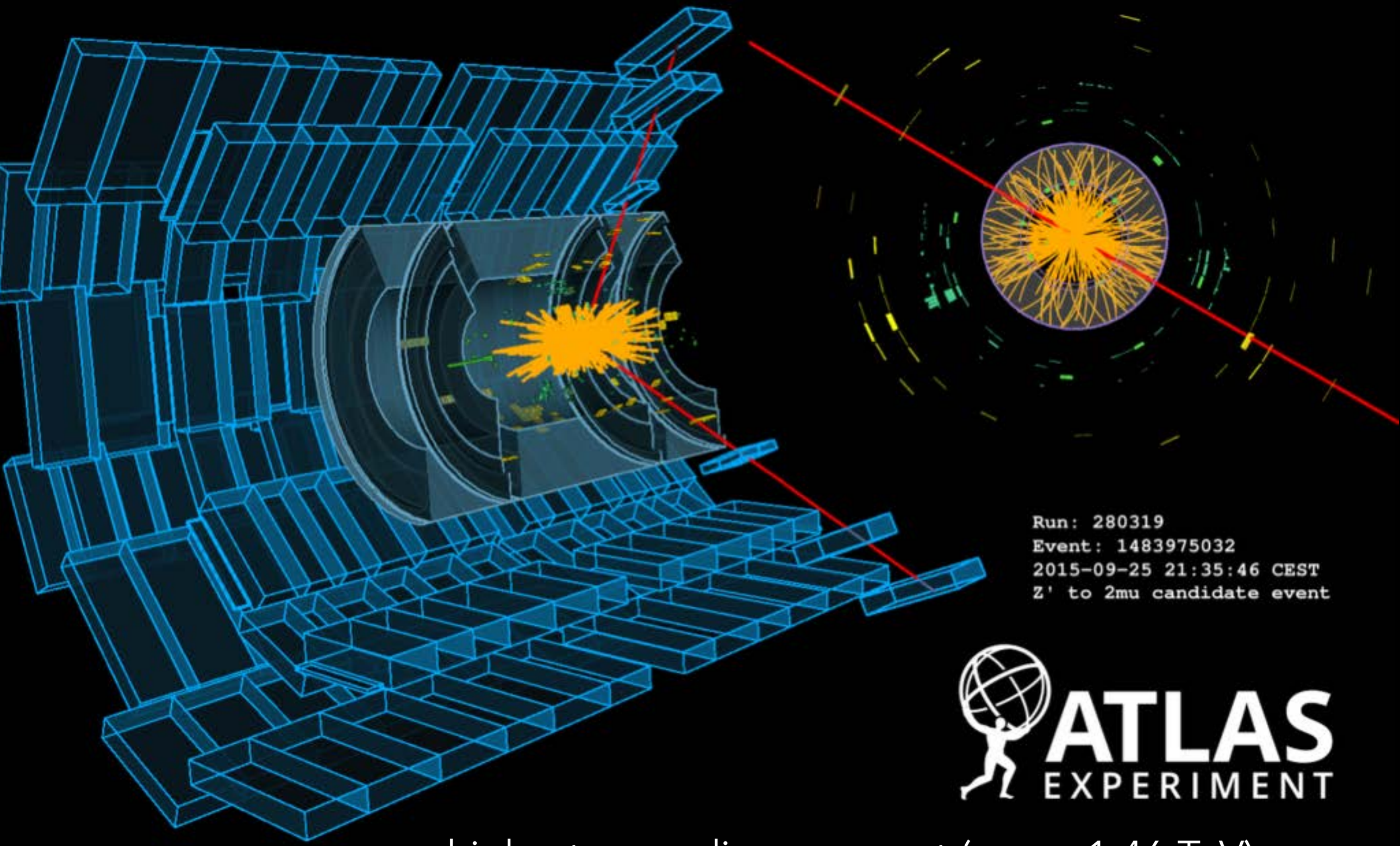
$pT_1 = pT_2 = 3.2$ TeV

$m_{JJ} = 6.9$ TeV

MET =46GeV



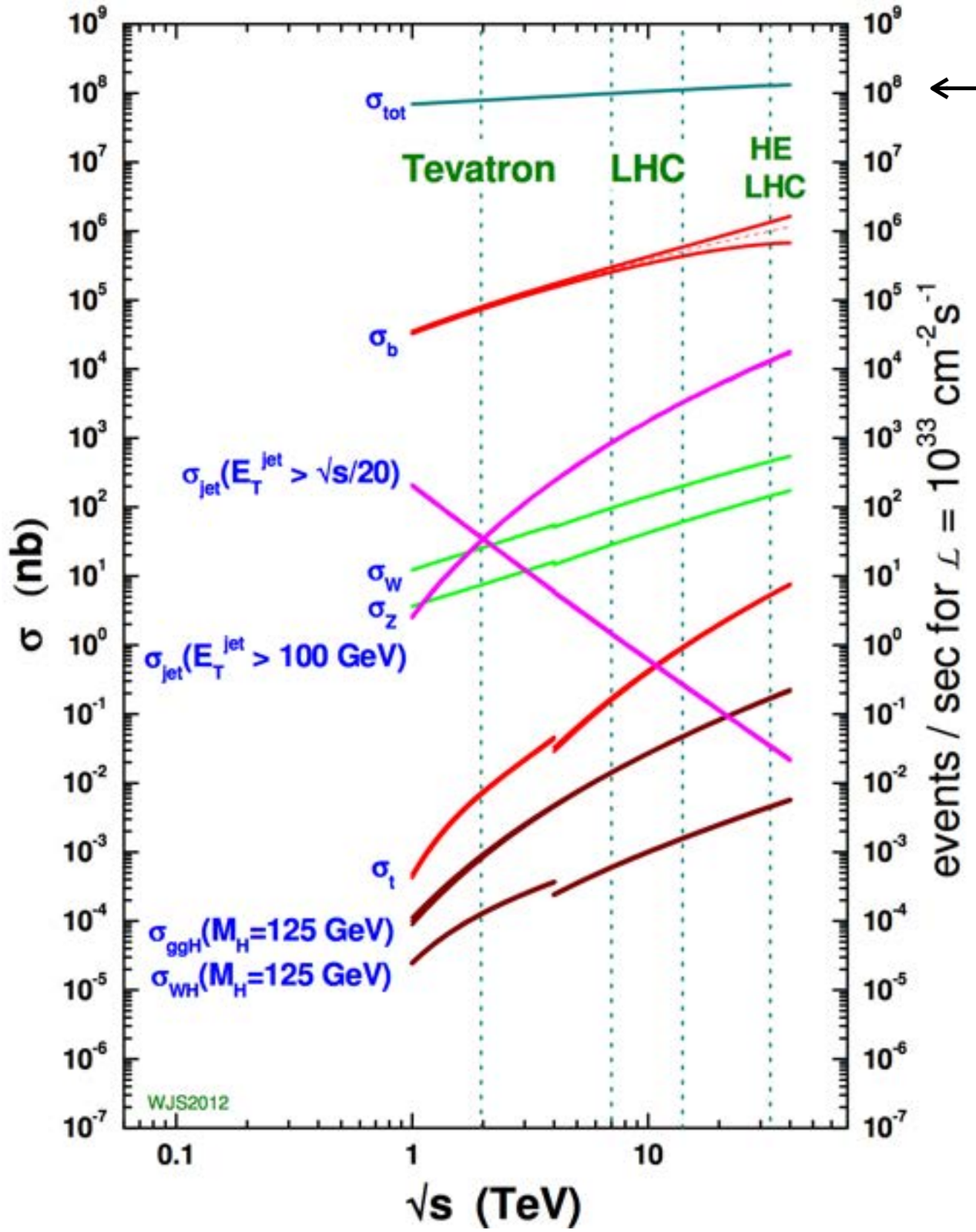
high mass dimuon event



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

production cross sections at the LHC

proton - (anti-)proton cross sections



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

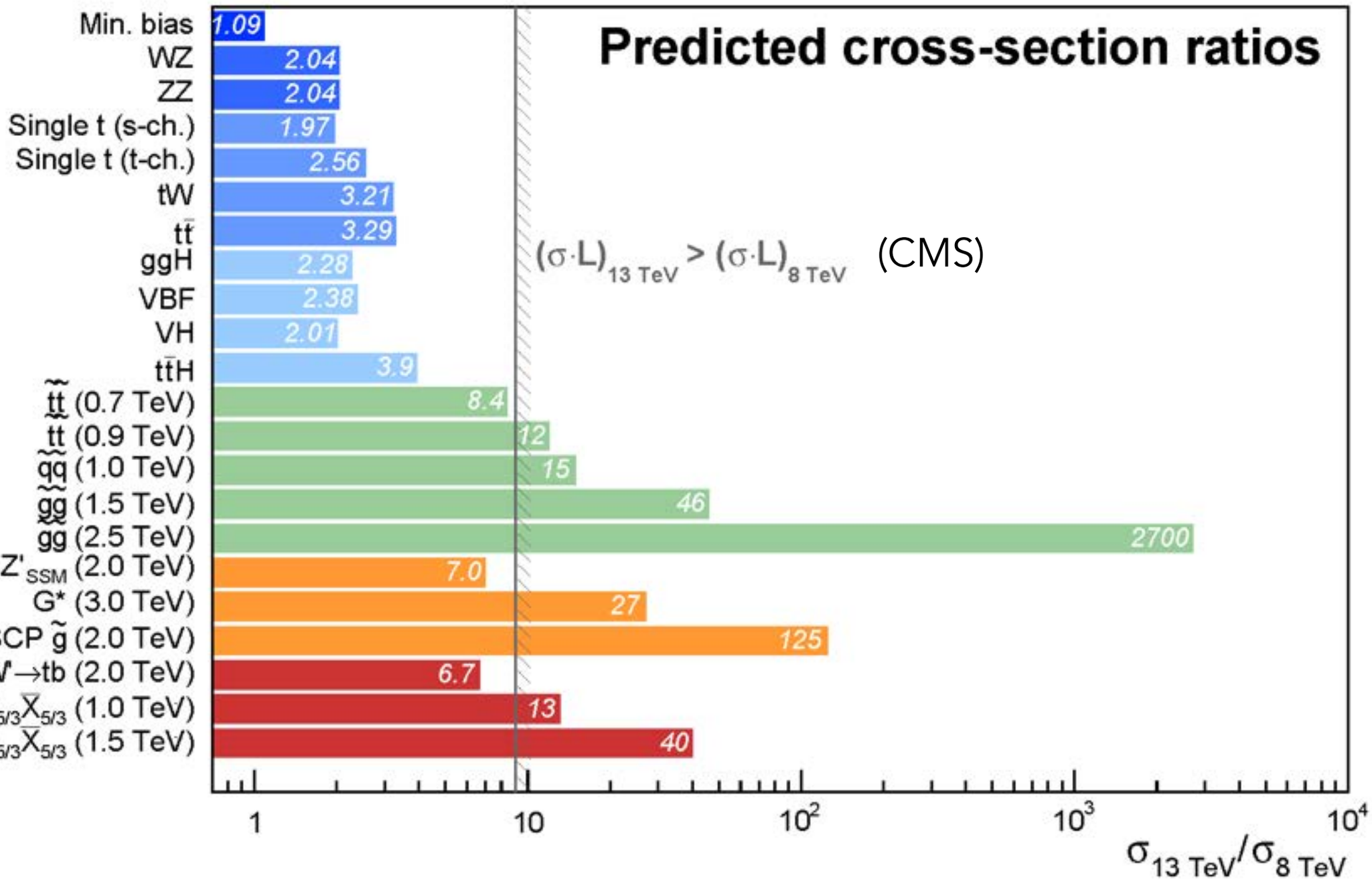
↔ max. read-out: ~ 10^3 evts/sec

↔ O(1) top-event/sec

↔ O(1) Higgs/min

production cross sections at the LHC

cross section ratios 13 TeV / 8 TeV

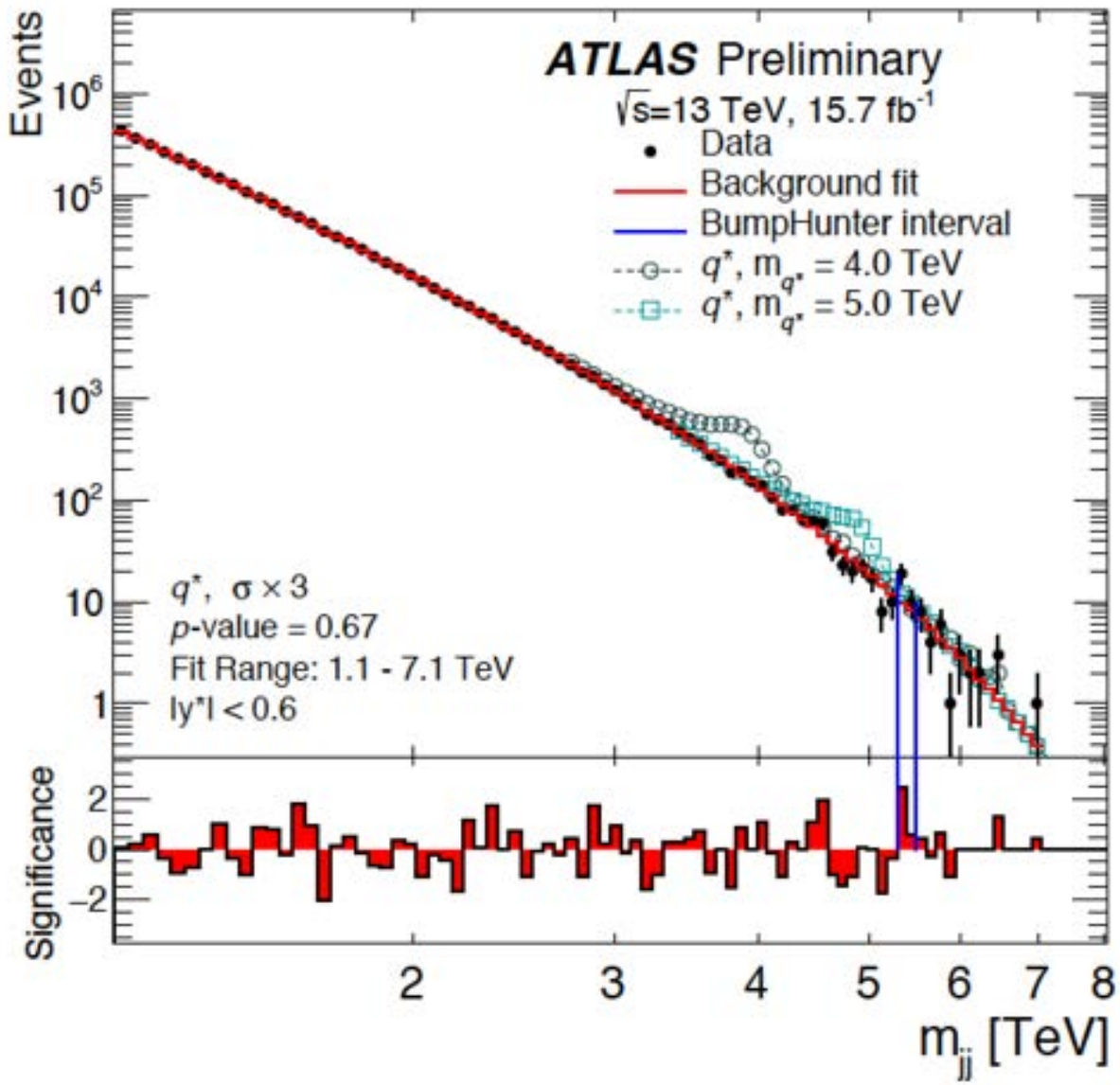


- for SM processes (top-quark; Higgs): x-sections increase by ~2…3 at 13 TeV
- for new phenomena and masses of O(TeV), increase of ~10 to 100s
- therefor, many results from run-II already surpass those from run-I

Searches for composite / excited quarks

13 TeV data: Dijet Resonant Searches

ATLAS-CONF-2016-069



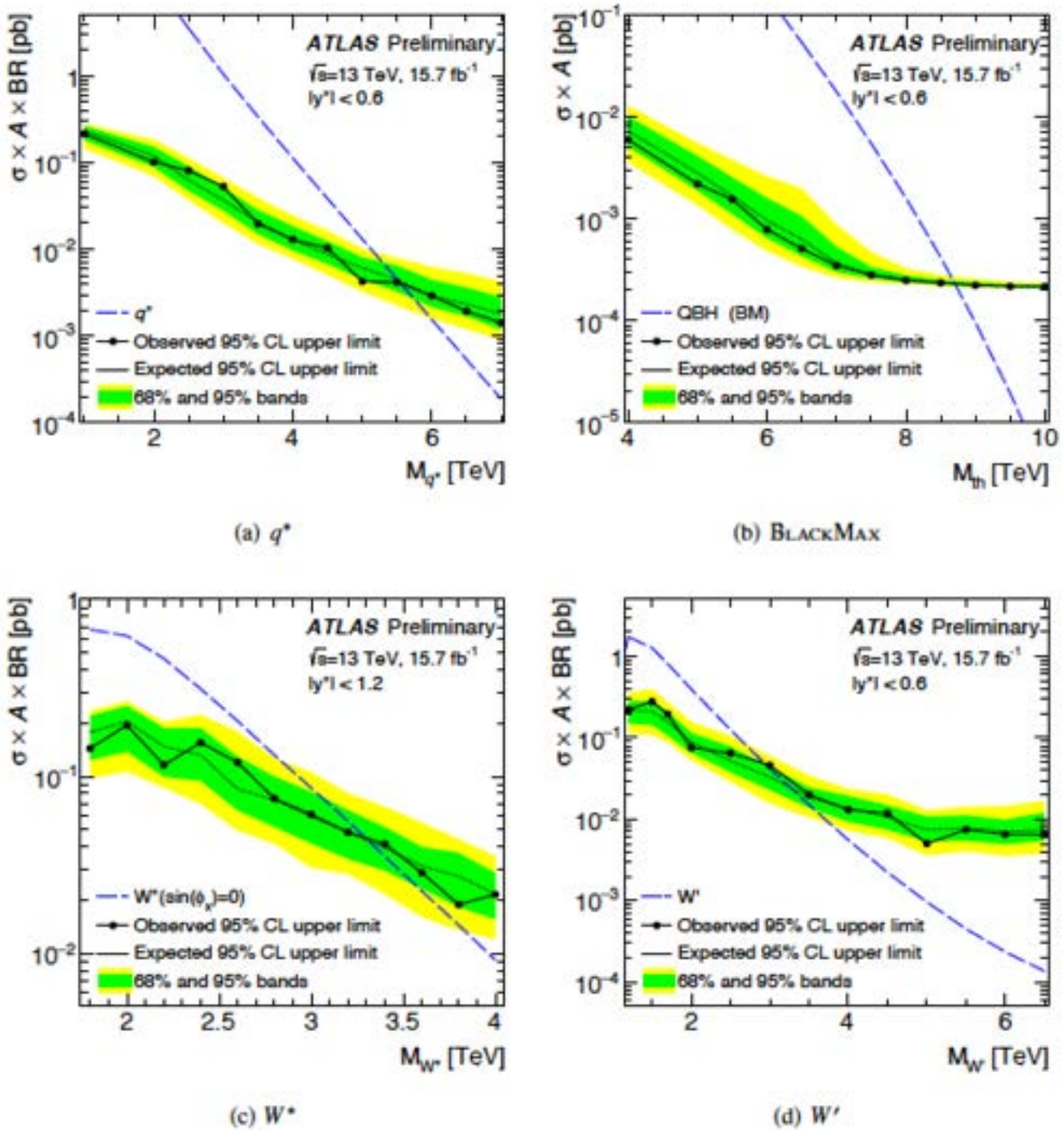


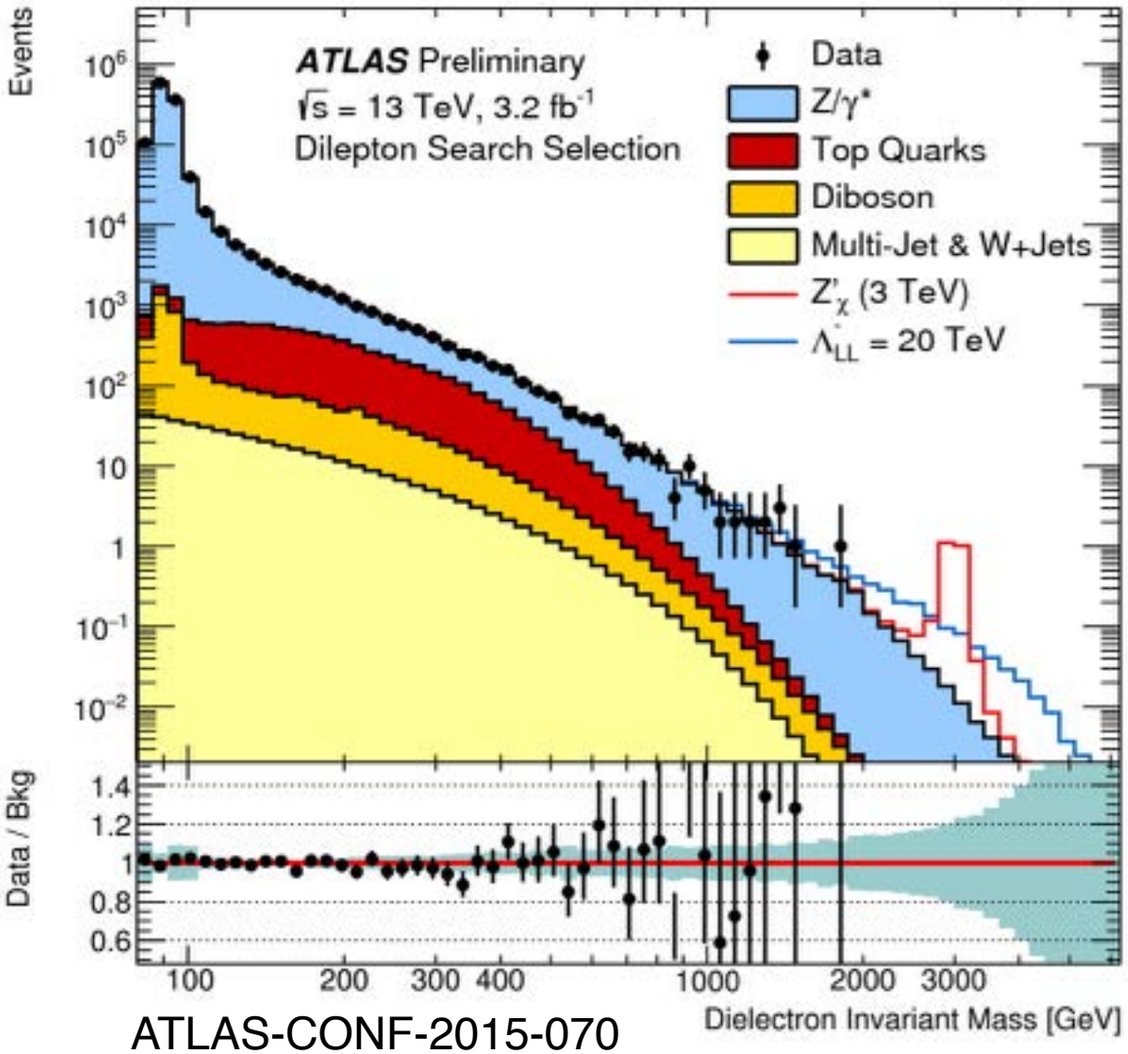
Figure 3: The 95% credibility-level upper limits obtained from the m_{JJ} distribution on cross-section, σ, times acceptance, A, for the models described in the text. Clockwise from top left: q^*, quantum black holes with $n = 6$ generated with BlackMax, W' and W^* where the first three use the nominal 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.

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

Searches for additional U(1)' Symmetry

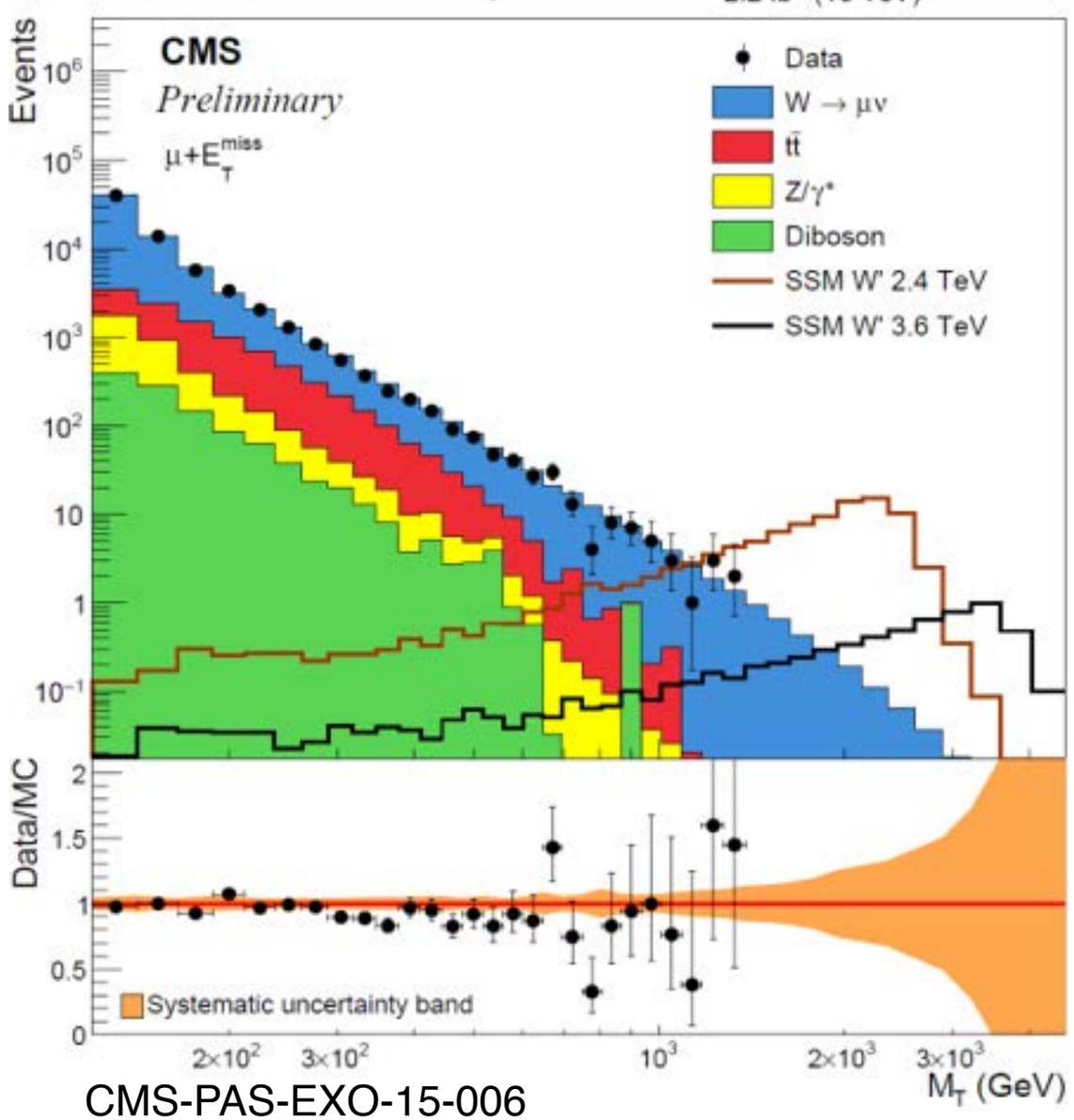
13 TeV data: Search for Heavy Gauge Bosons (Z' and W')

Dilepton Resonance Search



ATLAS-CONF-2015-070

Lepton plus missing E_T



CMS-PAS-EXO-15-006

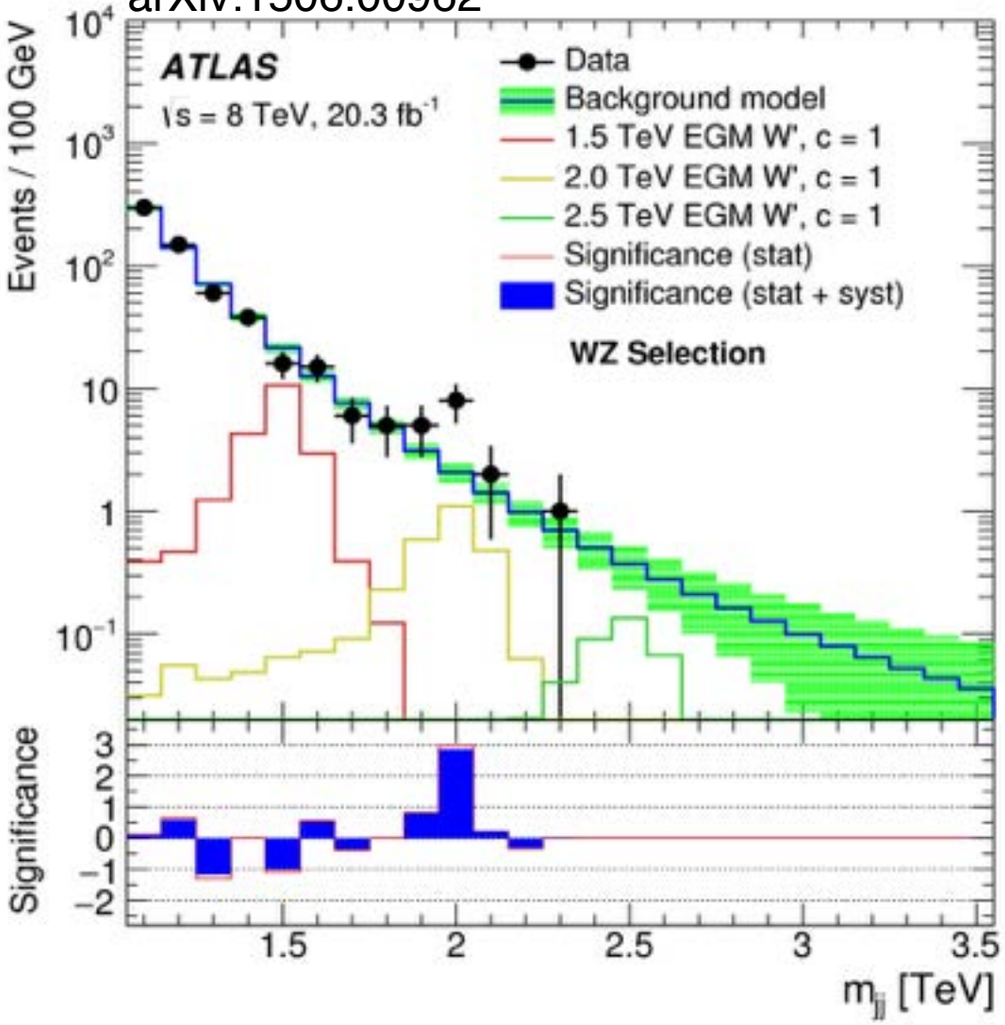
excludes e.g. Z' with $m_{Z'} < 3.4$ TeV, and llqq contact interactions with scales $\Lambda_{llqq} < 20$ TeV

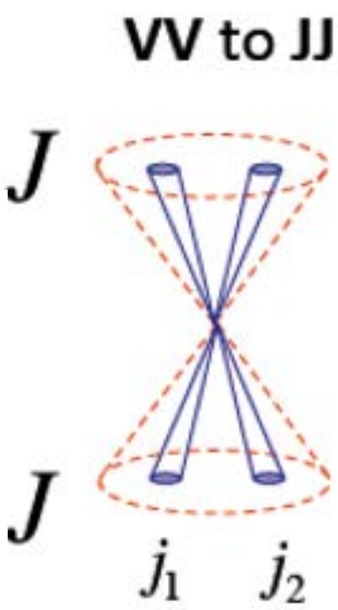
excludes $W' \rightarrow l\nu$ with $m_{W'} < 4.4$TeV

Searches for Diboson Resonances

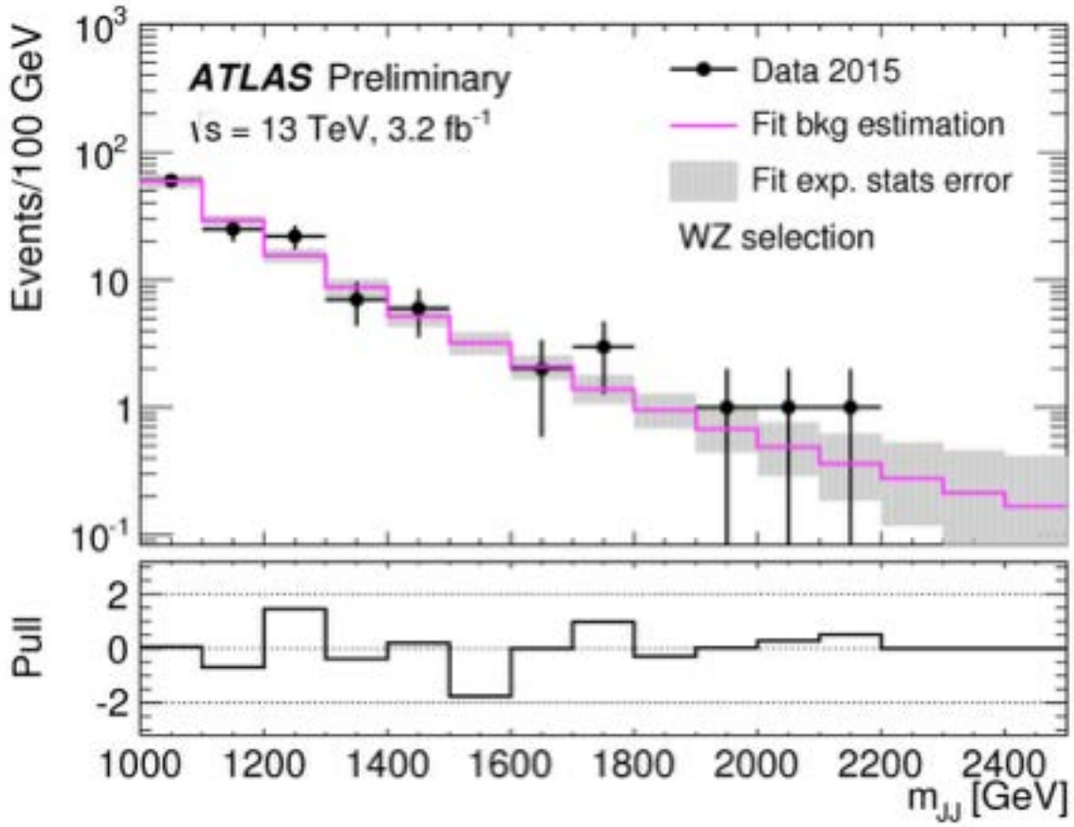
(new heavy gauge bosons; Kaluza-Klein excitations of the graviton,…)

arXiv:1506.00962





ATLAS-CONF-2015-073



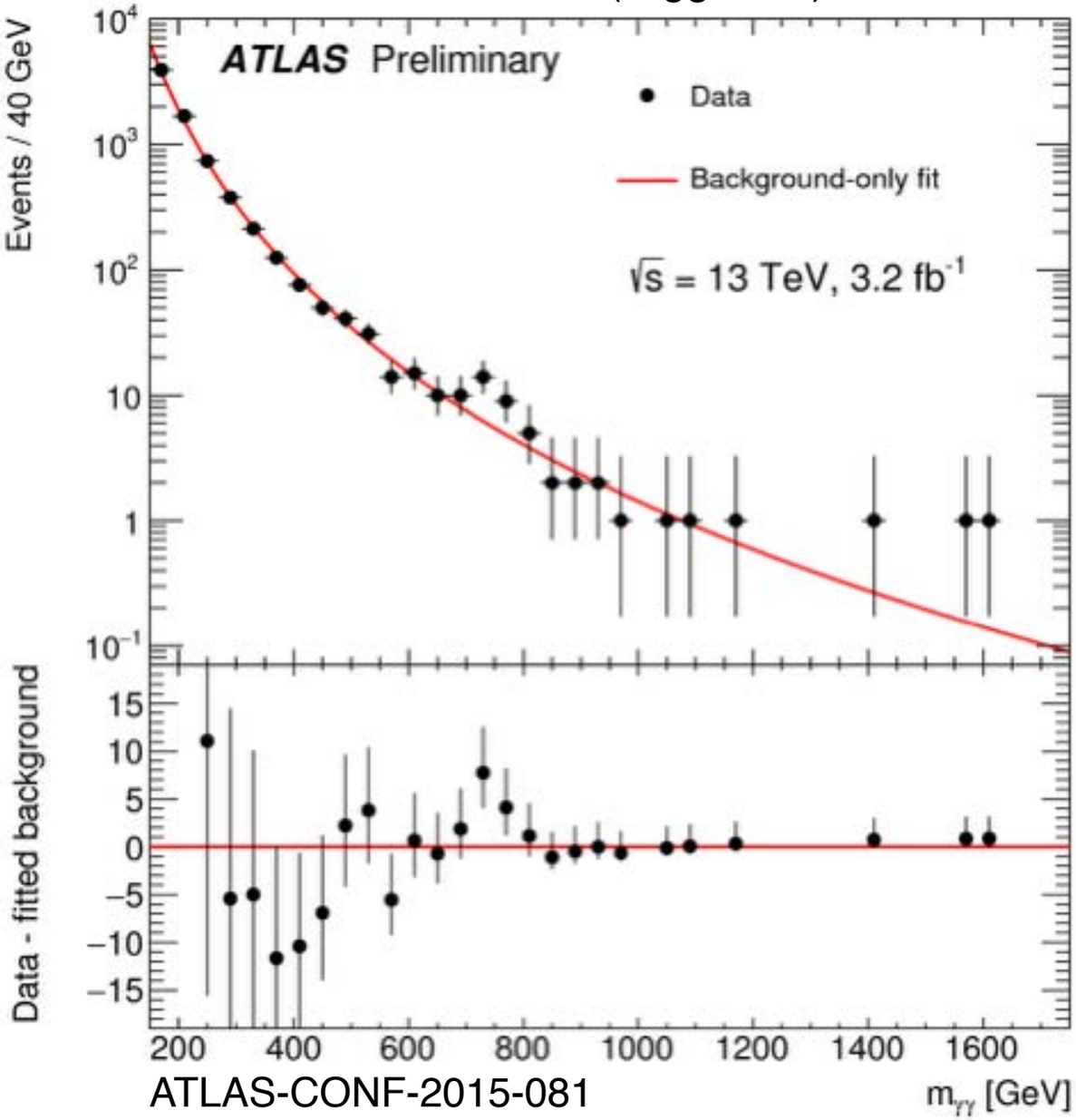
modest excess observed in run-I:
3.4 σ local, 2.5 σ global significance

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

Searches for Diphoton Resonances

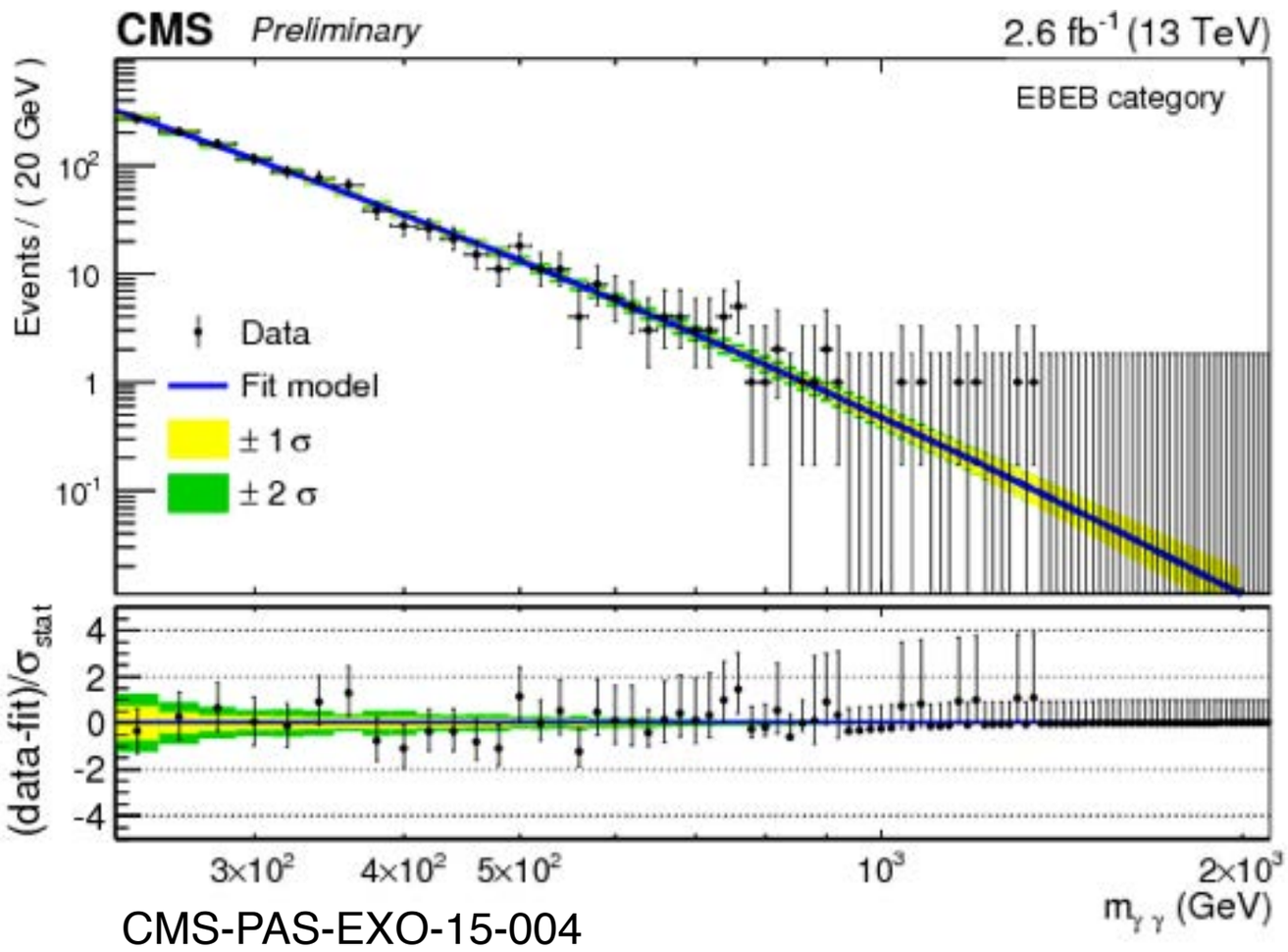
Higgs-like (spin 0) or Graviton-like (spin 2) objects

search for narrow width (Higgs-like) resonance



ATLAS-CONF-2015-081

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



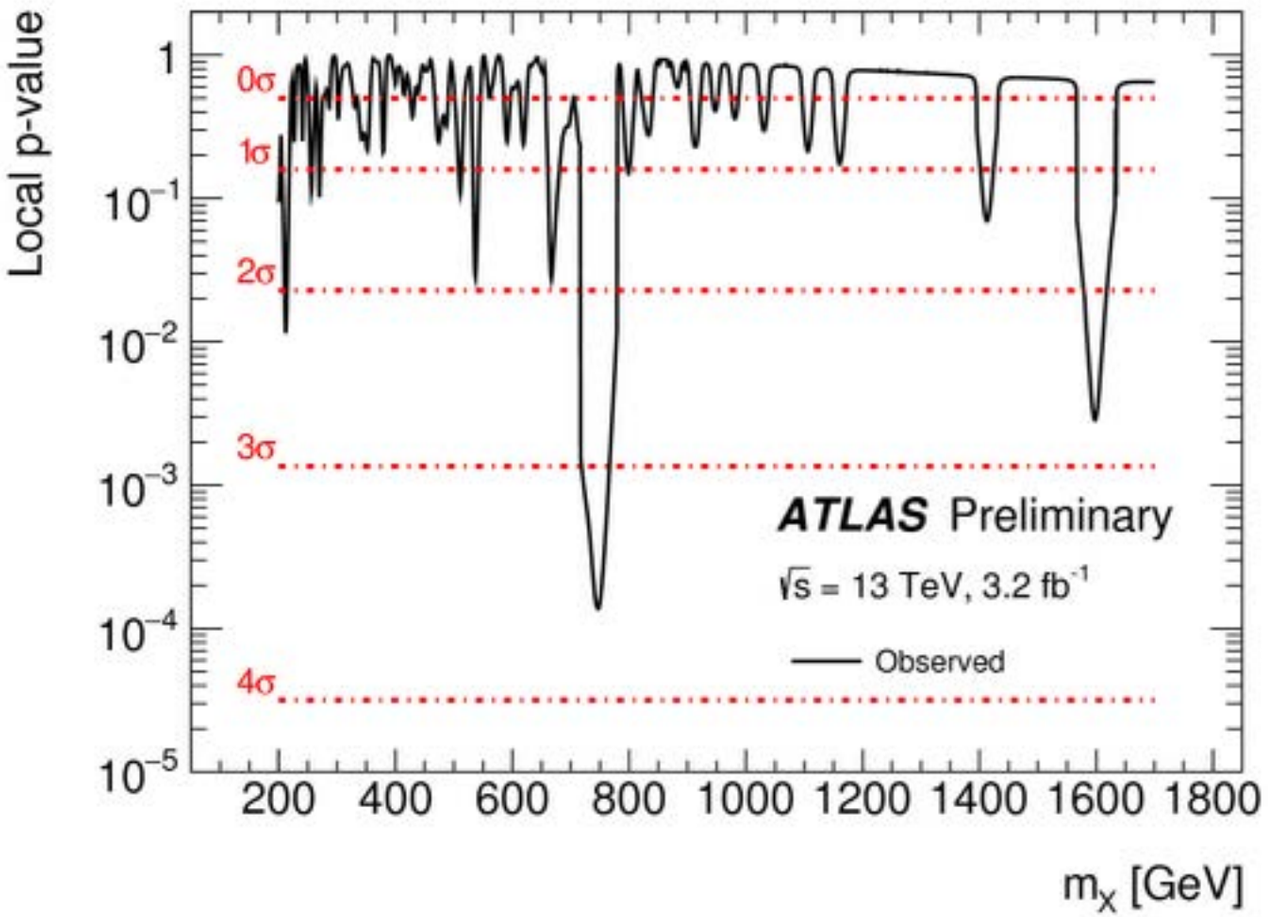
CMS-PAS-EXO-15-004

– $m_{\gamma\gamma}$ resolution: ~1% (ATLAS) ~1.1 / 1.8 % (CMS)

– different bin sizes: 40 GeV (ATLAS) 20 GeV (CMS)

Searches for New Phenomena

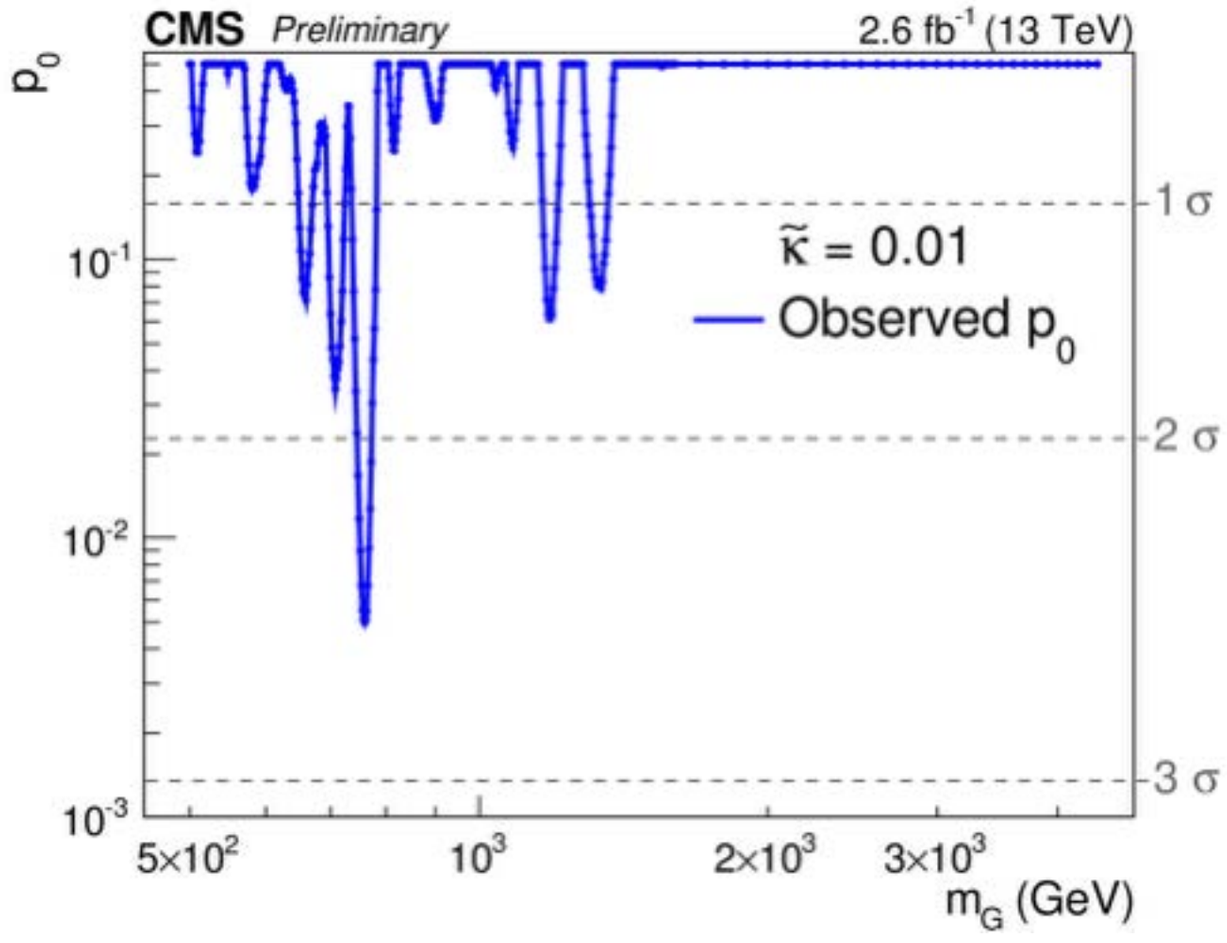
13 TeV data: Diphoton Resonant Searches (2015 data)



local p-value: 3.6 σ at 750 GeV

global p-value: 2.0 σ (200-2000 GeV)
[for narrow width assumption (Γ ~ 0.004 GeV)

best fit (largest p-value):
Γ~45 GeV, p-value 3.9 (2.3) σ



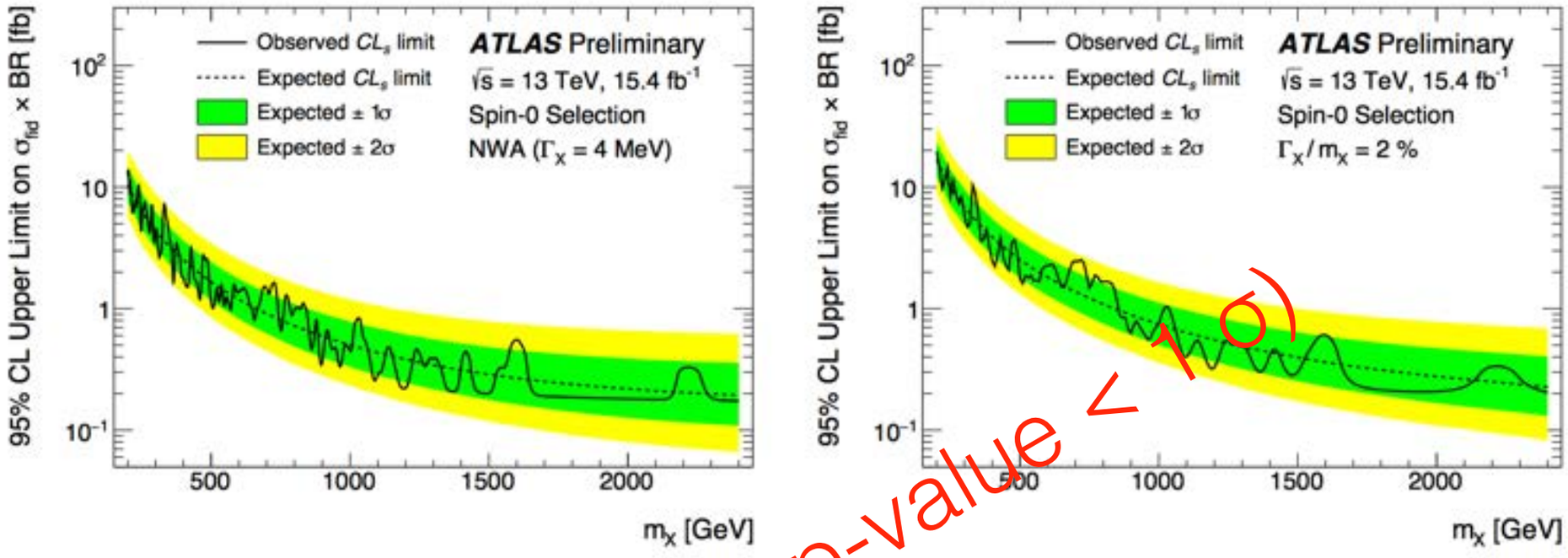
local p-value: 2.6 σ at 760 GeV

global p-value: <1.2 σ (500-4500 GeV)
[for narrow width assumption (Γ ~ 0.1 GeV)]

for large width (Γ ~ 42 GeV):
p-value 2.0 (< 1) σ

Searches for New Phenomena

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



ATLAS-CONF-2016-059

LHC - future planning:

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

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

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

from ~2025 - 2035:

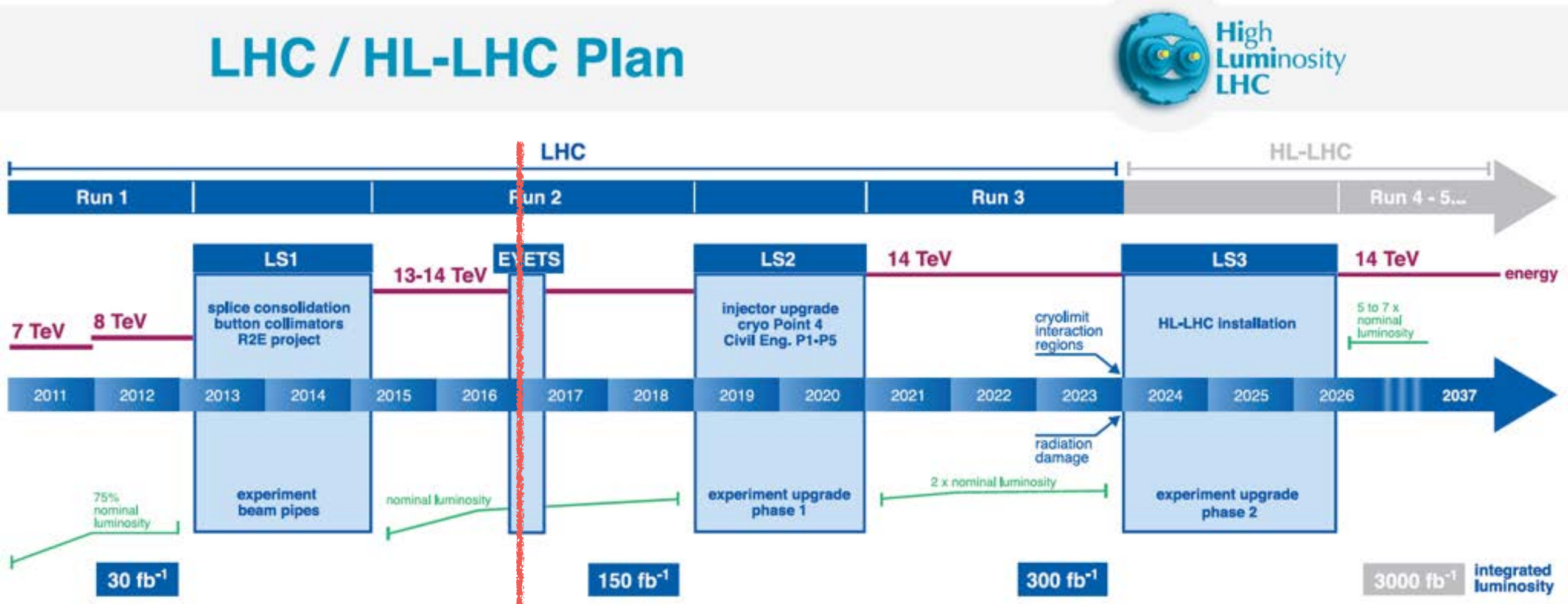
- upgraded LHC and detectors (hl-LHC; luminosity x 5))

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

>~ 2035:

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

LHC — future plans



we are here:

~70 fb^{-1}

(<3% of total planned)

hl-LHC with ~5-7 times luminosity

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

hl-LHC : challenges (detector upgrades)

- pile up (up to ~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?

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 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 ~25 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} cm^{-2} s^{-1} , and collected ~40 pb^{-1}
- modest excesses of potential New Physics signals seen in $\gamma\gamma$ final states at ~750 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 pb^{-1} of data