New Physics searches at the LHC
or
Latest results on BSM physics in the Higgs sector and beyond

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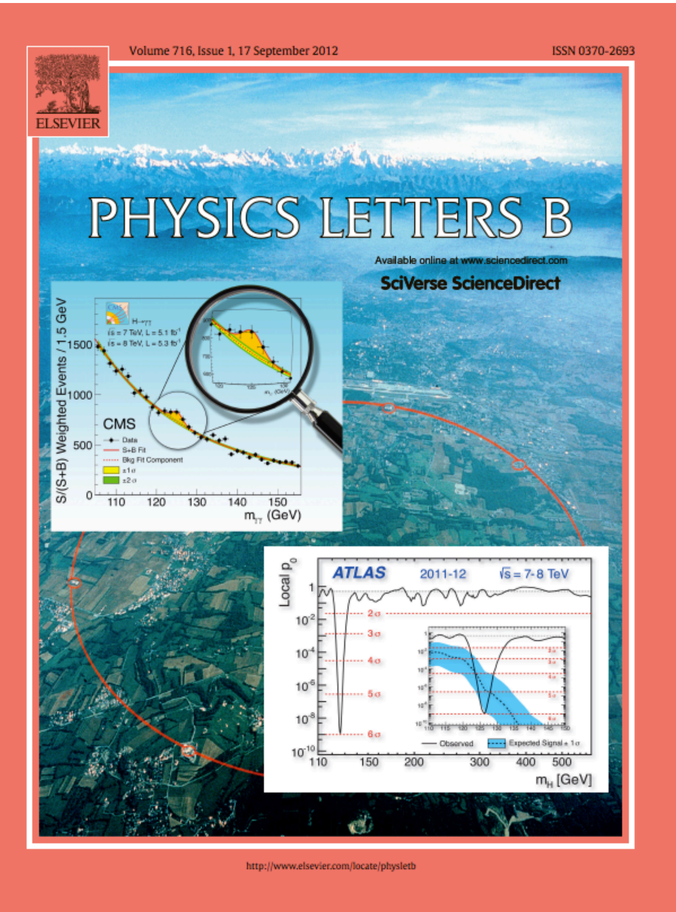
LIP Lisbon

March 28, 2018

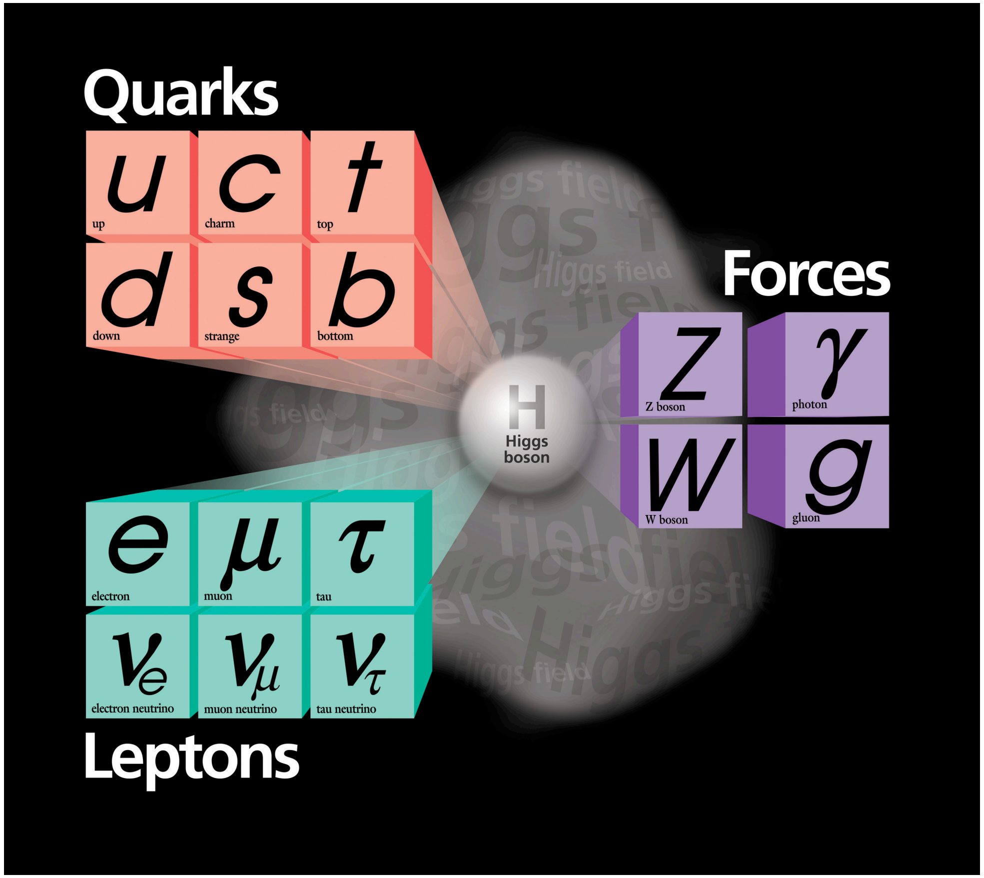
- ✓ Introduction
- ✓ Higgs, Dark matter, and Exotica searches
- ✓ Looking (backward) forward

2012: A new boson discovery

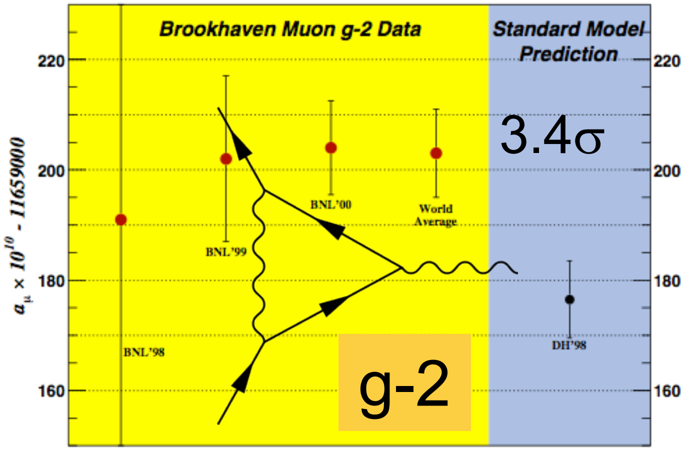


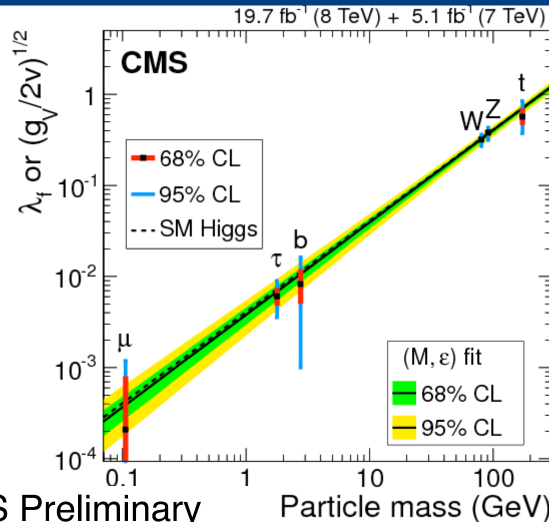
Standard Model theory of everything?

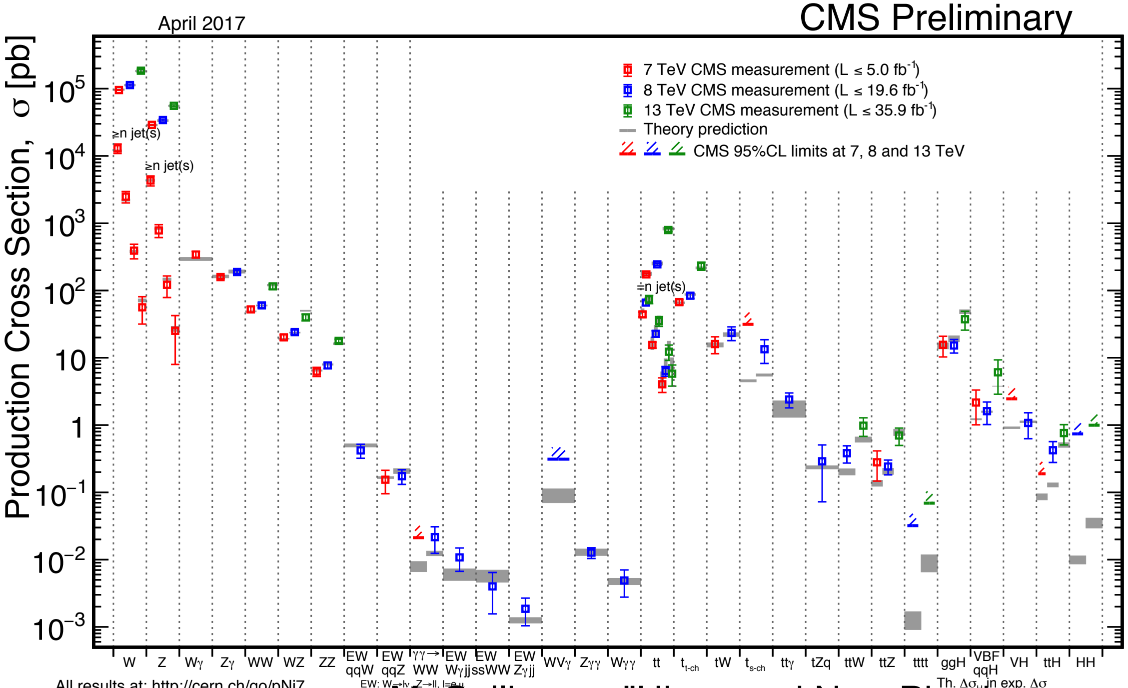
- Discovery of the Higgs boson marks the triumph of the SM
- However, even with the inclusion of the Higgs boson, SM is an incomplete theory

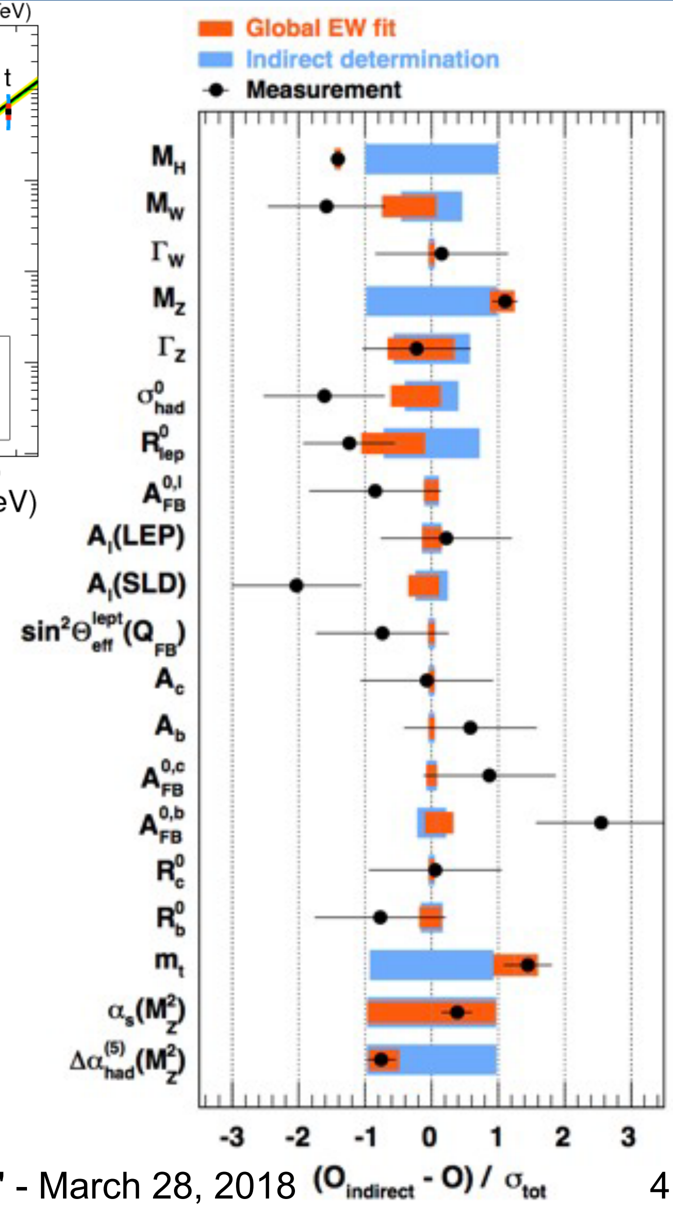


Tests of the SM









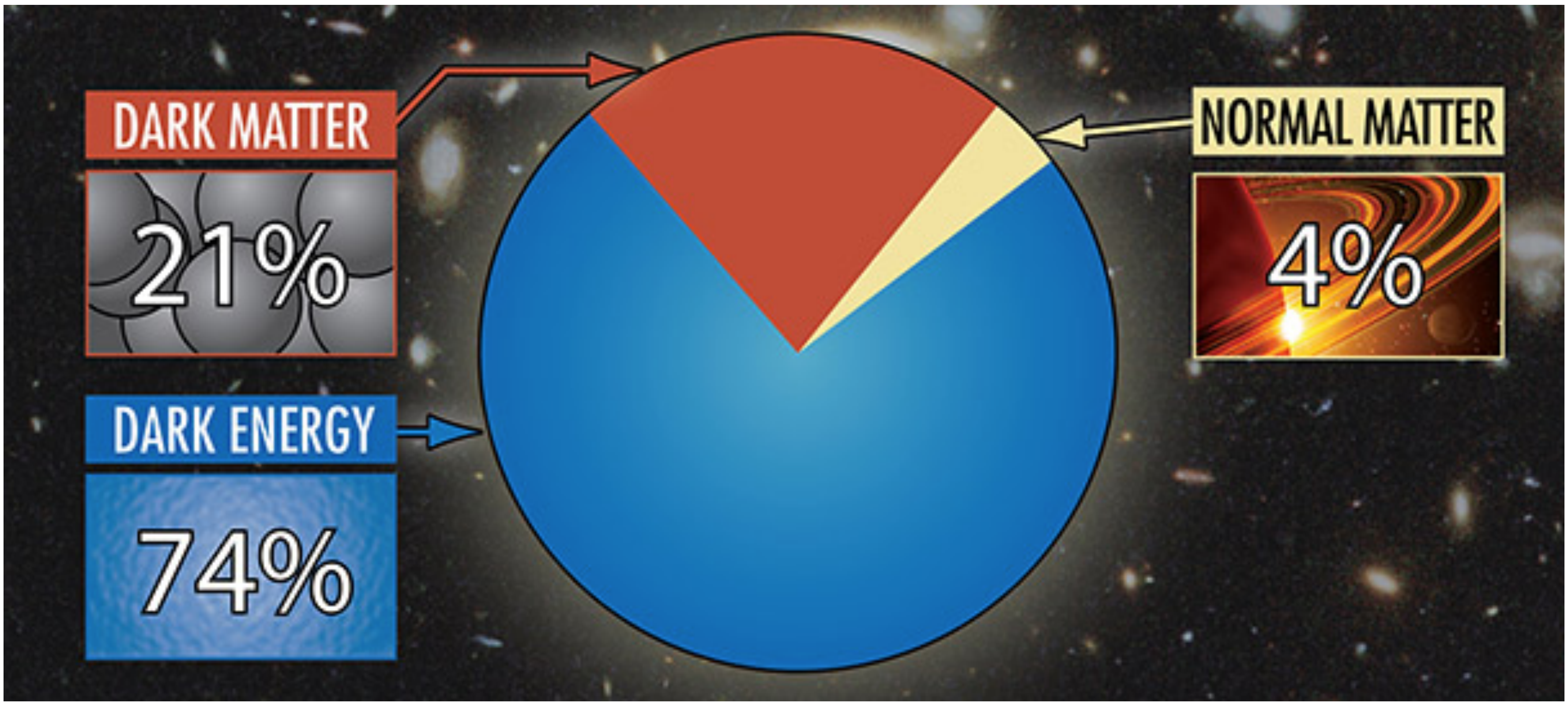
Beyond the Standard Model

The SM answers many of the questions about the structure of matter. But SM is not complete; still many unanswered questions:

a) Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?
b) What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?
c) Are quarks and leptons actually fundamental, or made up of even more fundamental particles?
d) Why are there three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?
e) How does gravity fit into all of this?

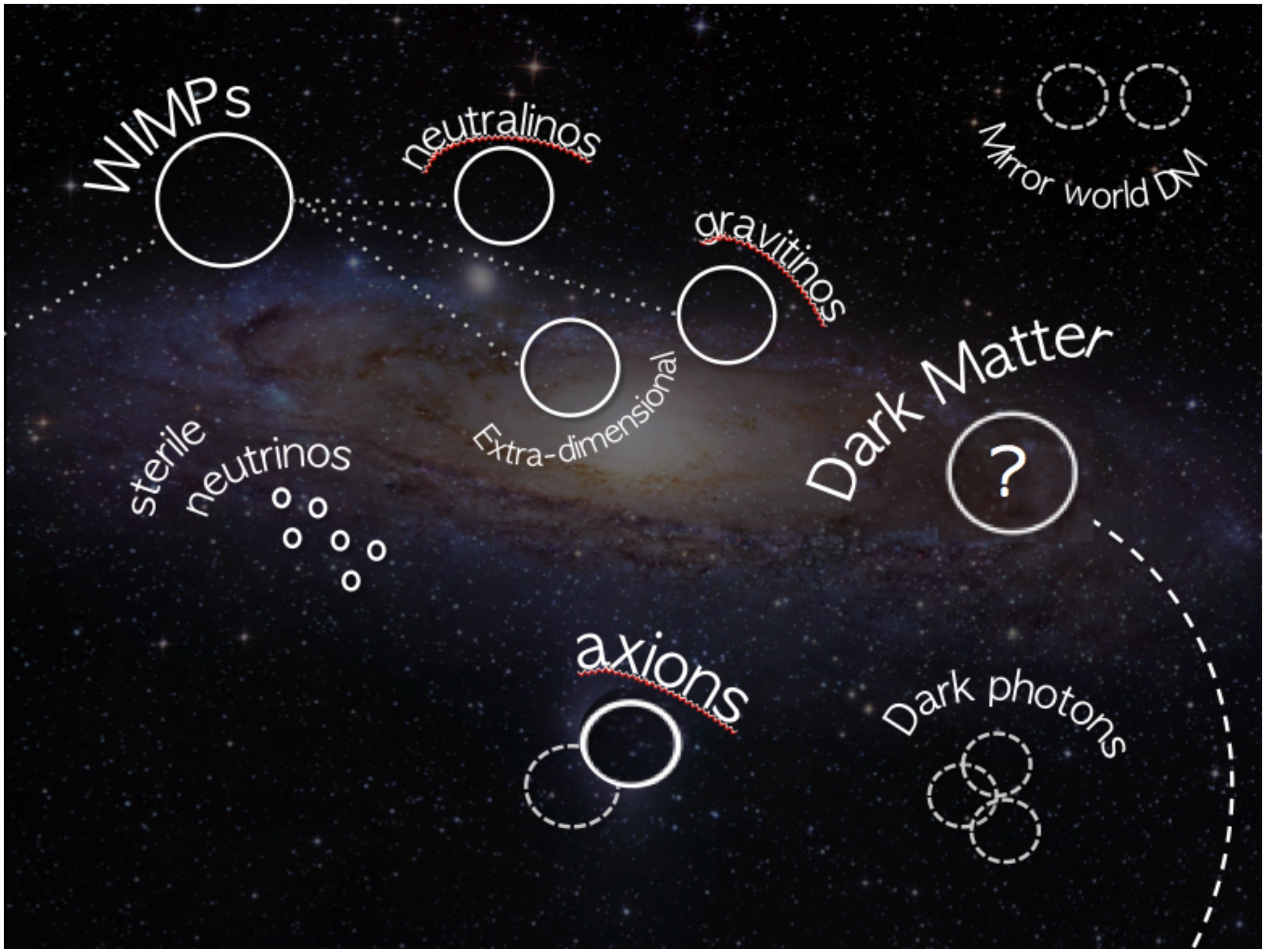
Dark matter and energy

- What is that accounts for 96% of the Universe? Nobody knows.
- It is one of the greatest mysteries of Science



What can we look for?

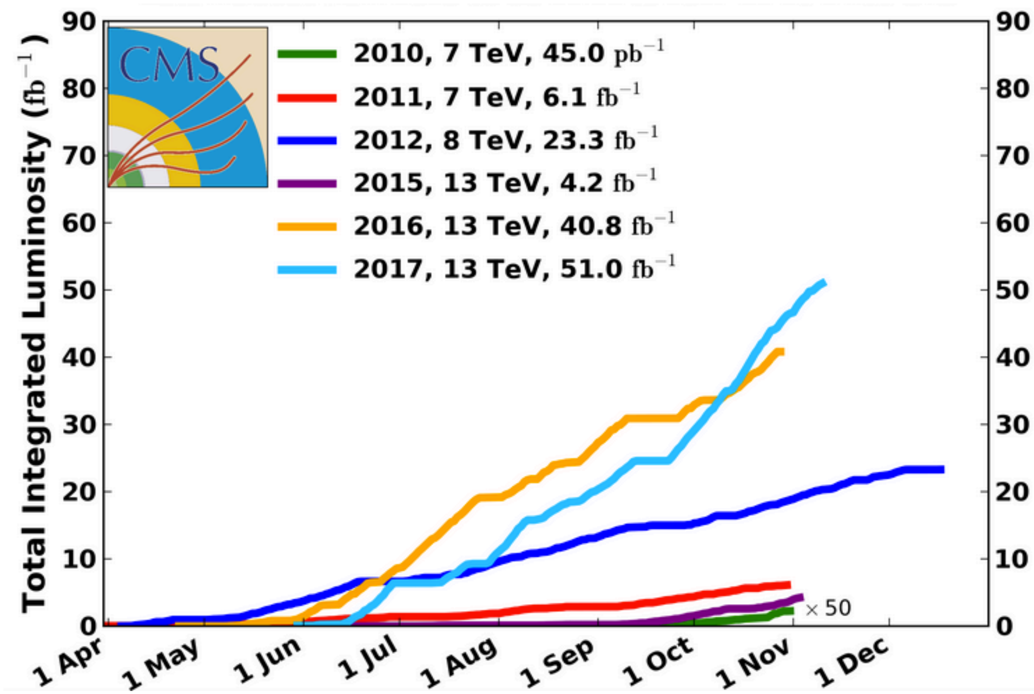
A crowded field. At the LHC we can search for some of these



How?

- Search for new phenomena
- Look for New Physics
- Indirect searches
  - precision measurements, event properties, etc.
- Direct searches
  - resonances, specific final states, model-(in)dependent searches, etc.
- Production and decay rates, event characteristics, advanced tools

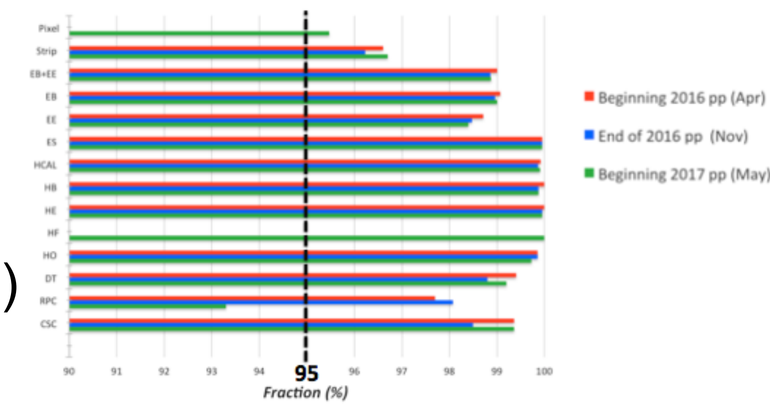
LHC performance



2017:

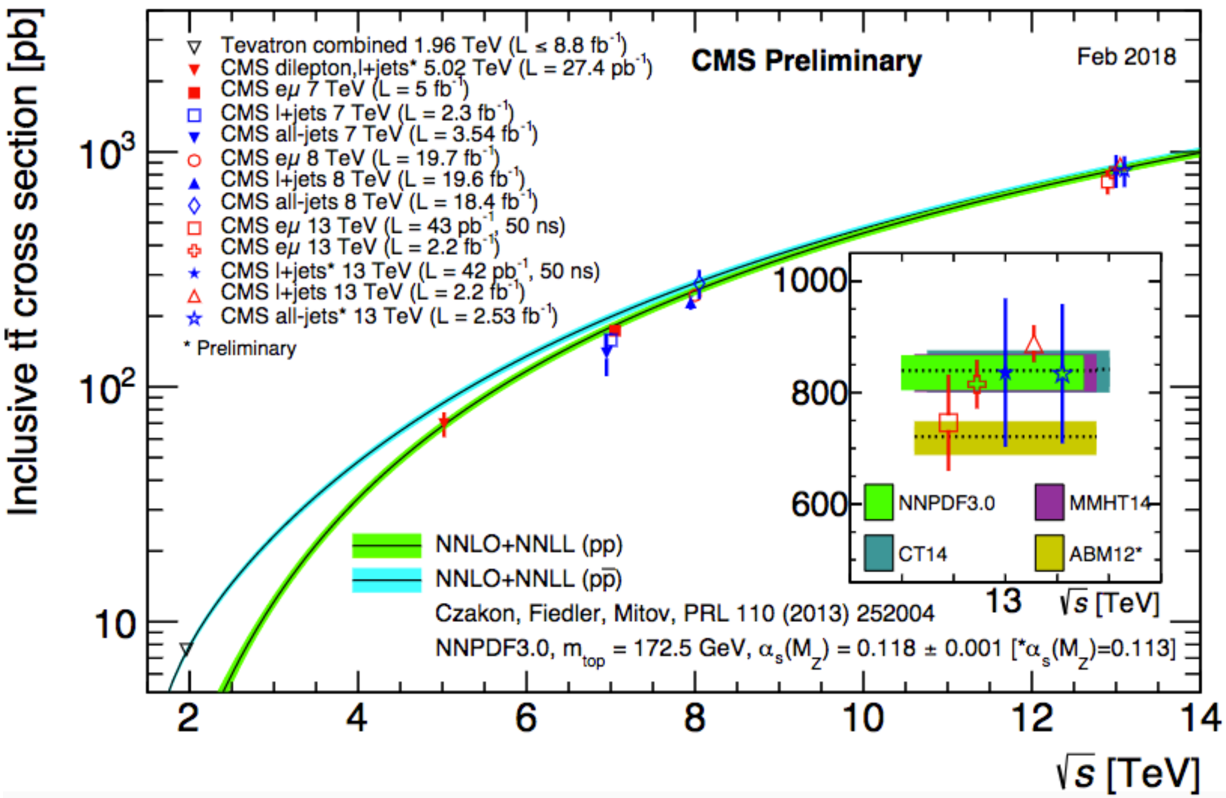
- LHC exceeded design goal
  - Peak luminosity: $2x10^{34}$ $cm^{-2}sec^{-1}$
  - Pileup ~35
  - 2208 colliding bunches
- LHC high availability: ~50%

- CMS record efficiency:
  - Excellent detector performance ~92.5%
  - Each sub-detector >96%



Data validated for all detectors is 95% of data recorded: ~50/fb to analyze (~70/fb expected for 2018)

Top quark cross sections



Top quark pair rate is large

⇒precise measurements and rare processes

- Single and double differential cross sections
- Rare (FCNC) decays
- CP violation
- Width and mass

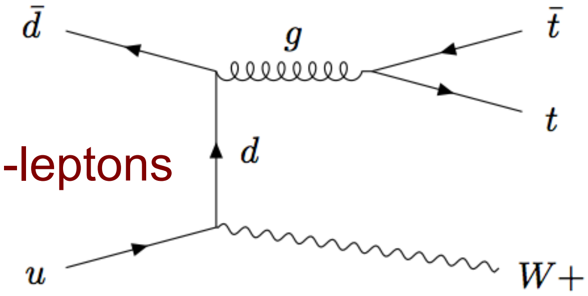
Pair production is mostly through gluon-gluon, thus providing information on gluon distribution

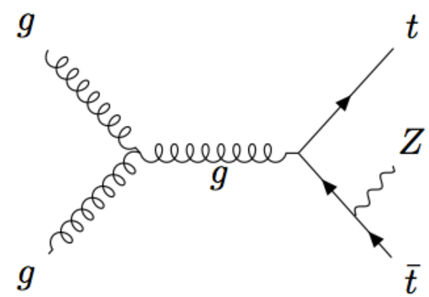
Top production: ttZ and ttW

arXiv:1711.02547

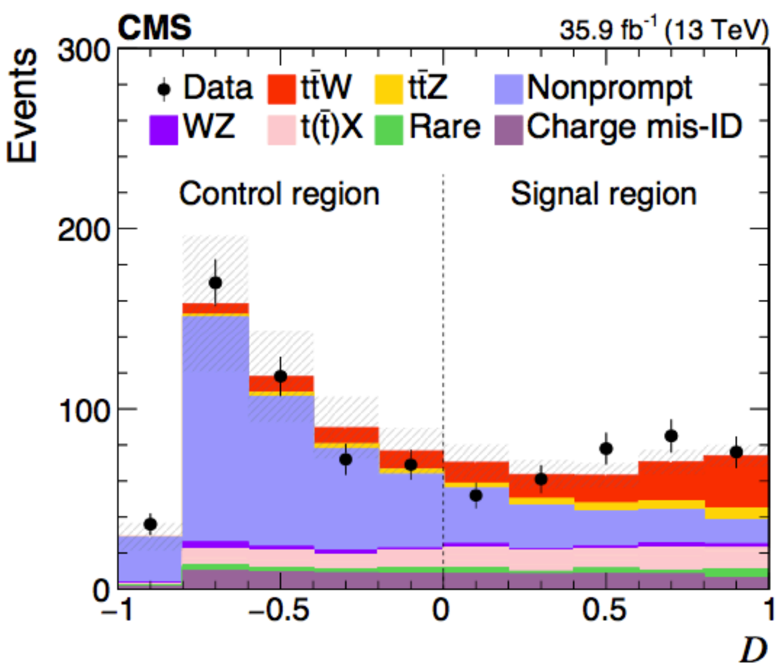
- Coupling of top to Z (direct measurement of background to many searches)

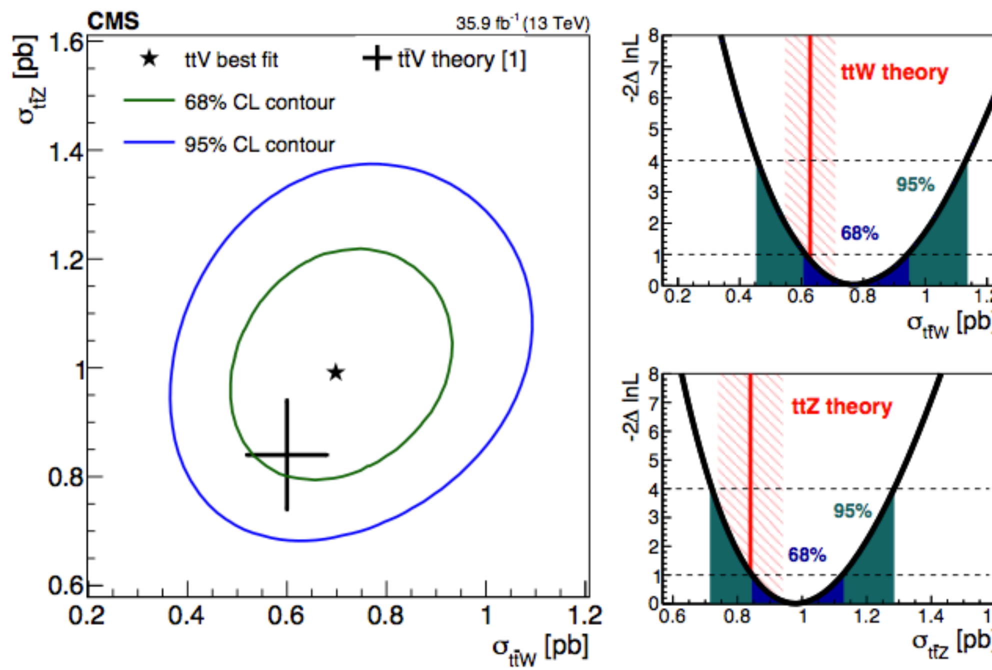
SS di-leptons





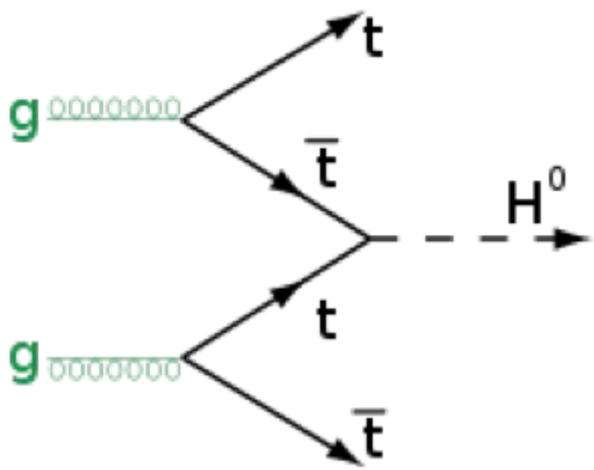
3,4 leptons





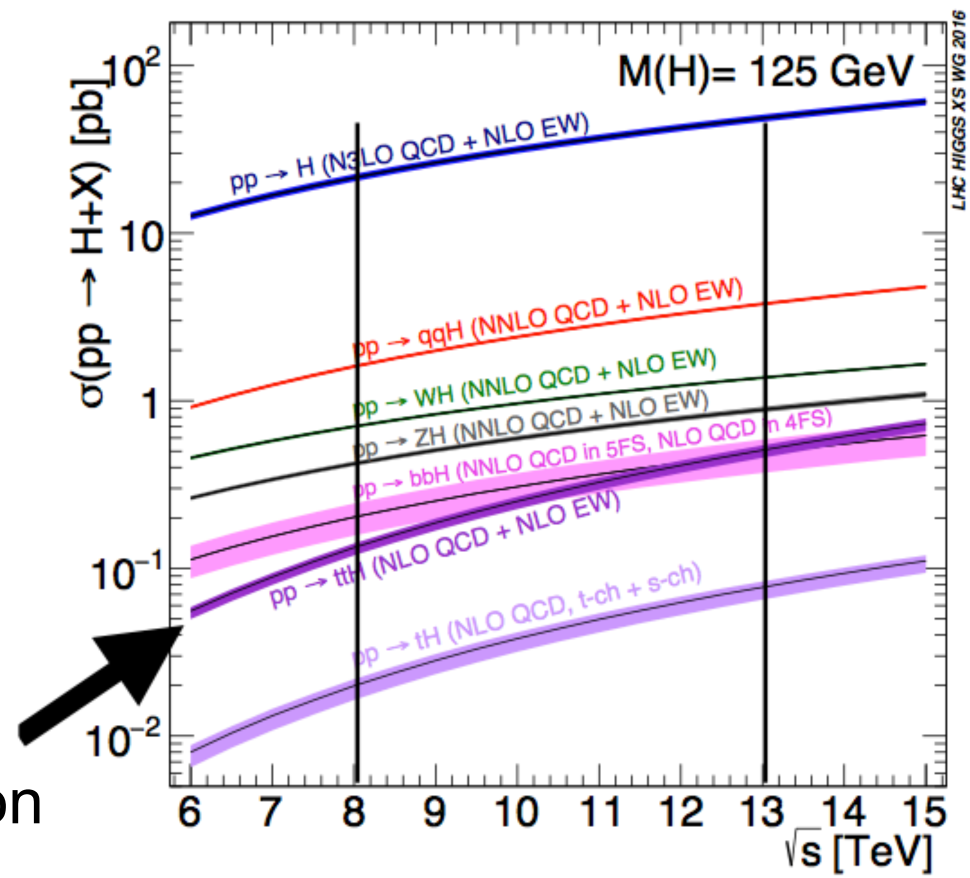
ttbar+Higgs

- ttbar produced in association with H
  - ttbar is a "clean" tag
- direct measurement of Higgs couplings



Cross section for $t\bar{t}H$ at the LHC:
0.13 pb (8 TeV)
0.61 pb (14 TeV)

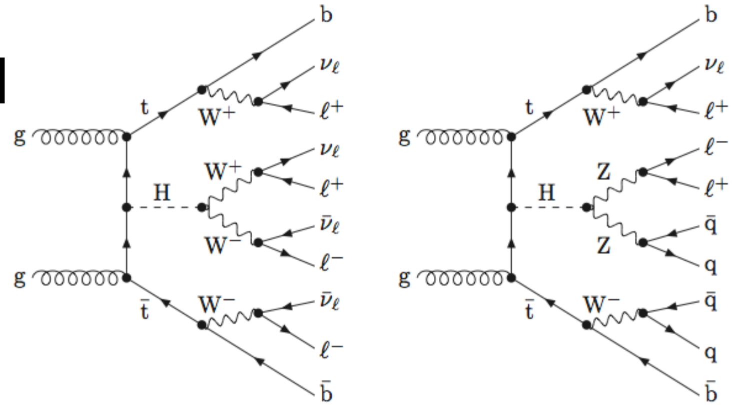
ttH ~1% of total Higgs cross section

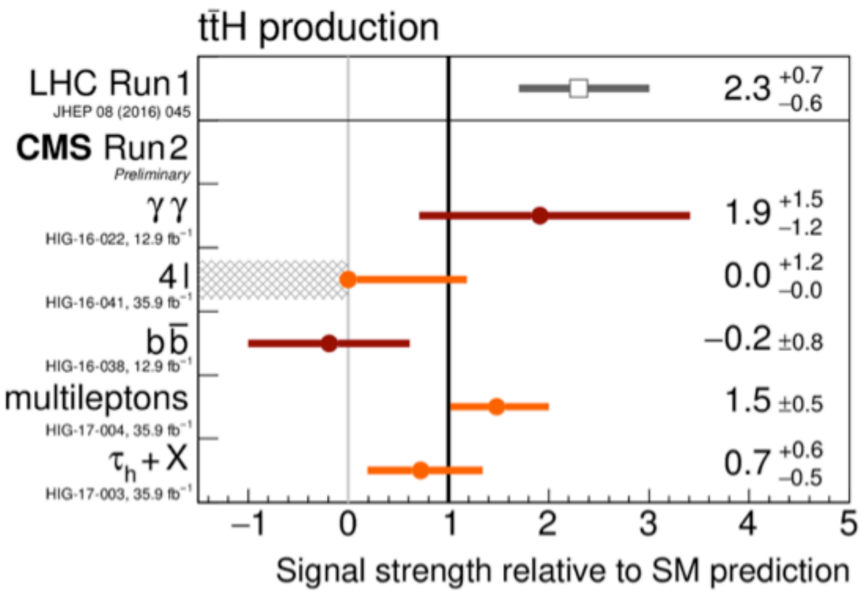


Higgs couplings to top quarks

CMS-HIG-17-004

ttH

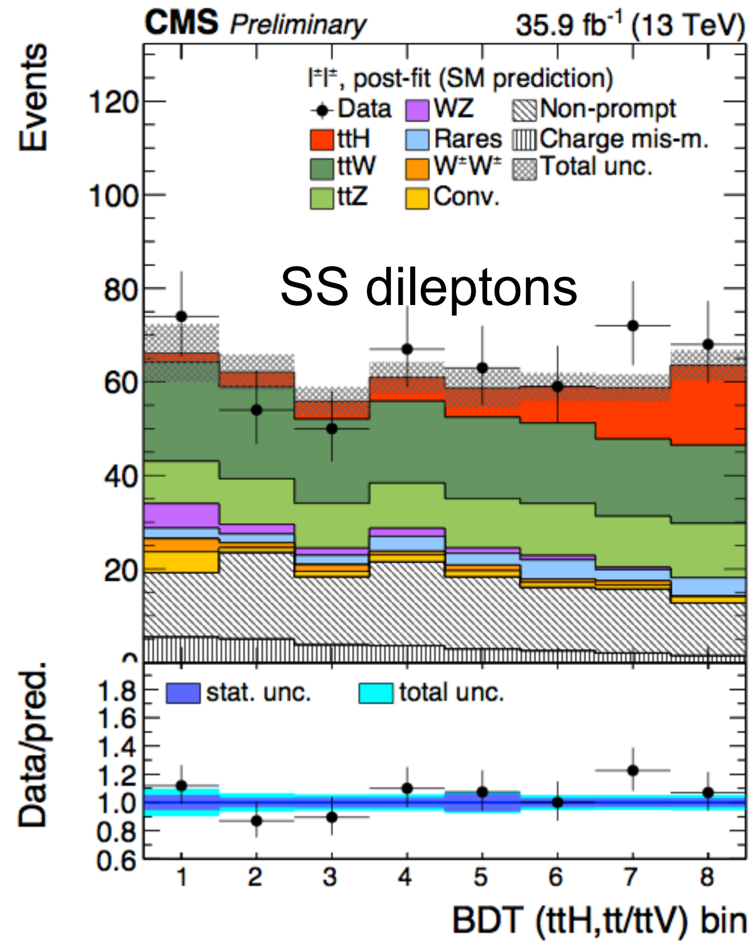




3σ evidence for ttH in multi-lepton final states 3.3 σ (2.5 expected)

- Multi-leptons: SS, 3L and 4L

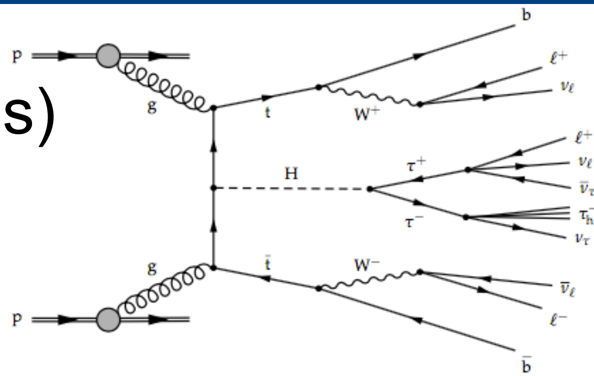
⇒categories per charge, flavor



Higgs couplings to top quarks (cont.)

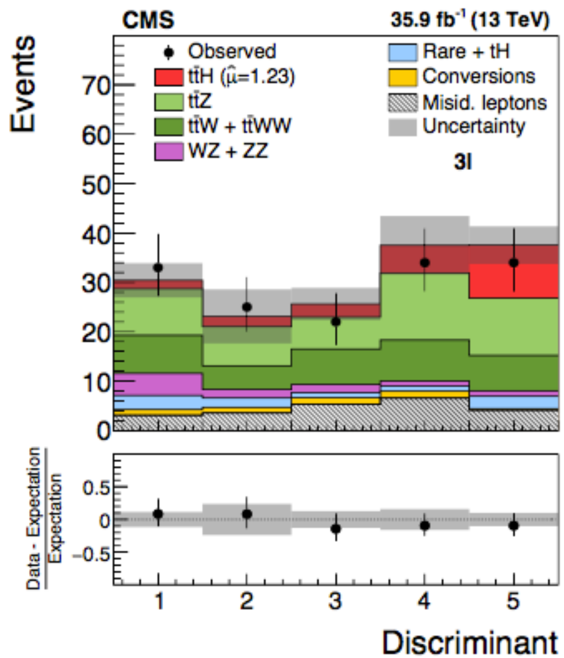
arXiv:1803.05485

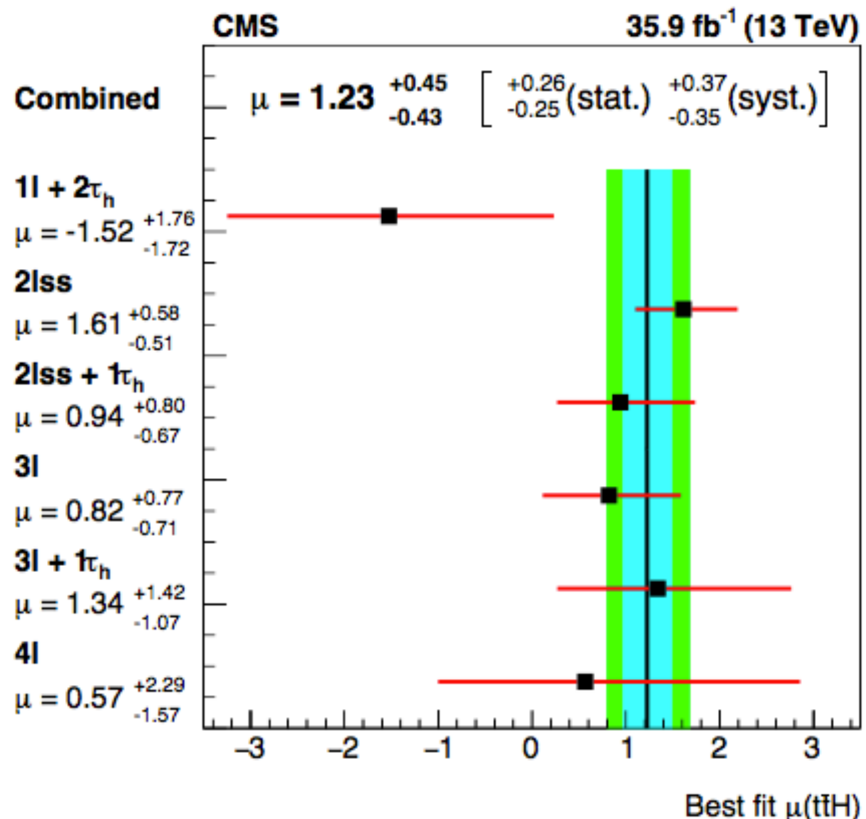
ttH (with taus)



- Lepton and tau:

⇒6 categories lept/tau multiplicity

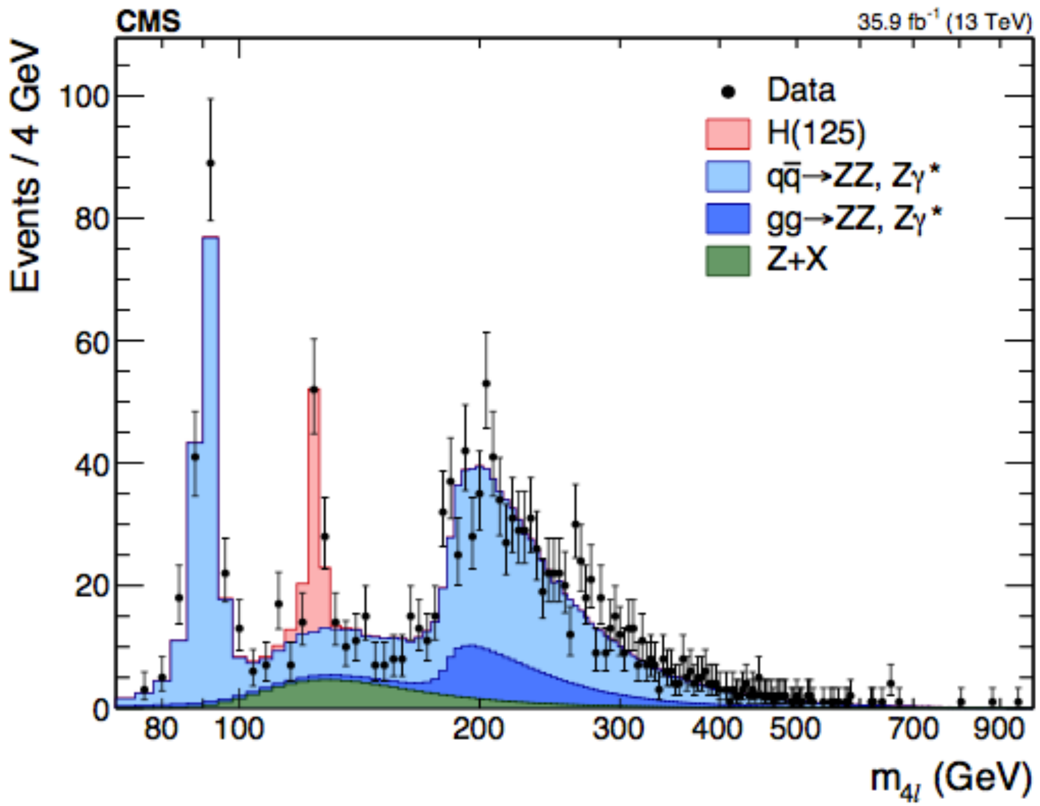


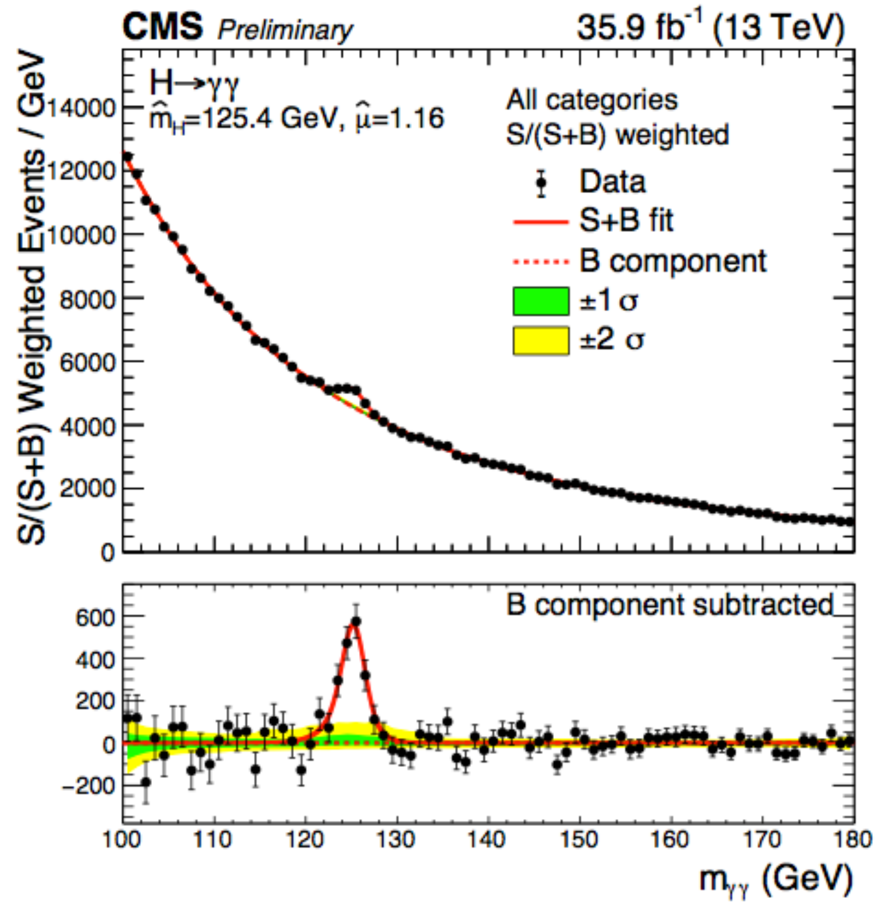


evidence for ttH in lepton+tau final states 3.2 σ (2.8 expected)

Higgs reloaded

HIG-16-040, arXiv:1706.09936

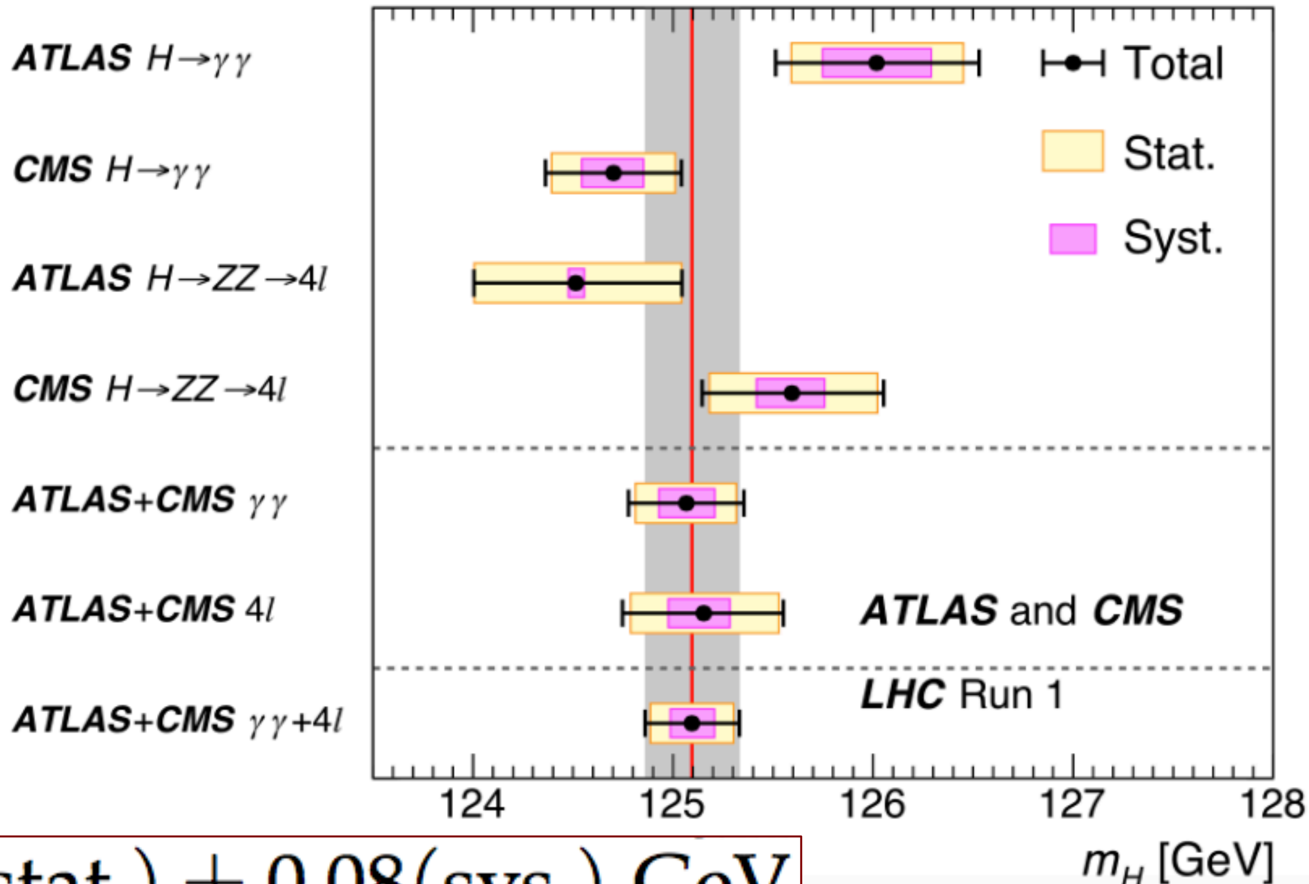




Higgs mass

PRL114(2016)191803, HIG-16-041

- One of most important properties
- Given the mass, all the rest is precisely predicted by SM
- Mass can be accurately measured from $H\to\gamma\gamma$ and $H\to 4l$ decays

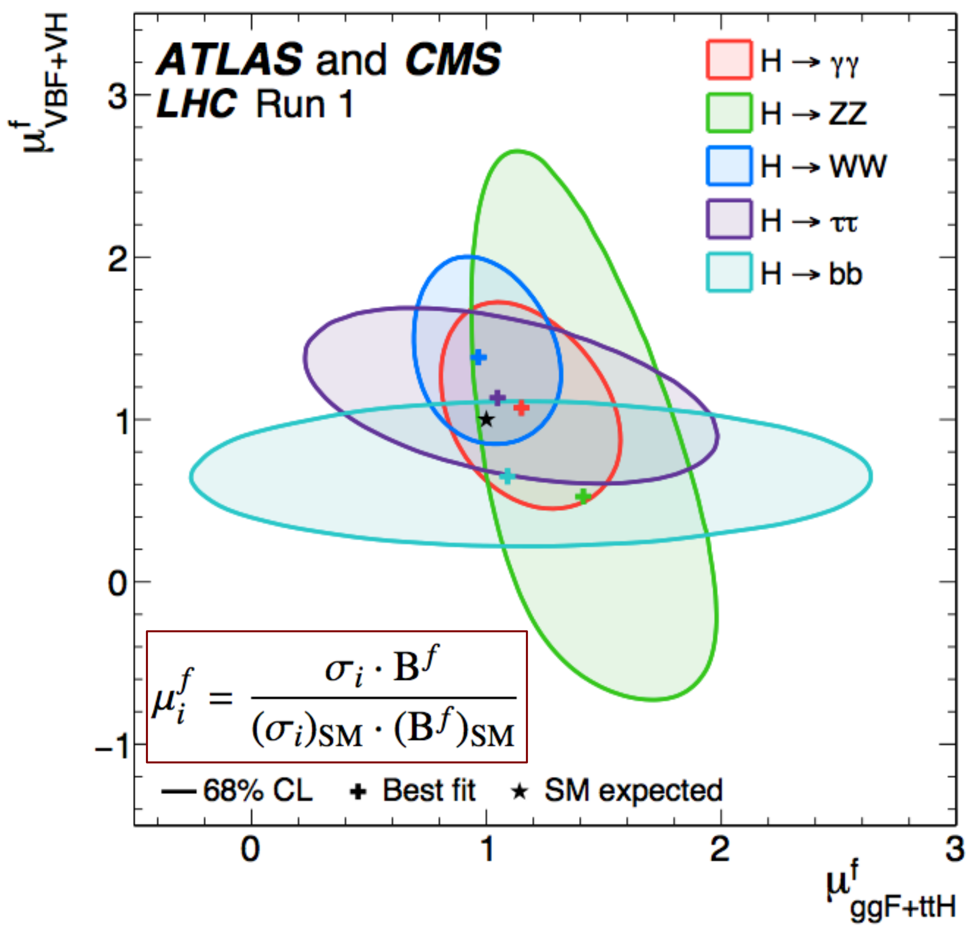


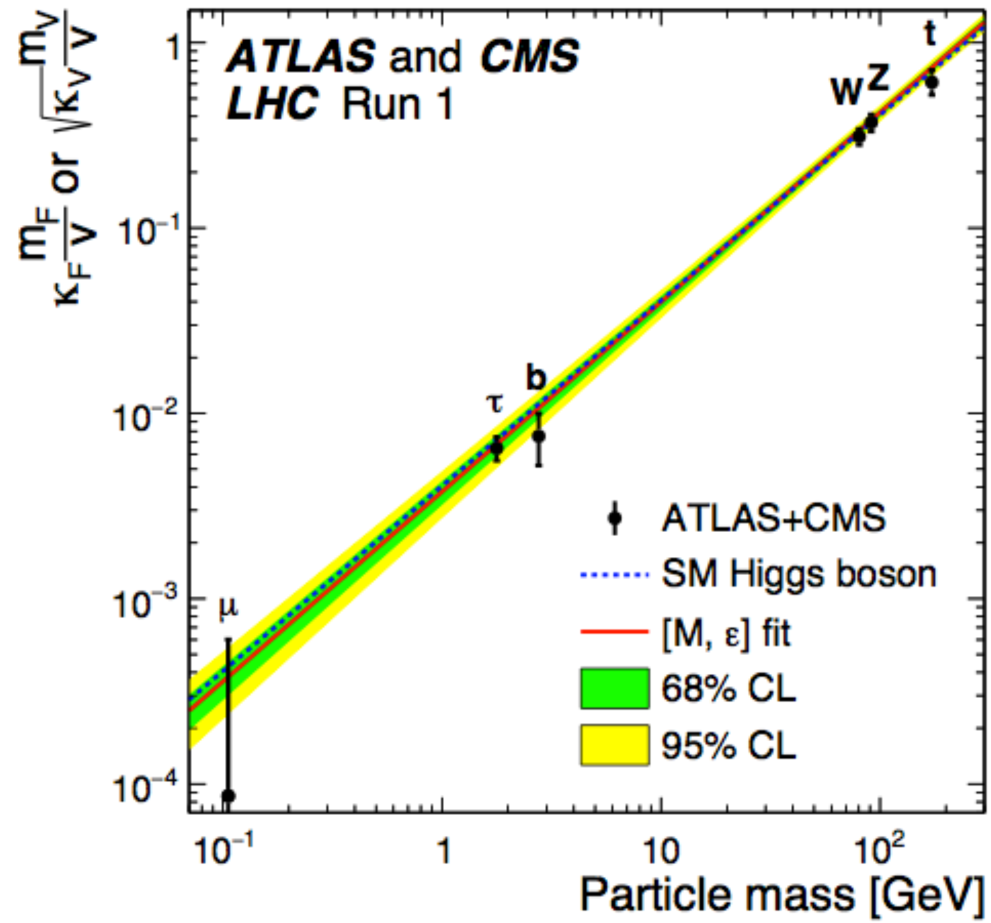
$$m_H = 125.26 \pm 0.20(\text{stat.}) \pm 0.08(\text{sys.})\ \text{GeV}$$

Accurately measured ⇒<0.2%!

Consistency with SM

JHEP 08(2016)45

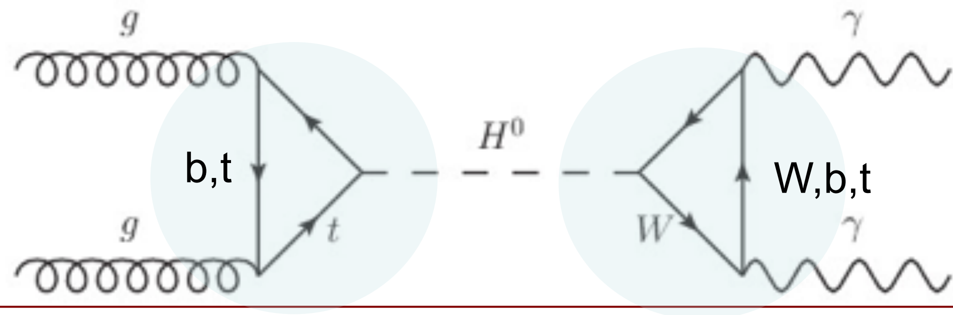




Higgs and BSM

arXiv:1606.02266

- Is there BSM physics hidden in the "Higgs sector"?



$$(\sigma \cdot \mathrm{BR})\,(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot \mathrm{BR}_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Strategy: parametrize deviations wrt SM in production and decay
⇒ loops are sensitive to BSM physics

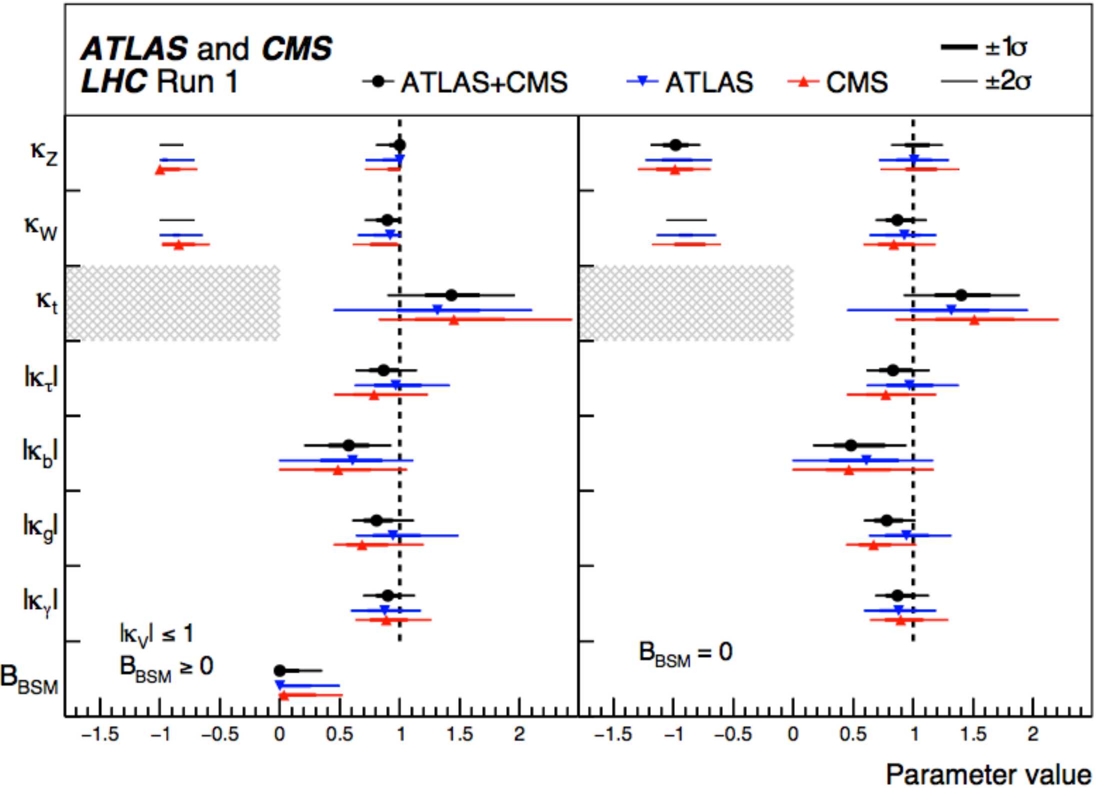
Experimental approach

- Measure H(125) properties
- Search for additional Higgs bosons
- Search for BSM in signatures with Higgs bosons
- Search for BSM Higgs decays

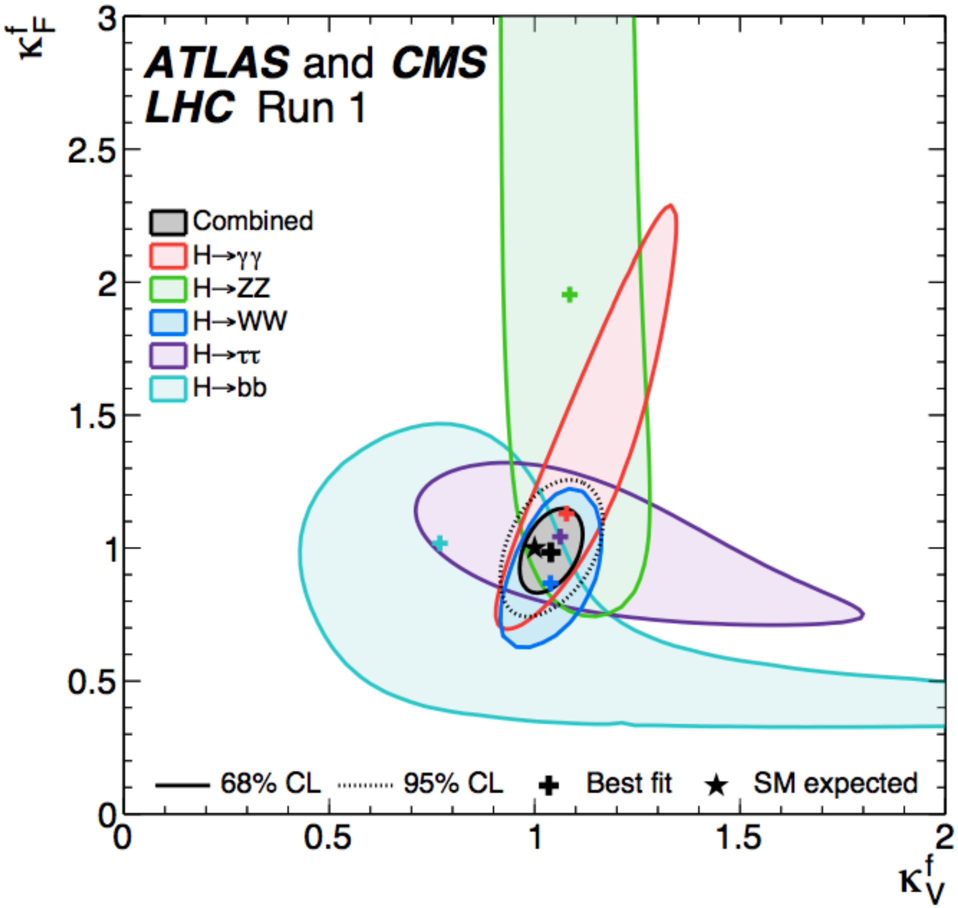
Couplings: decays

ATLAS-CONF-2015-044, CMS-HIG-15-002, JHEP08(2016)045

BSM physics in the loop



Vector and fermion couplings



BR_{BSM} can be measured

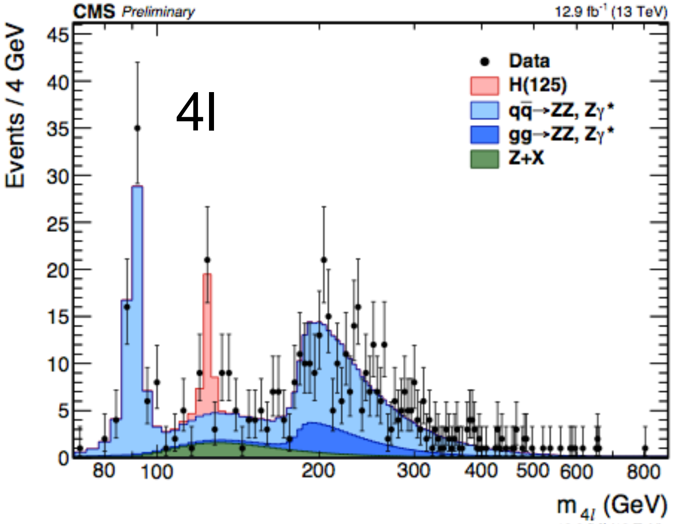
$BR_{BSM} < 0.34$ at 95% C.L. (assuming $\kappa_V \le 1$)

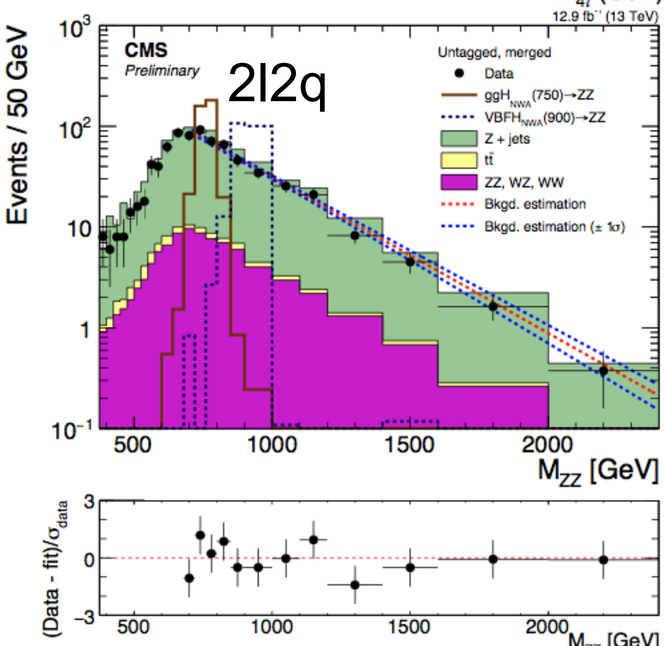
BR_{BSM} includes non standard decays, visible or invisible

⇒Results in agreement with SM (k_V=k_F=1) within 1σ

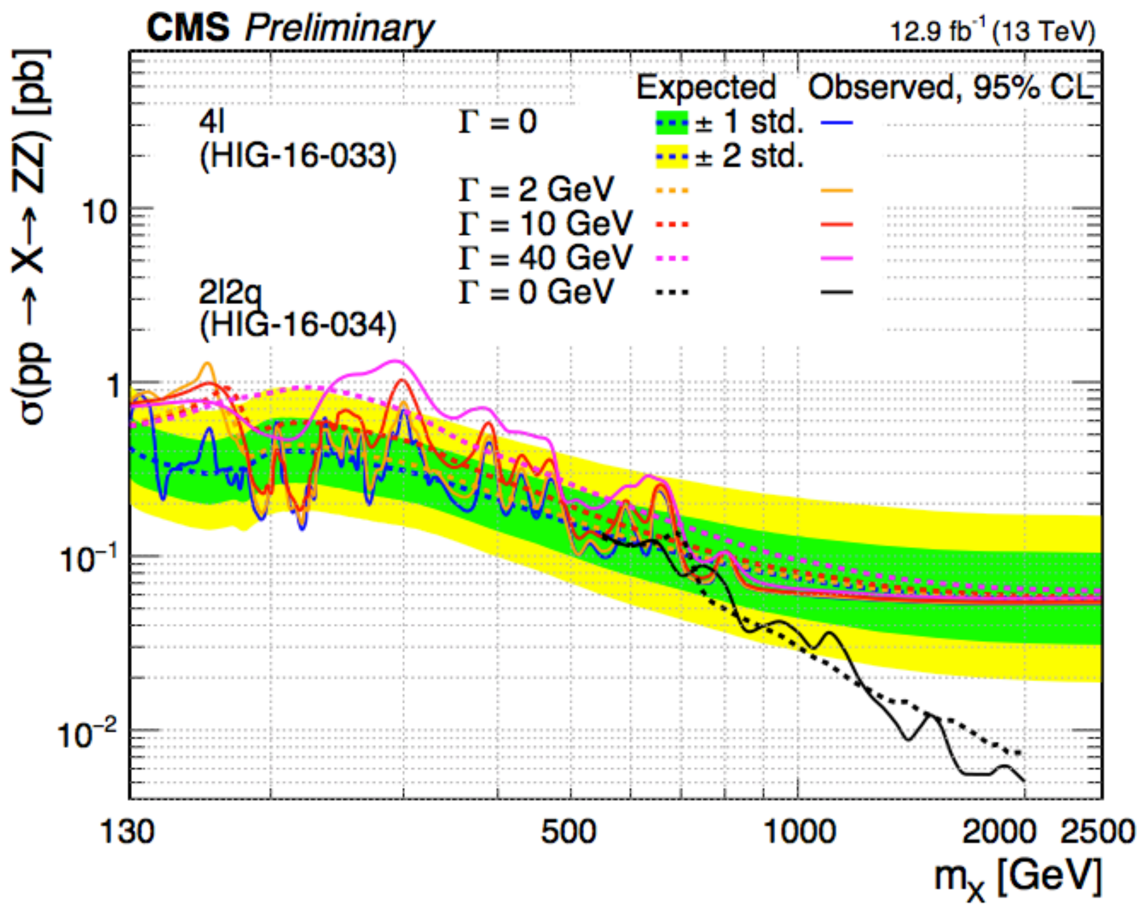
H→ZZ resonant search

CMS-HIG-16-033, HIG-16-034





- Search for spin-0 resonance with any different width
- Interference among X, H, and background



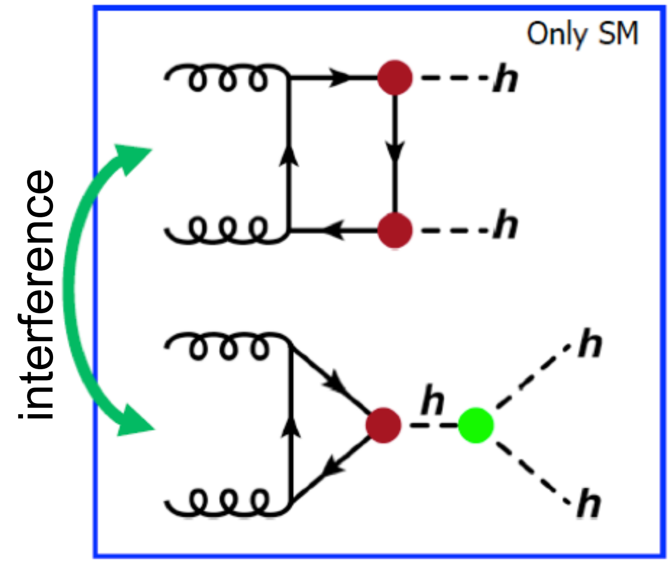
di-Higgs searches

- Destructive interference in SM
- Could be altered in BSM
- If constructive, it could be large enhancement
- In SM, only σ=33fb at 13 TeV
- Study different final states

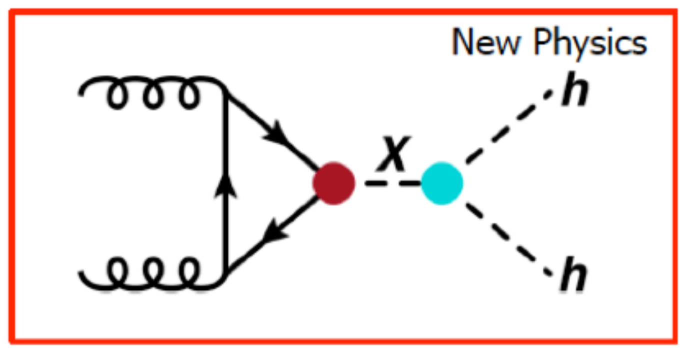
(X→)hh→

	BR	Mass scale
bbbb	34%	High
$bb\tau\tau$	7.3%	High
bbWW	27%	High
$bb\gamma\gamma$	0.26%	Low

non-resonant production



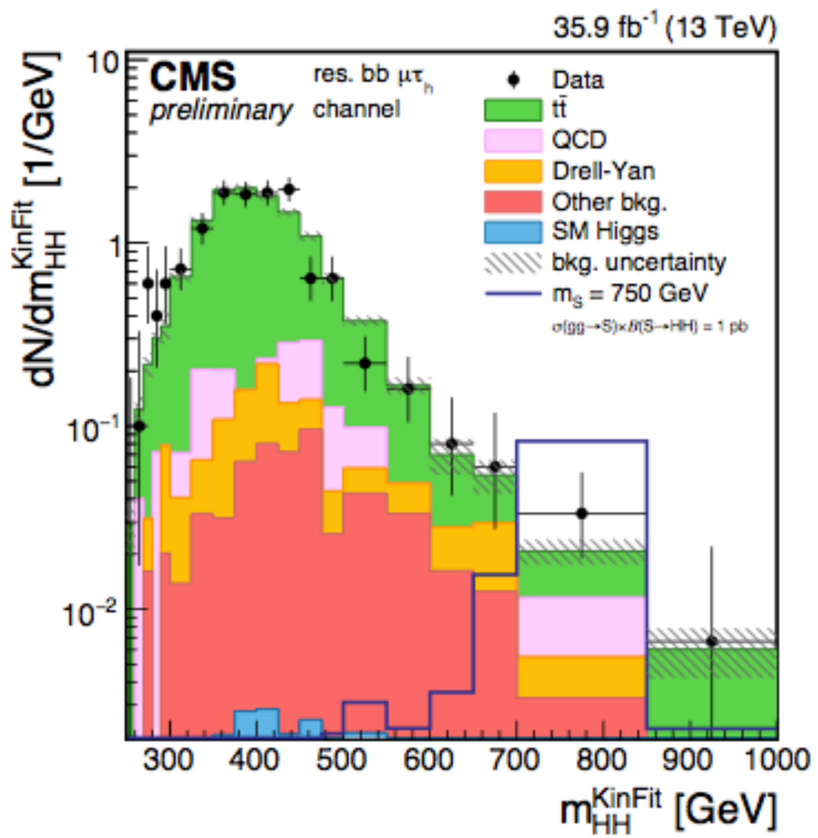
resonant production



Searches for HH production

CMS-EXO-15-008, CMS-HIG-16-012, CMS-HIG-17-002

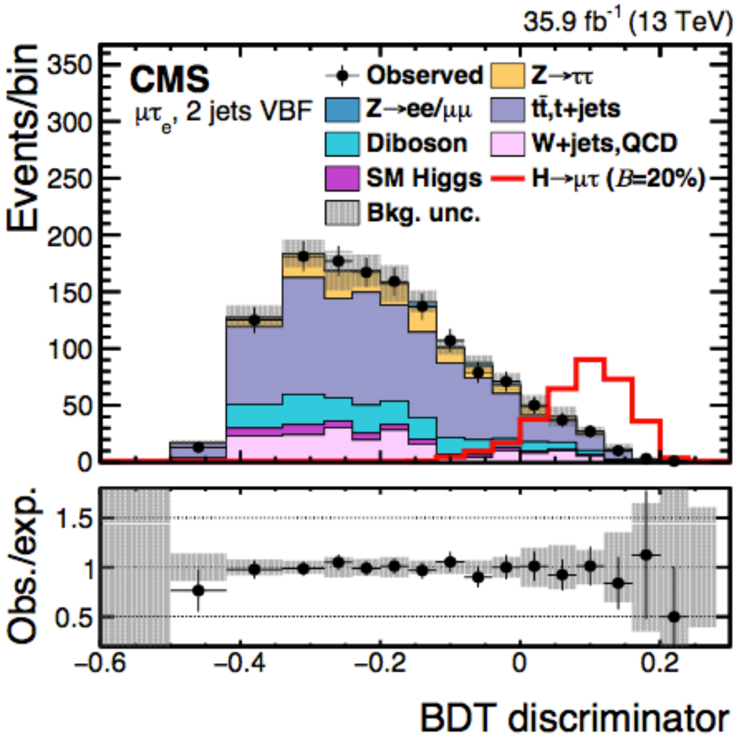
- Searches in: bbbb, bbWW, $bb\tau\tau$, $bb\gamma\gamma$, $\gamma\gamma$WW
- Resonant and non-resonant production
  - Double Higgs production to determine λ_{hhh}
  - Check couplings: $\kappa_\lambda=\lambda_{hh}/\lambda_{hhh}^{SM}$; $\kappa_t=y_t/y_t^{SM}$
  - BSM could enhance non-resonant hh production
  - $H\rightarrow h_{125}h_{125}\rightarrow bb\tau\tau$
- h_{125} decay products nearly collinear
  - boosted "single" merged jet ($\rightarrow$bb)
- use $\tau_e\tau_h$, $\tau_\mu\tau_h$, and $\tau_h\tau_h$ final states
  - sidebands/inverted isolation to estimate bkg
- set limits as function of mass

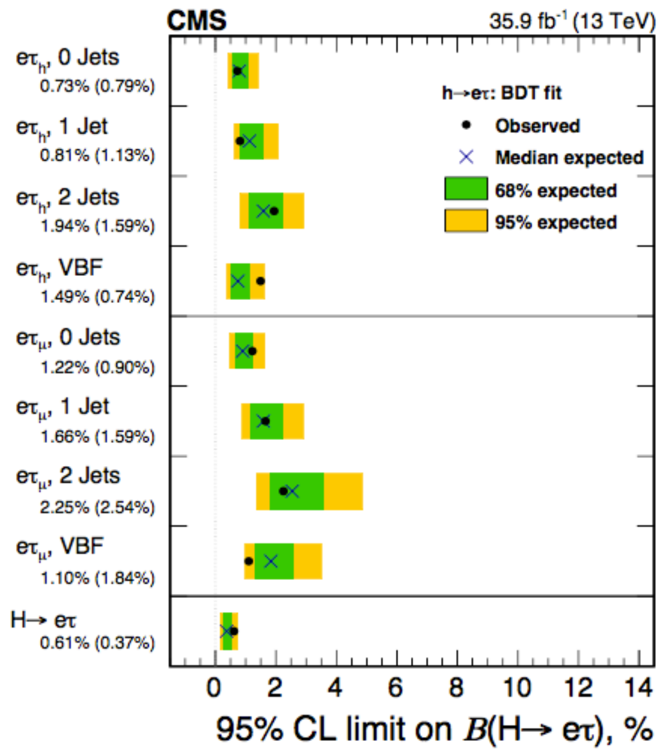


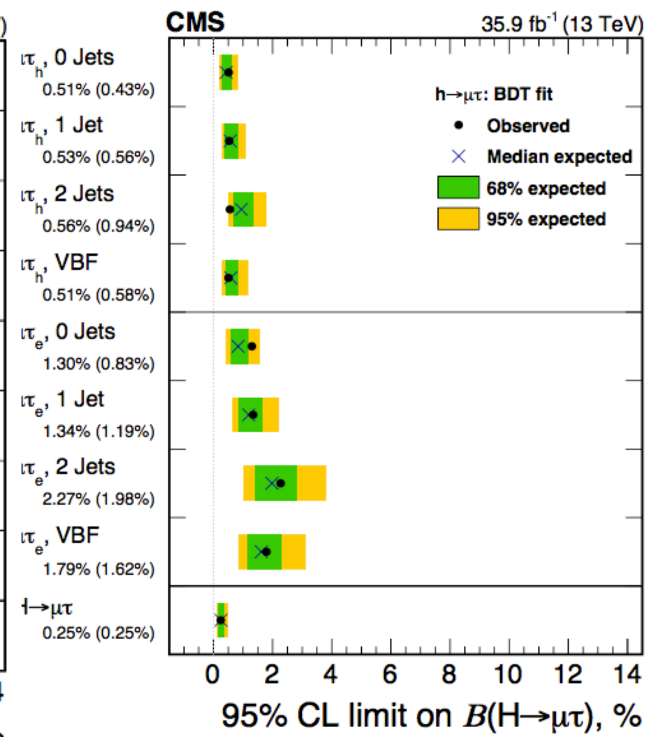
Rare decays

arXiv:1712.07173

- Search for LFV decays of Higgs boson to $e\tau$ and $\mu\tau$
- Previous 2.4σ hint in Run1 data not confirmed

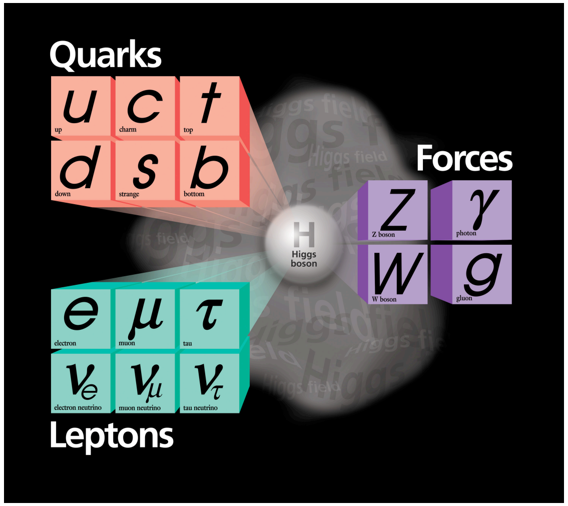




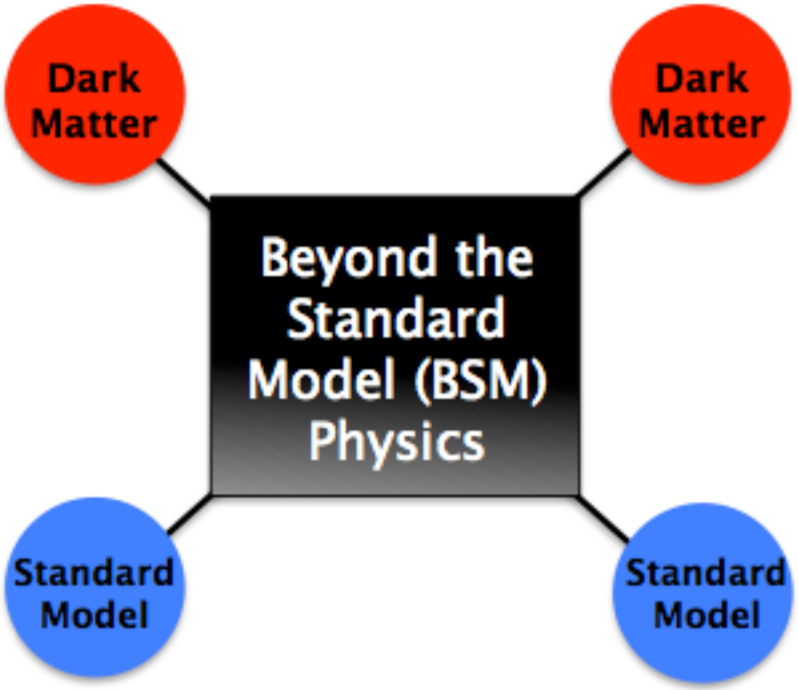


$\Rightarrow$Stringent limits well below 1%

Searching for DM



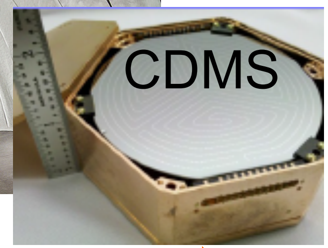
Stable(-ish) particles:
- Anti-nuclei
- Photons
- Anti-protons
- Positrons
- neutrinos



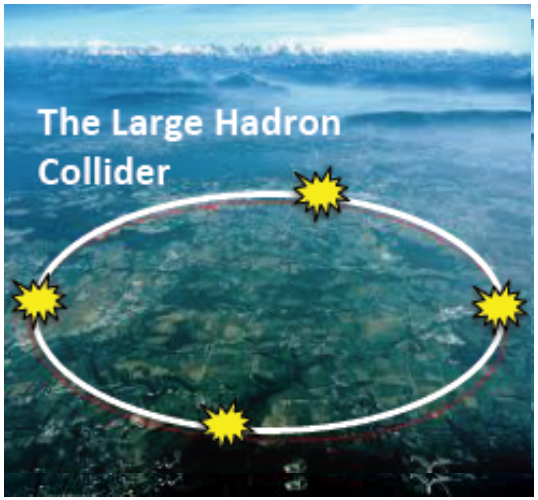
BSM:
- Supersymmetry, neutralinos, gravitinos
- Extra-dimensions
- Axions(-like) particles
- Sterile neutrinos

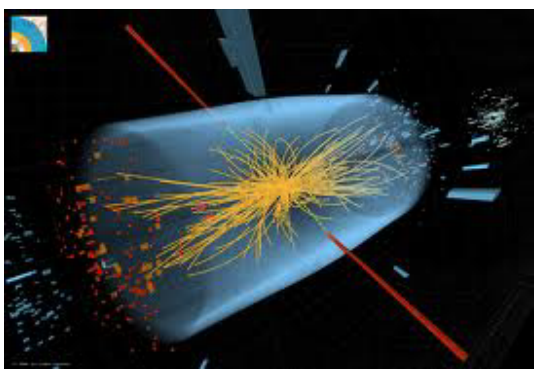
Searching for DM

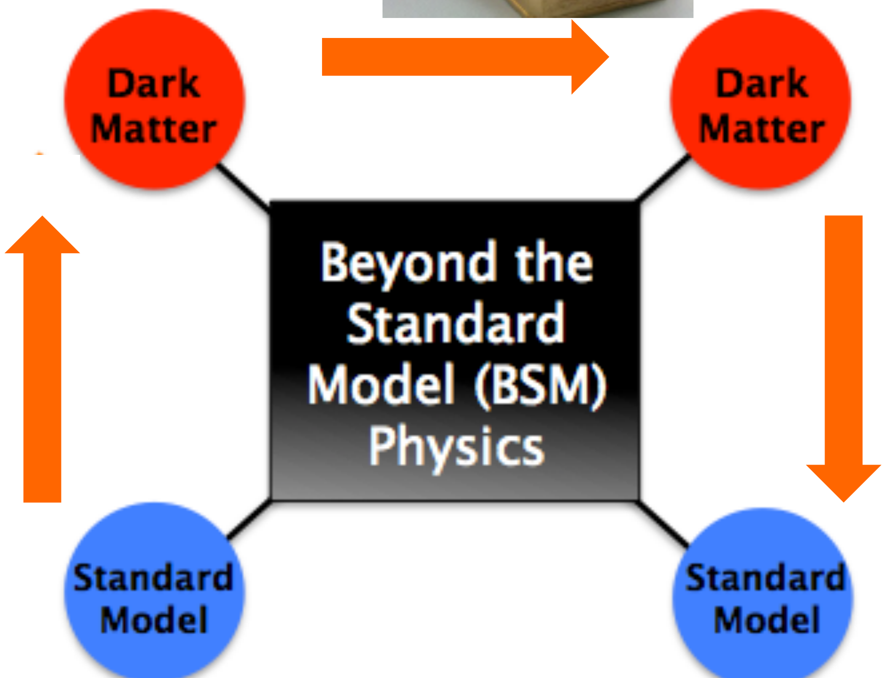
Direct Detection



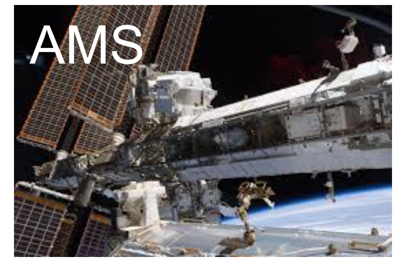
Particle Colliders

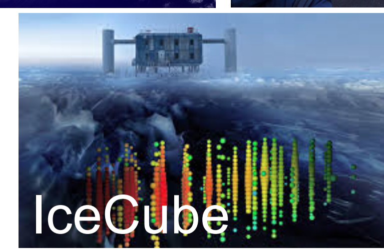






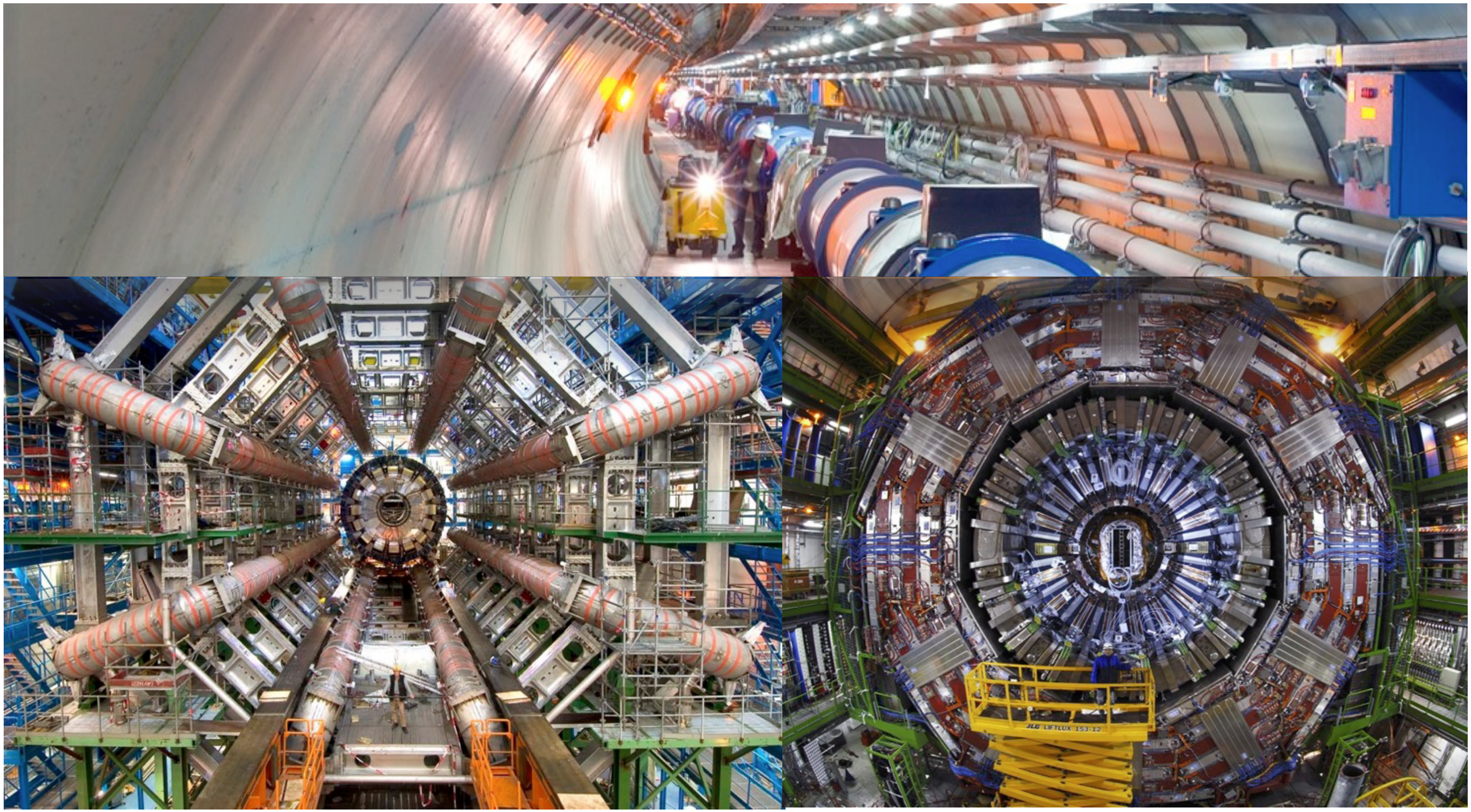
Indirect Detection





DM at the LHC

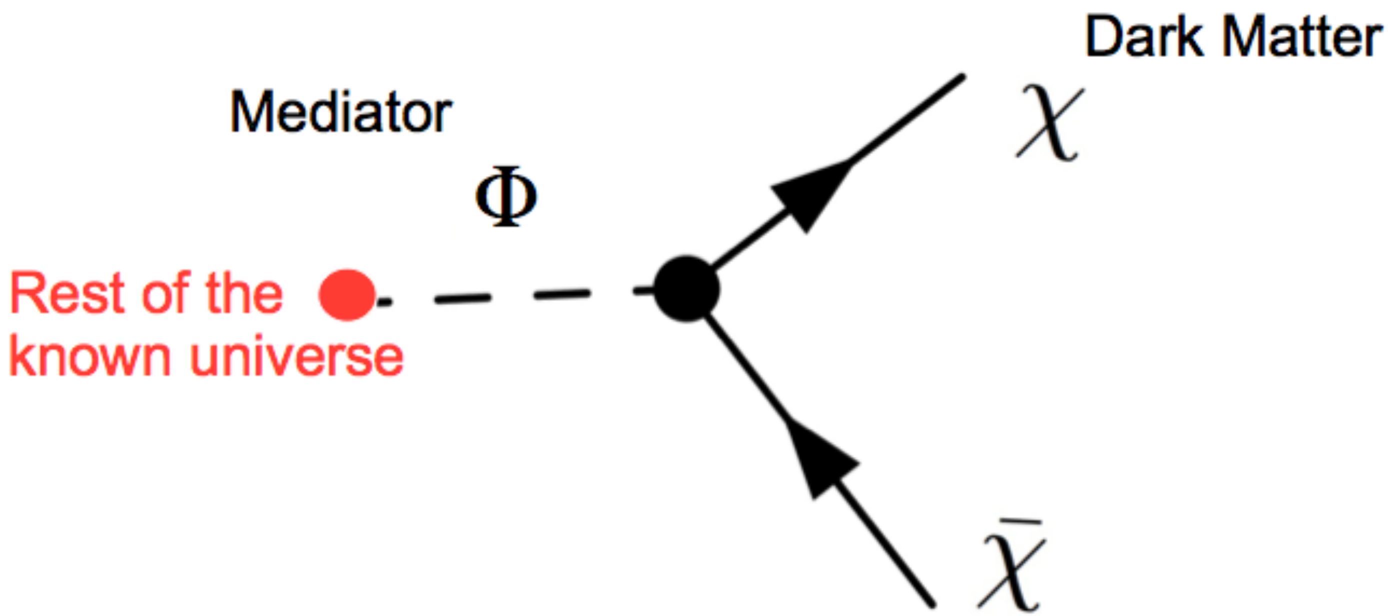
- CMS/ATLAS experiments not designed for DM searches



Dark Matter

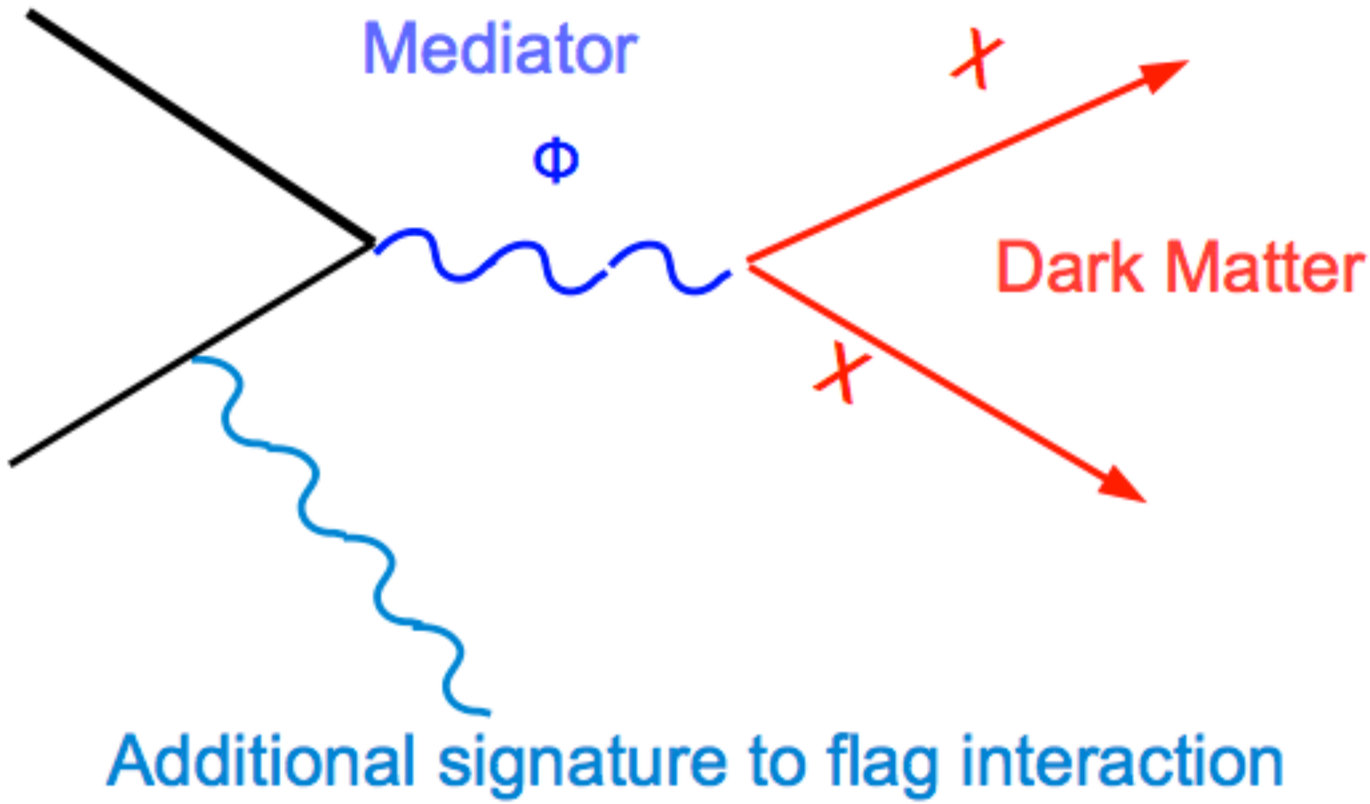
How do we find DM?

- Need to understand how it interacts with Universe
- Traditionally through a mediator
- Yields at least two new particles



How do we find it: @LHC

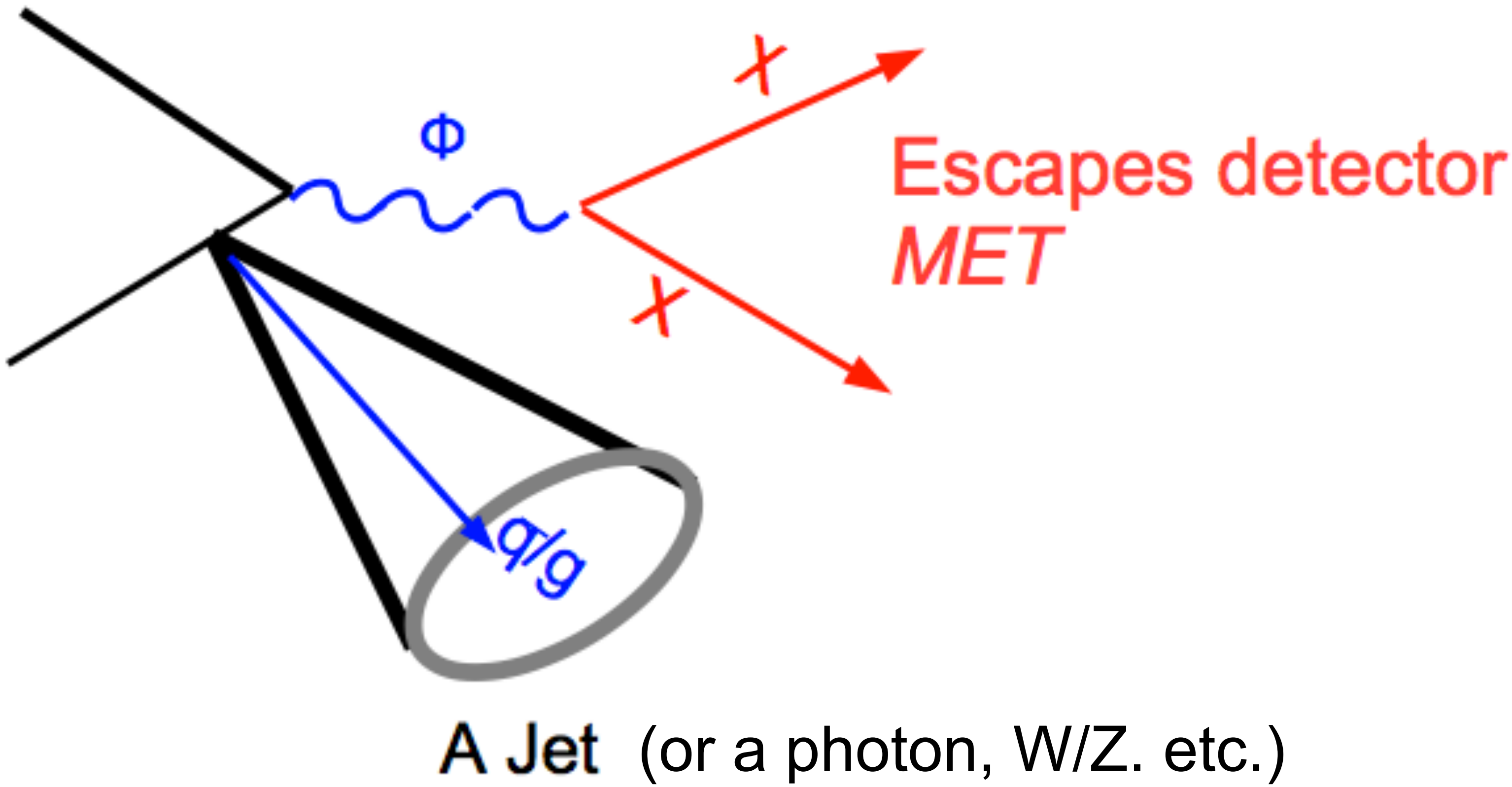
- Produced it through a mediator



DM searches at LHC

How do we find DM at the LHC?

- DM production gives MET signature

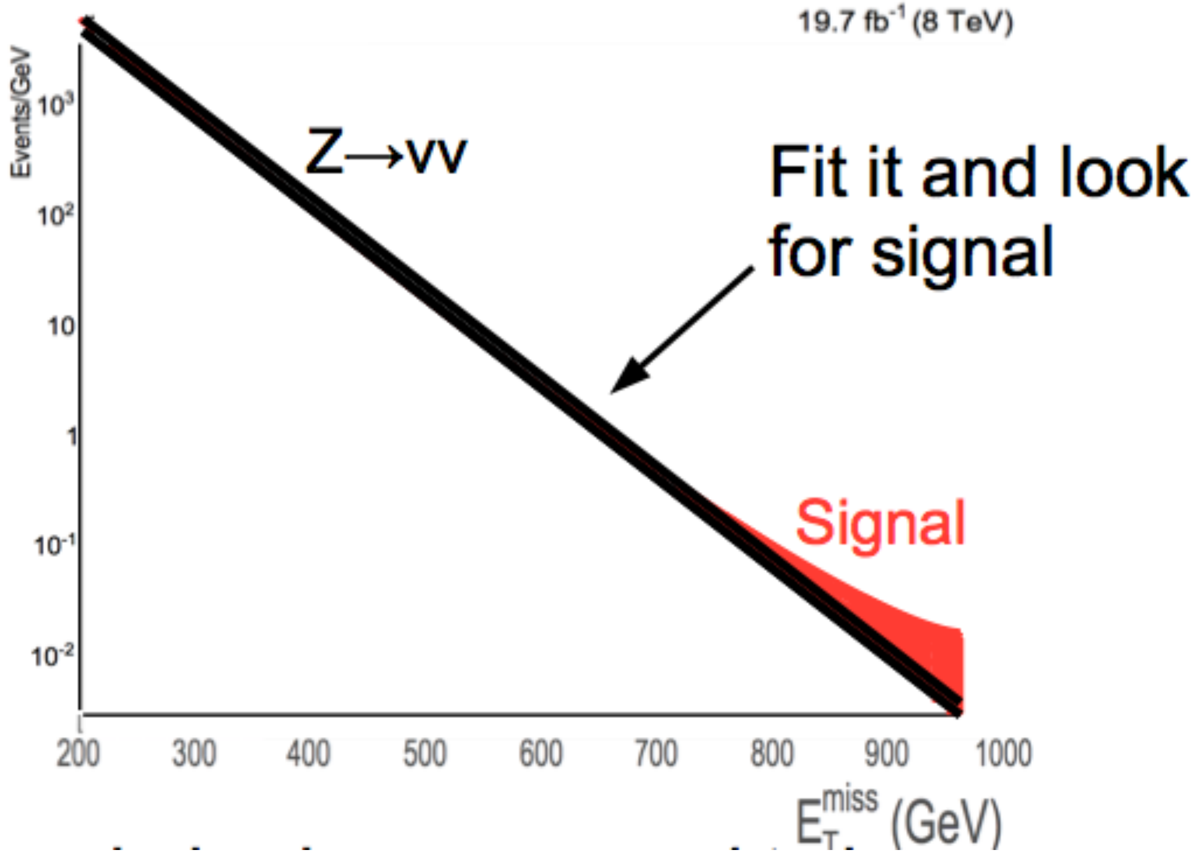


(or a photon, W/Z. etc.)

DM searches: backgrounds (cont.)

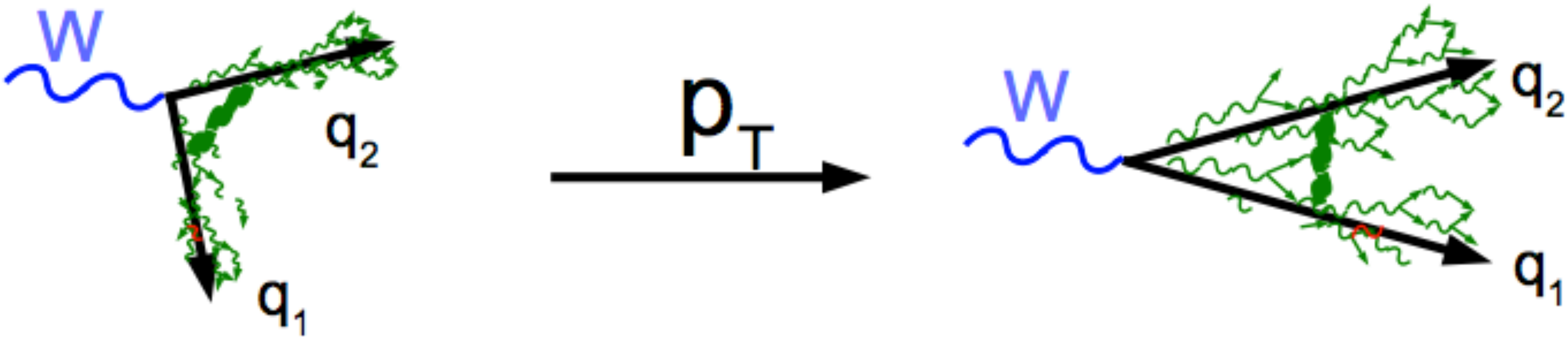
How to discriminate signal against the background?

- Can fit the shape and look for signal



Build a V-tagger

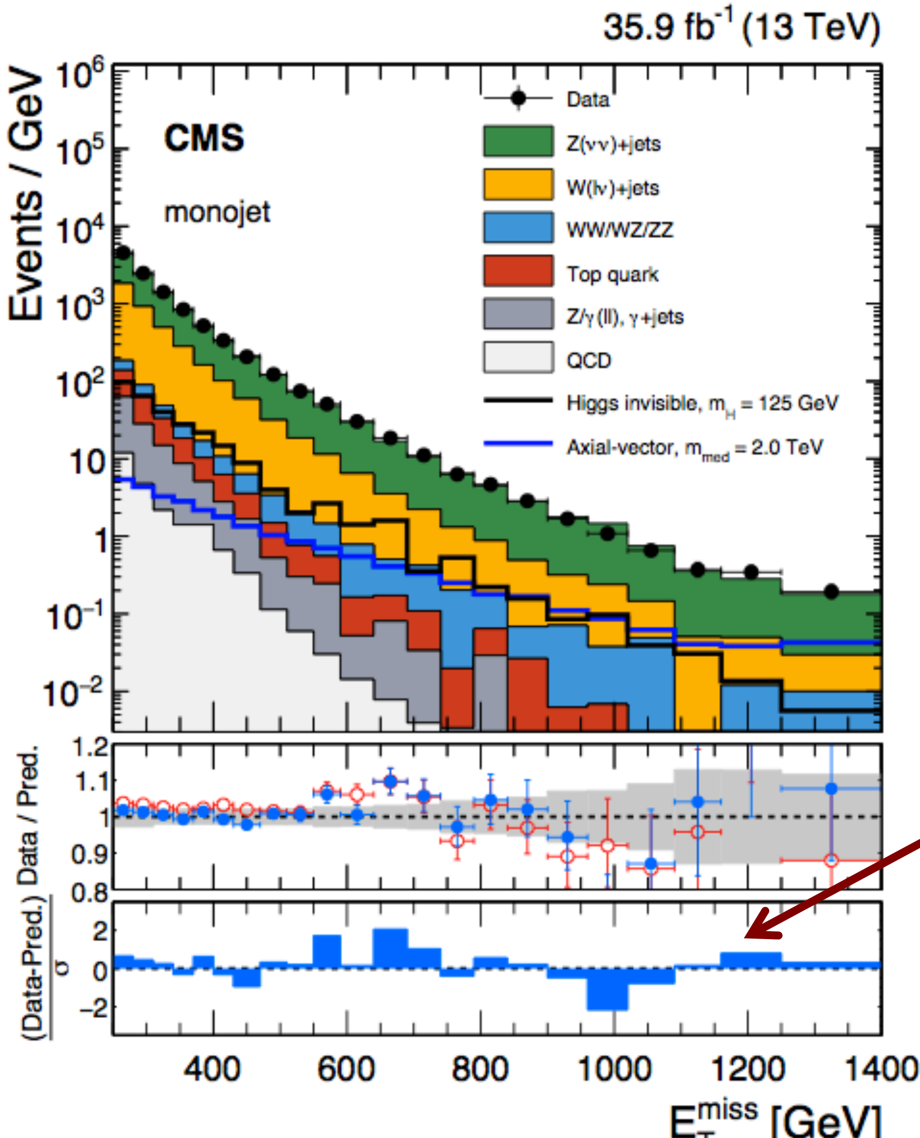
- Two jets are more collimated at high pT



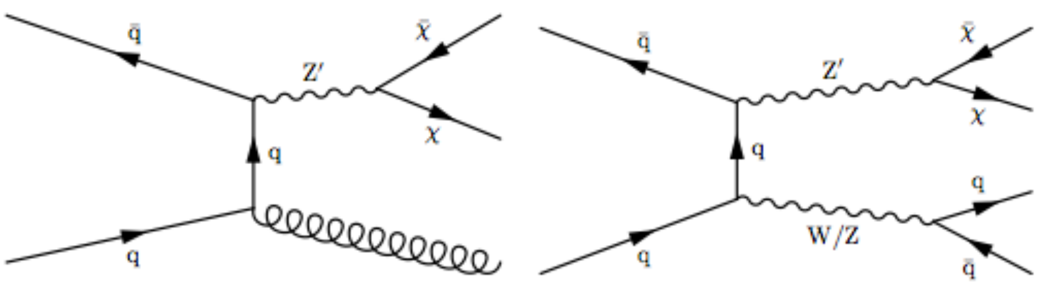
- At low pT jets are "resolved"
  - –Focus on reconstructing di-jets with mass near W mass
- At high pT get one "fat" jet
  - –Focus on identifying one jet with mass near W mass
- Use additional variables to improve discrimination

DM+jet/V

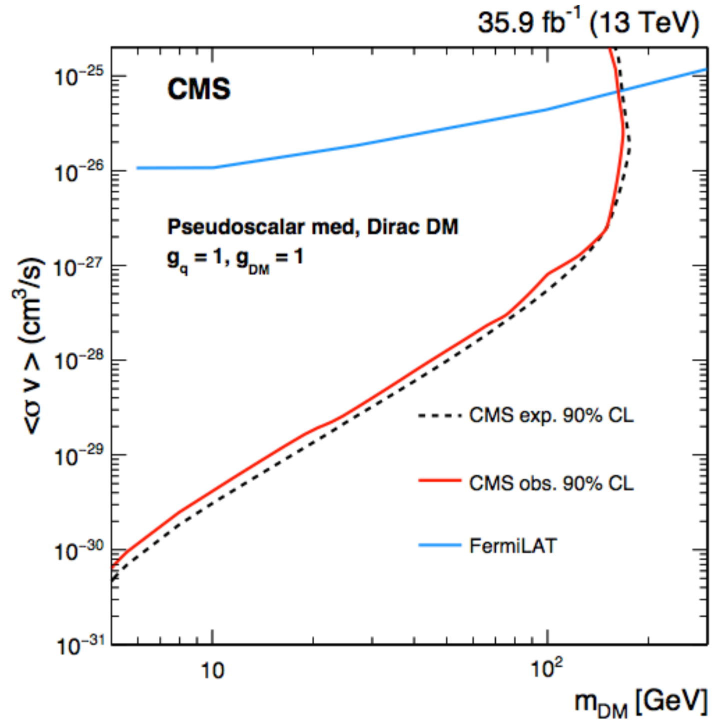
arXiv:1712.02345



DM search in mono-jet/V



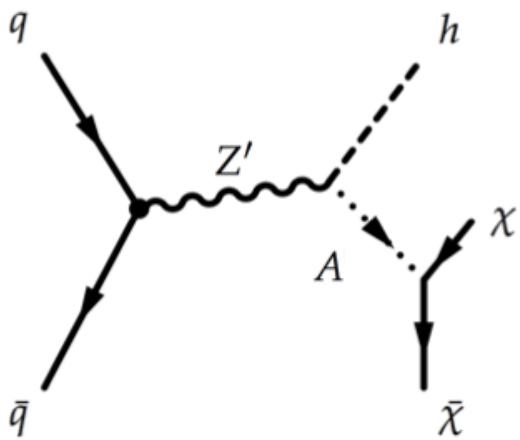
Need good control of systematics

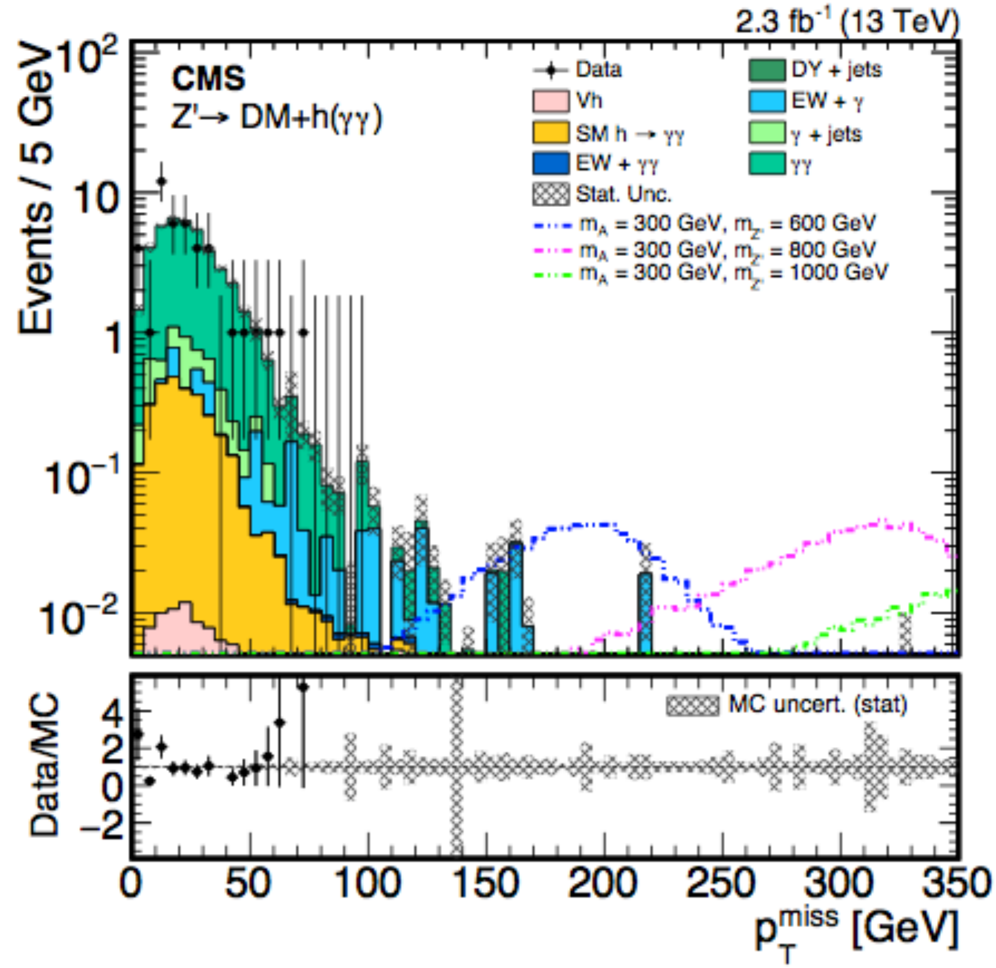


DM+Higgs

arXiv:1703.05236

- DM search with H(→bb,γγ)
- Model dependent search
- Z' 2HDModel

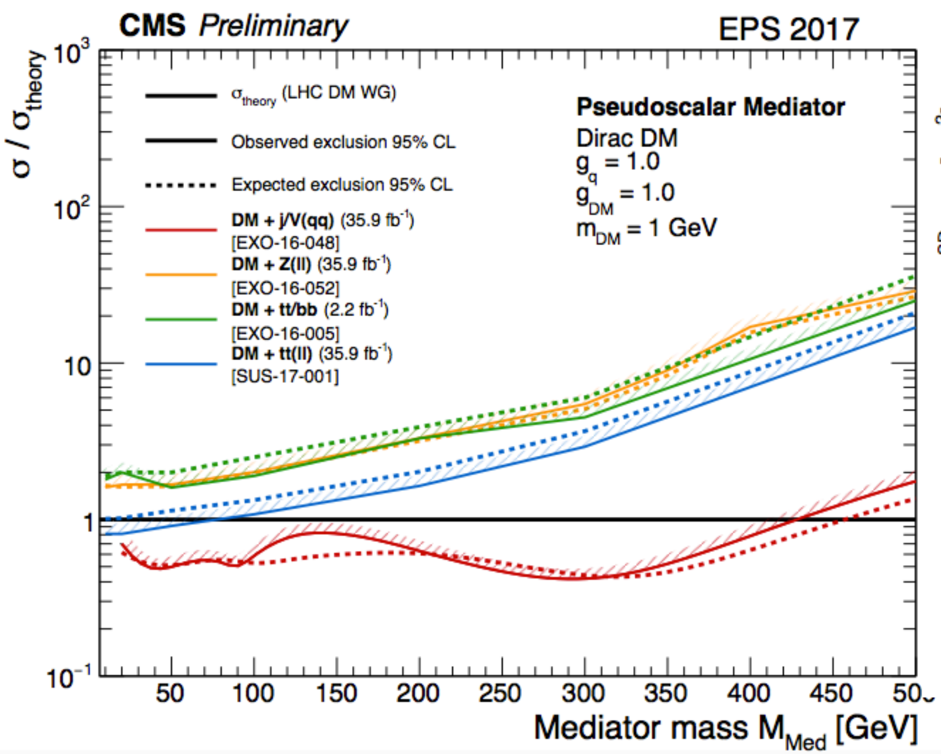


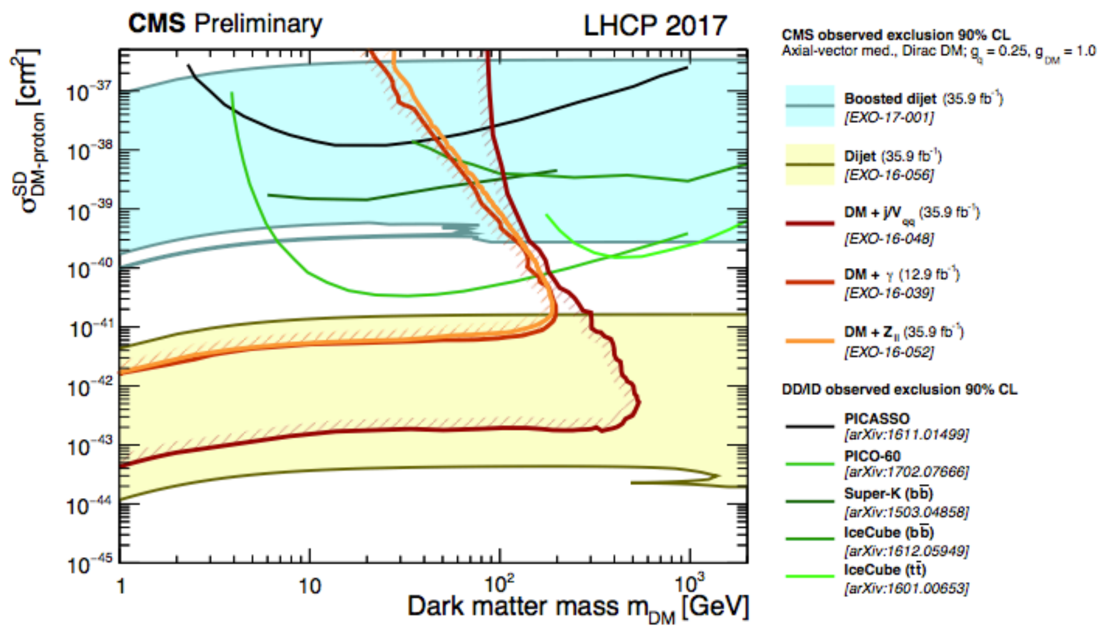


- No significant excess
- Set limits for coupling g=0.8

Experimental results

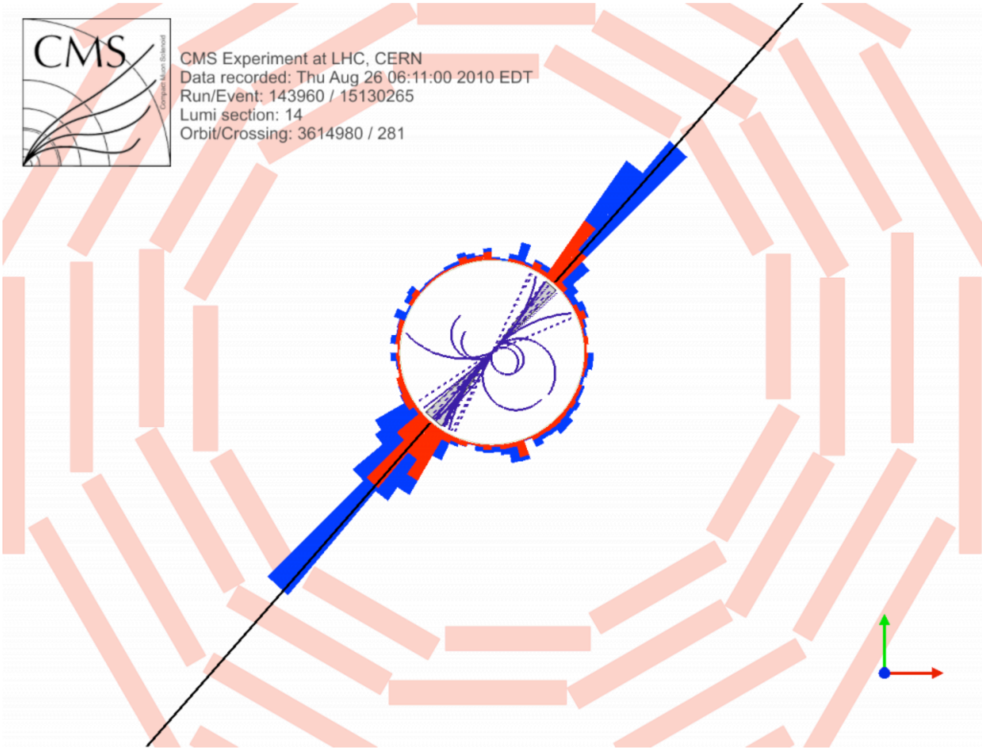
- Limits for given couplings between SM and DM interaction
- Competitive limits at low masses wrt other experiments





Search for heavy resonances

- Heavy BSM resonances (>1TeV) may decay into SM bosons (W,Z, H)
- Several final states
- Experimental challenges
  - SM bosons decay mostly to quarks
  - Due to large Lorentz boost, decay products merge into single jet
  - Clustered within a large-cone jet (R=0.8)
- Look into jet substructure
  - Jet "grooming": get rid of soft jet components from UE/pileup, keep constituents from hard scatter
  - Apply filters (mass drop, pruning, trimming)

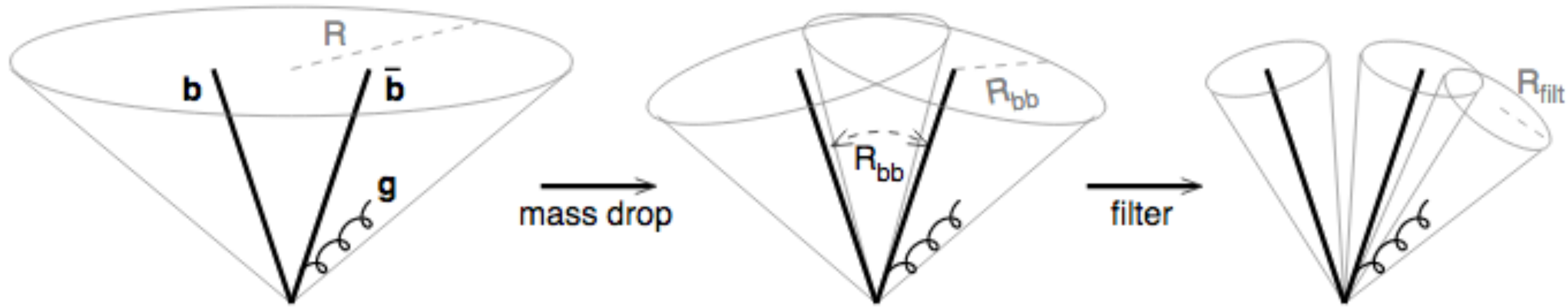


Jet grooming

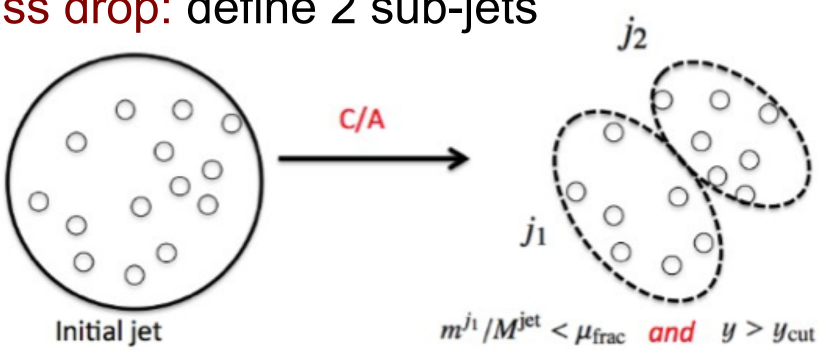
arXiv:0802.2470

Mass drop/filtering

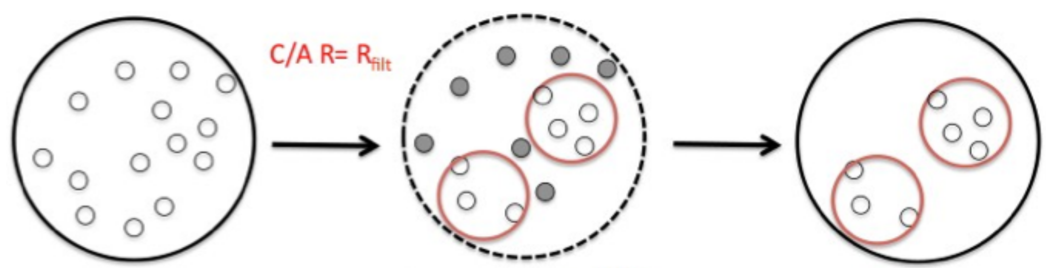
- Identify approx. symmetric sub-jets (with smaller mass than sum)



Mass drop: define 2 sub-jets



Filtering: re-cluster j1, j2 constituents

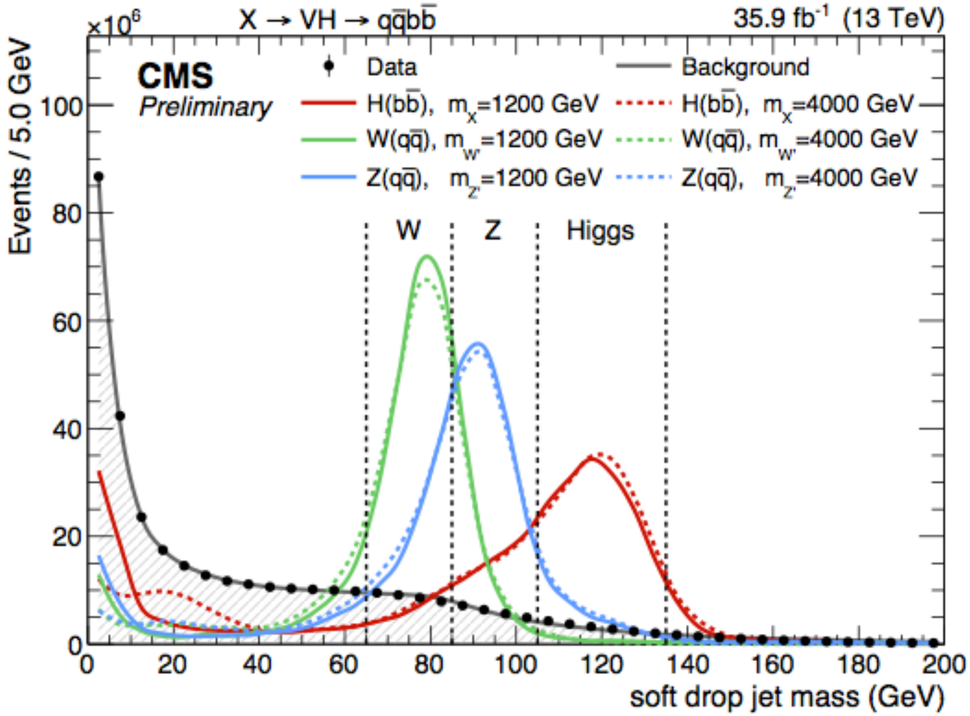


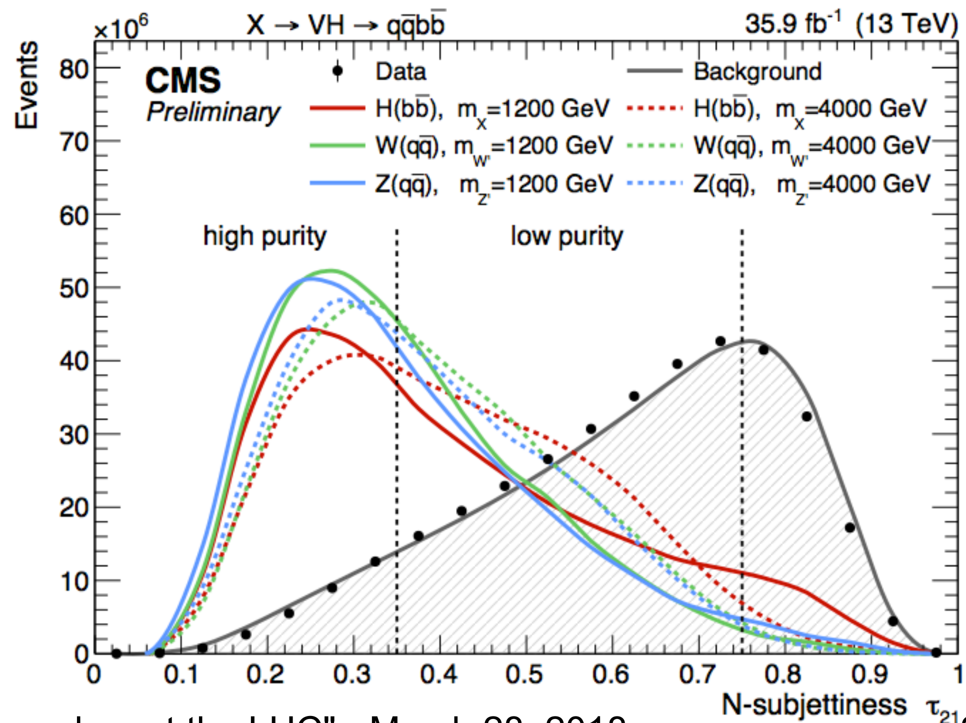
W, Z, H reconstruction

CMS-B2G-17-002

- Grooming and jet mass
  - Pruning
  - soft drop (stable w/pileup, and good jet mass resolution ~10%)

- Vector boson tagging (V→qq)
  - n-subjettiness τ_{21}: how consistent with 2 sub-jets
  - Categorization according to purity: high (<0.35) and high (>0.35)

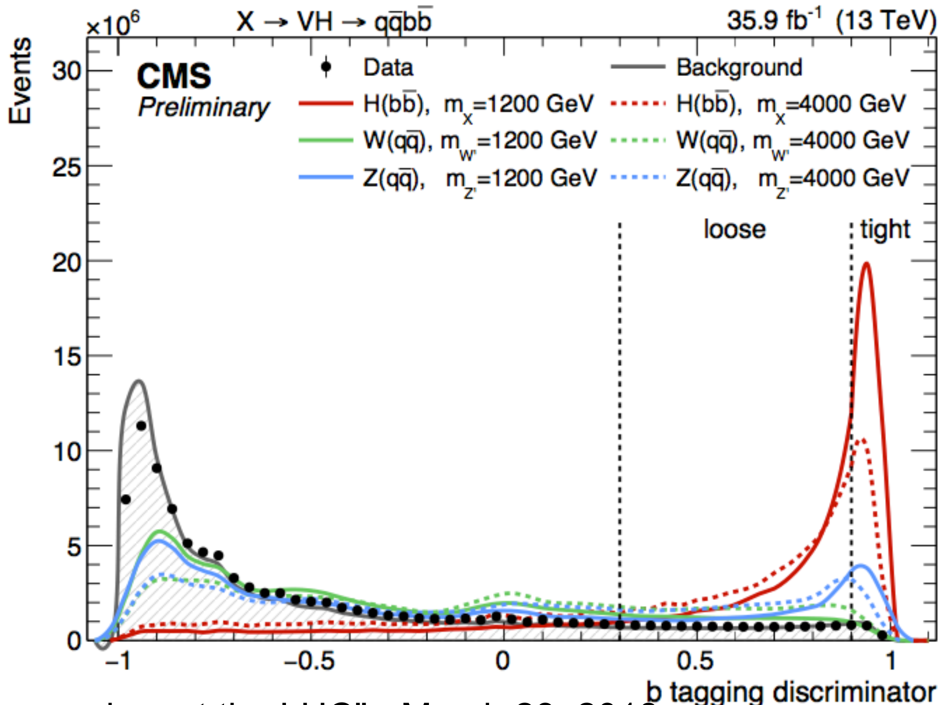




W, Z, H reconstruction (cont.)

CMS-B2G-17-002

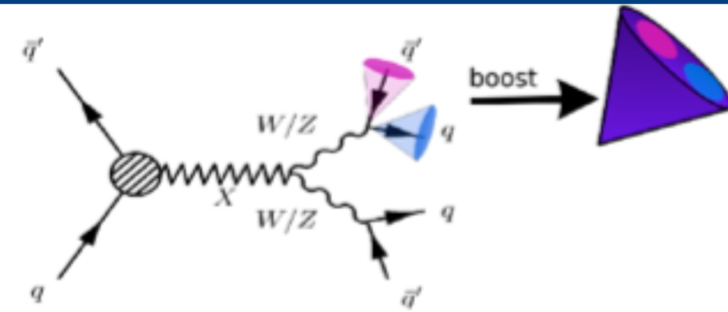
- Higgs boson tagging (H→bbar)
  - Double b-tagging
  - Exploit b-tagging to identify two b-quarks in same jet
  - Soft-lepton information
  - Combines tracking and vertexing in MVA

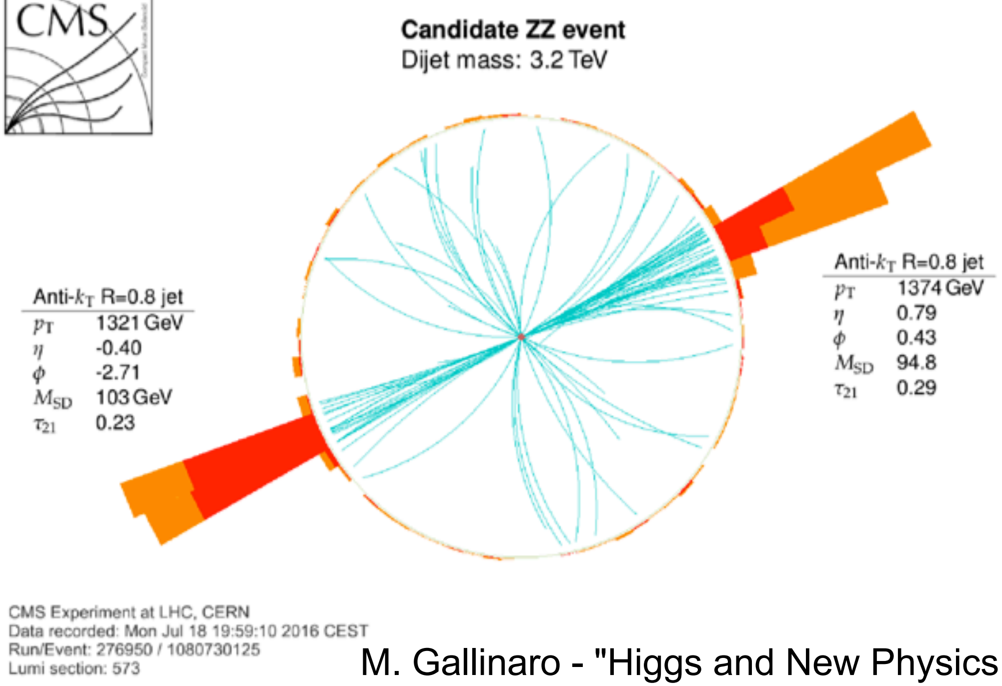


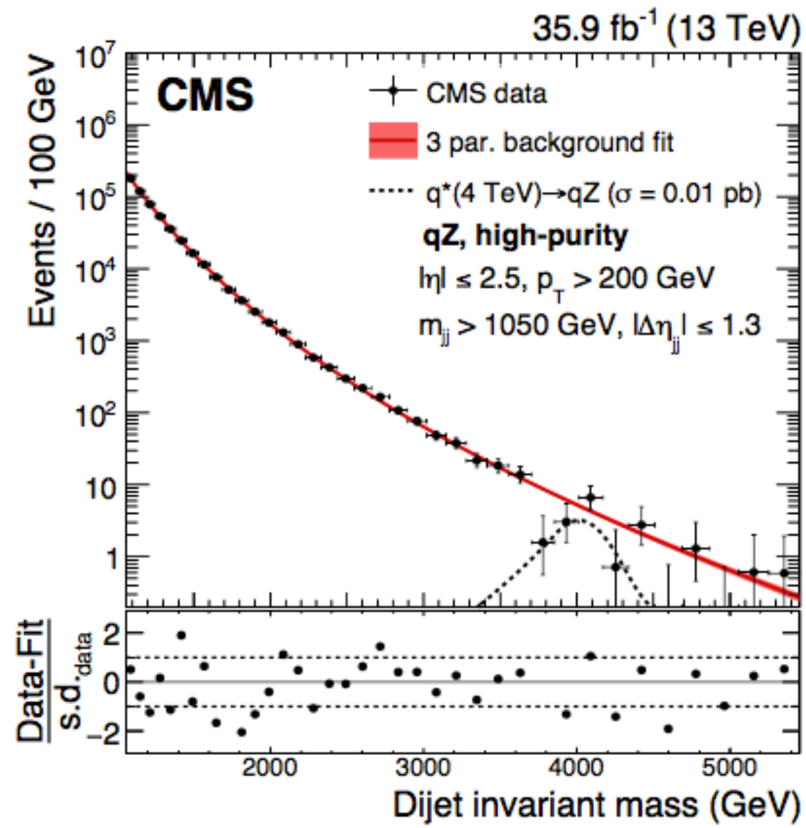
X→VV→qqqq

arXiv:1708.05379

- All hadronic resonance search with single (qV) or double (VV) V-tag
  - At least 2 back-to-back jets p_T>200GeV
  - Categorization (jet mass, τ_{21})
- Background estimation: "bump hunt" fit data with power law



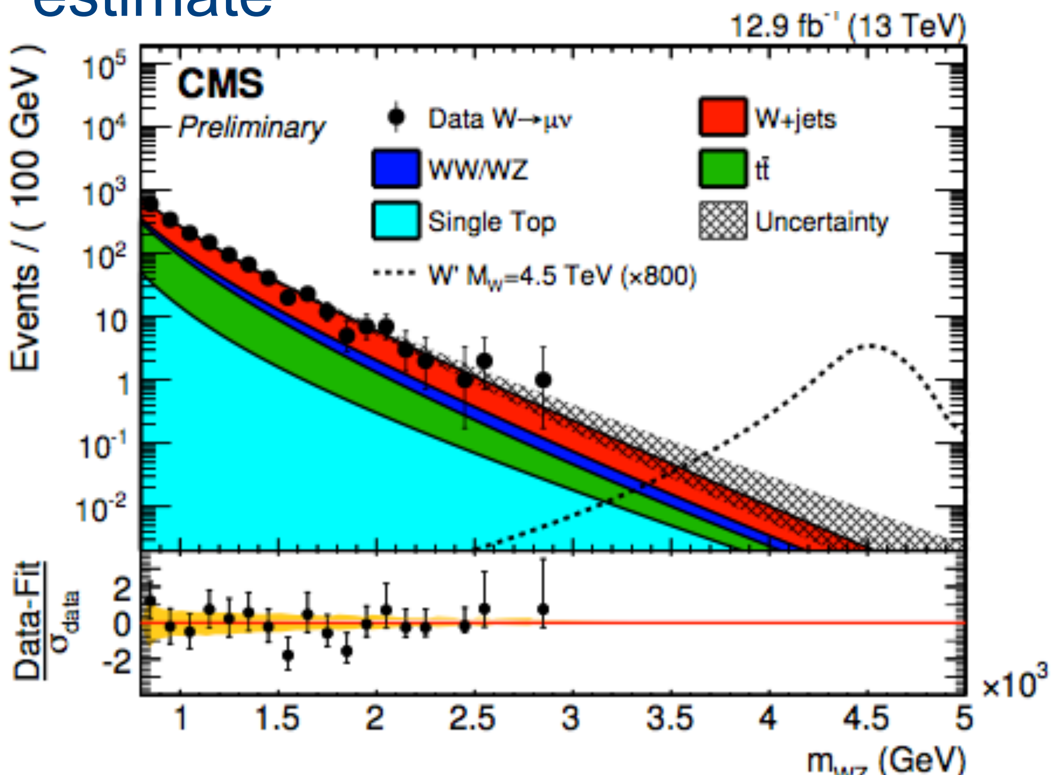


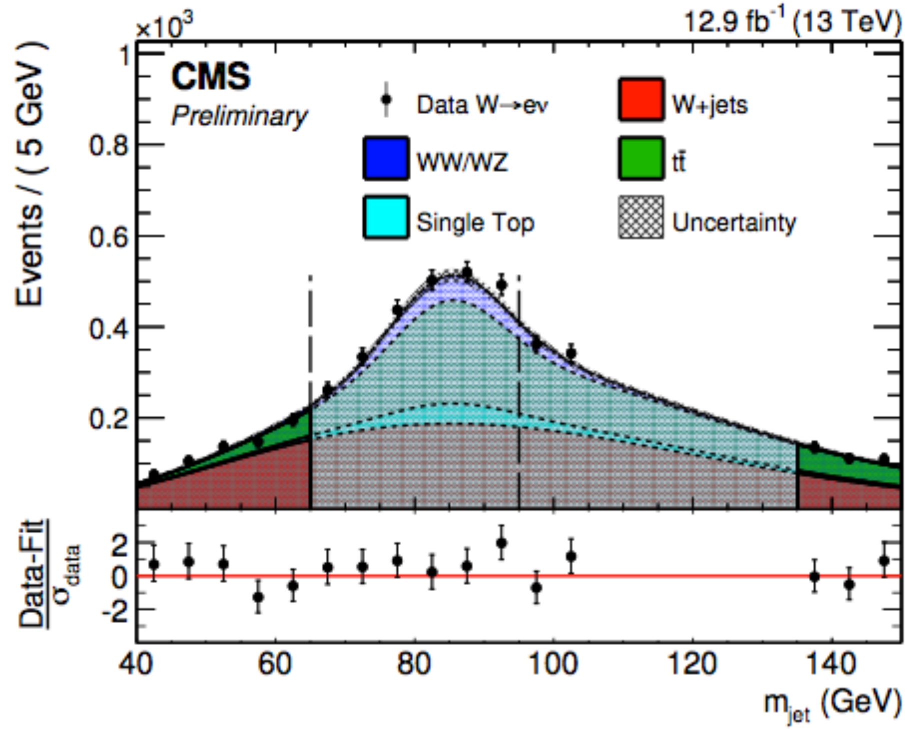


$X \to WV \to \ell\nu qq$

CMS-B2G-16-020

- Search for a resonance decaying to WV in leptonic channel
- Categorization in τ_{21} and W/Z mass
- Sideband+transfer function for bkg estimate



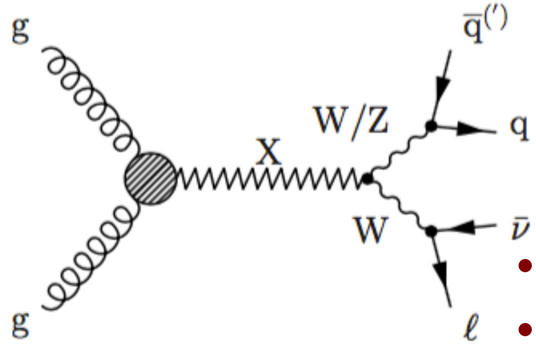


- Similar sensitivity to $Z(\ell\ell)V(qq)$ search
- Excluded up to 2 TeV

X→VH→ℓνqq

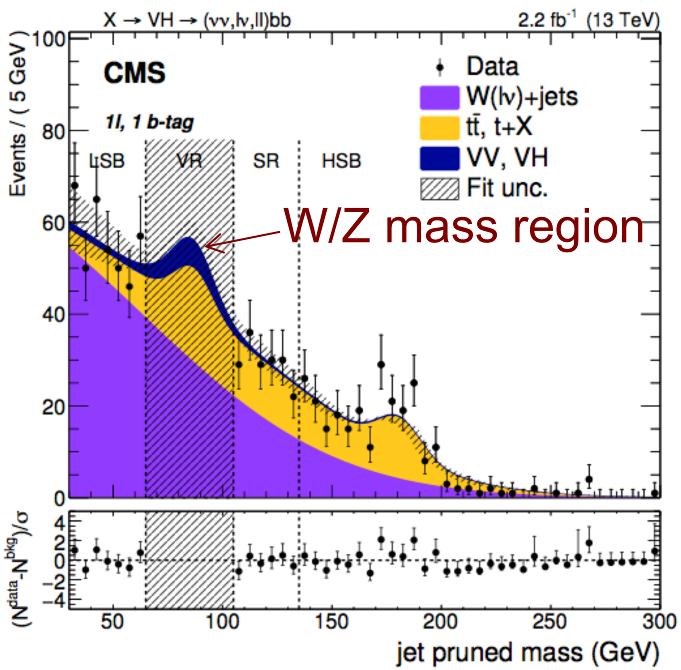
PLB 768(2017)137, arXiv:1802.09407

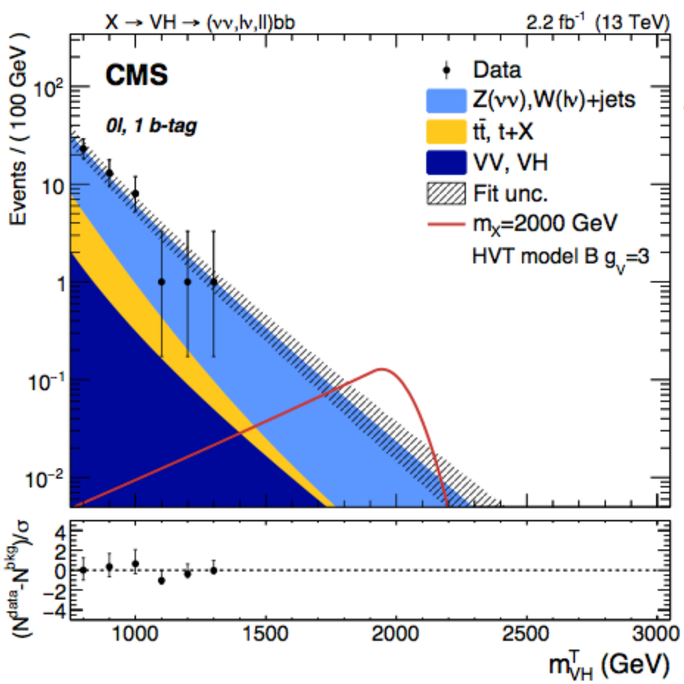
- Search for a resonance decaying to VH in leptonic channels
  - –Z→νν: transverse mass $m_T(VH)$
  - –W→ℓν: top control region
  - –Z→ℓℓ: high-efficiency dilepton ID
  - –H(bb) b-tagging

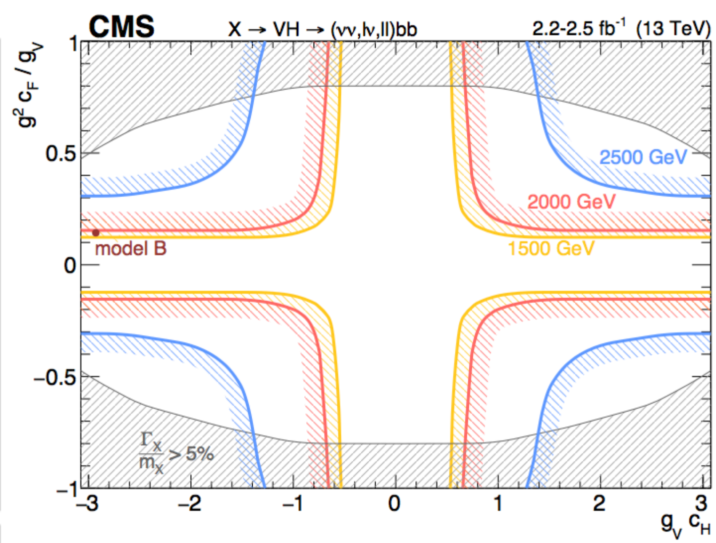


- Heavy vector triplet (Z', W')
- g_V, g_H (c_V, c_F): couplings

- Sideband bkg prediction



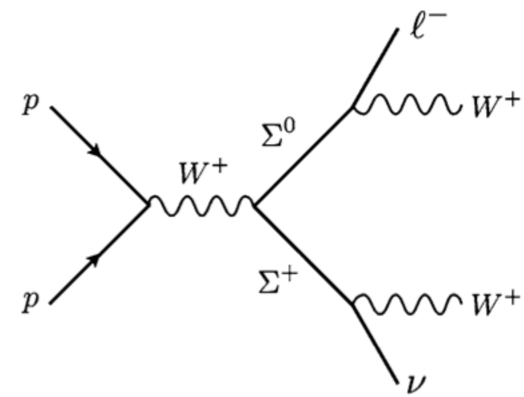


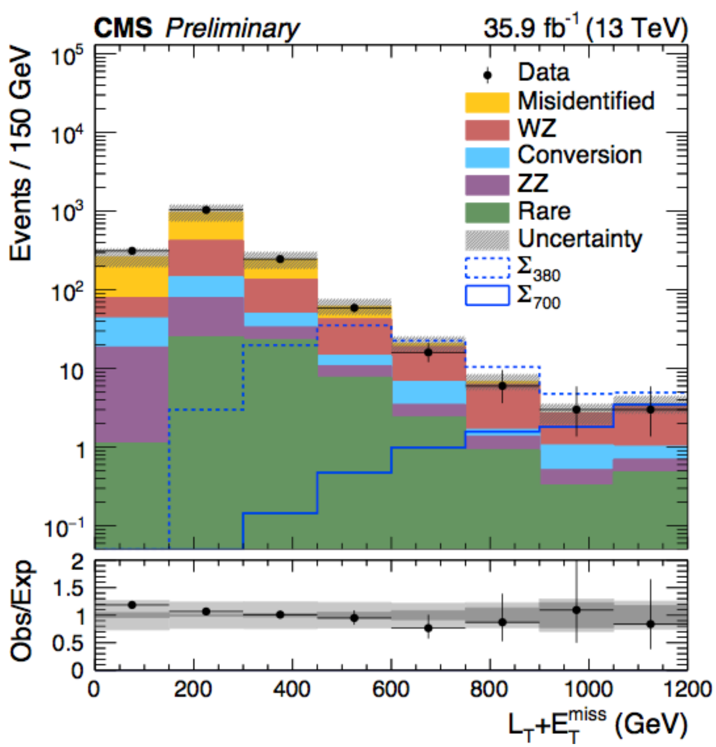


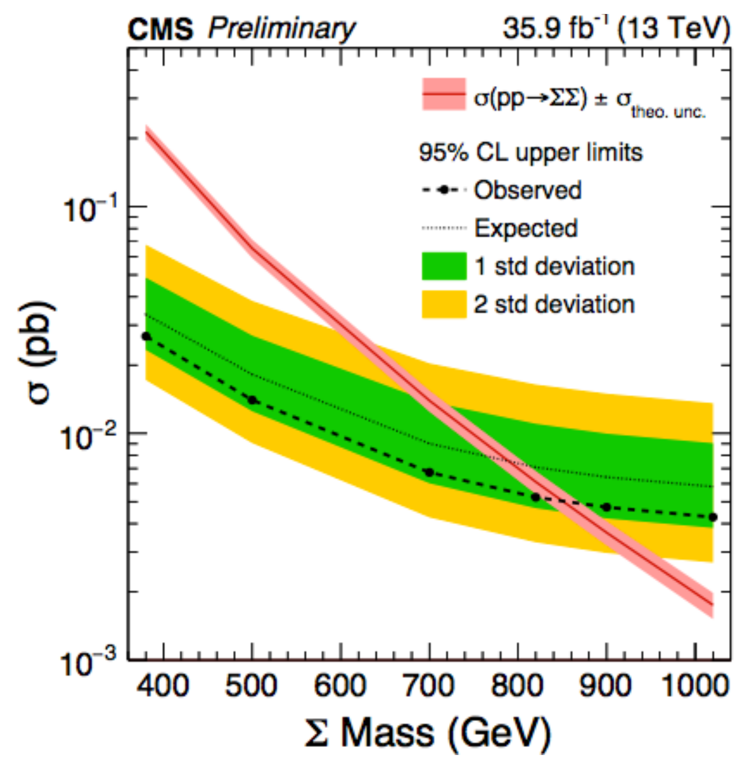
Search for multilepton final states

CMS-EXO-17-006, arXiv:1708.07962

- Type-III extension to SM
- Search for 3 or more lepton final states
- Pair production of W/Z/H→ΣΣ
- Scalar sum of lepton p_T (L_T)
- Bin and count (L_T+MET)

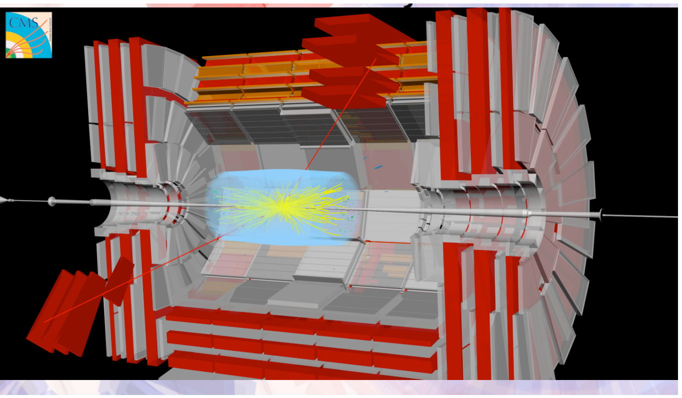


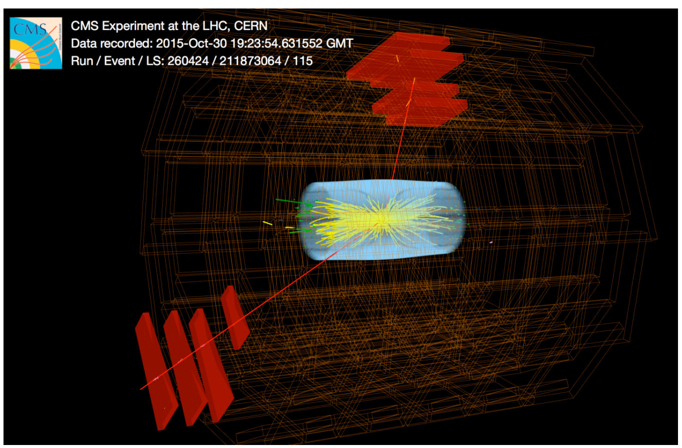


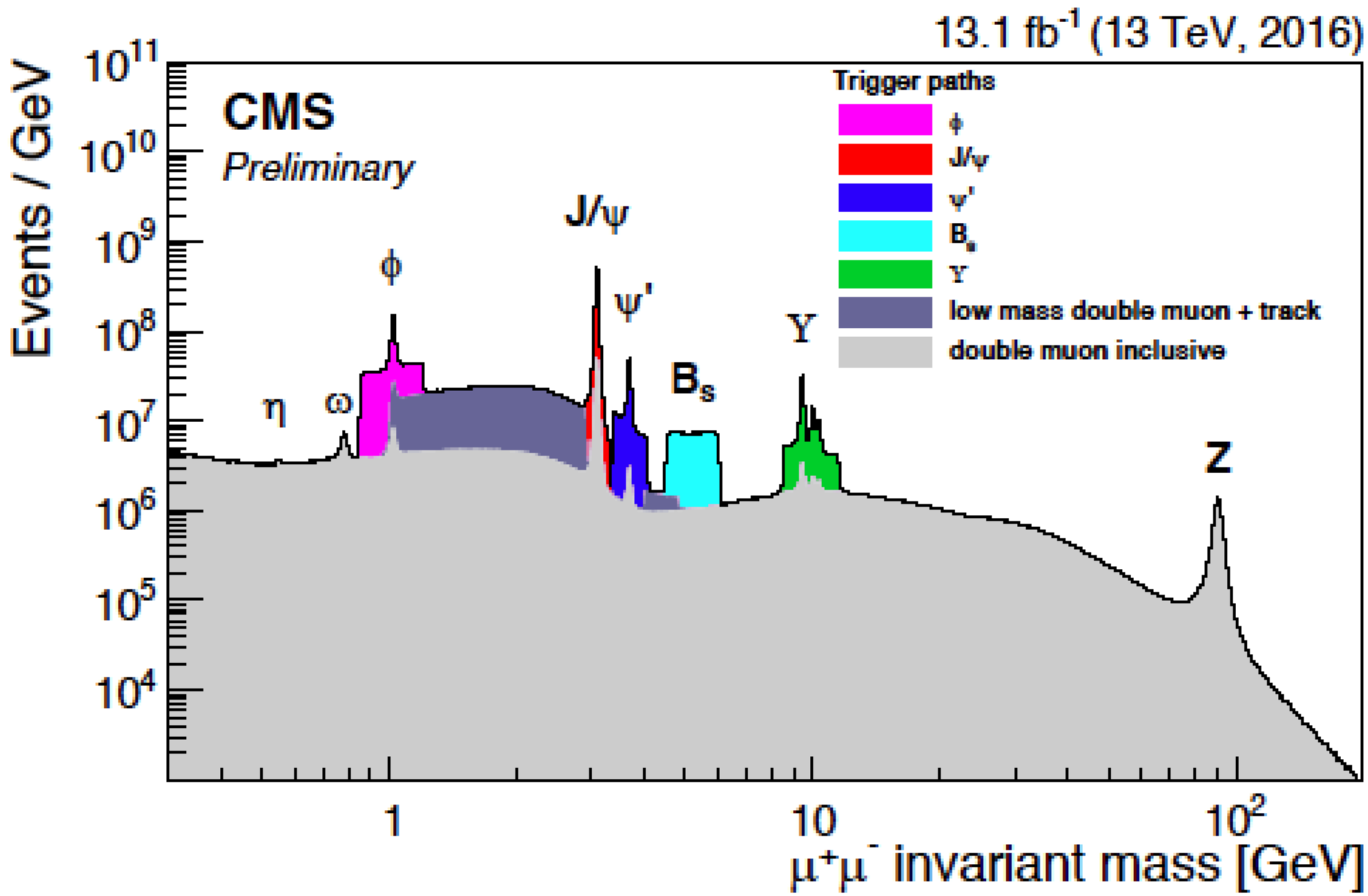


Resonances

- Di-muon events: a re-discovery of the SM



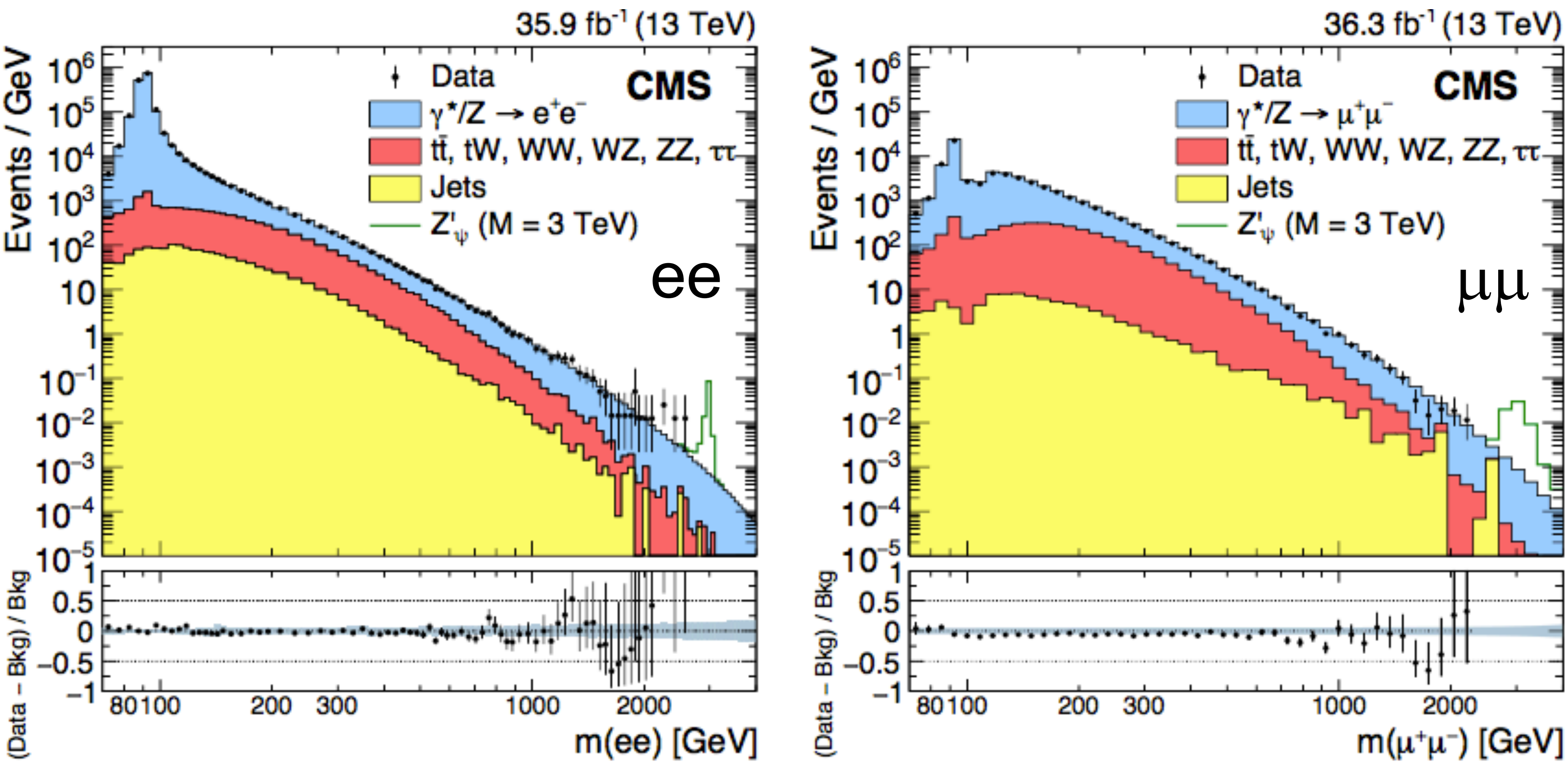




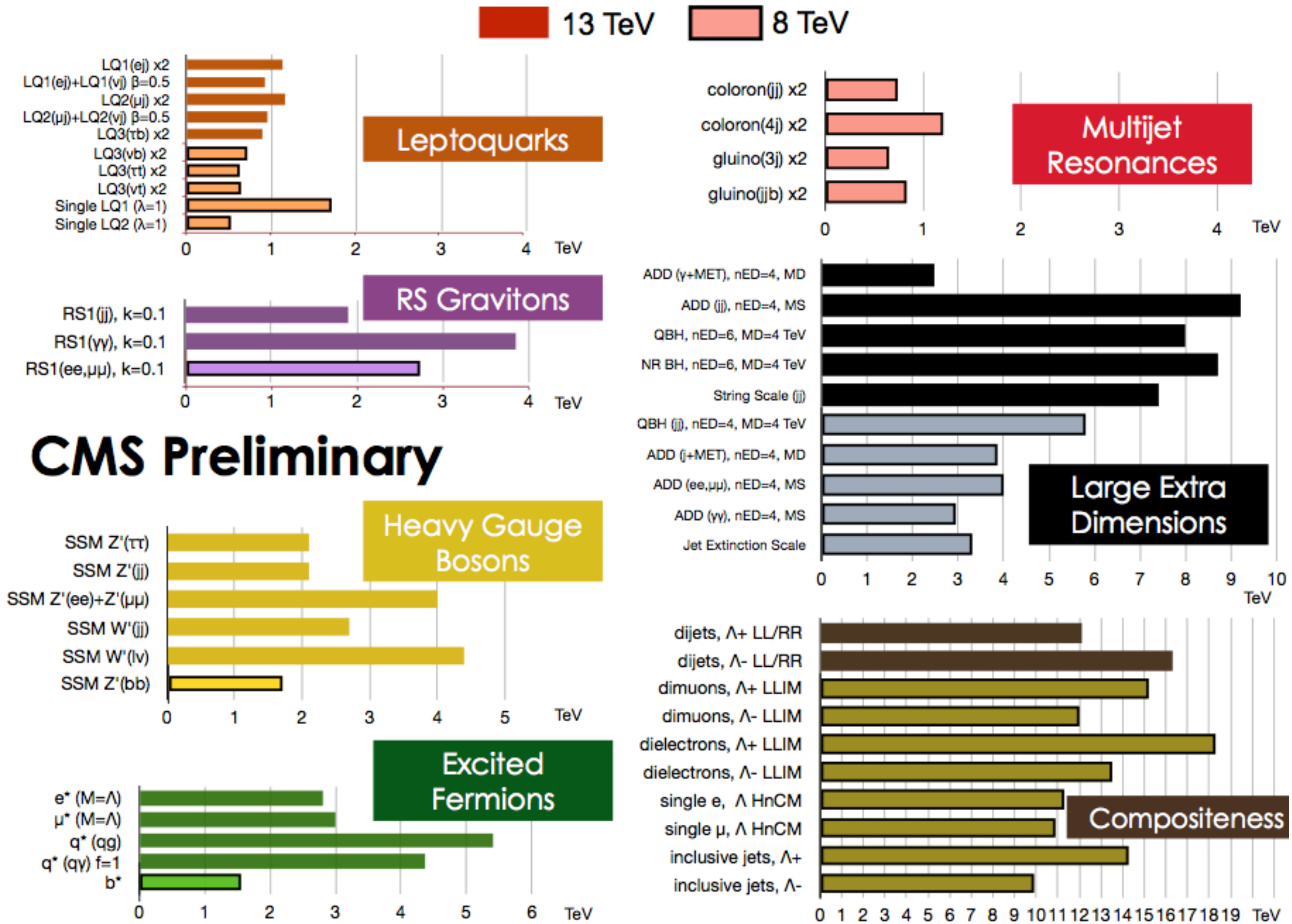
Dilepton resonances

arXiv:1803.06292

- Search for dilepton (ee,$\mu\mu$) resonance



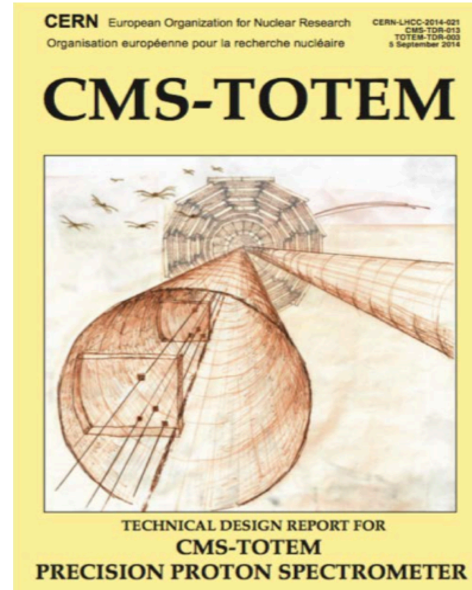
Resonance searches: Summary



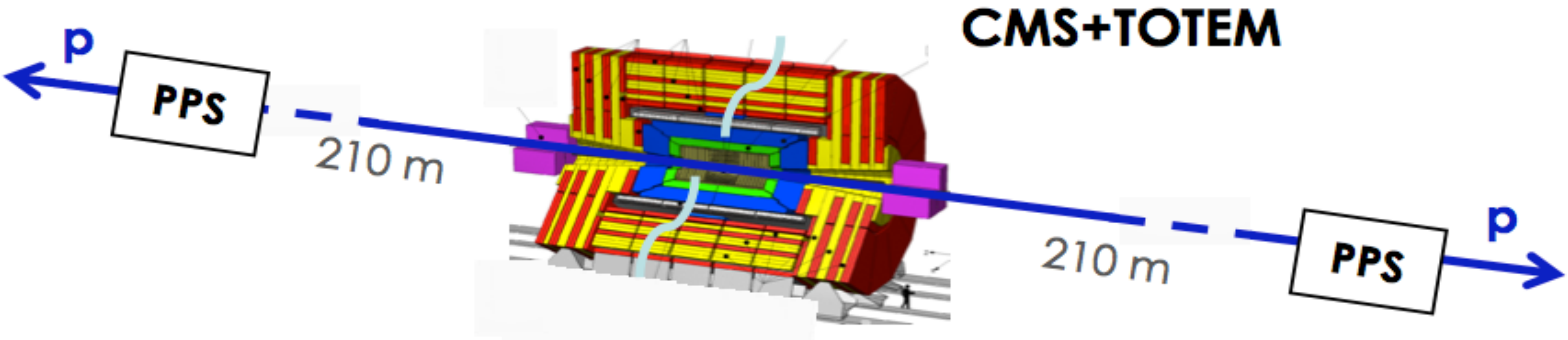
Looking forward: PPS

CERN-LHC-2014-021

- The Precision Proton Spectrometer is a joint CMS and TOTEM project that aims at measuring the surviving scattered protons on both sides of CMS in standard running conditions
- Tracking and timing detectors inside the beam pipe at ~210m from IP5
- Project approved in Dec. 2014 by LHCC
- Data taking started in 2016 (full scope from 2017)

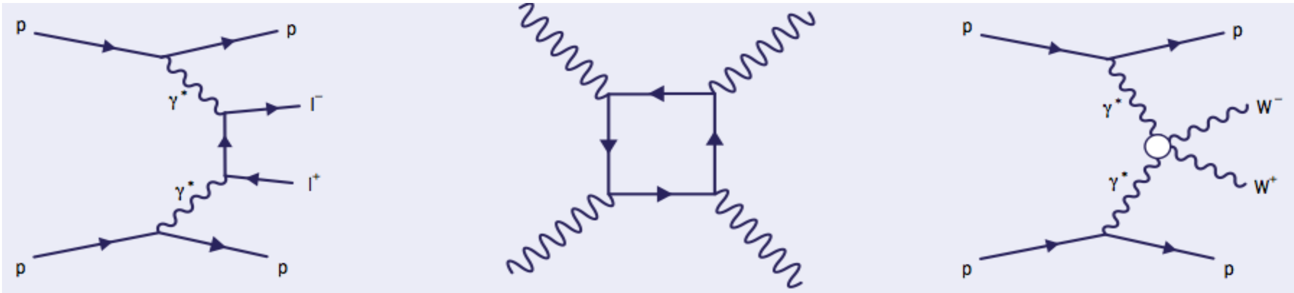


CERN-LHC-2014-021

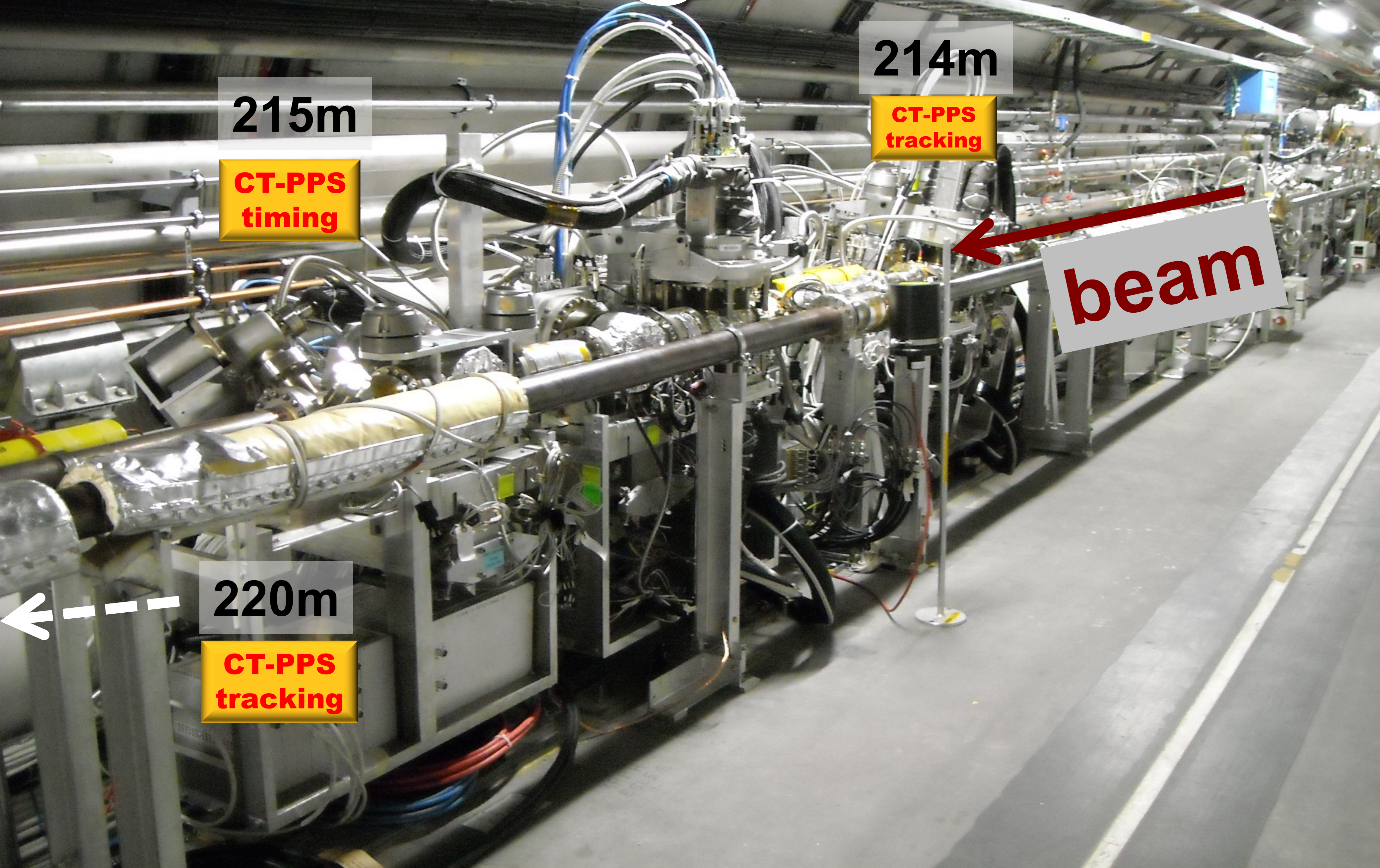


PPS: Physics motivations

- Central Exclusive Production
  - photon-photon collisions
  - gluon-gluon fusion in color singlet, $J^{PC}=0^{+}$
- High-p_T system in central detector, together with very forward protons in PPS
  - momentum balance between central system and forward protons, provides strong kinematical constraints
  - Mass of central system measured by momentum loss of the two leading protons
- Gauge boson production by photon-photon fusion and anomalous couplings ($\gamma\gamma$WW, $\gamma\gamma$ZZ, and $\gamma\gamma\gamma\gamma$)
- Search for new BSM resonances
- Study of QCD in a new domain



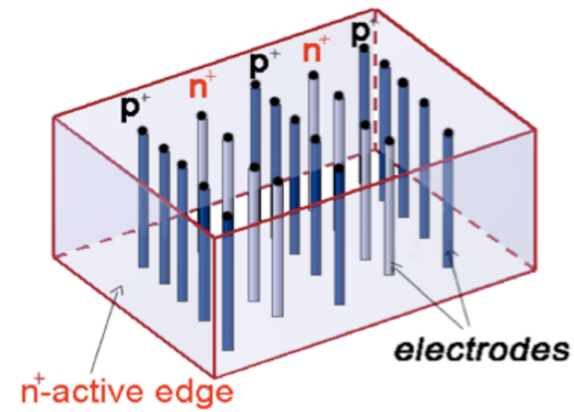
LHC tunnel @ PPS location



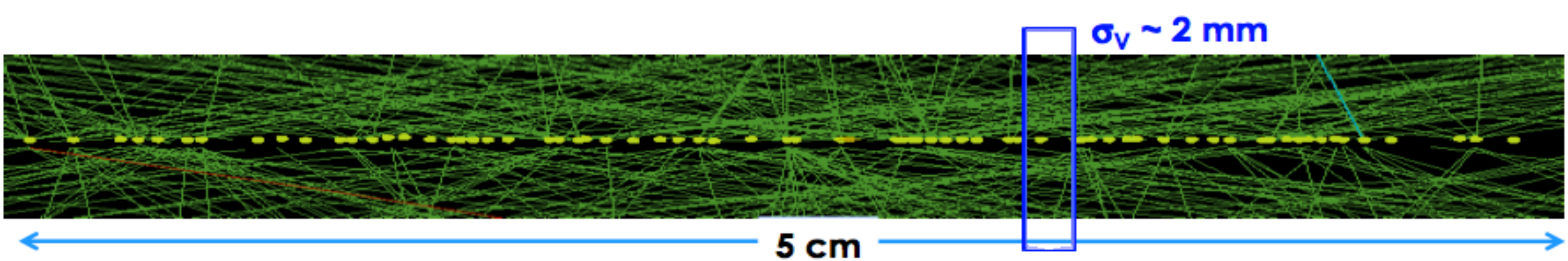
PPS detectors

- Tracking detectors
  - Goal: measure proton momentum
  - Technology: silicon 3D pixels (6 planes per pot)

"3D" pixel sensors with columnar electrodes



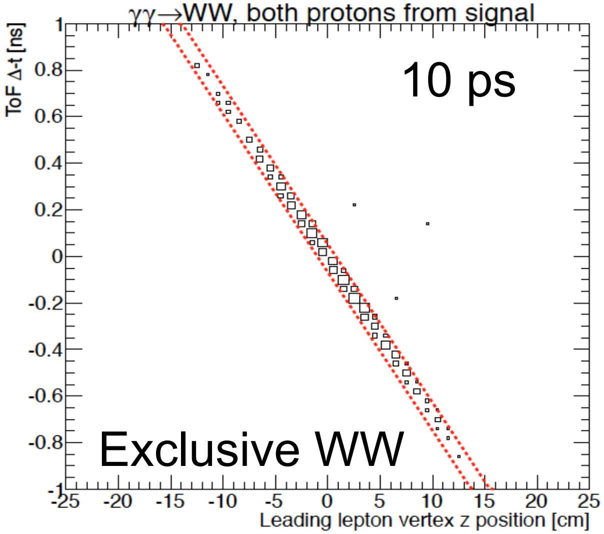
- Timing detectors
  - Goal: identify primary vertex, reject "pileup"
  - σ_{time}~10ps $\Rightarrow$ σ_z~2mm
  - Technology: silicon/diamond

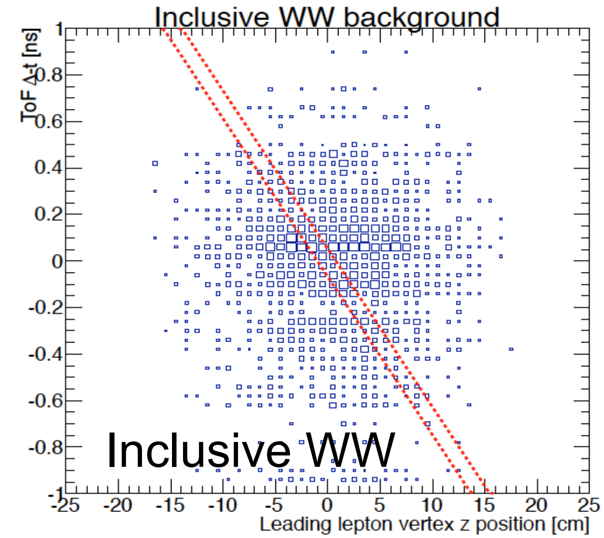


Timing detectors

Use timing to reject pileup background

- Two scenarios studied:
  - 10ps and 30ps time resolution
- Baseline: solid state detectors
- Detector options investigated:
  - Diamond sensors
  - Fast silicon sensors (UFSD, HFS)
- Status:
  - Diamond and LGAD detectors installed

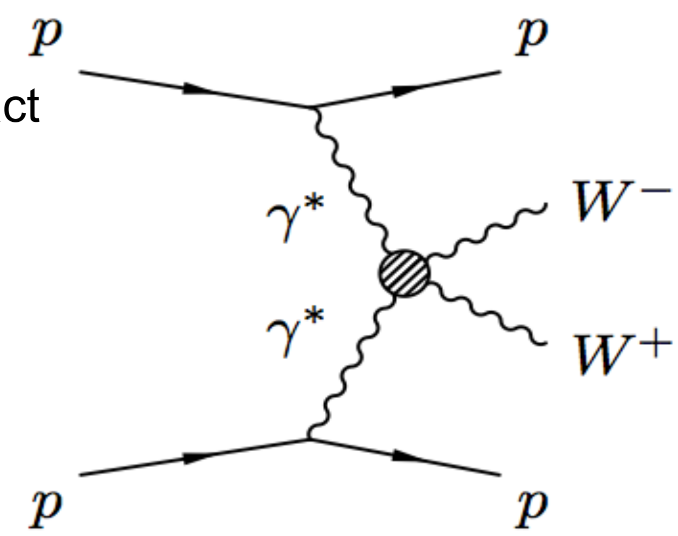




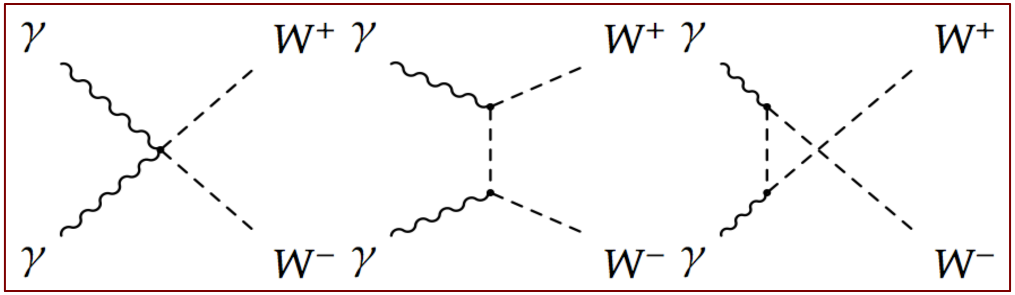
WW production

JHEP 08(2016)119

- Study of process: $pp \rightarrow pWWp$
  - Clean process: W in central detector and "nothing" else, intact protons can be detected far away from IP
  - Exclusive production of W pairs via photon exchange: QED process, cross section well known



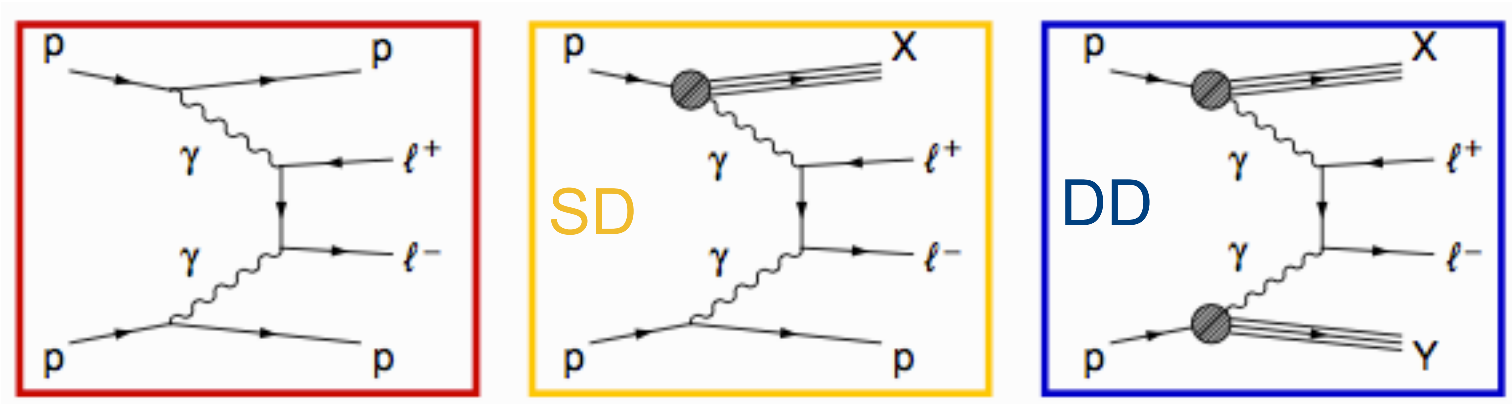
- Backgrounds:
  - inclusive WW, $\tau\tau$, exclusive two-photon $\gamma\gamma \rightarrow ll$, etc.
- Events:
  - WW pair in central detector, leading protons in PPS
- SM observation of WW events
- Anomalous coupling study
  - AQGCs predicted in BSM theories
  - parameters: a_0^W/Λ^2, a_c^W/Λ^2
- Deviations from SM can be large



Exclusive Dileptons

CMS-PPS-17-001

- Study exclusive processes at the EWK scale
- Search for two-photon production of opposite charge lepton pair with forward proton tagging



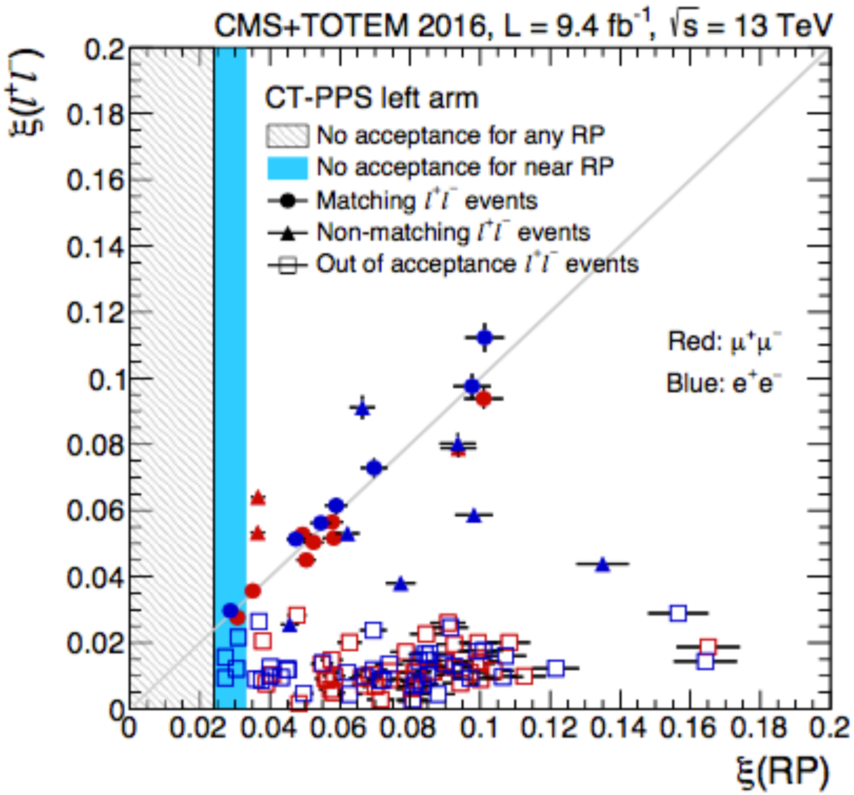
signal Background: SD, DD, DY, dibosons, PU

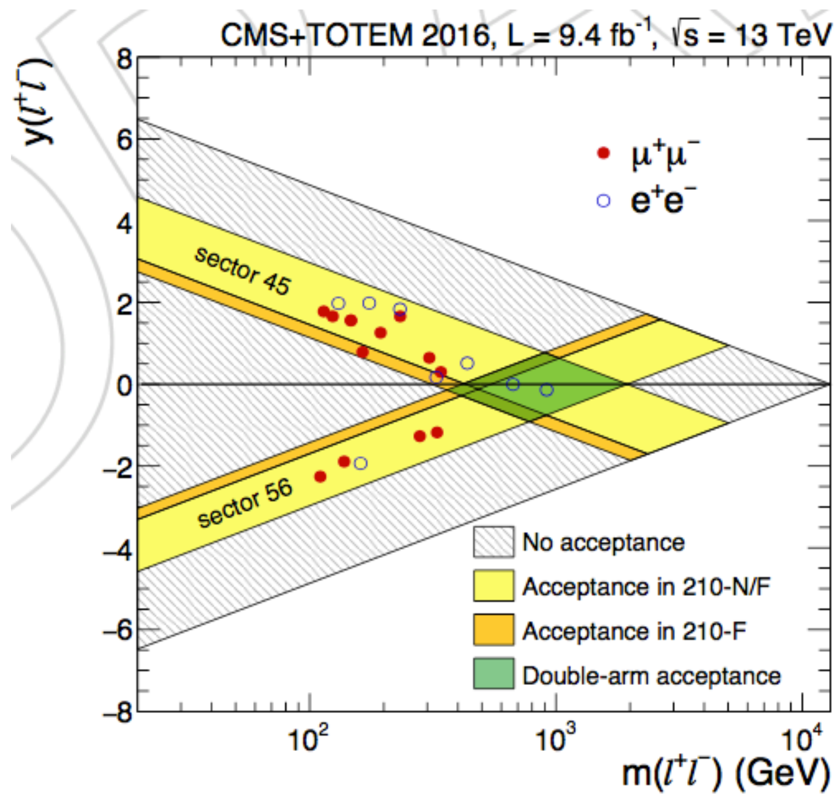
- Signal selected with:
- at least one proton tagged, muons, kinematic selection

Results

CMS-PPS-17-001

- Correlation between the ξ values in central system vs RP
- $12\mu\mu$, 8ee candidates observed (>5σ over expected bkg)
- First observation of two-photon production of a lepton pair at this mass range

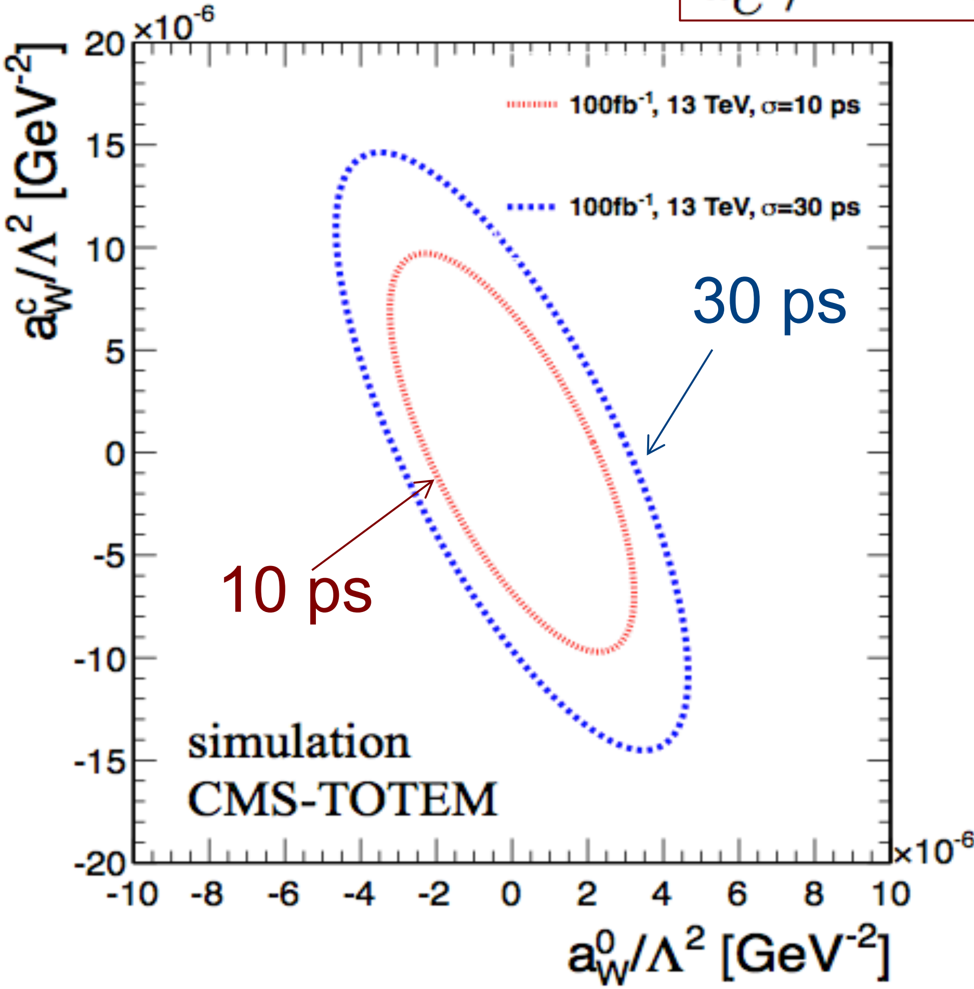


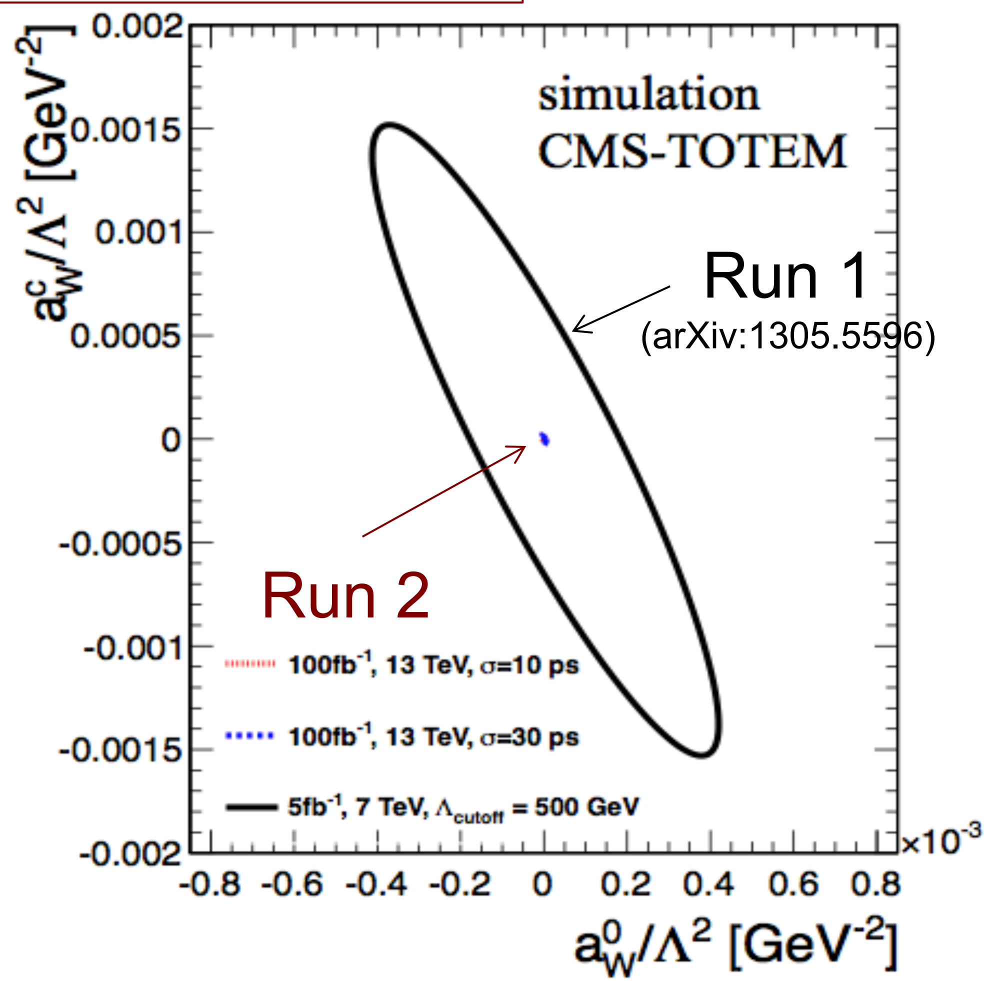


AQGC expected limits

Expected limits @95%CL:

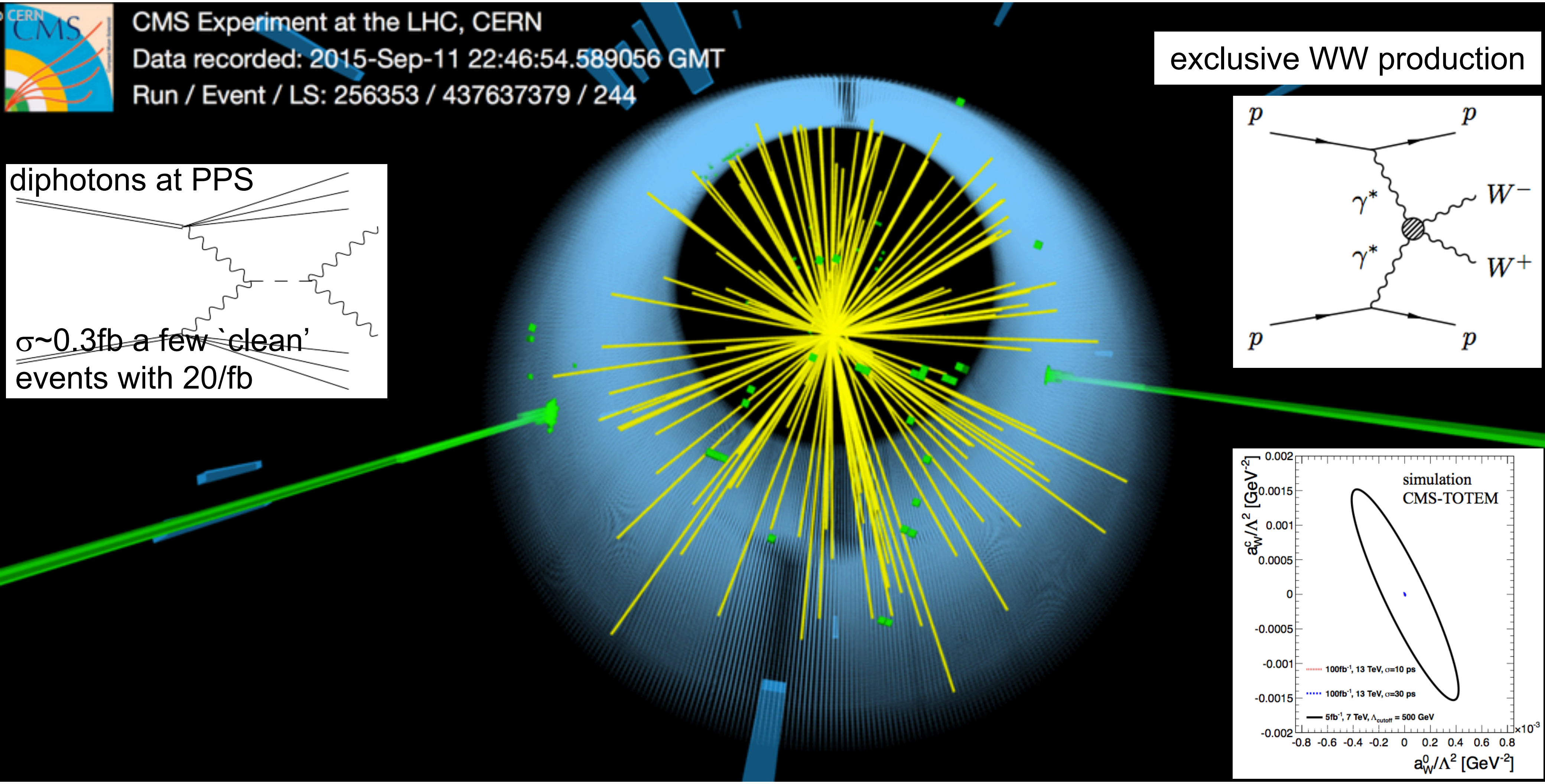
$$a_0^W/\Lambda^2 = 2 \times 10^{-6}\ (3 \times 10^{-6}),$$
$$a_C^W/\Lambda^2 = 7 \times 10^{-6}\ (10 \times 10^{-6}).$$



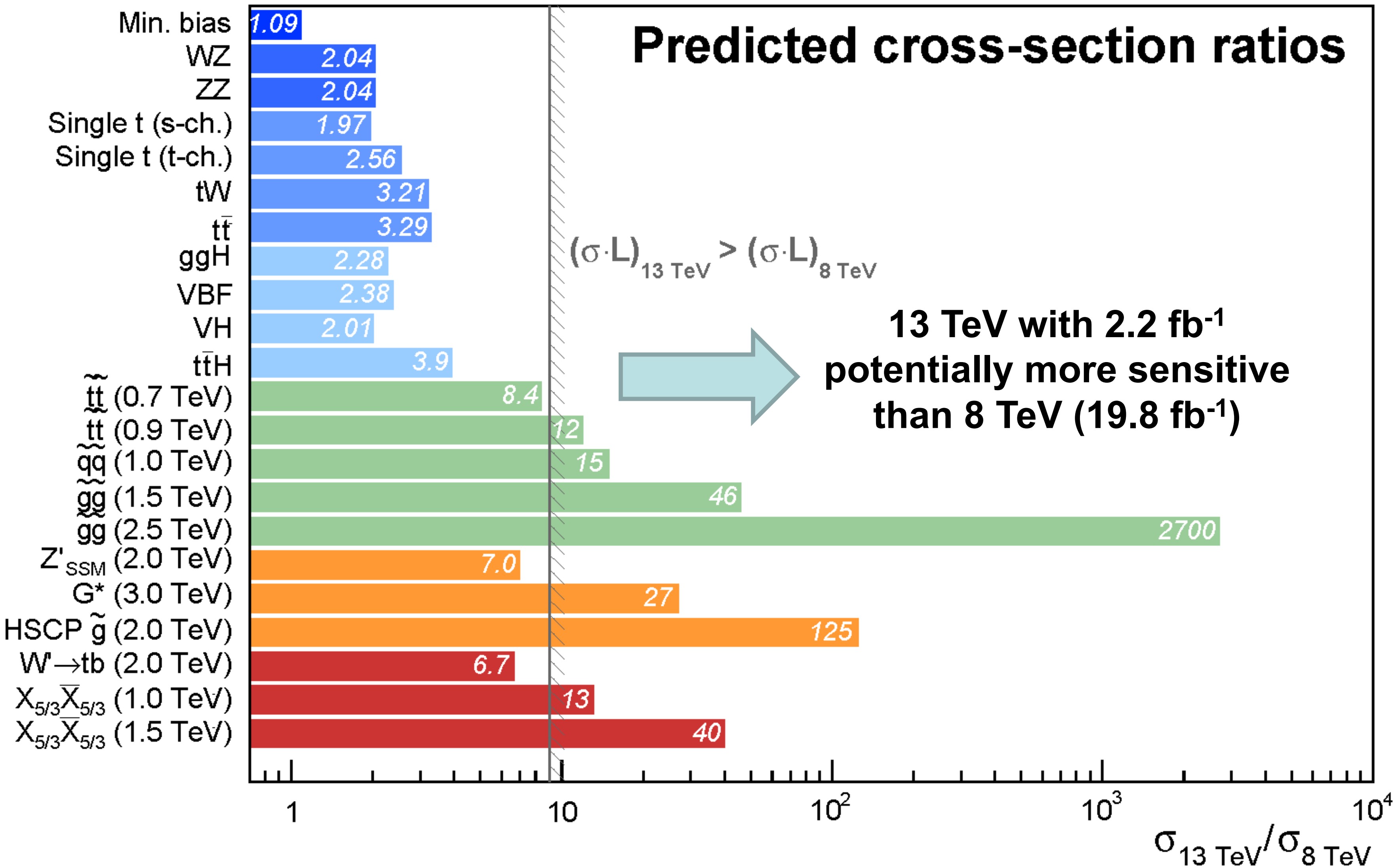


BSM searches: resonances, etc.

CMS-EXO-15-004, CERN-LHC-2014-021

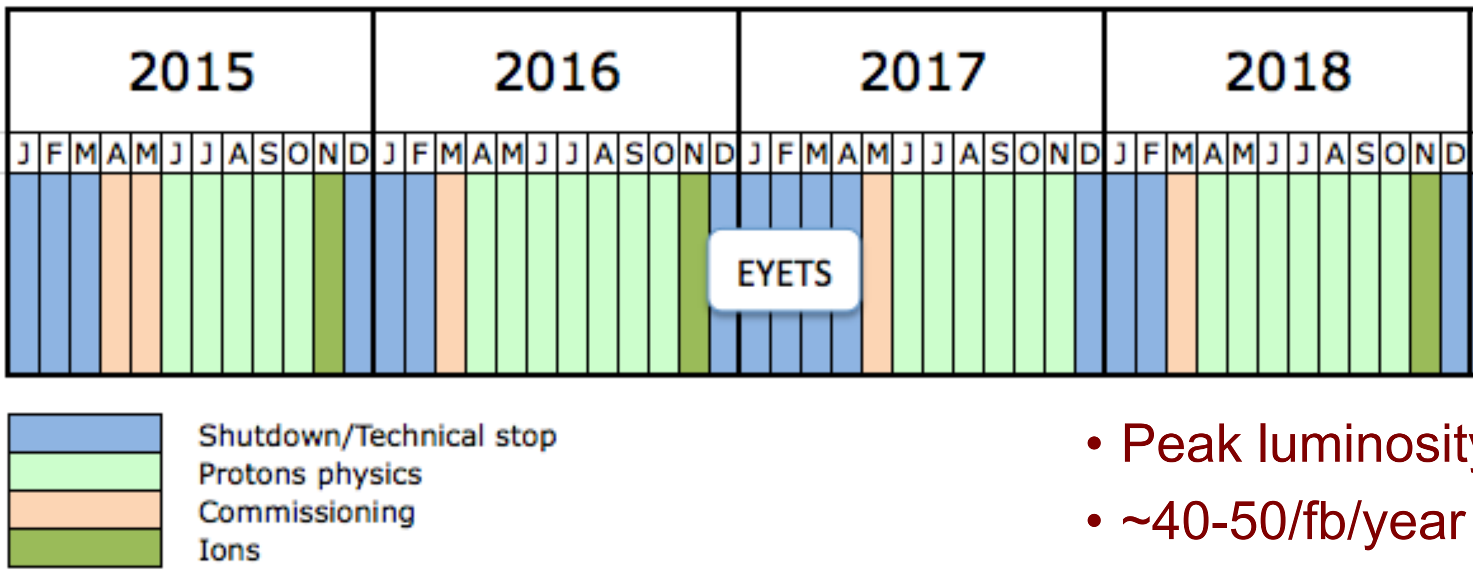


Increased reach at 13 TeV



Current status: LHC schedule

- Current status and plans
- CMS detector is closed
- Solenoid is cold and operating at 3.8T
- Running regularly on cosmics with magnet off
- All detectors included: reading out (including pixels)
- Ready for collisions

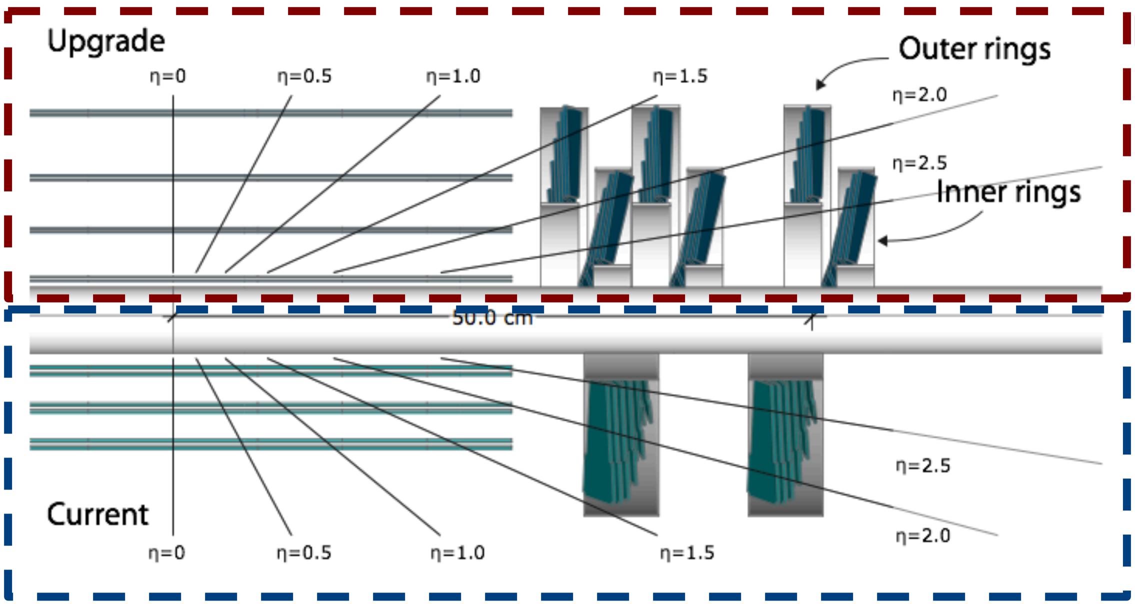


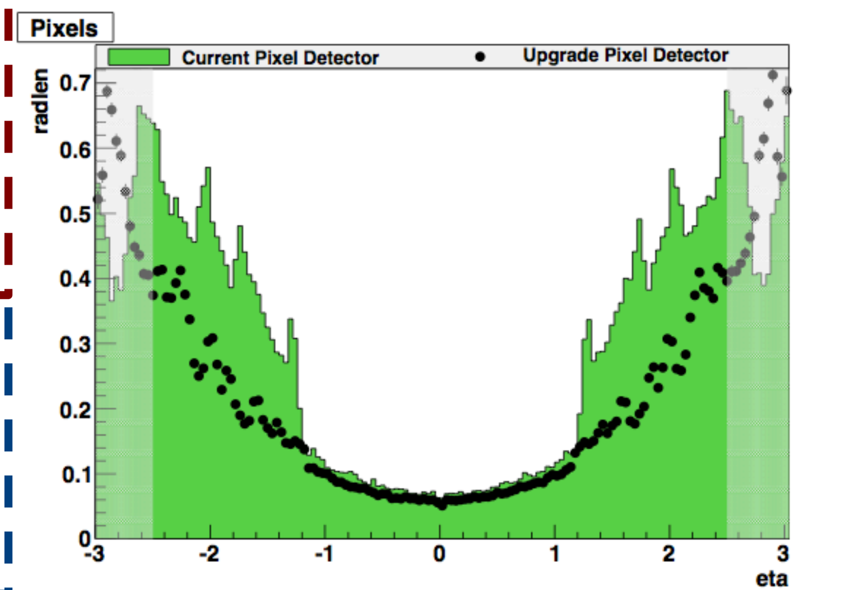
- Peak luminosity limit ~$2 \times 10^{34} cm^{-2} s^{-1}$
- ~40-50/fb/year in 2017/18,
- >100/fb in Run2

Phase 1 Pixel detector

Pixel upgrade: Installed for 2017 Run

- Baseline L=2x10^{34} cm^{-2}sec^{-1} (50 PU) with small efficiency loss
- More robust tracking: to 4 layers (can compensate losses in strips)
- Better readout (up to 2.5x10^{34}cm^{-2}s^{-1}) with no inefficiency
- Radiation hard to 500fb^{-1}
- Less material in front of outer tracker
- Inner layer closer to beam ⇒better vertex resolution





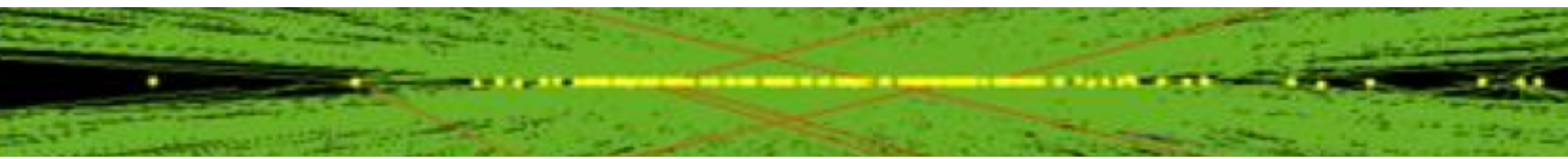
Other CMS upgrades for 2017

- Implement multi-anode on PMTs for Forward Hadron (HF) Calorimeter to reject spurious MET
- GEM-based muon detector slice in Endcap (first use of this technology for HL-LHC)
- Precision Proton Spectrometer new timing detectors

HL-LHC upgrades

Luminosity of ~3000 fb^{-1} expected for HL-LHC

- Tracking information in "L1 track-trigger"
  - Tracker designed to enable finding all tracks w/p_T>2GeV in $<4\mu s$
- Tracker is all silicon but with much higher granularity, up to $|\eta|=4$
  - >2billion pixels and strips
- High Granularity Endcap Calorimeters
  - Sampling of EM showers: every ~1λ (28 samples) w/pixels, and every ~0.35λ (24 samples) with pixels+scintillator to map 3D shower development
  - ~6M channels in all
- Precision timing to add a 4^{th} dimension to object reconstruction

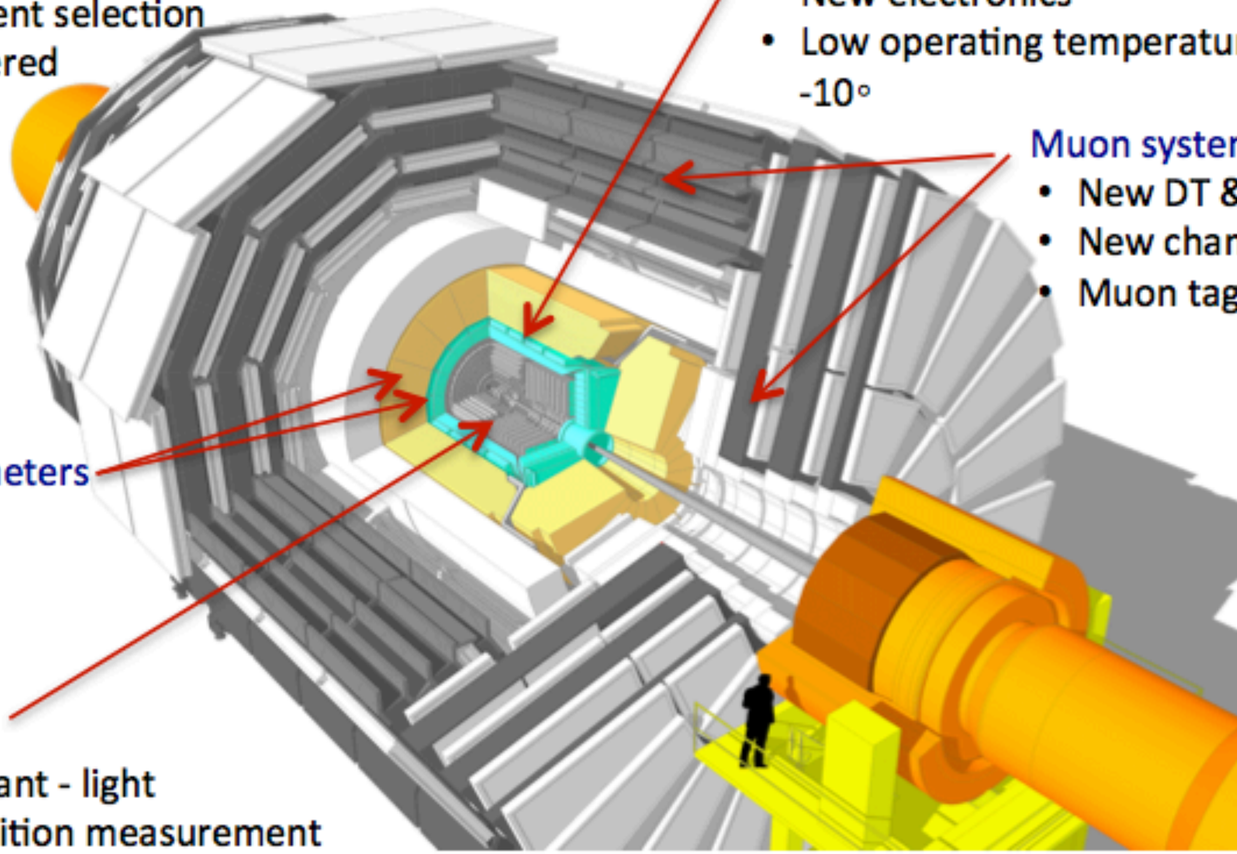


Future: HL-LHC upgrades

Trigger/HLT/DAQ
- Track information in hardware event selection
- 750 kHz hardware event selection
- 7.5 kHz events registered

Barrel EM calorimeter
- New electronics
- Low operating temperature ≈ -10°

Muon systems
- New DT & CSC electronics
- New chambers $1.6 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

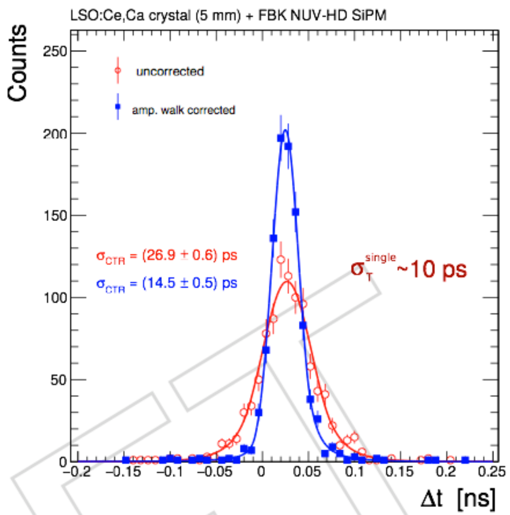


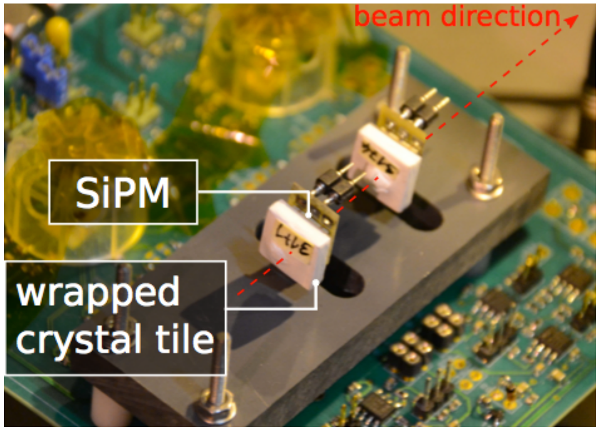
New Endcap Calorimeters
- Rad. Tolerant
- 5D measurement

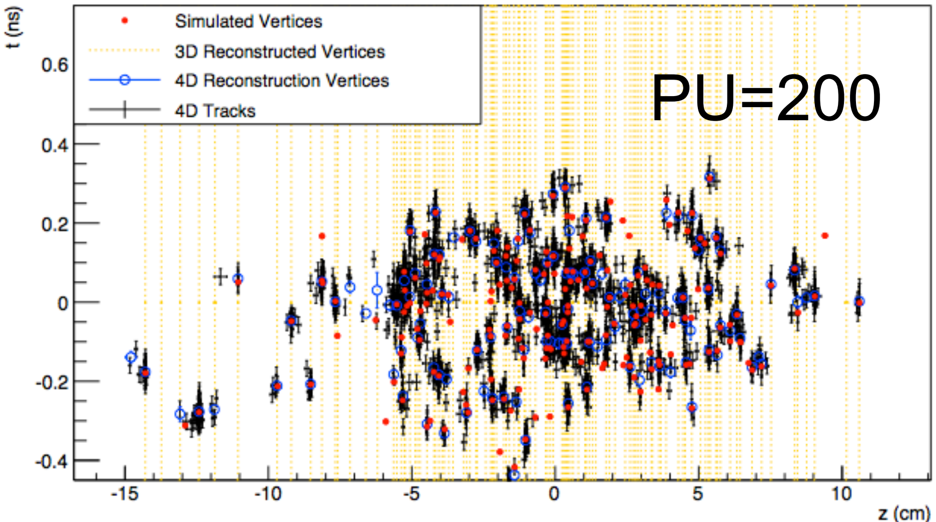
New Tracker
- Rad. Tolerant - light
- High Definition measurement
- 40 MHz selective readout for hardware trigger
- Extended Pixel coverage to $\eta \approx 3.8$

Beam radiation and luminosity
Common systems and infrastructure

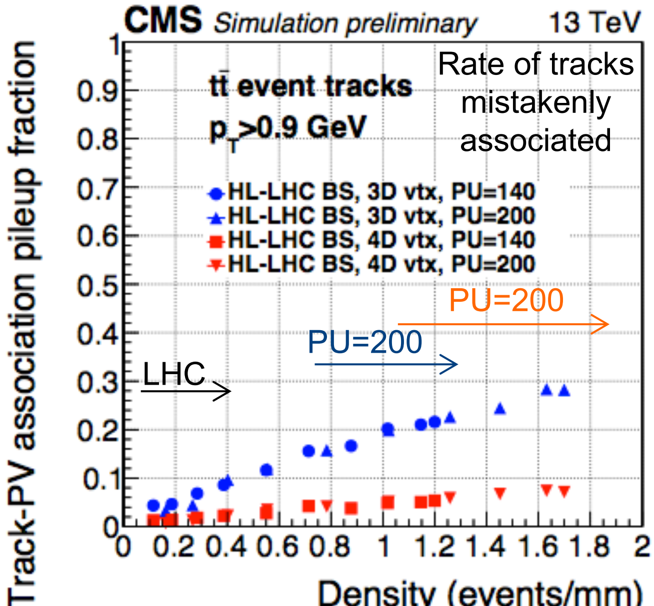
Precision Timing Layer







- Time-of-flight precision ~30ps
  - $|\eta|<3$, $p_T>0.7$GeV
  - Crystal+SiPM: rad hard to $2\times10^{14} n_{eq}cm^{-1}$
- Provide ~x4-5 effective PU reduction
  - 15% merged vertices reduce to 1.5%
  - Low PU track purity of vertices recovered
- Showers timed to 30ps in calorimeters



Summary

- LHC performing very well
  - High-availability of “stable beams”
- Excellent detector performance
  - Detector ready for data
- Excellent physics results
  - ~100fb^{-1} of data collected
  - >600 publications so far
- Installation of new detectors in 2017
- Upgrade program for HL-LHC underway
- Plenty of data expected in 2018-2022!

Evaluation

Review and present a seminar from one of these topics:

- di-Higgs production, Phys.Lett.B 778(2018)101: https://arxiv.org/abs/1707.02909
- inclusive Z measurement, JHEP 01(2011)080: http://arxiv.org/pdf/1012.2466
- charged Higgs, JHEP11(2015)018: https://arxiv.org/pdf/1508.07774.pdf
- Higgs observation, Science 338(2012)1569: http://science.sciencemag.org/content/338/6114/1569.full.pdf