

CMS 13 TeV Results

LPCC Special Seminar

December 15, 2015

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On behalf of the CMS Collaboration

Focus of this presentation: summary of 13 TeV physics results

For additional details on CMS operation in 2015, see talk at LHCC open session:

http://indico.cern.ch/event/460278/session/0/contribution/4/attachments/1197928/1744965/CMS_LHCC_Public_02_12_2015_v4.pdf



@LHC: Thank You!



An amazing year for the LHC Team!



The CMS Collaboration

1700 physicists, 700 students, 950 engineers/technicians, 180 institutions from 43 countries



Many thanks to all!



CMS Operation in 2015

- At the end of the Long Shutdown 1 we realized that the **performance of the cryogenic system feeding Liquid He to our Magnet was severely impaired by a contamination of the Cold box**
- This has affected our operation in 2015: a large effort from the **CERN cryogenic and technical departments associated to our Technical Coordination have limited the impact, allowing to collect $\sim\frac{3}{4}$ of the delivered luminosity with full magnetic field.**
- The detector and new acquisition system was ready from the start of LHC running at 13 TeV: **we have logged data with efficiency well above 90% with trigger thresholds similar or lower than the ones at Run I**
- **A detailed plan of repair and cleaning of the cryo system, to be executed during the Year End Technical Stop, is ready** and foresees the system to be ready for Physics production by the first week of April, i.e. well ahead of the start of physics production of LHC in 2016



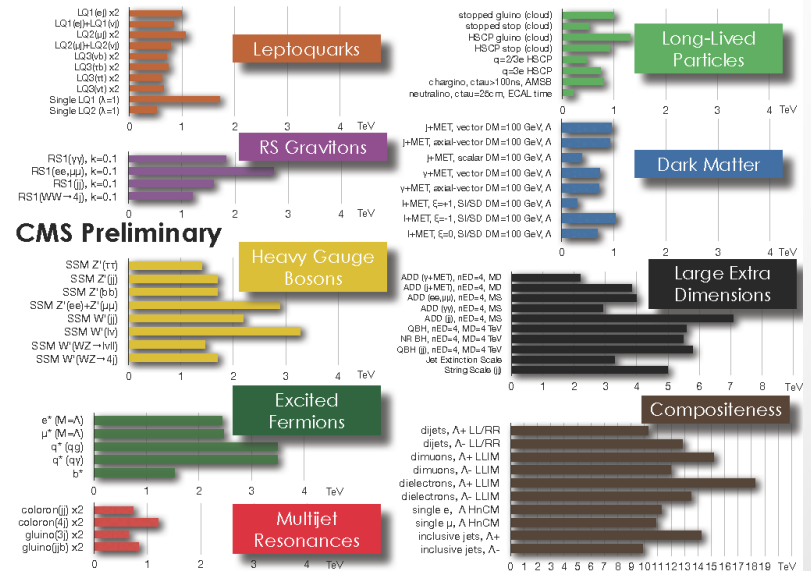
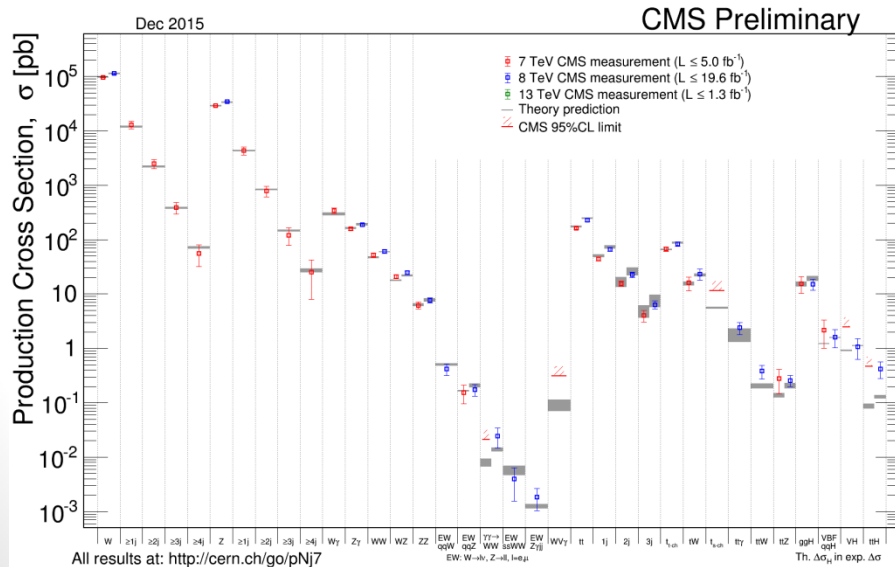
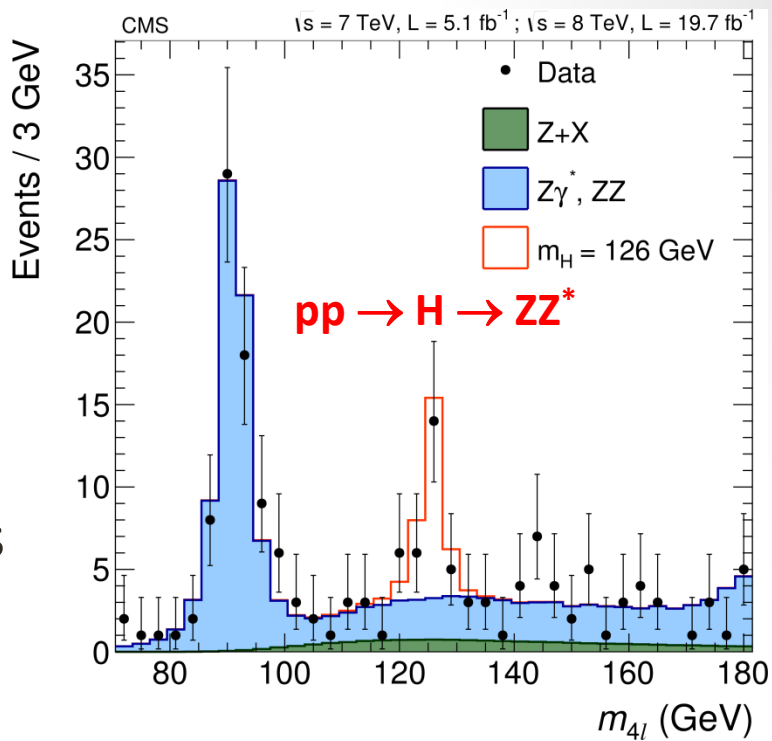
Run 1 Legacy

443 Run 1 publications (so far)

1 Higgs boson

Many precision SM measurements

Many BSM searches, a few bumps



CMS Publication Status

Exotica: 96

Standard Model: 79

Higgs boson: 60

Supersymmetry: 52

Top quark: 50

Heavy Ion: 38

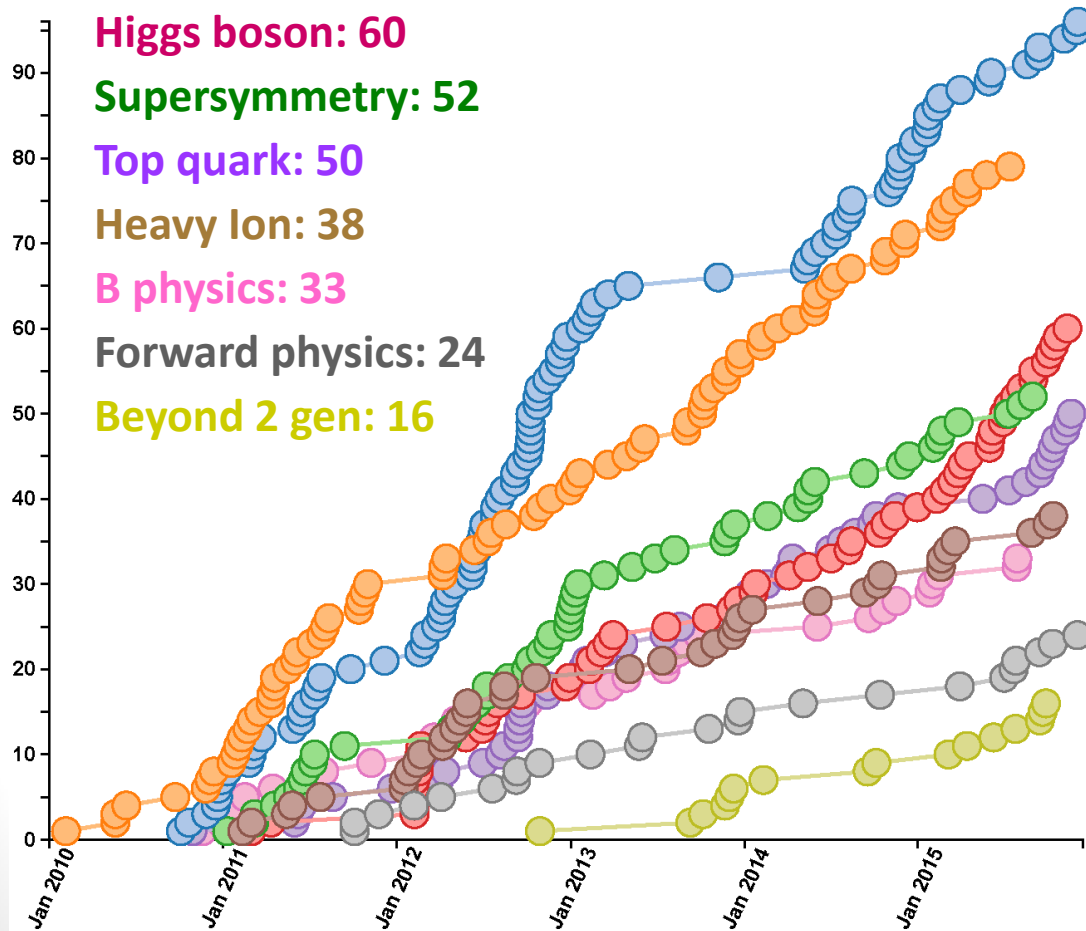
B physics: 33

Forward physics: 24

Beyond 2 gen: 16

447 Publications

submitted or published



Run 1 publications:

443 and still counting

Run 2 publications:

4 papers submitted

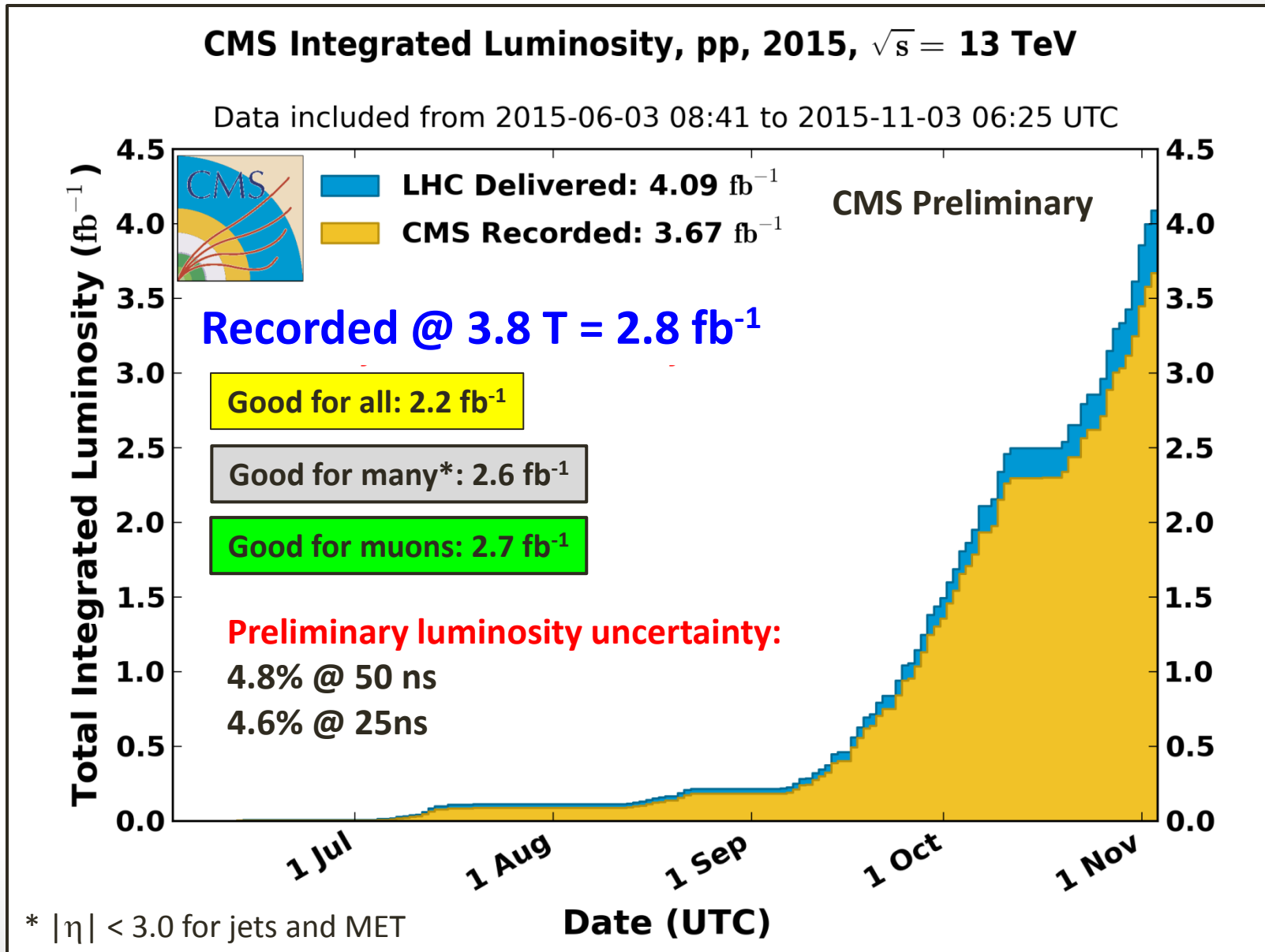
- $dN/d\eta$ – first 13 TeV paper (**published**)
- Two-particle correlations (“the ridge”)
- $t\bar{t}$ cross section
- **Search for dijet resonances** (first 13 TeV search, submitted to PRL)

+23 publications on first cosmic ray data recorded by CMS

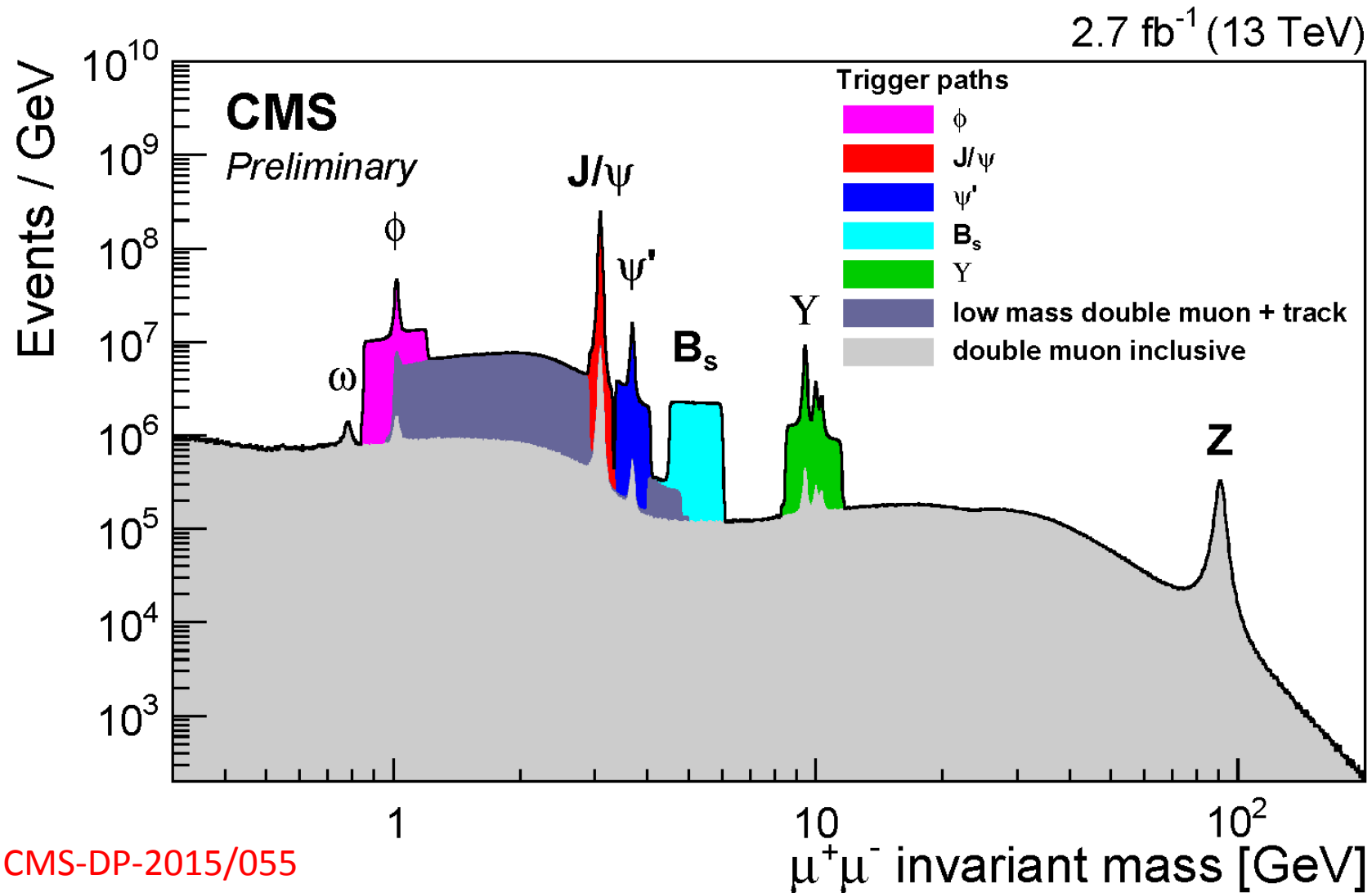
All CMS pubs: <http://cms-results.web.cern.ch/cms-results/public-results/publications/>



13 TeV dataset



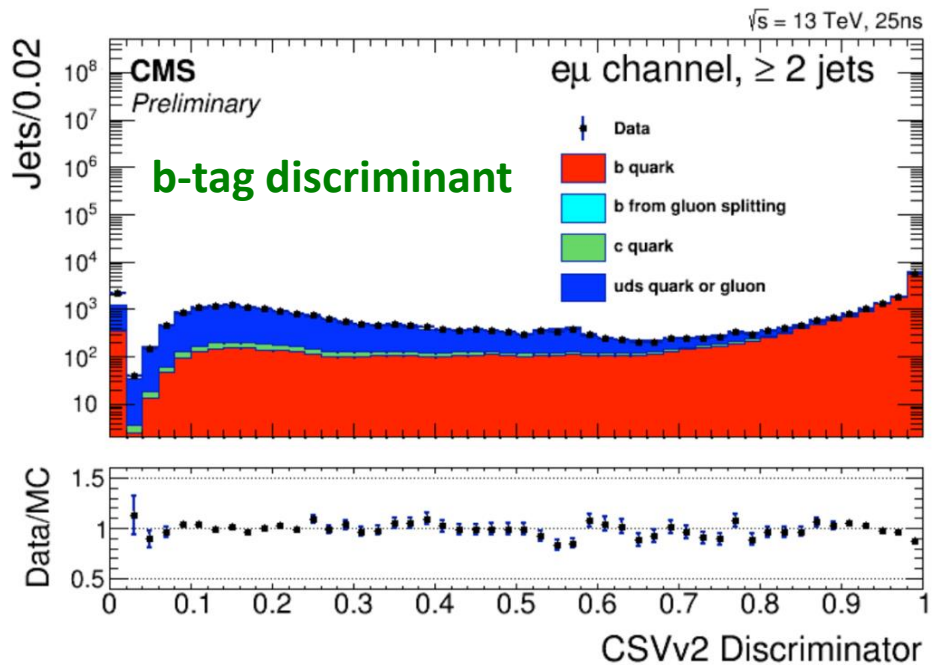
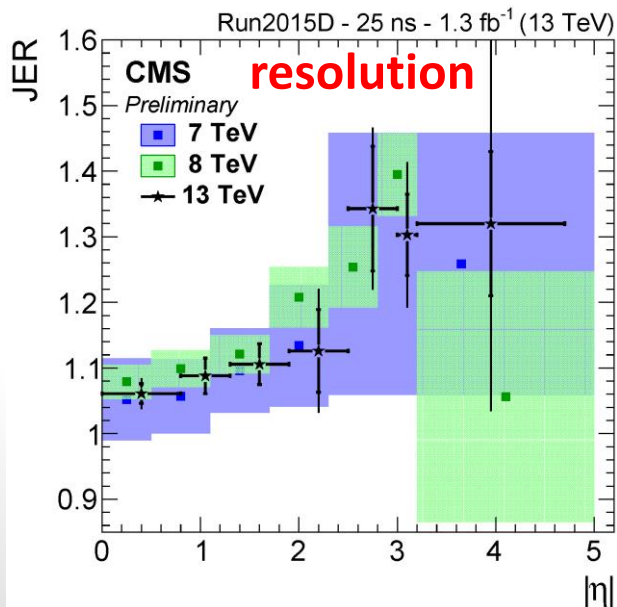
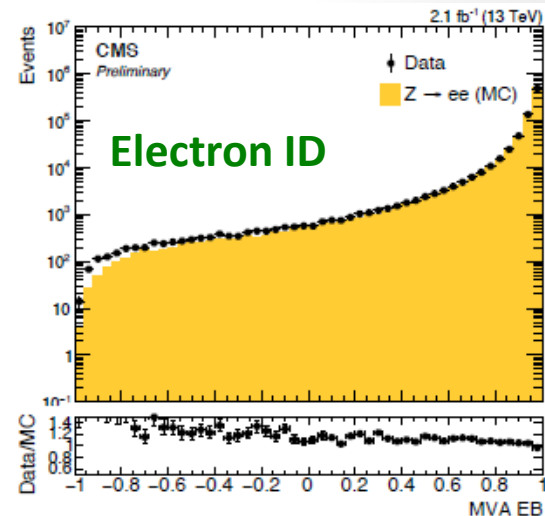
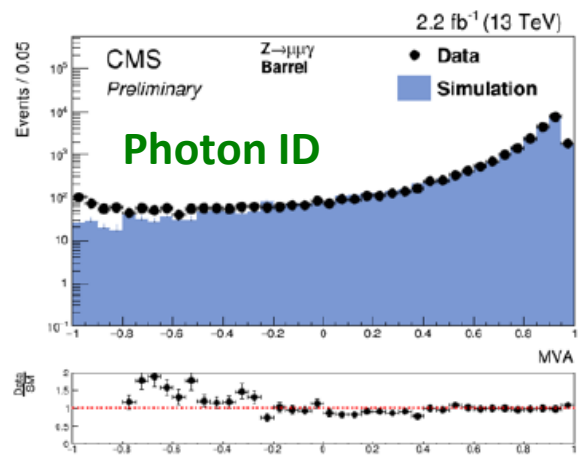
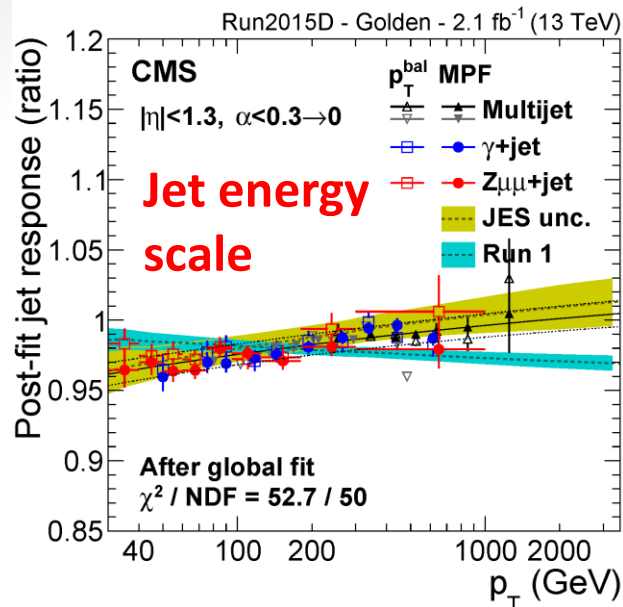
The Compact Muon Solenoid



CMS-DP-2015/055



Physics objects @ 25ns



CMS Public Results @ 13 TeV

Standard Model results (15):

BPH-15-004: B production cross section

FSQ-15-001: Pseudorapidity distributions of charged hadrons

FSQ-15-002: Two-particle correlations (the “ridge”)

FSQ-15-007: Underlying event

SMP-15-004: Inclusive W/Z cross section

Results highlighted in **blue**
shown here for the first time

SMP-15-005: ZZ production cross section

SMP-15-006: WZ production cross section

SMP-15-007: Inclusive jet production

SMP-15-010: Z+jets differential cross sections

TOP-15-003: Inclusive ttbar cross section in the emu channel

TOP-15-004: t-channel single top production

TOP-15-005: Differential tt cross section in the lepton + jets channel

TOP-15-010: Differential tt cross section in the dilepton channel

TOP-15-013: ttbar differential cross sections as function of HT,

TOP-15-017: Underlying Event studies in ttbar events



CMS Public Results @ 13 TeV

New Physics searches (18):

B2G-15-004: Search for $W' \rightarrow tb$ (semi-leptonic)

B2G-15-006: X53 in SS dilepton and lepton+jets

EXO-15-001: Search for dijet resonances

EXO-15-002: Search for diboson resonances

EXO-15-003: Search for dark matter in monojets

EXO-15-004: Search for diphoton resonances

EXO-15-005: Search for dilepton resonances

EXO-15-006: Search for W' in lepton + MET final state

EXO-15-007: Search for Black Holes

EXO-15-009: Search for new physics in dijets with chi

EXO-15-010: Search for Heavy Stable Charged Particles

SUS-15-002: Search for supersymmetry in multijet+MET

SUS-15-003: Search for new physics in the all-hadronic final state with the MT2

SUS-15-004: Inclusive search for supersymmetry using the razor variables

SUS-15-005: Search for supersymmetry using α_T

SUS-15-007: Search for supersymmetry in 1-lepton events using large radius jets

SUS-15-008: Search for SUSY in same-sign dilepton events

SUS-15-011: Search for SUSY in final states with opposite-sign dileptons

Results highlighted in **blue**
shown here for the first time

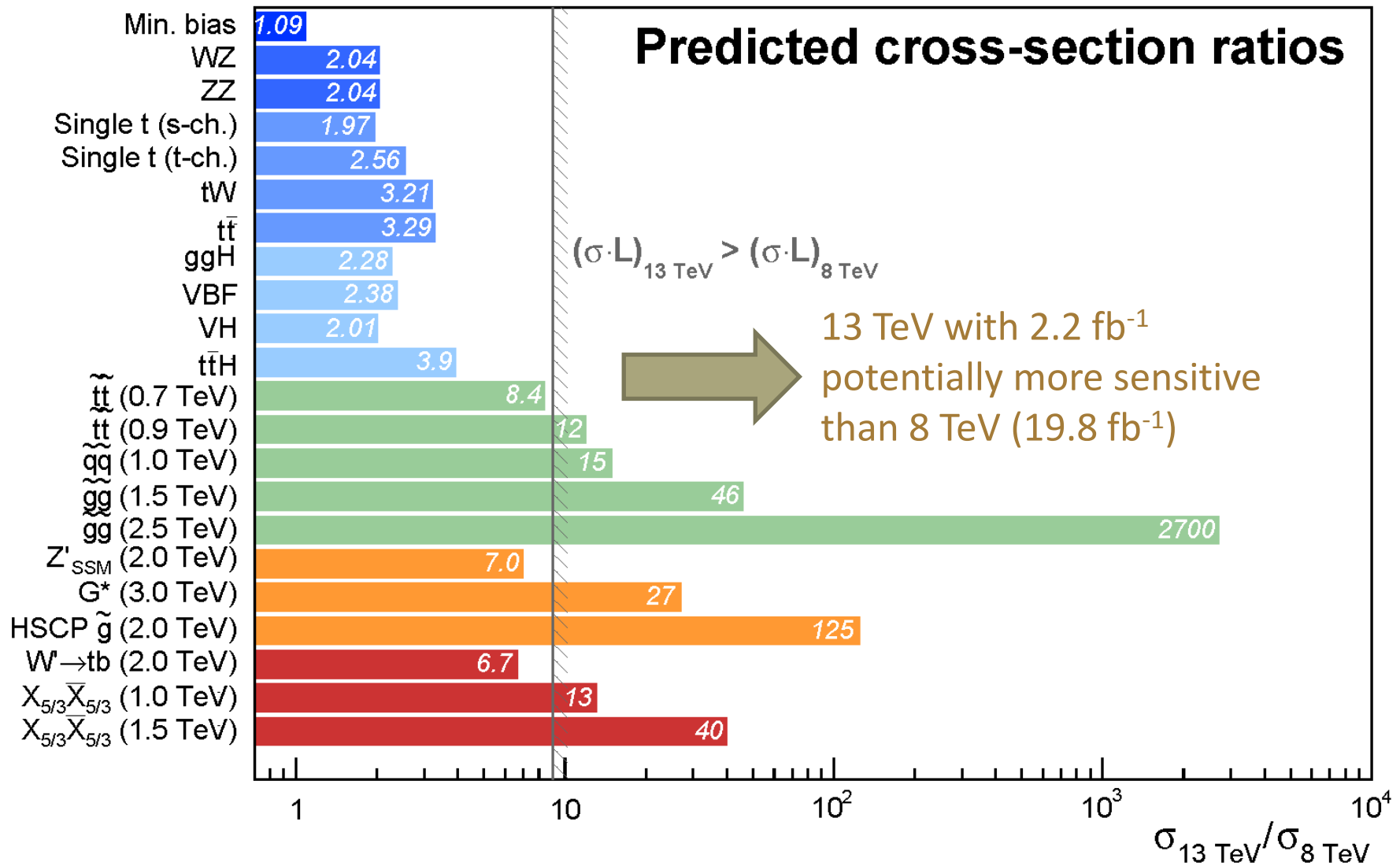
Exotica searches



SUSY searches



Reminder: increased reach @ 13 TeV



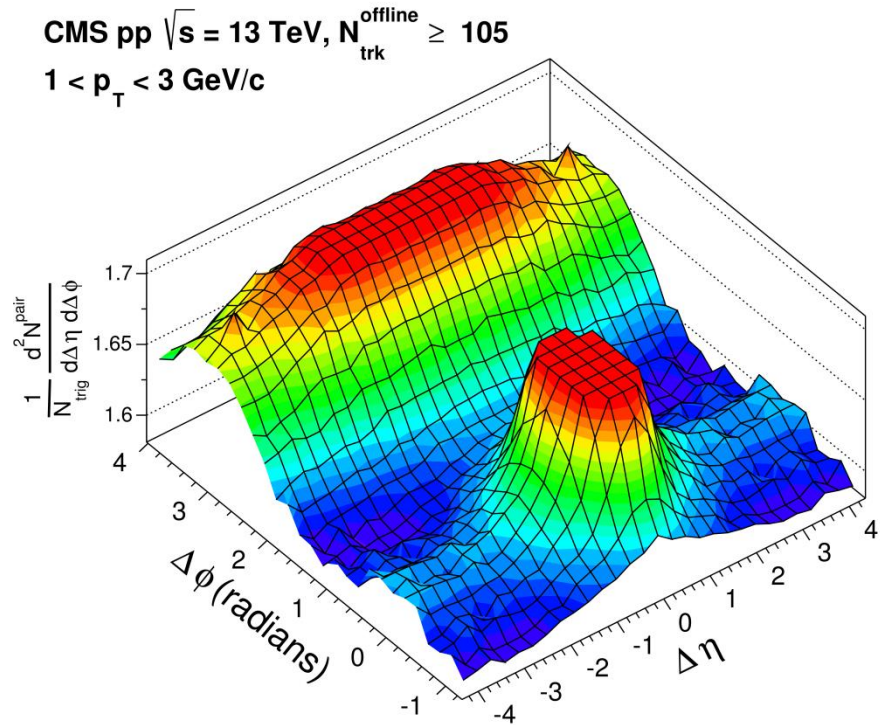
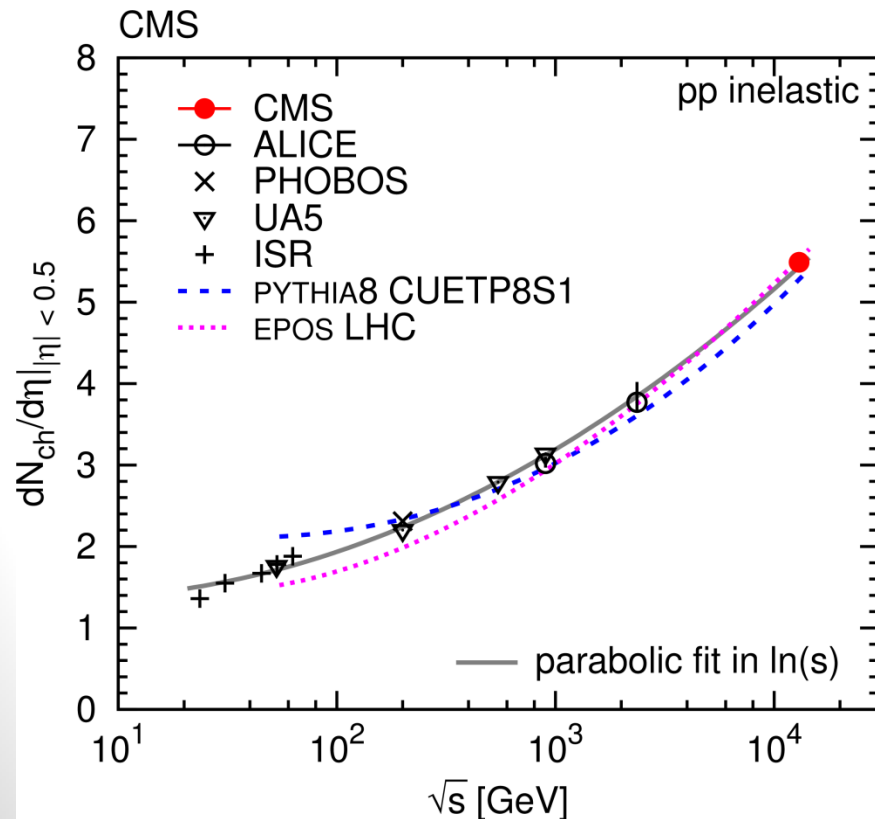
Seeing old friends:

SM measurements at 13 TeV



Event properties: $dN/d\eta$ and “the ridge”

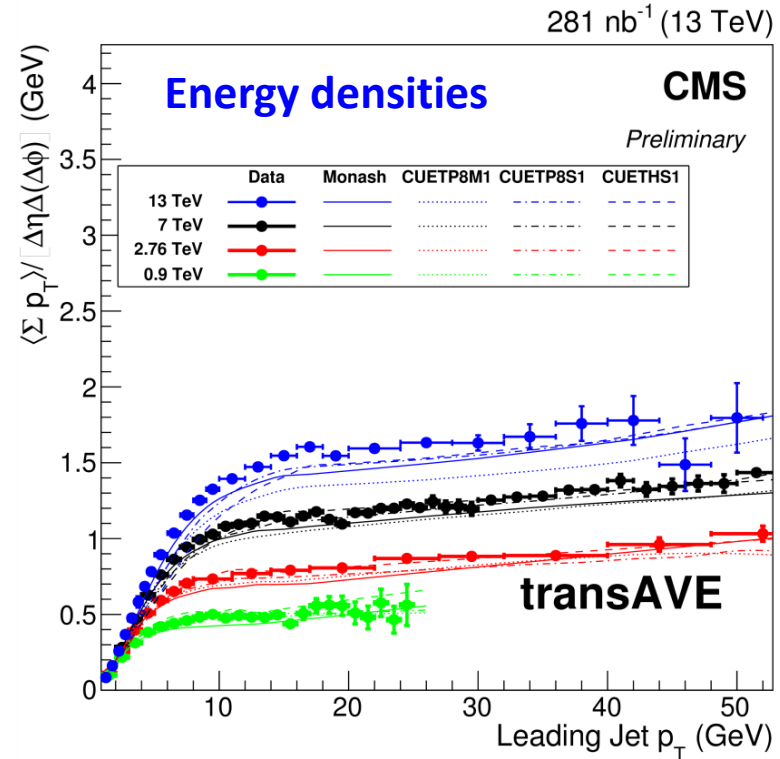
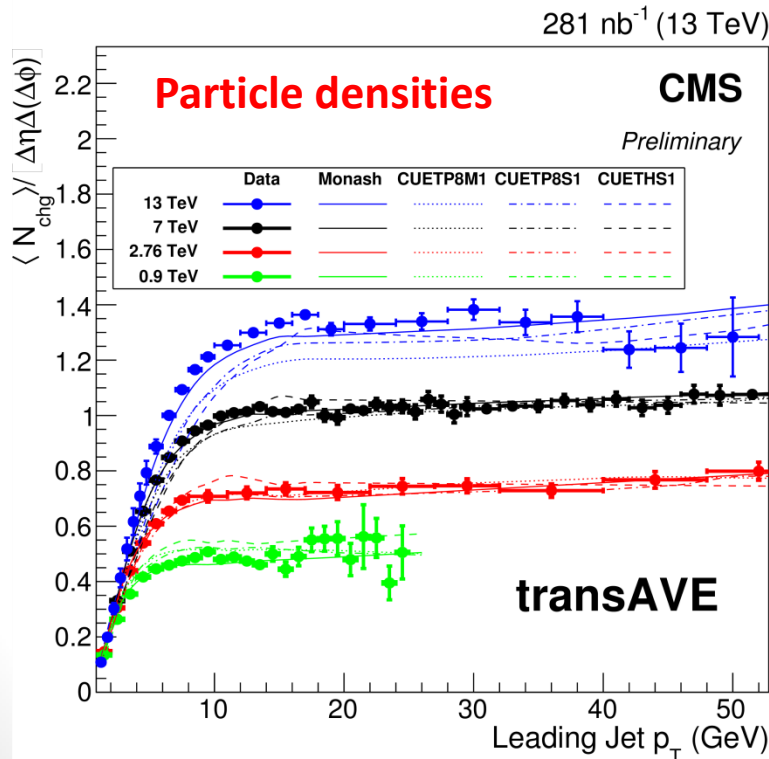
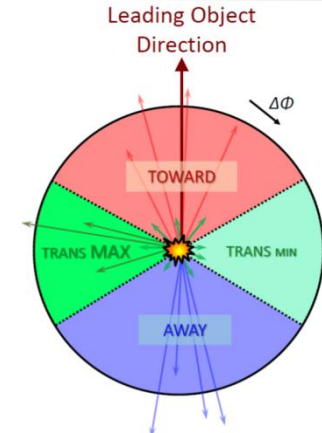
- **FSQ-15-001:** measurement of pseudorapidity distribution of charged hadrons, data consistent with expected dependence on centre-of-mass energy. Published in [PLB 751 \(2015\) 143](#).
- **FSQ-15-002:** two-particle correlations, confirming the presence of a ridge-like structure for same-side ($\Delta\phi \sim 0$) pairs in high-multiplicity events at 13 TeV. Submitted to PRL ([arxiv:1507.05915](#)).



Underlying event

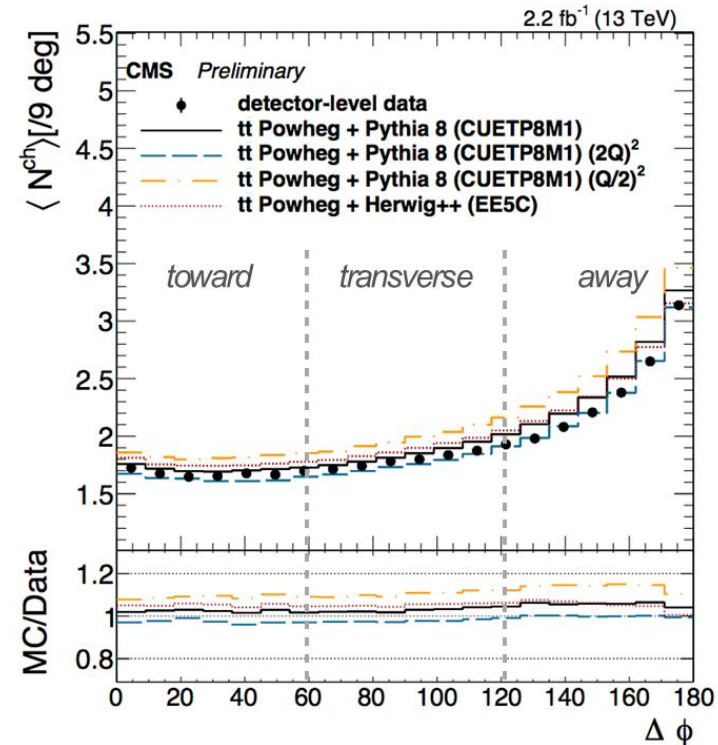
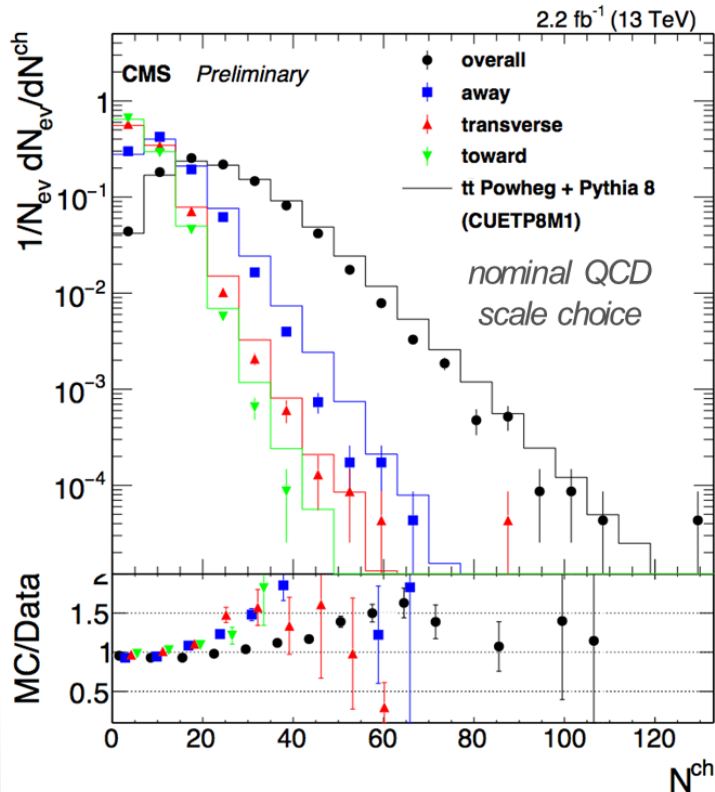
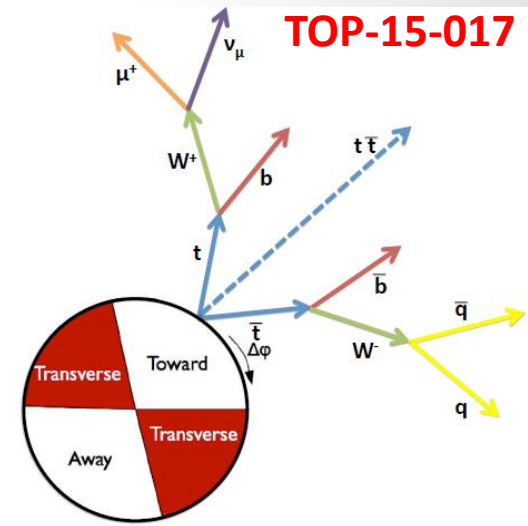
- Measurements of underlying event activity at 13 TeV compared to previous measurements at lower energies
- Data in reasonable (10-20%) agreement** with tested tunes; critical input for future improvements

FSQ-15-007



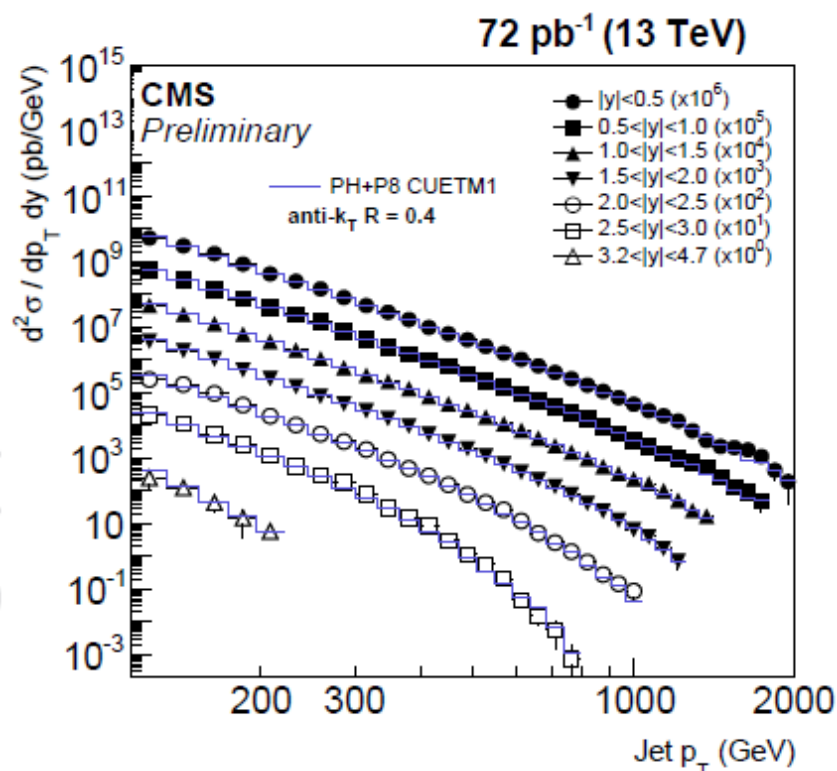
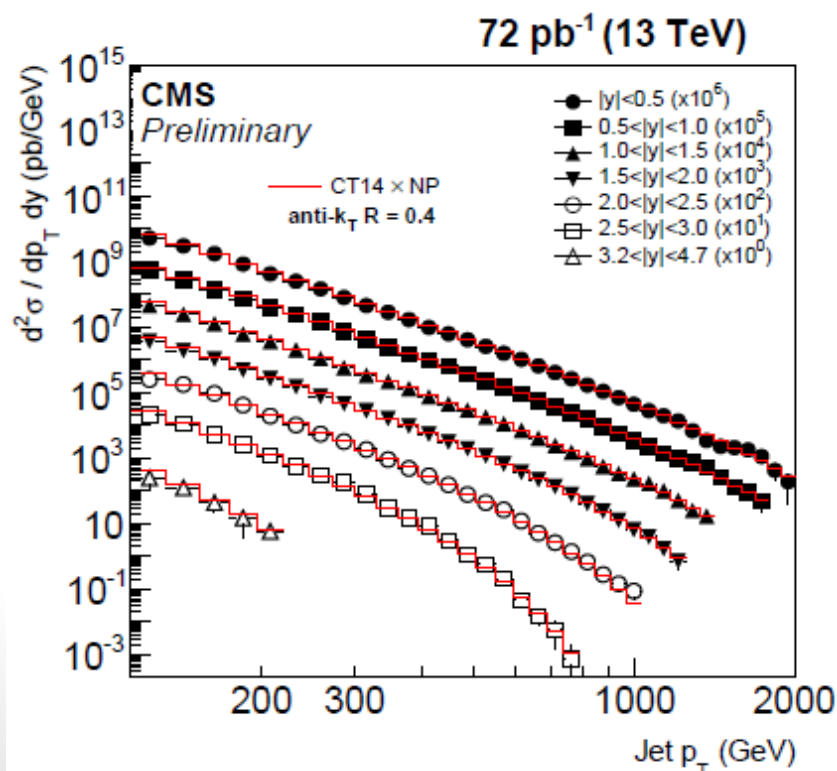
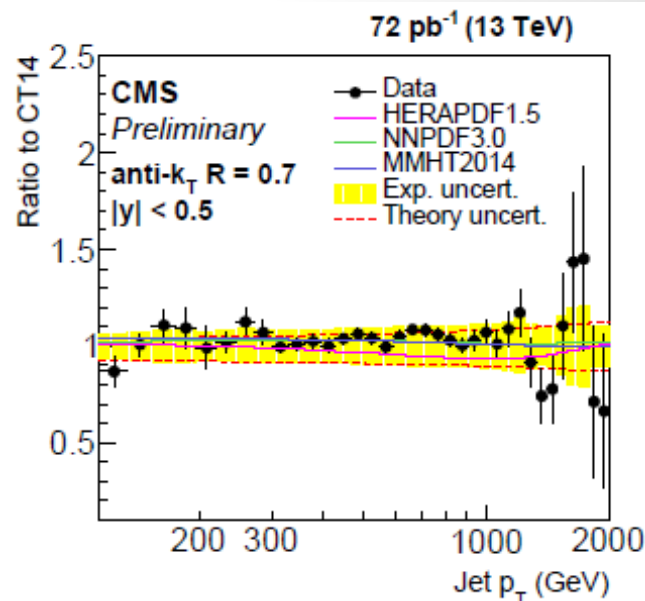
Top underlying event

- **Verify/improve** all aspects of event modeling in $t\bar{t}$ production environment
- Measure charged particle activity (N , Σp_T , $\langle p_T \rangle$) separately in regions relative to flight direction of the $t\bar{t}$ system, **as function of $p_T(t\bar{t})$ and for different jet multiplicities**



Inclusive jets

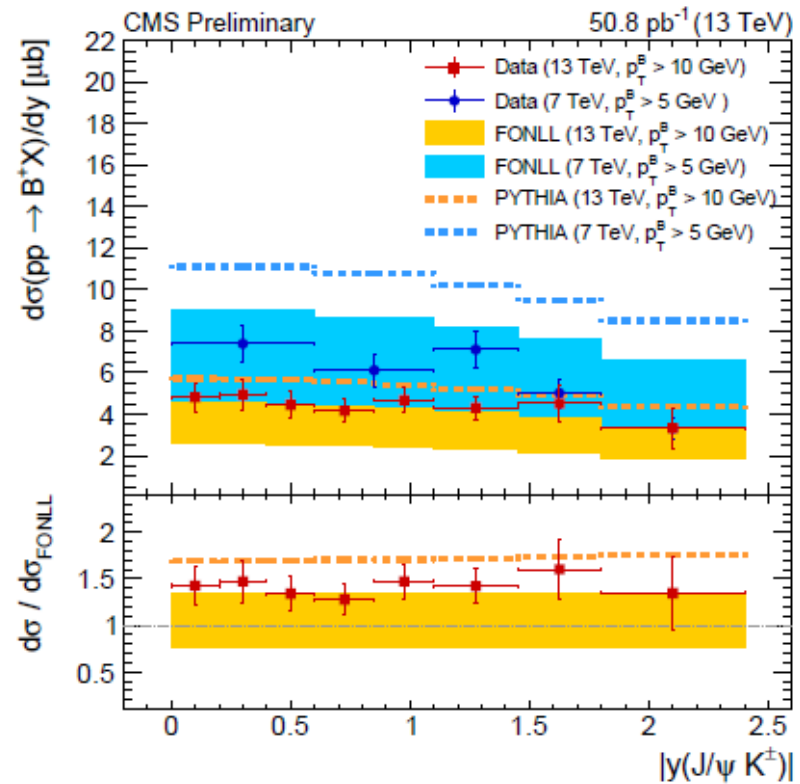
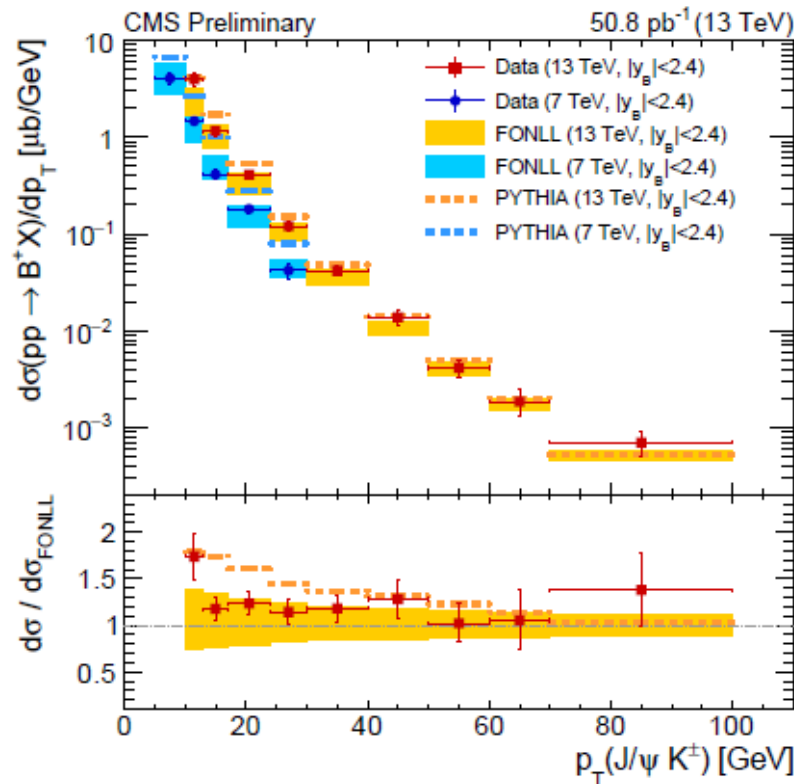
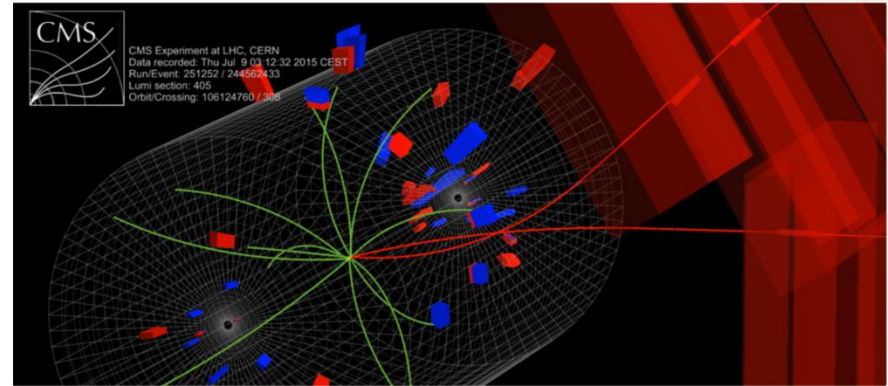
- Inclusive jet production cross section measured in bins of jet p_T and η
- Good agreement with predictions using different tunes
- Precision QCD @ 13 TeV!**



B meson production

BPH-15-004

- **B cross section vs. p_T and y** compared to FONLL predictions, and CMS data at 7 TeV
- Good agreement with theory up to **$p_T \sim 100$ GeV**

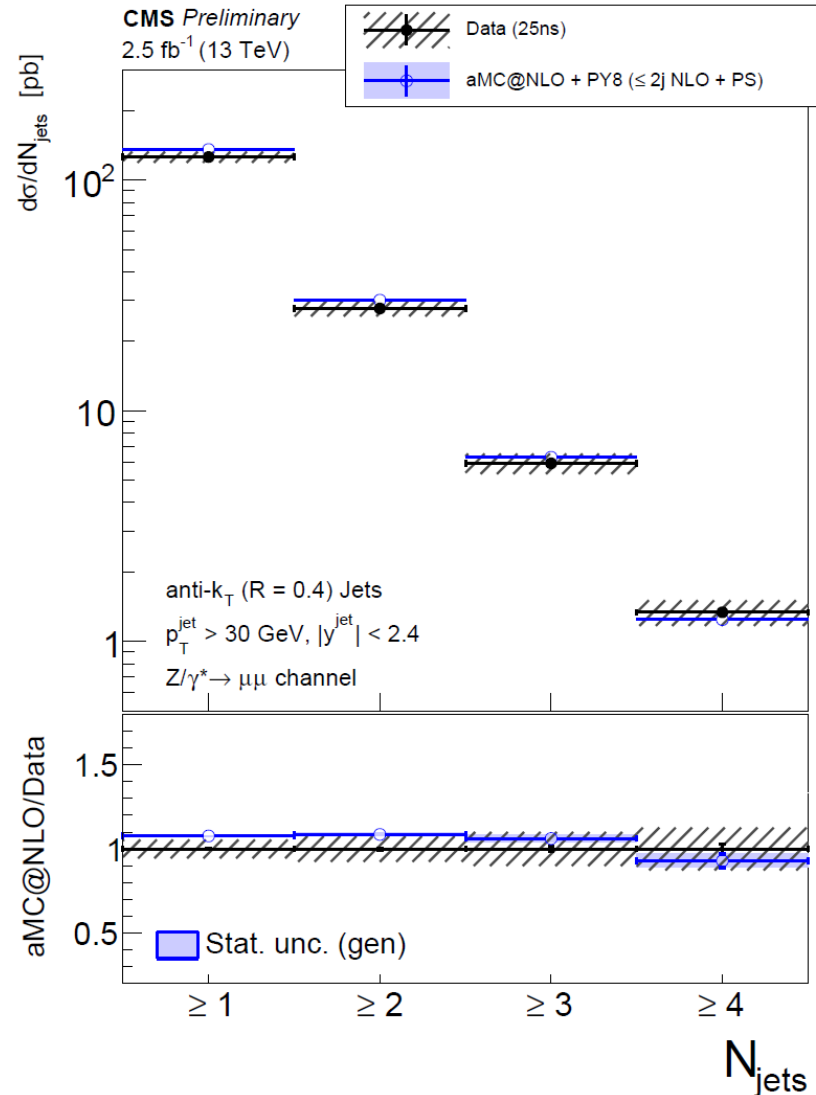
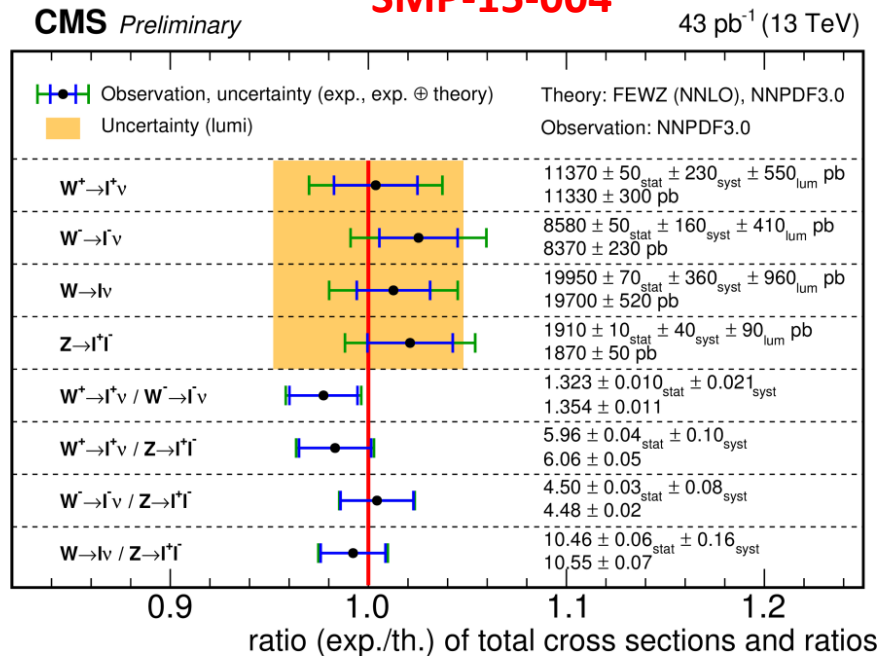


W and Z (+jets) production

SMP-15-010

- Measurements of **inclusive W and Z cross sections** and ratios (W/Z , W^+/W^-)
- New measurement of **Z+jets differential cross sections**

SMP-15-004

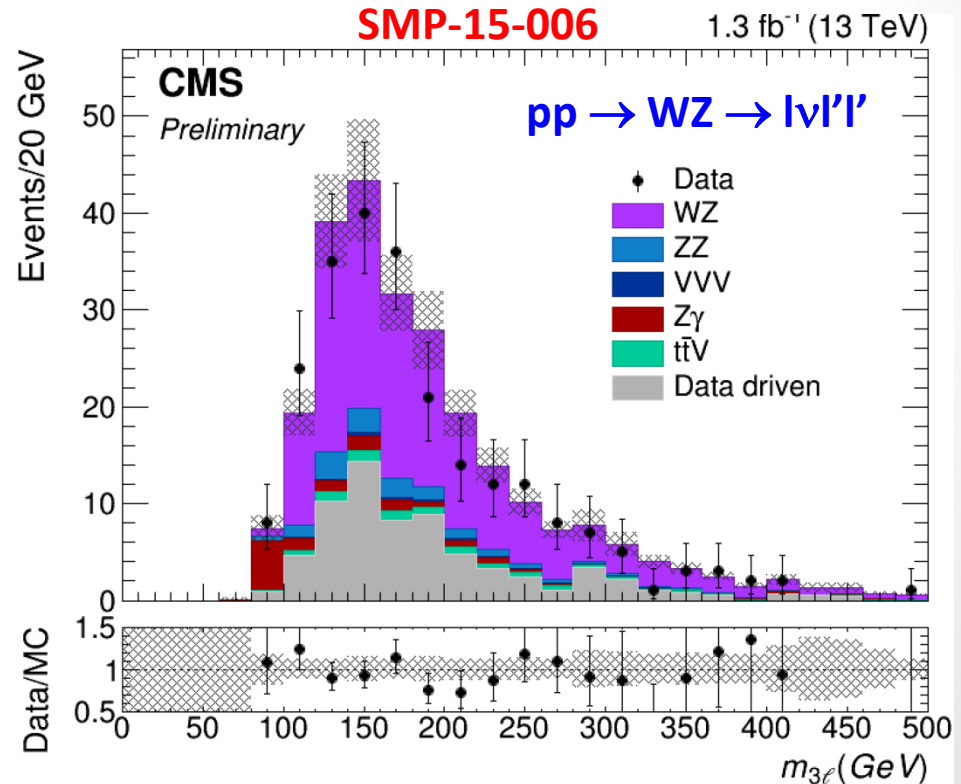
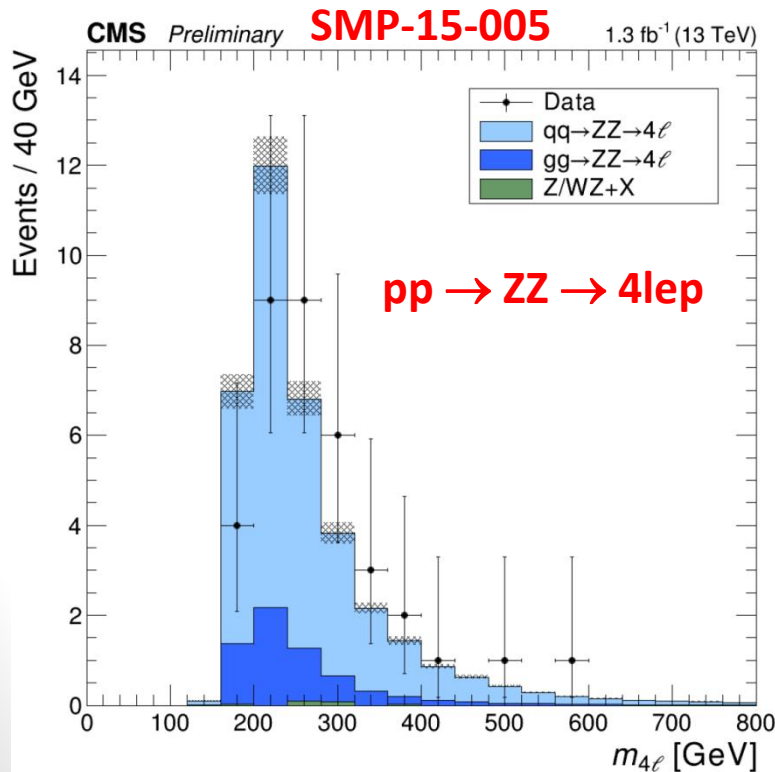


Diboson production: ZZ, WZ

- Critical measurements testing EWK theory at 13 TeV vs. 8 TeV
- Important background to measurements of Higgs properties

$$\sigma_{\text{fid}}(pp \rightarrow ZZ \rightarrow 4\ell) = 38.0^{+6.7}_{-6.0} (\text{stat})^{+1.5}_{-1.2} (\text{syst}) \pm 1.8 (\text{lum.}) \text{ fb}$$

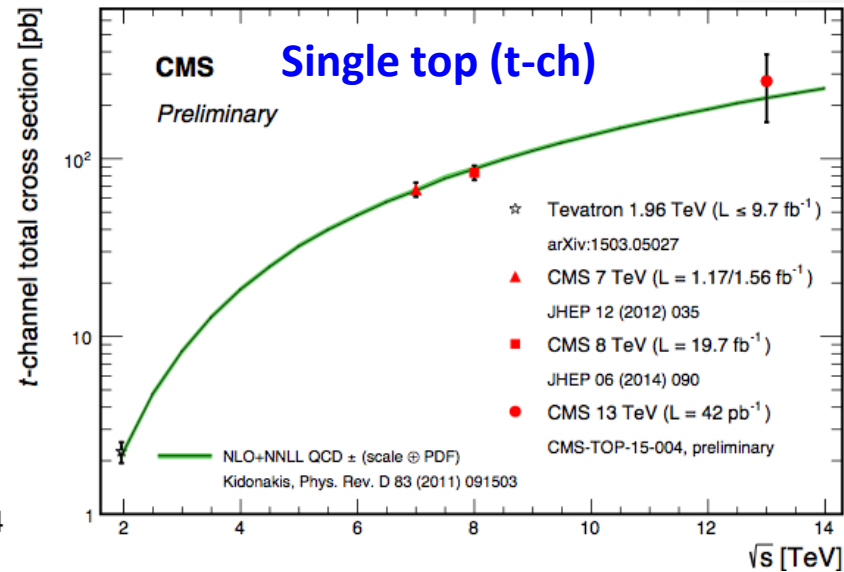
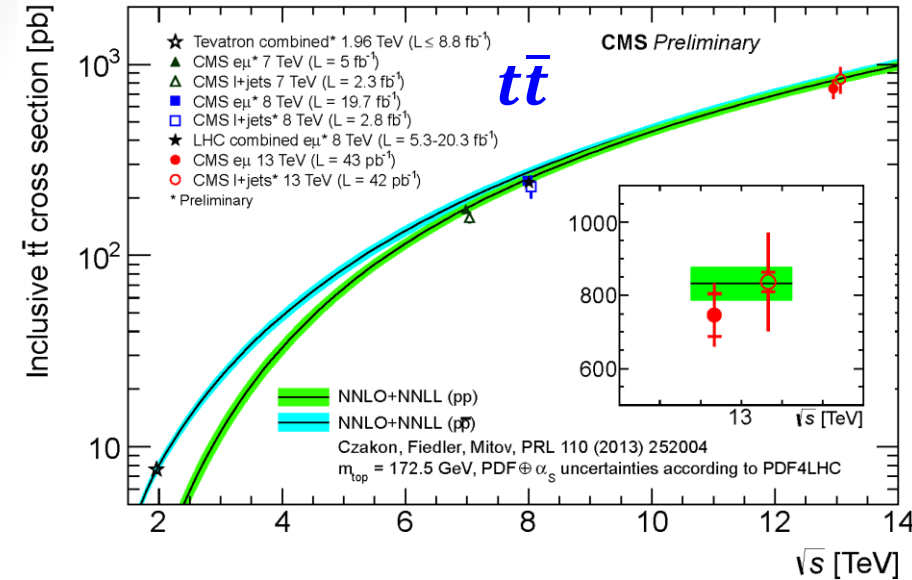
$$\sigma_{\text{fid}}(pp \rightarrow WZ \rightarrow \ell\nu\ell'\ell') = 239 \pm 29 (\text{stat})^{+52}_{-40} (\text{syst}) \pm 11 (\text{lum.}) \text{ fb}$$



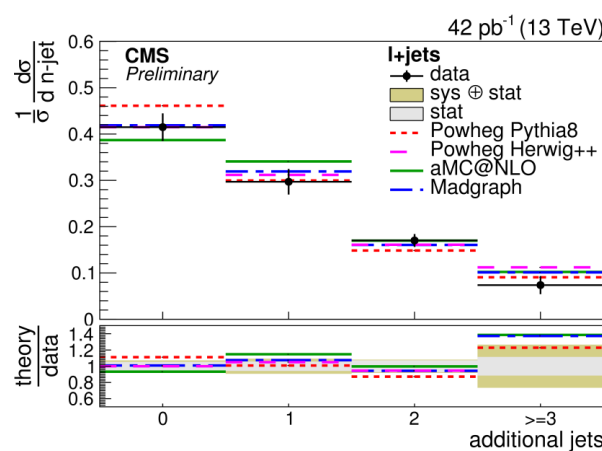
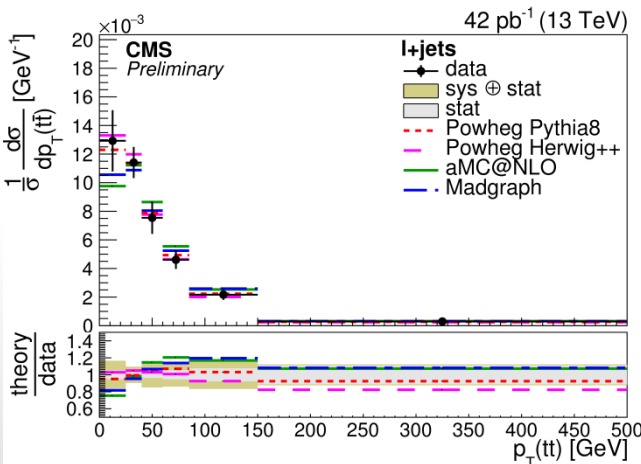
Top quark production

TOP-15-003 TOP-15-005

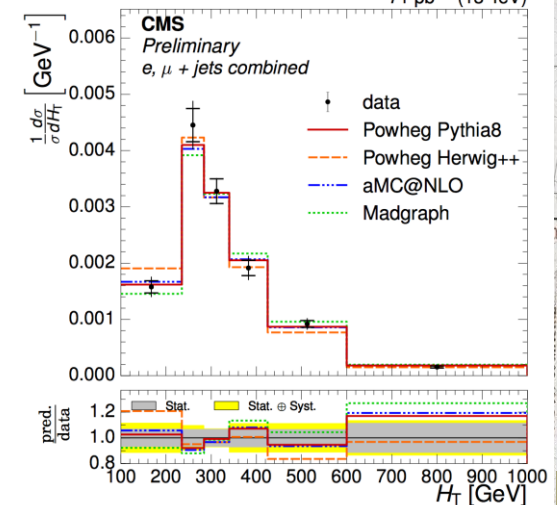
TOP-15-004



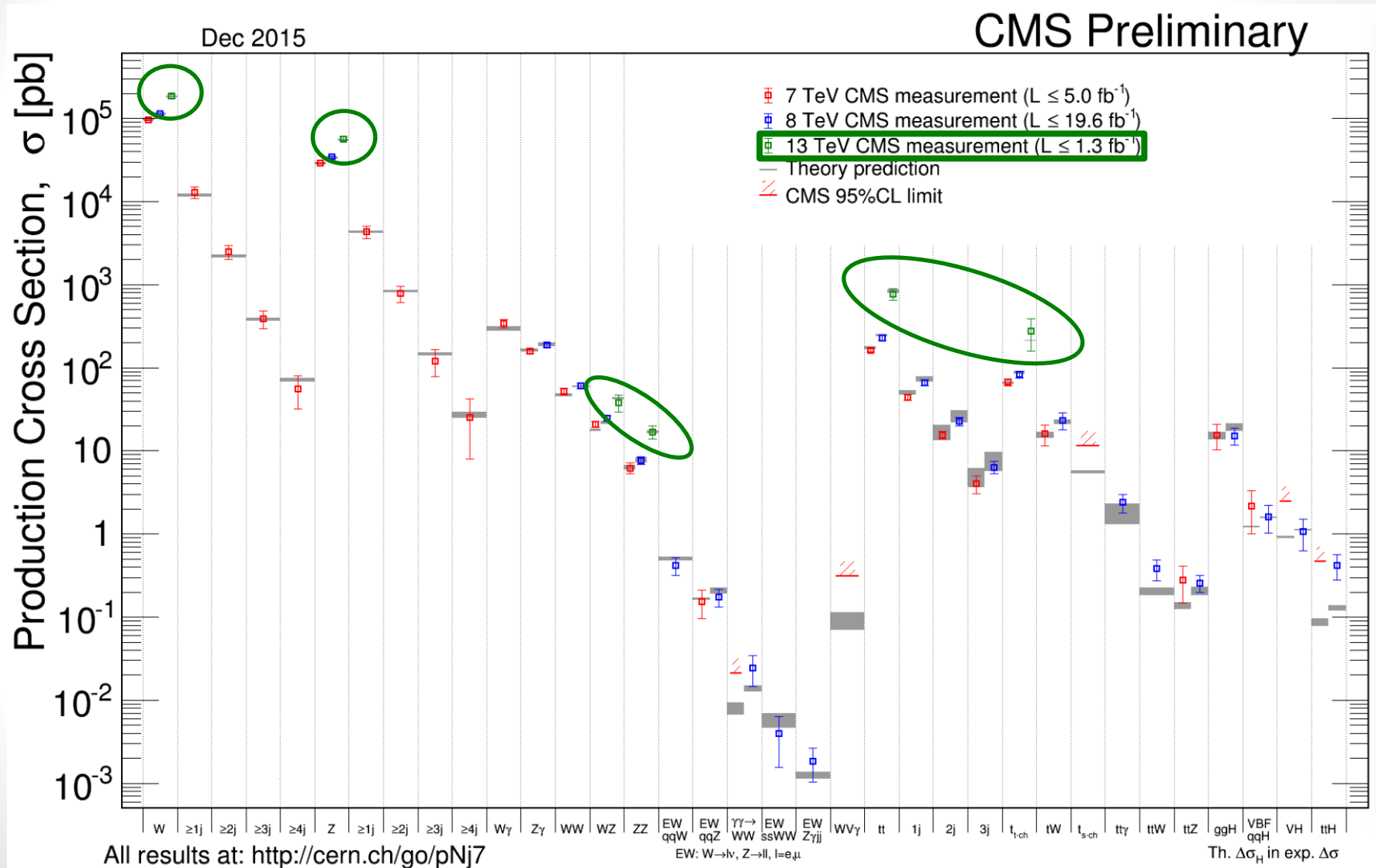
TOP-15-005



TOP-15-013



Standard Model: still going strong



Seeing new friends:

Preparing for Higgs rediscovery



Higgs physics at 13 TeV

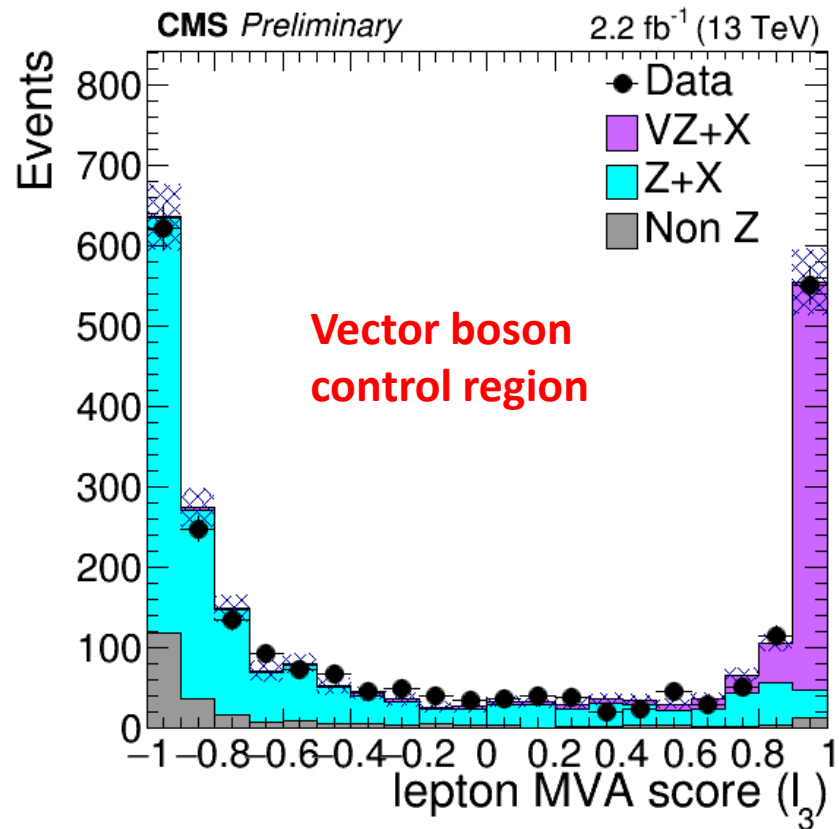
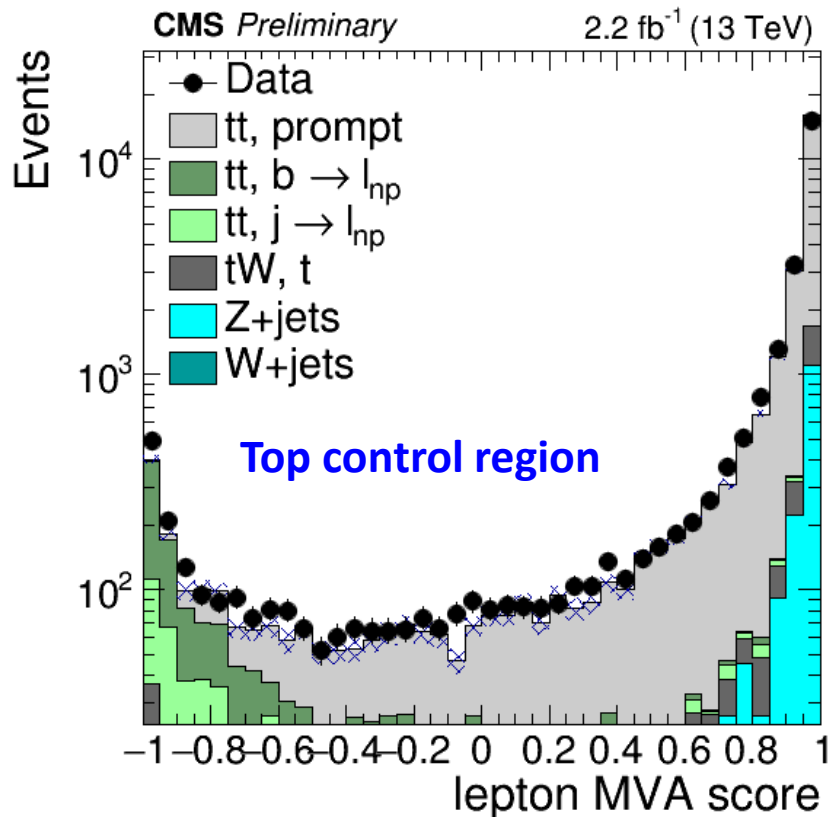
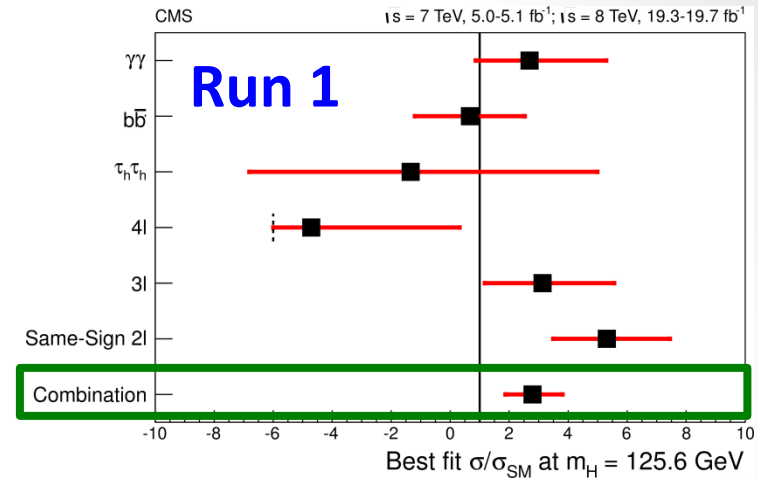
- **13 TeV vs. 8 TeV:**
 - Gluon fusion and VBF production get 2.6x boost relative to 8 TeV
 - Discovery channels visible with $\sim 5 \text{ fb}^{-1}$
- **Engaged in preparatory studies**
 - Preliminary studies of analysis-level inputs, control regions, etc
 - Measurements of trigger, ID, selection efficiencies in kinematic regions relevant for Higgs physics
- **Points to note:**
 - ttH production gets a factor $\sim 4x$ boost, key goal in Run 2: early check on observed excess in this channel in Run 1
 - $H \rightarrow b\bar{b}$ still not observed
 - Increased sensitivity (per fb^{-1}) for Higgs partners at high mass
 - Challenges: higher pile-up, increased background from top

All CMS Higgs analyses remain blind at this time

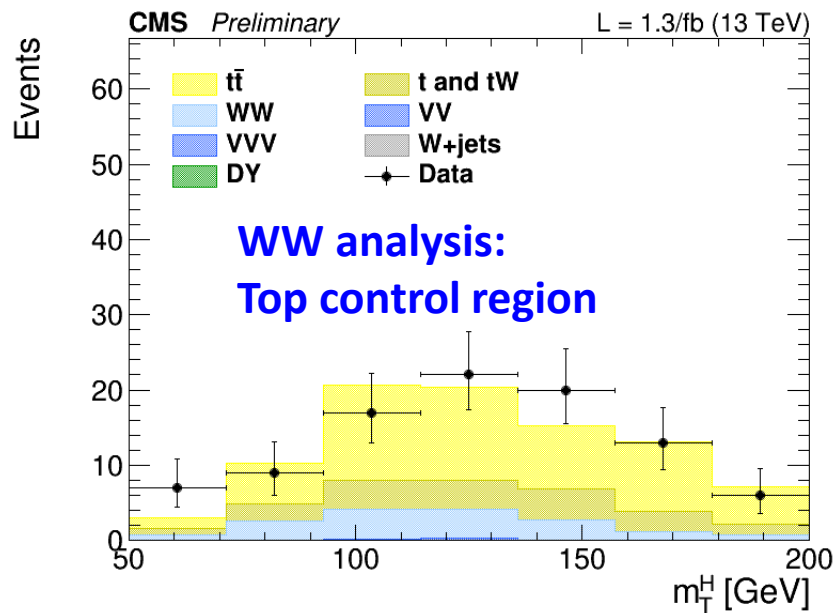
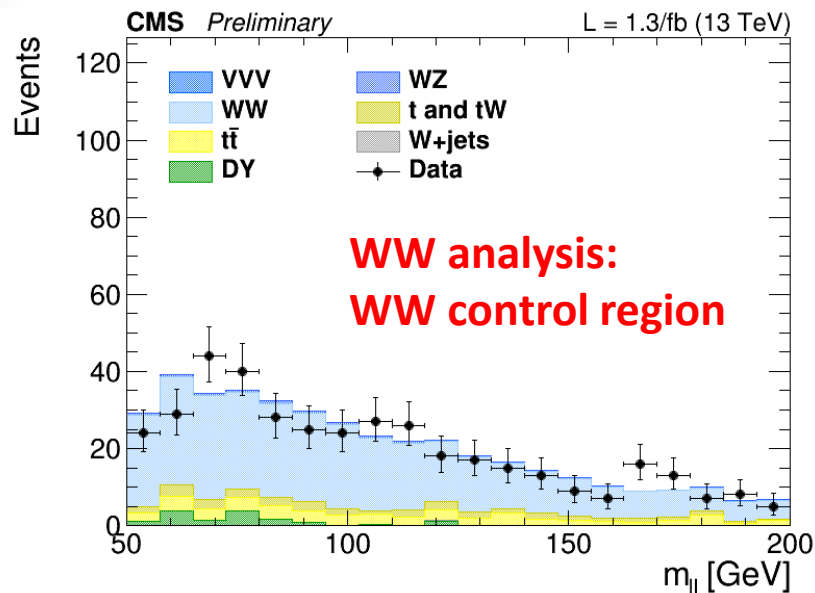


Higgs studies: ttH

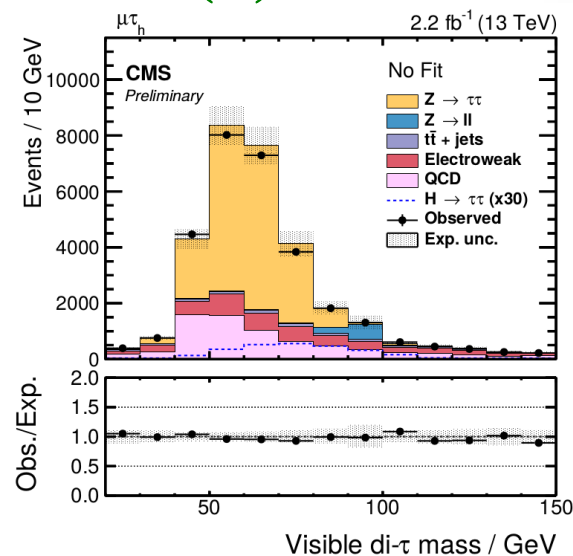
- Run 1:** combined ttH signal strength **$\sim 2\sigma$ above SM prediction**
- First look at **multilepton analysis** control regions



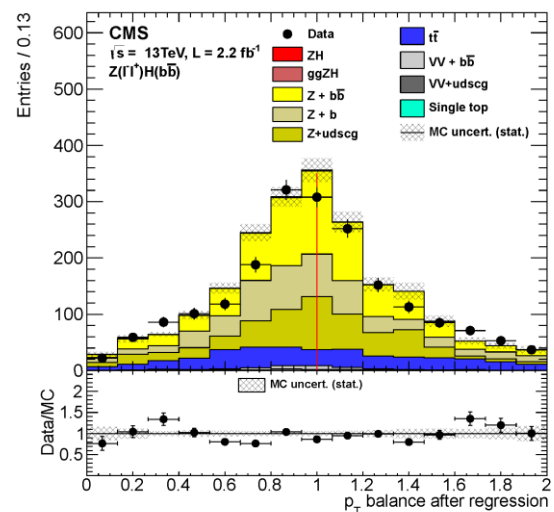
Higgs studies: WW , $\tau\tau$, bb



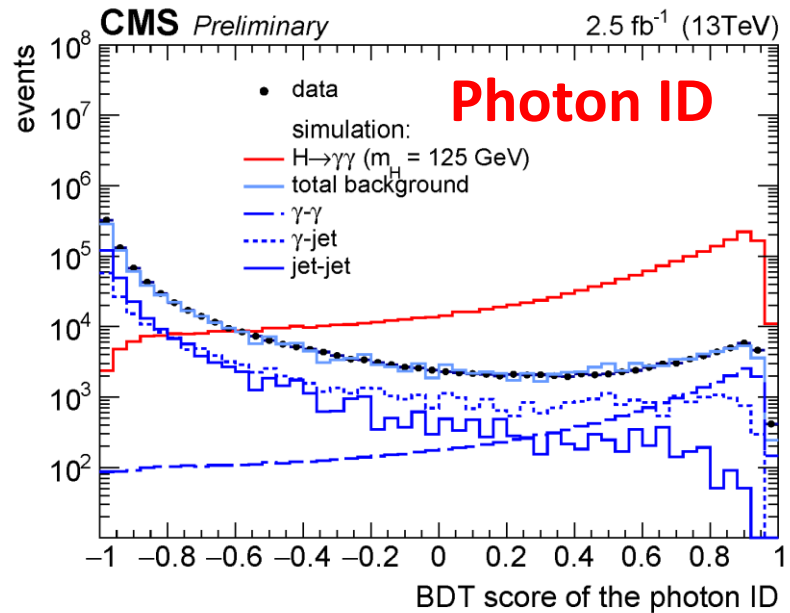
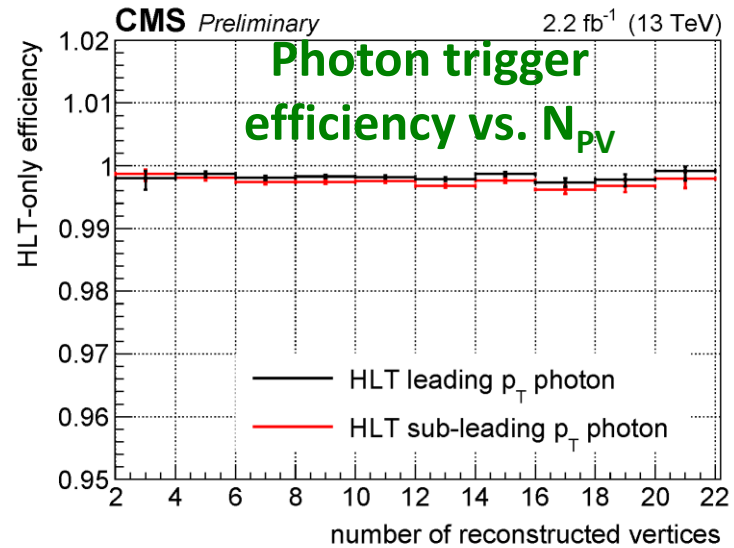
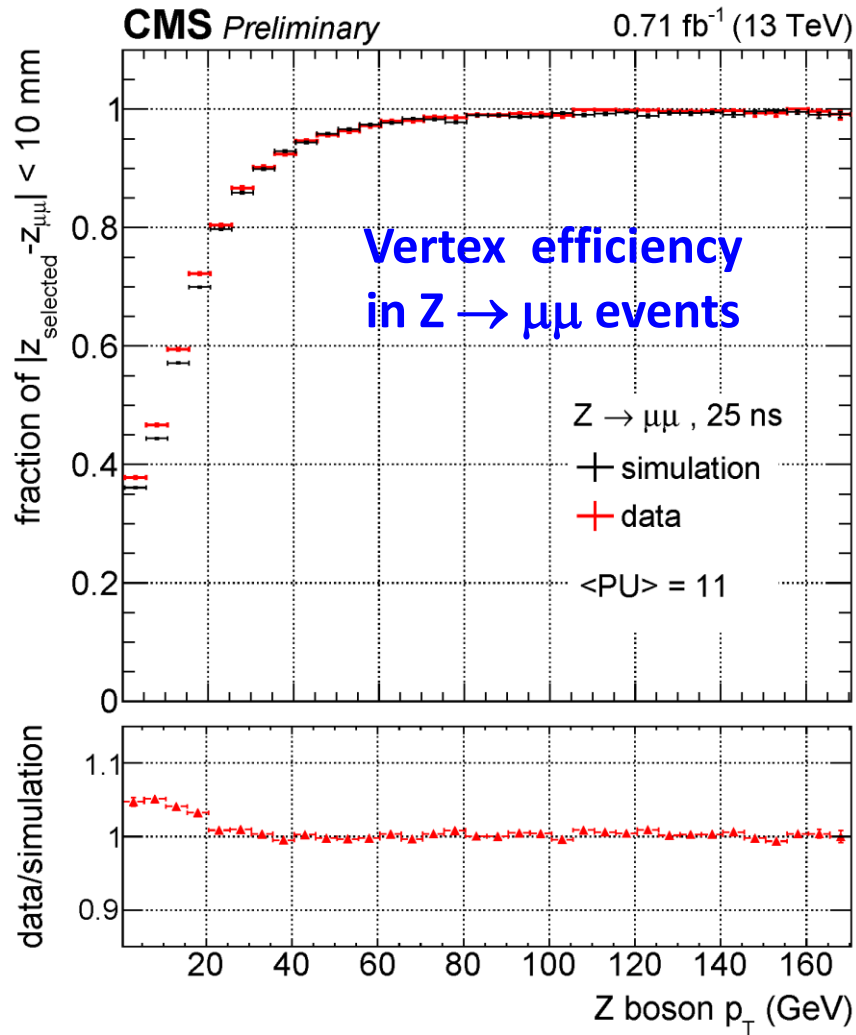
Visible $M(\tau\tau)$ reconstruction



p_T balance in $Z+bb$ after regression



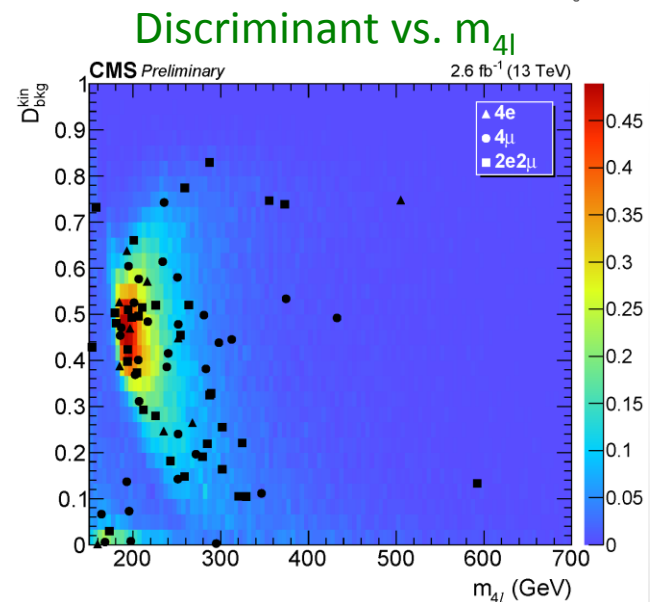
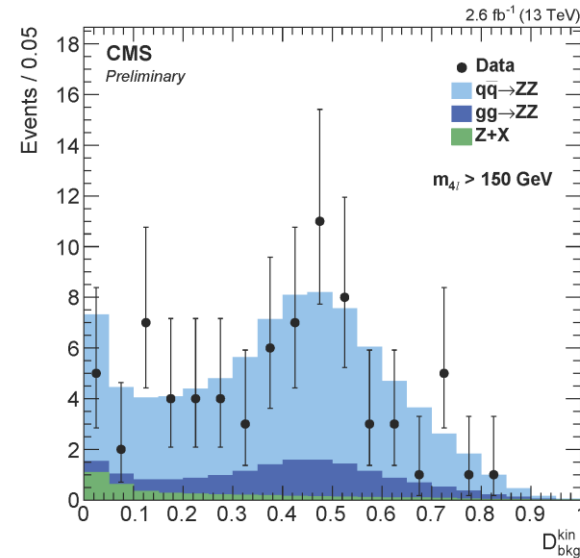
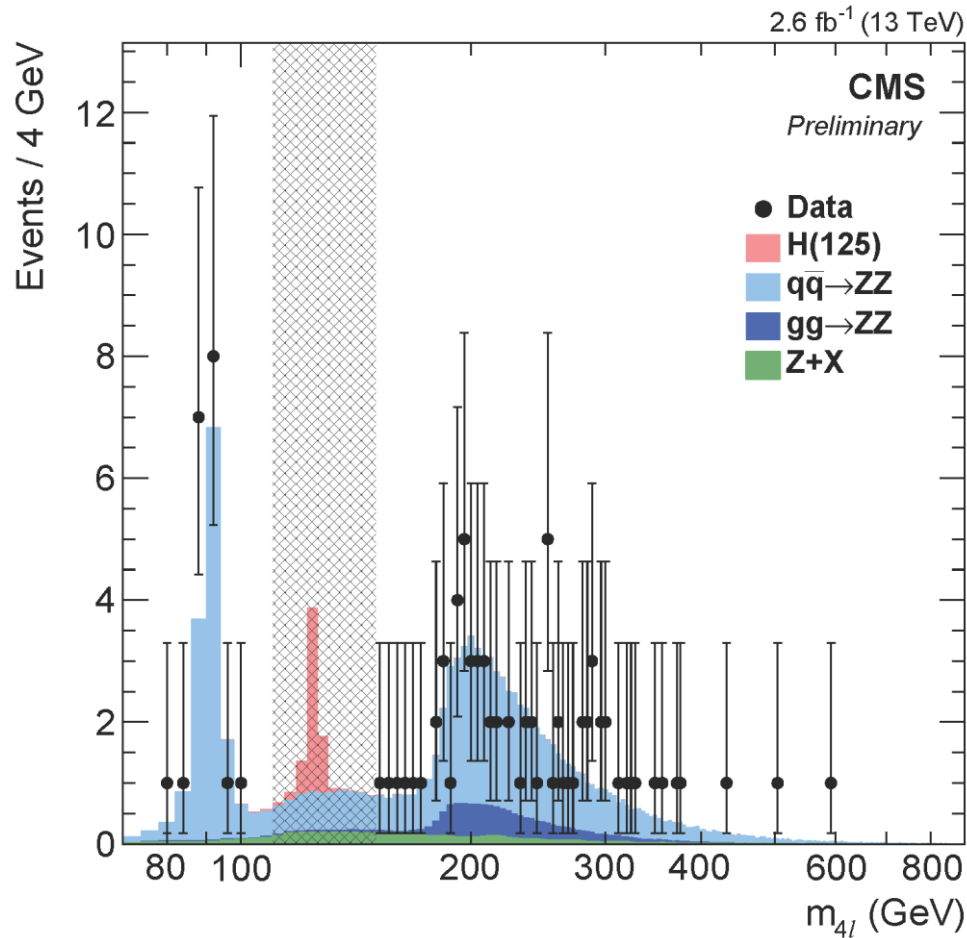
Higgs studies: $\gamma\gamma$



Higgs studies: ZZ(4l)

Kinematic discriminant for $m_{4l} > 150$ GeV

m_{4l} mass with Higgs region blinded



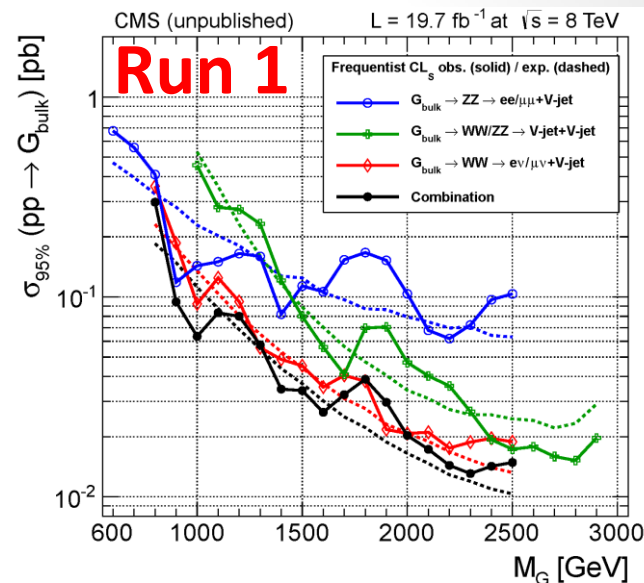
New physics searches:

Run 1 bumps, first look @ 13 TeV

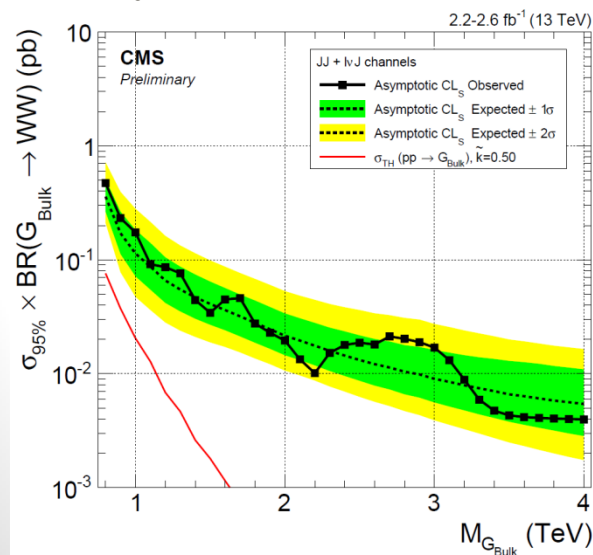


Search for diboson resonances

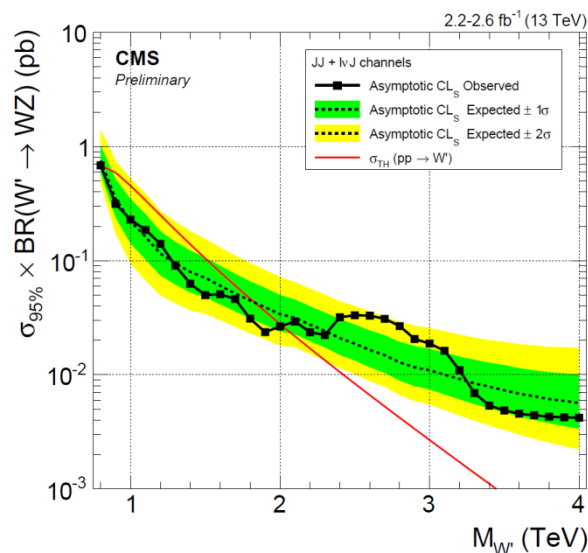
- **Run 1: CMS $\sim 2\sigma$ excess near 1.8-2.0 TeV**
- Repeat search at 13 TeV using most sensitive channels: lvJ , JJ
- **Analysis categorized in dijet mass** for optimal sensitivity to WW , WZ , ZZ signals
- **13 TeV: no excess observed in the region of interest near 2 TeV**
 - More data needed to fully exclude Run 1 excess



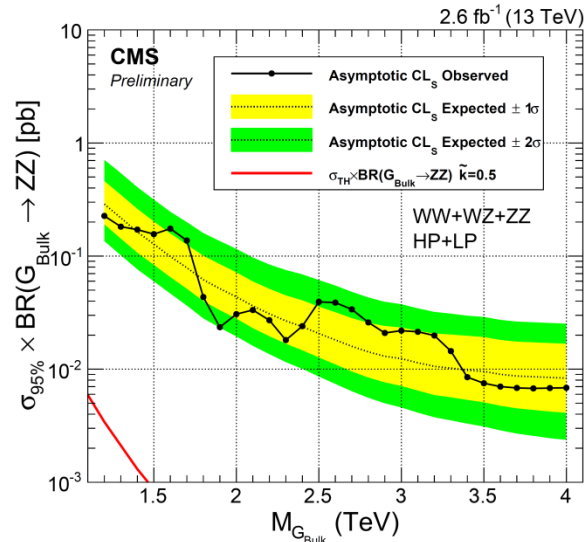
$G_{\text{Bulk}} \rightarrow WW (lvJ+JJ)$



$W' \rightarrow WZ (lvJ+JJ)$



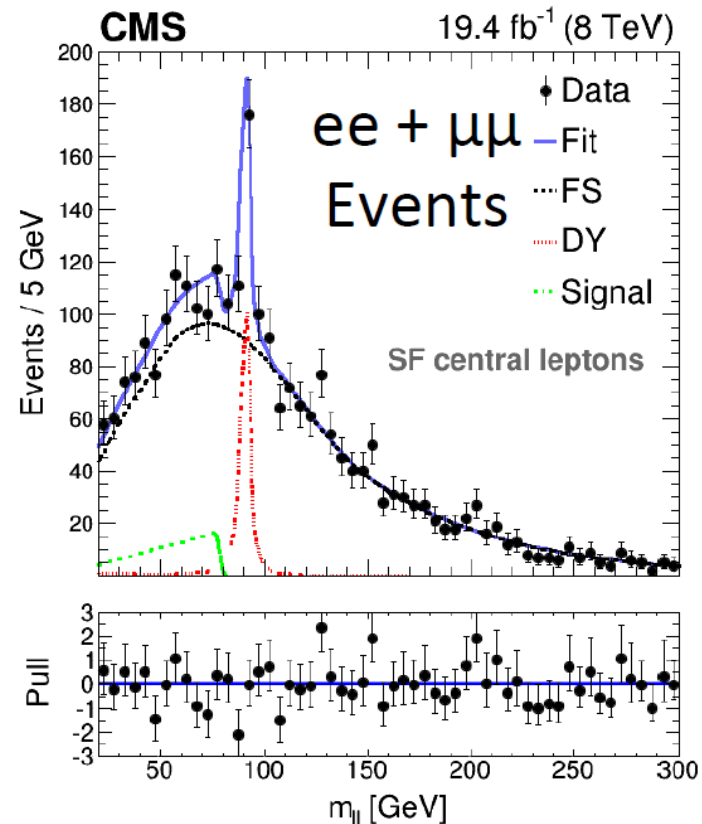
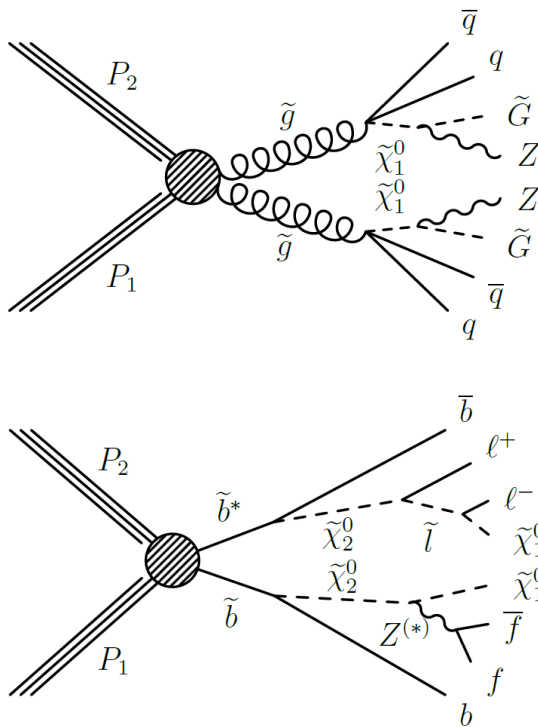
$G_{\text{Bulk}} \rightarrow ZZ (JJ)$



Opposite-sign dileptons

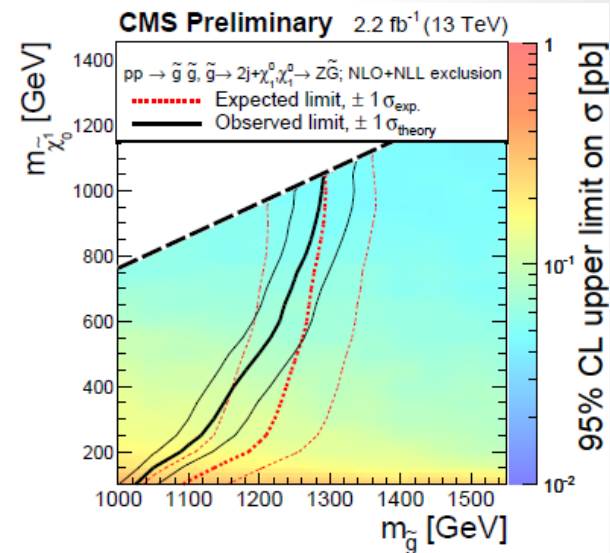
SUS-15-011

- **Bumps in Run 1**
 - **Off-peak:** CMS saw excess (“the edge”), no excess in ATLAS
 - **On-peak:** ATLAS saw excess in high H_T region, no excess in CMS
- **Important ‘first look’ channel for Run 2**

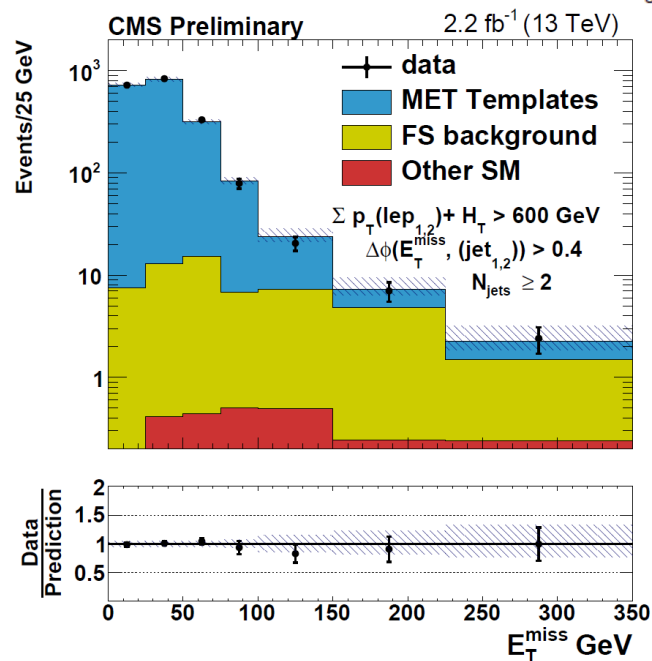
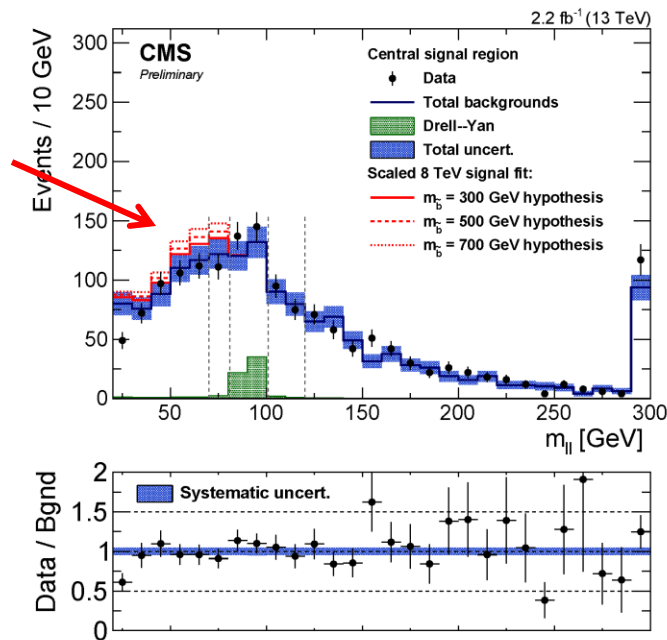


Opposite-sign dileptons: 13 TeV

- Off-peak selection similar to Run 1, on-peak analysis now includes a region targeting the ATLAS excess
- No significant signals are observed:**
 - Upper limits are below predicted yields scaling from the Run 1 excesses
 - For gluino masses in the range 500-1100 GeV



Run 1
excess



Searching for old friends:

Supersymmetry searches at 13 TeV



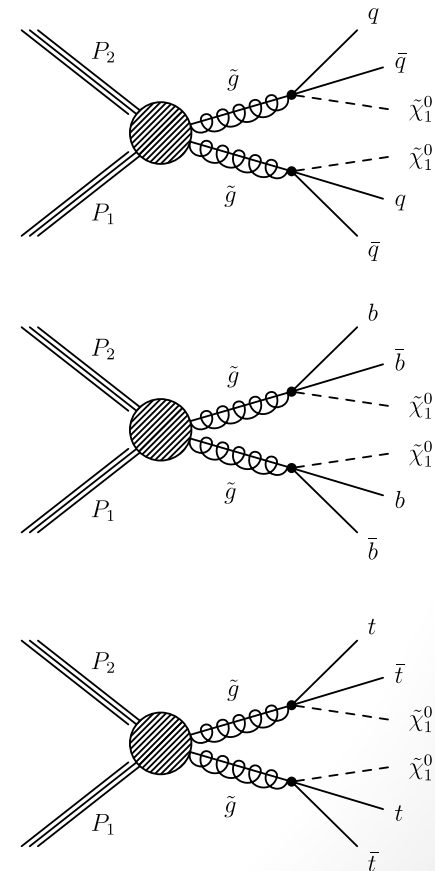
Gluino searches: overview

Multiple complementary final states and approaches

- **0 leptons**
 - MH_T, H_T (SUS-15-002)
 - MT2 (SUS-15-003)
 - Razor (SUS-15-004)
 - α_T (SUS-15-005)
- **1 lepton**
 - Sum of jet masses M_J (SUS-15-007)
 - Razor (SUS-15-004)
- **Same-sign dilepton (SUS-15-008)**
 - Rare SM signature
- **Run 1: limits range up to ~ 1.4 TeV**
 - ➔ Large σ boost at 13 TeV!

Early Run 2 SUSY studies reported in CMS-DP-2015-035

- Inclusive searches benchmarked with simplified models

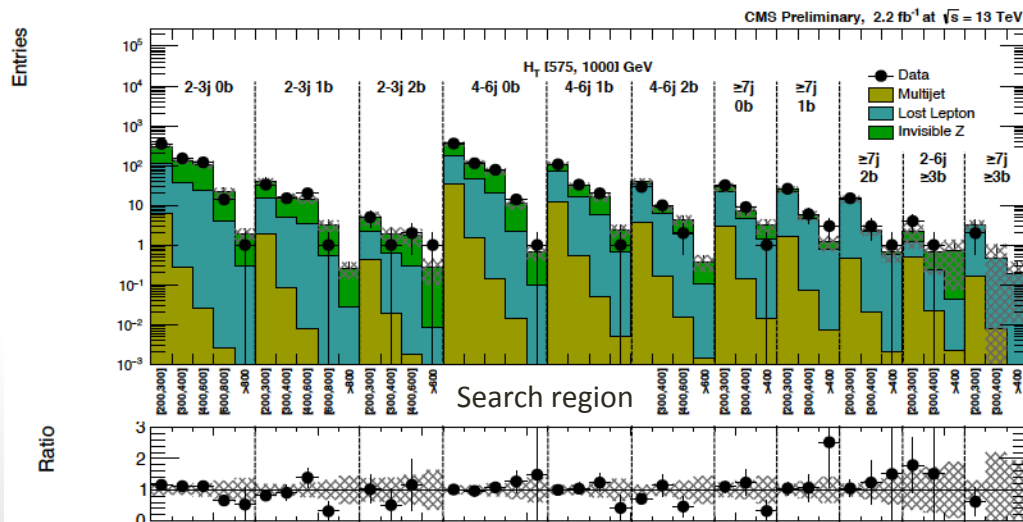
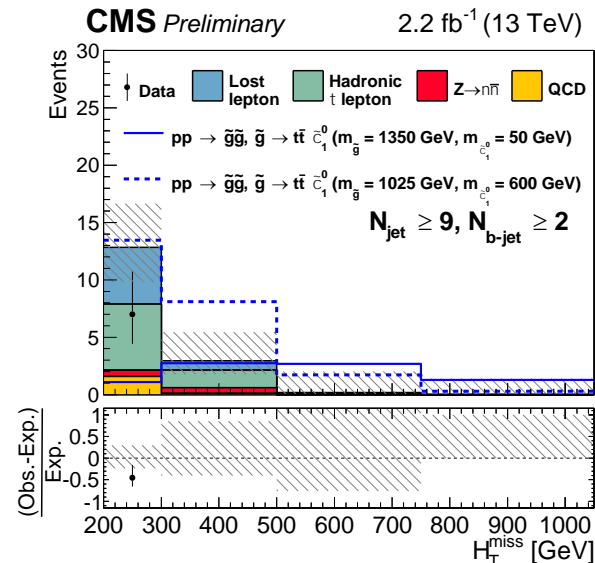


Gluino searches: hadronic

- **Broad Searches** binned in nJet, nB, HT, and MHT/MT2
- **Common features:** SM bkg determined using **data-driven techniques**:
 - Top and W+jets (“lost lepton”): estimated from single-lepton control samples
 - $Z \rightarrow \nu\nu$ (invisible): from γ + jets and $Z \rightarrow \mu\mu$
 - QCD multijet: suppressed with angular and missing energy variables

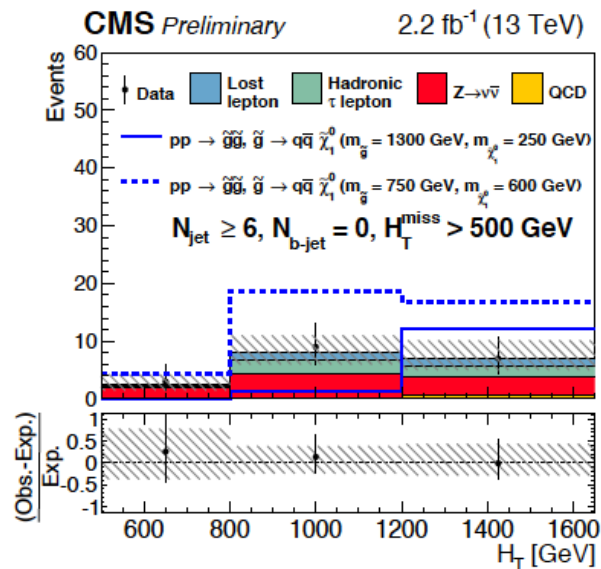
MH_T, H_T (SUS-15-002):

Extended to include nJet ≥ 9



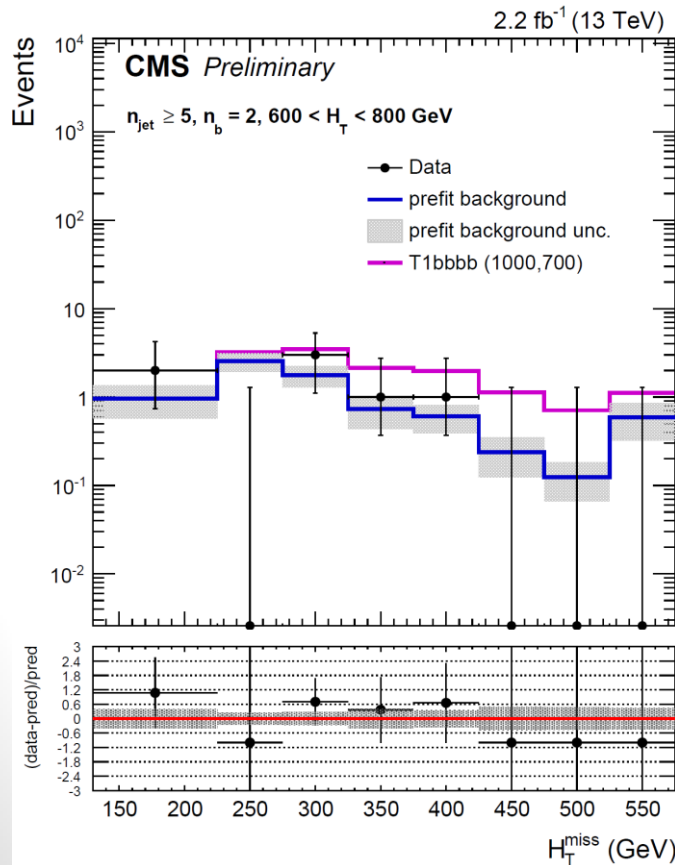
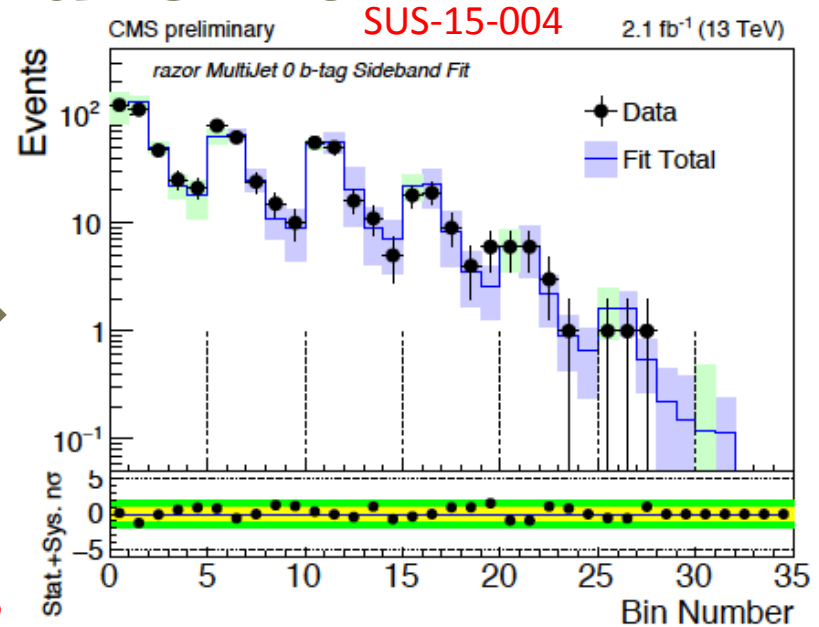
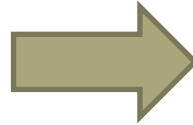
M_{T2} (SUS-15-003):

Extended to include monojet bins



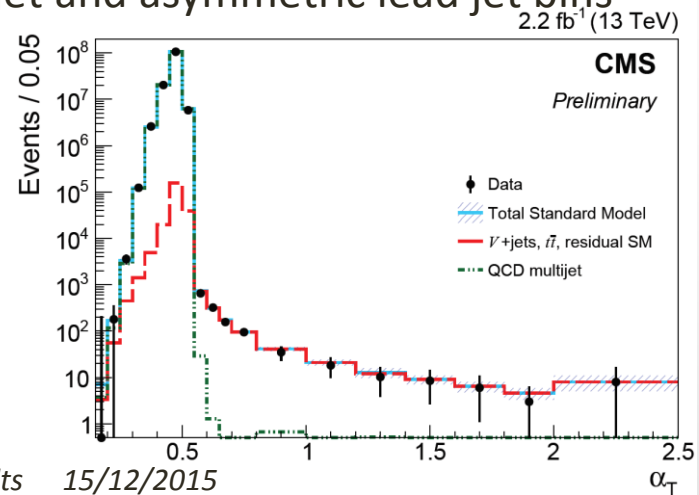
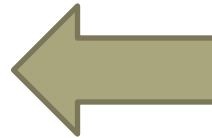
Gluino searches: hadronic

- **Razor Search:** signal bump in MR
- Utilize fits to kinematic variables R^2 and MR in data to characterize backgrounds
- Binned in nB



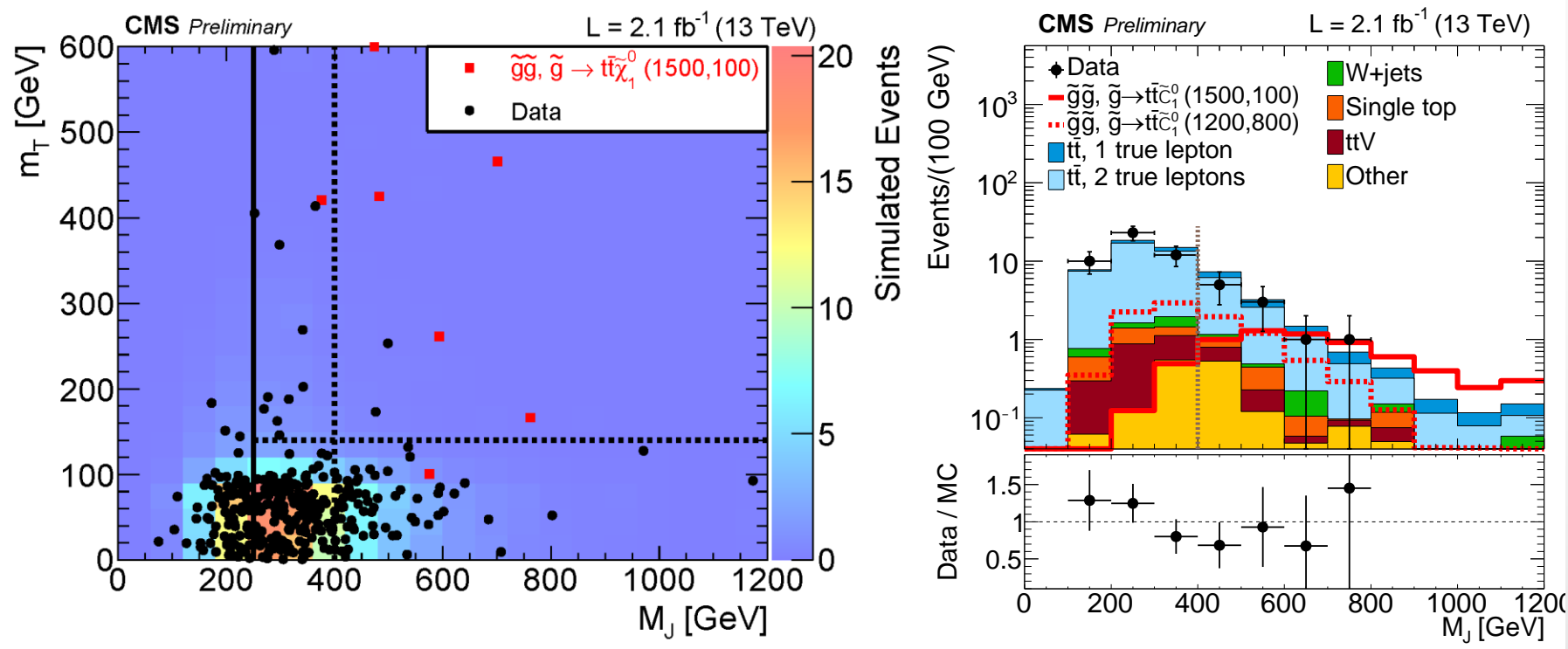
- SUS-15-005 α_T : Suppress QCD background

- Binned in HT, MHT, nJet, nB
- New: monojet and asymmetric lead jet bins



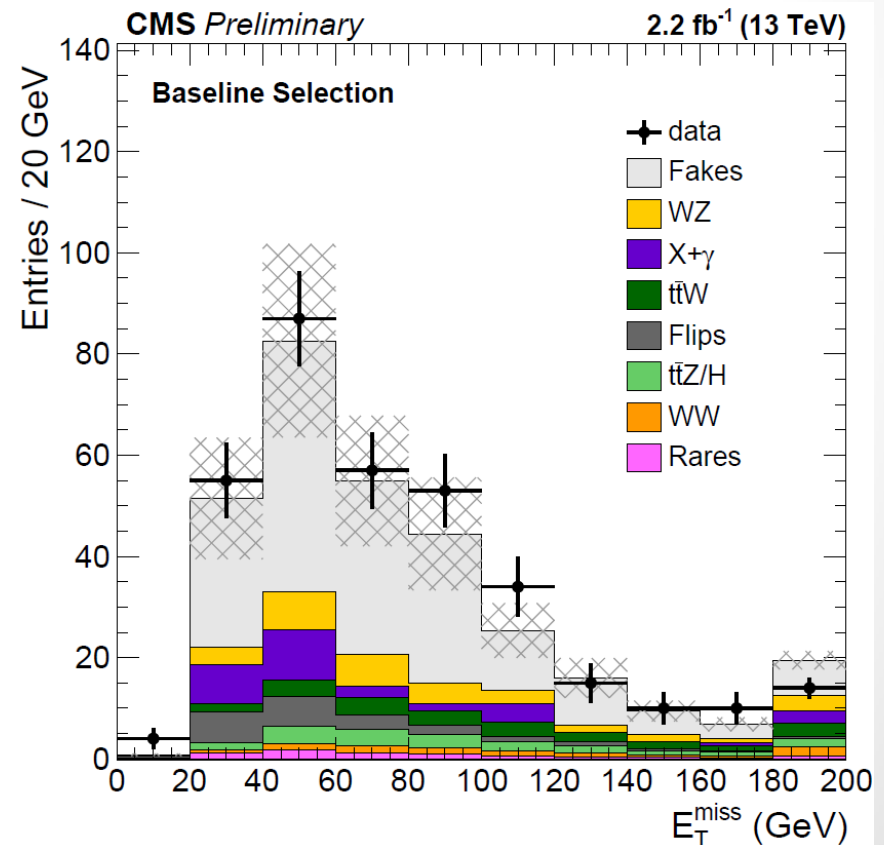
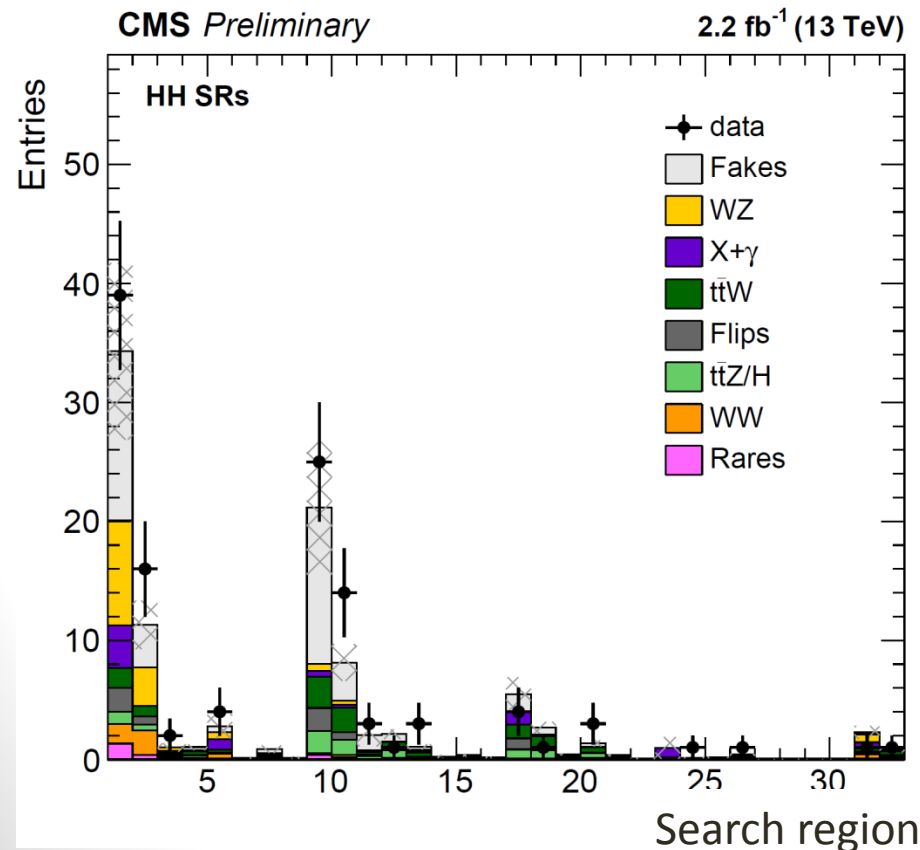
Gluino search in 1L + jets (M_J)

- **Signature:** 1 lepton + many jets and b-jets
- Search in events with large $\Sigma(\text{jet mass}) = M_J$
- **Data-driven bkg estimation at high M_J and M_T**



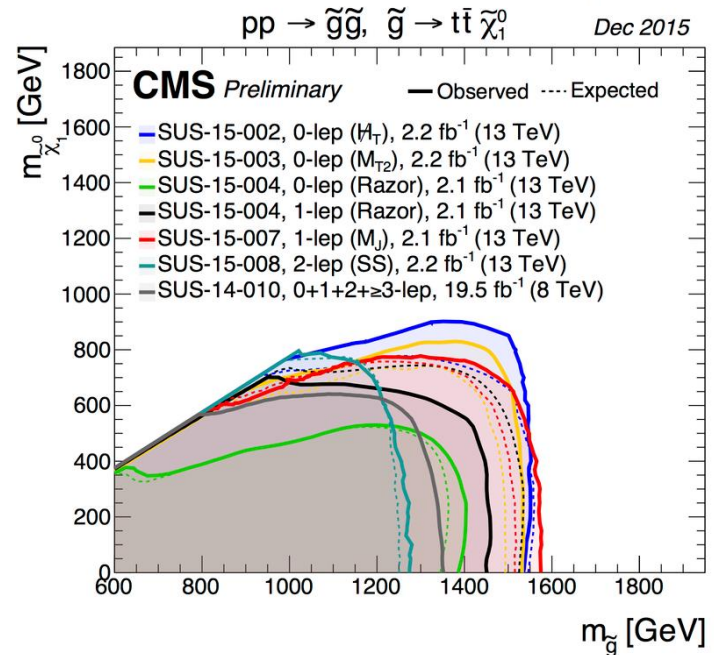
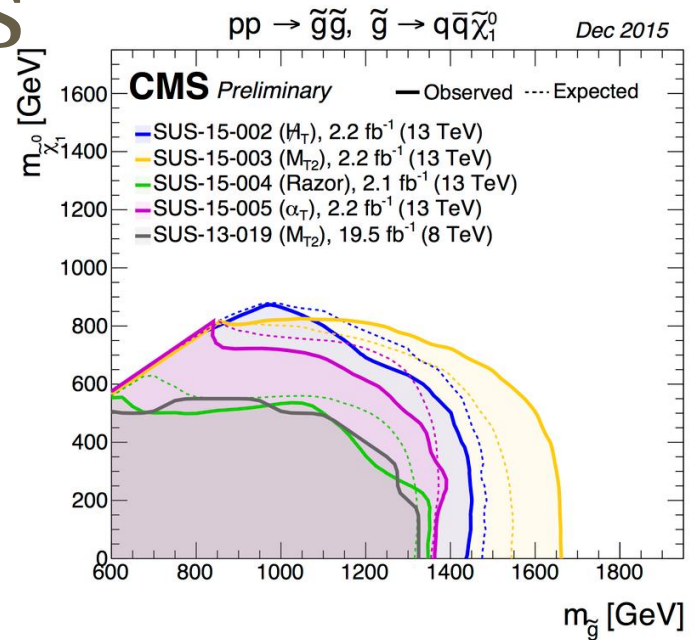
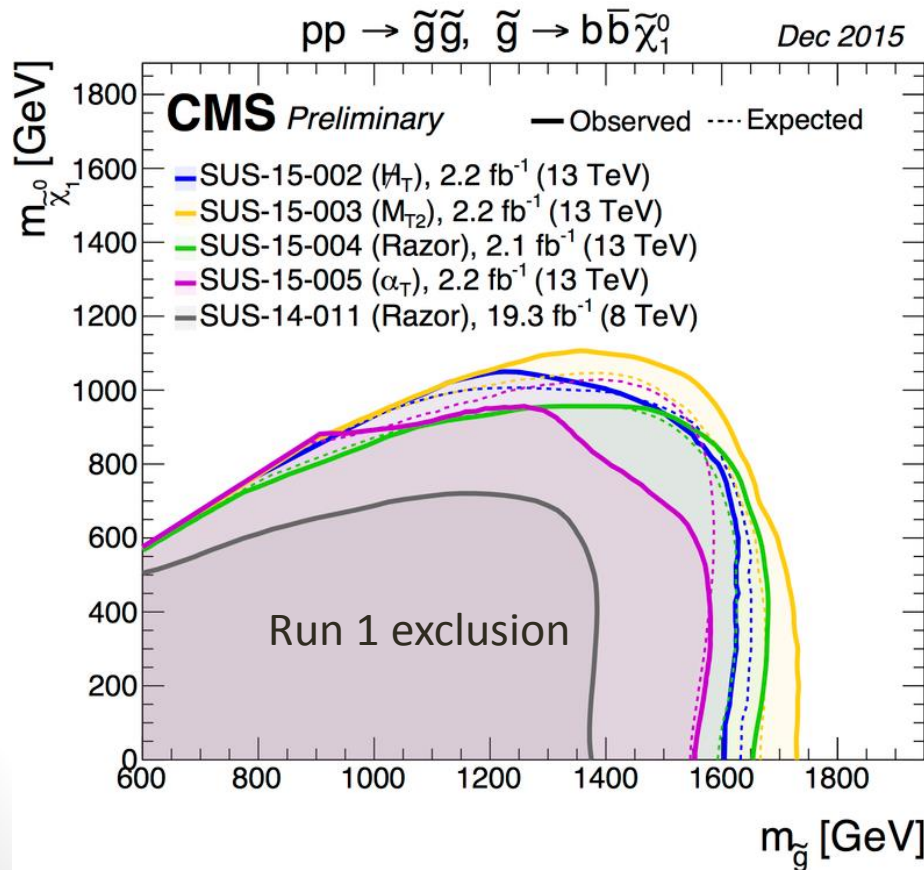
Search with same-sign leptons

- **Inclusive Search:** Binned in n -jet, n_B , MET, HT, MT
- Main background from non-prompt leptons measured in data
- Di-lepton trigger extends reach to very low MET



Gluino search results

- **No significant signals observed**
- **Exclusions reach to > 1.7 TeV***, significantly exceeding Run 1 limits



(*): in particular simplified models and for low LSP mass



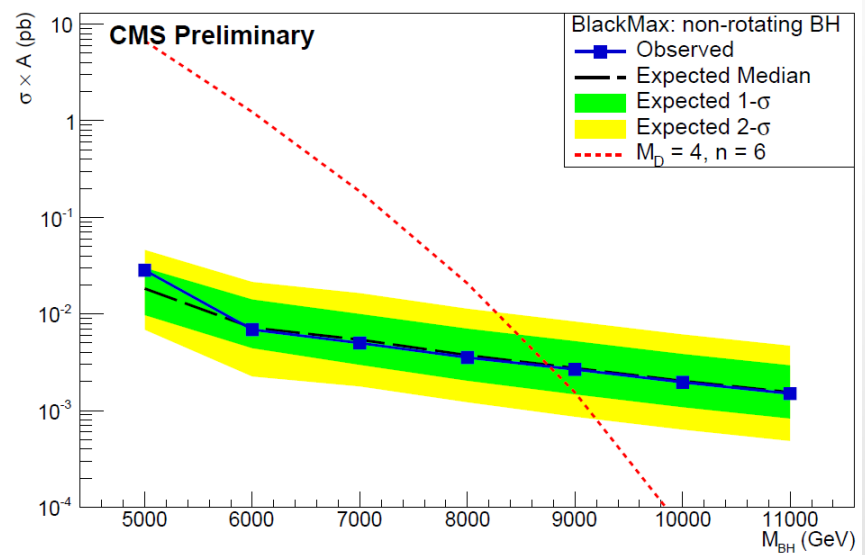
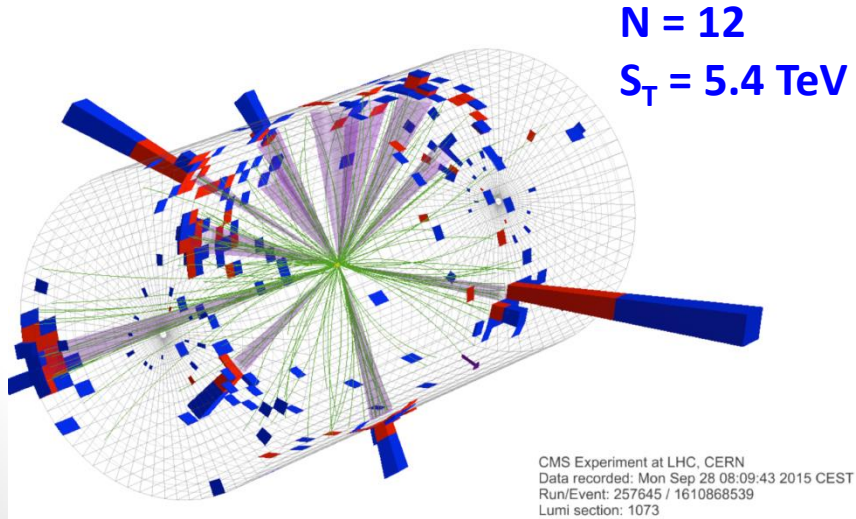
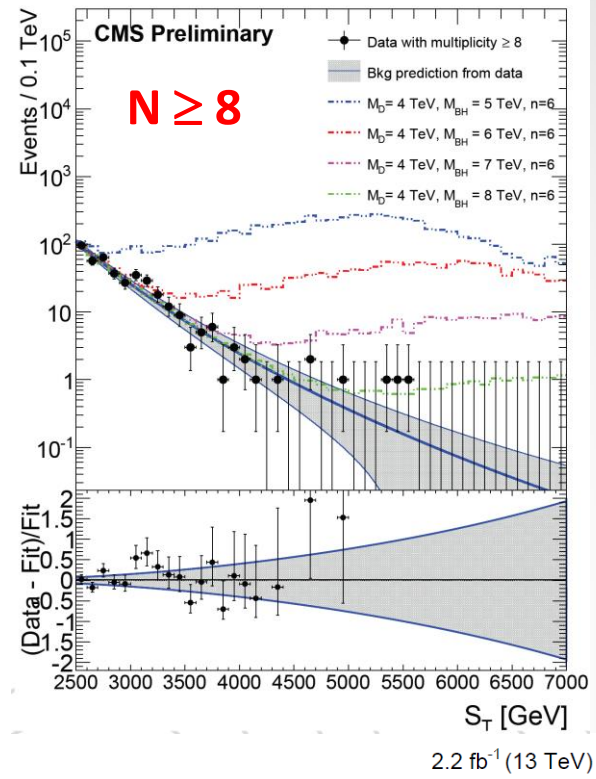
Searching for strange friends:

Exotica searches at 13 TeV



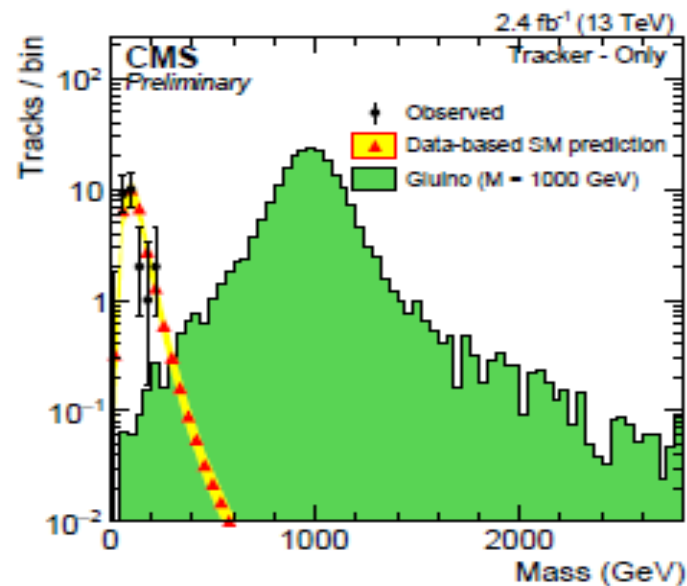
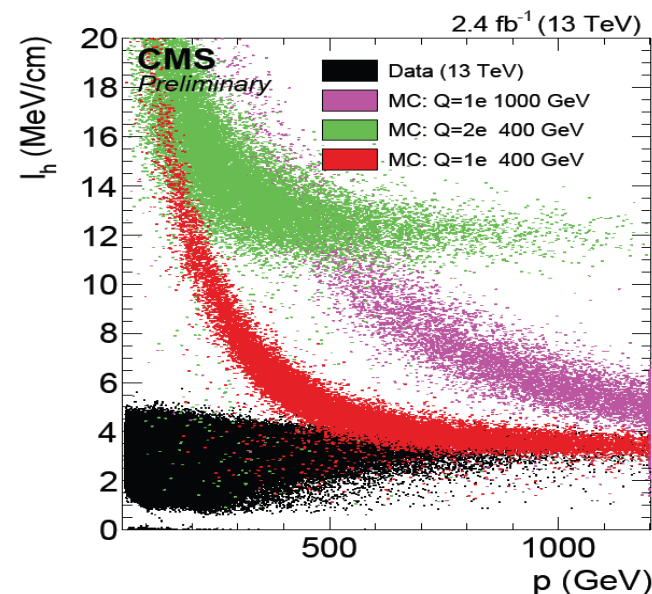
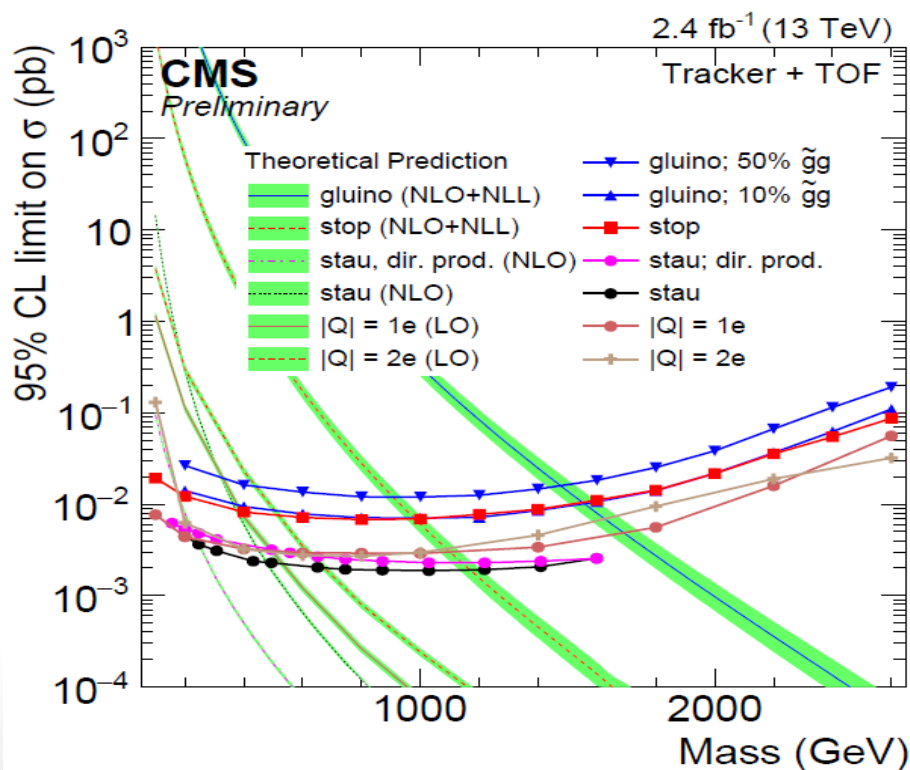
Search for black holes

- Search for semi-classical and quantum black holes
- Analysis binned in number of objects (jets, leptons, photons) and S_T
- Model-independent limits set as function of (N, S_T) , **mass limits are 8 TeV for QBH and 8.7 TeV for semi-classical** (Run 1: 5.5-6.0 TeV)



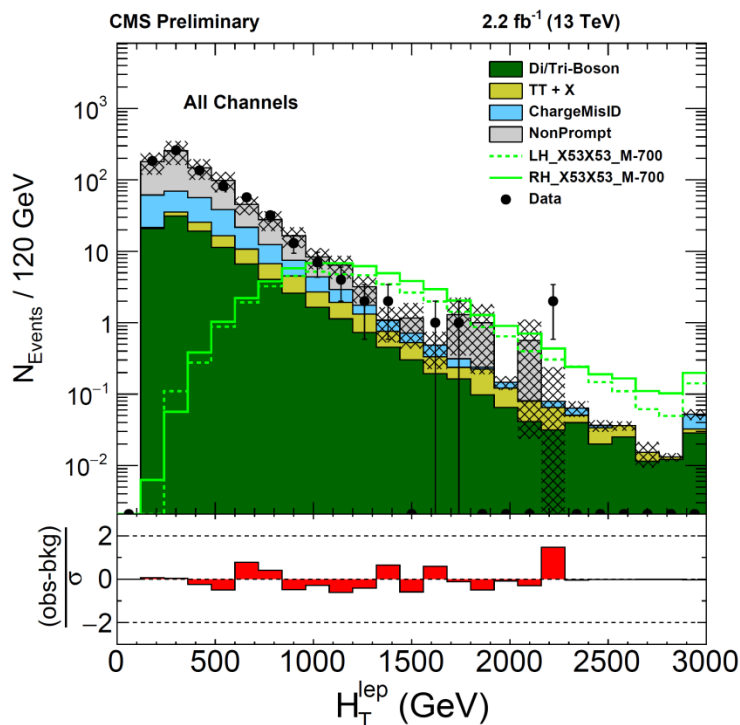
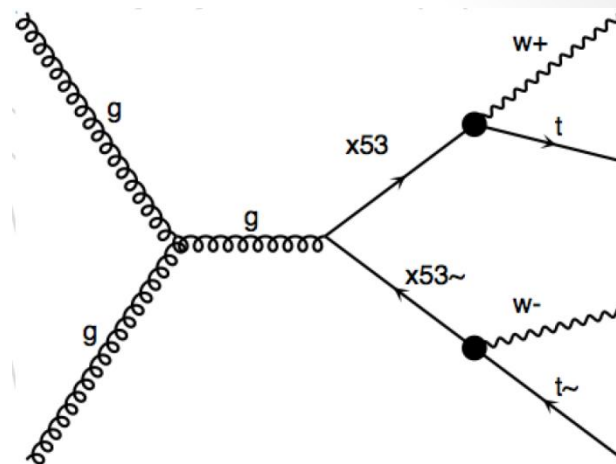
Heavy stable charged particles

- Signature:** tracks with high p_T , high tracker dE/dx , Long TOF from IP to Muon System
- Limits on gluino mass > 1.6 TeV (1.3 TeV in Run 1)**

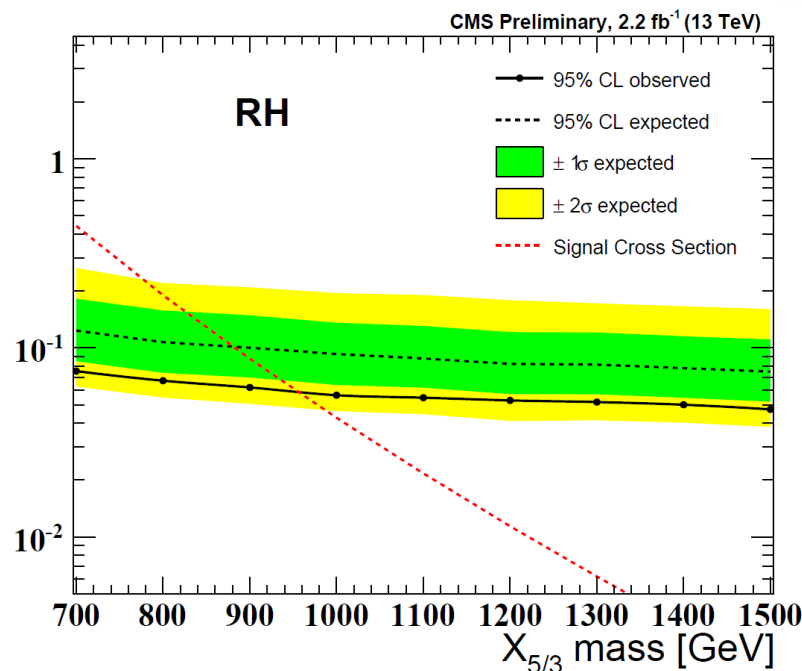


Top quark partners with $q = 5e/3$

- **Search for $X_{5/3} \rightarrow tW$** , predicted in composite Higgs models
- **Same-sign dilepton and lepton+jets** channels used to search for signal
- Limits set on right-handed (960 GeV) and left-handed (940 GeV) top partners

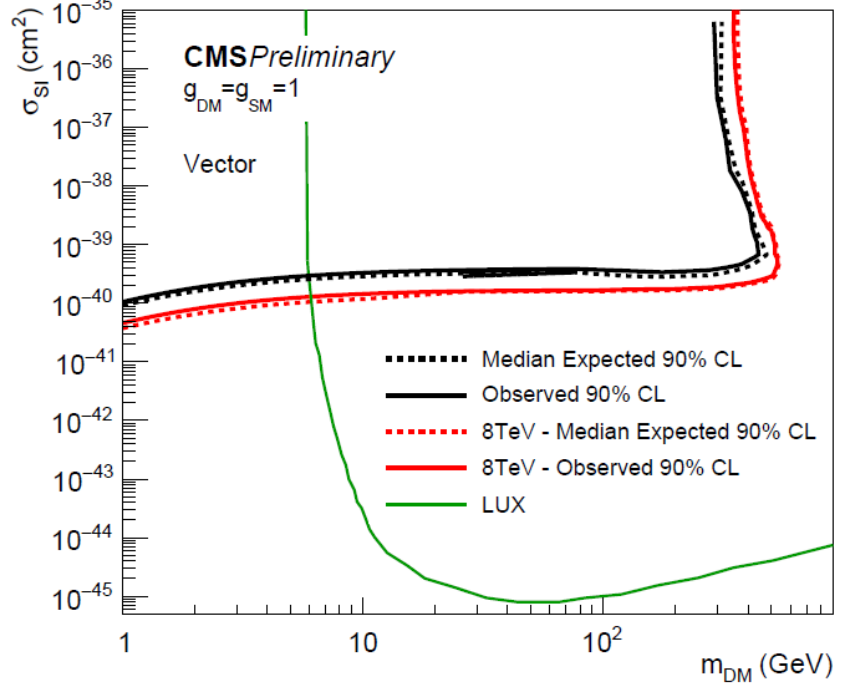
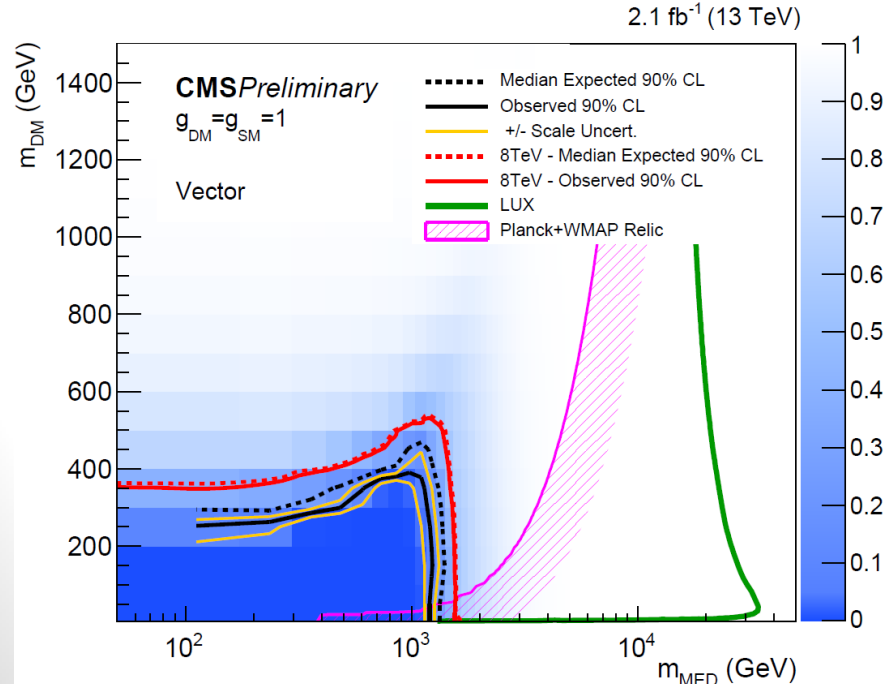
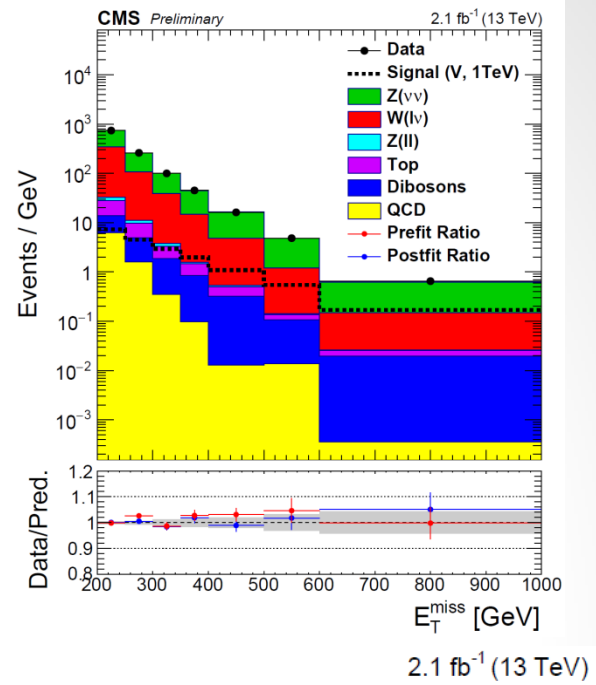


$\sigma(X_{5/3}) [\text{pb}]$



Search for dark matter

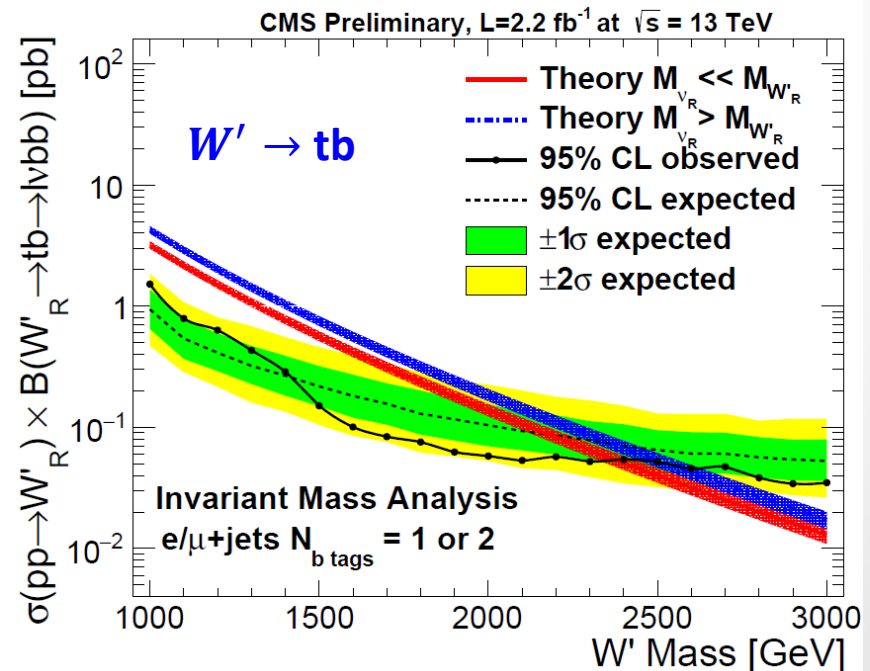
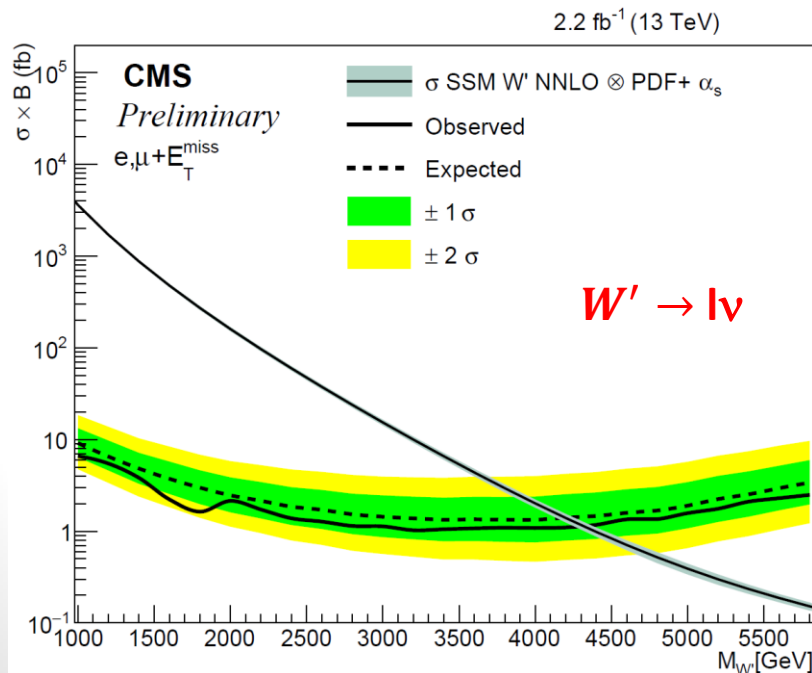
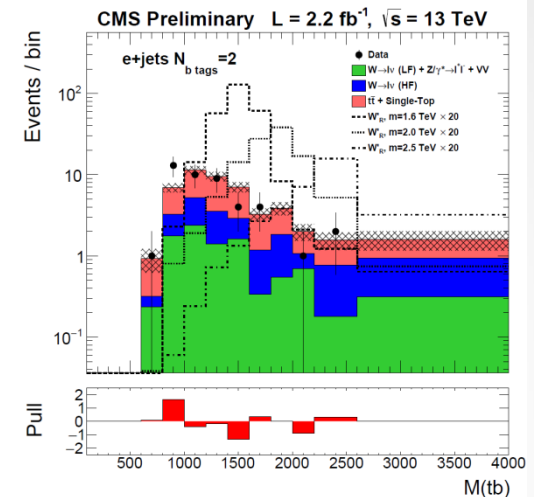
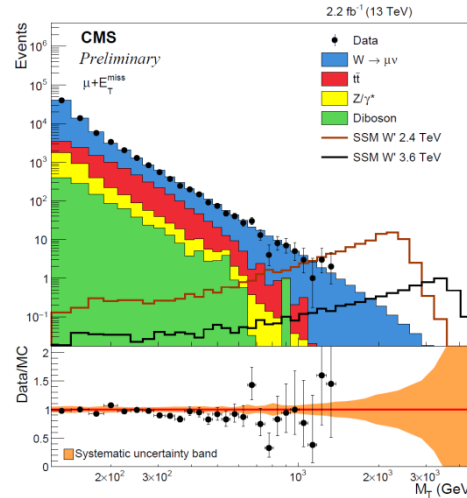
- Search for generic dark matter in **final states with jets and large missing transverse energy**
- Traditional monojet search extended to multijet final states, searching for DM pairs produced via a **vector mediator**
- Limits comparable to those set in Run 1



Search for $W' \rightarrow l\nu$ or tb

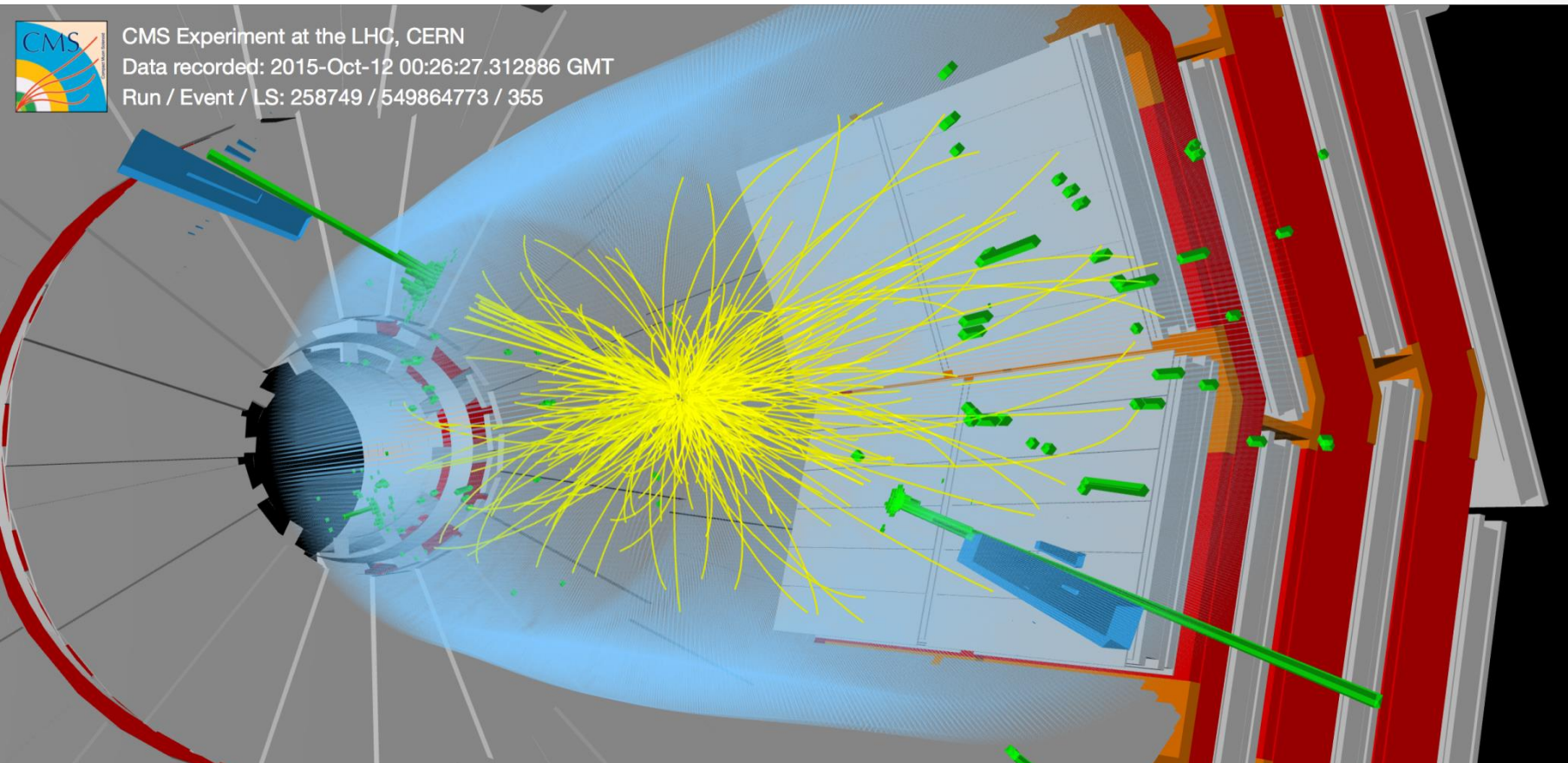
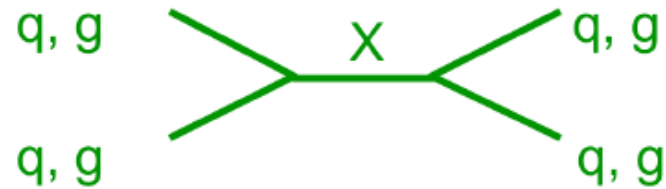
B2G-15-004
EXO-15-006

- Search for heavy gauge boson W' decaying to **leptons+MET** or **tb** in the lepton+jets channel
- Mass exclusions: < 4.4 TeV in lep+MET, < 2.38 TeV tb** (Run 1 limits ~ 2 -3 TeV)



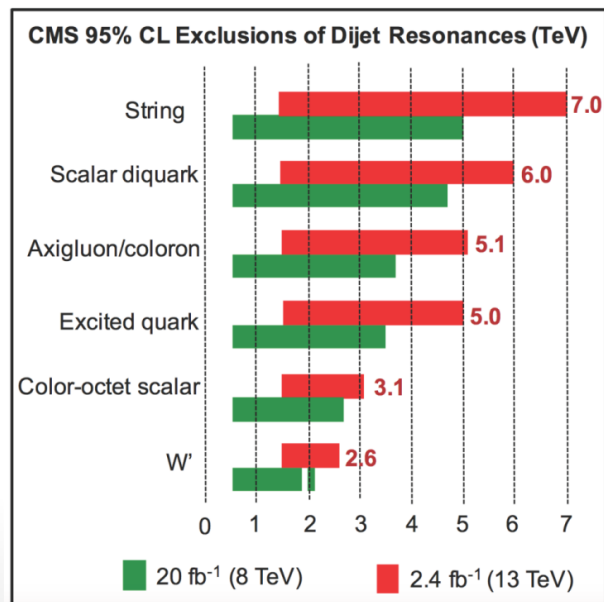
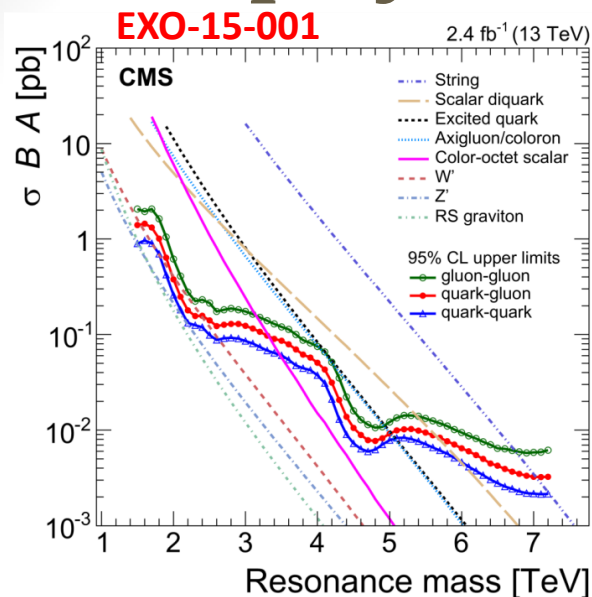
Search for dijet resonances

- Bump hunt on a smoothly falling background in m_{jj} testing s-channel production of new heavy resonance

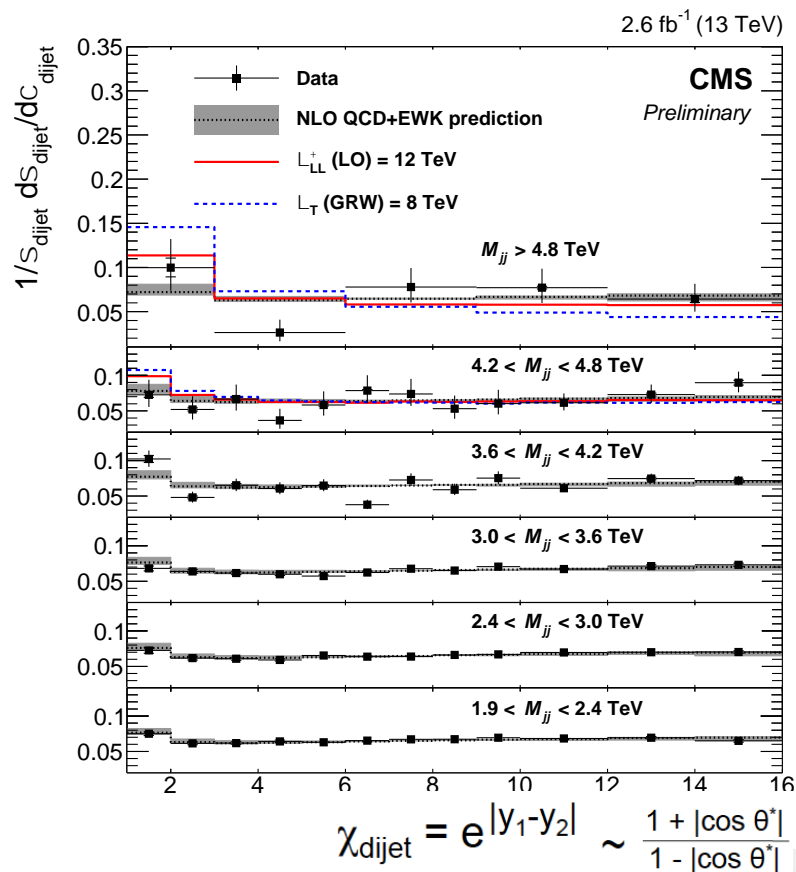


Highest mass dijet pair observed: 6.14 TeV

New physics searches in dijets



- Search for new physics using dijet angular distribution, 13 TeV limits:
 - Contact int. scale L: 12.1 – 16.3 TeV
 - Scale for ADD models: 7.7 – 10.8 TeV



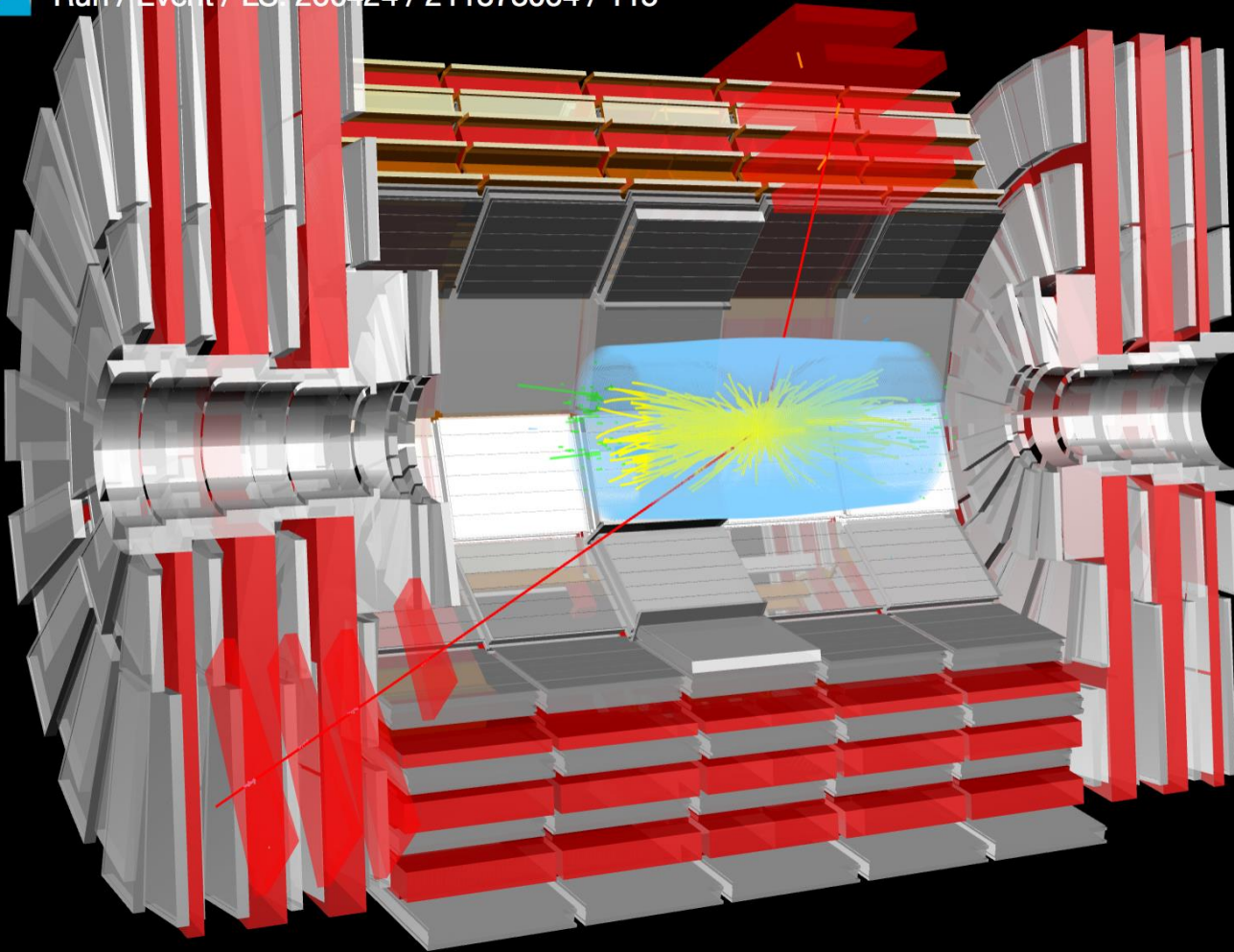
Search for dilepton resonances



CMS Experiment at the LHC, CERN

Data recorded: 2015-Oct-30 19:23:54.631552 GMT

Run / Event / LS: 260424 / 211873064 / 115



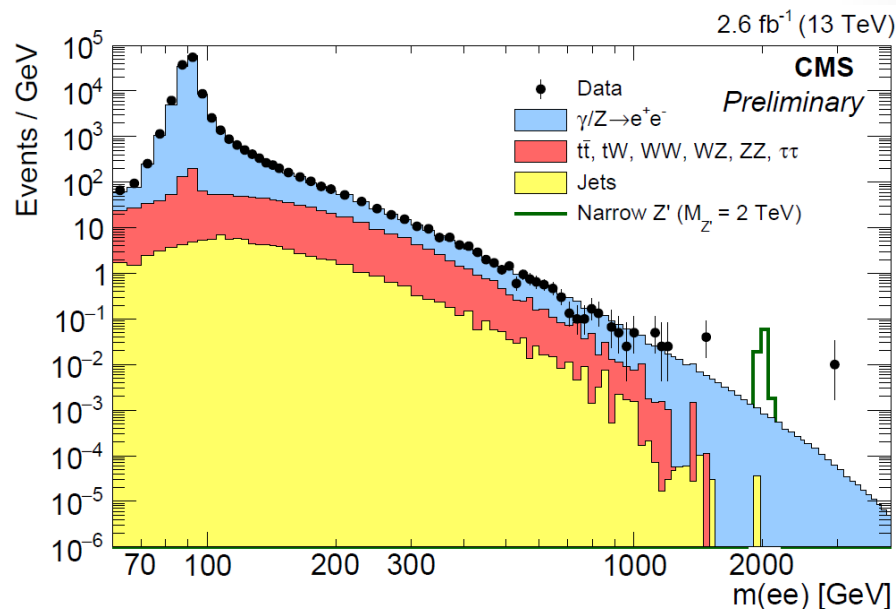
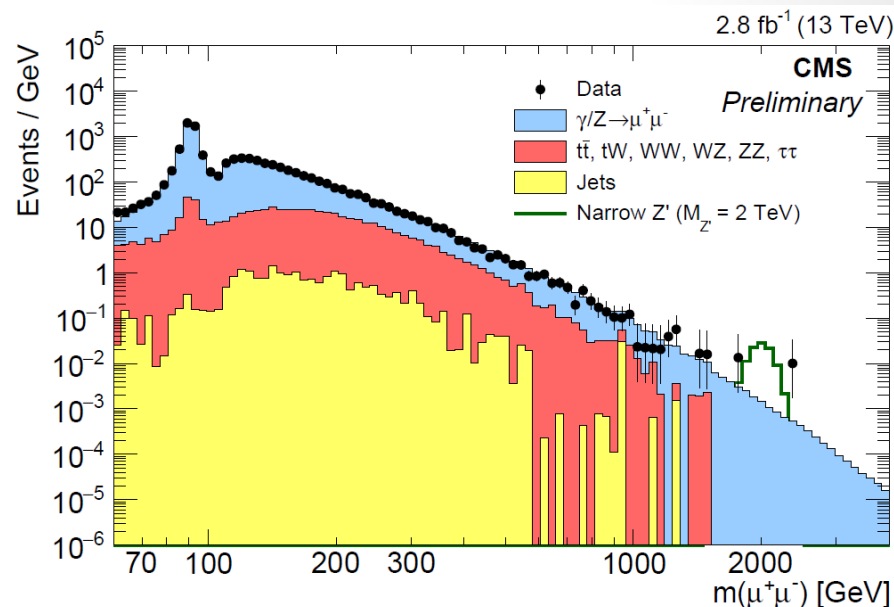
Highest mass dimuon pair observed: 2.4 TeV



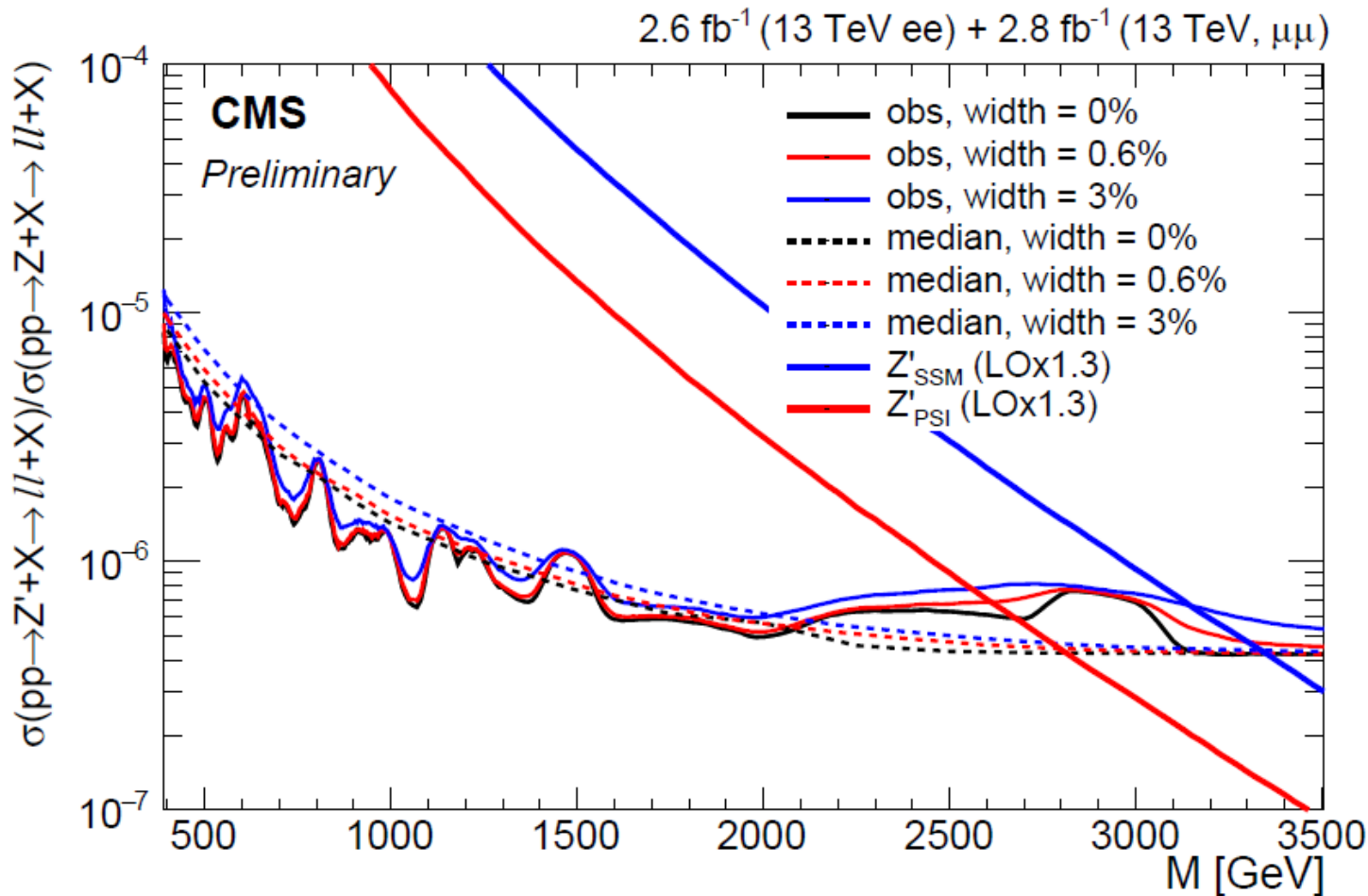
Search for dilepton resonances

- Search for localized excess in the mass spectra of muon and electron pairs, clean signature with very low background at high mass
- **Highest mass events:**
 - Muon – 2.4 TeV
 - Electron – 2.9 TeV
- **P-value to observe at least one event in the range $m(ee) > 2.8$ TeV is 3.6%**

Data consistent with SM

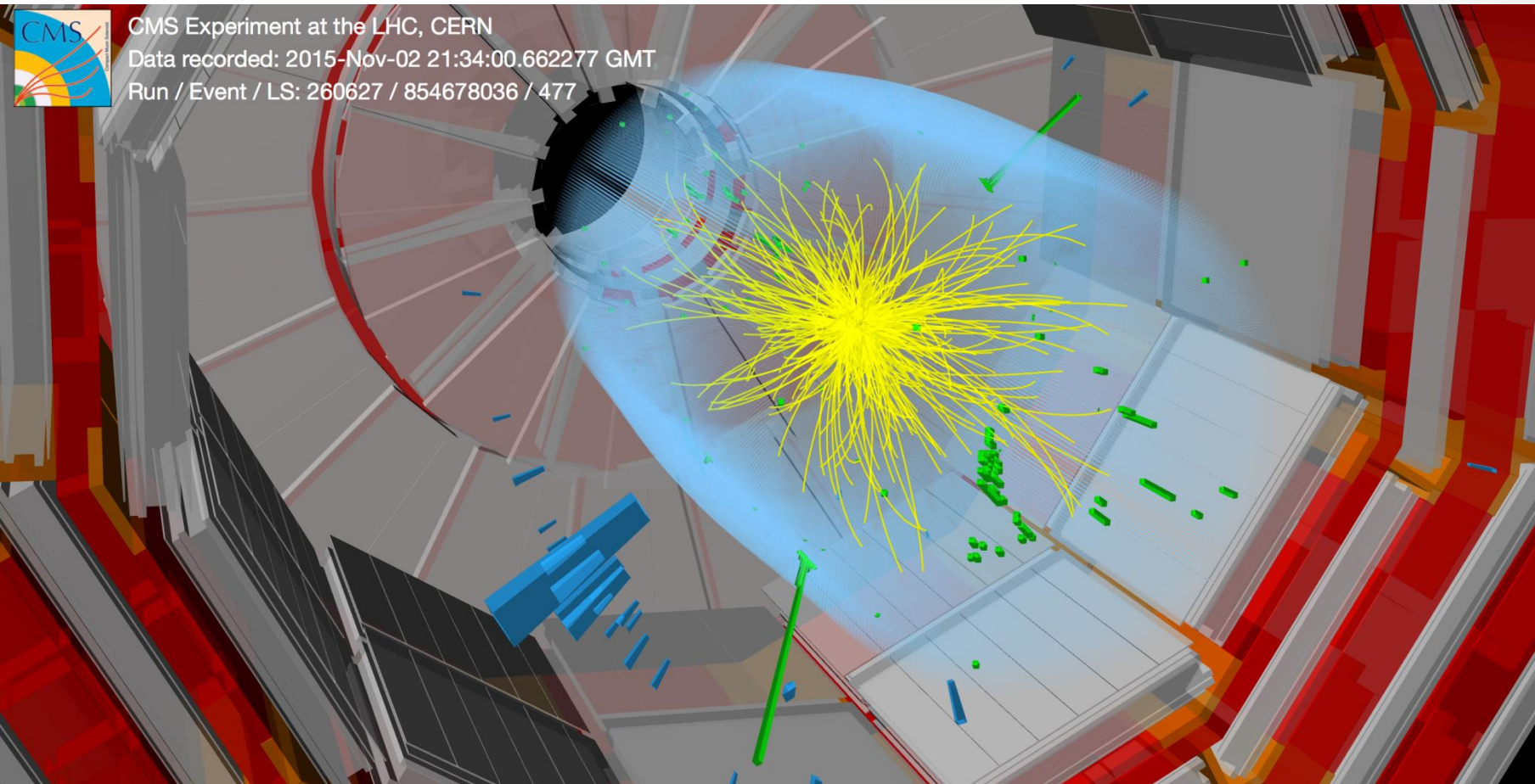


Limits on dilepton resonances



Combined Mass limits: > 2.60 TeV for $Z'(\psi)$, 3.15 TeV for $Z'(SSM)$

Search for diphoton resonances

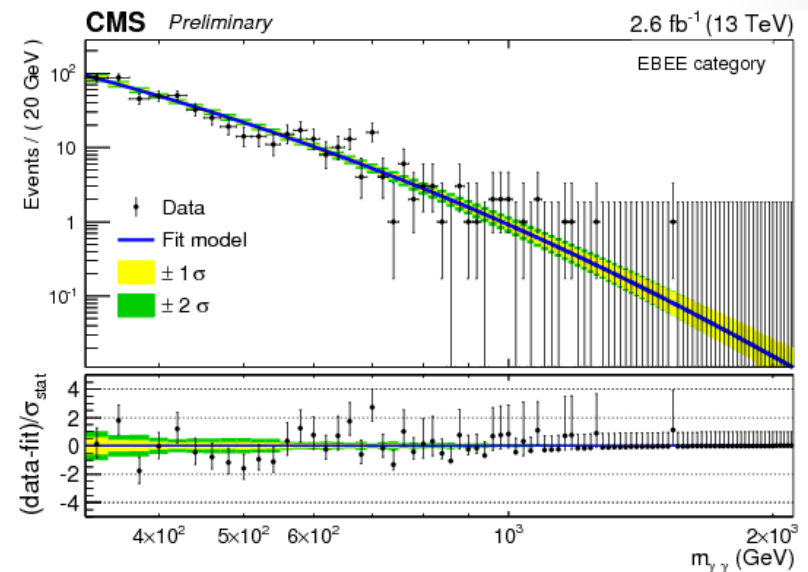
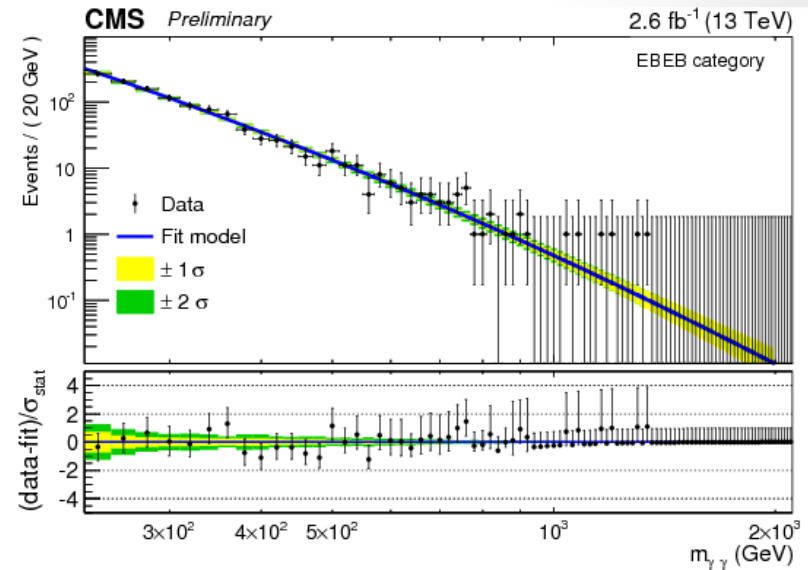


Diphoton event with $m(\gamma\gamma) = 745$ GeV

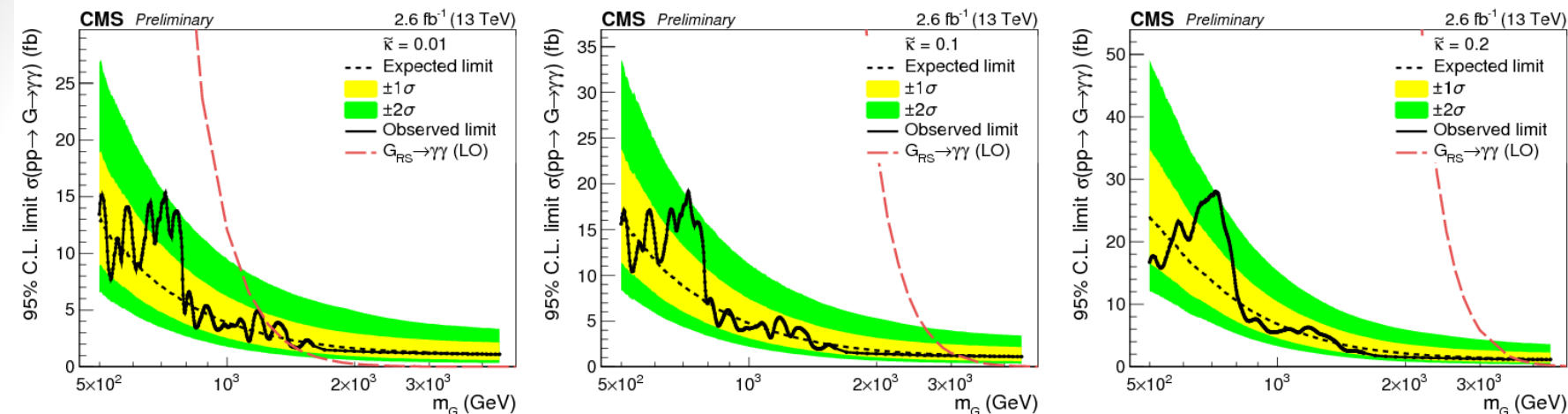


Search for diphoton resonances

- Two categories: **barrel-barrel (EBEB)**, **barrel-endcap (EBEE)**
- $p_T(\gamma) > 75 \text{ GeV}$, $I_{\text{ch}} < 5 \text{ GeV}$ (in 0.3 cone around photon direction)
- Efficiency, scale and resolution calibrated on $Z \rightarrow ee$ and high-mass DY events
- Search for RS graviton with three assumptions on coupling: $\tilde{\kappa} = 0.01$ (narrow), 0.1 , 0.2 (wide)
- Blind analysis, no changes have been made to the analysis since unblinding data in the signal region**



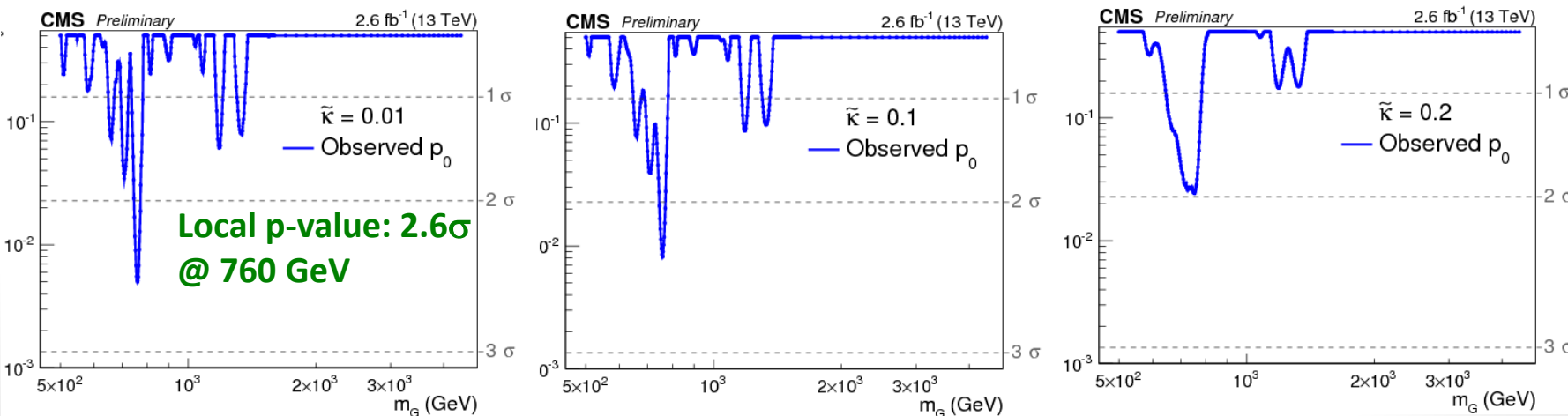
Combined limits and p-values



Narrow Width



Wide (6%) Width



Including LEE (0.5 - 4.5 TeV; narrow width), global p-value < 1.2σ

Summary and outlook

- **An extraordinary year for CMS**
 - LS1 work successfully completed
 - Recorded 90% of collisions delivered by LHC, 75% @ 3.8 T
 - Physics object commissioning well advanced
 - New challenge of 25 ns operation has been met
- **33 results on 13 TeV data so far**
 - SM measurements confirming general (and in some cases, precision) agreement at new energy
 - New Physics searches yielding many improved limits beyond Run 1
 - **On first look: two interesting excesses in 8 TeV not appearing at 13 TeV**
 - New (small) excess in diphoton spectrum, looking forward to more data

More (and updated) results coming for winter conferences!

All new results presented here will be available at this link:

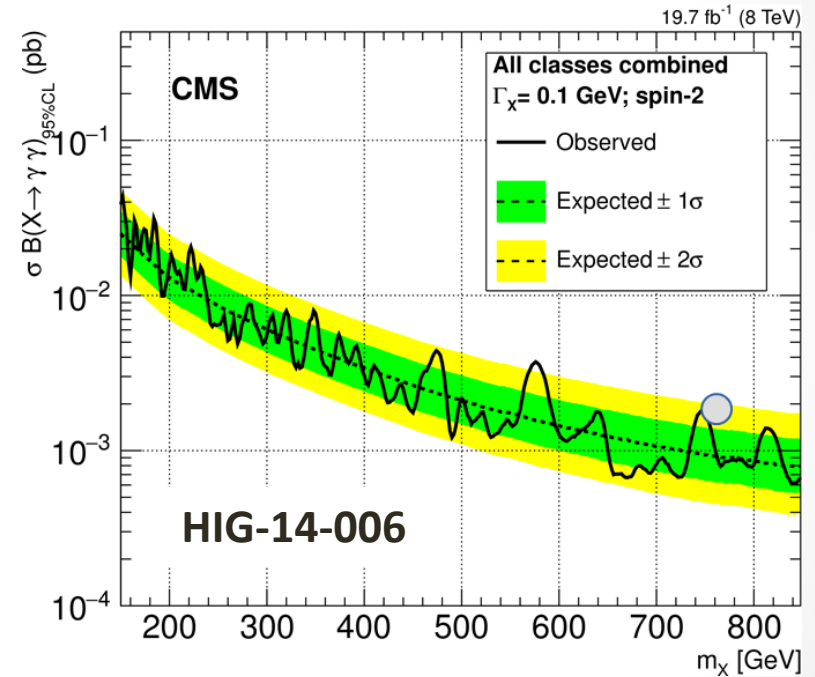
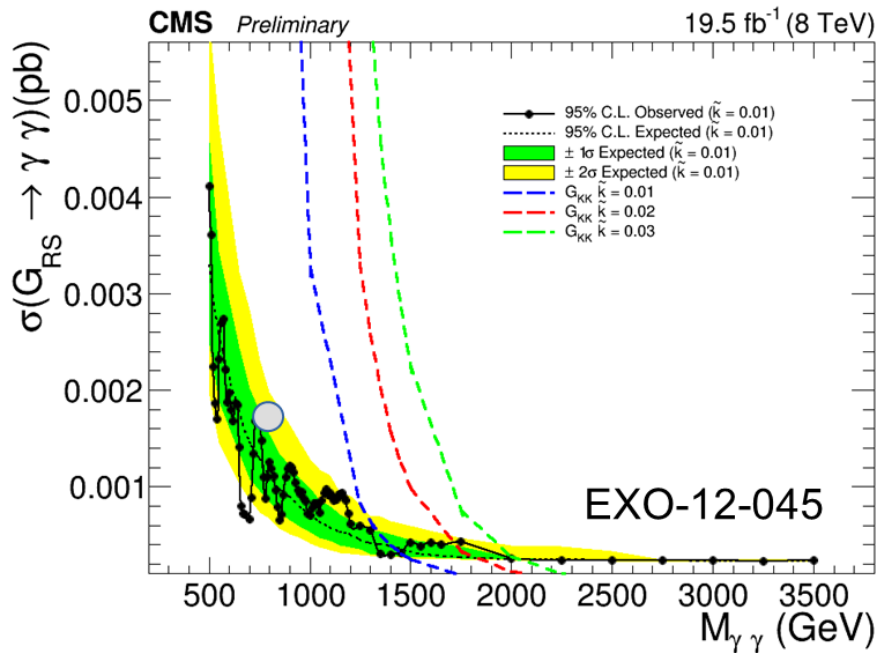
<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/LHC-Jamboree-2015.html>



Backup



Compatibility with Run 1



Excess not excluded by Run 1 searches



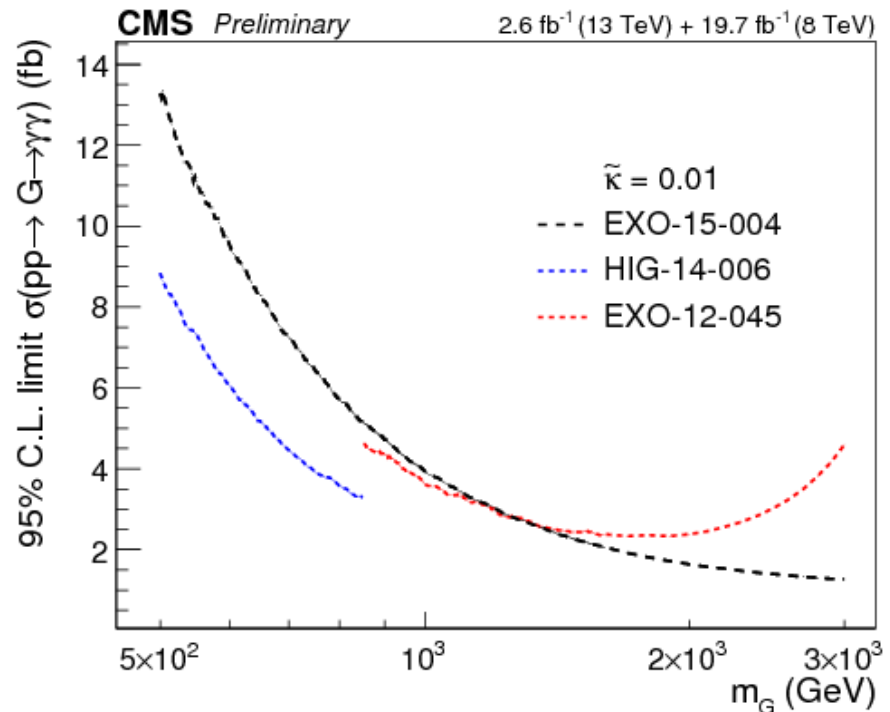
Combination of 8TeV and 13TeV results

- Combination performed assuming narrow RS graviton hypothesis.

- Results expressed in terms of equivalent 13TeV cross sections.

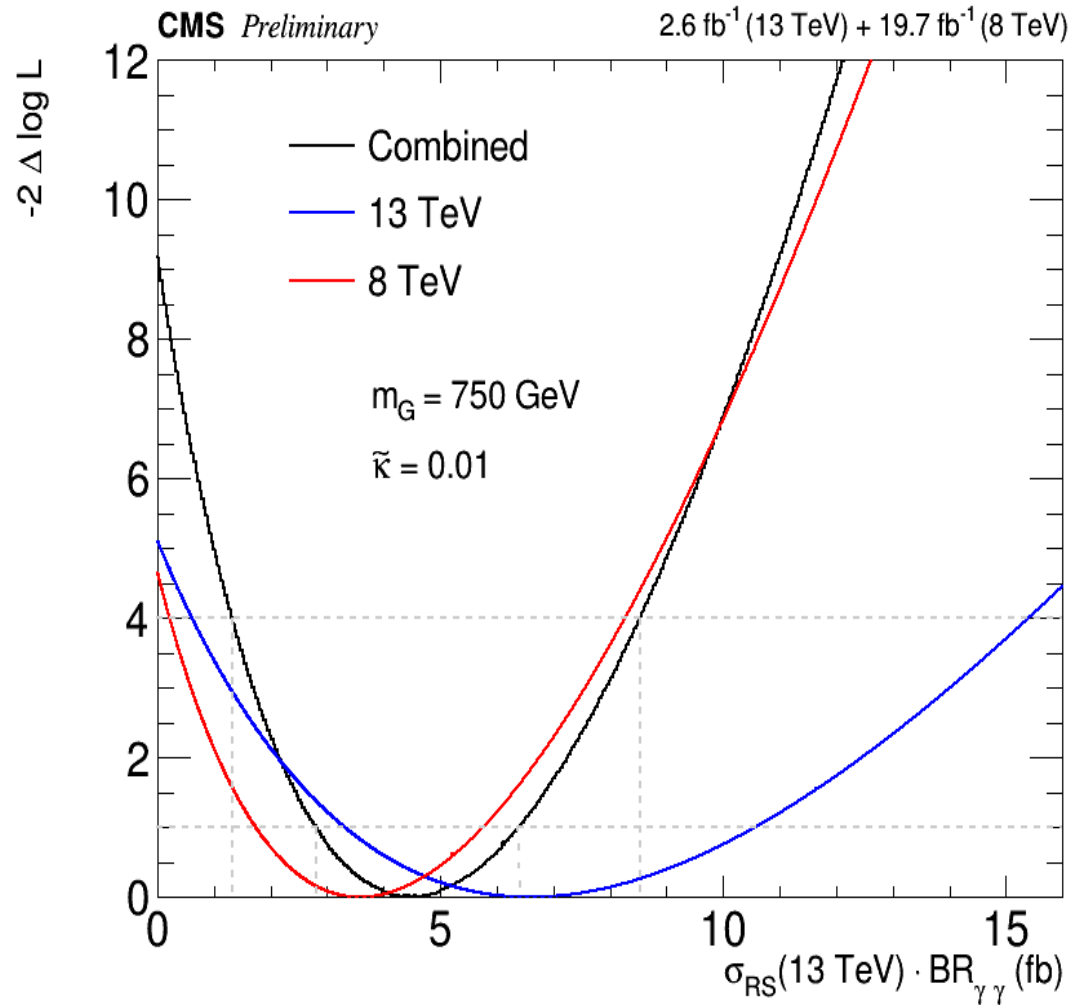
- Two analyses at 8TeV.

- HIG-14-006 and EXO-12-045
- HIG-14-006 is the most sensitive in the covered range (larger acceptance, plus categorization).



Log-likelihood scan at 750GeV

- Results are expressed in terms of equivalent 13TeV cross sections.



Combined limits and p-values

- Combined limit improves single analyses sensitivity by 20-30%.
 - Largest excess: $M_G = 750 \text{ GeV}$, local significance 3σ
 - global significance $< 1.7\sigma$

