Highlights from Moriond QCD 2018

with focus on recent experimental results from LHC

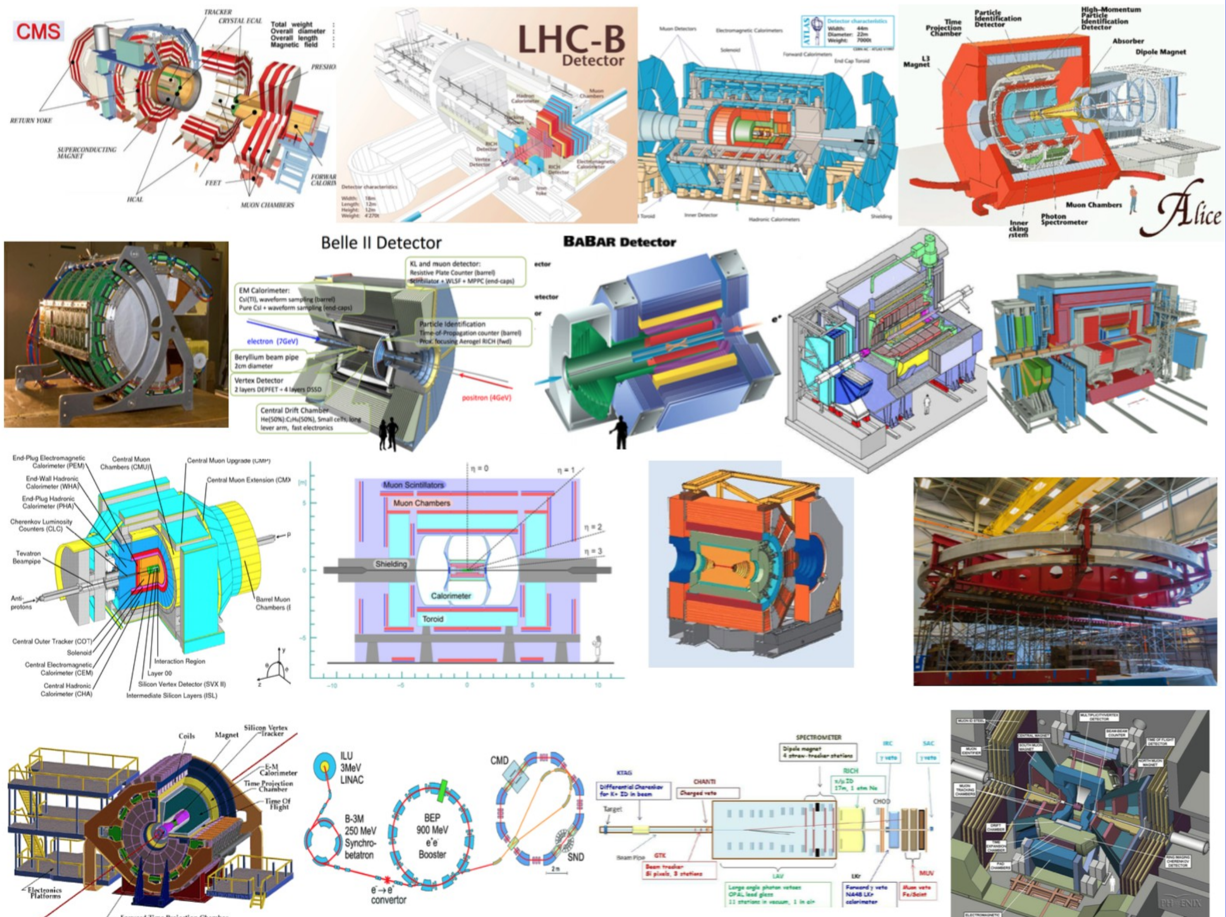
Alexei Raspereza

LHC Physics Discussion, 26/03/2016

General Overview

- almost 100 plenary talks
- 9 topical sessions
  - Higgs Physics
  - Top Physics
  - Electroweak physics
  - QCD
  - PDFs
  - Heavy Flavor Physics and CP mixing
  - Hadron Spectroscopy
  - Heavy Ion Physics
  - New Phenomena

Results from 17 experiments have been presented



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- selected topics
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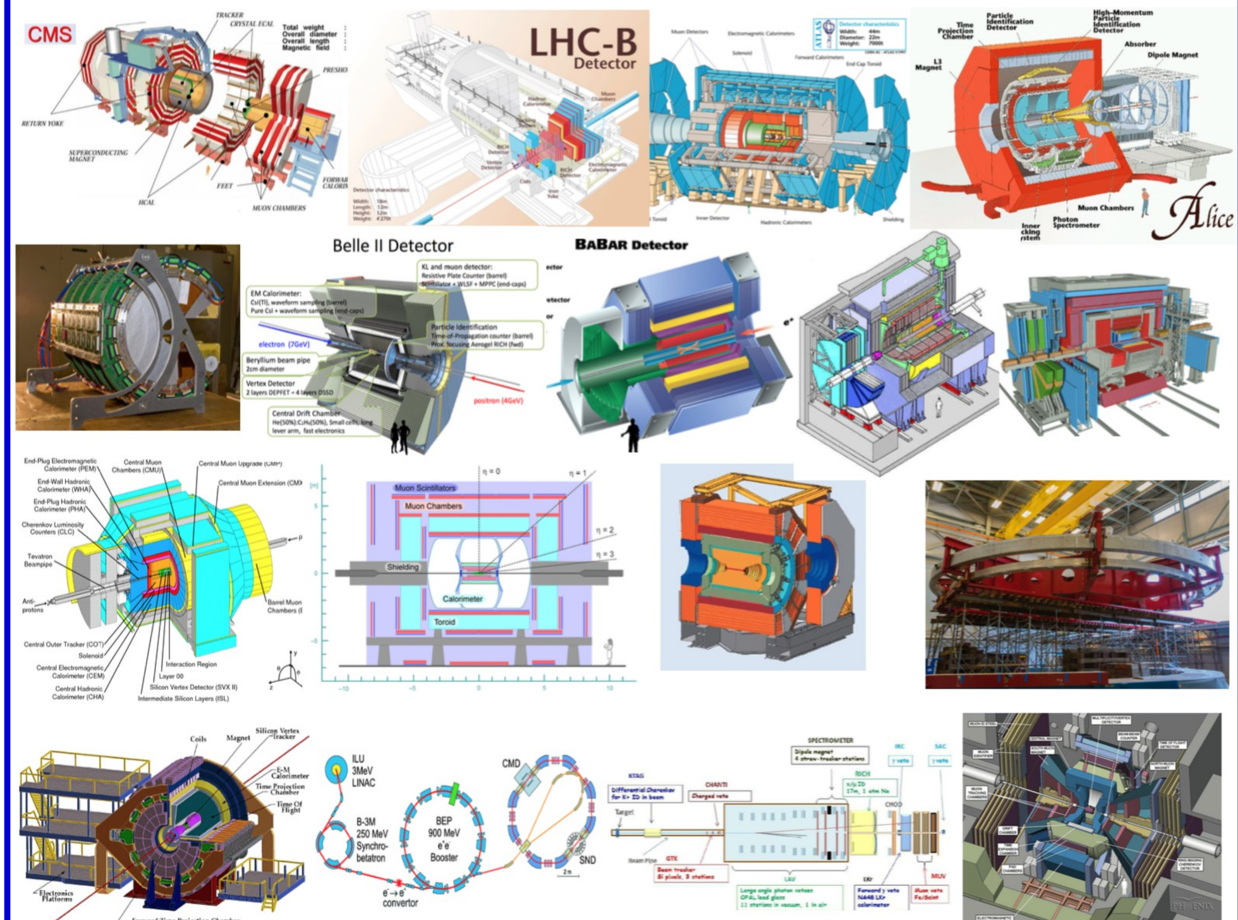
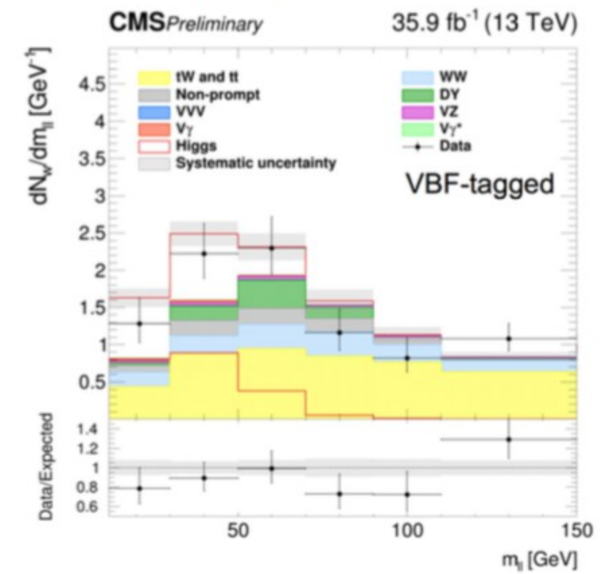


- full agenda with all presentations

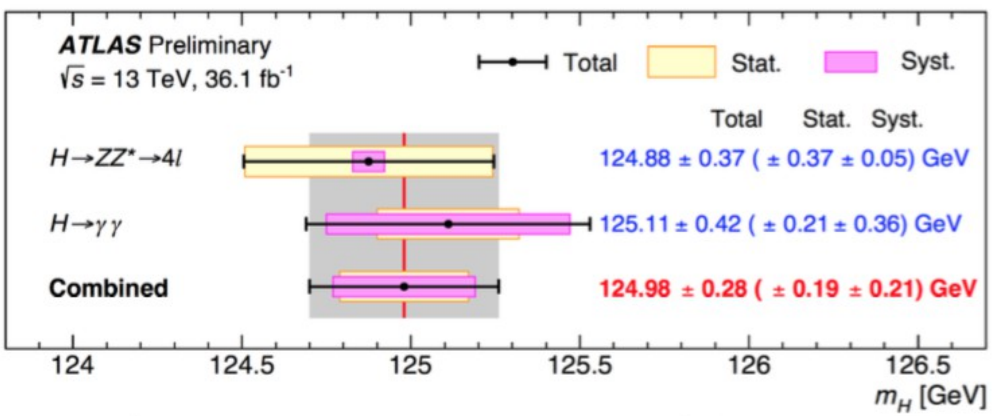
http://moriond.in2p3.fr/QCD/2018/MorQCD18Prog.html

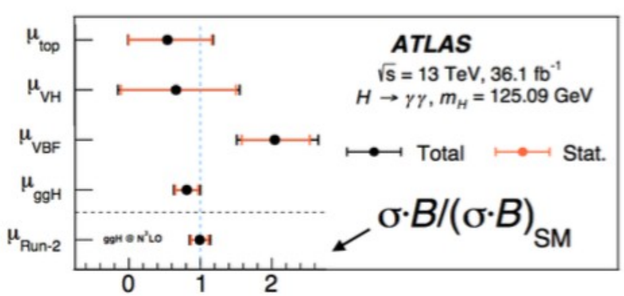
Higgs highlights

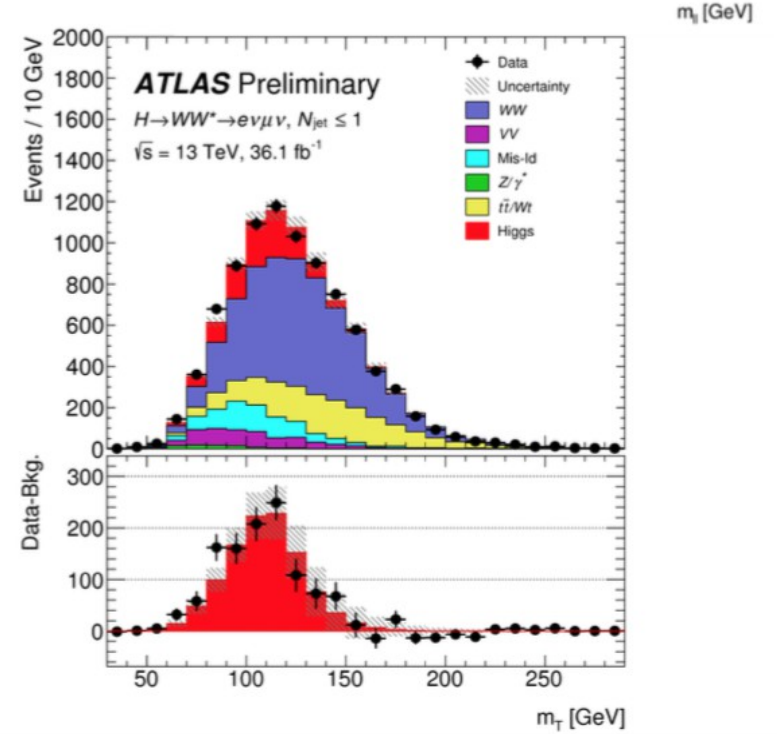
- In the 6 years since its discovery there has been significant progress in the Higgs sector:
  - Firmly established γγ, ZZ, ττ, WW decays
  - Single experiment observation (CMS): H→ ττ
  - bottom-Higgs and top-Higgs Yukawa couplings
  - excellent mass measurement



CMS $m_{\mathrm{H}} = 125.26 \pm 0.21\ (\pm 0.20\ \mathrm{stat.} \pm 0.08\ \mathrm{sys.})\ \mathrm{GeV}$

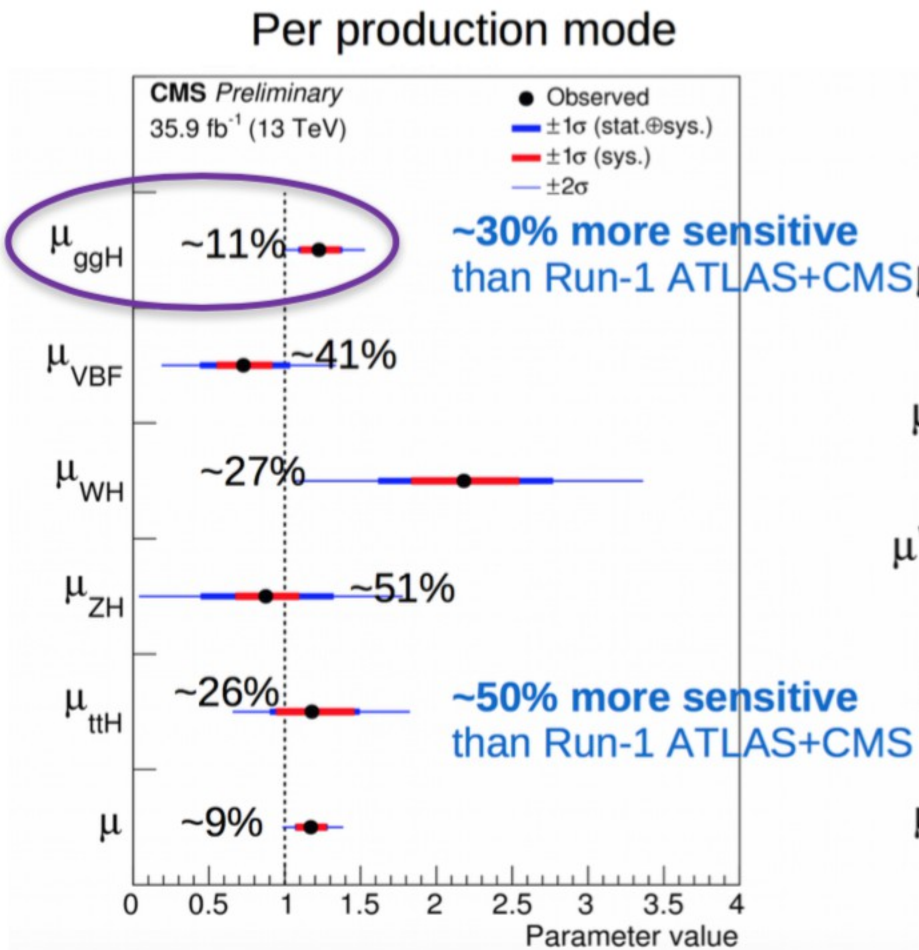


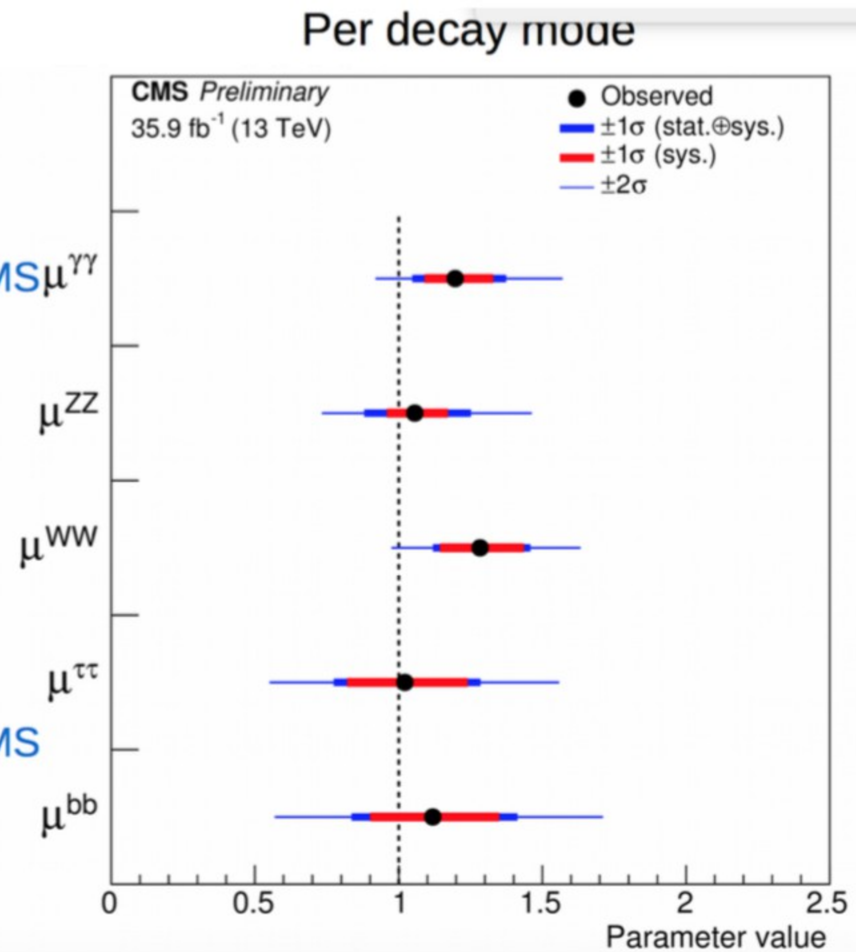




Higgs highlights

Combined 13TeV results surpassing Run 1 precision in key measurements





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

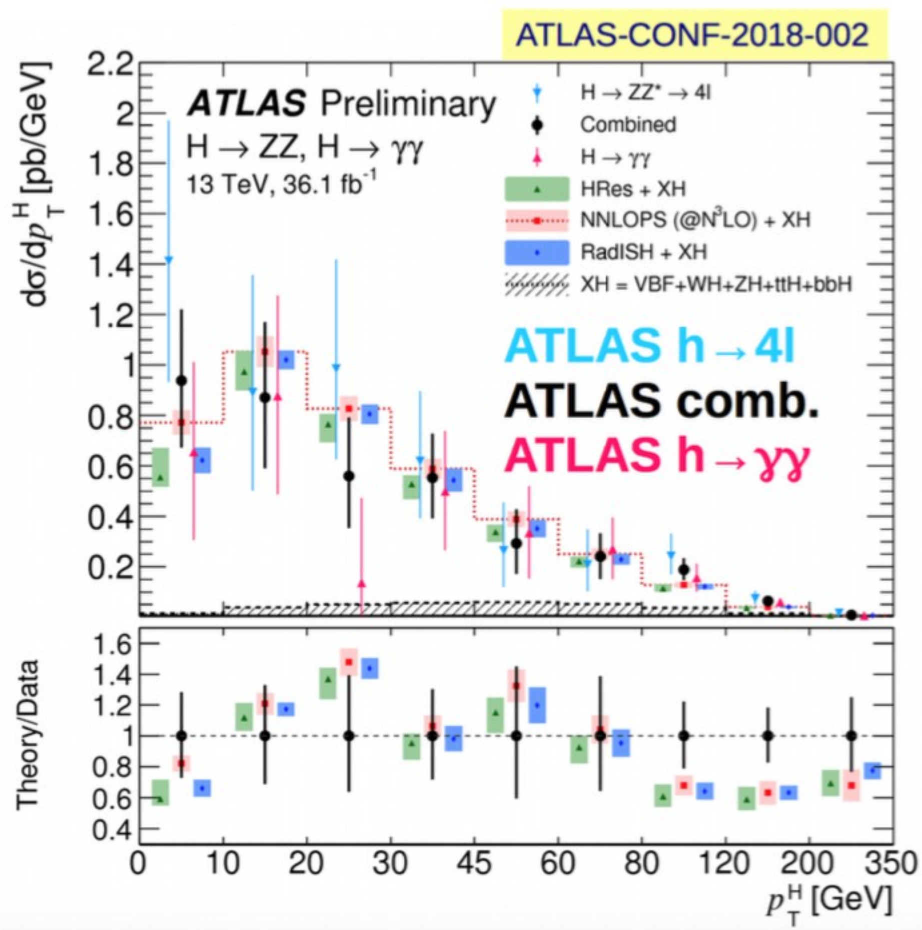
Most precise measurement of gluon fusion, ttH, and total signal strength

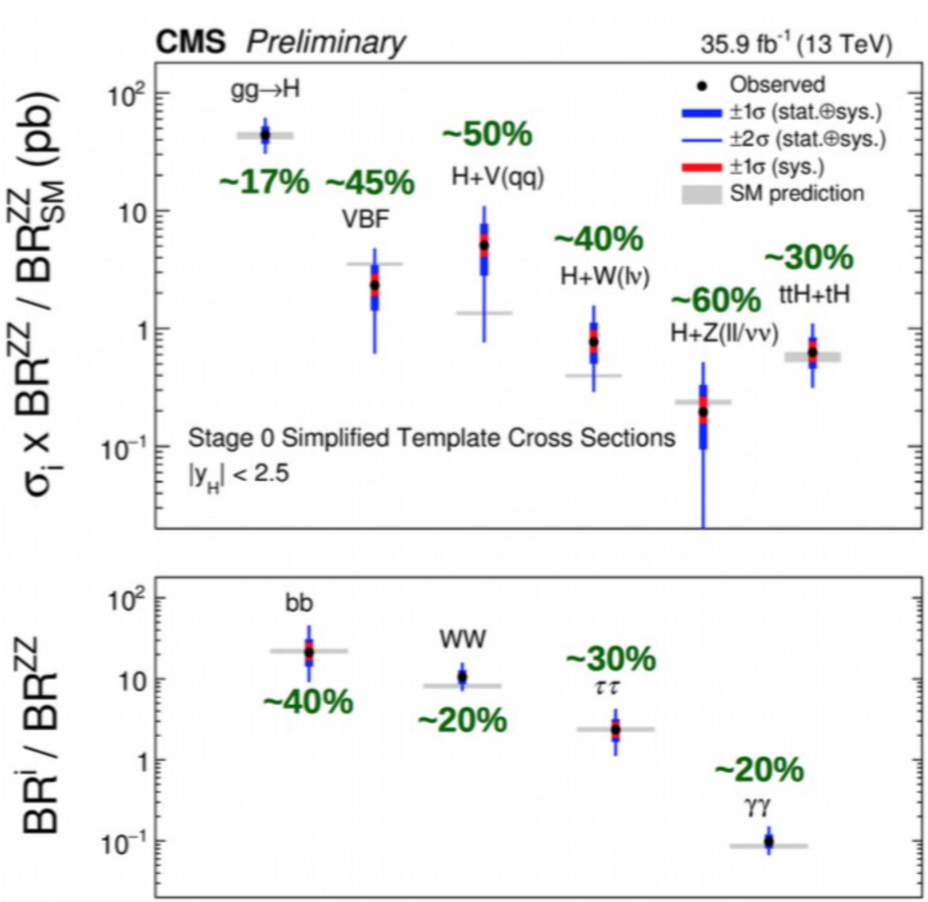
(ATLAS+CMS Run 1 combination: $\mu_{ggH} = 1.03^{+0.16}_{-0.14}$ **)**

Higgs cross sections

- Higgs physics has entered the ***precision*** era
  - Fiducial and differential cross section measurements comparing data to state-of-the-art calculations
  - Simplified template cross sections enable Higgs measurements that are less model dependent

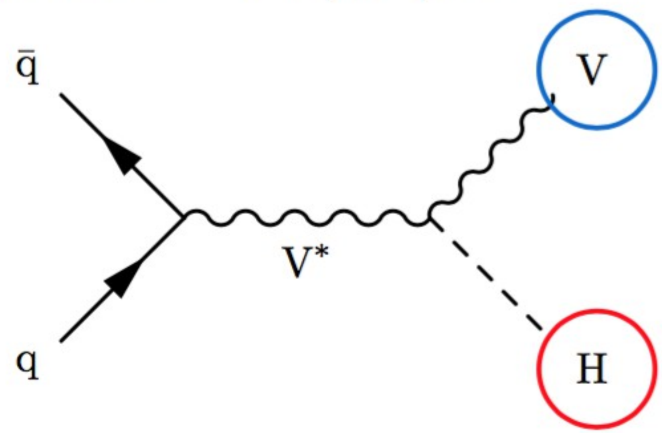
Best precisions of < 20% reached

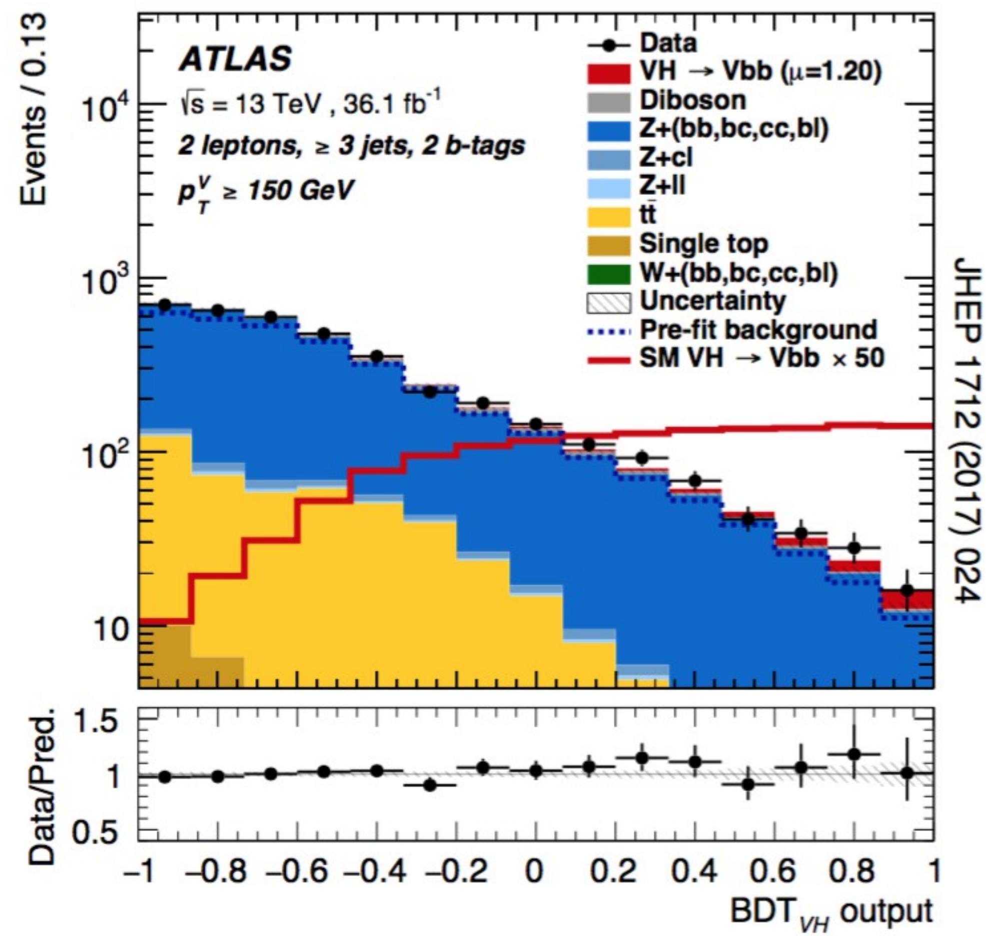




H→b$\bar{b}$ in HV

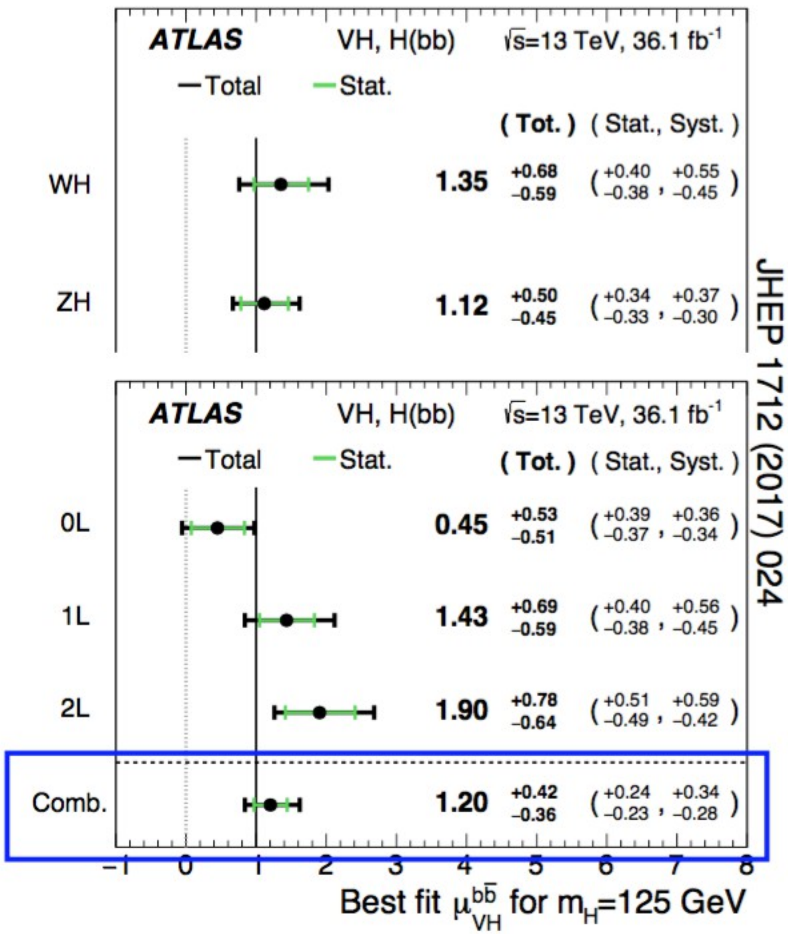
- Goal: measurement of bottom-Higgs Yukawa coupling
- Target events where **H → b$\bar{\text{b}}$ candidate recoils against V boson** to identify above multijet background
- Channels: **V** → ***ll***, ***l**ν*, *νν*

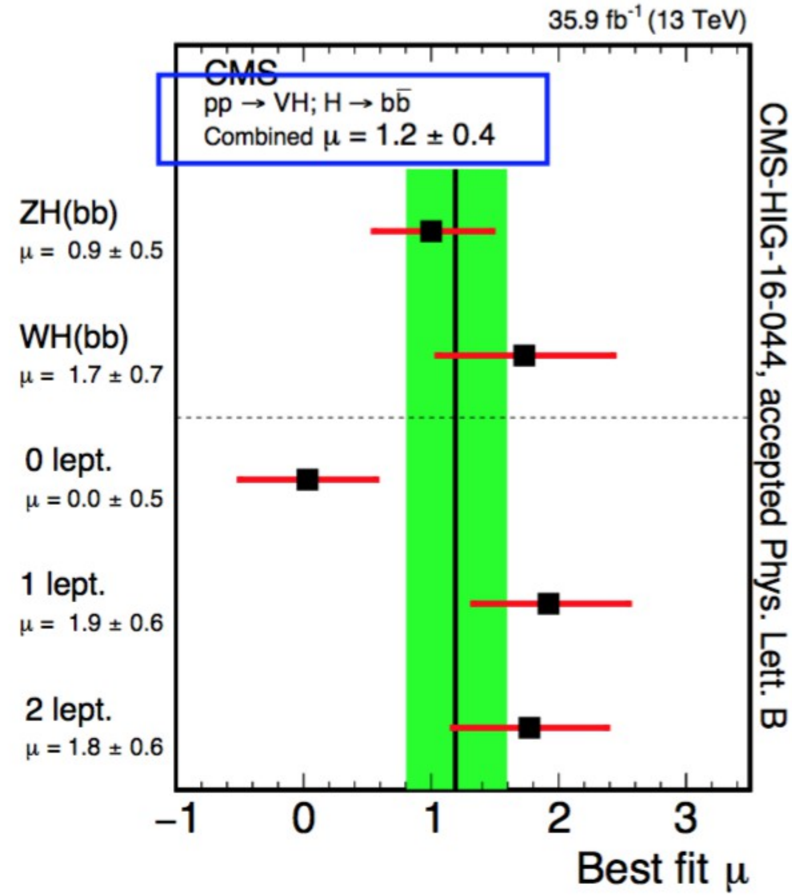




- **Boosted Decision Trees (BDT)** separating signal and background
  - V + jets, t$\bar{\text{t}}$

$H\to b\bar{b}$ in HV





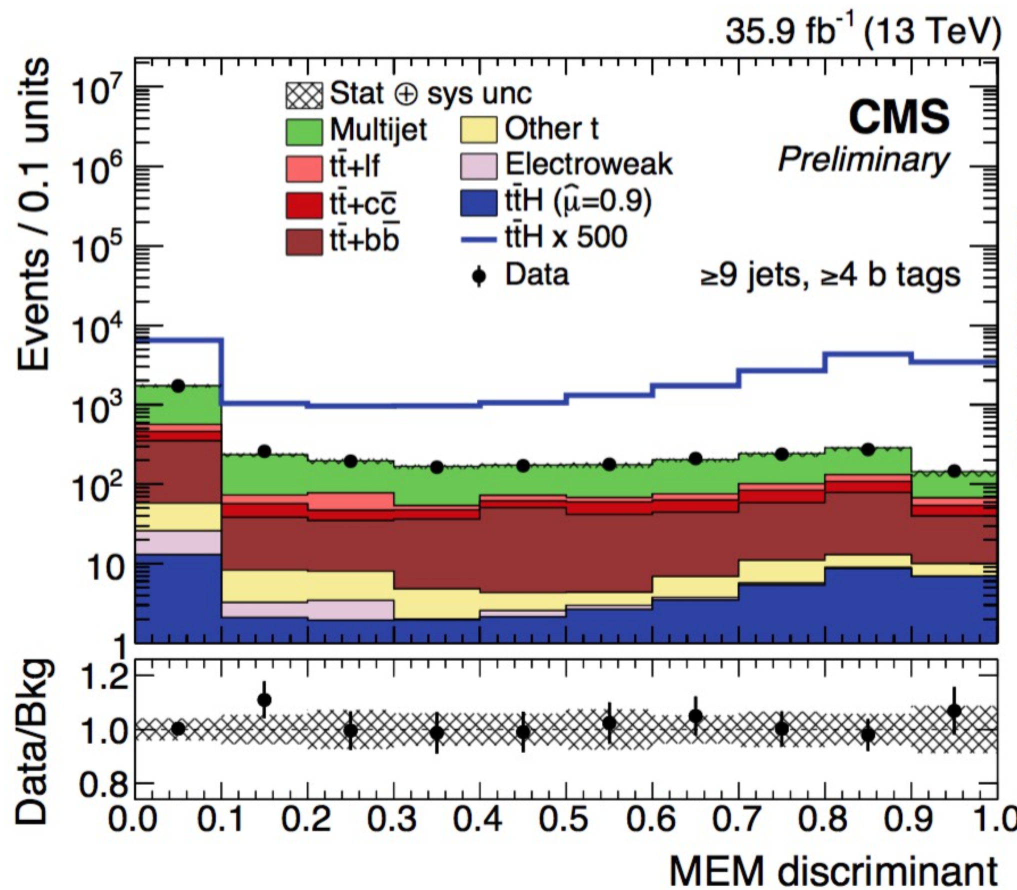
$$\mu \equiv \sigma/\sigma_{SM}$$

Evidence of $VH(b\bar{b})$ production

Observed (expected) significance	Run II	Run I+II
ATLAS	**3.5** (3.0) σ	**3.6** (4.0) σ
CMS	**3.3** (2.8) σ	**3.8** (3.8) σ

$H\to b\bar{b}$ in $t\bar{t}H$ (full hadronic) at CMS

- ≥ 7 jets, ≥ 3 b-tagged jets, $H_T > 500\,\text{GeV}$, no leptons
- Enhancement of quark-jet final states by quark-gluon jet discriminant
- Events categorised by **number of jets** and **b-tagged jets**
- **Dominant background**: QCD-multijet production
  - Shape from low b-tag multiplicity **control region in data**
  - Rate from final fit to data
- $t\bar{t}$ + jets background modelled as in leptonic analysis
- Final **discrimination by MEM**



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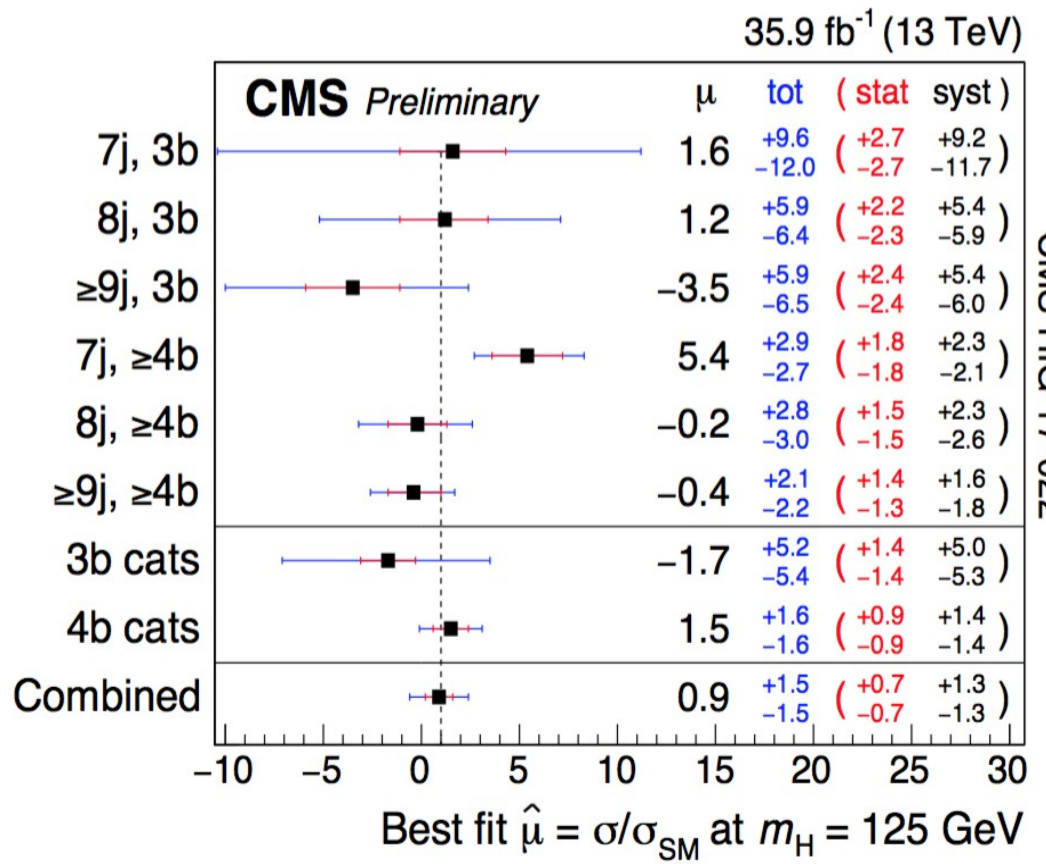
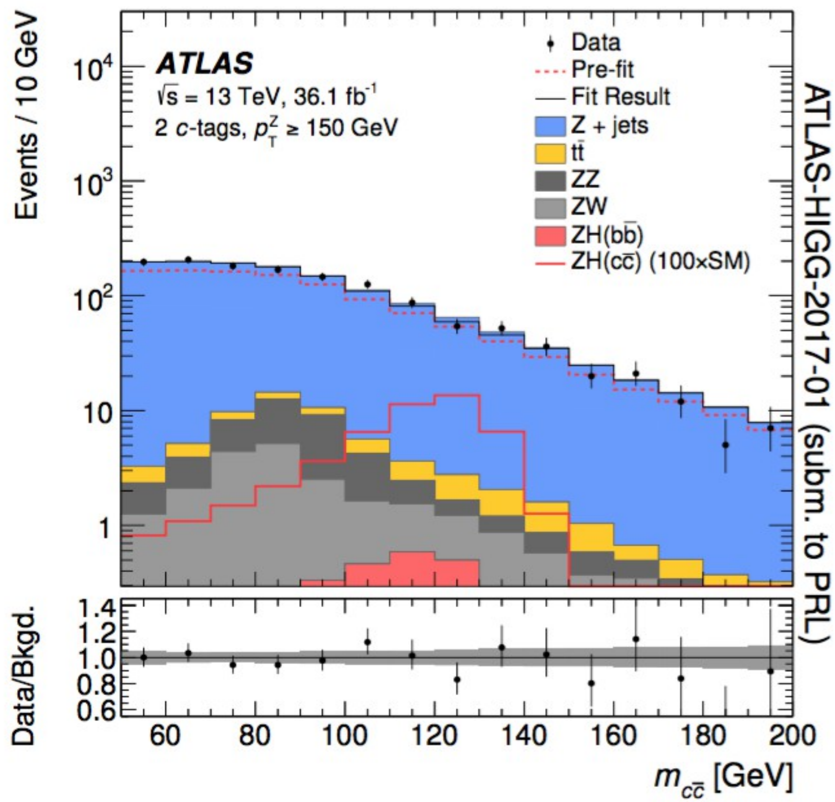
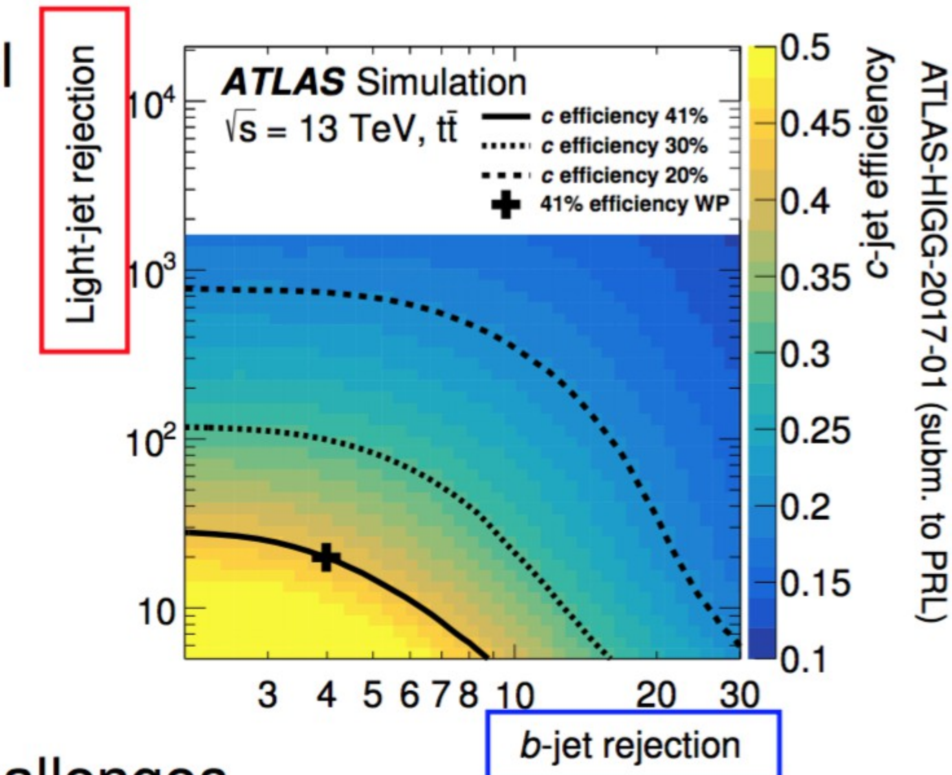


Search for H→cc in HZ($\ell^+\ell^-$)

- Search for **H** $\rightarrow$ **c$\bar{c}$** in Z(*ll*)H channel
- 2 **c-tagging discriminants** against b jets and light-quark jets





- Challenges
  - $\mathcal{B}(\mathrm{H} \rightarrow c\bar{c}) = 2.9\%$:
    $\sigma(pp \rightarrow ZH) \cdot \mathcal{B}(\mathrm{H} \rightarrow c\bar{c}) = 26$ fb
  - Large Z + jets background

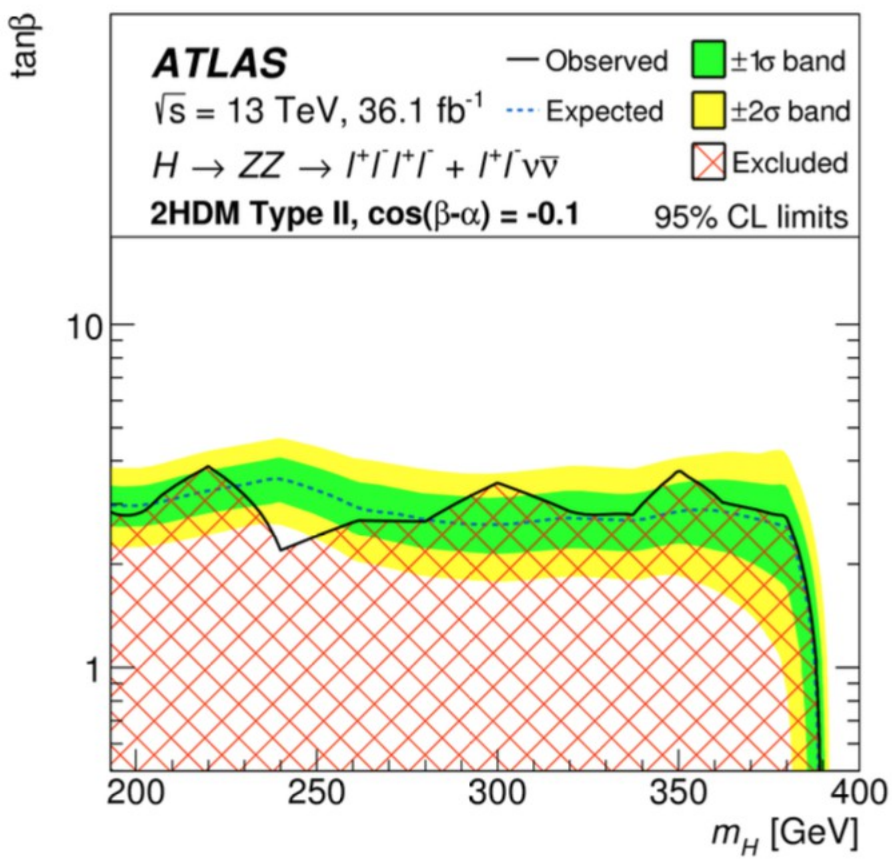
Upper limit on $\sigma(pp \rightarrow ZH) \cdot \mathcal{B}(\mathrm{H} \rightarrow c\bar{c}) < 110$ (150 exp.) $\times$ SM at 95% C.L.

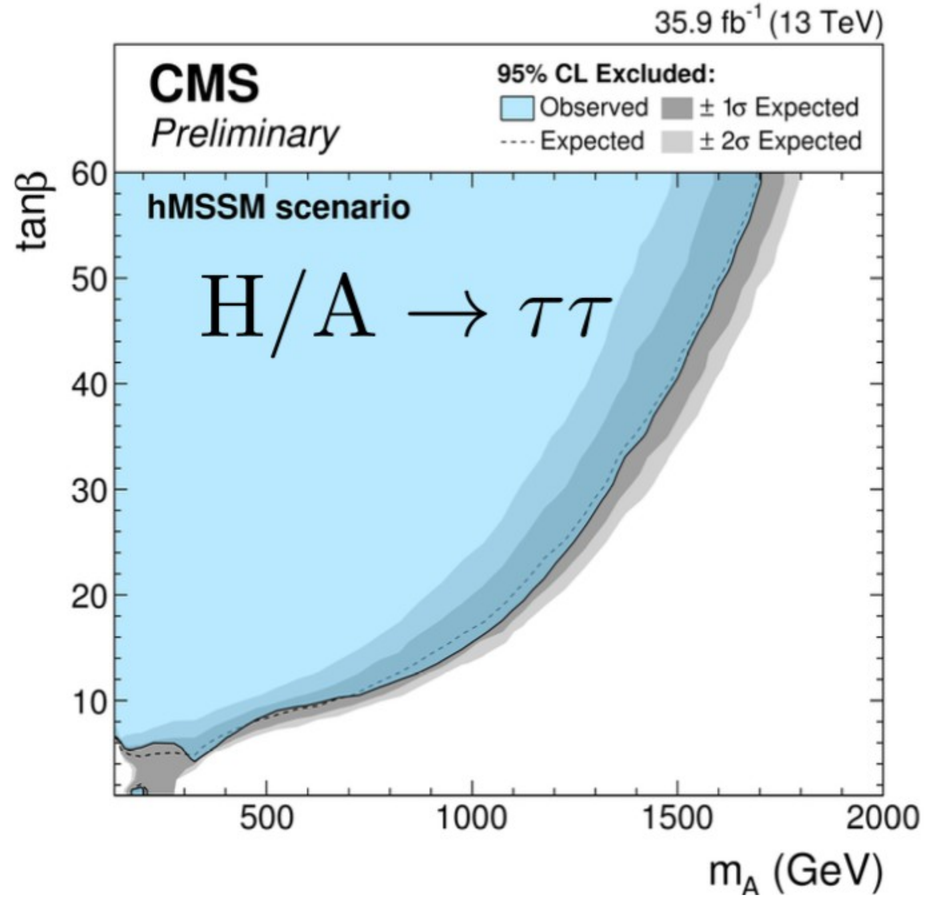
- **New approach**: best direct limit on H $\rightarrow$ c$\bar{c}$

Search for additional Higgs bosons

- Searches for additional Higgs bosons at LHC conventionally focus on 2HDM and MSSM

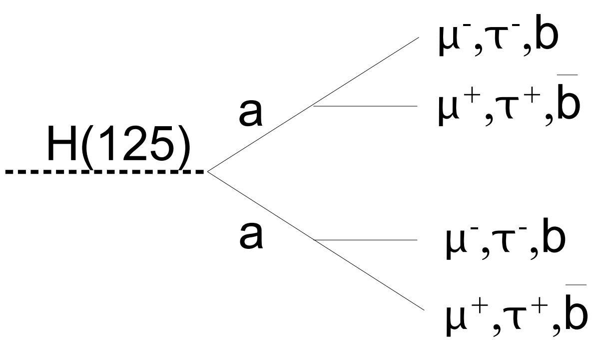
No signal is found → stringent constrains on model parameters are derived

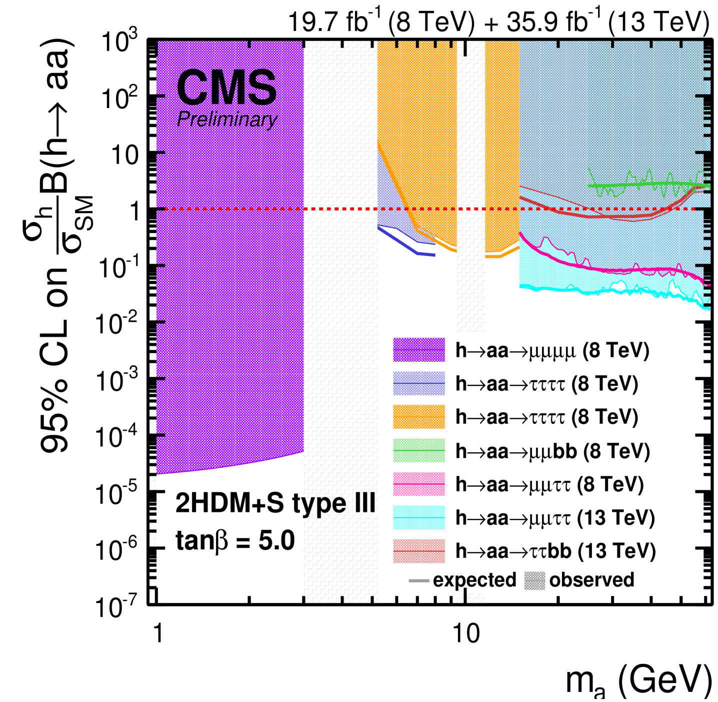




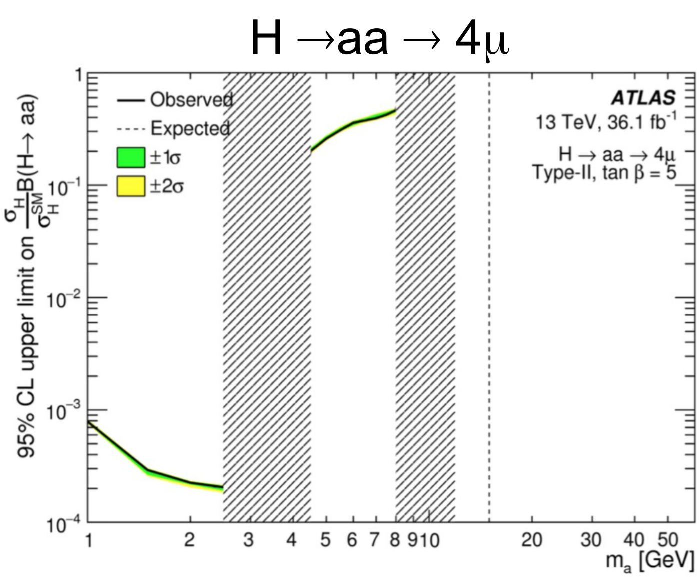
Exotic Higgs Bosons: Searches for H(125)→aa

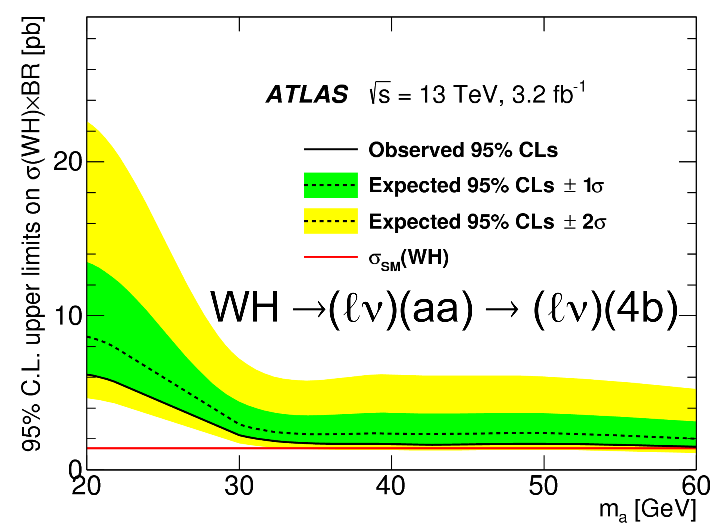
- 2 Higgs Doublets + 1 Singlet models
  7 physical states:
  3 CP-even $h_{1,2,3}$, 2 CP-odd $a_{1,2}$, 2 charged $h^{\pm}$
- peculiar scenario
  a_1 has large singlet component and $2m_{a1} < m_{H(125)}$
  - ➔ reduced rates of conventional production modes gg→ a and $b\bar{b}a$
  - ➔ accessible via H(125) → aa decays





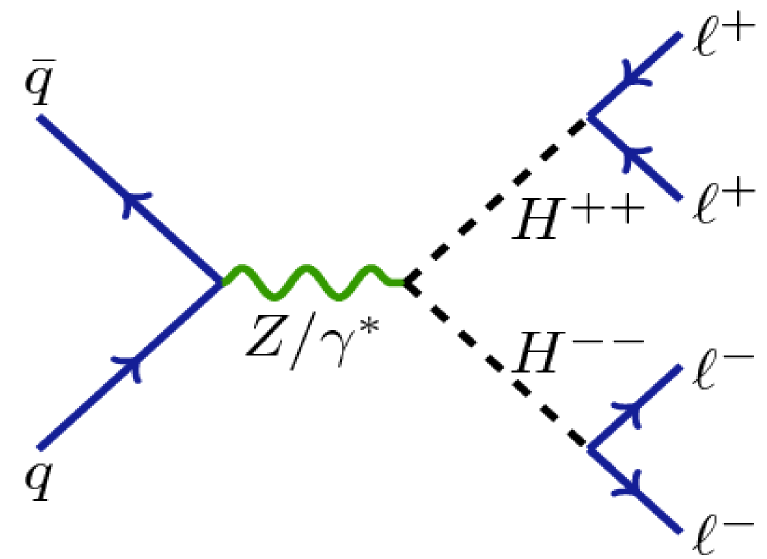
- analyses performed in large variety of channels
  - ➔ no signal found
  - ➔ stringent constrains on model parameters





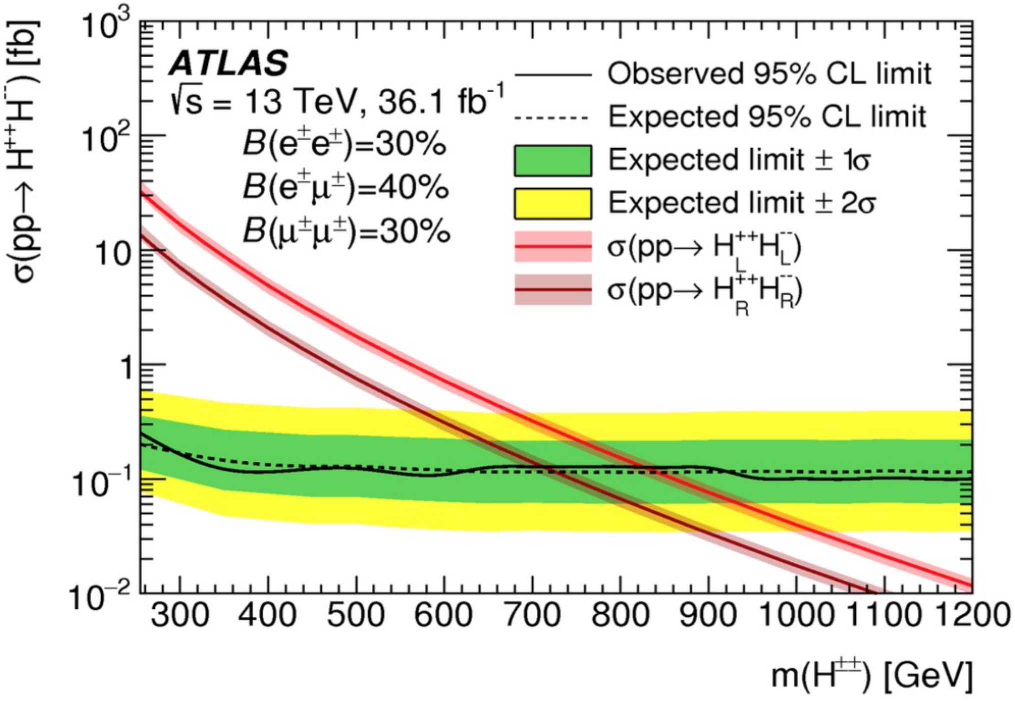
Exotic Higgs Bosons: Searches for $H^{\pm\pm}$

- $H^{\pm\pm}$ appear in Higgs triplet models addressing neutrino mass hierarchy
  - ➔ type-II see-saw models
  - ➔ left-right symmetric (LRS) models etc



- in many models the mass-coupling relation doesn't hold for $H^{\pm\pm}$
  - ➔ no preference for $\tau^{\pm}\tau^{\pm}$ decays
  - ➔ decays to lighter leptons also provide high sensitivity

$$H^{\pm\pm} \to \mathrm{e}^{\pm}\mathrm{e}^{\pm}, \mu^{\pm}\mu^{\pm}, \mathrm{e}^{\pm}\mu^{\pm}$$

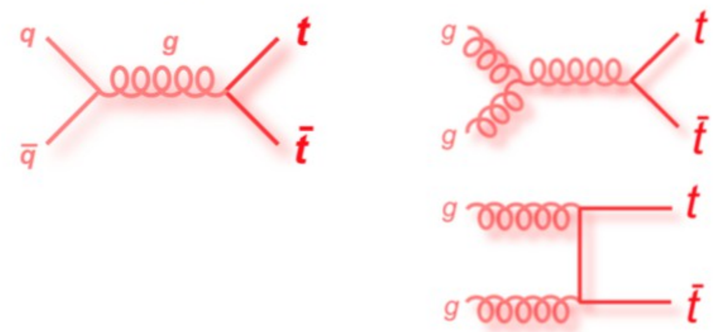


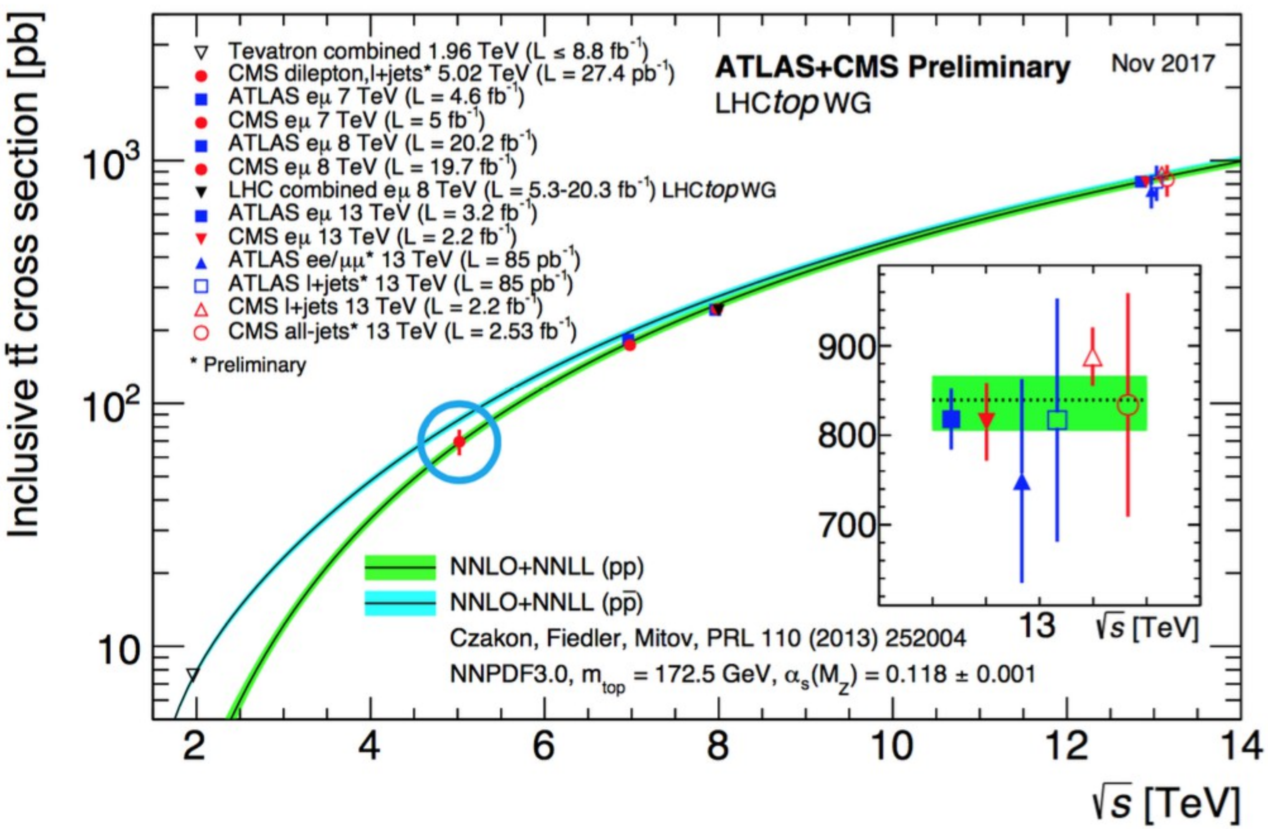
- subject of recent ATLAS analysis

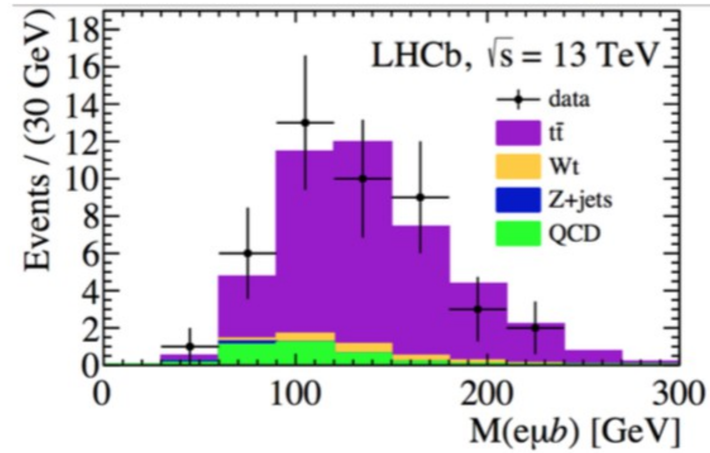
Top Quark

Top quark physics continues to be an important focus @ Tevatron and LHC

- Complementary measurements:
  - ~85% qq at Tevatron and >85% gg at LHC







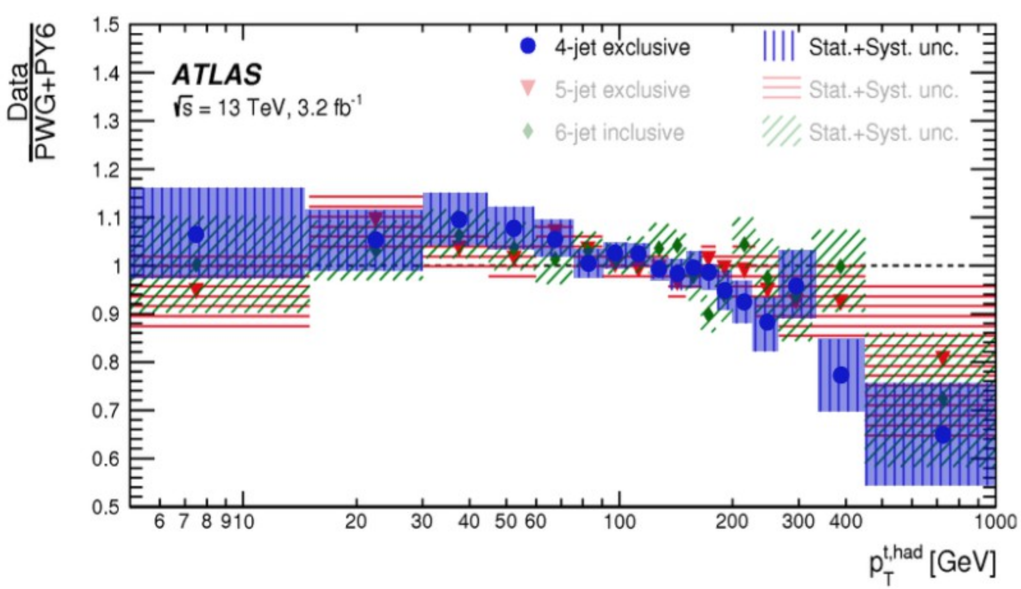
Precision top physics @ LHCb soon

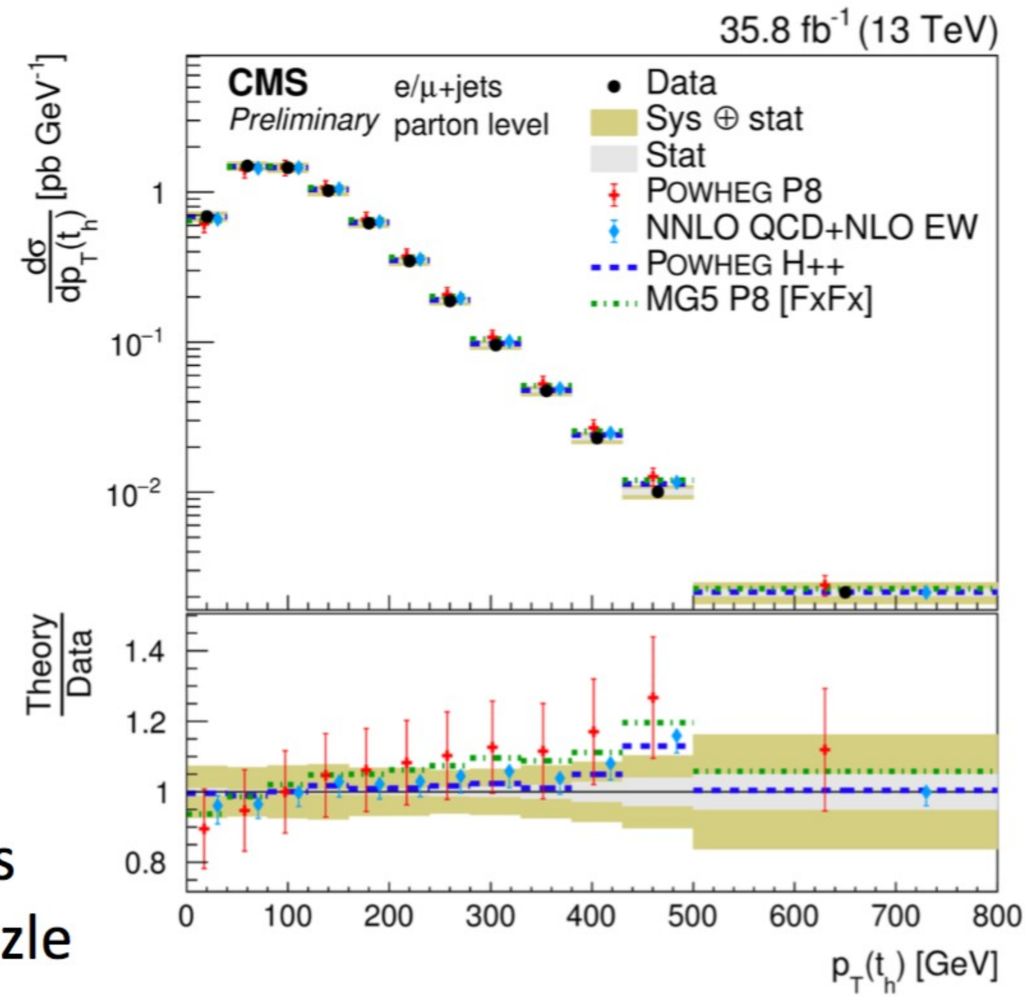
Forward region interesting for PDF constraints, charge asymmetries, ... less dilution, more quark-initiated prod.

Inclusive cross section well understood and agrees with NNLO predictions

Top production and properties

- Understanding the discrepancy in modelling of the top and ttbar system (e.g. in top p_T) continues to be a challenge
- Data softer at higher top quark transverse momentum than prediction:
  - Missing higher orders in pQCD: for production and/or decay ?
  - EW corrections ?
  - New physics…?



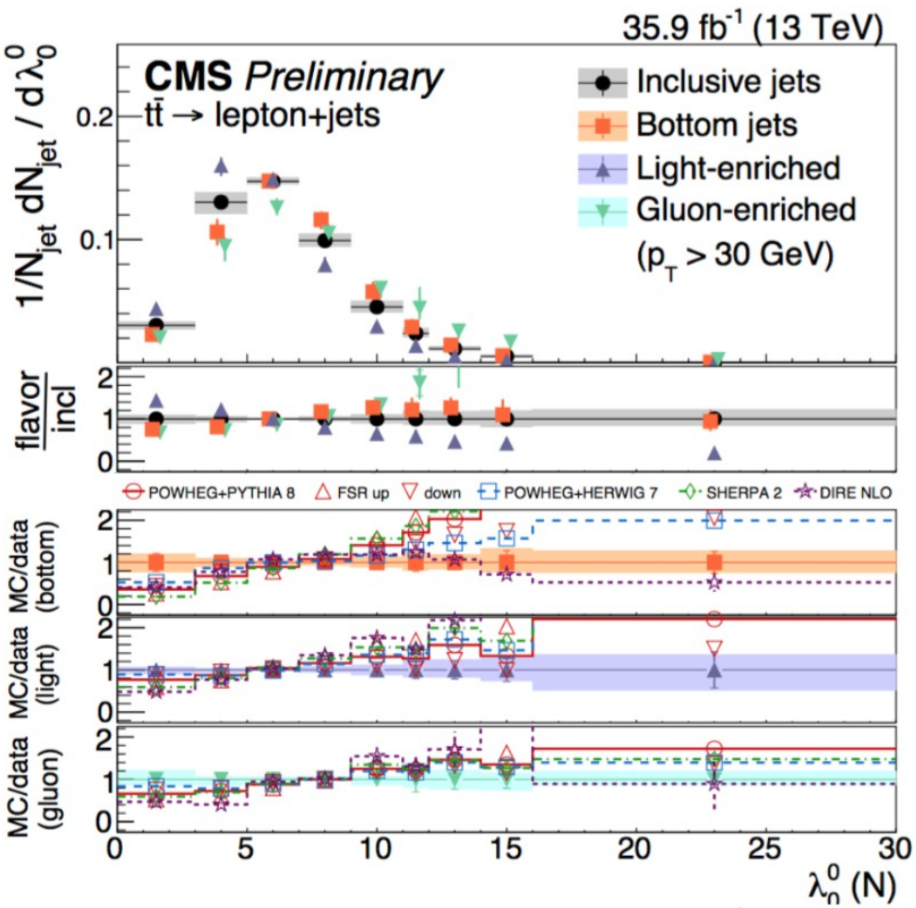


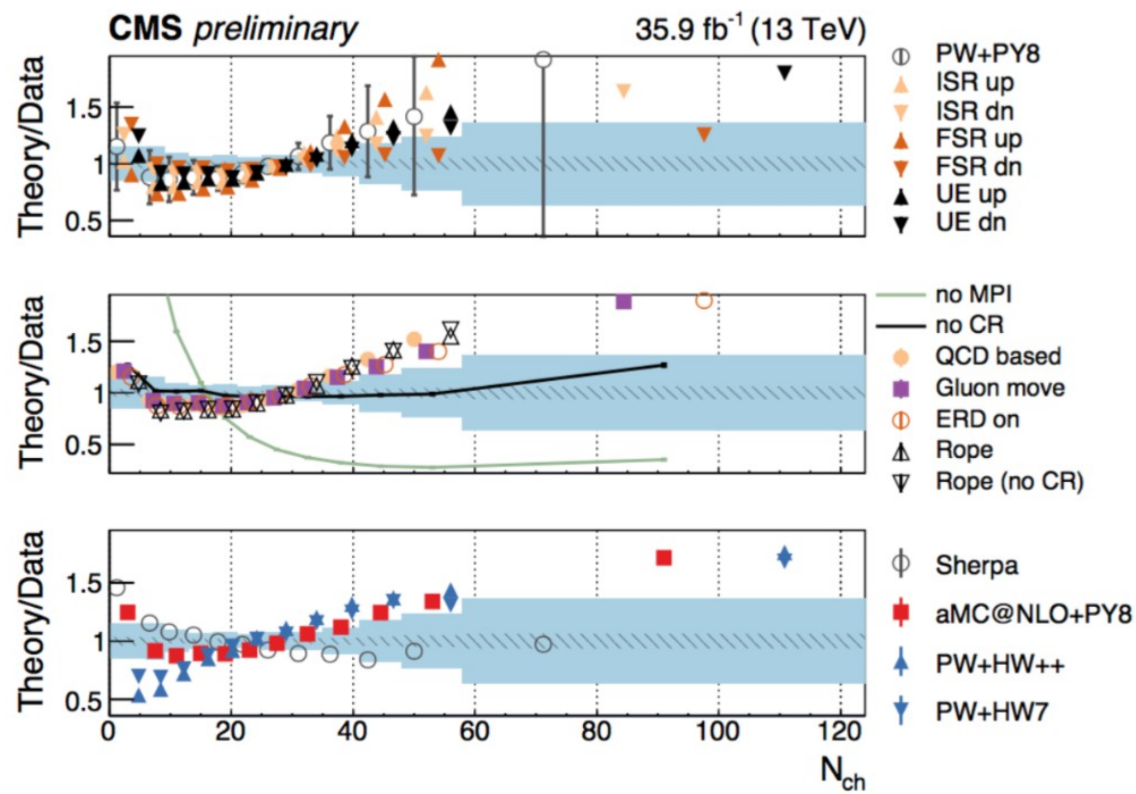
- (Double) differential measurements may provide the answer to this puzzle

Top production and properties

Jet substructure observables
in ttbar events

Underlying event
in ttbar events



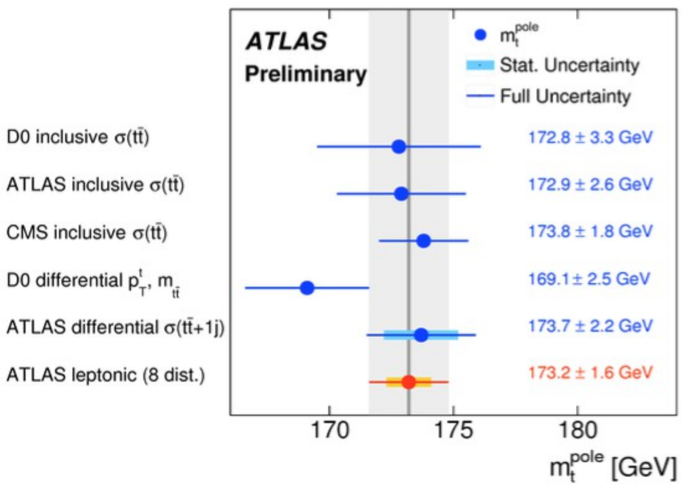


Sensitive to modeling in MC

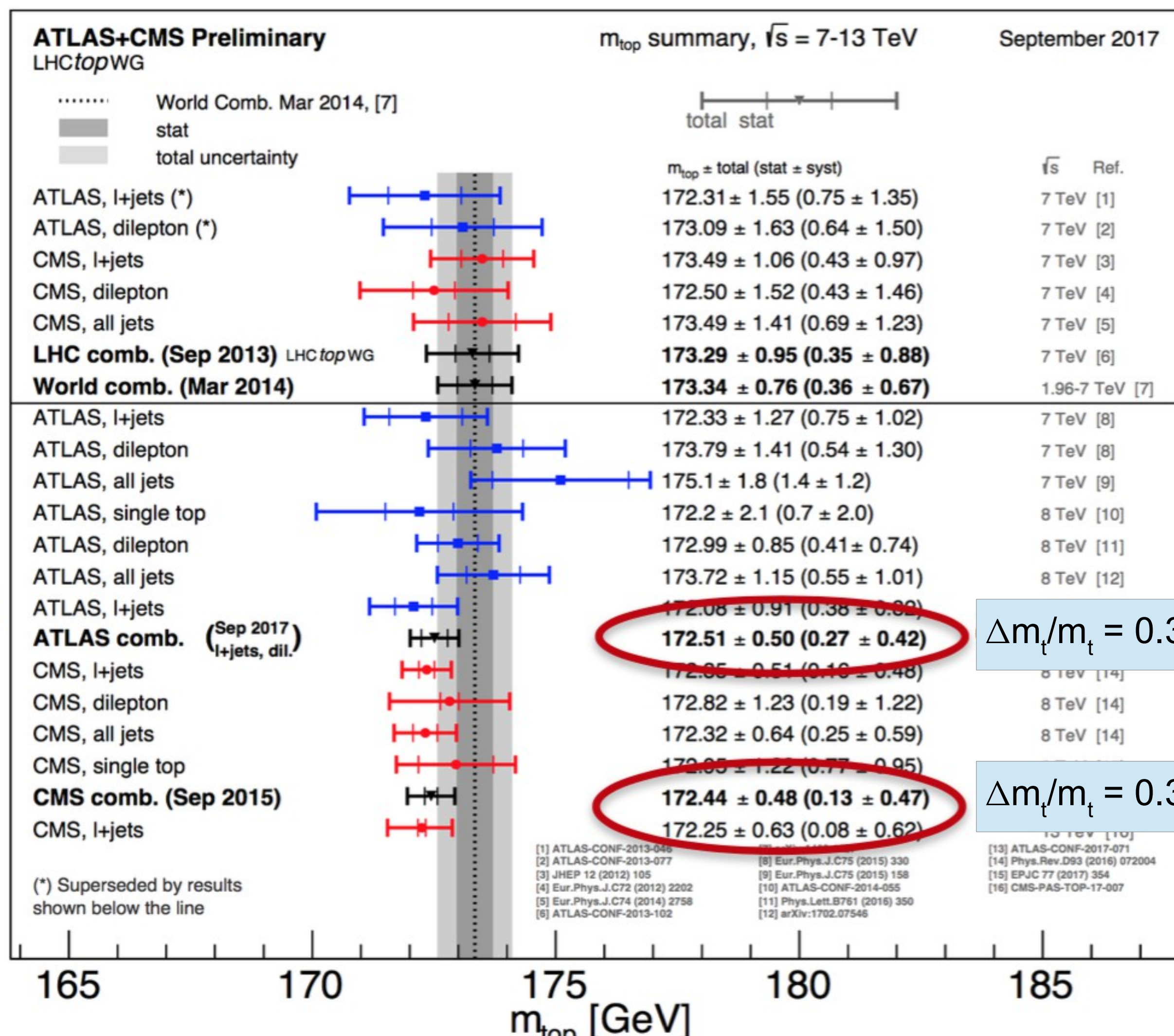
Crucial for understanding soft physics;
can have significant effects on
precision measurements (e.g. mass)

Top mass

- Diverse set of top mass measurements in different channels
  - Direct methods e.g. templates, matrix method, ideogram
  - Indirect methods e.g. extraction based on cross section



ATLAS: 0.9%; CMS precision at 1%
With ~5% theory uncertainty and ~2% exp → can reach 0.5% on pole mass)



$\Delta m_t/m_t$ = 0.3%

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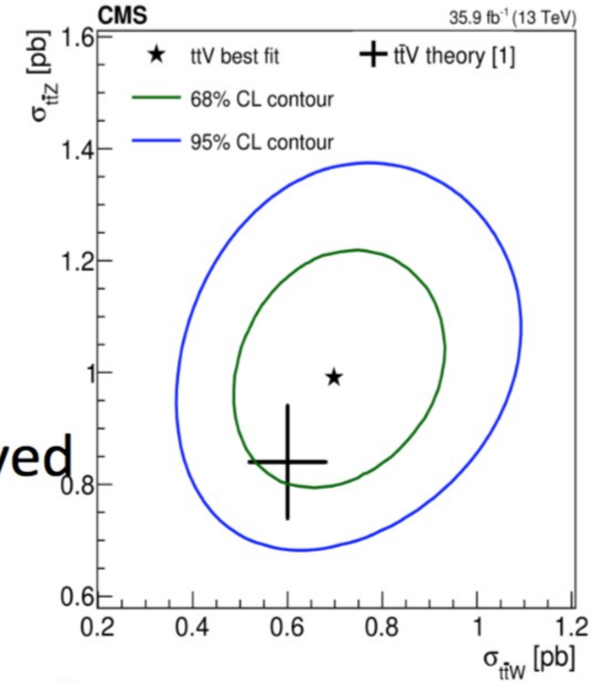
Tevatron top mass:

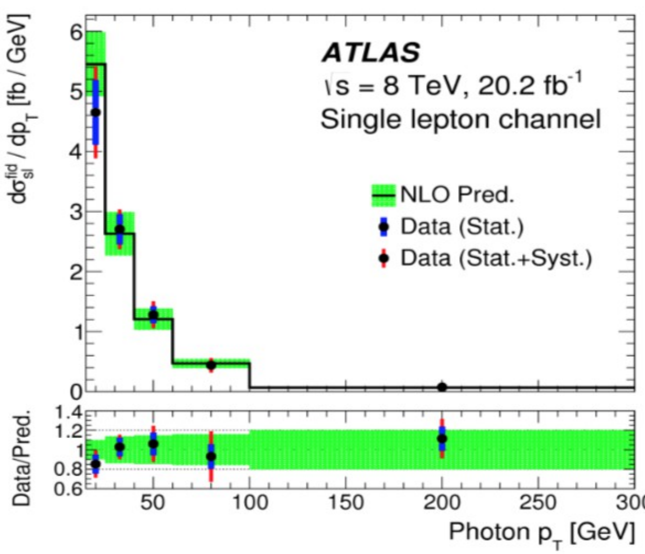
m_t = 174.30 ± 0.35 (stat) ± 0.54 (syst) GeV

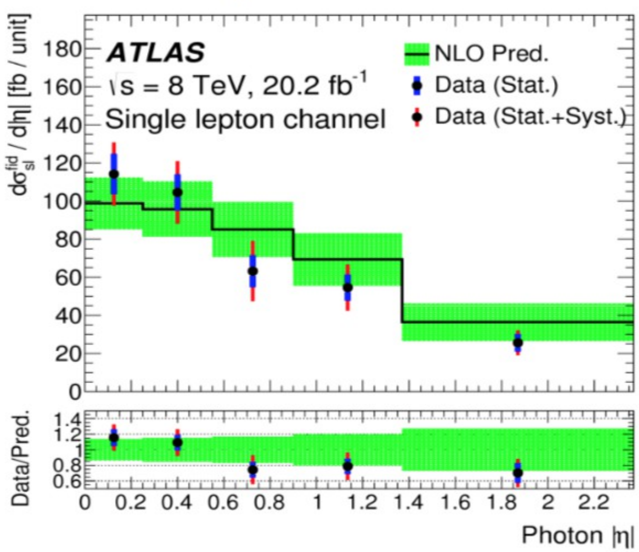
$\delta m_t/m_t = 0.37\%$

$t\bar{t}X$ production

- ttZ and ttW cross-sections measurements reach interesting precision
  - Both ttW and ttZ observed > 5σ
  - CMS dominated by object-related uncertainties, ATLAS by statistical uncertainty
- tttt cross-section measured and constraints on y_t derived (CMS)
- Measurement of ttγ fiducial cross-section and first differential cross-section measurements for photon p_T , η







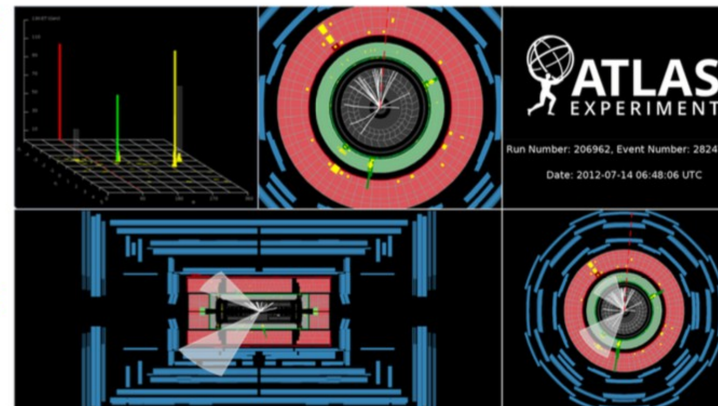
Multibosons at ATLAS and CMS

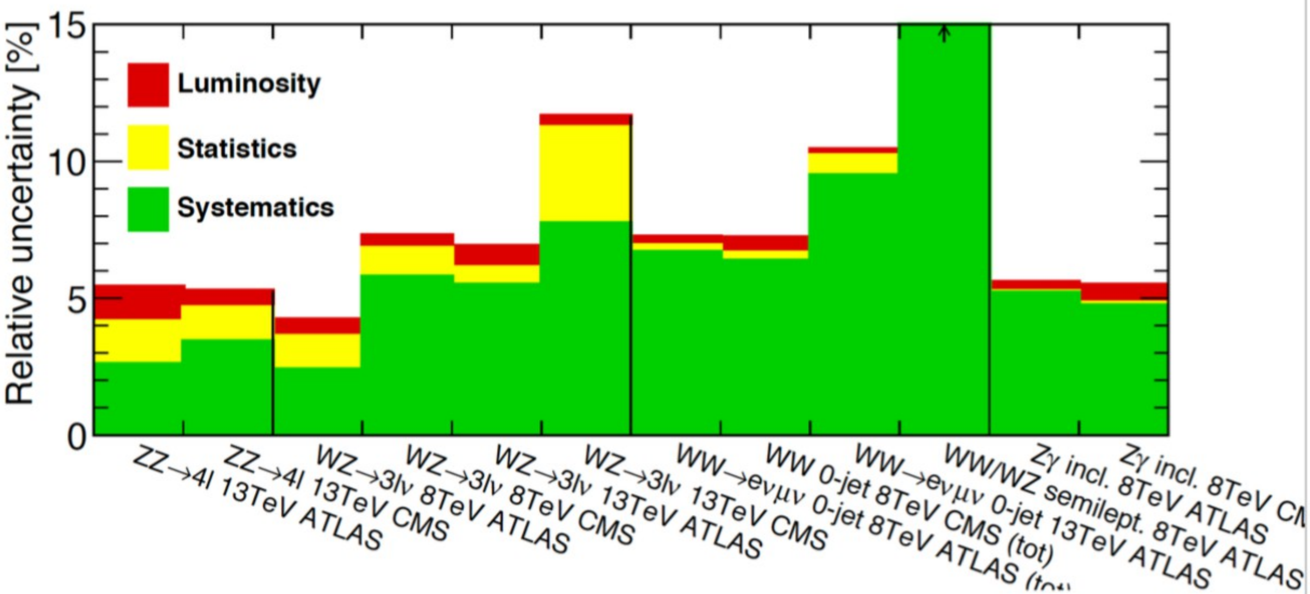
Diboson measurements are pushing for more precise theoretical calculations (NNLO or 3NLO QCD, NLO EWK, ...)

- Uncertainties on total cross section measurements are approaching lumi uncertainty
- Uncertainties on differential measurements still dominated by statistics
- Can mitigate lumi, theory uncertainties with ratios

Triboson aQGC

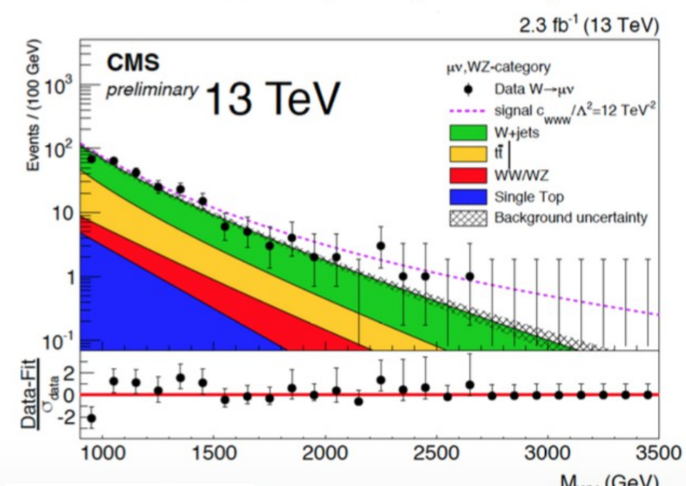
$WV\gamma \to e\nu jj\gamma$ candidate event





stack of uncertainties in quadrature: syst, $\sqrt{\text{syst}^2 + \text{stat}^2}$, ..

Significant increase of sensitivity for indirect search for NP (aTGC)



Hadron Spectroscopy at LHCb

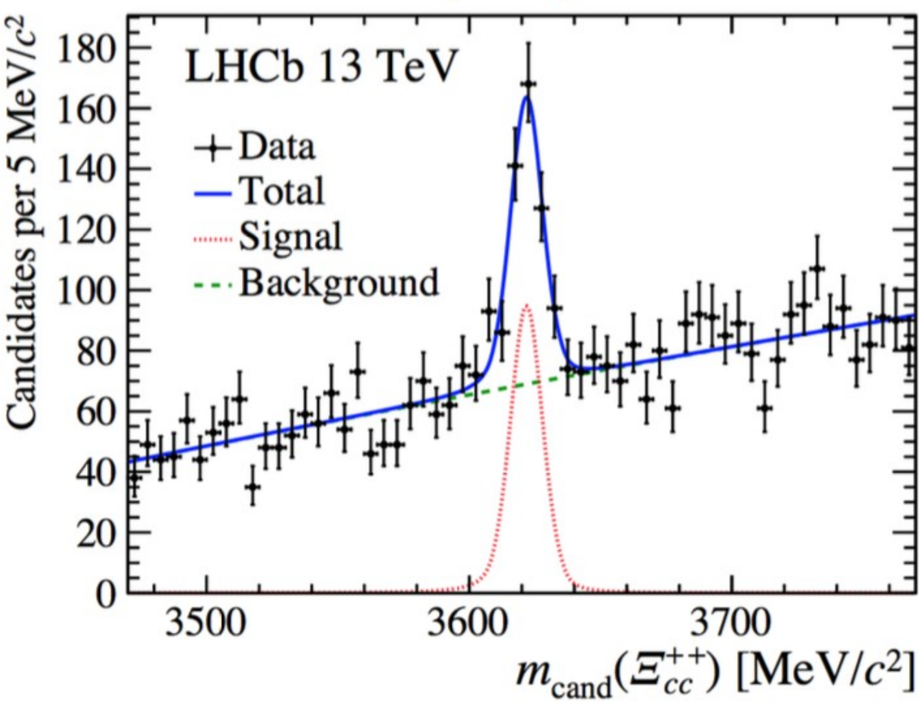
Significant (12σ) signal in 13 TeV and 8 TeV data sets (7σ)

$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst}) \pm 0.14\,(\Lambda_c^+)\ \text{MeV}/c^2$

Mass difference with the SELEX measurement (Δm = 103 MeV/c²) is too large to be an isospin partner

PRD 78 073013 PLB 698 251-255 PRD 96 033004

PRL 119 (2017) 112001

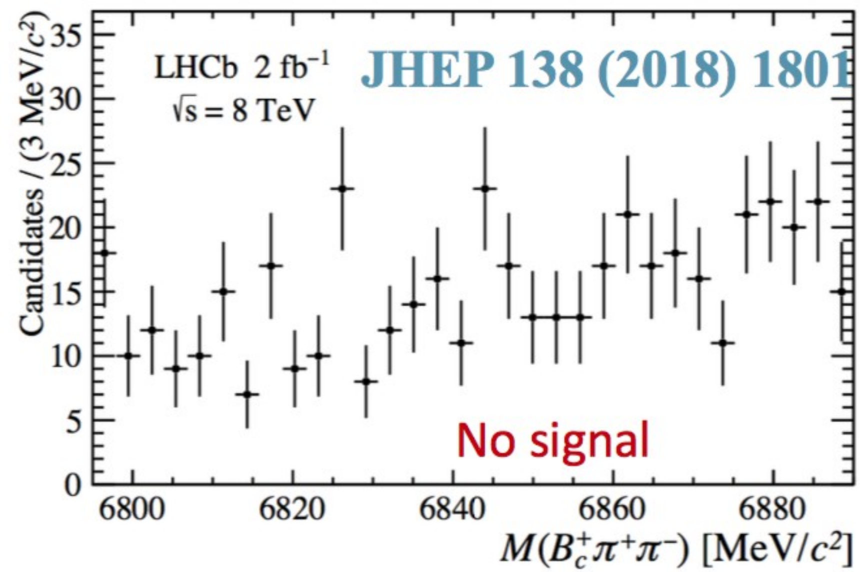


Search for excited $B_c(2S)^+$ states:

$$B_c(2S)^+ \to B_c^+\pi^+\pi^-$$

$$B_c(2S)^{*+} \to B_c^{*+}(\to B_c^+\gamma)\pi^+\pi^-$$

*not reconstructing the photon



Observation reported by ATLAS

m=6842±4(stat)±5(syst) MeV/c²

PRL 113 (2014) 212004

To be followed up…
does CMS see it ?

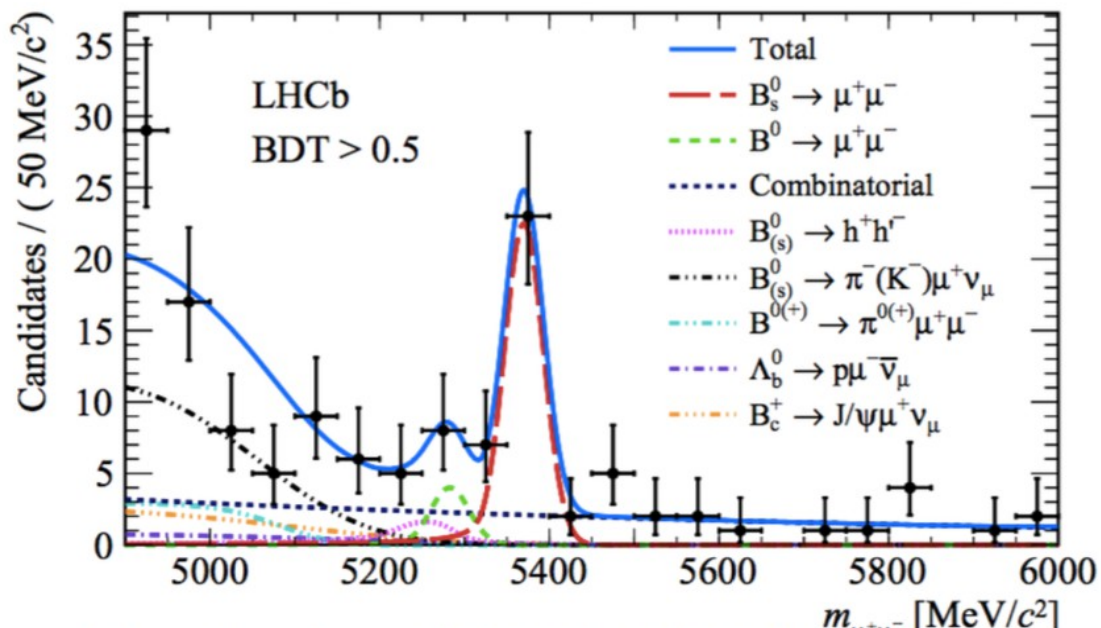
Search for new physics in rare decays

- Search both for small deviations in precisely predicted SM processes and for forbidden processes that can only occur through new physics
- New particles can appear at loop or tree level
- Flavor-changing neutral current (FCNC) processes
  - heavily suppressed → NP can appear at a similar or larger level as SM contributions

$B_s \rightarrow \mu^+\mu^-$: First single experiment observation (7.8σ)

(previously achieved w/ LHCb+CMS combination)

Results consistent with SM predictions, set stringent limits on possible NP models



[Phys. Rev. Lett. 118, 191801 (2017)]

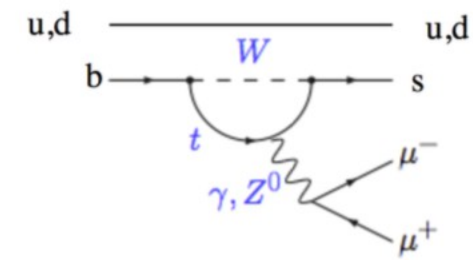
Lepton universality in $b \to s\, \ell^+\ell^-$

The tension wrt to SM observed in muon final states

If the effect is real, does it appear only for muons or is it universal for all leptons ?

Test in ratios of semi-leptonic decays

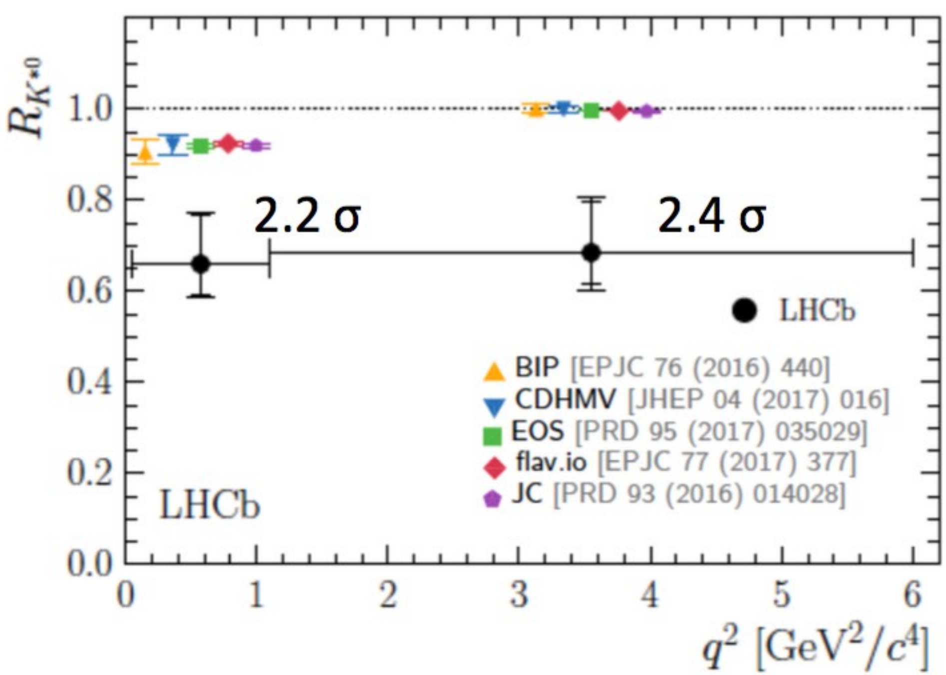
muons / electrons [$b \to s$]

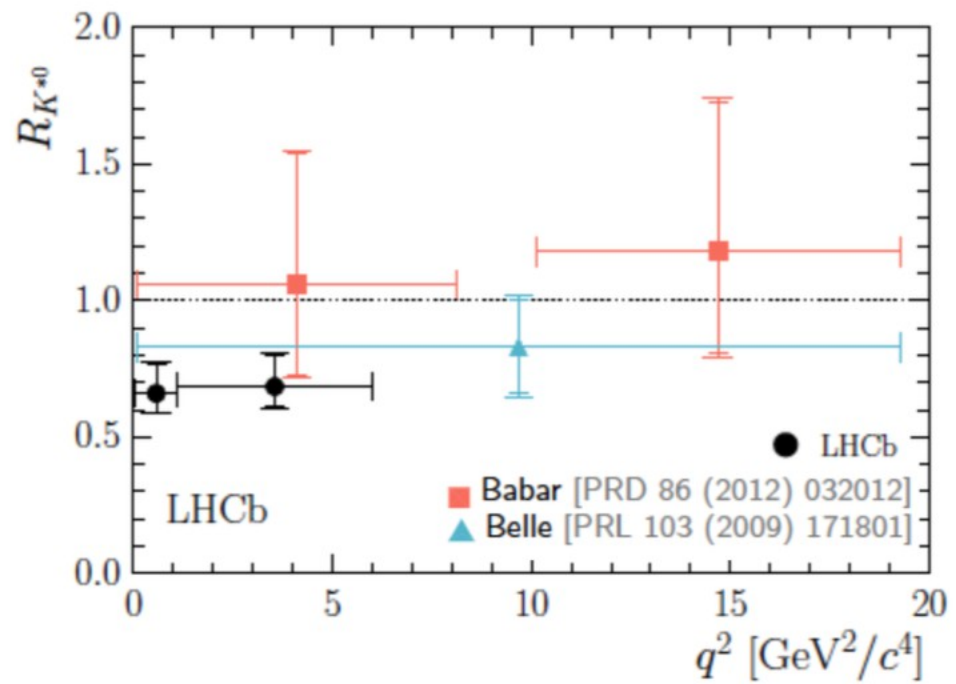


$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)}$$

Analogously: R_{K^*}

LHCb, 3fb-1 [JHEP 08 (2017) 055]

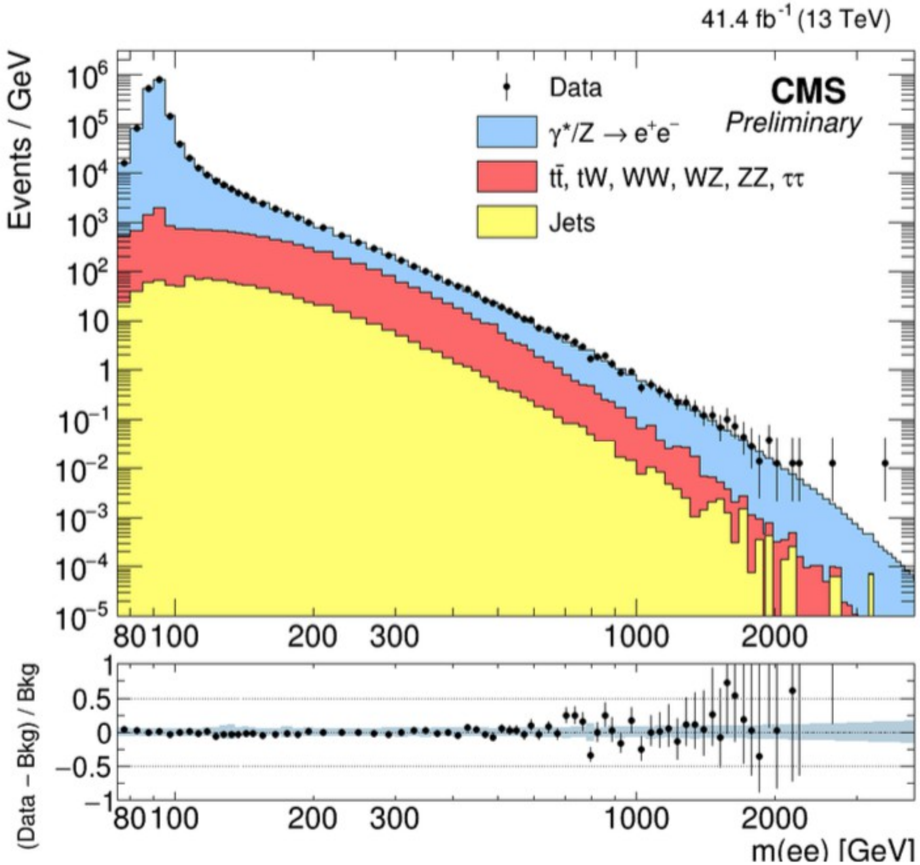


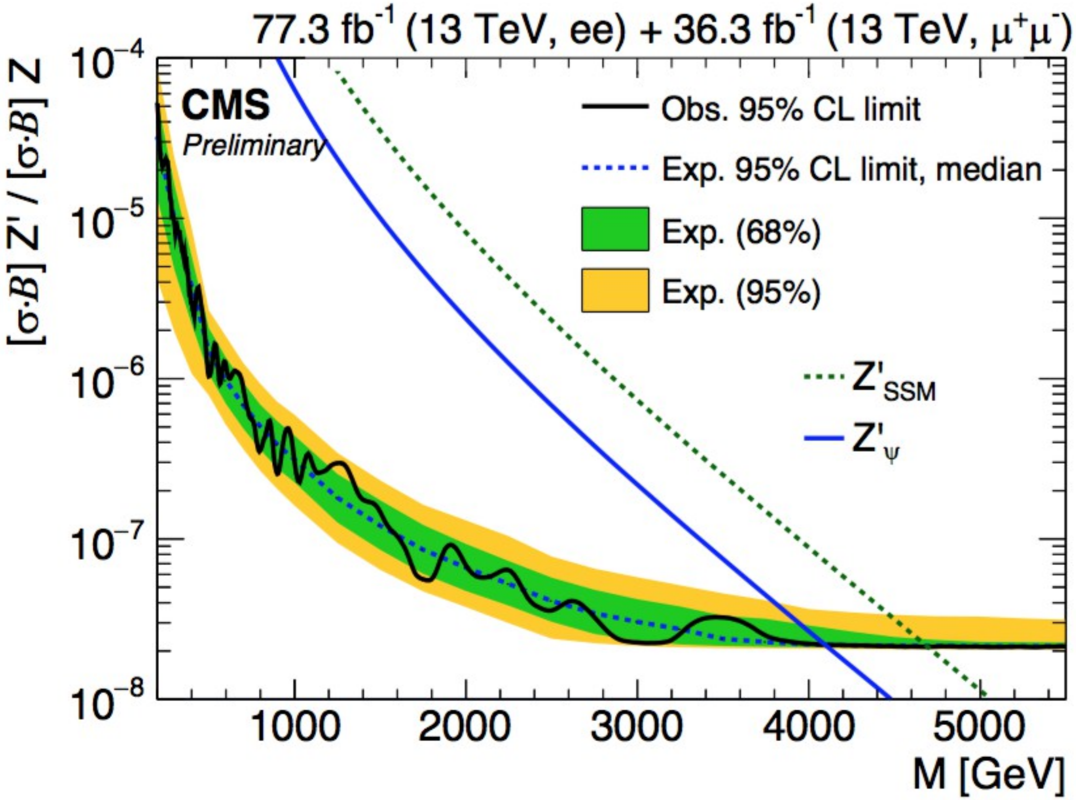


Searches for di-lepton resonances

High mass searches now using > 100 fb^{-1} , limits extending beyond 4 TeV!

Uses 2017 data!





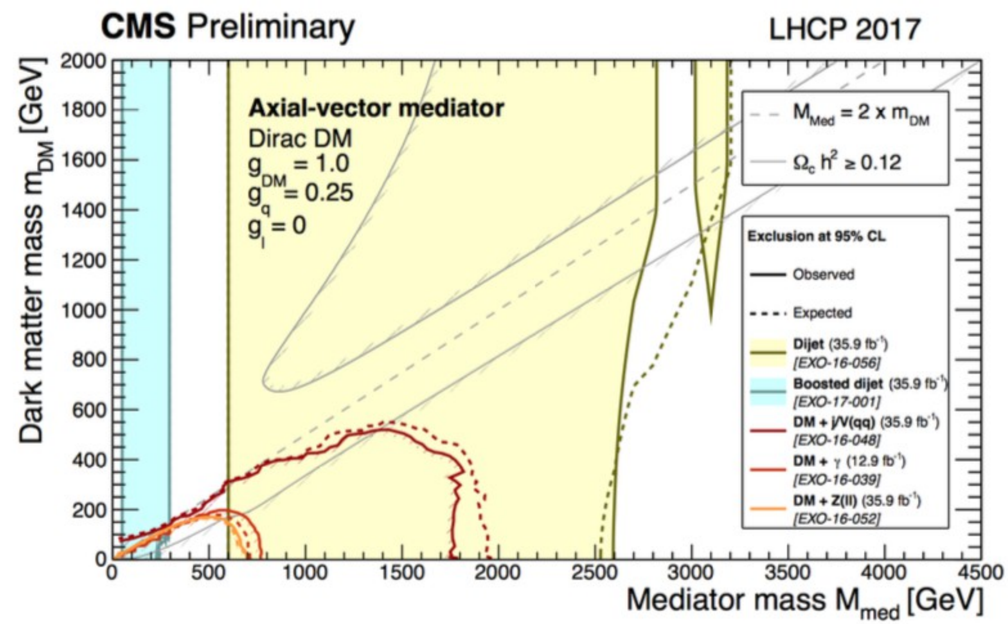
Channel	Model	Obs. limit (TeV)	Exp. limit (TeV)
ee (2017)	Z'_{SSM}	4.10	4.15
	Z'_{ψ}	3.35	3.55
ee (2016 and 2017) + $\mu\mu$ (2016)	Z'_{SSM}	4.7	4.7
	Z'_{ψ}	4.1	4.1

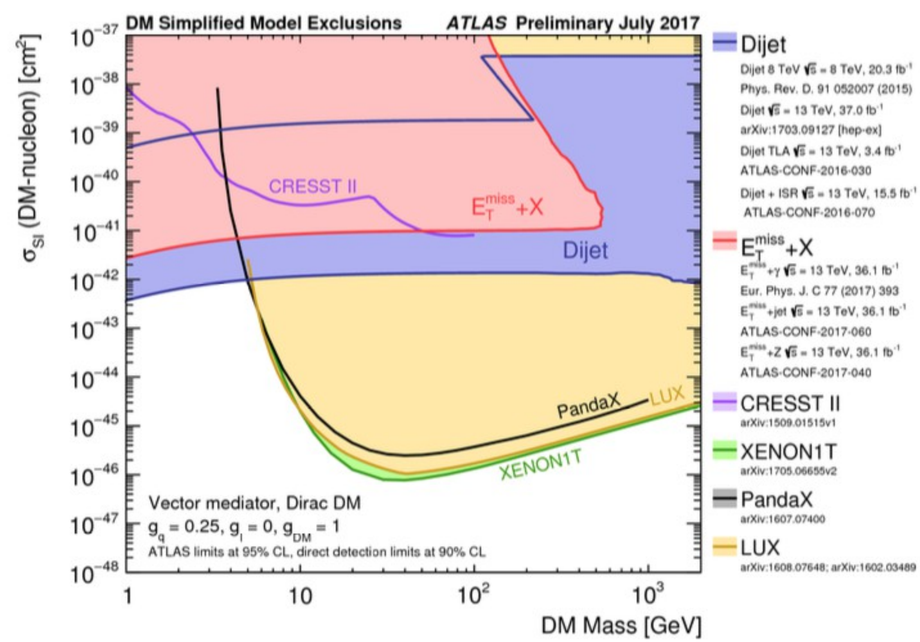
Searches for dark matter

- Dark Matter (DM) searches @ LHC remain a thriving field of research
- A large number of mono-X searches have been performed by ATLAS and CMS, already probing a large part of the parameter space
- No evidence for BSM physics so far but significant progress in exploring a variety of final states
  - incl. searches where Higgs mixes with new dark mediators

CMS-PAS-EXO-16-055 **PRL 119, 181804**

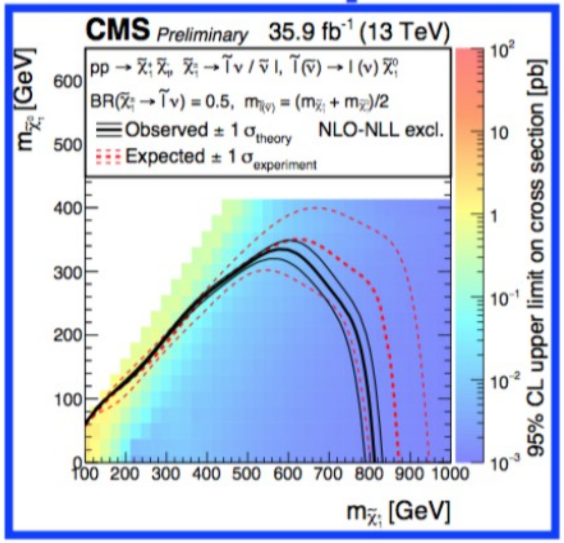
- LHC searches complementary to direct searches, providing improved sensitivity to low DM masses





Searches for EWK SUSY

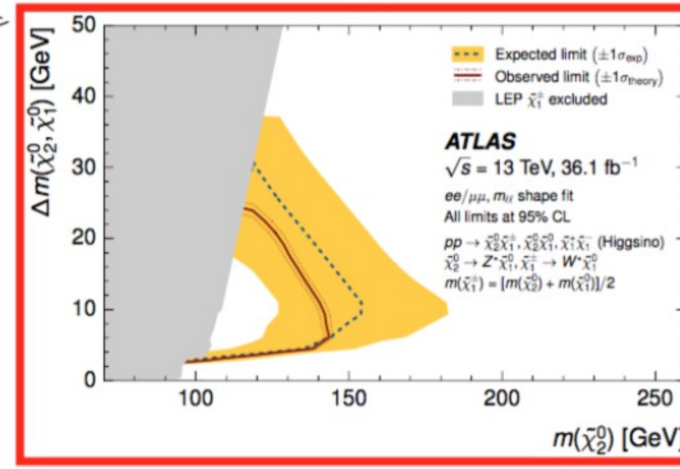
Di/multileptons



Standard signatures well covered

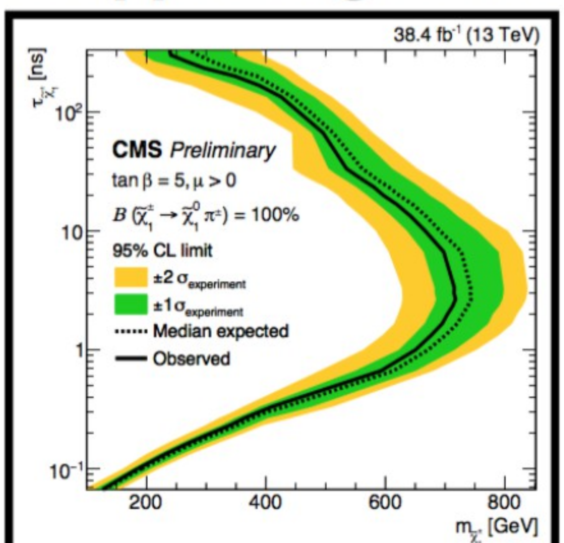
Stau still hiding

Soft leptons



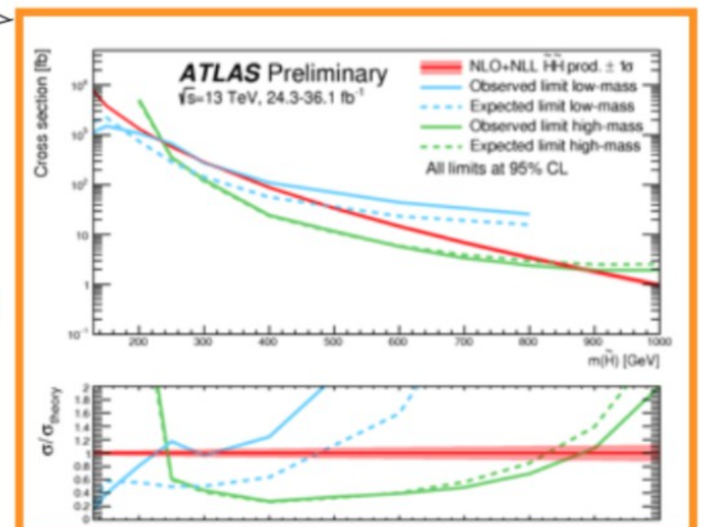
Degenerate spectra demanding for e/μ reconstruction/ID…

Disappearing tracks



… or require unconventional analyses

Hadronic searches

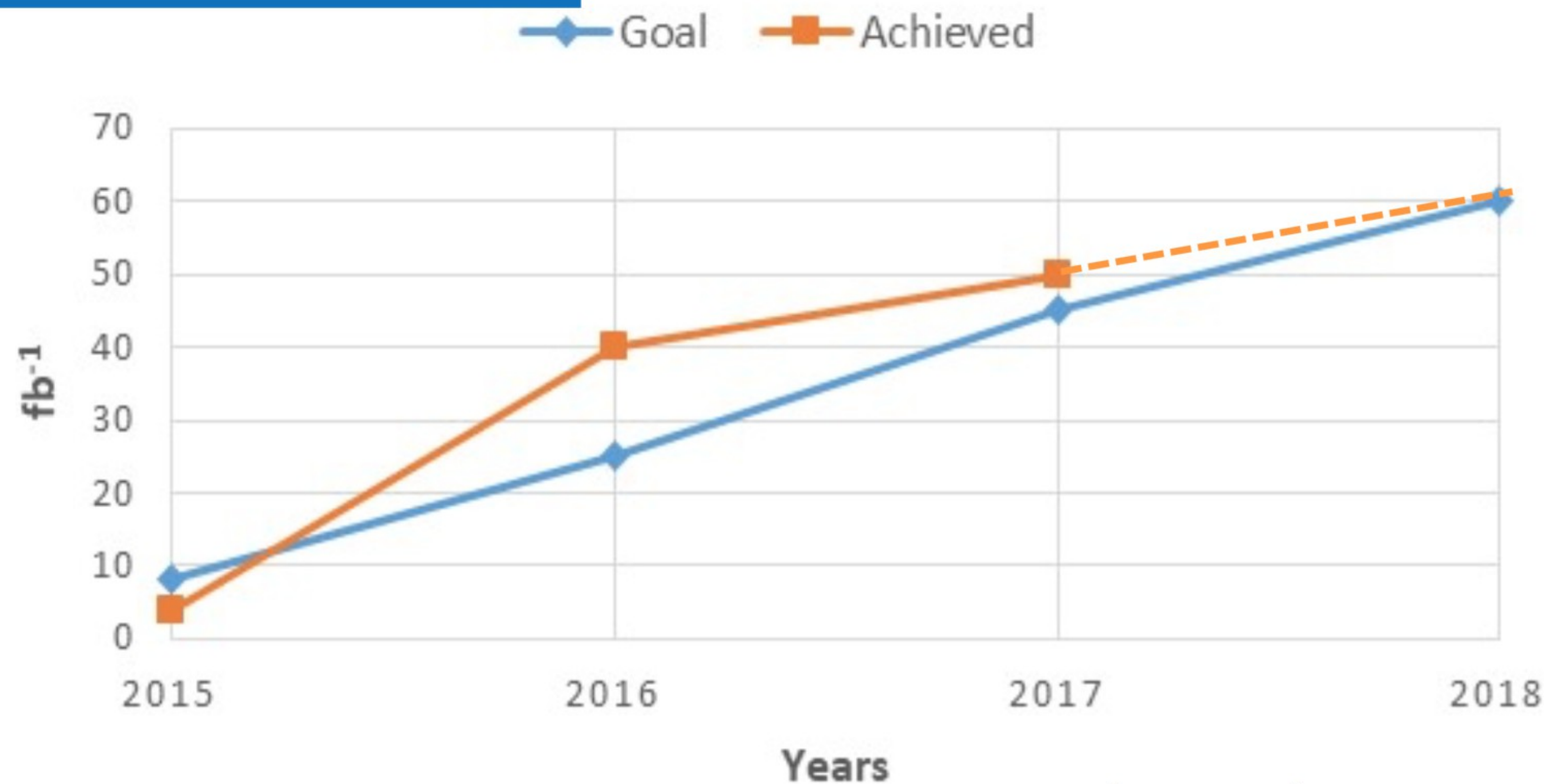


First sensitivity to Higgsinos aided by non-leptonic signatures

Moriond predictions and achievements

RUN 2

Frederick Bordry



LHC 2018

Goal 60 fb^{-1} ATLAS/CMS

2 fb^{-1} for LHCb

with 131 days of p-p physics

55 fb^{-1} and 1.8 fb^{-1} if 119 days

keeping the LHC high availability and >50% stable beams)

Concluding remarks

- Impressive variety of measurements and searches challenging SM, are being performed at ongoing experiments
- SM continue to withstand experimental tests
- No compelling signs of new phenomena in experimental data so far
- Perhaps we may have not see apparent signal of new physics yet, implying that we have to be cleverer and leave no stone unturn
  - develop and implement new ideas
  - Go in directions where no one has gone before