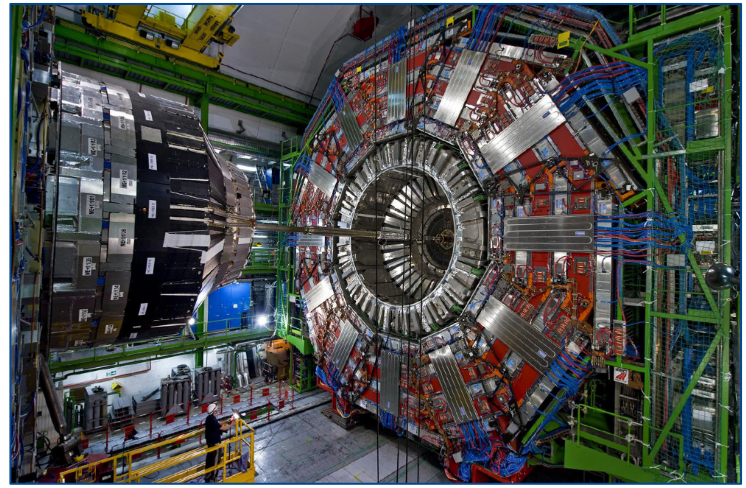


Latest Results from CMS Experiment

Mingshui Chen

中国科学院高能物理研究所

手征有效场论研讨会

2018.08.29 长春

Outline

- LHC and CMS status
- Recent Physics Results(*)
  - Higgs
  - SM Physics
  - Direct searches for BSM
- Outlook and Summary

(*)因时间有限，仅侧重于个人偏好的最新物理结果

CMS 所有物理结果请参考
http://cms-results.web.cern.ch/cms-results/public-results/publications/

Large Hadron Collider (LHC) at CERN

周长27km，跨越瑞士法国国境，位于地下100米

世界上最大、能量最高(质心系能量13TeV)、最贵(～44亿美元)的加速器

Large Hadron Collider (LHC) at CERN

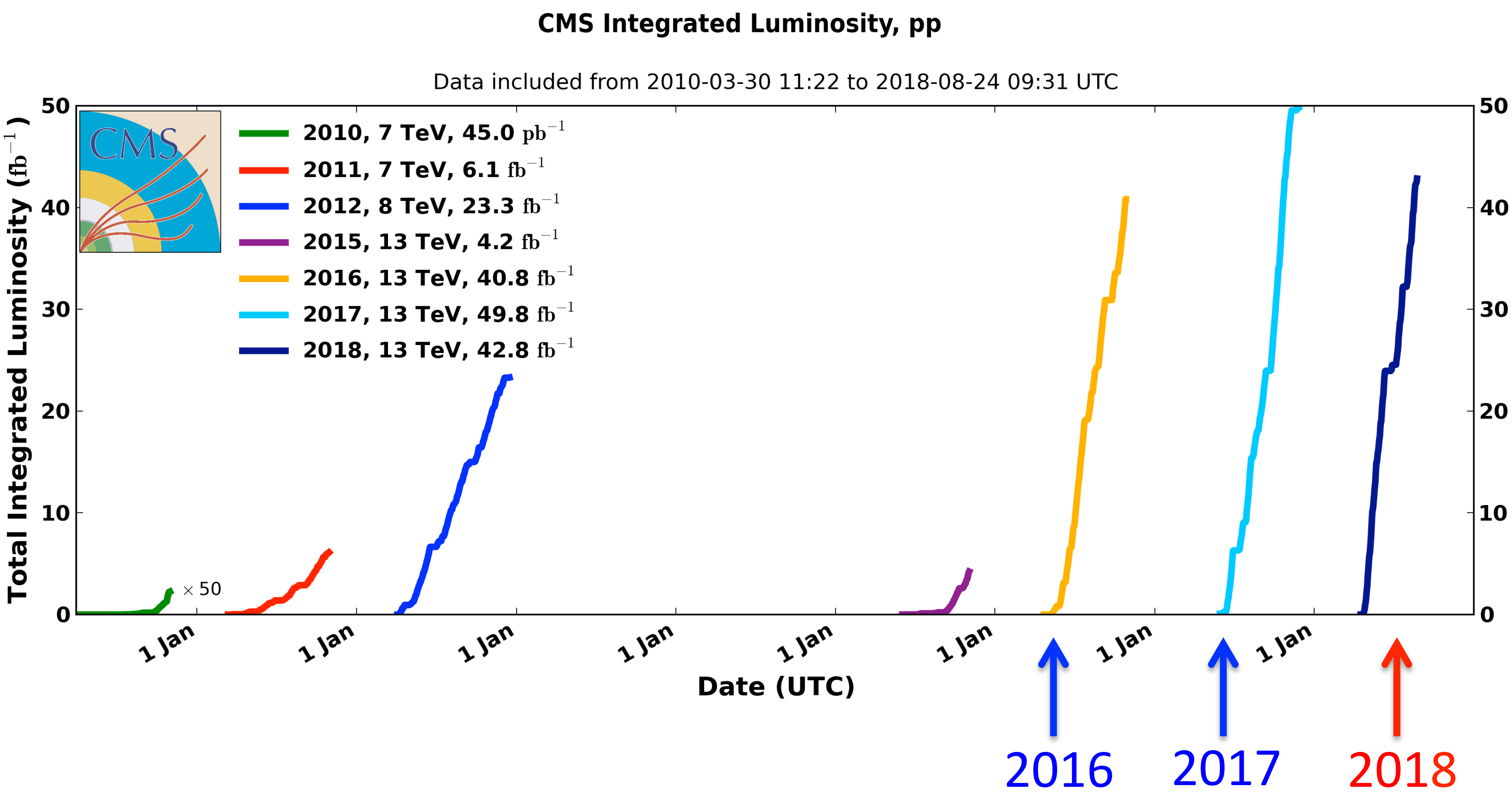
The Higgs boson, found in 2012, “completes” the Standard Model of particle physics.

But ...

- The SM model still does not explain many of the phenomena of our physical universe
  - neutrino masses, baryon asymmetry of the universe, dark matter .....
- Need “Beyond the Standard Model (BSM)”: many ideas, theories and models
  - A broad investigation on many fronts is necessary
- At LHC, we are
  - Studying the properties of the the Higgs that, through its coupling directly to MASS, can make contact with hidden sectors that are invisible to us otherwise
  - Looking for deviations from the precise predictions of the SM
  - Searching directly for new particles and new forces

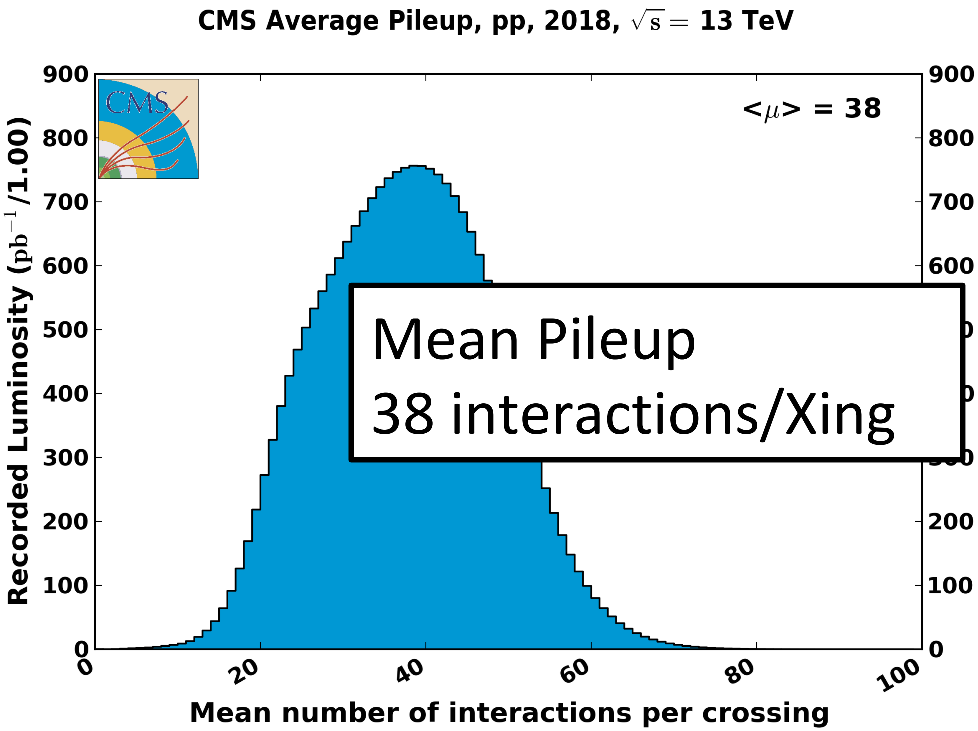
→**All three strategies require more statistics**

Run Status



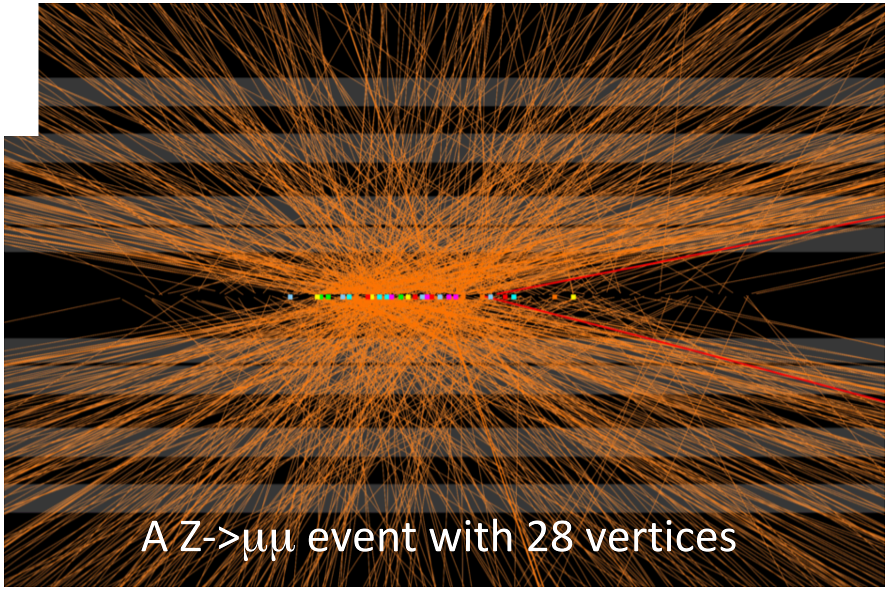
Results shown here mostly based on 2016 w/wo 2017 data

Challenge to the experiments



Mean Pileup
38 interactions/Xing

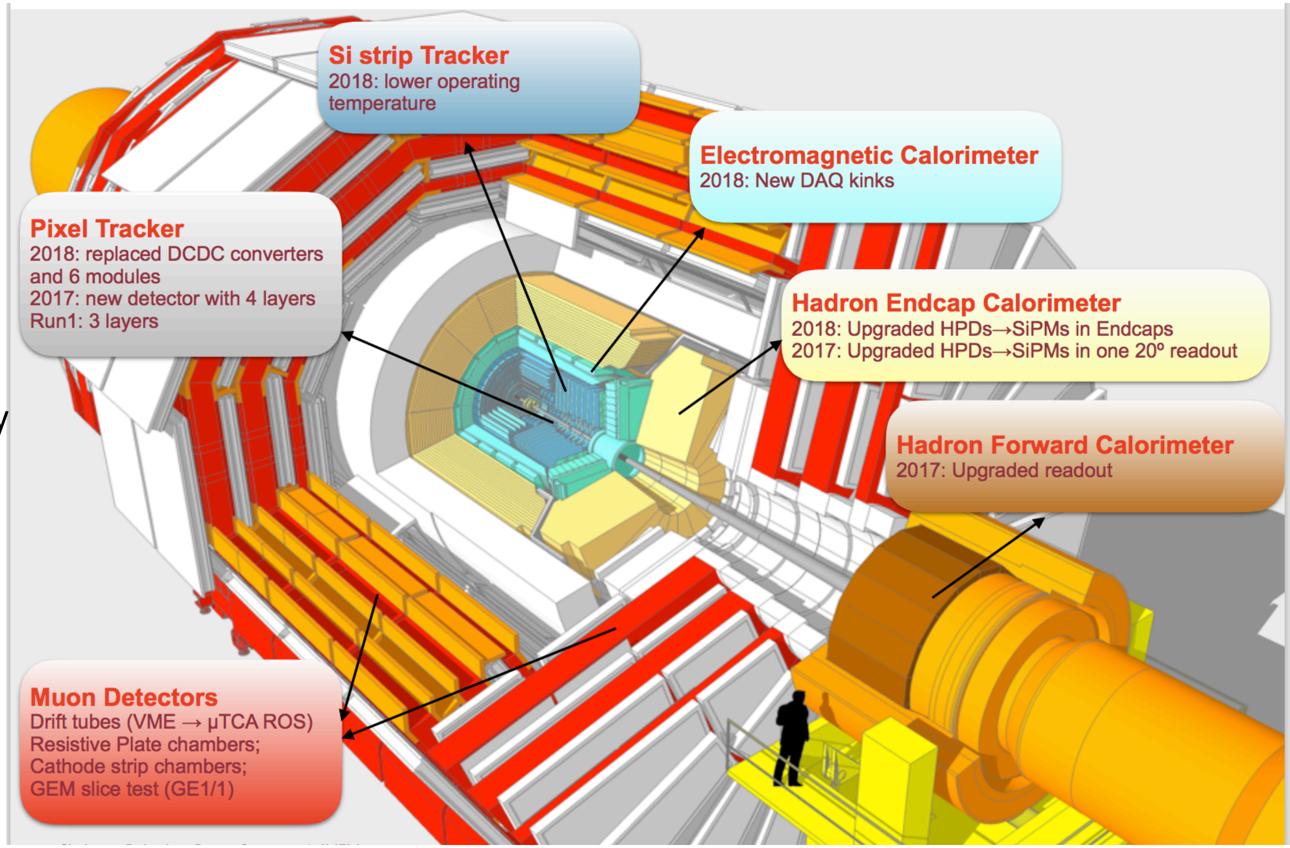
Peak Lumi.
$\sim 2x10^{34} cm^{-2}s^{-1}$



CMS Evolution in 2017/18

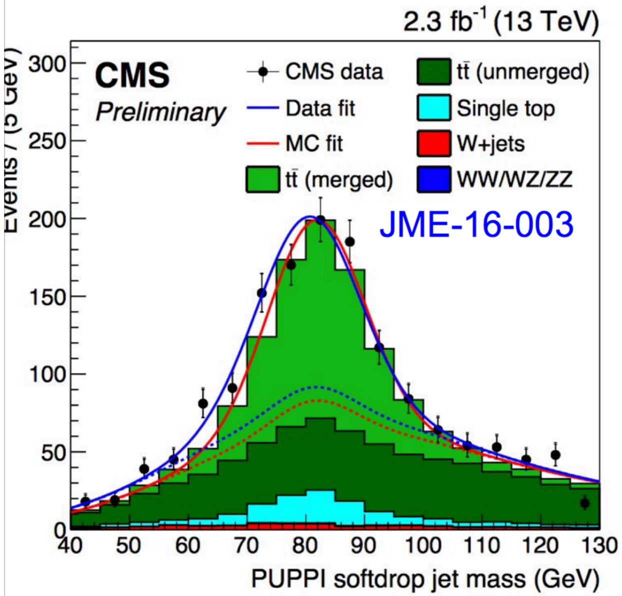
CMS Design

- Very large solenoid - 6m diameter x 13 m long
  - Tracking and calorimetry fit inside
- Very strong field – 3.8T
  - Excellent momentum resolution
- Chambers in the return iron track and identify muons, leading to a very compact system
- A lead tungstate crystal calorimeter (~76K crystals) for photon and electron reconstruction
- Hadron calorimeters for jet and missing E_t reconstruction to η~5
- Charged Particle Tracking with all-silicon components
  - A silicon pixel detector out to radius ~ 20 cm
  - A silicon microstrip detector from there out to 1.1 m
- Weight, dominated by steel, is 14,000 Tons

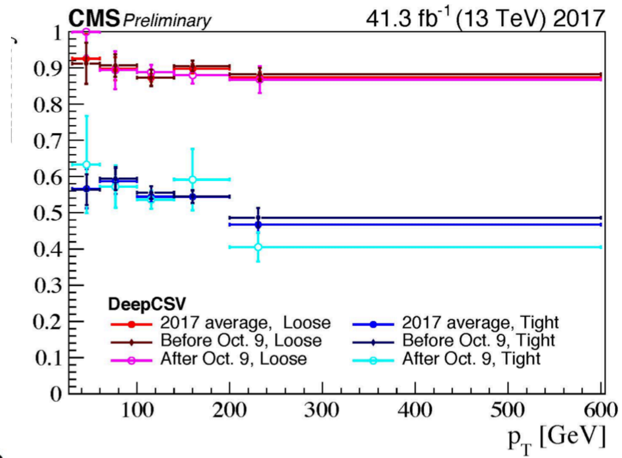


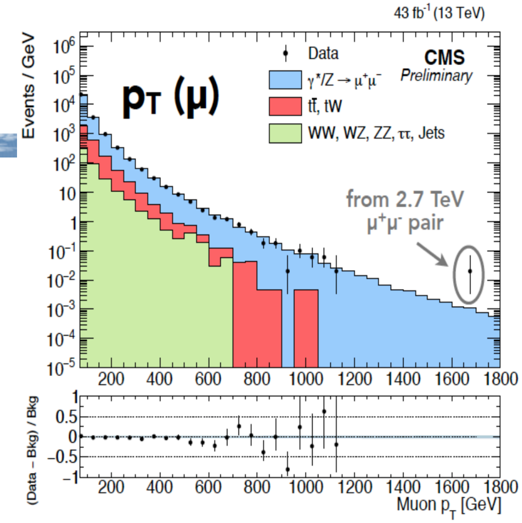
CMS is continuously upgraded to handle higher luminosity and do better physics

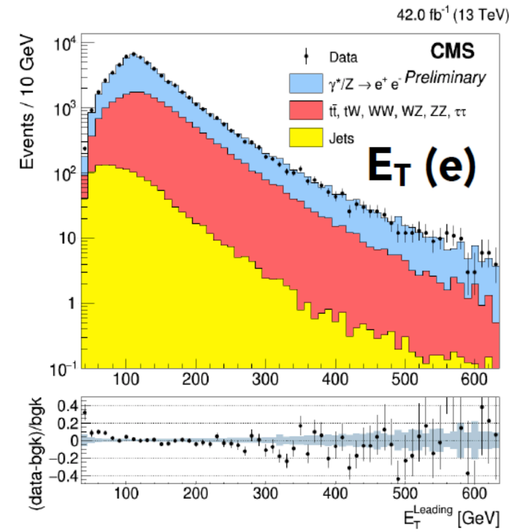
Detector performance

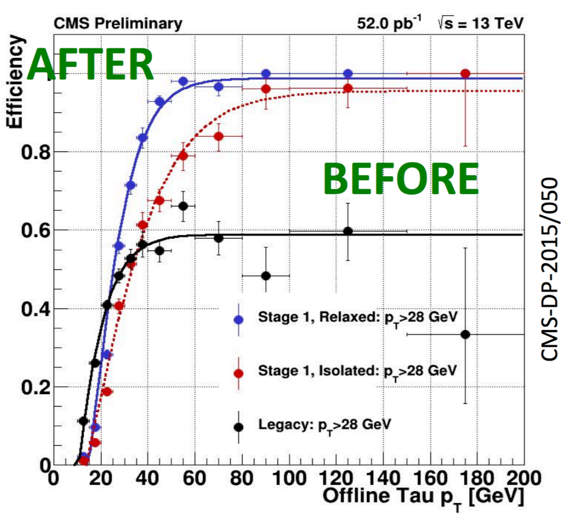


b tagging efficiency

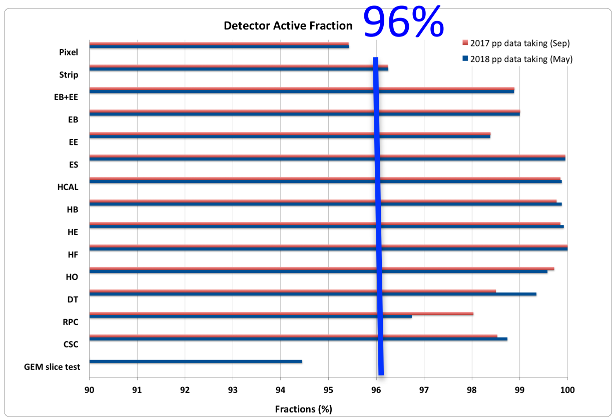




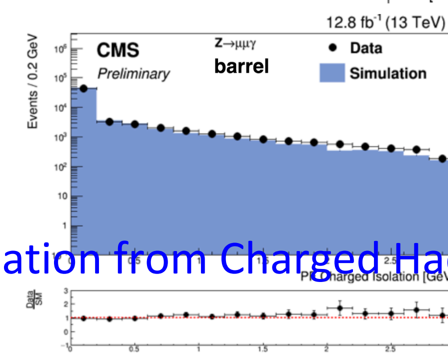




Tau trigger efficiency

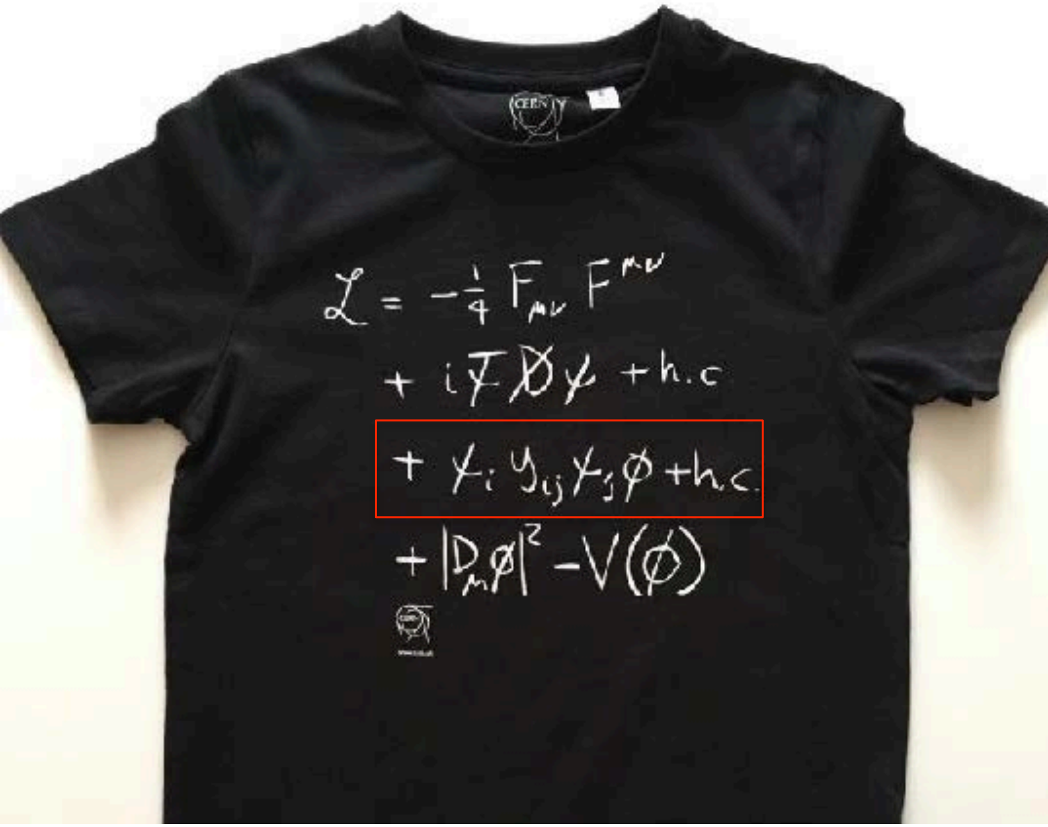


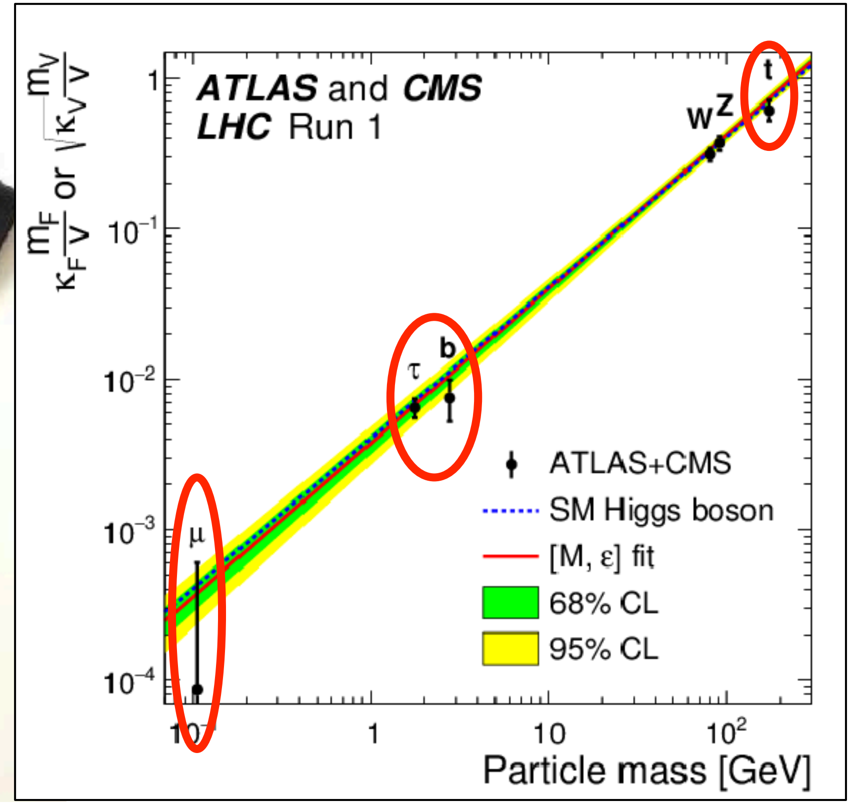
fraction of active channels



Photon Isolation from Charged Hadron

- LHC and ATLAS/CMS status
- Physics Results
  - Higgs
  - SM Physics
  - Direct searches for BSM
- Outlook and Summary





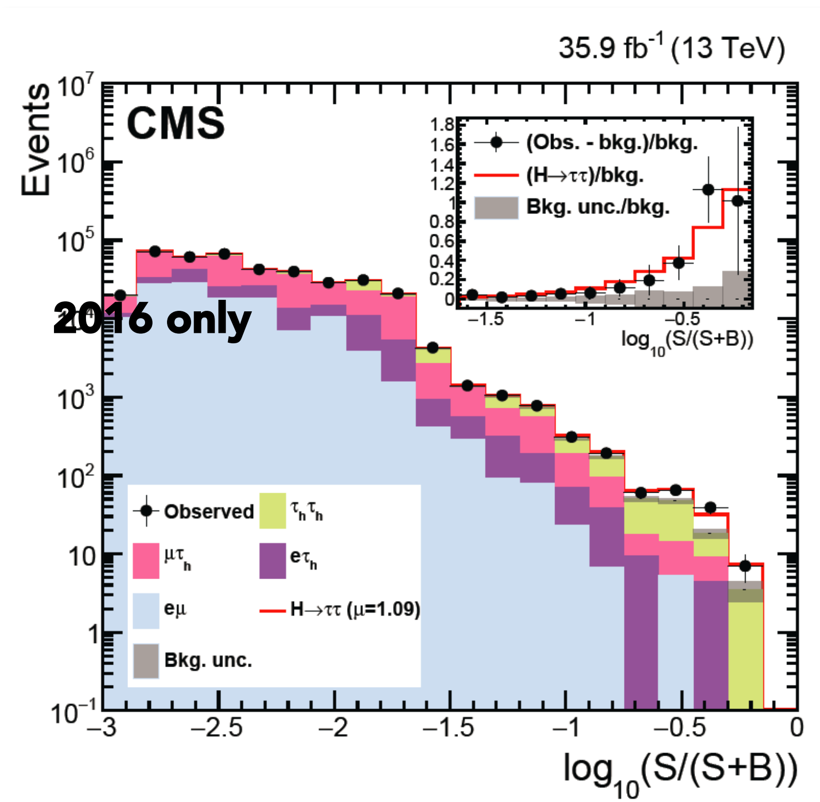
Over the last few years, CMS has worked hard to establish the Yukawa couplings to the heaviest fermions, τ, b, top

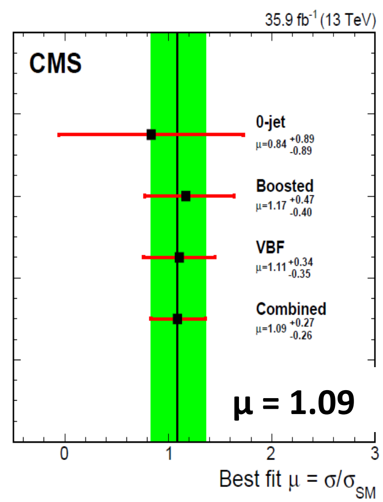
→ The Higgs Yukawa interaction is a highly motivated conjecture to give mass to the fermions

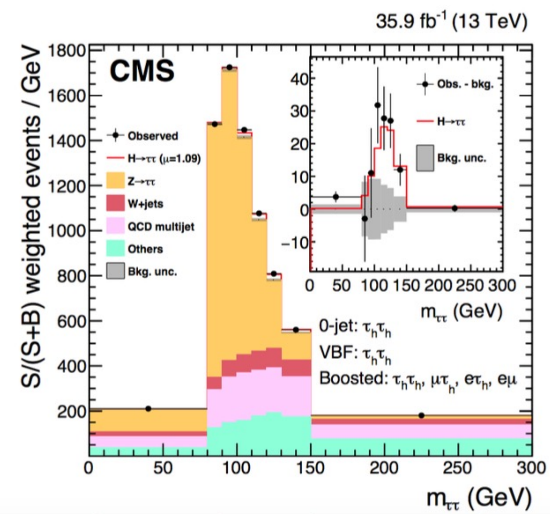
Observation of H→$\tau^+\tau^-$

PLB 779 (2018) 283

- BR~ 6.3%, best channel to establish coupling of Higgs boson to fermions
- Final states: $\tau_h\tau_h$; eτ_h; μτ_h; eμ → Significance of 4.9σ observed (4.7σ expected) with 2016 13 TeV data
- Combination with 7, 8 TeV data: 5.9σ obs. (5.9σ exp.) and μ = 0.98 ± 0.18







First direct observation by a single experiment of Higgs coupling to fermions!

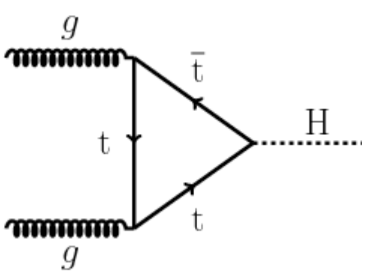
-Observed before in CMS+ATLAS combination

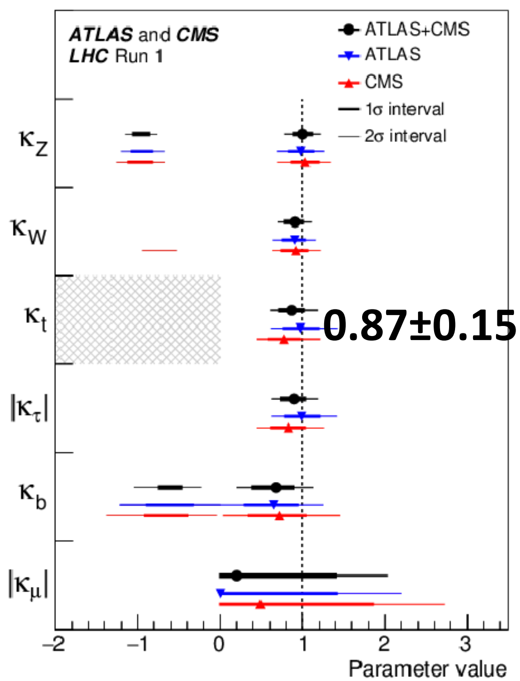
First direct observation of H coupling to leptons and to fermions of the 3rd generation!

$t\bar{t}H$ coupling (two years ago)

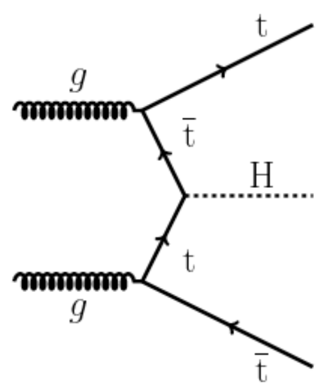
JHEP 08 (2016) 045

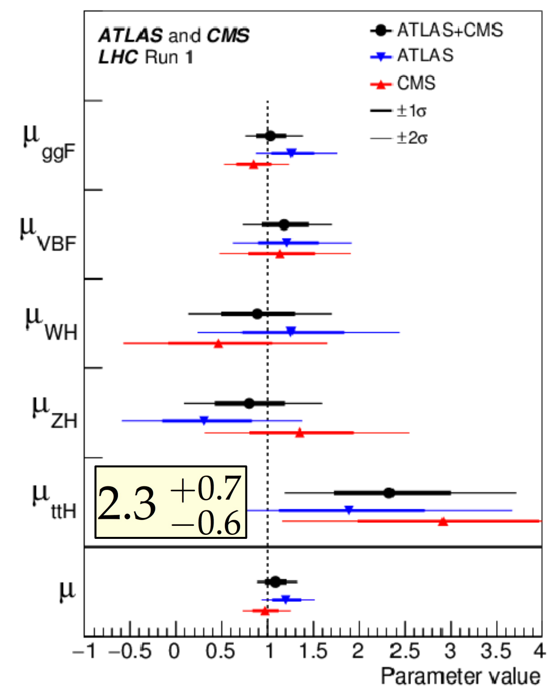
- Indirectly established at Run 1 through the ggH loop process, but model dependent
- The direct ttH coupling was evident, but somewhat higher than expectation





SM structures and no BSM assumed

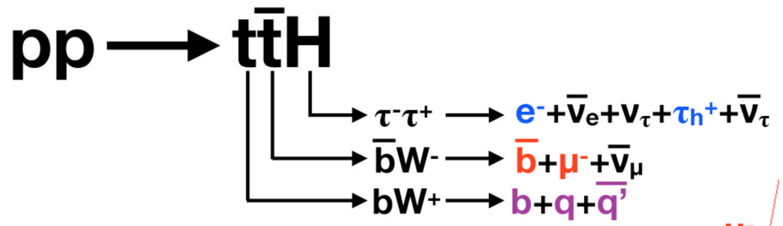


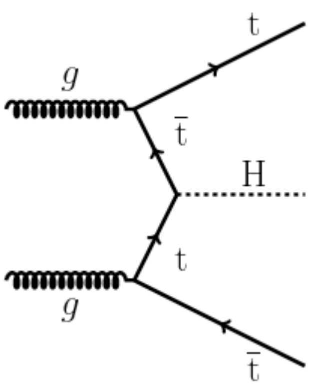


Obs. (exp.) 4.4σ (2.0σ)

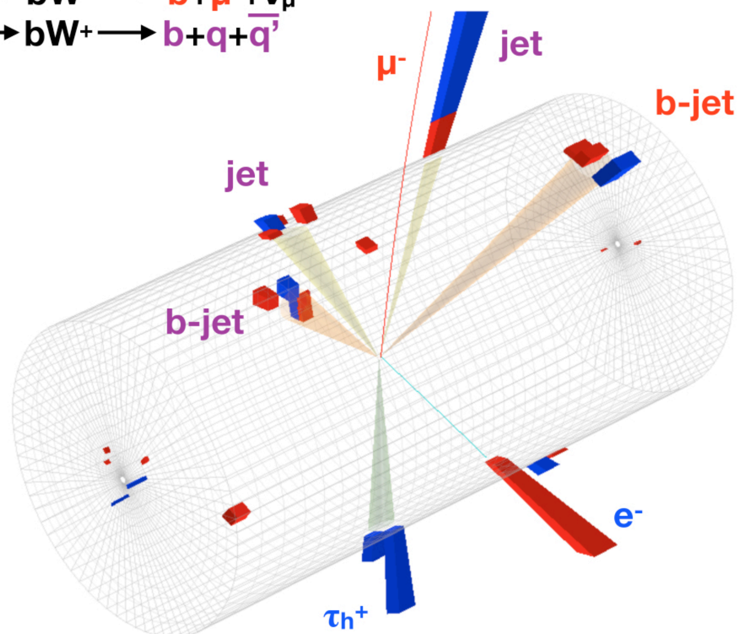
Now we have the $t\bar{t}H$ observation

- First 5σ observation of $\bar{t}tH$
- Very sophisticated analyses, pushing detector performance very far, many channels, MVAs...





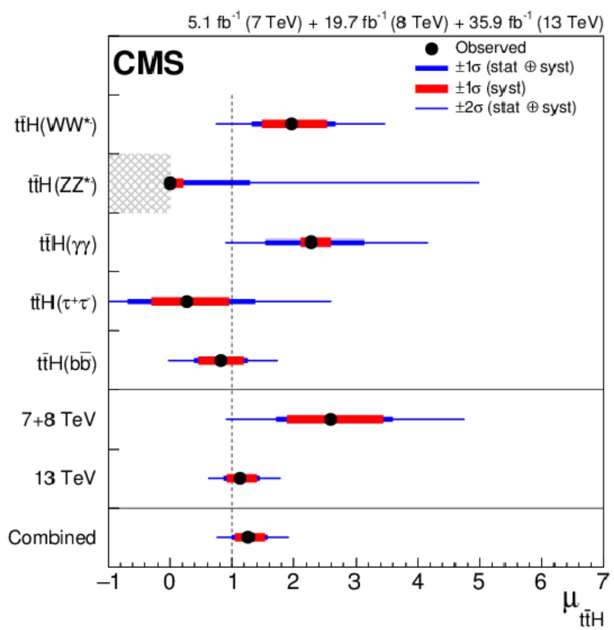
CMS ttH candidate event

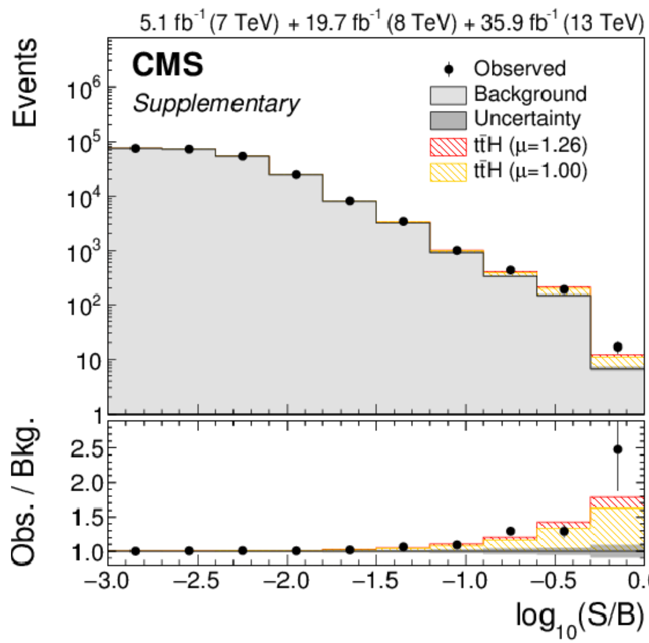


Now we have the $t\bar{t}H$ observation

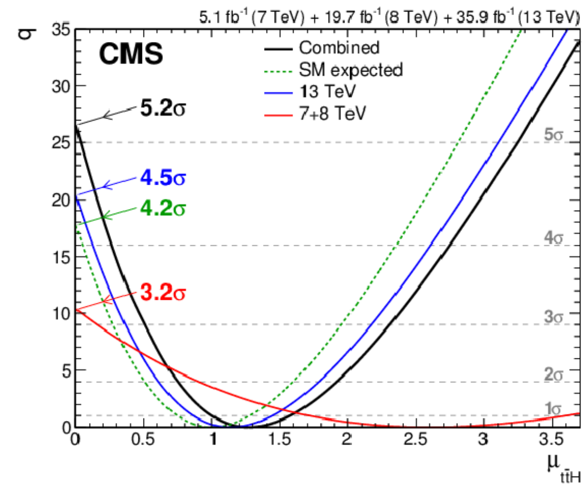
Phys. Rev. Lett. 120, 231801 (2018)

- First 5σ observation of $\bar{t}tH$
- Very sophisticated analyses, pushing detector performance very far, many channels, MVAs...





Obs. (exp.) 5.2σ (4.2σ)



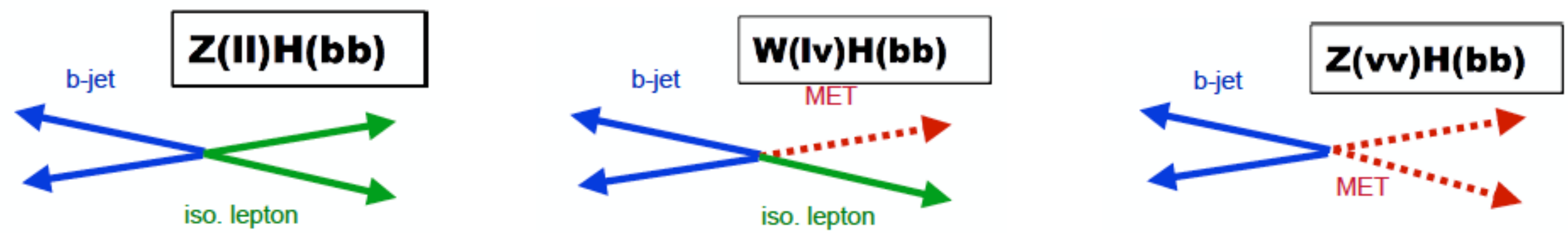
$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16}(\text{stat.})\,^{+0.17}_{-0.15}(\text{exp.})\,^{+0.14}_{-0.13}(\text{bkg. th.})\,^{+0.15}_{-0.07}(\text{sig. th.})$$

Establishes directly the tree-level coupling to an up-type quark

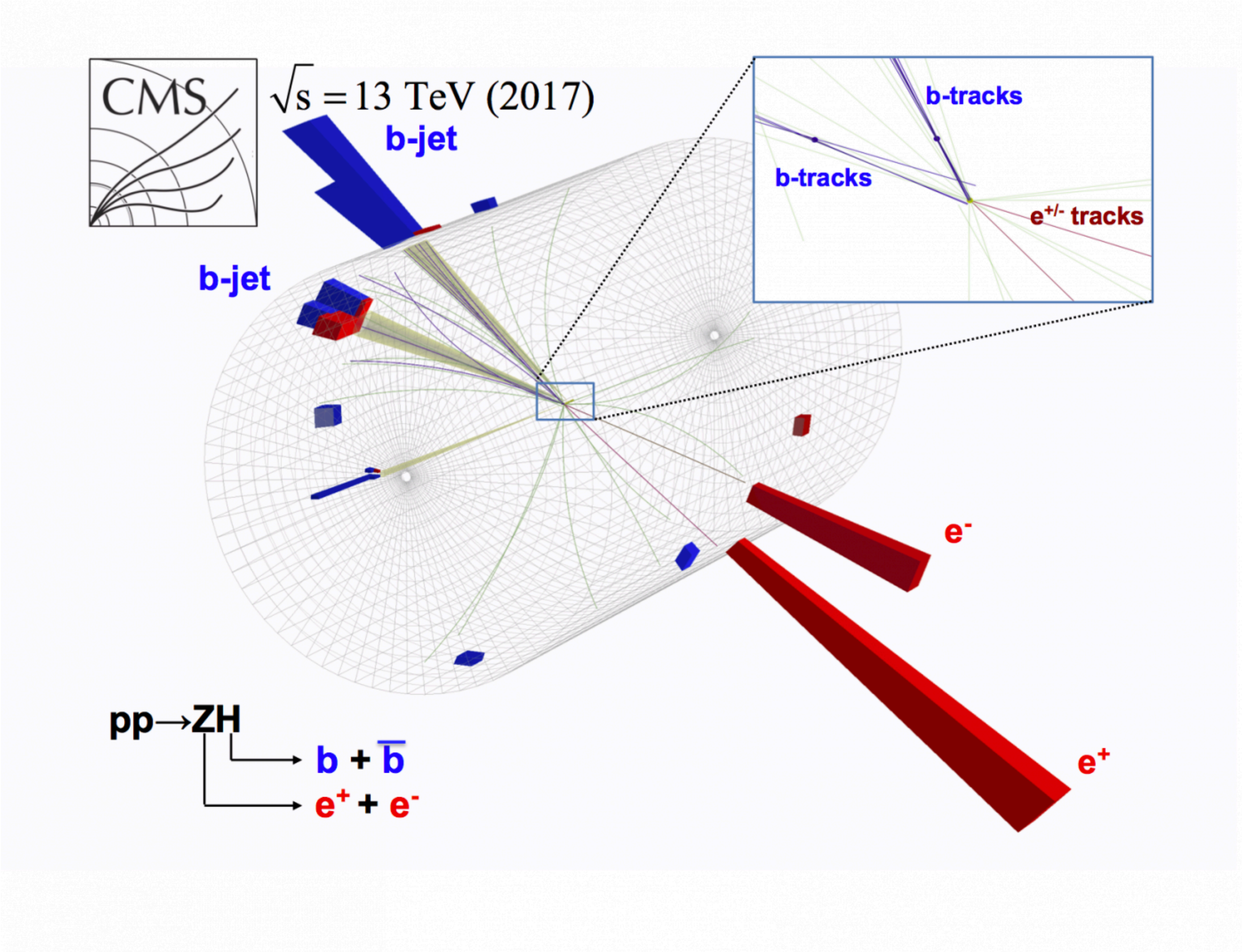
Higgs → bb

arxiv:1808.08242

- **Biggest branching fraction, but massive bb background from QCD** processes
  - Choose a weak interaction production mode to reduce hadronic backgrounds (QCD multijet, top, mainly **Associated Production with a W or Z, VH(bb)**
- Signal is a di-jet mass enhancement which has many challenges
- Three channels in VH(bb): V(W→*l* n,Z→*ll*,Z→*nn*) H(bb)
  - Require Vector Boson to be back-to-back w.r.t. the bb system
- Several Improvements for 2017 analysis, including heavy reliance on DNNs, DEEPCSV
- Analysis validated using VZ(bb)



A ZH(bb) Candidate Event



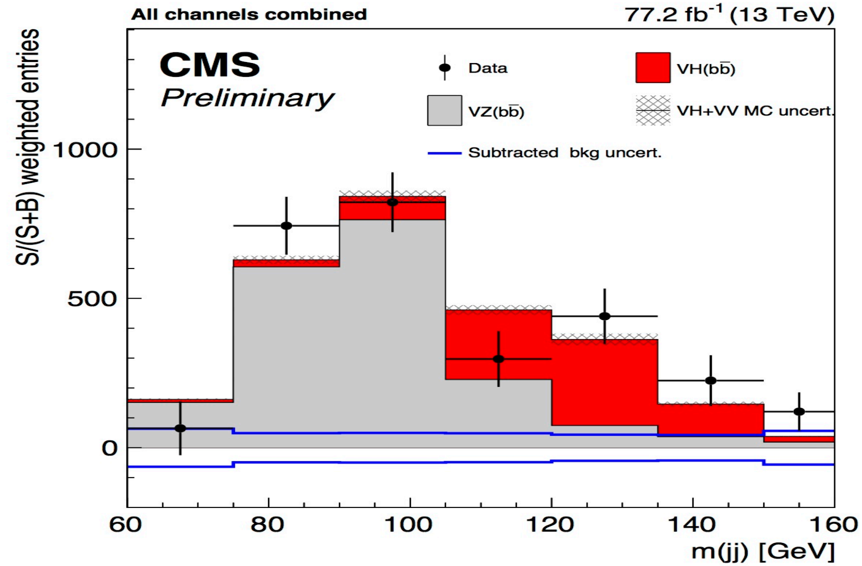
Combination of all H->bb results from Run 1 and 2

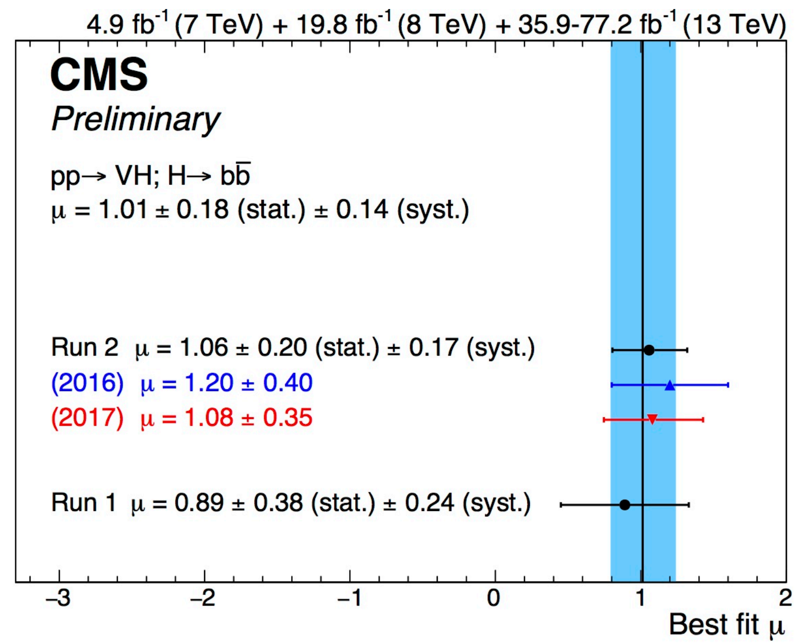
arxiv:1808.08242

- **VH(bb) from 2016/17 at 13 TeV, 77.2 fb^{-1}**
  - **Significance: 4.4 σ obs (4.2 exp)**
- With VH(bb) including also 7 and 8 TeV
  - Significance: 4.8 σ obs (4.9 exp)
- Including new results and all published data from Run 1 and Run 2
  - Run 1:
    - ttH(bb), VBF H→bb, VH(bb)
  - Run 2:
    - ttH(bb), Boosted ggH(bb) (2016)
    - VH, H→bb (2016 + 2017)

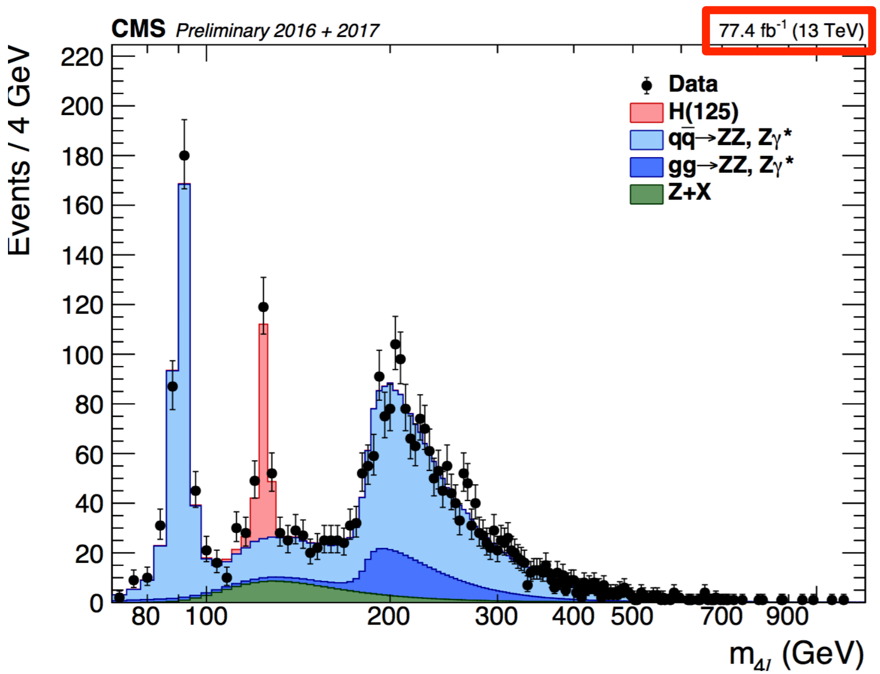
5.6 (5.5) σ observed (exp.) for H→bb!

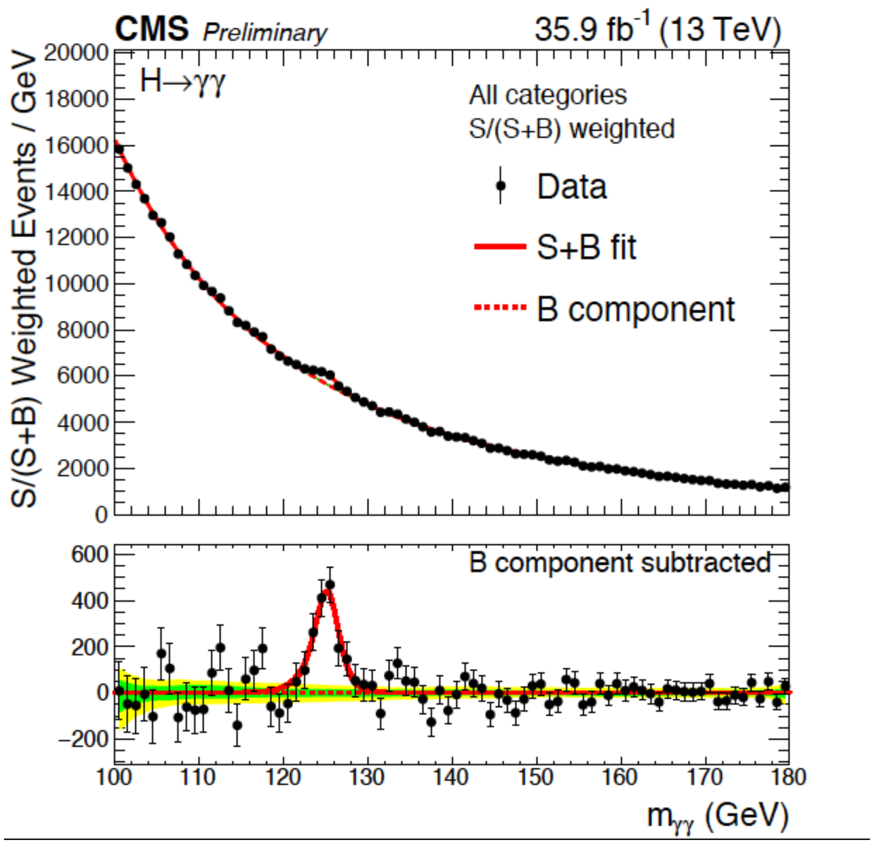
$$\mu = 1.04 \,^{+0.20}_{-0.19}$$





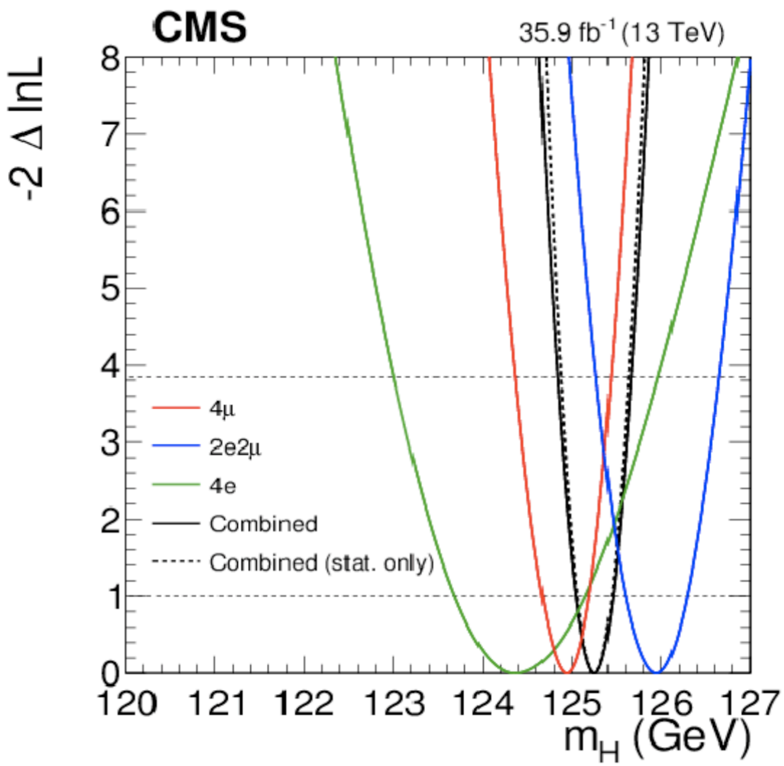
Higgs to bosons – entering precision era

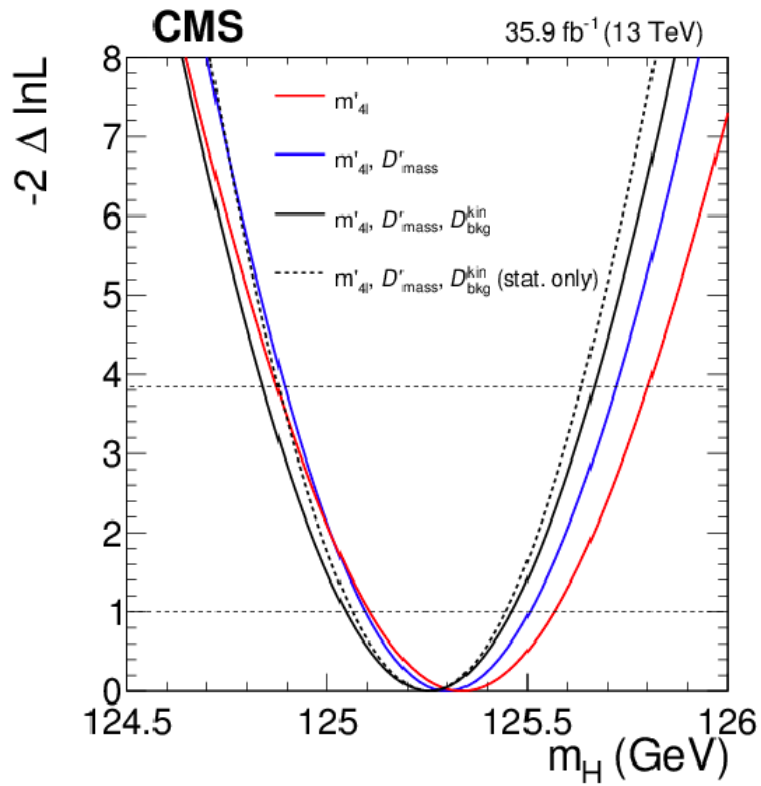




Higgs mass

JHEP 11 (2017) 04

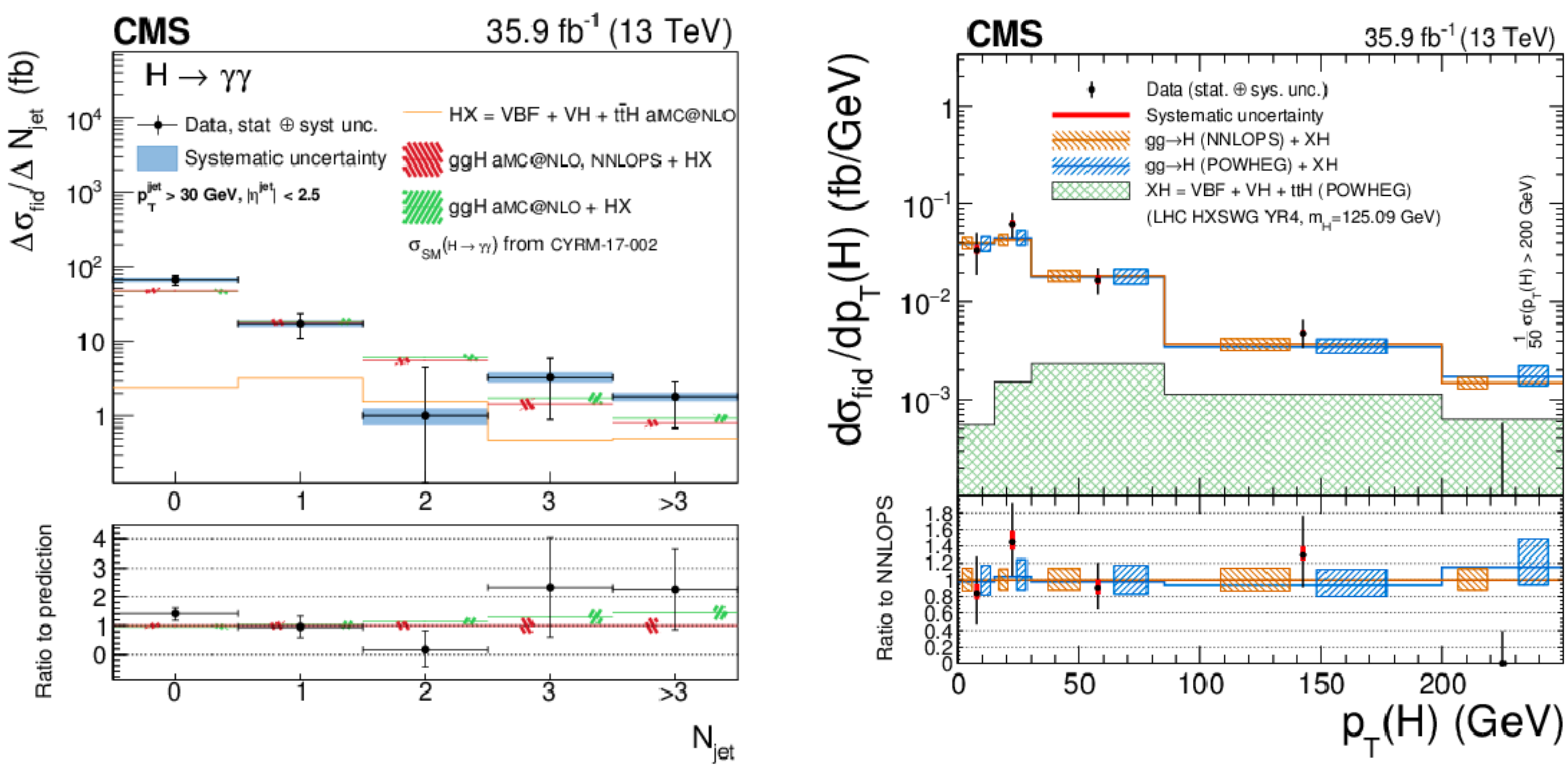




- Most precise measurement at the moment comes from CMS $H \rightarrow ZZ \rightarrow 4l$ mass measurement with 2016 data
  m_H = 125.26±0.21 GeV
- Still limited by statistical uncertainties → impact on coupling ~0.5%

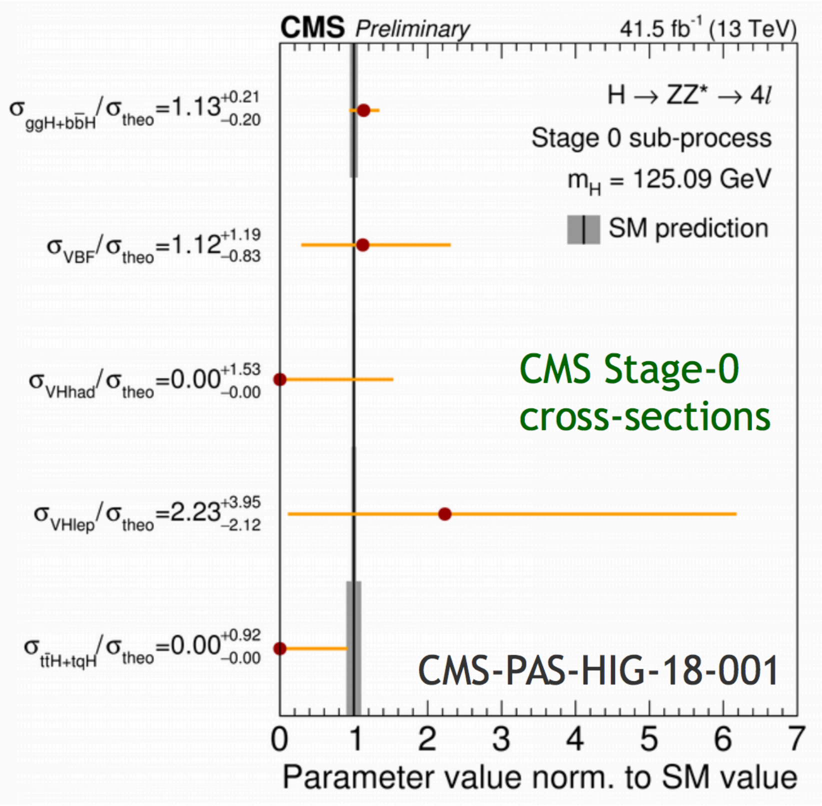
Higgs differential cross sections

- Measurements of fiducial and differential cross-section distributions made already at Run-1 with low statistics
- Now with more bins and better precision

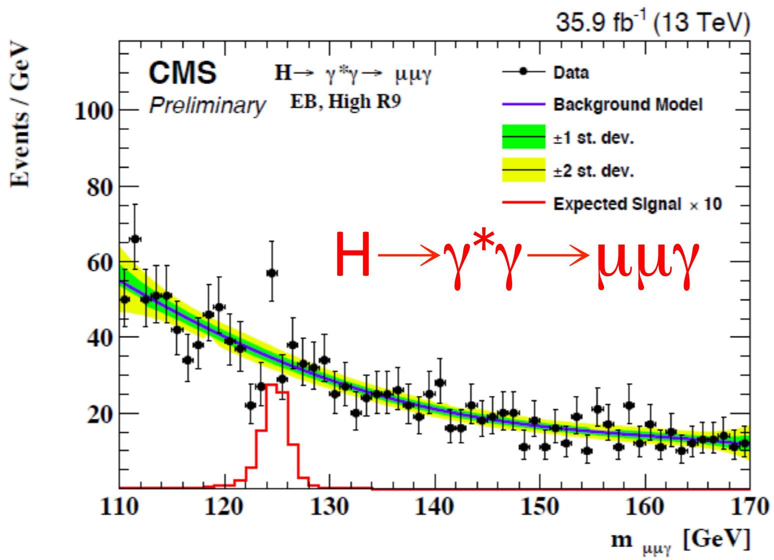


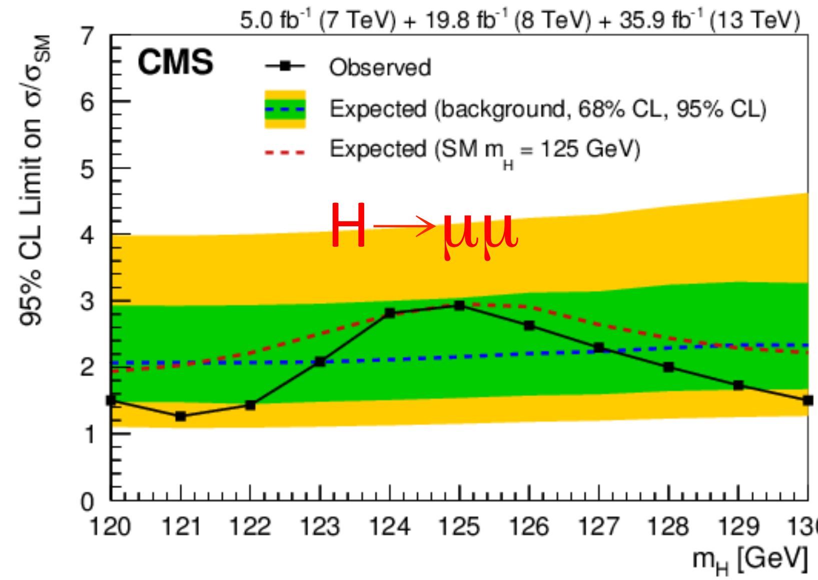
Simplified template cross sections

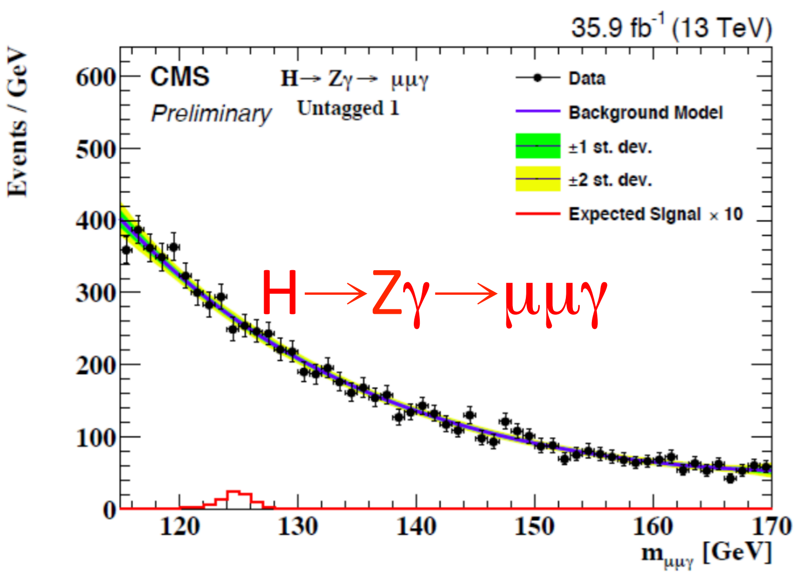
- Simplified template cross-sections (STXS) defined by common effort in LHC Higgs cross-section group
- Using these, and/or individual experimental measurements, EFT fits will allow more detailed SM tests – and perhaps provide hints of BSM structure

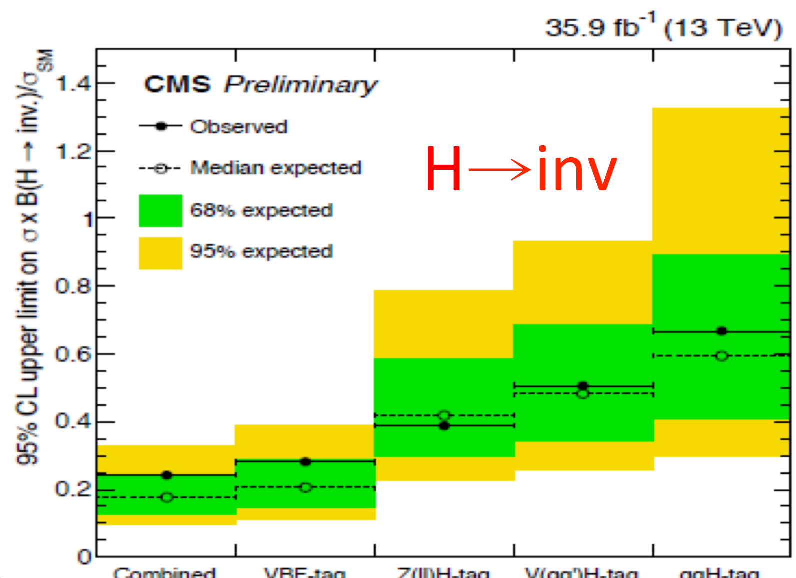


Higgs rare decays









Many studies, all compatible with SM predictions

Combined Higgs boson couplings

CMS-PAS-HIG-17-031

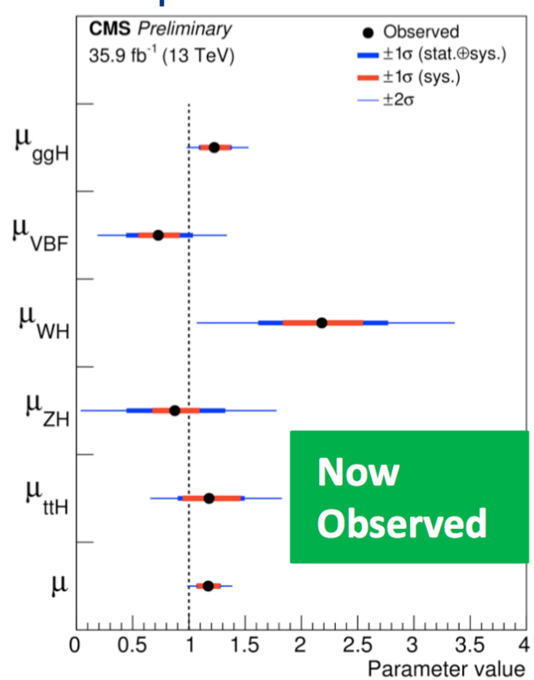
- Overall signal strength compatible with the SM
- Not anymore dominated by statistics, already moving to less inclusive measurements

	ggF	VBF	VH	ttH
H→ZZ→4l	●	●	●	●
H→γγ	●	●	●	●
H→WW	●	●	●	●
H→bb	●		●	●
H→ττ	●	●		●
H→μμ	●	●		
H→inv	●	●	●	

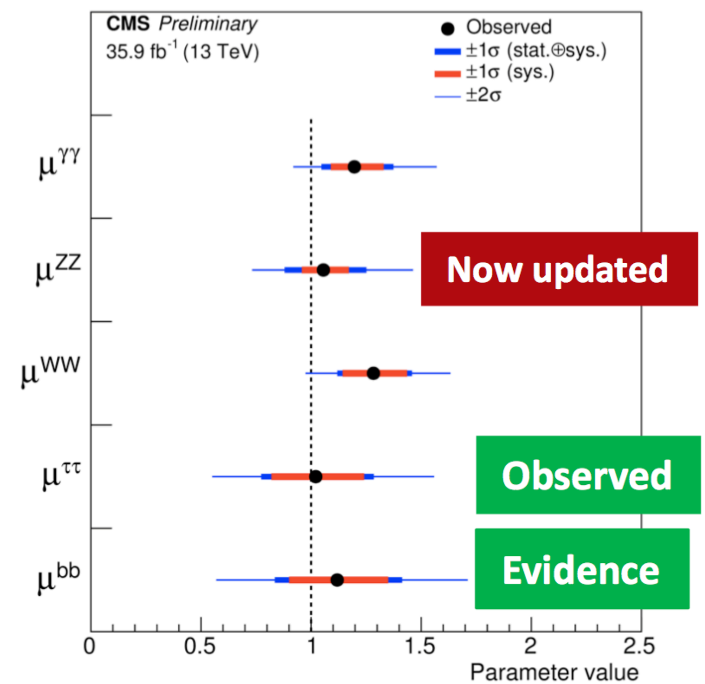
Close to have observed the couplings with all 3rd generation fermions

- **One of the targets of LHC Run2**

Per production mode



Per decay mode



CMS 13 TeV 2016 combination

$$\mu = 1.17^{+0.10}_{-0.10} = 1.17\,^{+0.06}_{-0.06}\,(\text{stat.})\,^{+0.06}_{-0.05}\,(\text{sig. th.})\,^{+0.06}_{-0.06}\,(\text{other sys.})$$

- LHC and ATLAS/CMS status
- Physics Results
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  - SM Physics
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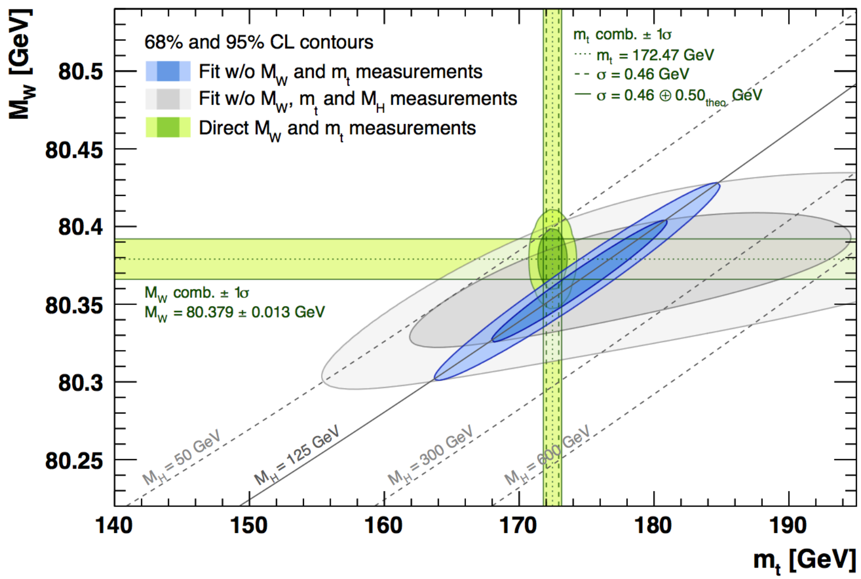
SM measurements: motivation

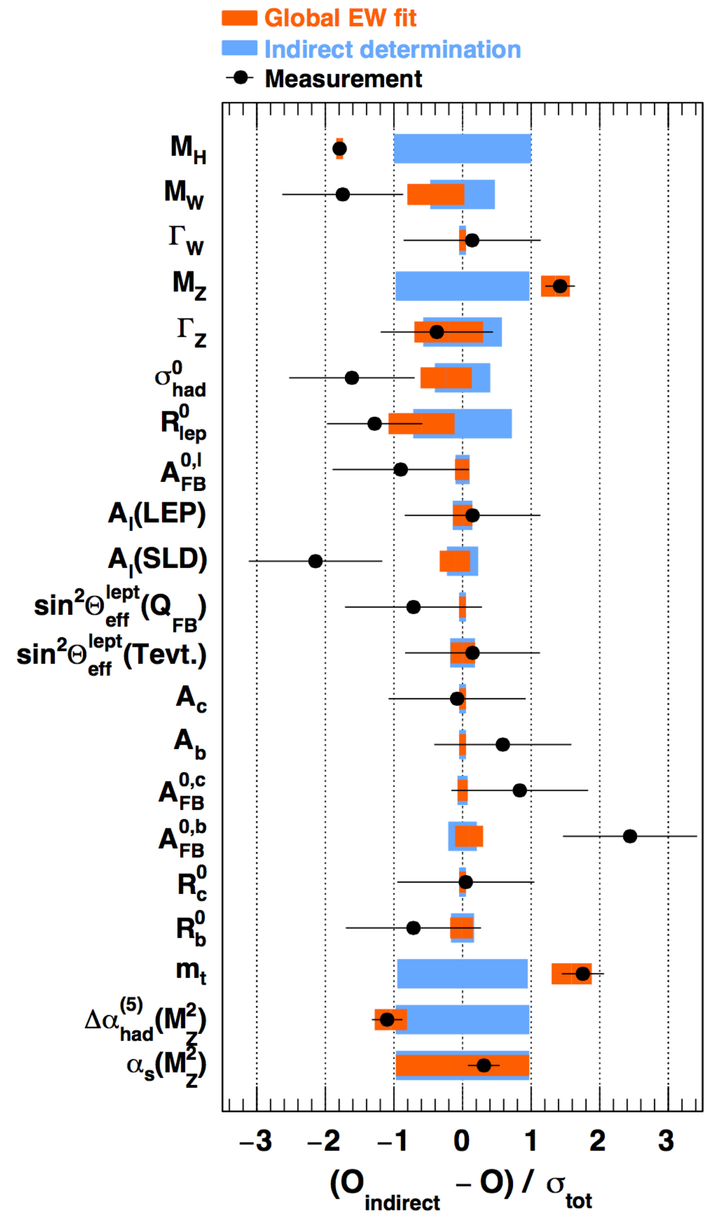
- Self-consistency test of the Standard Model

  → over-constrain the system:

e.g. $\sin^2\theta_W = 1 - M^2_W/M^2_Z$ (@ tree)

- Probe new physics





[Gfitter: Haller, Hoecker, Kogler, Mönig, Stelzer '18]

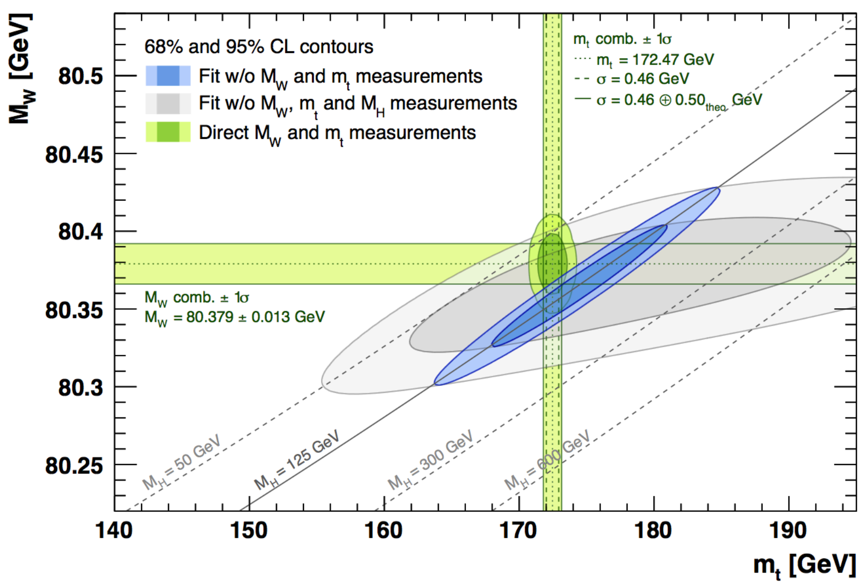
Precision W/top masses

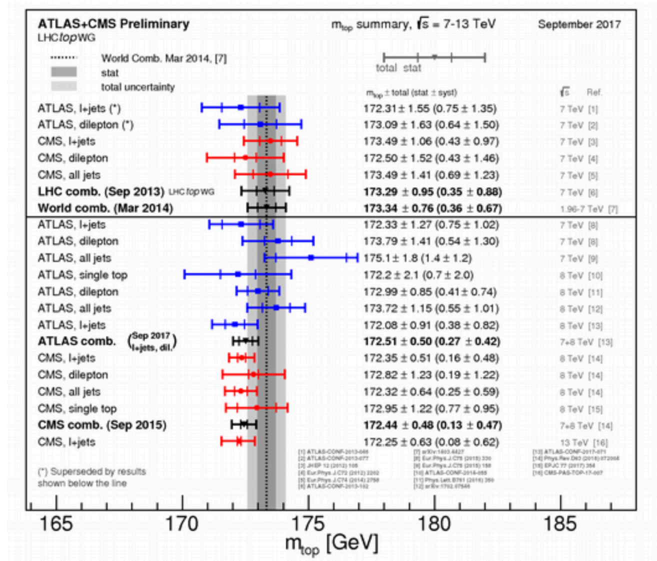
- Self-consistency test of the Standard Model

  → over-constrain the system:

e.g. $\sin^2\theta_W = 1 - M^2_W/M^2_Z$ (@ tree)

- Probe new physics





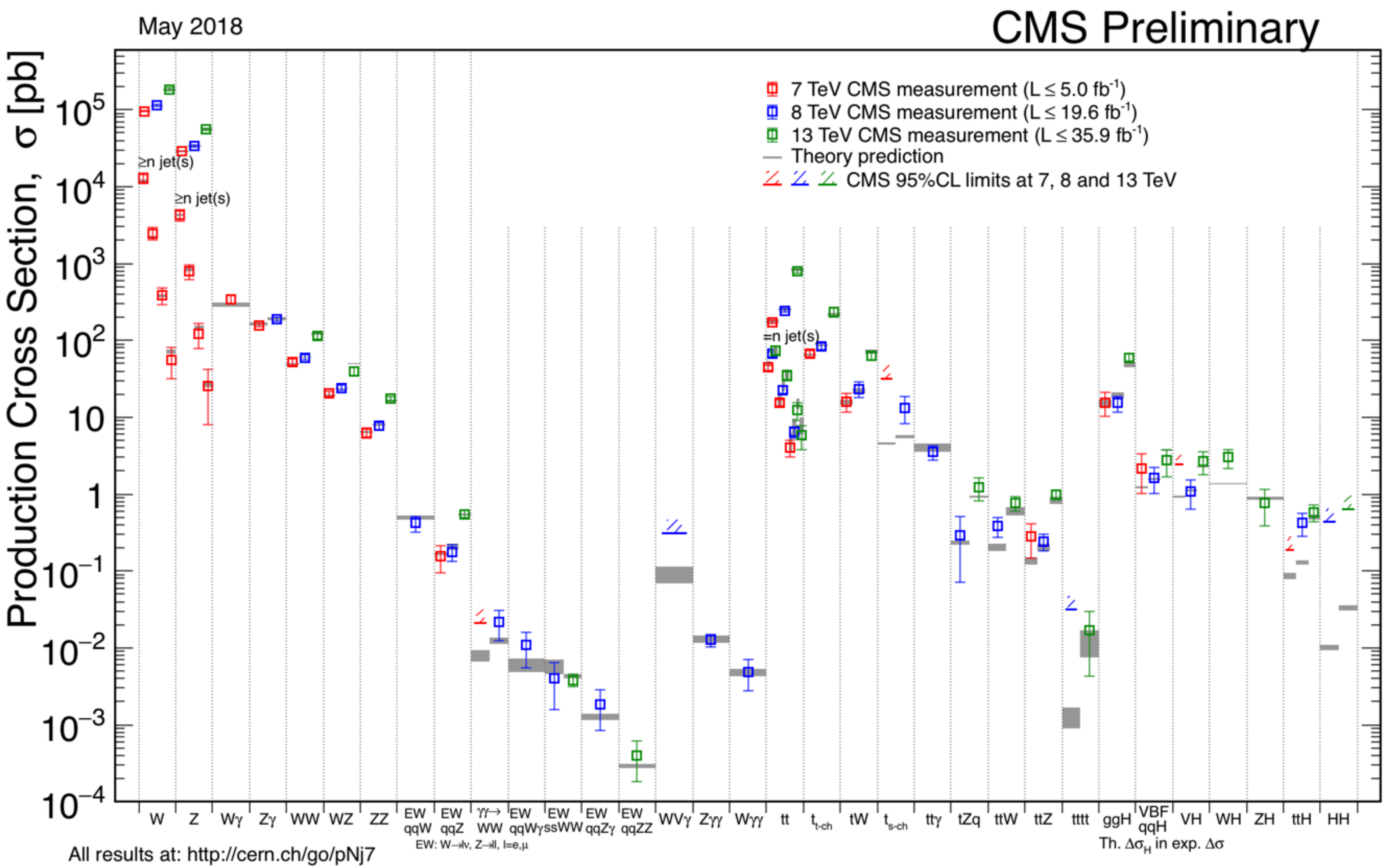
m_{top} error (ATLAS or CMS) from direct reco ~0.5 GeV

W mass @LHC only from ATLAS

±19 MeV m_W from ATLAS

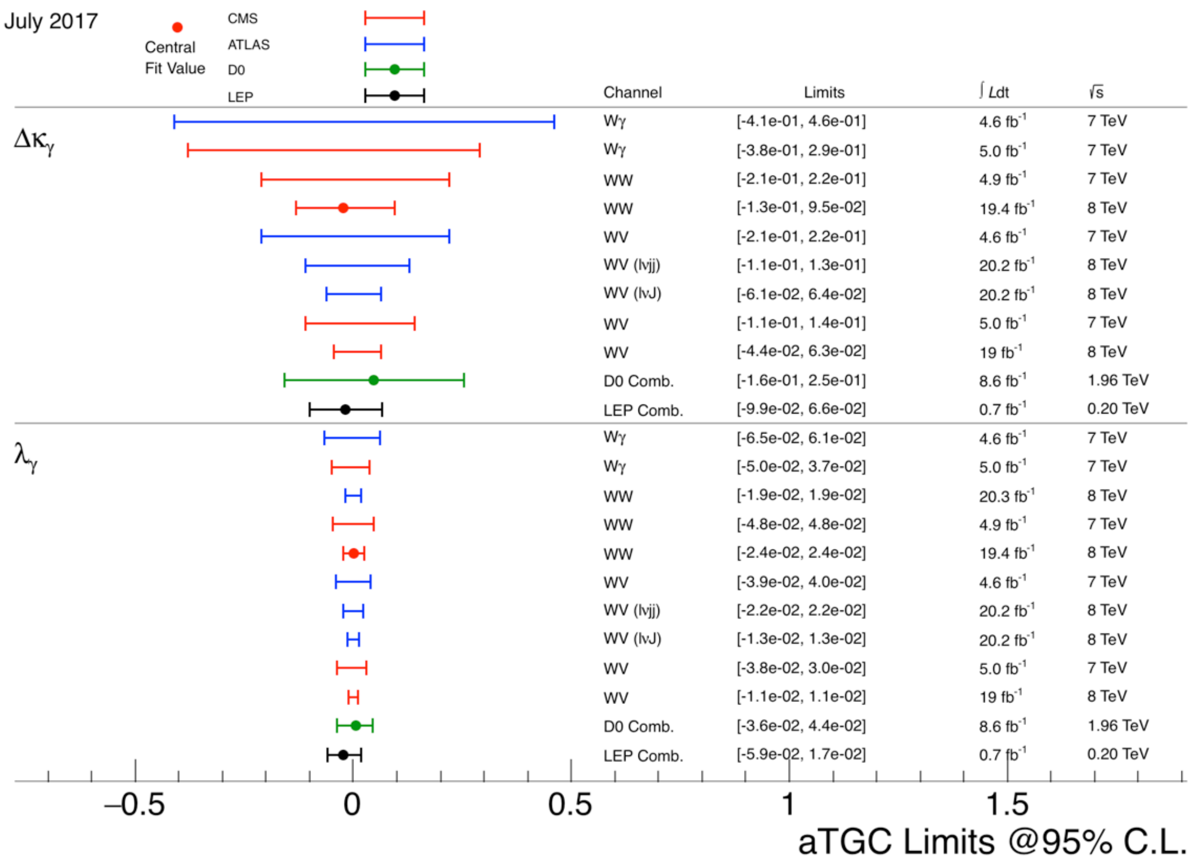
EPJC78 (2018) 110

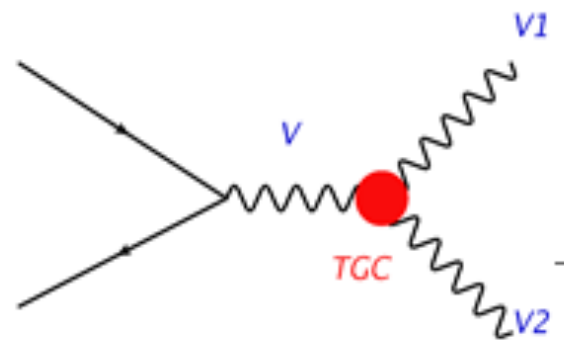
SM production cross section measurements

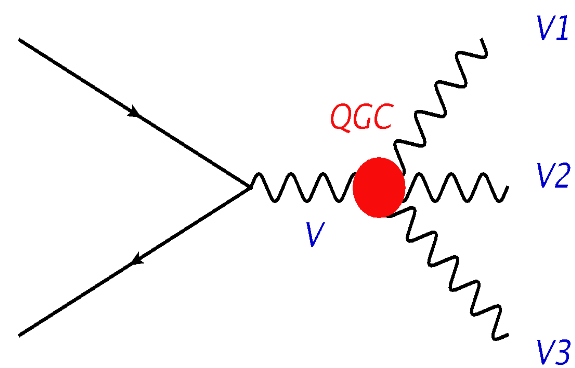


Overall good agreement with SM over 9 orders of magnitude

Probing anomalous TGC/QGC



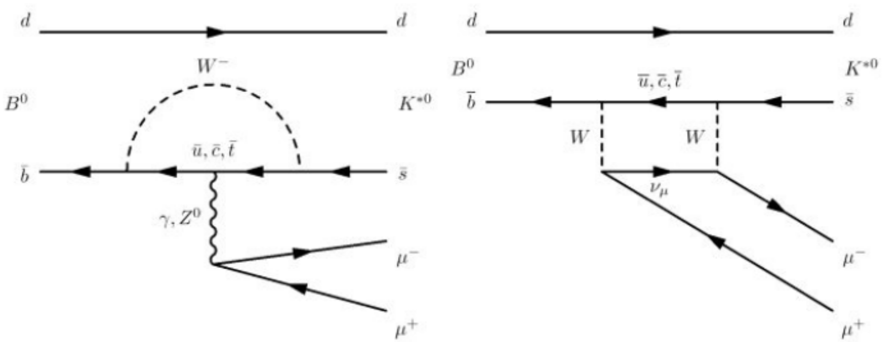


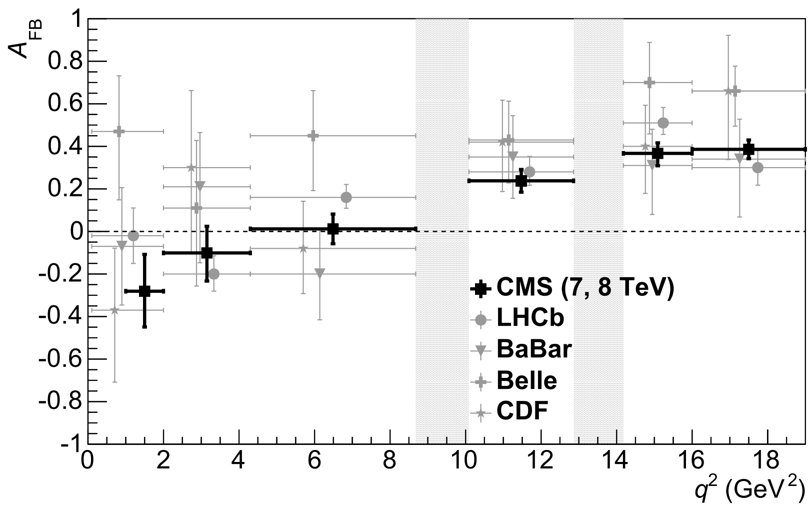


Heavy flavor

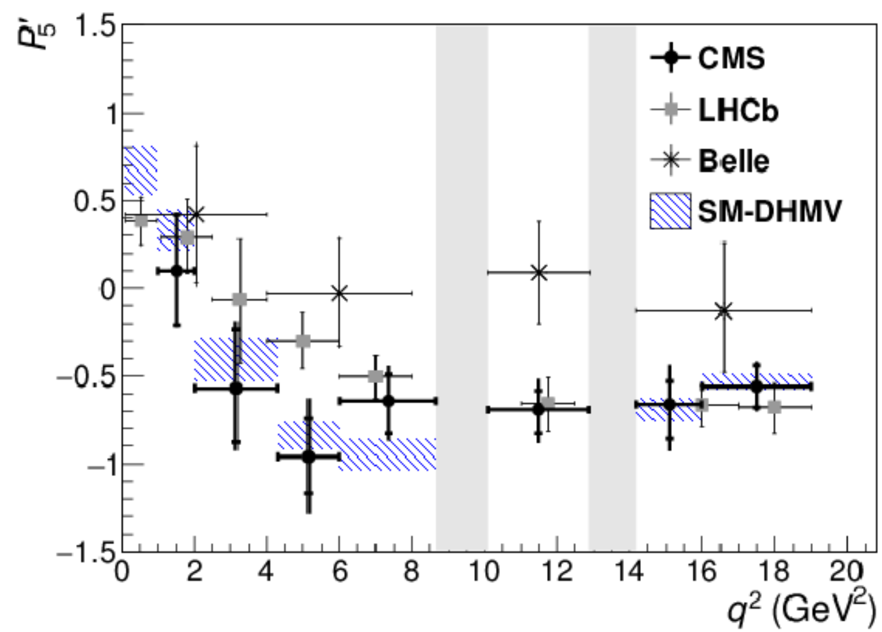
PLB753 (2016) 424, PLB781 (2018) 517

- Angular analyses of flavor-changing neutral current decay $B \rightarrow K^{(*)}\mu^+\mu^-$





Forward-backward asymmetry of the muons (A_{FB}) vs. dimuon invariant mass squared (q^2)



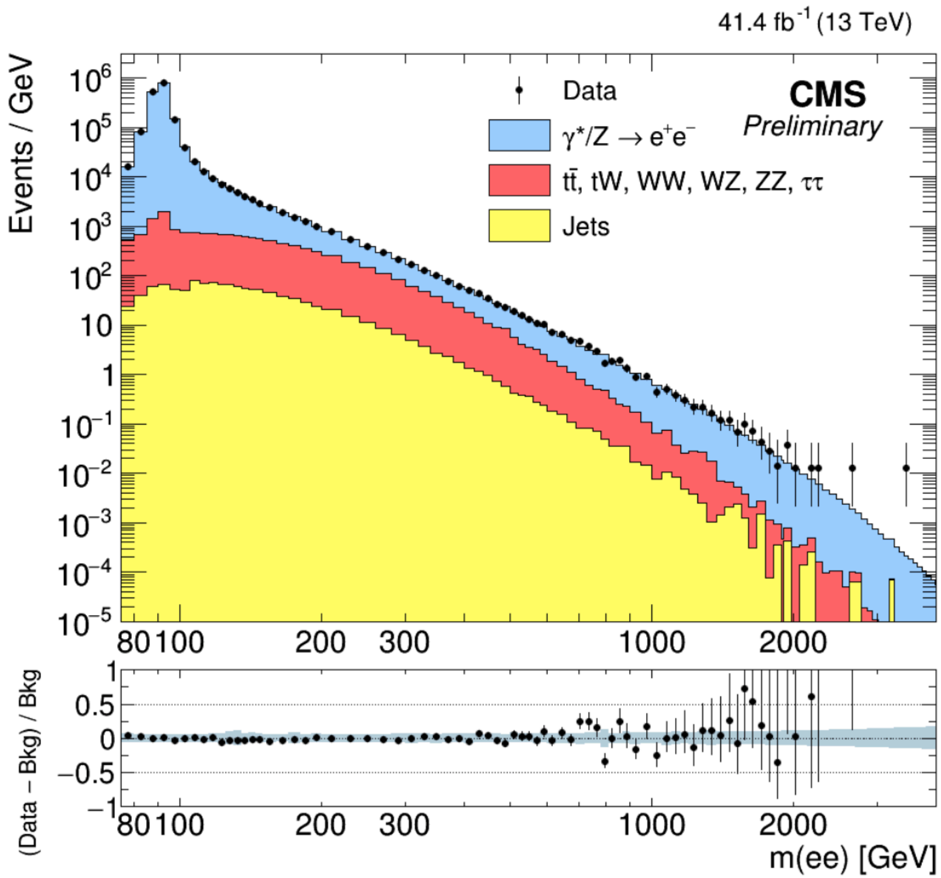
P'_5 : a form factor independent observable

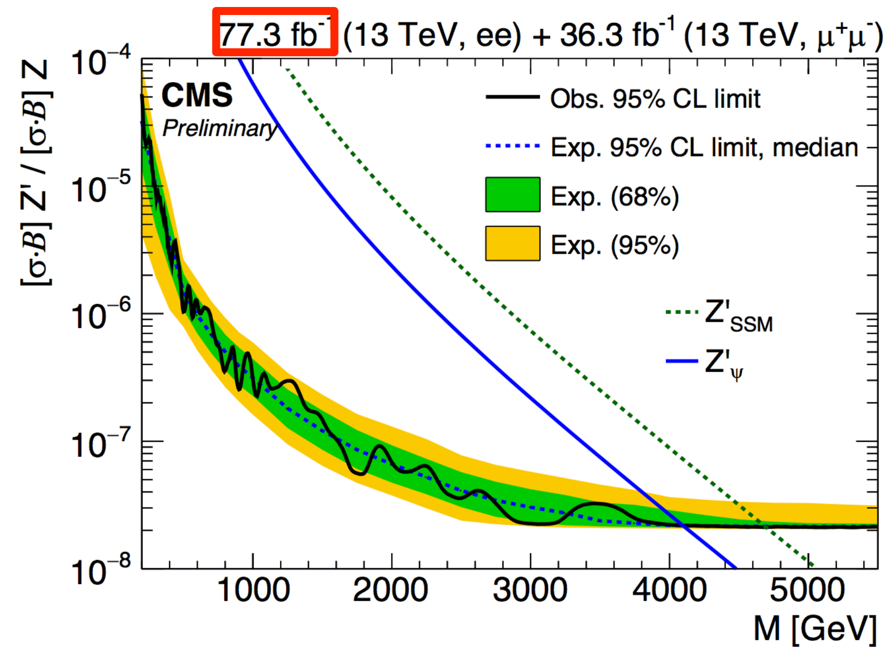
- LHC and ATLAS/CMS status
- Physics Results
  - Higgs
  - SM Physics
  - Direct searches for BSM
- Outlook and Summary

Search for high-mass di-lepton resonances

CMS-PAS-EXO-18-006

- Limits for high mass searches extending beyond 4 TeV with first 2017 data analyses

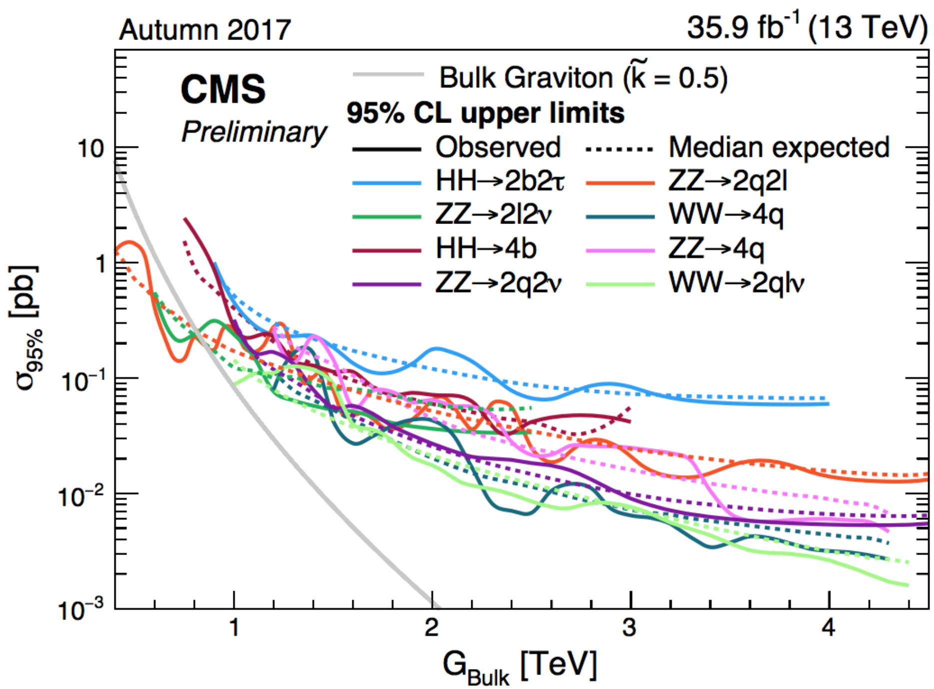




Channel	Model	Obs. limit (TeV)	Exp. limit (TeV)
ee (2017)	Z'_{SSM}	4.10	4.15
	Z'_{ψ}	3.35	3.55
ee (2016 and 2017) + $\mu\mu$ (2016)	Z'_{SSM}	4.7	4.7
	Z'_{ψ}	4.1	4.1

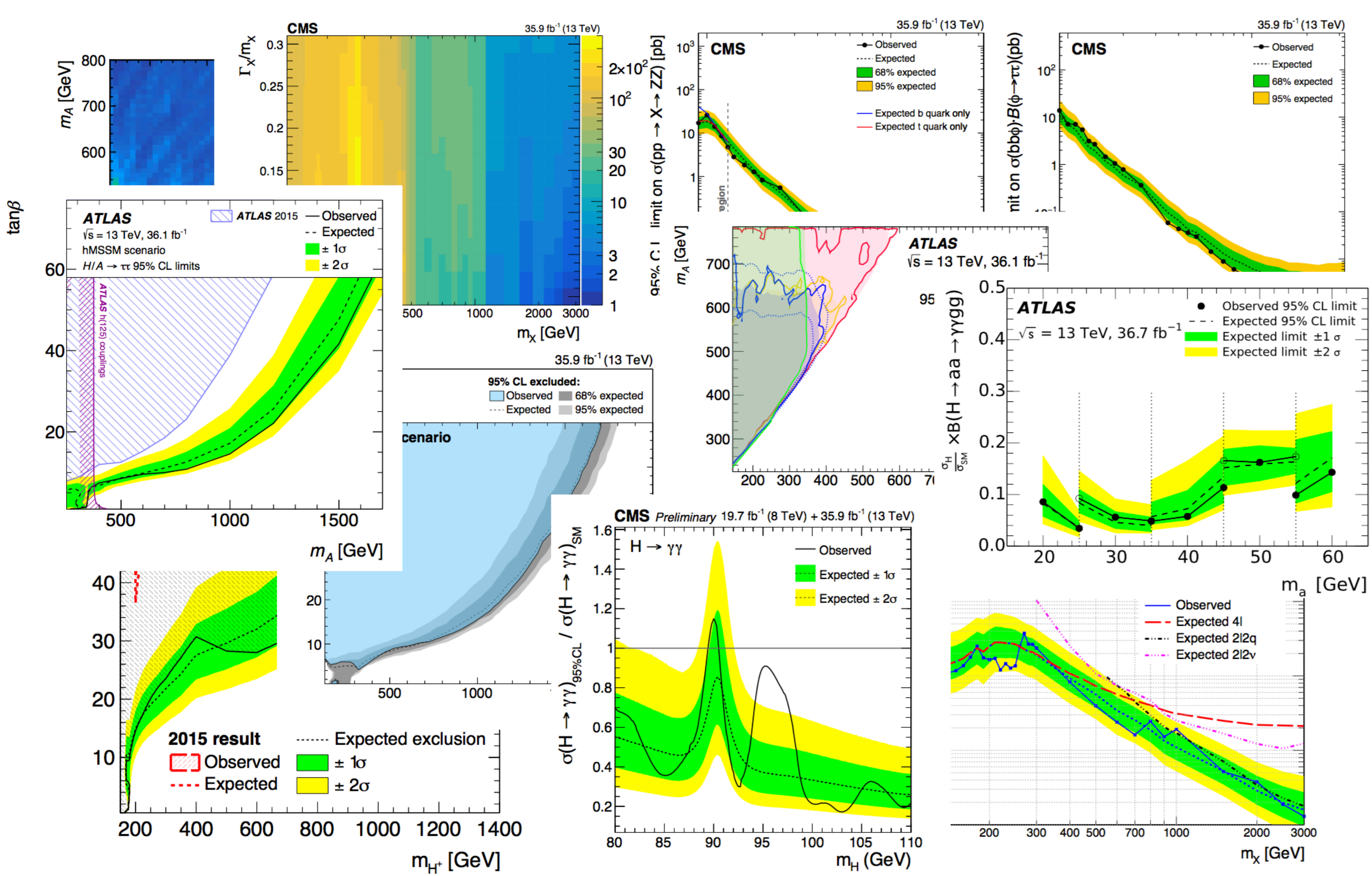
Di-boson resonance searches

- Substructure techniques (for jets, b-tagging) used for maximizing sensitivity to boosted topologies, large mass range
  - Includes using the Higgs as a discovery tool ("Higgs-tagging")



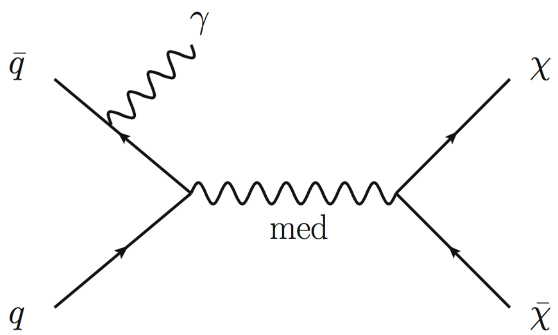
Comprehensive di-boson search programs

Additional Higgs ?

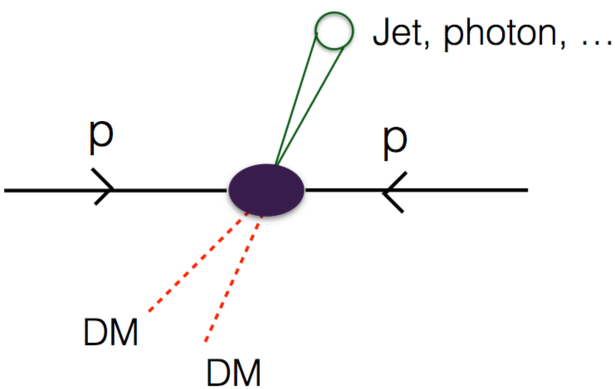


Many searches, no significant excess yet

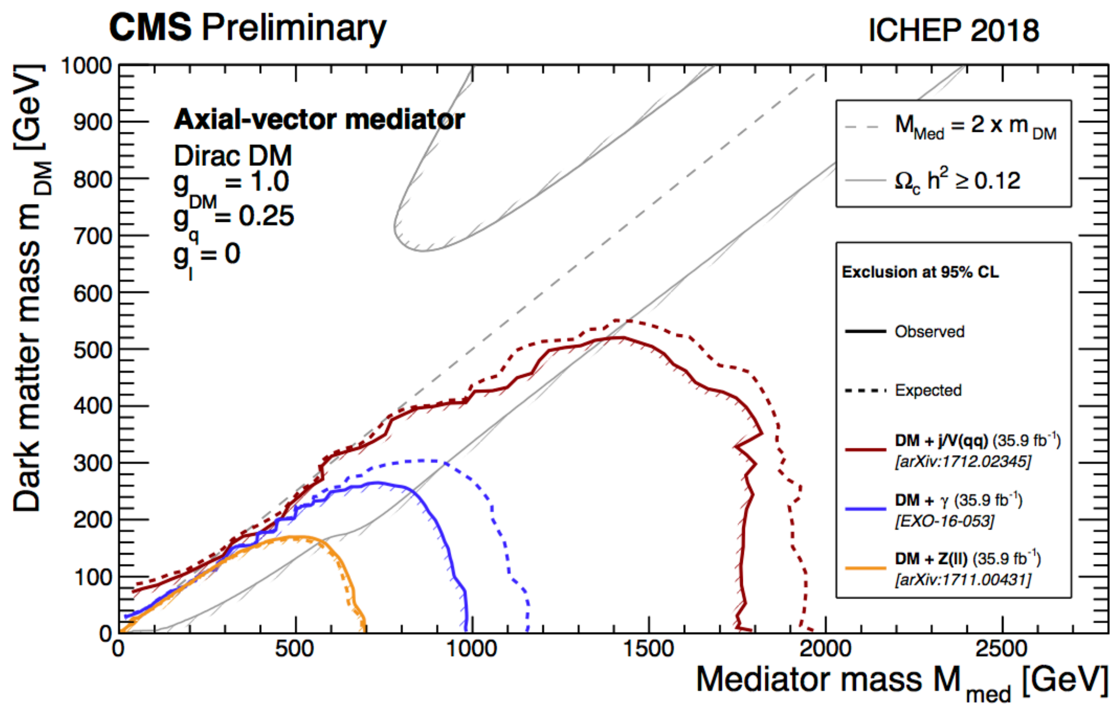
Dark matter searches



Visible, high p_T object(s)

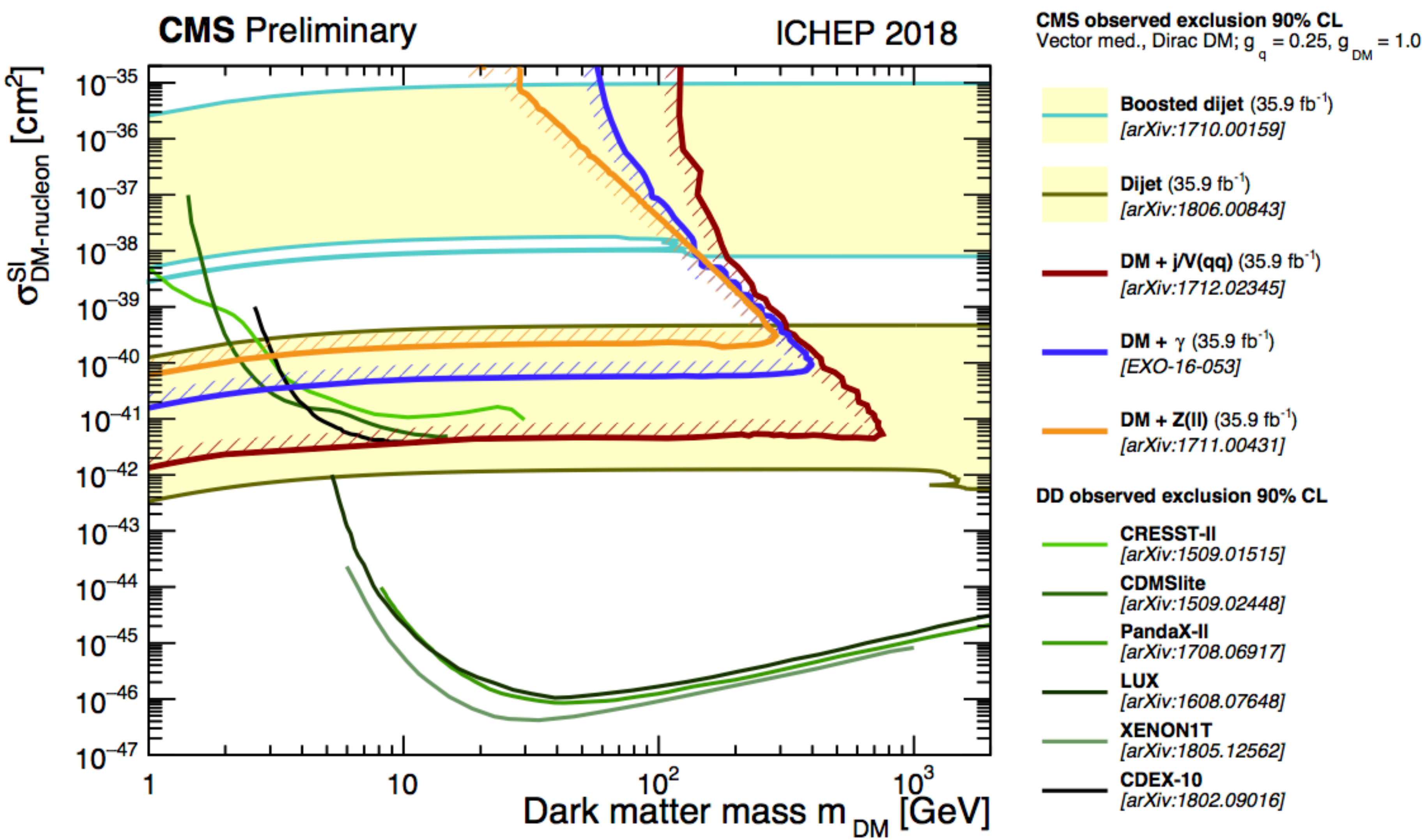


Large MET



mono-X type search

Dark matter searches

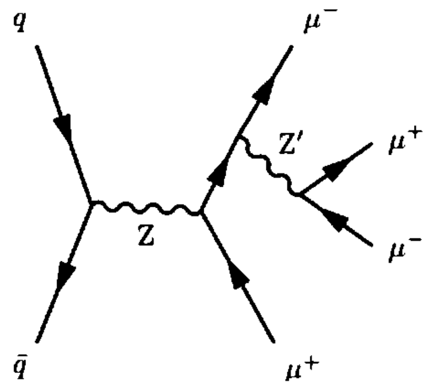


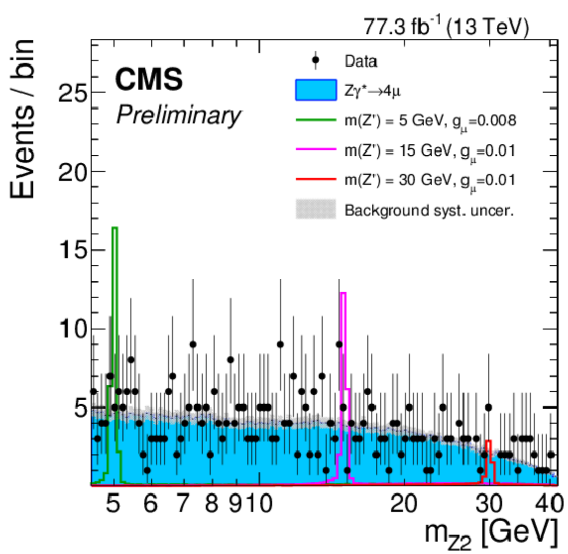
No hints at LHC yet

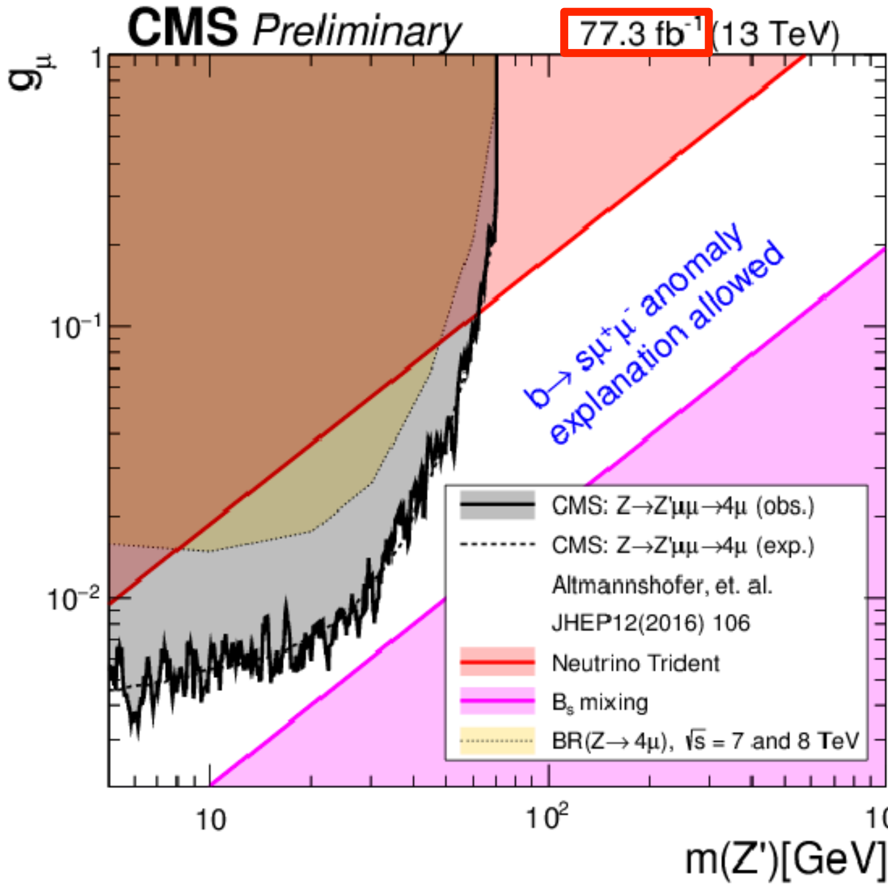
What if Dark Matter doesn't couple to quarks

CMS-PAS-EXO-18-008

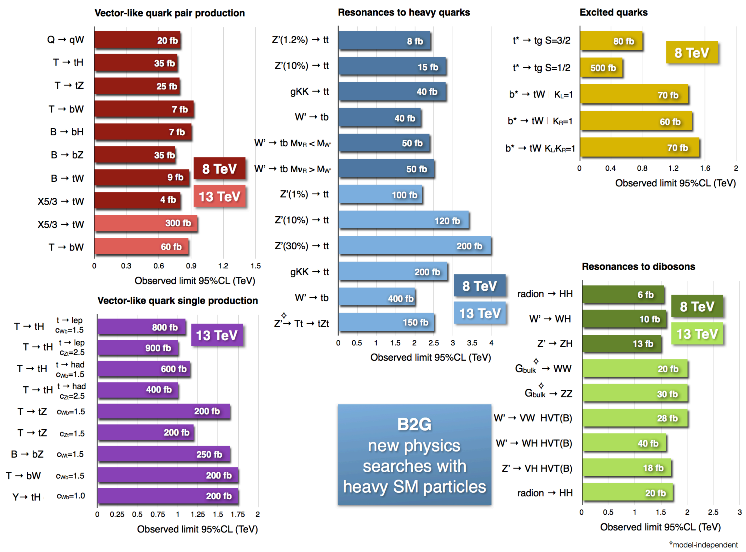
- Also motivated by LFU tensions and muon g-2
- Search for an L_μ-L_τ gauge boson: a narrow light Z' decaying in $\mu^+\mu^-$ with Z→4μ events

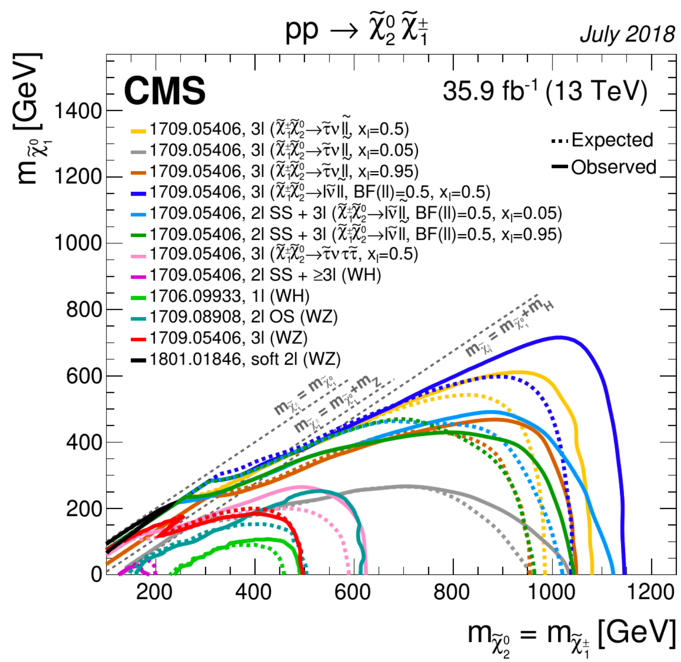


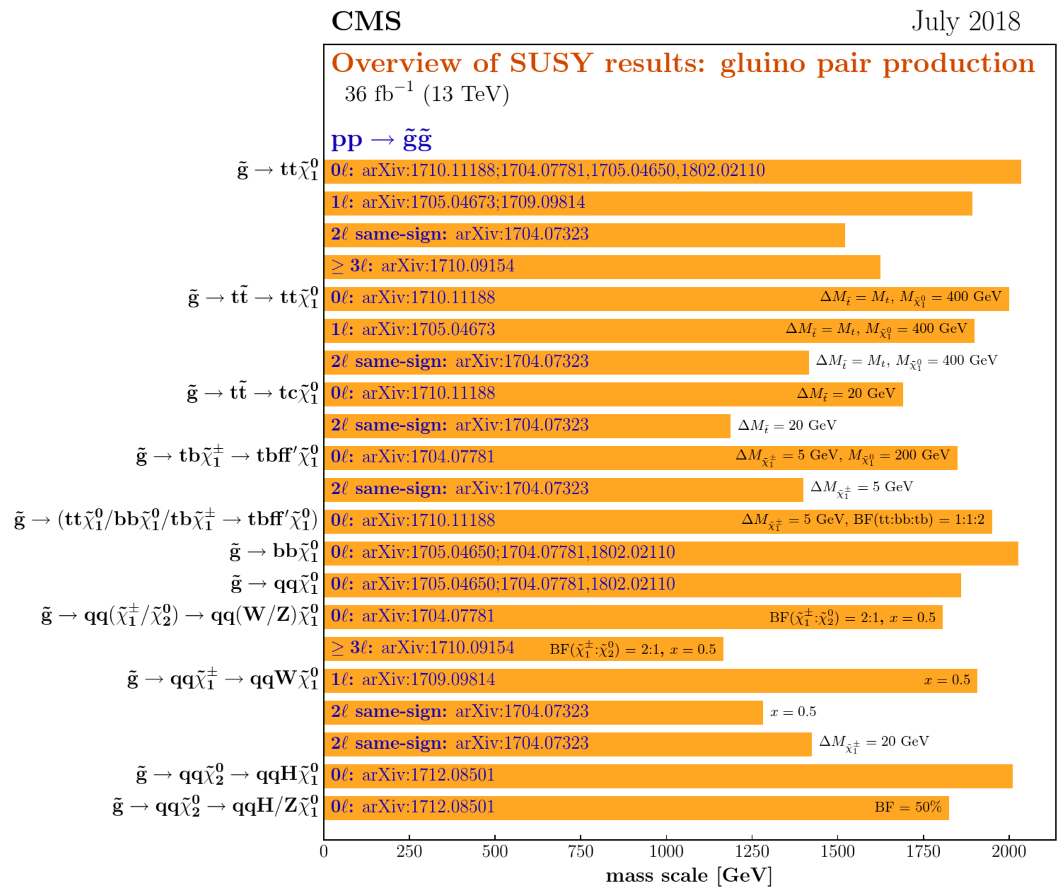




Many other exotica and SUSY searches

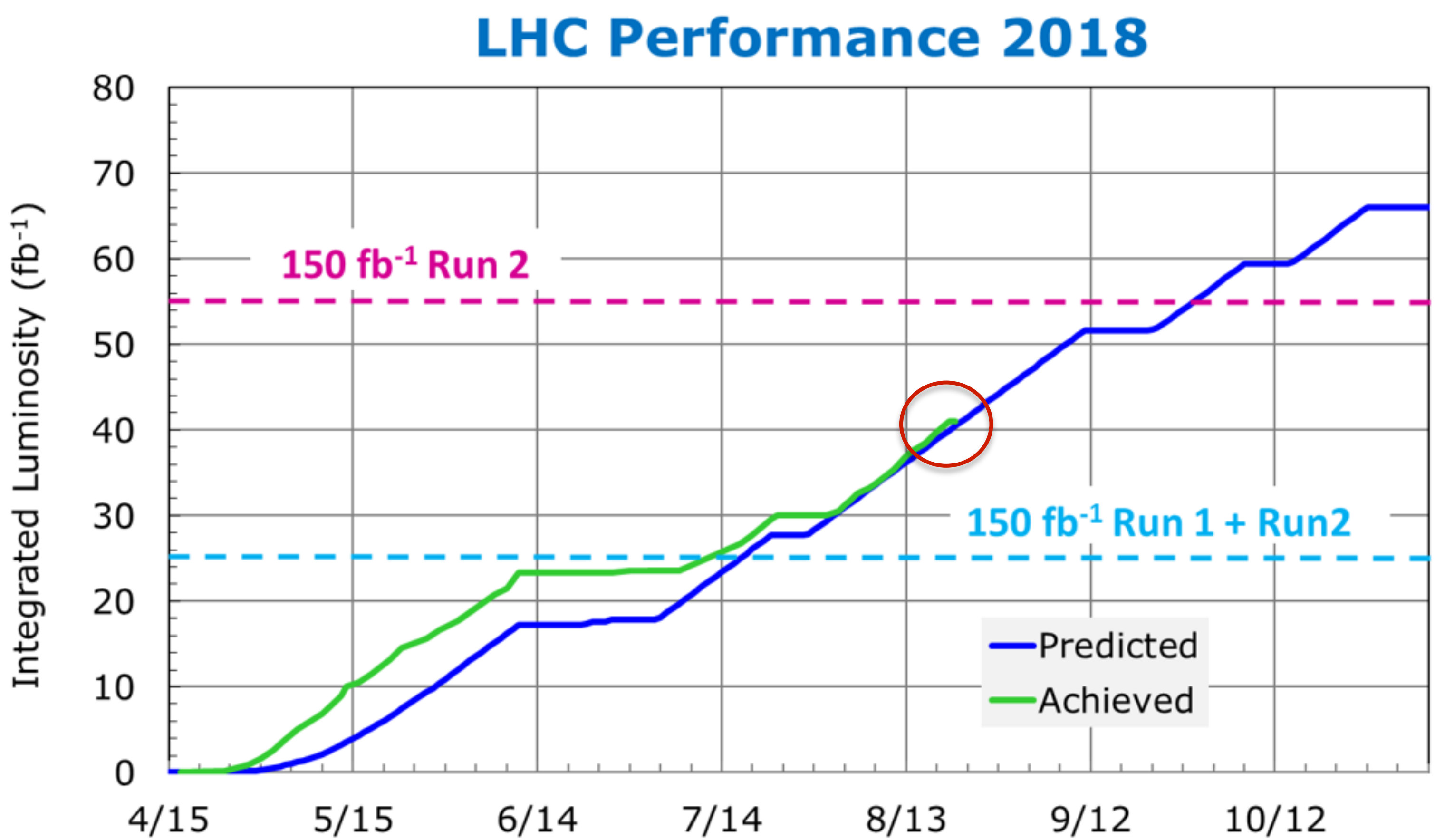






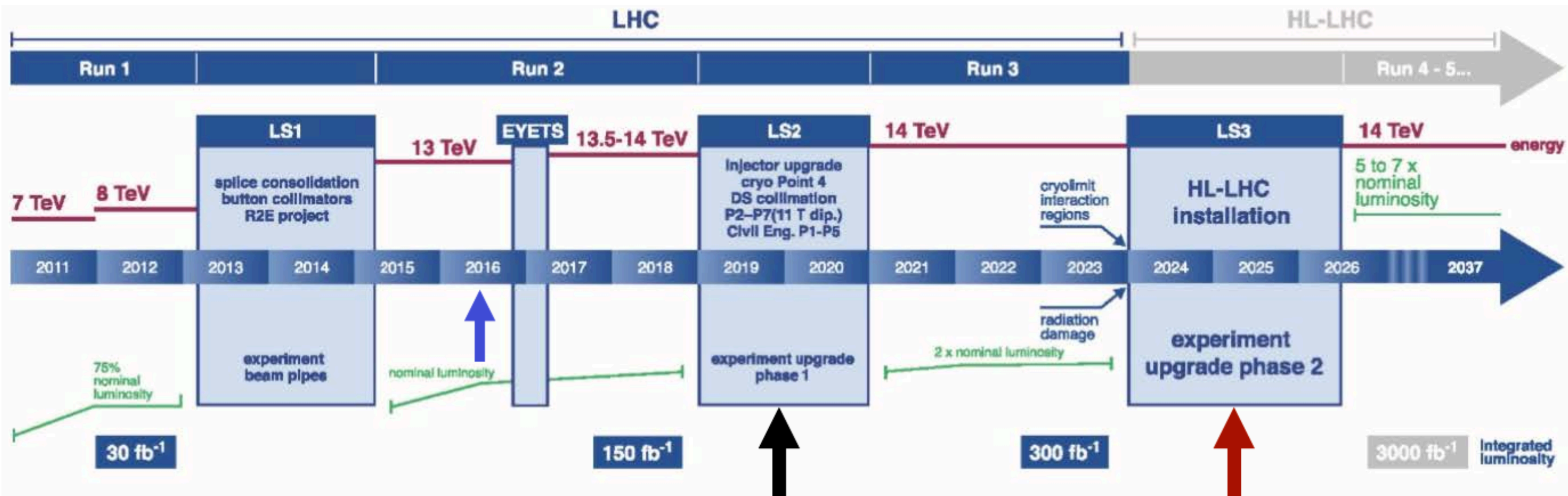
Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

Looking forwards



Expect ~150 fb^{-1} (almost double 2016+2017) by the end of 2018

Much more work now devoted to upgrades



LS2 (2019-2020):

- ❑ LHC Injectors Upgrade (LIU)
- ❑ Civil engineering for HL-LHC equipment P1,P5
- ❑ First 11 T dipoles P7; cryogenics in P4
- ❑ Phase-1 upgrade of LHC experiments

LS3 (2024-2026):

- ❑ **HL-LHC installation**
- ❑ Phase-2 upgrade of ATLAS and CMS

Schedule driven by radiation damage to inner triplet (eol: 2023)

Summary

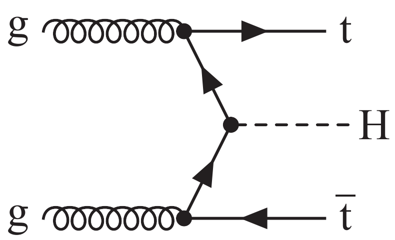
- Approaching a decade after the start, the LHC is now a mature machine, and the detectors are stable, and very well understood
- Direct observation on ttH: it's there at tree-level, and $y_t \approx 1$
- Established the Yukawa couplings to the heaviest fermions, τ, b, top
- Still no significant deviation/excess from CMS, but only two percents of the full LHC data sample analyzed!
- Completion of Run-2, upgrades and then much more data beyond
- **Let's hope something is still hiding out there**

The future is bright!   “钱”景光明!

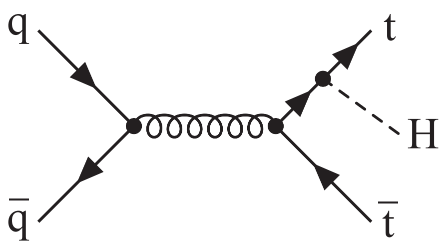
back up

ttH

Phys. Rev. Lett. 120, 231801 – Published 4 June 2018



Higgs is too light to decay into two tops

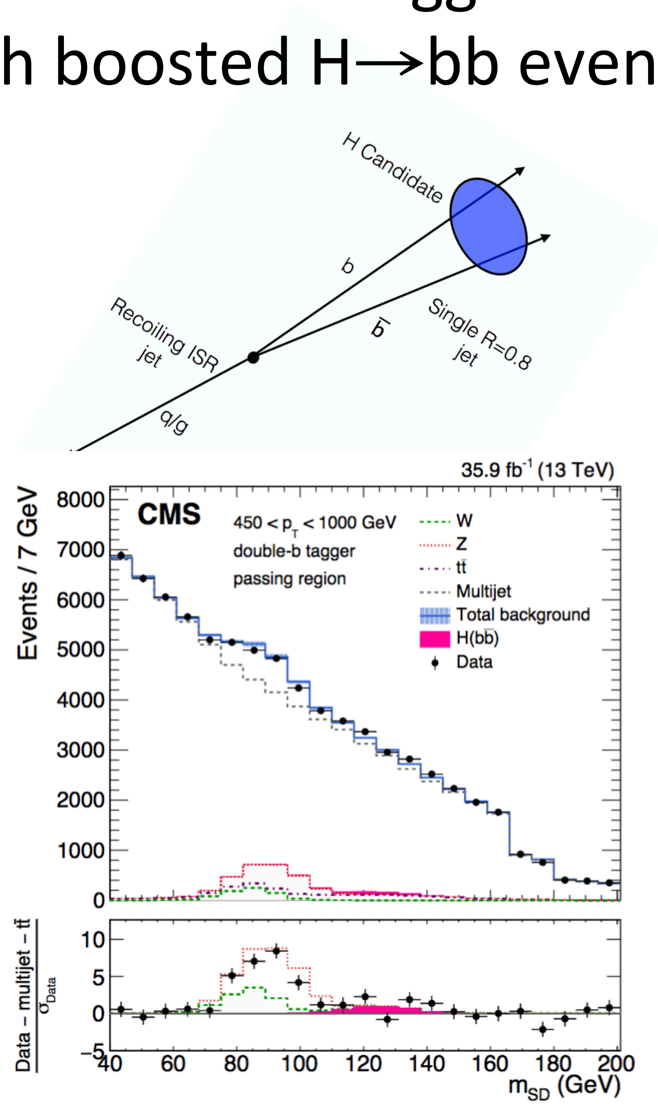


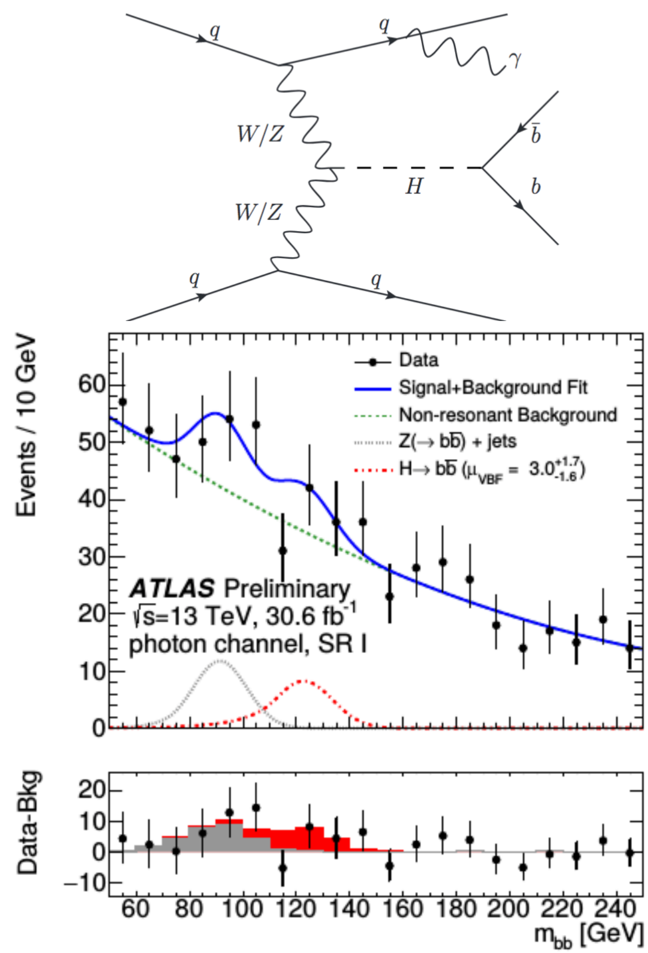
- Signature is production of two top quarks and a Higgs
  - The top is observed its its decay to Wb with the W decaying leptonically or hadronically
  - The analysis uses Higgs decays to bottom-quark-anti quark pairs, $\tau^+\tau^-$, $\gamma\gamma$, WW* and ZZ* (various quark and multi-lepton channels)
    - Hadronic τ decays, τ_h, are used
  - A total of 88 different event topologies, consisting of leptons, photons and jets, are combined to get the result
  - Use of Deep Neural Nets is pervasive
- Main systematic uncertainties are
  - Experimental: lepton and b jet identification efficiencies; τ_h and jet energy scales
  - Theory on background calculations: modelling uncertainties in tt production in association with a W or Z or a pair of b or c jets
  - Theory on signal calculations: effect of higher order corrections on ttH cross sections and uncertainty in proton PDFs
- The $\gamma\gamma$ and ZZ* states are limited by statistics; H→ bb and H→leptons by systematics

$H \rightarrow b\bar{b}$: explore new regimes/ideas

Phys.Rev.Lett. 120 (2018) 071802, CERN-EP-2018-140

- Direct search for $gg \rightarrow H \rightarrow bb$ with boosted $H \rightarrow bb$ events
- Search for VBF, with an additional high p_T photon





Higgs → $\mu^+\mu^-$

CMS-HIG-17-019

- Best chance at measuring a coupling to a second generation fermion, even though branching fraction (BR) ~ 2.2×10^{-4}, about 1/10 of $\gamma\gamma$.
- CMS has looked for this in 7,8, and 13 TeV (2016 only) data
- Current 95% CL upper limit on BR is 6.4×10^{-4}, 2.92 (observed) vs 2.16 (expected) of the SM prediction.