Overview of CMS results

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Institute of High Energy Physics
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Outline

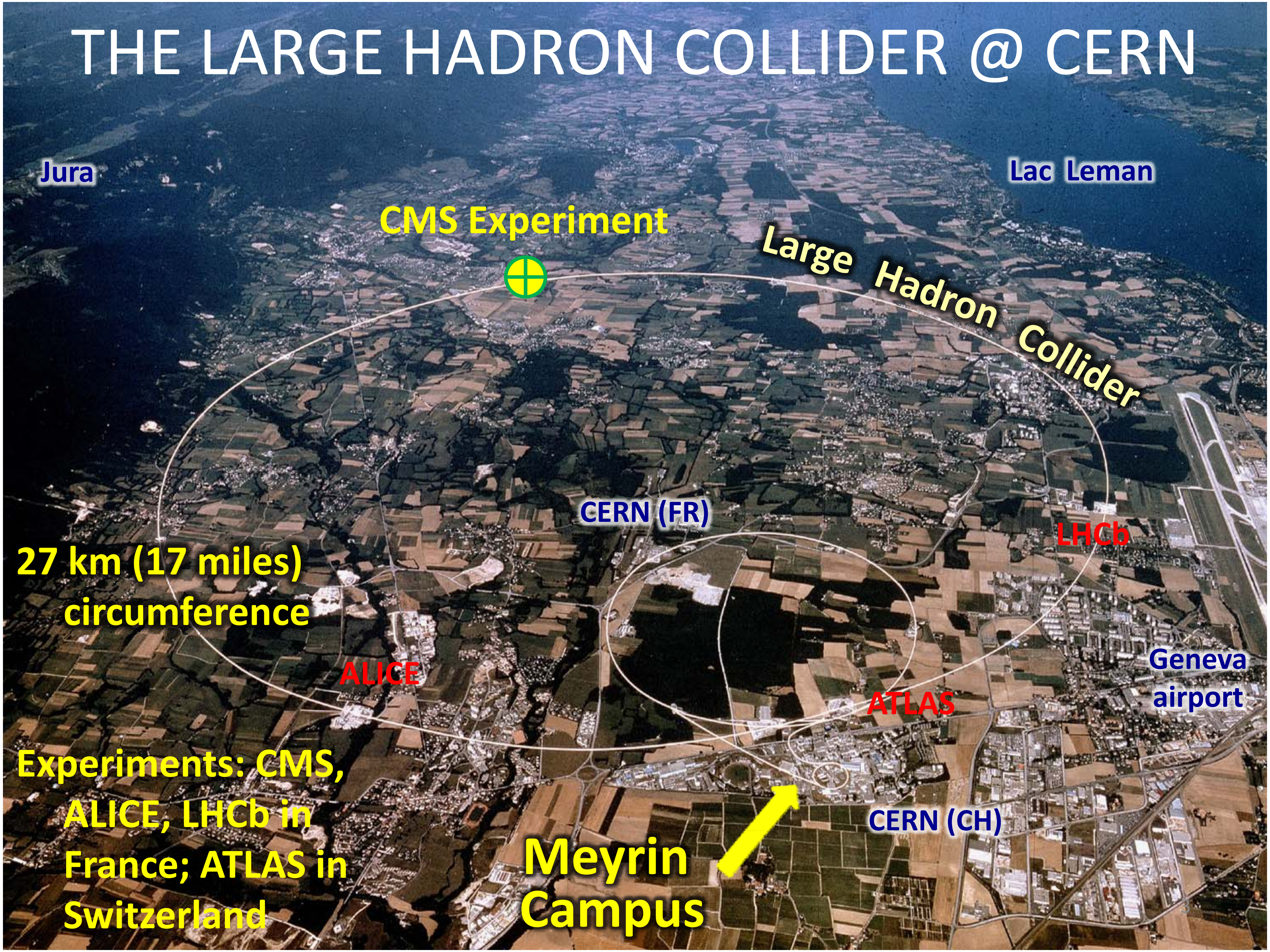
- **CMS experiment and performance**

- **Selected CMS physics results**

  - **Soft QCD, forward scattering, quarkonia production, heavy ions**
  - **SM measurements**
  - **Top physics**
  - **Higgs physics**
  - **Search for BSM physics**
  - **Search for high mass resonances**

Many new, interesting results at new energy regime, could discuss only few.

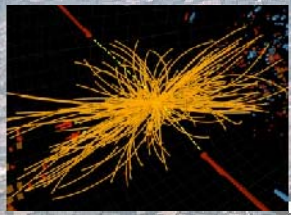
- **Summary**


THE LARGE HADRON COLLIDER @ CERN
Jura
Lac Leman
CMS Experiment
Large Hadron Collider
CERN (FR)
LHCb
27 km (17 miles) circumference
ALICE
ATLAS
Geneva airport
Experiments: CMS, ALICE, LHCb in France; ATLAS in Switzerland
CERN (CH)
Meyrin Campus

Compact Muon Solenoid (CMS) at LHC

Jura

CMS Experiment



Lac Leman

Total weight: 12,500 Tons

Diameter: 15 m

Length: 21 m

Field: 4 Tesla

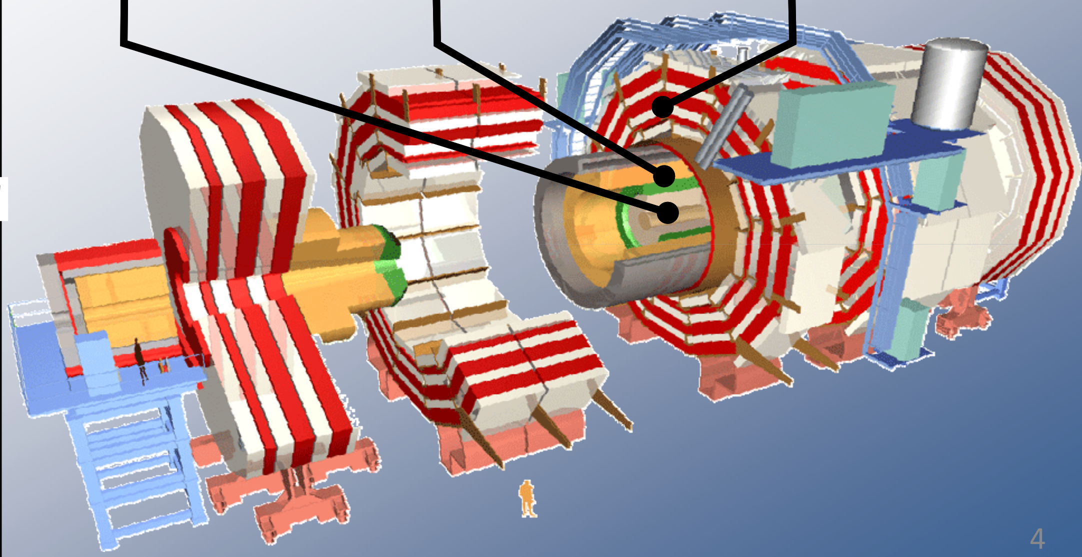
Readout channels: ~80M

Compact Muon Solenoid

Silicon Detectors
measure tracks left by charged particles

Calorimeters
Absorb particles and measure their energy

Muon Detectors
Identify and measure muons that penetrate



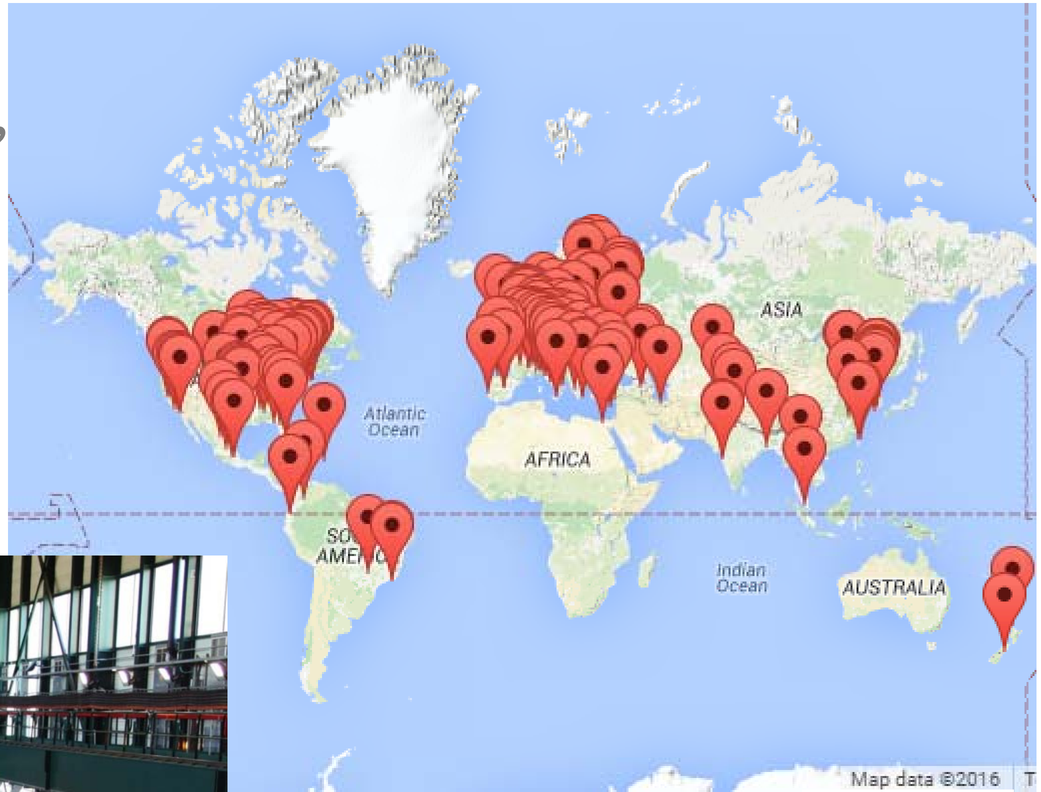
CMS collaboration

~4700 members

1900 physicists,
1800 students,
950 eng./ techn

~200 institutes

~40 countries



(only about 15% of CMS members are in the photo!)

3 institutes from 

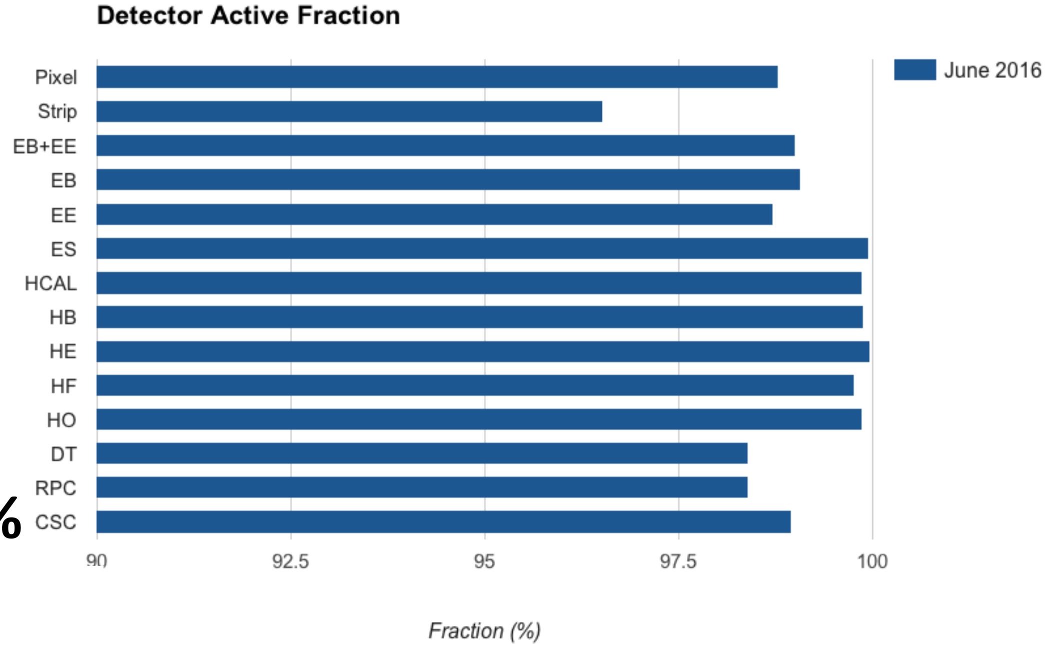
Beihang University,
IHEP/CAS,
Peking University

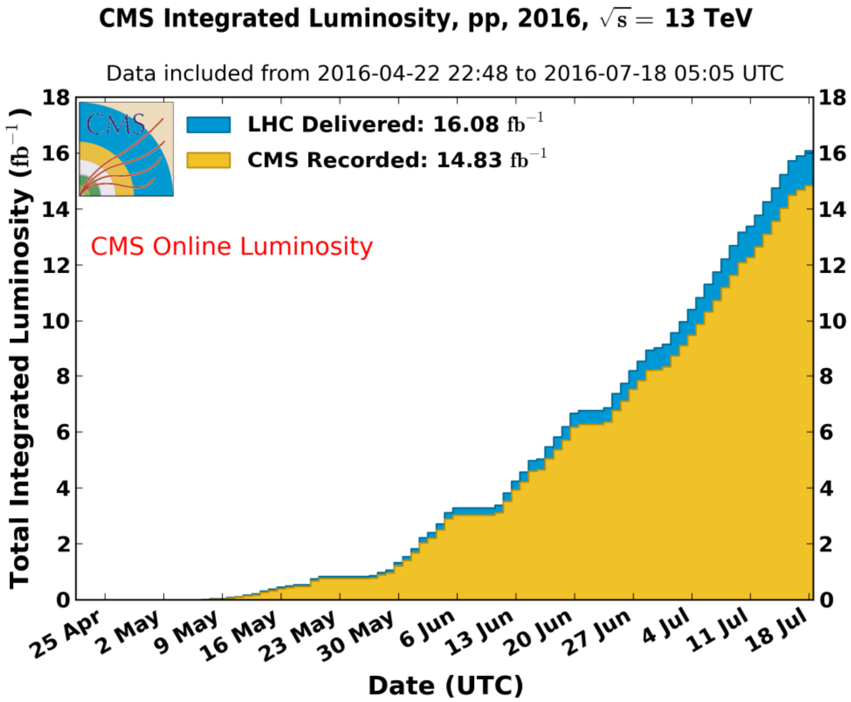
CMS performance

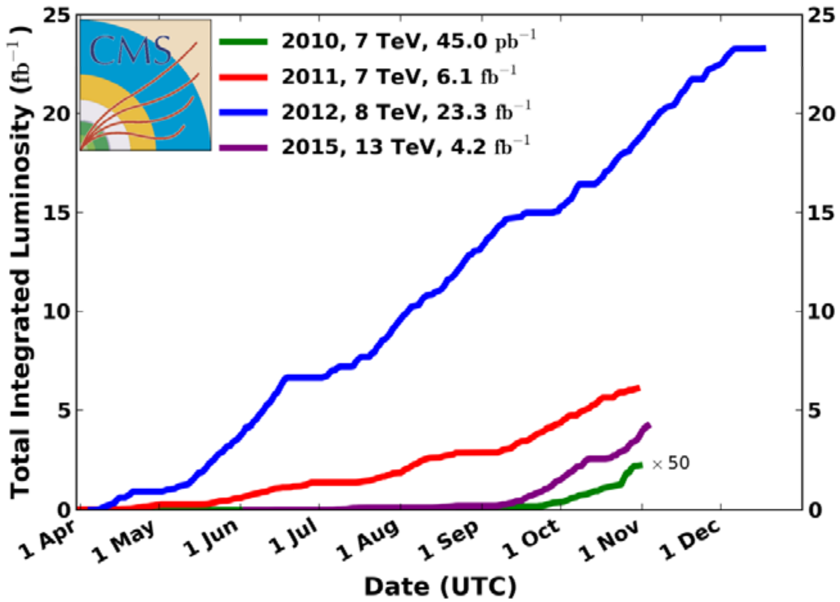
Very good performance in Run1 and Run2

Subdetectors active fraction > 95% (2016)

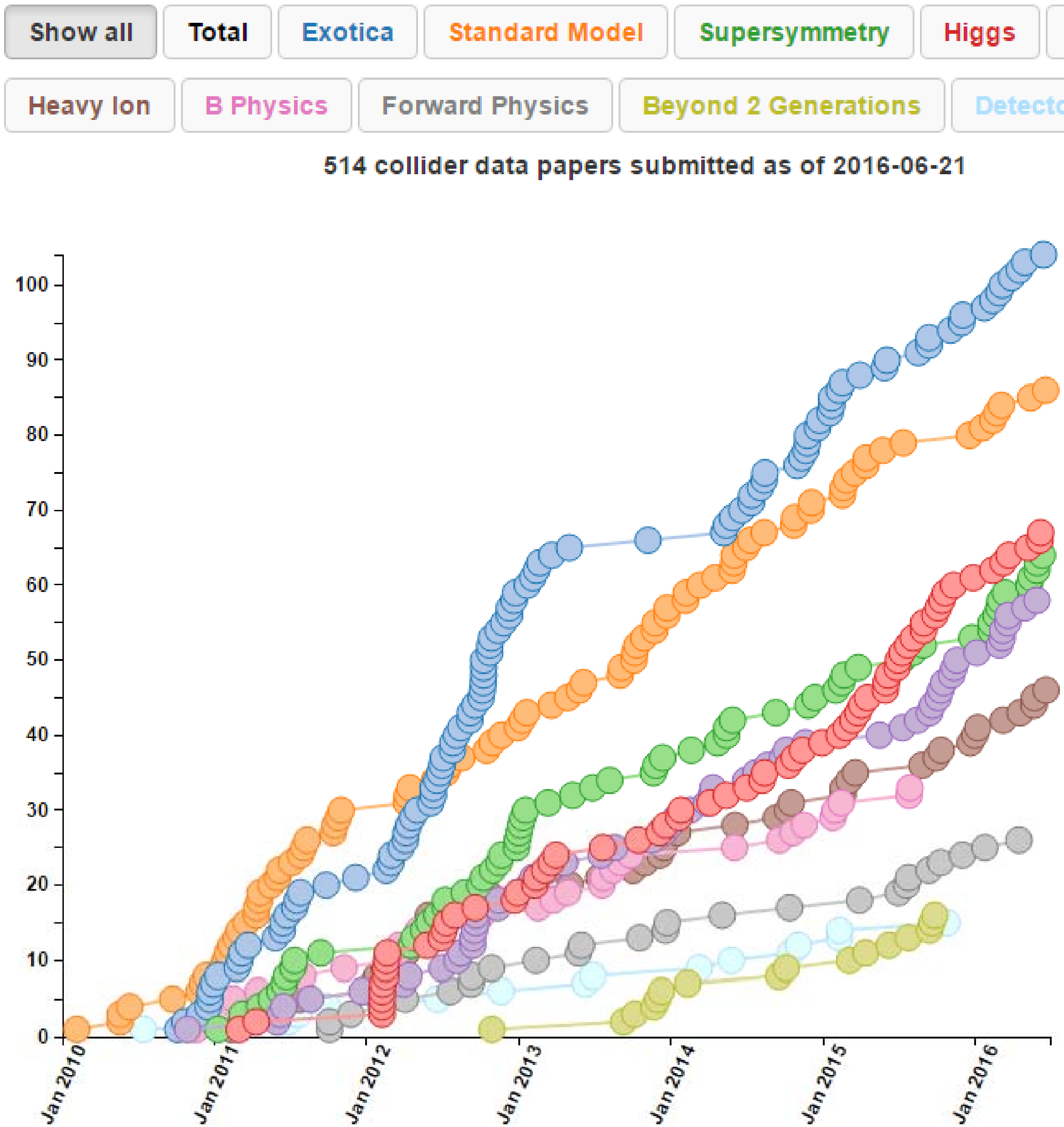
Data collection efficiency > 92%







CMS physics results



- ➢ More than 500 papers submitted/published
- ➢ ~ 100 public results already with Run2 data
- ➢ Few more analyses continuing with Run1 data focusing on precision measurements

LHC Run 1

- ➢ **Very successful Run 1 of the LHC (2010-2012)**
  - ◊ **Discovery of the 125 GeV Higgs boson**
  - ◊ Rare $Bs^0 \rightarrow \mu^+\mu^-$ decay
  - ◊ Top-quark mass measurement, SM tests over vast magnitudes

- ➢ **In additional huge number of CMS searches**
  - ◊ A few > 2σ effects
  - ◊ Run 2 allow to follow up on those effects and importantly extend the reach of LHC

The Nobel Prize in Physics 2013

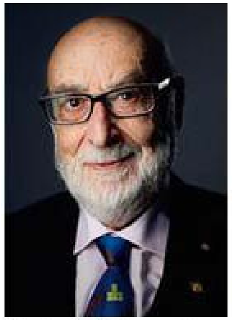


Photo: A. Mahmoud
François Englert
Prize share: 1/2

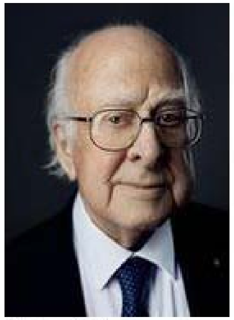
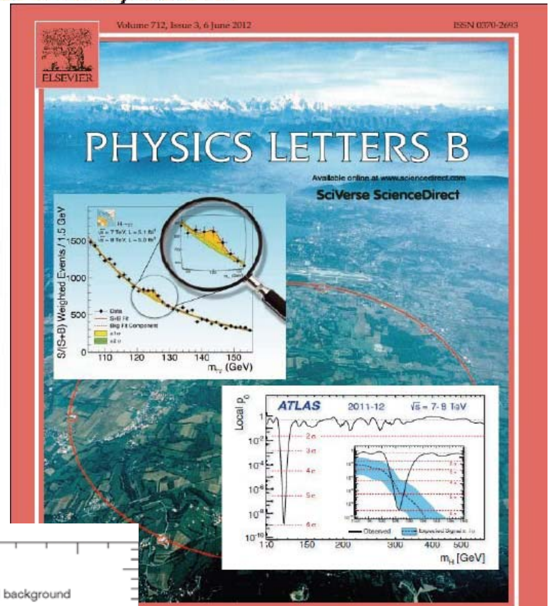
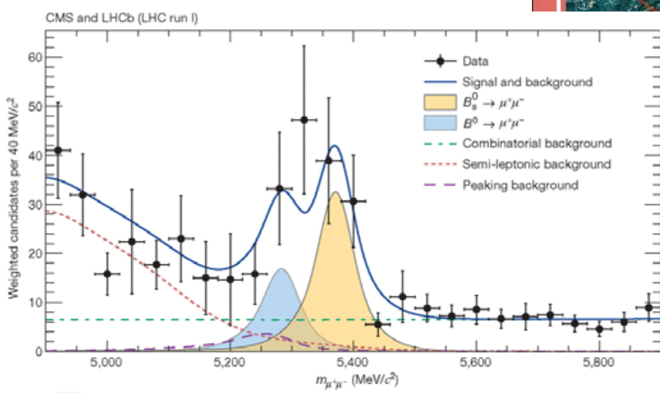
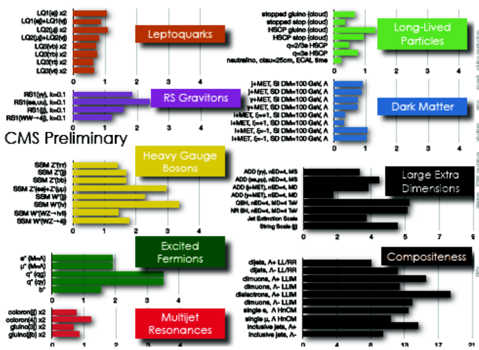
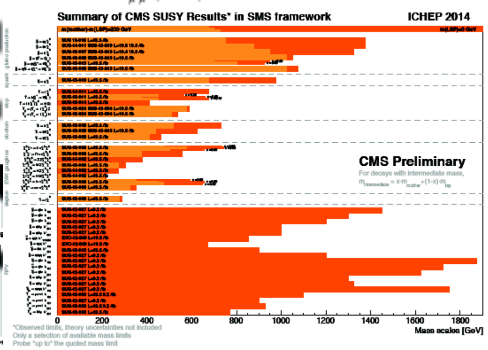


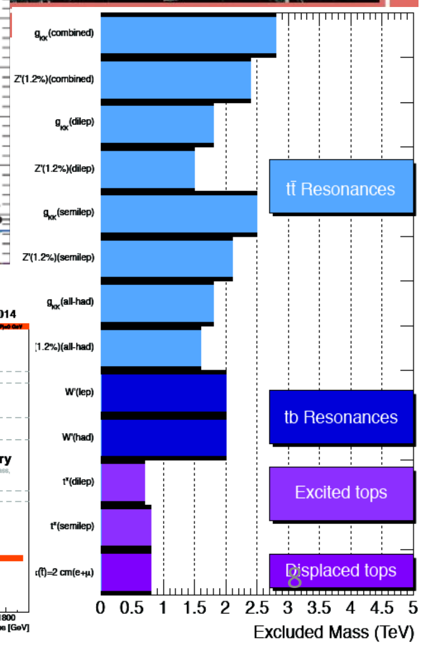
Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2











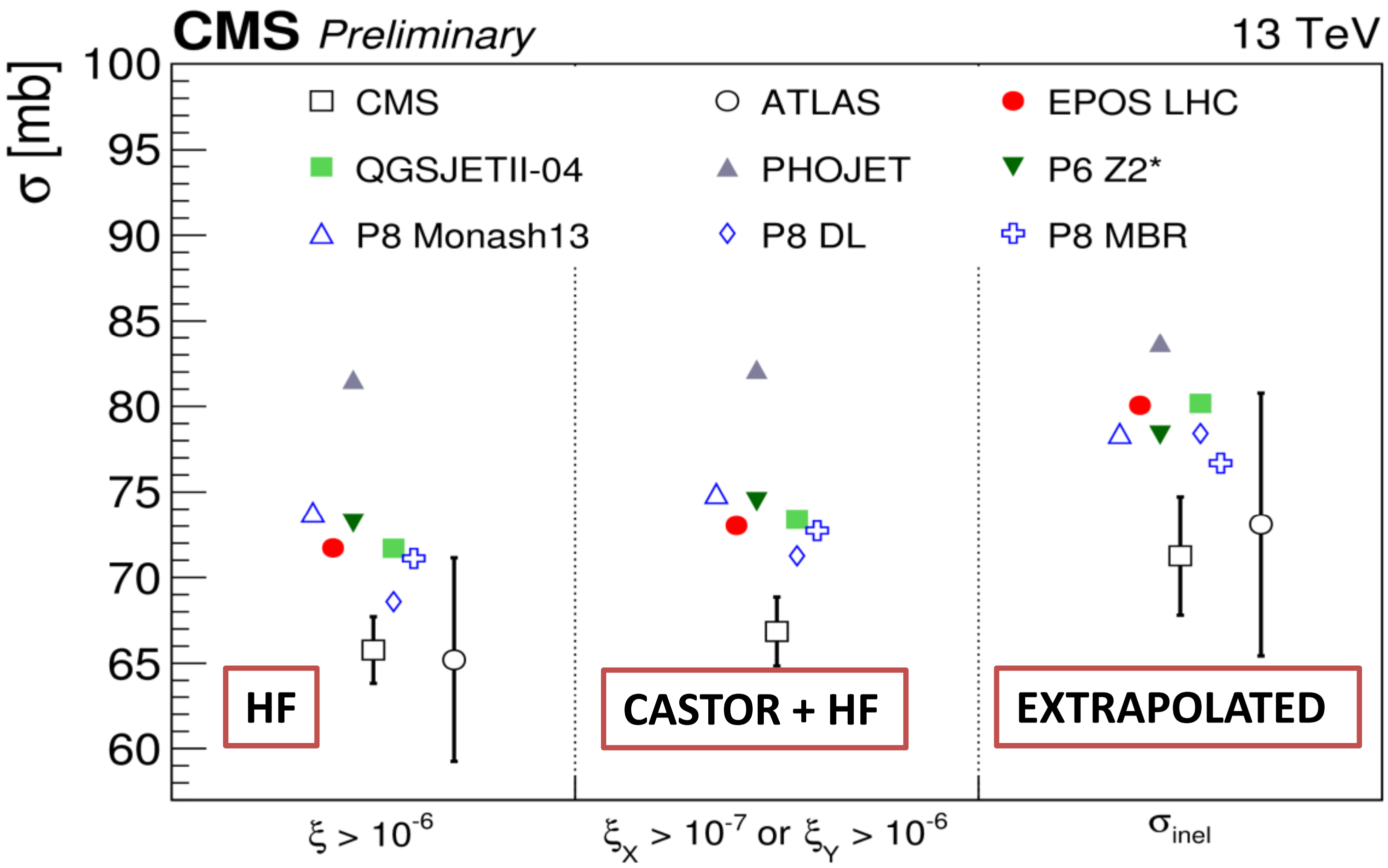
Soft QCD, forward scattering, quarkonia production, heavy ions

Total Inelastic cross section at √s = 13 TeV

- Experimental measurement within 3.0 <η <5.2 & -6.6<η<-3.0
- Within full phase space of inelastic domain,

σ = 71.3 ± 0.5 (exp.) ± 2.1 (lumi.) ± 2.7 (extrapolation) mb

FSQ-15-005



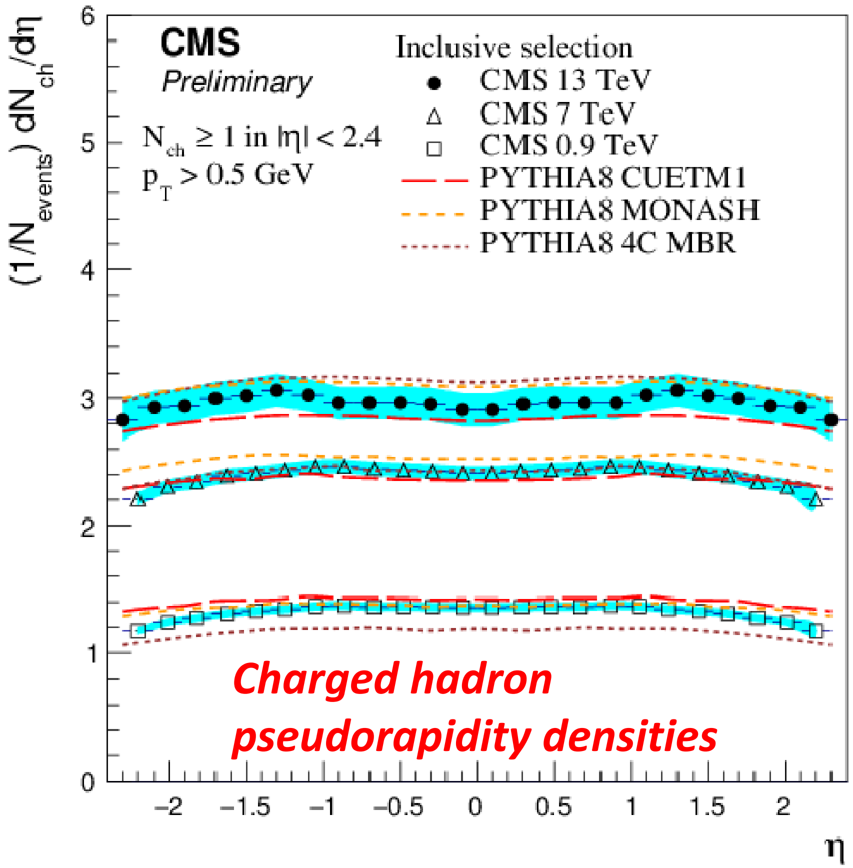
$$\xi = M^2/s$$

ς = fractional momentum loss of the scattered proton
M= mass of the diffractive dissociated system moving in a particular rapidity direction

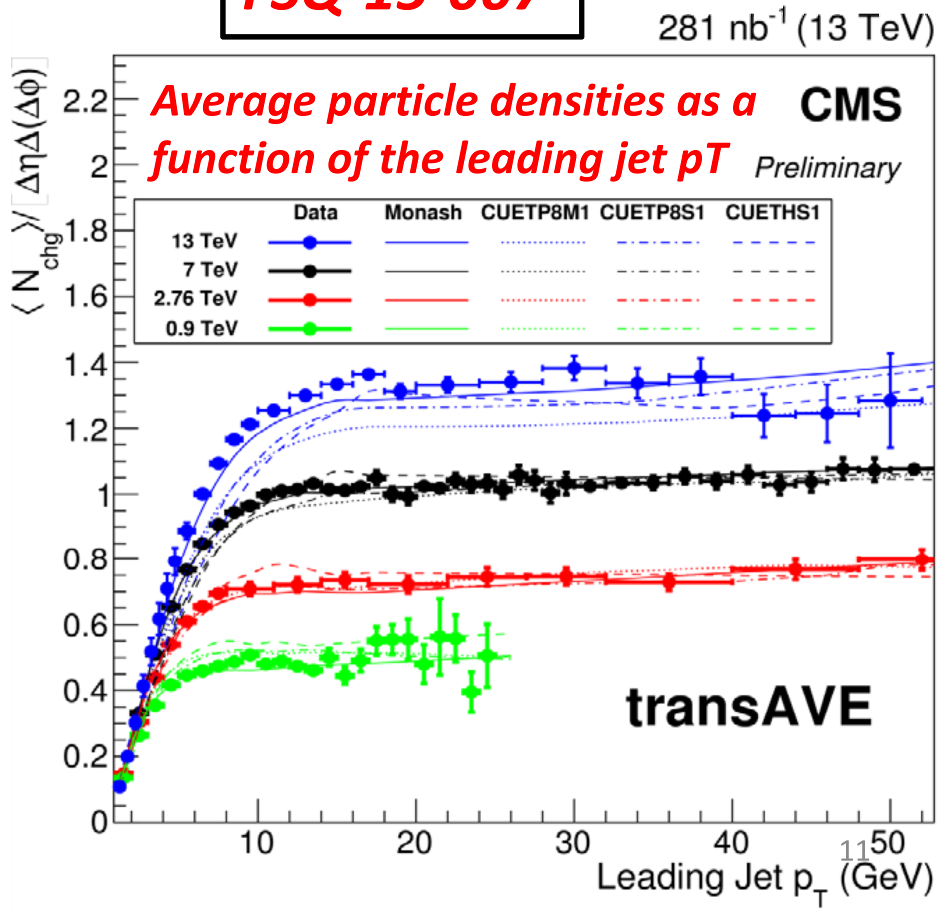
Charged particle production

- ➢ Soft particle production from low energy processes,
- test description of MC models with various tunes.
- underlying events accompanying hard scattering
- also important for description of pile-up.

FSQ-15-008

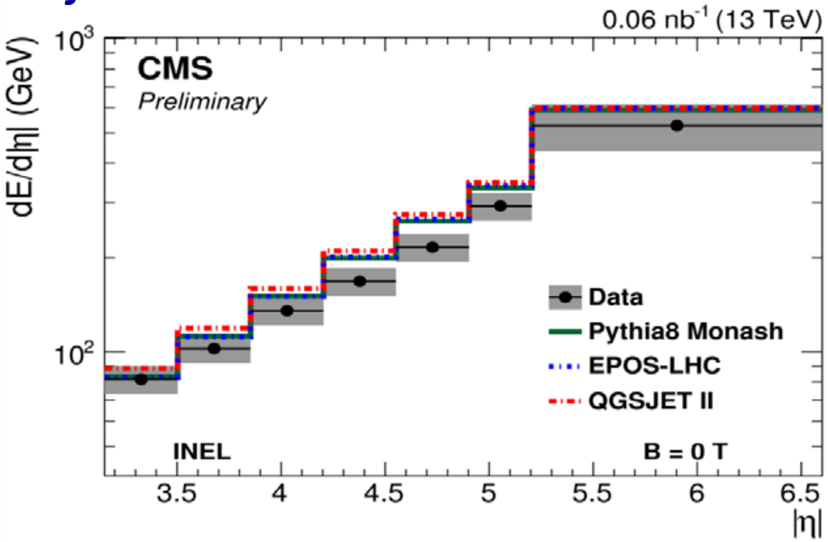


FSQ-15-007

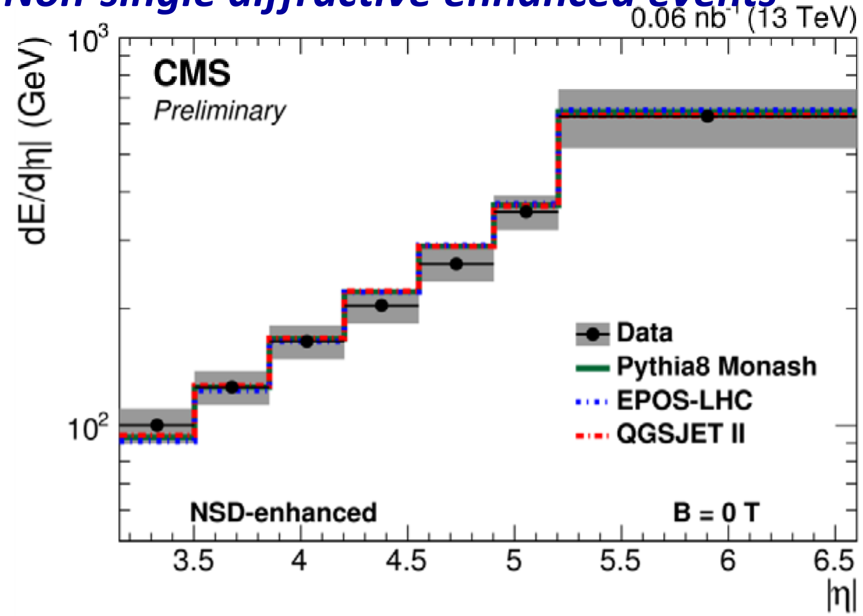


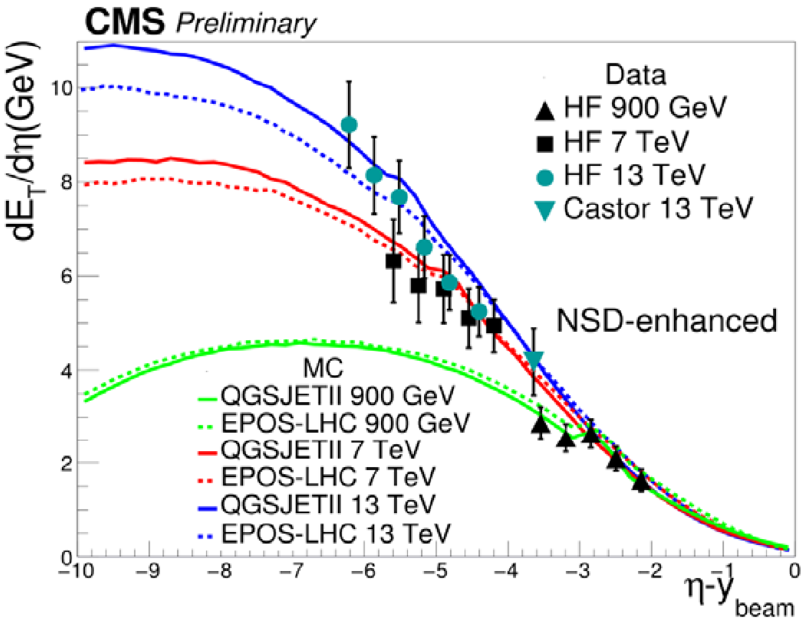
Energy flow in forward direction (3.15 <|η|<6.6) at √s = 13 TeV

Soft inclusive inelastic events



Non-single diffractive enhanced events

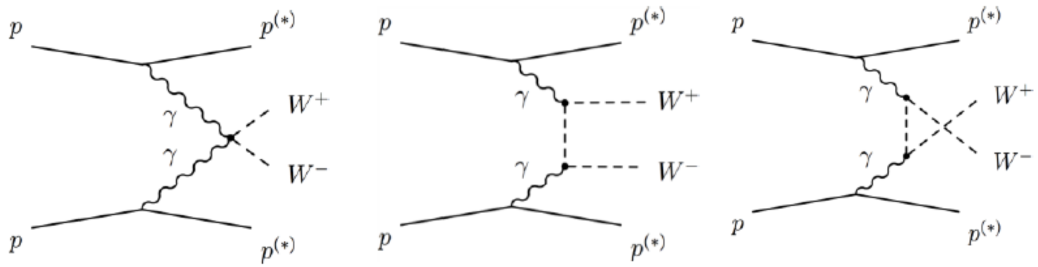




FSQ-15-006

Consistent results with the hypothesis of the limiting fragmentation.

Exclusive γγ→WW production at √s = 8 TeV

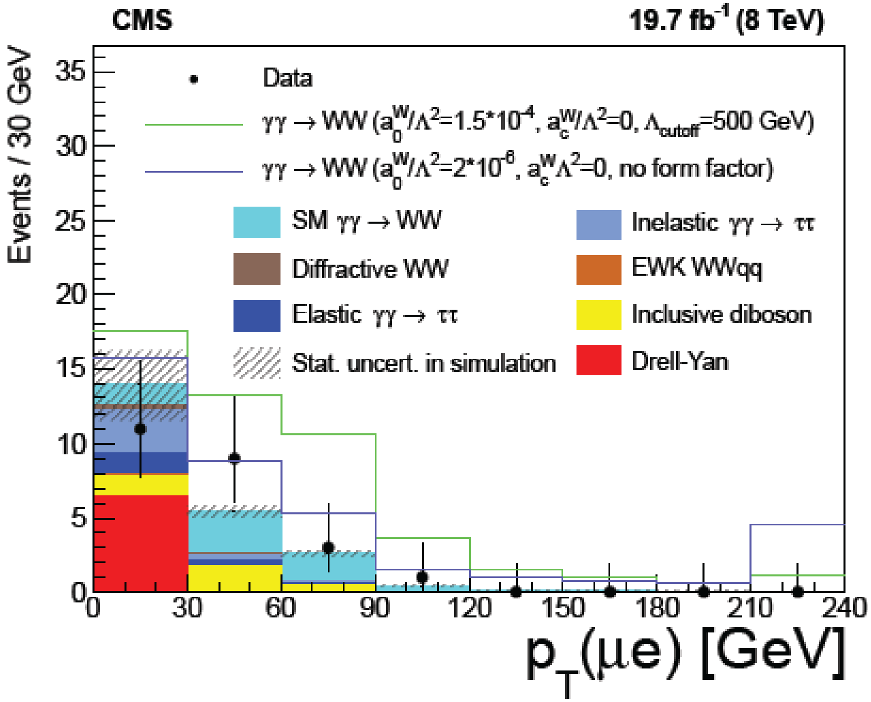


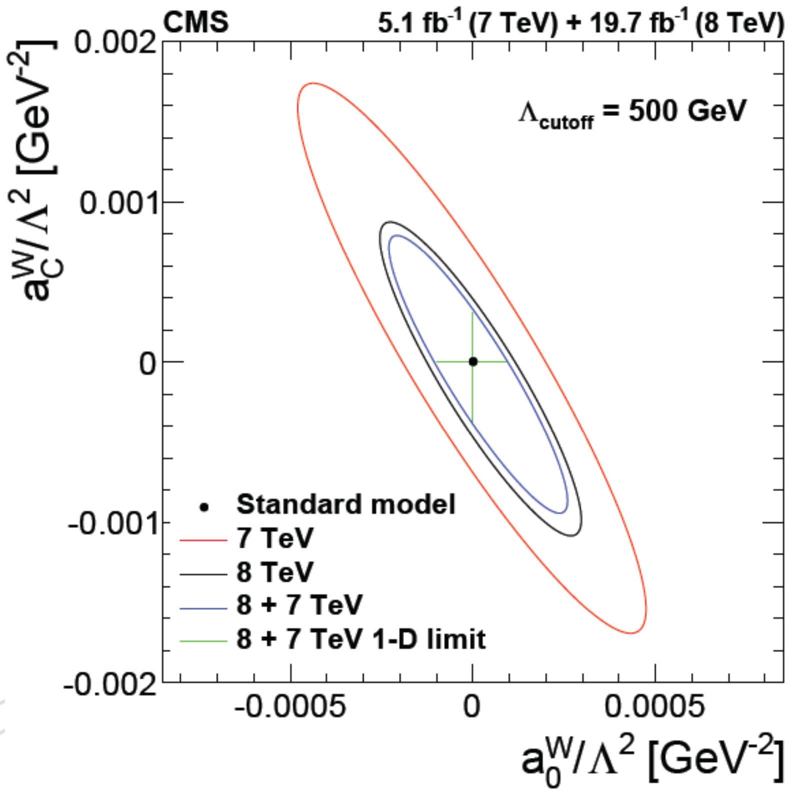
- ***No additional track in the detector other than decay product of Ws (e, μ)***
- **Evidence: 3.4 σ excess over background (15 events vs. ~4.5 background expected)**

FSQ-13-008

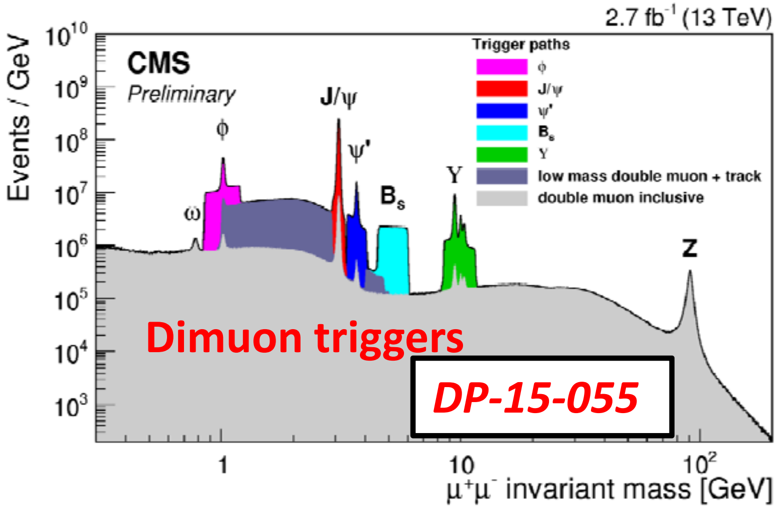
- **Best limits on anomalous quartic gauge couplings !**

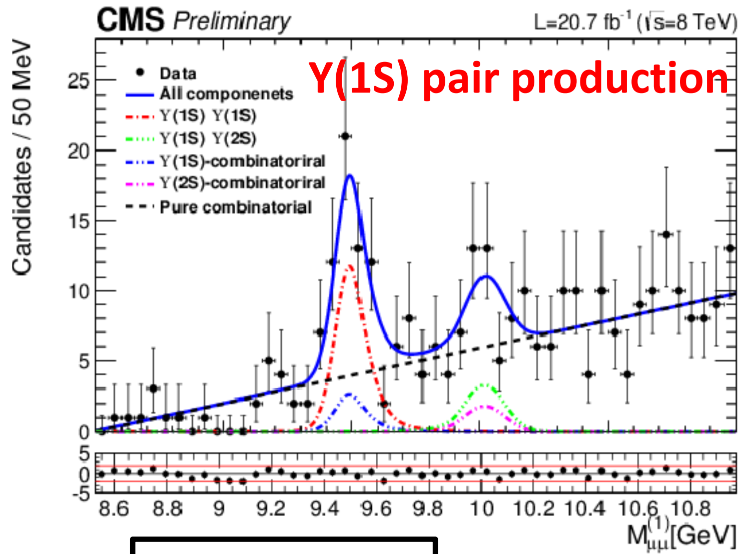
- **No significant deviations** from the SM are observed in the pT *distribution*





Quarkonia production at √s = 8, 13 TeV

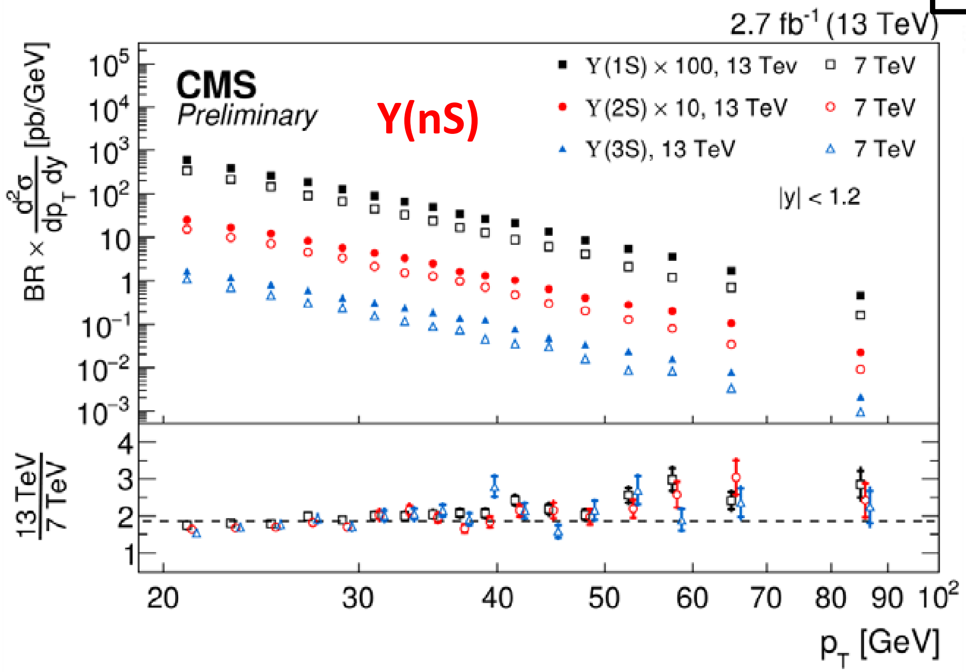


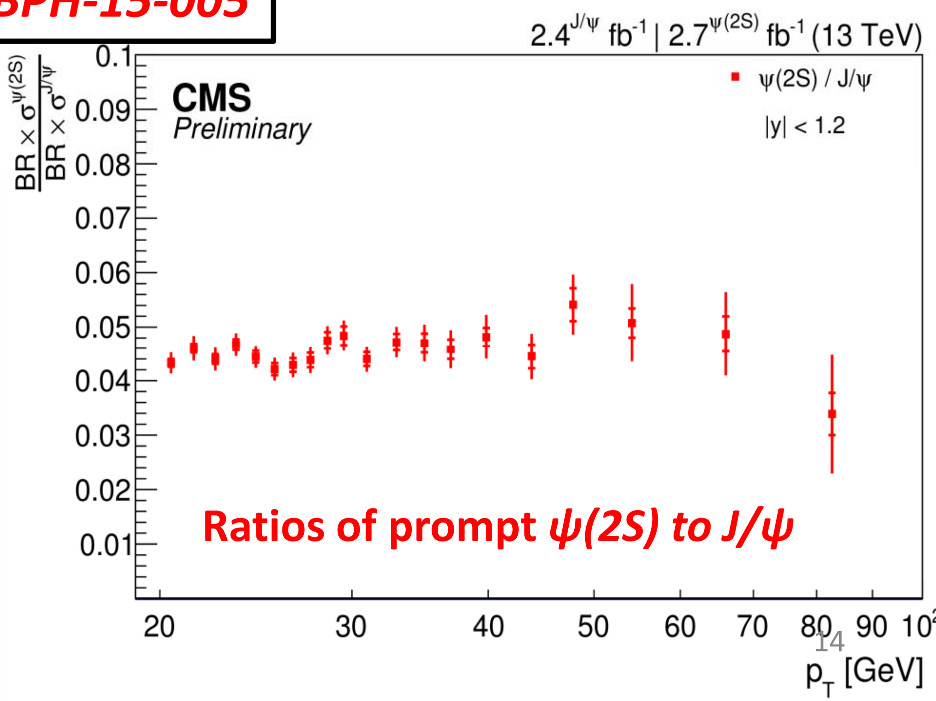


BPH-14-008

Υ(1s) Υ(1s) prod.
- ✓ ~69 pb @ 8TeV
- ✓ 38 events
- ✓ > 5σ Obs.

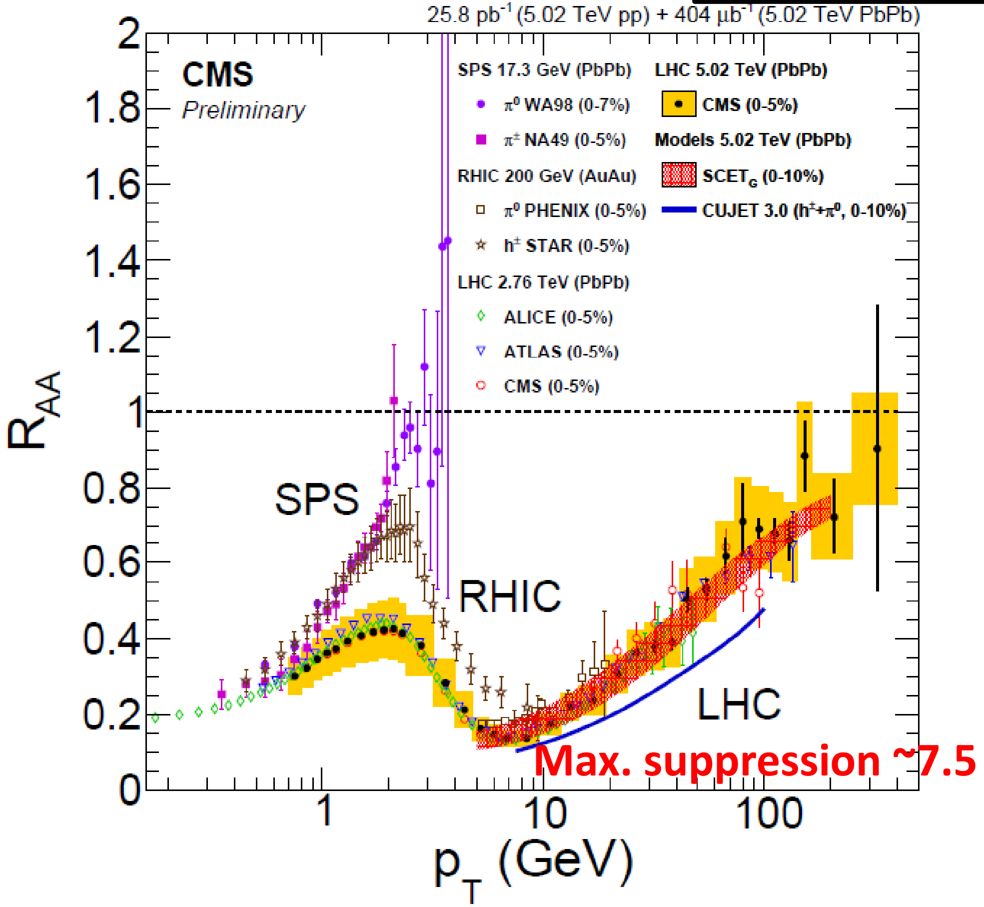
BPH-15-005



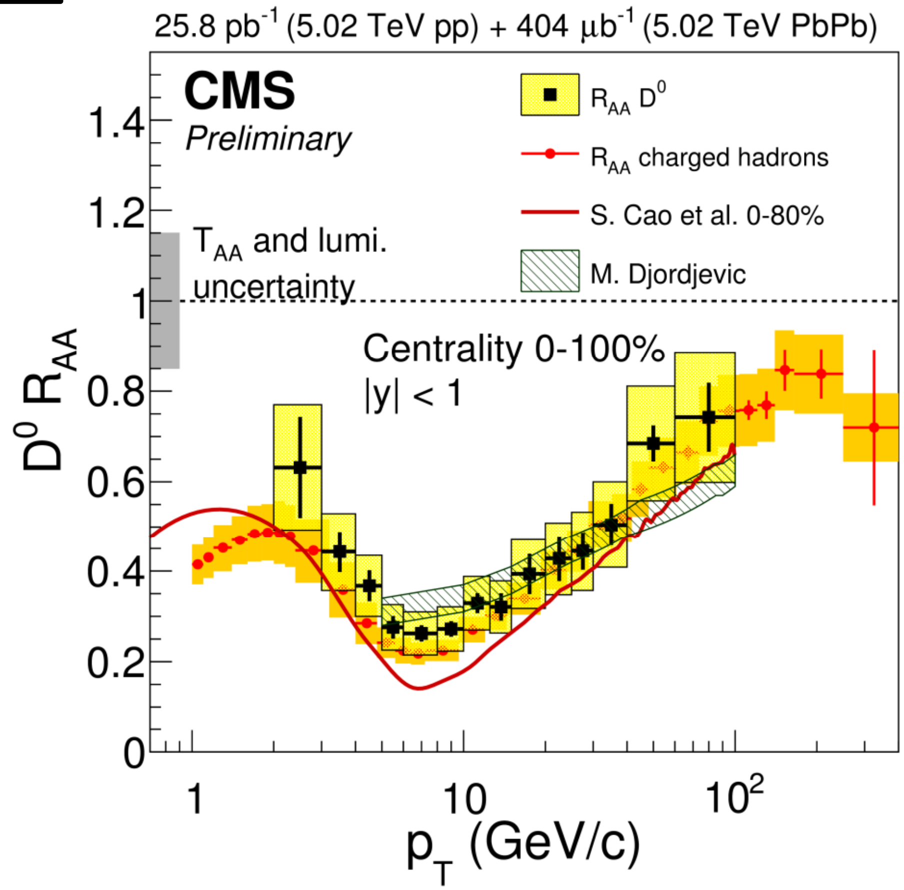


Nuclear modification factor in Pb-Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV

For charged particles **HIN-15-015**



For D-mesons **HIN-16-001**

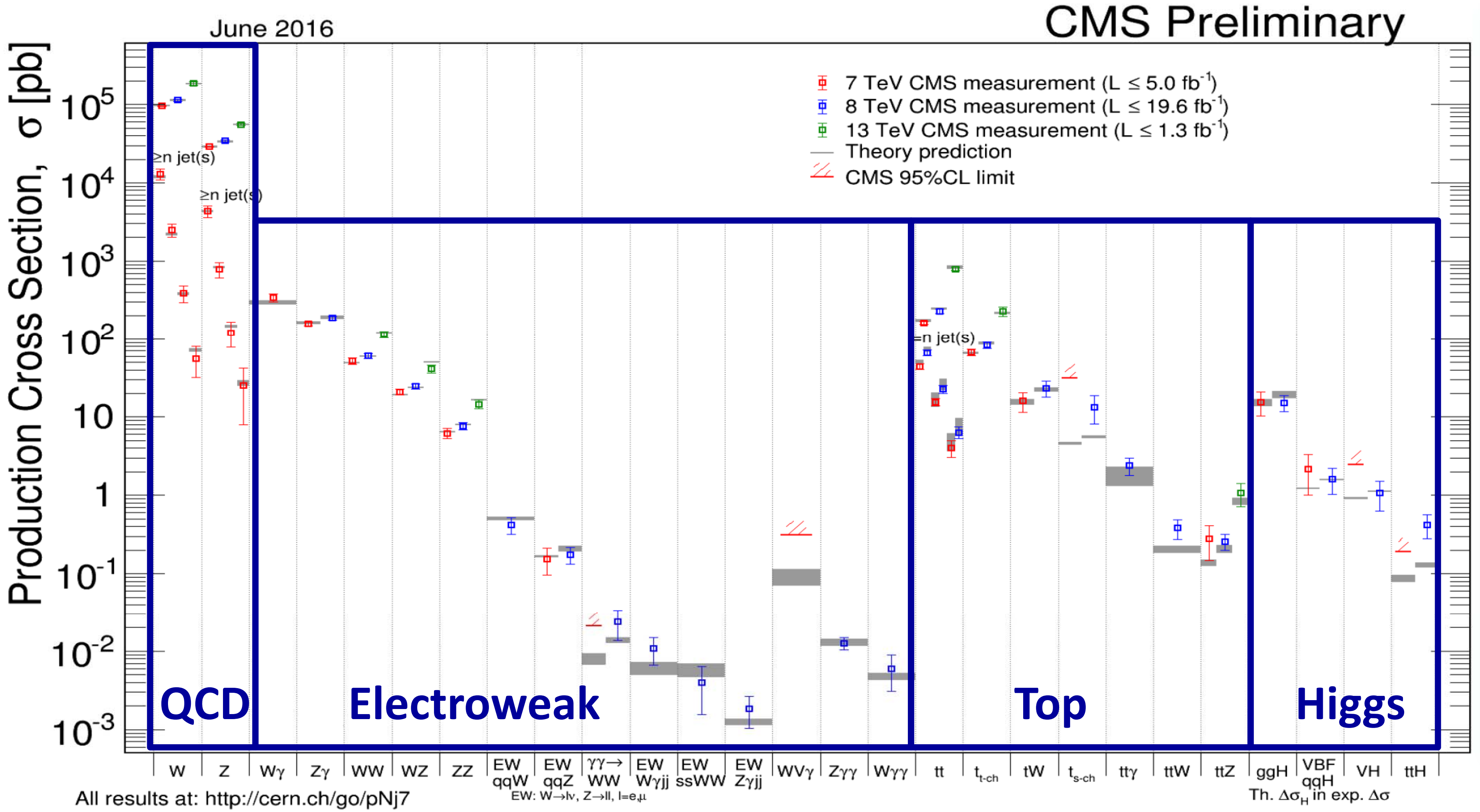


Strong suppression of light and heavy flavours with comparable magnitude over wide pT range

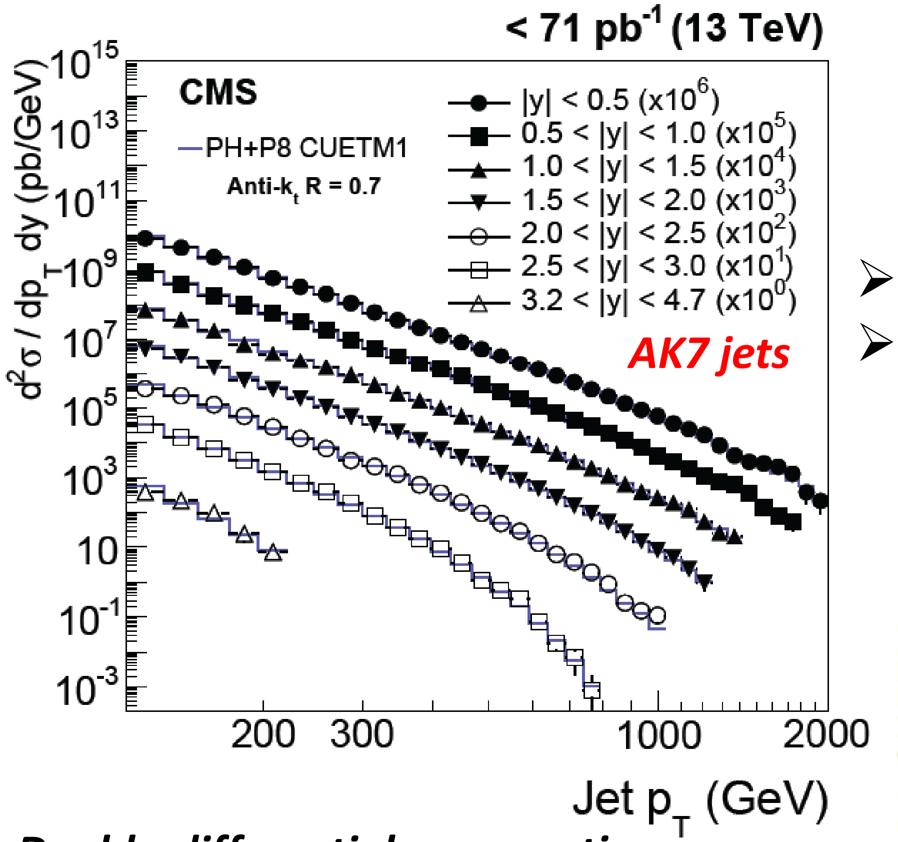
March of standard model

Cross section measurements at √s =7, 8, 13 TeV

All measurements consistent with standard model



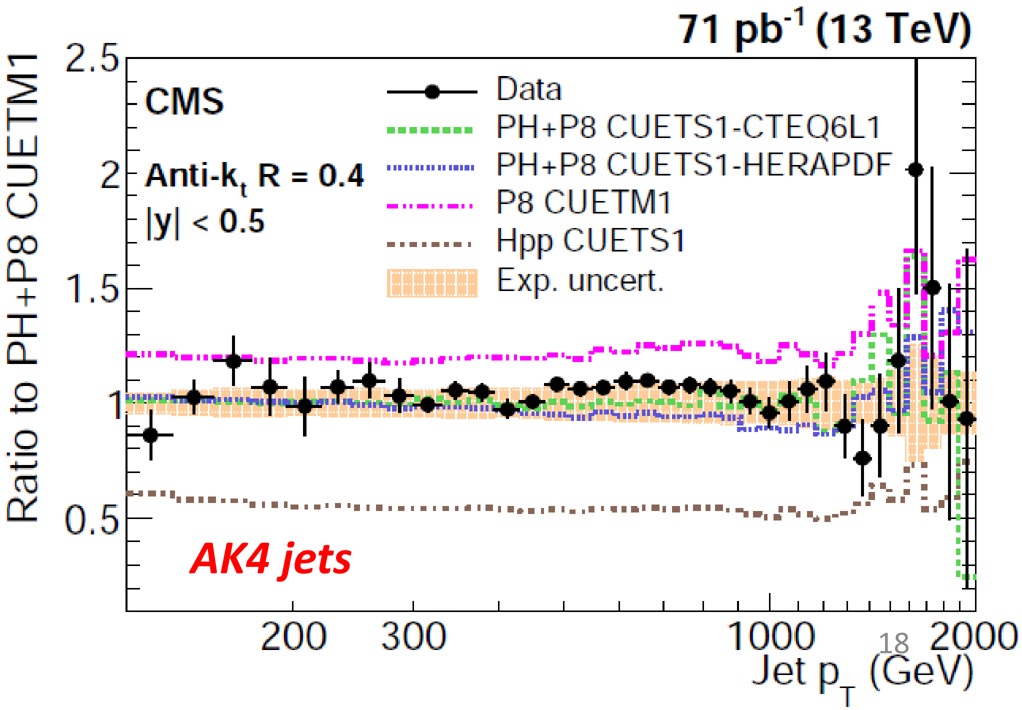
Inclusive jet measurements at √s = 13 TeV



Double-differential cross section

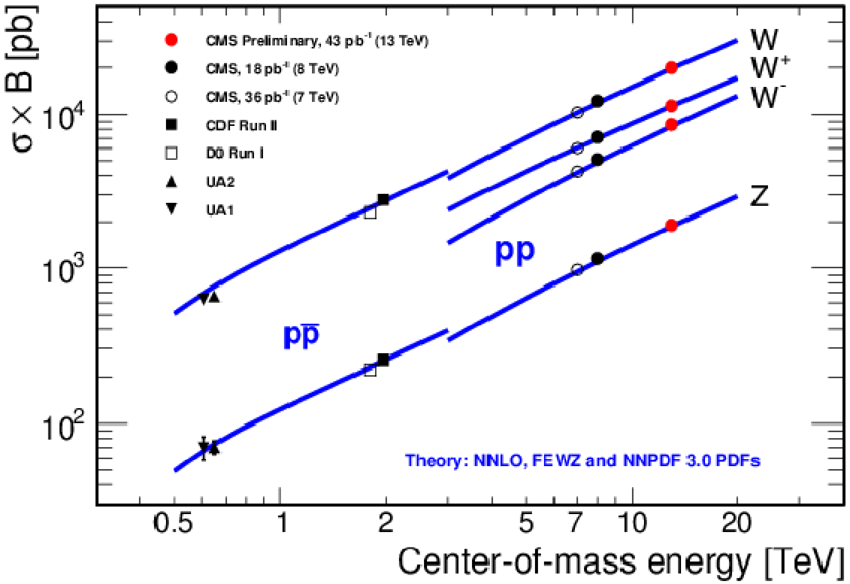
SMP-15-007
arXiv:1605.04436

- Measurements up to jet pT = 2 TeV
- Data matches better with cone radius of 0.7



Over accessible kinematic range data agrees well with POWHEG+Pythia8

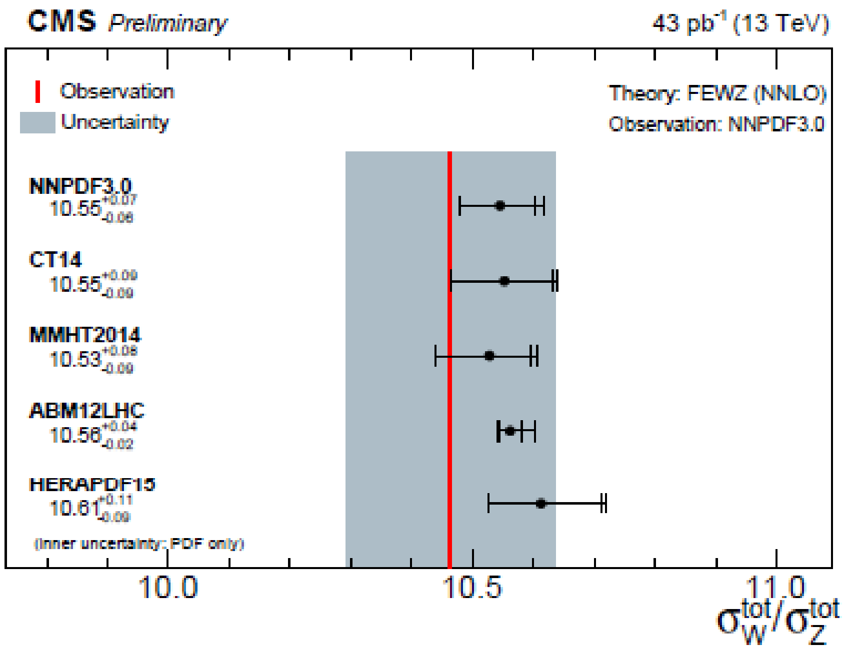
Inclusive W,Z production at √s = 13 TeV

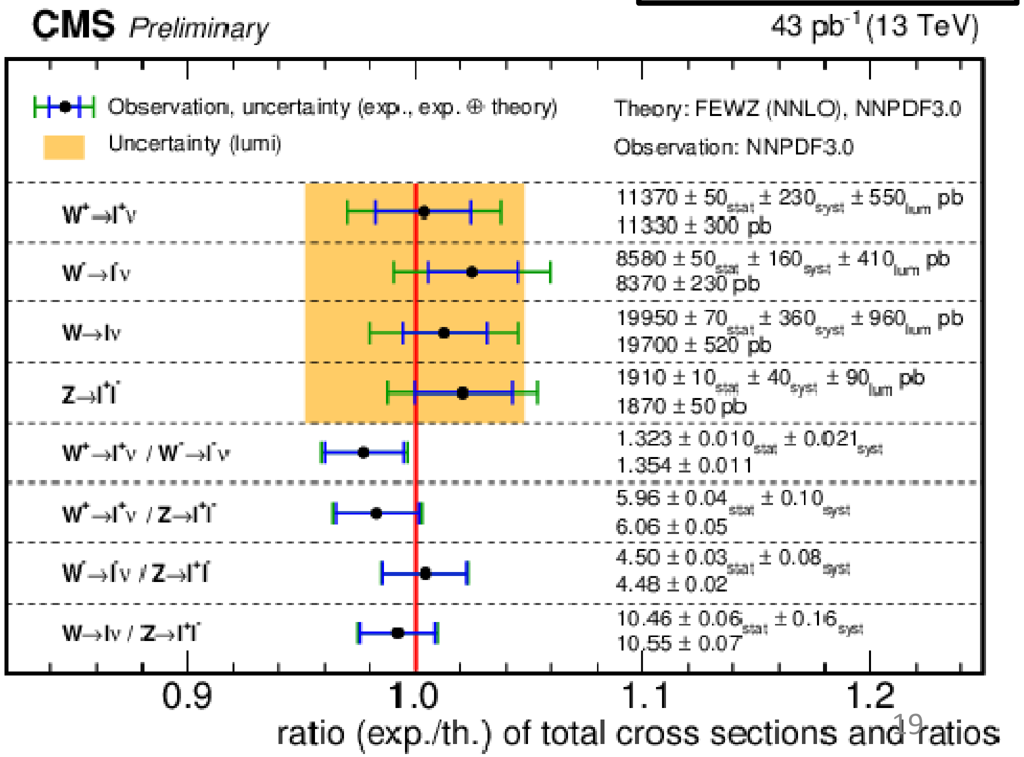


Measured values, including √s dependence,
agree with NNLO QCD predictions

Ratios of production rates → tools to constrain PDFs

SMP-15-004
SMP-15-011





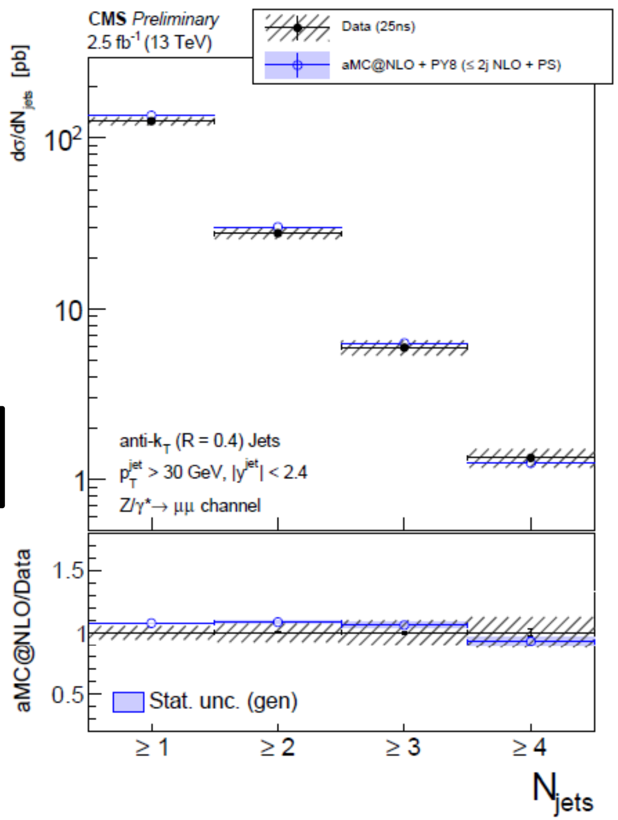
W/Z + jets production

SMP-14-023

- **Fundamental** **test of predictions for QCD radiations.**

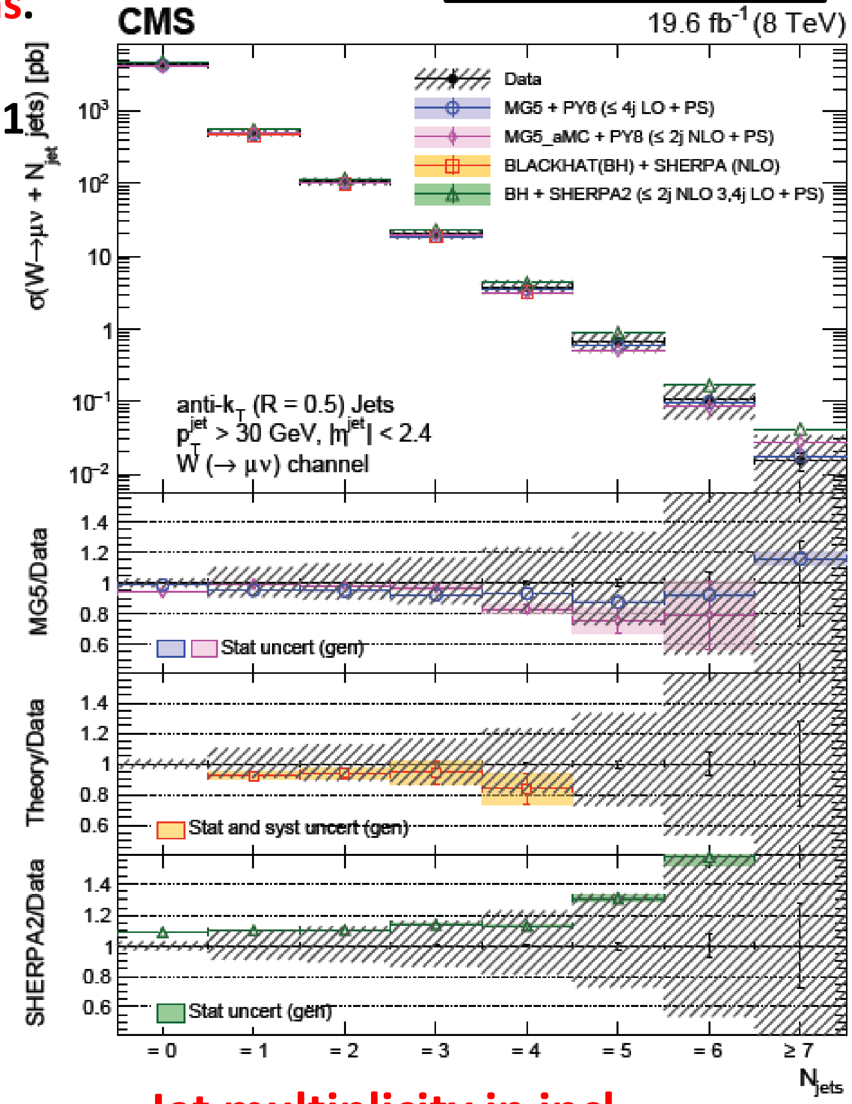
- **Theory calculation** **W/Z productions with up to V+1 jet at NNLO or at NLO (up to V+2 jets, with 0,1,2 multiplicities combined) + parton-shower.**

- **Background for many analyses** **→ contributions must be estimated well.**



Jet multiplicity in incl. Z production at 13 TeV

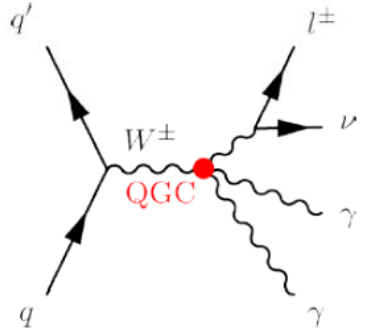
SMP-15-010

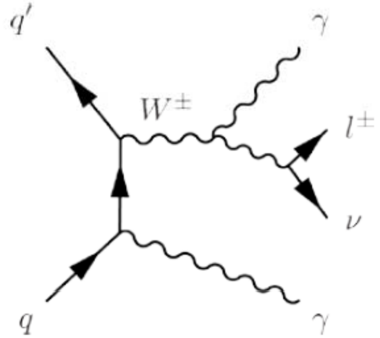


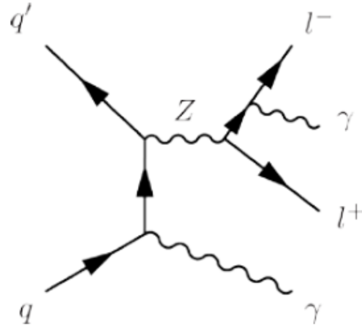
Jet multiplicity in incl. W production at 8 TeV

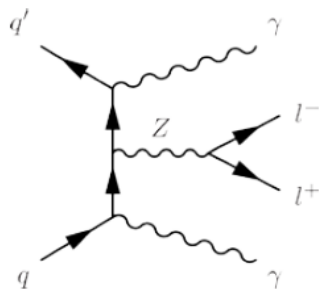
Wγγ, Zγγ production and quartic gauge coupling at √s = 8 TeV

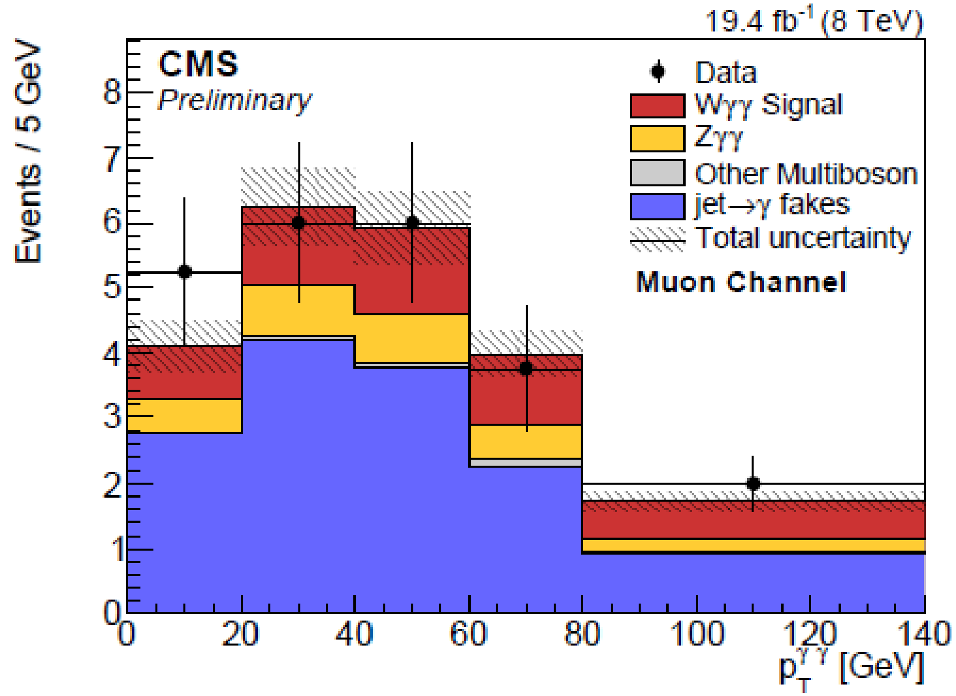
SMP-15-008











$$\sigma^{\rm fid}_{\rm W^\pm\gamma\gamma} \cdot {\rm BR}\,({\rm W} \to \ell\nu) = 6.0 \pm 1.8\,({\rm stat}) \pm 2.3\,({\rm syst}) \pm 0.2\,({\rm lumi})\,{\rm fb}\,.$$

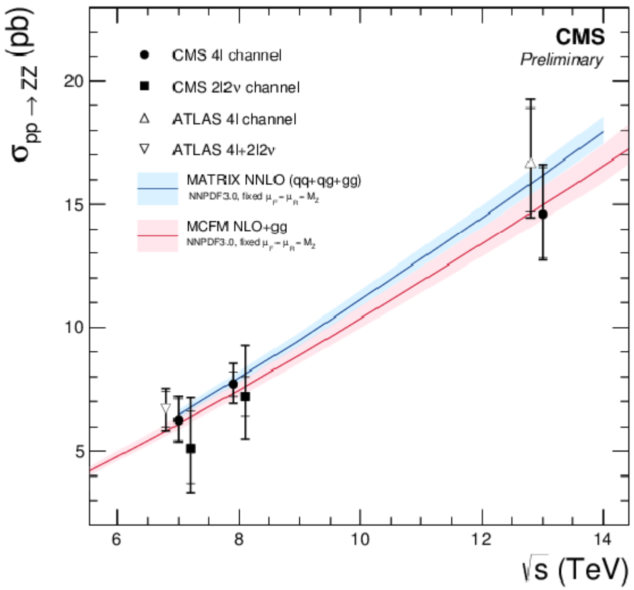
$$\sigma^{\rm fid}_{\rm Z\gamma\gamma} \cdot {\rm BR}\,({\rm Z} \to \ell\ell) = 12.7 \pm 1.4\,({\rm stat}) \pm 1.8\,({\rm syst}) \pm 0.3\,({\rm lumi})\,{\rm fb}$$

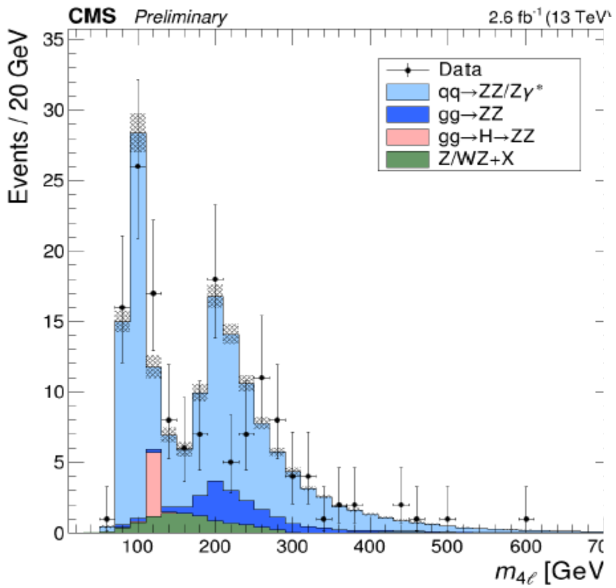
$W^{\pm}\gamma\gamma$	Expected (TeV^{-4})	Observed (TeV^{-4})
f_{T0}/Λ^4	[-26.5, 27.0]	[-33.5, 34.0]
f_{T1}/Λ^4	[-34.5, 34.8]	[-44.3, 44.8]
f_{T2}/Λ^4	[-74.6, 73.7]	[-93.8, 93.2]
f_{M2}/Λ^4	[-549, 531]	[-701, 683]
f_{M3}/Λ^4	[-916, 950]	[-1170, 1220]

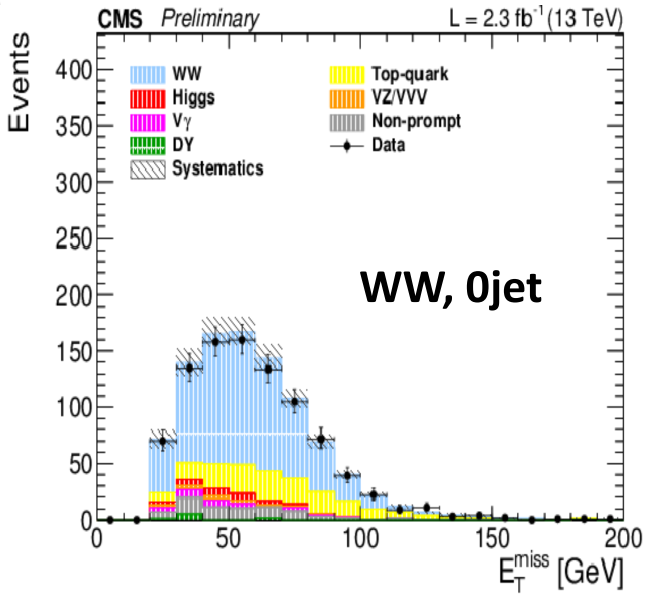
- **Wγγ process observed with significance 2.4 σ**
- **Zγγ process observed with significance 5.9 σ**
- **Limits on anomalous quartic gauge (dim-8) couplings**

Diboson productions at √s = 13 TeV

- Measurements **test SM prediction**
- Theoretical predictions accurate up to **NNLO**
- Diboson are **backgrounds to many searches** → need to know the rates accurately





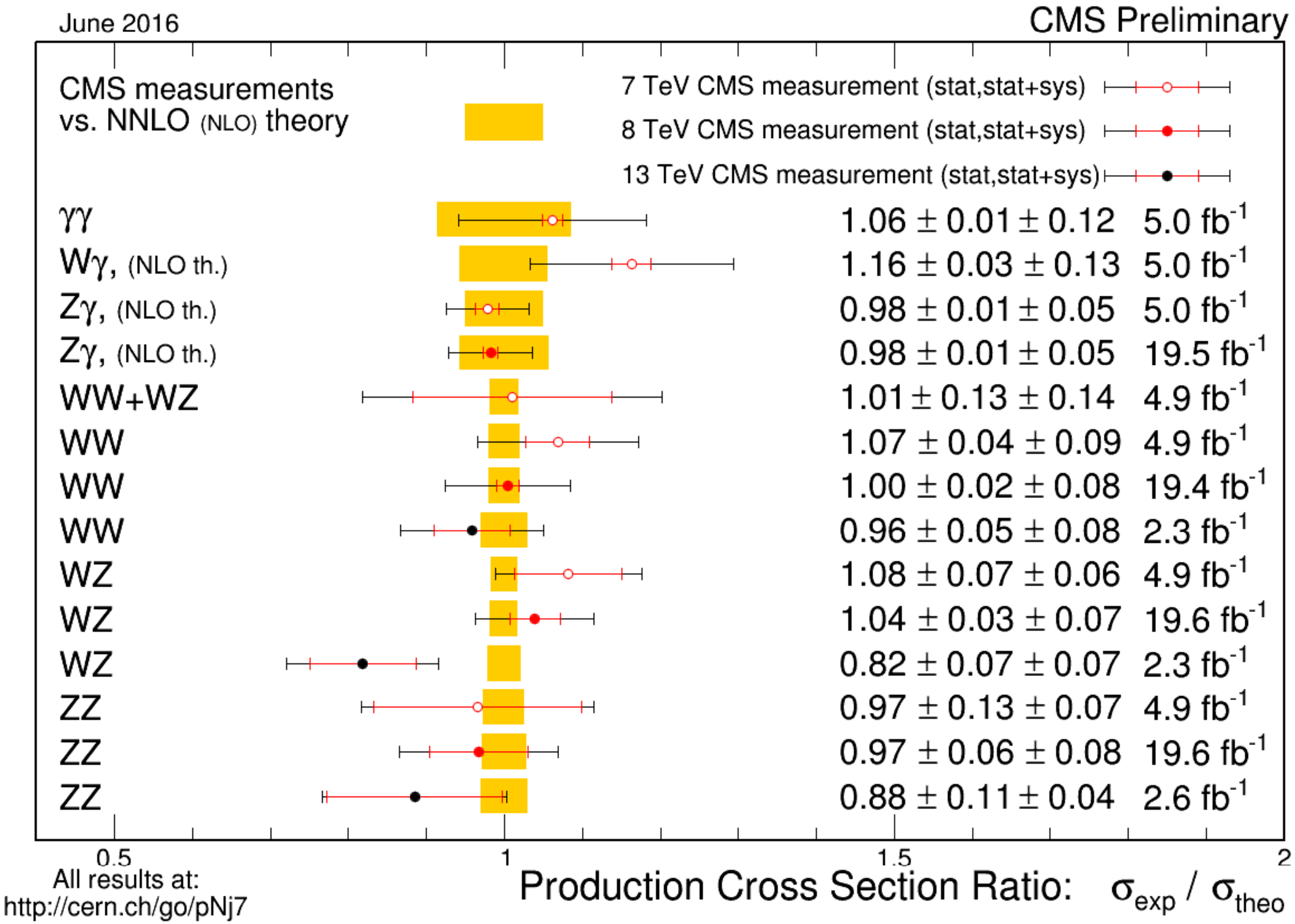


$\sigma(pp \to W^+W^-) = 115.3 \pm 5.8\ (stat) \pm 5.7\ (exp) \pm 6.4\ (theo) \pm 3.6\ (lumi)$ pb **SMP-16-006**

$\sigma(pp \to ZZ) = 14.6^{+1.9}_{-1.8}\,(stat)^{+0.5}_{-0.3}\,(syst) \pm 0.2\,(theo) \pm 0.4\,(lum)$ pb **SMP-16-001**

$\sigma(pp \to WZ) = 40.9 \pm 3.4\,(stat)\ ^{+3.1}_{-3.3}\,(syst) \pm 0.4\,(theo) \pm 1.3\,(lumi)$ pb. **SMP-16-002**

Summary of diboson production at Run 1 & Run 2

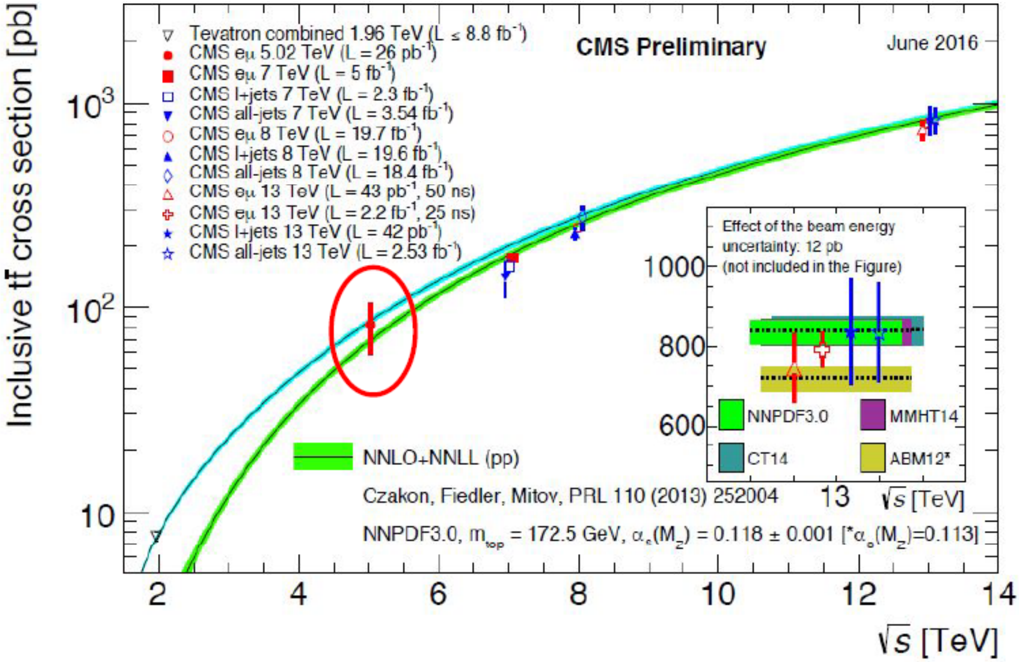


So far, no smoking-gun indicating disagreement between SM predictions and experimental measurements

–Improvement in experimental accuracy and prediction precision makes tests more and more stringent

Top Physics

Top pair production



TOP-16-015

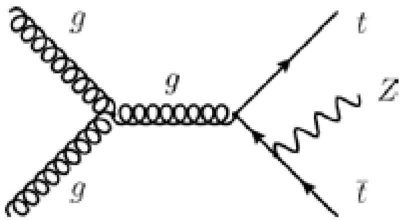
σ(tt) @ 5.02 TeV , 26 pb^{-1}
= 82 ±20(stat)± 5(syst) ±10 (lumi) pb

first measurement!

TOP-16-005

σ(tt) @ 13 TeV , 2.2 fb^{-1}
= 793 ± 8(stat)± 38 (syst) ±21 (lumi) pb

- **Top-pair in association with Z at √s = 13 TeV**



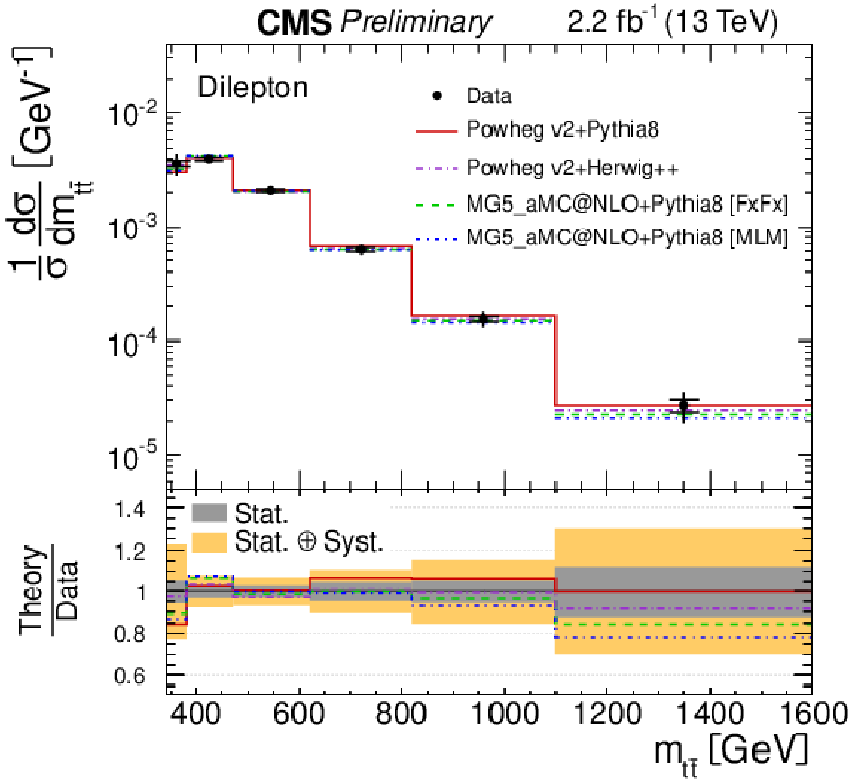
TOP-16-009

$\sigma(ttZ) = 1065\ ^{+352}_{-313}\,(stat)\ ^{+168}_{-142}\,(sys.)$ fb

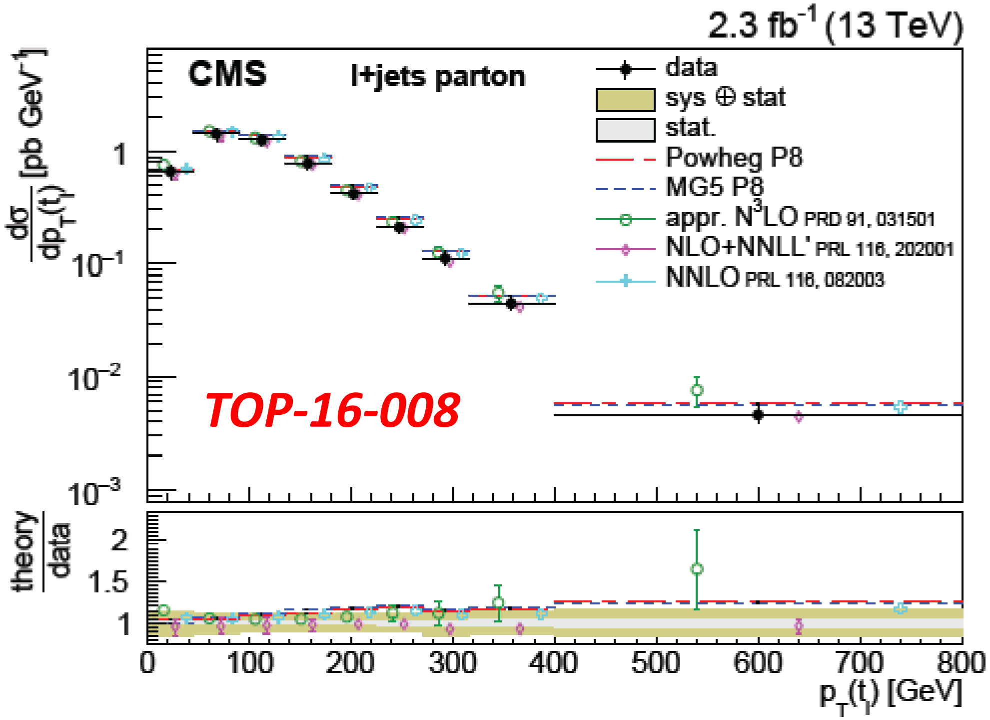
Channel	Expected significance	Observed significance
3ℓ analysis	2.9	3.5
4ℓ analysis	1.2	0.9
3ℓ and 4ℓ combined	3.1	3.6

Top pair differential cross sections at 13 TeV

- Tests QCD description
- New ME generator and PS codes used in Run 2
- PT spectrum better described by NNLO



TOP-16-011

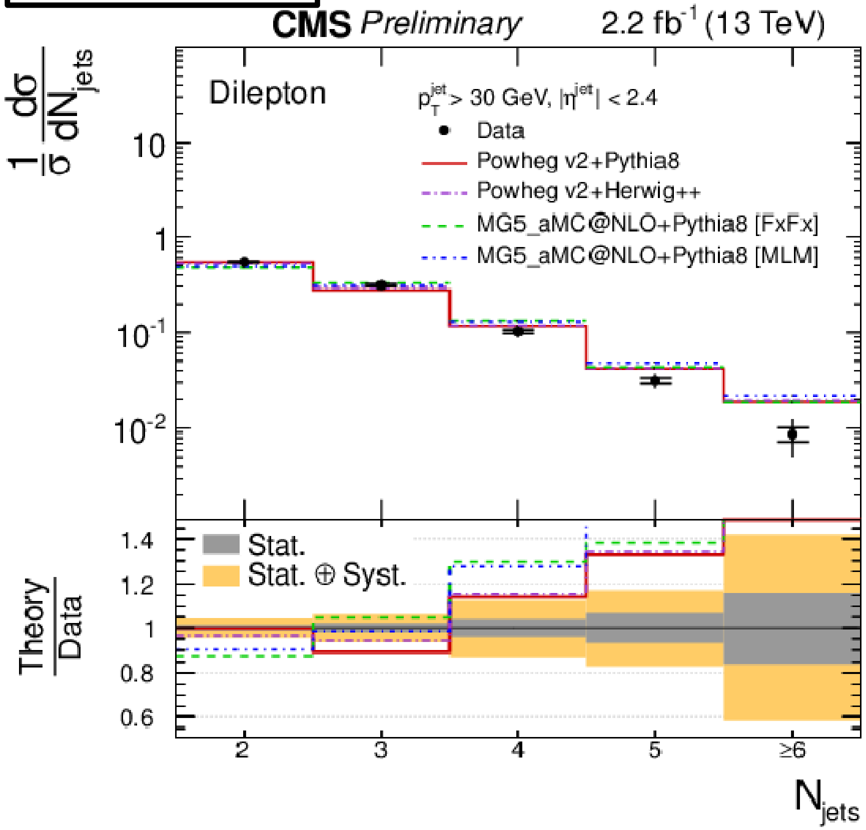


TOP-16-008

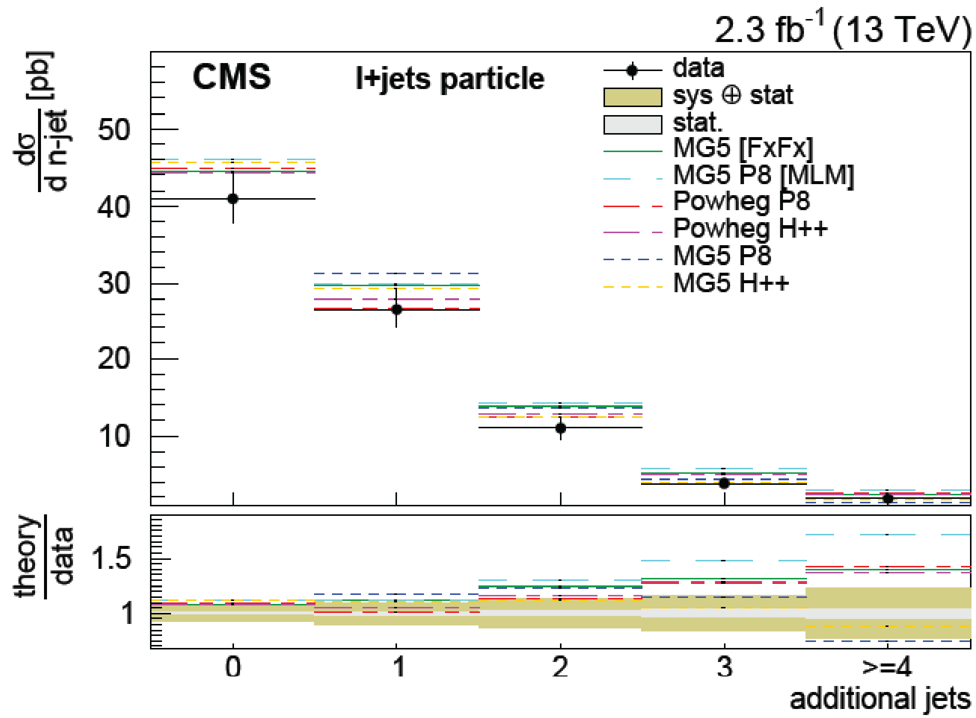
Jet multiplicity in top events

- **tt+jets important background to ttH**

TOP-16-011

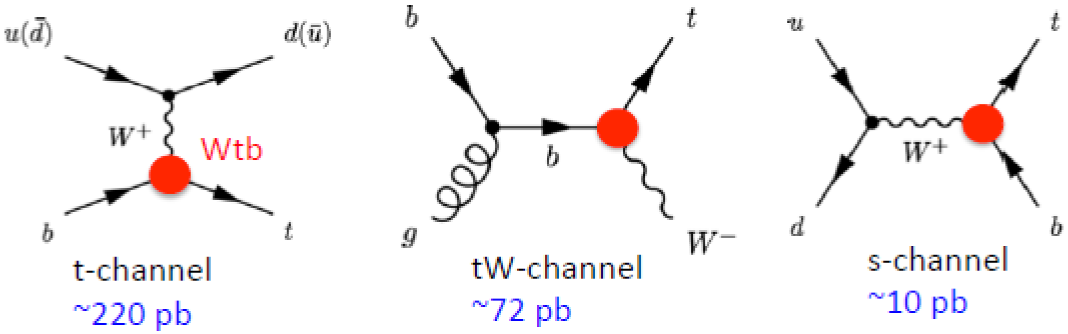


TOP-16-008



- Low jet multiplicity →sensitive to ME and matching to parton shower
- High jet multtiplicity → parton shower α_s tuning

Electroweak production of single top at 13 TeV



$\sigma^{13TeV}_{t-chan} \sim 2.5 \times \sigma^{8TeV}_{t-chan}$

- NNLO precision for **single top t-channel production** rate
  - Theory: ~ 1%
  - Measurements:

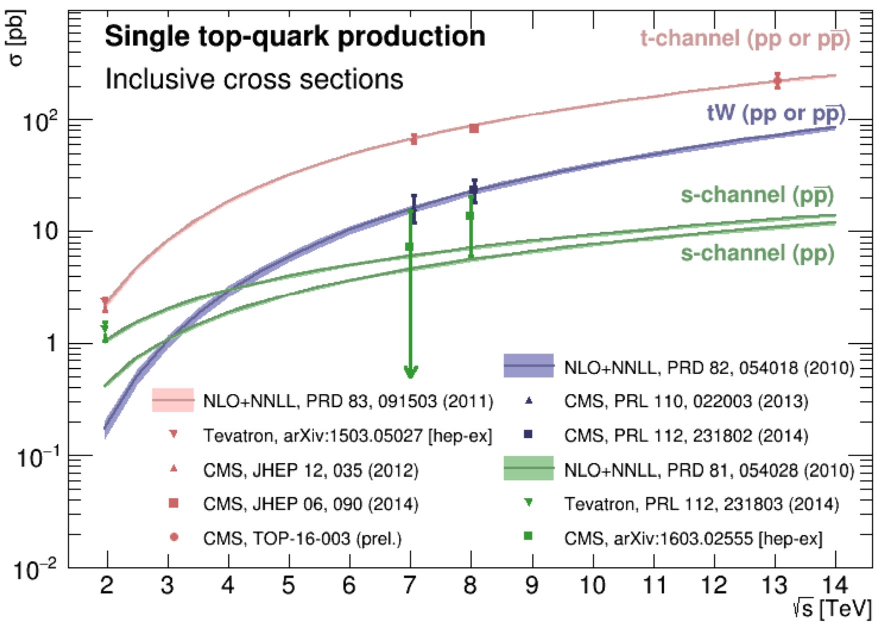
~10% at 8 TeV, with 20 /fb

~15% at 13 TeV with 2.3 /fb

$$\sigma_{t\text{-ch.},t} = 149.6 \pm 9.9\,(\text{stat}) \pm 10.6\,(\text{exp})\,^{+18.1}_{-18.3}\,(\text{theo}) \pm 4.0\,(\text{lumi})\ \text{pb}$$

$$\sigma_{t\text{-ch.},\bar{t}} = 82.6 \pm 5.2\,(\text{stat}) \pm 8.1\,(\text{exp})\,^{+10.7}_{-11.2}\,(\text{theo}) \pm 2.2\,(\text{lumi})\ \text{pb}$$

TOP-16-003



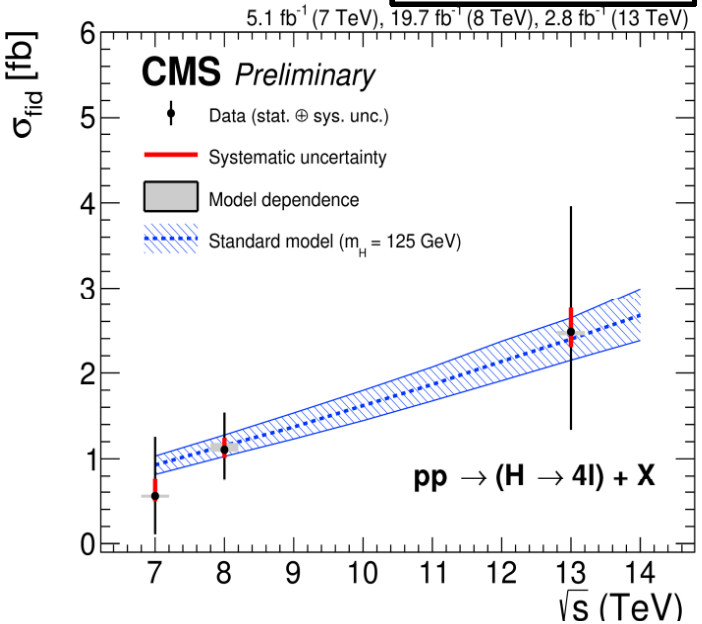
- **Within experimental uncertainty no significant deviation observed**

Higgs Physics

Standard Model Higgs measurements at 13 TeV

H→ ZZ*→4l

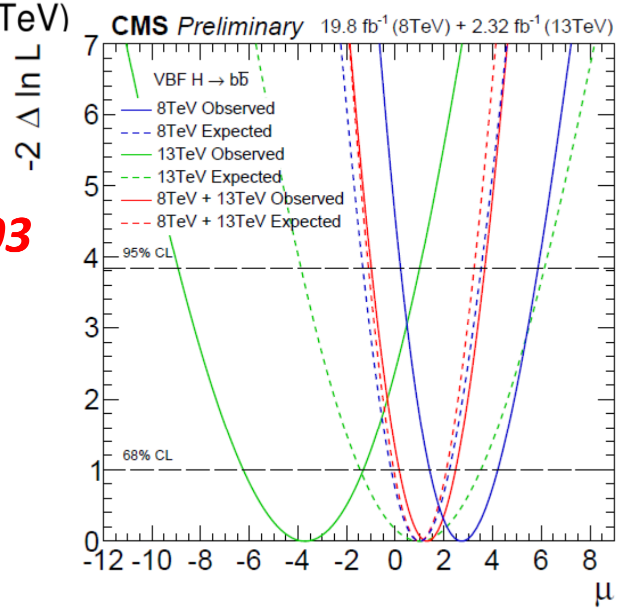
HIG-15-004

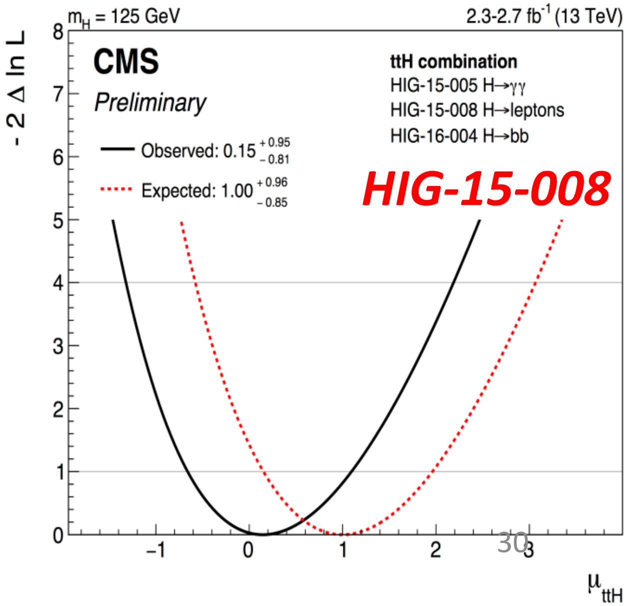


- **VBF H, H→bb, μ for combined 8 and 13 TeV = $1.3^{+1.2}_{-1.1}$**

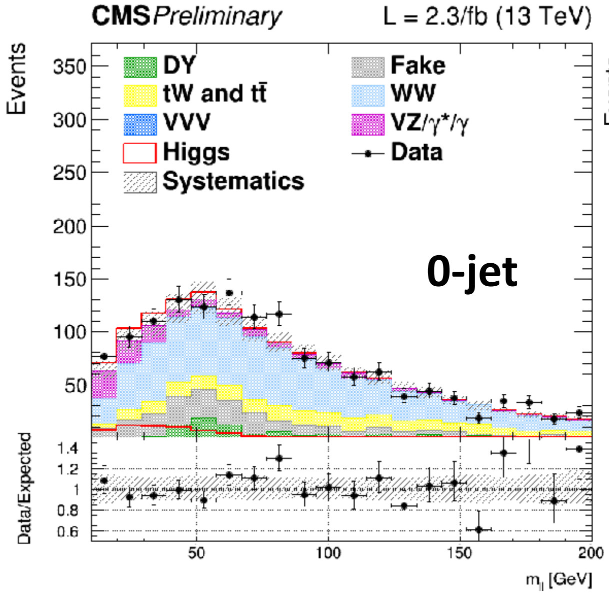
- **ttH , H→WW, ZZ, ττ**
  - **Explored same sign dilepton or 3 lepton (+b-tagged jets) final states**
  - **$\mu_{ttH} = 0.15^{+0.95}_{-0.81}$ Compare with SM expectation: $1.00^{+0.96}_{-0.85}$**

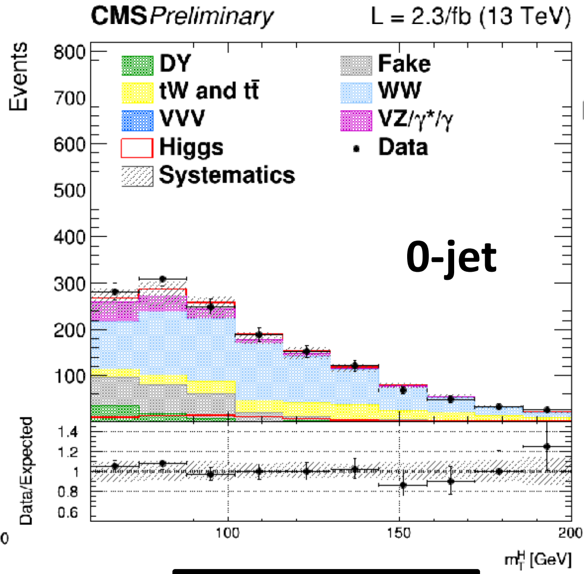
HIG-16-003

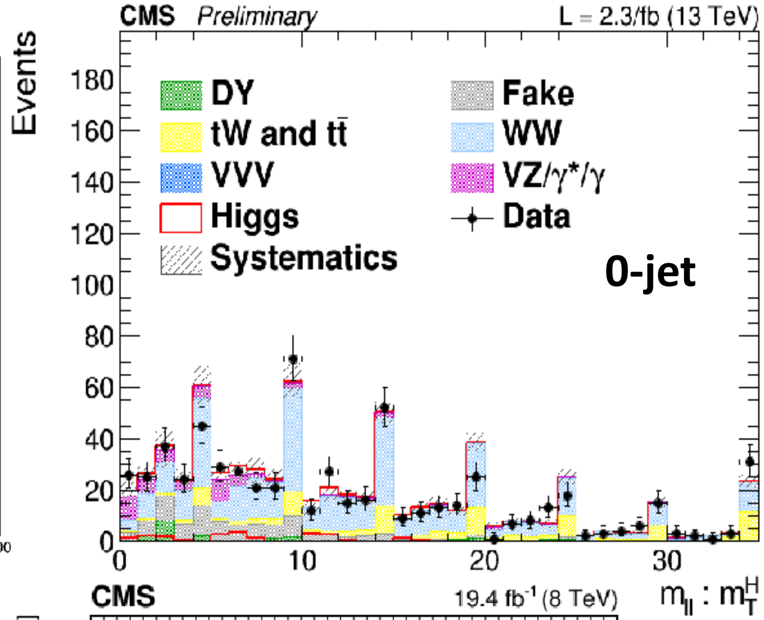




H→ WW (→e μ +X) at 13 TeV

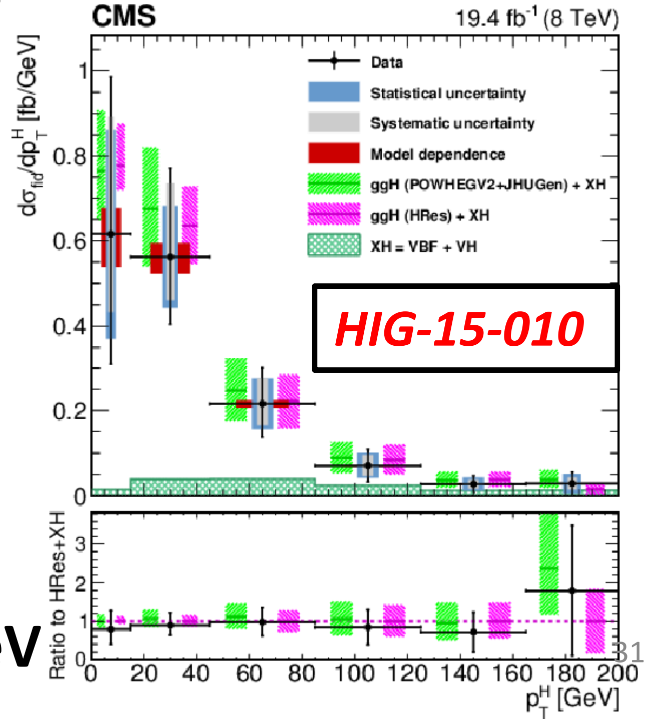






- Similar for 1-jet category **HIG-15-003**
- Bi-dimensional analysis in *m_{ll} (5 bins) m_T^H (10 bins)*

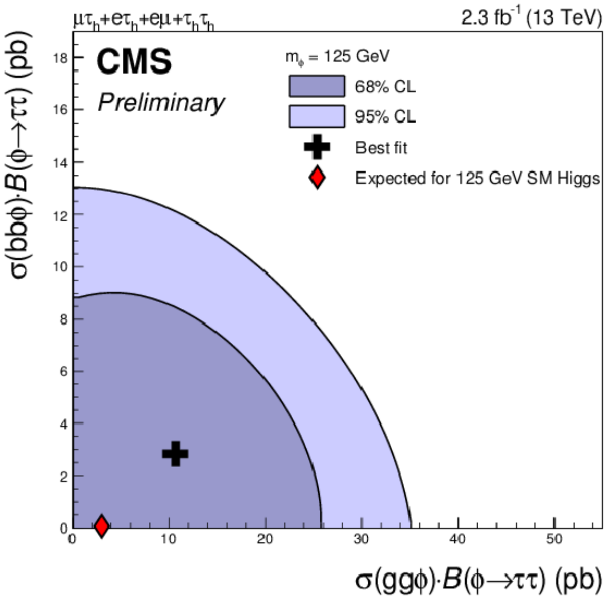
- **observed (expected) significance: 0.7 σ (2.0 σ)**
- **signal strength μ = 0.3 ±0.5**

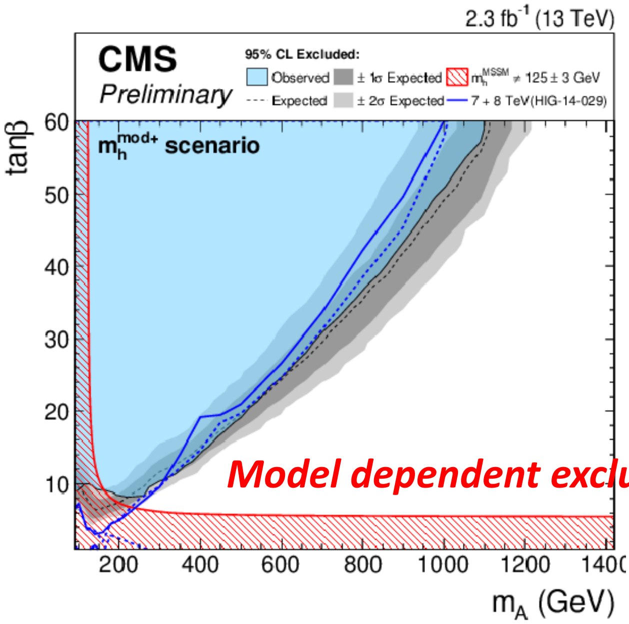


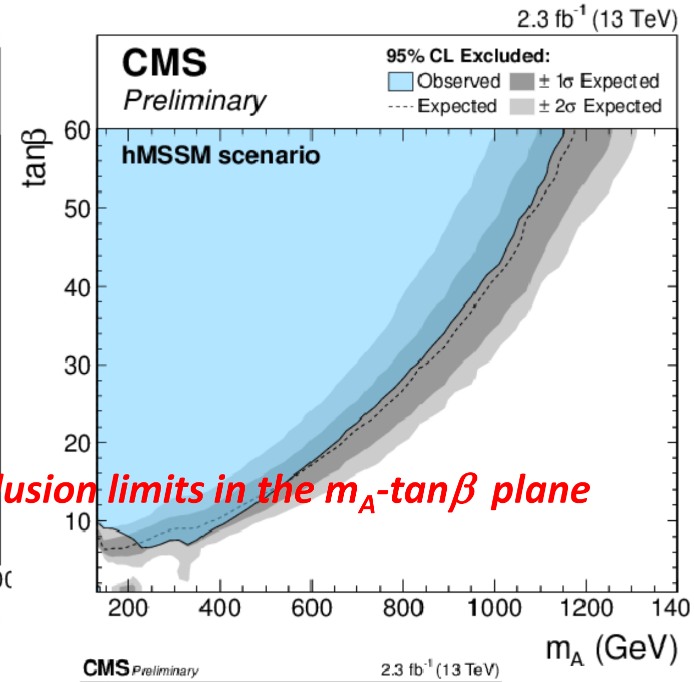
Transverse momentum of Higgs at √s =8 TeV

Search for beyond standard model physics

Searches for BSM Higgs at √s = 13 TeV







Model dependent exclusion limits in the m_A-$\tan\beta$ plane

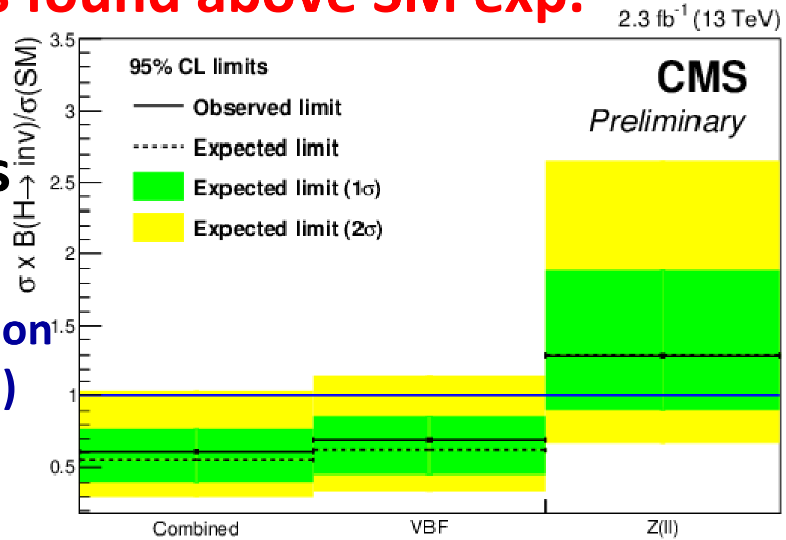
MSSM H→ ττ *HIG-16-006*

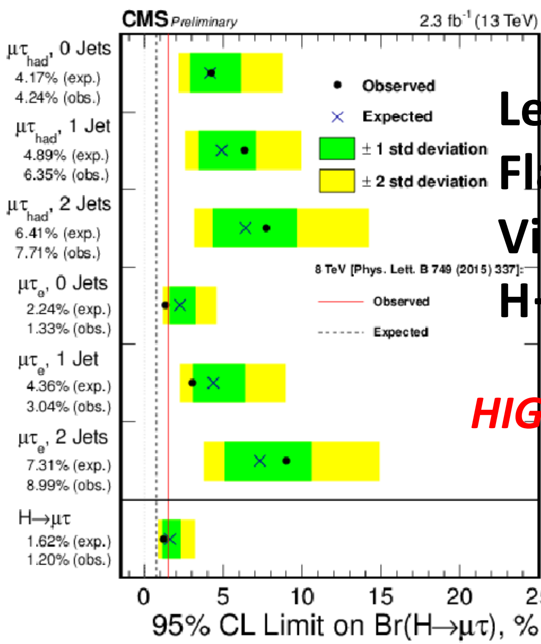
No excess is found above SM exp.

Invisible Higgs

HIG-16-009

8+13 TeV combination observed (expected) UL on Br(H→inv.)= 32% (26%)





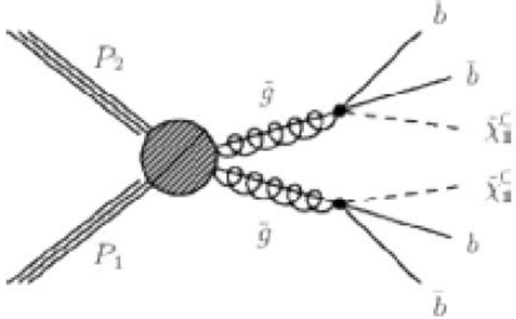
Lepton Flavour Violation H→ τμ

HIG-16-005

Search for Supersymmetry at √s = 13 TeV

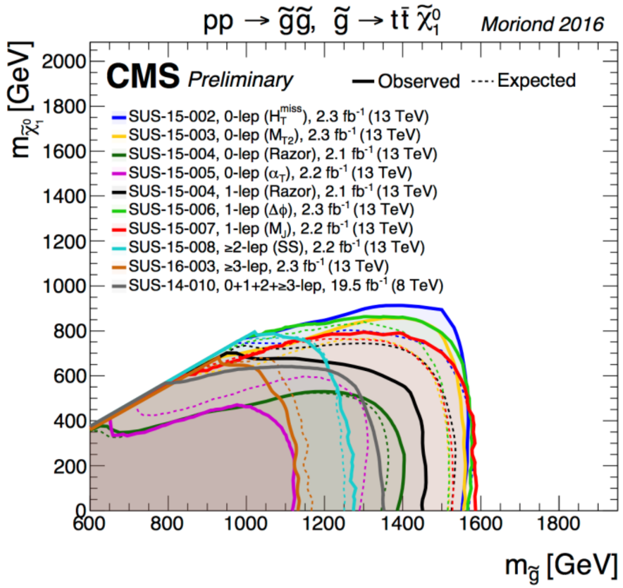
➢ **Many searches with jets, leptons , photons, missing energy in final state**

- **Sensitivity for both strong and weak production of SUSY particles.**
- **Interpretation of final states in terms of simplified models, eg. T1bbbb**

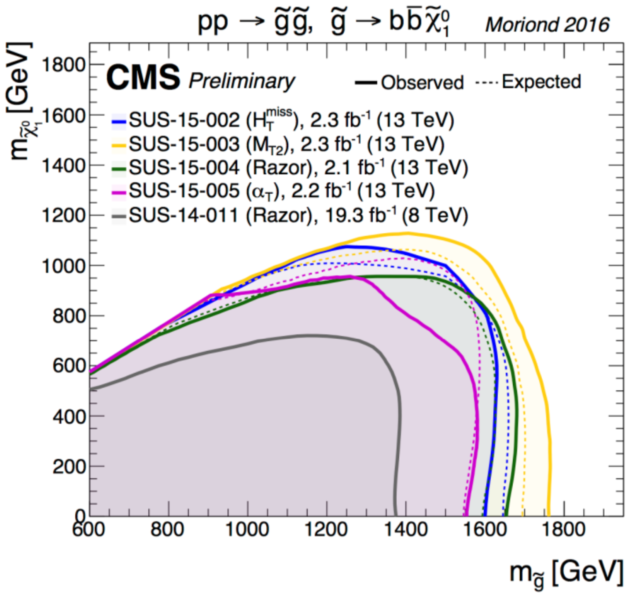


Gluino searches   SUS-15-002, PLB 758(2016) 152

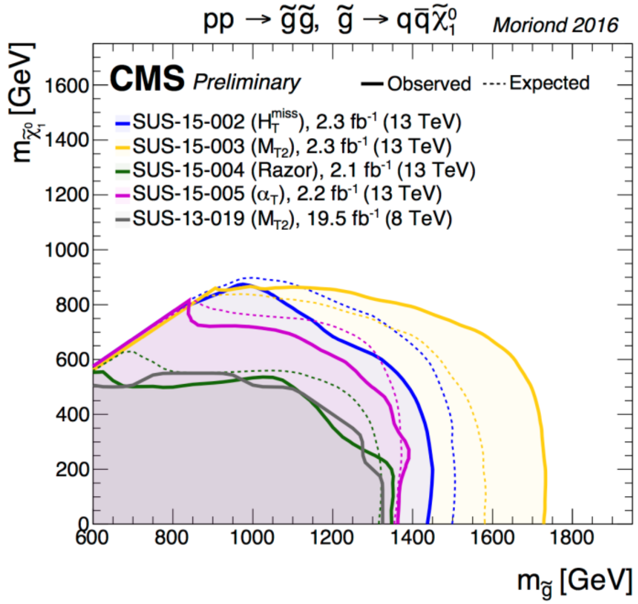
Gluino pair to 4 tops



Gluino pair to 4 bottoms



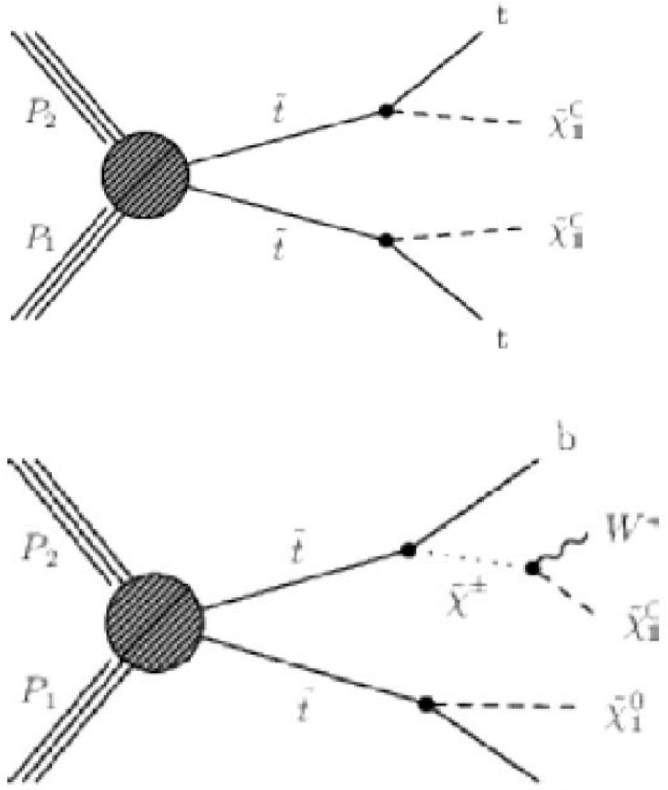
Gluino pair to light quarks

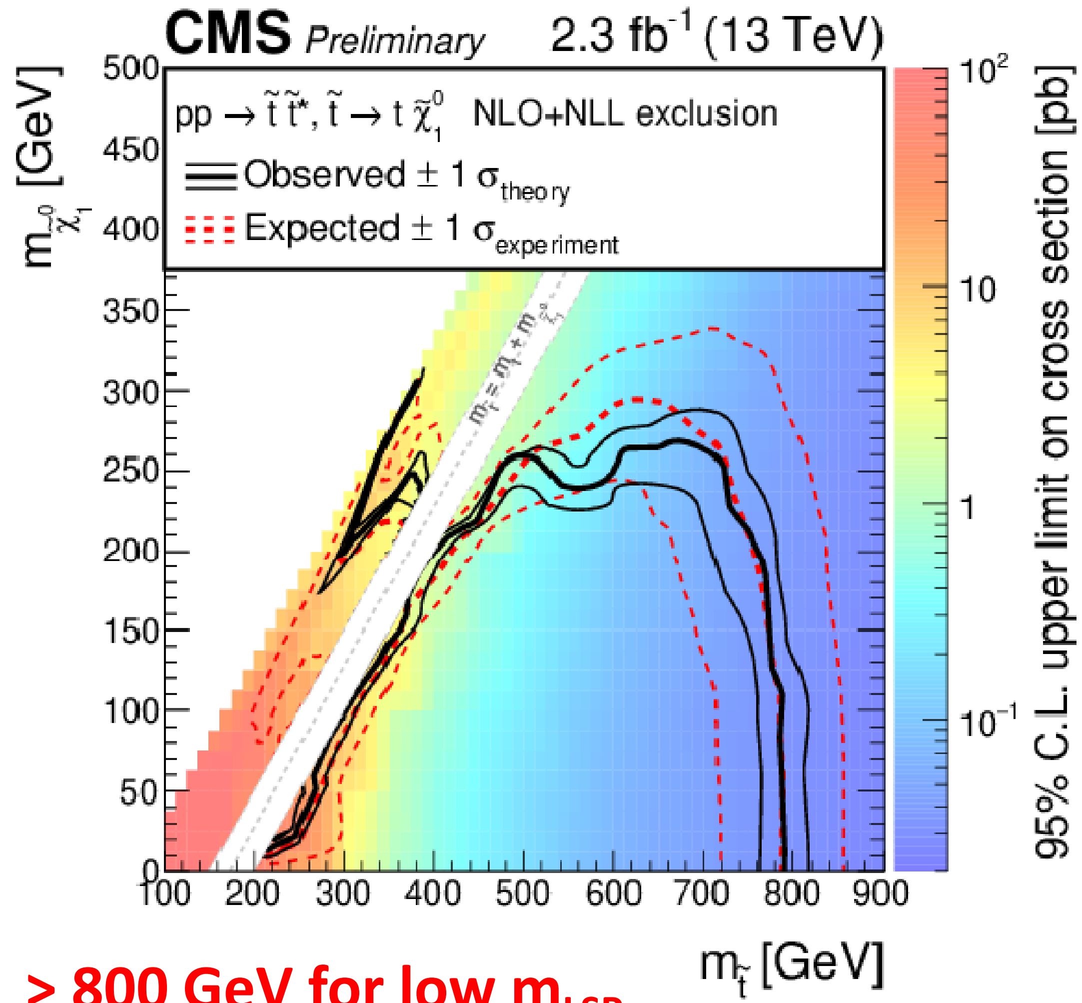


Direct production of stop pairs

➢ **Searches in hadronic final state**

SUS-16-007





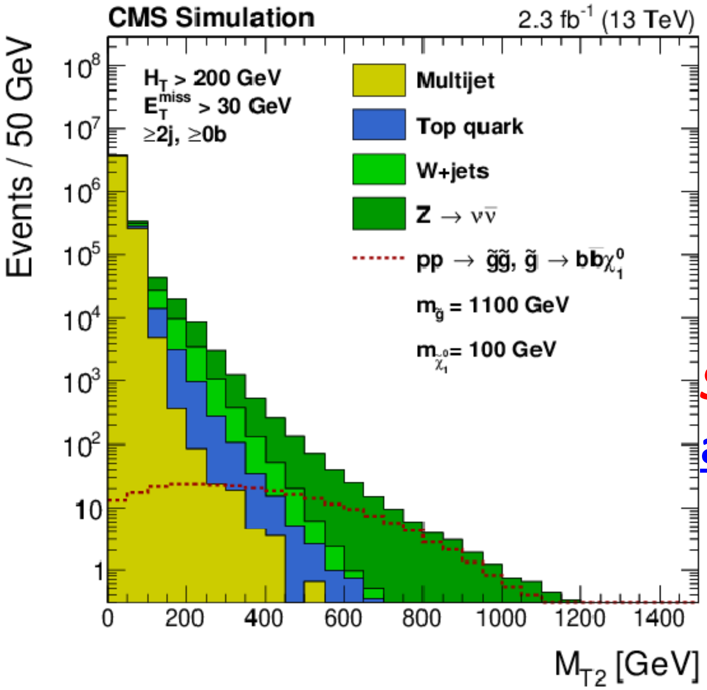
m_{stop} > 800 GeV for low m_{LSP}

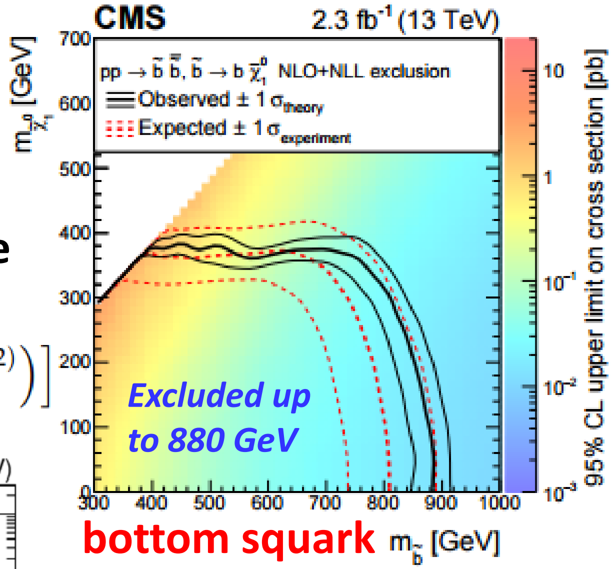
Search in multi-jet + missing E_T final state

use kinematic variables with categorization

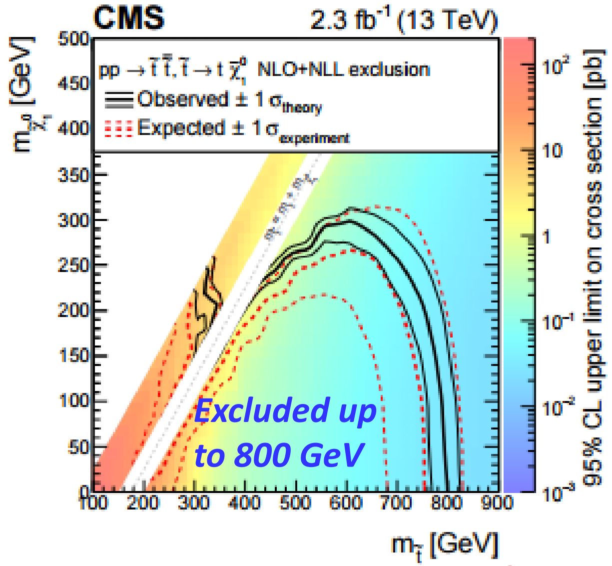
An extension of the transverse mass in events with two invisible particles

$$M_{T2} = \min_{\vec{p}_T^{\,\mathrm{miss}X(1)} + \vec{p}_T^{\,\mathrm{miss}X(2)} = \vec{p}_T^{\,\mathrm{miss}}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$$





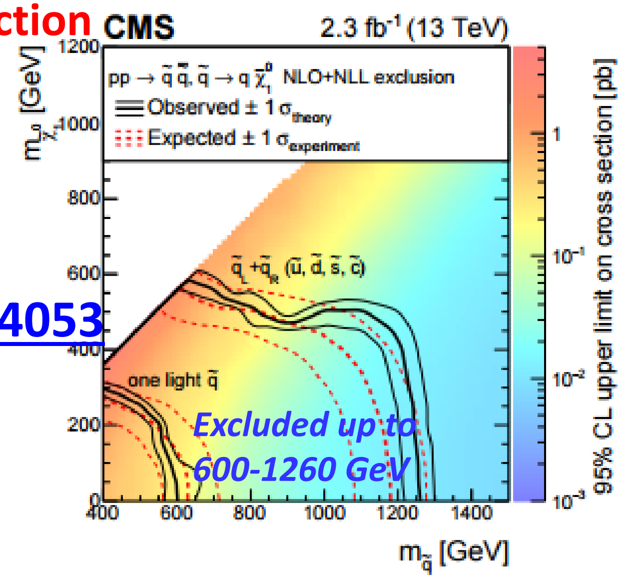
bottom squark pair production



top squark pair production

SUS-15-003

[arXiv:1603.04053]



light-flavor squark pair production

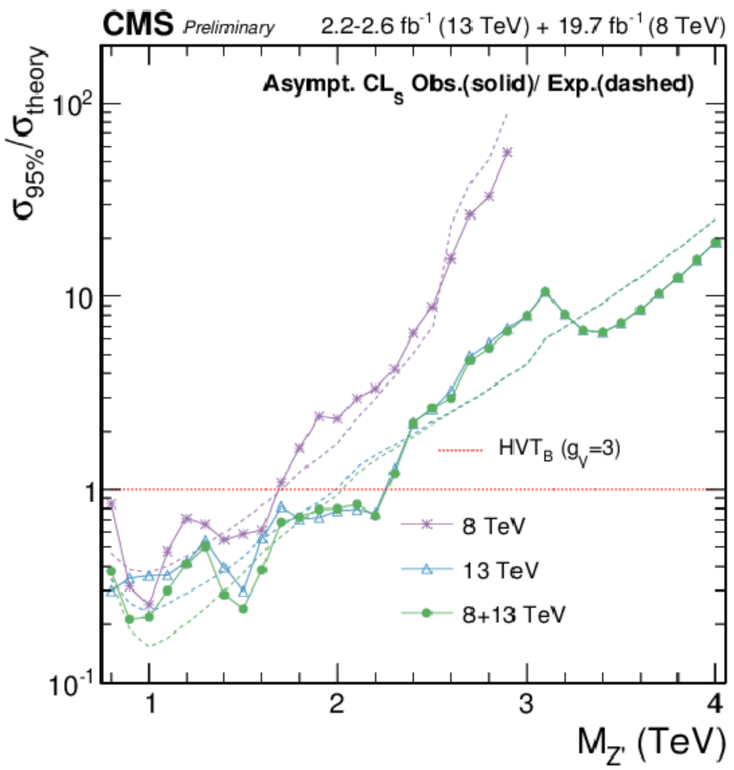
Combination of diboson (WW/WZ/ZZ/WH/ZH) productions

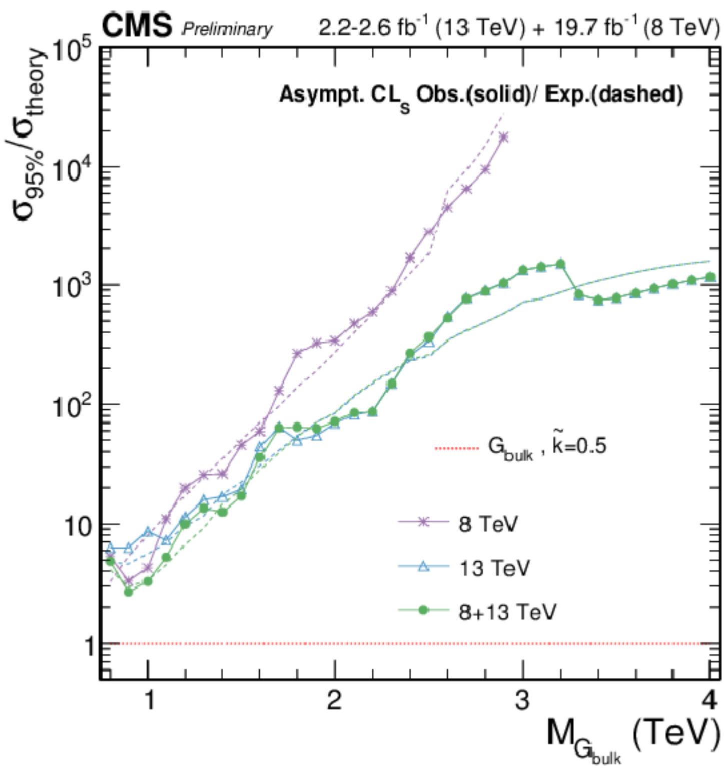
B2G-16-007

➢ Exotica searches

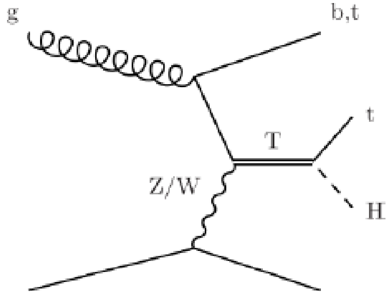
- Heavy Vector Singlet/Triplet model: **W' → WZ, WH** or **Z' → WW, ZH**
  exclusion: W' > 2.3 TeV, Z' > 1.8 TeV, triplet > 2.4 TeV
- A narrow **Bulk Graviton → WW, ZZ** : **0.9σ significance for W' (1.9-2 TeV)**

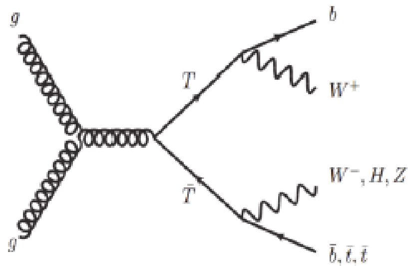
➢ Run 1 had anomaly (slight excess around 2 TeV) at the level of 2 to 2.5 σ , not confirmed at Run 2.

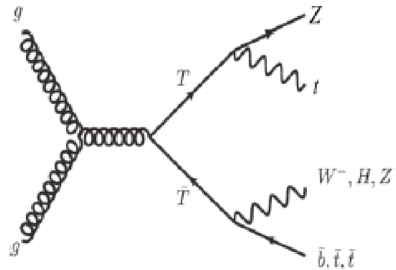


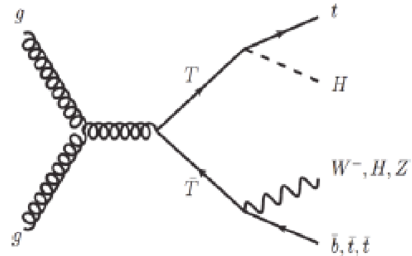


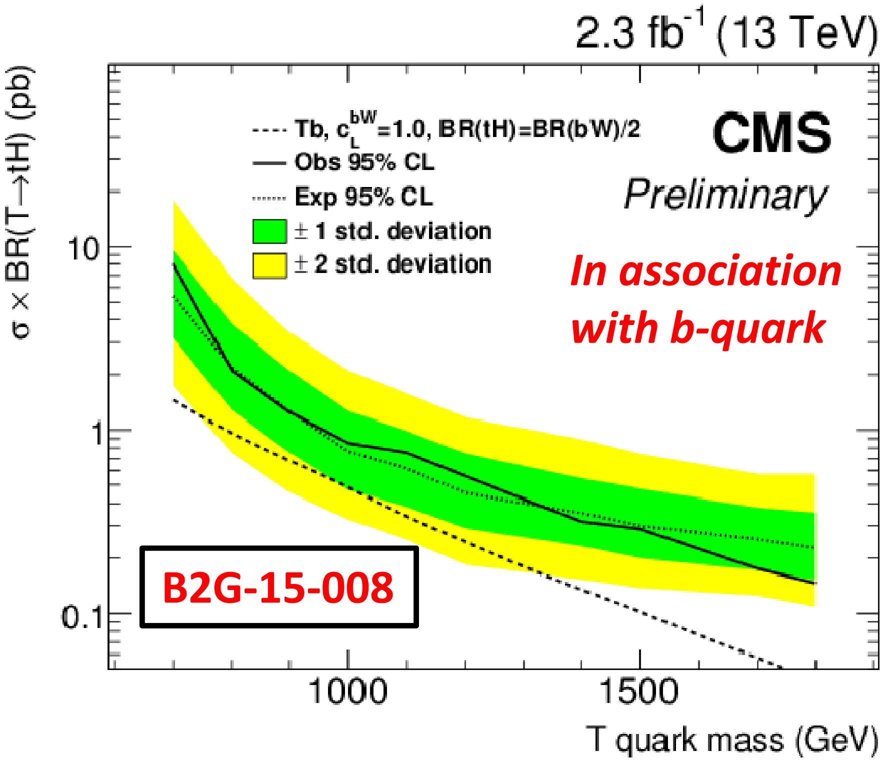
Search for massive vector-like quark (charge 2/3) production

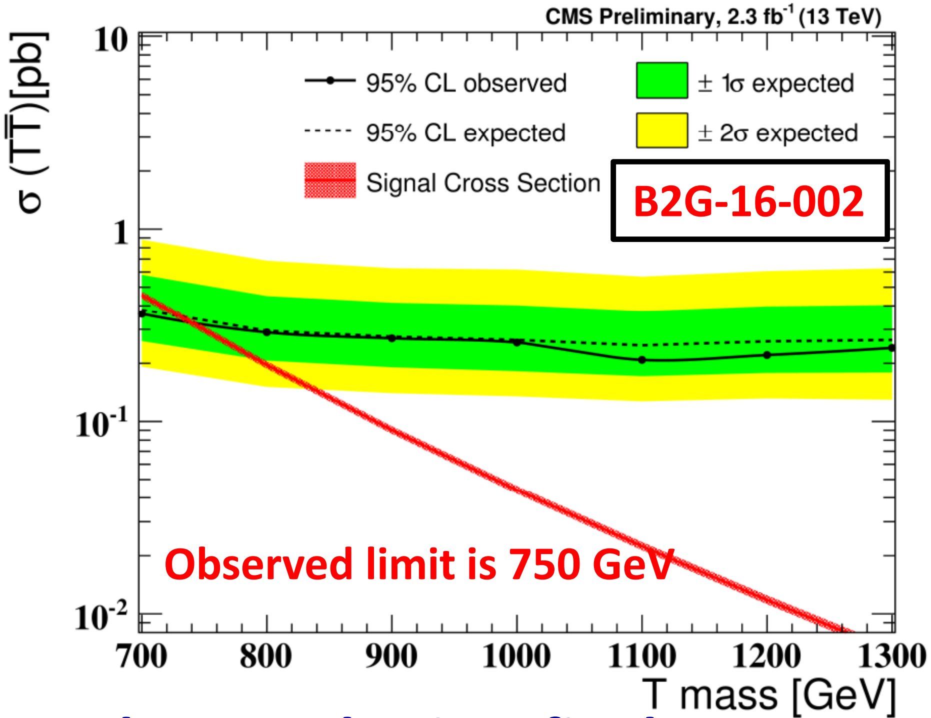






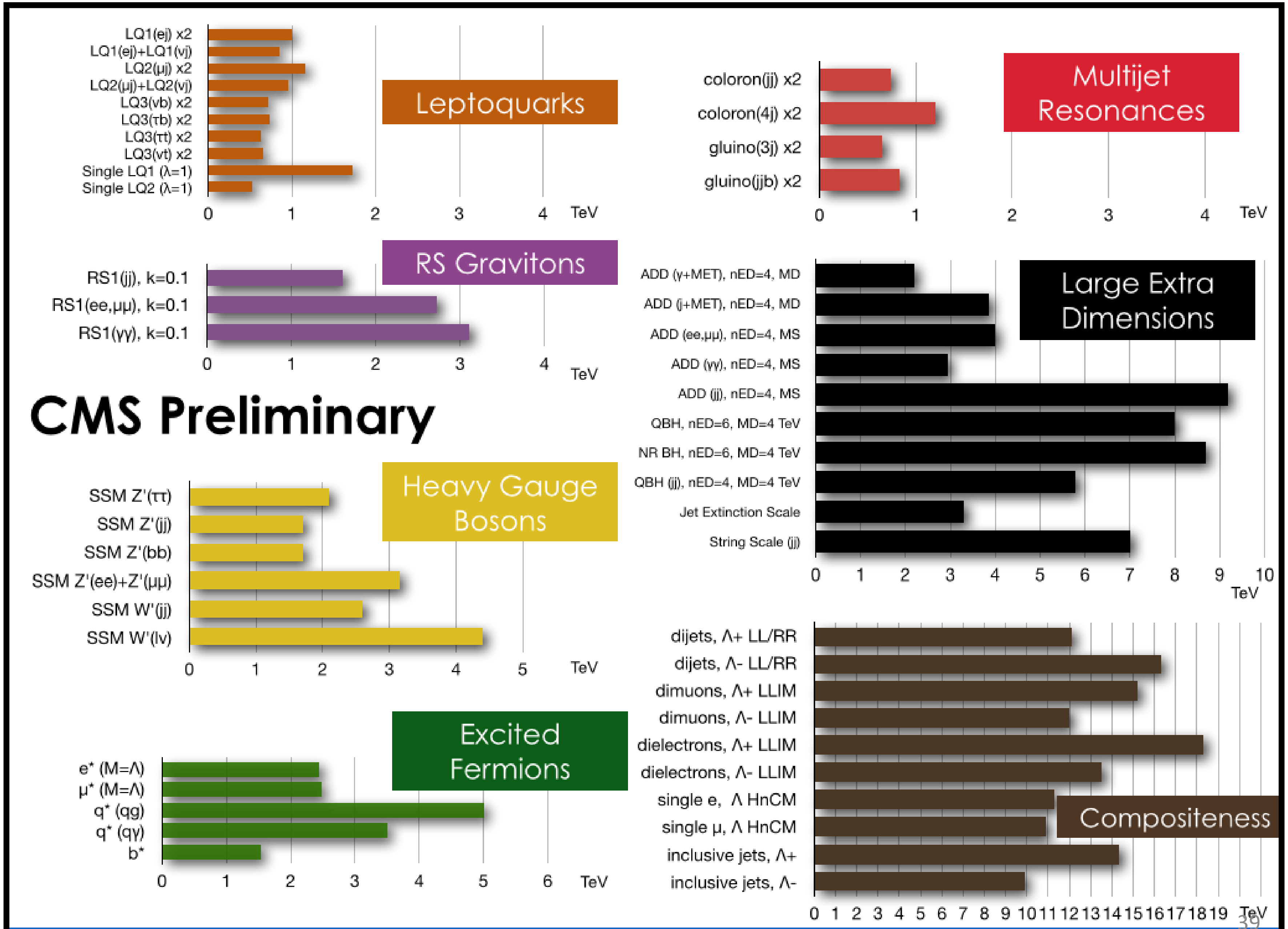




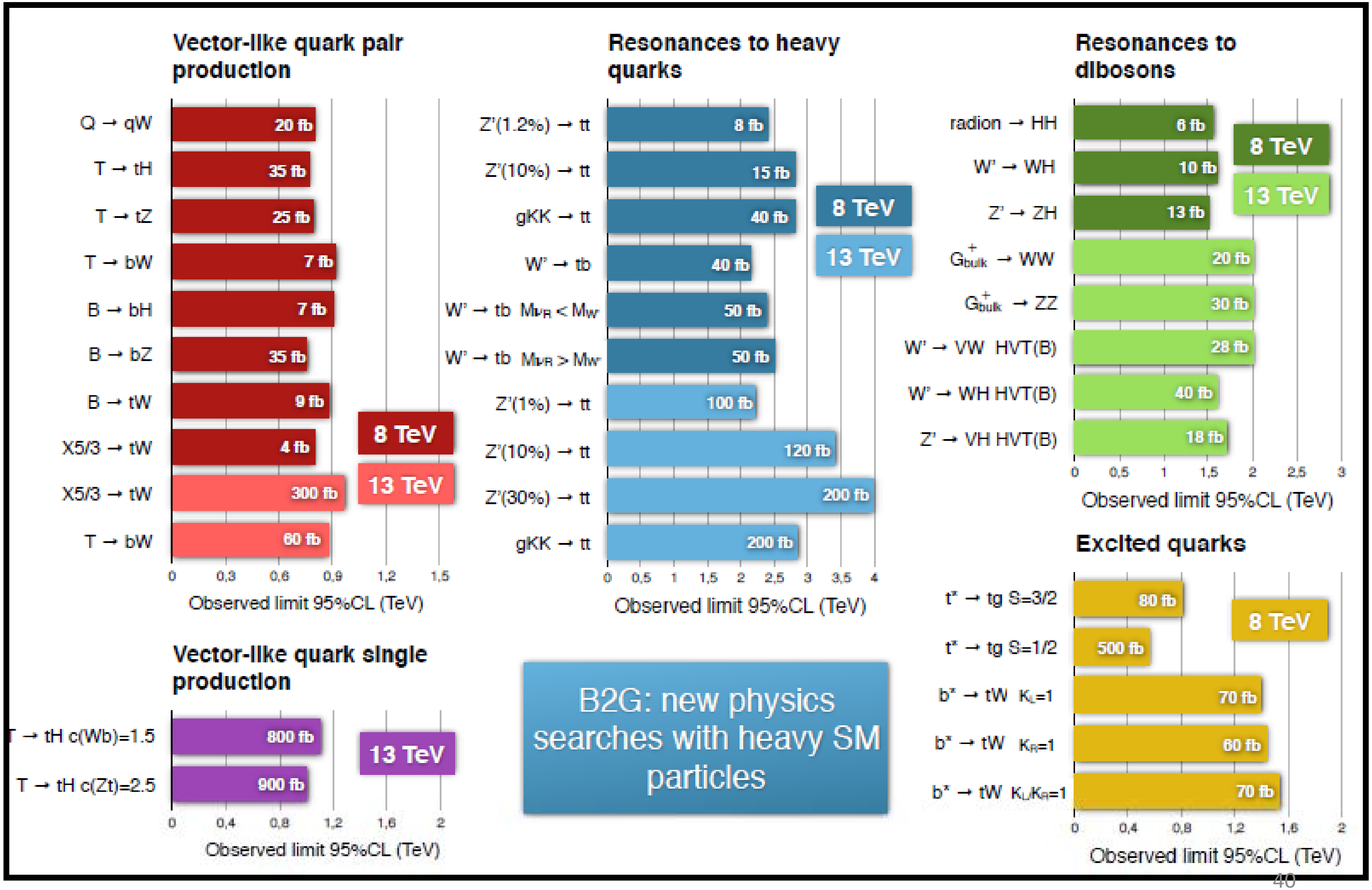


lepton plus jets final state

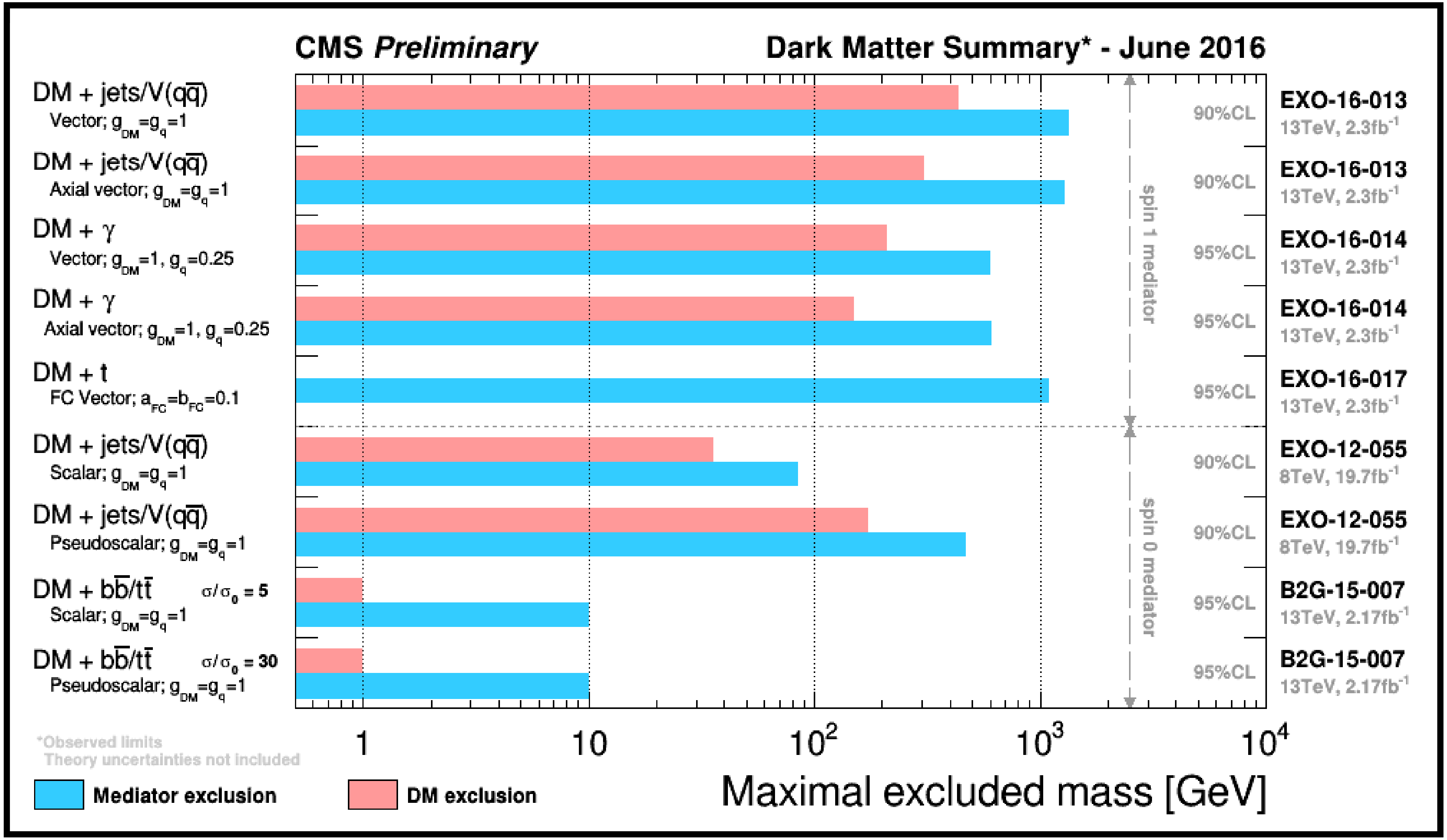
Exotica searches: June 2016



Summary of searches for beyond 2nd generation

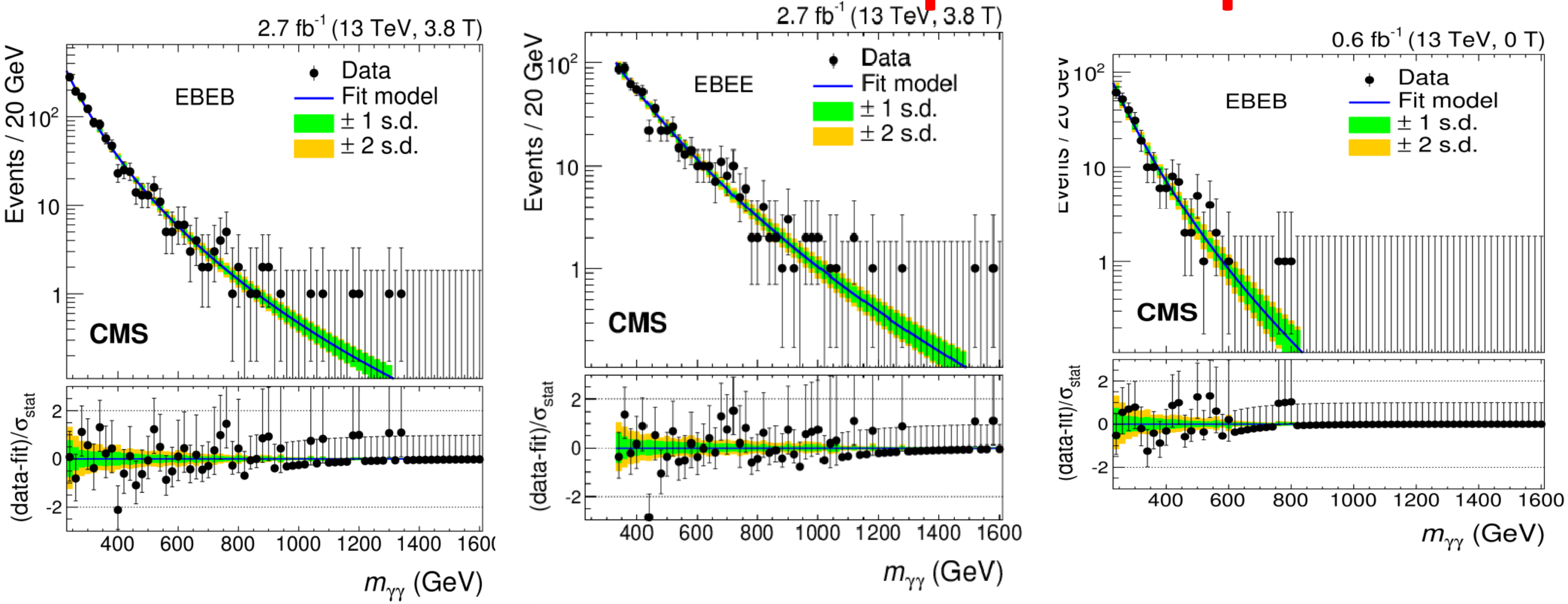


Dark Matter searches, June 2016



Search for high mass resonances

Resonance structure in Diphoton spectrum

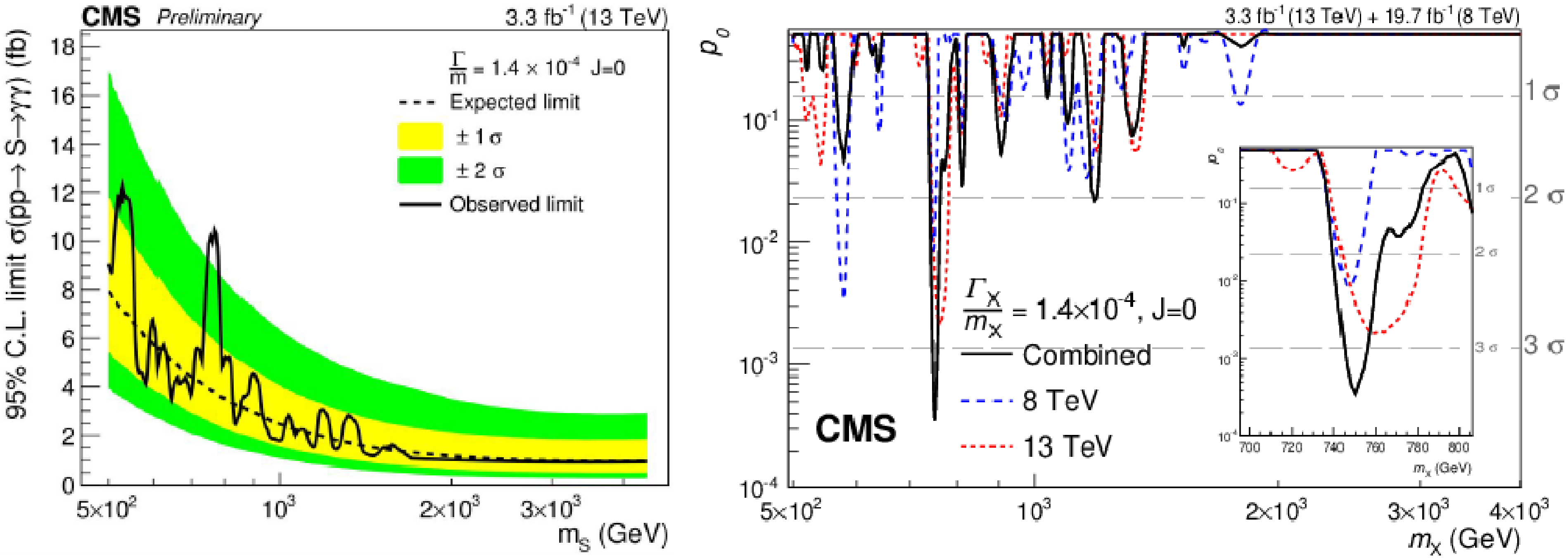


- Total 2015 data analysed: 3.3 fb^{-1} (B=3.8T, 0T)
- Consistent with 8 TeV data: 19.7 fb^{-1}
- Local significance = 3.4σ,
- Global significance (accounts for mass range, spin, width) = 1.6 σ

EXO-16-018

- Search for spin 0, spin-2 resonance,
- Γ/m between 1.4*10^{-4} to 5.6*10^{-2}

Limits

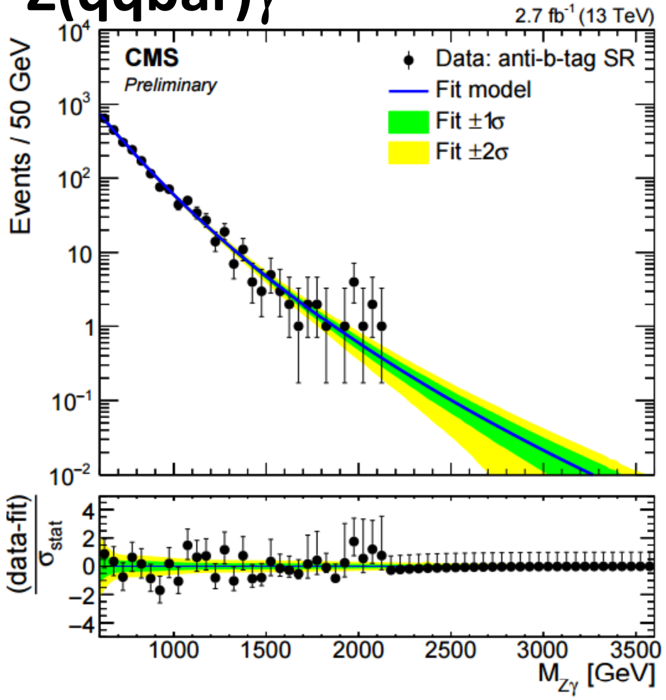


- Set limits assuming gg fusion, RS-graviton (spin 2)
- Excess at 750 GeV, for Γ_X / m_X =1.4*10^{-4}

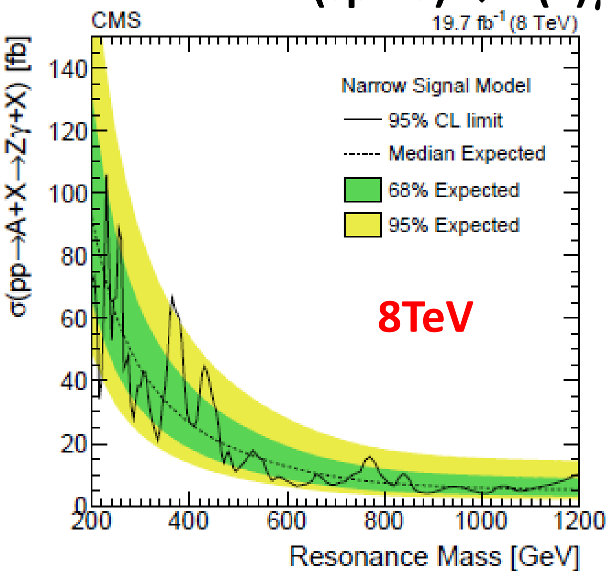
- More data required to confirm existence of resonance.
- 2016 data highly crucial: in August (ICHEP) update with ~10 fb^{-1}

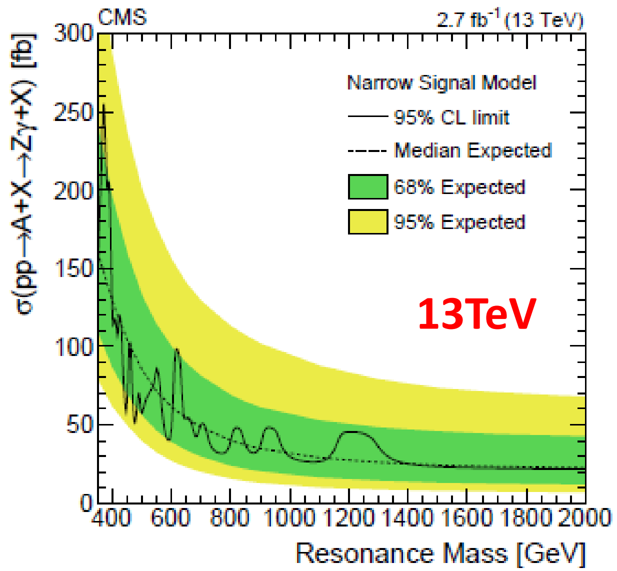
Results from some of the related searches

Z(qqbar)γ *EXO-16-020*



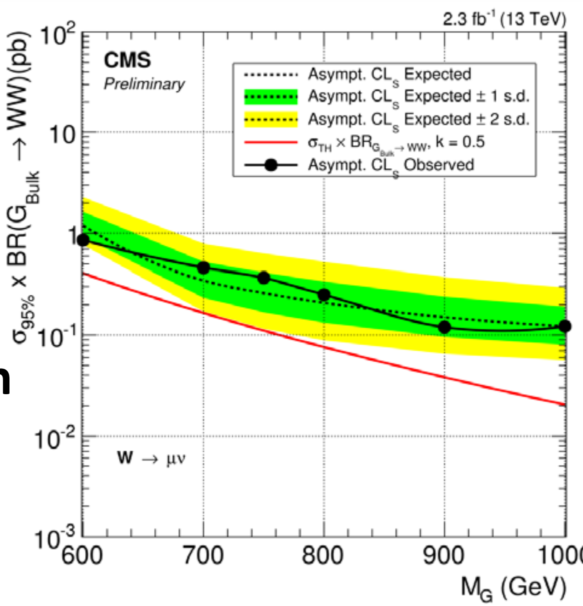
A (spin0) → Z(ll)γ *EXO-16-021*



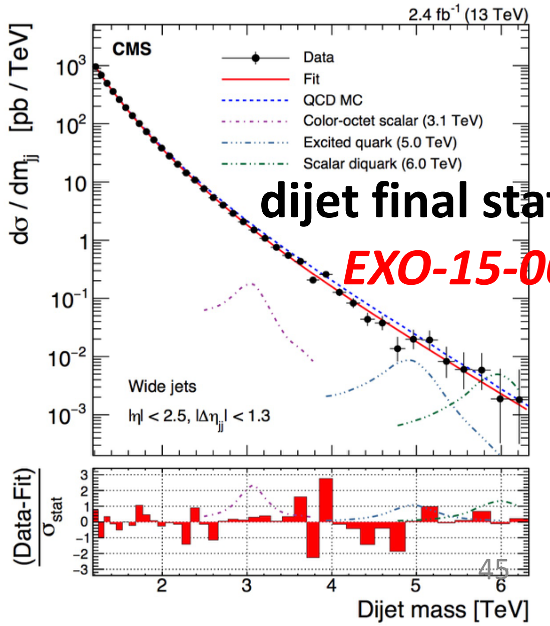


No obvious excess is found

High mass search in WW→ lvqq
B2G-16-004



dijet final state
EXO-15-001



Summary

- CMS experiment is performing well in Run 2.

- Precision results using Run 1 data are crucial for better understanding of LHC physics.

- Energy barrier for probing TeV scale physics is overcome exciting times ahead!

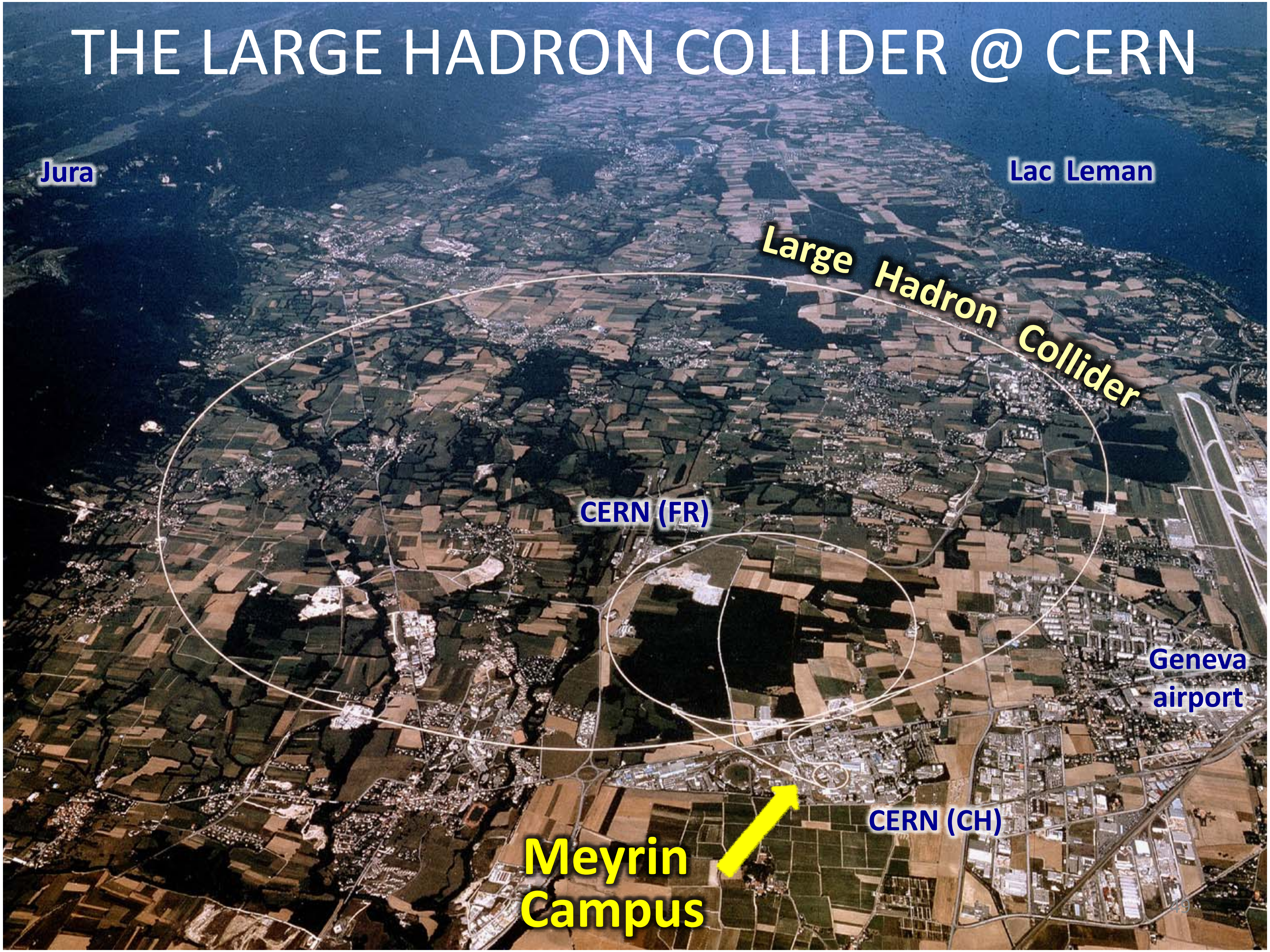
- **Data collected in 2016 is crucial to settle the issue of 750 GeV resonance.**

- ***Stay tuned*** **…. ICHEP2016 !**

Thanks for your attention!

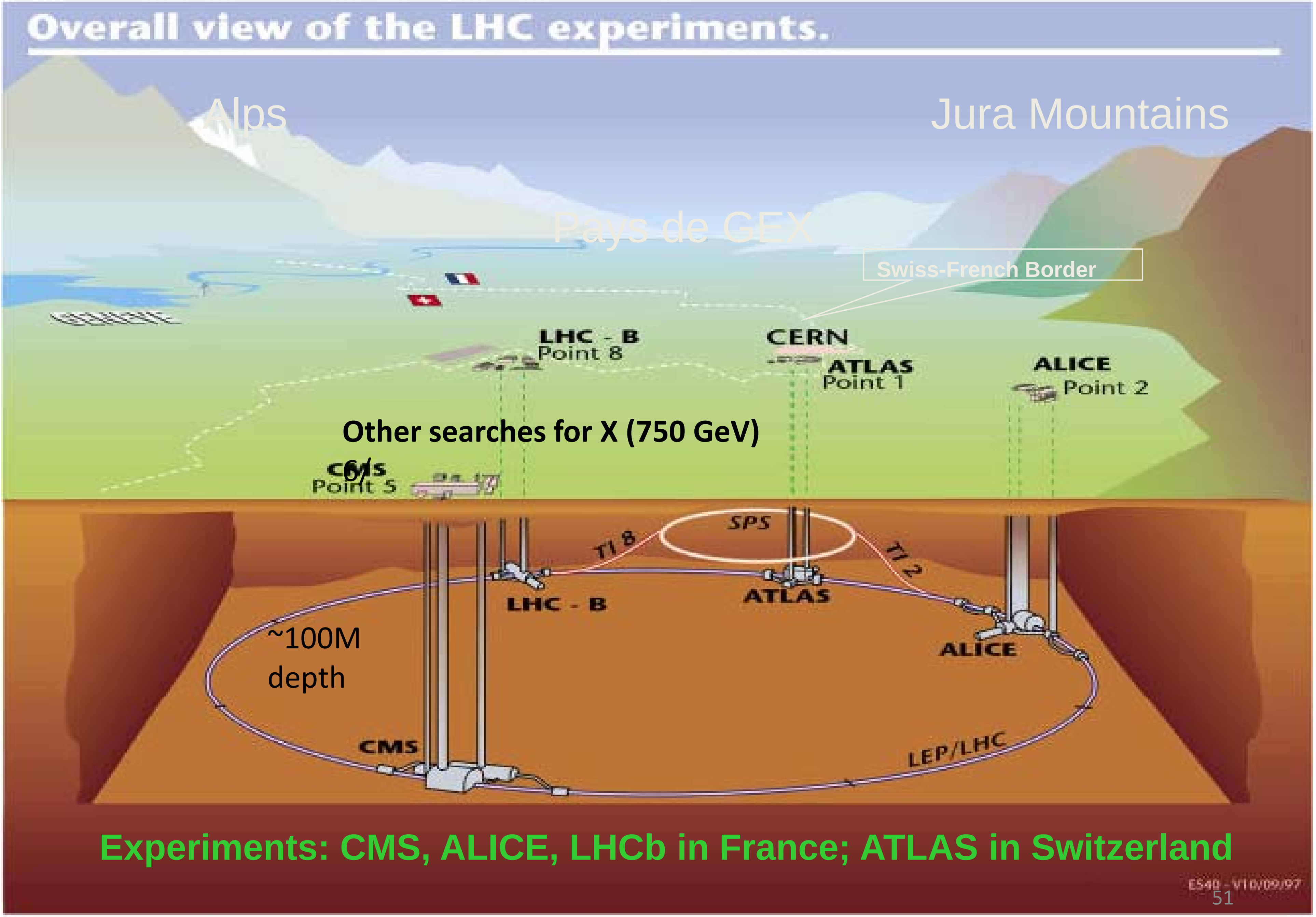
Many thanks to 4400+ CMS members
and **to the LHC Team *!***

EXTRA


THE LARGE HADRON COLLIDER @ CERN
Jura
Lac Leman
Large Hadron Collider
CERN (FR)
Geneva
airport
CERN (CH)
Meyrin
Campus

THE LARGE HADRON COLLIDER @ CERN

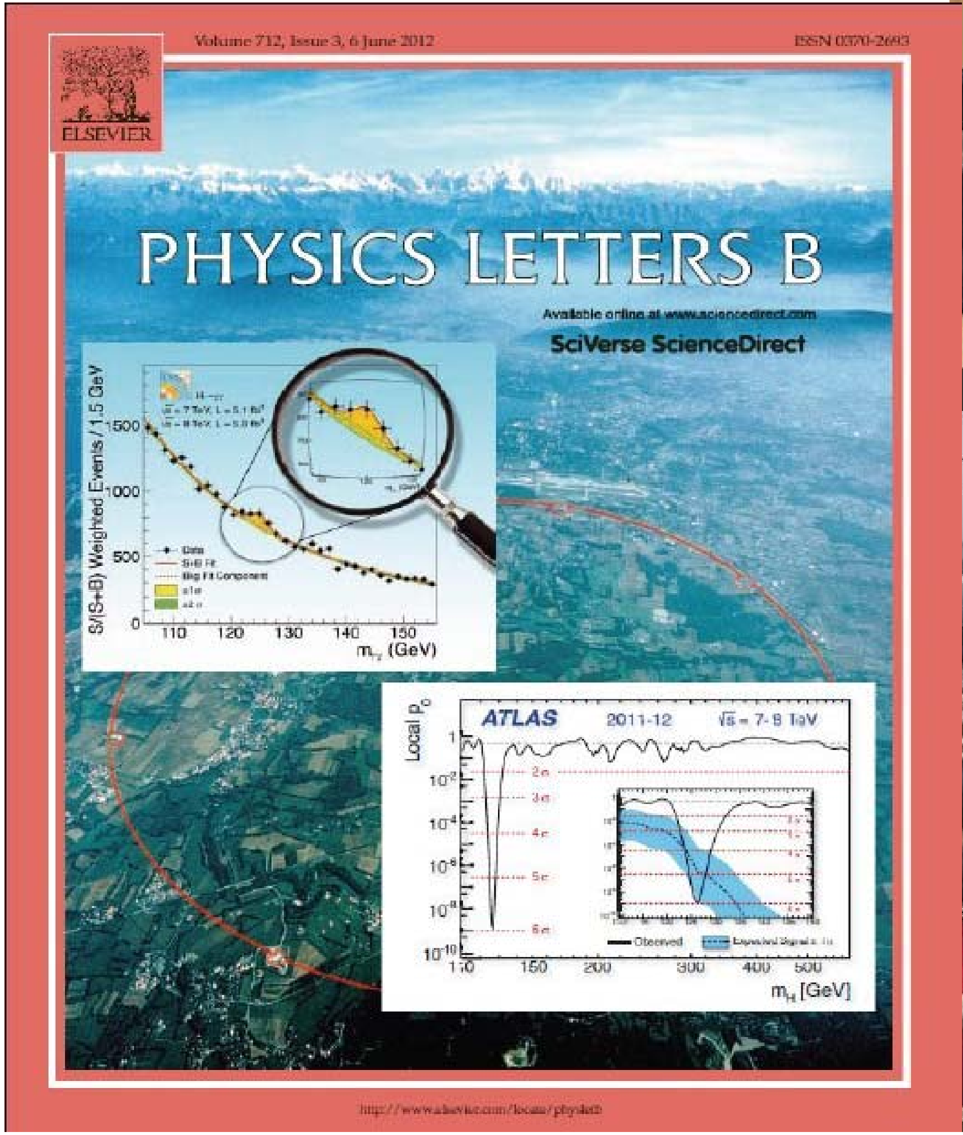
- 27 km (17 miles) circumference
- 1600 superconducting magnets at 1.9° K (-271.3 ℃ or – 459.7 ℉)
- 120 tonnes of liquid helium
- Accelerates beams of protons to 99.9999991% the speed of light


Overall view of the LHC experiments.
Alps
Jura Mountains
Pays de GEX
Swiss-French Border
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
Other searches for X (750 GeV)
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
~100M
depth
CMS
LEP/LHC
Experiments: CMS, ALICE, LHCb in France; ATLAS in Switzerland
ES40 - V10/09/97

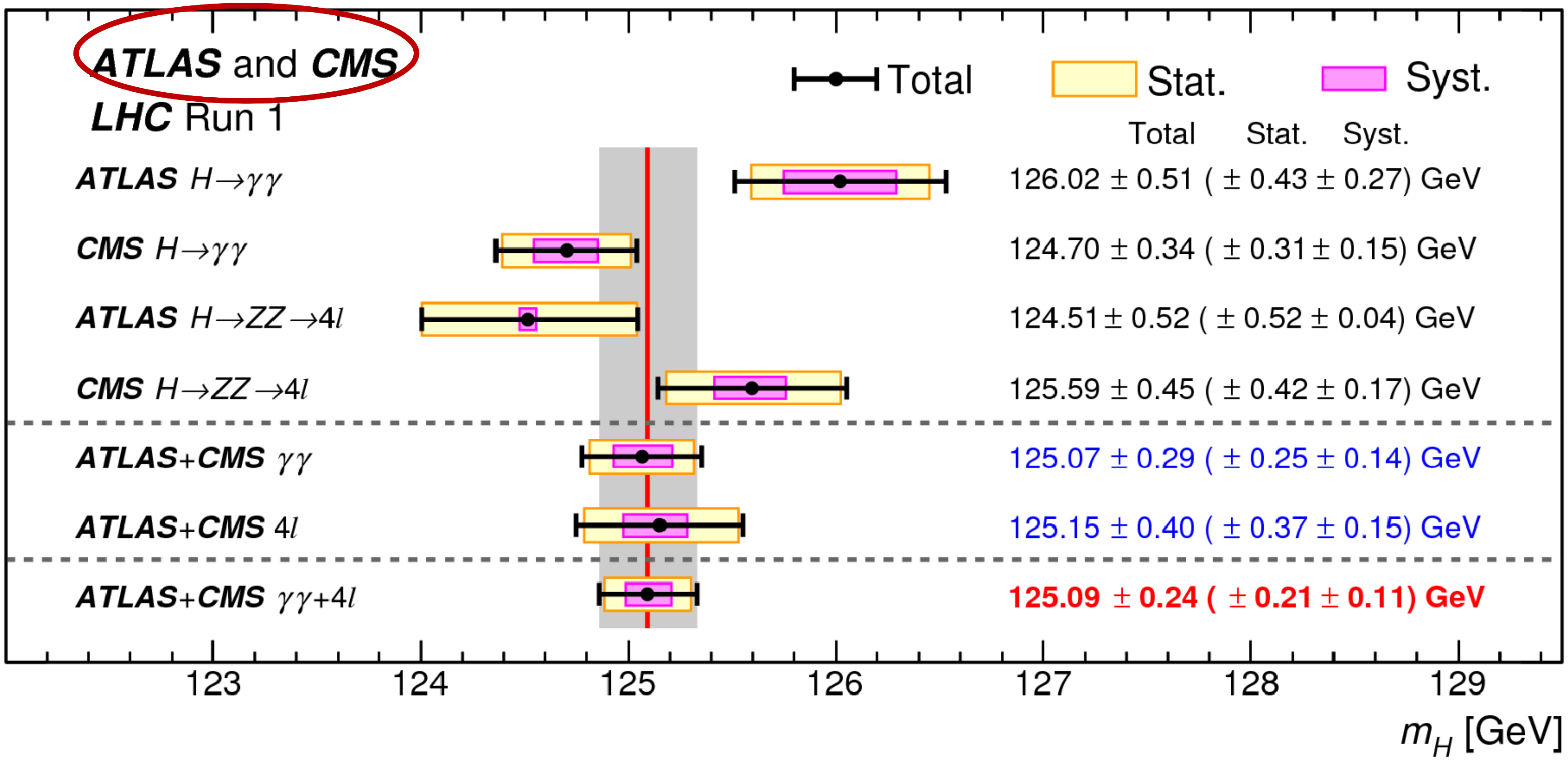
Higgs-Boson discovery

Great achievement to a four decade long quest

A Higgs-like state pinned down at 125 GeV mass



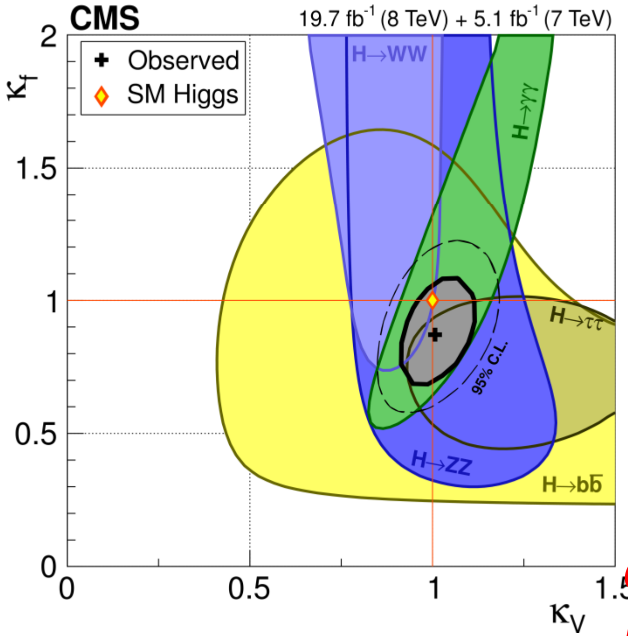
Higgs-Boson mass

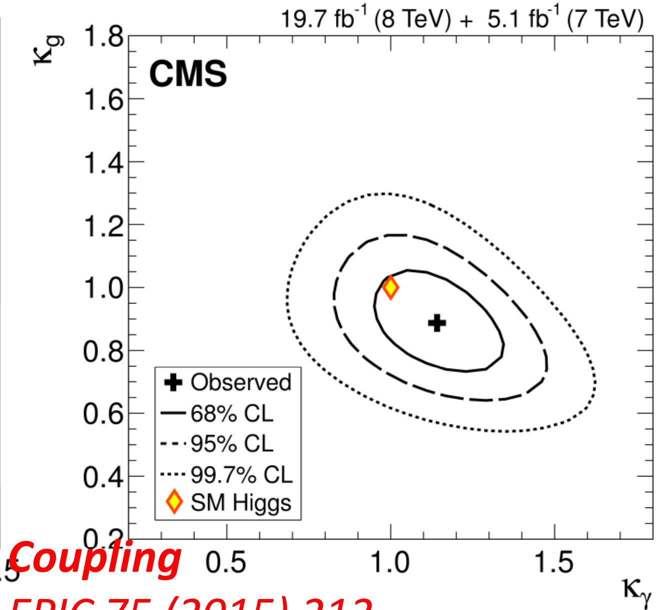


0.2% precission !

Phys. Rev. Letter 114, 191803(2015)

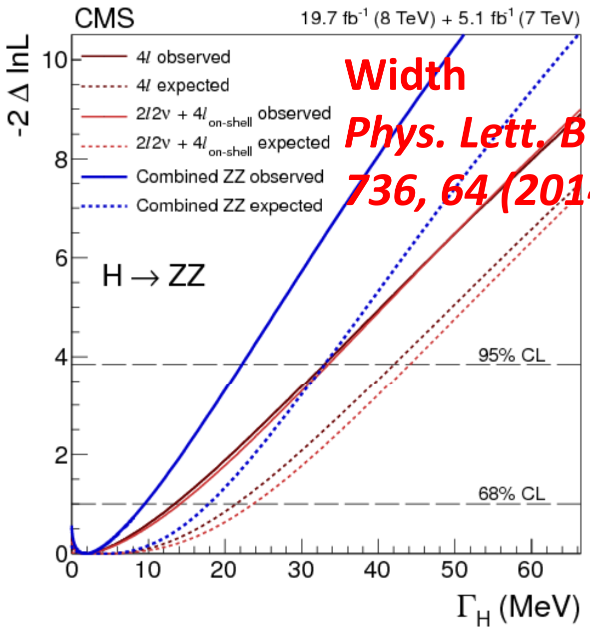
Higgs properties





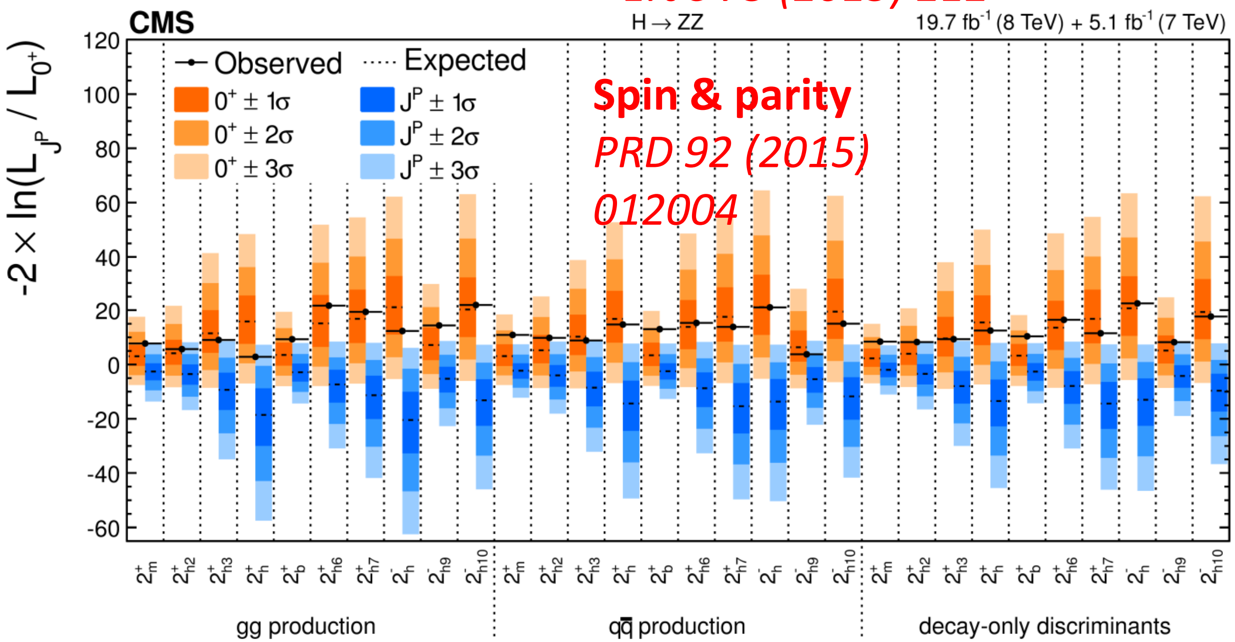
Coupling

EPJC 75 (2015) 212



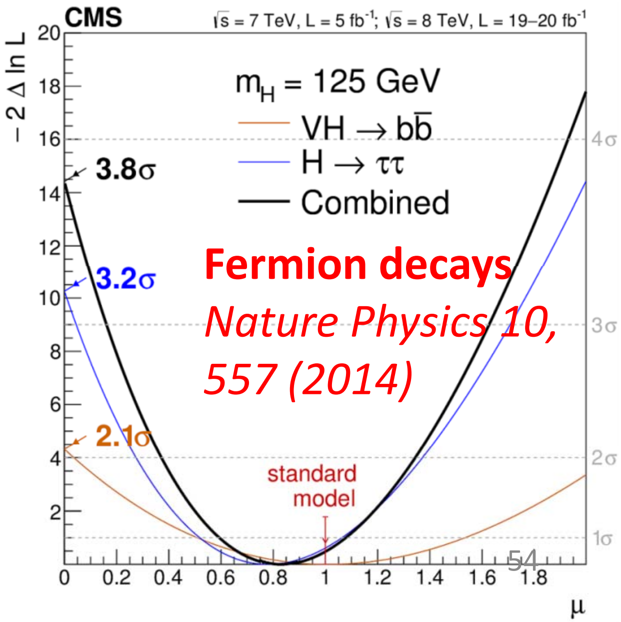
Width

Phys. Lett. B 736, 64 (2014)



Spin & parity

PRD 92 (2015) 012004



Fermion decays

Nature Physics 10, 557 (2014)

Higgs story so far

- We know it exists! Phys. Lett. B 716 (2012) 30
- We know its a **boson**.

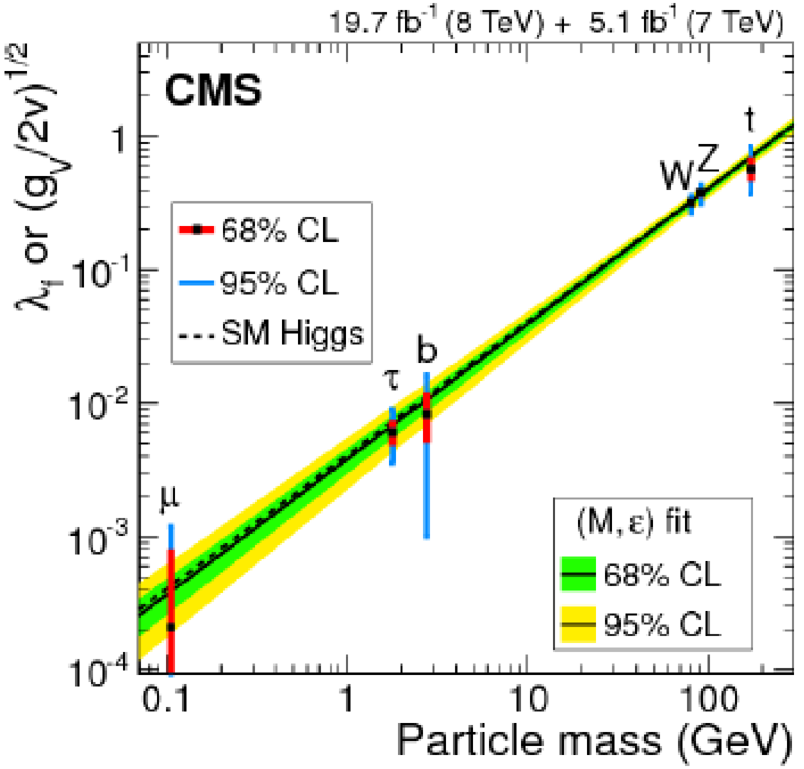
- We know its **mass** : CMS PAS HIG-14-009

$$m_H(\text{CMS}) = 125.03 \; ^{+0.26}_{-0.27} \; (\text{stat}) \; ^{+0.13}_{-0.15} (\text{syst})$$

- We have strong evidence that it **couples to fermions** Nat. Phys. 10 (2014) 557
  Couplings are determined within 15 to 20% accuracy, leaving room for **BSM physics**

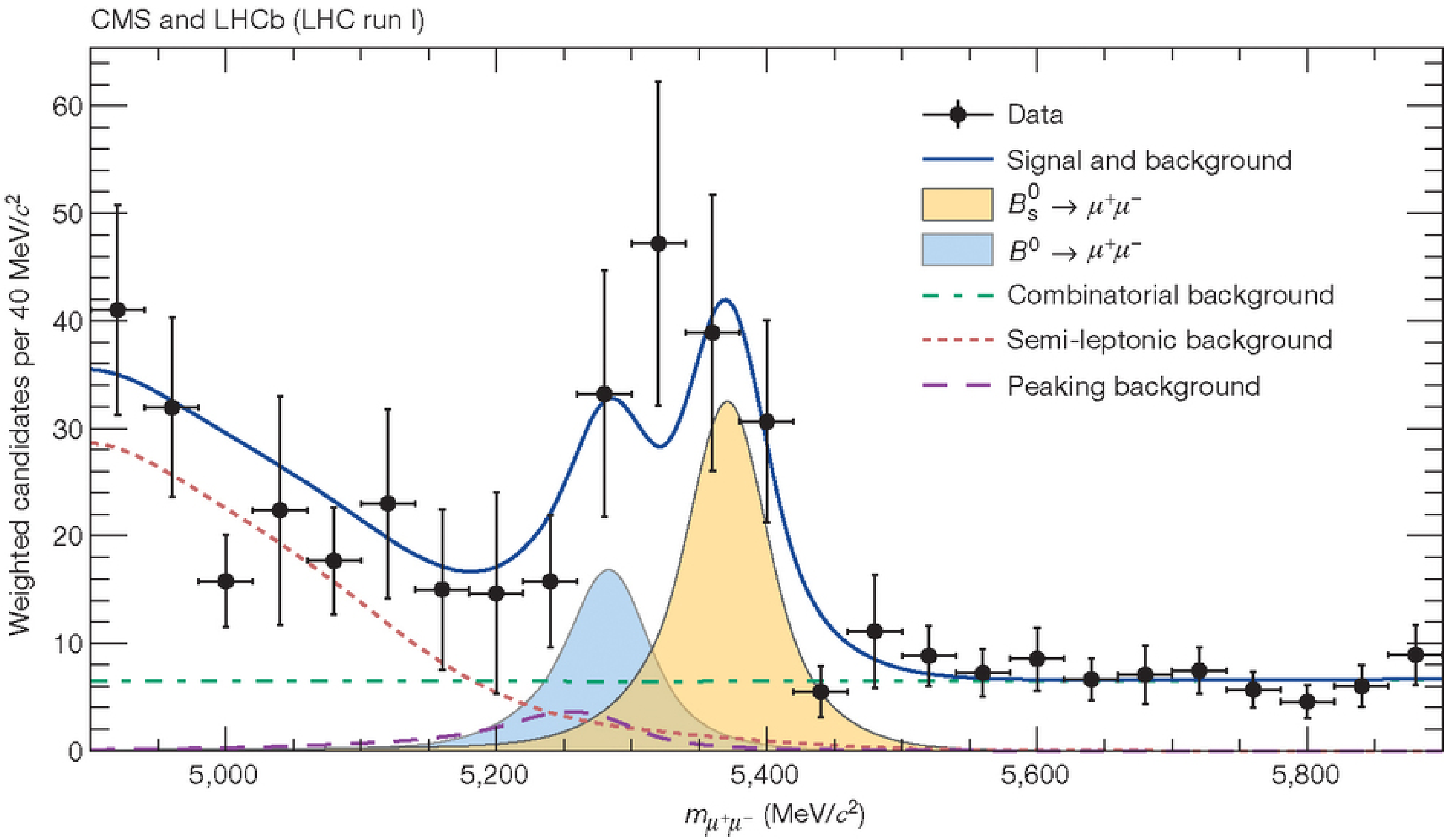
- We have reasons to believe that it is a **spin 0 CP even** object
  Phys. Rev. D 89 (2014) 092007

- We know it's a **Higgs boson**!



Is this **THE Higgs** boson (of the SM) or is it just **A Higgs** boson?

First observation: $B_s^0 \rightarrow \mu^+\mu^-$ (CMS & LHCb)

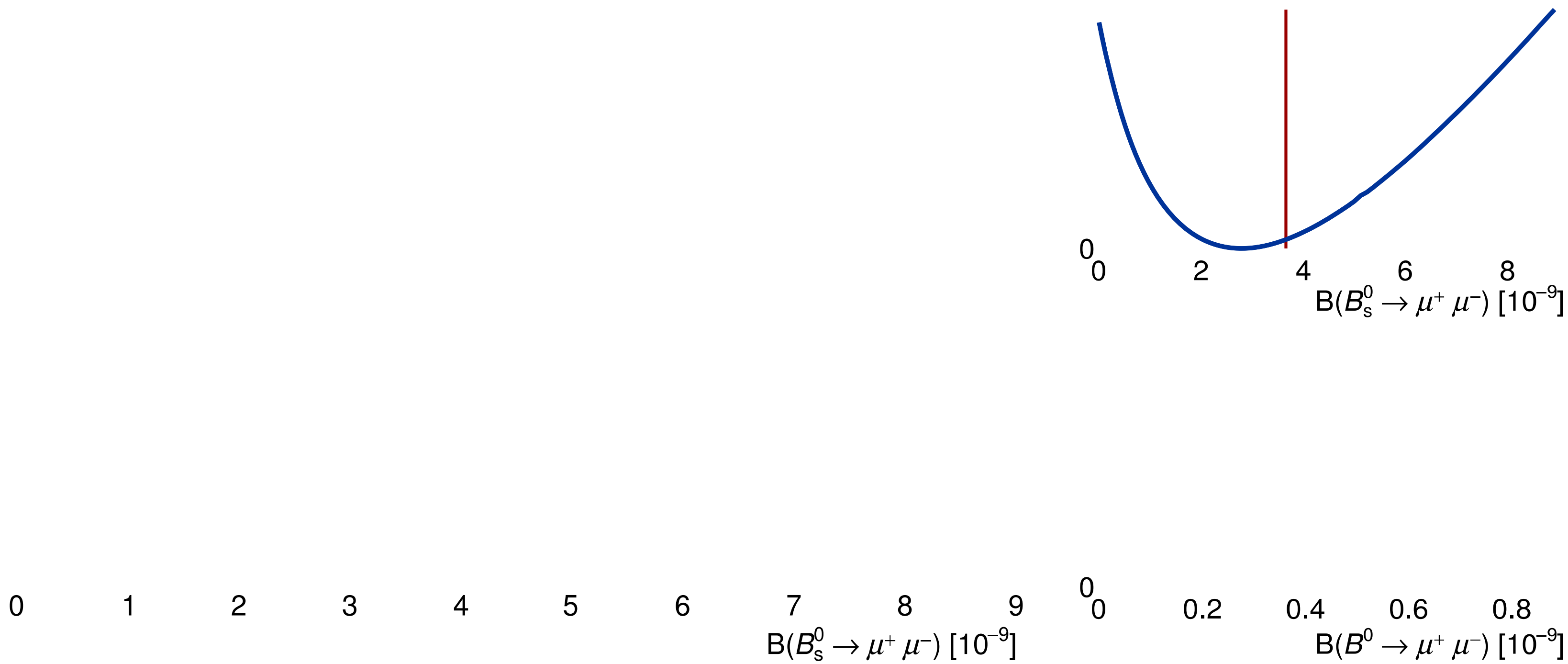


Weighted distribution of Dimuon mass-spectrum, superimposed in a combined fit the **$B_s^0 \rightarrow \mu^+\mu^-$** and **$B_s^0 \rightarrow \mu^+\mu^-$** components

➡ first **observation** of **$B_s^0 \rightarrow \mu^+\mu^-$ decay** and **evidence** for **$B^0 \rightarrow \mu^+\mu^-$ decay**

Nature 522 (2015) 68

Combined result $B_s^0 \to \mu^+\mu^-$: (CMS & LHCb)



Likelihood in $B_s^0 \to \mu^+\mu^-$ vs $B_s^0 \to \mu^+\mu^-$ branching plane

Branching $B_s^0 \to \mu^+\mu^-$: (2.8+0.7-0.6) x10^{-9} (0.76+0.20-0.18 x SM)

Branching $B^0 \to \mu^+\mu^-$: (3.9+1.6-1.4) x10^{-10} (3.7 + 1.6 - 1.4 x SM)

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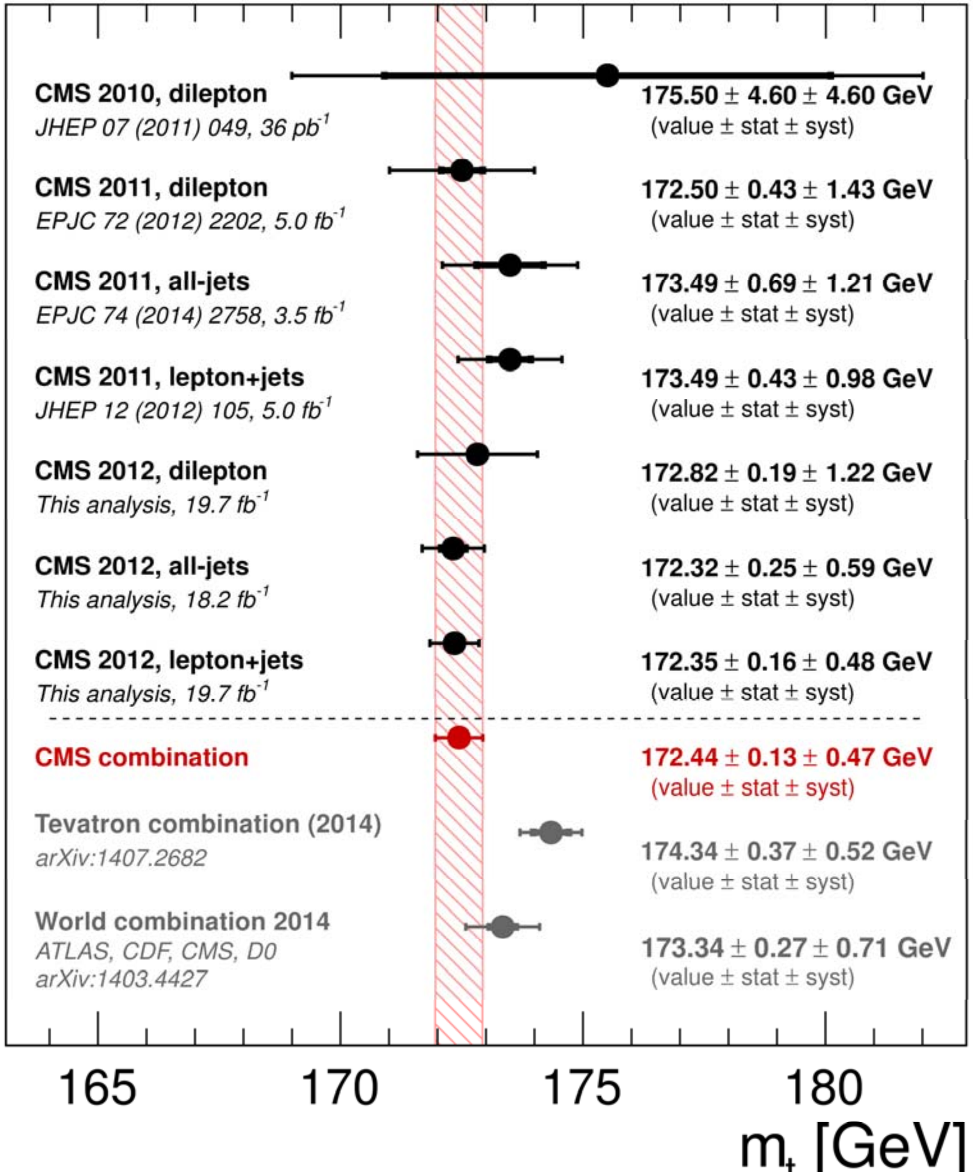
top mass measurements



Top is the heaviest quark in the SM:

decays into W+b jet

Combined top mass using all CMS Run I measurements at 7 and 8 TeV

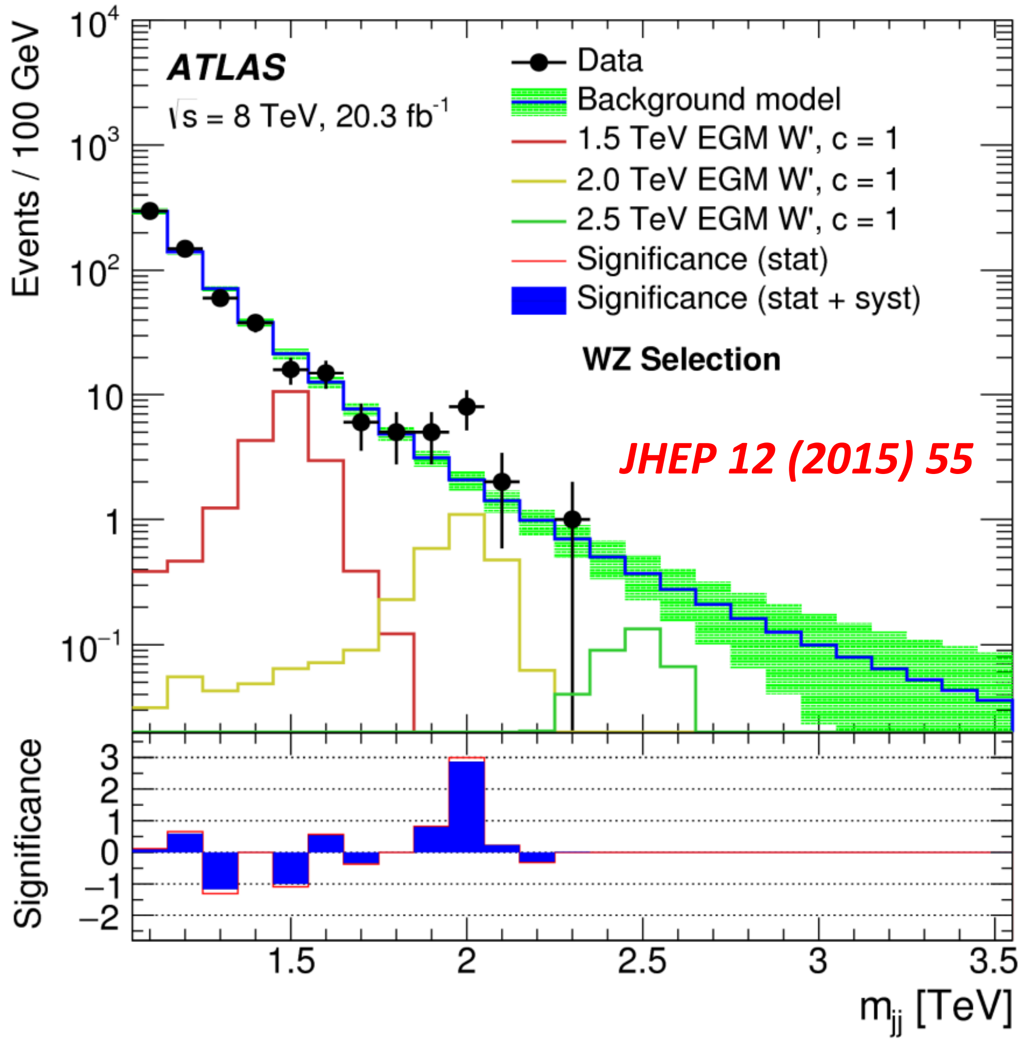
Previous result combining results from ATLAS, CDF, CMS, D0:

173.34±0.27(stat)±0.71(syst) GeV

TOP-14-022 ***Phys. Rev. D 93, 072004 (2016)***

Search for Diboson VV Resonances

ATLAS saw 3.4σ local/2.5σ global excess in Run1 : WW+WZ+ZZ



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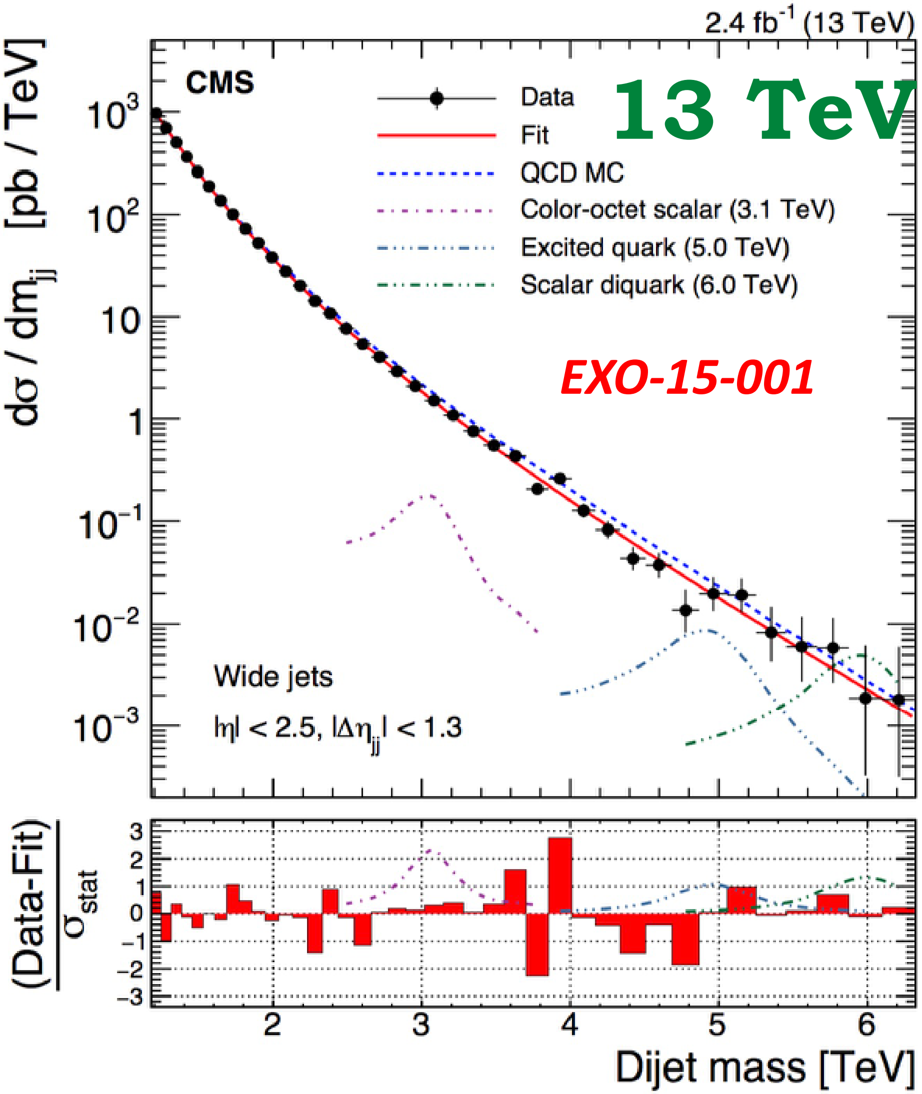
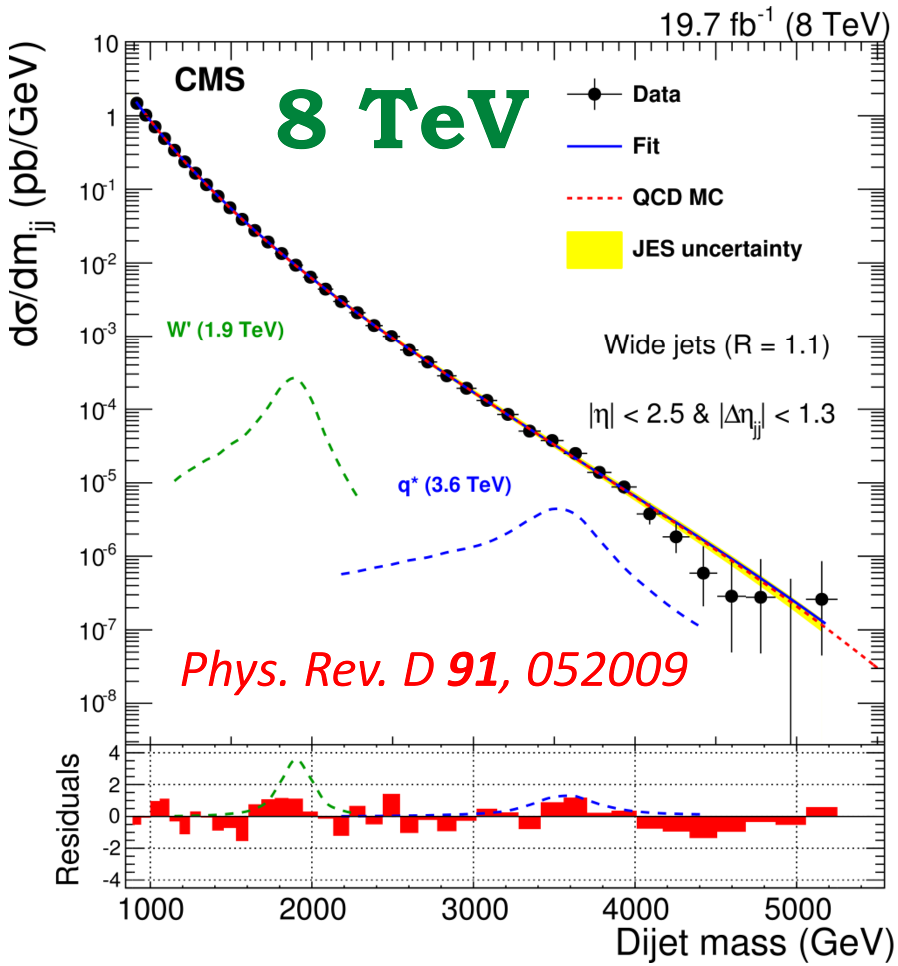
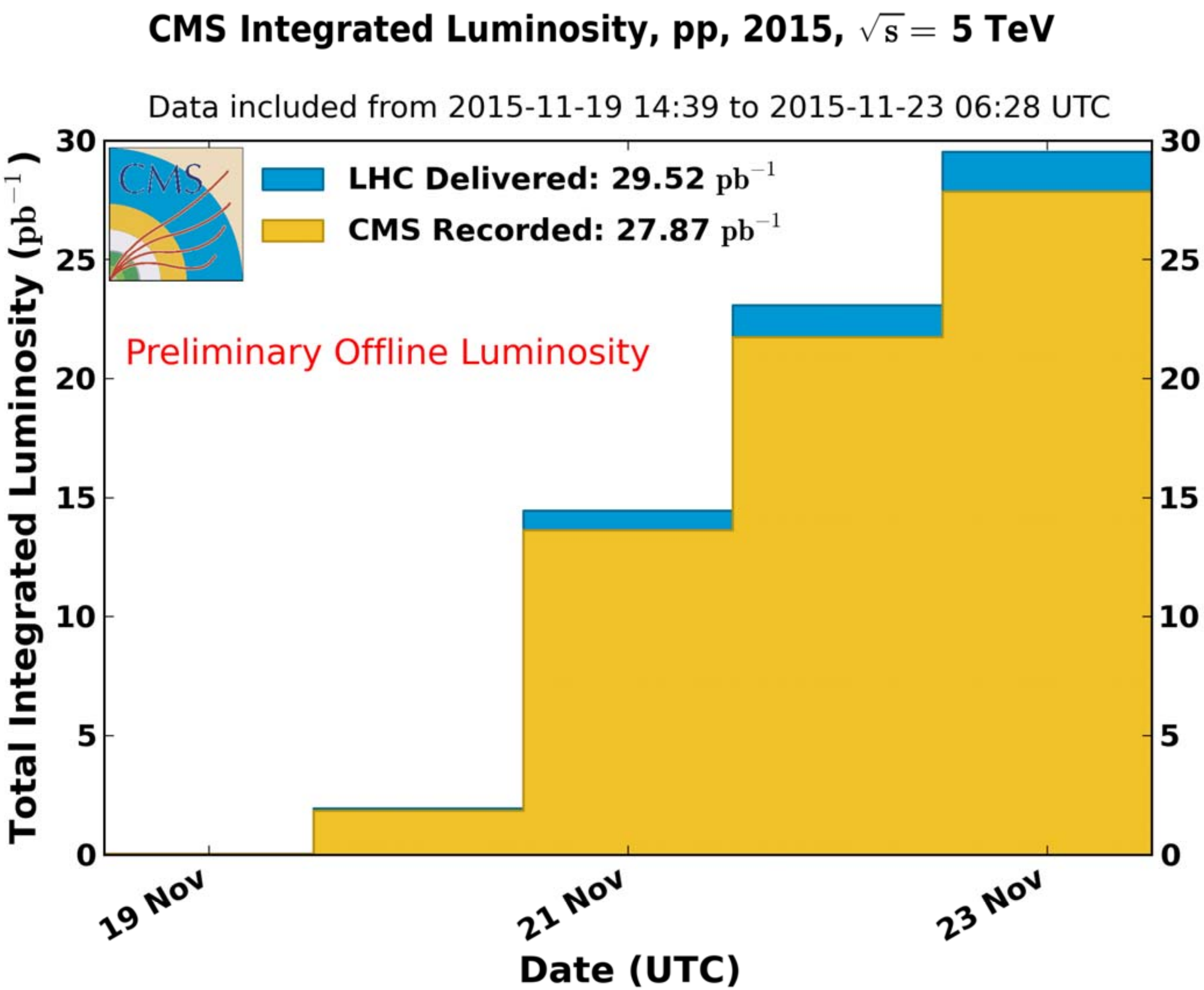
Di-Jet Mass Spectra 13 TeV ↔ 8 TeV

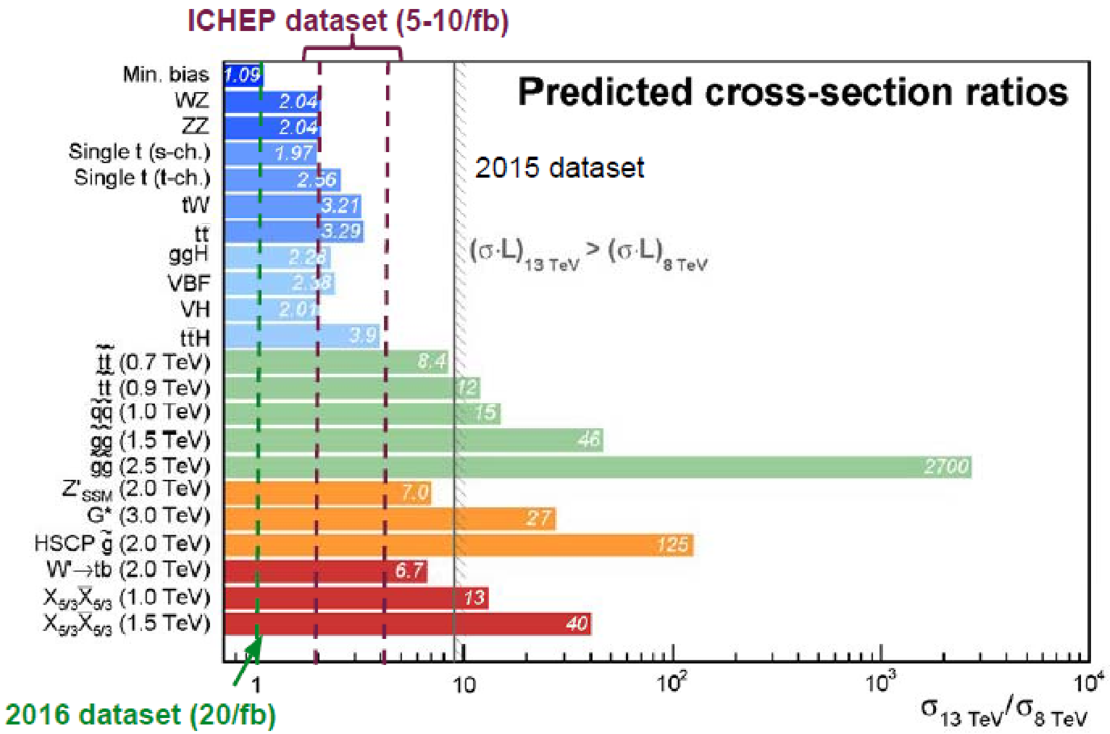




Data collection at 5TeV



2016 Physics reach

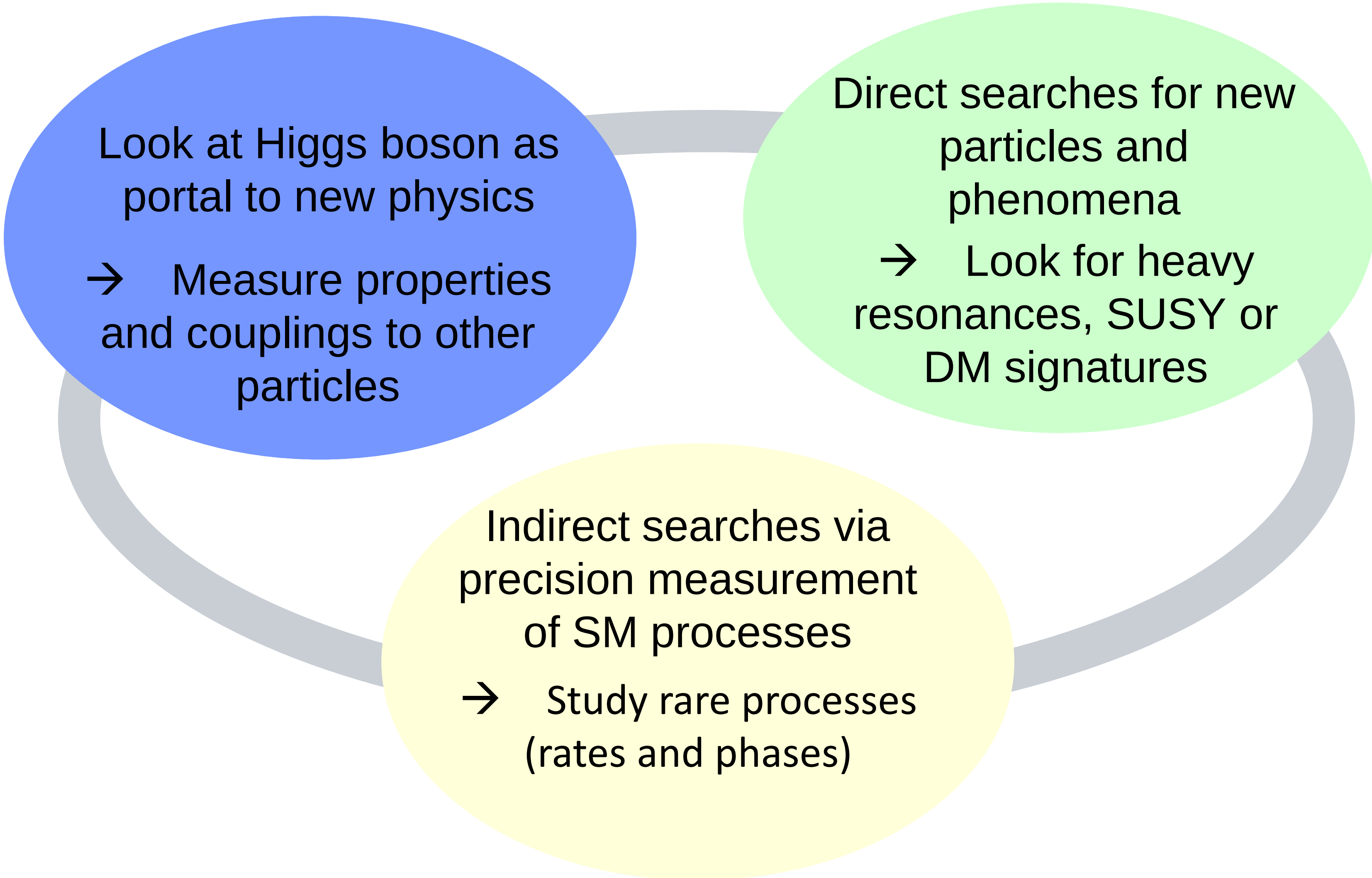


Example physics potential with L ~ 10 fb^{-1}

- 750 GeV mass resonance searches (if gg-produced)
- H(125) full programme
- Better sensitivity for Dark Matter in high-mass mediator region
- Searches for X->VV with M_X ~ TeV
- New vector-like quarks
- SUSY via EWK interactions
- Search for anomalous couplings

How to find New Physics?

The discovery of the Higgs completes the SM and Initiates in earnest the search for p
that extends it. Three complementary approaches:

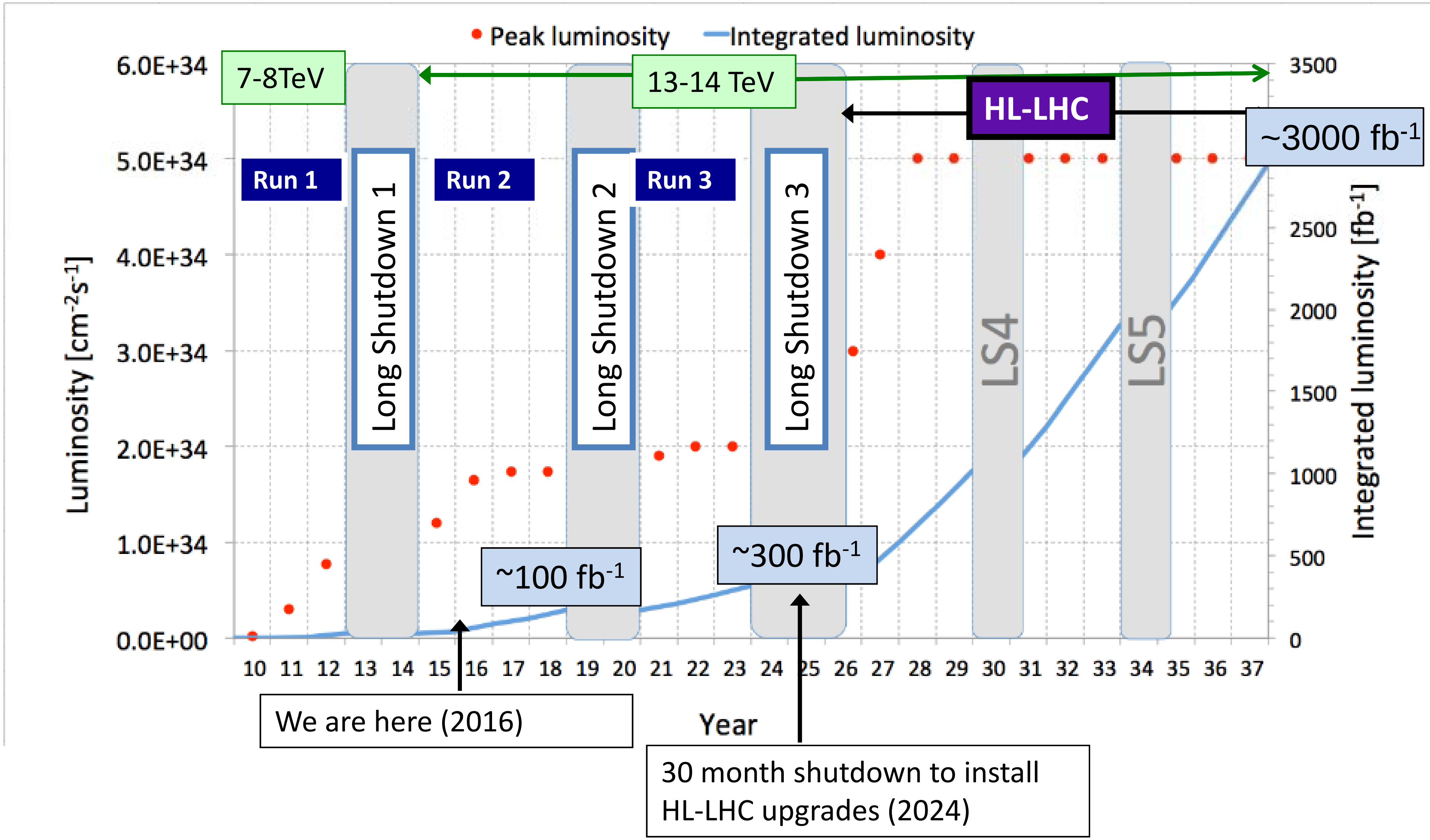


Other searches for X (750 GeV)

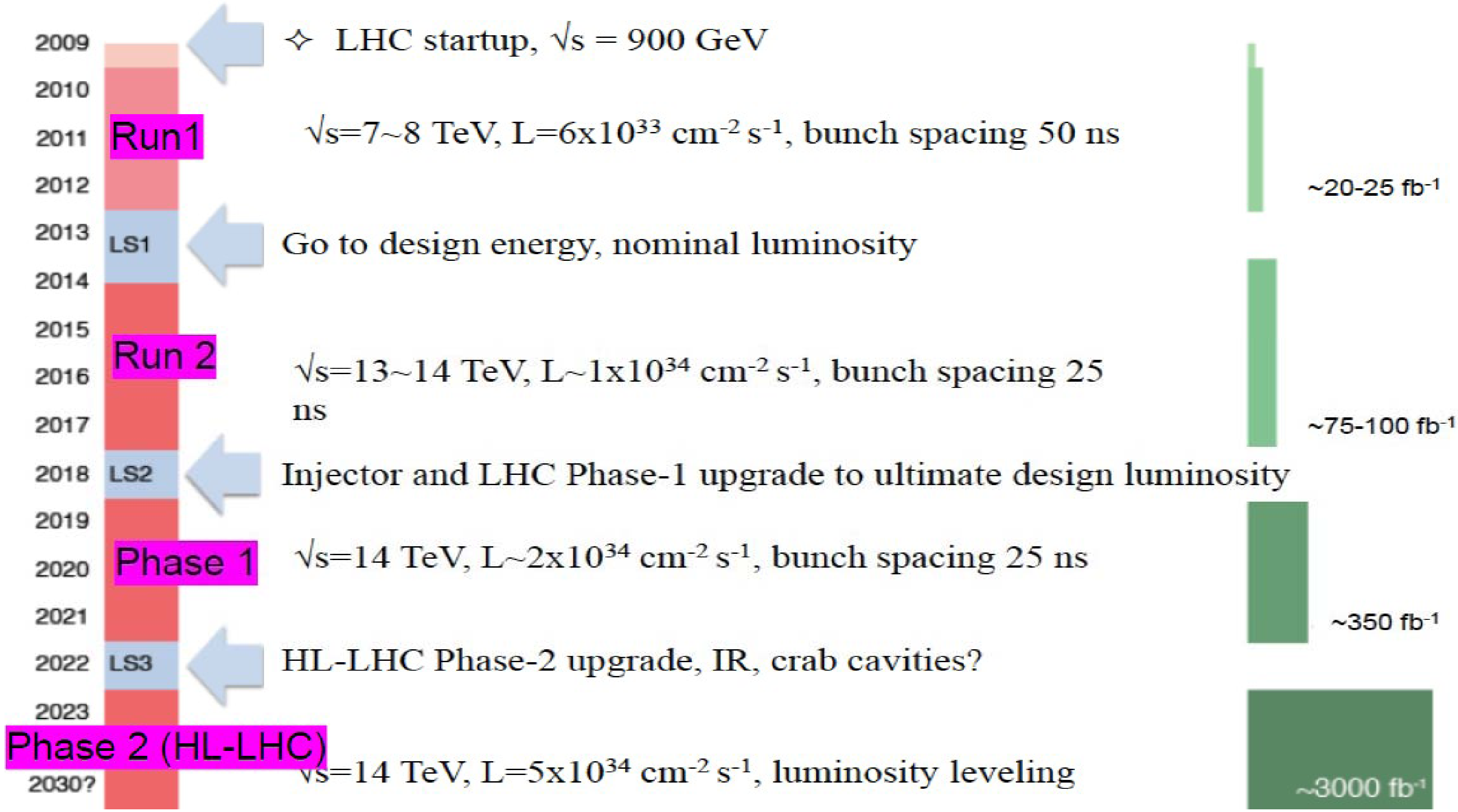
LH

- pp → X → Zγ
  - llγ: EXO-16-016 (13 TeV), HIG-16-014 (8 TeV), EXO-16-021 (8+13 TeV combination)
  - qqγ: EXO-16-020
- pp → X → ZZ
  - 4 lepton: HIG-15-004
  - 2l 2ν: HIG-16-001
- pp → X → ZH(125)
  - H(125) → bb: B2G-16-003
- pp → X → HH
  - bbbb: HIG-16-002
  - bbττ: HIG-16-013 (13 TeV), HIG-15-013 (8 TeV)
  - WWbb: HIG-16-011
- pp → X → WW
  - lνqq: B2G-16-004
- pp → X → $t\bar{t}$
  - Semileptonic: B2G-15-002
  - All-hadronic: B2G-15-003

LHC future: the path to High Luminosity



LHC: The 20 years plan



- **~75-100 fb^{-1} will be collected during LHC Run 2**
- Long shutdown in 2018 to upgrade detector for **Run 3 (x2 inst. lumi)**
- Long shutdown in 2022 to prepare for **HL-LHC**

◊ Goal of collecting 3000 fb^{-1} at $5x10^{34}$ $cm^{-2}s^{-1}$ beyond 2030