# CMS Overview
# Physics Highlights

Compact Muon Solenoid
experiment at the CERN's LHC

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National Centre
for Nuclear Research
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on New Frontiers in Physics
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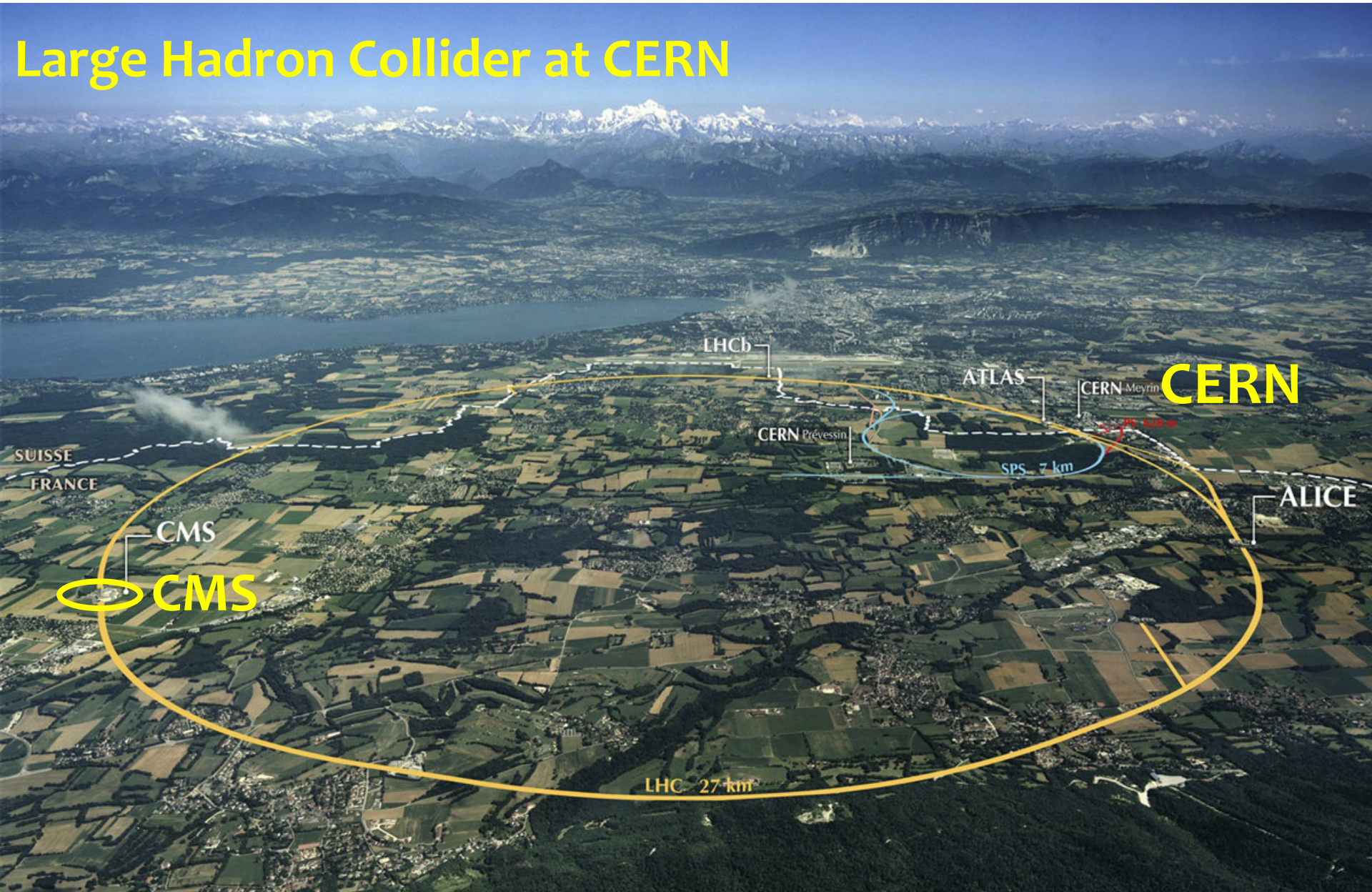
# Outline

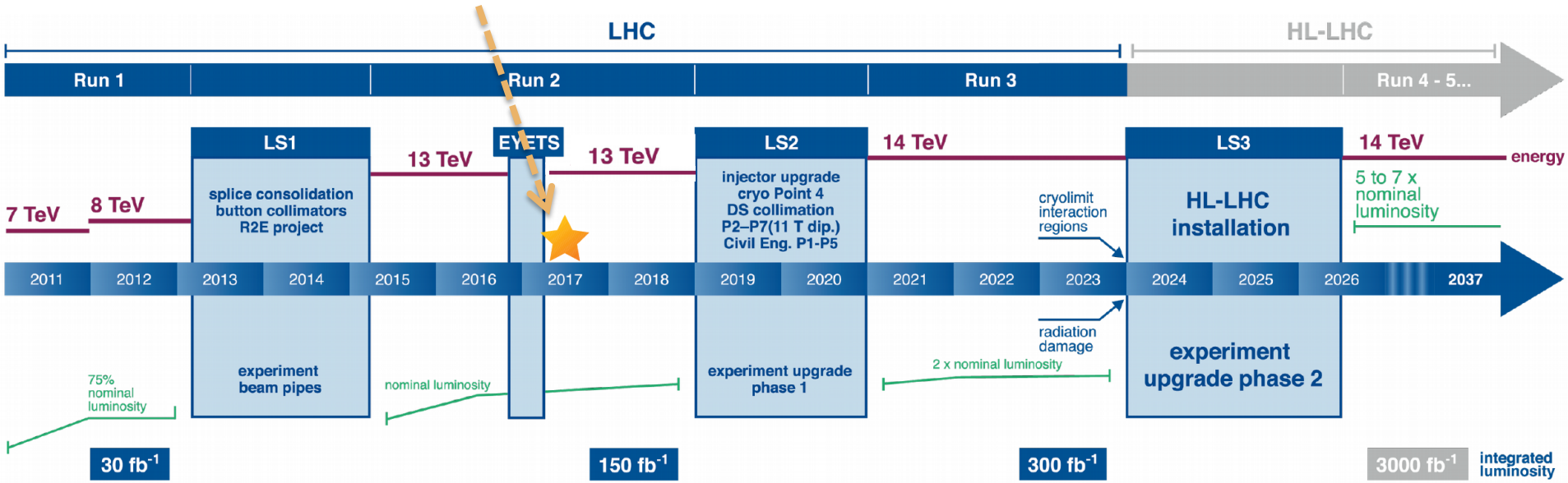
- **LHC** short intro
- **CMS Detector** status
  - Subdetector upgrades for data-taking in 2017
    - New: Pixel detector, L1 Trigger, HF calorimeter readout
    - 2017 Performance
- **CMS Physics highlights** with full 2016 **36/fb 13 TeV** data
  - 79 new results in 2017 realised at:
    - Moriond'17 – 39 publications
    - LHCP'17 – 22
    - EPS-HEP'17 – 20
  - In this talk – only selected *fresh* proton-proton results
    - during this conference – other 22 presentations and 4 posters

# Introduction

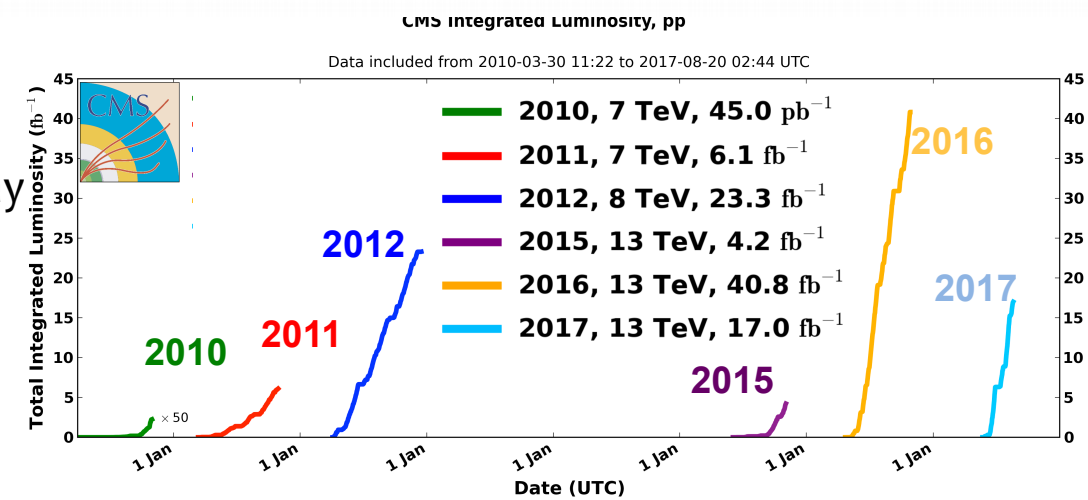


# LHC schedule

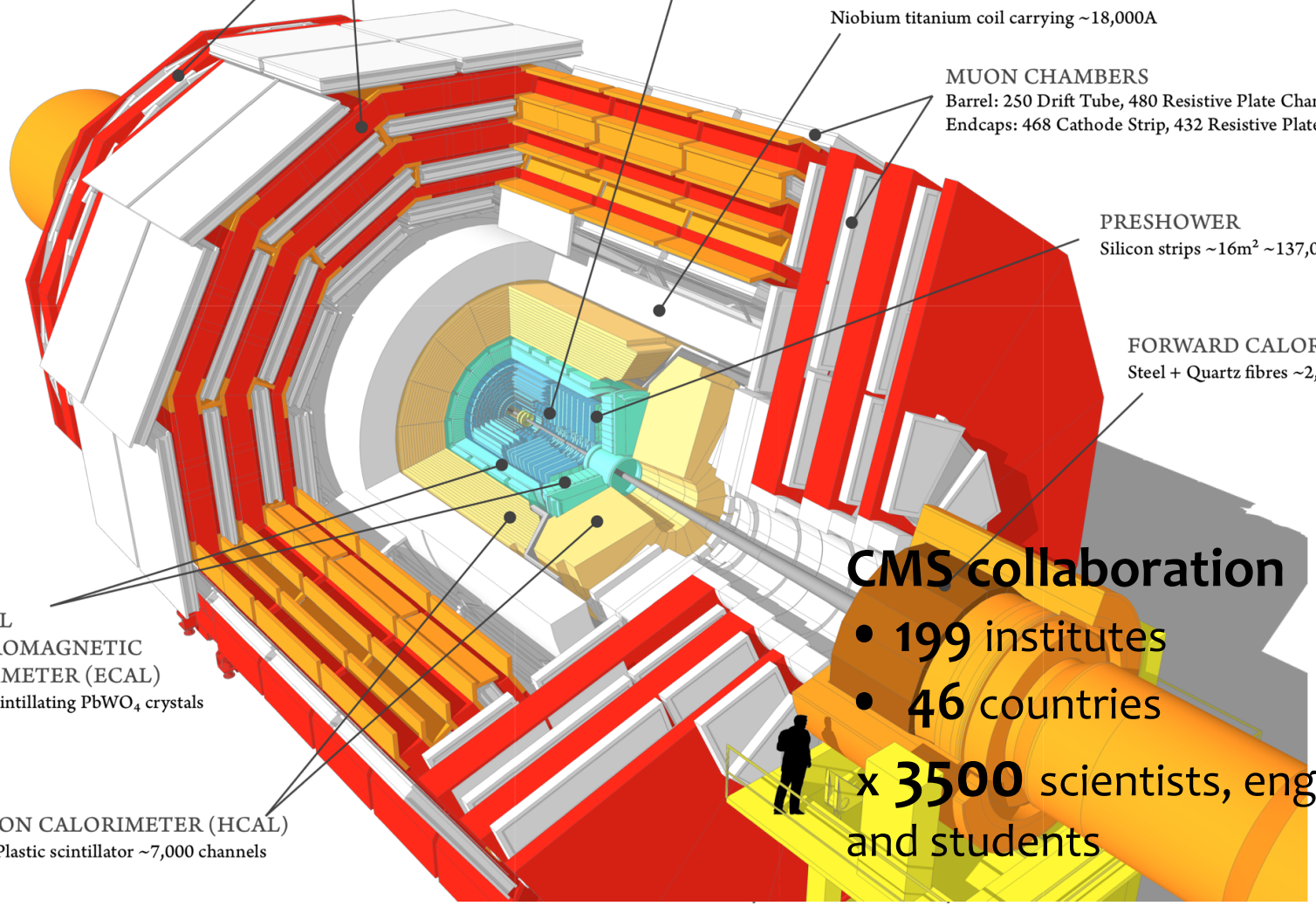
- LHC past, present, and future




- LHC proton-proton **data delivered** to CMS till yesterday
- **Run 2: ~60/fb**
  - 2016: 41/fb
  - 2017: 17/fb



# Compact Muon Solenoid




**CMS collaboration**

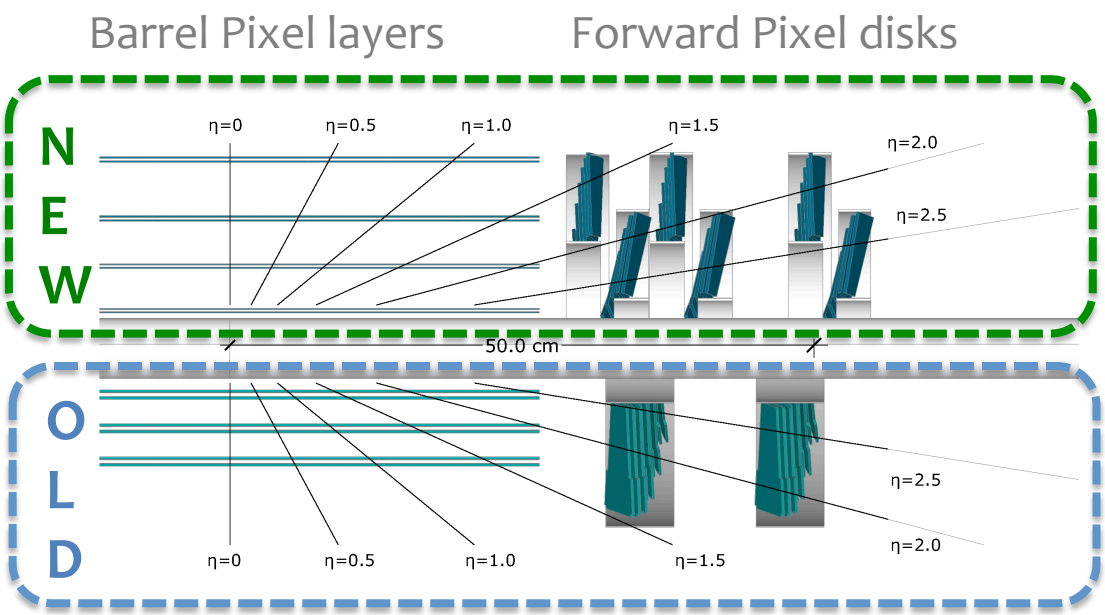
- **199** institutes
- **46** countries

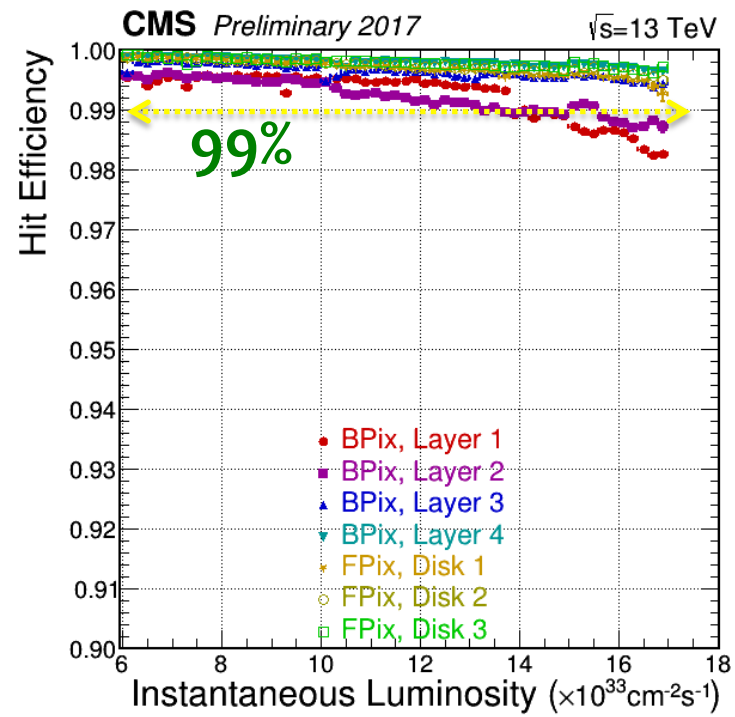
x **3500** scientists, engineers, and students

# CMS upgrades in 2016/17

*Recent upgrades are not yet used for current results*

- New **CMS Pixel detector**:
  - 3 layers (barrel) / 2 disks (endcaps) → **4 layers / 3 disks**
    - Improved readout electronics
    - Innermost barrel layer closer to the interaction point
    - Lower material budget
  - Very good efficiency up to **99%** for all pixel detector at $L=1.5e^{34}cm^{-2}s^{-1}$
- Expected improvements in tracking, vertexing and b-tagging

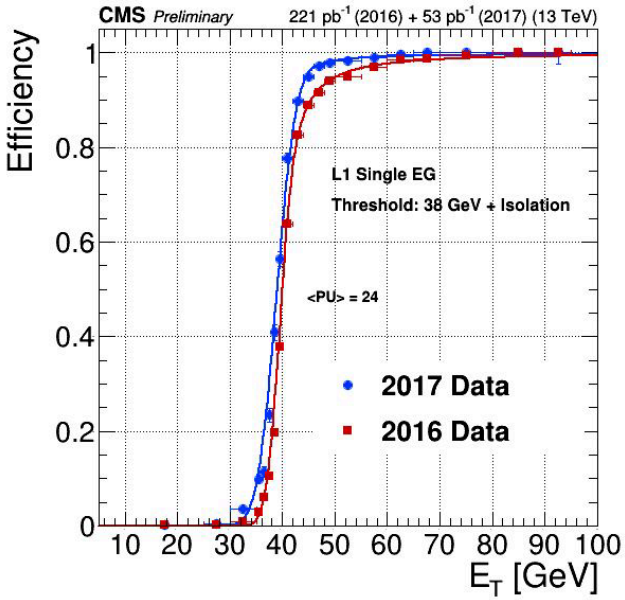


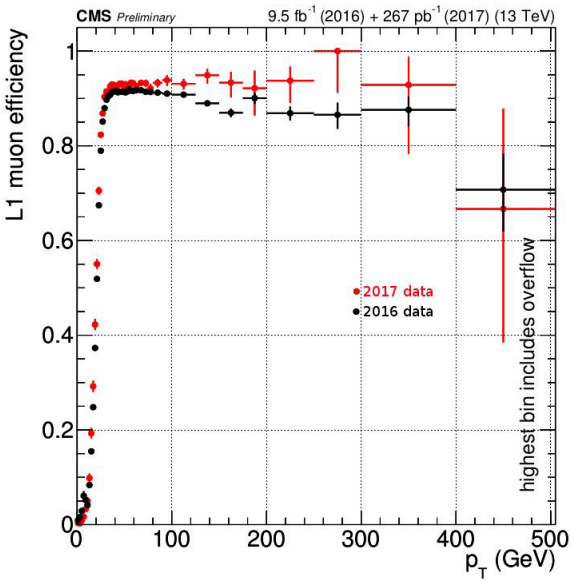



# CMS upgrades in 2016/17

CMS-DP-2017-024

- Full upgrade of **L1 trigger** system
  to manage with high inst. luminosity of $1e^{34}$ $cm^{-2}s^{-1}$ and high pile-up



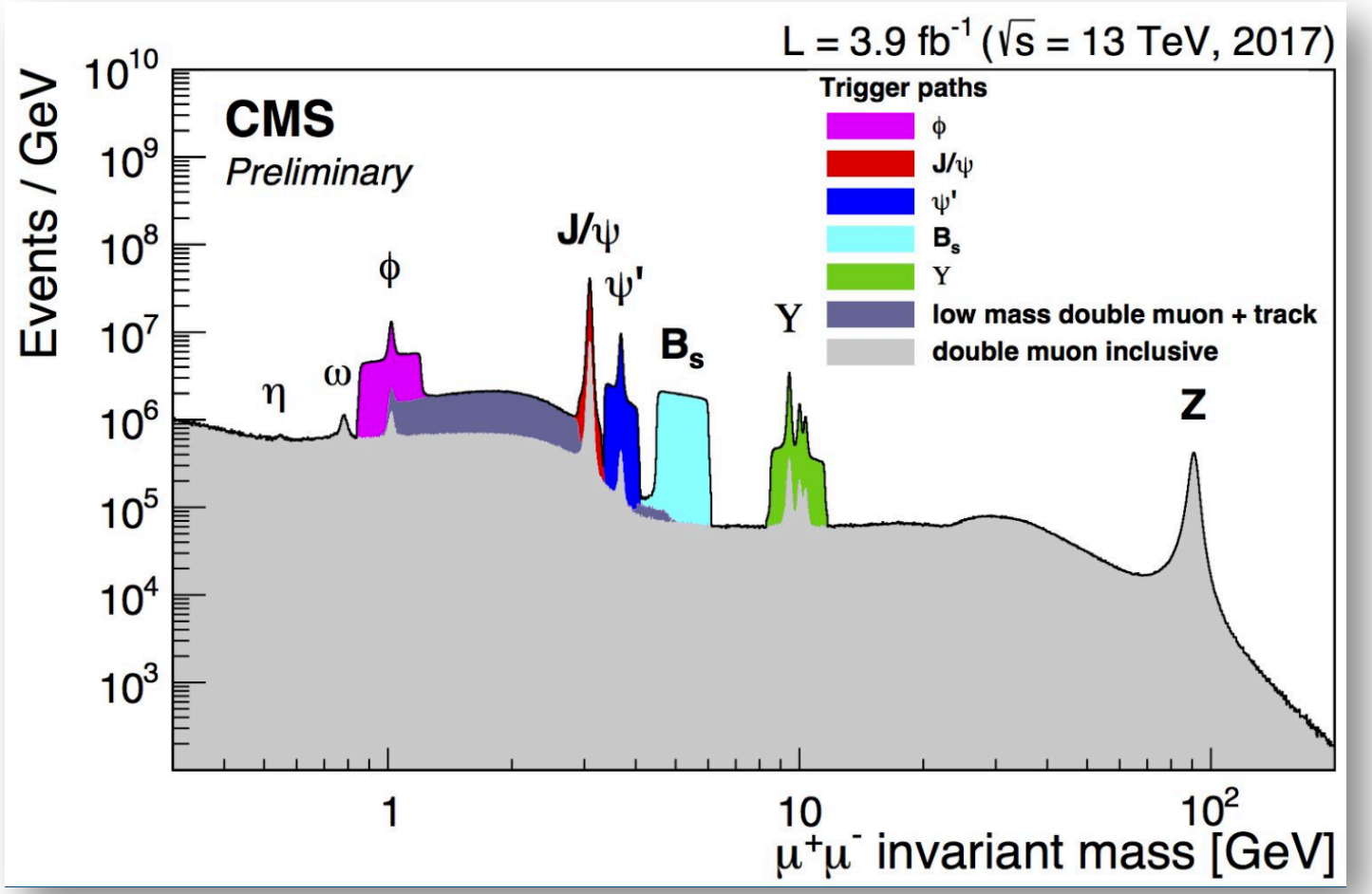




- **L1 electron/photon** trigger **re-optimization**
- better resolution → sharper turnON
- 20% rate reduction
- 15% gain in efficiency
  (keeping almost no PU dependence)

- **L1 muon** trigger **new track finders**
- Improved L1 muon track finding and $p_T$ resolution, and efficiency
- Lowest unprescaled threshold 25 GeV in 2017

# CMS Performance in 2017

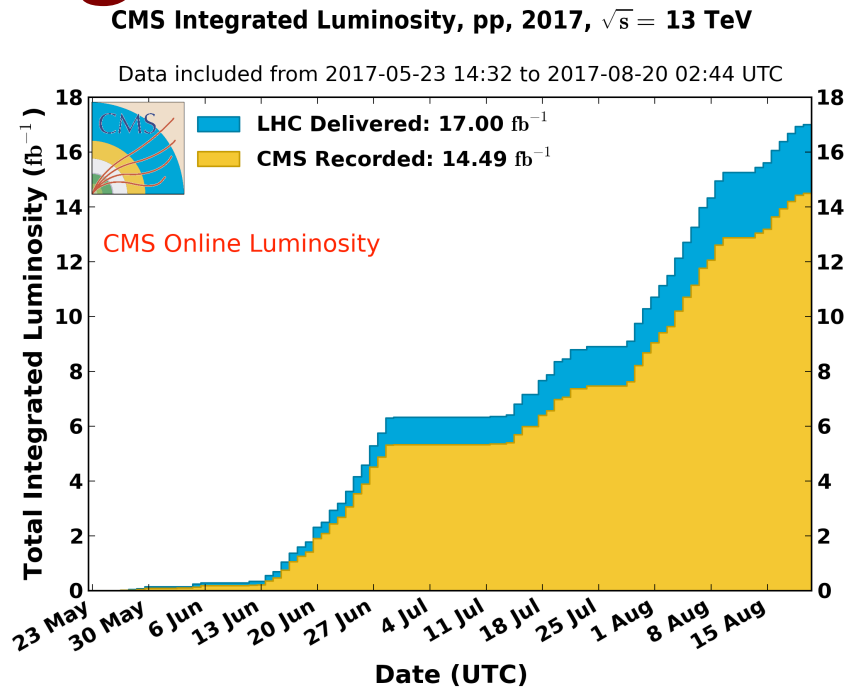
- First illustration of di-muon spectrum taken with inclusive and dedicated muon trigger paths

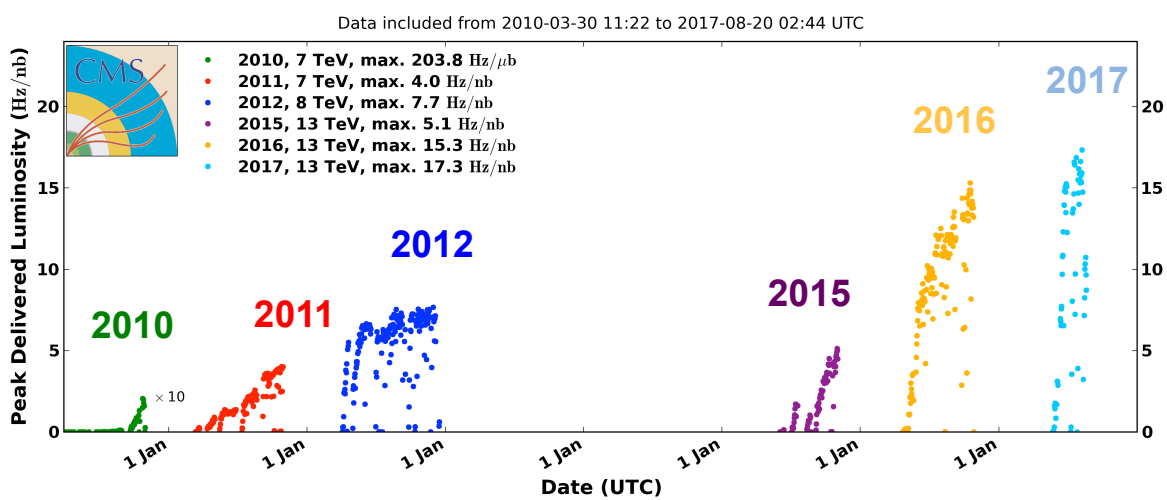


# Data taking in 2017

CMSLumi2017

- CMS data-taking efficiency **> 85 %**
- Some time was dedicated for testing the new Pixel detector
- Successful restart of the LHC
- Reaching inst. luminosity of **1.7e$^{34}$ cm$^{-2}$s$^{-1}$**

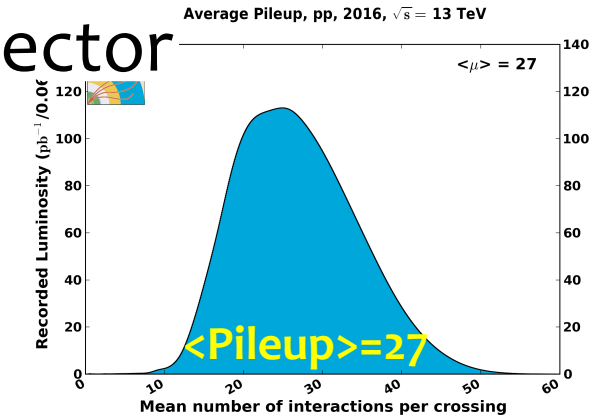


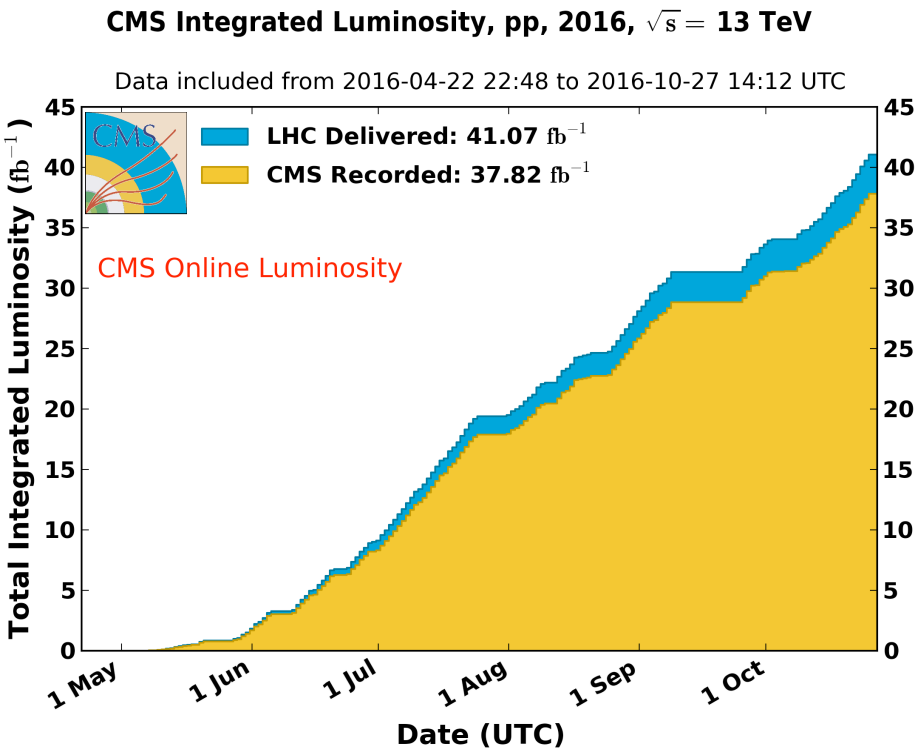



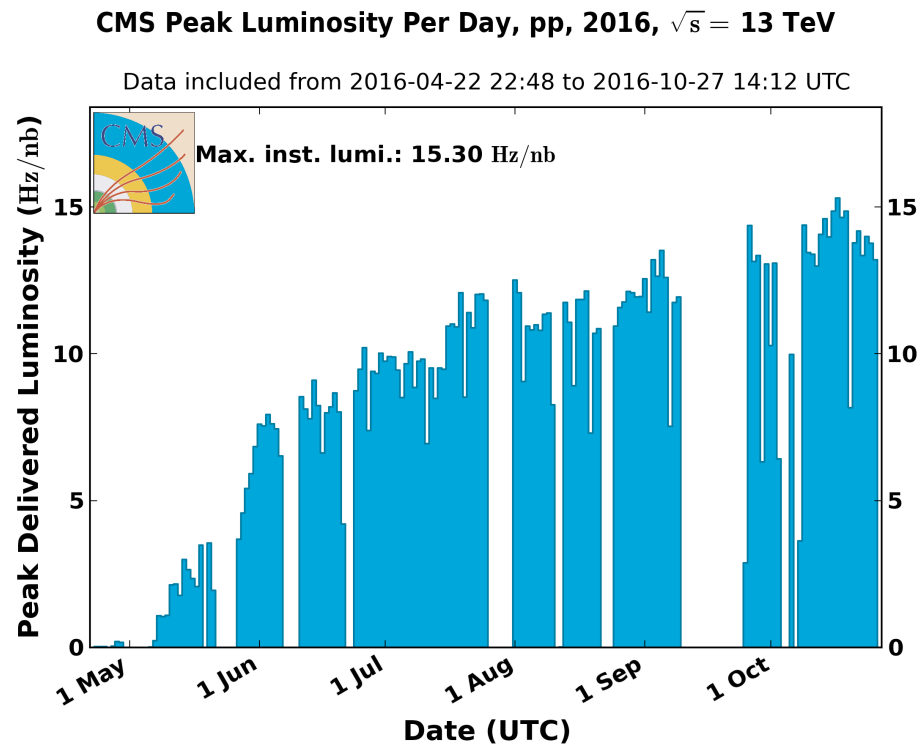
# Data in 2016 → new results

CMSLumi2016

- Excellent performance of the CMS detector
  - Efficiency of data-taking (41/fb) for:
    - 38/fb, recording > 92%
    - 35.9/fb, good for physics > 87%

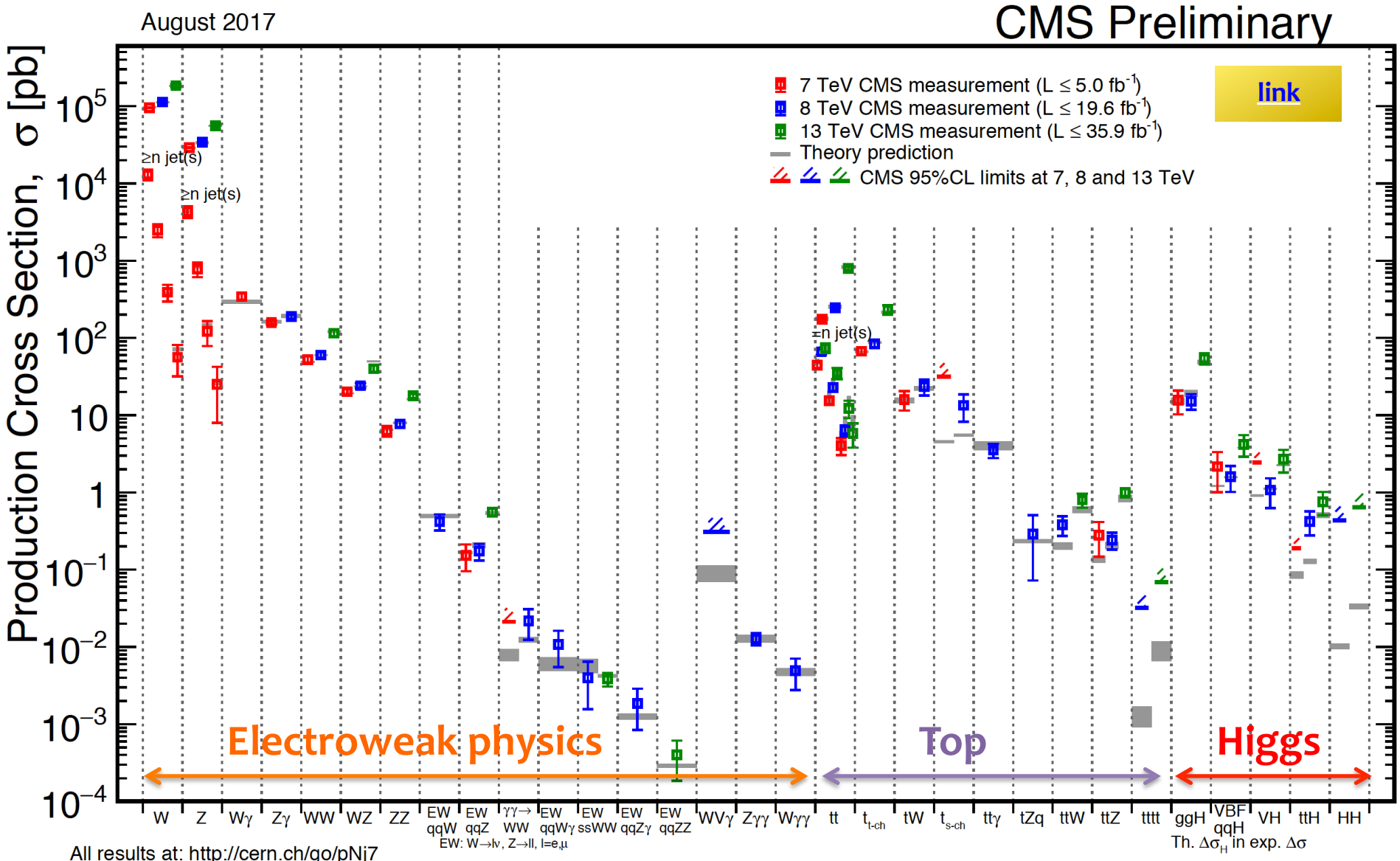


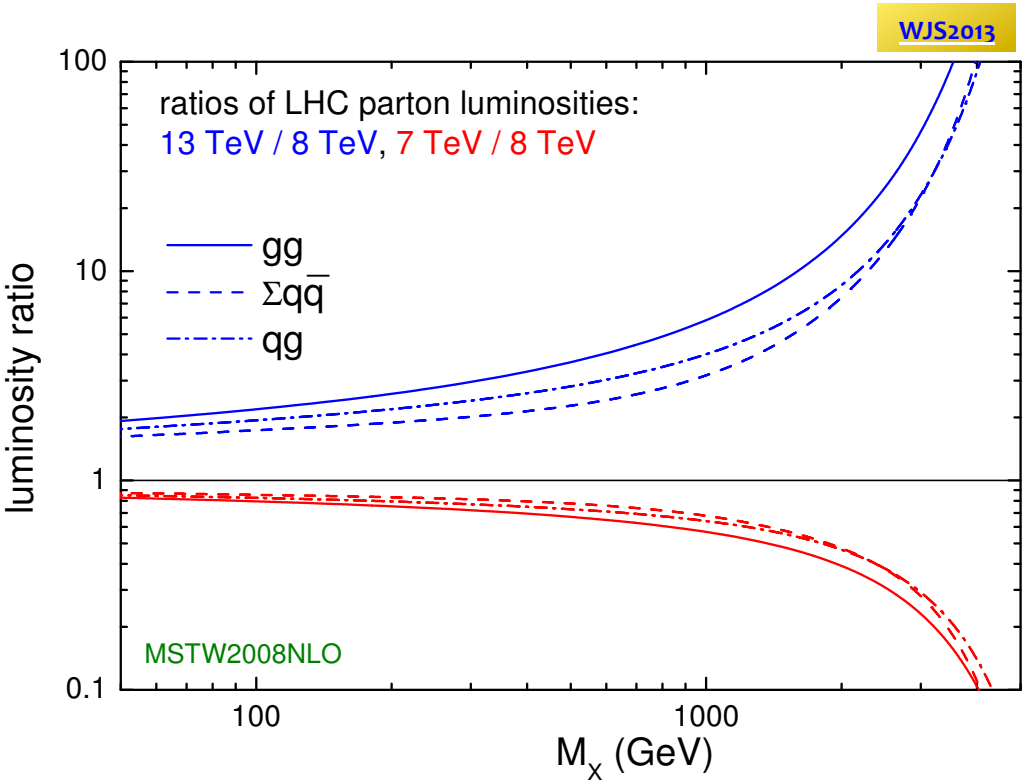
# Run 1&2 legacy – Nature is SM-like

- Theoretical description of high-$Q^2$ processes is with high agreement with LHC data



# Run 2 continues – opened perspective

- **Higgs boson** and **precise SM measurements**
  new possibilities for deciphering the properties opened up




## New Physics

– no sign, but….

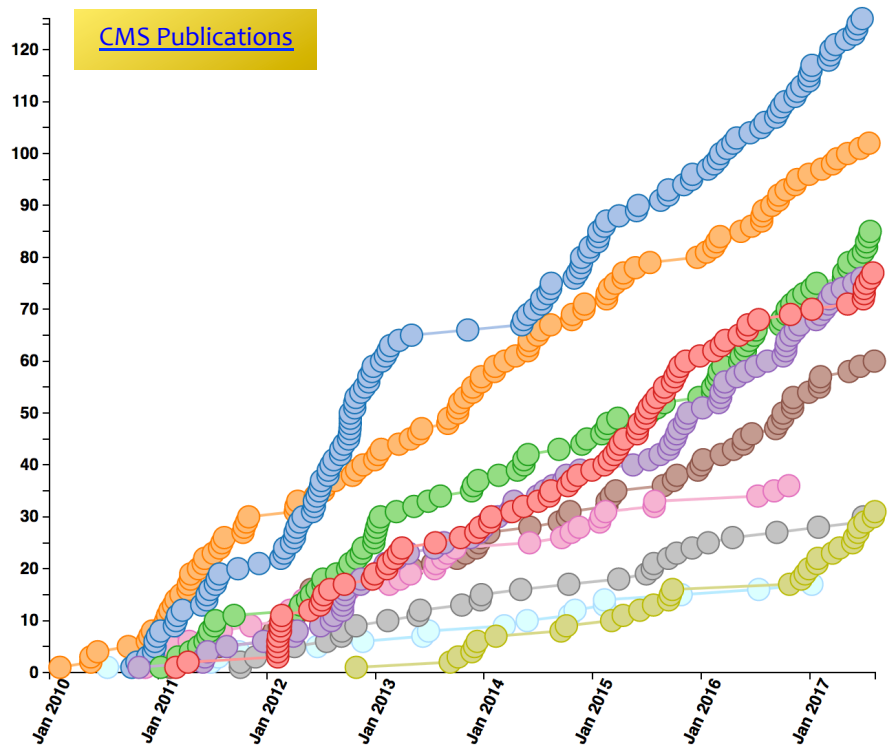
- Large increase in signal xsecs for heavy particles from 8→13 TeV
- Strong gluino pair production privileged

# CMS Physics Highlights

CMS pp Physics (in this talk):

- **Standard Model**
  - Electroweak Physics
- **Higgs**
- **Top Physics**
- Searches:
  - **SUSY**
  - **Exotica**
    - Dark Matter

**639 collider data papers submitted as of 2017-08-11**




Exotica | Standard Model | Supersymmetry | Higgs | Top Physics

Heavy Ion | B Physics | Forward Physics | Beyond 2 Generations | Detector Performance

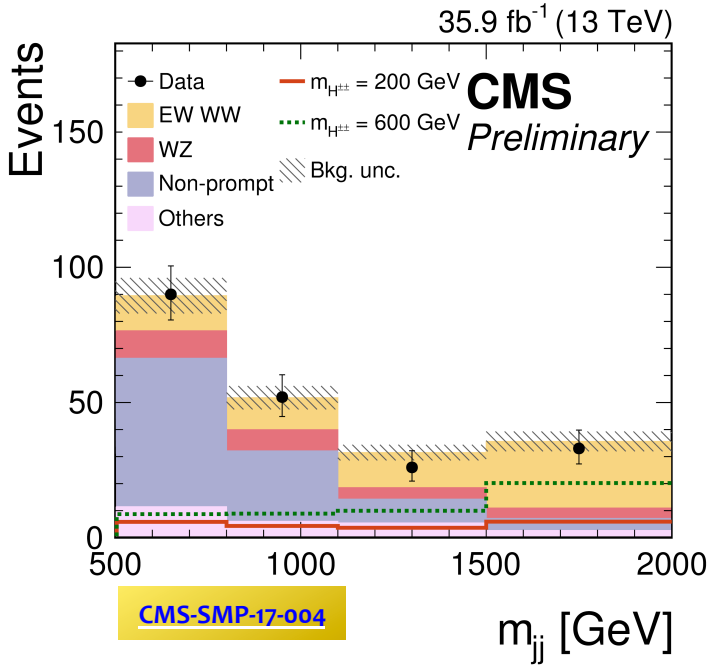
# Electroweak precise measurements

- Challenging Standard Model predictions

# EWK Gauge Couplings

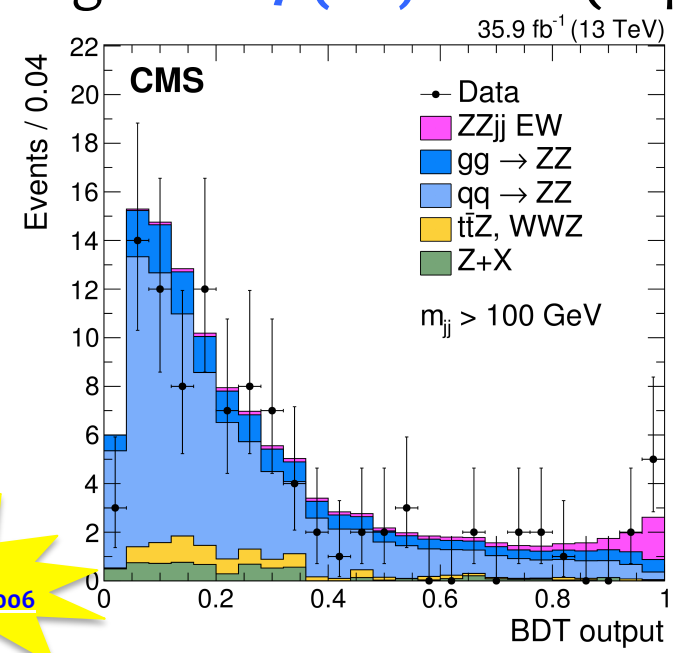
- **Diboson** and **W/Zjj processes** extensively studied
- Vector-boson scattering is the ideal testbench to study of the EWK sector

- First **5.5σ observation** of **EWK same-sign WWjj** production
  - Evts: two leptons of the same charge, moderate MET, 2 jets with large rapidity separation and large dijet mass
  - Bkg: non-prompt leptons and the WZ →3ℓν




CMS-SMP-17-004

- **First measurement of VBS** in the **ZZjj** channel at the LHC
  - Evts: fully leptonic (*4l*) final state
- **EWK ZZjj** is measured with sign. of **2.7 (1.6) σ** obs.(exp.)




$\sigma_{th} = 0.29^{+0.02}_{-0.03}$ fb

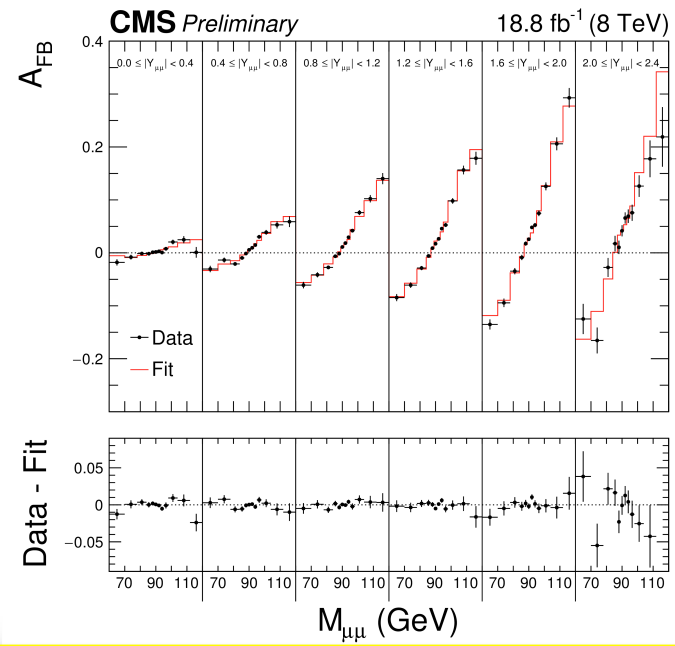
$\sigma_{EW}(pp \to ZZjj \to \ell\ell\ell'\ell' jj) = 0.40^{+0.21}_{-0.16}$ (stat) $^{+0.13}_{-0.09}$ (syst) fb

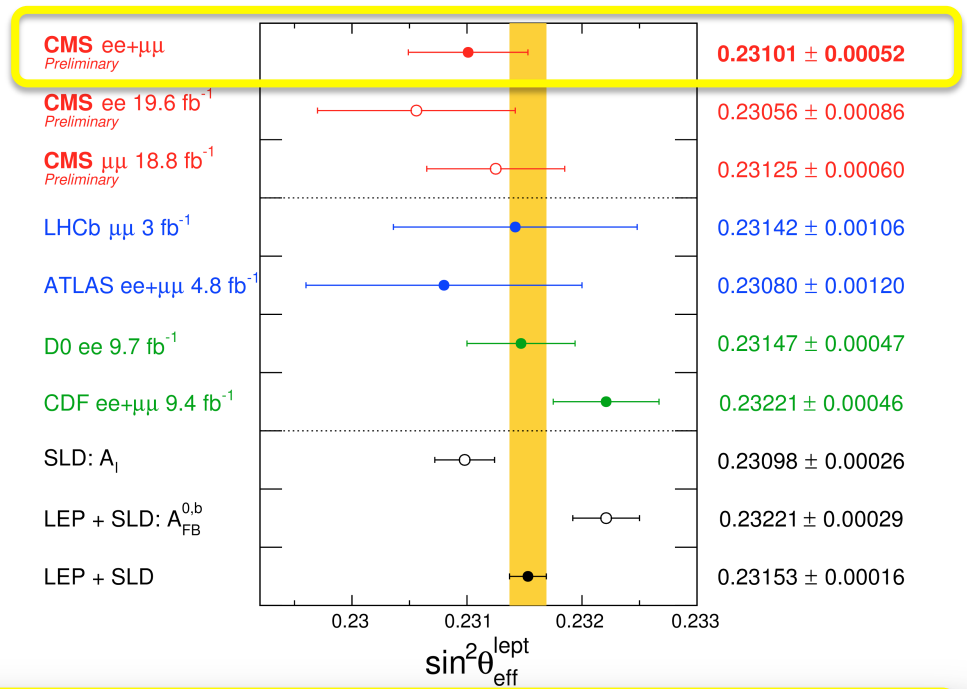
NEW
CMS-SMP-17-006

# Electroweak mixing angle at 8 TeV

CMS-SMP-16-007

- Precise measurement with the forward-backward asymmetry $A^{FB}$ of Drell-Yan (ee and μμ) events at 8 TeV
  Improved lepton momentum calibration, angular event weighting, and additional PDF constraints
- $\sin^2\theta$ extraction by fitting $A^{FB}$ inv. mass and rapidity bins
- **Most precise measurement of $\sin^2\theta$ at the LHC**
- Allows to constrain PDFs

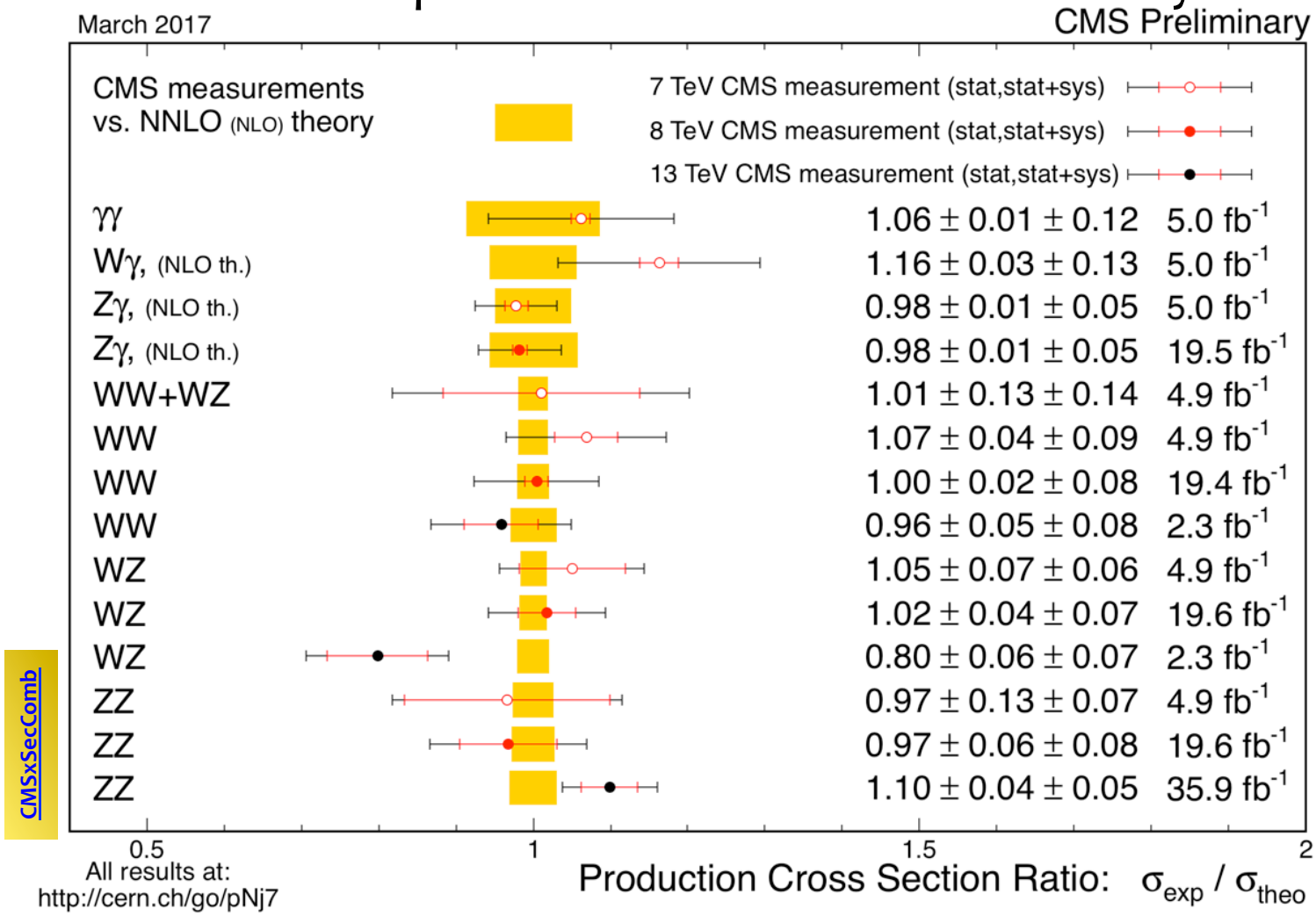



$$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23101 \pm 0.00036({\rm stat}) \pm 0.00018({\rm syst}) \pm 0.00016({\rm theory}) \pm 0.00030({\rm pdf})$$

# EWK boson measurements

- **Good agreement with SM to date**
- Precision will be improved with increased luminosity




Production Xsec Ratio:exp/theo

# EWK boson measurements

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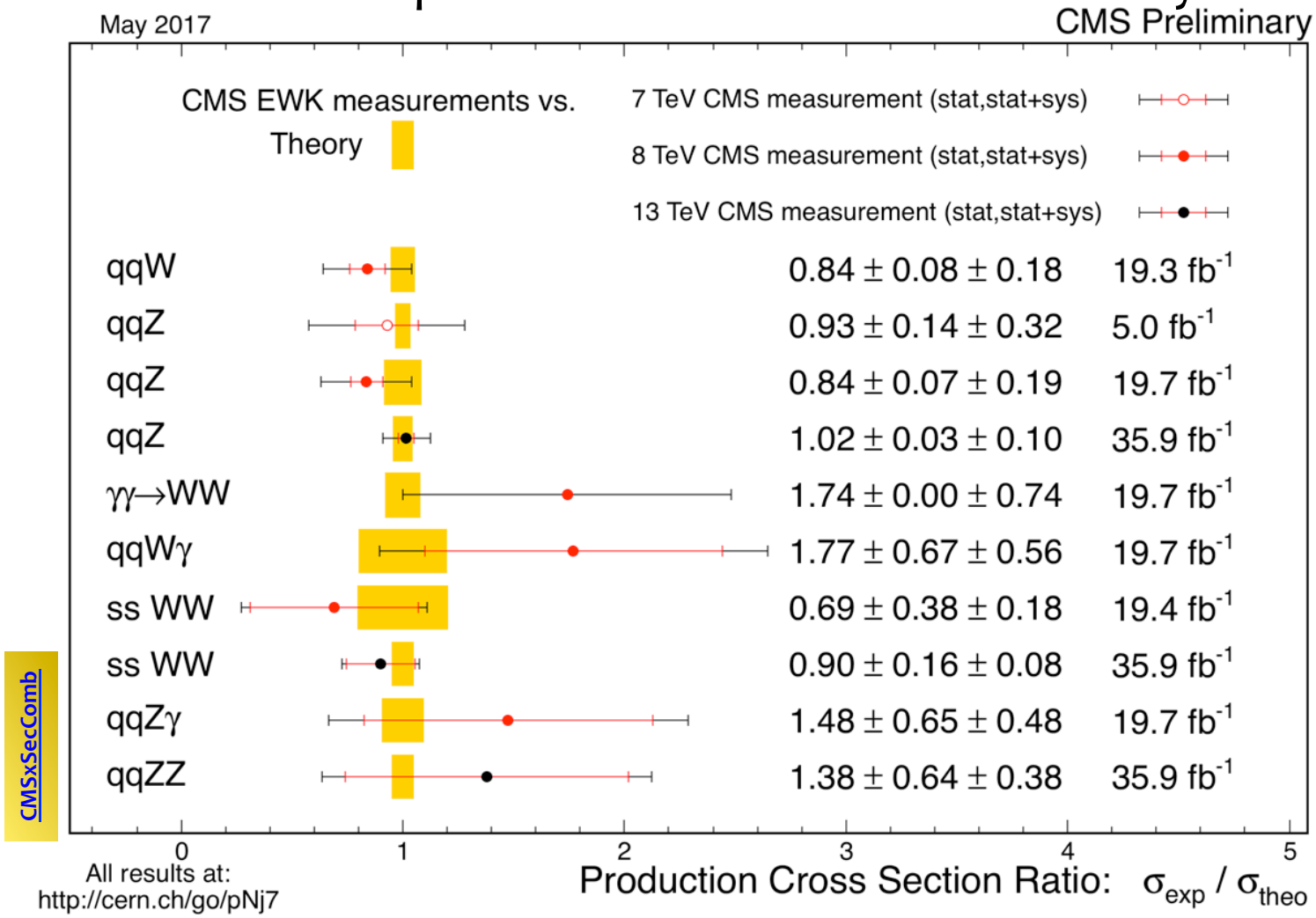
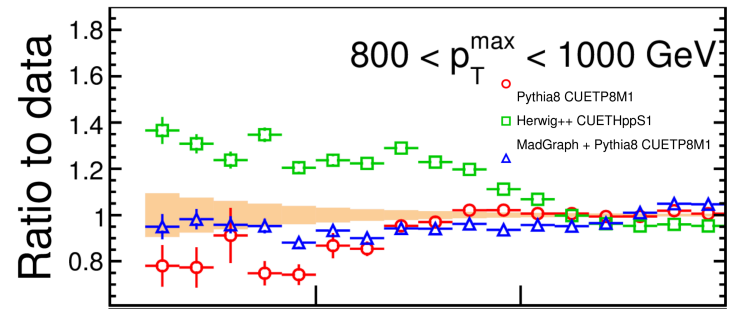


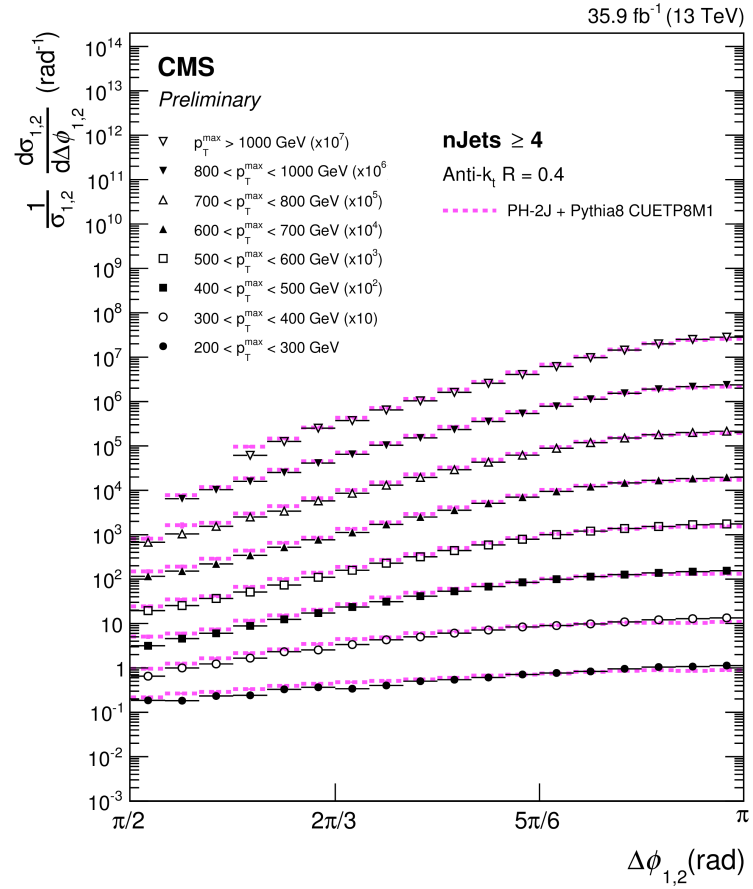

Production Xsec Ratio:exp/theo

# QCD stress tests

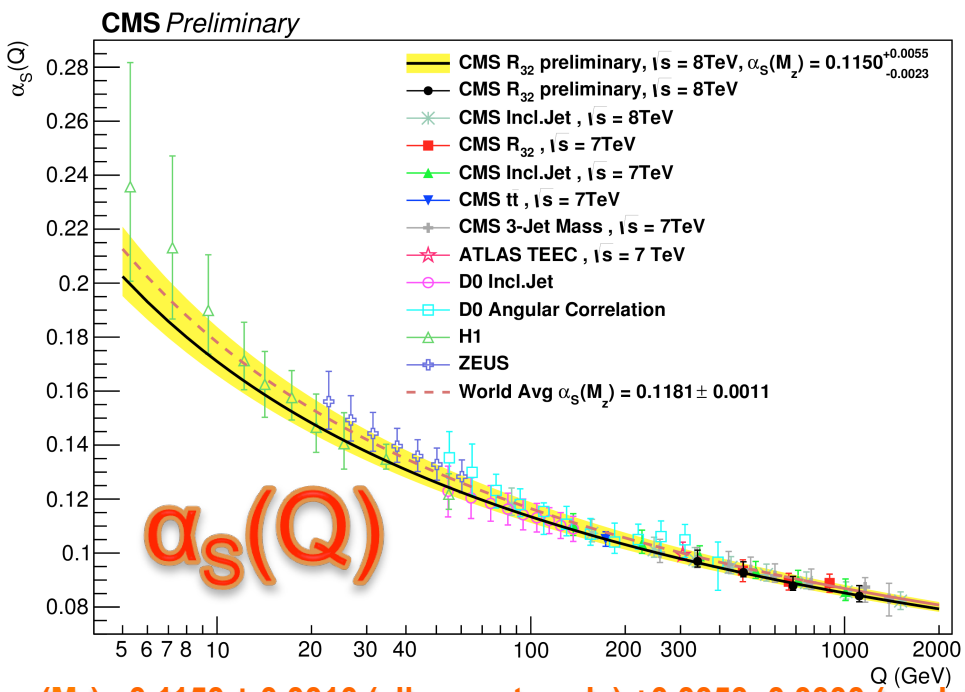
CMS-SMP-16-014

- Jet production at 13 TeV with full 2016
- Measurements of the normalized inclusive 2-jet, 3-jet, and 4-jet xSec. differential in $\Delta\phi_{1,2}$
  - Observations emphasize the need to improve predictions for multijet production
- $\alpha_s(M_Z)$ inferred from a fit of the ratio of the 3-jet over 2-jet event xSec



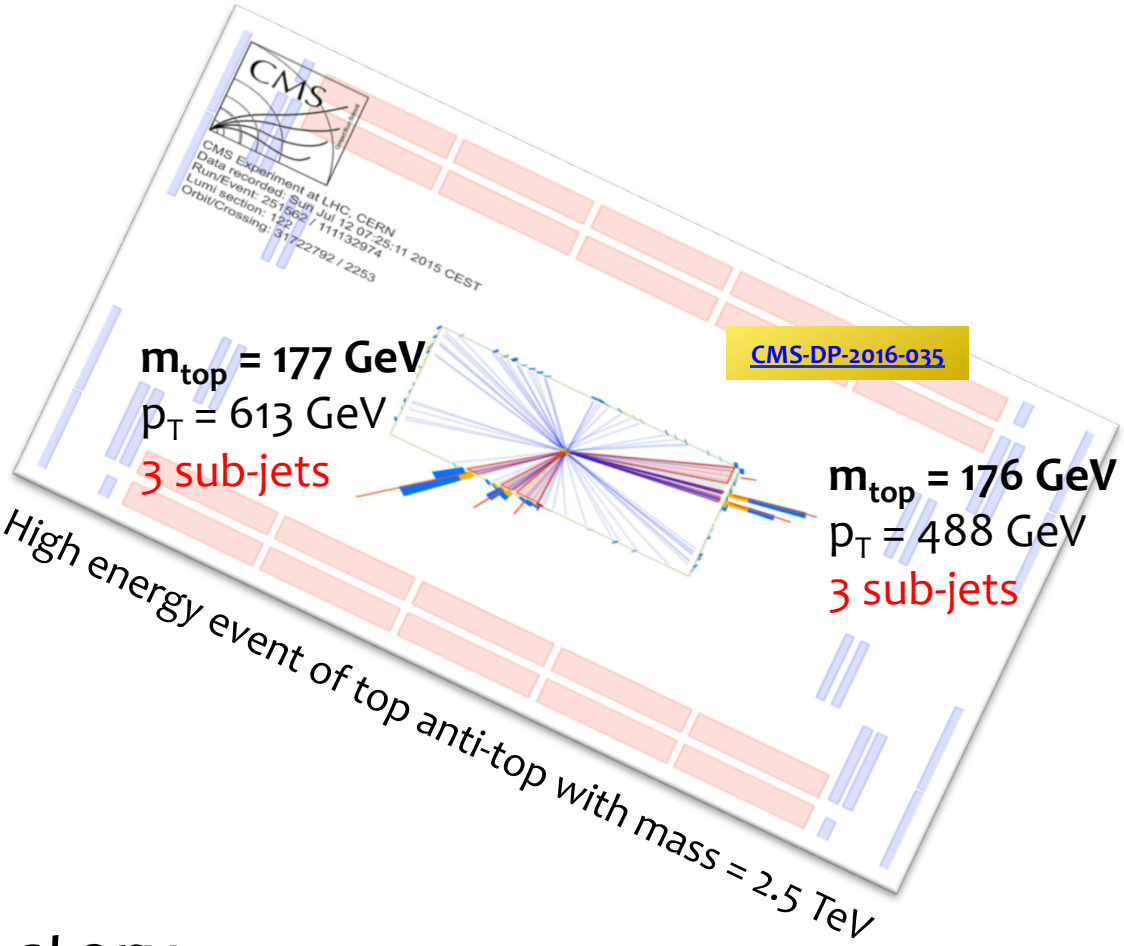

4-jet xSec. in $\Delta\phi_{1,2}$ for 8 $p^T_{max}$ regions




$\alpha_S(M_Z)$= 0.1150 ± 0.0010 (all except scale) +0.0050−0.0000 (scale)

CMS-SMP-16-008

# Top quark



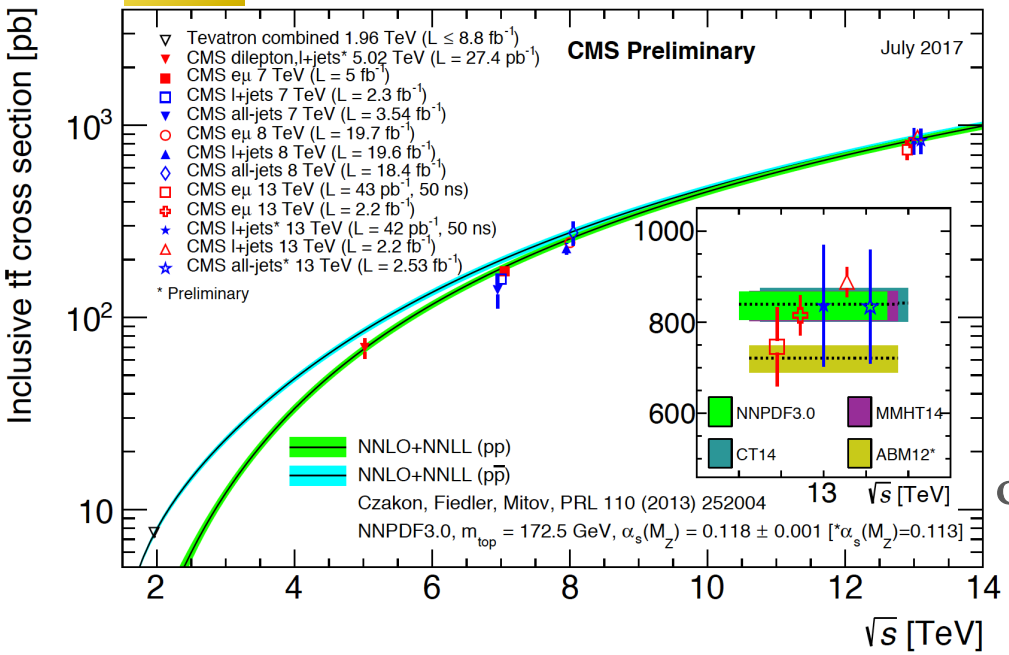

High energy event of top anti-top with mass = 2.5 TeV

**LHC** is a top quark factory

- ~10 top pairs every second @ $10^{34}$ $cm^{-2}s^{-1}$ inst. luminosity
- Wide and detailed studies under top quark
- Testing SM and BMS physics

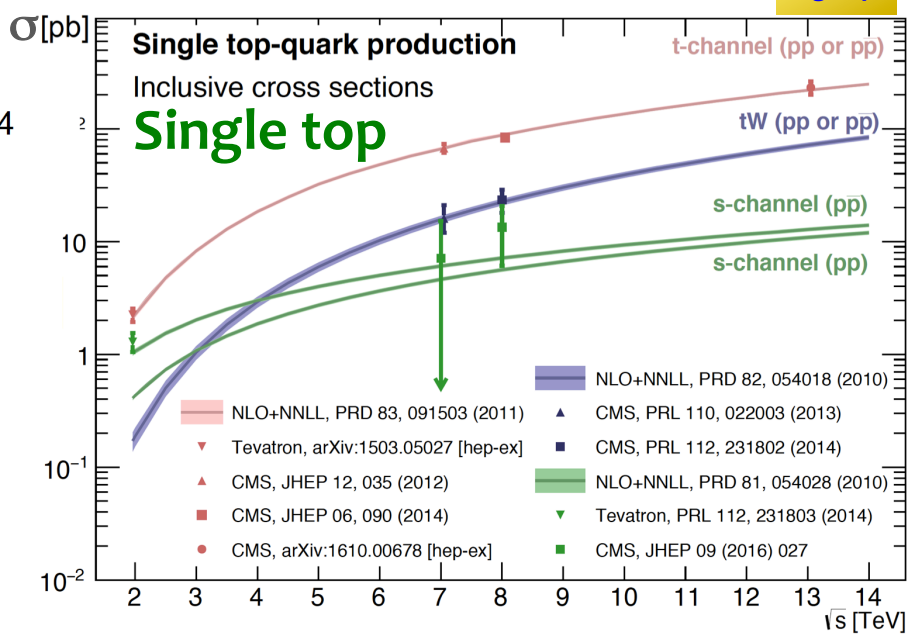
# Top quark production

TtSig




| √s | σ(tt) [pb] | L[fb⁻¹] |
|---|---|---|
| 5 TeV | ~70 | 0.03 |
| 7 TeV | ~170 | 5 |
| 8 TeV | ~250 | 19.7 |
| 13 TeV | ~800 | 2.3 |

SglTop

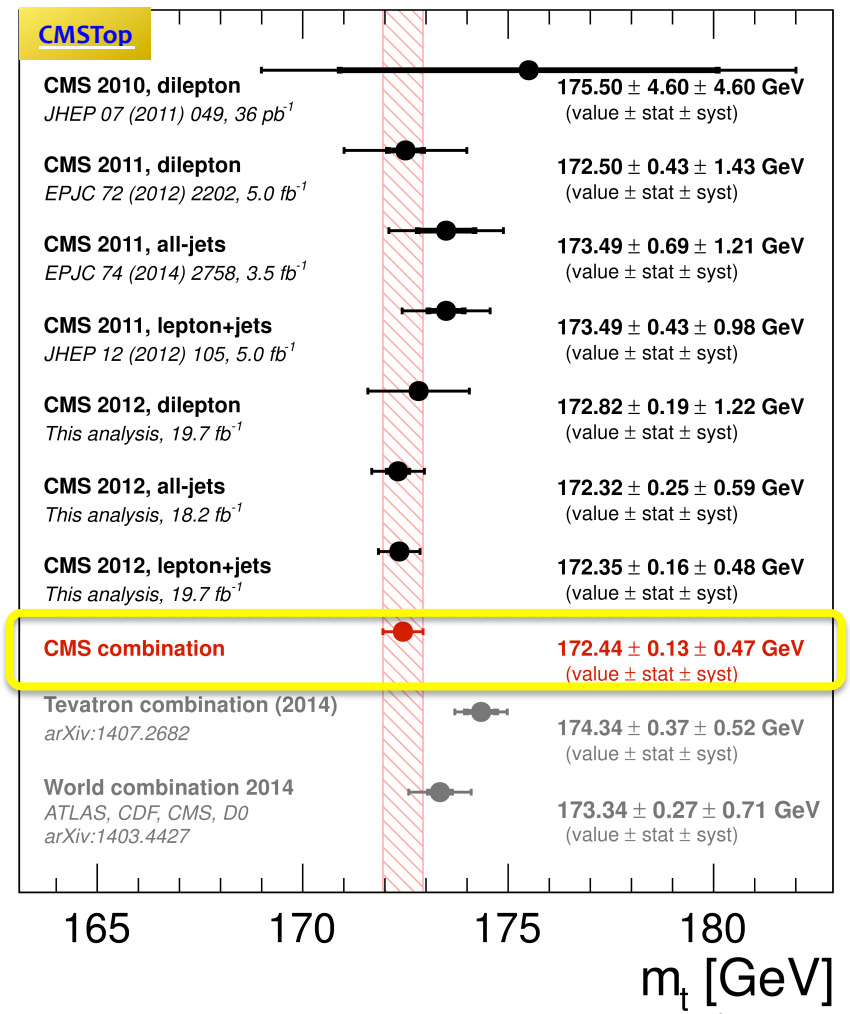



CMS-TOP-16-023

- New **xsec** (69.5 ± 8.4 pb) **for tt pair** prod. **@ 5 TeV**
  (special short run in 2016, L=27.4/pb)
- Evts: 1 muon and at least 4jets, 2b-tag

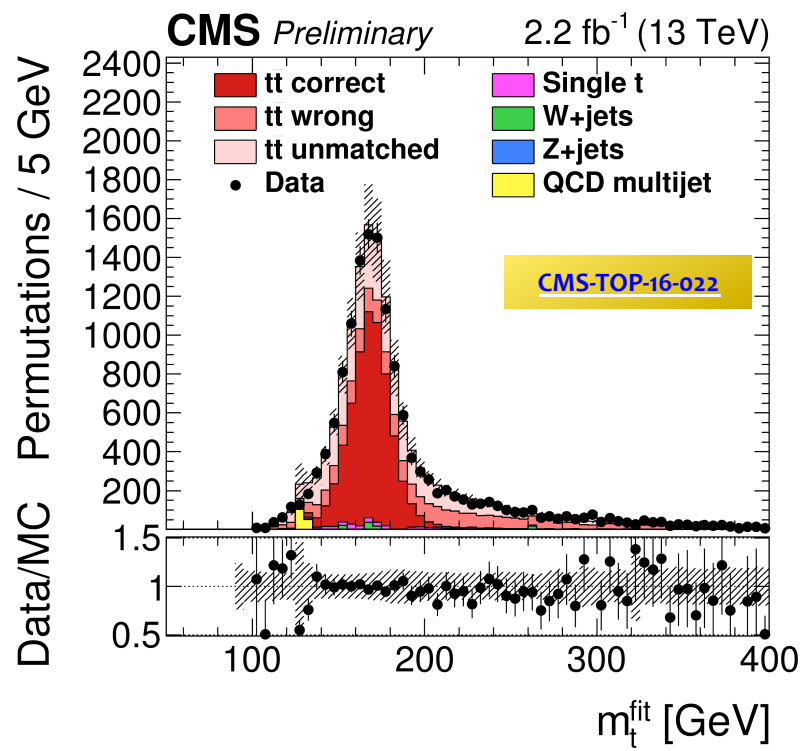
# Top quark mass

- Great accuracy (~0.3%) in the CMS **top mass** measurement from Run 1




- First **top mass** measurement from **μ +jets** with 13TeV with only 2.2/fb

$M_{top}$ = 172.62 ± 0.38± 0.70 GeV



# Rare top processes

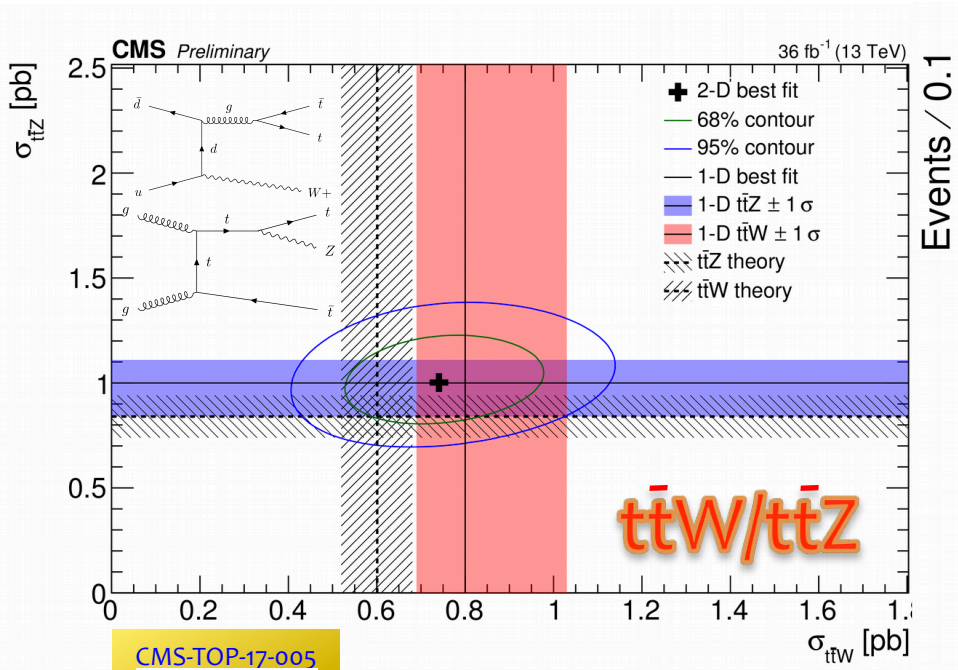
- **Top pair prod. with W/Z**
  Same me-charge dilepton, 3- and 4-lepton final states where the jet and b-jet multiplicities are exploited to enhance the signal-to-bkg ratio
- Measured xSec. are in agreement with SM predictions

$\sigma(ttZ) = 1.00^{+0.09}_{-0.08}(stat.)^{+0.12}_{-0.10}(sys.)$ pb

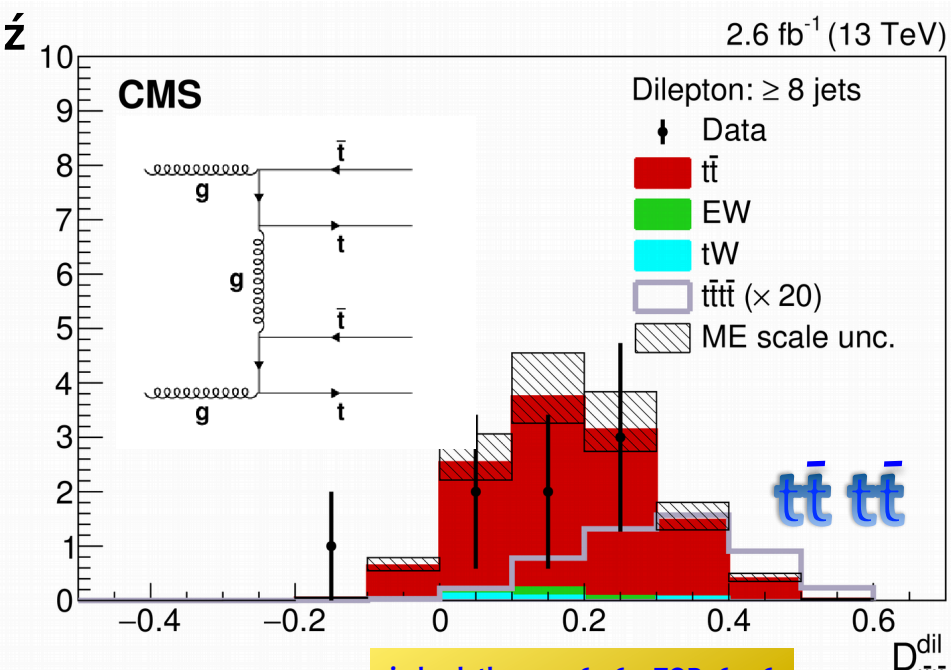
$\sigma(ttW) = 0.80^{+0.12}_{-0.11}(stat.)^{+0.13}_{-0.12}(sys.)$ pb

- **Four top production**
  Single-lepton +jets and the opposite-sign +jets channels
  Boosted decision trees to combine information on the global event and jet properties to distinguish between $tt^-tt^-$ and $tt^-$ production
- Upper limit on xSec.
  combined with same-sign dilepton search

$\sigma(tttt) < 69$ fb @ 95% C.L. (7.4xSM)

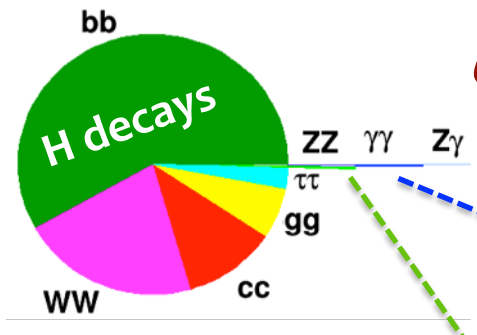


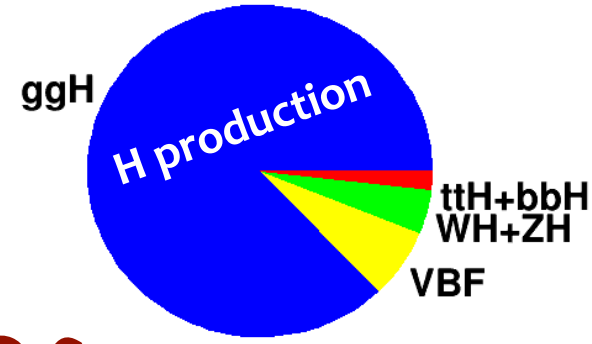

CMS-TOP-17-005



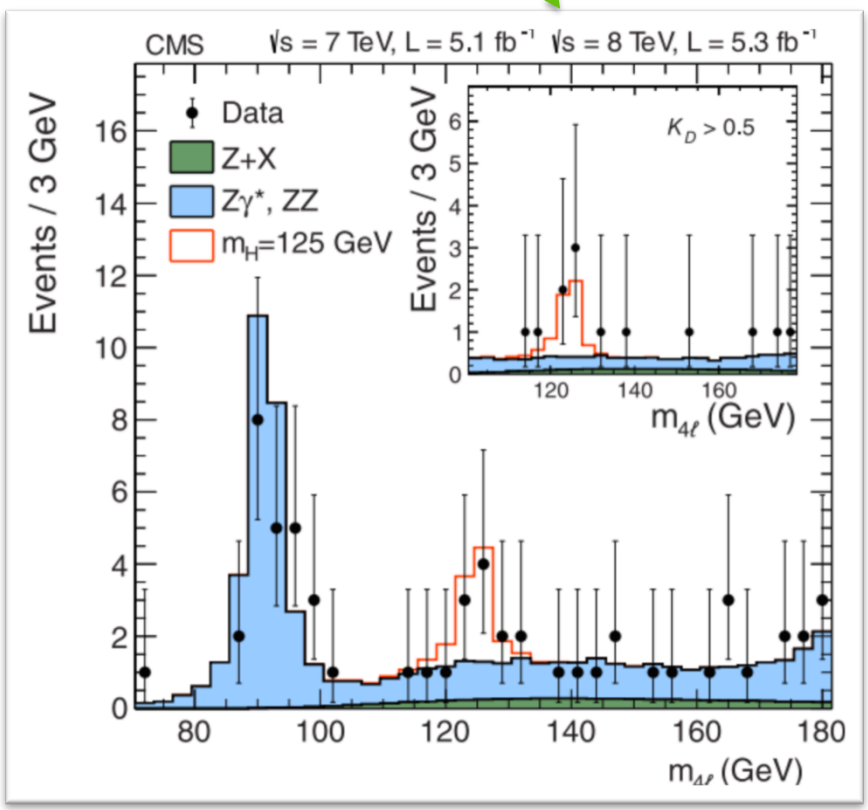

j.physletb.2017.06.064, TOP-16-016

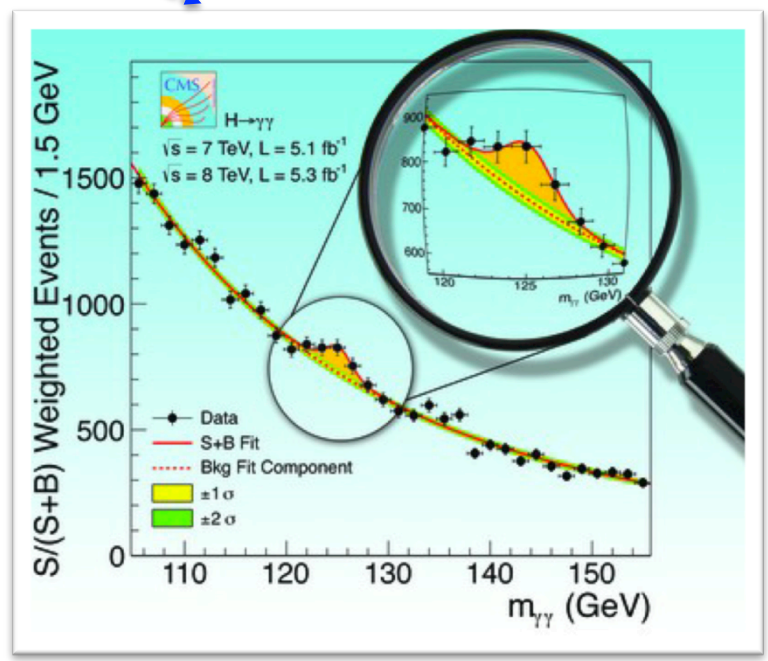
# 5th anniversary of the Higgs boson



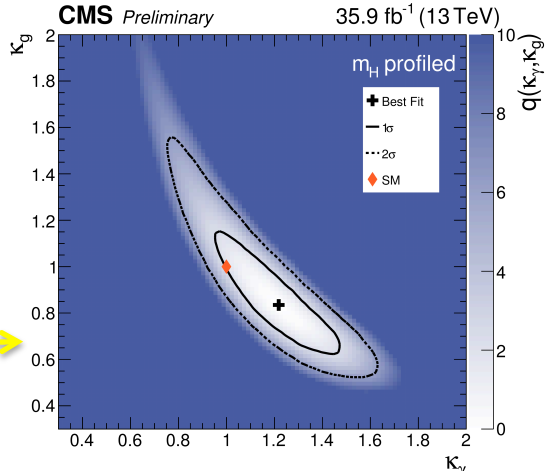

4th July 2012

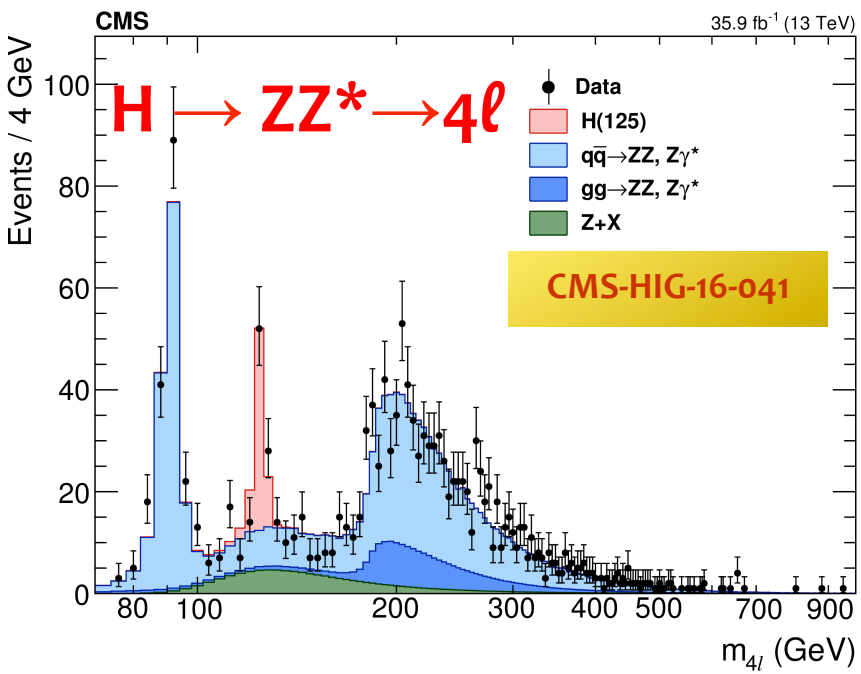


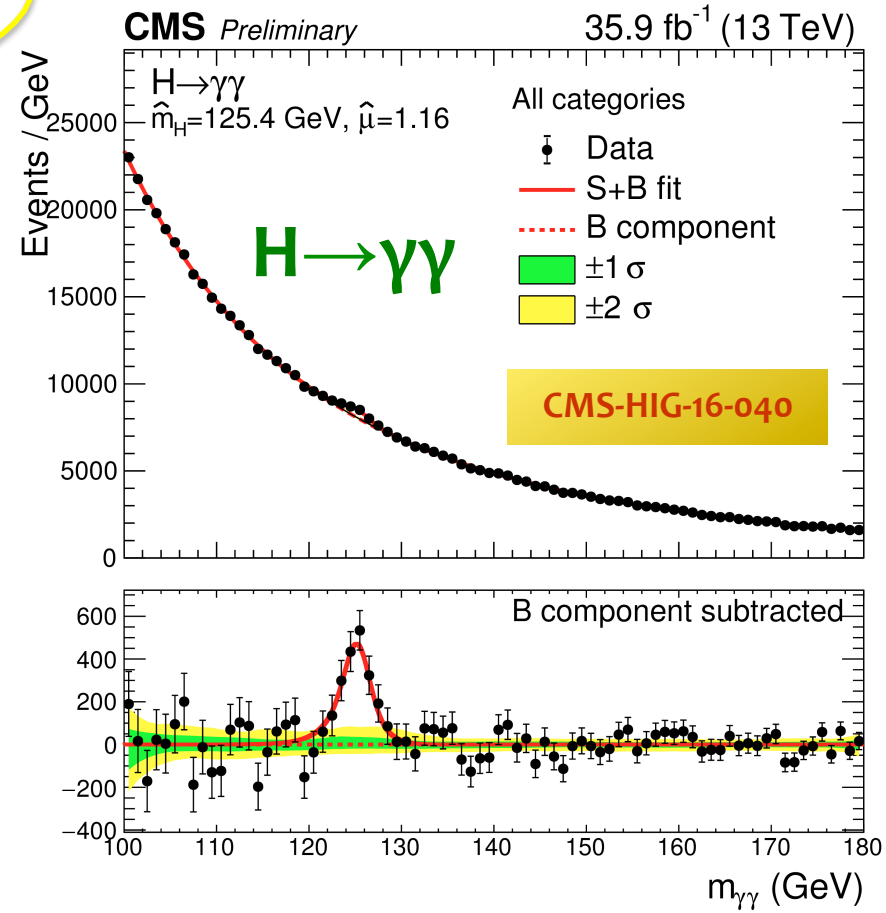



# Higgs boson production

- New measurement at 13 TeV in **H → ZZ*→4ℓ** and **H→γγ**
- Discovery channels despite small BF of **~0.013% (4ℓ)**, **~0.23%(γγ)**
- Consistent with SM



arXiv:1706.09936, CMS-HIG-16-041

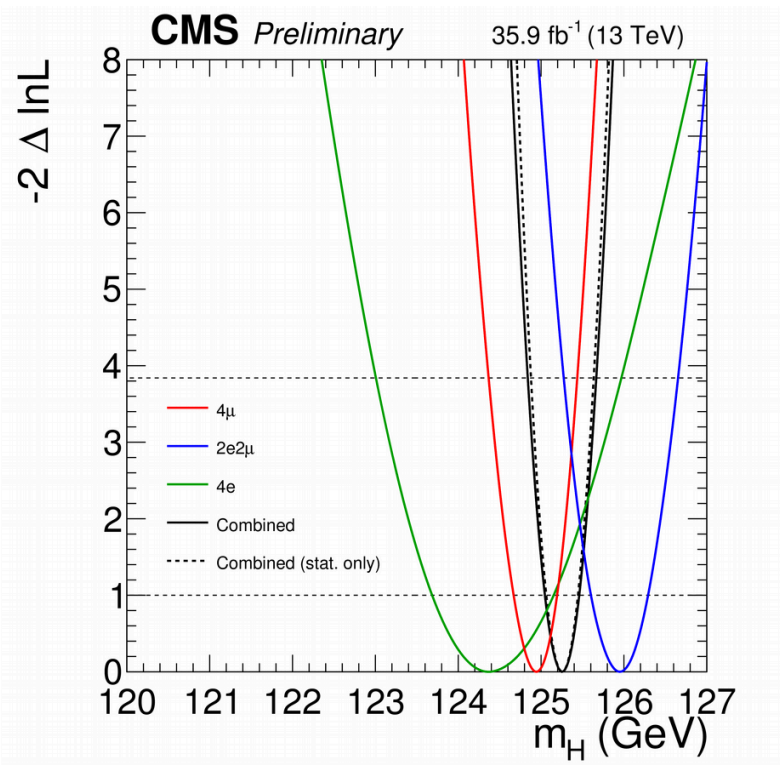
# Higgs mass and xSec

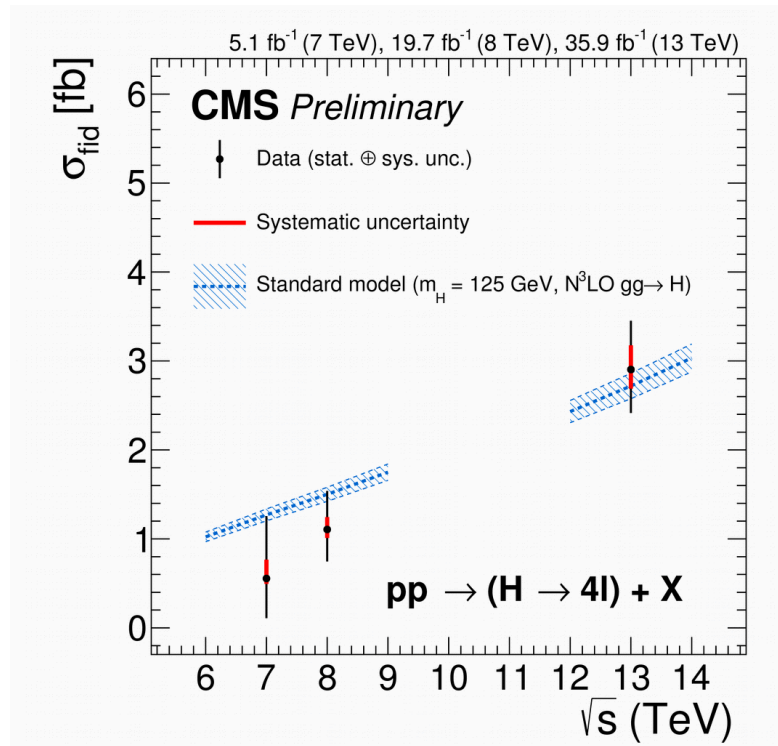
- Mass measurement in golden channel: **H → ZZ*→4ℓ** via ggH, VH, VBF

$$m_{\mathrm{H}} = 125.26 \pm 0.20(\mathrm{stat.}) \pm 0.08(\mathrm{sys.})\ \mathrm{GeV}$$

- As good as the world average of the ATLAS+CMS combination from Run 1

$$m_H = 125.09 \pm 0.21\ (\mathrm{stat.}) \pm 0.11\ (\mathrm{syst.})\ \mathrm{GeV}$$



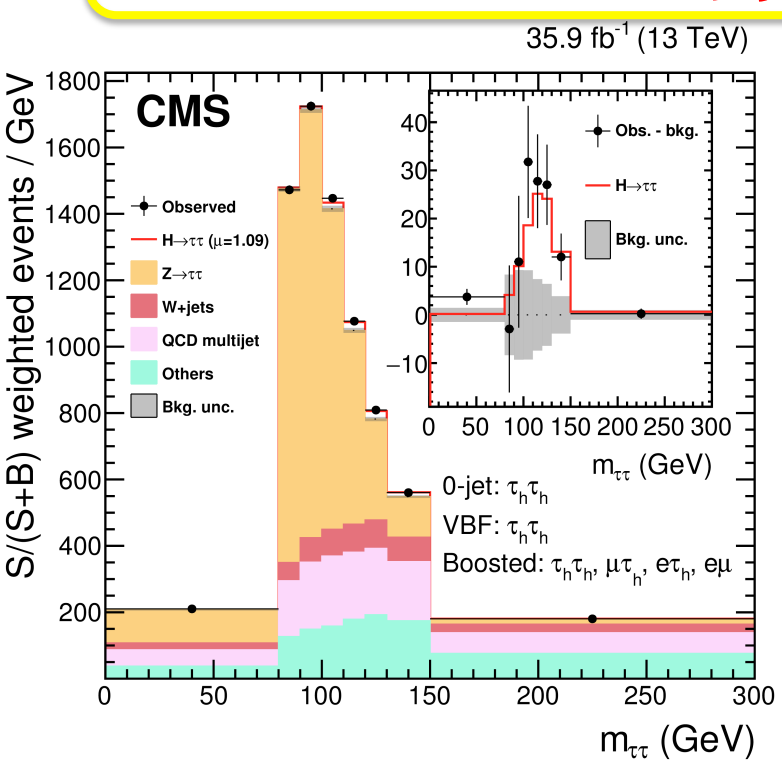



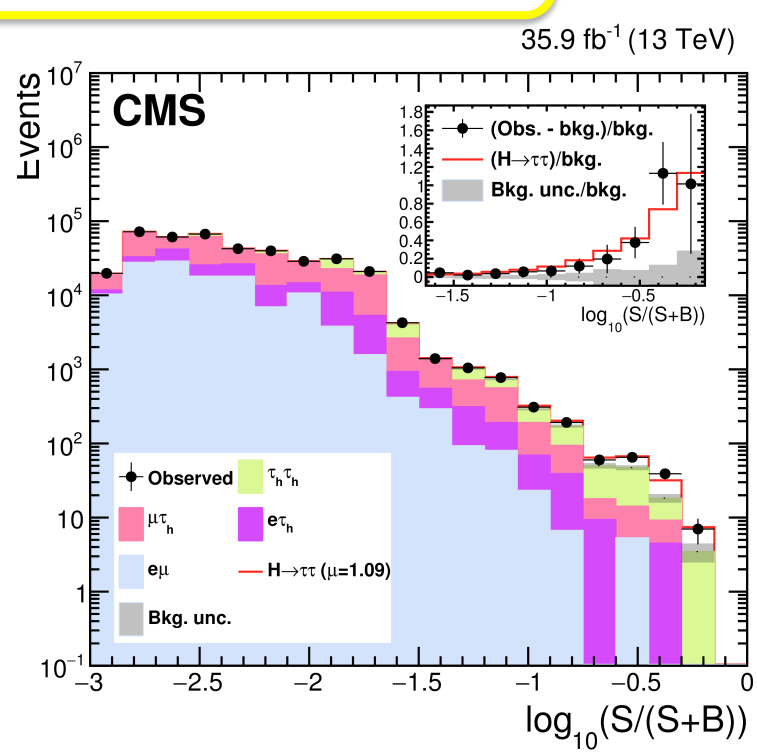

Fiducial cross sections as a function of √s

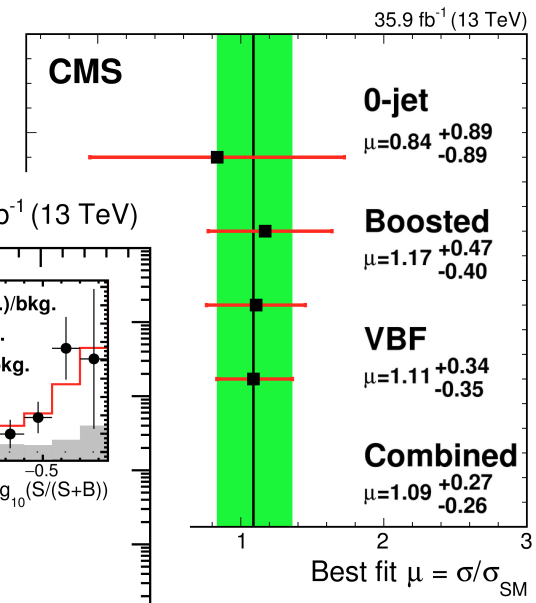
arXiv:1708.00373, CMS-HIG-16-043

# Higgs couples to τ lepton

- **First observation** of **H→ττ** at CMS with the full 2016 dataset using **excellent CMS tau tagging**
- Tau semi-hadronic & leptonic decay channels
  - 4 final states (**ττ, μτ, eτ,** eμ)
  - 3 categories (0-jet, VBF, Boosted)
- CMS observed **H→ττ** at **4.9 σ** wrt **4.7 σ** expected
- Run 1 + Run 2'16 result: **5.9 σ**




Best fit
$\mu = \sigma/\sigma_{SM}$

$$\mu = 1.09^{+0.27}_{-0.26}$$

# Higgs Physics: H→bb

NEW
CMS-HIG-16-044

- Dominant H decay channel (58.1%), but with huge QCD bb background
- Presence of the vector boson (leptons, MET) **supresses highly QCD**

- **Sig:** 2b-tag jets + 2 lep (+1 leptMET), (+MET) extracted via a simultaneous fit of all control regions and signal regions
- **Bkg:** fitted in simultaneous fit for V+jets and ttbar

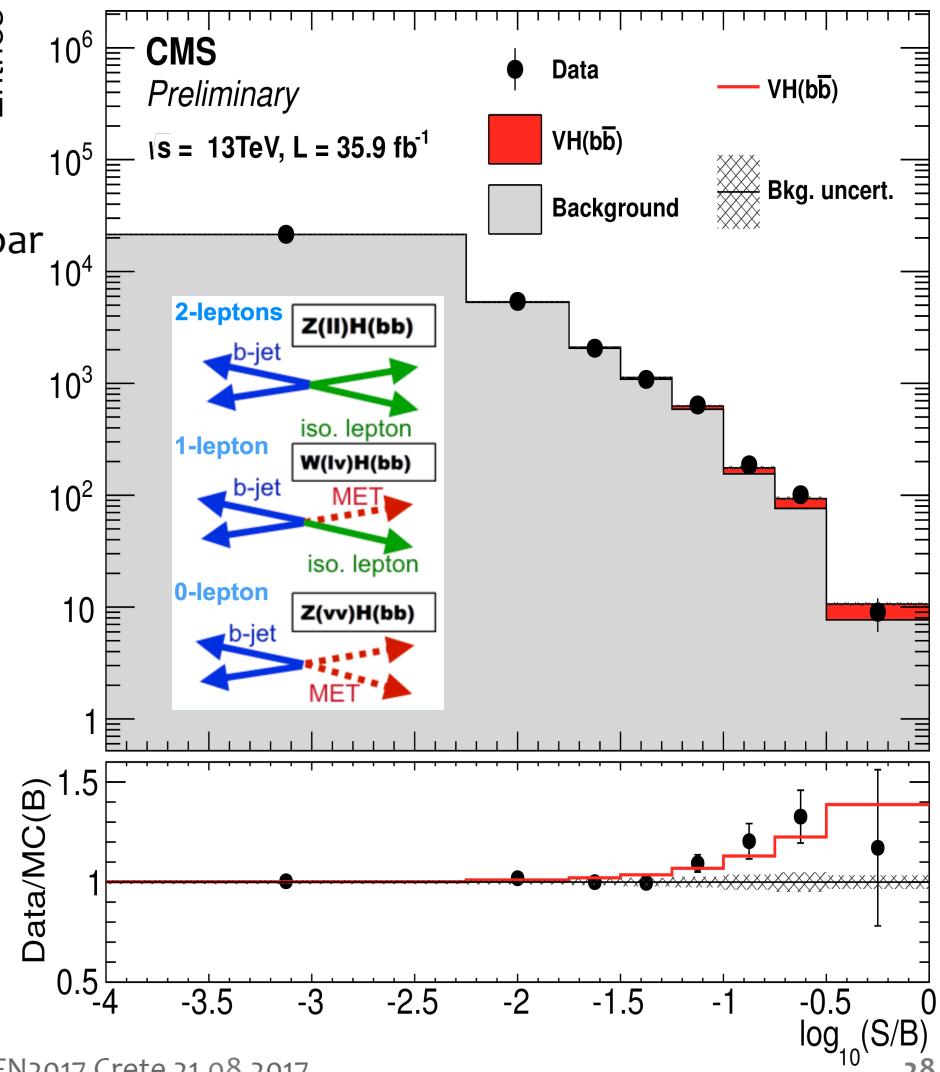
- Analysis **validated for Z→bb**
  - **5.0 σ observation**

- **For $m_H$ = 125 GeV,**
  **Run 1&2 excess** of **events observed** with local sig. of
  **3.8 σ** (**3.8 σ** SM exp.)

Strong evidence

- Signal strength

$$\mu = \sigma/\sigma_{SM} = 1.06^{+0.31}_{-0.29}$$



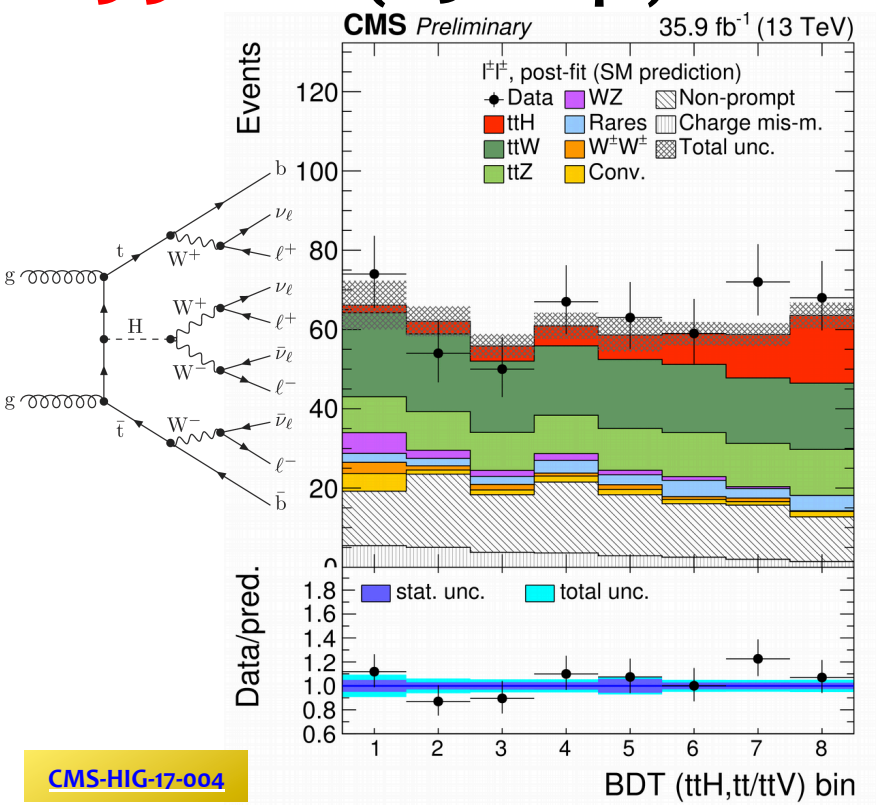
# Higgs – top production

- Direct test of **H-t coupling** using ttH and tHq channels
- H decaying to WW*, ZZ* or ττ
  - 2 same-sign leptons or at least 3 leptons , and b-tag jets
- **Evidence for ttH signal**

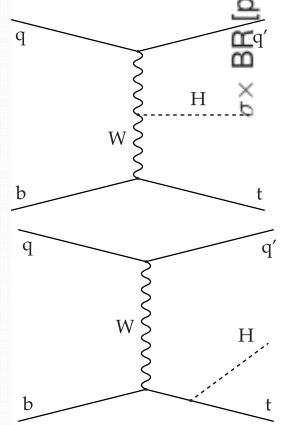
  **3.3σ obs. (2.5σ exp.)** comb.2015 & 2016

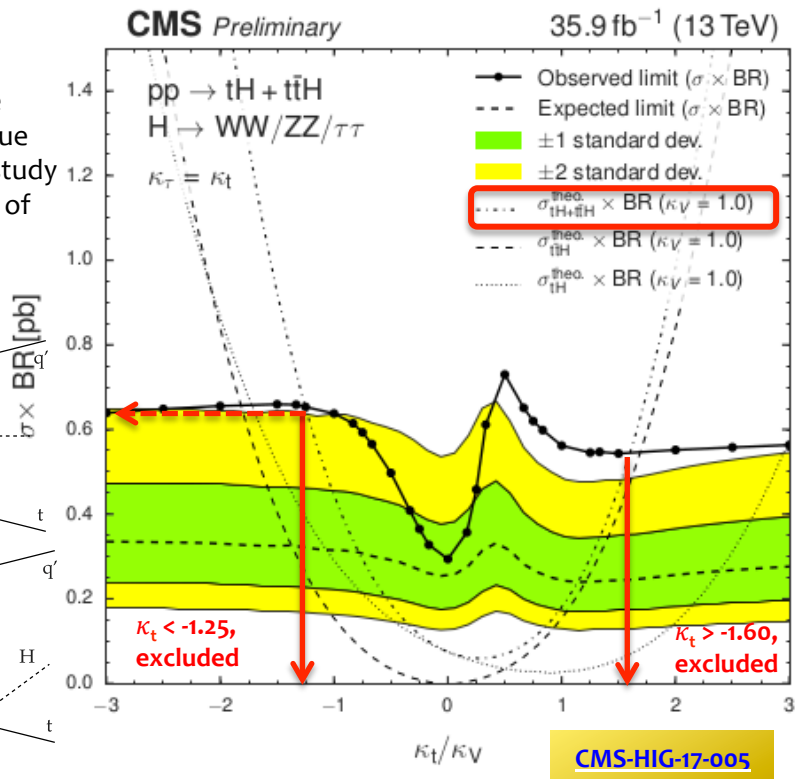
**Upper limit on σ $^{tH+ttH}$ x BR**

**0.64 pb obs. (0.32 exp.)**




Single top in the t-channel – unique opportunity to study the relative sign of the coupling





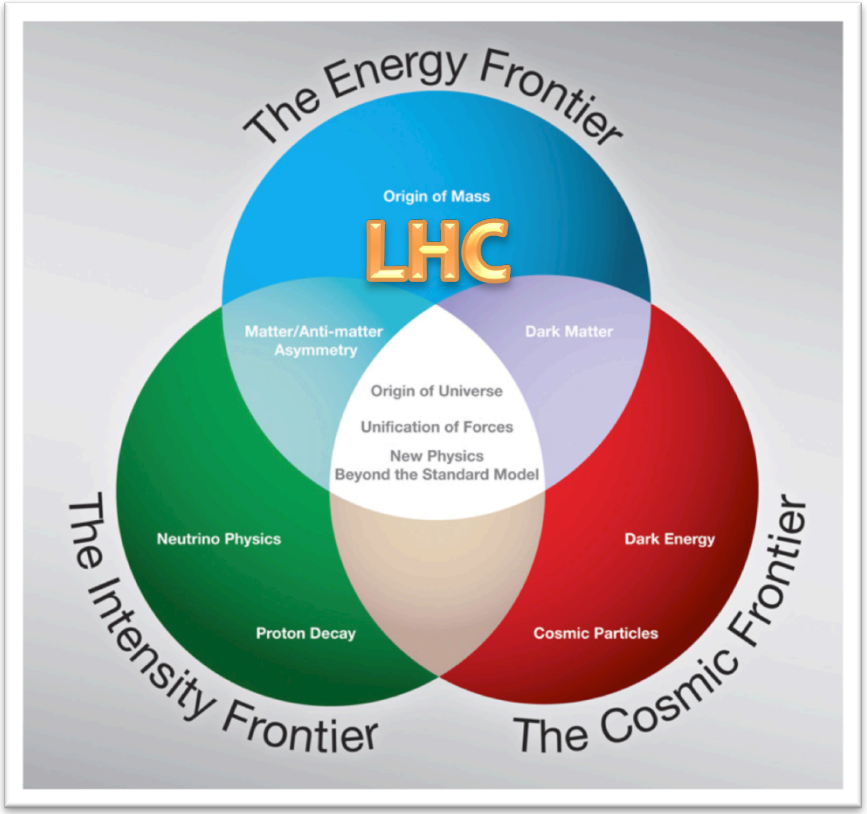

CMS-HIG-17-004

CMS-HIG-17-005

# Searches

**LHC** is a unique place to search for **new particles**

- **directly** and
- **indirectly**
  - precise SM measurements

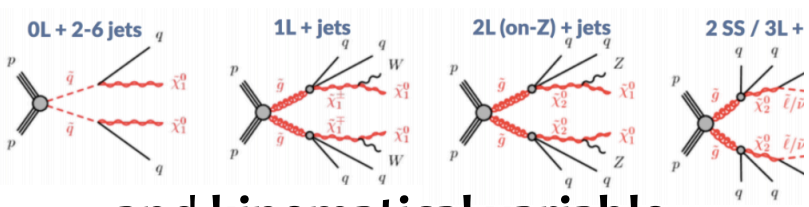


# Strong SUSY

- Gluino or squark (gg,qq,gq) production
- **Sig.:** Jets+MET

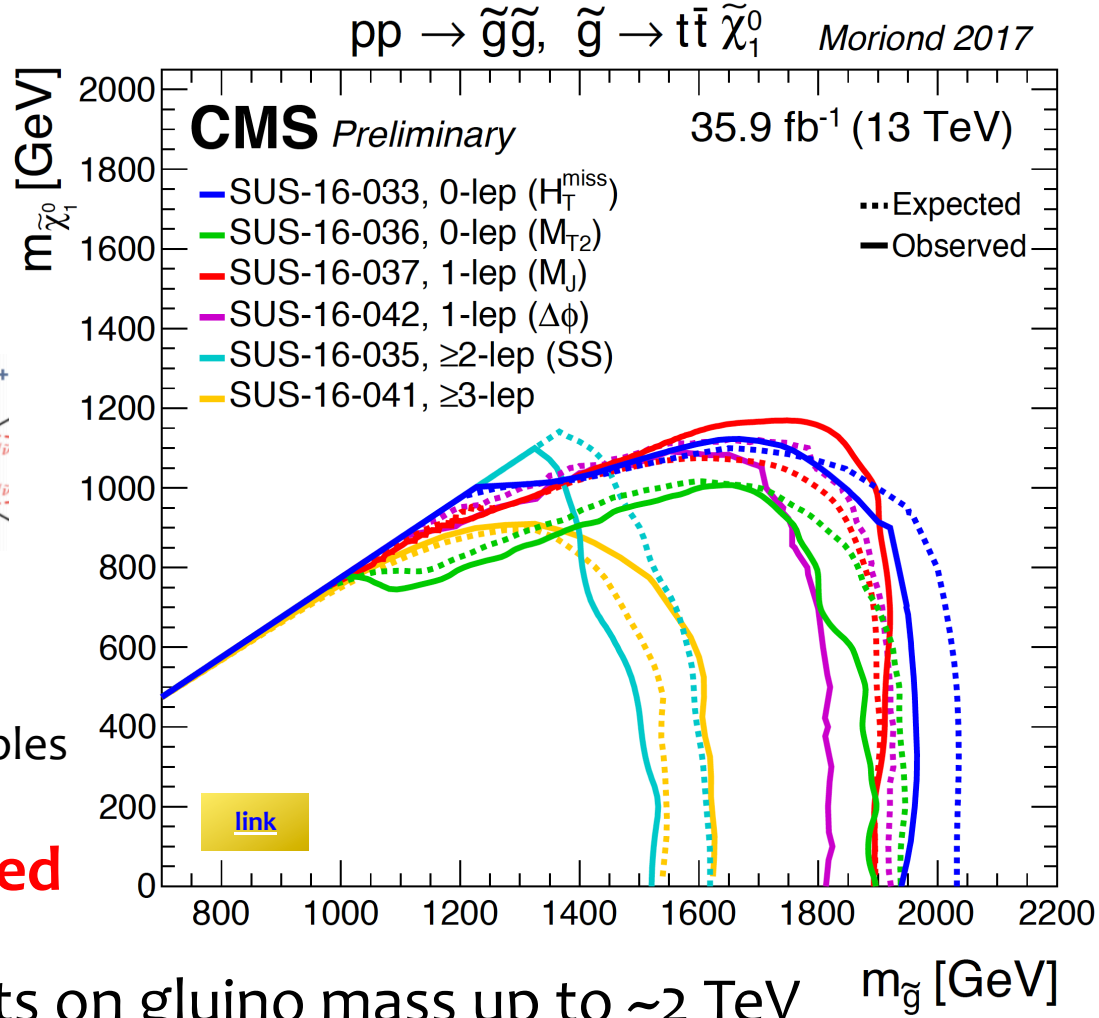
  $+N_{jet} + N_{b\text{-}tag\ jet}$

- Experimental search based on **signatures**




- and **kinematical variable** sensitive to SUSY
- Multiple signal regions and searches in bins of different variables

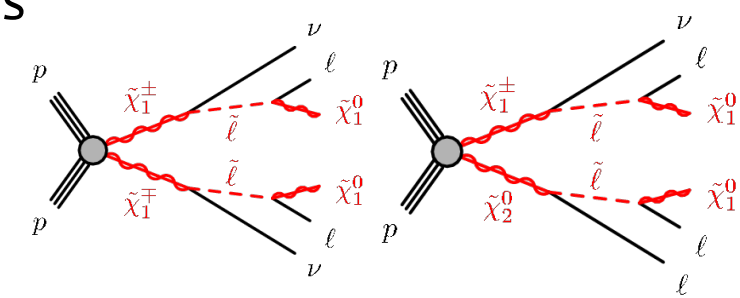
- **No SUSY particles detected**

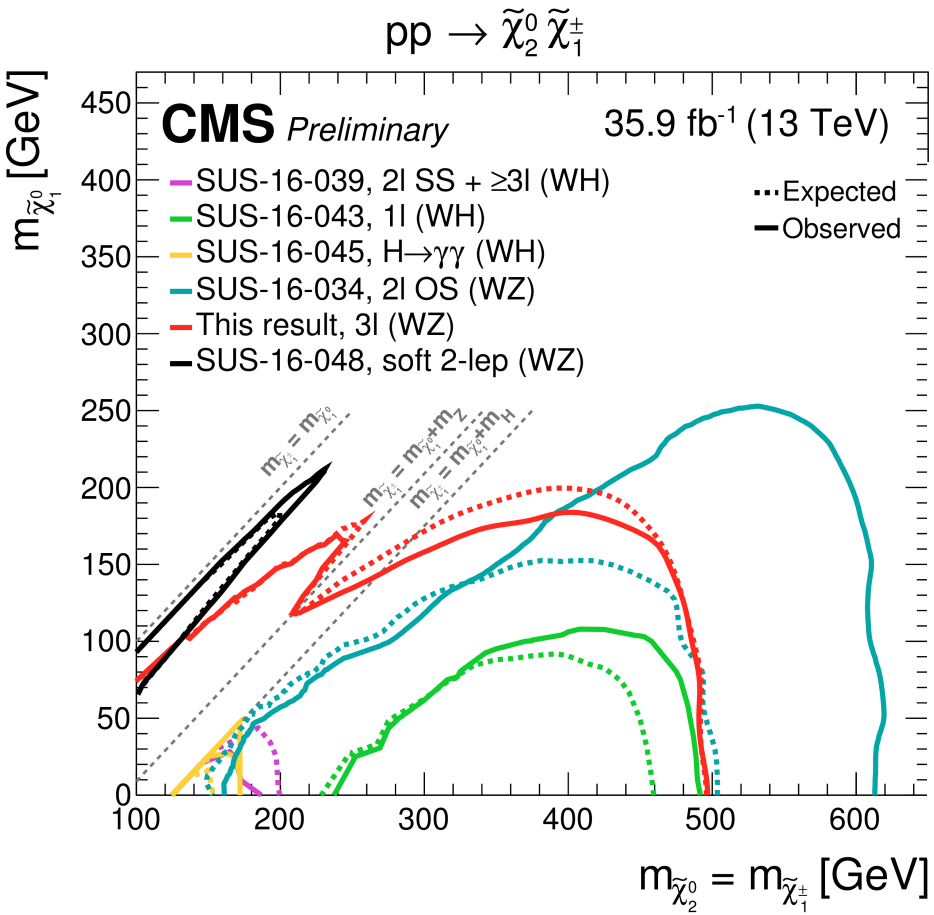


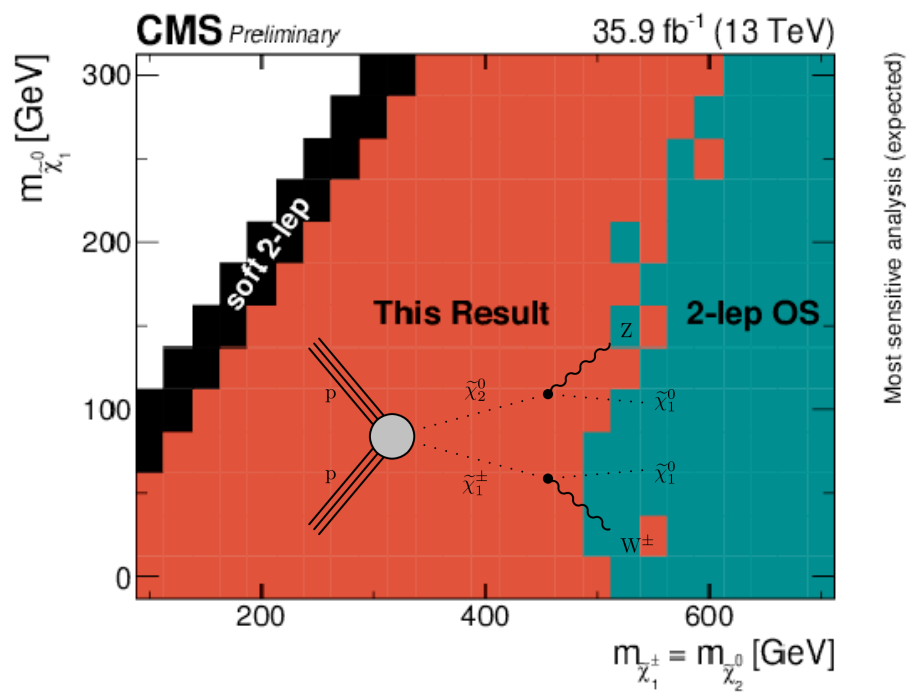

**Run 2'16 at 13 TeV:** Limits on gluino mass up to ~2 TeV

# Electroweak SUSY

- Electroweak SUSY production and decays of **chargino** and **neutralino**
- Statistical combination of several searches
  - Improvement of 40 GeV on the limit mass
- Optimized **analysis with 2- and 3-leptons**



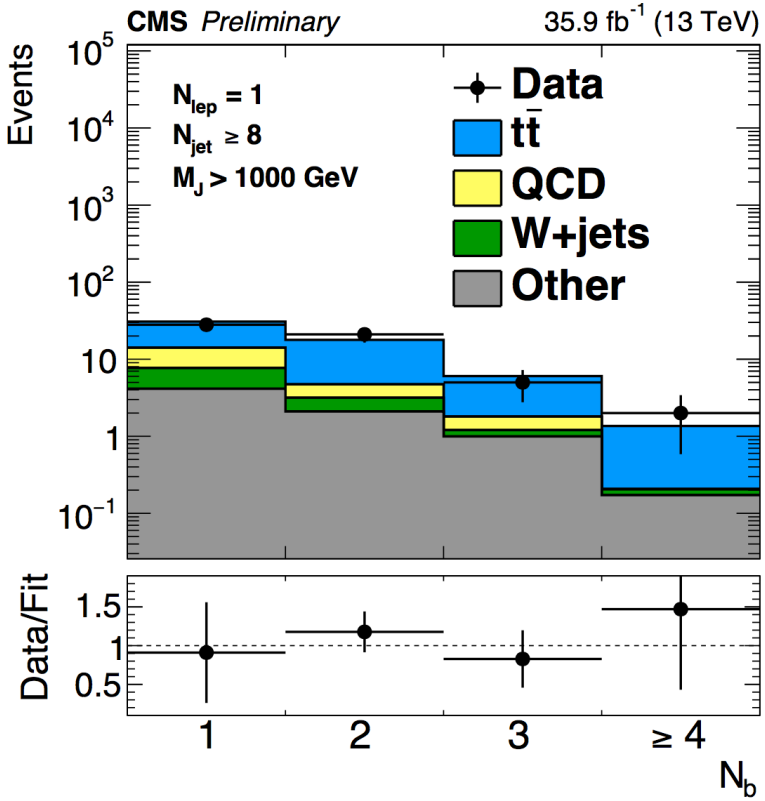


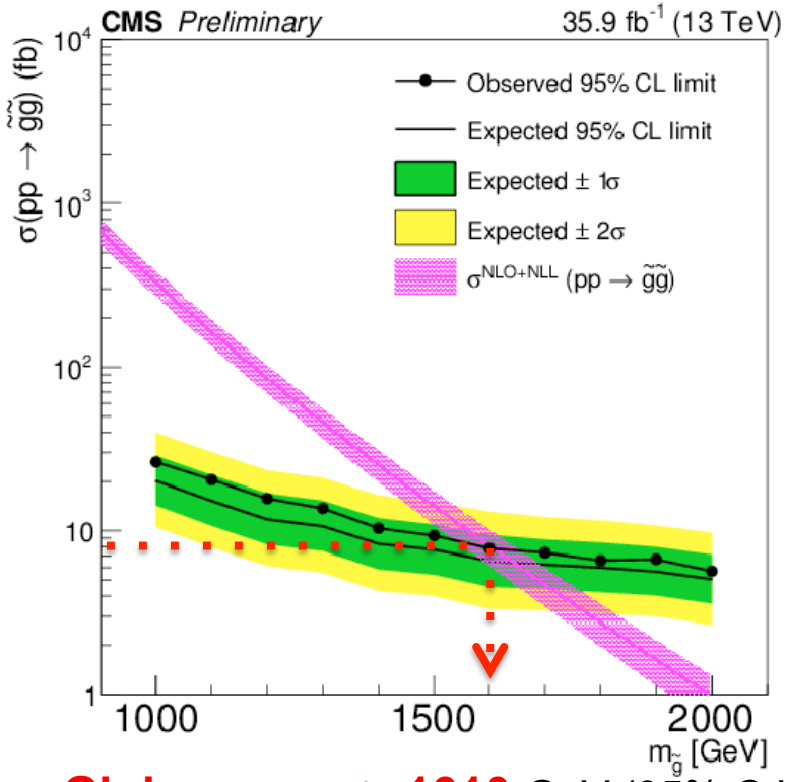



# SUSY R-parity violation

NEW
CMS-SUS-16-040

- R-parity can be not conserved!
- Minimal flavour violation, $\lambda_{tbs}$, $g \rightarrow t\,t \rightarrow t\,b\,s$
- **Signature:** single lepton, large jet multiplicity, and large q-quark jet multiplicity, NO requirement on MET
- Signal extraction through shape fit to $N_b$ in bins of $N_{jet}$ and $M_J$



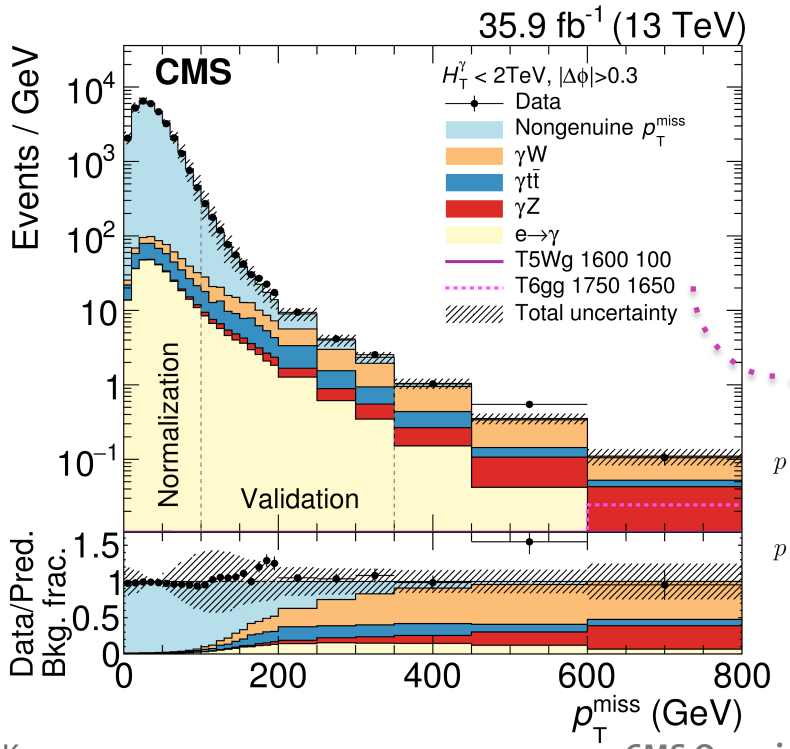



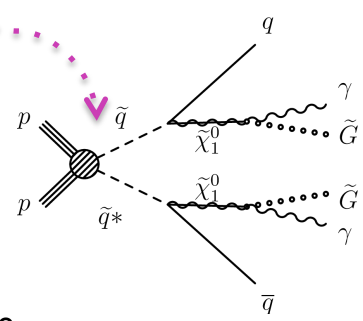

**Gluino mass > 1610** GeV (95% C.L.)

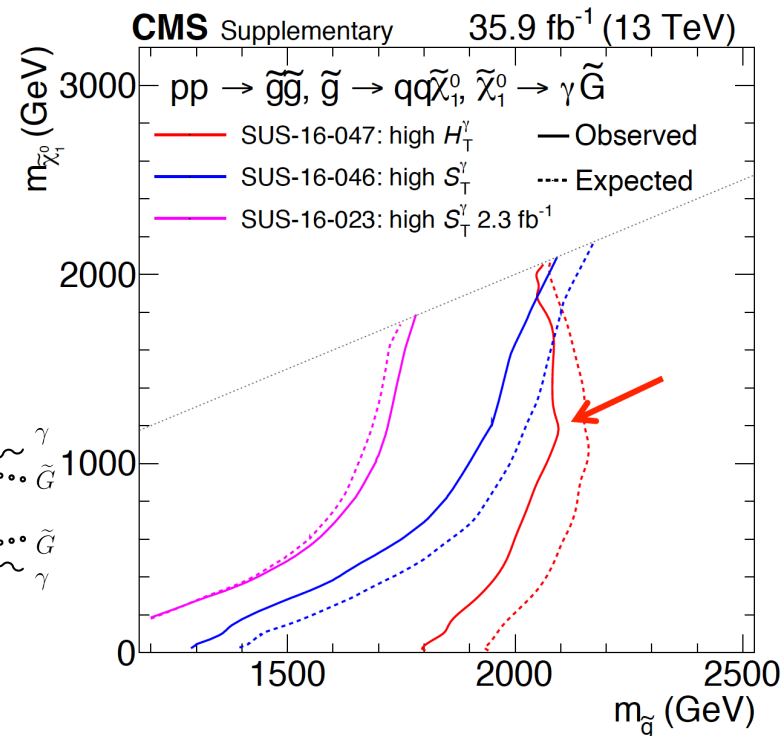
# Gauge Mediated SUSY

arXiv:1707.06193, CMS-SUS-16-047

- Search for BSM with at least 1 photon, large MET, and large $H_T$
- **Sig:** strongly produced GMSB with N1⟶ γ G
- **New limits** depending $m_{neutralino}$ & BR:
  - $m_{gluino}$ up to **1.5-2.0 TeV**
  - $m_{squark}$ up to **1.3-1.65 TeV**
- **Complementary searches:**
  - γ V, γγ, γ+lepton, multi-lepton
  - Provide weaker limits



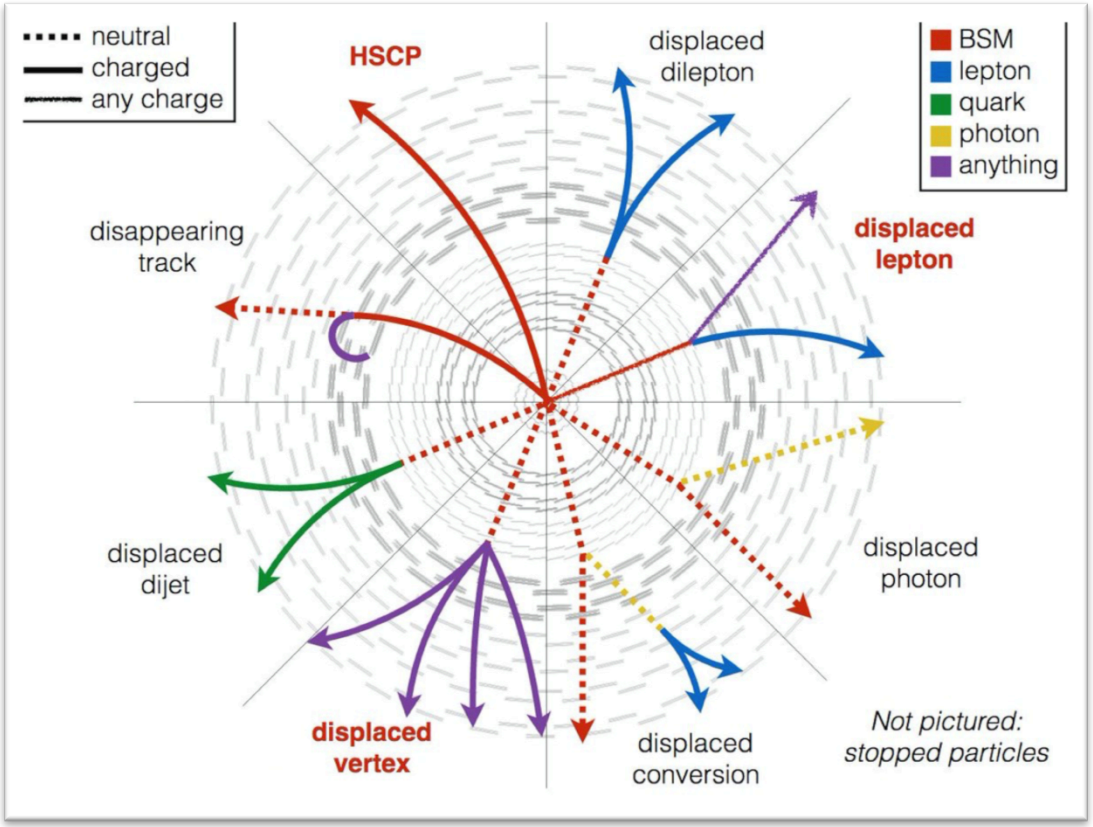



# Long-lived particles

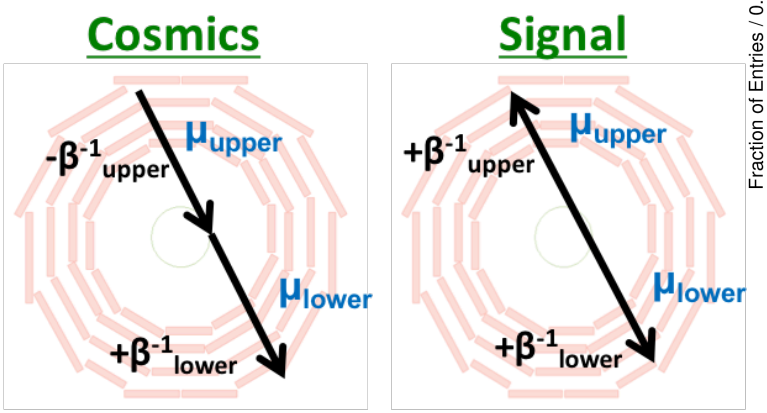
**LLPs** are foreseen by many BSM models

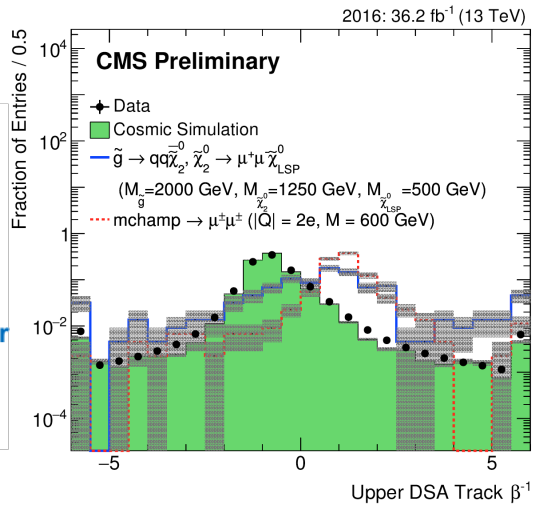
- Small coupling, small mass splitting, hidden sector
- **Signature depends on lifetime**

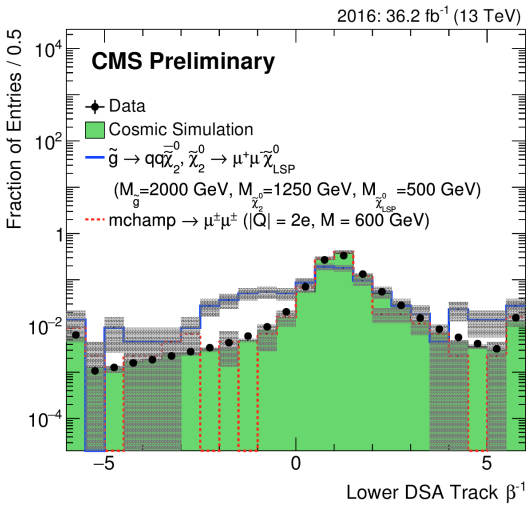


# LLP: stopped particles

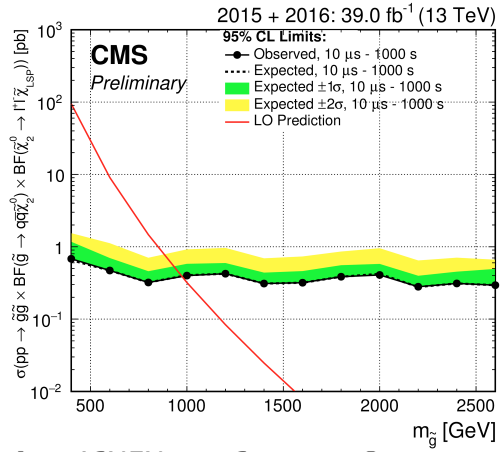
- **LLP** (gluino or |Q|=2e) is **stopped inside the detector** and **decay to muons** from rest after unknown time (sensitivity to lifetimes between 0.1 μs and $10^6$ s)
- Events recorded **out-of-time with collisions** with the custom trigger

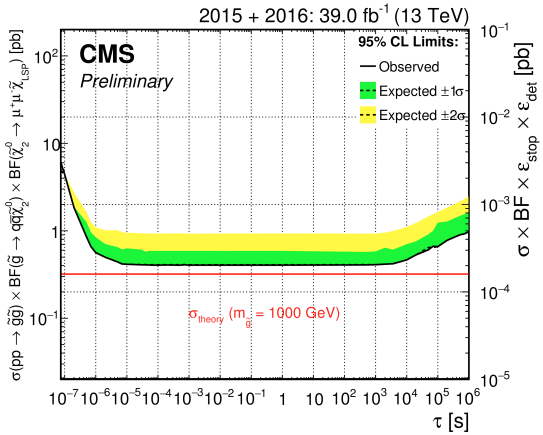



- **No events** observed
- 13 orders of magnitude of the lifetime tested
- Excluded gluinos with mass between 400 and 970 GeV, assuming 100% BF to muons

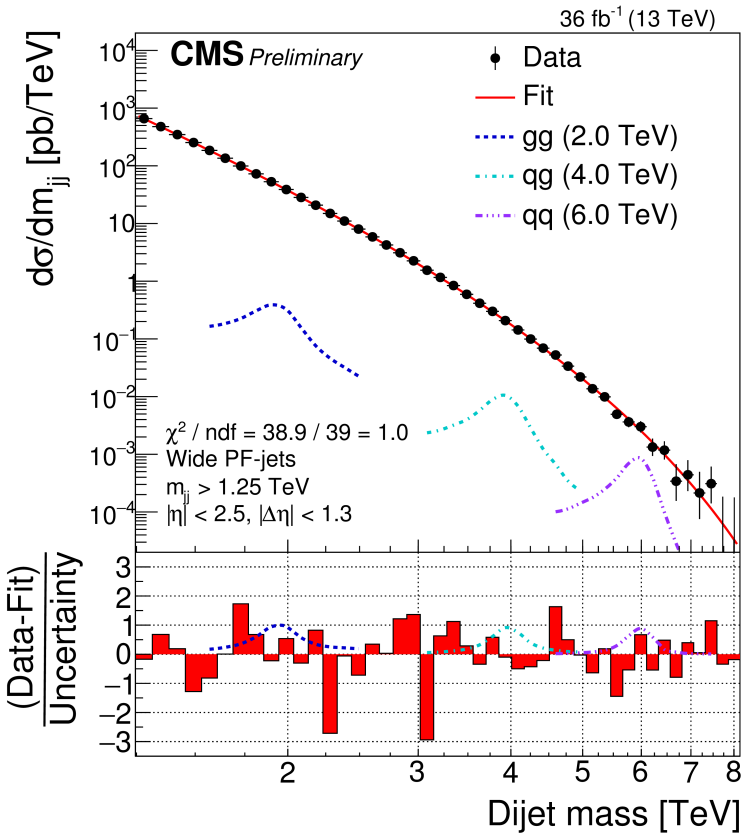


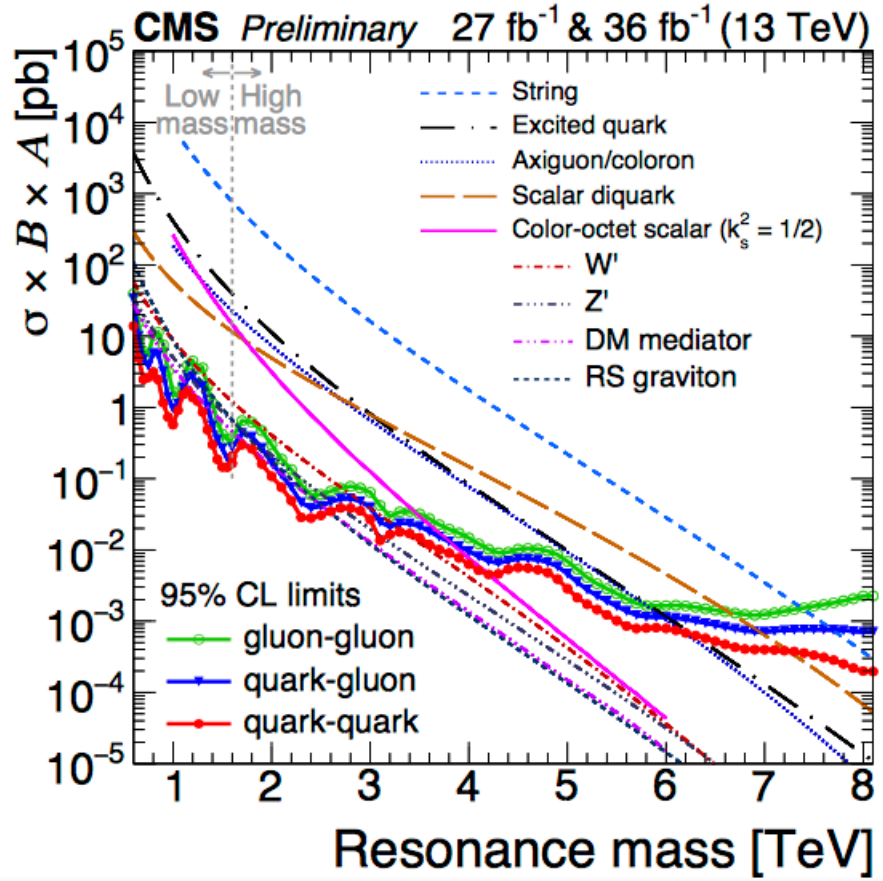
CMS-EXO-16-056

# Heavy resonance searches

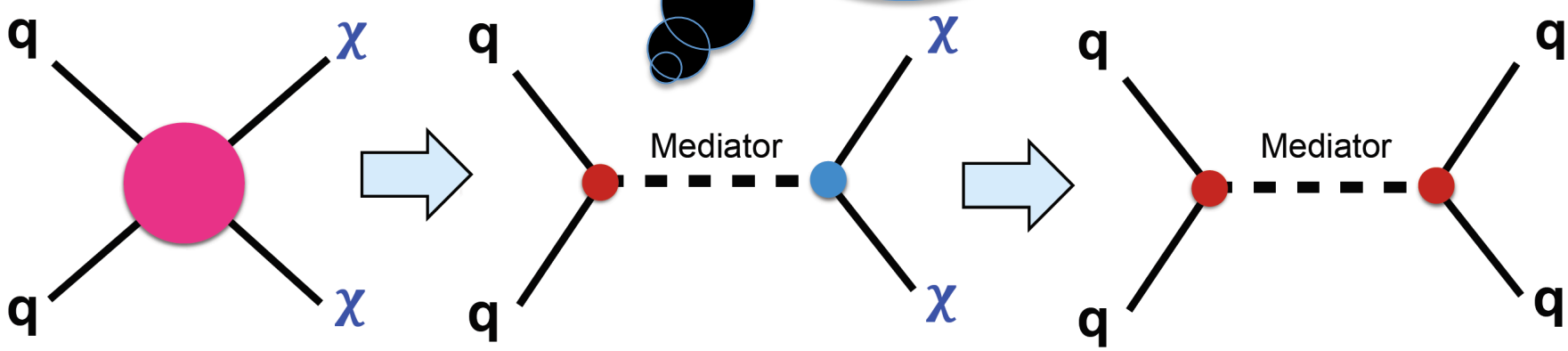
- Many BSM models predict narrow **di-X resonances**
  - X – many object in the final state analysed
- Di-jets (from Axigluons, colorons, W'/Z' bosons, color octet scalars, string resonances, RS, etc)




Generic limit on di-jet resonances, up to 7.7 TeV



# Dark Matter




Indirect searches  direct searches

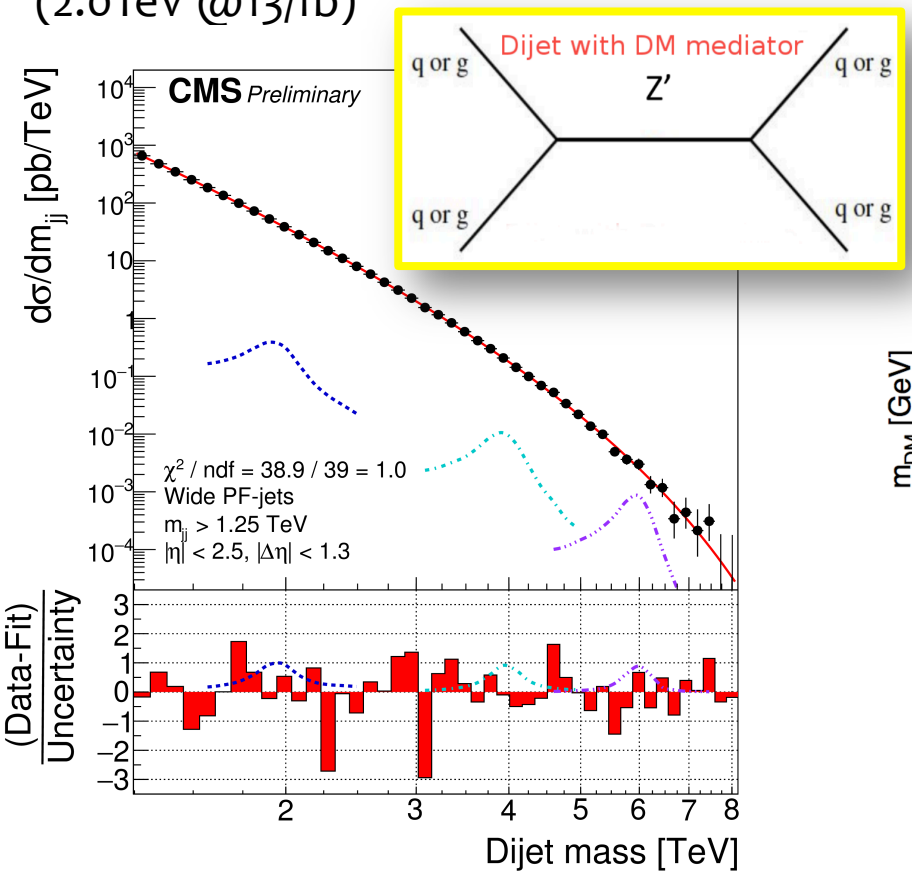
**Vector** and **scalar** interactions → **spin-independent (SI)** DM-nucleon interactions

**Axial-vector** interactions → **spin-dependent (SD)** DM-nucleon interactions

CMS-EXO-16-056

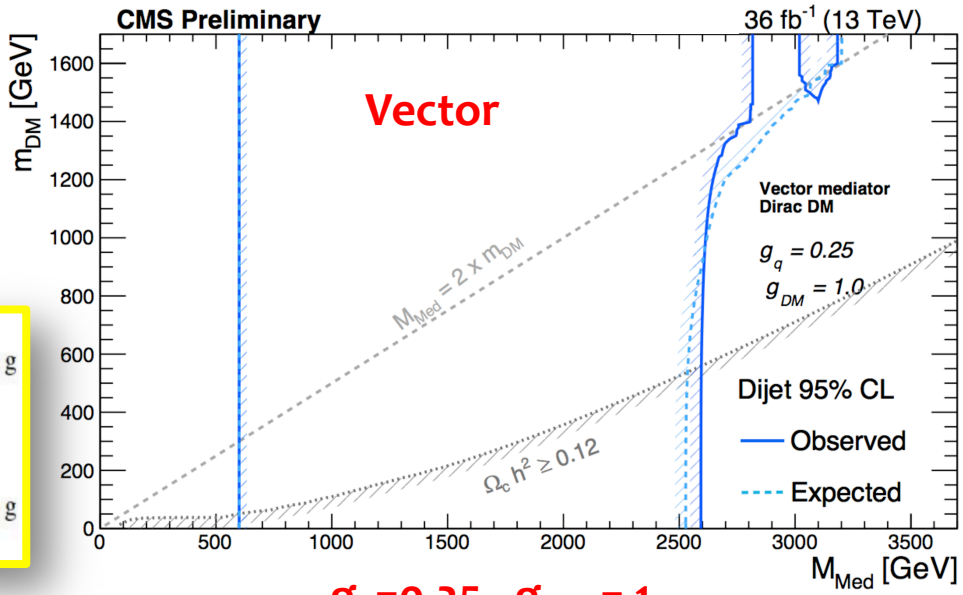
# Dijet searches

- **Used for the DM interpretation**
- New 36/fb **upper limit on mass of mediator 2.6 TeV** extends previously reported limits in the dijet channel (2.0TeV @13/fb)

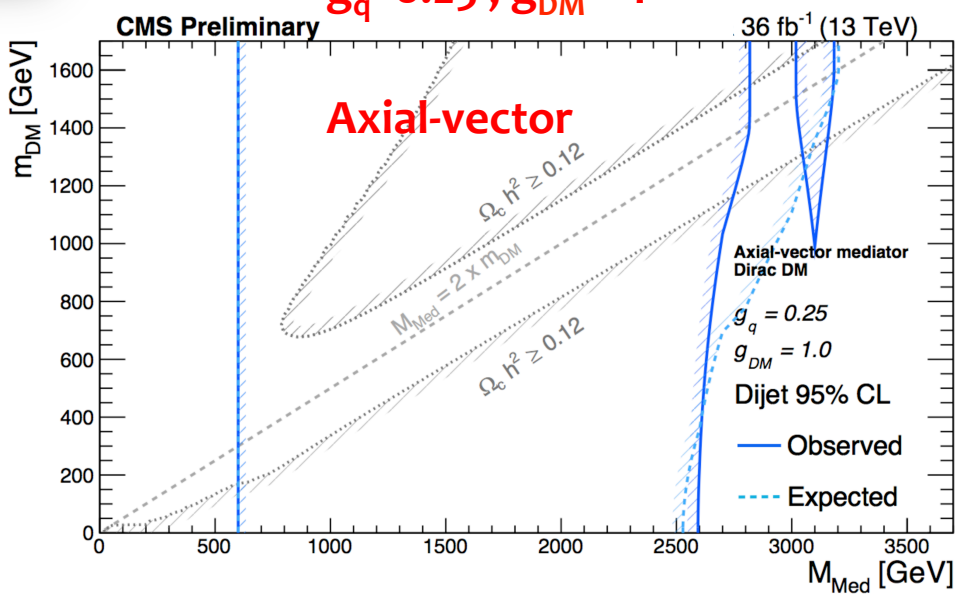






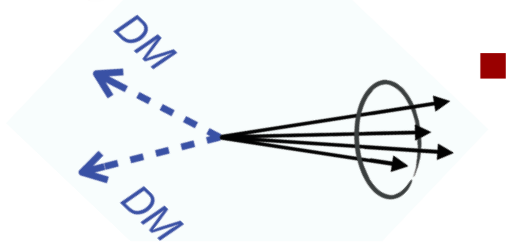



$g_q$=0.25 , $g_{DM}$ = 1

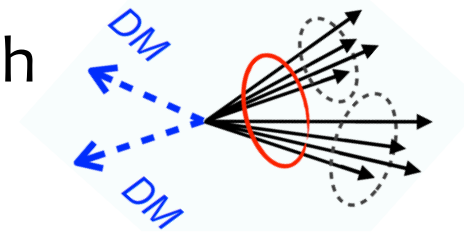


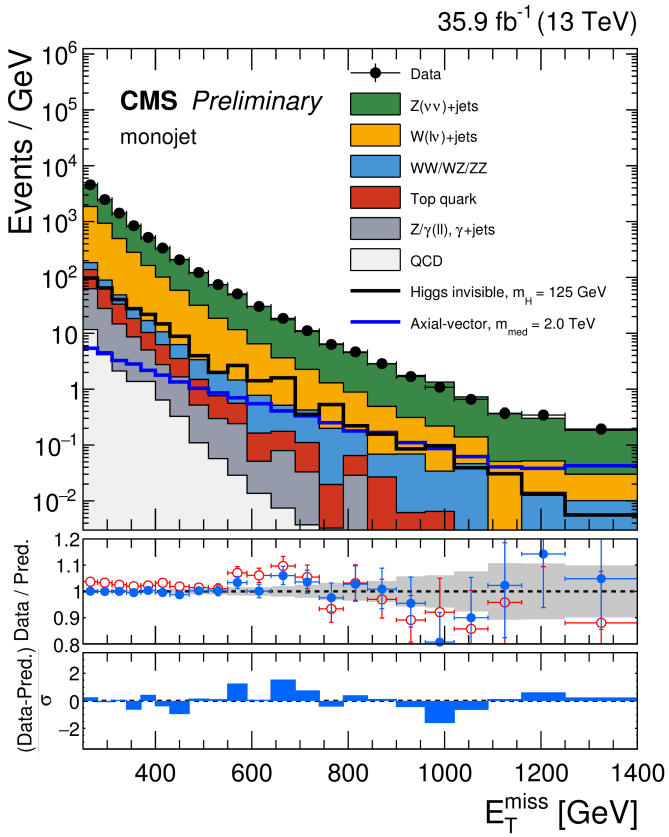
CMS-EXO-16-048

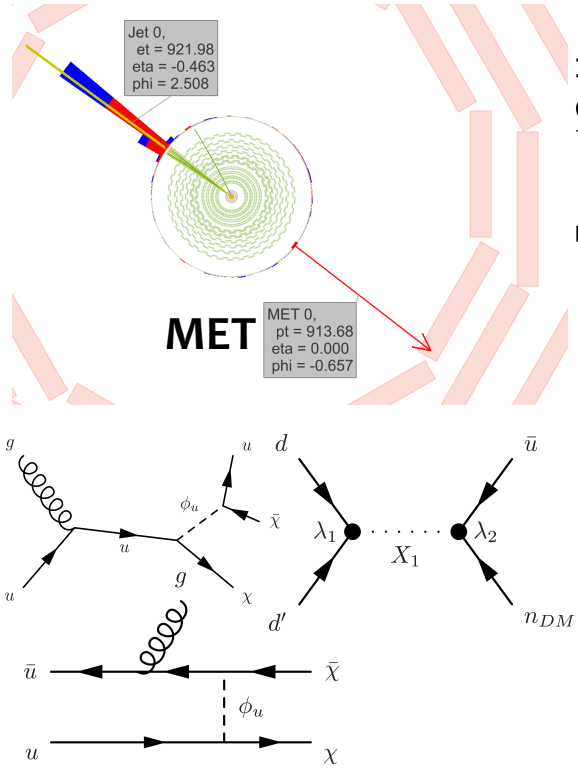
# Mono-object searches for DM

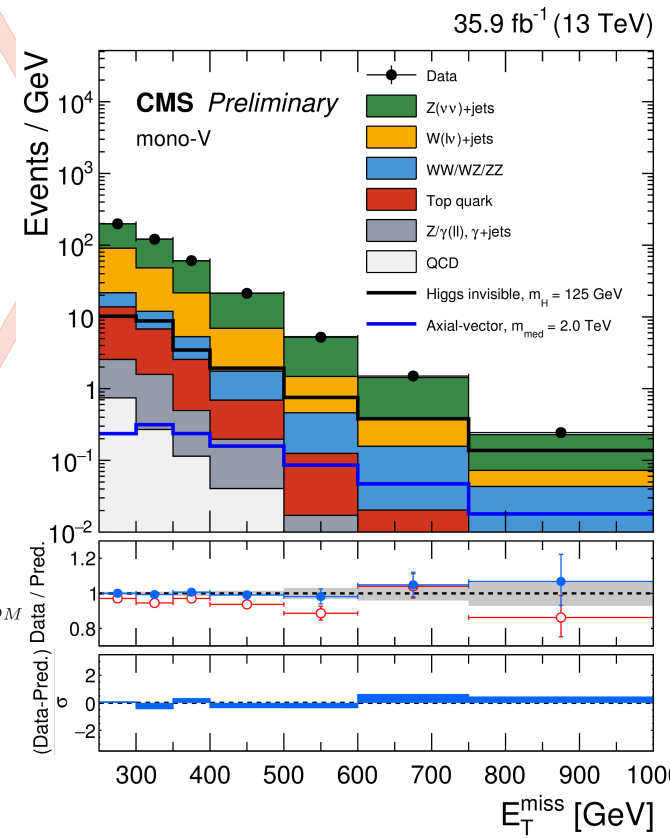



- Searching for **excess on MET** with **mono-jet** or **mono-V**



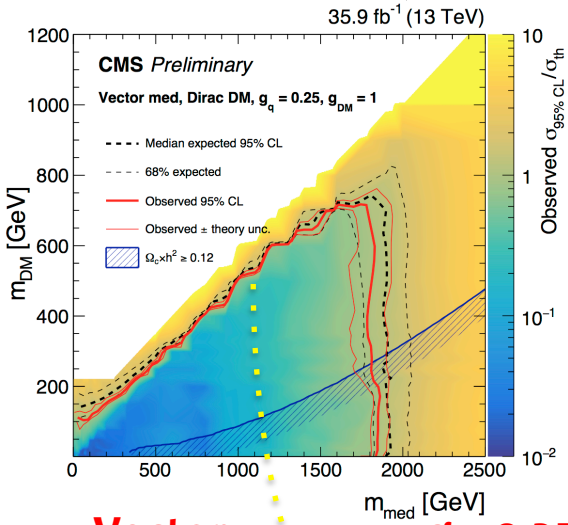



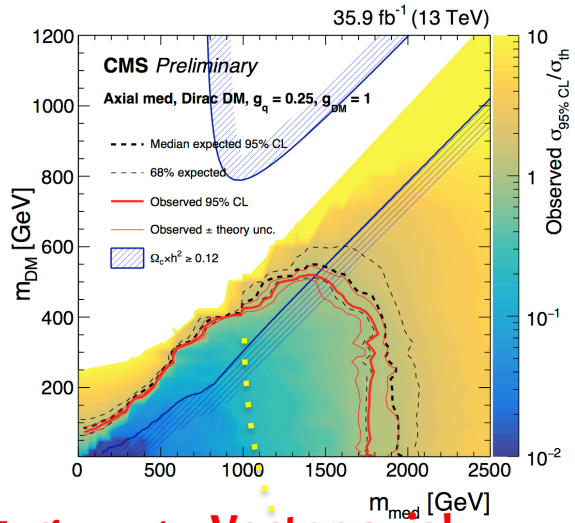

Bkg. evaluated with combined fit to the data in control samples

No significant excess of events is observed with respect to the SM backgrounds

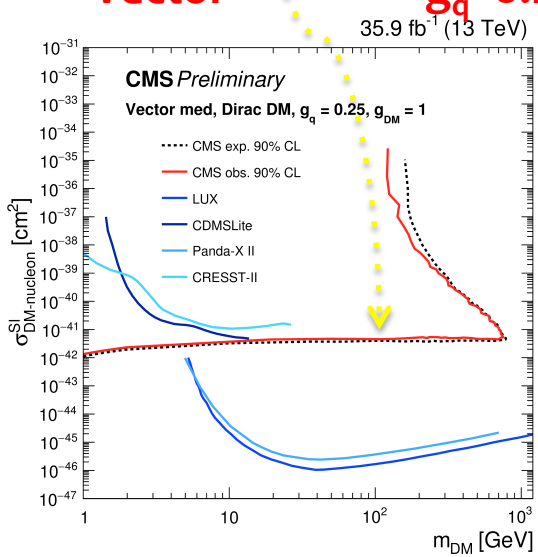
# Mono-object search results

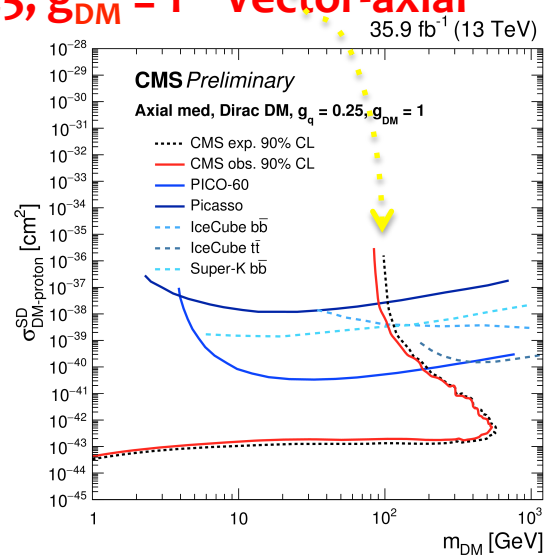
- **Limits* for simplified models** in which **DM** production is mediated by **spin-1 (vector or vec-axial)** or spin-0 (scalar, pseudo-scalar) particles




**Vector** $g_q$=0.25, $g_{DM}$ = 1 **Vector-axial**

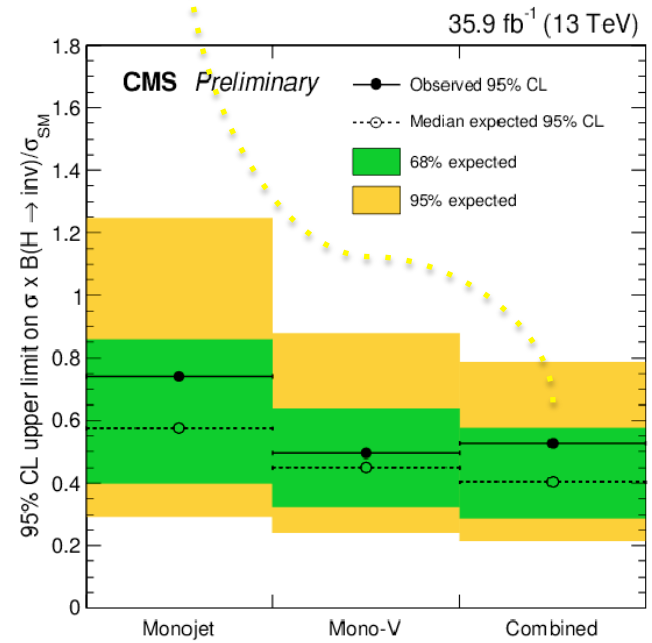



* **strongly depend on** the chosen couplings and model scenario

**Boson as a mediator**

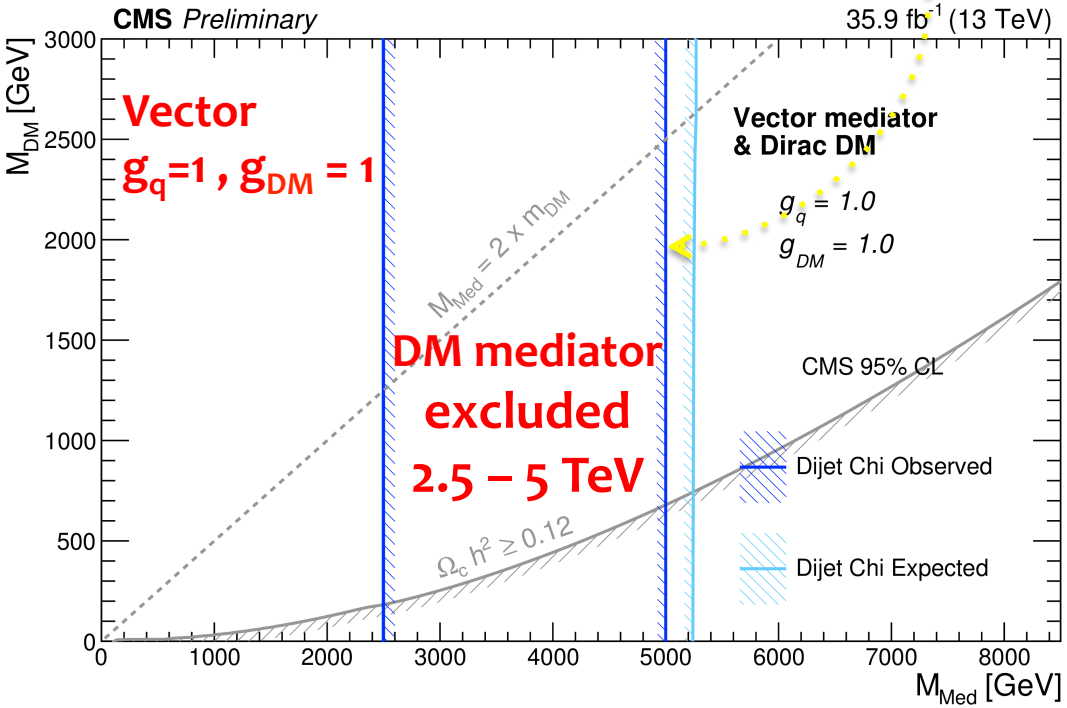
Obs. (exp.) 95% C.L. upper limit of 0.53 (0.40) on the invisible BR of **SM-like 125 GeV Higgs**

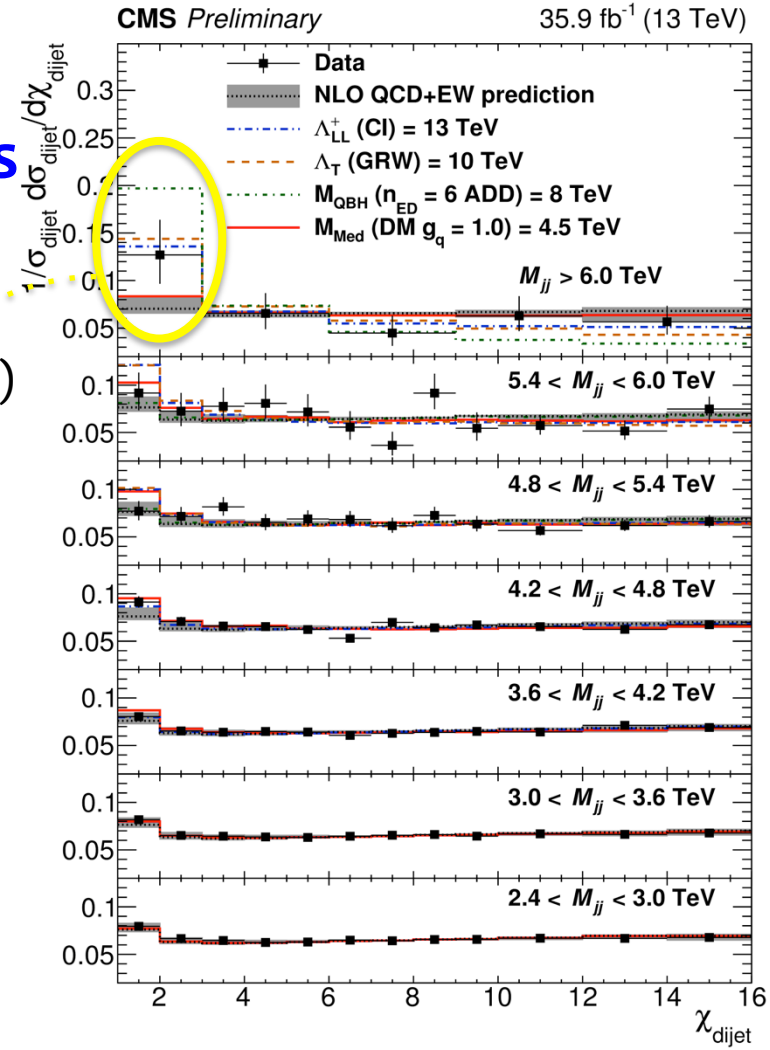


CMS-EXO-16-046

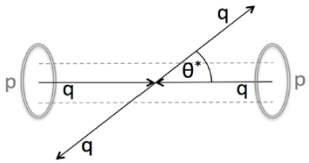
# Dark Matter searches

- **Dijet angular correlation** search probes **interactions** between **quarks** and **DM particles**
- Also constrains models of
  - quark contact inter. ($scale^{limit}_{CI}$ = 13.1 – 17.4 TeV)
  - ExDim ($mass^{limit}_{graviton}$ = 10.6 TeV)
  - quantum black holes ($mass^{limit}_{BH}$ =6.3 –8.0 TeV)




$$\chi_{dijet} = e^{|y_1 - y_2|} \sim \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$



# CMS Highlights summary

- **Excellent performance** of LHC and the CMS detector resulting in **publications with the 13 TeV data of Run 2'16**

- **Precise measurement of Higgs and Standard Model**
  starting with the increase of luminosity
  - **Higgs is very SM-like**
    **the observation of decays to taus** and **an evidence for decays to b-quarks**

- **New Physics can be discovered** if it exists at the TeV scale
  - ~3 times more data (**150/fb**) till end of 2018 than now (>**50/fb**)
  - and ~3 orders of magnitude (**3000/fb**) more for HL-LHC

*References:*

- **Next CMS presentations during the conference**
  Details and much more about the CMS physics , its performance, and the future

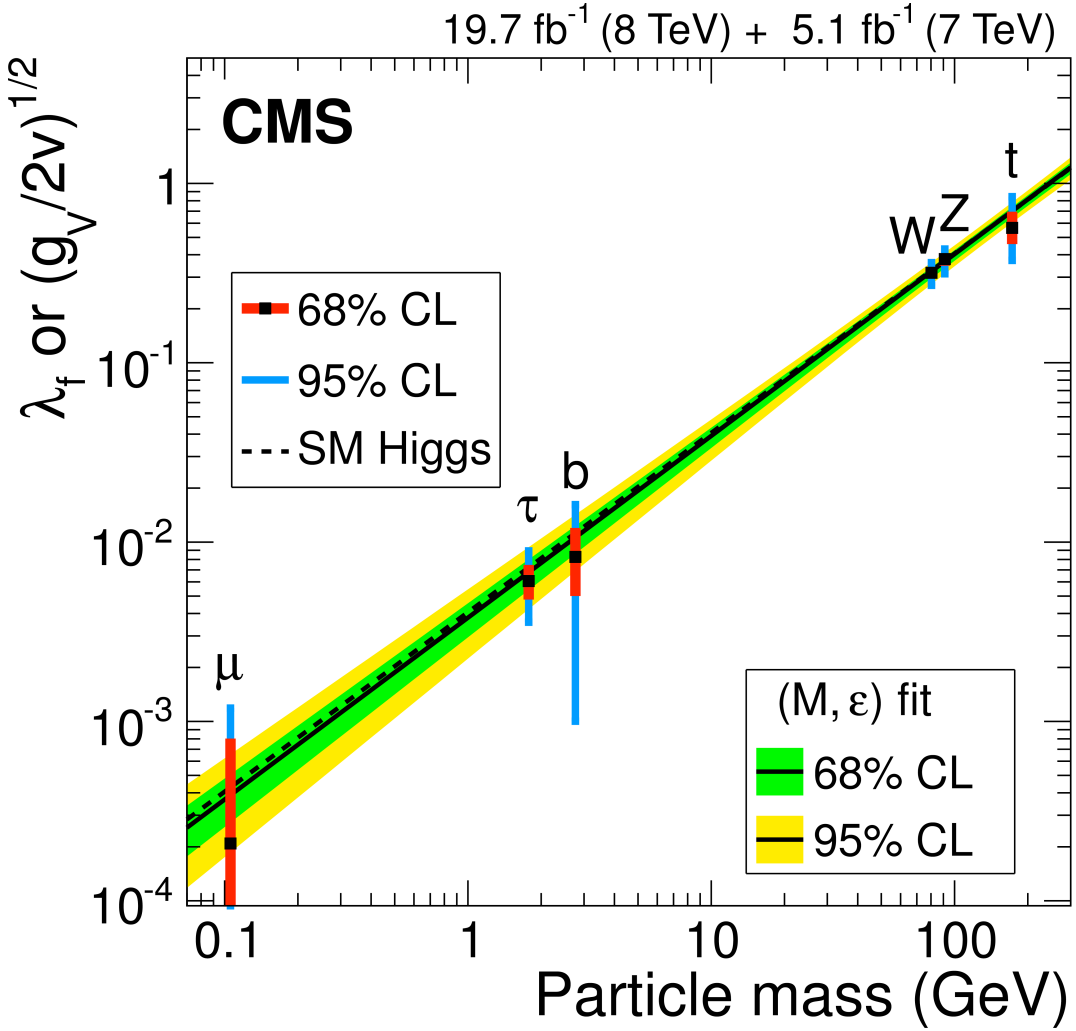
- All CMS public results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

# Thank you!

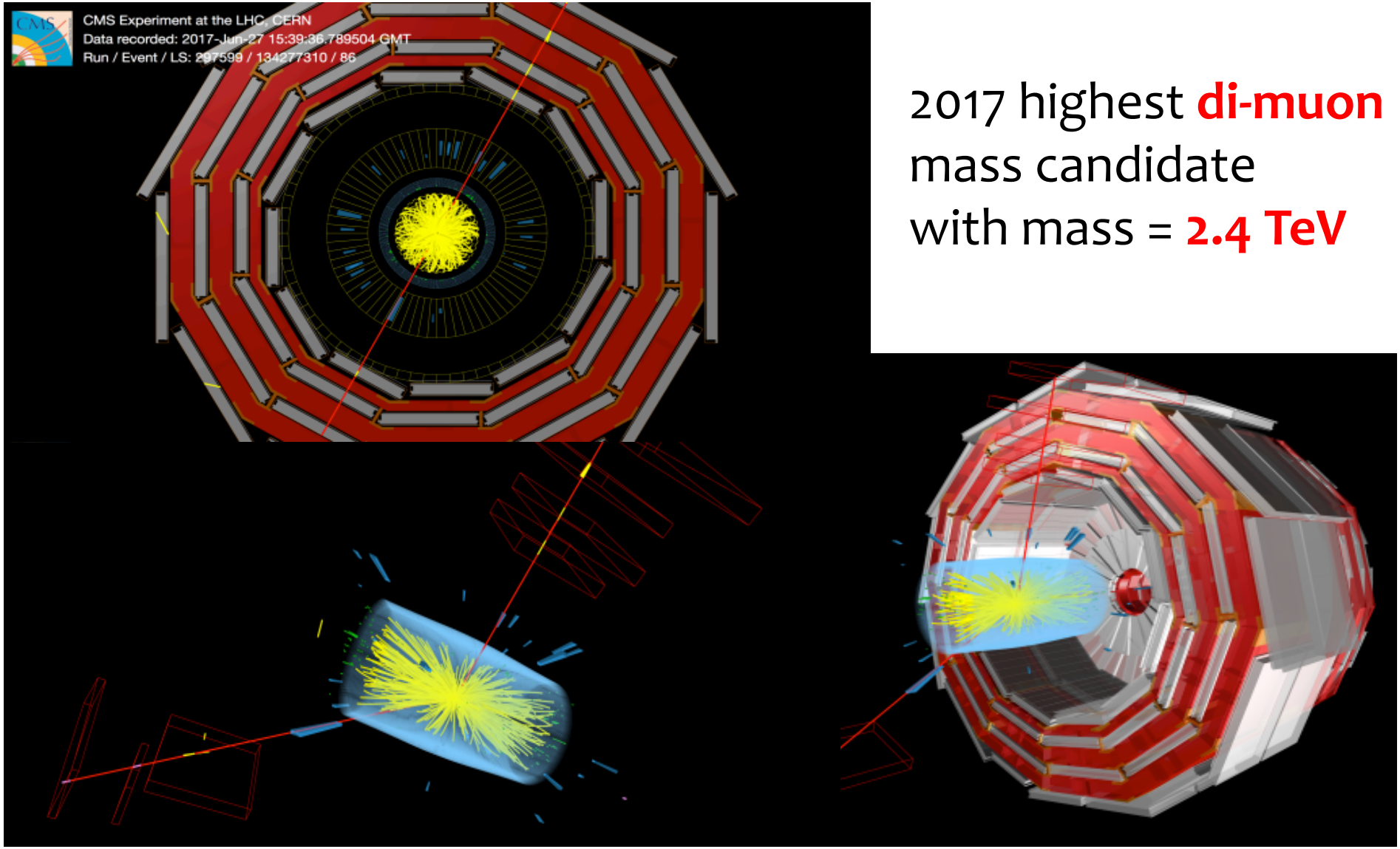
Supported in part by the NCN grant:
**2014/039982014/15/B/ST2/03998**

# BACKUP

# Higgs


19.7 fb$^{-1}$ (8 TeV) + 5.1 fb$^{-1}$ (7 TeV)
CMS
$\lambda_f$ or $(g_V/2v)^{1/2}$
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
68% CL
95% CL
SM Higgs
μ
τ
b
W
Z
t
(M, ε) fit
68% CL
95% CL
0.1
1
10
100
Particle mass (GeV)

# High Pt event in 2017




2017 highest **di-muon** mass candidate with mass = **2.4 TeV**