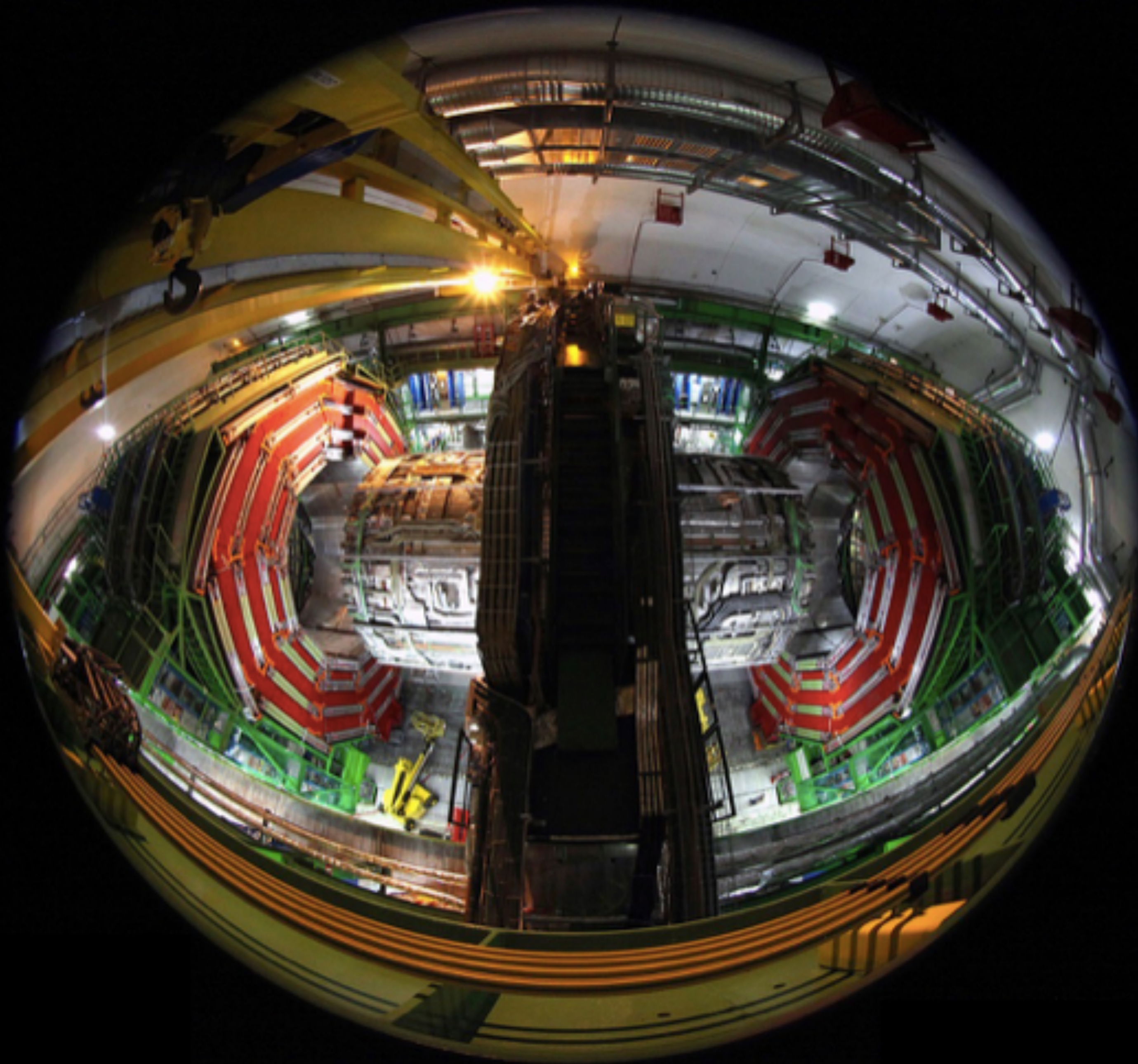


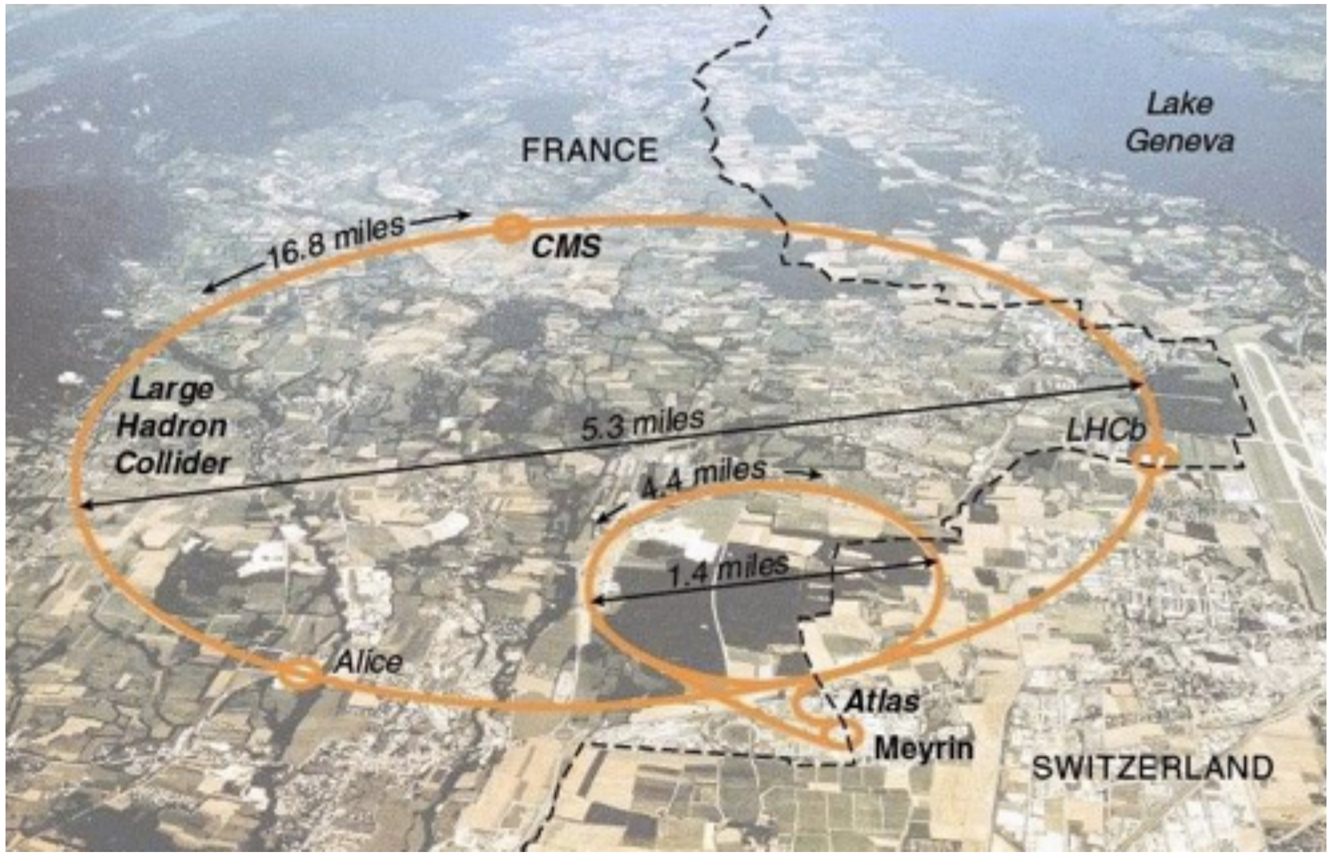
Highlights from CMS

Brookhaven Forum 2017: In Search of New Paradigms
October 11th, 2017
Markus Klute (MIT)

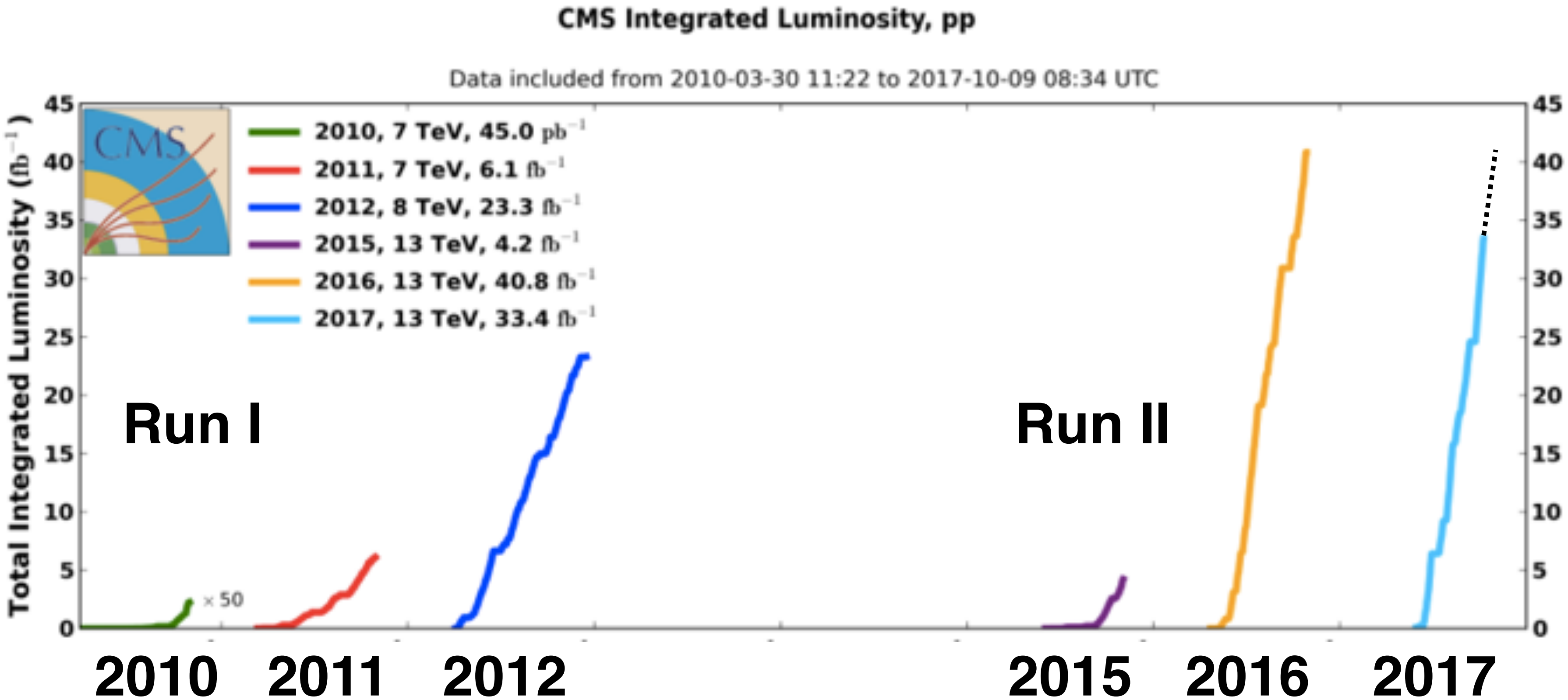
Happy 25th Birthday

➡ **Letter of intent for CMS submitted to the LHCC October 1st, 1992**

LHC Performance

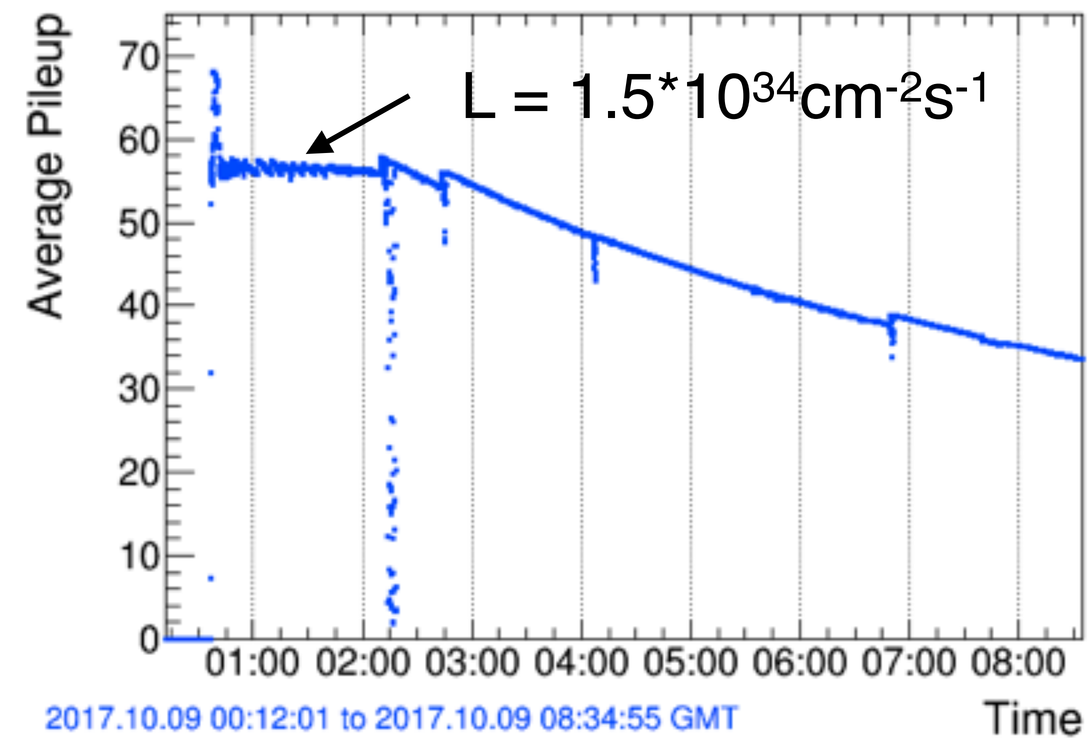


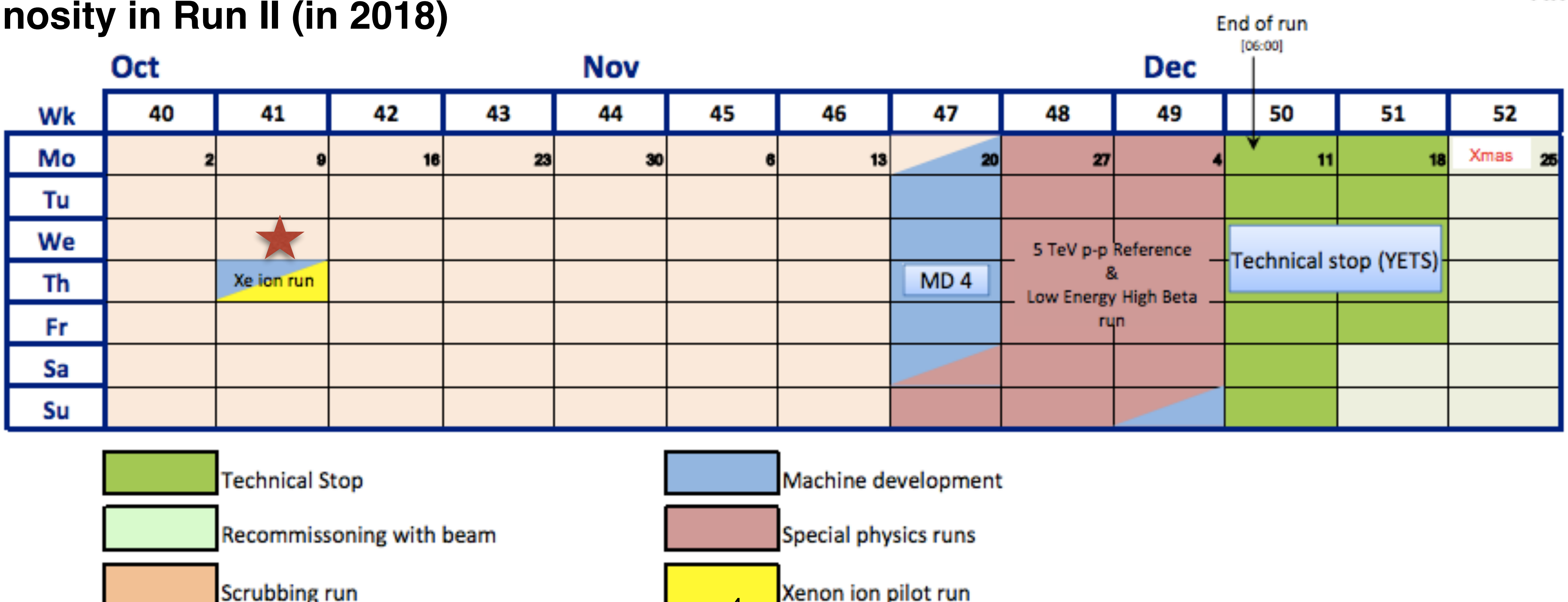
- ➡ > $100 fb^{-1}$ luminosity delivered
- ➡ Intensity $1.8*10^{34} cm^{-2} s^{-1}$ exceeds design
- ➡ Exceptional duty cycle
  - 58% in 2016
  - 10h fills with 7h turn-around
- ➡ Expecting > $40 fb^{-1}$ in 2017
- ➡ Big Thanks to the LHC team!



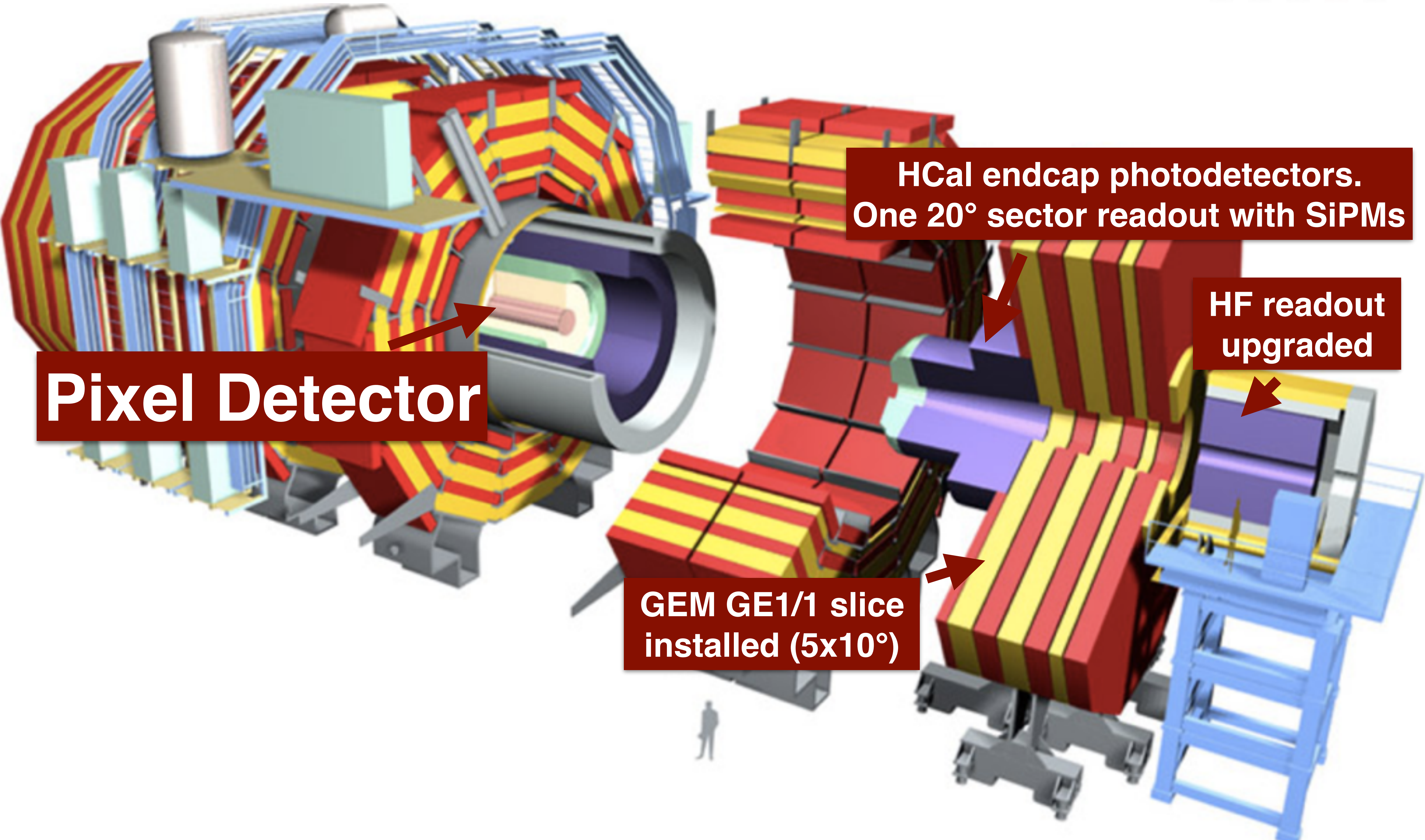
LHC Performance

- **2017 LHC operation not w/o problems**
  - significant losses at point 7 possibly due to air intake
  - resulted in high frequency of dumps during intensity ramp up
  - modified filling scheme to reduce heat load
  - limits number of bunches to 1866
- **Luminosity leveling deployed to limit pile up**
- **Modified 2017 run plan to maximize integrated luminosity in Run II (in 2018)**



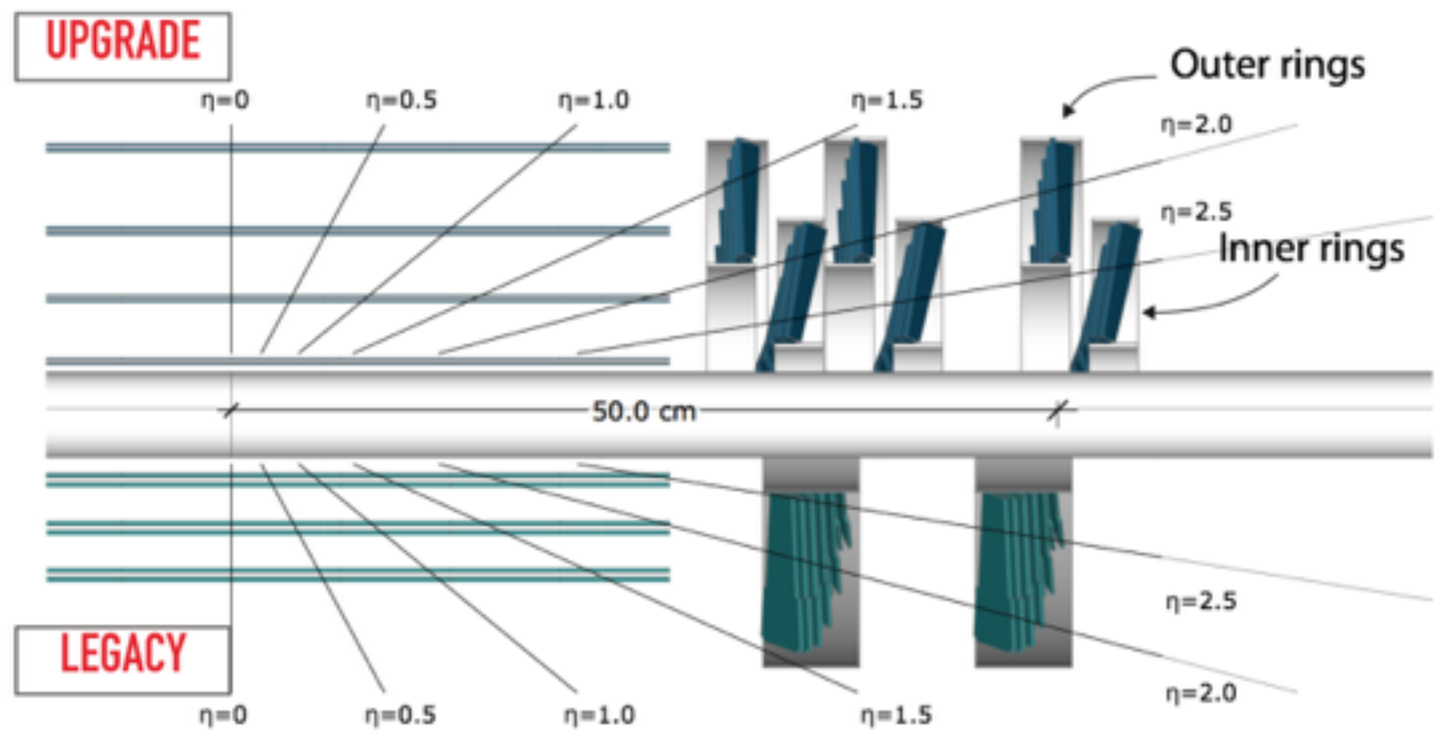


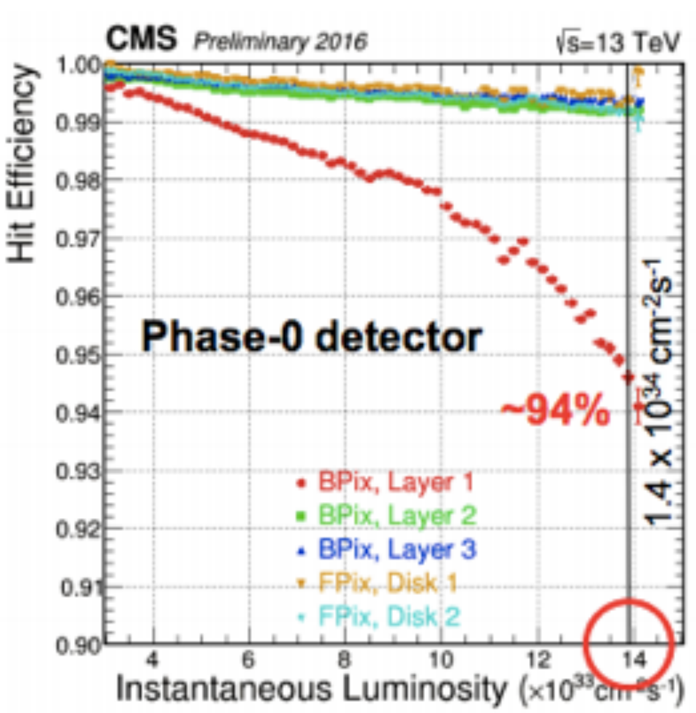
CMS Detector Update

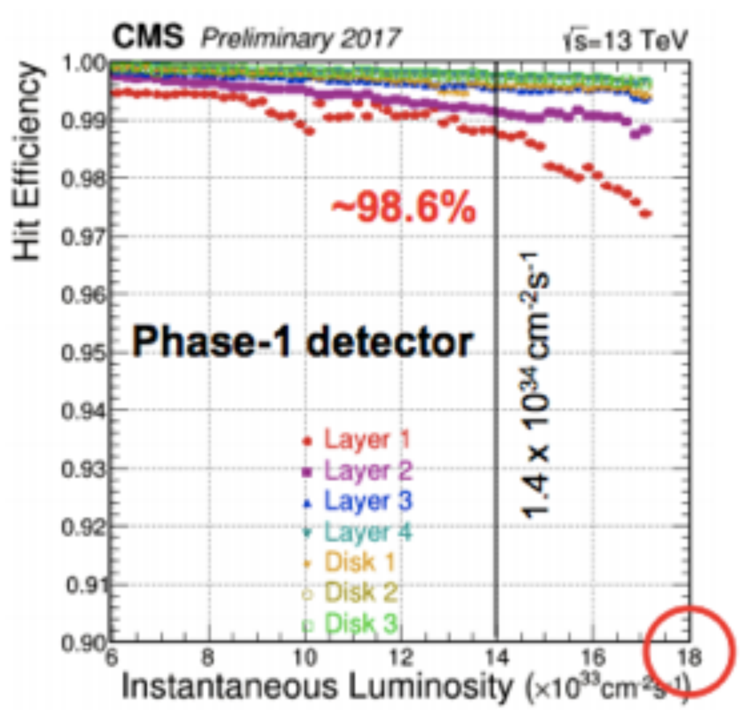


CMS Pixel Detector

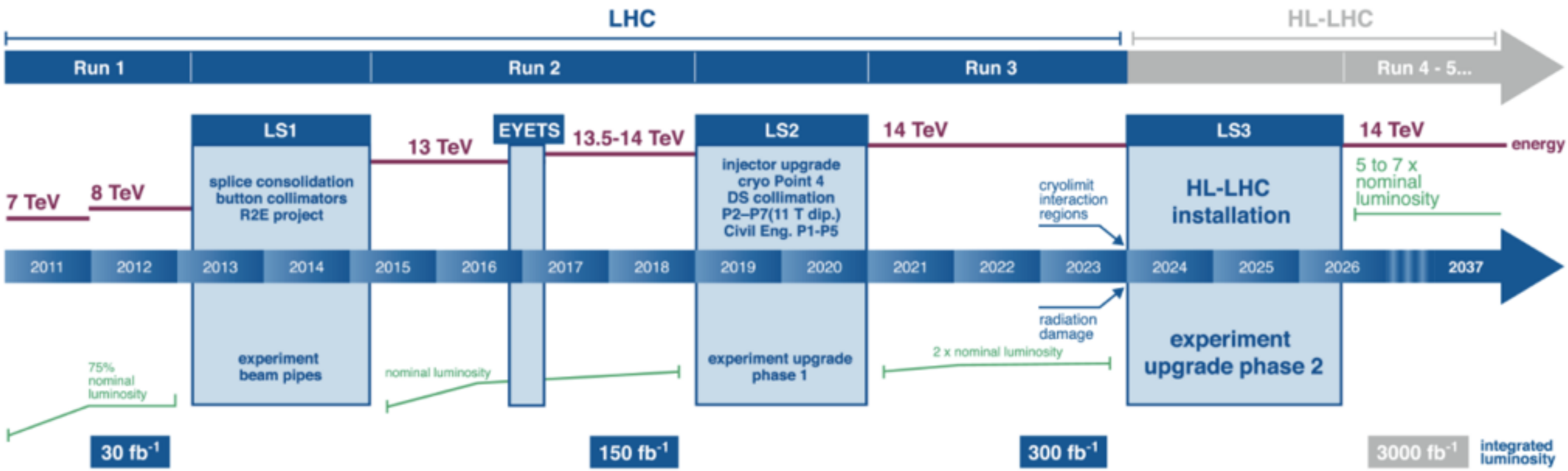
- ➡ Doubled number of channels and active area ($2m^2$)
- ➡ Number of layers increased from 3 to 4 in barrel and 2 to 3 in endcaps
- ➡ Innermost layer closer to beam pipe (4.4cm to 2.9cm)
- ➡ New readout chips allows higher rates and less dynamic inefficiency at high instantaneous luminosity
- ➡ DC-DC conversion powering system and CO^2 cooling
- ➡ Significant reduction of material
- ➡ Commissioning of the detector was challenging

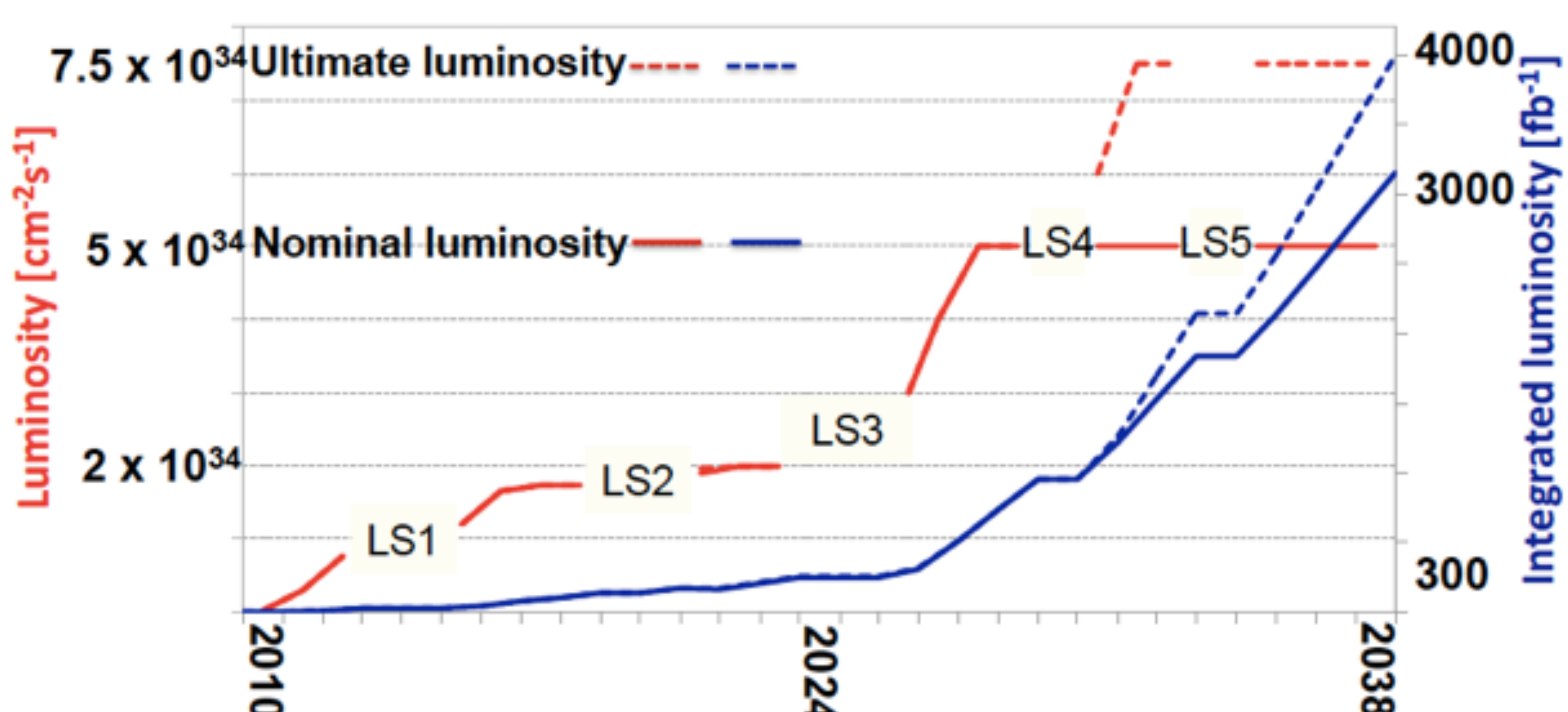






High Luminosity LHC



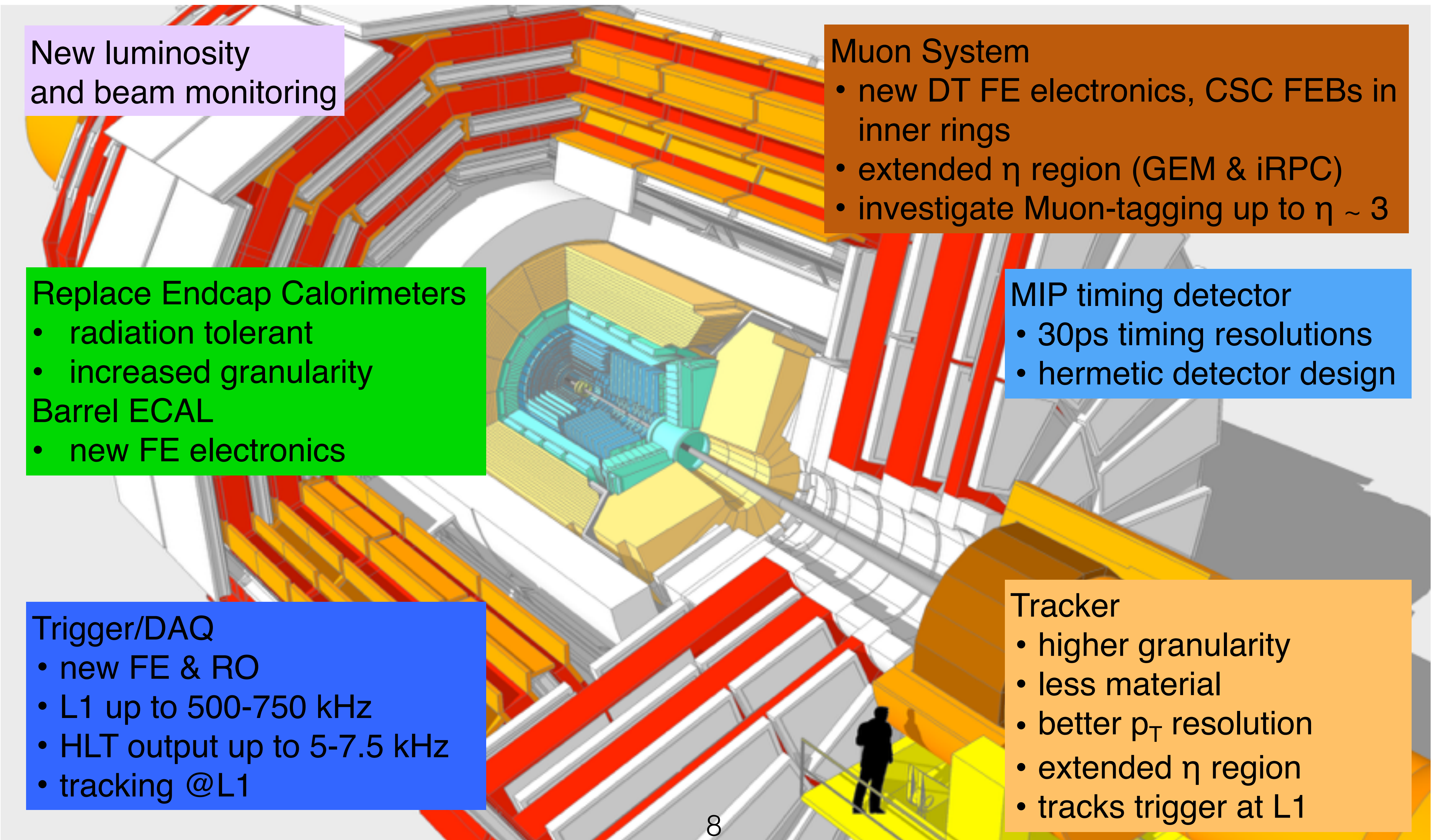


CMS Detector Upgrade

➡ **Phase-II upgrades aim to fully exploit HL-LHC program**

➡ **Exciting new detector concepts**

➡ **Documenting projects in Technical Design Reports or interim reports**

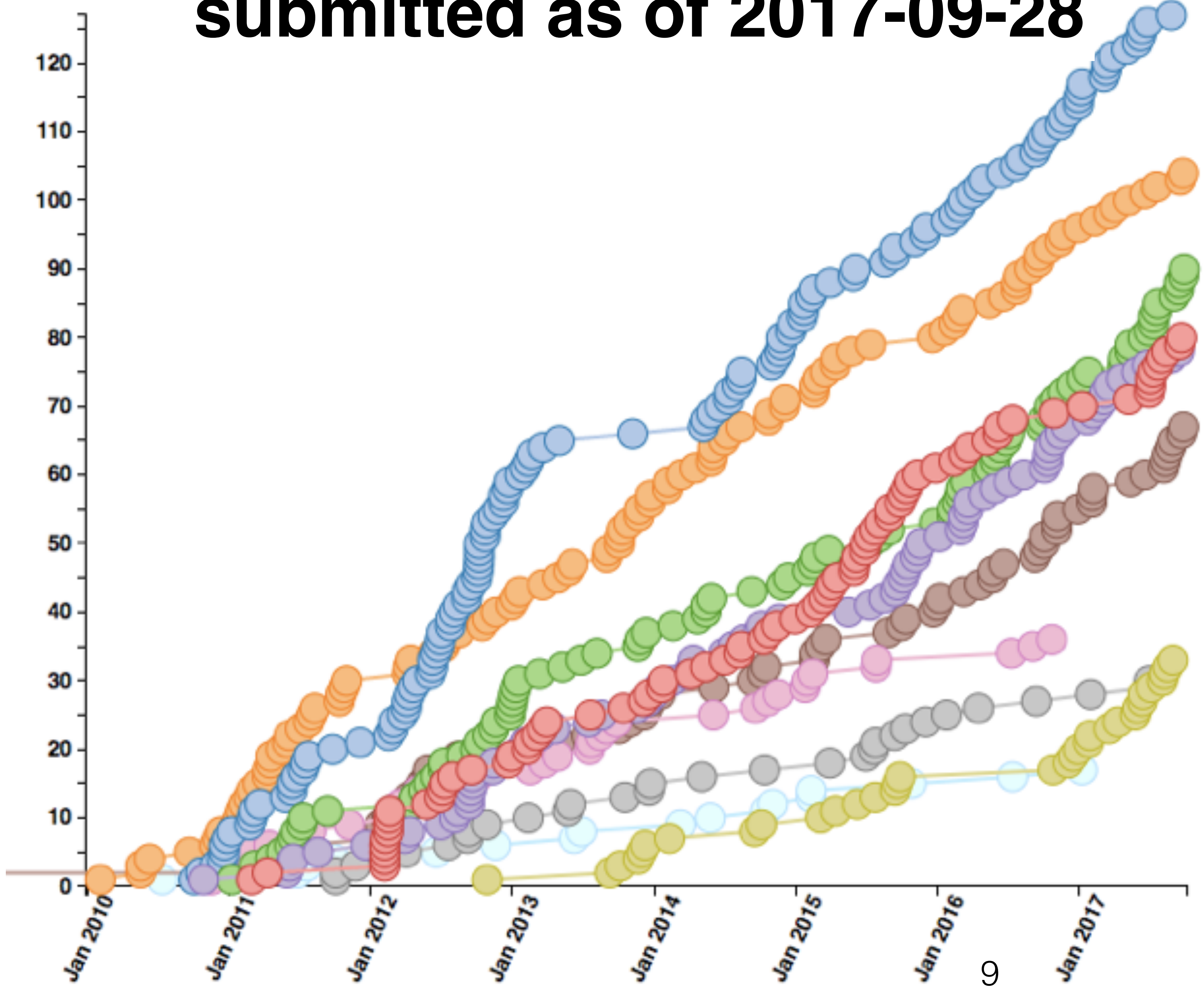


CMS Results

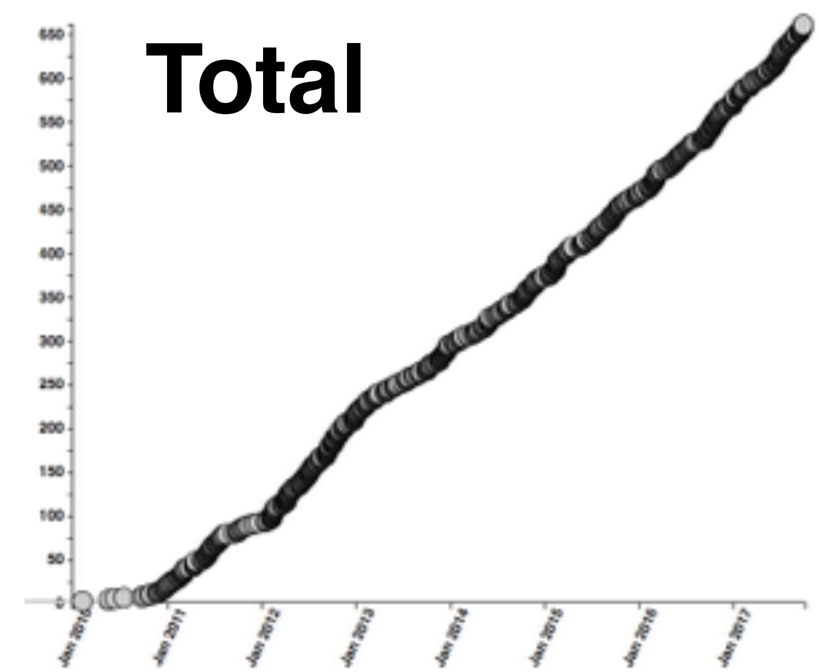
Show all | Total | Exotica | Standard Model | Supersymmetry | Higgs | Top Physics

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

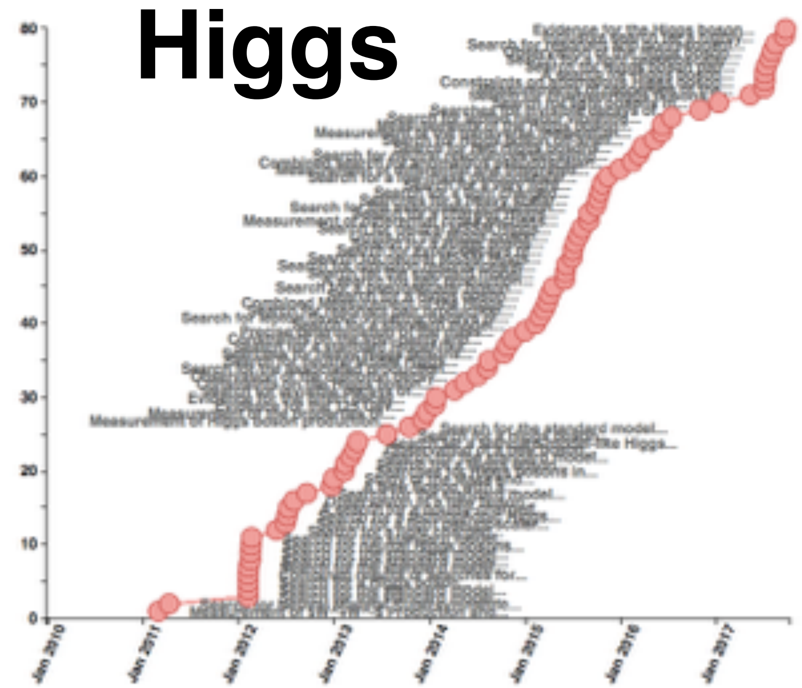
661 collider data papers submitted as of 2017-09-28



Total



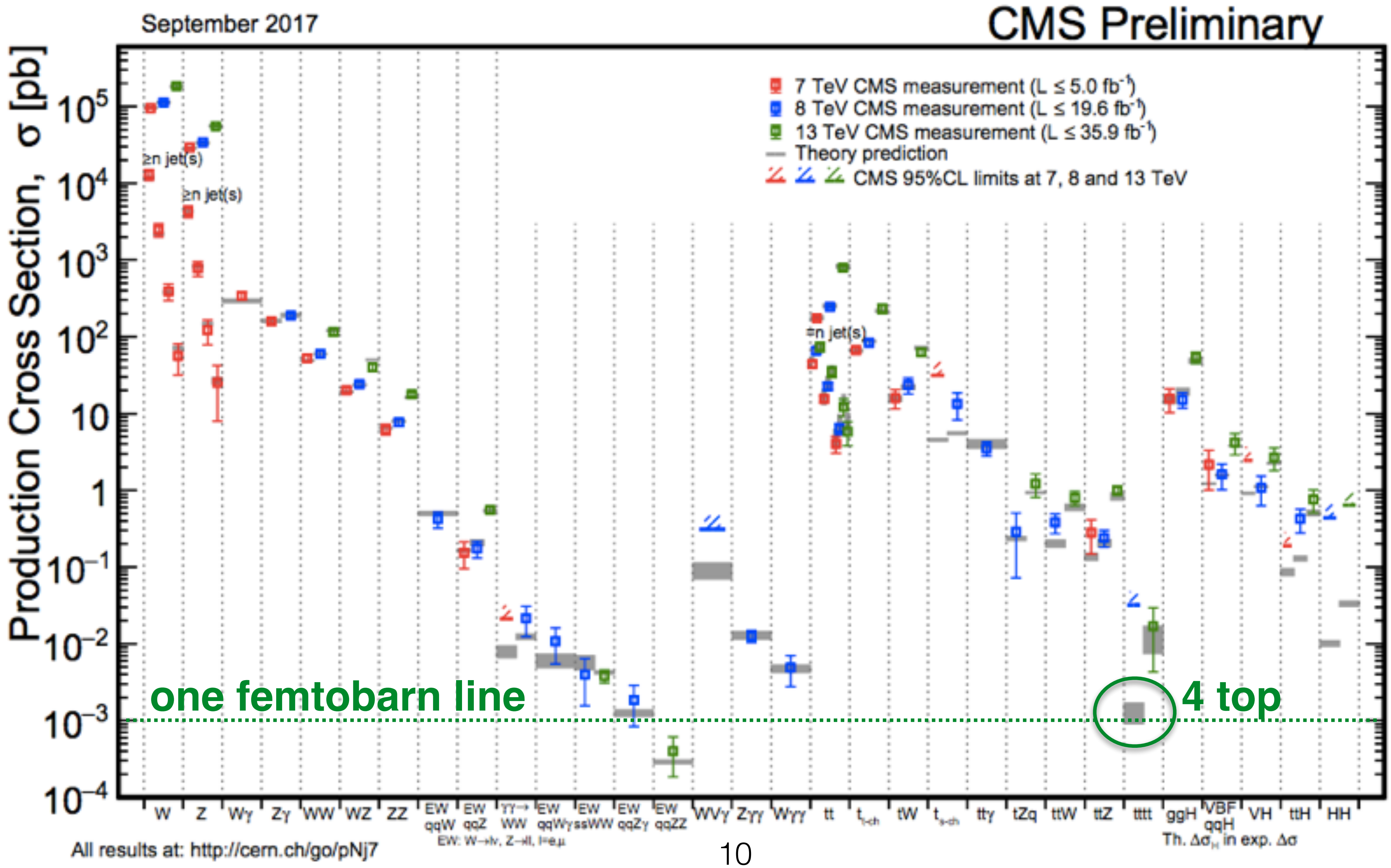
Higgs



Challenging the SM

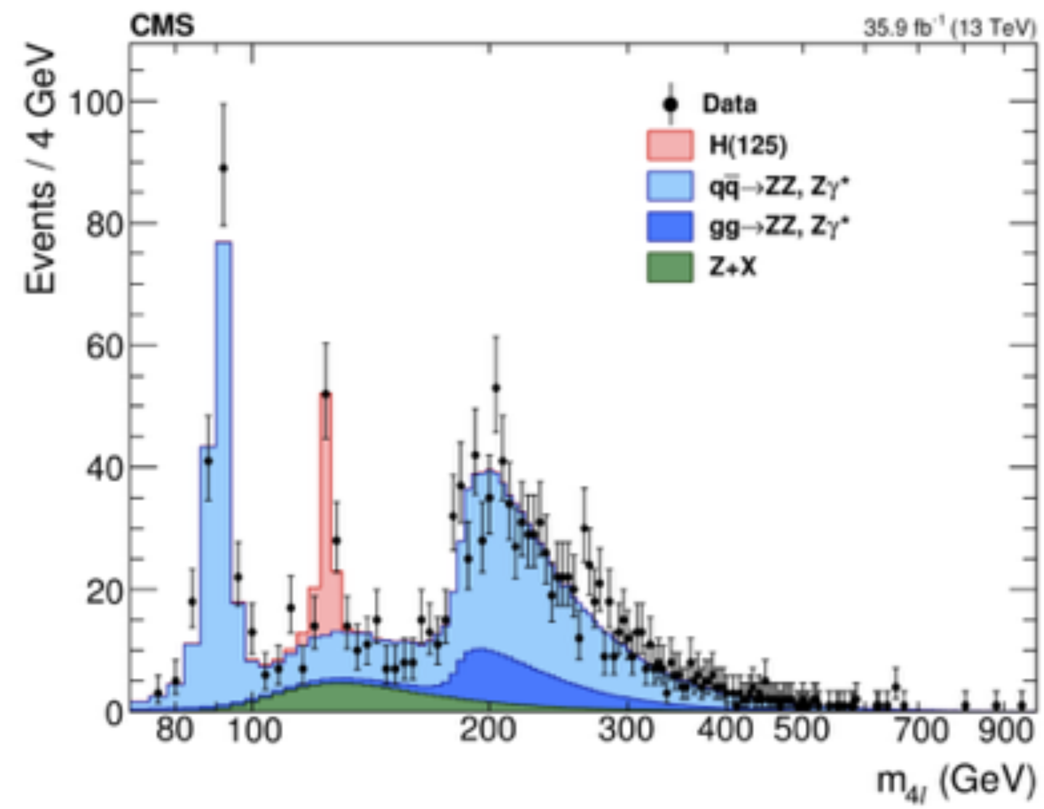
➡ **Standard Model of Particle Physics is very predictive**

- there are a finite number of free parameter
- "infinite" number of measurements are in excellent agreement

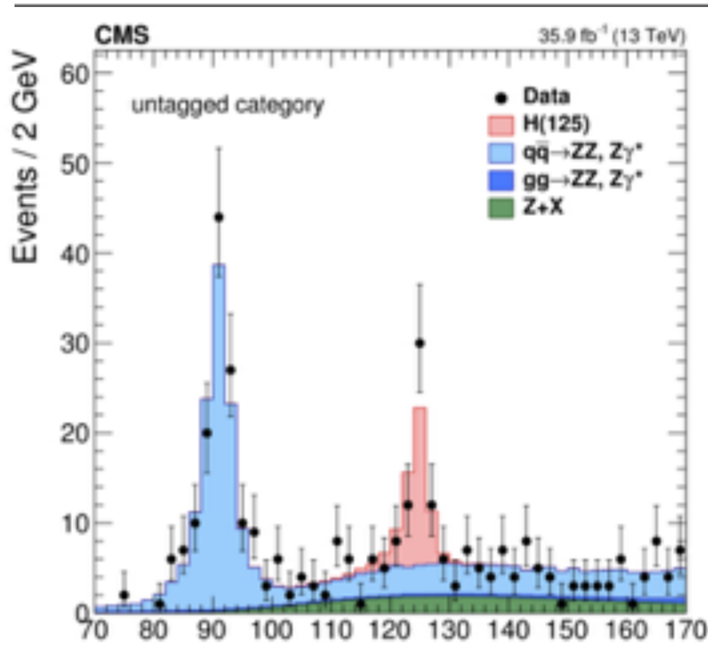


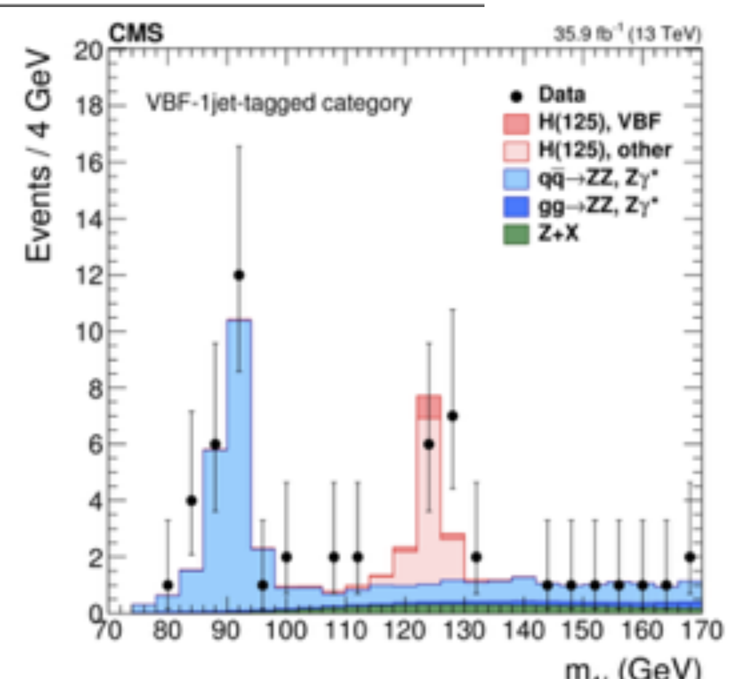
H⇒4l Mass and Properties

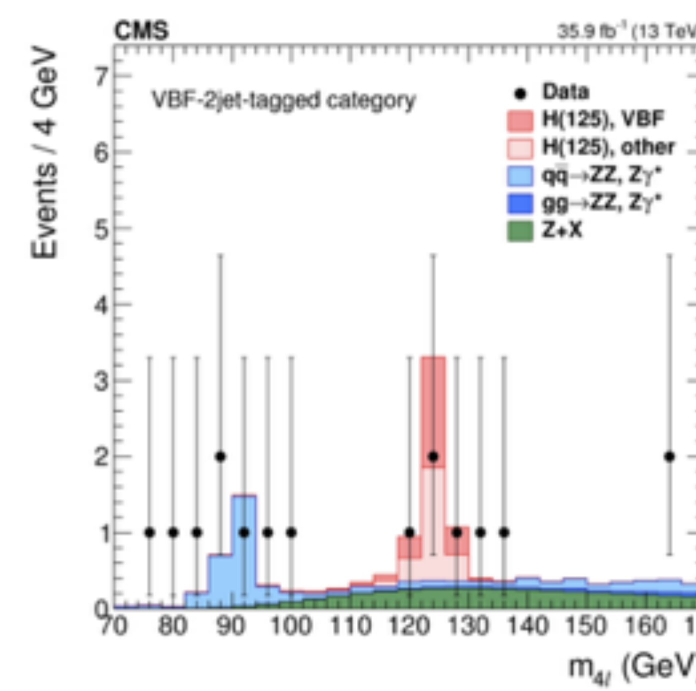
- ➡ Studies performed with gluon fusion, vector-boson fusion and Higgs-strahlung production modes
- ➡ New mass measurement in H→4l is more precise than Run I combination of ATLAS+CMS
- ➡ Signal strength μ = 1.05 ± 0.18
- ➡ Fiducial and differential cross section measurements



Channel	4e	4μ	$2e2\mu$	4ℓ
$q\bar{q} \to ZZ$	193^{+19}_{-20}	360^{+25}_{-27}	471^{+33}_{-36}	1024^{+69}_{-76}
$gg \to ZZ$	$41.2^{+6.3}_{-6.1}$	$69.0^{+9.5}_{-9.0}$	102^{+14}_{-13}	212^{+29}_{-27}
Z+X	$21.1^{+8.5}_{-10.4}$	34^{+14}_{-13}	60^{+27}_{-25}	115^{+32}_{-30}
Sum of backgrounds	255^{+24}_{-25}	463^{+32}_{-34}	633^{+44}_{-46}	1351^{+86}_{-91}
Signal	$12.0^{+1.3}_{-1.4}$	23.6 ± 2.1	30.0 ± 2.6	65.7 ± 5.6
Total expected	267^{+25}_{-26}	487^{+33}_{-35}	663^{+46}_{-47}	1417^{+89}_{-94}
Observed	293	505	681	1479

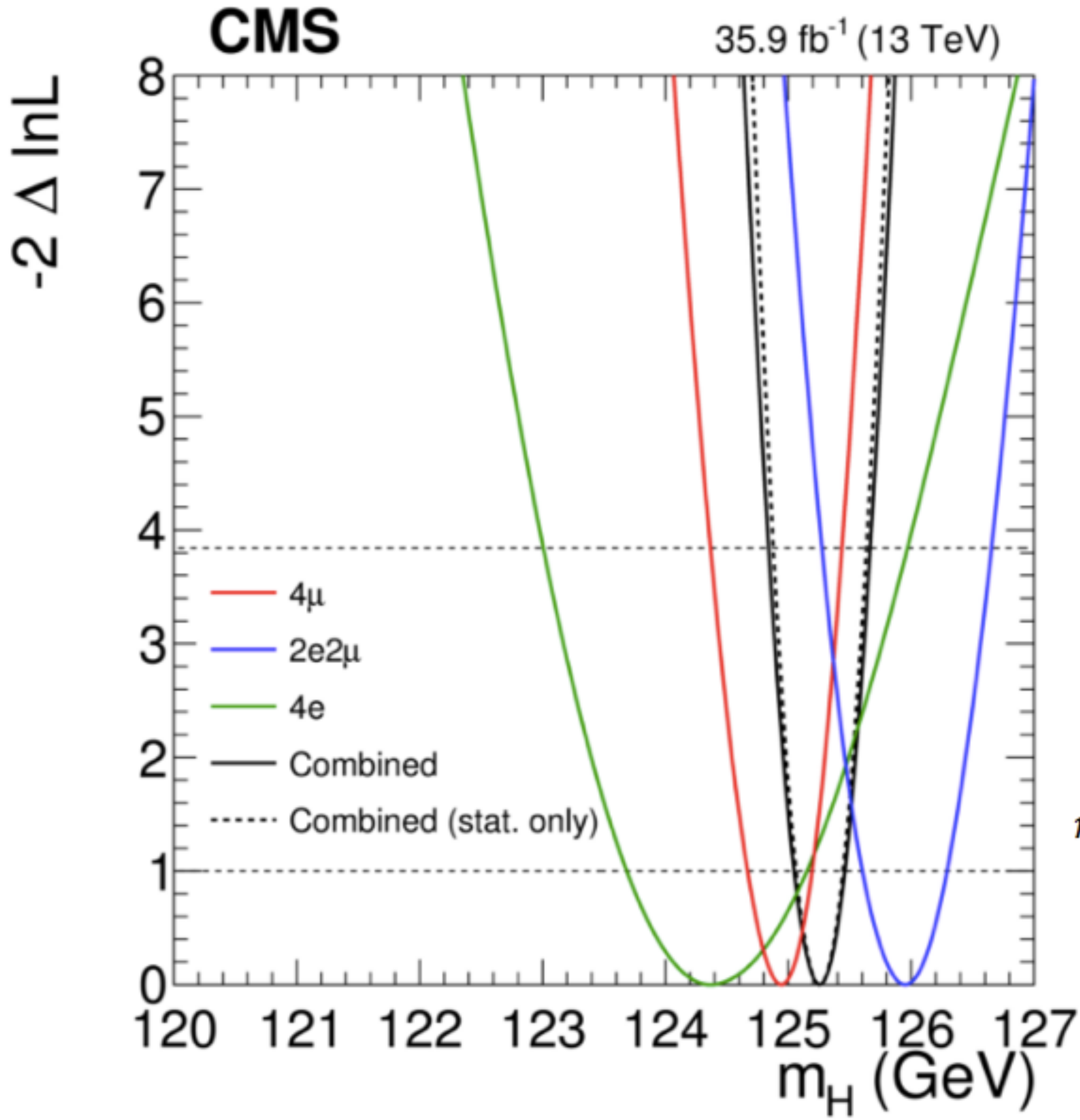


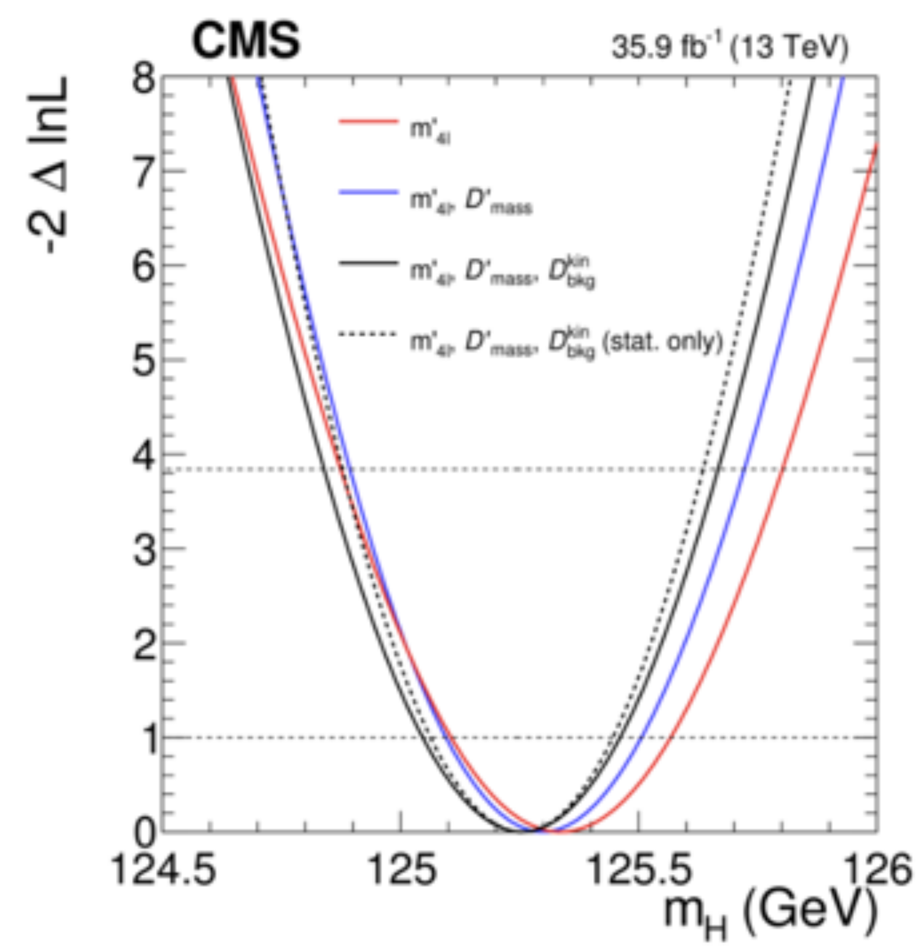




CMS-PAS-HIG-16-041 submitted to JHEP

H⇒4l Mass and Properties

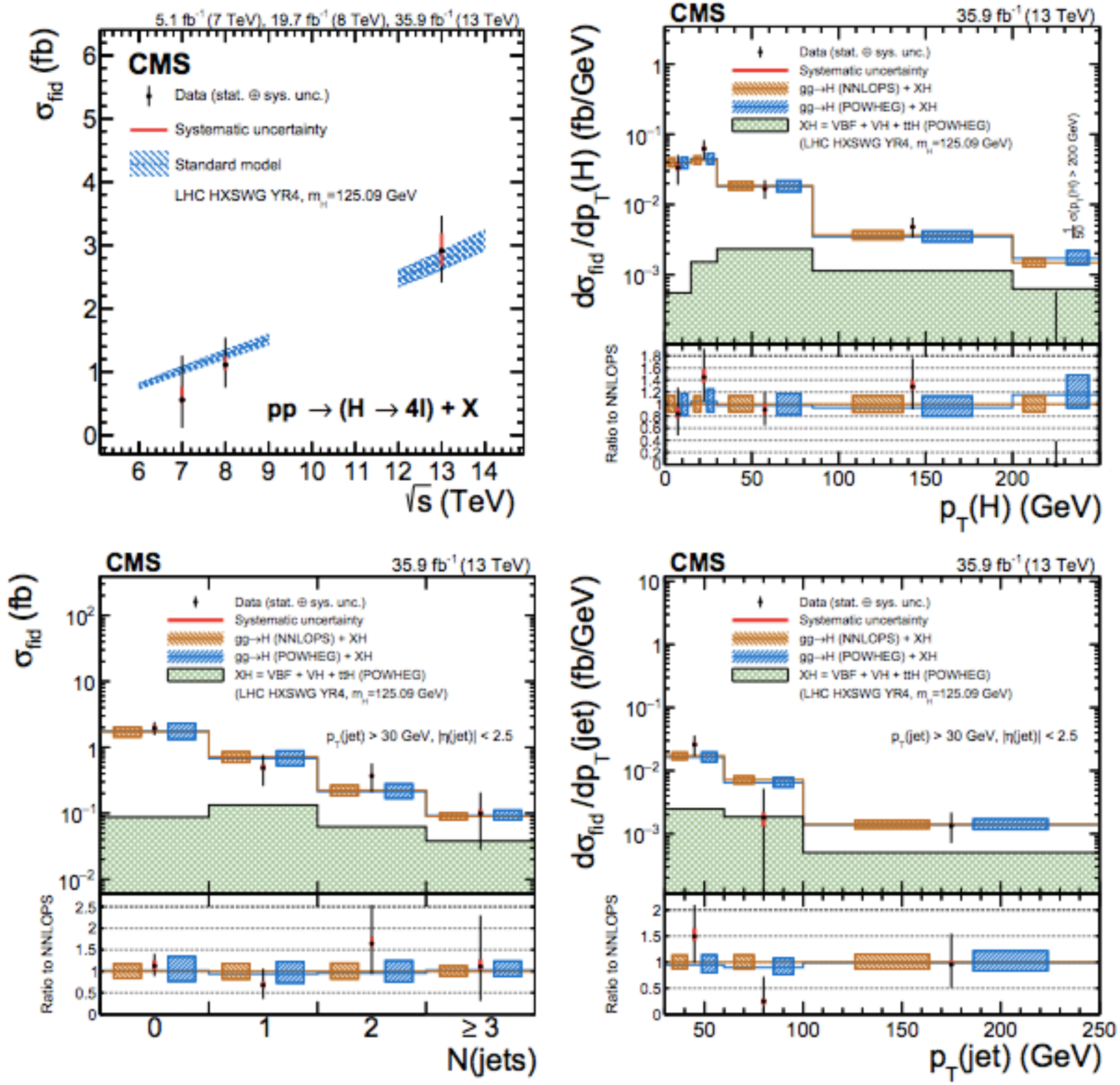




$$m_{\rm H} = 125.26 \pm 0.20\,({\rm stat}) \pm 0.08\,({\rm syst})\ {\rm GeV}$$

CMS-PAS-HIG-16-041 submitted to JHEP

H⇒4l Mass and Properties

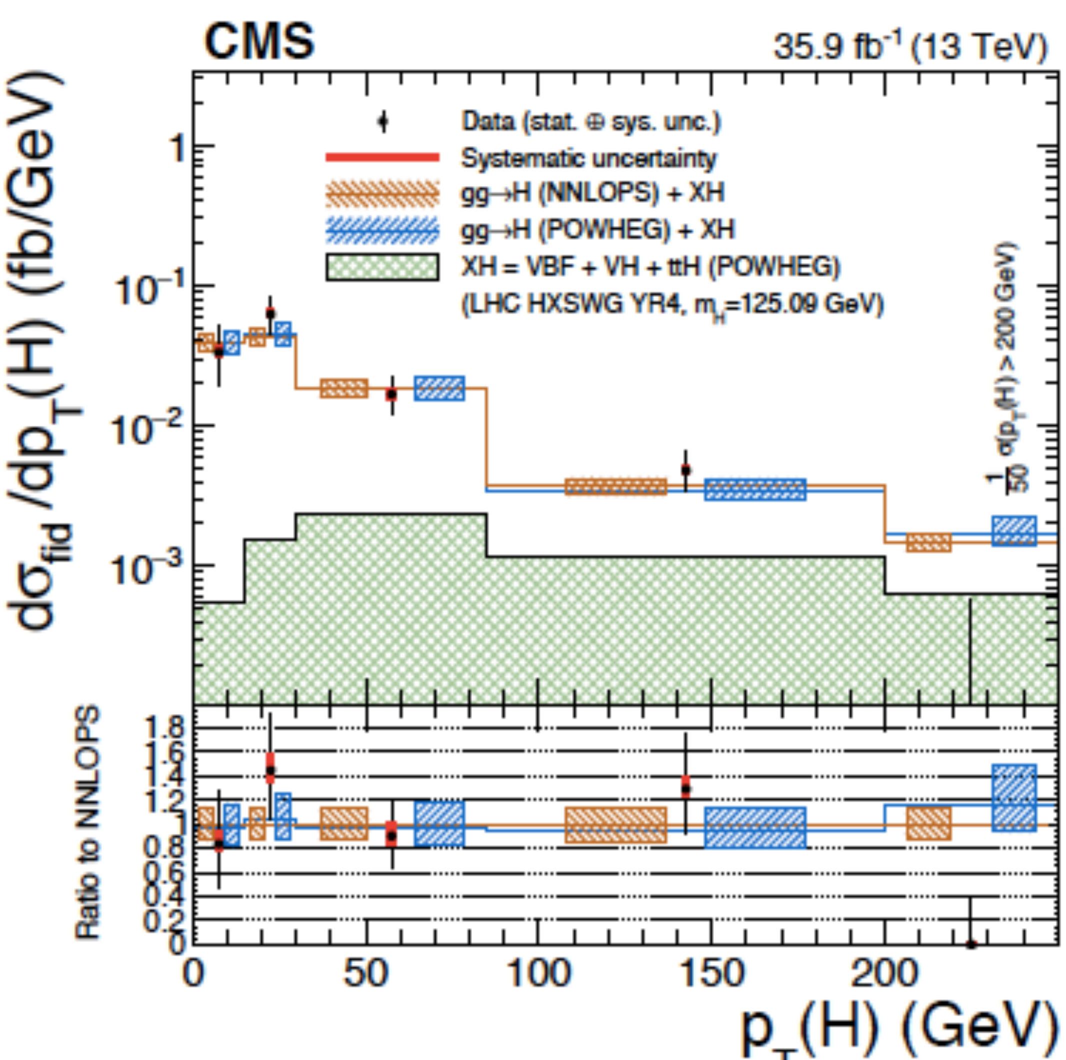


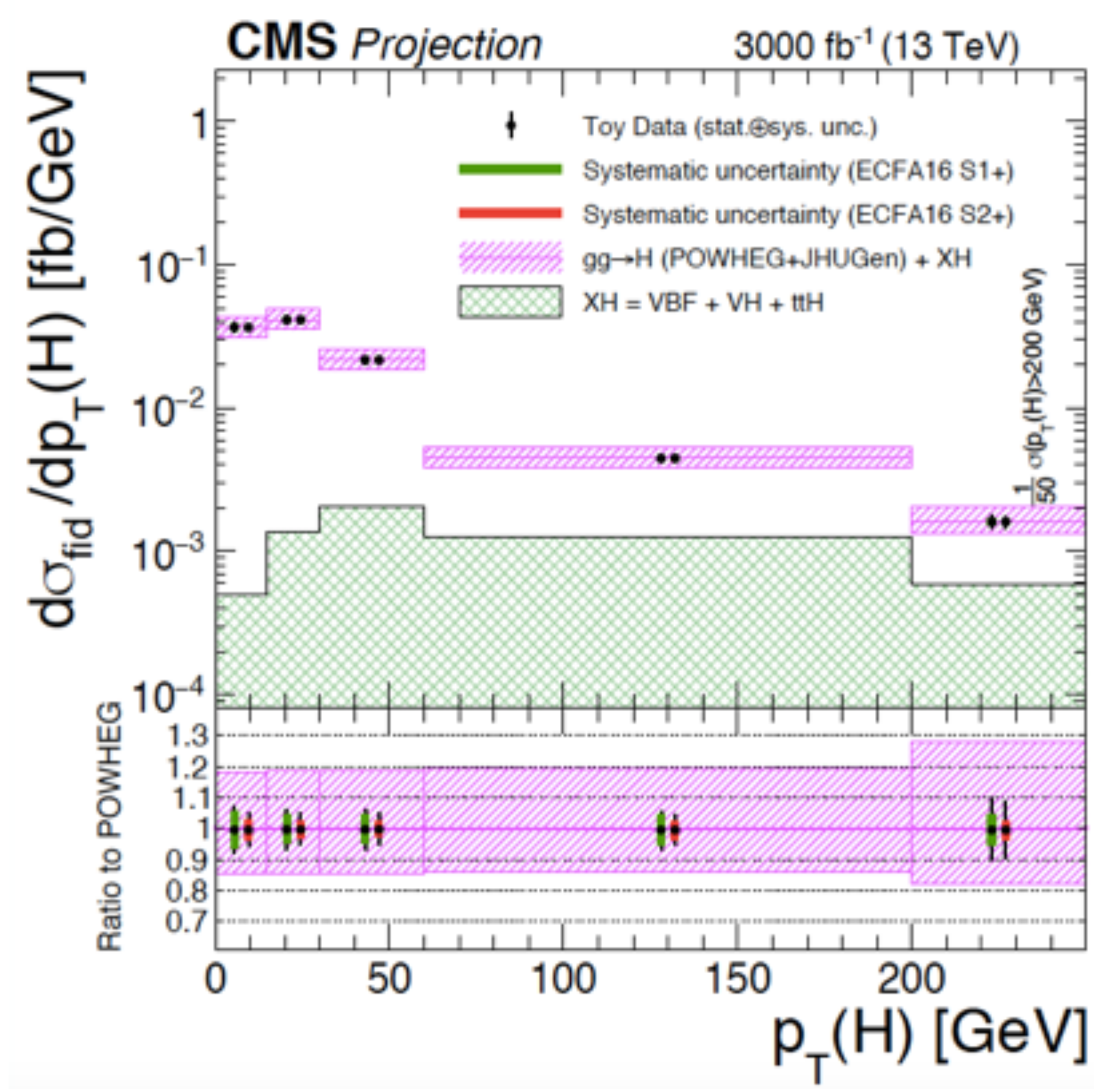
CMS-PAS-HIG-16-041 submitted to JHEP

H⇒4l Mass and Properties

➡ **Prospects for differential measurements (impact of 100 times larger dataset)**

- Showing this only to give you a flavor
- H→ZZ channel shows 4-10% uncertainty
- Experimental results will challenge theoretical precision
- Other channels will be exploited
- Sensitivity to NP

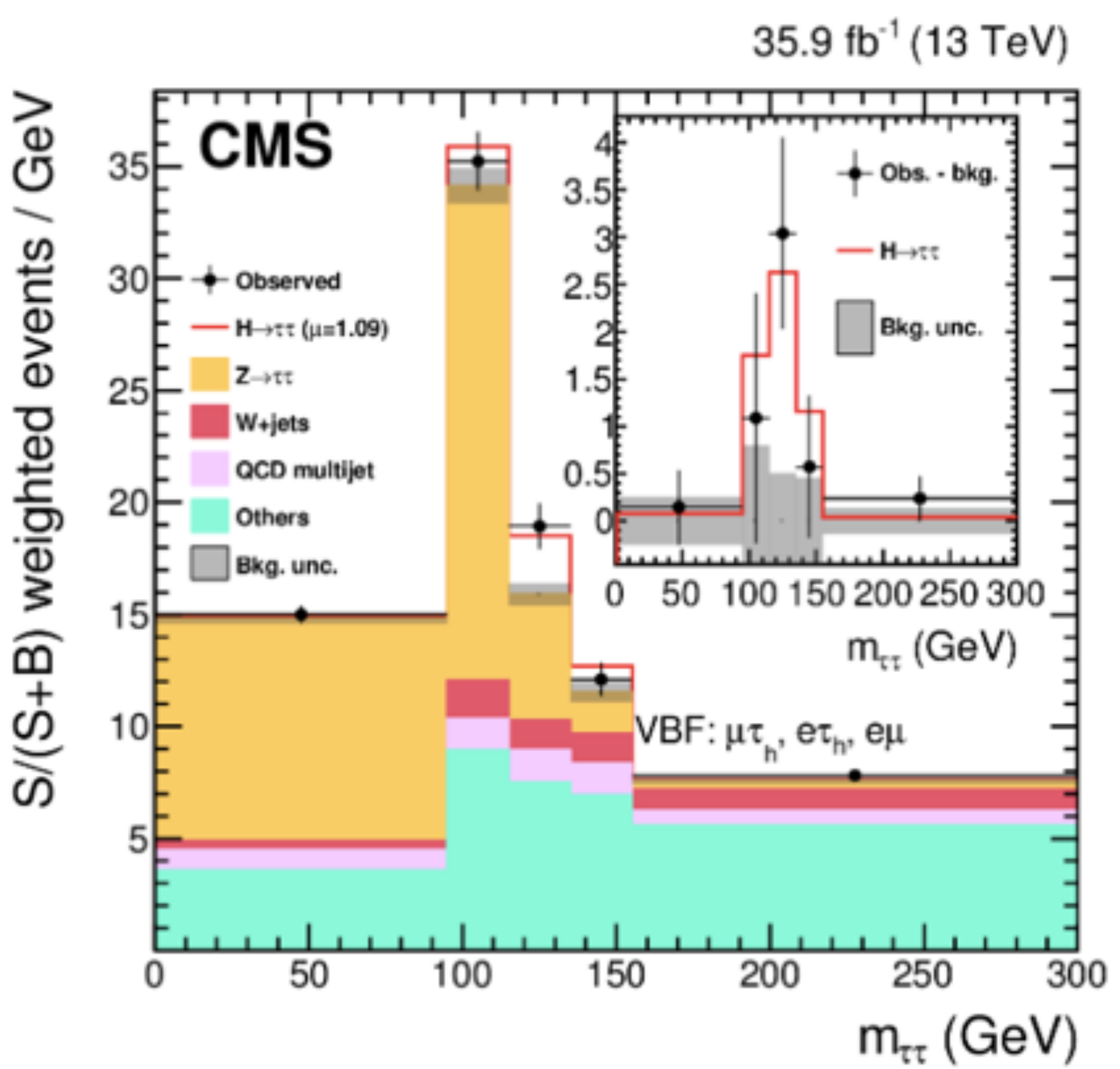


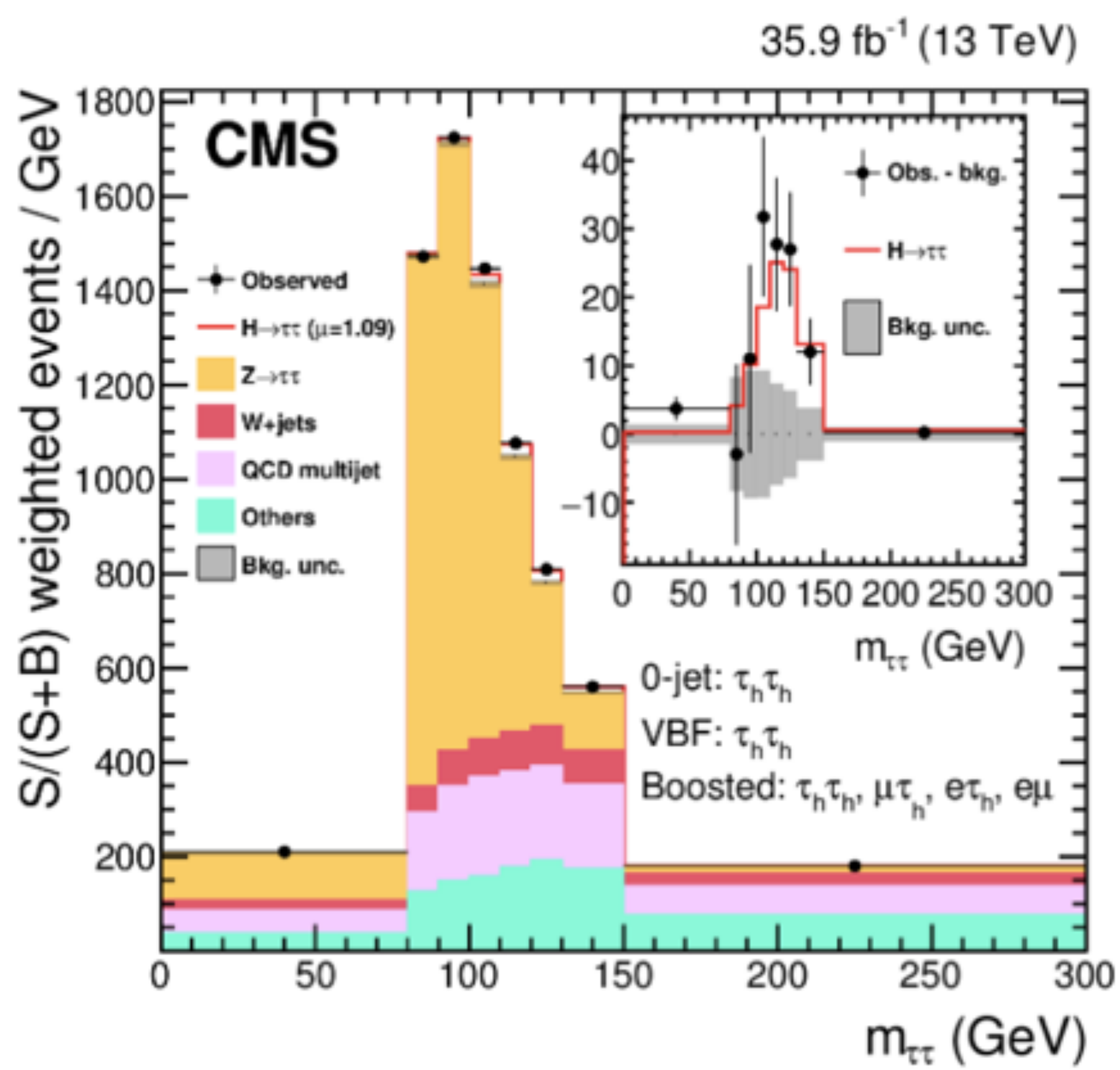


CMS-PAS-HIG-16-041 submitted to JHEP

Observation of H⇒ττ

- Single experiment evidence for Higgs to tau decays in Run I. Observation in combination with ATLAS
- First single experiment observation of Higgs couplings to taus
  - 5.9σ in combination of 7,8 and 13 TeV results
- Exploring di-tau mass distribution in 12 categories: VBF, 0-jet, and boosted for combination of hadronic and leptonic tau decays

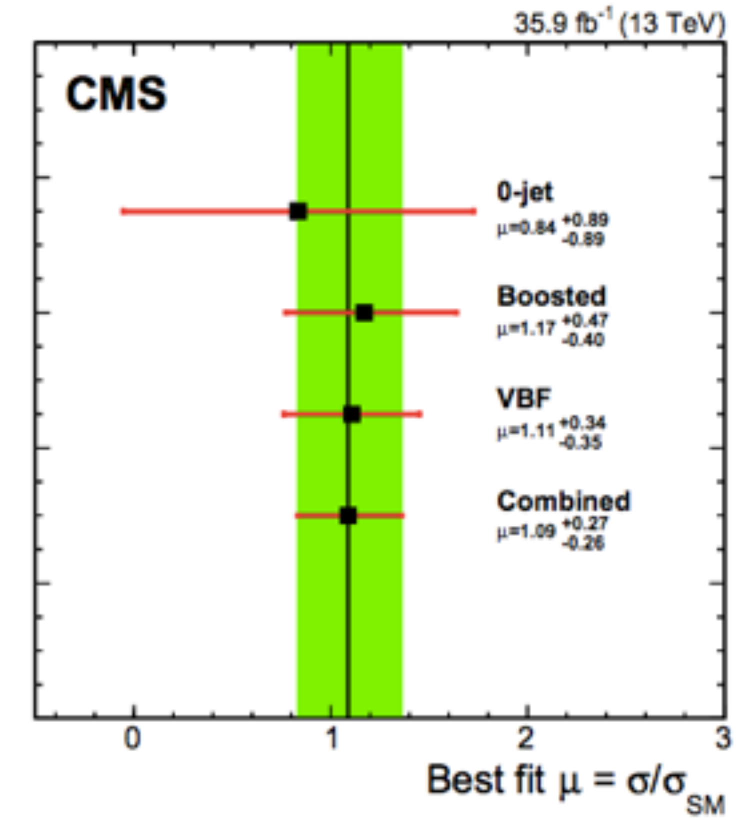


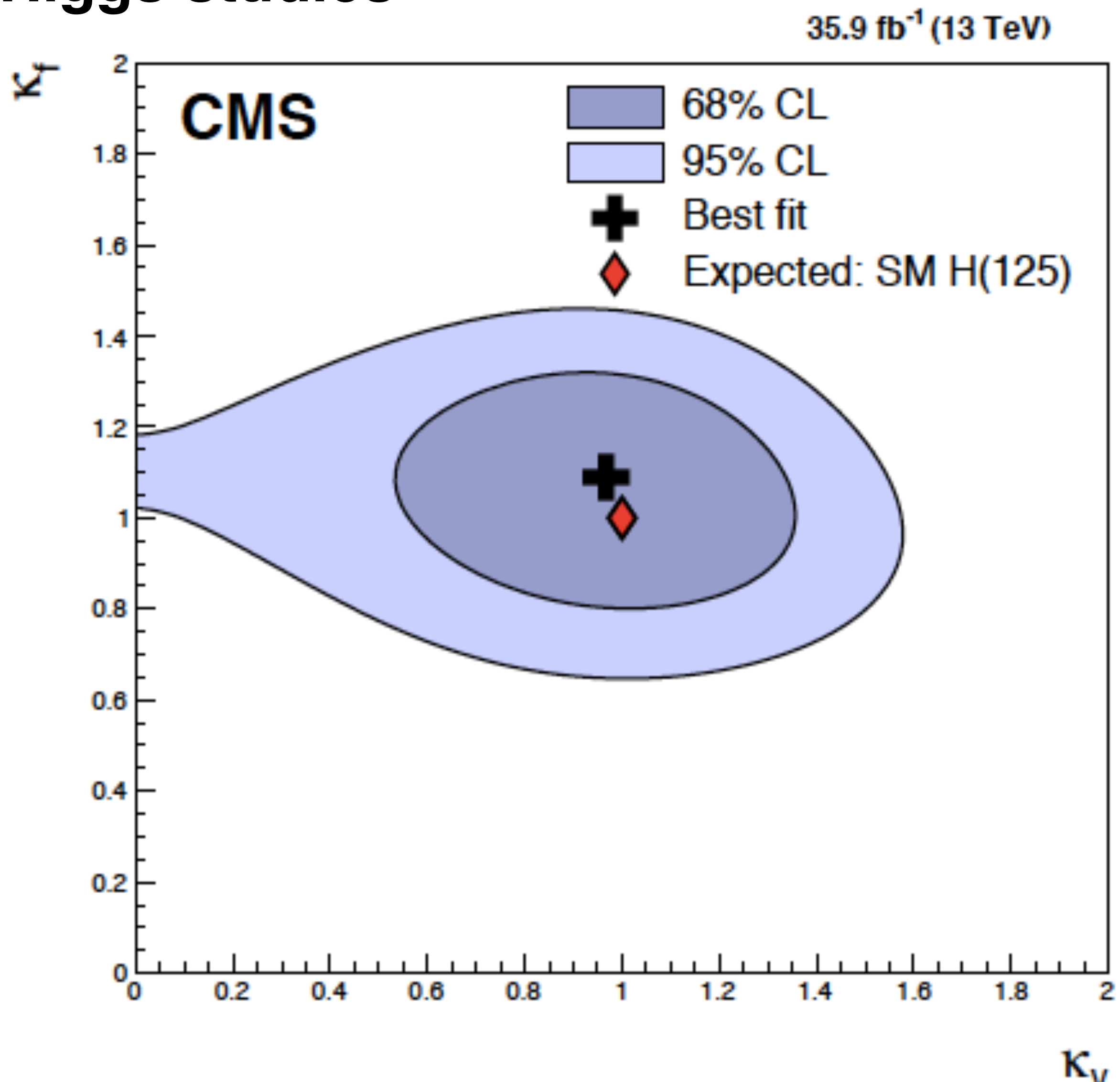


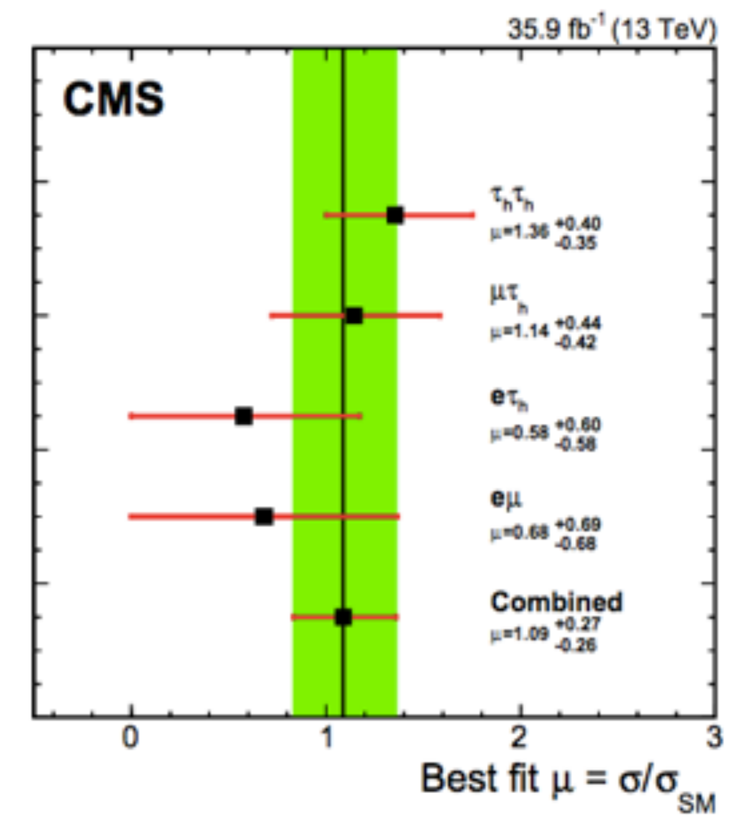
CMS-PAS-HIG-16-043 submitted to Phys.Lett.B

Study of H⇒ττ

- ➡ **Results consistent with SM expectation**
- ➡ **Signal strength μ = 0.98 ± 0.18**
- ➡ **Coupling modifiers to bosons and fermions tested**
- ➡ **Couplings will be fully explored in combination with other Higgs studies**

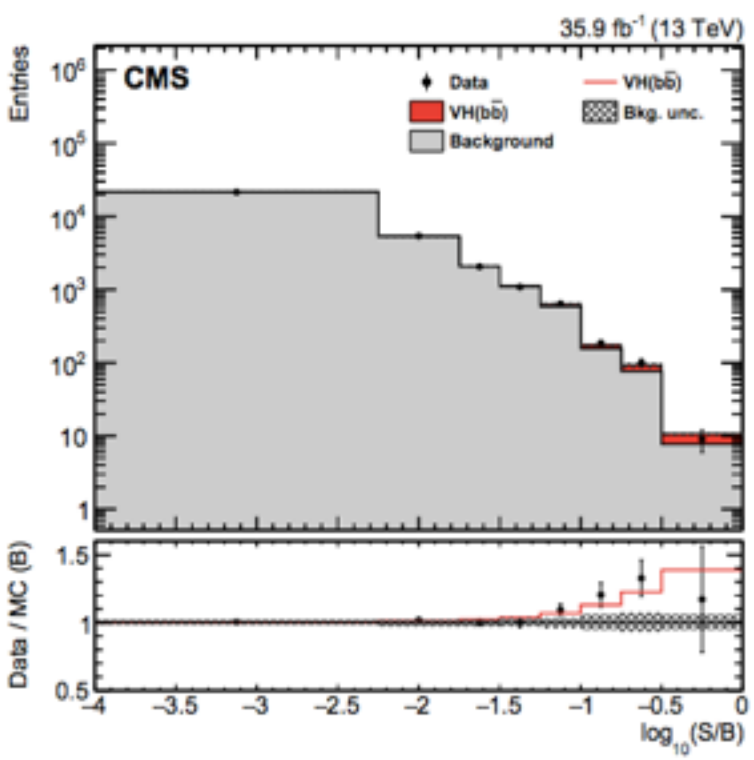


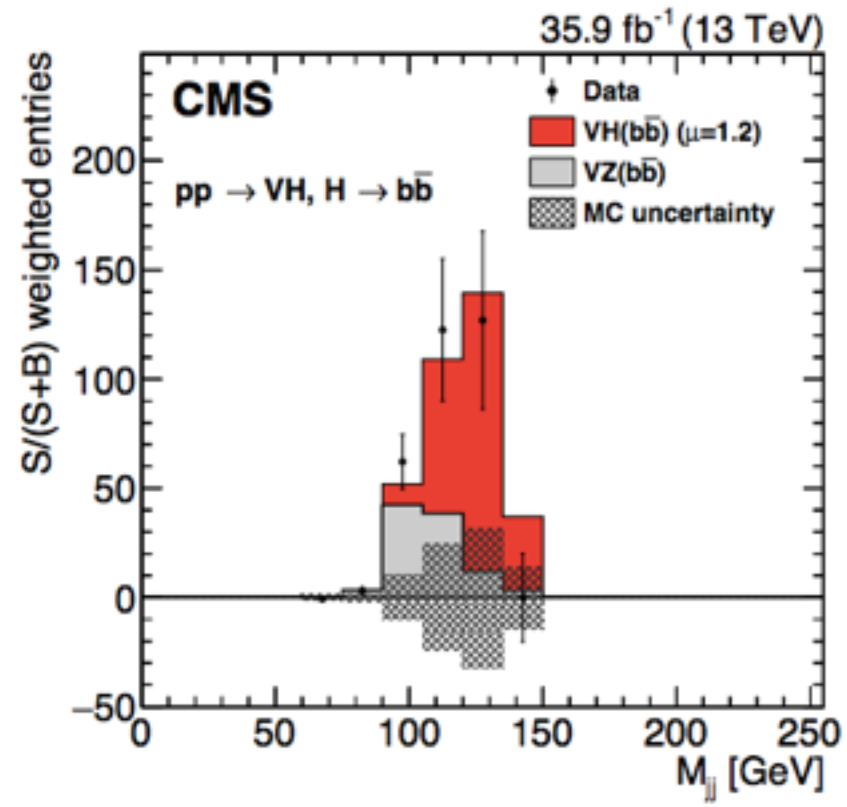


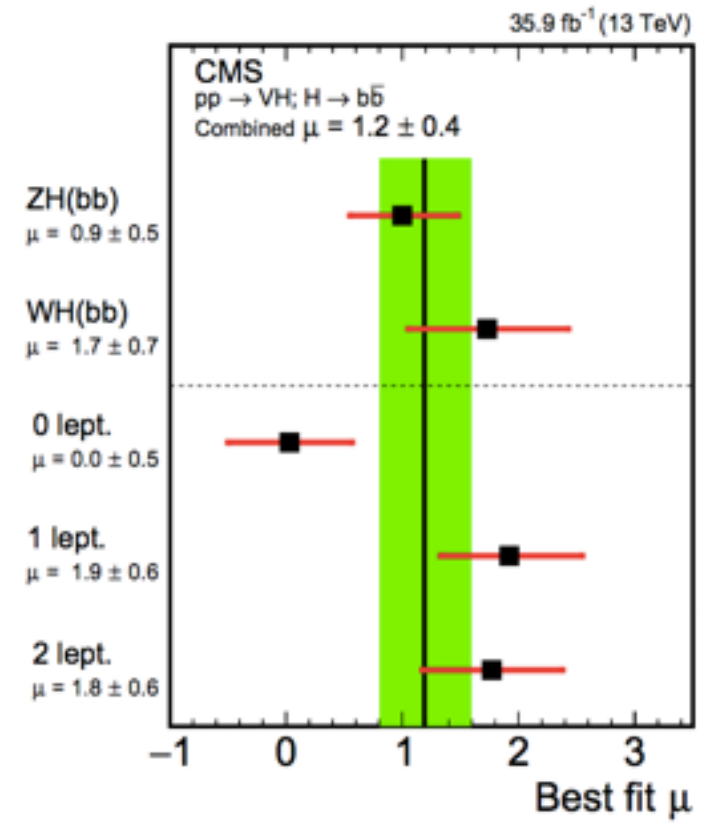


Evidence for H⇒bb

- ➡ Exploring ZH and WH production mode, with Z→ee, μμ, νν and W →eν, μν
- ➡ Split sample in 0-, 1-, and 2-lepton channels
- ➡ Signal extracted from combined fit to signal and control regions





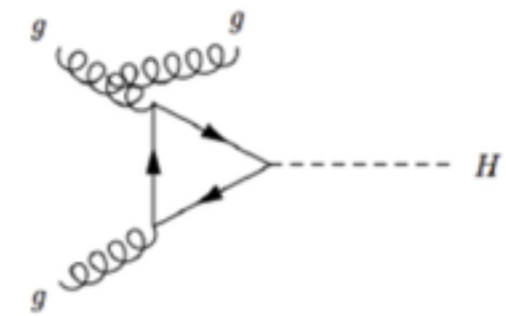


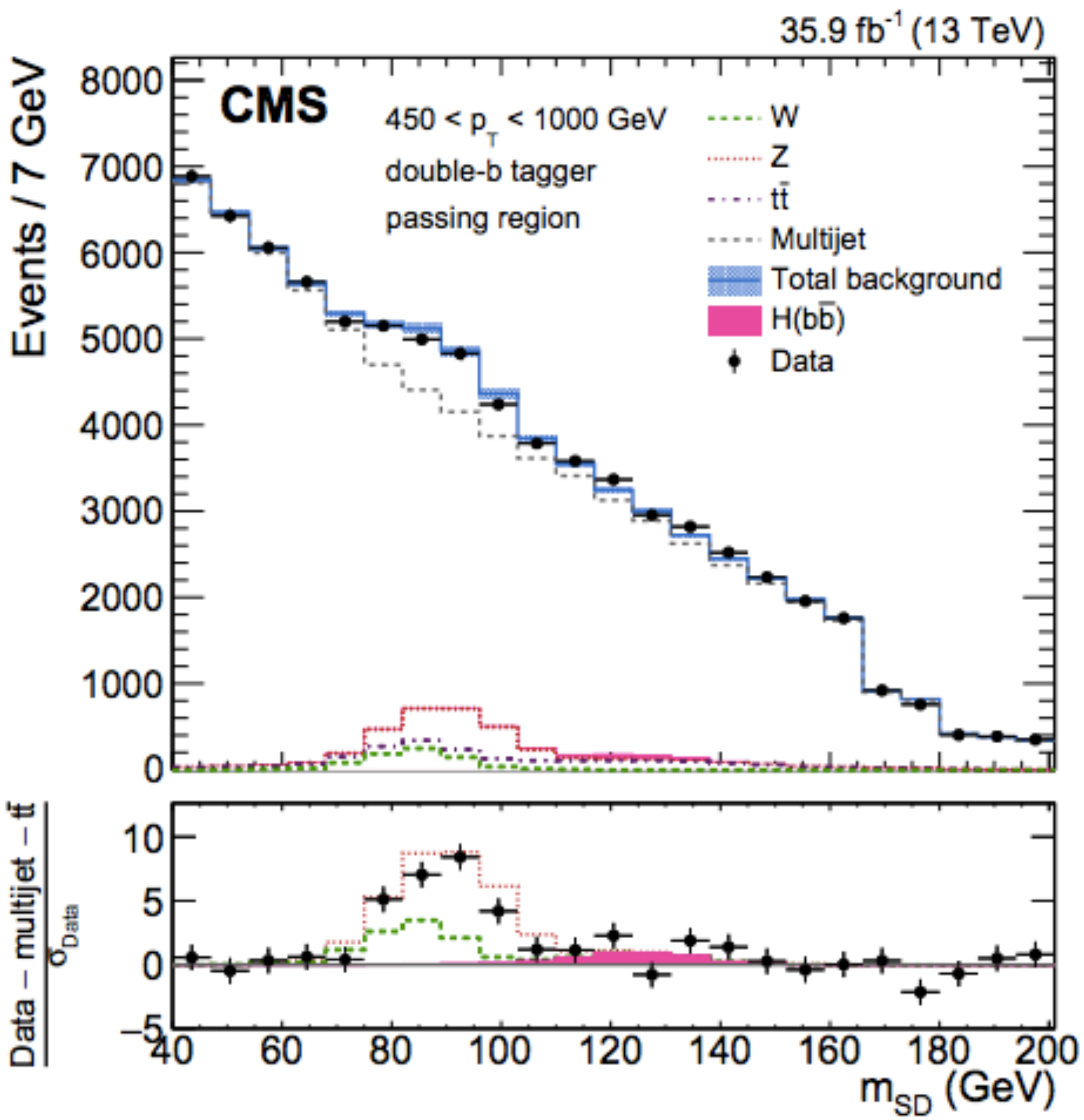
Data used	Significance expected	Significance observed	Signal strength observed
Run 1	2.5	2.1	$0.89^{+0.44}_{-0.42}$
Run 2	2.8	3.3	$1.19^{+0.40}_{-0.38}$
Combined	3.8	3.8	$1.06^{+0.31}_{-0.29}$

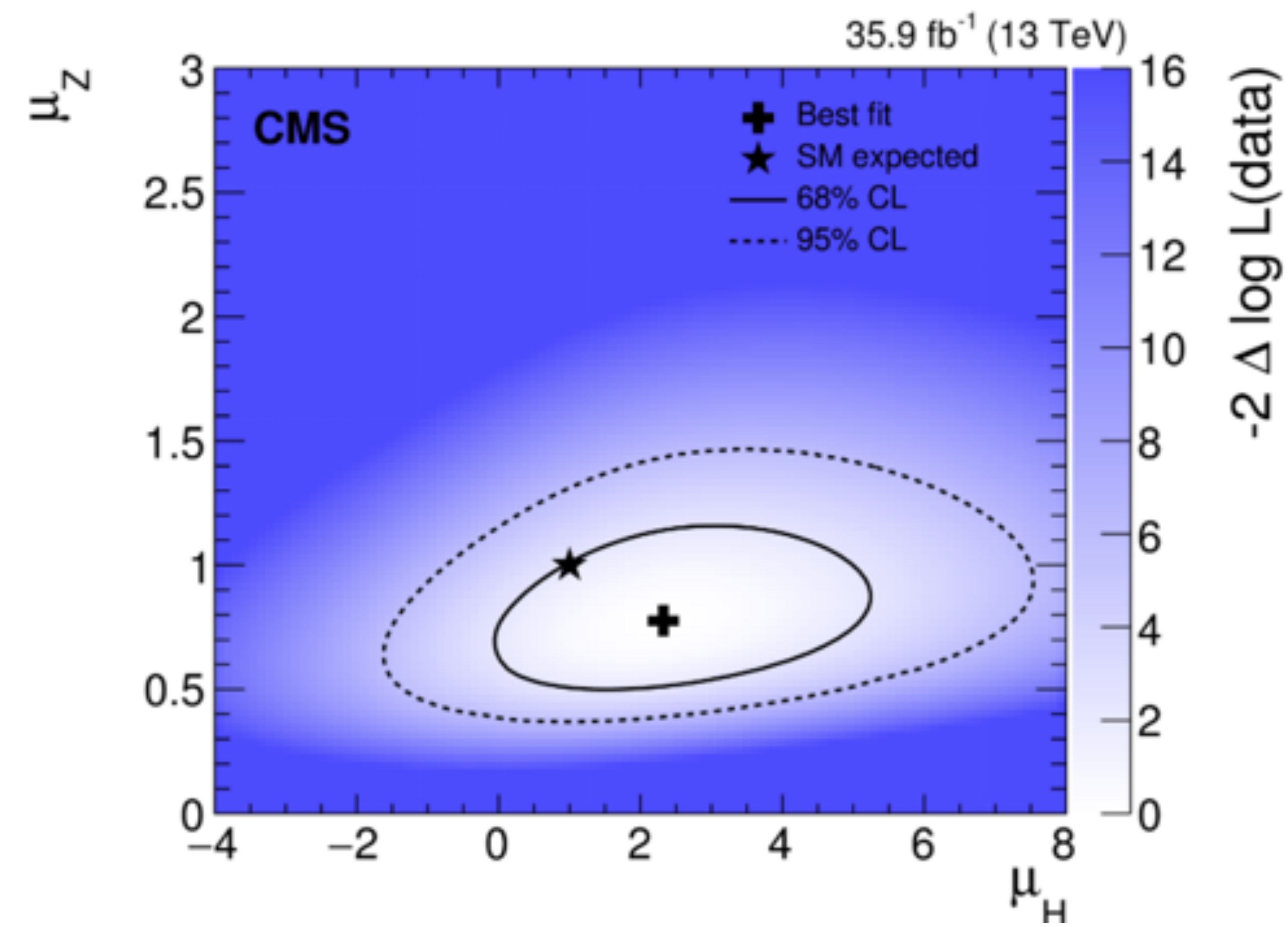
CMS-HIG-16-044 subm. to Phys.Lett.B

Boosted H⇒bb

- ➡ **Deemed to be impossible**, targeting dominate production and decay mode
- ➡ W, Z, and Higgs bosons identified as one large jet containing two b-quarks, highly boosted ($p_T > 450$ GeV) and recoiling against a jet







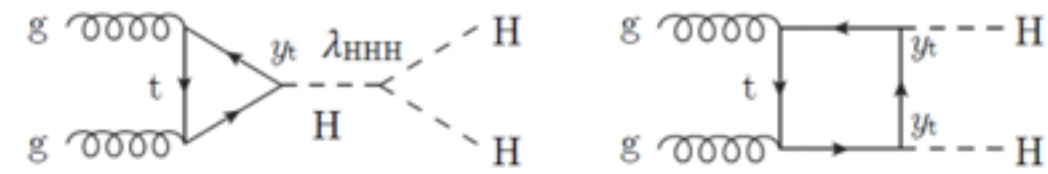
	H	H no p_T corr.	Z
Observed signal strength	$2.3^{+1.8}_{-1.6}$	$3.2^{+2.2}_{-2.0}$	$0.78^{+0.23}_{-0.19}$
Expected UL signal strength	< 3.3	< 4.1	—
Observed UL signal strength	< 5.8	< 7.2	—
Expected significance	0.7σ	0.5σ	5.8σ
Observed significance	1.5σ	1.6σ	5.1σ

CMS-HIG-17-010 submitted to PRL

Di-Higgs Production

➡ **Study of H self coupling very challenging at the LHC**

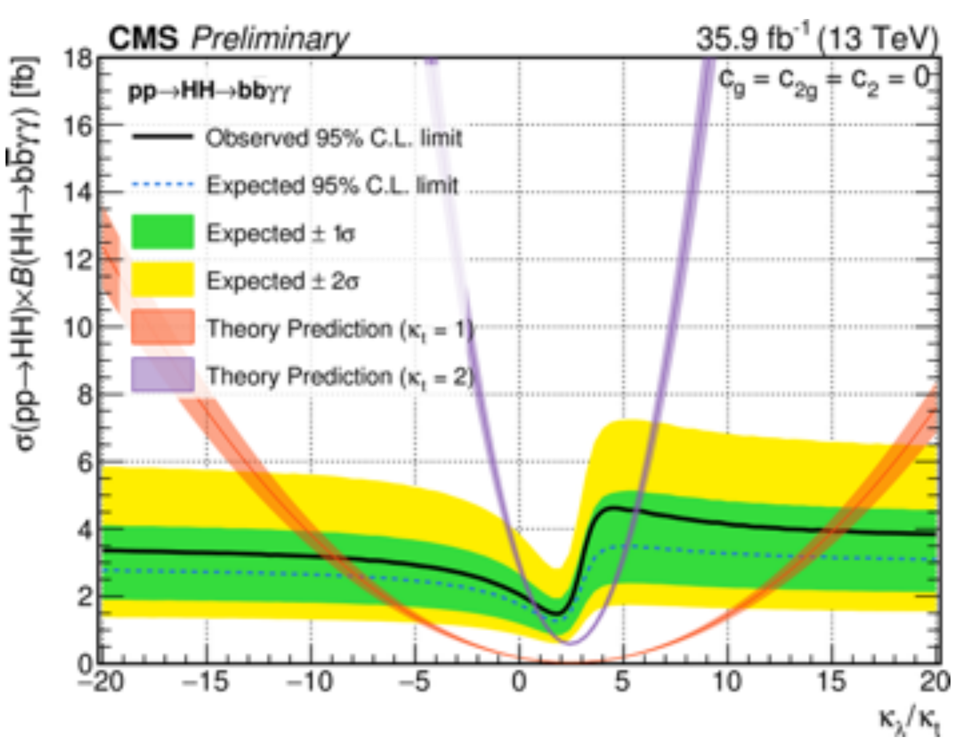
- 2σ single experiment sensitivity to SM cross section with HL-LHC

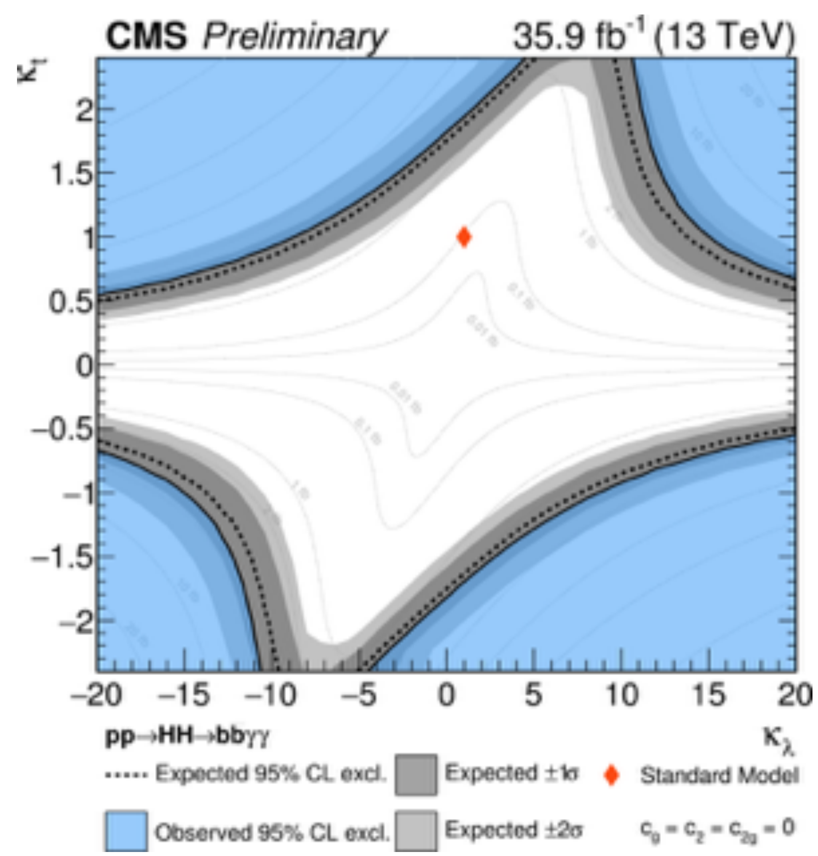


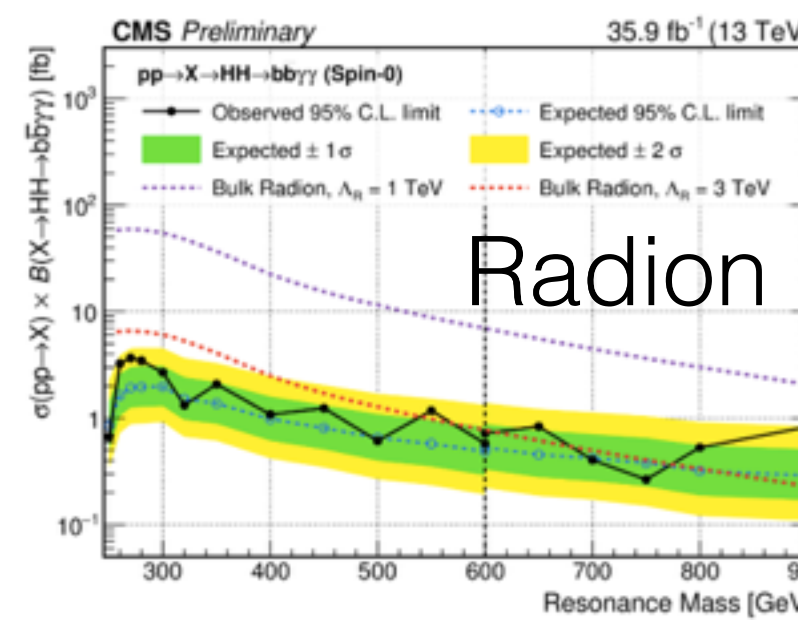
➡ **Cross section may be enhanced**

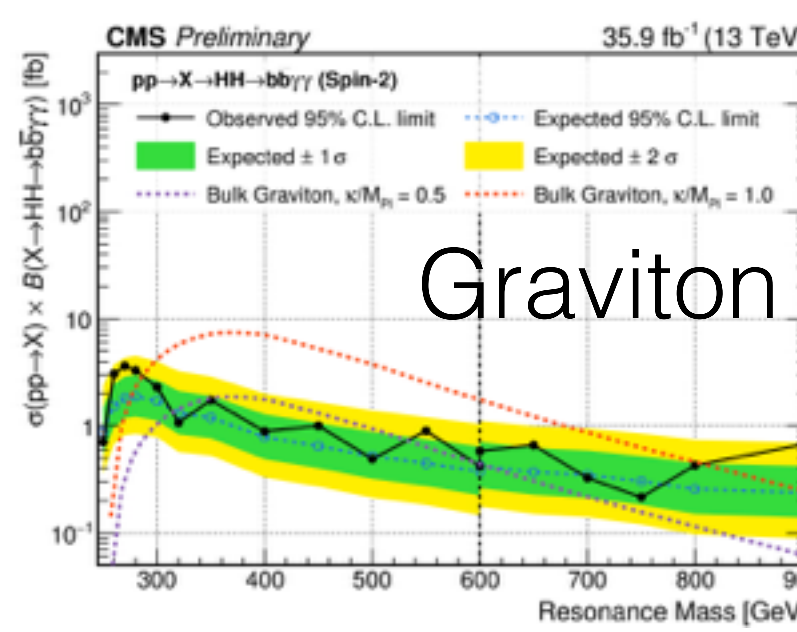
➡ **Search for resonant and non-resonant production performed using 2D-fits in di-jet and di-photon mass**

➡ **Observed 95% CL limits on Xsec 19.2 x SM Xsec**





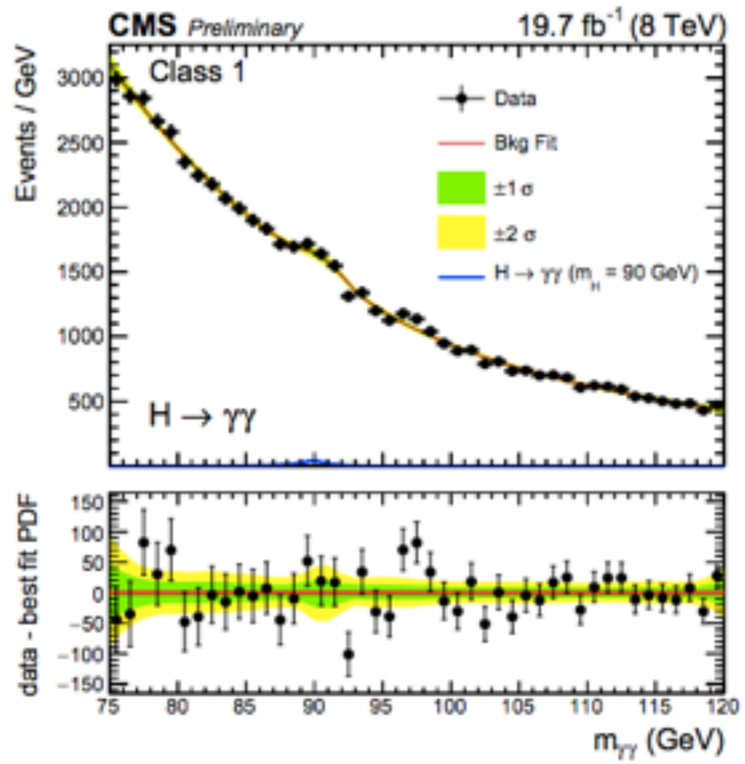


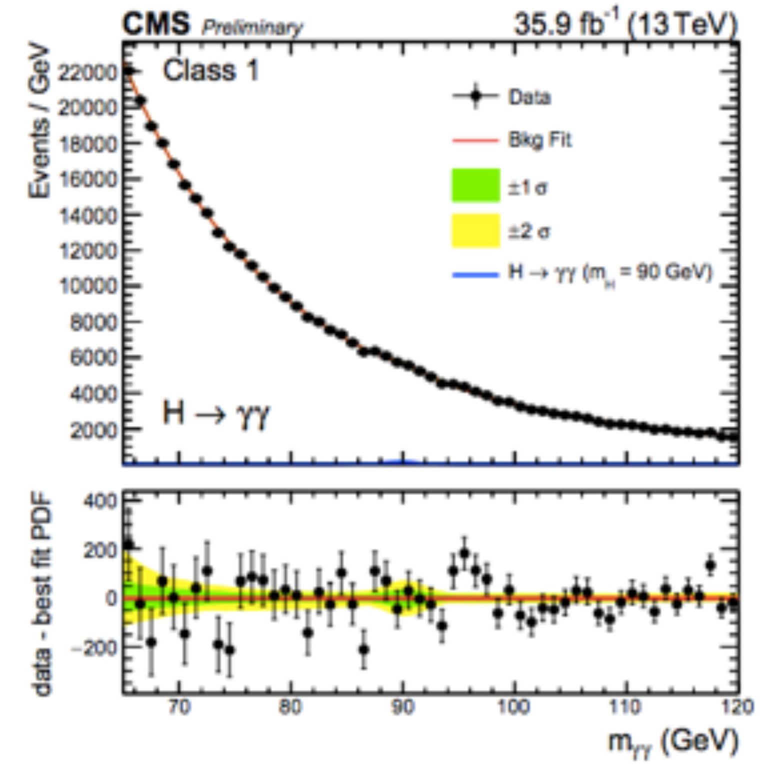


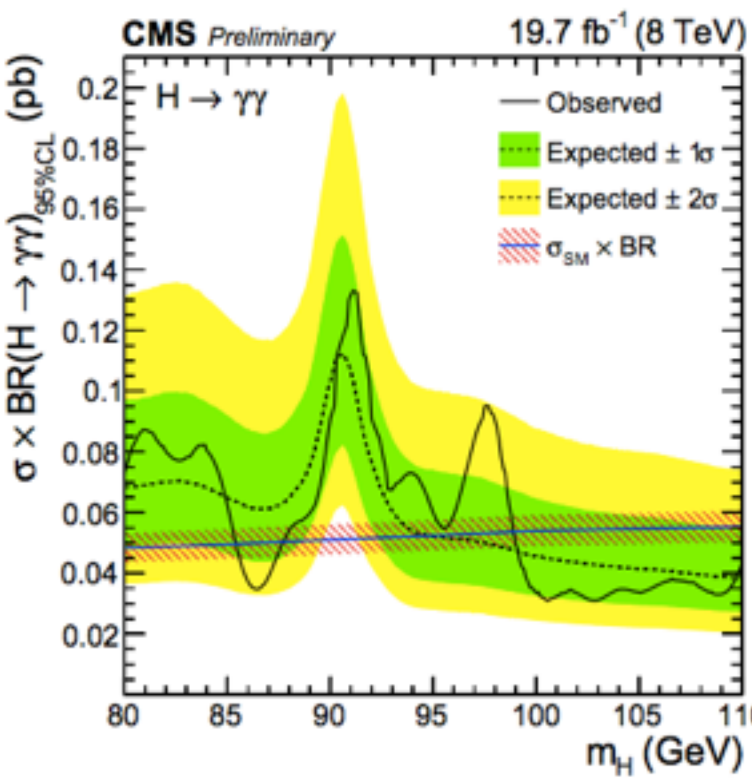
CMS-PAS-HIG-17-008

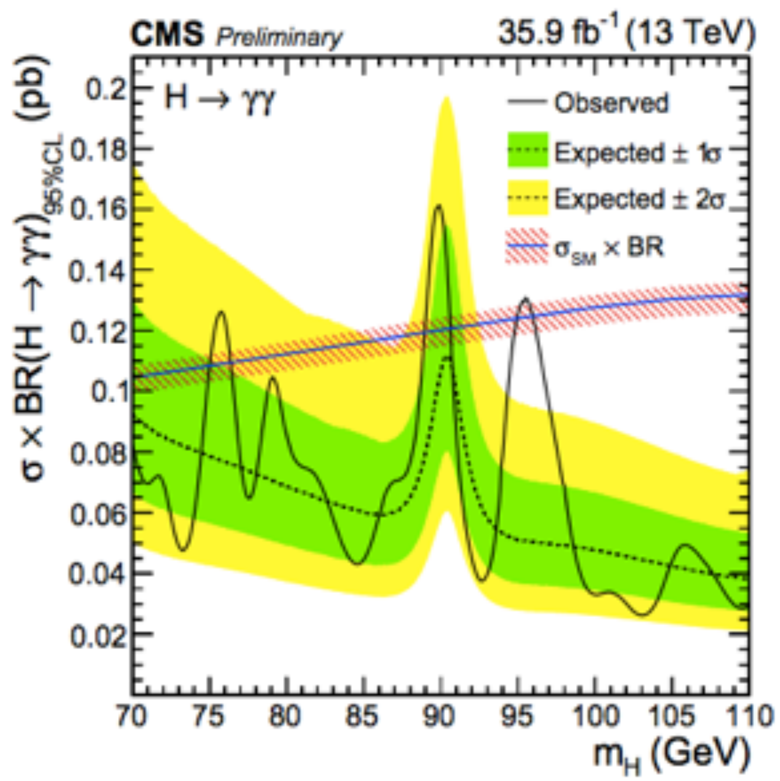
Low Mass Higgs

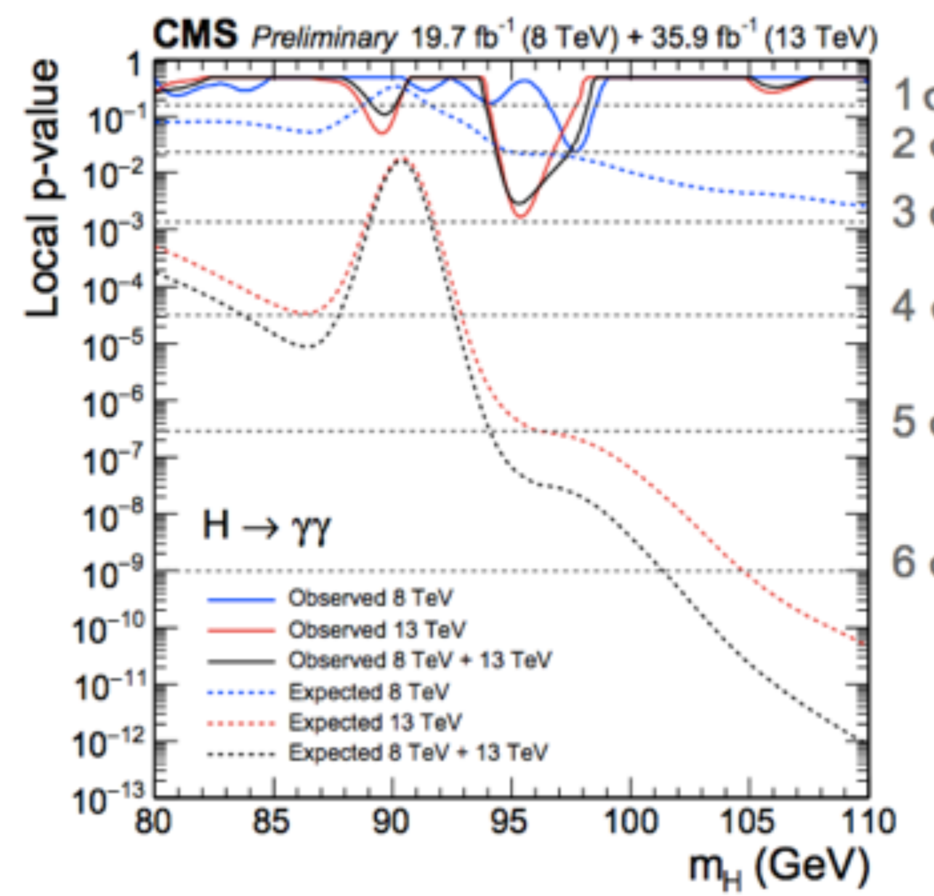
- ➡ **Search for additional Higgs bosons extends to high and also low masses**
- ➡ **Diphoton mass spectrum explored from 70 GeV in 4 event categories**
- ➡ **Excess with 2.9σ (local) and 1.4σ (global) significance at 95 GeV diphoton mass**







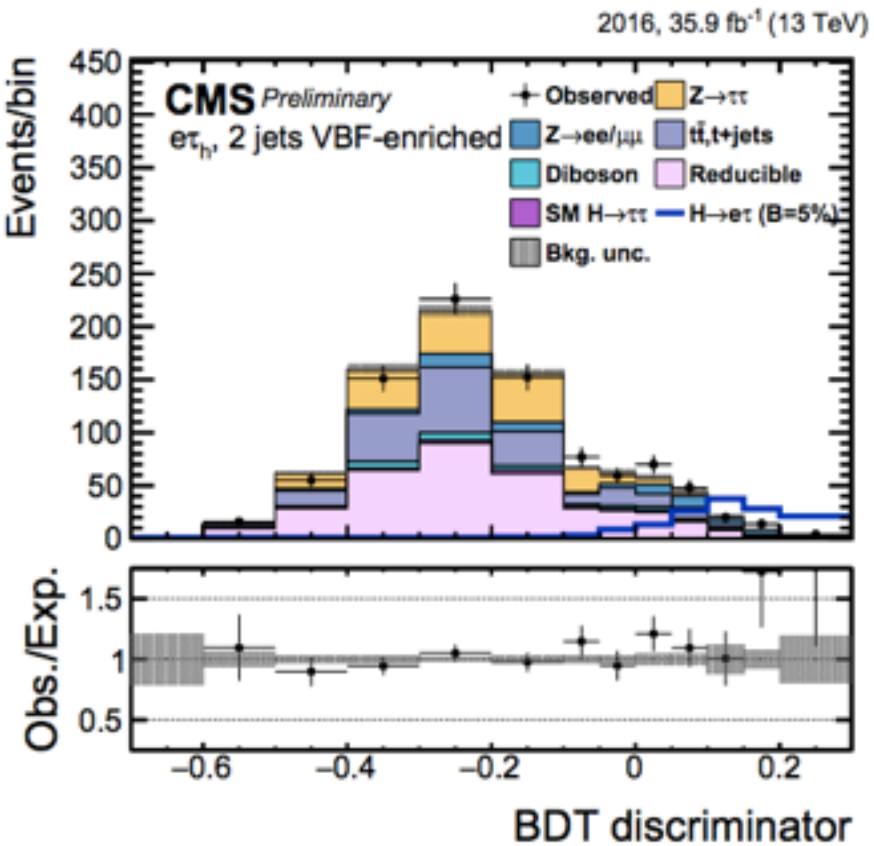


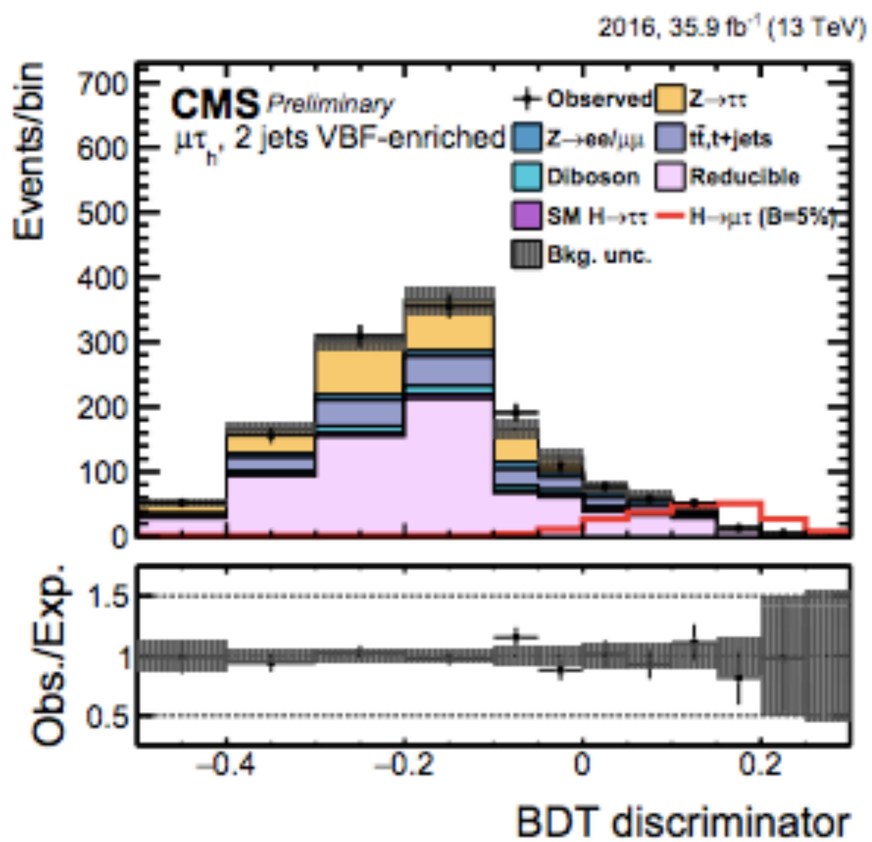


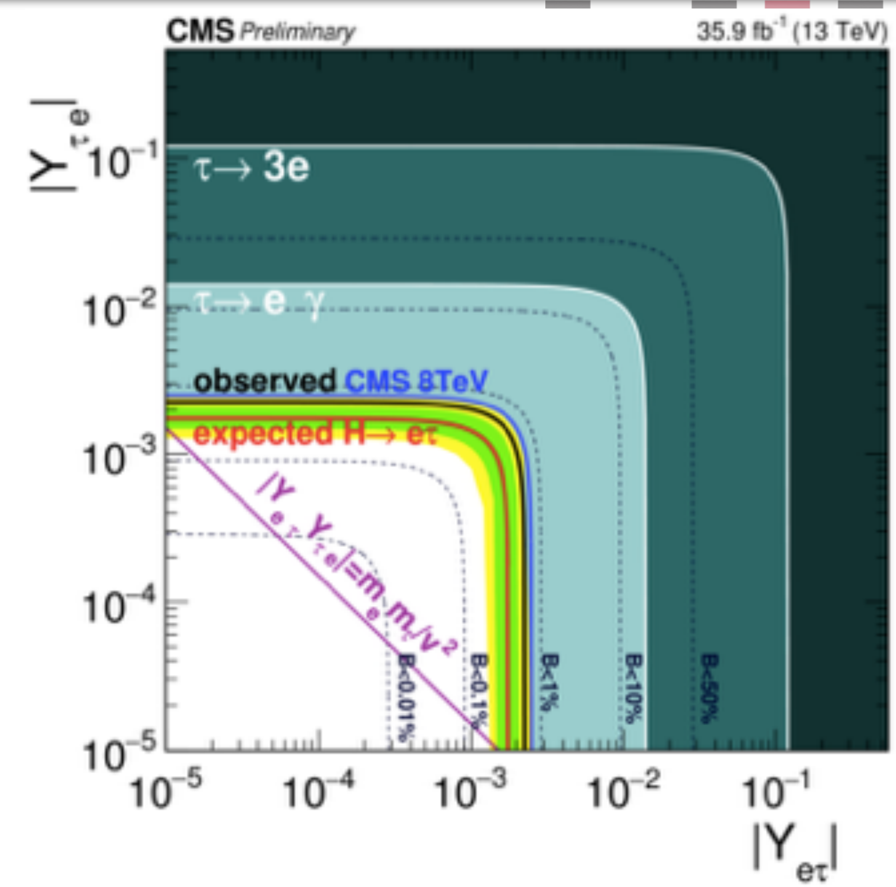
CMS-PAS-HIG-17-013

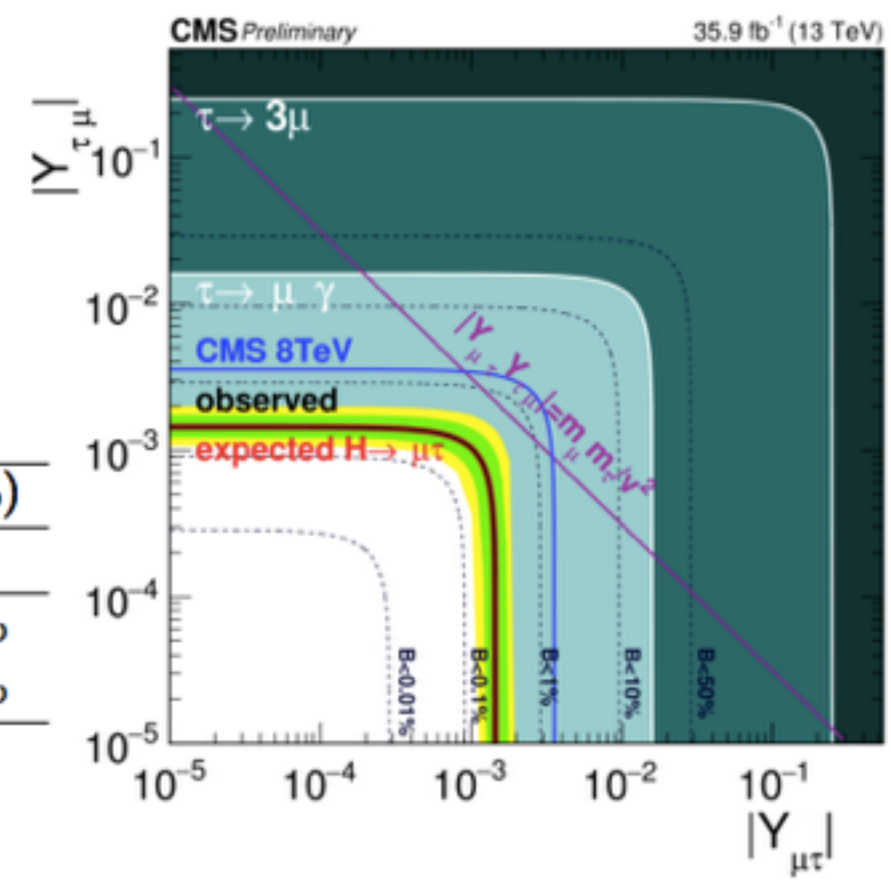
Flavor Violating Higgs Decays

- ➡ **Exploring off-diagonal Yukawa couplings**
- ➡ **Excitement in Run-I with 2.4σ excess**
- ➡ **Two different analysis techniques are deployed (M_{col} and BDT)**
- ➡ **New limits supersede Run-I results**









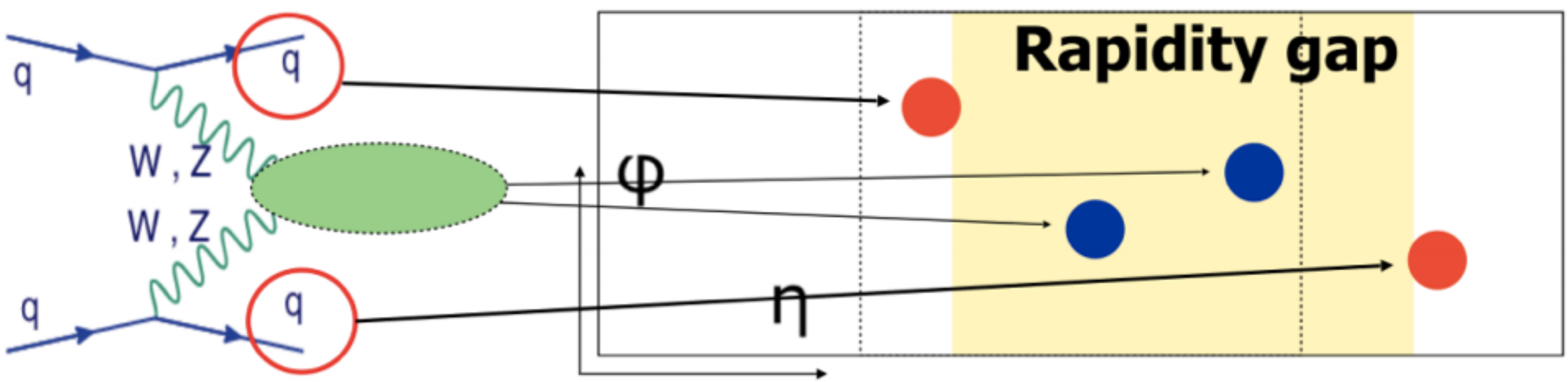
	Observed(Expected) limits (%)		Best fit branching fraction (%)	
	M_{col}-fit	BDT-fit	M_{col}-fit	BDT-fit
$H \rightarrow \mu\tau$	<0.51 (0.49) %	<0.25 (0.25)%	$0.02 \pm 0.20\%$	0.00 ± 0.12 %
$H \rightarrow e\tau$	<0.72 (0.56) %	<0.61 (0.37) %	0.23 ± 0.24 %	0.30 ± 0.18 %

CMS-PAS-HIG-17-001

Vector Boson Scattering

➡ **Electroweak di(tri)boson measurements**

- Test of EW sector of the SM
- Sensitive to anomalous triple and quartic gauge couplings (aTGC/qQGC)
- Neutral, charged or doubly charged Higgs bosons
- WW/WZ/ZZ (VV) scattering (massive, weak) vector boson scattering (VBS)
  - measurable key process linked with EWSB
  - final state: diboson plus at least two jets
- Background to Higgs searches and BSM searches



Vector Boson Scattering

- **Diboson final states**
  - **$W^{\pm}W^{\pm} \rightarrow l^{\pm}\nu l^{\pm}\nu$: best ratio σ_{EW} / σ_{QCD} ratio**
  - $W^{\pm}W^{\mp} \rightarrow l^{\pm}\nu l^{\mp}\nu$: relatively large top background
  - $W^{\pm}Z \rightarrow 3l\nu$: clean channel with three leptons
  - $ZZ \rightarrow 4l$: very clean, limited number of events
  - $ZZ \rightarrow 2l2\nu$: challenging analysis, but relatively large branching fraction
- **Semi-leptonic: ZW/Z → lljj & WW/Z → lνjj**
  - More difficult due to larger backgrounds
  - High m_{VV} generates boosted jets which can be merged

Vector Boson Scattering

Evidence for Electroweak Production of $W^{\pm}W^{\pm}jj$ in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector

G. Aad *et al.* (ATLAS Collaboration)
Phys. Rev. Lett. **113**, 141803 – Published 3 October 2014

3.6σ observed
2.8σ expected

ABSTRACT

This Letter presents the first study of $W^{\pm}W^{\pm}jj$, same-electric-charge diboson production in association with two jets, using 20.3 fb^{-1} of proton-proton collision data at $\sqrt{s} = 8$ TeV recorded by the ATLAS detector at the Large Hadron Collider. Events with two reconstructed same-charge leptons ($e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, and $\mu^{\pm}\mu^{\pm}$) and two or more jets are analyzed. Production cross sections are measured in two fiducial regions, with different sensitivities to the electroweak and strong production mechanisms. First evidence for $W^{\pm}W^{\pm}jj$ production and electroweak-only $W^{\pm}W^{\pm}jj$ production is observed with a significance of 4.5 and 3.6 standard deviations, respectively. The measured production cross sections are in agreement with standard model predictions. Limits at 95% confidence level are set on anomalous quartic gauge couplings.

Study of Vector Boson Scattering and Search for New Physics in Events with Two Same-Sign Leptons and Two Jets

V. Khachatryan *et al.* (CMS Collaboration)
Phys. Rev. Lett. **114**, 051801 – Published 2 February 2015

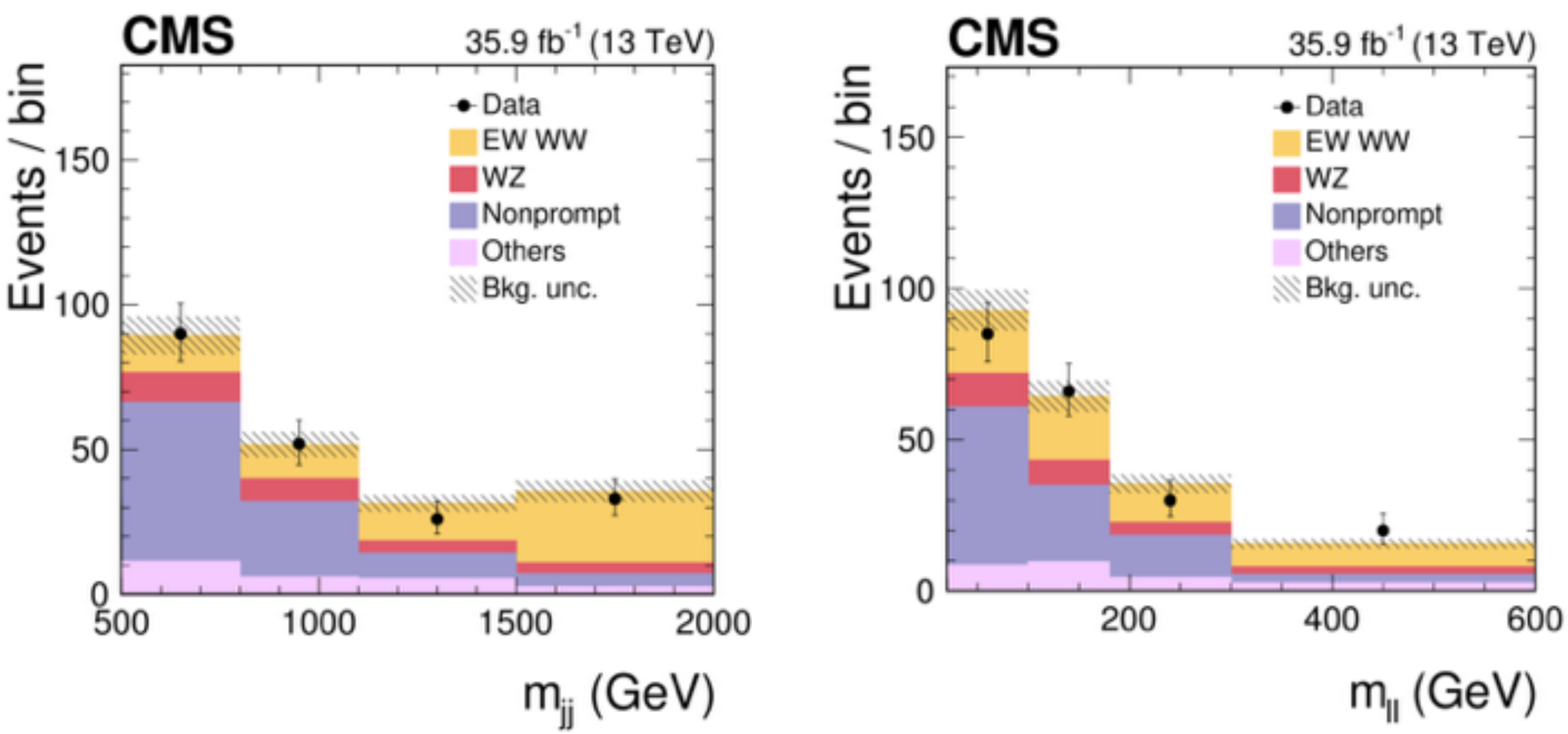
2.0σ observed
3.1σ expected

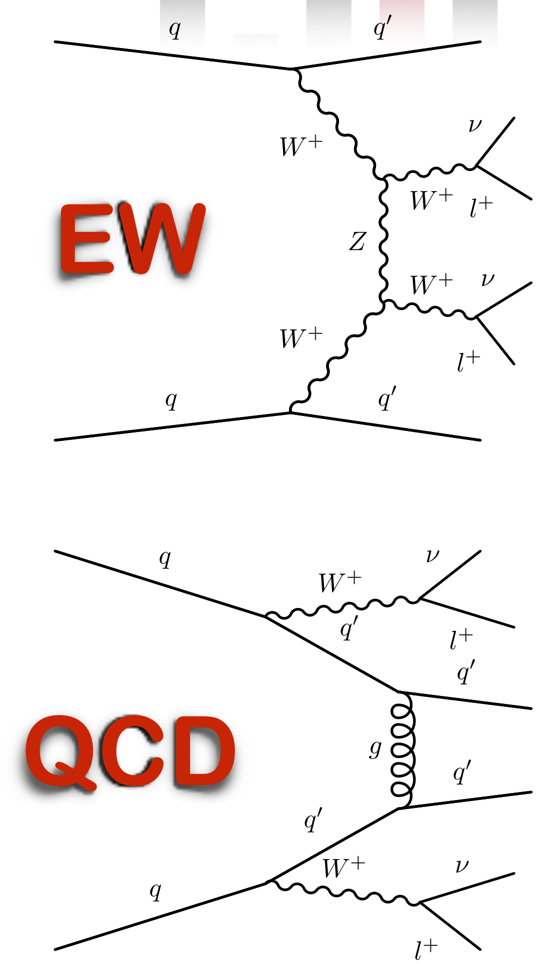
ABSTRACT

A study of vector boson scattering in pp collisions at a center-of-mass energy of 8 TeV is presented. The data sample corresponds to an integrated luminosity of $19.4\mathrm{fb}^{-1}$ collected with the CMS detector. Candidate events are selected with exactly two leptons of the same charge, two jets with large rapidity separation and high dijet mass, and moderate missing transverse energy. The signal region is expected to be dominated by electroweak same-sign W-boson pair production. The observation agrees with the standard model prediction. The observed significance is 2.0 standard deviations, where a significance of 3.1 standard deviations is expected based on the standard model. Cross section measurements for $W^{\pm}W^{\pm}$ and WZ processes in the fiducial region are reported. Bounds on the structure of quartic vector-boson interactions are given in the framework of dimension-eight effective field theory operators, as well as limits on the production of doubly charged Higgs bosons.

Vector Boson Scattering

- ➡ **Selecting same-sign W pair events using di-lepton final state with VBF topology**





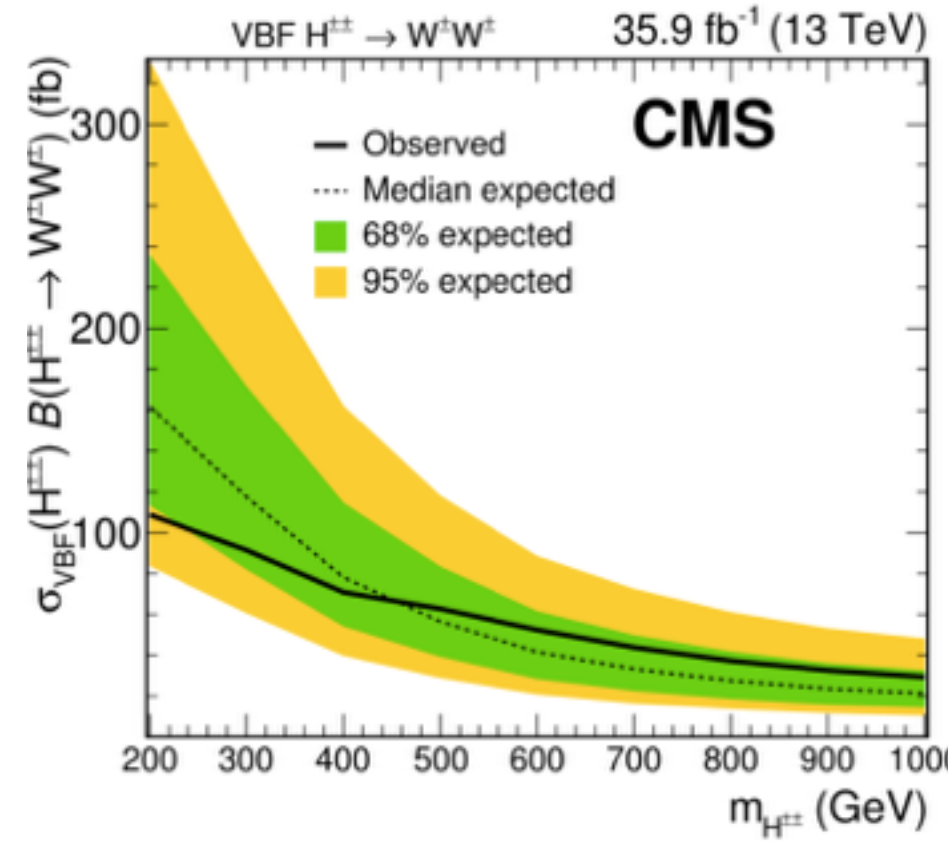
	e^+e^+	$e^+\mu^+$	$\mu^+\mu^+$	e^-e^-	$e^-\mu^-$	$\mu^-\mu^-$	Total
Data	14	63	40	10	48	26	201
Signal + total bkg.	19.0 ± 1.9	67.6 ± 3.8	44.1 ± 3.4	11.8 ± 1.8	38.9 ± 3.3	23.9 ± 2.8	205 ± 13
Signal	6.2 ± 0.2	24.7 ± 0.4	18.3 ± 0.4	2.5 ± 0.1	8.7 ± 0.2	6.5 ± 0.2	66.9 ± 2.4
Total bkg.	12.8 ± 1.9	42.9 ± 3.8	25.7 ± 3.4	9.4 ± 1.8	30.2 ± 3.3	17.4 ± 2.8	138 ± 13
Nonprompt	5.6 ± 1.7	24.9 ± 3.6	18.4 ± 3.3	5.0 ± 1.6	19.9 ± 3.2	14.2 ± 2.8	88 ± 13
WZ	3.0 ± 0.2	8.5 ± 0.3	4.4 ± 0.2	1.9 ± 0.2	5.2 ± 0.3	2.2 ± 0.1	25.1 ± 1.1
QCD WW	0.6 ± 0.1	1.7 ± 0.1	1.3 ± 0.1	0.2 ± 0.1	0.6 ± 0.1	0.4 ± 0.1	4.[illegible] ± 0.4
$W\gamma$	1.4 ± 0.5	3.6 ± 0.9	0.2 ± 0.2	0.8 ± 0.4	2.3 ± 0.7	—	8.3 ± 1.6
Triboson	0.8 ± 0.2	2.2 ± 0.4	1.2 ± 0.3	0.3 ± 0.1	0.9 ± 0.3	0.5 ± 0.2	5.8 ± 0.8
Wrong sign	1.5 ± 0.6	1.4 ± 0.4	—	1.1 ± 0.5	1.2 ± 0.4	—	5.2 ± 1.1

CMS-SMP-17-004 submitted to PRL

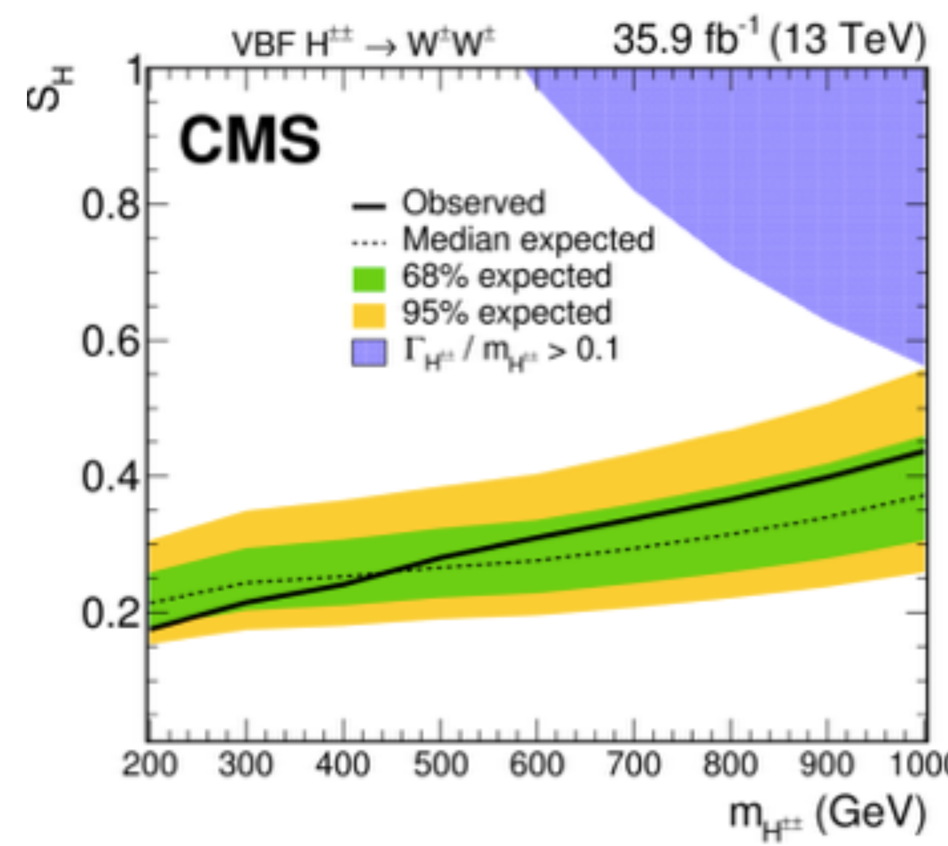
Vector Boson Scattering

➡ **Main results of same-sign W boson pair study**

- Observation of EW production of same-sign W pairs
  - ✓ **5.5σ observed**, 5.7σ expected
- Fiducial cross section measurement
  - ✓ Signal strength μ = 0.90±0.22
- Limits on doubly-charged Higgs boson production
  - ✓ Model independent limits and interpretation in Georgi-Machack model
- Limits on anomalous quartic gauge couplings (aQGCs)
  - ✓ factor of up to 6 times better than previous results



	Observed limits (TeV^{-4})	Expected limits (TeV^{-4})	Previously observed limits (TeV^{-4})
f_{S0}/Λ^4	[−7.7, 7.7]	[−7.0, 7.2]	[−38, 40] , [11]
f_{S1}/Λ^4	[−21.6, 21.8]	[−19.9, 20.2]	[−118, 120] , [11]
f_{M0}/Λ^4	[−6.0, 5.9]	[−5.6, 5.5]	[−4.6, 4.6] , [36]
f_{M1}/Λ^4	[−8.7, 9.1]	[−7.9, 8.5]	[−17, 17] , [36]
f_{M6}/Λ^4	[−11.9, 11.8]	[−11.1, 11.0]	[−65, 63] , [11]
f_{M7}/Λ^4	[−13.3, 12.9]	[−12.4, 11.8]	[−70, 66] , [11]
f_{T0}/Λ^4	[−0.62, 0.65]	[−0.58, 0.61]	[−0.46, 0.44] , [37]
f_{T1}/Λ^4	[−0.28, 0.31]	[−0.26, 0.29]	[−0.61, 0.61] , [37]
f_{T2}/Λ^4	[−0.89, 1.02]	[−0.80, 0.95]	[−1.2, 1.2] , [37]

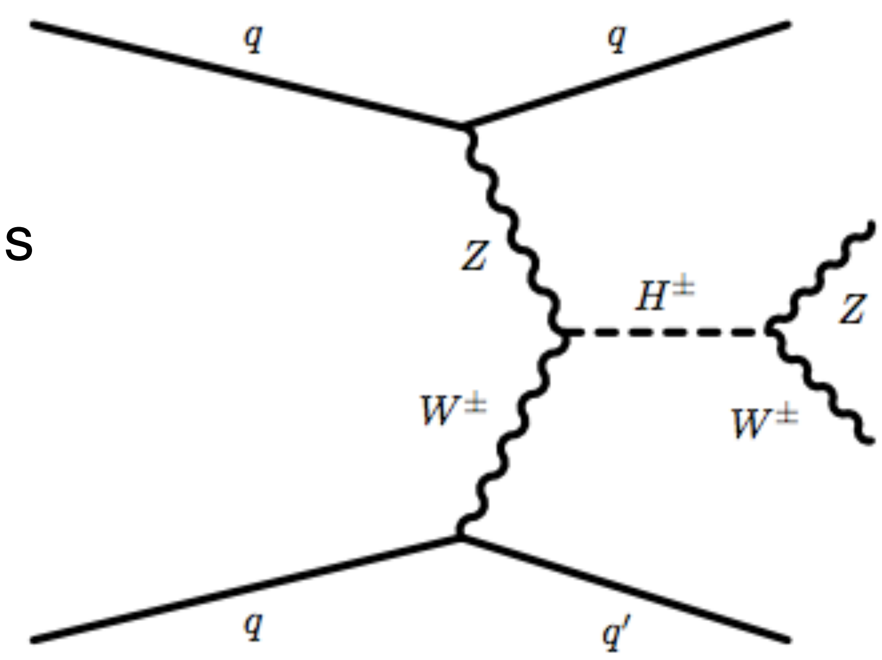


CMS-SMP-17-004 submitted to PRL

Vector Boson Scattering

➡ "Sister" analysis

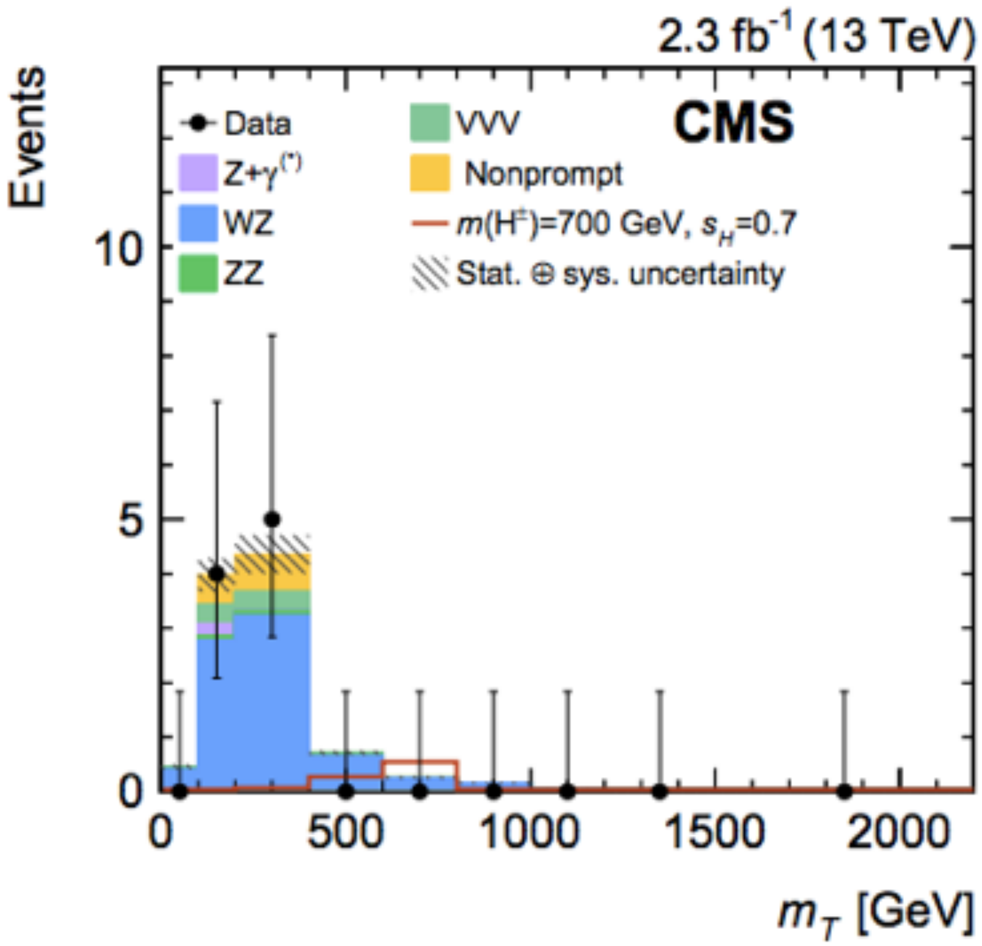
- Search for charged Higgs bosons produced via vector boson fusion and decaying into a pair of W and Z bosons
- 3 leptons + VBS topology
- Analyzed 13 TeV data from 2015 & 2016 (15.2 fb^{-1})
- Signal extracted using transverse mass

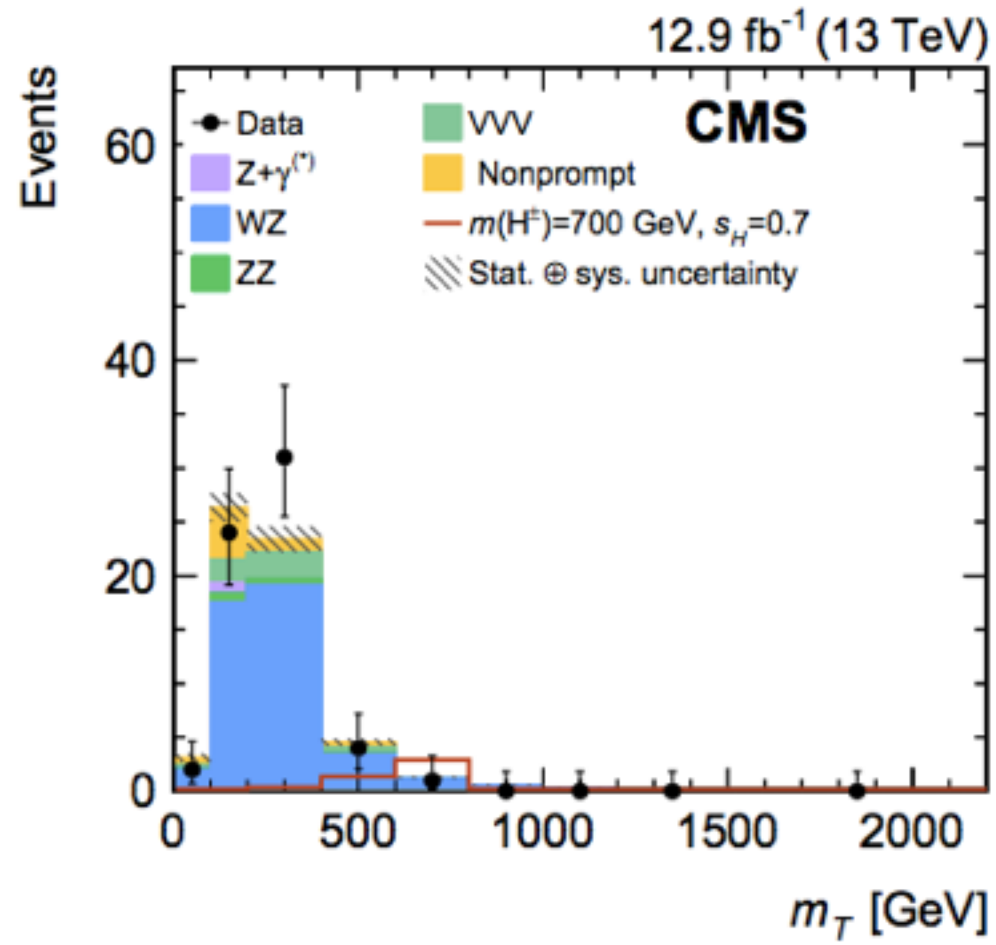


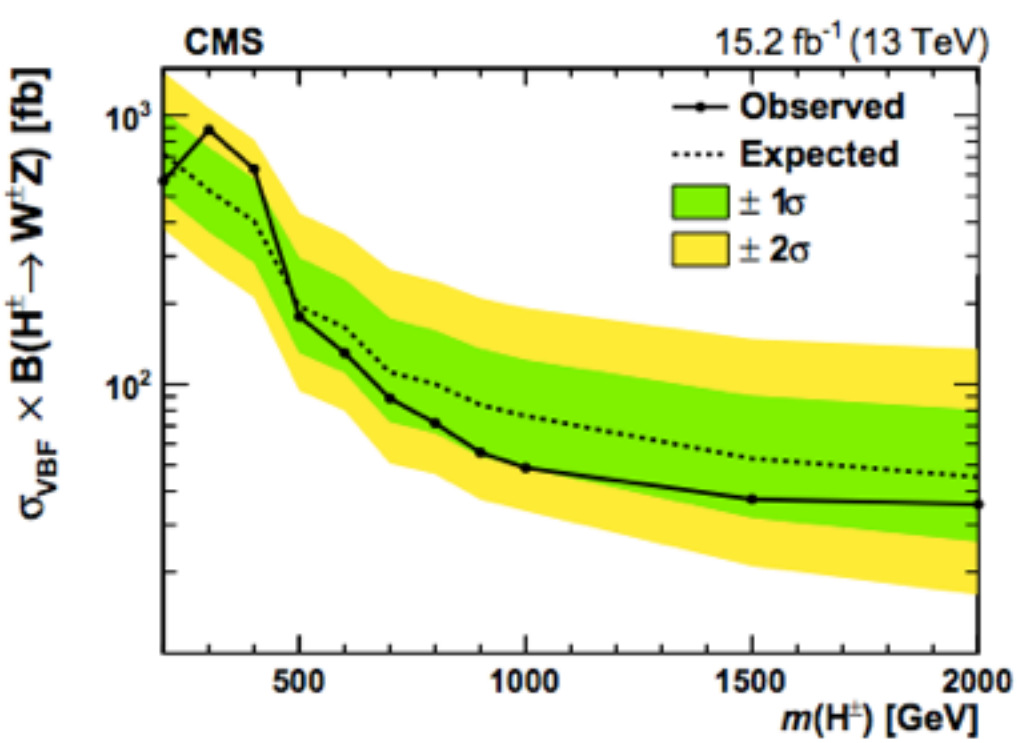
Dataset	2015	2016
Data	9	62
WZ	7.5 ± 0.5	44.4 ± 2.5
ZZ	0.2 ± 0.1	1.6 ± 0.1
VVV	0.8 ± 0.1	5.5 ± 0.3
Zγ	0.2 ± 0.1	1.0 ± 0.4
Nonprompt	1.3 ± 0.5	7.4 ± 2.0
Total bkg.	10.0 ± 0.8	59.9 ± 3.5
Signal ($m(\mathrm{H}^\pm) = 700\,\mathrm{GeV}$)	0.9 ± 0.1	4.7 ± 0.5

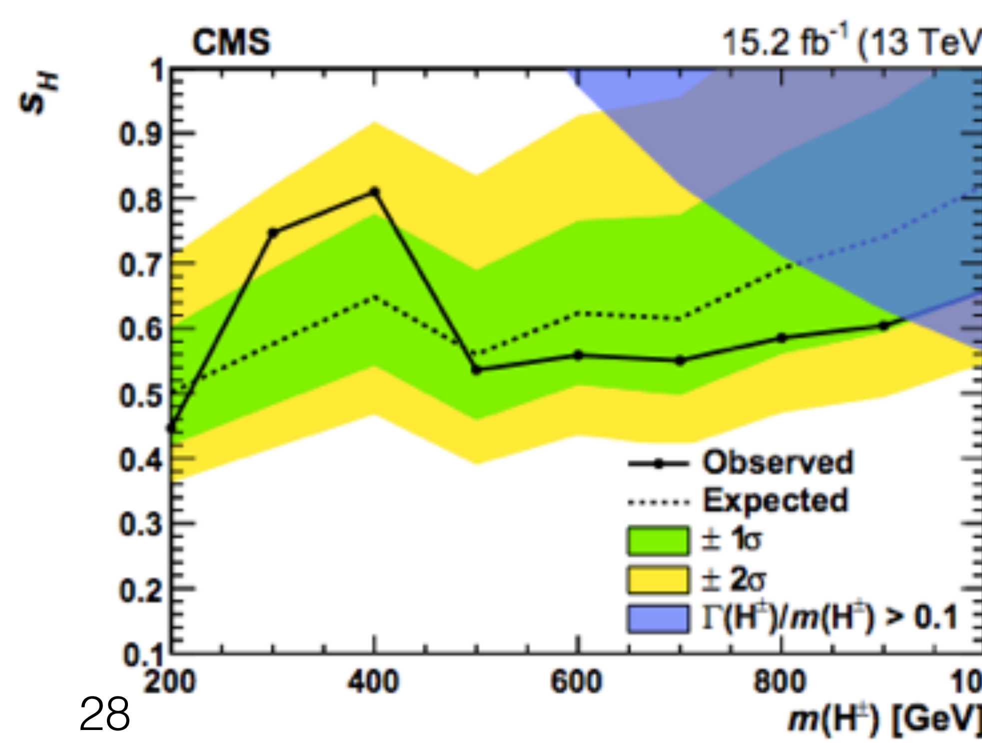
CMS-HIG-16-027 published in PRL

Vector Boson Scattering



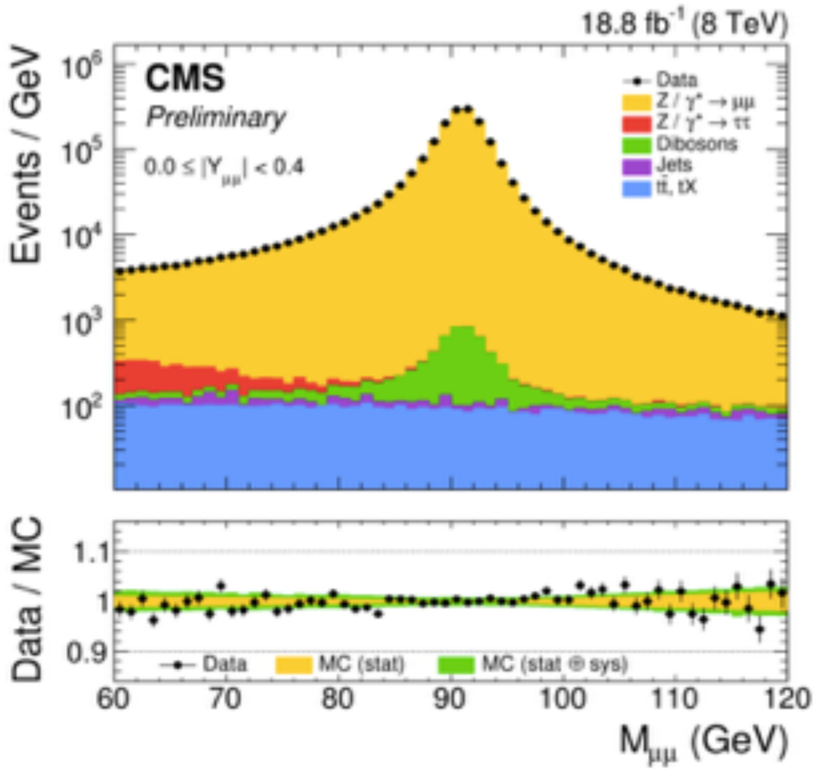


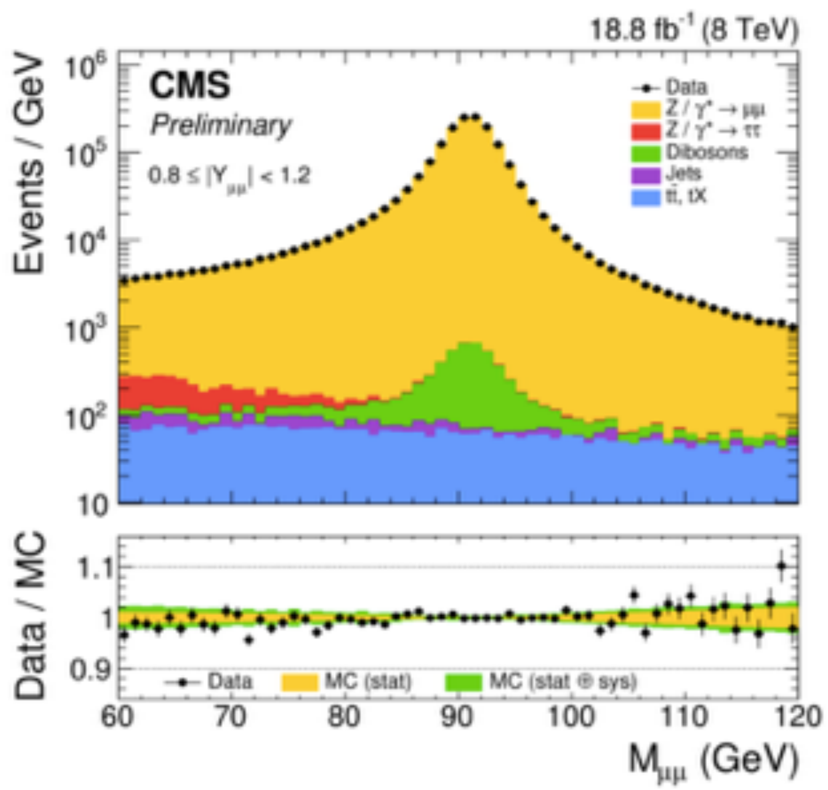


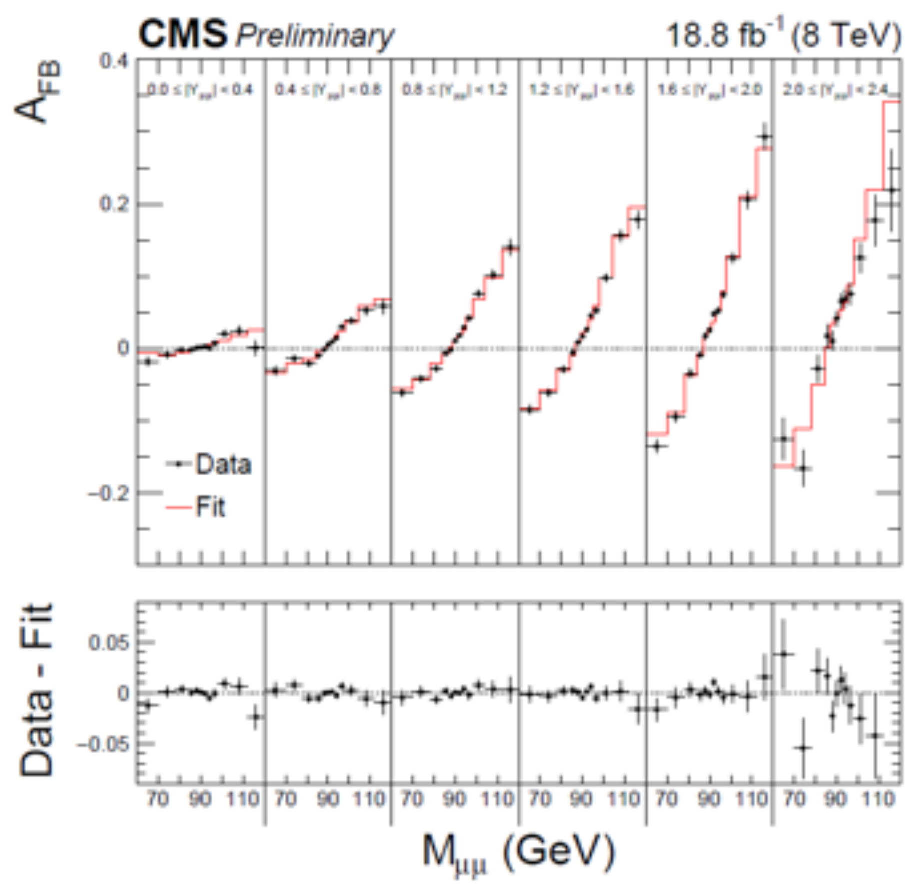


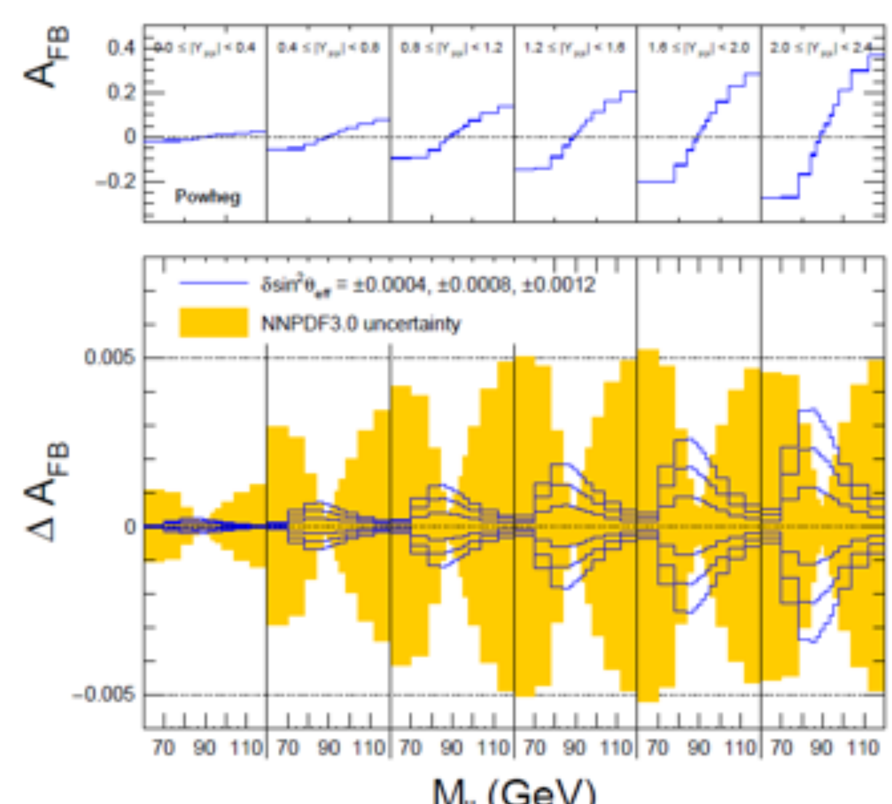
EW Mixing Angle

- ➡ **EW Mixing angle from forward-backward asymmetry in dilepton (5M dielectron and 8M dimuon) events**
- ➡ **Sample binned in dilepton mass and rapidity**
- ➡ **Interplay of PDF uncertainties, constrains and mixing angle in fit**





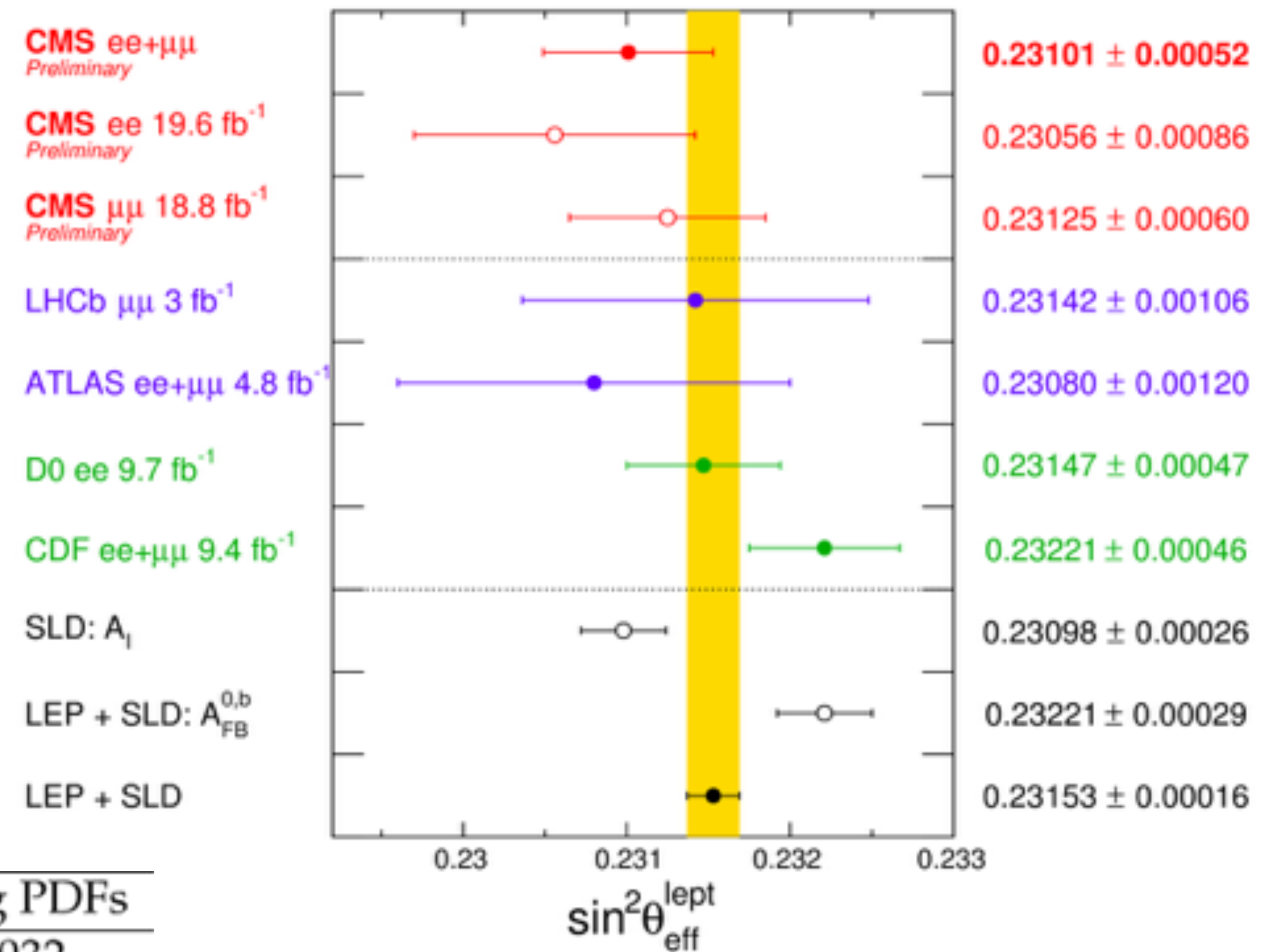




CMS-PAS-SMP-16-007

EW Mixing Angle

- ➡ **Most precise LHC measurement**
- ➡ **Performance comparable to Tevatron experiments**
- ➡ **Measurements still dominated by statistical uncertainties**
- ➡ **Ultimately limited by PDF uncertainties**



Channel	without constraining PDFs	with constraining PDFs
Muon	0.23125 ± 0.00054	0.23125 ± 0.00032
Electron	0.23054 ± 0.00064	0.23056 ± 0.00045
Combined	0.23102 ± 0.00057	0.23101 ± 0.00030

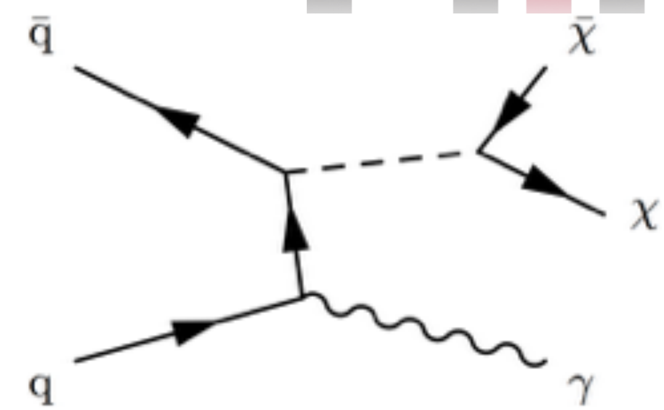
$$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = 0.23101 \pm 0.00036(\mathrm{stat}) \pm 0.00018(\mathrm{syst}) \pm 0.00016(\mathrm{theory}) \pm 0.00030(\mathrm{pdf})$$
$$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = 0.23101 \pm 0.00052.$$

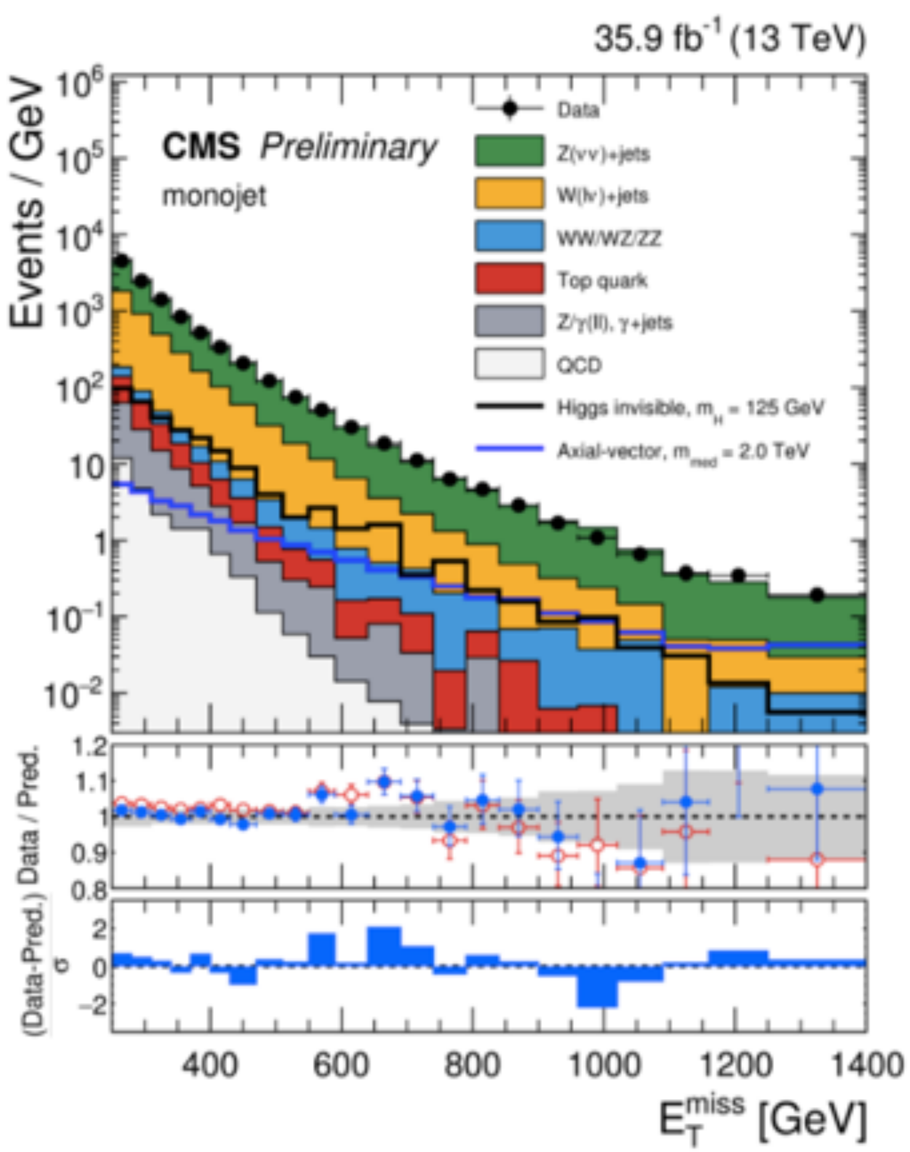
CMS-PAS-SMP-16-007

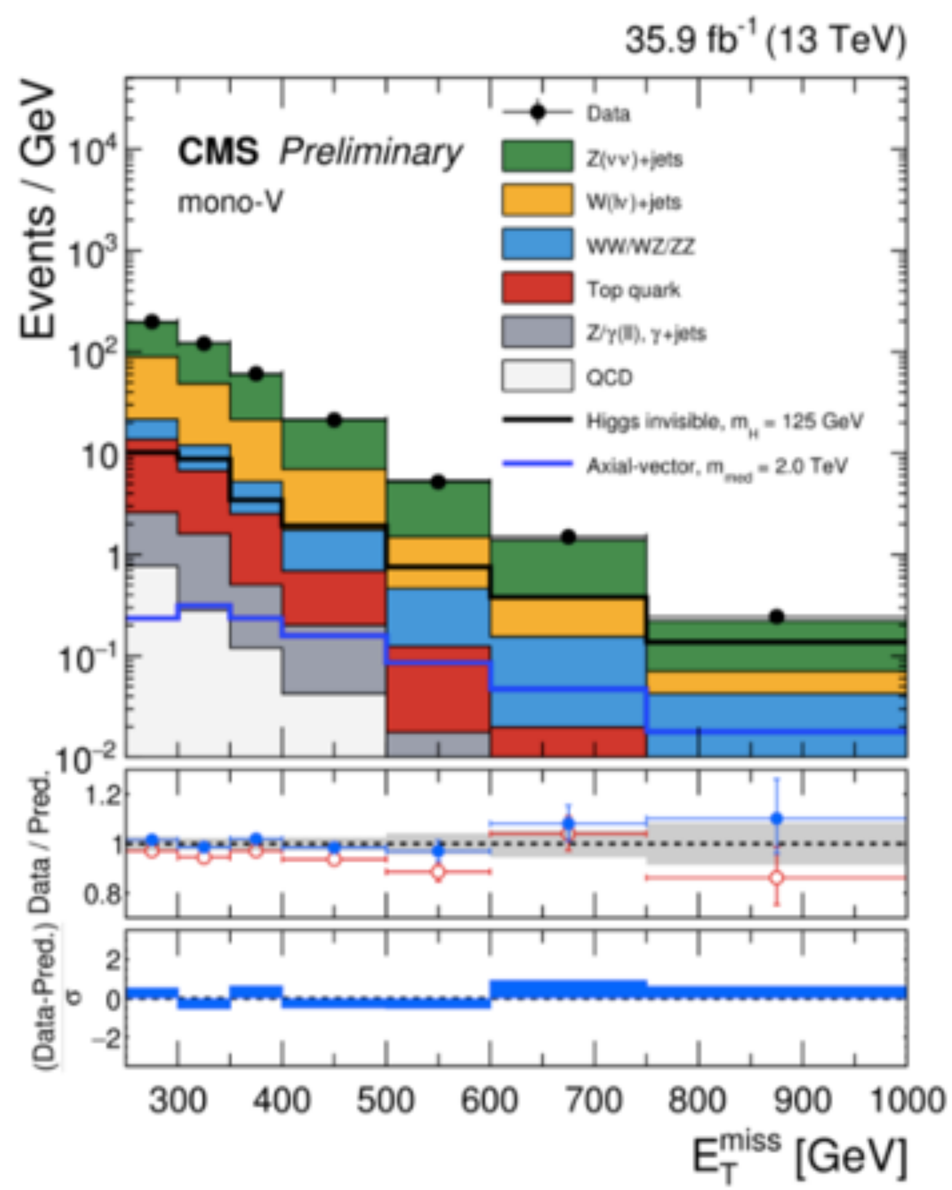
Dark Matter Searches

➡ **Shining light on dark matter with ISR or associate particles**

- Jets, photons, W or Z bosons, top, Higgs, … + missing transverse energy signature
- Key is to understand (perform precision measurements of) SM backgrounds





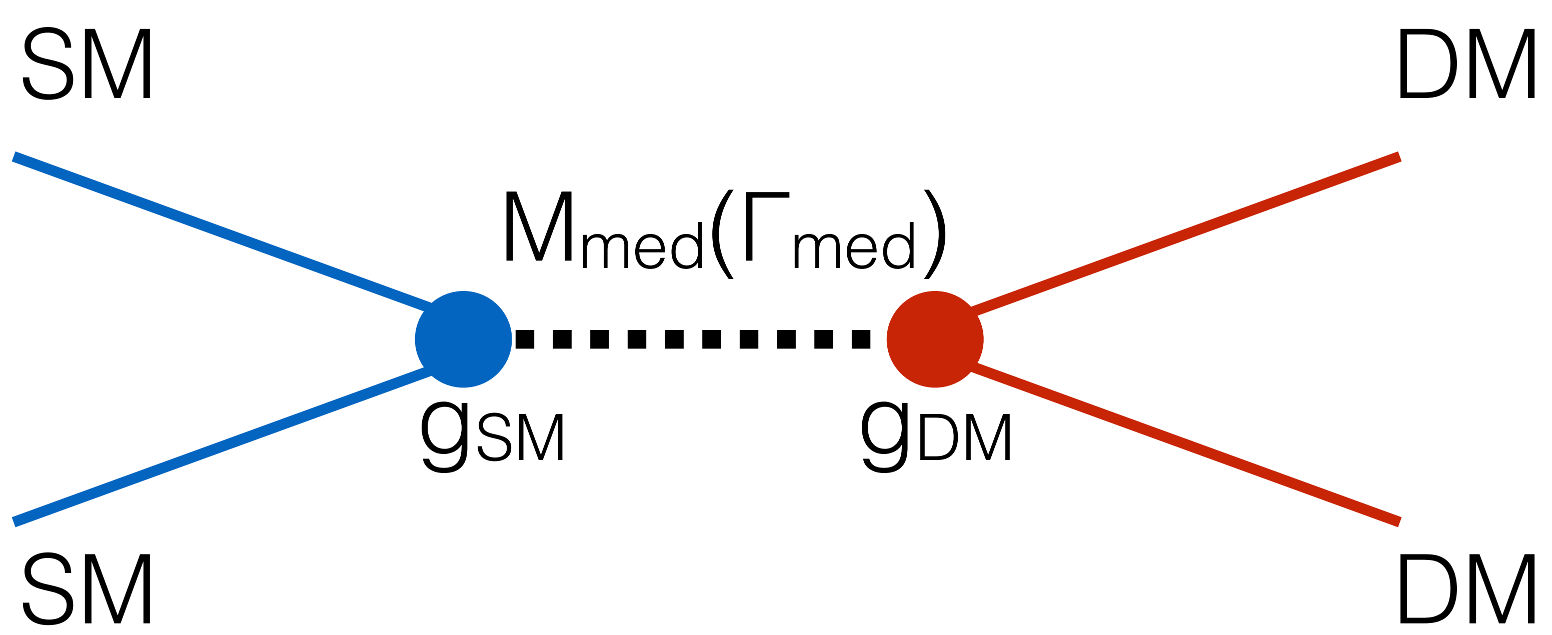


CMS-PAS-EXO-16-048

Dark Matter Searches

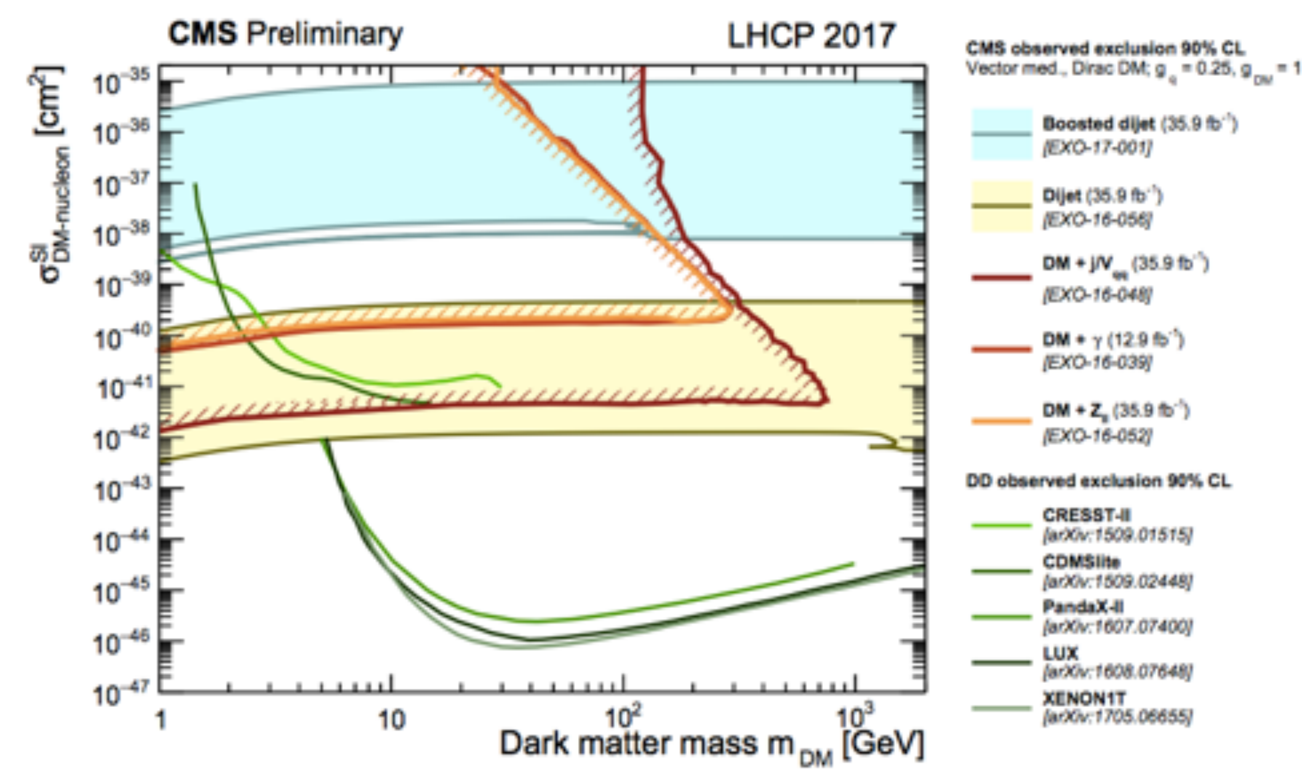
➡ **Interpretation discussed / agreed on in LHC DM WG**

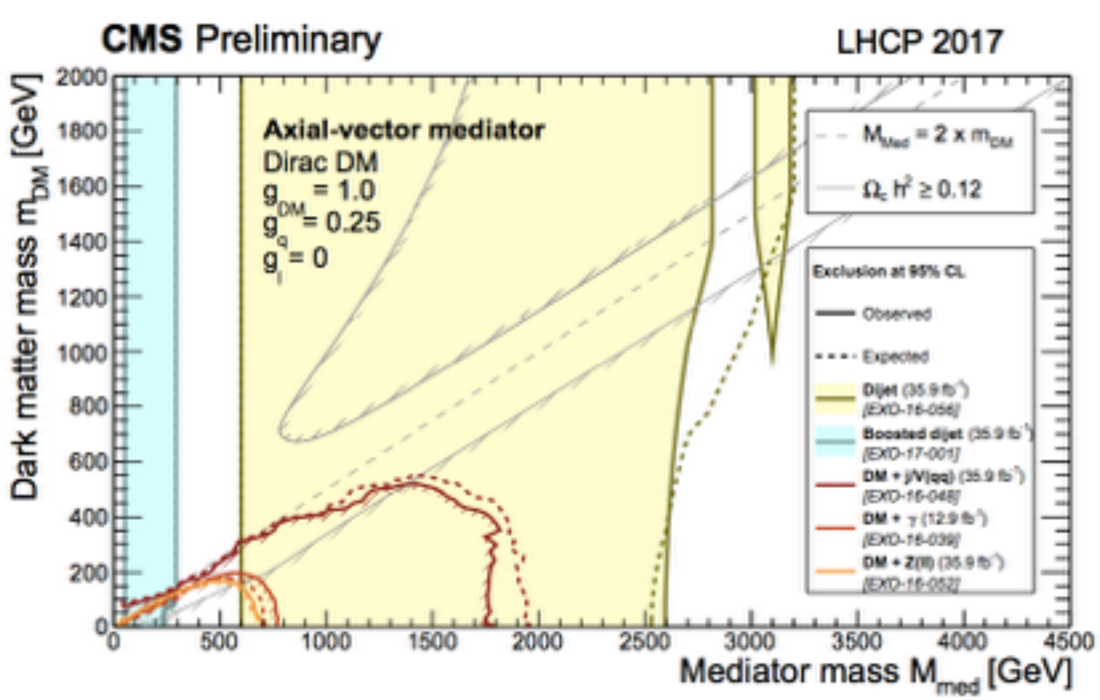
- ArXiv:1407.8257, 1507.00966, 1603.04156
- Define simplified model with (minimum) 4 parameter (mediator mass, DM mass, mediator coupling, DM coupling)
- Nature of dark matter candidate (Dirac fermion, Majorana fermion, Scalar (real), Scalar (complex))
- Nature of mediator (Vector, Scalar, Axial-vector, Pseudoscalar)

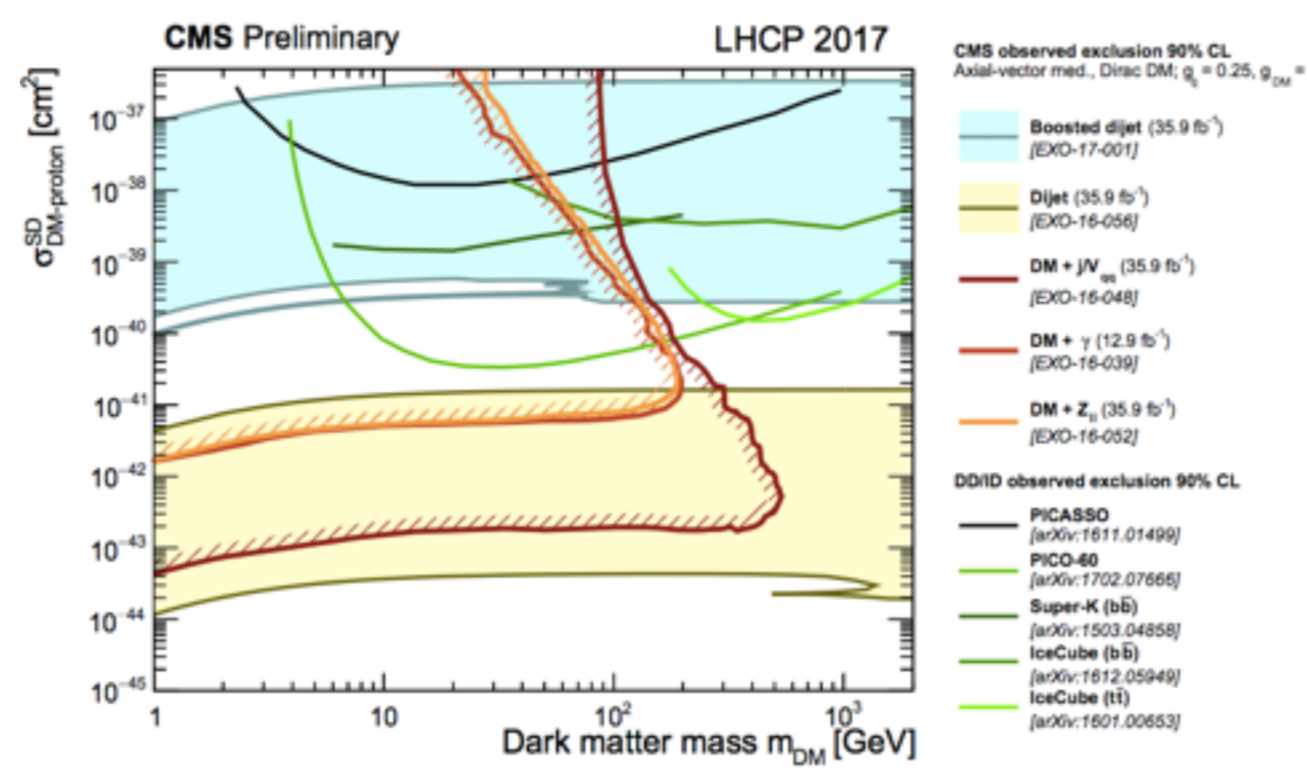


Dark Matter Searches

- ➡ **Results are always model-dependent**
- ➡ **Complementarity of direct dark matter experiment and LHC searches**
- ➡ **Example shows Vector and Axial-vector mediator**



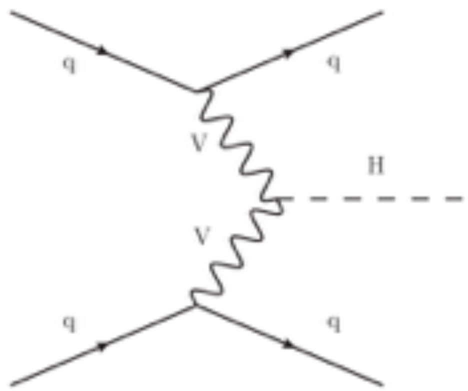


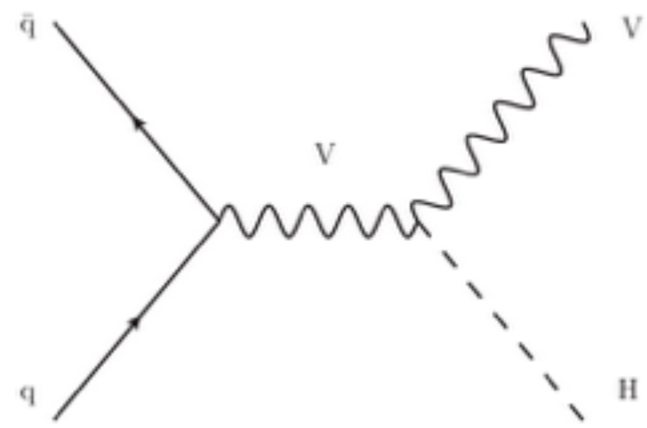


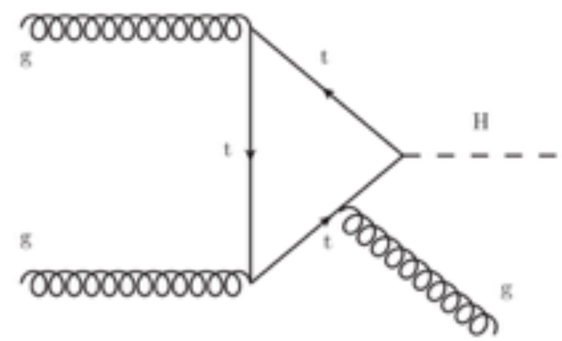
CMS DM Summary (Jul'17)

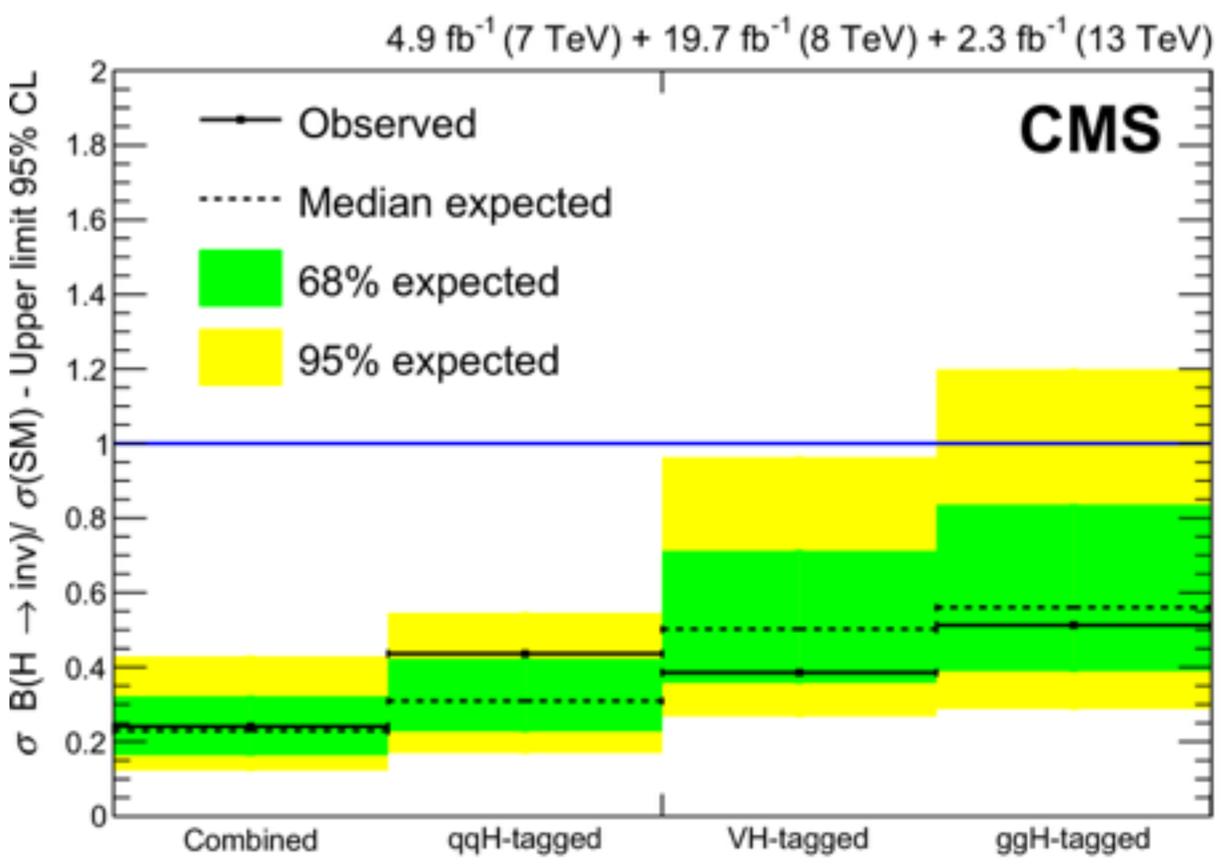
Dark Matter Searches

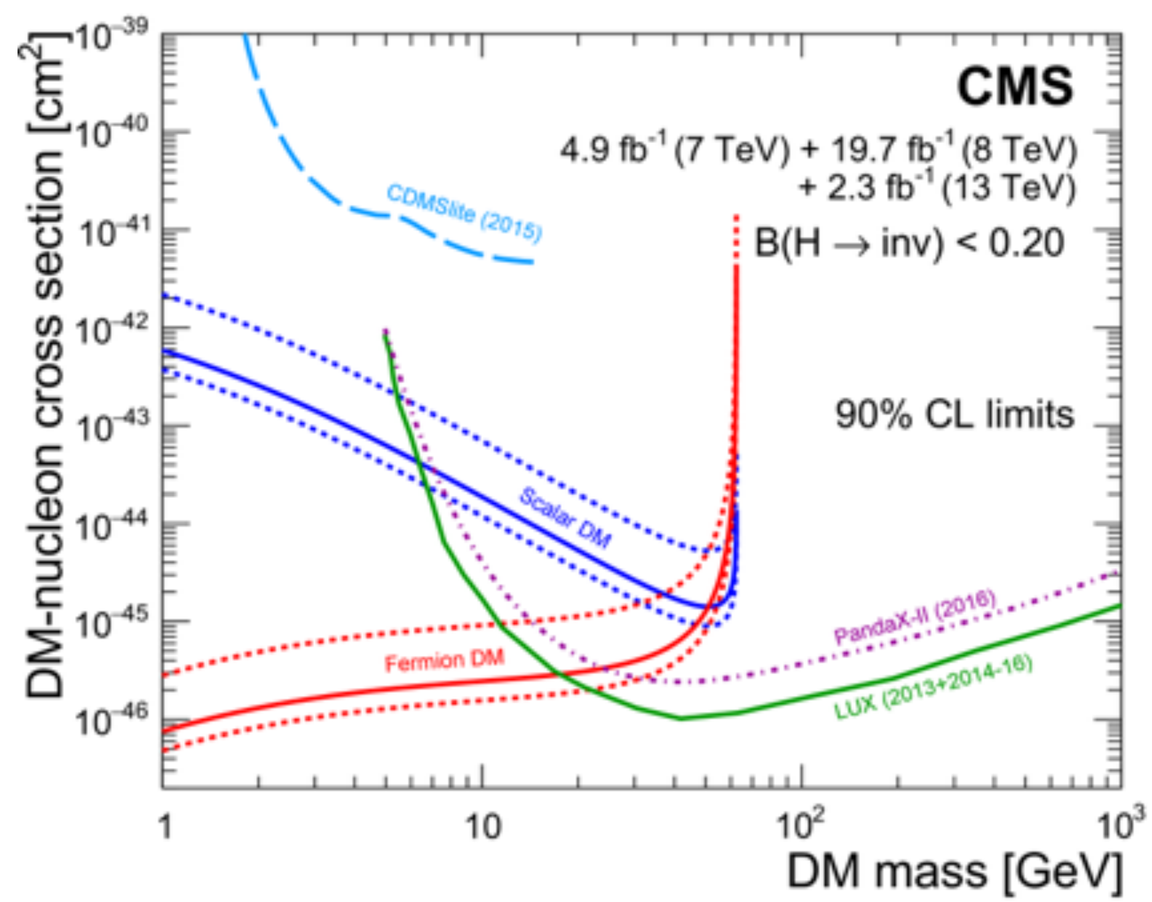
➡ **Higgs boson as portal to new physics**









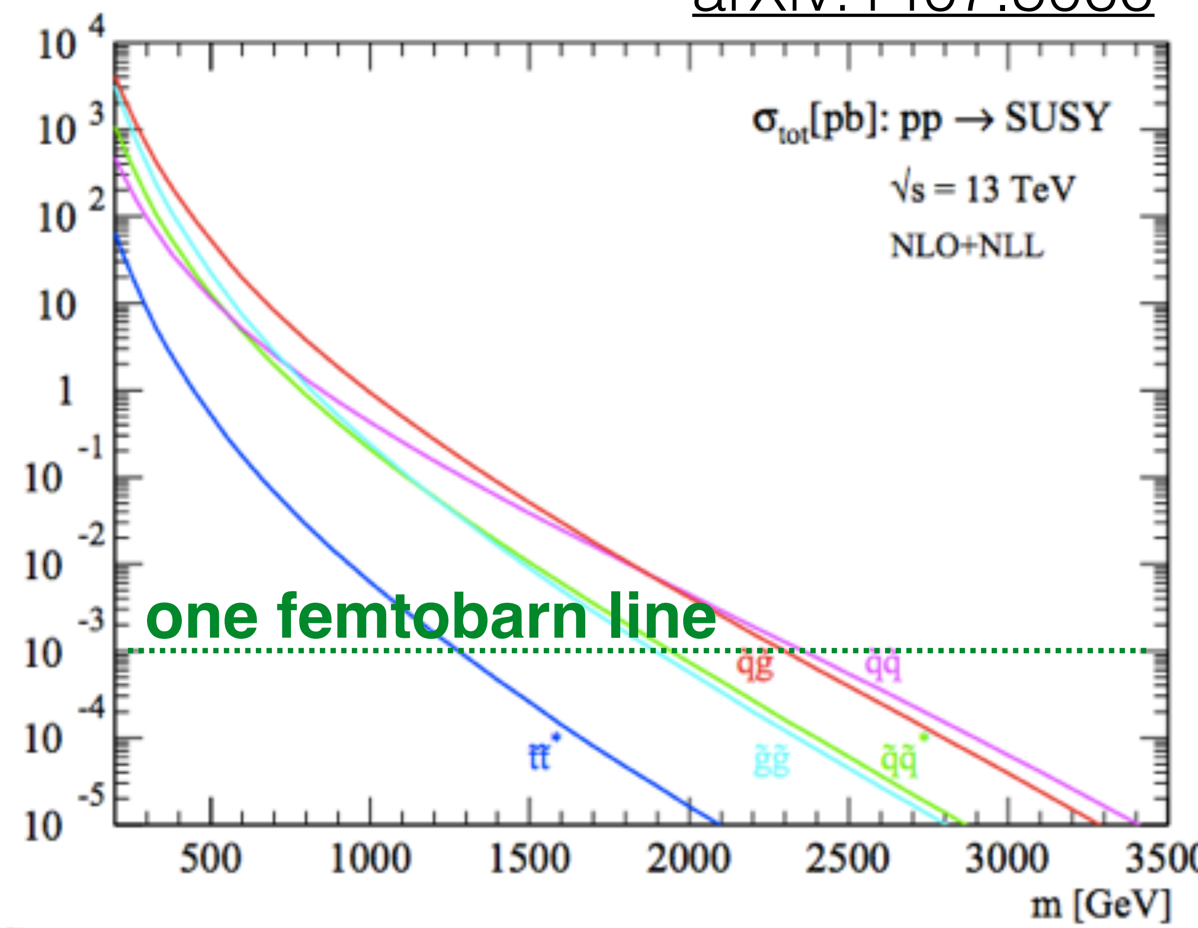


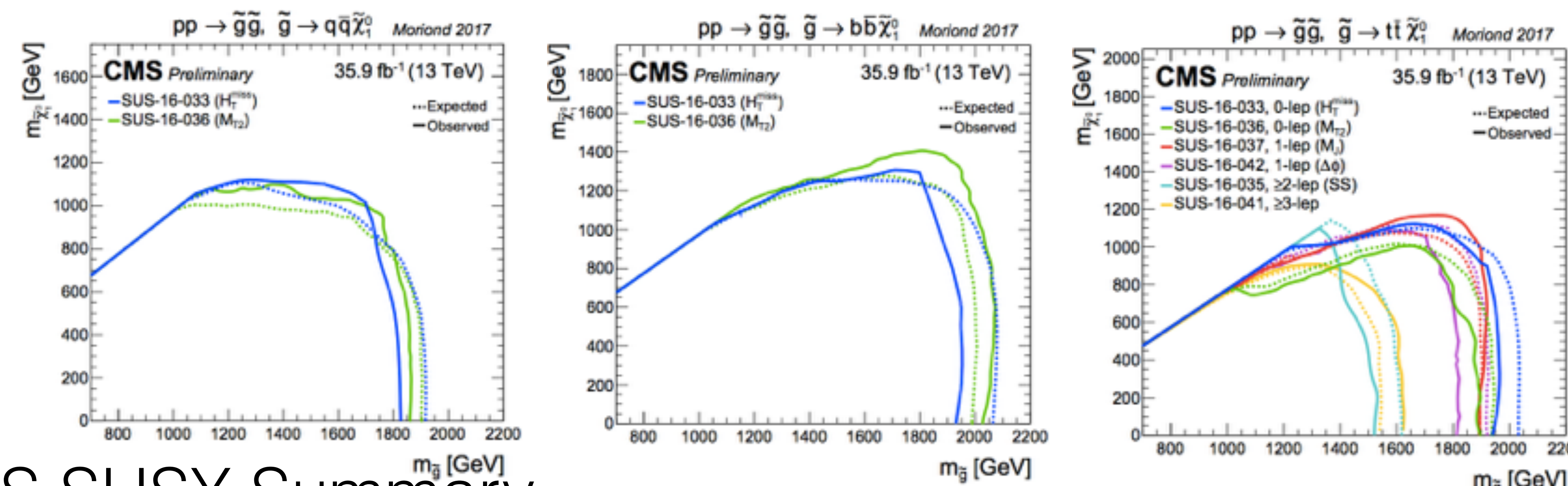
CMS-HIG-16-016 published in JHEP

Supersymmetry

arXiv:1407.5066

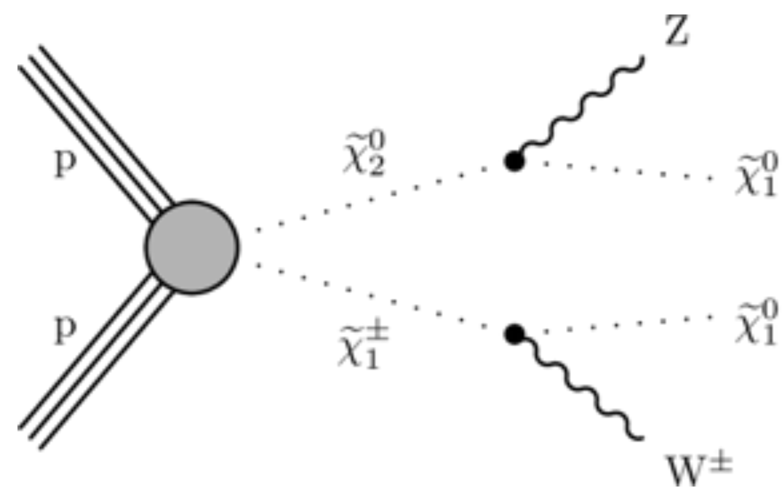
- ➡ **Possibility to discover massive new particles**
- ➡ **Gluinos and 1st/2nd generation squarks up to ~2 TeV**
- ➡ **3rd generation squarks up to ~1 TeV**
- ➡ **Charginos, neutralinos, and sleptons produced via weak interaction with smaller cross sections**
- ➡ **Example: gluino results considering various decay chains (light quarks, bottom, or top)**

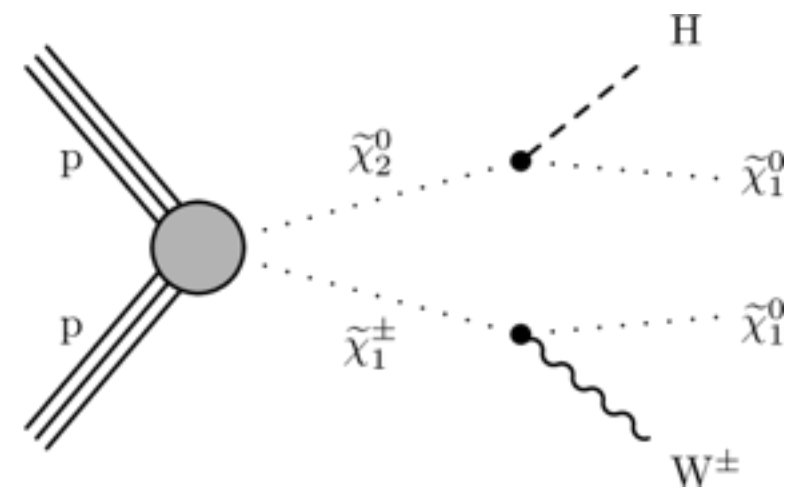


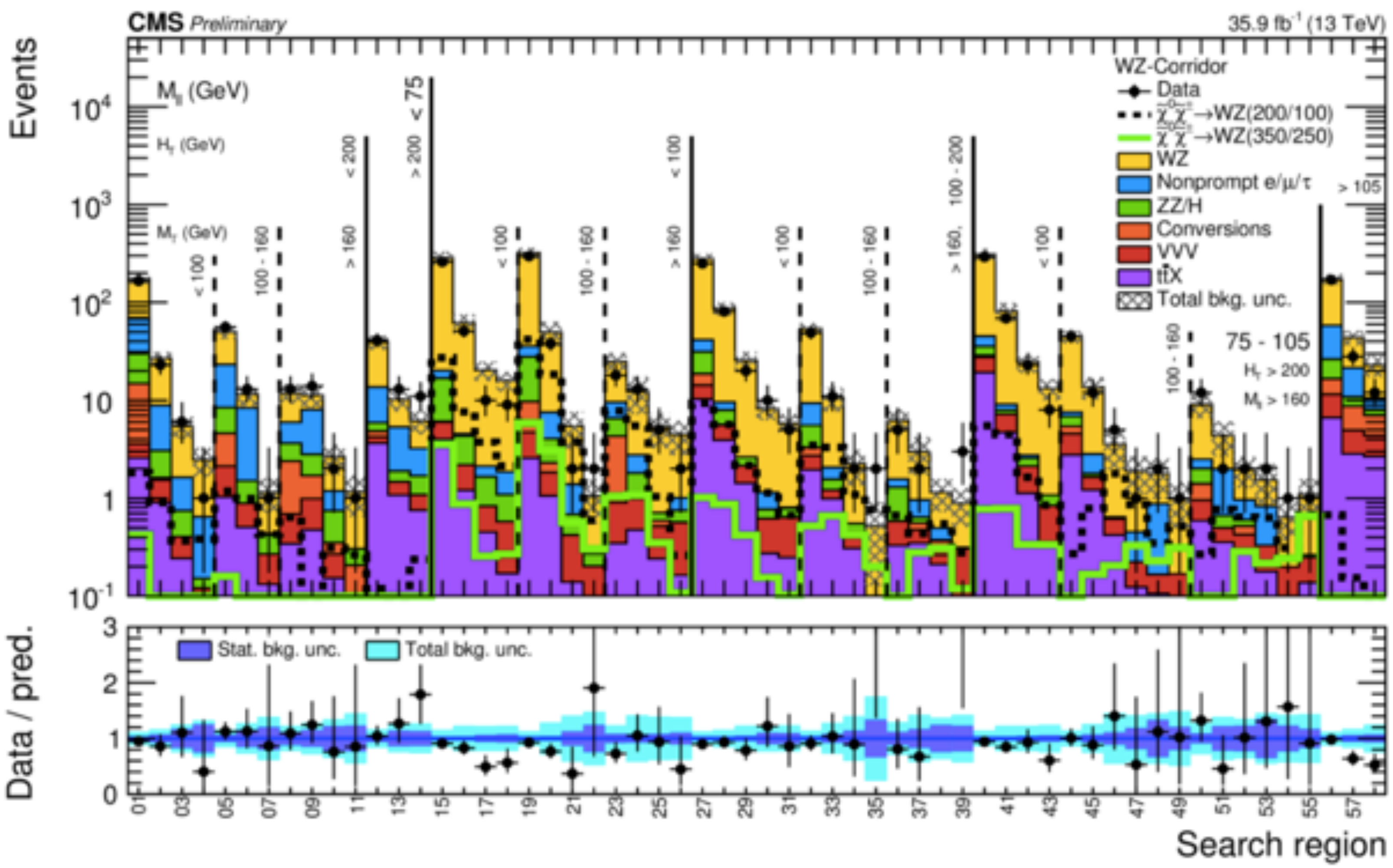


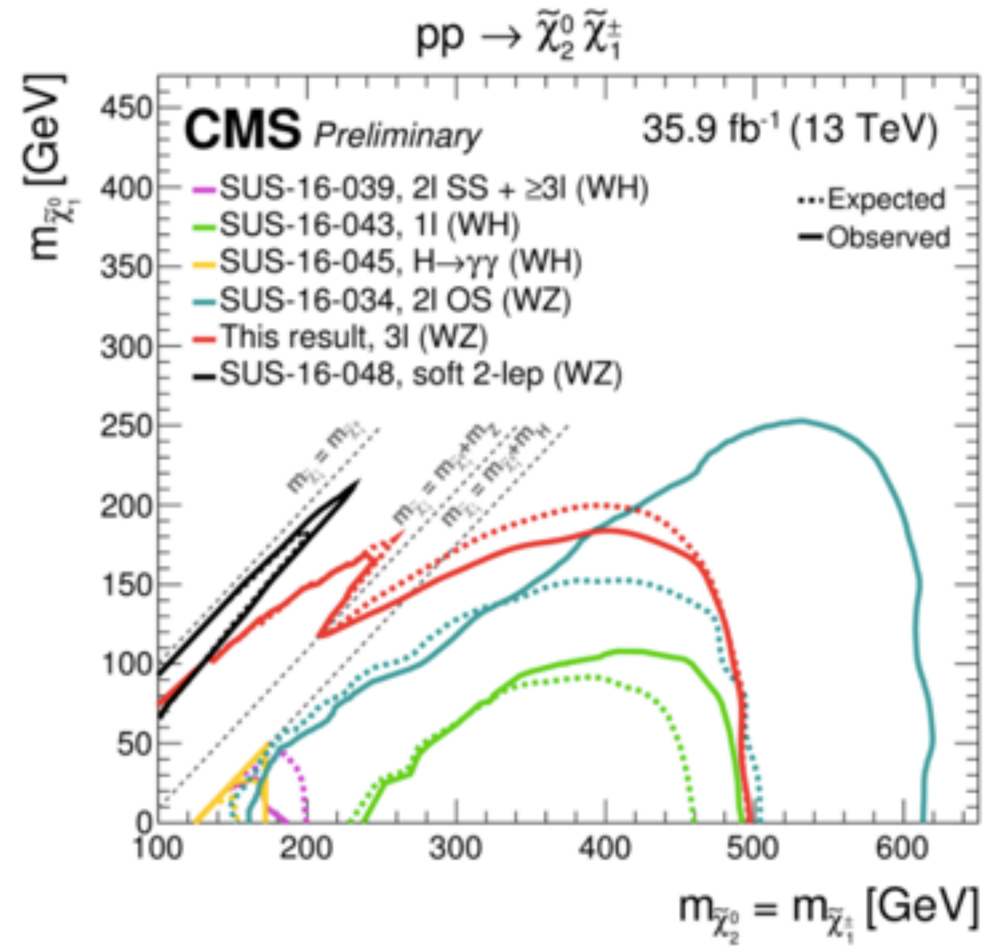
CMS SUSY Summary

Electroweak SUSY



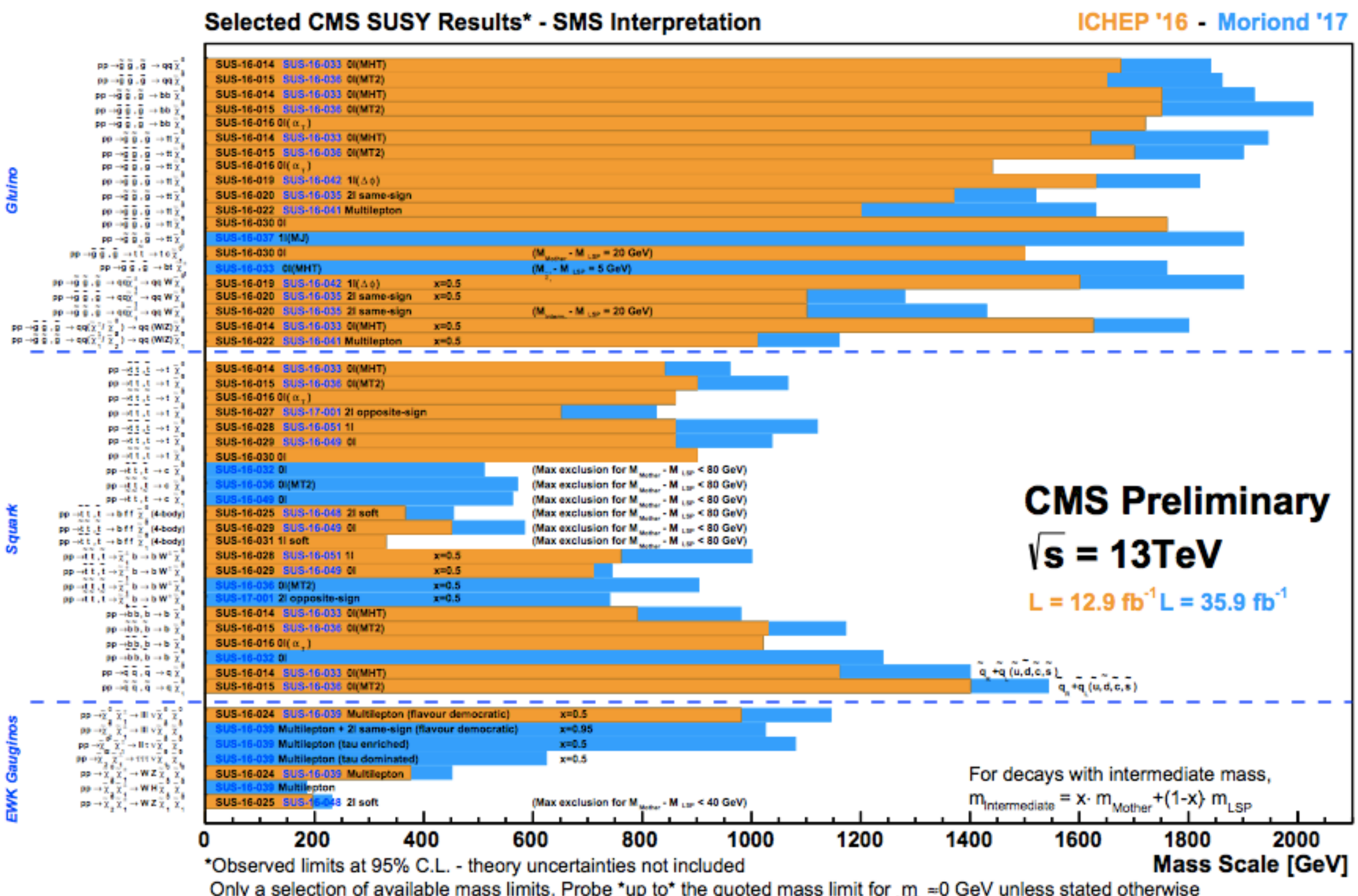






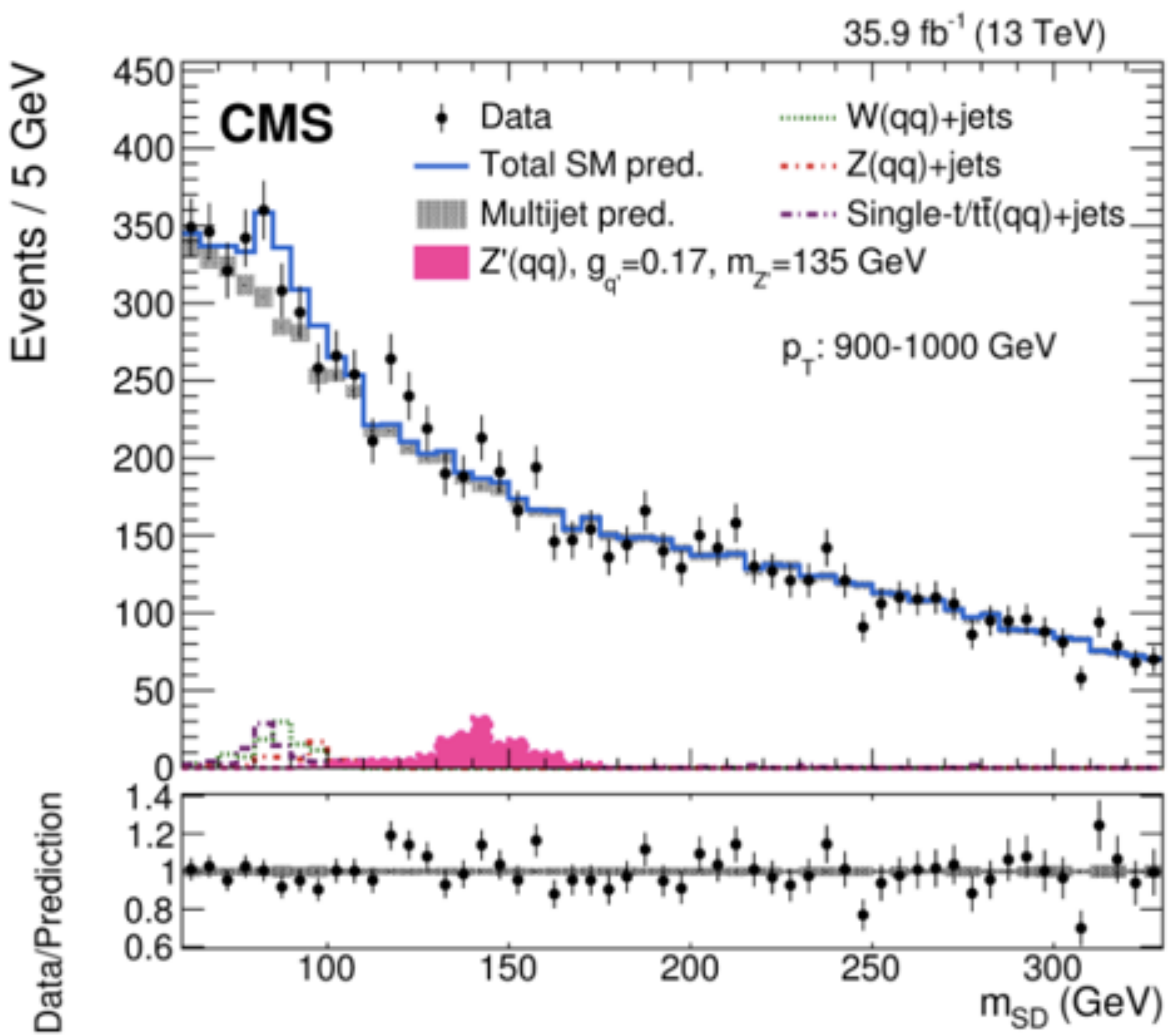
CMS-PAS-SUS-17-004

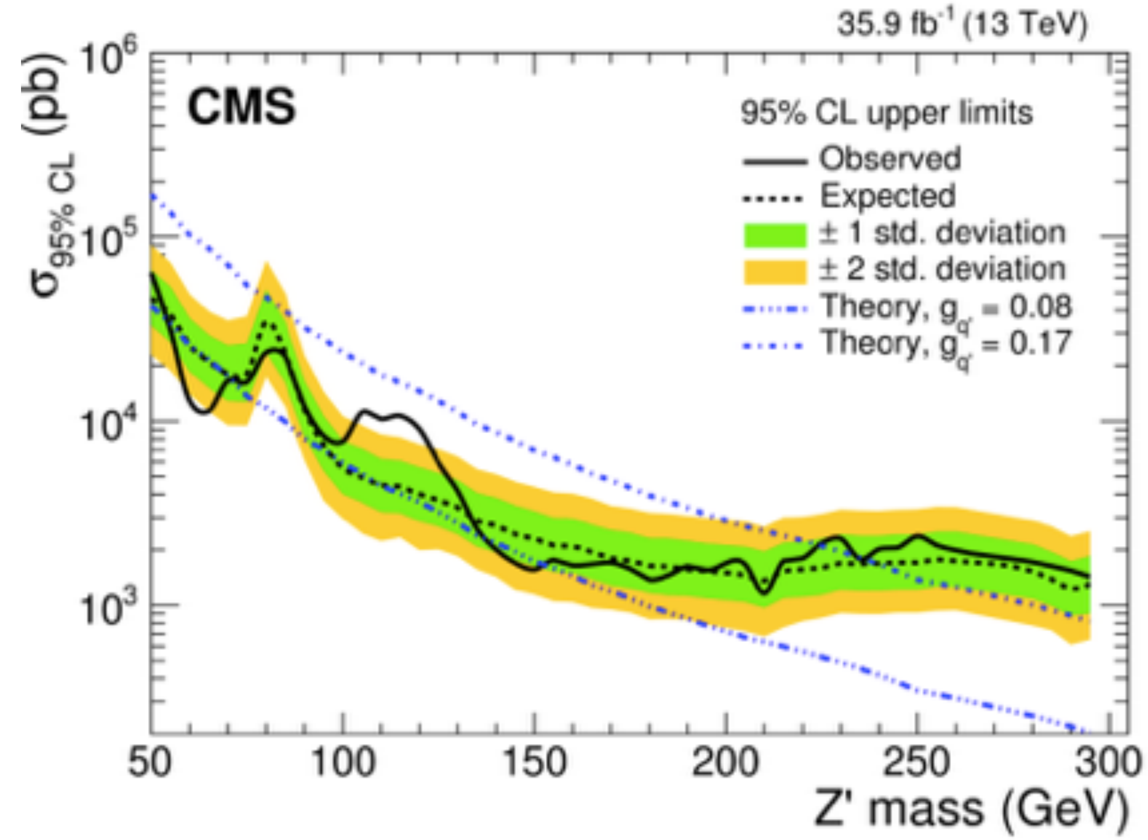
Supersymmetry

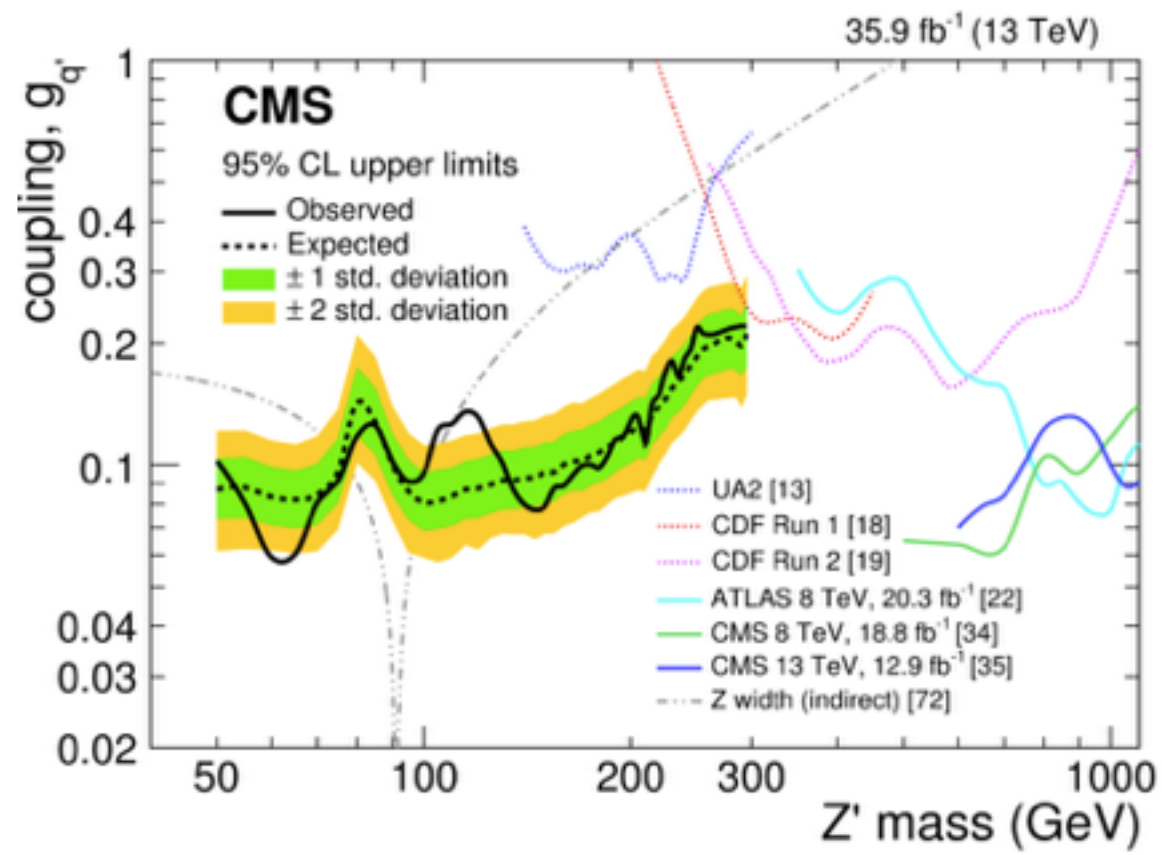


Resonances: Dijets

- ➡ Search for **low mass** vector resonances
- ➡ Utilizing boosted events (ISR) with p_T > 500 GeV
- ➡ Excess at 115 GeV with 2.9σ (2.2σ) local (global) significance

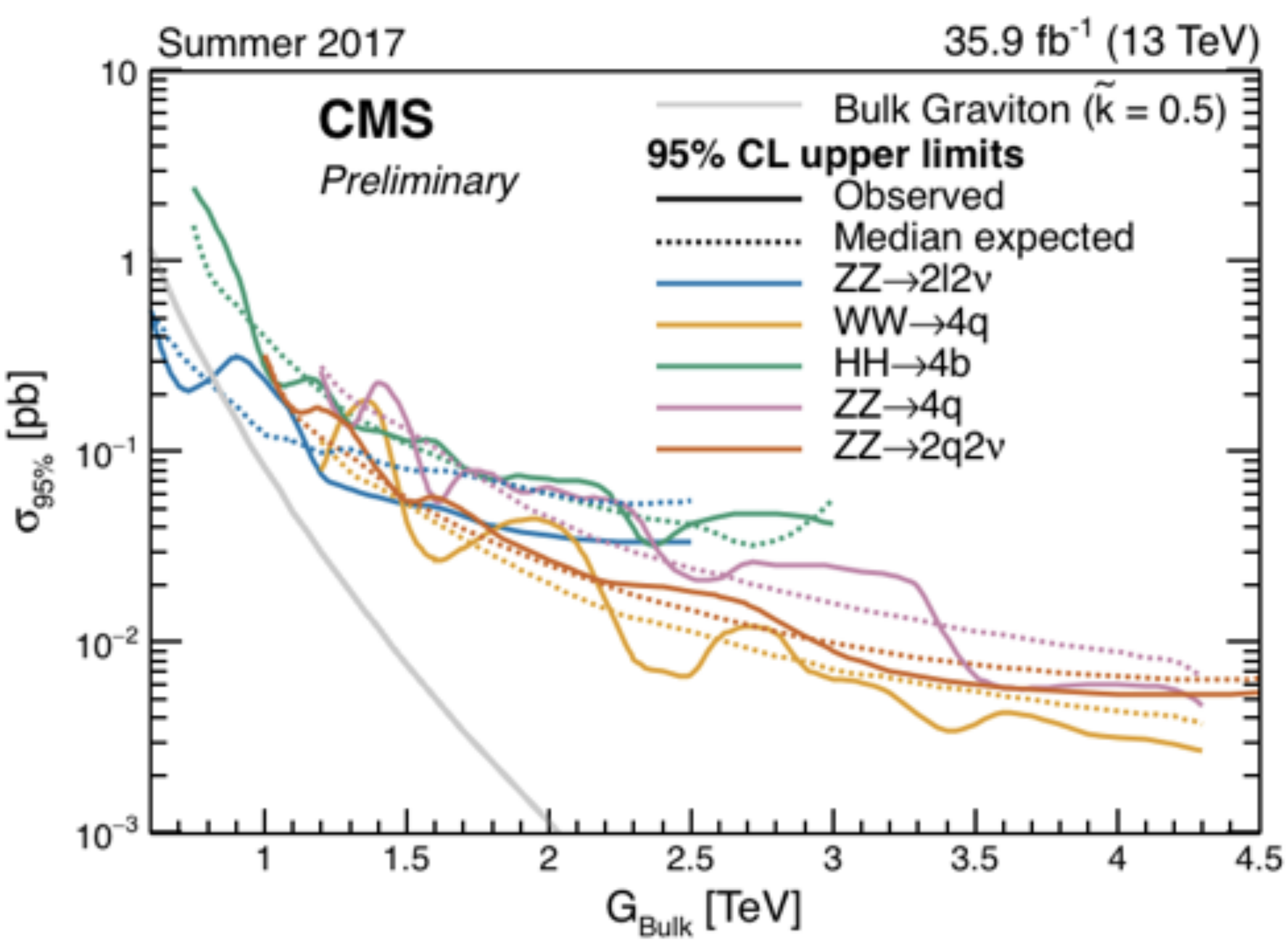


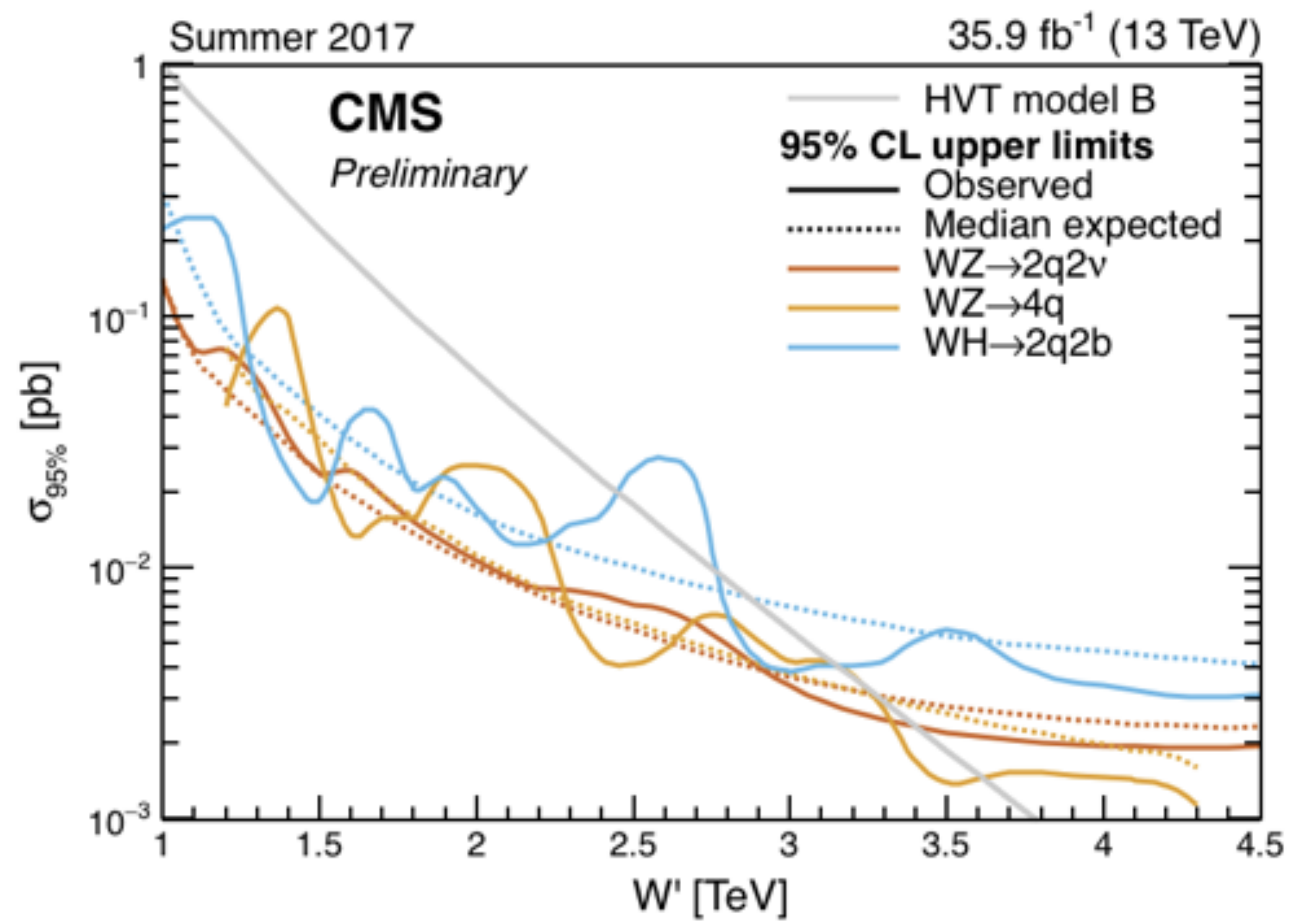




Resonances: Dibosons

- ➡ **Exhaustive list of signatures considered**
- ➡ **Exploring VBF and gluon fusion production modes**
- ➡ **Interpretations in various models**

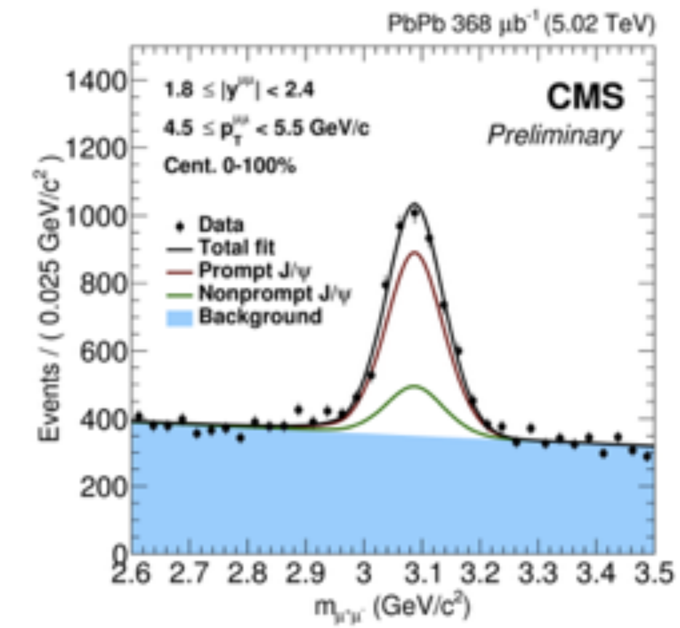


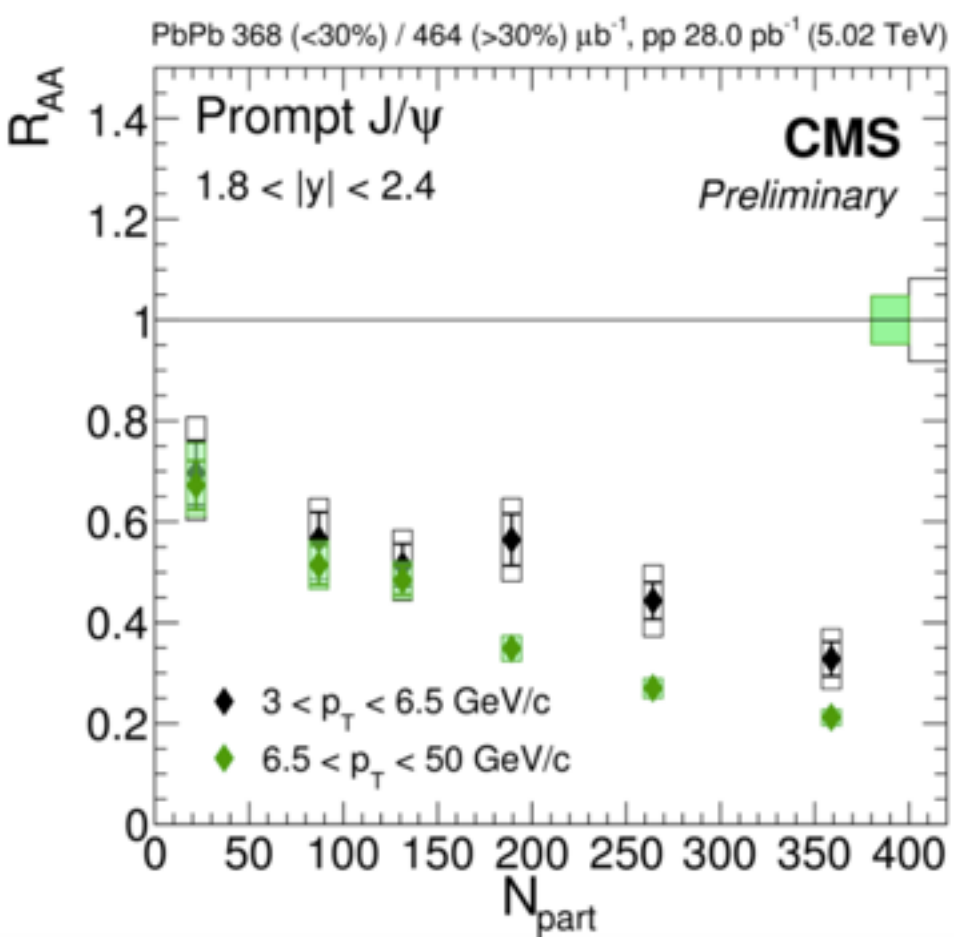


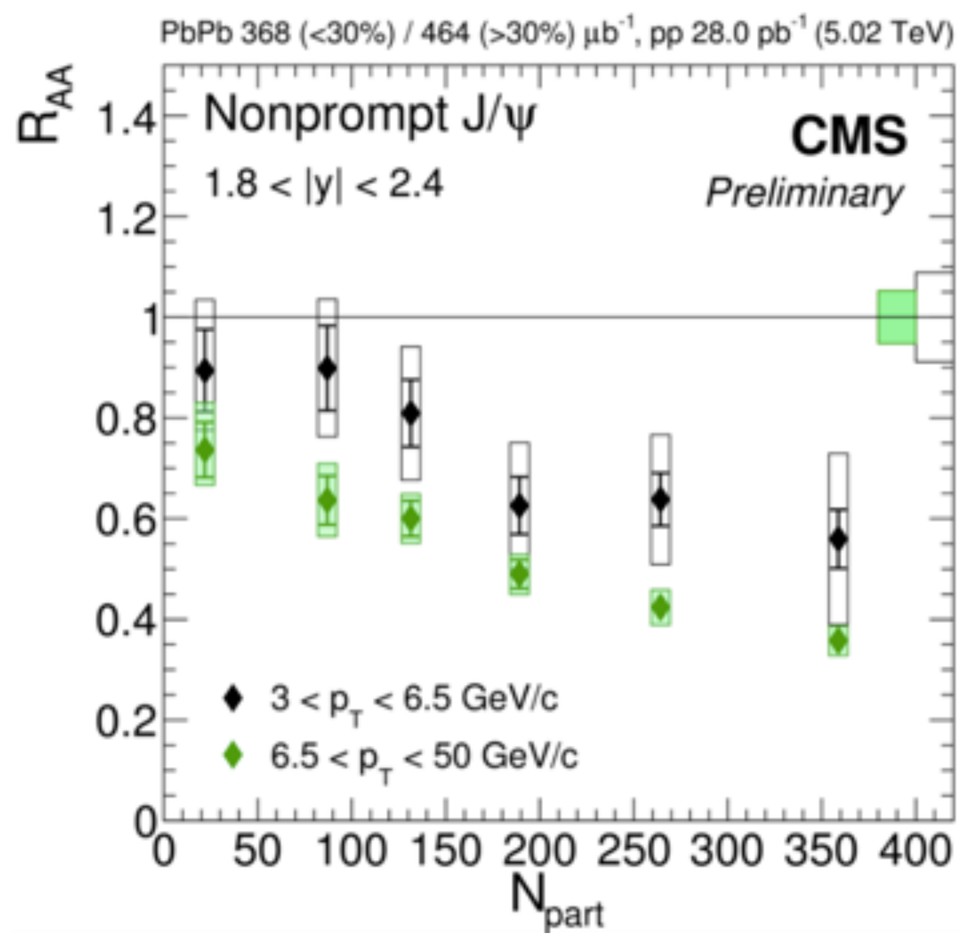
CMS Diboson Summary

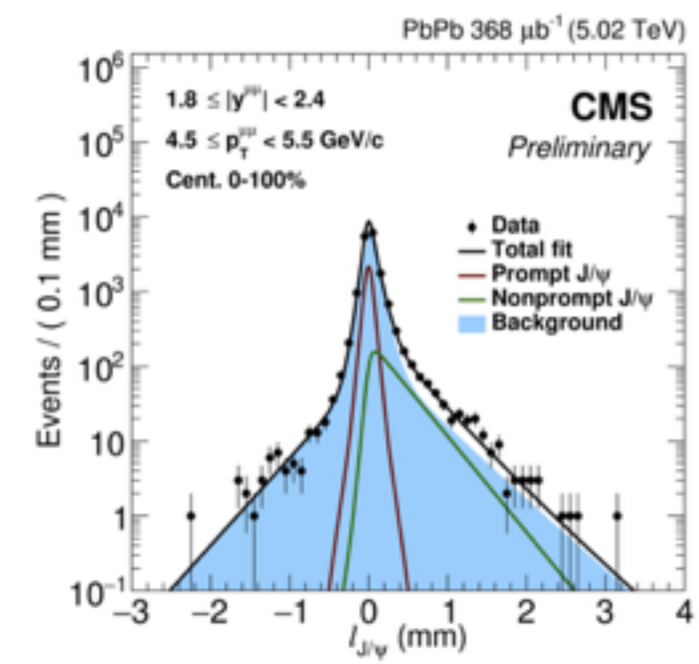
Heavy Ion Physics

- ➡ **Charmonium suppression in PbPb collisions at 5.02 TeV**
- ➡ **Studied in prompt and non-prompt J/ and (2S) production and compared to pp collisions**
    - Large kinematic reach: 3 GeV < p_T < 50 GeV, |y| < 2.4
- ➡ **Two potential effects in nuclear modification factor**
    - Suppression due to screening in hot medium. Probing deconfinement & quark gluon plasma formation
    - Recombination of heavy quarks when abundantly produced at low p_T
- ➡ **Indications for smaller suppression at lower p_T**









CMS-PAS-HIN-16-025

Conclusion

- ➡ **CMS celebrated its 25th Birthday, aiming for additional 20+ years of data taking and physics production**
- ➡ **Prepared detector with Phase-I upgrade for more challenging environment. Phase-II upgrades are well under way to address HL-LHC demands**
- ➡ **Large dataset provided by the LHC allows to probe smaller coupling and larger mass range**
  - Observing new SM processes and improving precision on old friends
  - Higgs physics turning into precision program
  - Stringent limits on Dark Matter, SUSY, and other Exotics
    - A few excesses to look out for
  - Heavy Ion program exploring rich datasets. Adding XeXe collisions tomorrow
- ➡ **Doubling 13 TeV dataset in 2017 with big expectations for 2018**