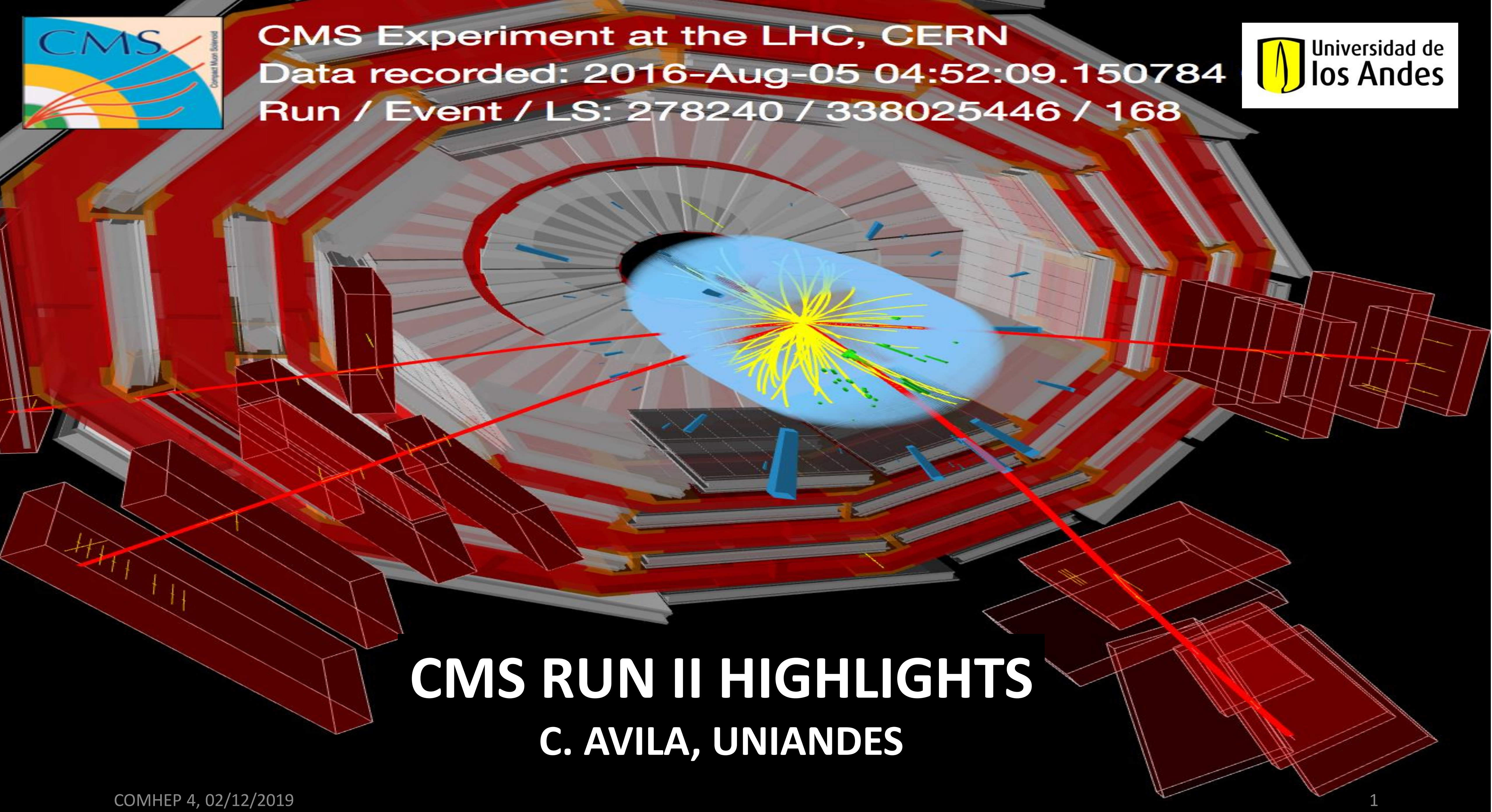


Universidad de los Andes

CMS RUN II HIGHLIGHTS

C. AVILA, UNIANDES

TALK OUTLINE

1. Introduction

2. Status of CMS Experiment

- CMS Performance 2015-2018, 13 TeV

3. Highlights of run II Measurements, 13 TeV

- Higgs Physics Results
- Few BSM searches

(other three talks in this workshop covering other important topics:
- Searches for exotic signatures with the ATLAS detector: Gabriela Navarro
- Heavy favor physics in CMS: Jhovanny Mejia
- Searches for DM at the LHC: Andreas Albert)

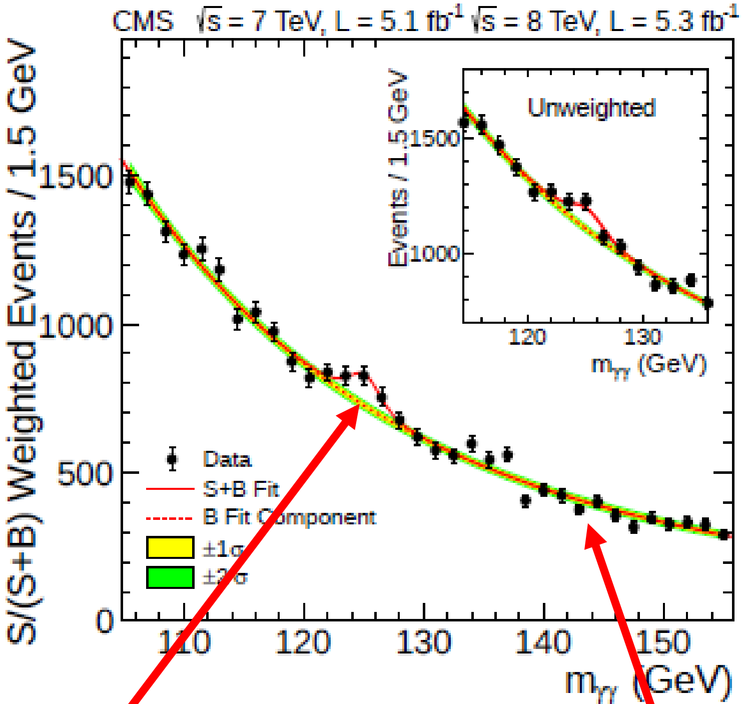
4. Prospects for HL-LHC

5. Summary and conclusions

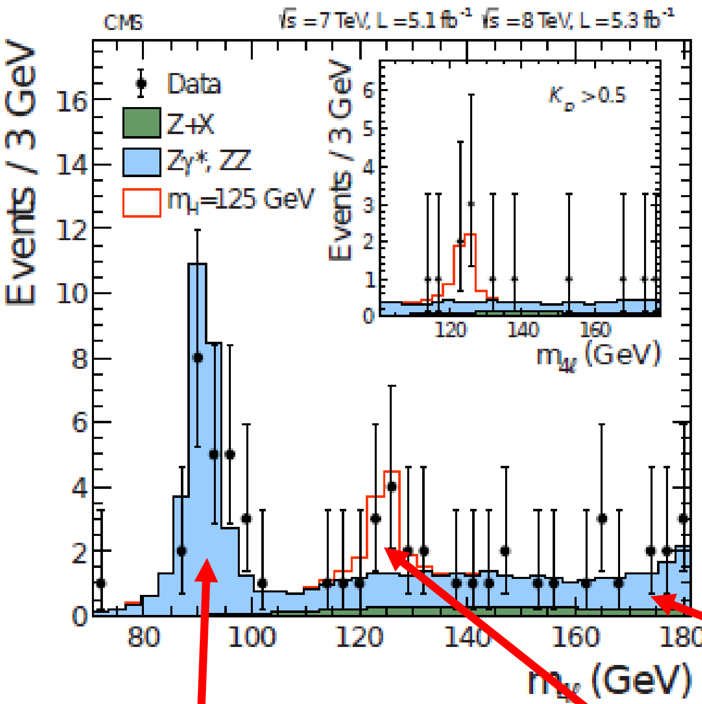
1. INTRODUCTION

MAIN ACHIEVEMENT OF LHC RUN I : HIGGS BOSON DISCOVERY

H→ γγ

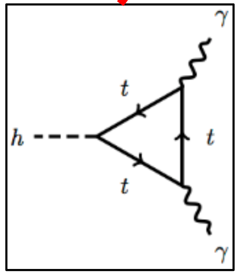


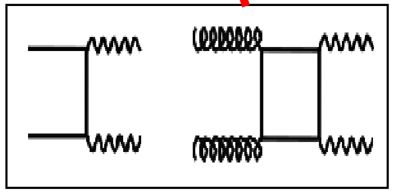
H→ZZ→4ℓ (4μ, 2e2μ,4e)

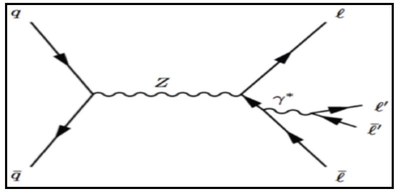


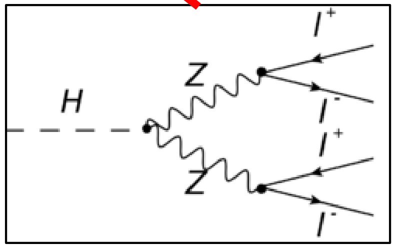
[Phys. Lett. B 716 (2012) 30](#)

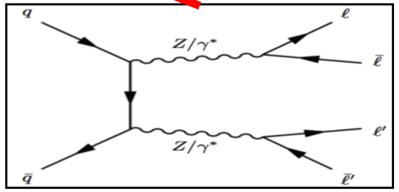
- Discovery announced on July 4 2012 with ~ 10 fb^{-1} of data.
- Main Discovery channels: Full final states reconstructed.
- Full kinematics info very important to reduce backgrounds.







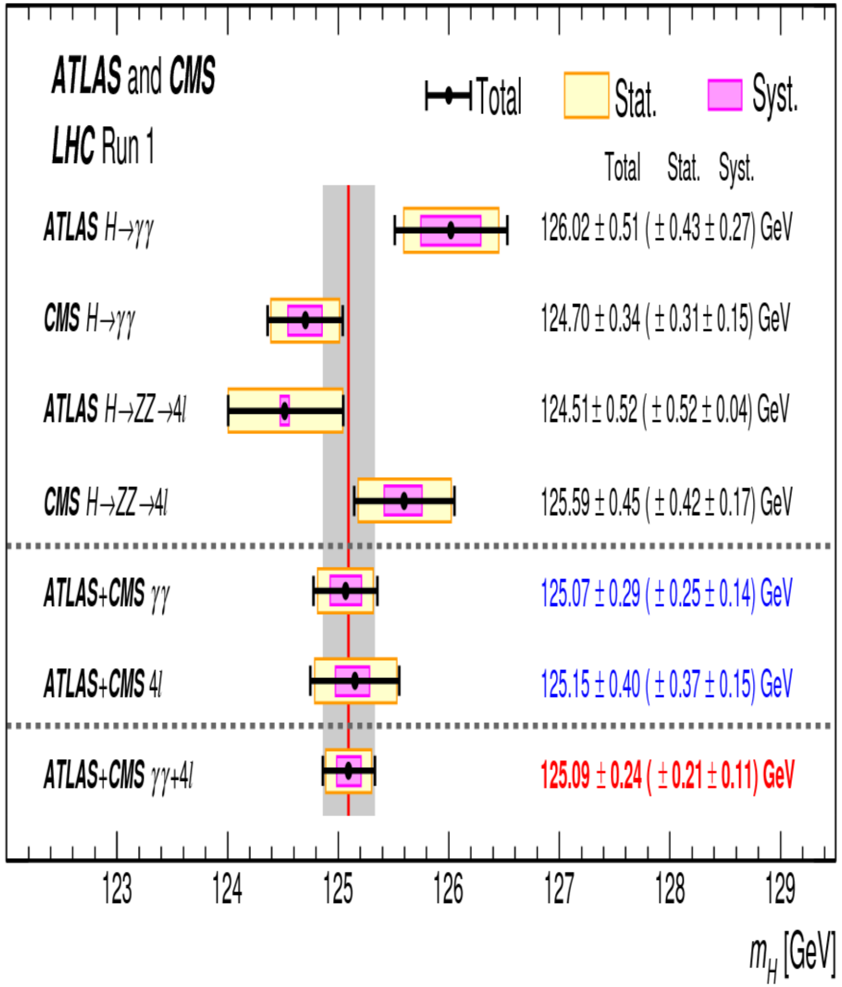


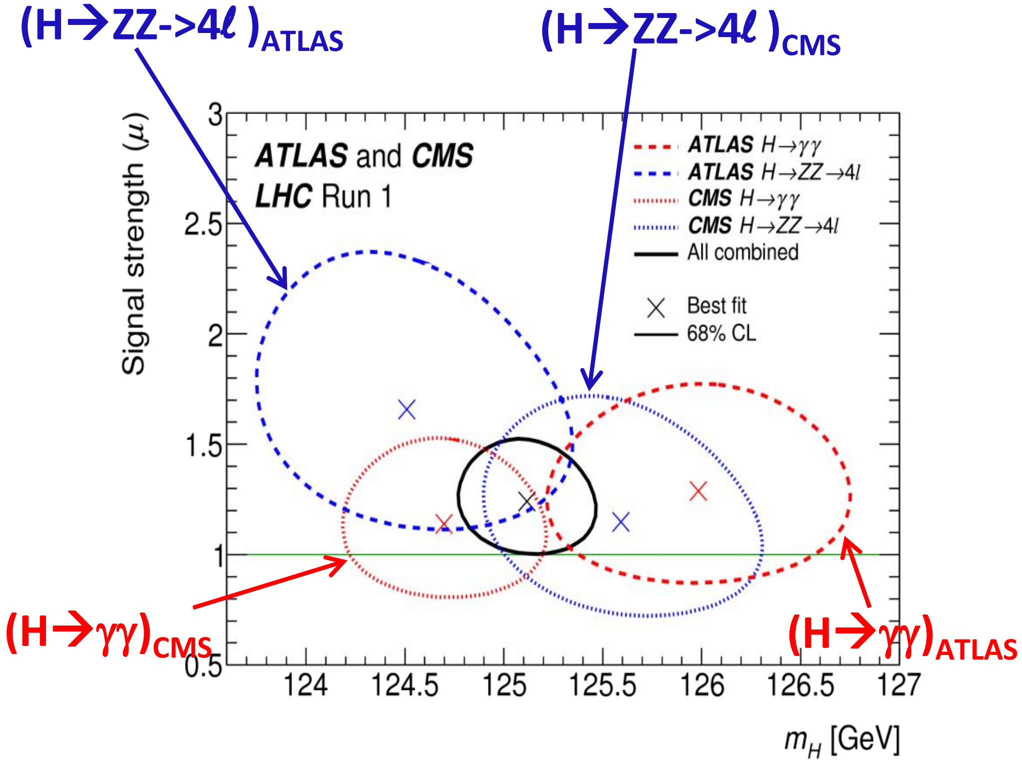


RUN I MASS MEASUREMENT

Combined measurement of ATLAS + CMS (H→ γγ , H→ZZ)

Phys. Rev. Lett. 114 (2015) 191803




$(H \to ZZ\text{->}4\ell)_{ATLAS}$

$(H \to ZZ\text{->}4\ell)_{CMS}$

$(H \to \gamma\gamma)_{CMS}$

$(H \to \gamma\gamma)_{ATLAS}$

$$\boxed{m_H = 125.09 \pm 0.21 \pm 0.11 \text{ GeV}}$$

0.19 % Uncertainty, dominated by statistics

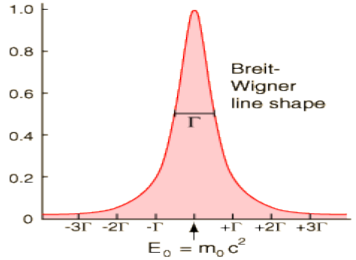
OTHER HIGGS PROPERTIES MEASURED WITH RUN I DATA

- Higgs width (Γ_H^{SM} ~ 4 MeV) from on-shell/off-Shell ZZ and WW production, combined (JHEP 09 (2016) 051):

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm_{ZZ}^2} \sim \frac{g_{ggH}^2\, g_{HZZ}^2}{\left(m_{ZZ}^2 - m_H^2\right)^2 + m_H^2\Gamma_H^2}$$

$$\boxed{\frac{\sigma^{\text{off-shell}}}{\sigma^{\text{on-shell}}} \sim \Gamma_H}$$

Γ_H< 13 (26) MeV at 95% CL



- Lifetime ($\tau_{H,SM}$ = 16 x 10^{-8} fs) (Phys. Rev. D 92, 072010 (2015)):

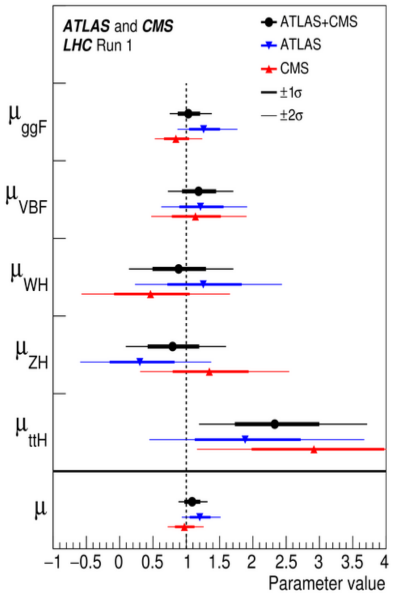
$$\Delta t = \frac{m_{4\ell}}{p_T}\left(\Delta\vec{r}_T \cdot \hat{p}_T\right)$$

τ_H<1.9x10^{-13} s 95% CL

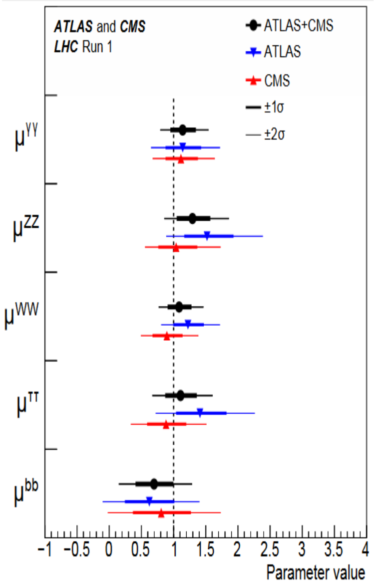
- Signal strength : $\mu = \frac{\sigma}{\sigma_{SM}}$ (JHEP 08 (2016) 045)

$$\boxed{\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\ (\text{stat})\ ^{+0.04}_{-0.04}\ (\text{expt})\ ^{+0.03}_{-0.03}\ (\text{thbgd})^{+0.07}_{-0.06}\ (\text{thsig})}$$

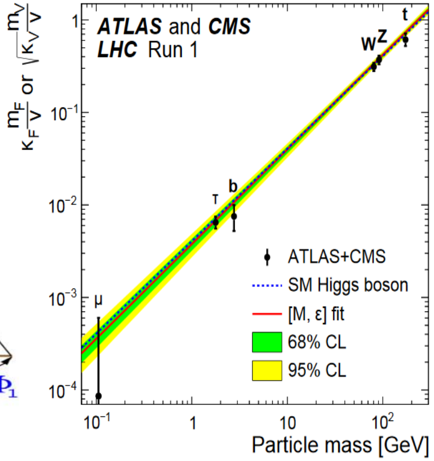
$\mu_{\text{PRODUCTION}}$



μ DECAY

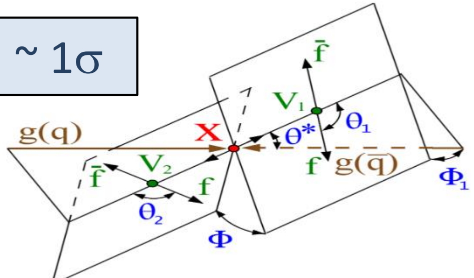


- Higgs couplings (JHEP 08 (2016) 045):

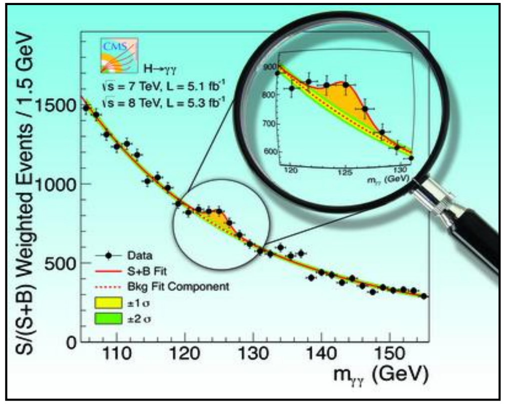


- SPIN-Parity (Phys. Rev. D 92, 012004 (2015))

- Data are compatible with 0^+ within ~ 1σ



RUN I MEASUREMENTS OF HIGGS PROPERTIES



HIGGS PROFILE AT LHC RUN I (~25 fb^{-1})

Fully compatible with SM, within uncertainties

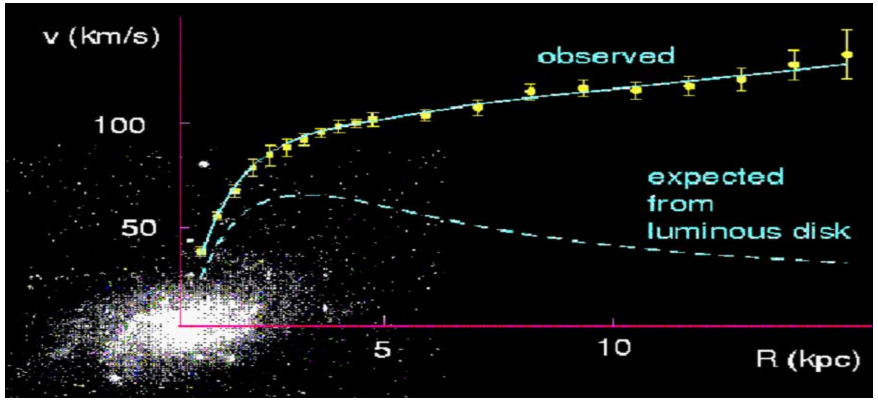
1. Mass ✓
2. Width – Lifetime ✓
3. Signal Strength ✓
4. Couplings ✓
5. Spin – Parity ✓

All particles predicted by the SM are now experimentally confirmed.
Great success of the SM!

SM HIGGS

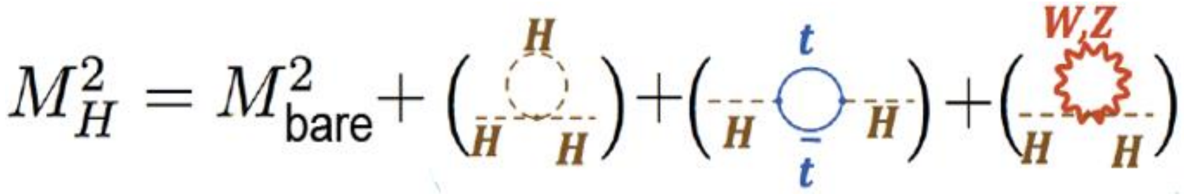
Despite all its success, the SM cannot be the complete story:

- SM does not explain dark matter



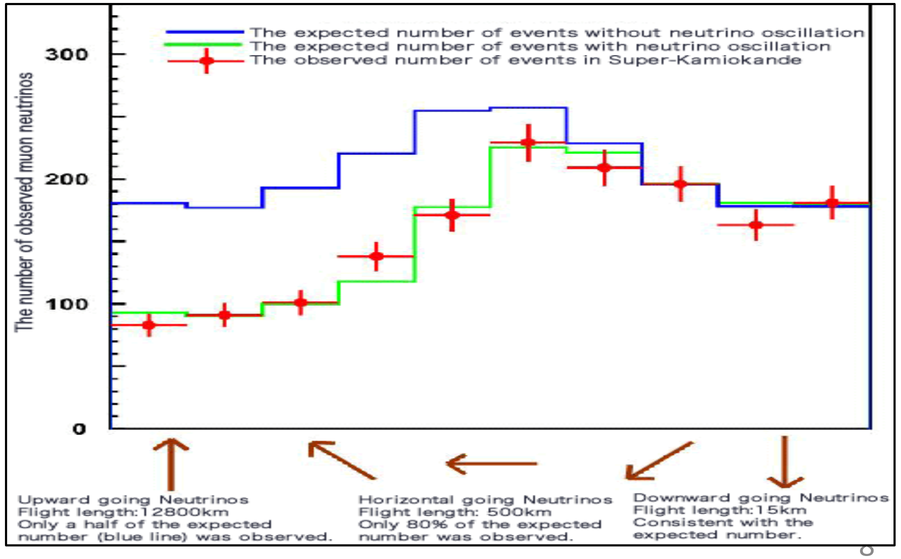
- Hierarchy problem: Loop corrections

to the Higgs Mass



$$M_H^2 = M_{\text{bare}}^2 + (\;) + (\;) + (\;)$$

- SM does not explain mass of neutrinos

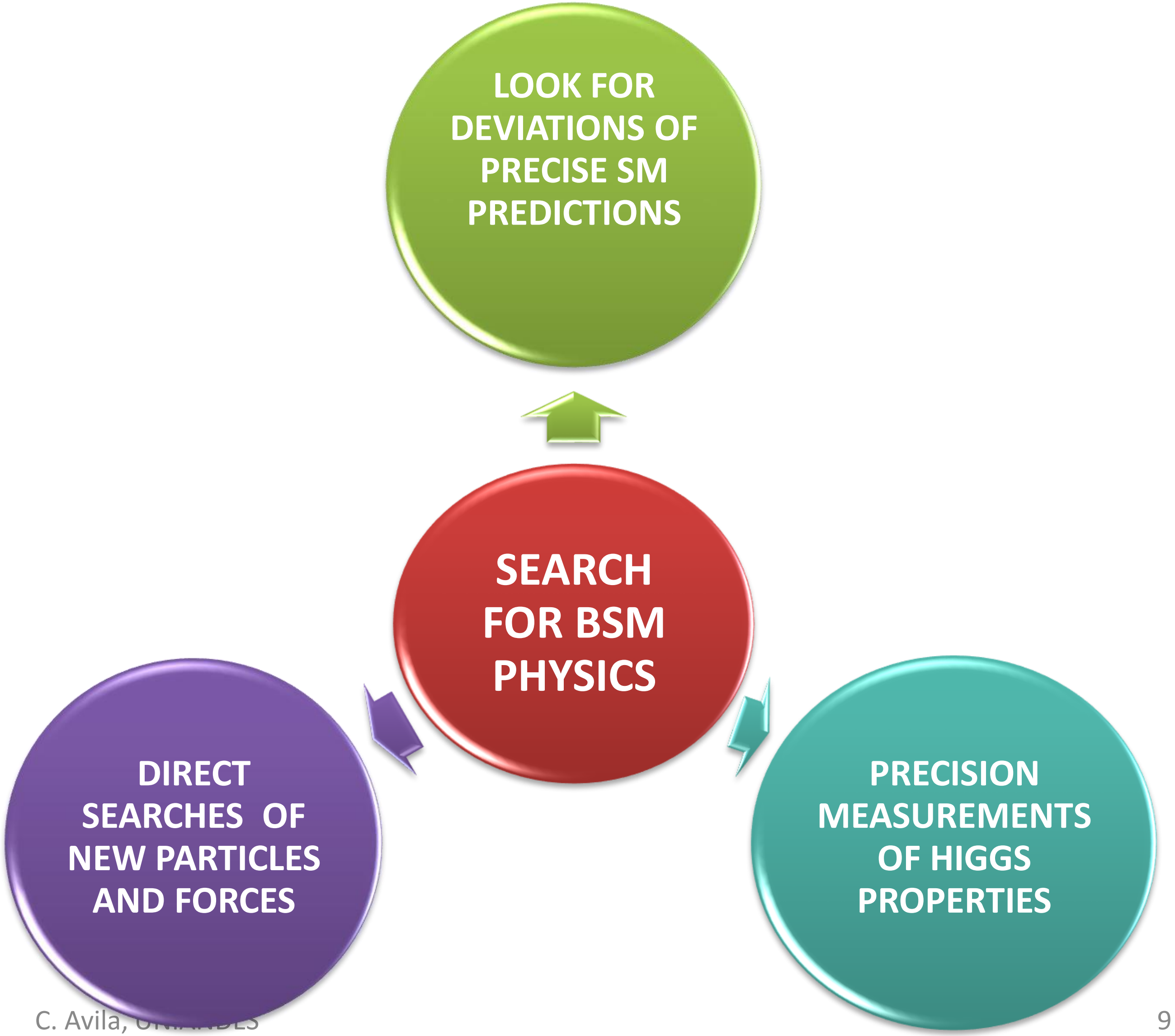


- SM does not include gravity

MAIN GOAL OF THE LHC EXPERIMENTS: SEARCH FOR BSM PHYSICS

- Strong physics motivation to search for signs of BSM at the TeV scale accesible to the LHC (natural SUSY, WIMP miracle, composite Higgs, etc.)

- No clear guidance on the parameter space to search for. (i.e. MSSM has 124 unknown parameters → Huge parameter space).



LOOK FOR DEVIATIONS OF PRECISE SM PREDICTIONS

SEARCH FOR BSM PHYSICS

DIRECT SEARCHES OF NEW PARTICLES AND FORCES

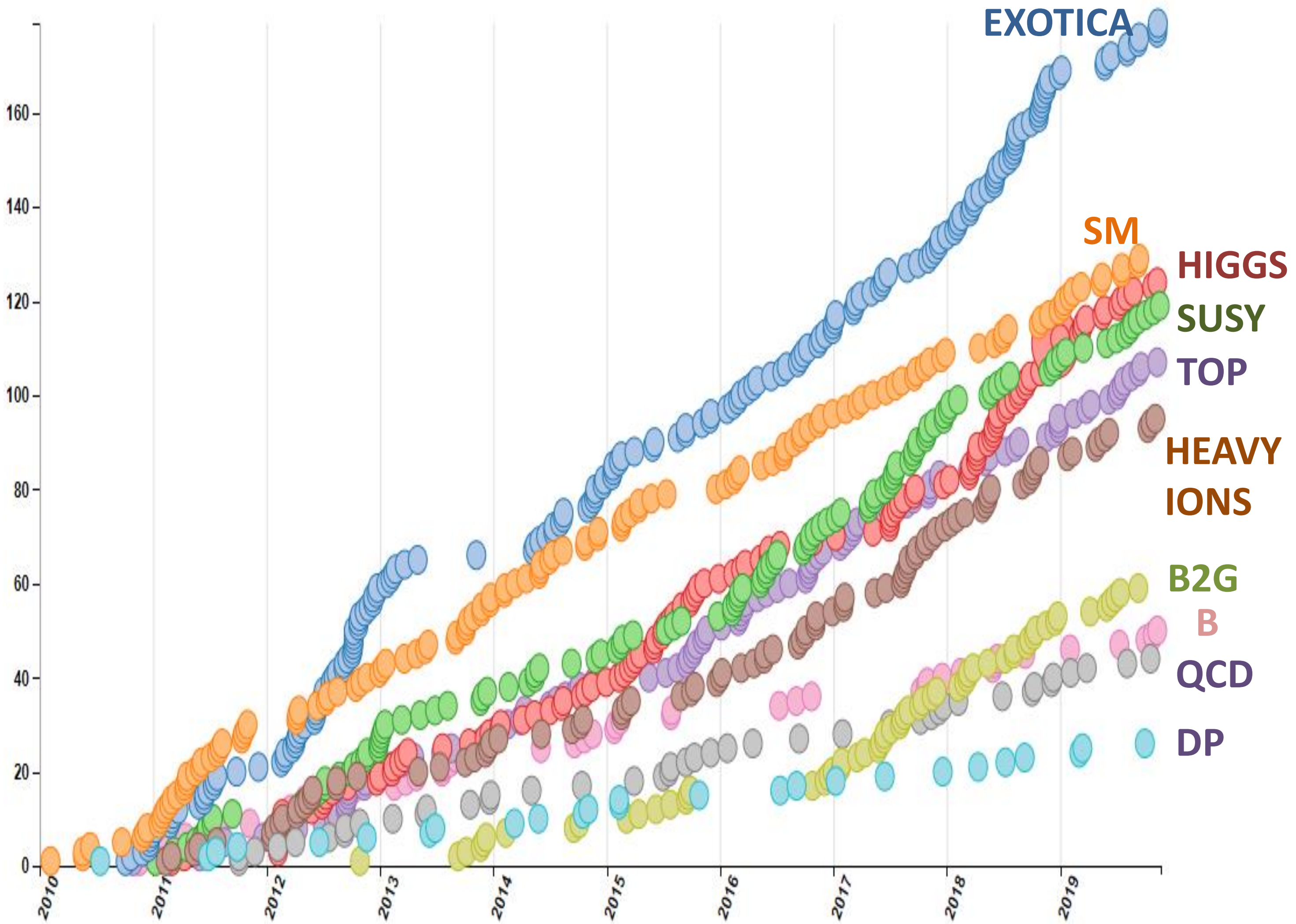
PRECISION MEASUREMENTS OF HIGGS PROPERTIES

FOCUS OF THIS TALK:

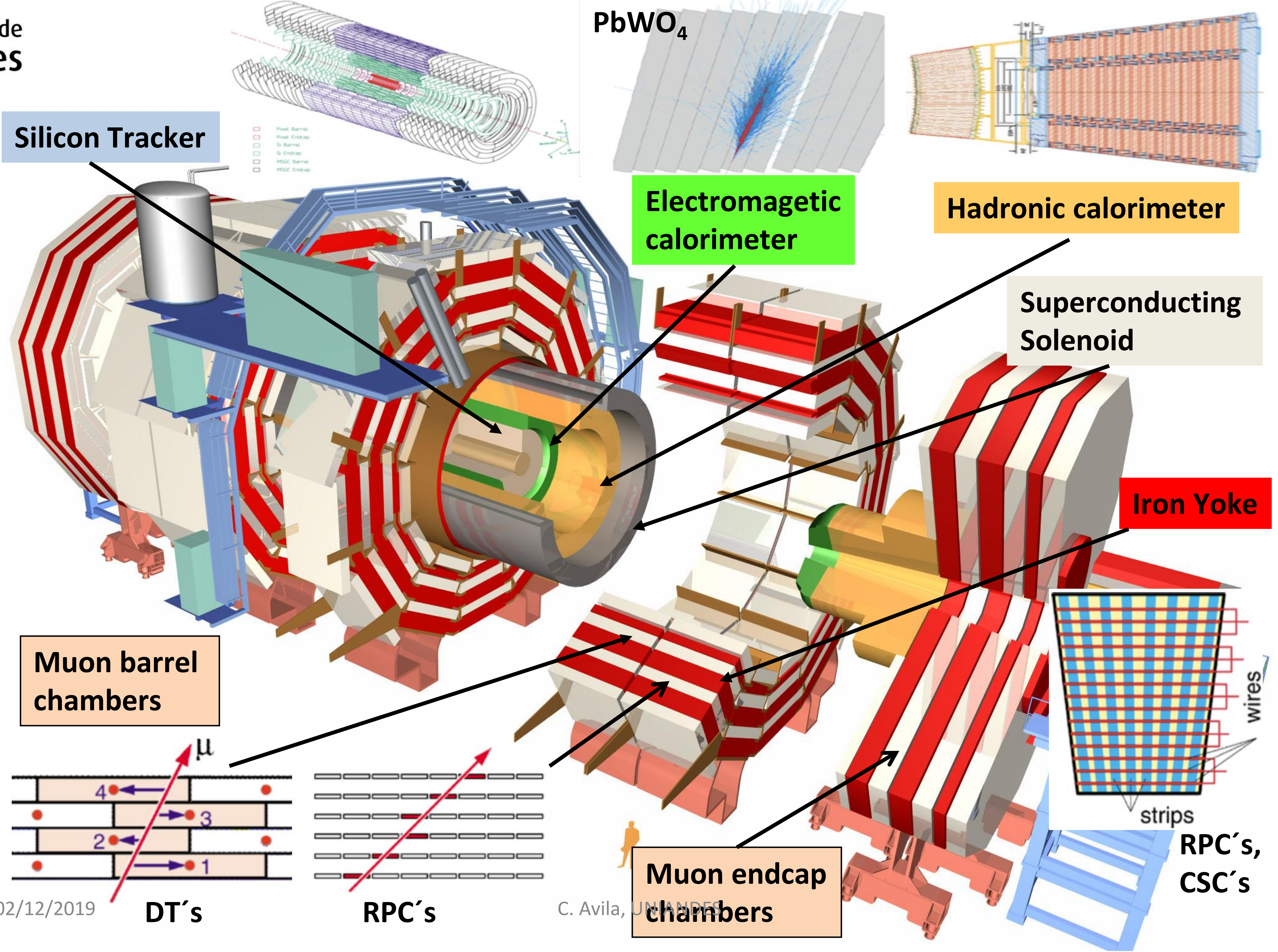
CMS PUBLICATIONS

- More tan 934 publications as of november 29 2019. Imposible to sumarize all results in one single talk.
- **This talk summarizes some recent results on:**
  - **Higgs Physics**
  - **Searches : SUSY and Exotica**
- Three other talks in COMHEP 4, covering other topics:
  - Searches for exo signls with ATLAS det.
  - Heavy Flavor Physics
  - Searches for DM at the LHC

 # CMS COLLIDER DATA PUBLICATIONS AS OF NOV-2019



2. STATUS OF CMS EXPERIMENT



Silicon Tracker

$PbWO_4$

Electromagetic calorimeter

Hadronic calorimeter

Superconducting Solenoid

Iron Yoke

Muon barrel chambers

DT´s

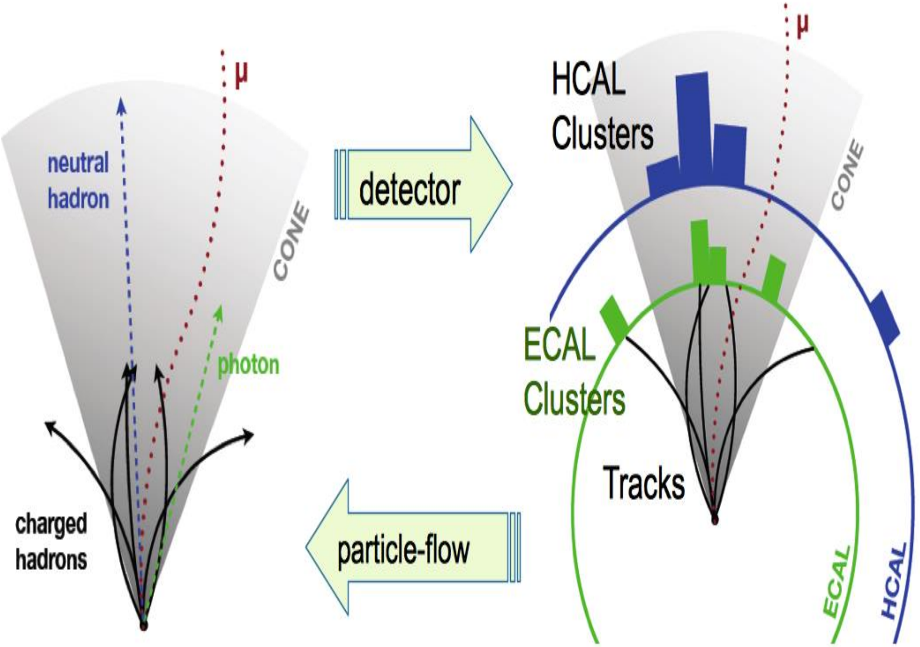
RPC´s

Muon endcap chambers

RPC´s, CSC´s

Particle Flow

Combine info from all subsystems to generate a list of reconstructed particles to descrcibe the entire event



- Find µ´s and remove
- Find e´s and remove
- Find charged hadrons and remove
- Find photons and remove
- Find neutral hadrons and remove

A large B field, good calorimeter granularity and high resolution tracking are needed for efficient PF.

e,µ,γ, charged and neutral hadrons

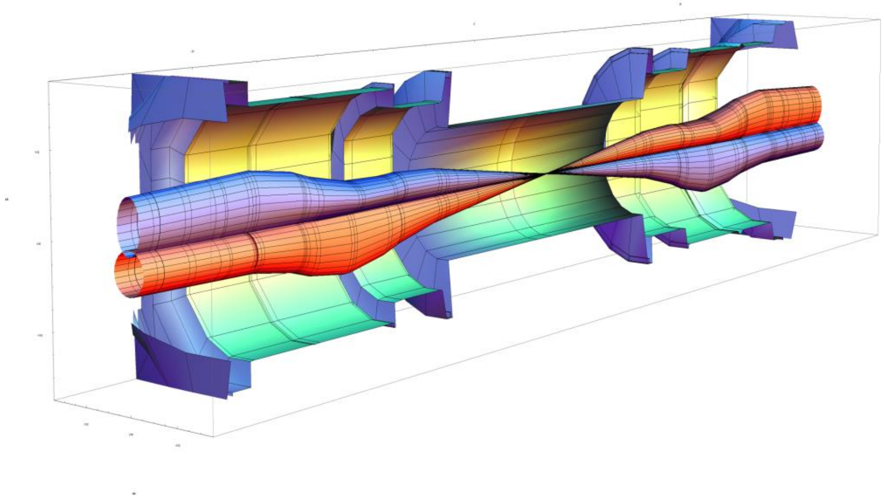
- Used in the event as a list of generated particles in the event.
- Used to reconstruct jets, taus, missing energy, isolation and identification of particles in multiple proton-proton collisions.

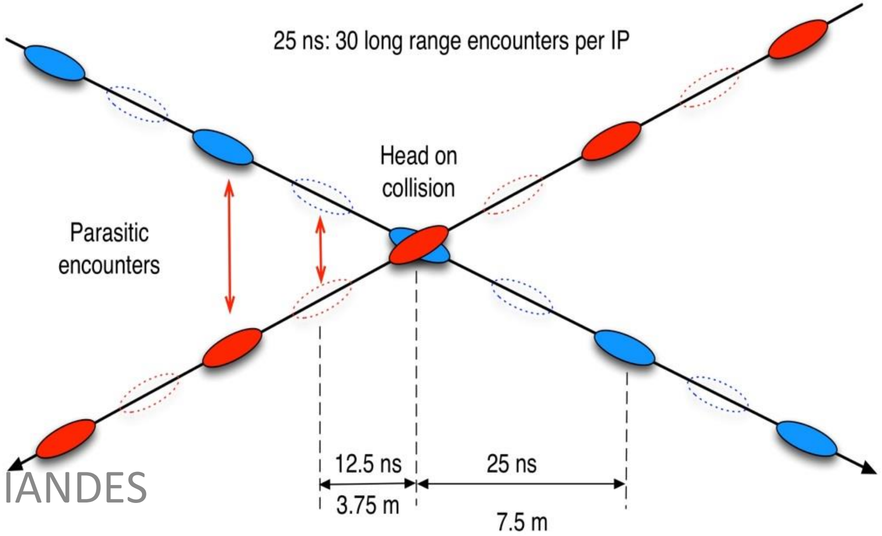
Achieving High Luminosity

$$\mathcal{L} = \frac{n_b \cdot N_1 \cdot N_2 \cdot f_{rev}}{4\pi \cdot \sigma_x . \sigma_y} \cdot F$$

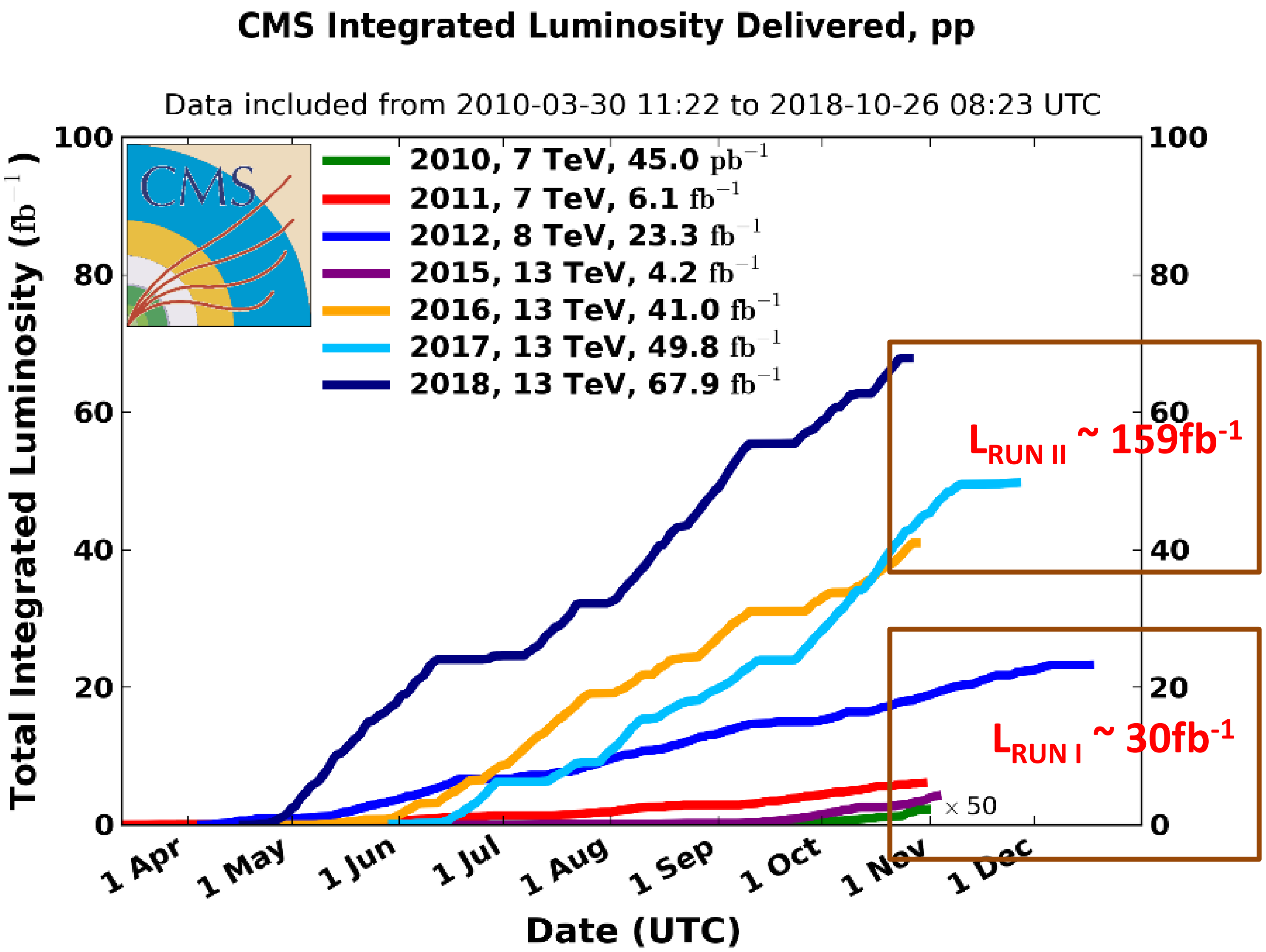
f_{rev} is determined by accelerator radius = 11246 HZ for LHC

1) Increase number of bunches, n_b, in the accelerator, 2808 for LHC
2) Increase number of protons in the bunches, N_1, $N_{2,}$ ~10^{11}
3) Minimize the beam size at the collision point,
4) Improve geometric factor F (beam offsets and crossing angles)
5) Improve machine efficiency : reduce dead time between beam injection, etc.





LHC PERFORMANCE

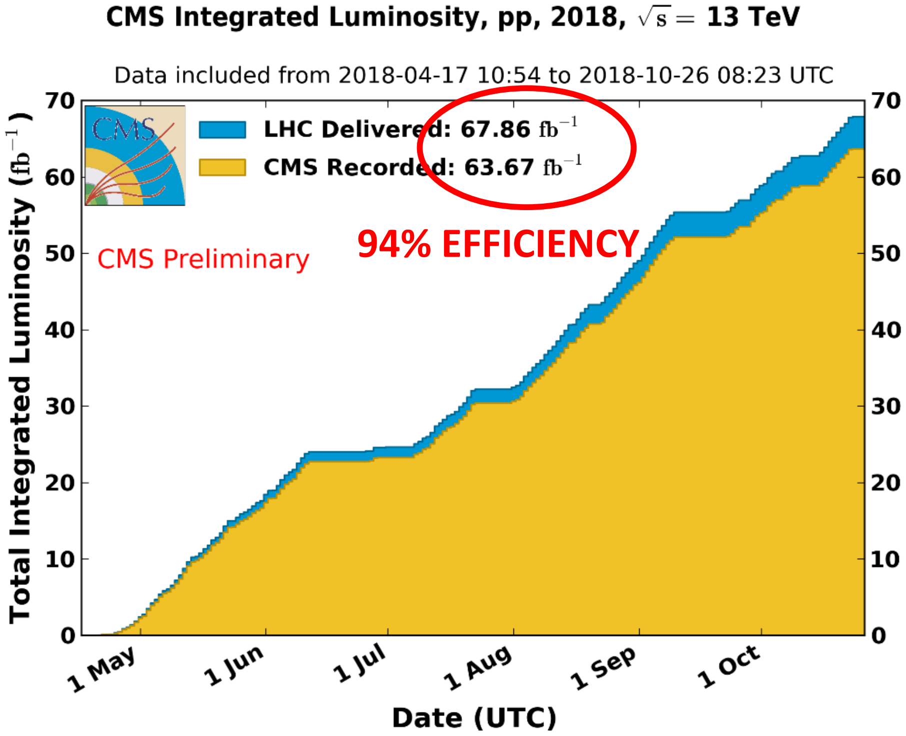


$L_{RUN\ II}$ ~ 159fb^{-1}

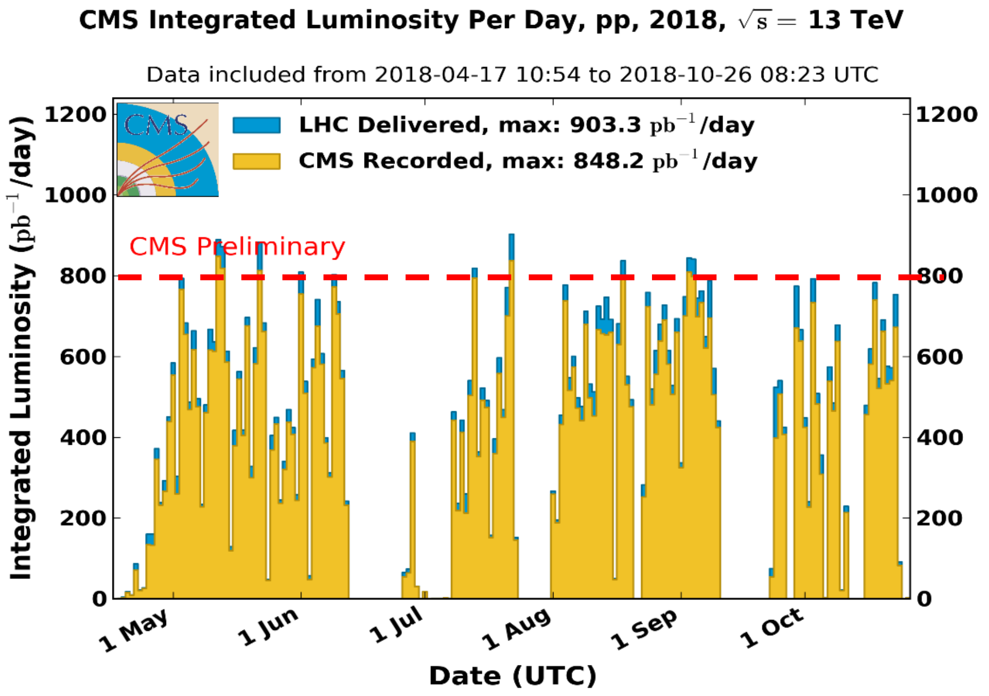
$L_{RUN\ I}$ ~ 30fb^{-1}

- 3 years of sustained high luminosity at 13 TeV
- >50% of the time in stable operation
- 2018 maximum peak luminosity ~2x10^{34} cm^{-2} s^{-1} with mean pileup ~ 38
  → twice the design lumi.
- Rapid turn-around between fills (5 hours typical, ~2 hours record)

CMS LUMINOSITY

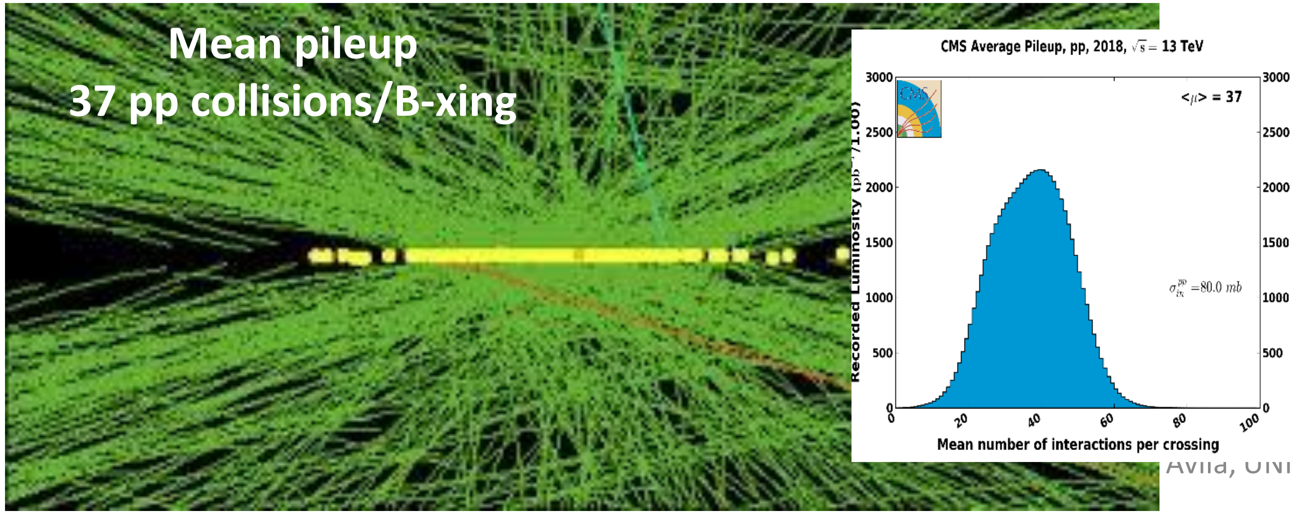

CMS Integrated Luminosity, pp, 2018, $\sqrt{s} = 13$ TeV

Data included from 2018-04-17 10:54 to 2018-10-26 08:23 UTC


CMS Integrated Luminosity Per Day, pp, 2018, $\sqrt{s} = 13$ TeV

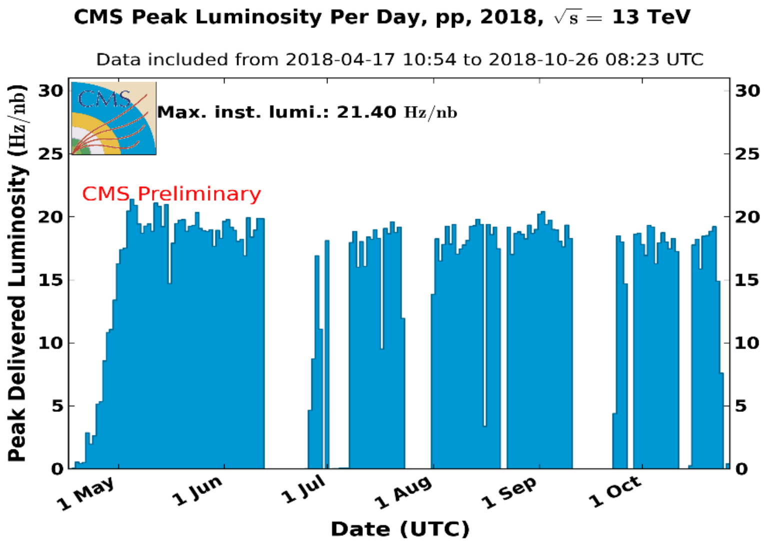
Data included from 2018-04-17 10:54 to 2018-10-26 08:23 UTC

CMS could record 0.8 fb^{-1} in a single day.


Mean pileup

37 pp collisions/B-xing

CMS Average Pileup, pp, 2018, $\sqrt{s} = 13$ TeV


CMS Peak Luminosity Per Day, pp, 2018, $\sqrt{s} = 13$ TeV

Data included from 2018-04-17 10:54 to 2018-10-26 08:23 UTC

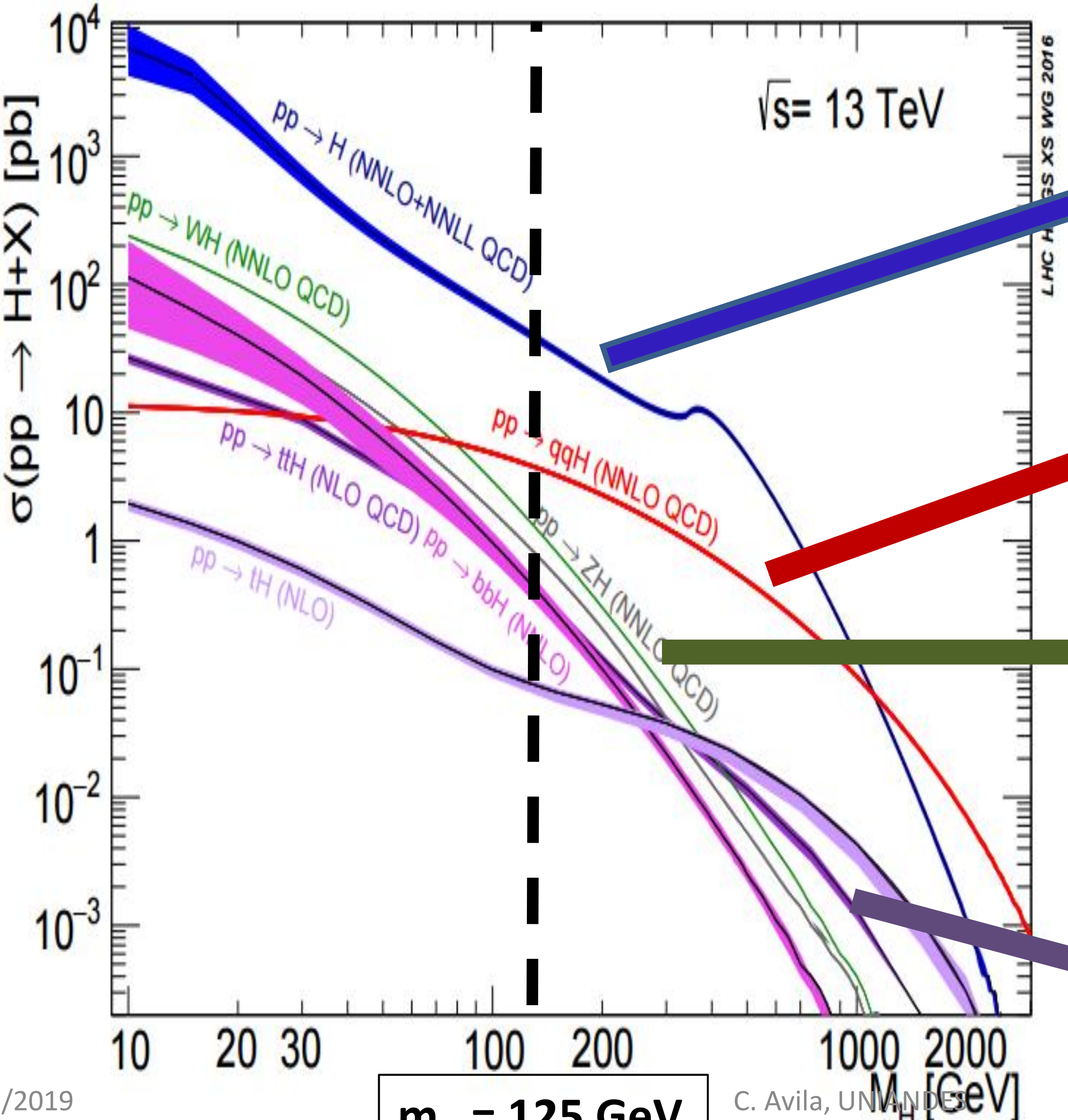
Peak lumi ~ 1.8×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$

3. PHYSICS RESULTS AT 13 TeV

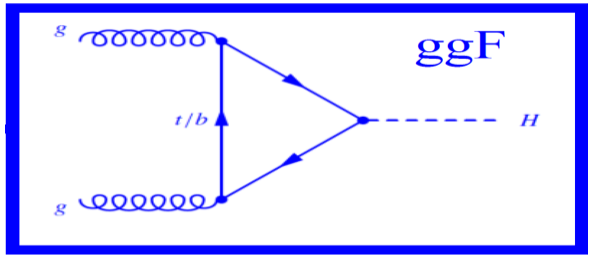
➢ Higgs Physics Results

SM HIGGS CROSS SECTIONS

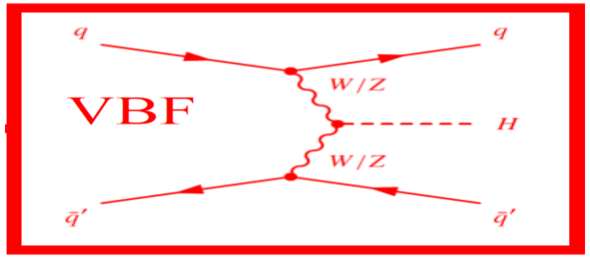
arXiv:1307.1347v2



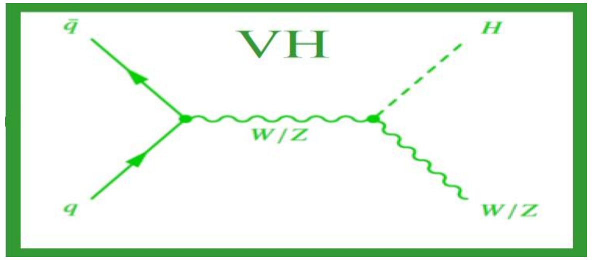
m_H = 125 GeV



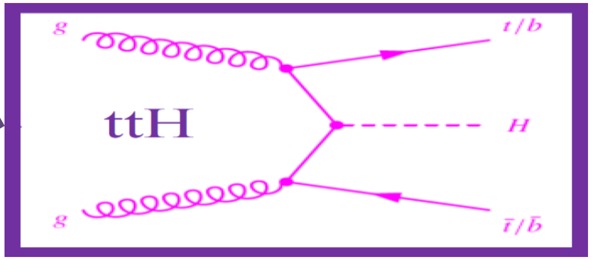
~87%



~7%

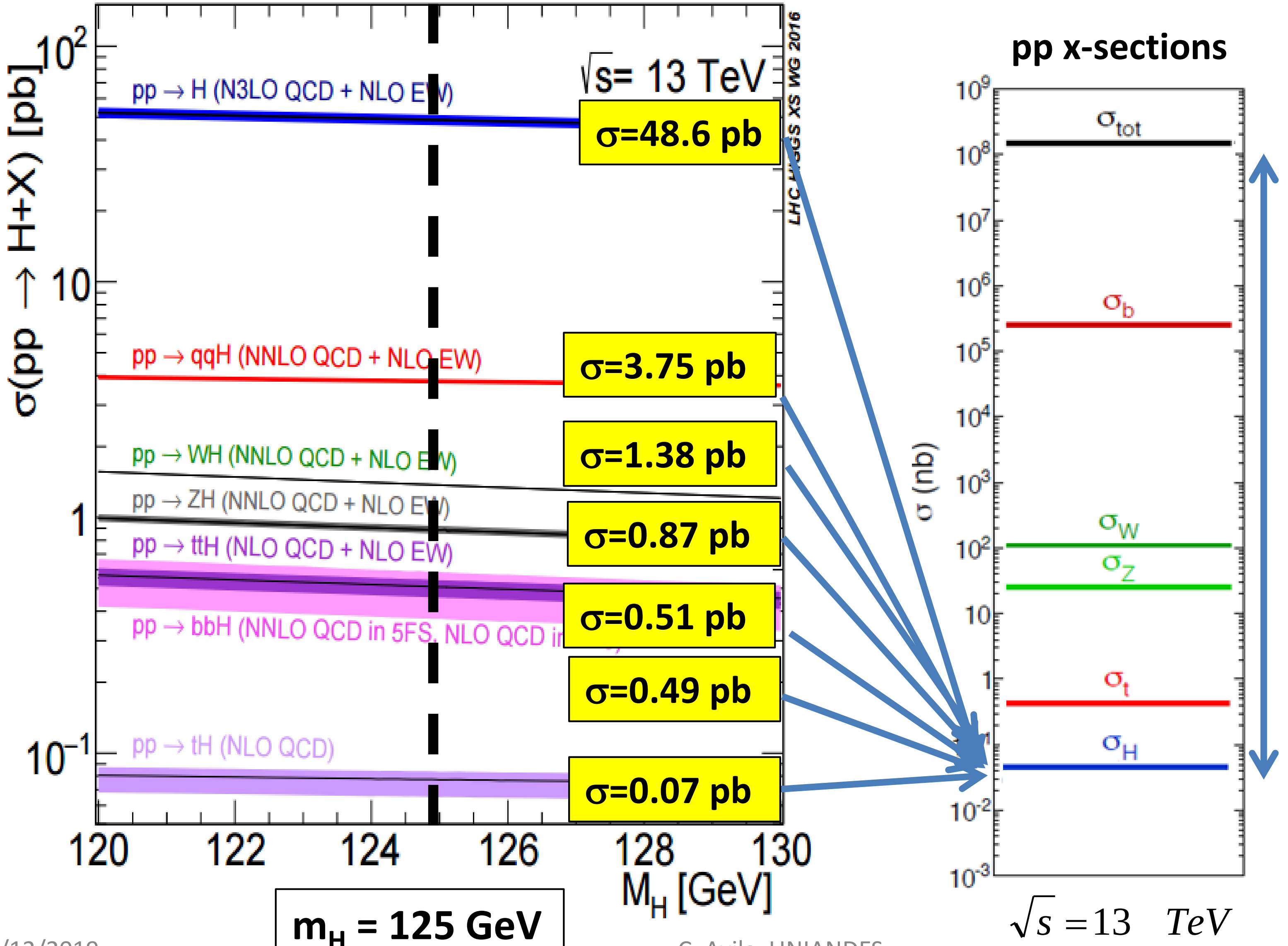


~4%



~2%

SM HIGGS CROSS SECTIONS



m_H = 125 GeV

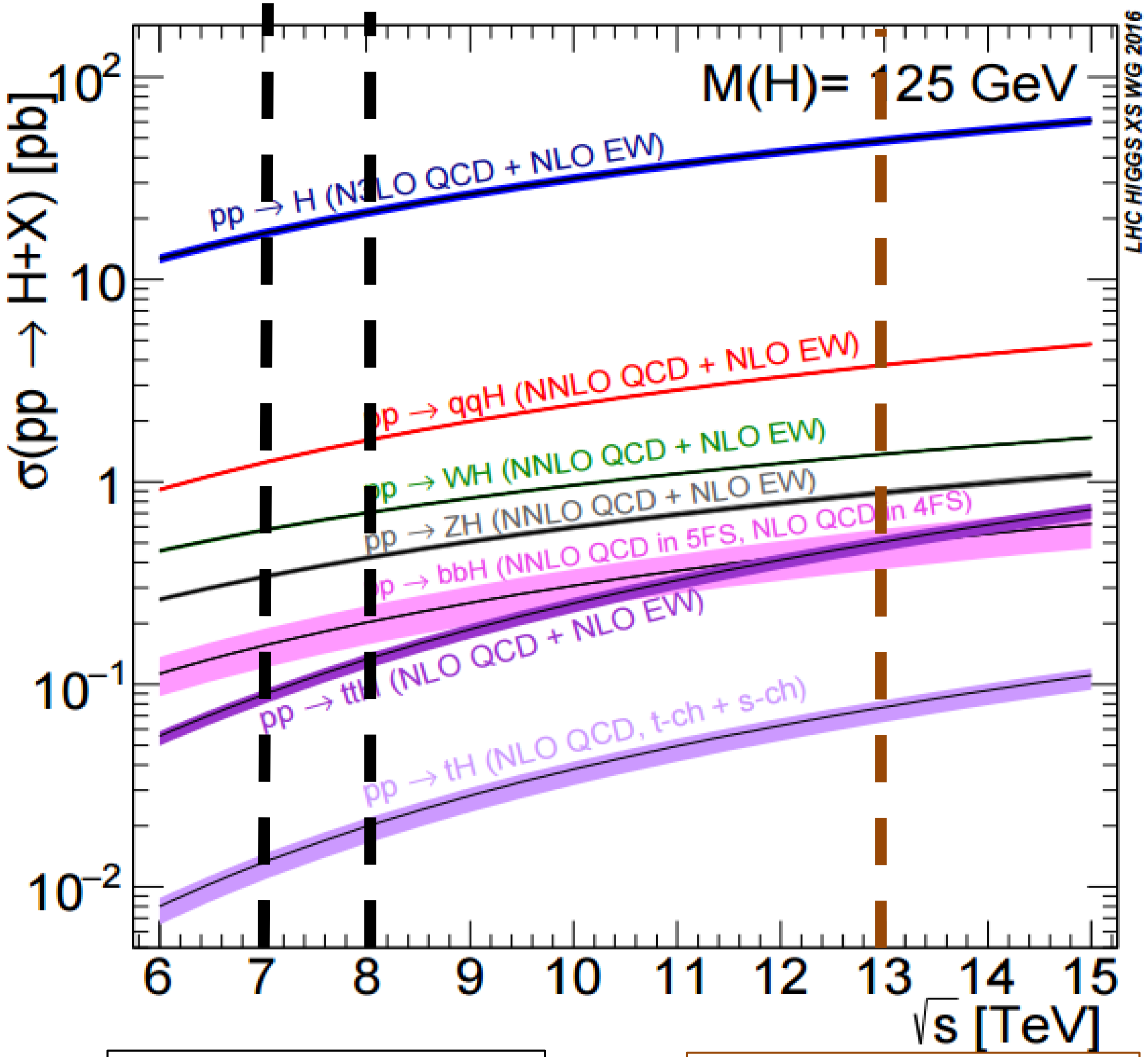
2 Higgs produced every 10^9 pp collisions

$L_{RUN\ II}$ = 150 fb^{-1}

~ 8.5 M Higgs produced in RUN II

~0.5 M Higgs produced in Run I, L= 25 fb^{-1}

HIGSS CROSS SECTIONS VS ENERGY



RUN I (2011-2012)

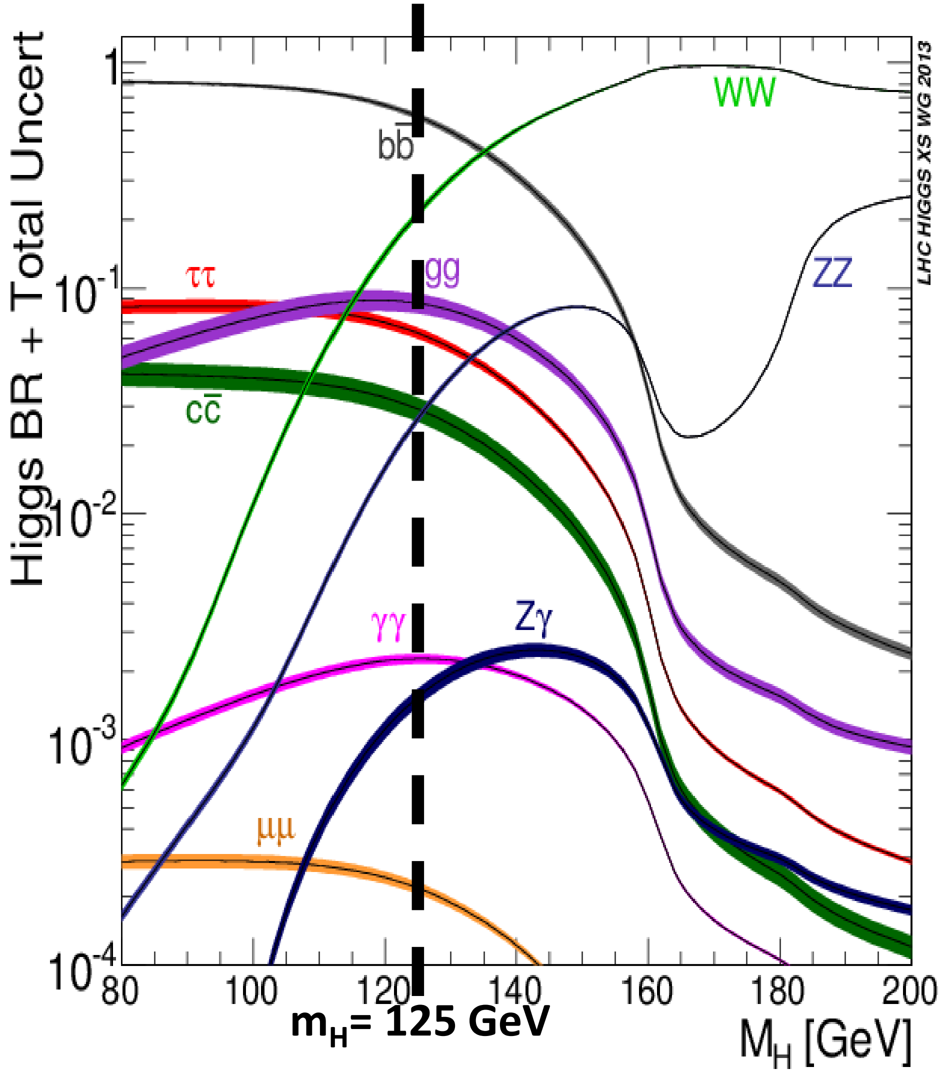
RUN II (2015-2018)

process	σ[pb] 8 TeV	σ[pb] 13 TeV	ratio
ggF	19.3	48.6	2.5
VBF	1.58	3.75	2.4
WH	0.705	1.38	2.0
ZH	0.415	0.870	2.1
ttH	0.129	0.509	**3.9**
bbH	0.204	0.488	2.4

63% increase in energy→ >200% increase in cross section

SM HIGGS DECAYS

arXiv:1307.1347v2



m_H= 125 GeV

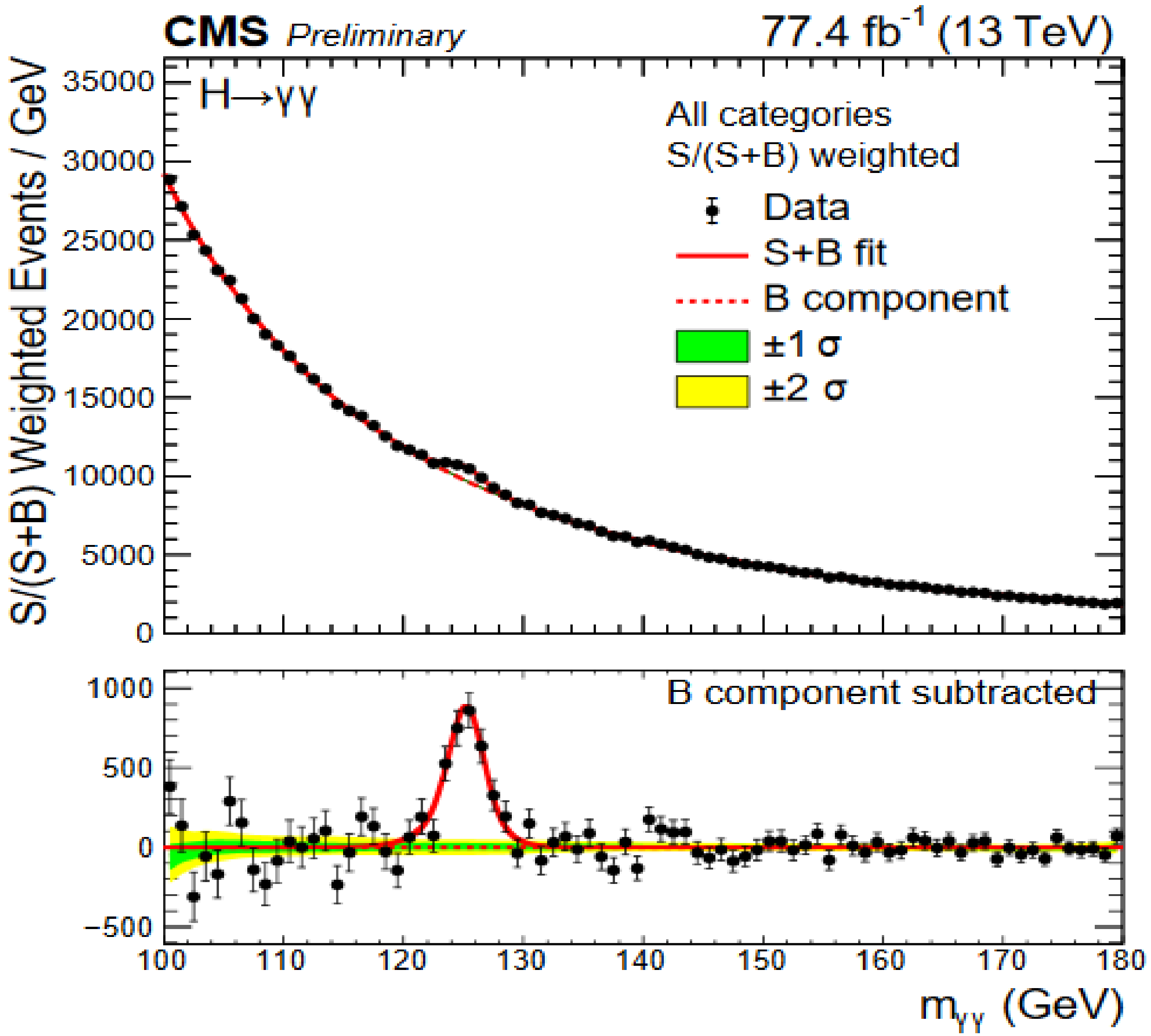
Decay	BR(%)
H→bb	57.7
H→WW	21.5
H→ττ	6.3
H→ZZ	2.6
H→ γγ	0.23
H→ Zγ	0.15
H→μμ	0.02
H→gg	8.6
H→cc	2.9
H→ss	0.02

Main Decay Channels

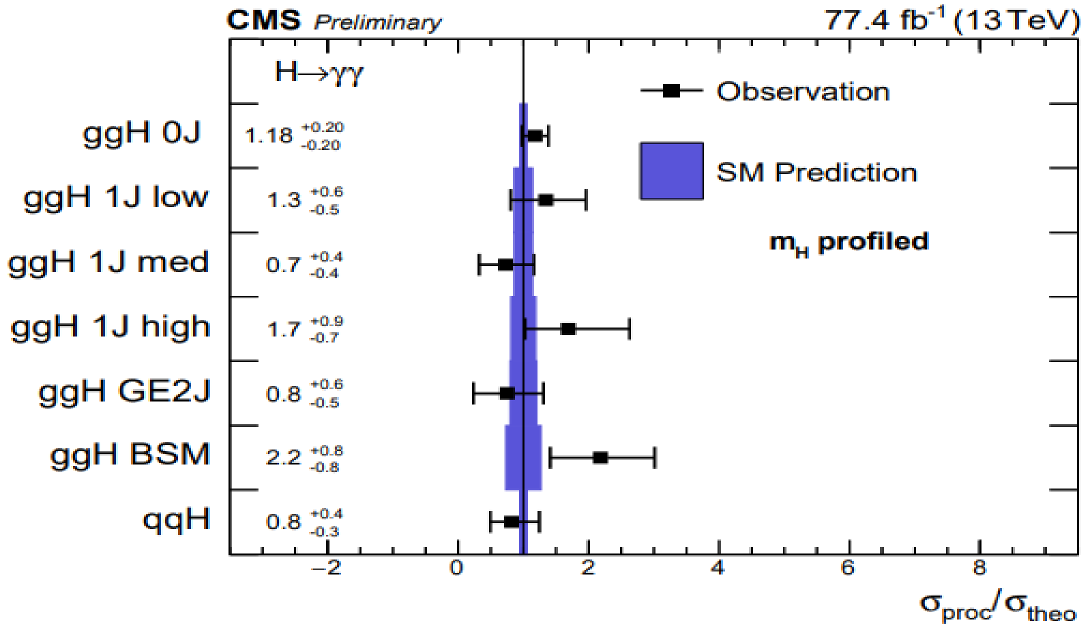
- H→ γγ
- H→ZZ
- H→WW
- H→ττ
- H →bb
- H→ Zγ
- H→μμ

H→ γγ

CMS PAS HIG-18-029

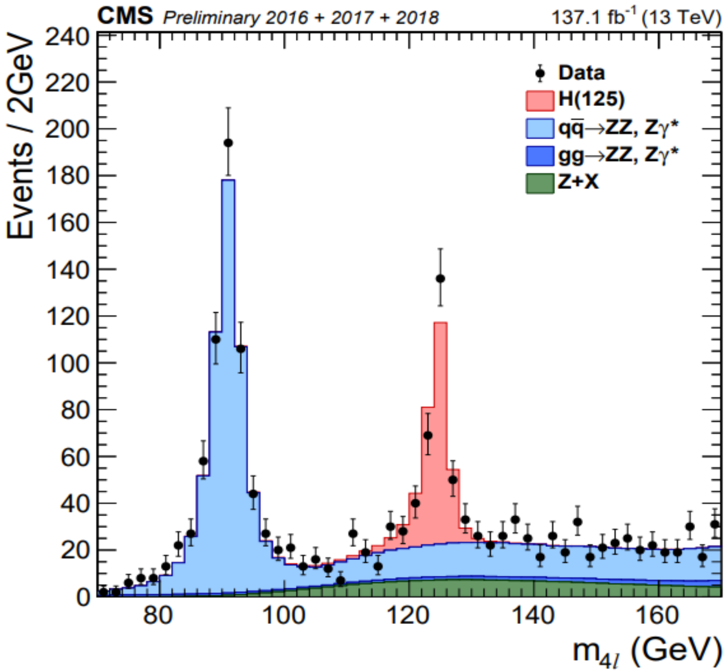


- $\sigma(gg\rightarrow H)/\sigma_{SM}(gg\rightarrow H) = 1.15 \pm 0.15$
- $\sigma(pp\rightarrow qqH)/\sigma_{SM}(pp\rightarrow qqH) = 0.8^{+0.4}_{-0.3}$
- Signal strength for different events categories (STXS Framework):
  - Number of jets
  - Higgs PT (boundaries of 60, 120 and 200 GeV)



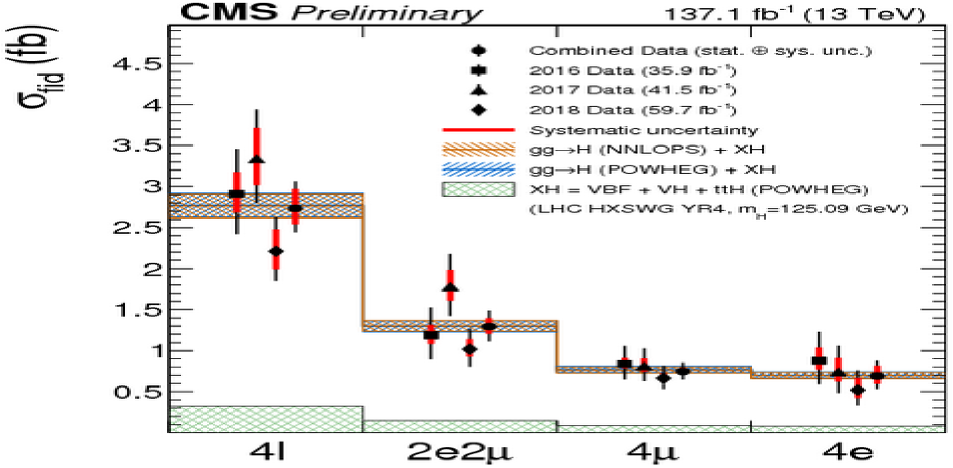
$H\rightarrow ZZ\rightarrow 4\ell$ (4μ, 2e2μ,4e)

CMS-PAS-HIG-19-001

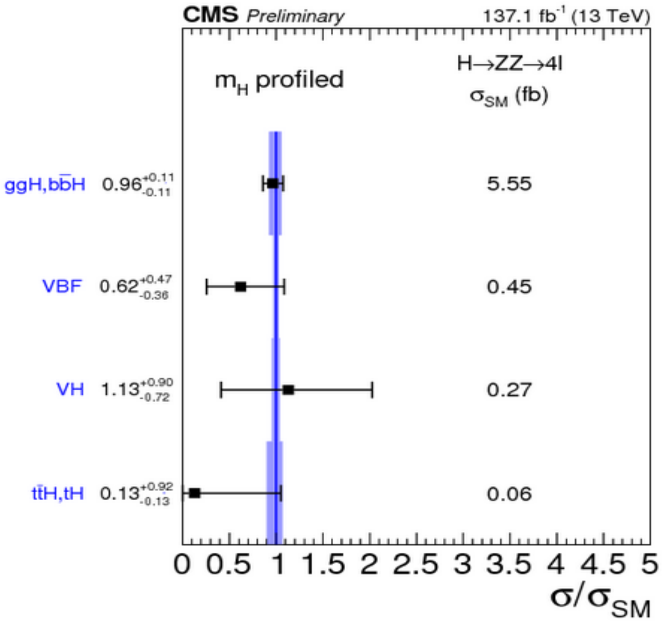


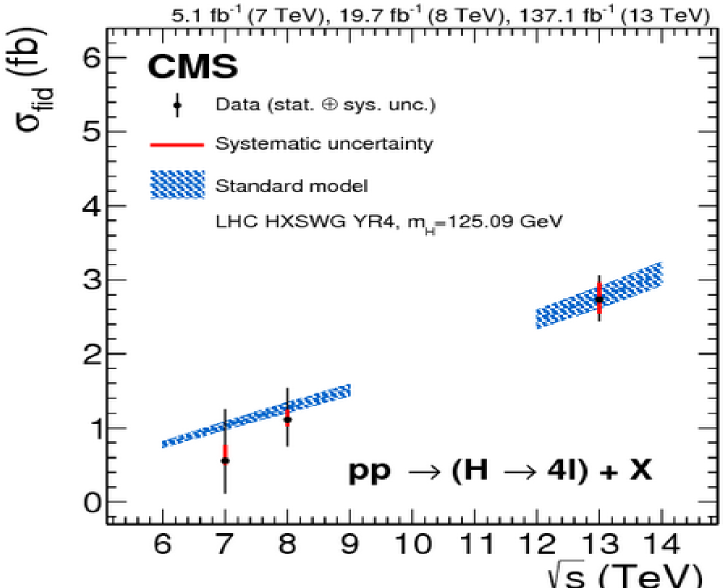
Strategy:

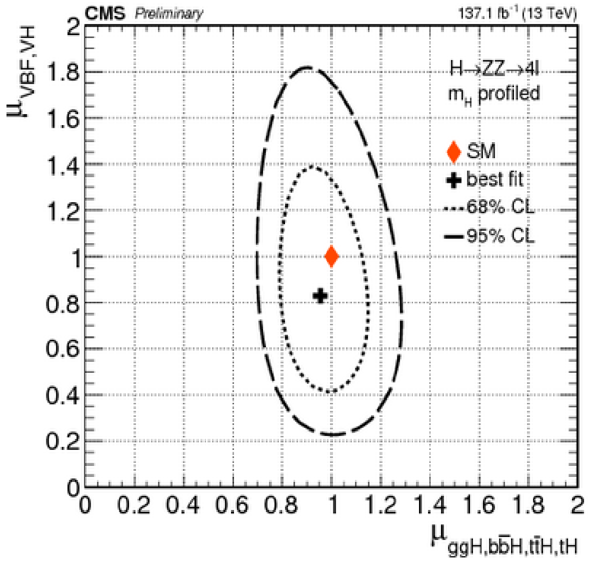
- Extract signal strength for each category
- Combine in terms of production channel
- Combine for inclusive result



- $\sigma_{fid} = 2.73^{+0.23}_{-0.22}(stat)^{+0.24}_{-0.19}(syst.)$ fb
- $\sigma^{fid}_{SM} = 2.76 \pm 0.14$ fb
- $\mu = 0.94^{+0.07}_{-0.07}(stat)^{+0.08}_{-0.07}(stat)$

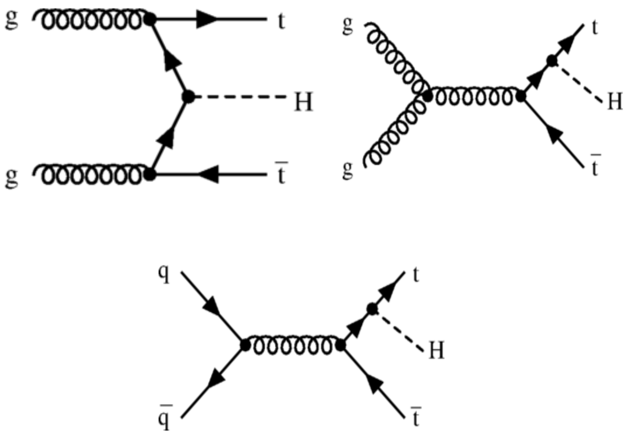




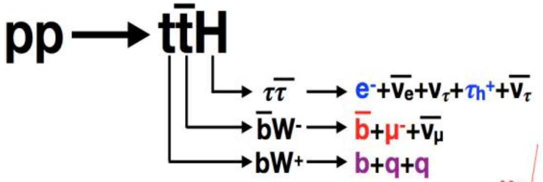


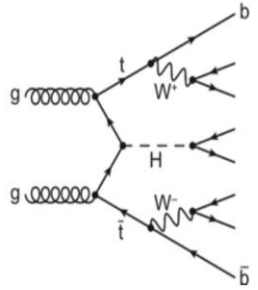
Recent Discovery : ttH

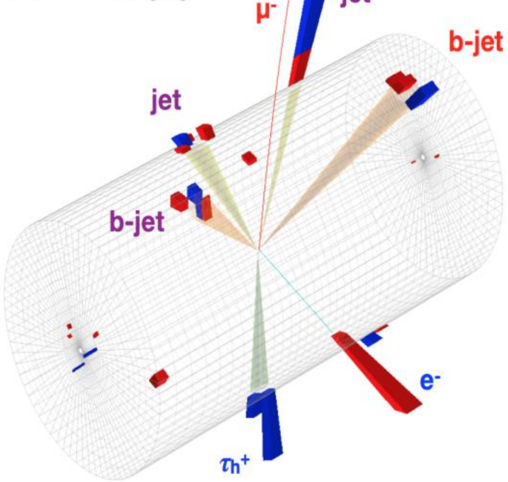
PRL 120 (2018) 231801

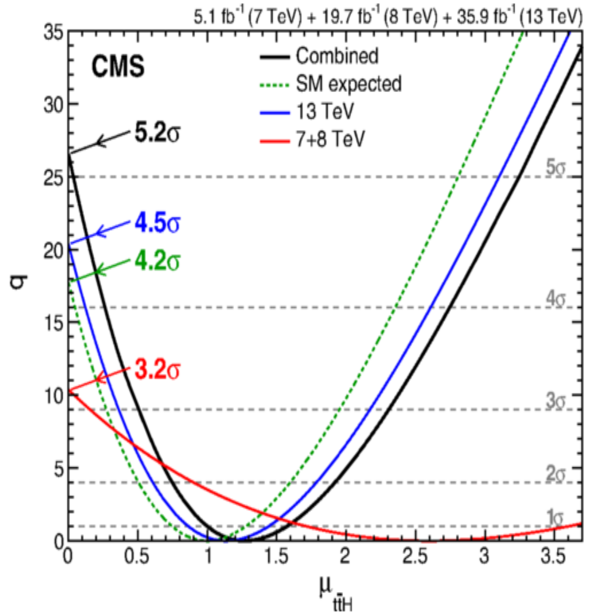


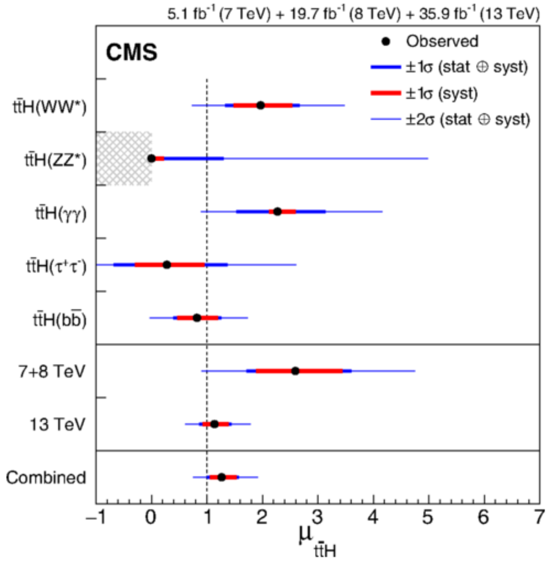
- ttH observed with run I (7 TeV+ 8 TeV) + 2016 (13 TeV) data
- H→ WW, H→ ZZ, H→ ττ, H→bb, H→ γγ combined together to maximize sensitivity
- Background prediction based on data (control regions) if possible
- Reduction of backgrounds using multivariate analyses (MVAs)
- **first confirmation of the tree-level coupling of the Higgs boson to top quarks**
- Important way to access *yt* (t Yukawa coupling): top quarks not produced in Higgs decay because of their mass







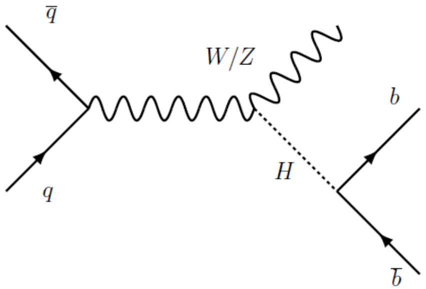




$$\mu = 1.26^{+0.31}_{-0.36}$$

Recent Discovery : (V)H→ bb

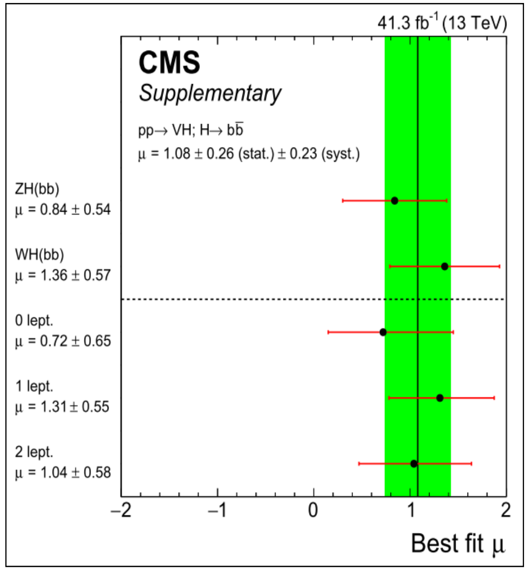
PRL 121 (2018) 121801

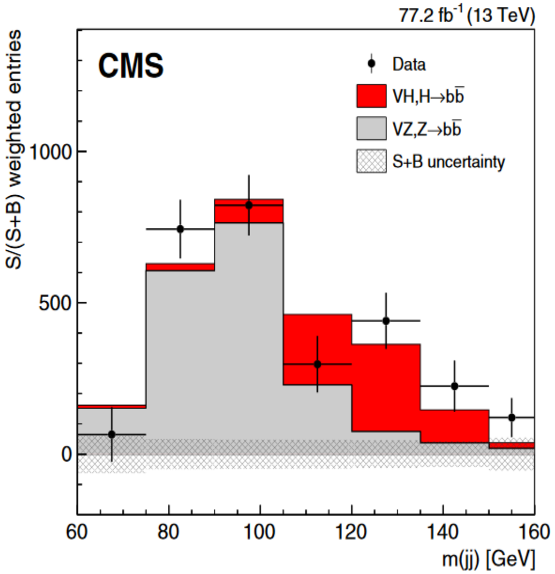


- It has the biggest branching fraction but huge QCD backgrounds (~10^3 times the signal in this mass region) → Choose a weak interaction production mode to reduce hadronic backgrounds (QCD multijet, top).
- Advantage of VH: clear signature due to additional V (using 0, 1 or 2 leptons + 2 b jets)

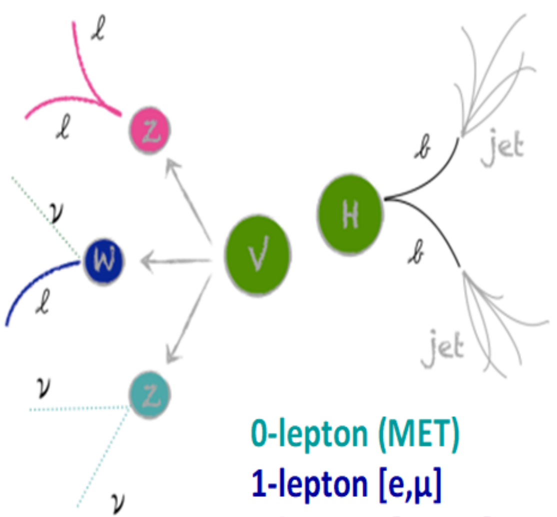
Analysis strategy:

- **3 channels** with 0, 1, and 2 leptons and 2 b-
  - To target Z(νν)H(bb), W(lν)H(bb)and Z(ll)H(bb) processes
- **Signal region designed to increase S/B**
  - **Large boost** for vector boson
  - **Multivariate analysis** exploiting the most discriminating variables ($m_{b\bar{b}}$, $\Delta R_{b\bar{b}}$, b-tag)
- **Control regions** to validate backgrounds and control/constrain normalizations



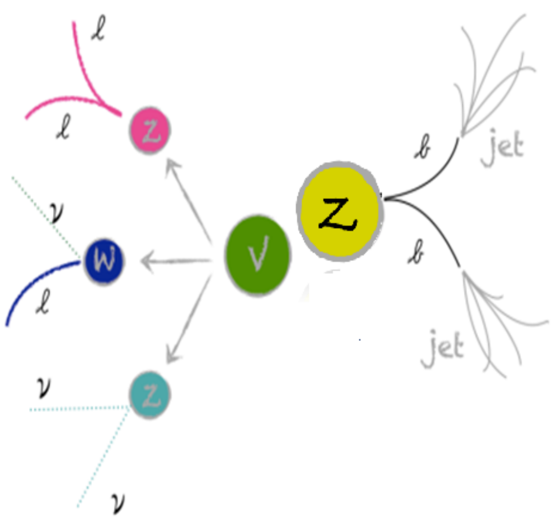


signal



0-lepton (MET)
1-lepton [e,μ]
2-leptons [ee,μμ]

irreducible backgrounds



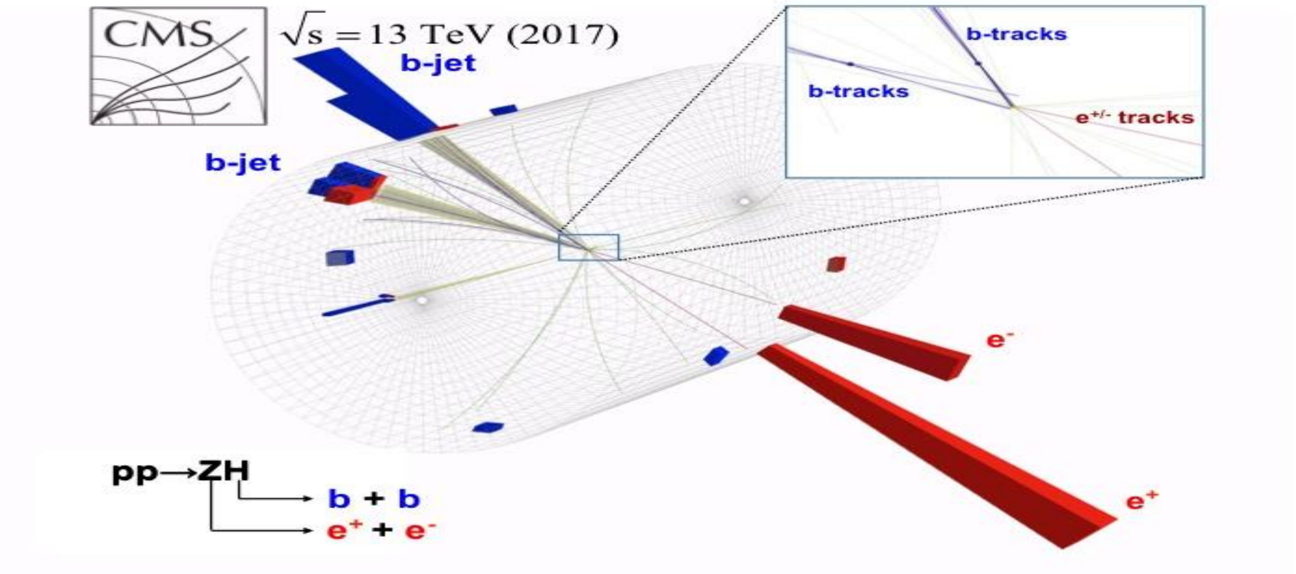
used to validate the analysis strategy

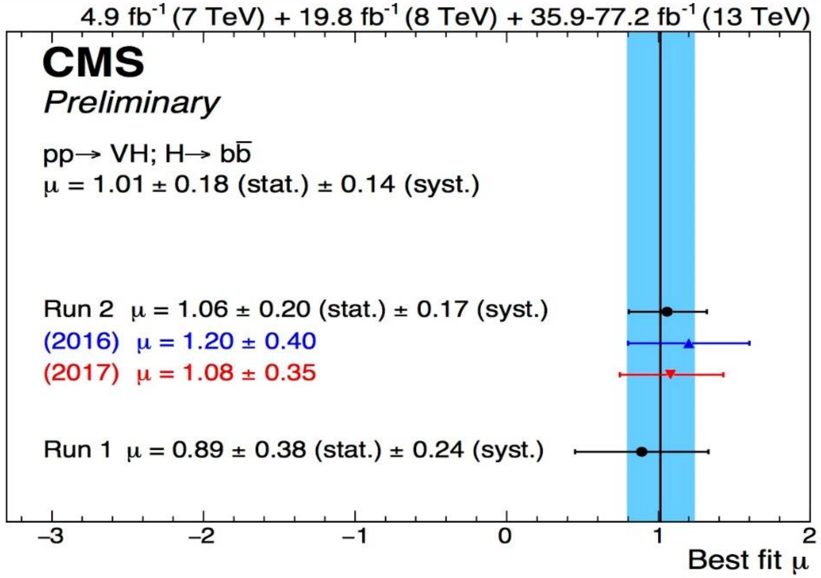
(V)H→ bb : COMBINATION OF RUN I AND RUN II DATA

- **VH(bb) from 2016/17 at 13 TeV, 77.2 fb^{-1}**
  - **Significance: 4.4 σ obs (4.2 exp)**

- **VH(bb) including also 7 and 8 TeV**
  - **Significance: 4.8 σ obs (4.9 exp)**

- **Including new results and all published data fron Run 1 and Run 2**
  - Run 1:
    - ttH(bb): 5 fb^{-1}(8 TeV) + 19.8 fb^{-1} (13 TeV)
    - VBF, H→bb: 19.8 fb^{-1} (8 TeV)
    - VH, H→ bb, 5 fb^{-}1 (8 TeV) + 19.8 fb^{-1} (13 TeV)
  - Run 2:
    - ttH(bb), leptonic channels (2016)
    - ttH(bb), hadronic channels
    - Boosted ggH, H→ bb (2016)
    - VH, H→bb (2016 + 2017)





$$\mu = 1.04^{+0.20}_{-0.19}$$

5.6 (5.5) σ observed (expected) for all H→bb

H → $\mu^+\mu^-$

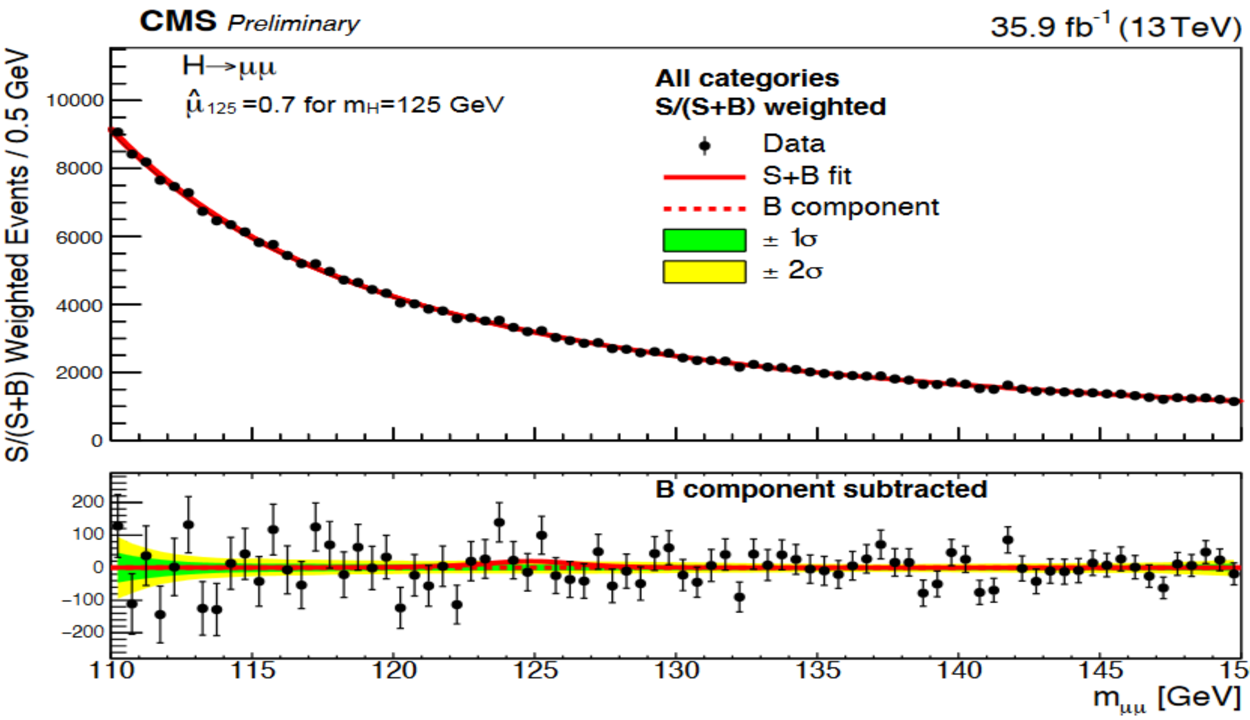
CMS-HIG-17-019

- Best chance at measuring a coupling to a second generation fermion, although branching fraction (BR) ~ 2.2×10^{-4}, about 10% of γγ.

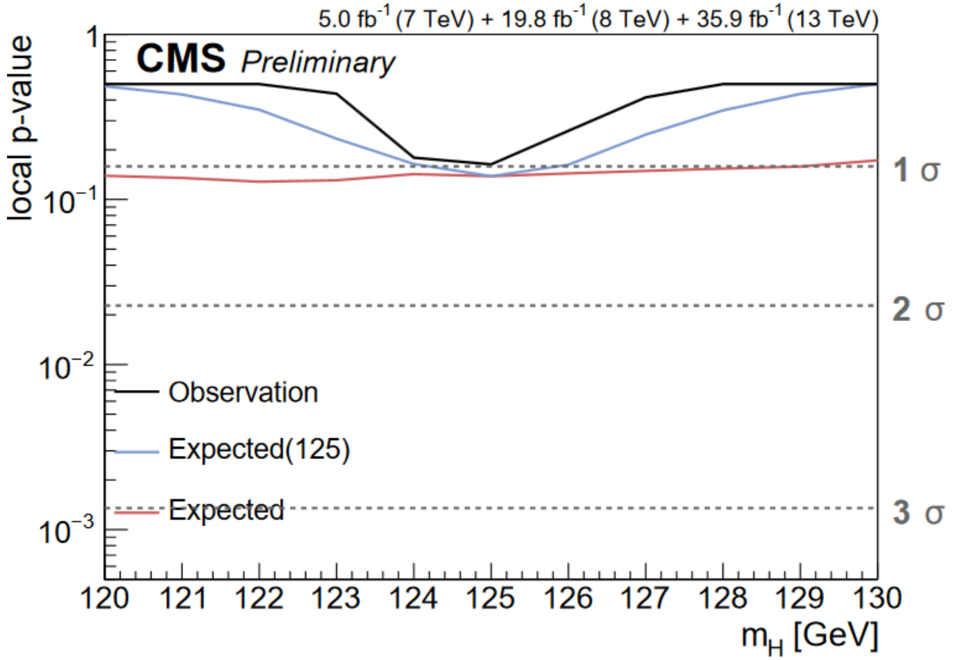
- CMS has looked for this in 7, 8, and 13 TeV (2016 only) data

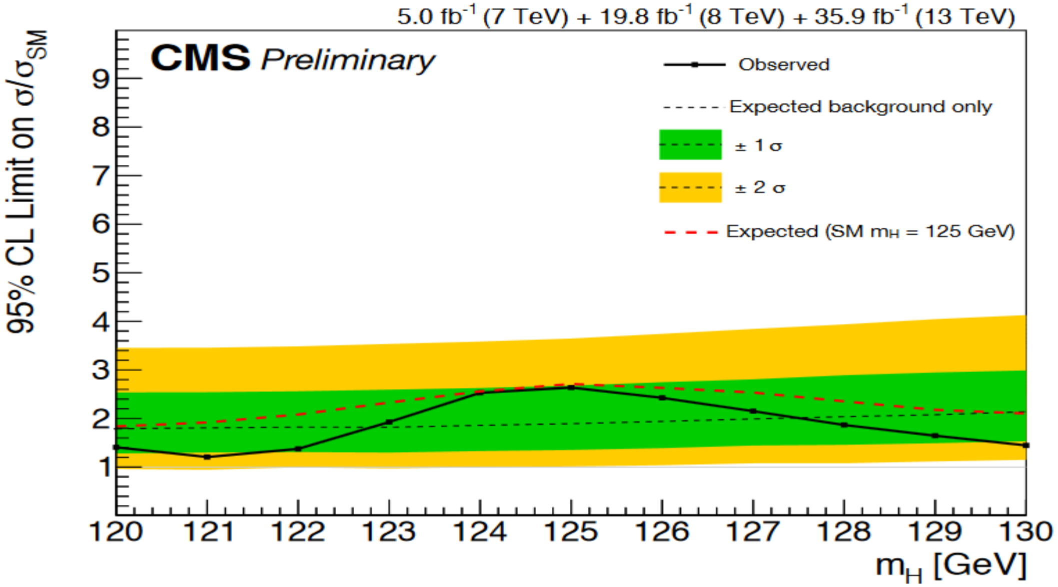
Current 95% CL upper limit on BR is

5.7×10^{-4}, 2.64 X BR_{SM} (observed) vs 2.08 X BR_{SM} (expected).



DES





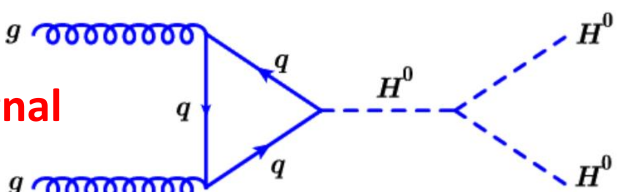
HIGGS BOSON PAIR PRODUCTION

PRL 122 (2019) 121803

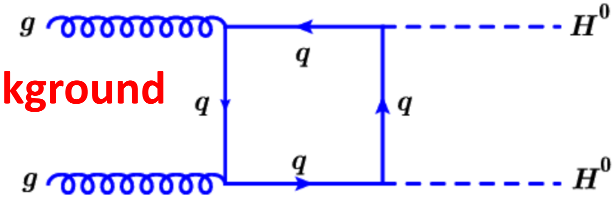
- Access to the Higgs boson trilinear coupling can be obtained by measuring the production of pairs of Higgs bosons (HH) at the LHC.

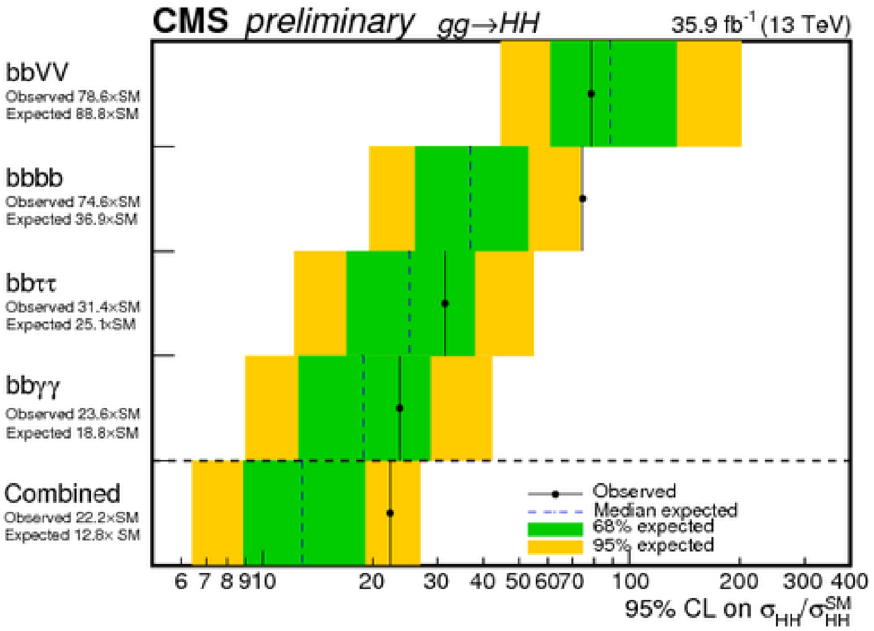
- $\sigma_{HH}^{SM} \approx 33.5\ fb$

signal



Background



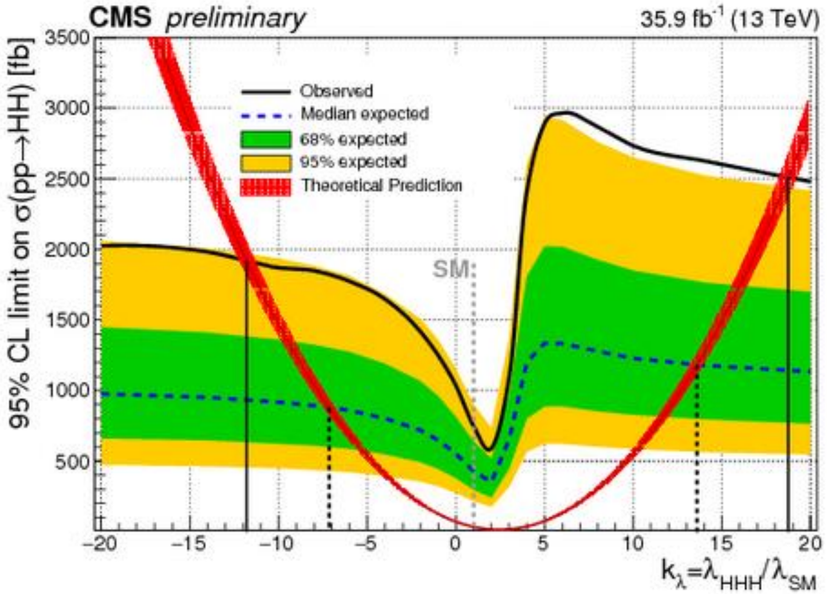


- Constraining coupling modifier $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$

- Not yet close to SM sensitivity, limited by statistics.

- Most sensitive channel (CMS): bbγγ despite low BR=0.13%

→ Combine several channels (bbγγ + bbττ+bbbb+bbVV) to become more sensitive



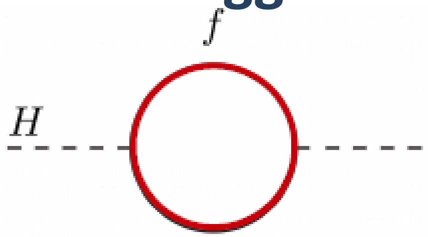
3. PHYSICS RESULTS AT 13 TeV

- Few BSM searches

Why to searh for supersymmetry?

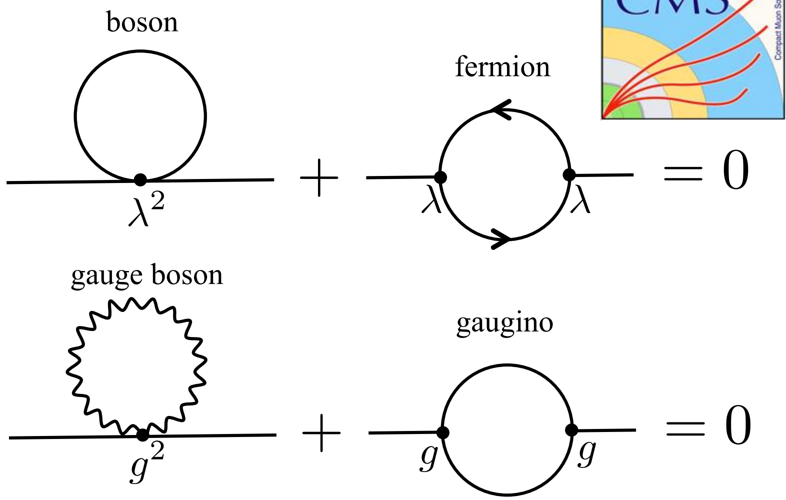
It solves many of the SM problems, among them:

1. SM Higgs Mass Hierarchy problem:

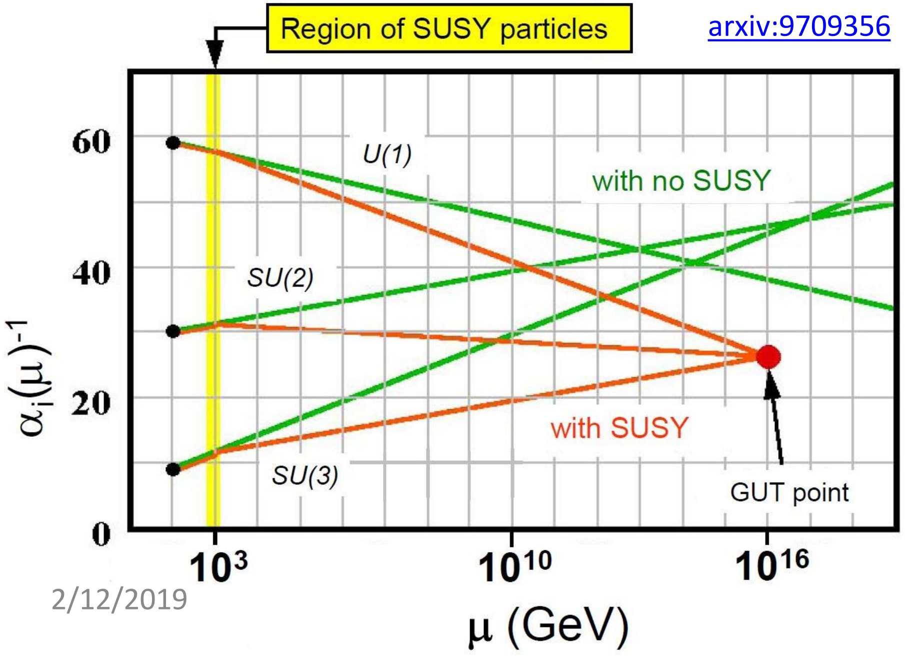


$$(125\text{GeV})^2 = m_H{}^2 = m_{H,0}{}^2 + \Delta m_H{}^2$$

SUSY SOLUTION: Increase the SM particle spectra



2. Unification of gauge couplings :



arxiv:9709356

3. Dark Matter:

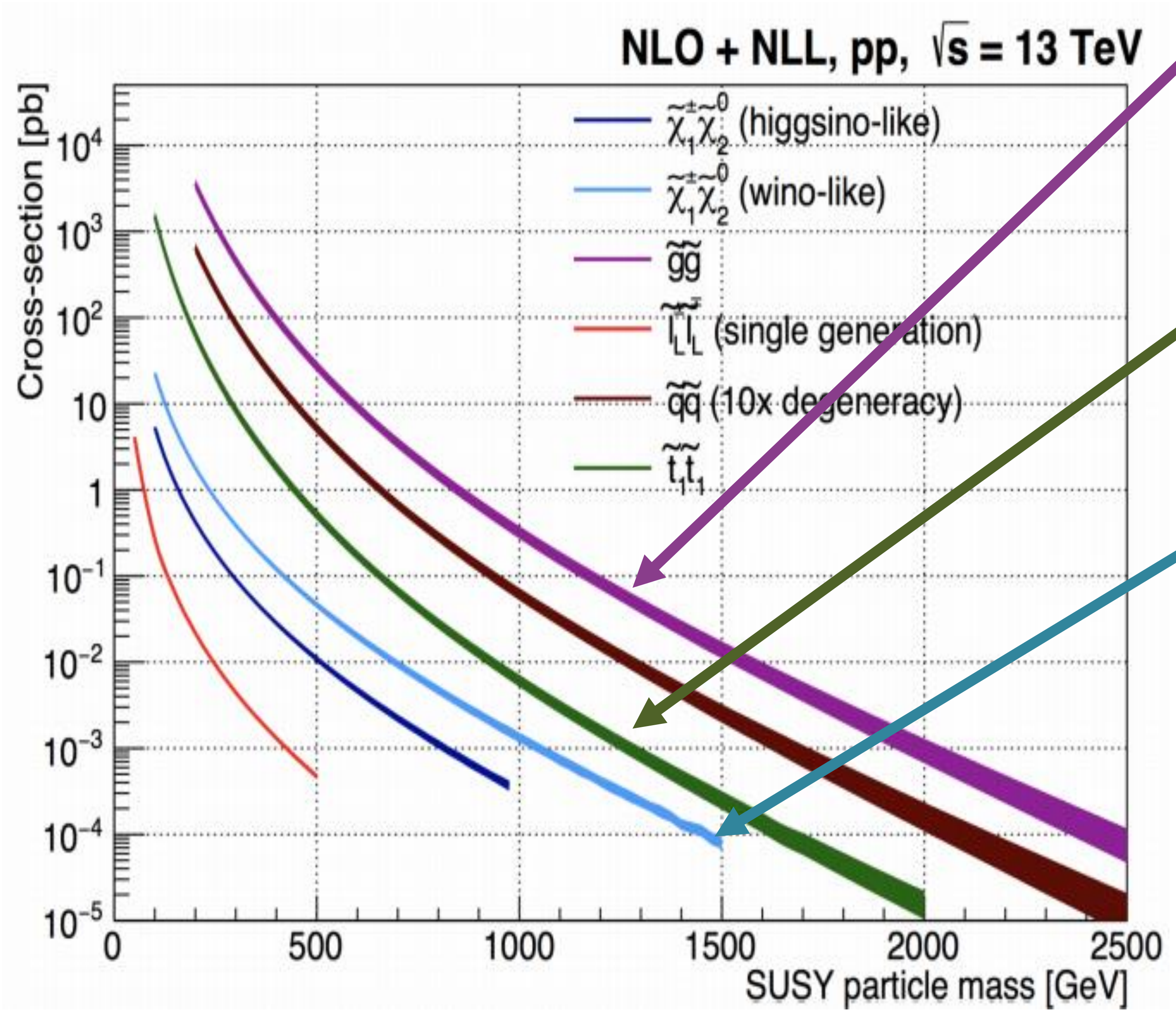
In R parity conserved models: LSP is the DM candidate particle. In most of RPC models:

1. $|\tilde{\chi}_1^0>$ =|DM>=|WIMP>
2. SUSY particles produced in pairs

$$R = (-1)^{3(B-L)+2S} = \begin{cases} +1 & for\ SM\ particle \\ -1 & for\ SUSY\ particle \end{cases}$$

MSSM is the supersymmetric extension of the SM with minimal number of particle states = twice SM # particles + extended Higgs sector. SUSY partners for gauge bosons mix as charginos ($\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}$) and neutralinos ($\tilde{\chi}_i^0, i = 1,..,4$)

SUSY CROSS SECTIONS



Strong-production channels

- copious production at hadron colliders
- MET-based generic channels

Third-generation sparticles

- naturalness ➔mass of *O*(<TeV)
- lighter than other squarks

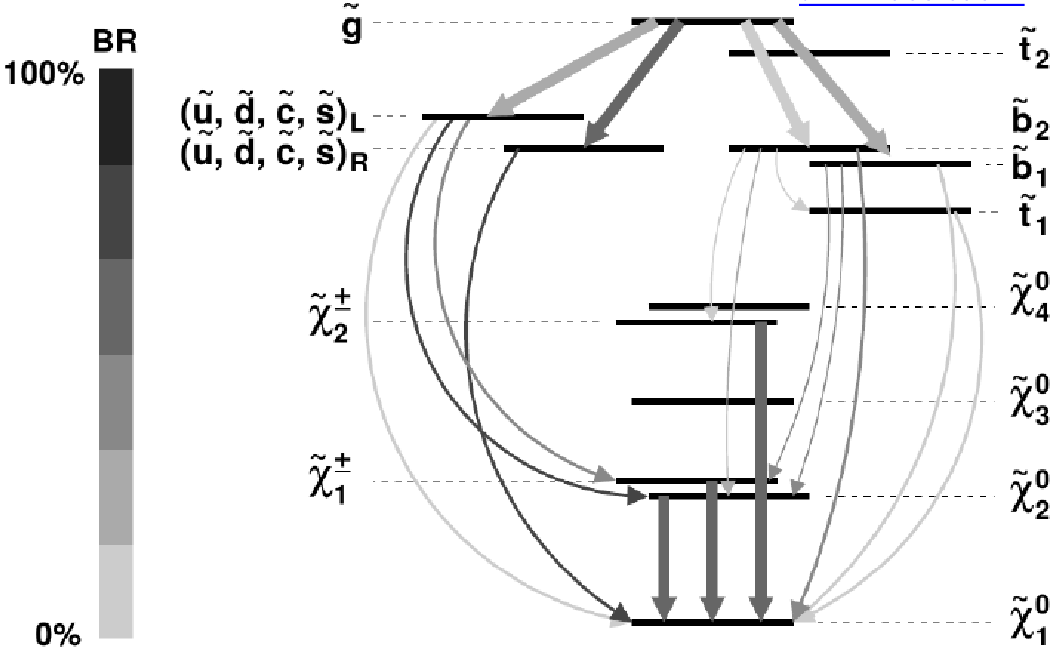
Electroweak production

- coloured spartners too heavy
- direct **gaugino/slepton** production
- relevant for **dark matter** searches

RPC or RPV

- RPC ⇒ more leptons/jets and less MET
- RPV → prompt or delayed LSP decay

Data interpretation Frameworks



arXiv:1908.09672

A major difficulty with the MSSM:
Huge parameter space: 124 parameters

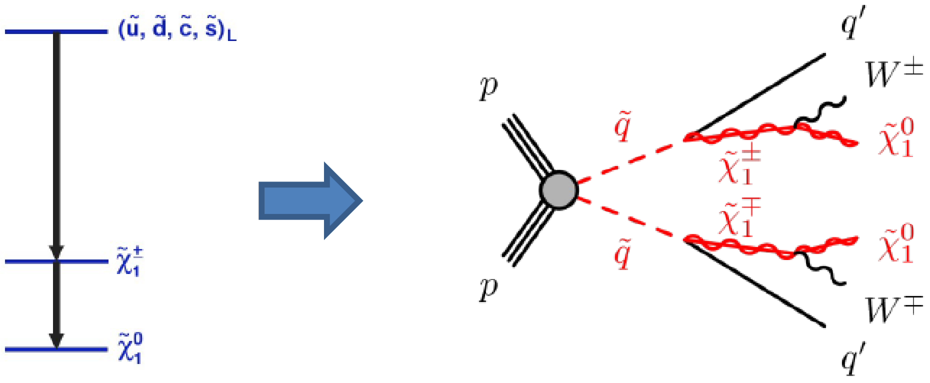
LHC DM W.G.

Two possibilities to overcome this issue:

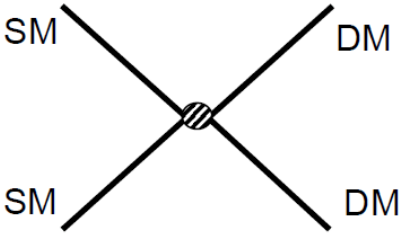
1. **Efective Field Theories**
2. **Simplified Models**

SIMPLIFIED MODELS (Adopted for LHC searches):

- Emphasize features of a broad set of models
- Drives phenomenolgy for model independent searches
- Usually concéntrate in one specific decay chain:



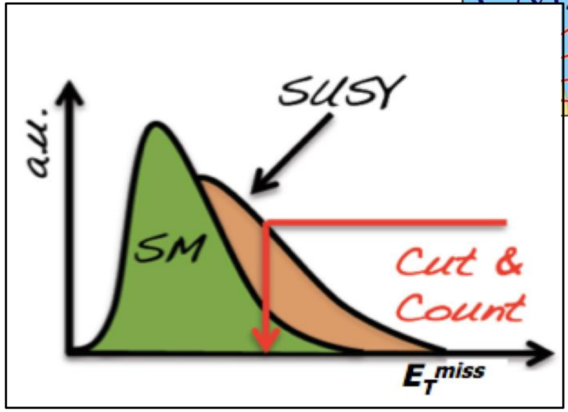
EFECTIVE FIELD THEORIES



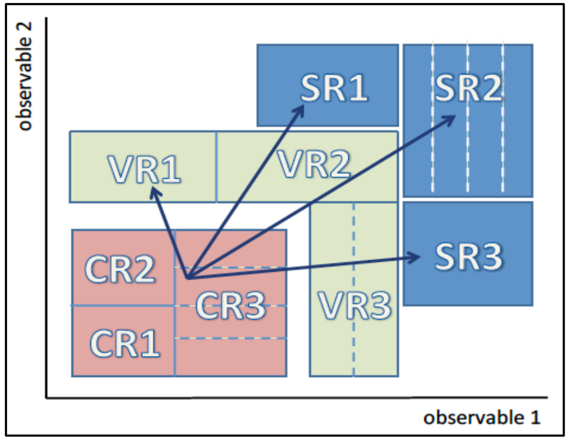
- Contact interaction between SM and DM particles
- Few parameters
- Model independent searches
- Valid only for $Q^2 << M_{mediator}$
  → Issue for LHC

Typical SUSY Search

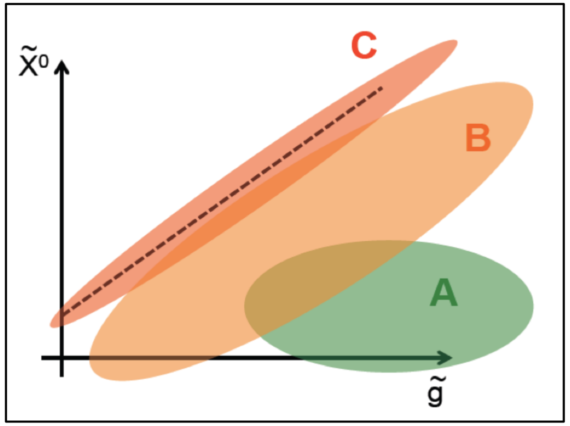
- **Signal region (SR)**
  - may be single-bin (“cut & count”) or multibin
  - optimised for best discovery in targeted productioon/decay mode
  - to cover different mass hierarchies ➝few SRs for each final state



- **Data-driven background estimate**
  - irreducible backgrounds estimated using control region (**CR**) data as a constraint and Monte Carlo to extrapolate from CR to SR
  - reducible background (fake/non-isolated leptons, MET from jet mis-measurement) from data
  - validation regions (**VR**) to check background estimate method and CR→SR variable modelling



- **Likelihood fit of data in SRs and CRs**
  - hypothesis testing of signal models ➝95% CL cross-section upper limits
  - background versus data ➝model-independent upper limits at 95% CL



Squarks & gluinos: 0L + jets + MET

- **Events with no isolated lepton (e/μ) in the final state**

-→ rely on high MET and hadronic activity.

- **Various strategies:**

a) multibin SRs: shape of jet-related variables,

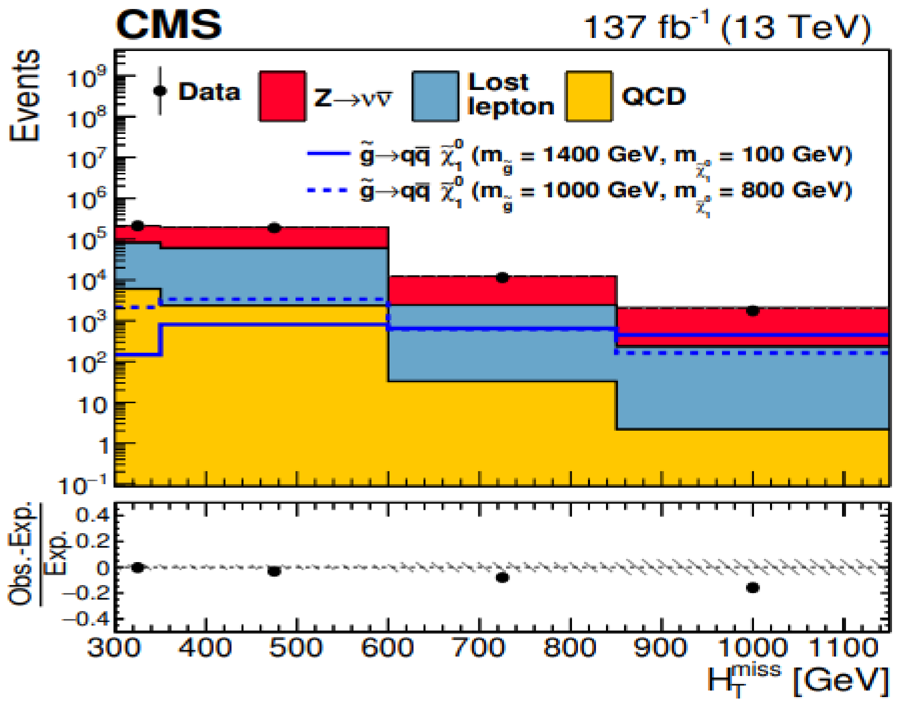
e.g. $m_{eff} = \sum_{jets} P_T^j$

b) Boosted Decision Tree (BDT) trained against SM

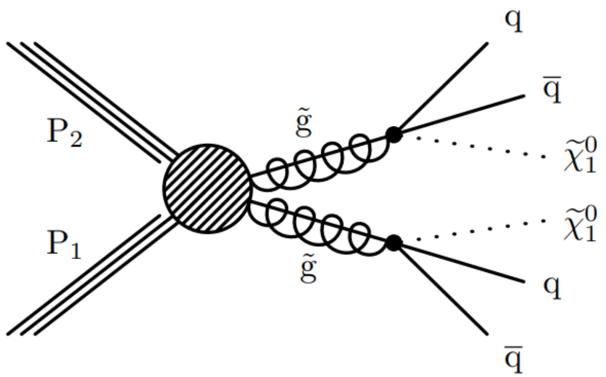
c) split events into two pseudojets and compute MT2(j1; j2)

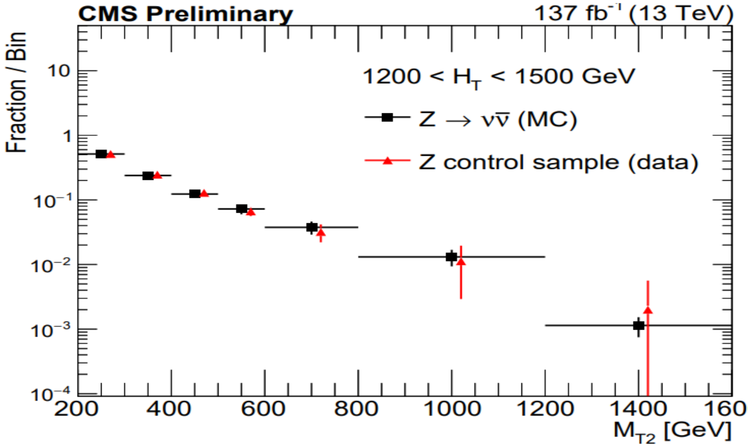
d) use MHT = $\left\| -\sum_{jets} \vec{P}_T^j \right\|$

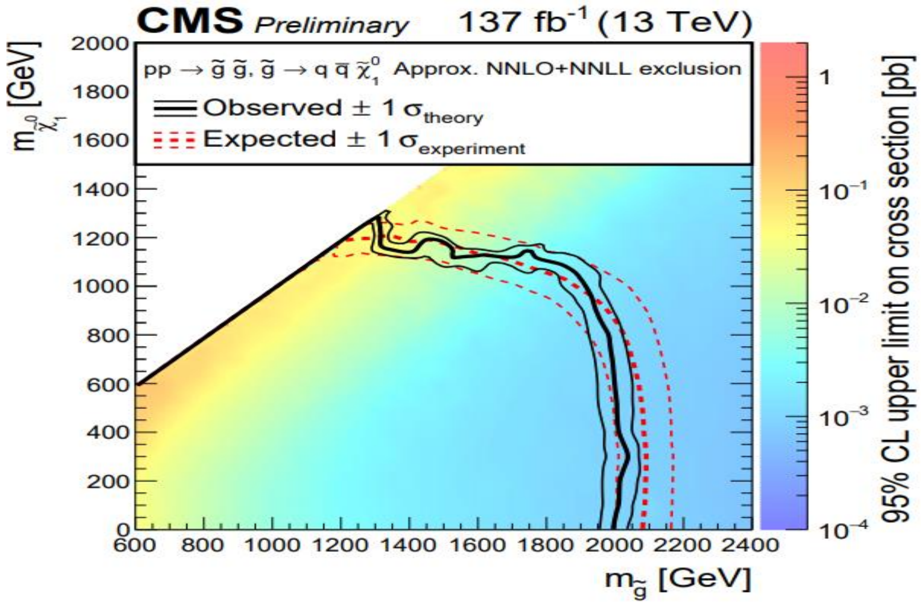
JHEP (2019) 2019: 244



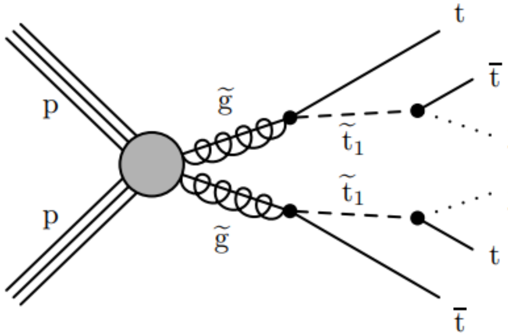
CMS-PAS-SUS-19-005

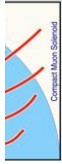






Same-sign 2 Leptons & 3 Leptons

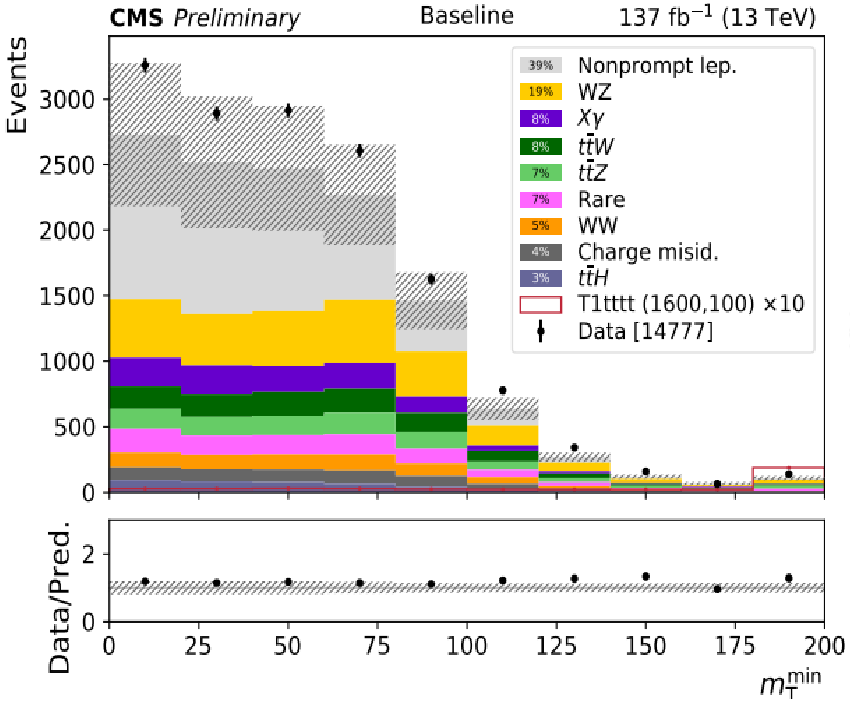


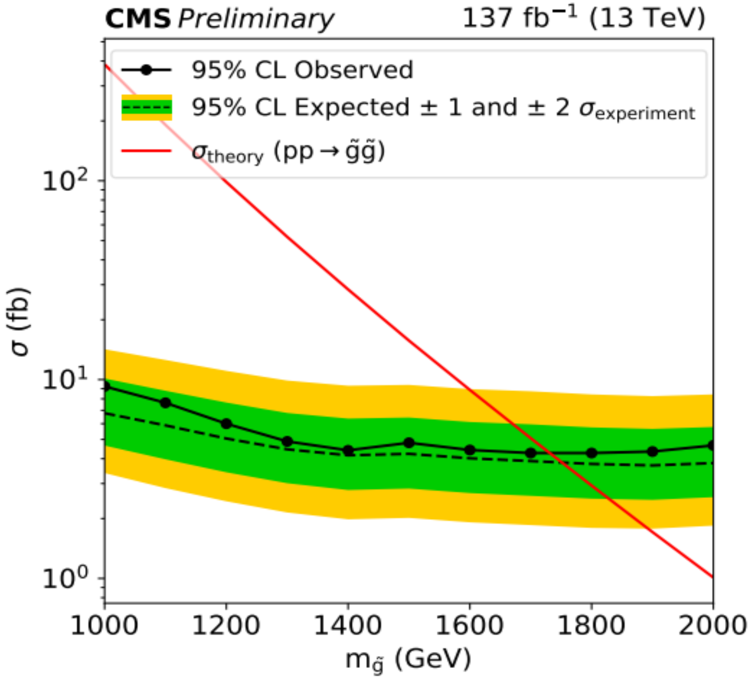


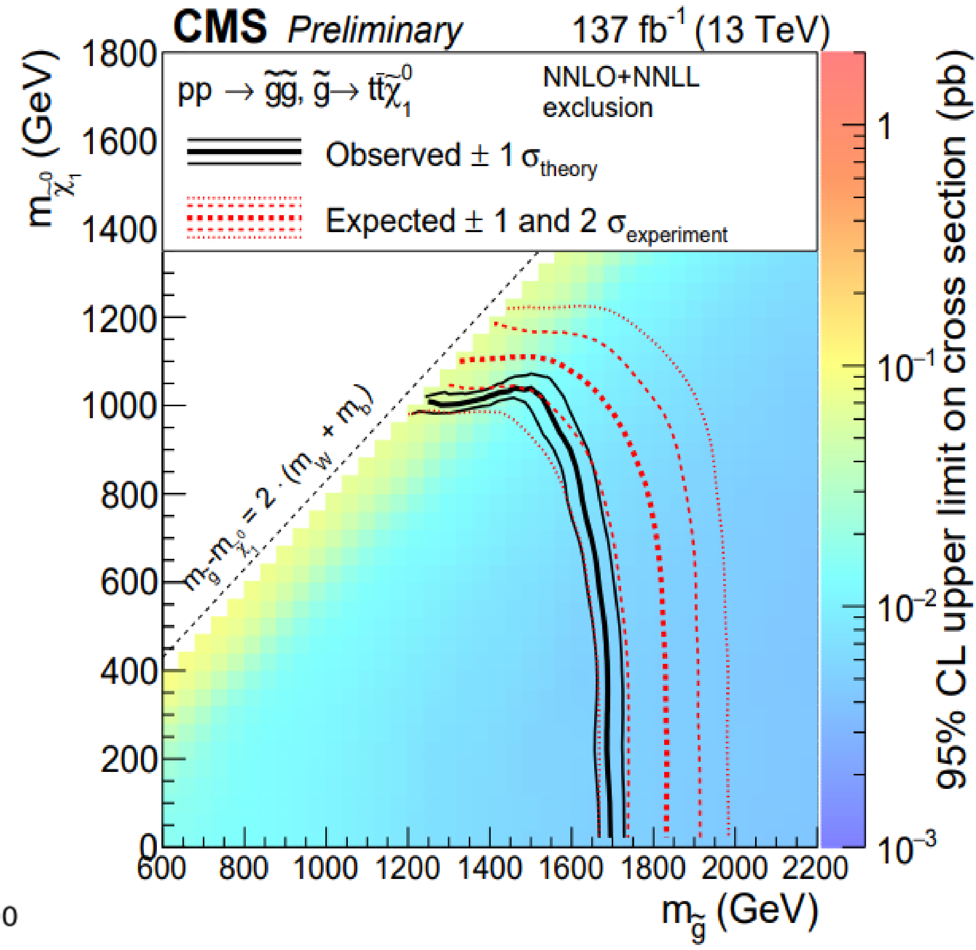
Targets leptonic decay signals (including *R*-parity violation)

- limited SM (irreducible) same-sign lepton backgrounds
- reducible detector backgrounds non negligible: fake/non-prompt leptons, electron charge flip, ... ➔estimated from data

CMS-PAS-SUS-19-008

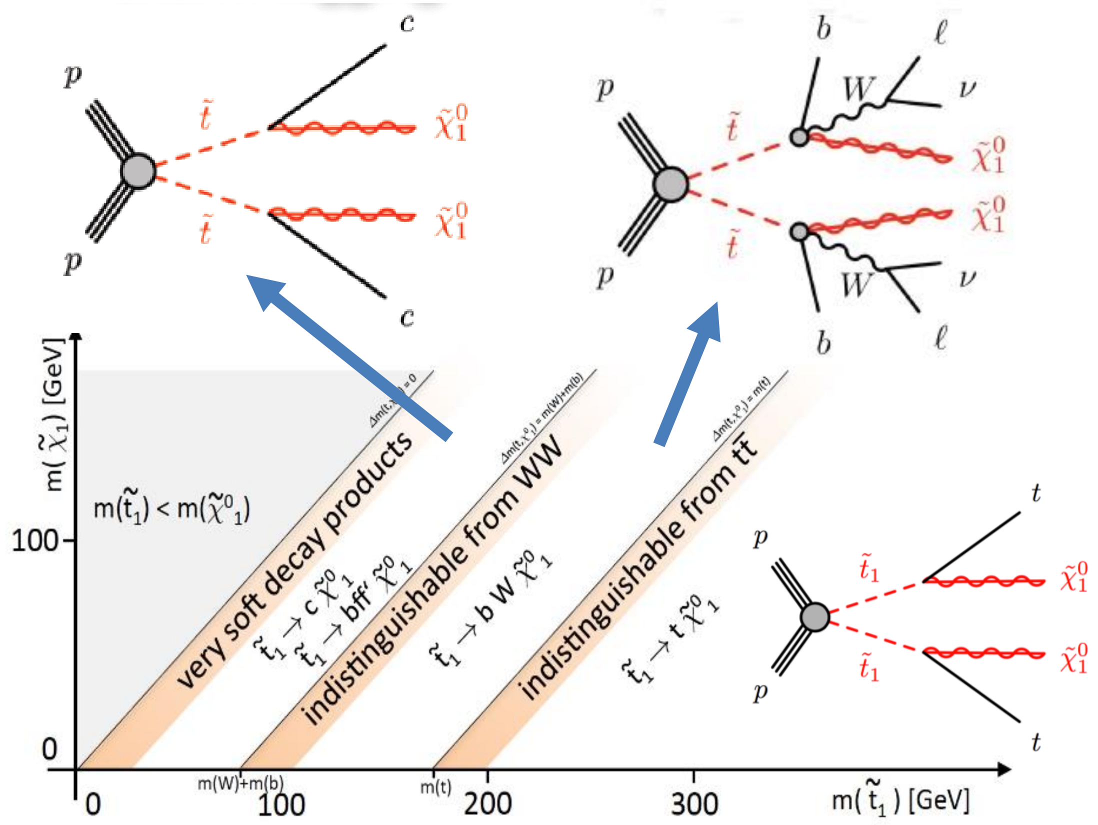


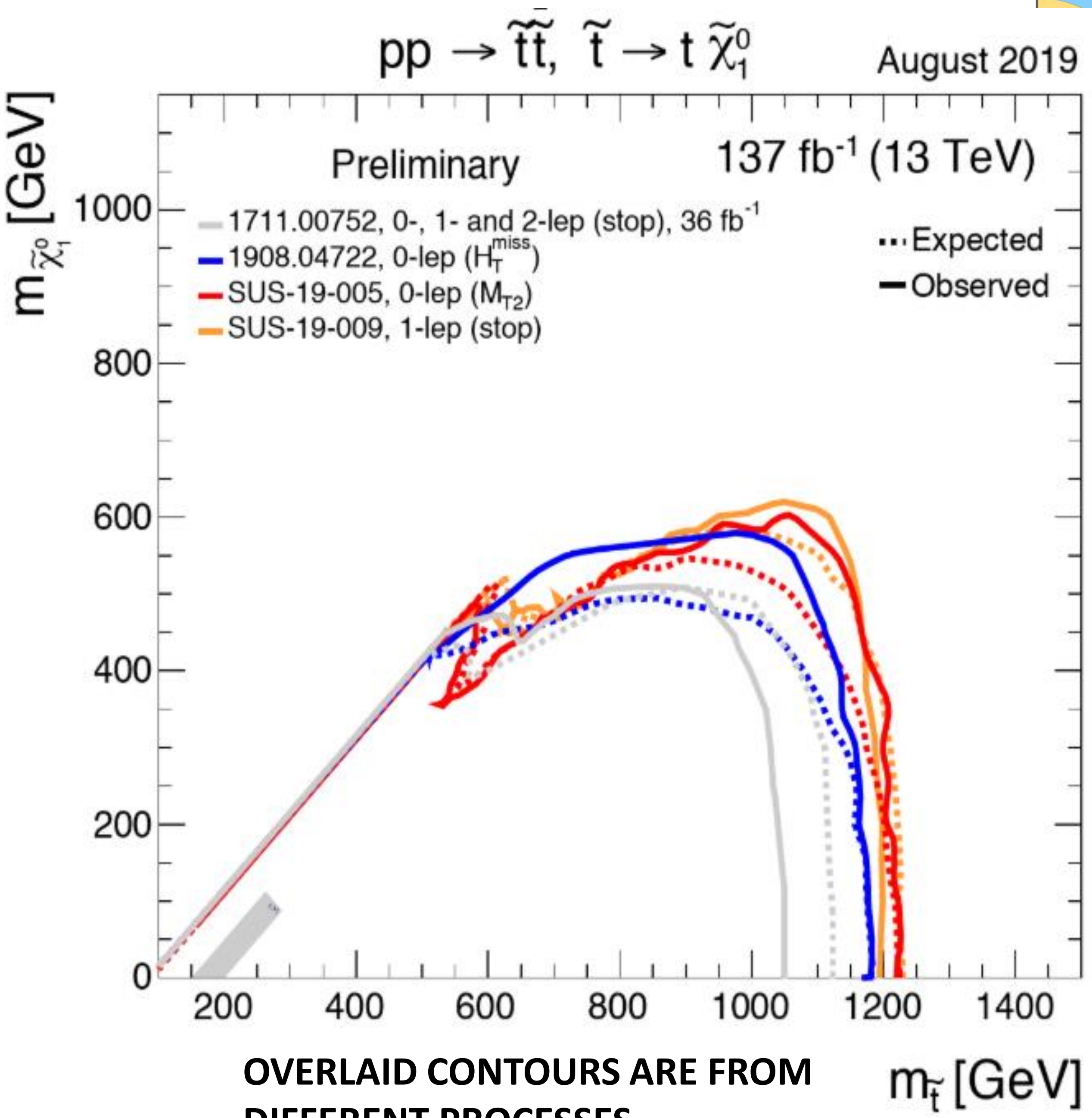




Stop searches

- Different analysis strategies depending on the mass difference : $\Delta m = m_{\tilde{t}} - m_{\chi_1^0}$
- Compressed regions studied with ISR jet.

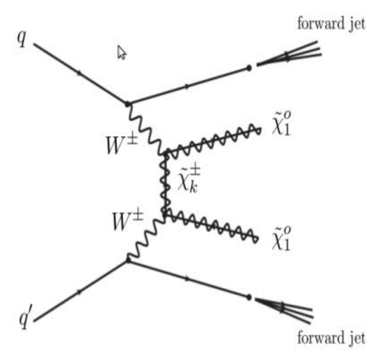


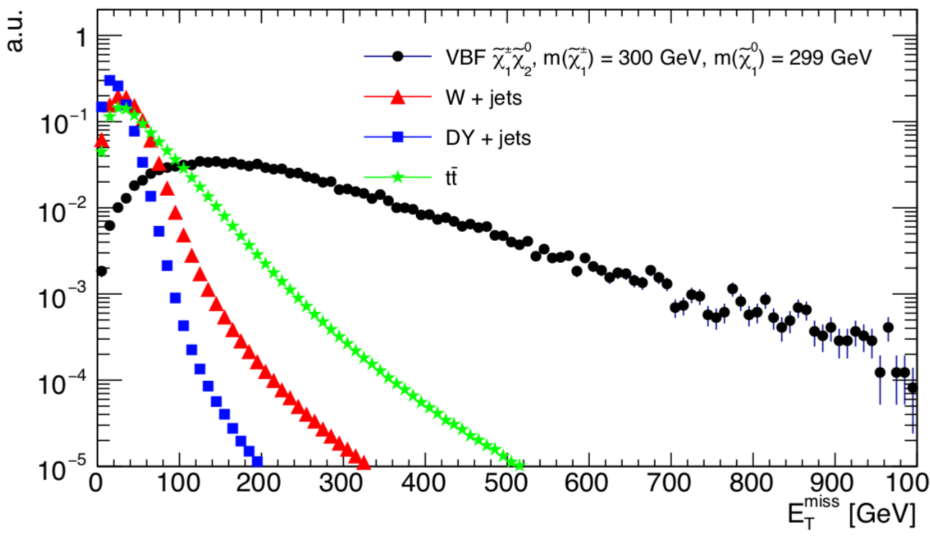


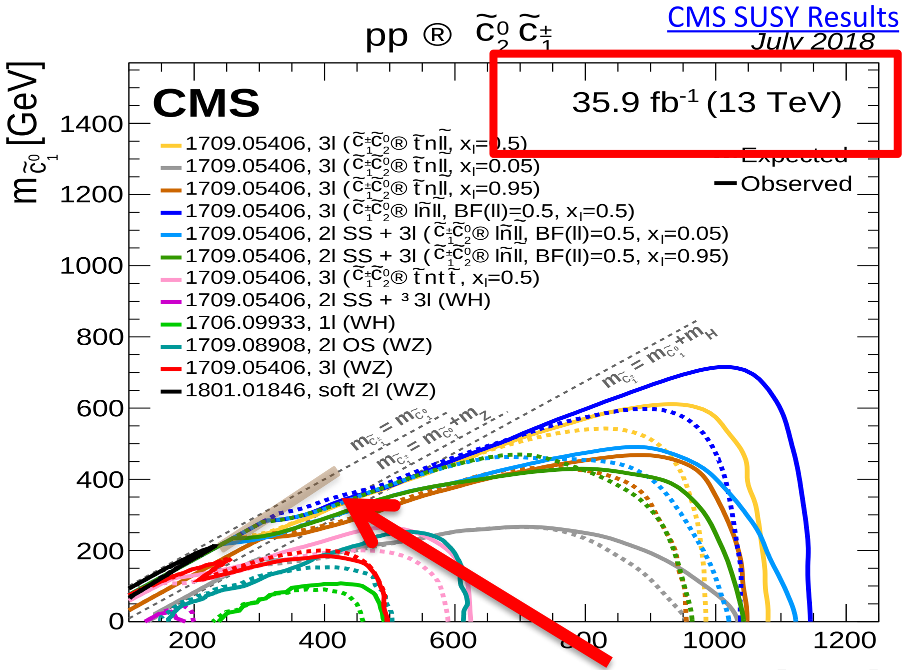
OVERLAID CONTOURS ARE FROM DIFFERENT PROCESSES

VBF Electroweakinos

VBF selection: jet candidates with the following requirements
- ✓ large eta separation
- ✓ in opposite hemispheres
- ✓ large dijet invariant mass



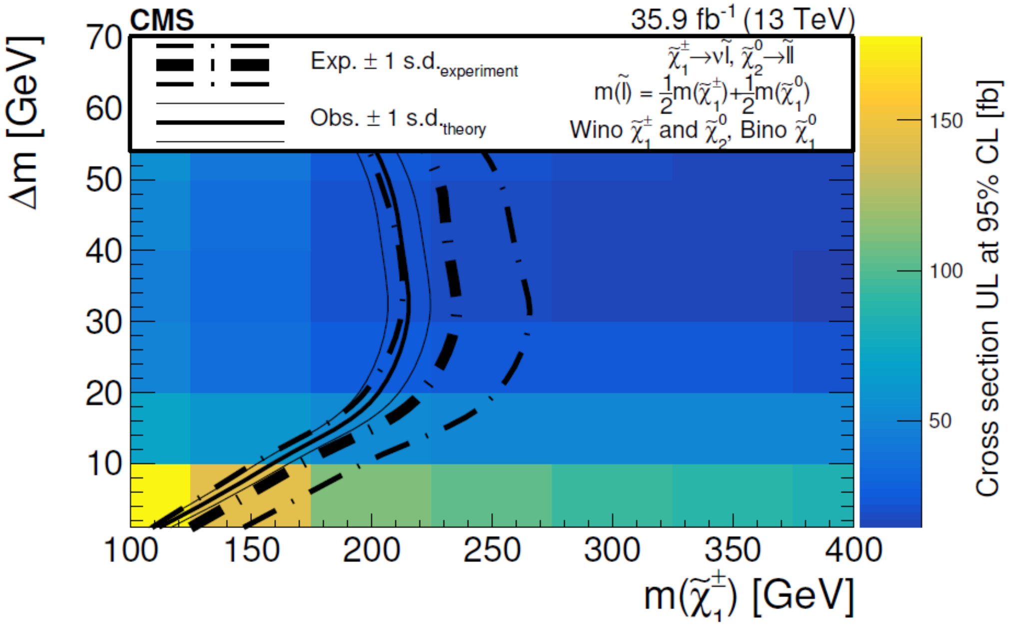




Region under exploration!

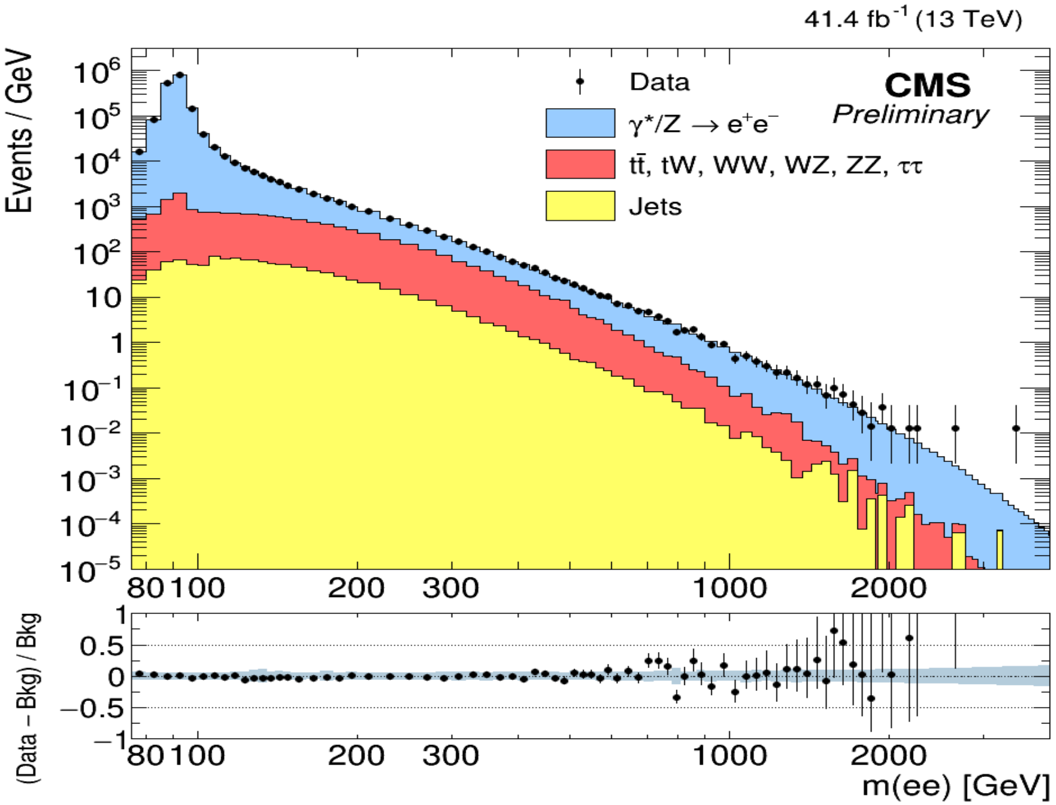
$\Delta m = m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$ = 1 – 50 GeV

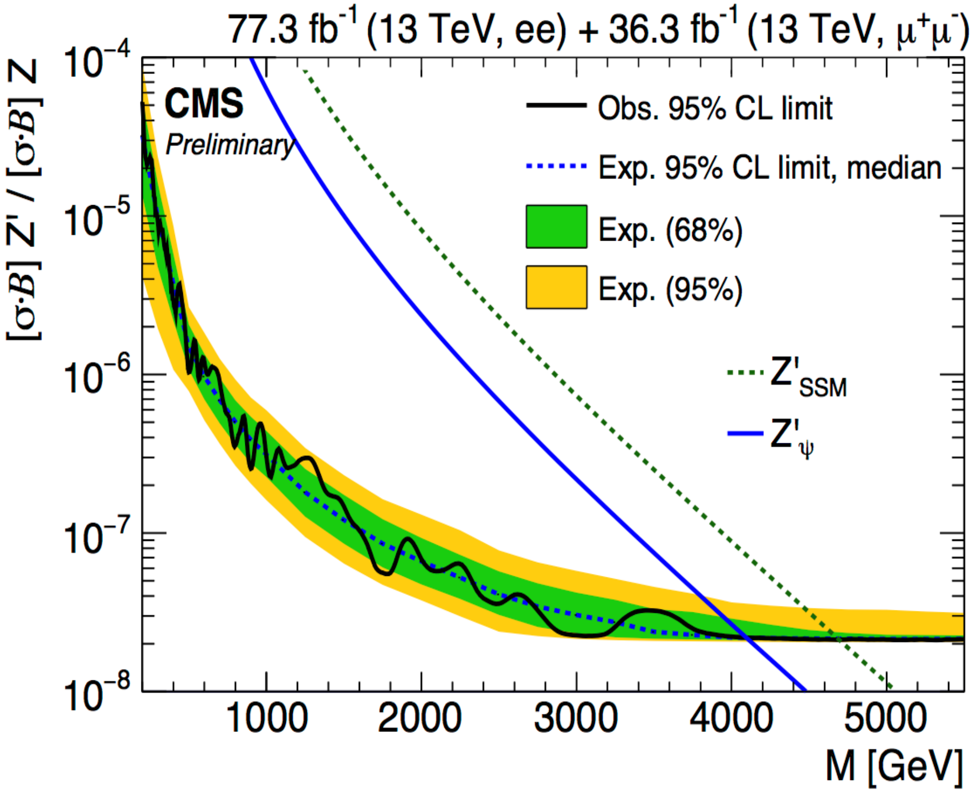
VBF topology suffers from smaller cross sections, but benefits from lower contamination from SM backgrounds.



High Mass e^+e^- Resonance Search

CMS PAS EXO-18-006





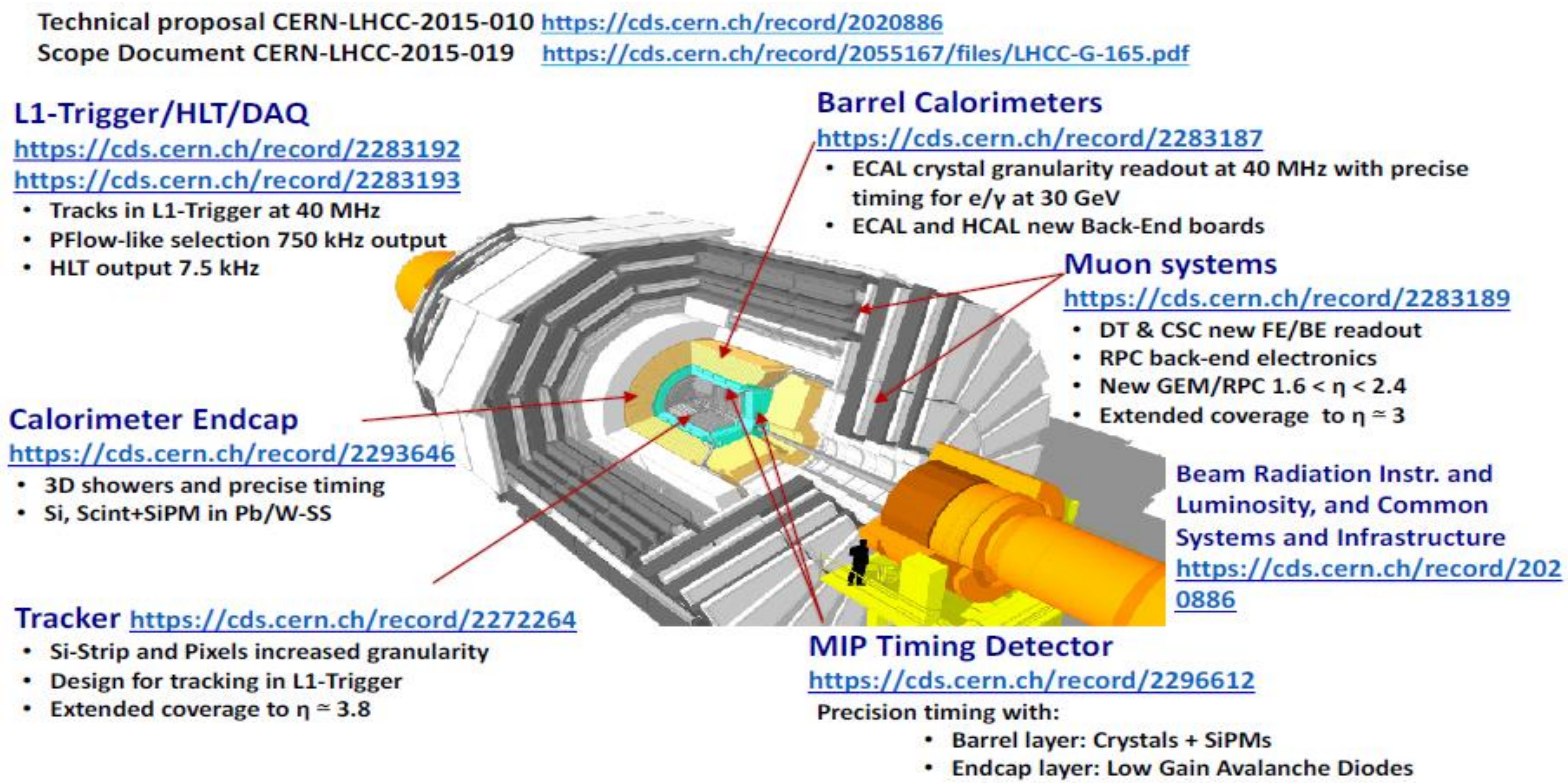
2017 dielectrons

2017 dielectrons + 2016 dimuons

Exclusion limits for some models already ~ 4-5 TeV

4. PROSPECTS FOR HL-LHC

CMS PHASE II UPGRADE



Technical proposal CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886
Scope Document CERN-LHCC-2015-019 https://cds.cern.ch/record/2055167/files/LHCC-G-165.pdf

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

Calorimeter Endcap
https://cds.cern.ch/record/2293646

- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

Tracker https://cds.cern.ch/record/2272264

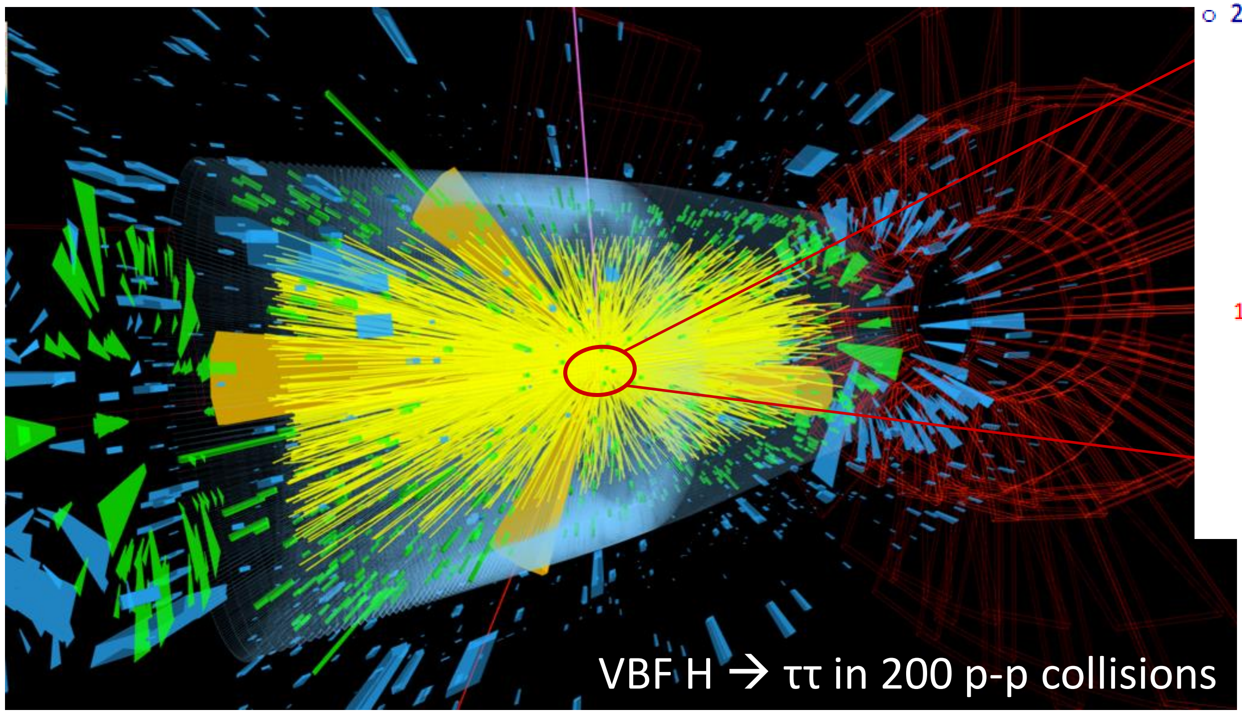
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector
https://cds.cern.ch/record/2296612

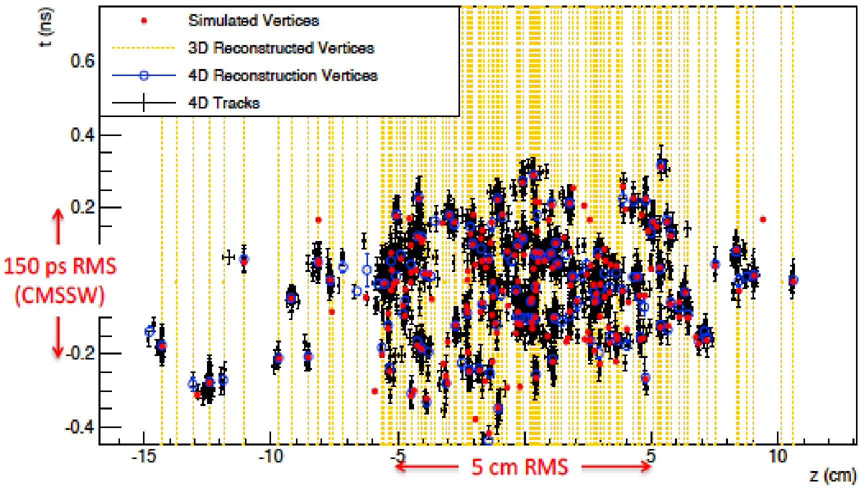
Precision timing with:

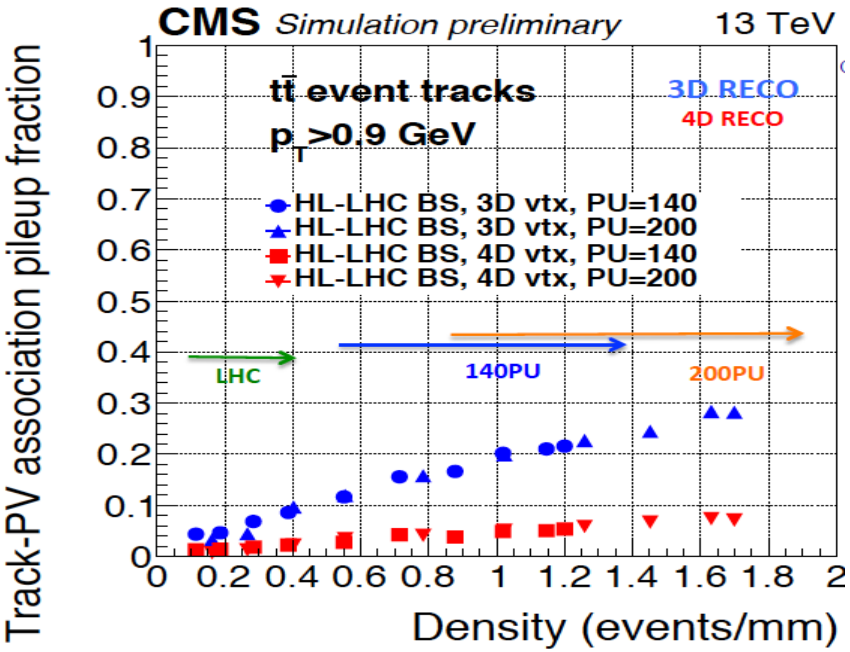
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

MIP Precision Timing Detector


VBF H → ττ in 200 p-p collisions

○ 200 pileup collisions





Time of flight precision ≃ 30 ps, |η|< 3, p_T > 0.7 GeV "Provide a factor 4-5 effective pile-up reduction"

- ~ 15% merged vertices reduce to ≃ 1.5%
- Low pileup track purity of vertices recovered

- **All showers timed to 30 ps in calorimeters**

MAIN ASPECTS OF CMS PHASE II -UPGRADE

Goal: Be as efficient, and with low background/fake-rate, at 200-250 pileup as we are today, with extended acceptance and new capabilities

- Tracker is AGAIN ALL SILICON but now with much higher granularity, and extends to $|\eta| = 4$, >2 billion pixels and strips
- Tracking information in “L1 track-trigger”
  - Tracker is designed to enable finding of all tracks with $P_T >\sim 2$ GeV in under 4 μs for use in the lowest level trigger
- High Granularity Endcap Calorimeters
  - Sampling of EM-showers every $\sim 1\lambda_{rad}$ (28 samples) with small silicon pixels and then every $\sim 0.35\lambda_{abs}$ (24 samples) with combination of silicon pixels and scintillator to map full 3-dimensional development of all showers (~6M channels in all)
- Precision timing of all objects, including single charged tracks, provides a 4th dimension to CMS object reconstruction to combat pileup (~200K sensors in barrel section)

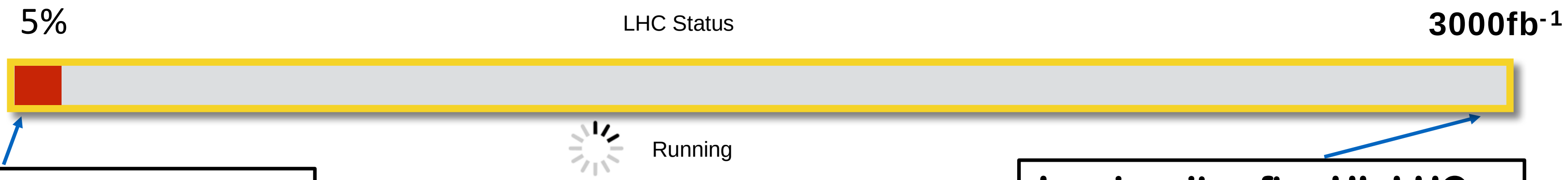
The LHC Luminosity Plan

We are in the middle of LS2

x5 Run1

x2 Run2

x10 Run3



Luminosity so far

Luminosity after HL-LHC

CONCLUSIONS AND OUTLOOK

1. Great performance of the accelerator and the CMS experiment during run II (2015-2018).
2. The LS2, in parallel to the upgrade of the detector, allows to complete the analyses of the run II data.
3. The LHC will be running in 2021 at 14 TeV with higher luminosity.
4. Even if we do not have signs of any BSM signal yet. We are optimistic that it will reveal at some point with higher luminosity. So far, we have recorded only 5% of the full lumi expected at the LHC.
5. How a BSM signal might reveals is a mistery: A striking signal might show up in a single channel or may appear in several channels emerging slowly over large backgrounds. BSM might appear in channels we have been looking for long time, or perhaps with signatures we are still not looking at or triggering on.
6. BSM physics is still puzlling us, but that is what Physicists most enjoy: Finding answers to the puzles of nature. So the futures is bright for physicist: Plenty of work to do.

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Deadline:
March 30th, 2020

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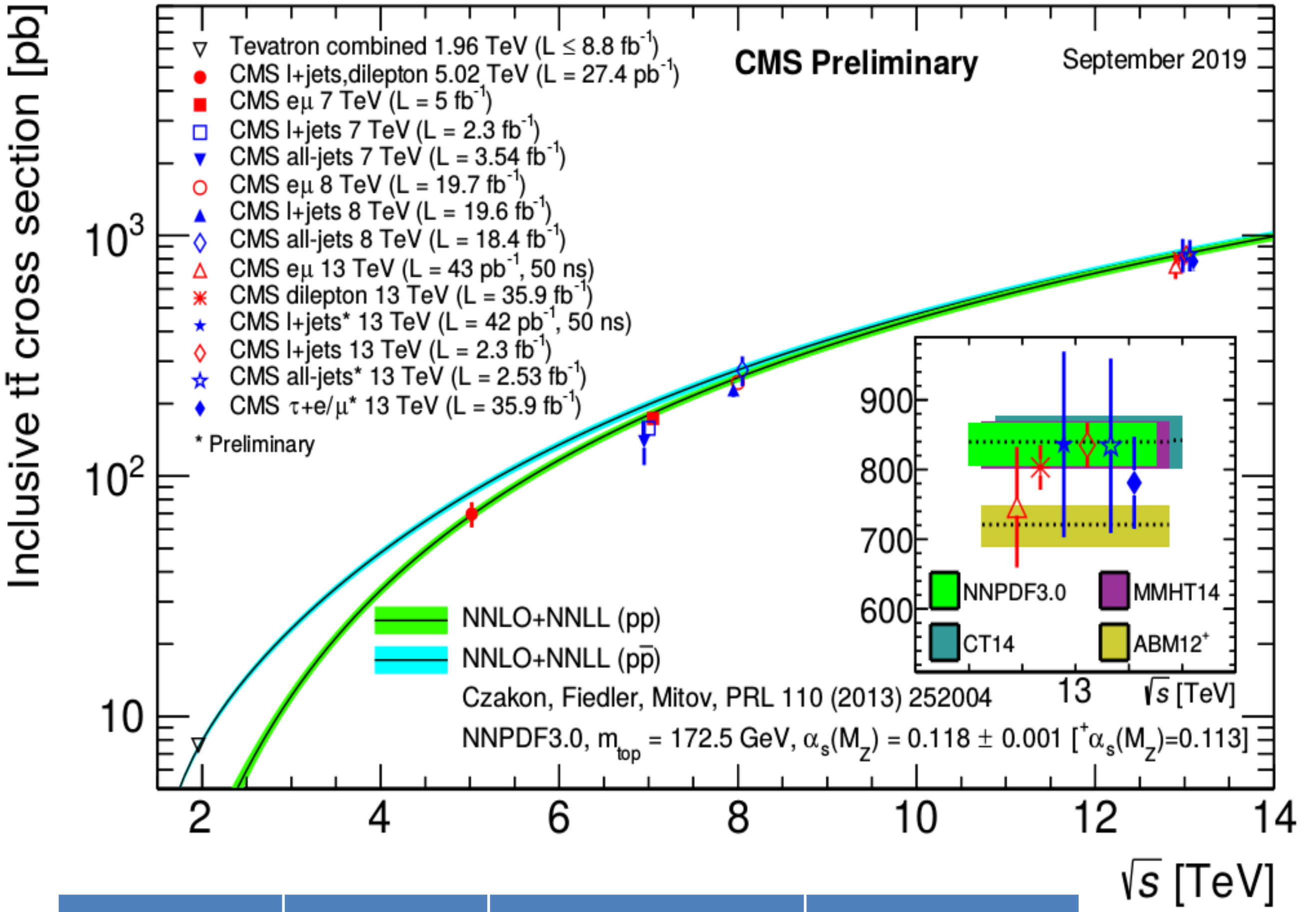
THANKS !

BACKUP SLIDES

$t\bar{t}$ CROSS SECTIONS



CMS: 835 ± 33 pb
Theory: 816 ± 42 pb

At 13 TeV

Top pair rate is > 10 Hz, enabling us to address much more precise questions

- Single, double, and triple differential cross sections
- Rare (FCNC) decays
- CP violation (a beginning)
- Width and more complex methods for measuring the mass

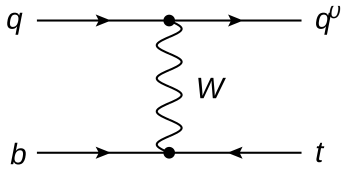
Top pair production at 13 TeV CM energy is mainly (80%) produced by gluons, providing important information on the gluon distribution at relatively high x_F, up to ~0.25

Factory	Quark	Cross Section (nb)	Luminosity (cm-^{2}s^{-1})
B (KEKb)	Bottom	1.15 (Υ(4S))	2.11x10^{34}
LHC	Top	0.82 (incl t-t)	2.01x10^{34}

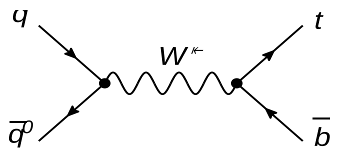
SINGLE TOP CROSS SECTIONS

13 TeV

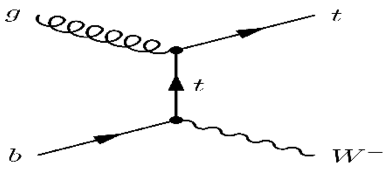
t-channel ~220 pb



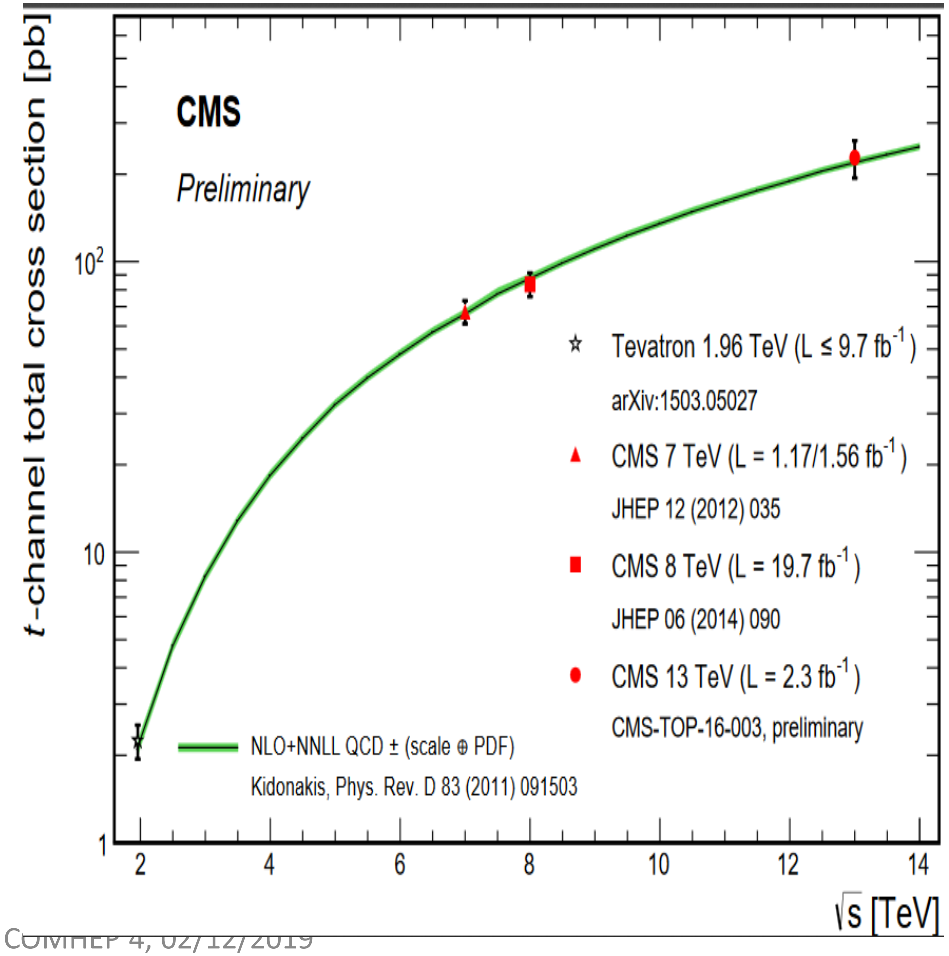
s-channel~ 10pb

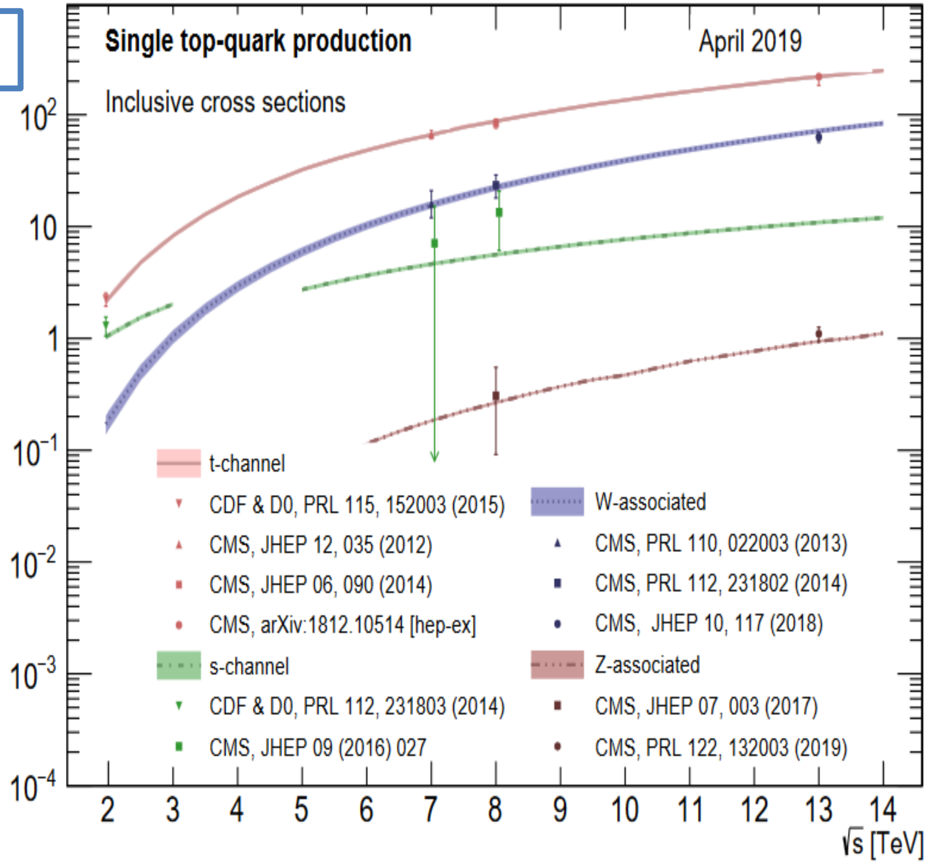


tW channel ~70 pb

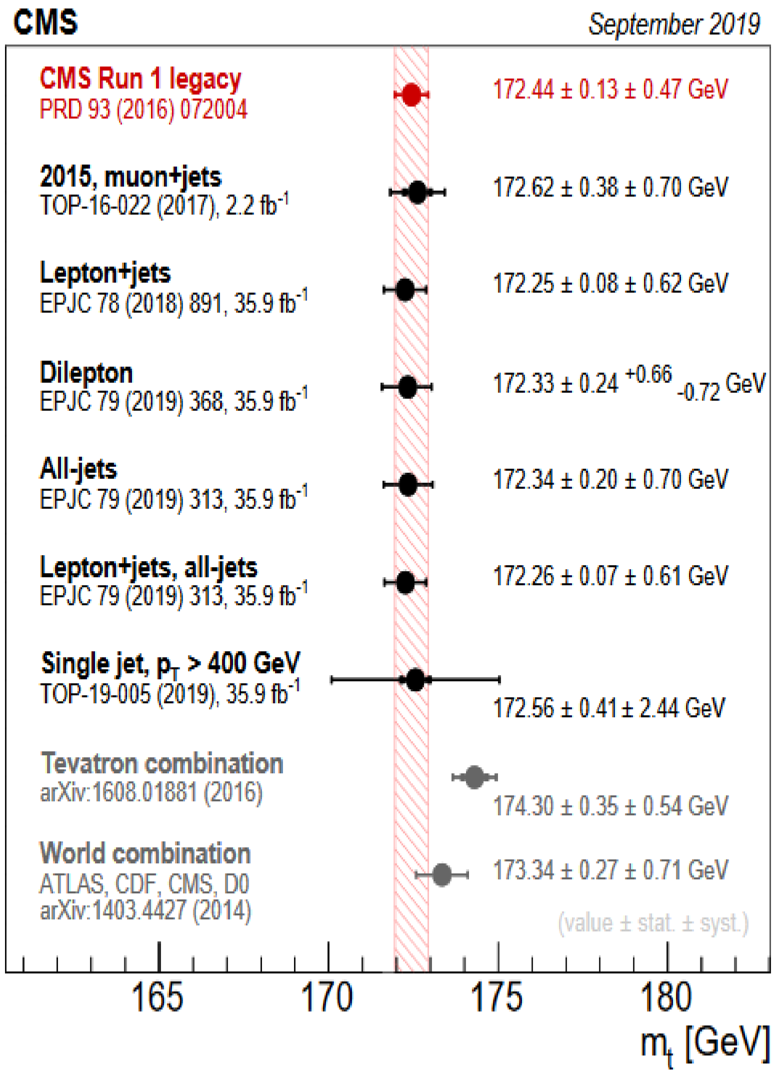


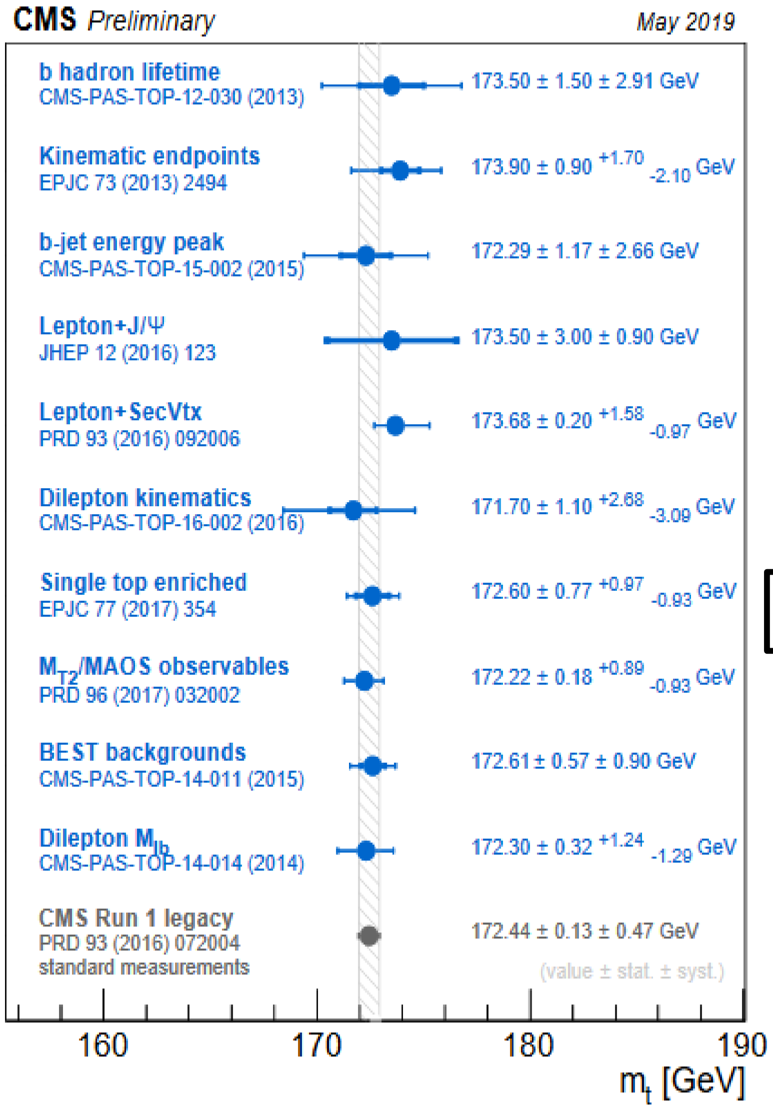
Not seen at LHC

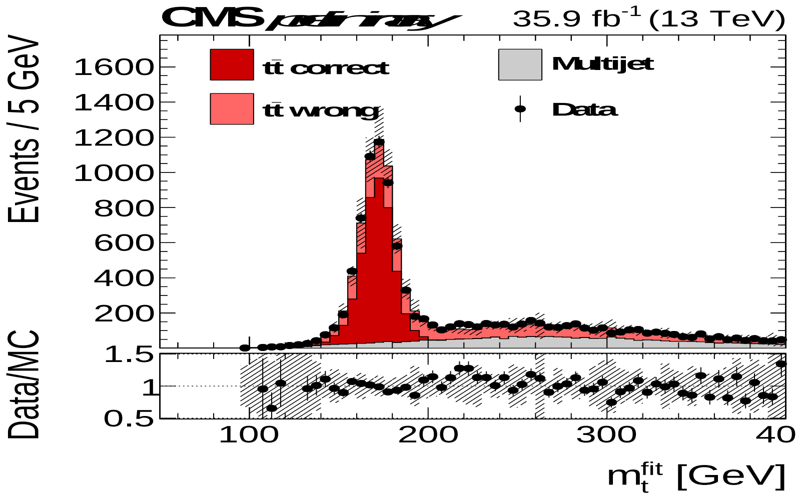




TOP QUARK MASS







CMS all-jet (13 TeV)

172.34 ±0.20 (*stat*+*JSF*)±0.76 (*syst*) GeV

Alternative methods are not as accurate now, but will become so and we hope the one or more will have ultimately more favorable systematics

RUN I HIGGS WIDTH LIMIT

From off-shell ZZ production

Phys. Lett. B 736 (2014) 64

H→ZZ→4ℓ , H→2ℓ2ν, (ℓ=e,μ),

Breit-Wigner production gg→H→ZZ:

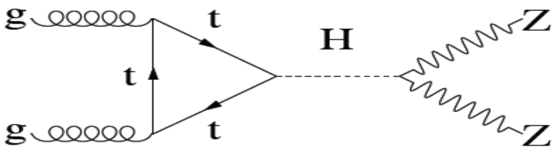
$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{\left(m^2_{ZZ}-m^2_H\right)^2 + m^2_H\Gamma^2_H}$$

On-peak ($105.6<m_{4\ell}<140.6$ GeV) and off-peak cross sections ($m_{4\ell}> 220$ GeV):

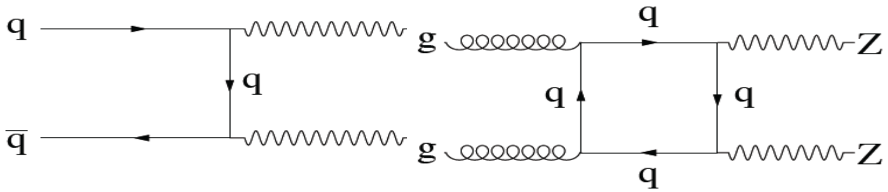
$$\sigma^{\mathrm{on-shell}} = \int_{|m-m_H|\le n\Gamma_H} \frac{d\sigma}{dm}\cdot dm \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{m_H\Gamma_H}$$

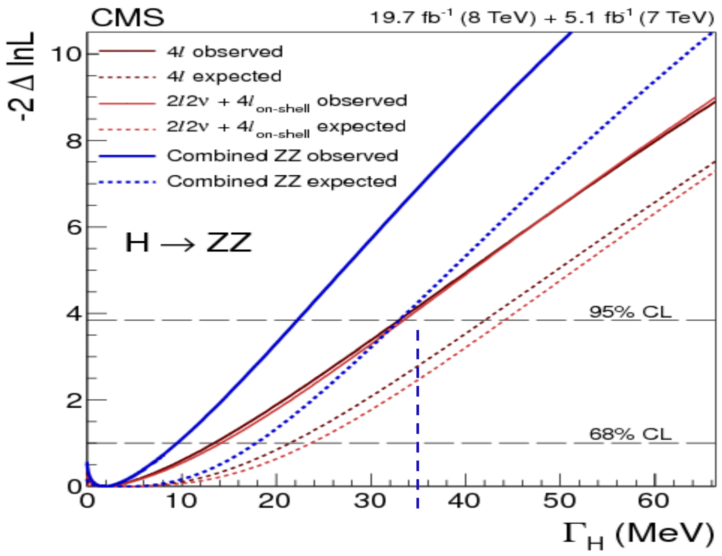
$$\sigma^{\mathrm{off-shell}} = \int_{m-m_H \gg \Gamma_H} \frac{d\sigma}{dm}\cdot dm \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{(2m_Z)^2}$$

$$\boxed{\frac{\sigma^{\mathrm{off-shell}}}{\sigma^{\mathrm{on-shell}}} \sim \Gamma_H}$$



Dominant backgrounds:





$\Gamma_H < 22$ MeV at 95% CL

- Must include interference between gg→H→ZZ and gg→Box→ZZ
- K-factor of gg→ZZ not well known, assume the same as signal and add a sytematic uncertainty.
- This method is a SM-model-dependent interpretation of the off-shell/on-shell ratio

RUN I HIGGS WIDTH LIMIT

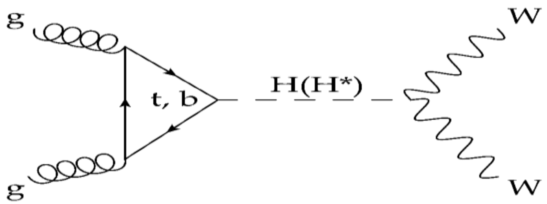
From off-shell WW production

$H \to WW \to e\nu\mu\nu$

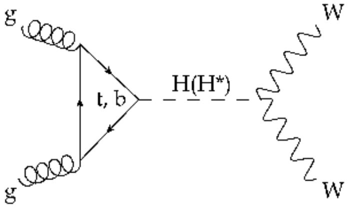
. Worst mass resolution than$H \to ZZ$ but higher BR

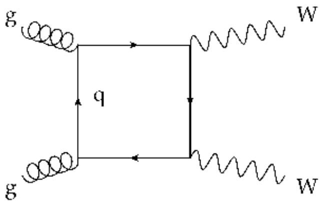
. Same procedure as $H \to ZZ \to 4\ell$, (ℓ=e,μ) is followed.

$\Gamma_H < 26$ MeV at 95% CL

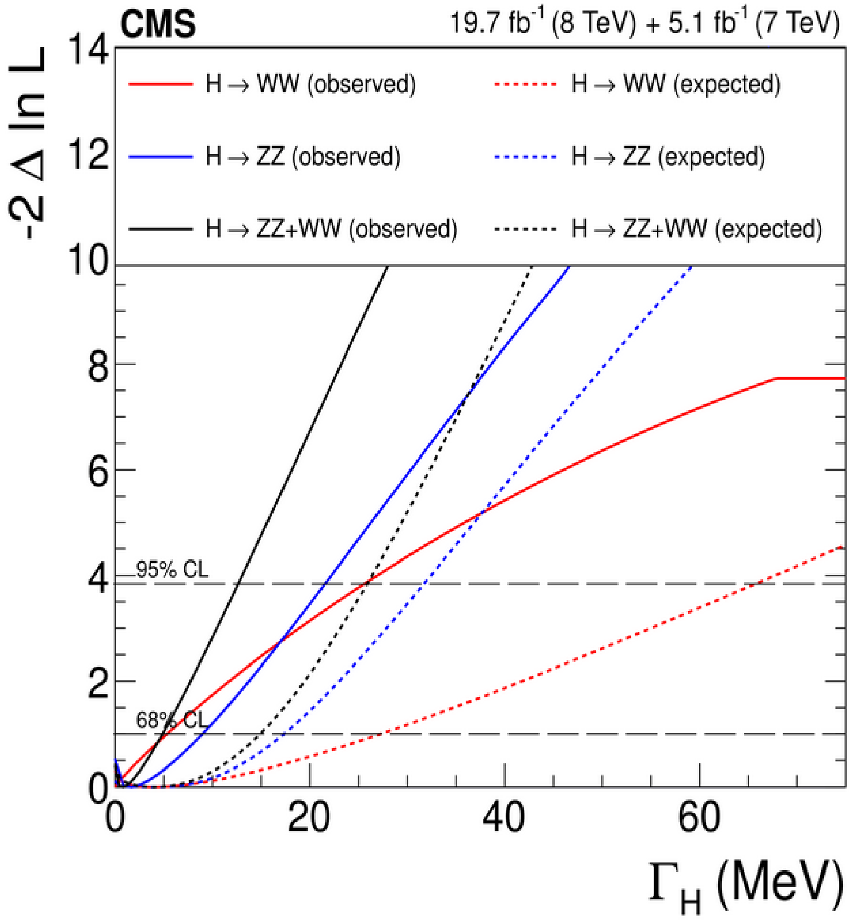


Dominant backgrounds:





JHEP 09 (2016) 051



Combination of ZZ and WW channels:

$\Gamma_H < 13$ (26) MeV at 95% CL

RUN I HIGGS LIFETIME & WIDTH LIMITS

H→ZZ→4ℓ , (ℓ=e,μ), Phys. Rev. D 92, 072010 (2015)

$\tau_{H,SM}$ = 16 x 10^{-8} fs, beyond instrumental precision, we can stablish an upper limit.

- Lifetime derived from flight distance in the CMS detector: $$\Delta t = \frac{m_{4\ell}}{p_T}\left(\Delta\vec{r}_T \cdot \hat{p}_T\right)$$

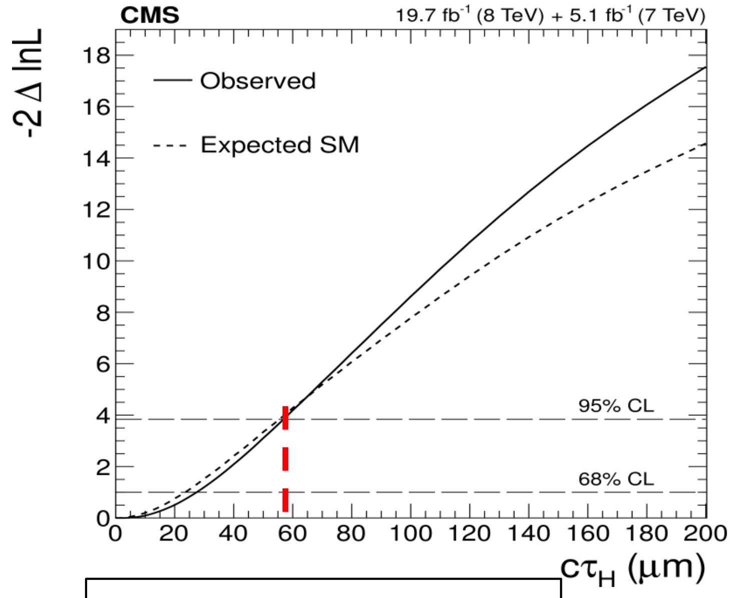
$\Delta\vec{r}_T$ = displacement vector between H production vertex and decay

- Γ_H obtained from off-shell production technique + Anomalous H→VV couplings.

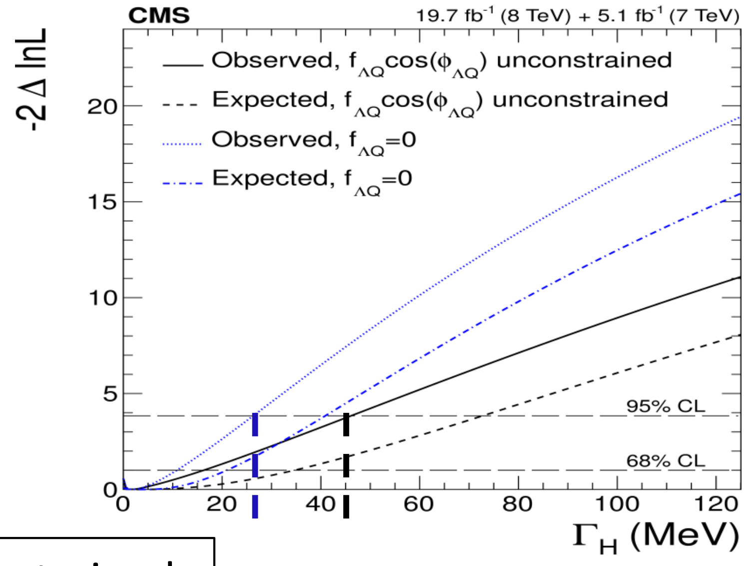
Effective cross section fraction:

$$f_{\Lambda Q} = \frac{m_H^4/\Lambda_Q^4}{|a_1|^2 + m_H^4/\Lambda_Q^4}$$

$$A(\mathrm{HVV}) \propto \left[a_1 - e^{i\phi_{\Lambda Q}}\frac{(q_{V1}+q_{V2})^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda 1}}\frac{(q_{V1}^2+q_{V2}^2)}{(\Lambda_1)^2}\right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$



$\tau_H < 1.9\times10^{-13}$ s 95% CL



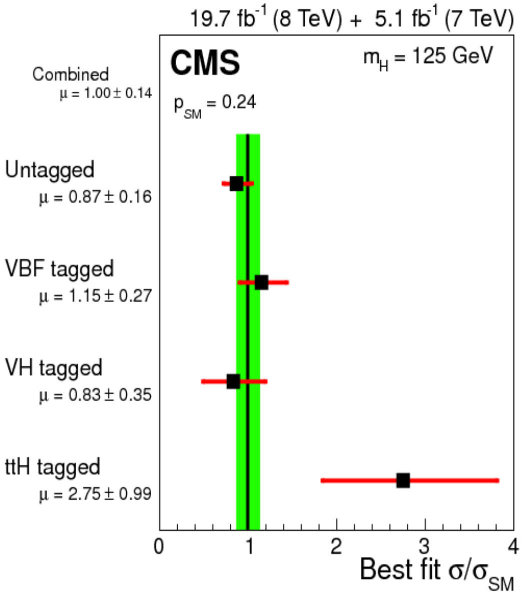
$\Gamma_H < 26$ MeV for $f_{\Lambda Q}=0$

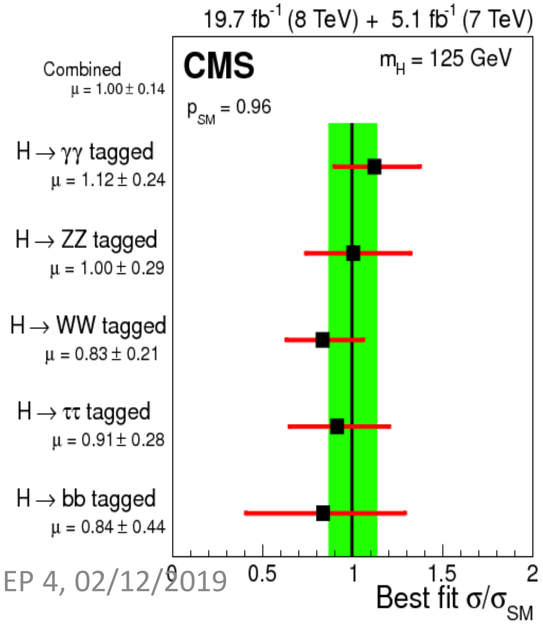
$\Gamma_H < 46$ MeV with $f_{\Lambda Q}$ unconstrained

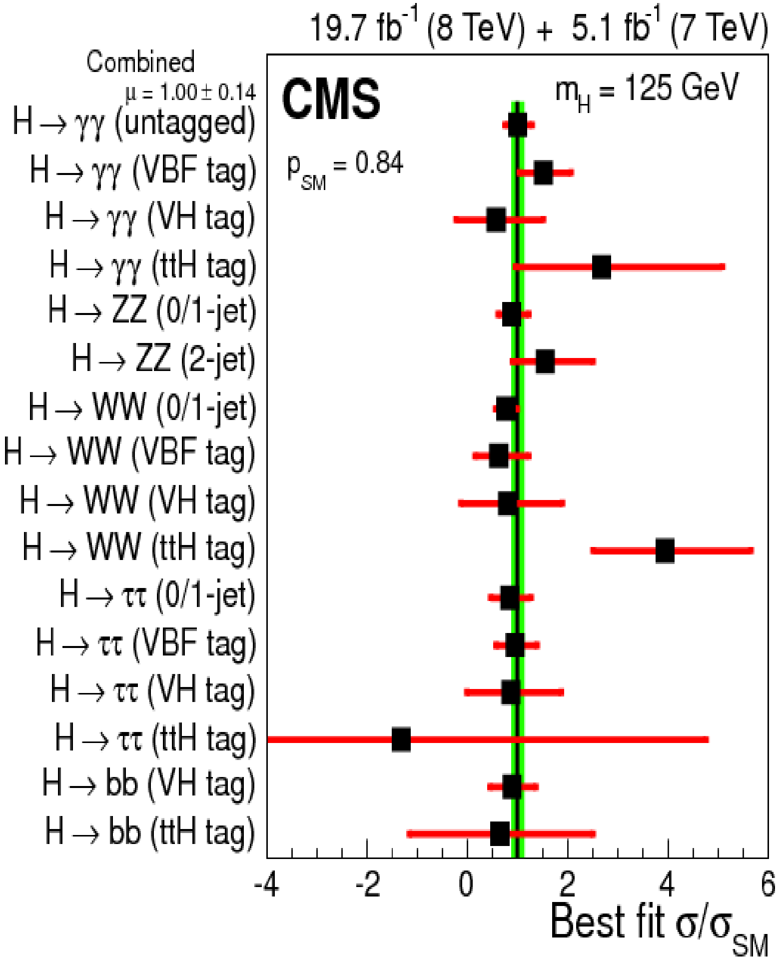
At 95% CL.

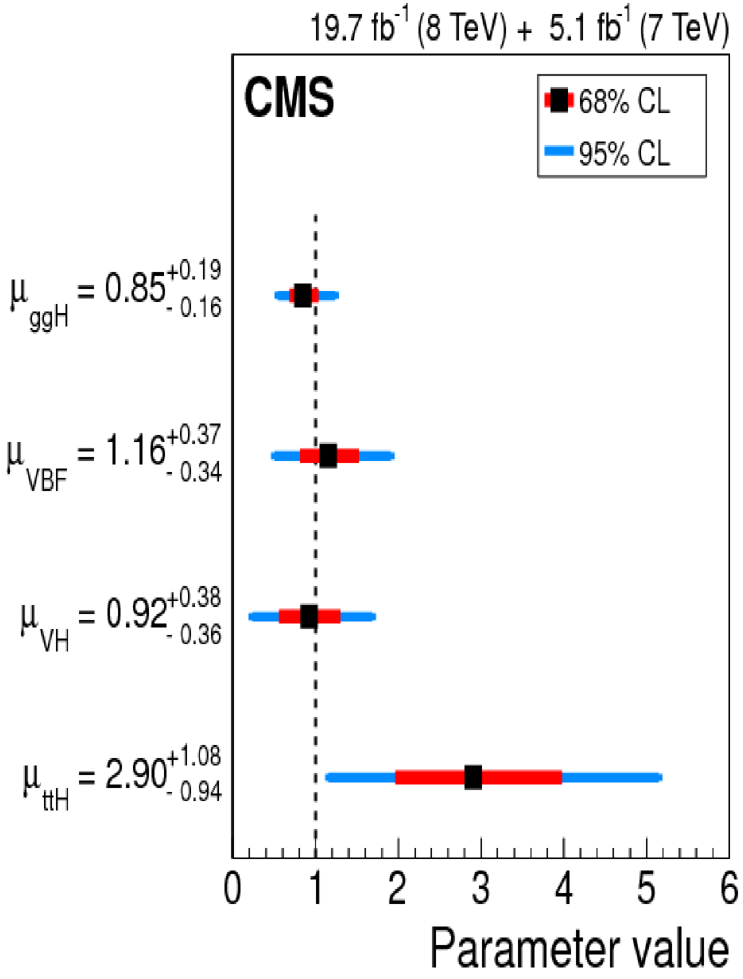
RUN I SIGNAL STRENGTH, $\mu=\sigma/\sigma_{SM}$

EPJ C 75 (2015) 212









μ = 1.00 ± 0.09 (stat.) ± 0.08 (theory) ± 0.07 (syst.)

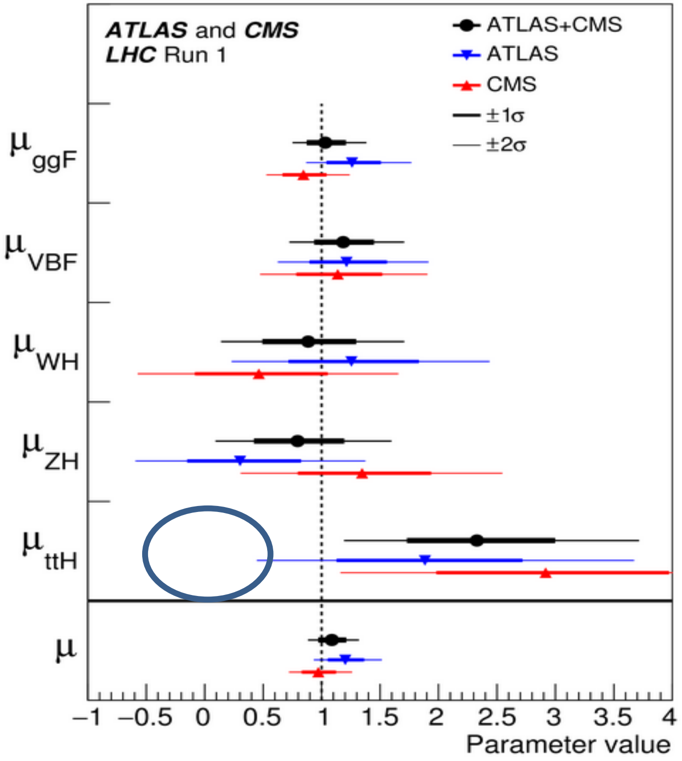
Syst. Uncertainty < theory uncertainty

RUN I SIGNAL STRENGTH, $\mu=\sigma/\sigma_{SM}$

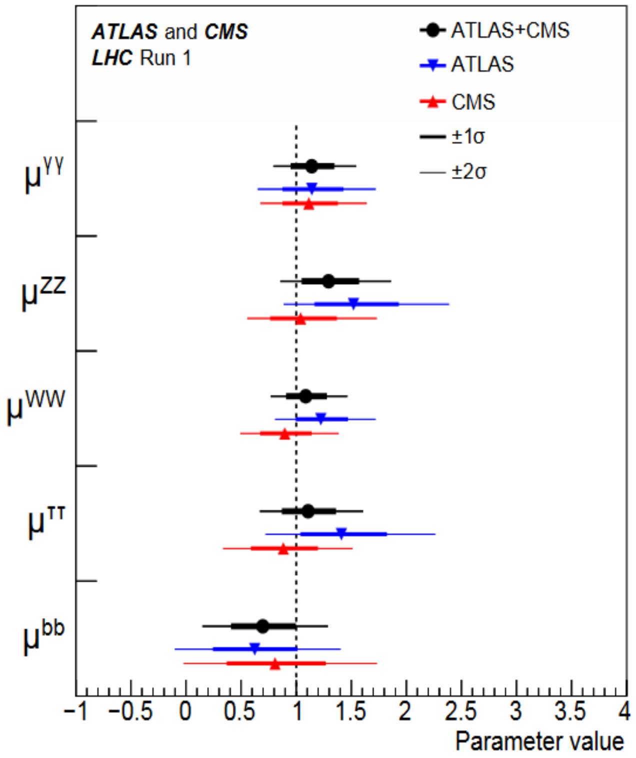
Combined measurement of ATLAS + CMS

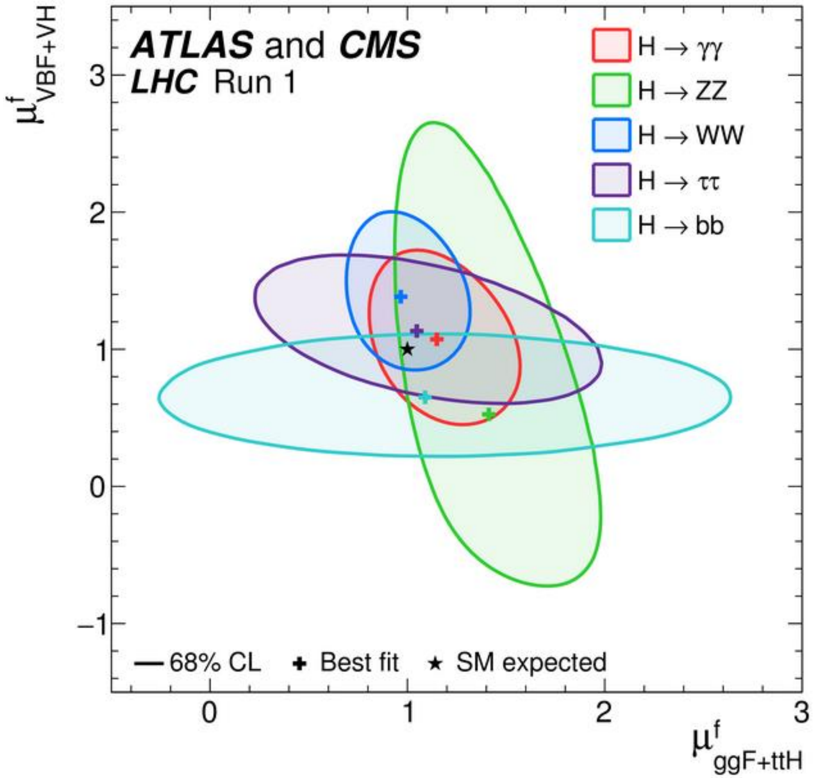
JHEP 08 (2016) 045

$\mu_{PRODUCTION}$



μ_{DECAY}





- M_H assumed to be 125.09 (ATLAS+CMS combination)
- Assume a single SM Higgs state
- Uncertainty is dominated by theoretical uncertainty in σ_{ggH}

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$

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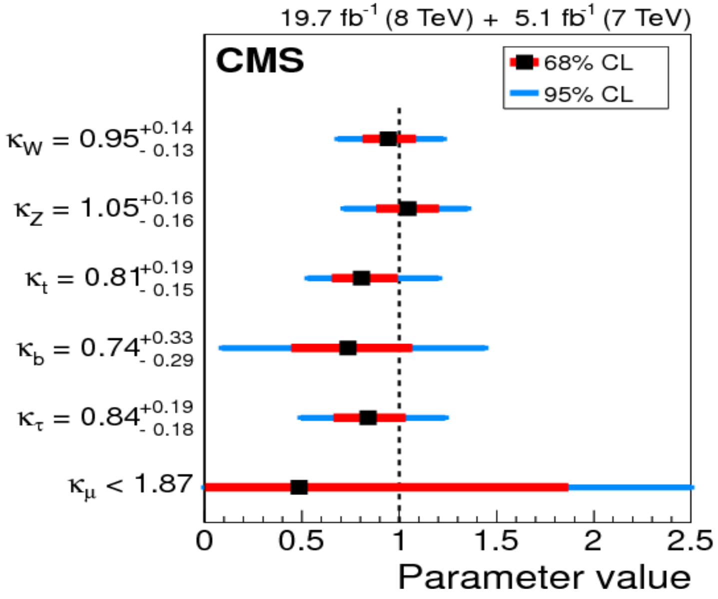
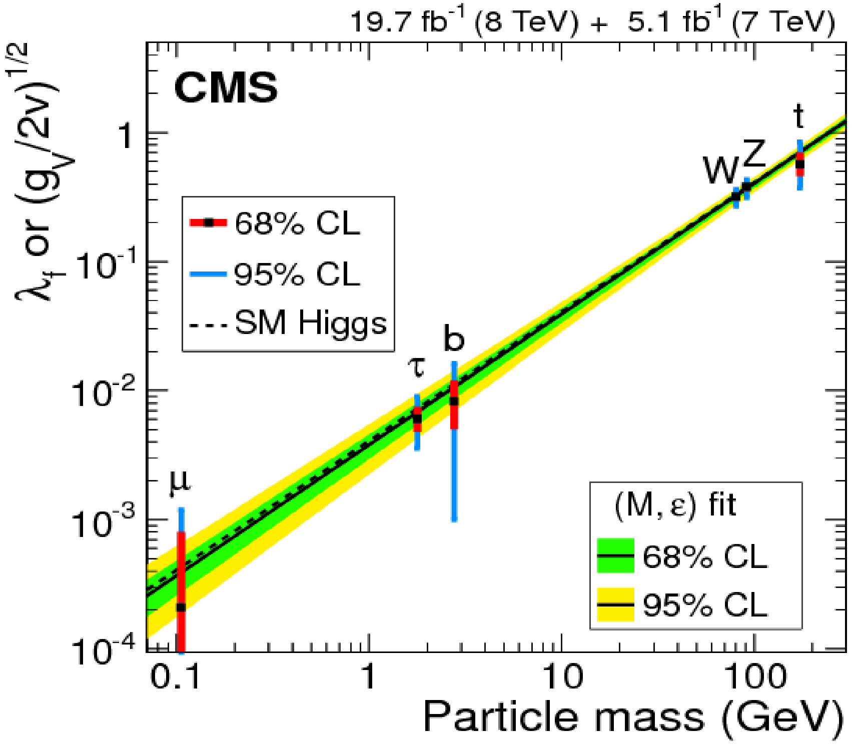
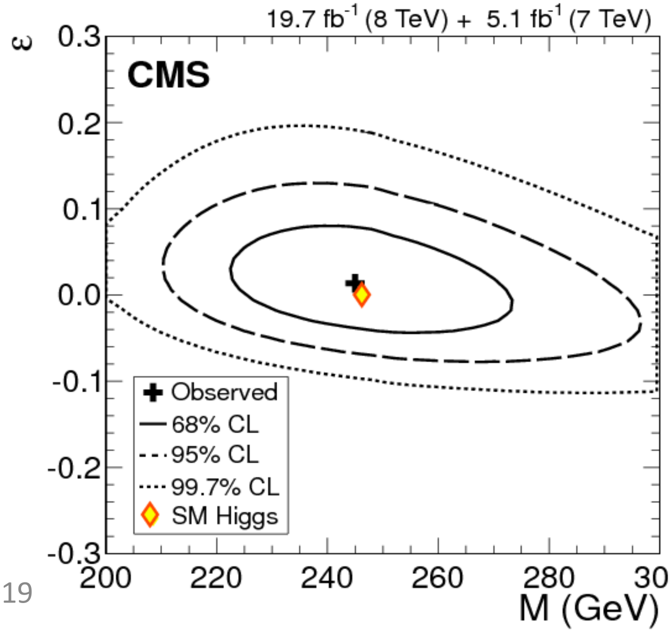
RUN I COUPLING TESTS

EPJ C 75 (2015) 212







$$\kappa_f = \mathrm{v}\frac{m_f^{\varepsilon}}{M^{1+\varepsilon}} \qquad \kappa_{\mathrm{v}} = \mathrm{v}\frac{m_{\mathrm{v}}^{2\varepsilon}}{M^{1+2\varepsilon}}$$

$$g_{\mathrm{v}} = \kappa_{\mathrm{v}}\frac{2m_{\mathrm{v}}^2}{\mathrm{v}} \qquad \lambda_{\mathrm{f}} = \kappa_{\mathrm{f}}\frac{m_{\mathrm{f}}}{\mathrm{v}}$$

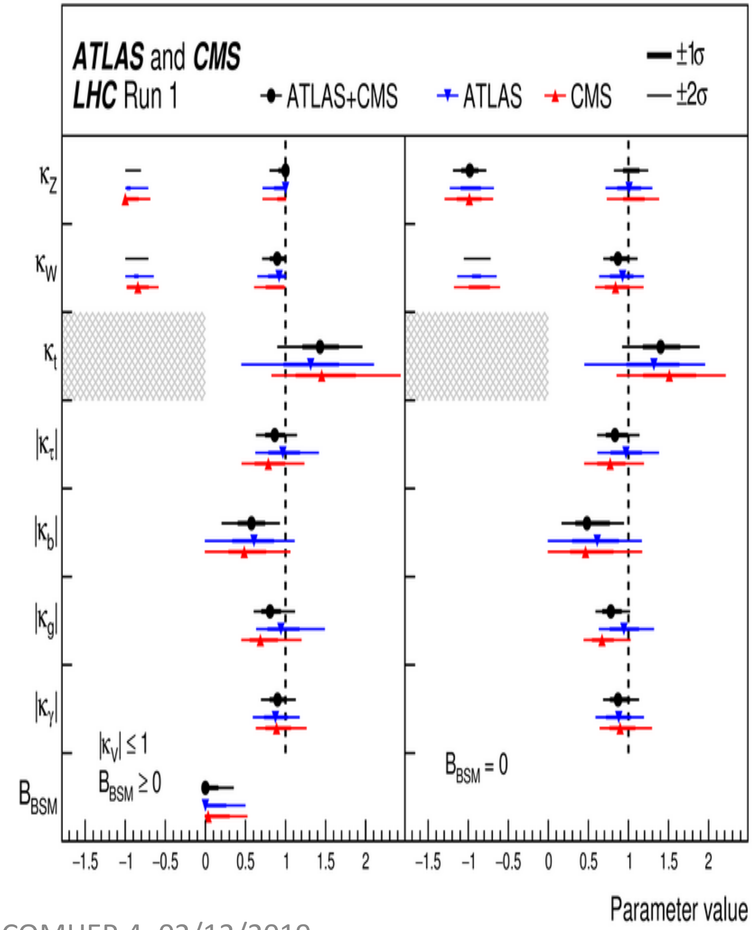
v = 246.2 GeV

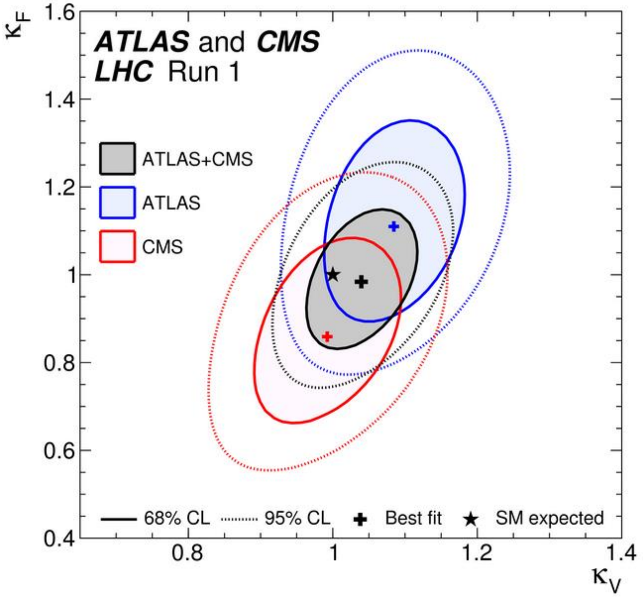
RUN I HIGGS COUPLINGS

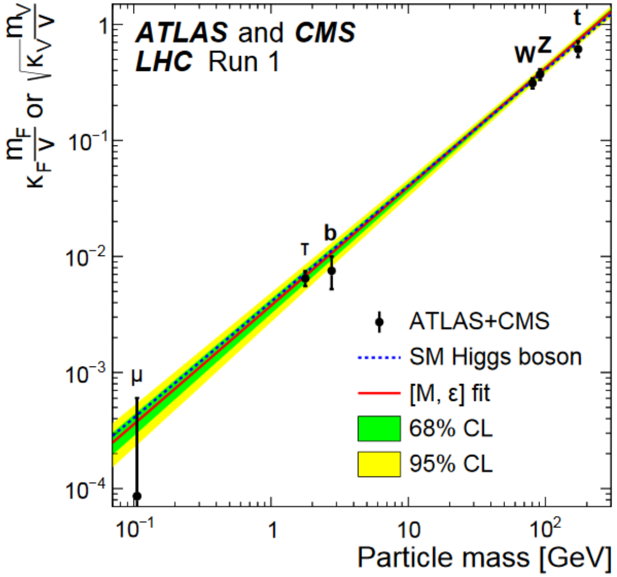
Combined measurement of ATLAS + CMS

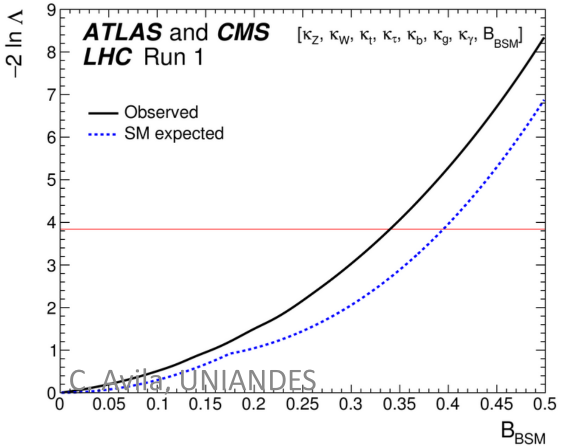
JHEP 08 (2016) 045

- Two relevant frameworks
  1) |κV| < 1 (same sign for κZ and κW) + BBSM>0
  2) BBSM = 0









Upper limit at 95% CL
On BBSM:
BBSM<0.34

HIGGS COUPLINGS

EPJ C 75 (2015) 212

- All signals observed are assumed to come from a single state ($J^{PC}=0^{++}$) with mass of ~125 GeV.
- Zero width approximation is used: $\sigma \times BR(x \to H \to yy) = \frac{\sigma_x \Gamma_{yy}}{\Gamma_{tot}}$
- Scaling factors κ_i are defined to test deviations from SM: $\kappa_i^2 = \frac{\sigma_i}{\sigma_{SM}}$; $\kappa_i^2 = \frac{\Gamma_{ii}}{\Gamma_{ii}^{SM}}$;

$$\sigma \cdot BR(PC \to H \to DC) = \sigma_{SM}(PC \to H).BR(H \to DC) \cdot \frac{\kappa_{PC}^2 \kappa_{DC}^2}{\kappa_H^2}$$

PC=Production Channel ; DC=Decay Channel ; $\kappa_H^2 = \frac{\Gamma_{tot}}{\Gamma_{tot}^{SM}}$; Γ_{tot}^{SM} = SM value of total width

DIFFERENT STUDIES:

- **Test of Custodial Symmetry:** $\lambda_{WZ}=\kappa_W/\kappa_Z$
- **Scaling of vector boson and fermion couplings:** $\kappa_V = \kappa_W = \kappa_Z$; $\kappa_f = \kappa_t = \kappa_b = \kappa_\tau$
- **Assimetries in Fermion couplings:** $\lambda_{du}=\kappa_d/\kappa_u$; $\kappa_u = \kappa_t = \kappa_c$; $\kappa_d = \kappa_b = \kappa_s = \kappa_\tau = \kappa_\mu$; $\lambda_{lq}=\kappa_l/\kappa_q$
- **Scaling of couplings with SM masses:** σ_{ggH}, Γ_{gg}, $\Gamma_{\gamma\gamma}$ are functions of κ_W , κ_Z , κ_t , κ_b , κ_τ , κ_μ
- **M, ε Model**: $\kappa_f = v\frac{m_f^\varepsilon}{M^{1+\varepsilon}}$; $\kappa_v = v\frac{m_v^{2\varepsilon}}{M^{1+2\varepsilon}}$

SPIN-PARITY

Phys. Rev. D 89 092207 (2014)

Phys. Rev. D 92, 012004 (2015)

- Non-zero Spin → correlation of kinematic distributions of production and decay.
- H→WW, ZZ, $\gamma\gamma$ useful to study spin-parity of the Higgs.

H→ZZ→4ℓ :

- 4ℓ system is fully reconstructed (8 observables)
- Use MELA approach.

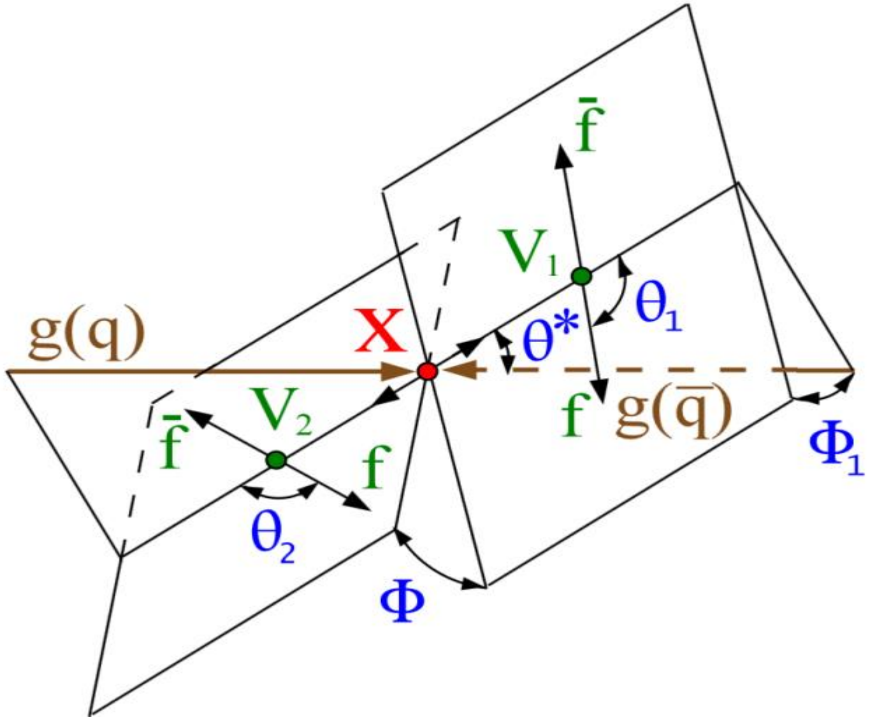
H→WW→ℓν ℓν:

- 2 observables sensitive to X(J^P): $m_{\ell\ell}$, M_T

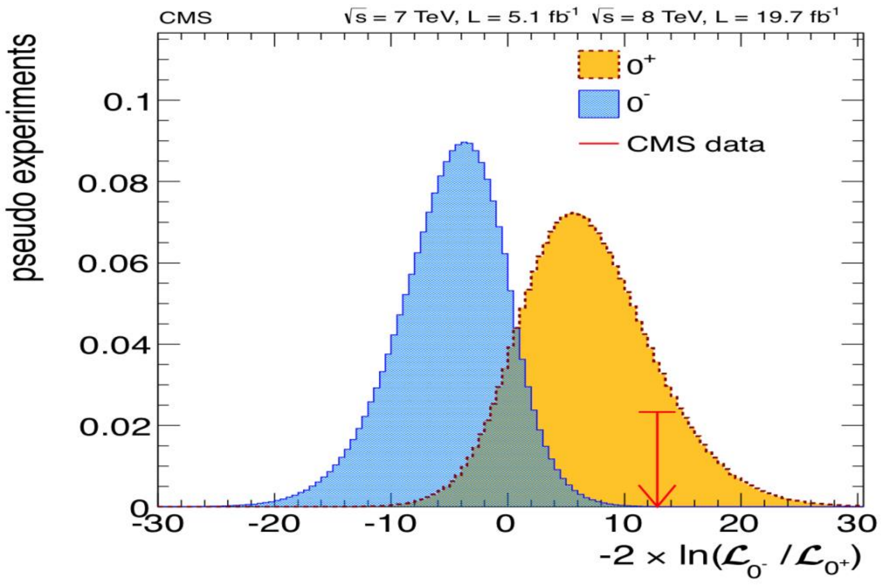
$$M_T^2 = 2 p_T^{\ell\ell} E_T^{miss} \left(1 - \cos\Delta\phi\left(\ell\ell, \vec{E}_T^{miss}\right)\right)$$

H→γγ :

- J=1 forbidden (Landau-Yang Theorem)
- cosθ* is the only sensitive variable of J^P at leading order



RUN I SPIN-PARITY



Phys. Rev. D 89 092207 (2014)

Phys. Rev. D 92, 012004 (2015)

$$q = -2\ln\frac{L\left(data\middle|J^{P}+bkg\right)}{L\left(data\middle|H+bkg\right)}$$

- $J^P=0^-, 1^+, 1^-$ excluded at 99.9% CL
- Ten $J^P=2$ models excluded at 99% CL
- Data are compatible with 0^+ within ~ 1σ