LHC Frontier

Qiang Li

Peking University, Beijing, China

2018. 05. 18

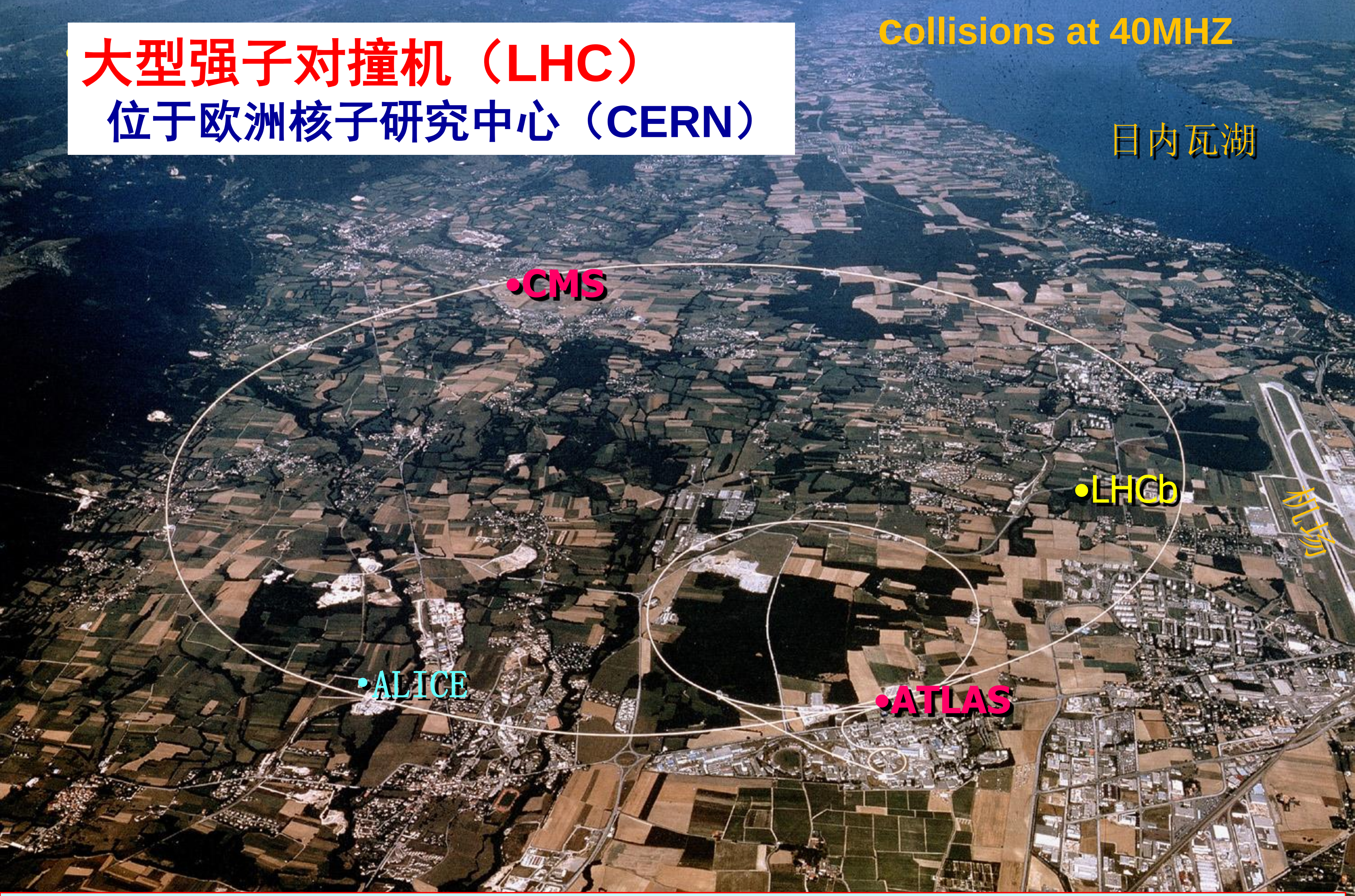
Based largely on Moriond EW2018 and slides from Josh McFayden, D'Alfonso and Efe Yazgan

PHEP2018: School for future colliders

A Brief History

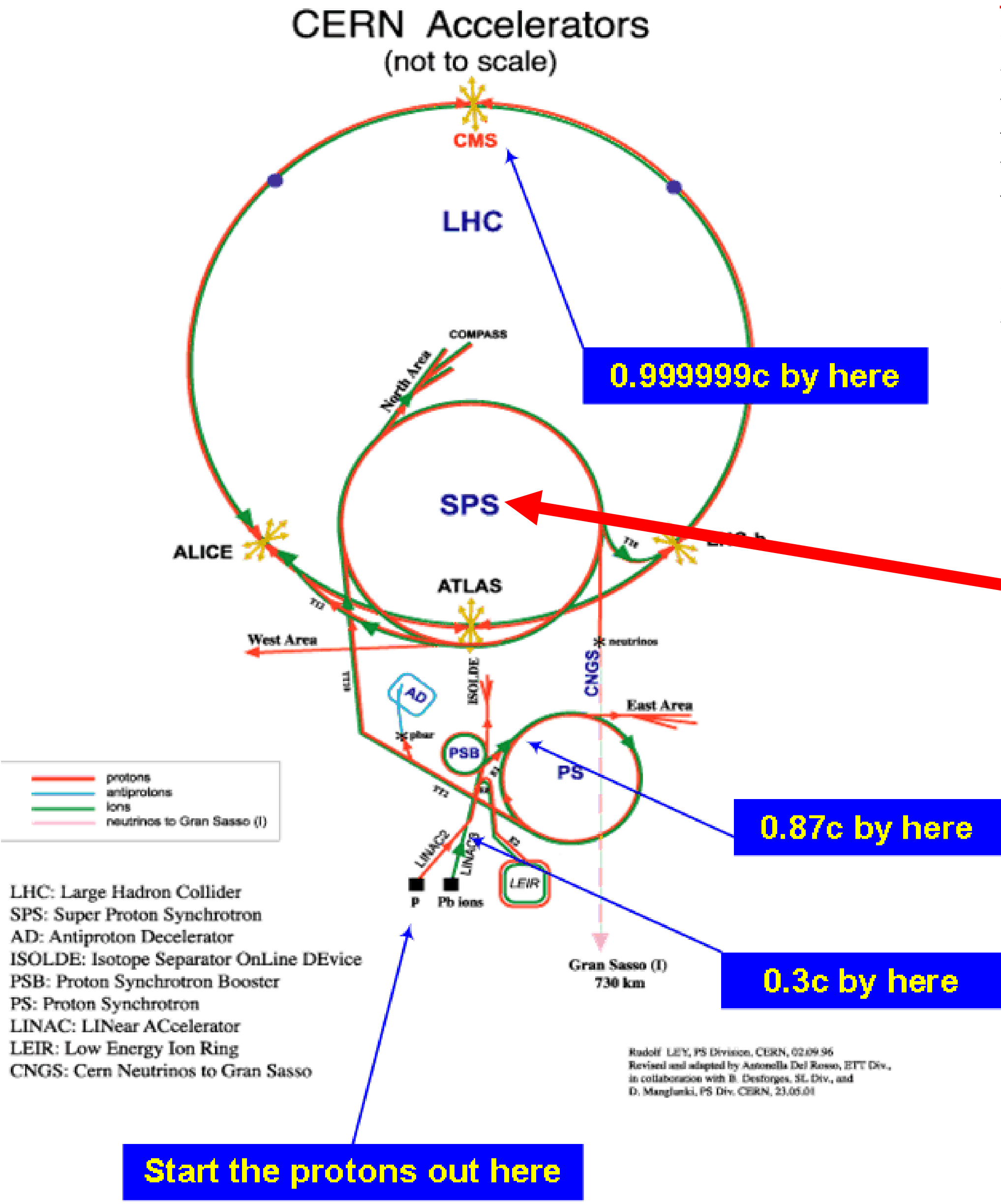
大型强子对撞机（LHC）

位于欧洲核子研究中心（CERN）



- 周长27km，跨越瑞士法国国境，总投资40亿美元
- 世界能量最高最大的加速器，质心系能量-〉7,8,13/14TeV($14x10^{12}$eV)

$$P[GeV/c] = 0.3 \times q[e] \times B[Tesla] \times r[m]$$



Energies:

Linac 50 MeV
PSB 1.4 GeV
PS 28 GeV
SPS 450 GeV
LHC 3.5 TeV
4.0 TeV
6.5 TeV

The Nobel Prize in Physics 1984

Carlo Rubbia
Prize share: 1/2

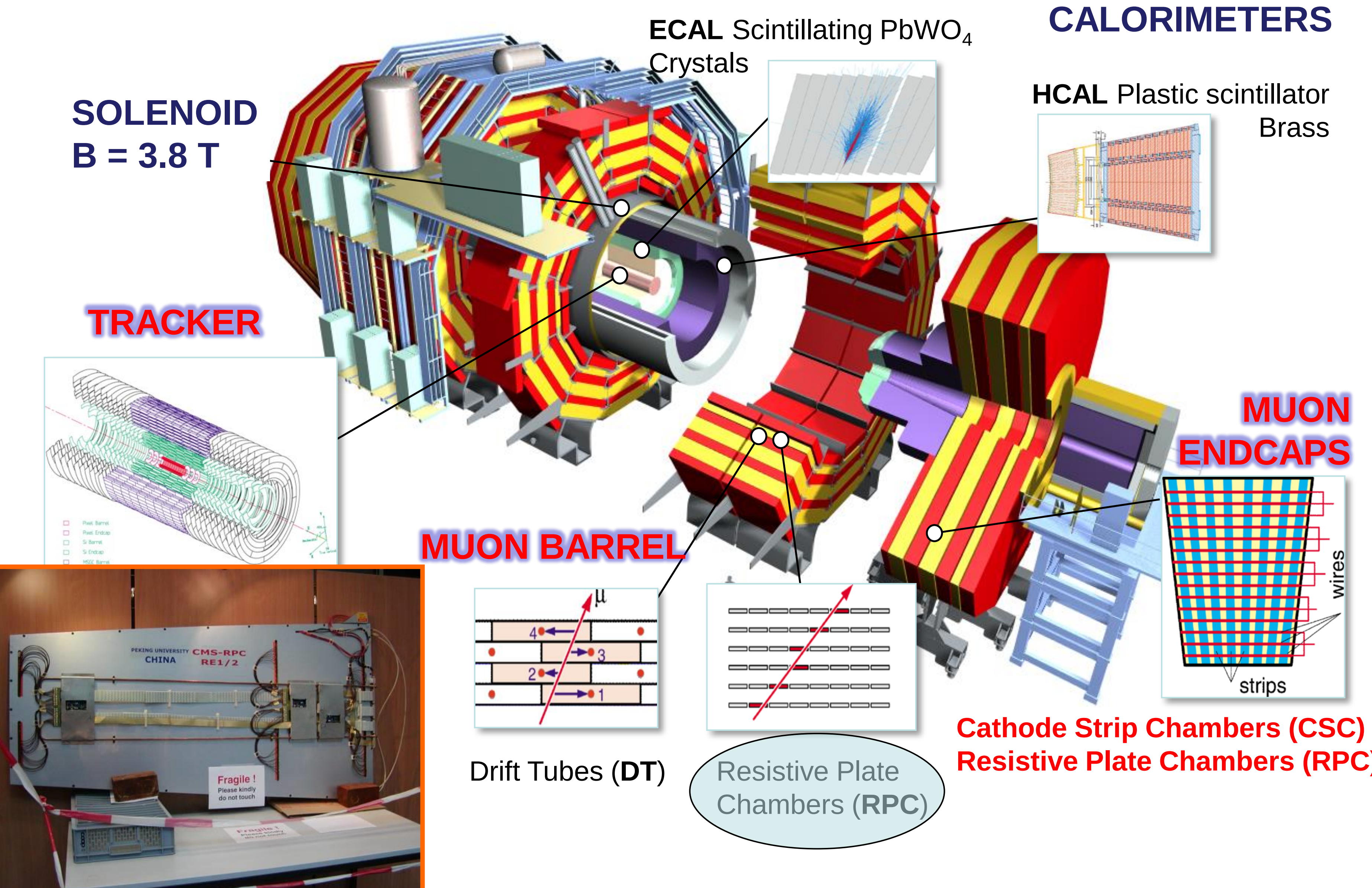
Simon van der Meer
Prize share: 1/2

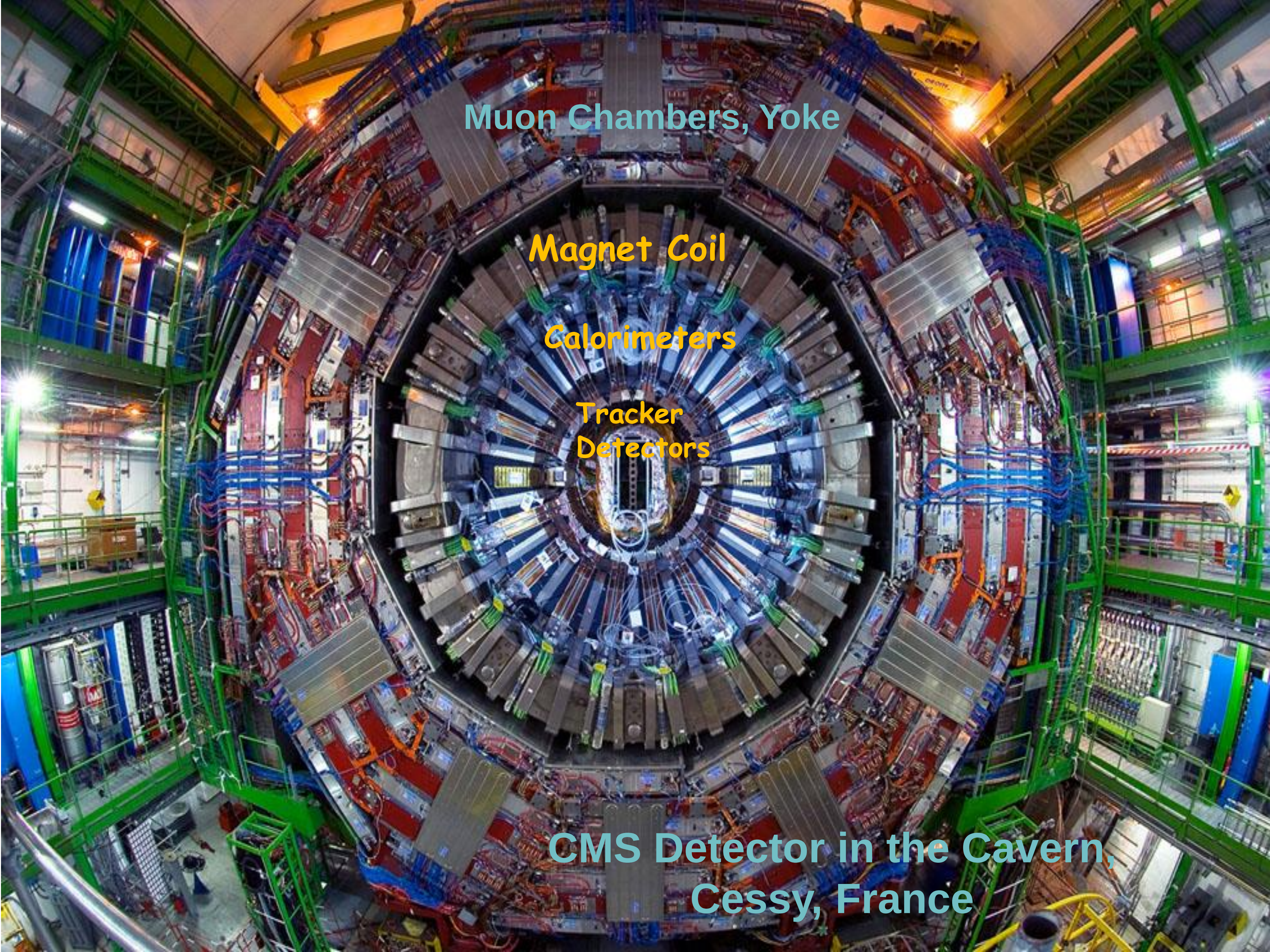
The Nobel Prize in Physics 1984 was awarded jointly to Carlo Rubbia and Simon van der Meer *"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"*

1983 UA1 Experiment W/Z boson discoveries

weight: 12500 t
overall diameter: 15 m
overall length: 21.6 m

CMS Detector




Muon Chambers, Yoke
Magnet Coil
Calorimeters
Tracker
Detectors
CMS Detector in the Cavern,
Cessy, France

With the Help of the Worldwide LHC Computing Grid

The Worldwide LHC Computing Grid combines the computing resources of more than 100,000 processors from over 170 computing centers in 36 countries, producing a massive distributed computing infrastructure that provides more than 8000 physicists around the world with near real-time access to LHC data, and the power to process it.

~170 computing Centers

~36 countries

~250K cores

~100 million gigabytes of disk

(10 million DVDs)

Lessons learned in managing, securing and linking up on this global scale have driven innovation in computing grids all over the world. Grids are being used in the fight against disease, climate change, air pollution, etc.

CMS COLLABORATION RRB CMS-D 98-31

The European Organization for Nuclear Research (CERN)
and
Chinese Academy of Sciences (CAS), Beijing
and
The National Natural Science Foundation of China (NSFC), Beijing
declare that they agree on this Memorandum of Understanding.

For the original version as approved on 27 April 1998 by the CMS Resources Review Board

Done in Geneva, Switzerland on 30 April 1998

For CERN

Lorenzo Foà
Director of Research

For the revisions to the original version
(cf. Annexes 5, 6, 8 A, 9.3 A, 9.3 B, 9.5 B, and page 4 of Annex 10, as well as Annex 1, page 1 and Annex 4, page 2)

Done in Geneva, Switzerland on 28 April 1999

For CERN

R.J. Cashmore
Director of Research

Done in Geneva, Switzerland
on 28 April 1999

For NSFC

WANG Nai-Yan
Vice-President

Done in Beijing, China
on ____________

For CAS

ZHU Xuan
Secretary-General

29 April 1998 (revised 25 March 1999) Page 9/9 Memorandum of Understanding

中科院高能所、北大 1998-1999加入CMS

Chinese NSFC vice-president WANG Naiyan and CERN research director for collider programs Roger Cashmore sign a new agreement. Peking University president CHEN Jia-er was involved in negotiations

NSFC and CAS signed contract with CERN to join CMS experiments.
Supported well by NSFC, CAS and MOST

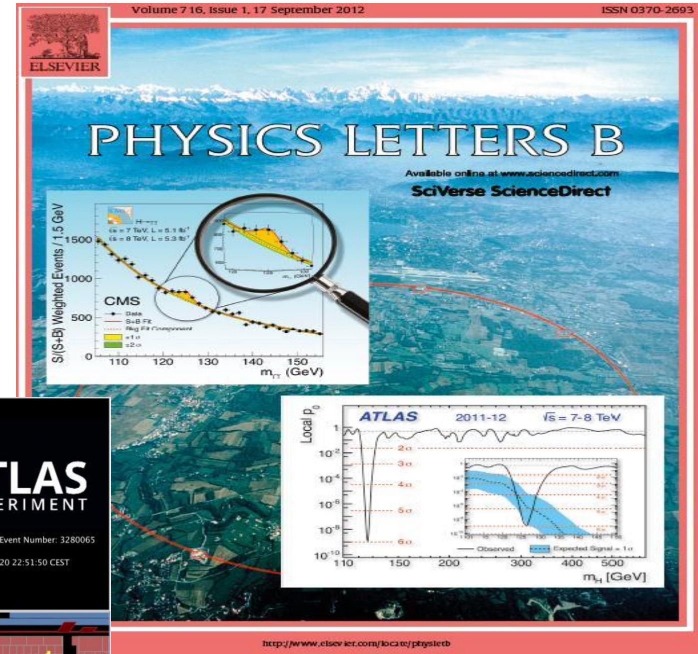
1999-2006: Detector Works
2007-: Data Analysis
2013-2014 : Phase I, II Upgrade

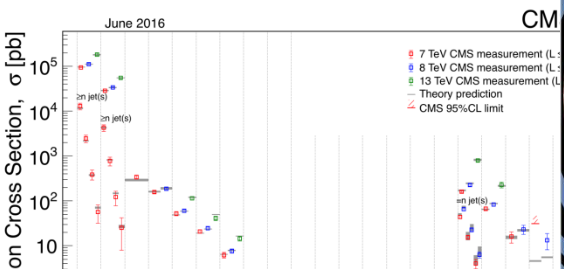
Rich Physics

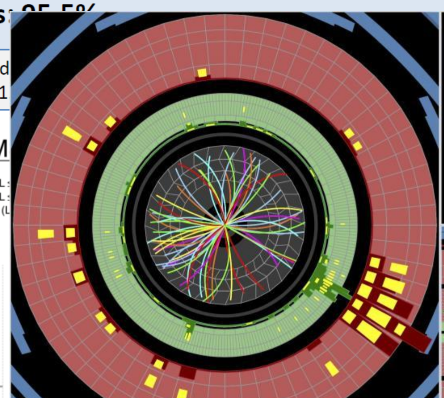
Successful LHC & SM

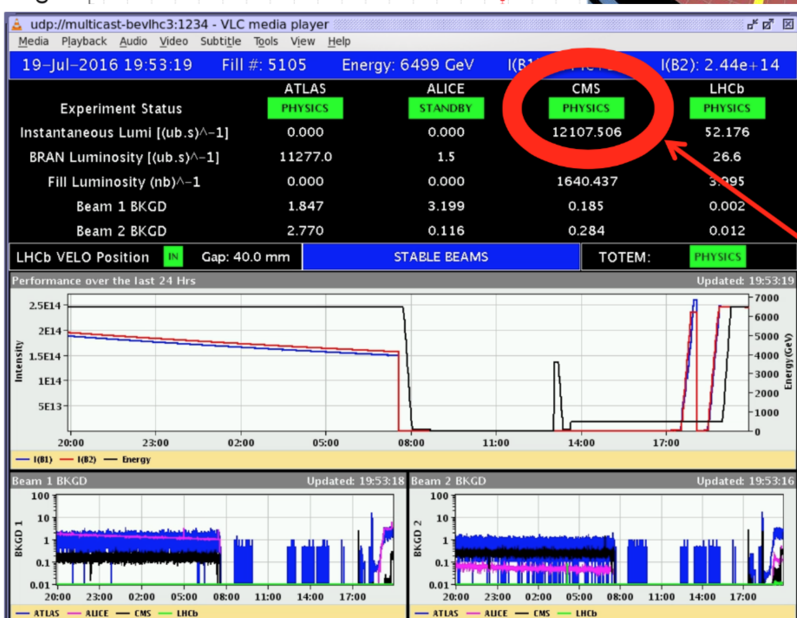
ATLAS p-p run: April-December 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.1	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.5%										

Luminosity weighted relative detector uptime and good quality data d… √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21…









Fill 5105 : (19/7/2016)

Record peak lumi: 1.2 x 10^{34} in CMS !

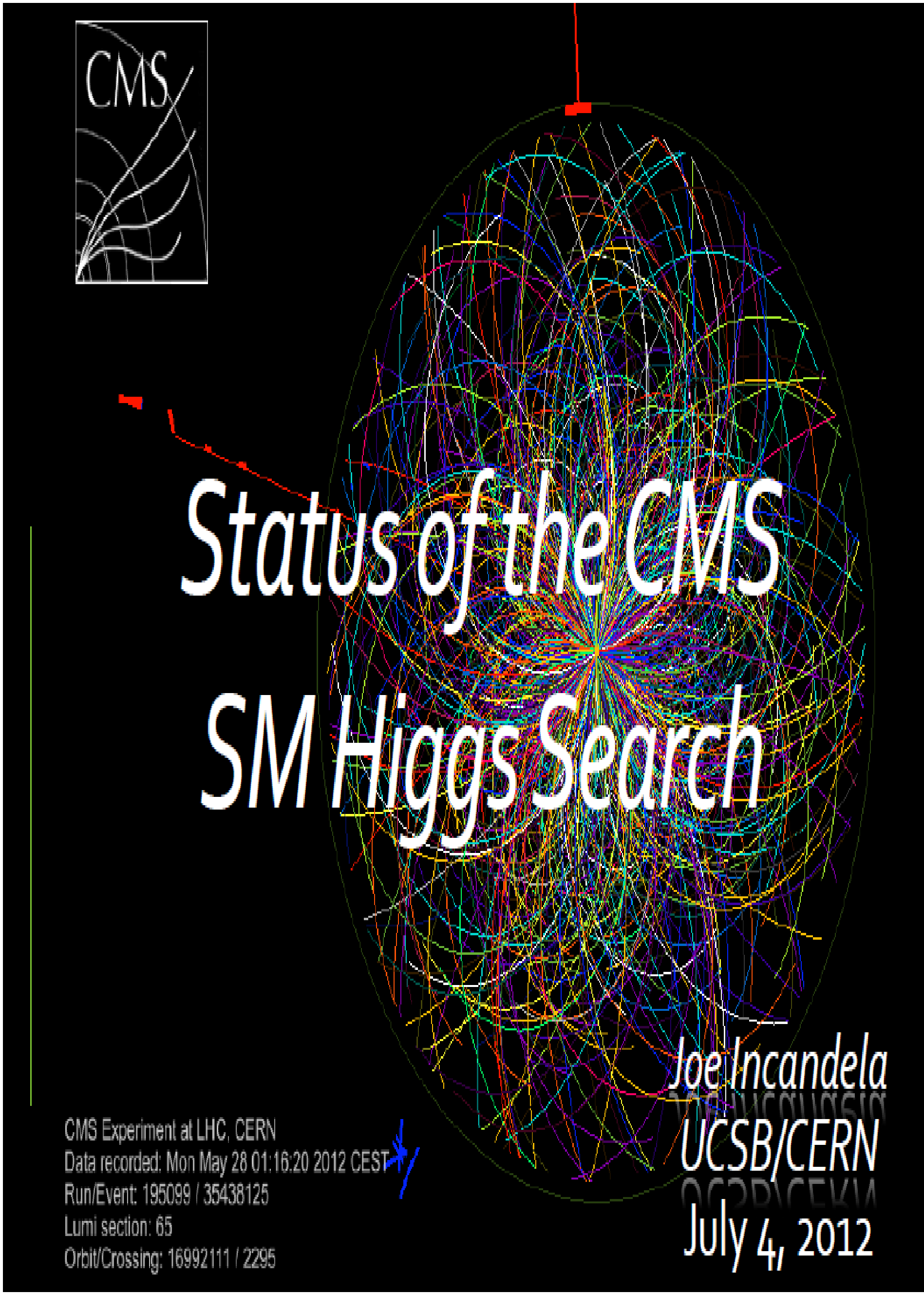
Expect more…

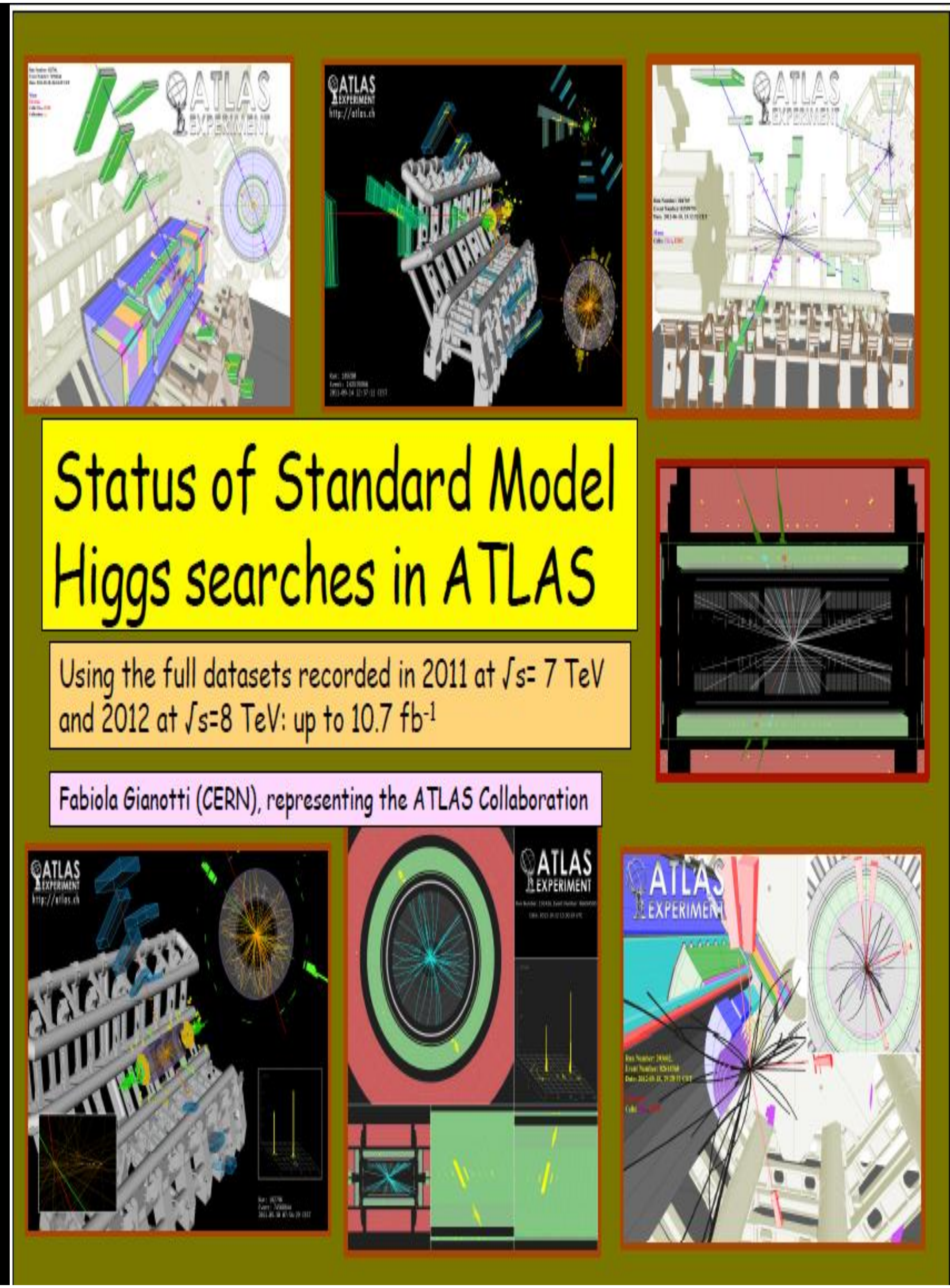
The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*


CMS
Status of the CMS
SM Higgs Search
Joe Incandela
UCSB/CERN
July 4, 2012
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295


ATLAS EXPERIMENT
Status of Standard Model Higgs searches in ATLAS
Using the full datasets recorded in 2011 at √s= 7 TeV and 2012 at √s=8 TeV: up to 10.7 fb-1
Fabiola Gianotti (CERN), representing the ATLAS Collaboration

2012.07 Big Discovery

arXiv.org > hep-ex > arXiv:1207.7214

Search or A

High Energy Physics - Experiment

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC

The ATLAS Collaboration

(Submitted on 31 Jul 2012)

A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^-1 collected at sqrt(s) = 7 TeV in 2011 and 5.8 fb^-1 at sqrt(s) = 8 TeV in 2012. Individual searches in the channels H->ZZ^(*)->llll, H->gamma gamma and H->WW->e nu mu nu in the 8 TeV data are combined with previously published results of searches for H->ZZ^(*), WW^(*), bbbar and tau^+tau^- in the 7 TeV data and results from improved analyses of the H->ZZ^(*)->llll and H->gamma gamma channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 +/- 0.4(stat) +/- 0.4(sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7x10^-9, is compatible with the production and decay of the Standard Model Higgs boson.

Comments:	24 pages plus author list (39 pages total), 12 figures, 7 tables, submitted to Physics Letters B
Subjects:	**High Energy Physics - Experiment (hep-ex)**
Report number:	CERN-PH-EP-2012-218
Cite as:	arXiv:1207.7214v1 [hep-ex]

5.9sigma

Phys.Lett. B716 (2012) 1-29

arXiv.org > hep-ex > arXiv:1207.7235

Search or Art

High Energy Physics - Experiment

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

The CMS Collaboration

(Submitted on 31 Jul 2012)

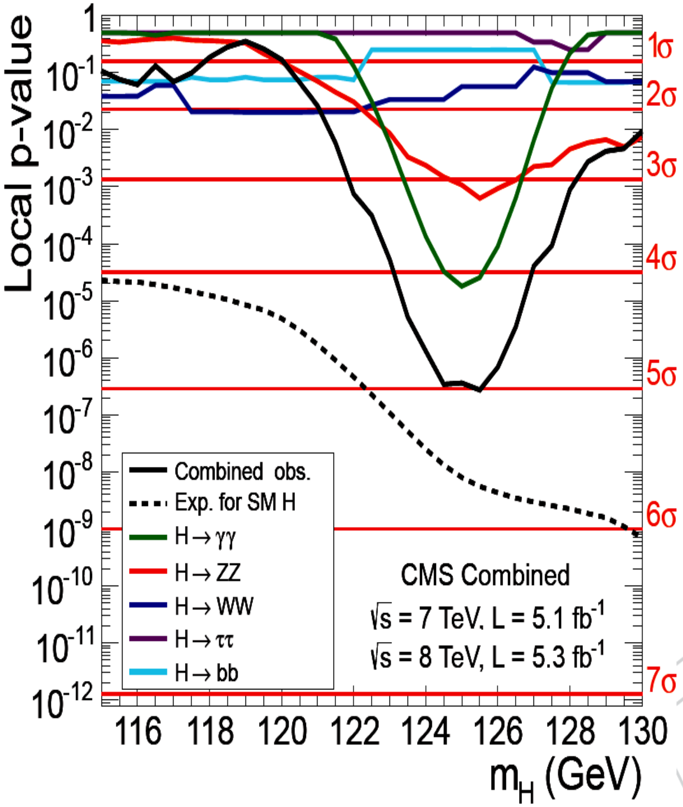
Results are presented from searches for the standard model Higgs boson in proton-proton collisions at sqrt(s)=7 and 8 TeV in the CMS experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 inverse femtobarns at 7 TeV and 5.3 inverse femtobarns at 8 TeV. The search is performed in five decay modes: gamma gamma, ZZ, WW, tau tau, and b b-bar. An excess of events is observed above the expected background, a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, gamma gamma and ZZ; a fit to these signals gives a mass of 125.3 +/- 0.4 (stat.) +/- 0.5 (syst.) GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

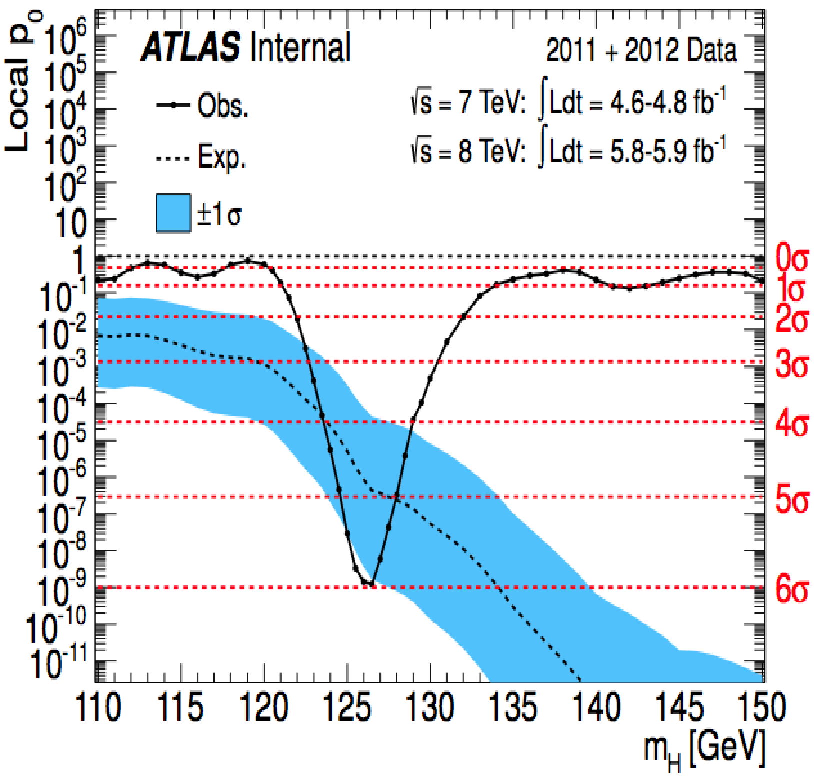
Comments:	Submitted to Phys. Lett. B
Subjects:	**High Energy Physics - Experiment (hep-ex)**
Report number:	CMS-HIG-12-028; CERN-PH-EP-2012-220
Cite as:	arXiv:1207.7235v1 [hep-ex]

5.0sigma

Phys. Lett. B 716 (2012) 30

Discovery of a new boson.





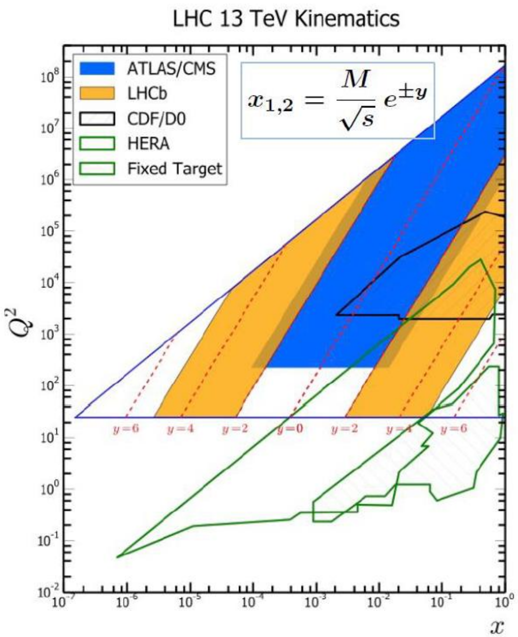
Combined significance 5.0σ for CMS and 5.9σ for ATLAS

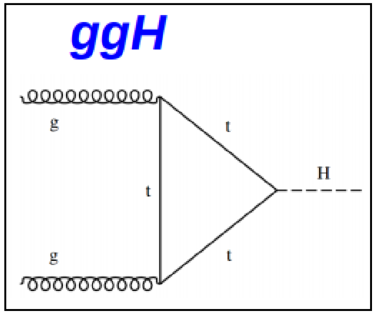
125.3+-0.4+-0.5GeV
0.87+-0.23

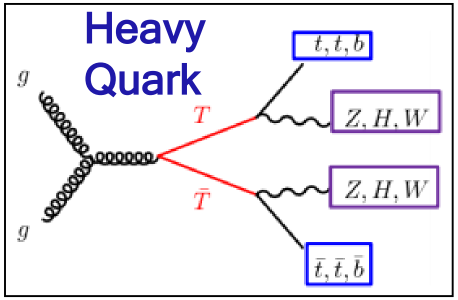
126.0+-0.4+-0.4GeV
1.4+-0.3

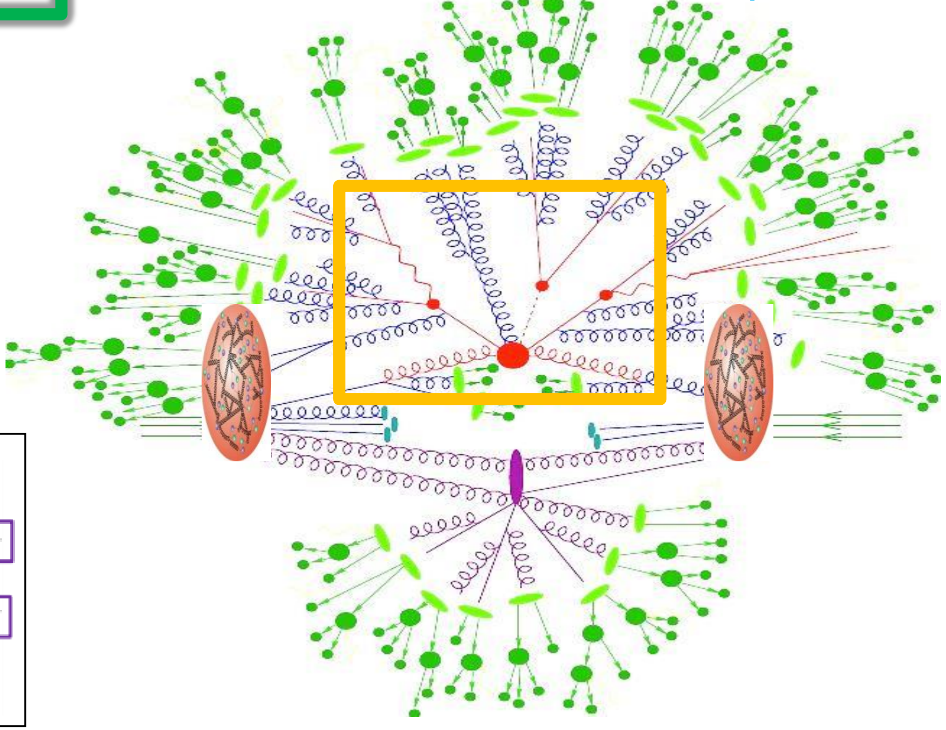
Rich Physics, Rich measurements

Courtesy Sherpa



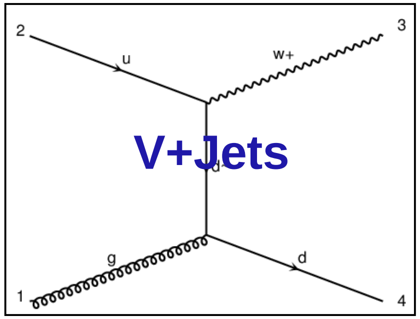


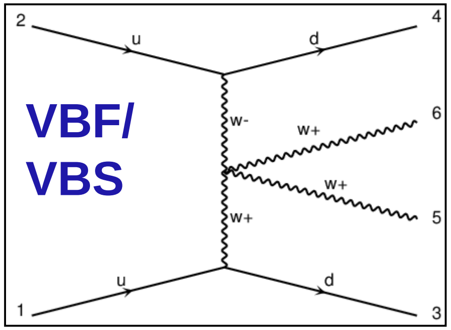


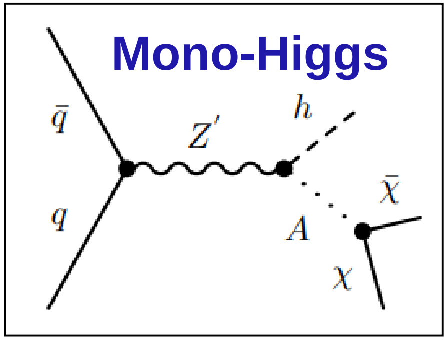


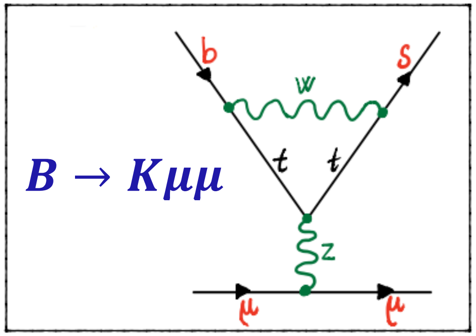
PDF,NLO QCD/EWK, NNLO QCD, Resummation, PS, Merging,Matching(MLM,CKKW,FXFX, MEPS)…

Tools: Pythia6/8 , Herwig, MG5_AMC, POWHEG, Sherpa, DYNNLO, FEWZ, MCFM,MCSANC,RESBOS…







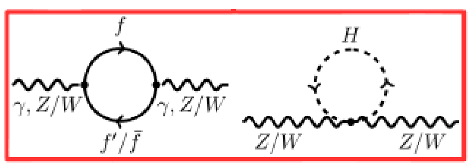


Standard Model

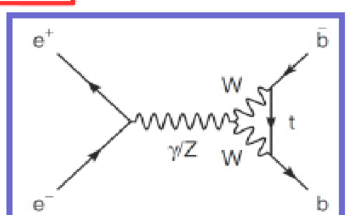
α_{em}, G_F, M_Z, M_W, $\sin^2\theta_W$, m_{top}, M_H , α_S

- **Consistency test of the over-constrained Standard Model**
- **Improved understanding of PDFs and bkg for NP searches**
- **Gauge boson anomalous couplings to probe NP indirectly**
- **High Energy/Luminosity open new phase space to explore**
- **Active region on both experimental and theoretical sides**

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

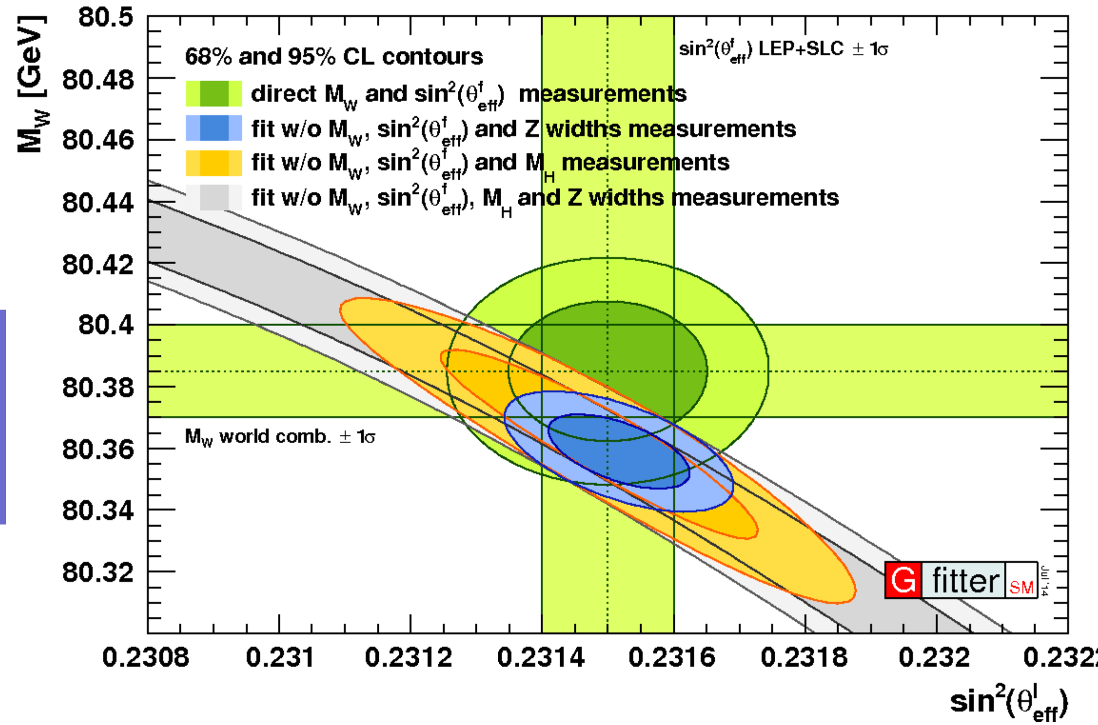


$$sin^2\theta_W = 1-\frac{M_W^2}{M_Z^2}$$

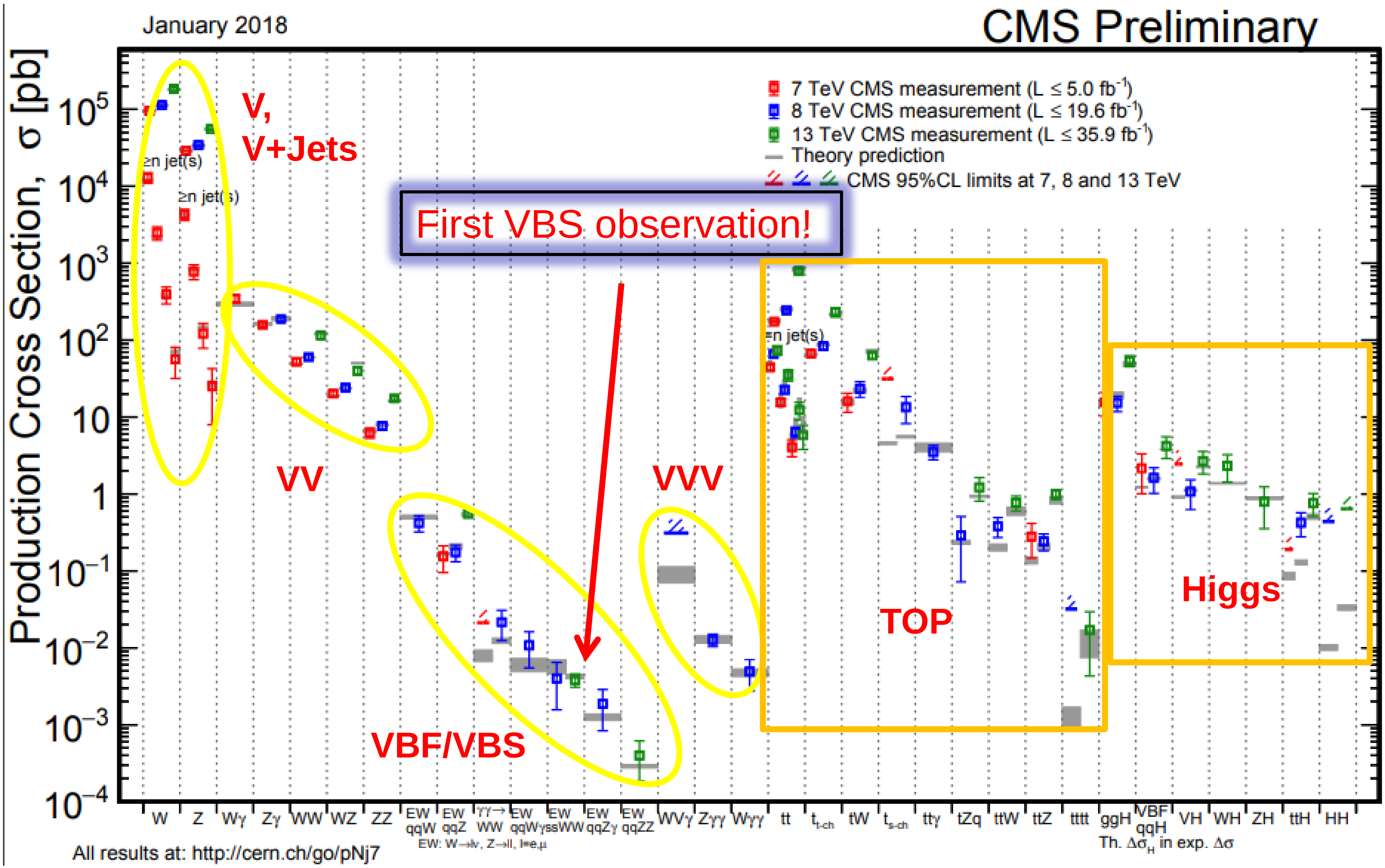


$$sin^2\theta_{eff}^{Lept} = \mathrm{Re}[\kappa_l(M_Z)]\cdot sin^2\theta_W$$

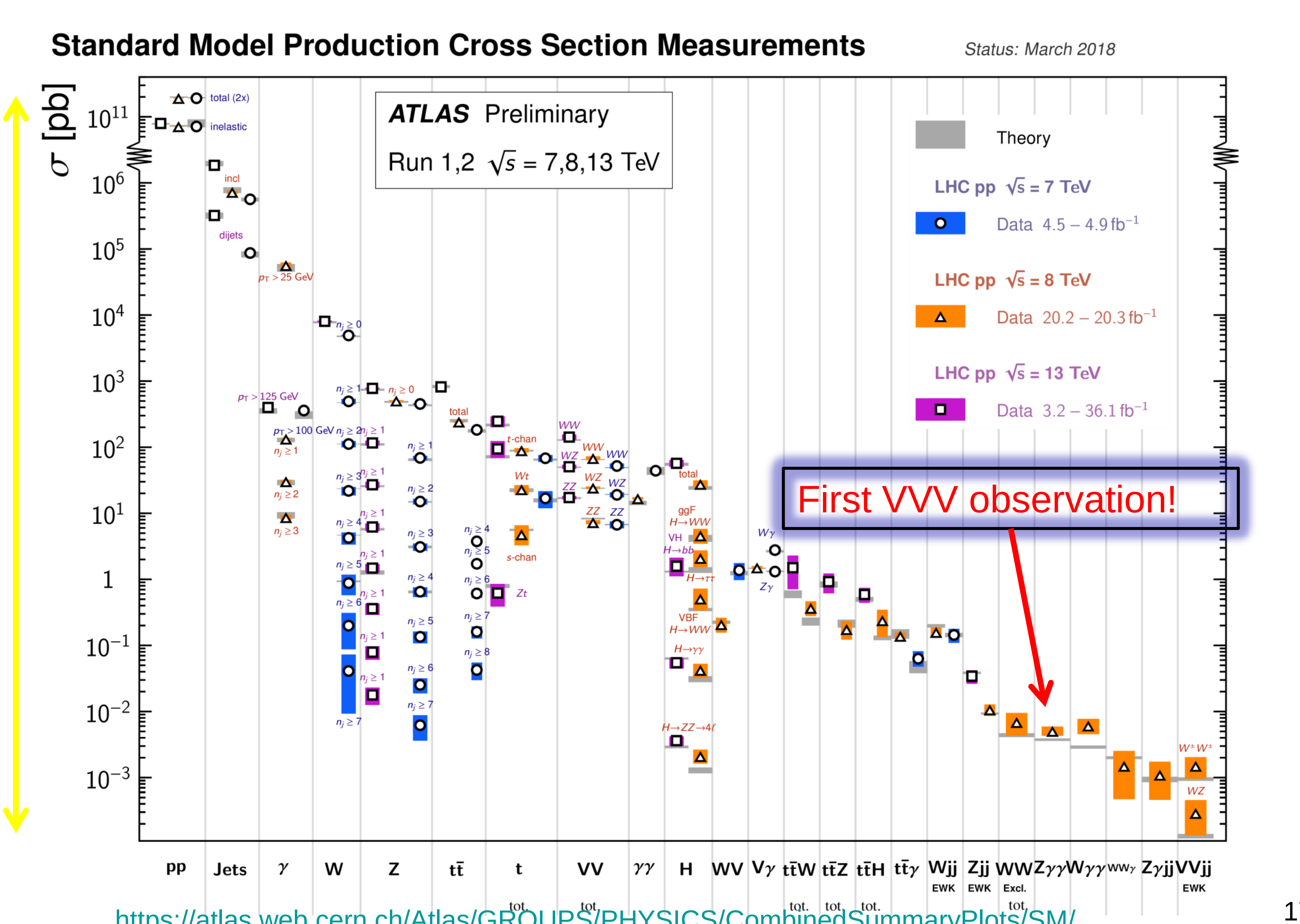
("effective", Zfitter)



13TeV SM measurements with full 2016 dataset!



Spread over large scales of Xsec. V+up to 7 Jets!



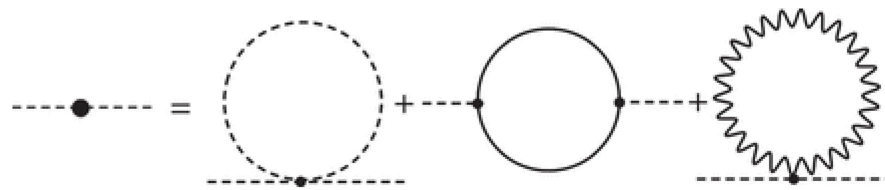
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

TeV Scale New Physics

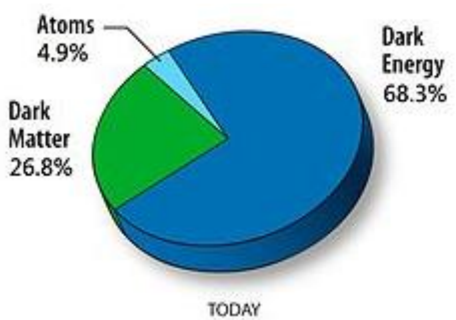
LHC Run1

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

- **Fine Tuning**
- **Dark matter**
- **Gauge Unification**
- **Flavor structure**
- **Baryon Asymmetry**



$$\delta M_h^2 = \left(\frac{1}{4}(9g^2 + 3g'^2) - 6y_t^2 + 6\lambda\right)\frac{\Lambda^2}{32\pi^2}$$



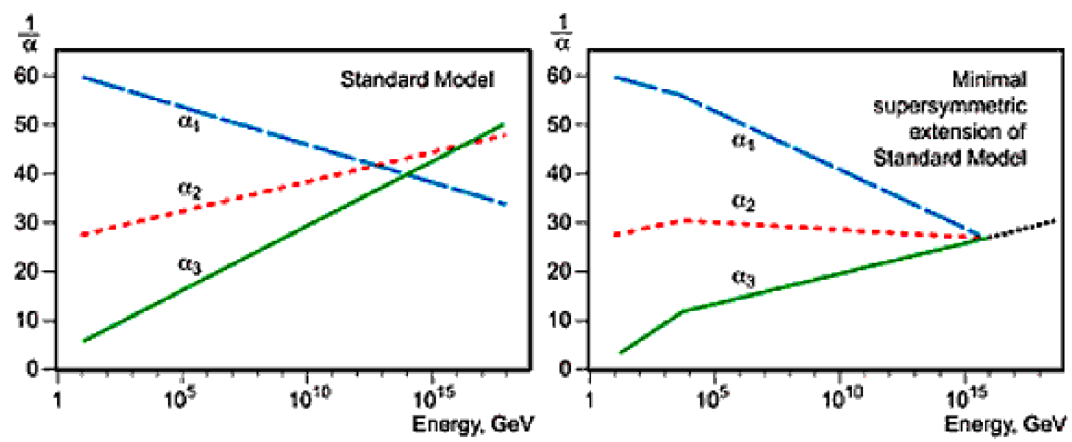
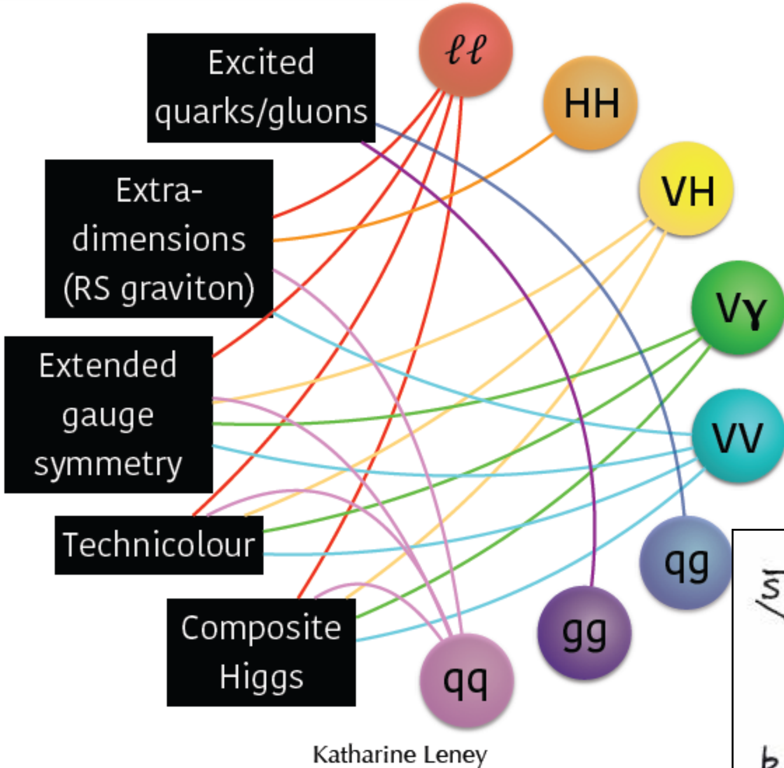
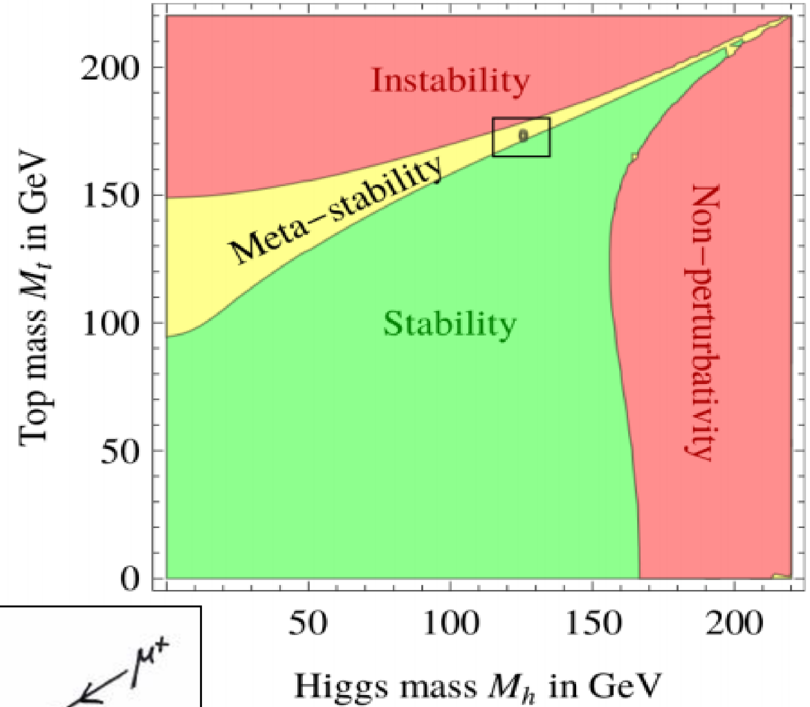


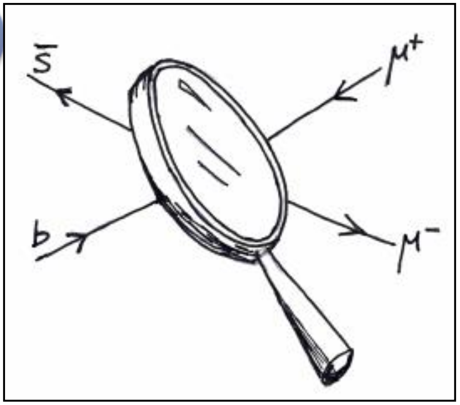
FIG. 8: Unification of interactions helped by SUSY

- **SUSY**
- **Extra Dimensions**
- **Extra Gauge Symmetry: W', Z'**
- **Exotic heavy Quarks, Leptons, Leptoquarks …**
- **Compositeness: contact interaction …**

BSM Searches

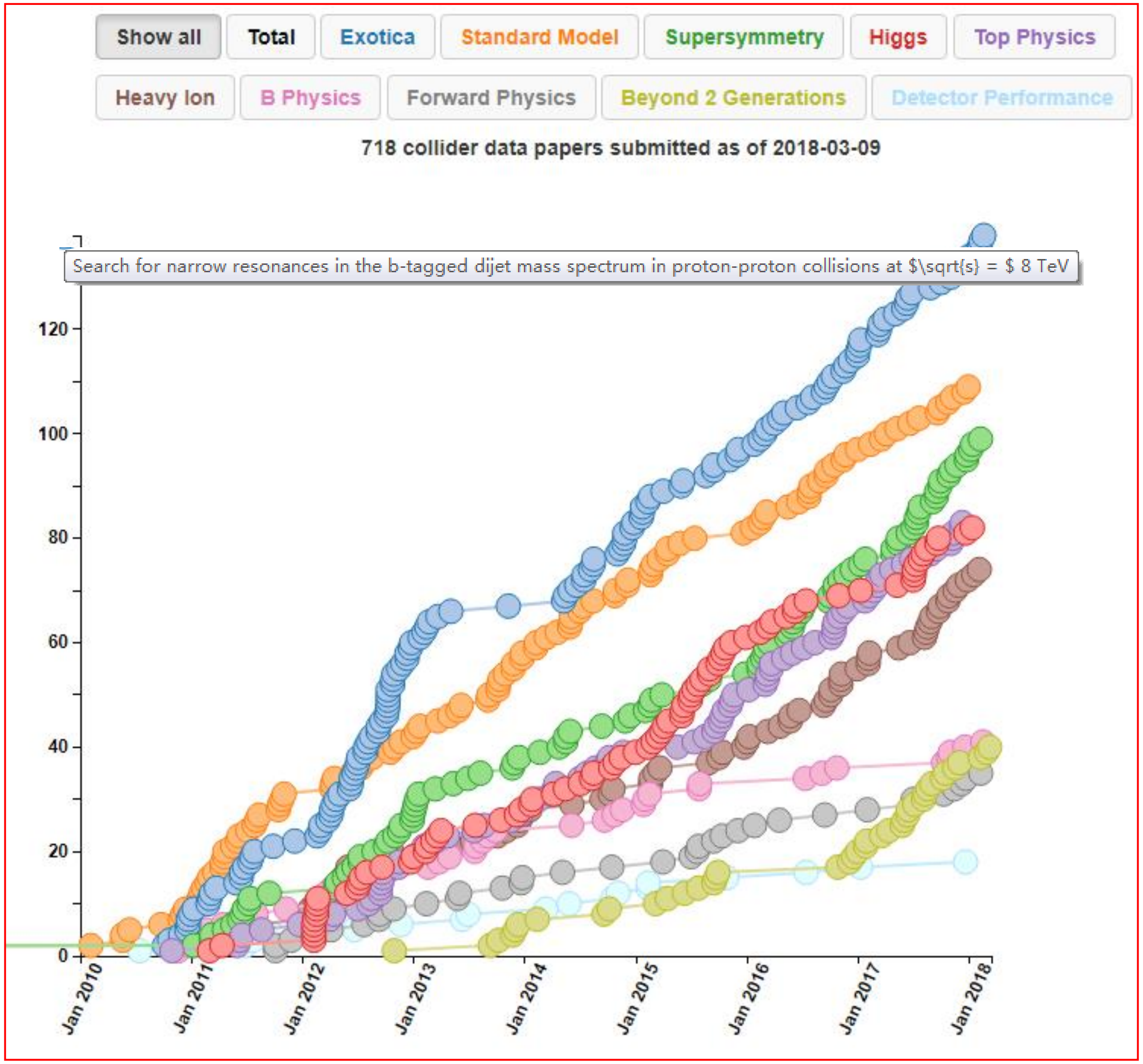


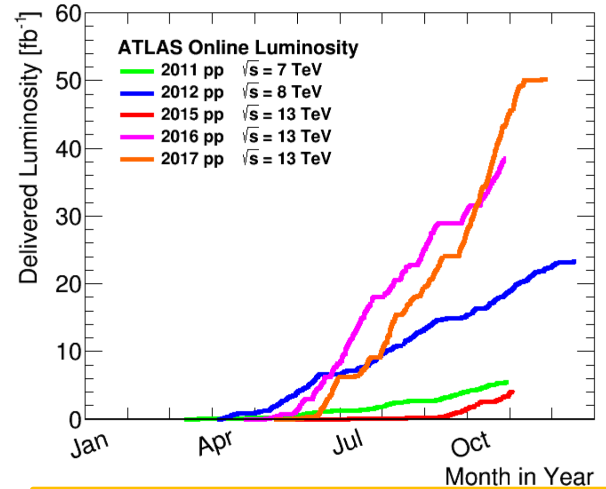


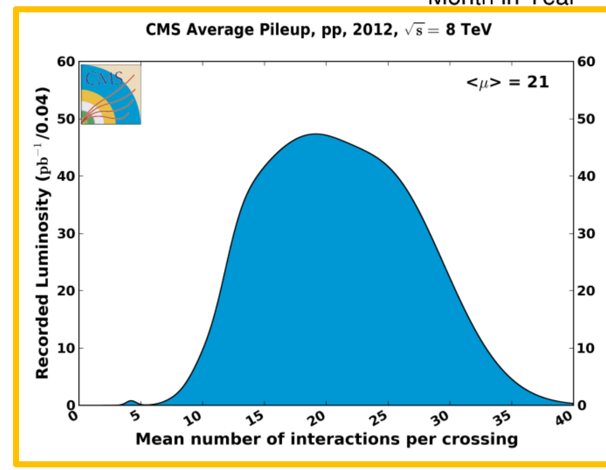


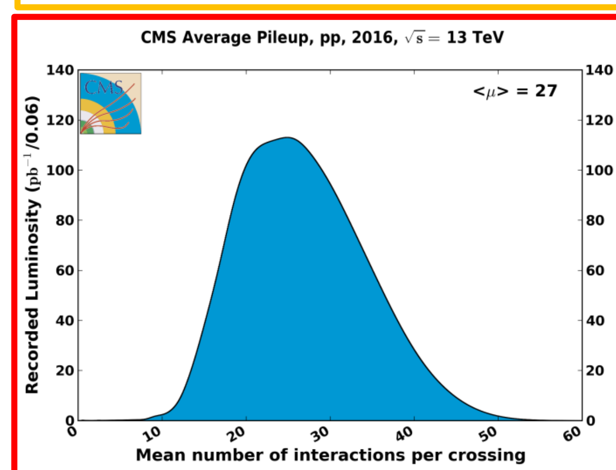
Resonance, Shape , Rate

ATLAS/CMS Experiments









Excellent detector and Physics performance

Crucial High Order Effects

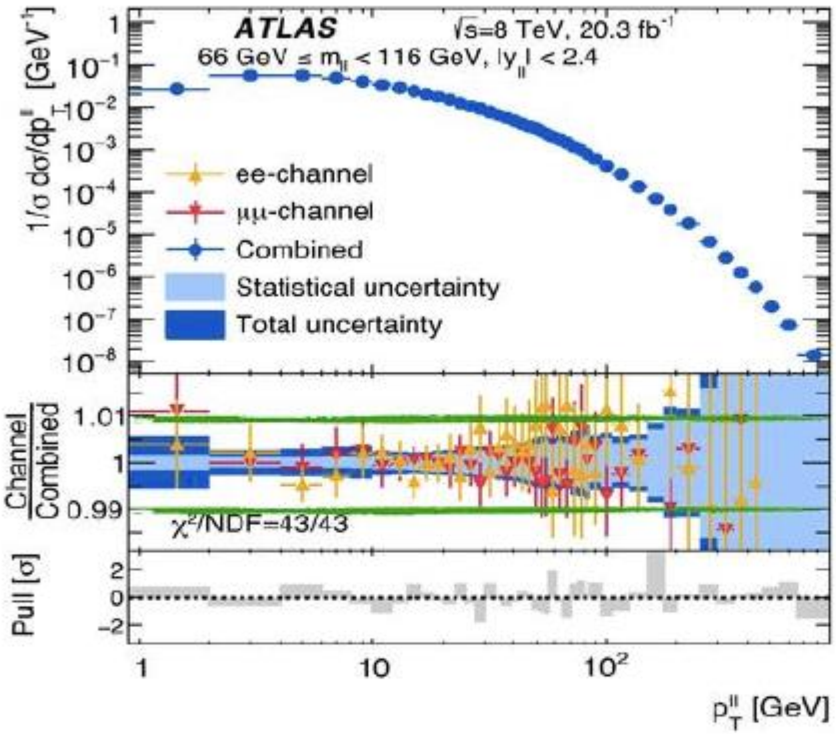
We’re well past the “low hanging fuit” type of measurements

- measurements are systematics level dominated and we need to go beyond from the early type prescription

How much can the precision of SM predictions be improved ?

- Should be enough to be sensitive to small departures from SM behavior

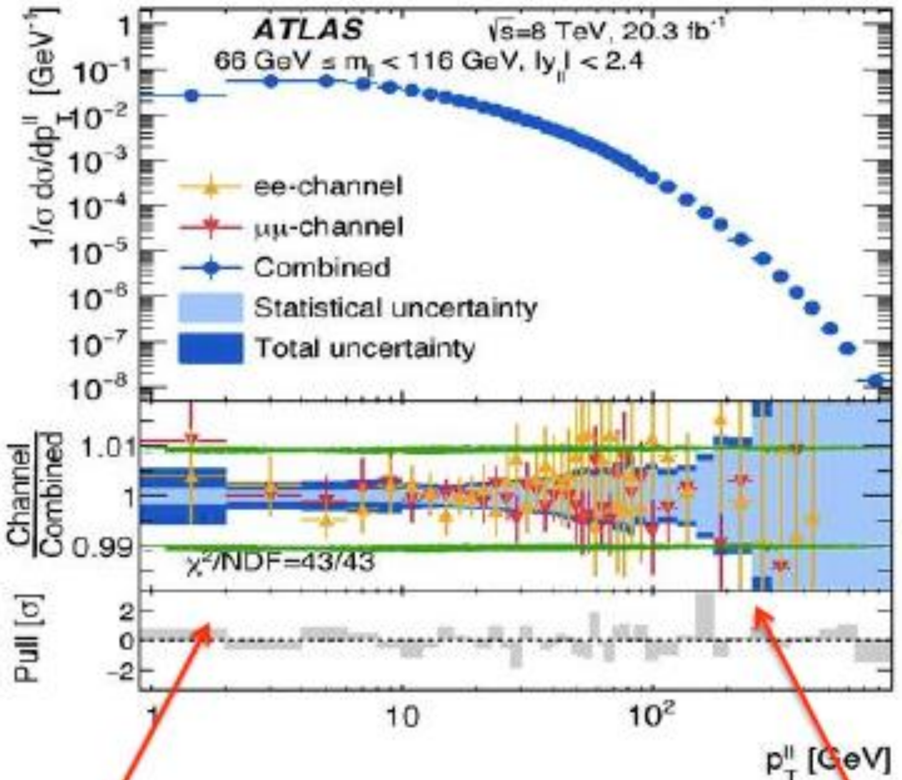
Z production



Normalised to Z fiducal σ

Esperimentally this is already at 1% for pt=1-200 GeV

Z production



The entire Zpt spectrum cannot be described yet by the single MC calculation

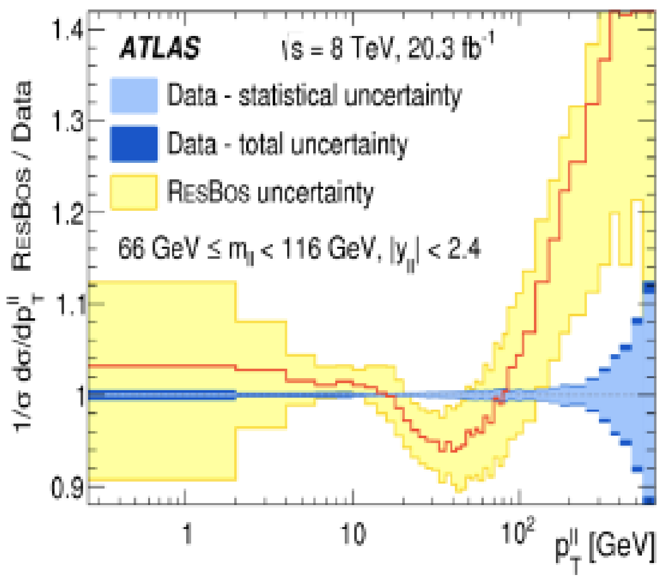
Similar duality for the Higgs PT

ptV << MV:
Soft gluon resummation
non perturbative effects

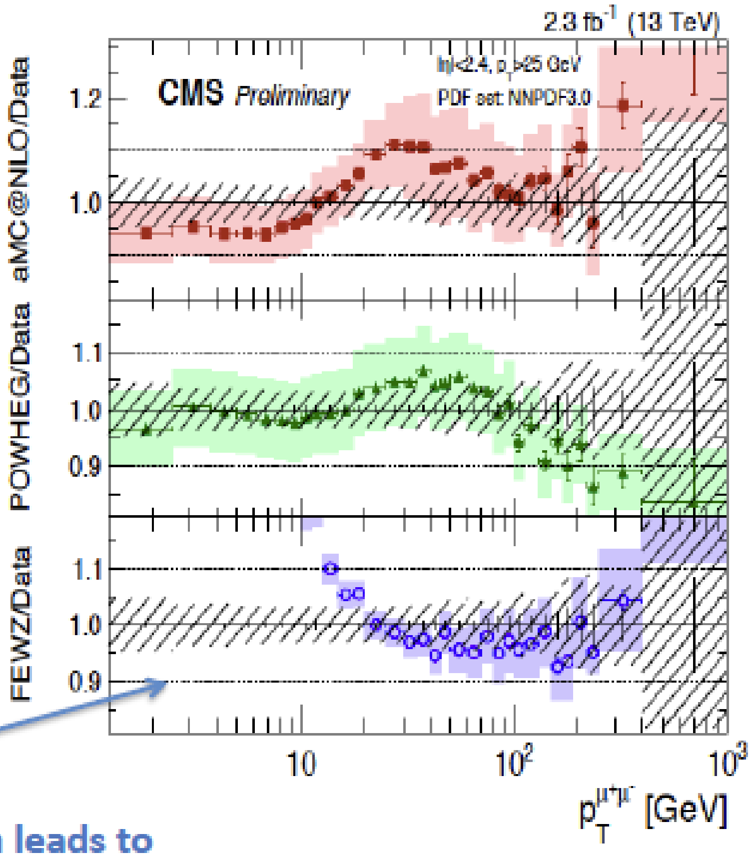
ptV ~ MV
Fixed order perturbative QCD
Parton shower with the missing higher order QCD
EWK correction

Comparison with MC

ATLAS/PAPERS/STDM-2014-12/



CMS-PAS-SMP-15-011

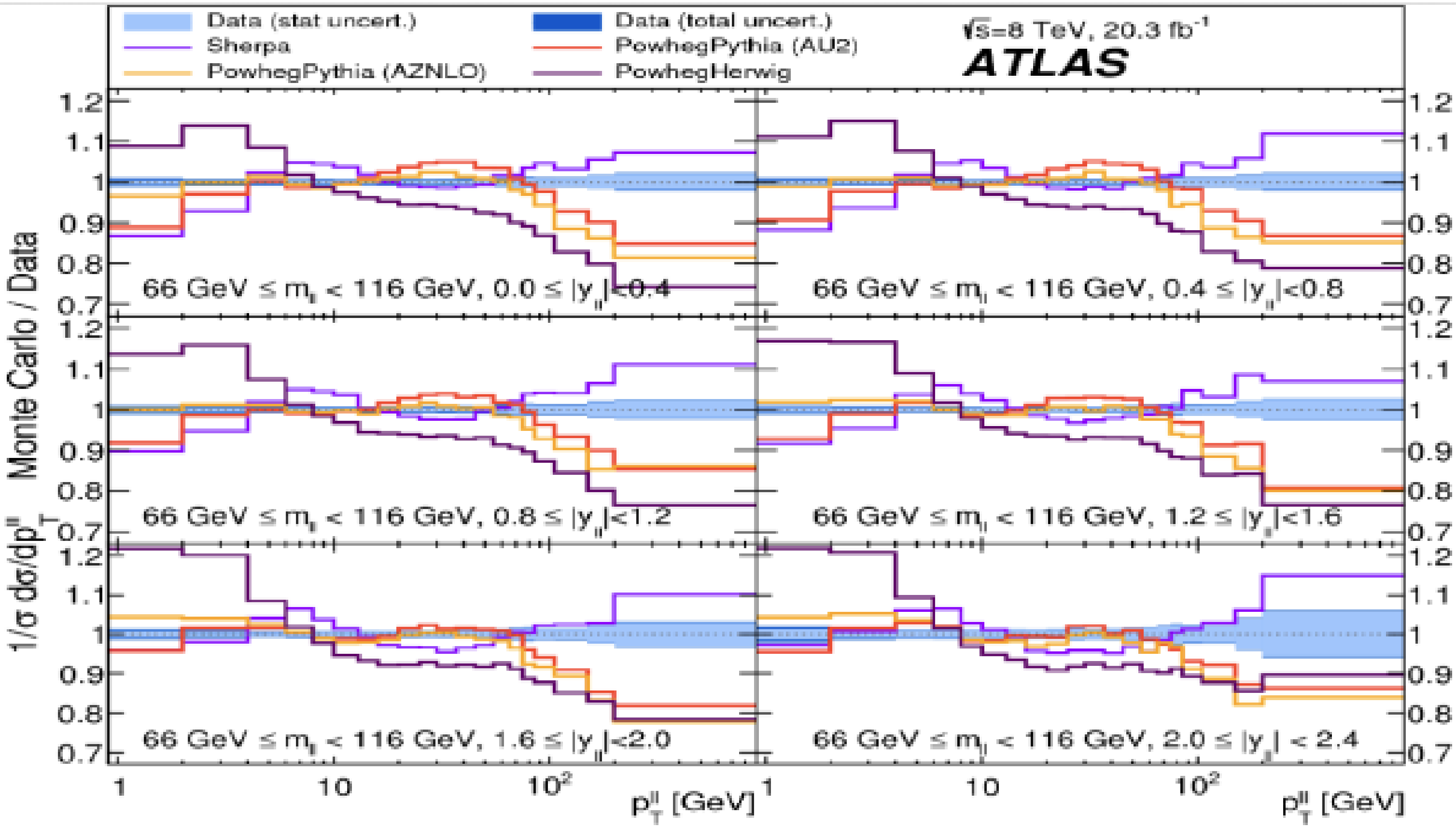


Absence of resummation in FEWZ calculation leads to expected deviations at low transverse momentum

This is also why ATLAS W-mass Measurement sticked to Pythia AZTune

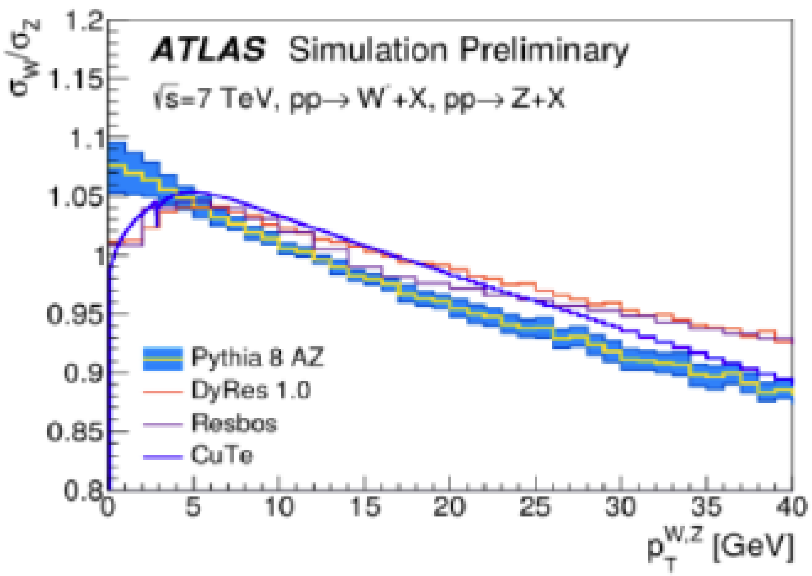
Eur. Phys. J. C 78 (2018) 110

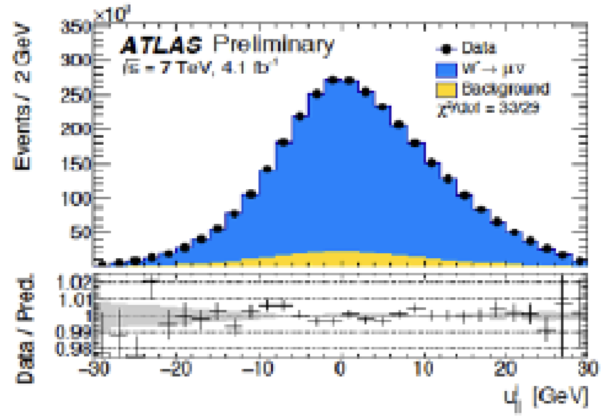
Z production & parton shower

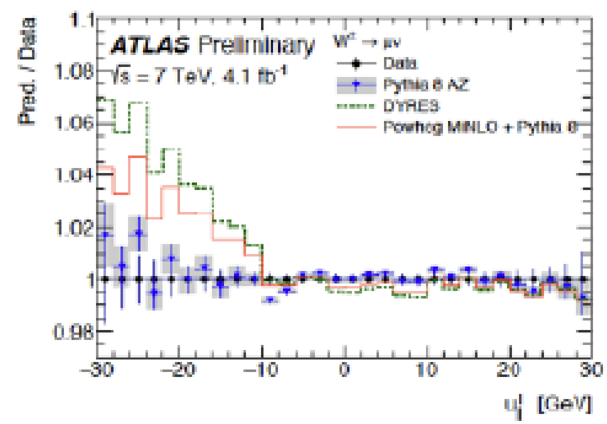


ATLAS tuned on Z @ 7TeV, give the best description at lowPT

Low Z pt production (ptZ< MZ)







Resummation codes predict
an harder pT W spectrum for a
given measured pT Z spectrum

MINLO and NNLL resummed predictions as Resbos, Cute, and DyRes
are strongly disfavoured by the u|| distribution in data

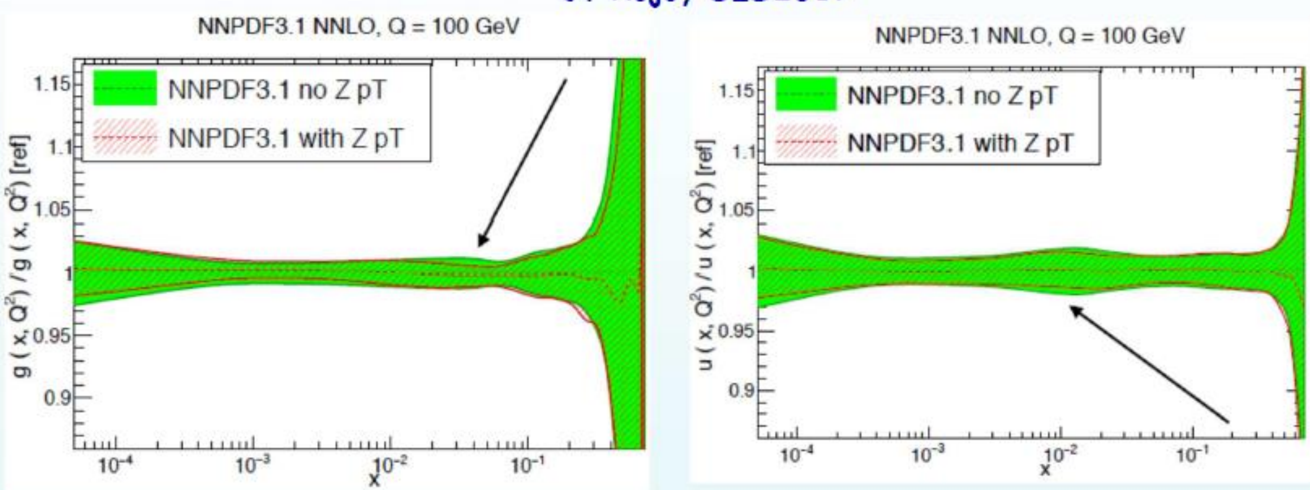
CMS differential W/Z measurements in pp

	7 TeV	8 TeV	13 TeV
	CMS label, arXiv		
DY m,y	SMP-13-003, 1310.7291	SMP-14-003, 1412.1115	SMP-16-009 (PAS)
Z p_T,y	EWK-10-010, 1110.4973	SMP-14-012, 1606.0586 SMP-13-013, 1504.03511	SMP-15-010 (PAS)
W p_T,y		SMP-14-012, 1606.0586	
W asym.	SMP-12-021, 1312.6283	SMP-14-022, 1603.01803	

used e.g. by NNPDF

W/Z P_T → PDF

J. Rojo, DIS2017



- **Moderate error reduction in the intermediate-x** region, excellent consistency with the other experiments in the global fit.
- Given very high precision (sub-percent) of these experiments, this is quite a non-trivial achievement
- The ATLAS Z p_T 7 TeV data not included in NNPDF3.1. If included, **poor data/theory agreement, χ^2 = 3.5,** and shifts in gluon and quarks. ***Tension with 8 TeV data?***

WW -> 2l2ν

Uncertainty dominated by systematics:

- jet veto (theory)
- background estimates (experimental)
- lepton selection (experimental)

total σ [pb] 8TeV	theory
CMS: 60.1 ± 0.9 (stat) ± 3.2 (exp) ± 3.1(th) ± 1.6 (lumi)	$59.8^{+1.3}_{-1.1}$ (NNLO)
Atlas: $71.4^{+1.2}_{-1.2}$ (stat) $^{+5.0}_{-4.4}$ (syst) $^{+2.2}_{-2.1}$ (lumi)	$58.7^{+3.0}_{-2.7}$ (qq NLO, gg LO) H->WW included

ATLAS / CMS 7 TeV
ATLAS 8 TeV
→ Excess over NLO predictions

CMS 8TeV: good agreement with theory

Might be explained by

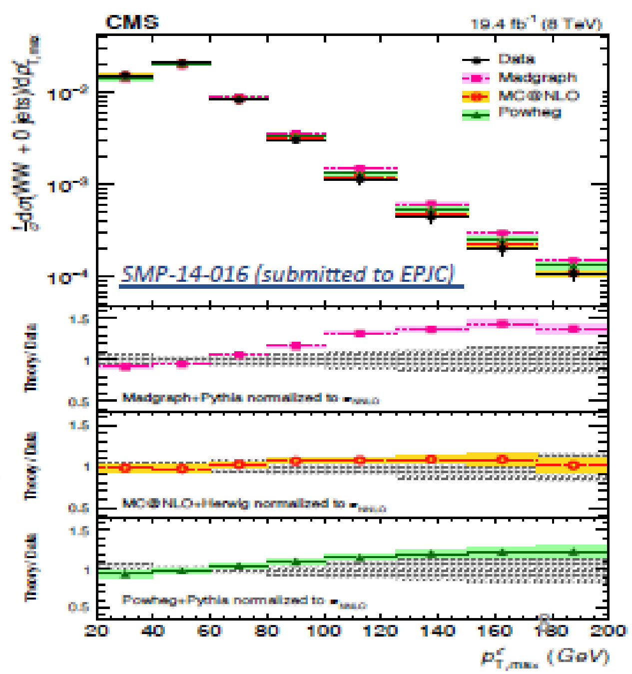
- NNLO contributions, ~10%
- Gluon resummation effects
  - correlated with jet veto efficiency

Differential cross-sections also measured

- in fiducial region with zero jets
- after unfolding

Good agreement between data and theory

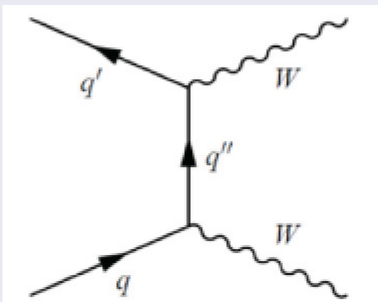
- few differences depending on generator/variable



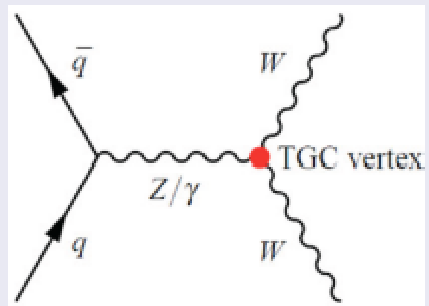
pp $\rightarrow$ W^+W^- Production at LHC

W^+W^- process crucial to test the SM predictions

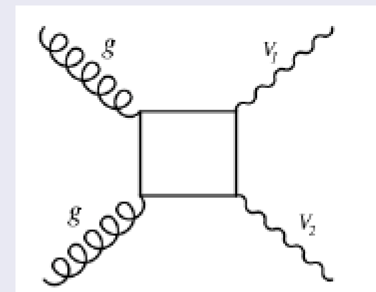
- Production **cross section** higher than WZ and Z^+Z^-
- Sensitive to new physics $\rightarrow$ could probe the **presence of ATGCs** or verify the gauge structure of the SM
- **Irreducible background** for new physics searches and Higgs boson analysis



qq $\rightarrow$ WW t-channel



qq $\rightarrow$ WW s-channel



gg $\rightarrow$ WW

- Luminosity: 19.4 fb^{-1} @ 8TeV
- **gg $\rightarrow$ H $\rightarrow$ WW** considered as a **background**
- Events with **0 Jet** or **1 Jet**

$\Longrightarrow$ analysis sensitive to **high-order QCD corrections**

$\Longrightarrow$ gluon **resummation** by reweighting p_T(WW) of qq $\rightarrow$ WW MC to a **NLO + NNLL** p_T resummation calculation **correlated with jet veto**

- **Fully leptonic** (ee, eμ, $\mu\mu$) final state:

$\Longrightarrow$ 2 lepton with p_T > 20 GeV, $|\eta|$ < 2.4 (2.5) for e (μ)

$\Longrightarrow$ real MET from nuetrinos

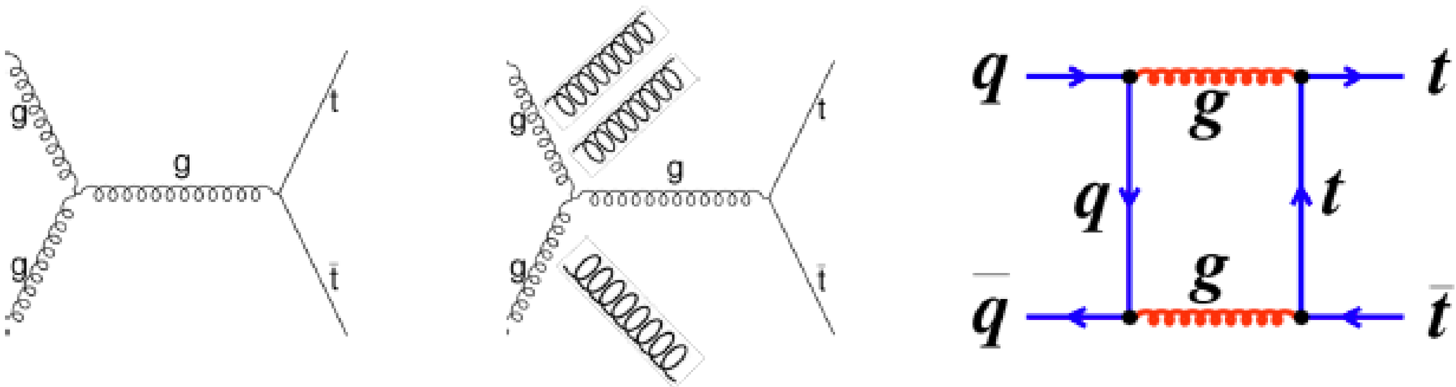
Monte-Carlo Simulations

Event Modeling in CMS

- Most measurements at hadron colliders rely on large scale Monte Carlo production.
  - Understanding and interpretation of data – test SM with more precise and complex calculations.
  - Many cases in which irreducible backgrounds extrapolated to signal phase-space regions for new physics searches through predictions using MC simulations.
- At the LHC, most events are accompanied by additional hard jets from initial or final state QCD radiation.
  - SM measurements
  - Many searches select or veto these extra jets.

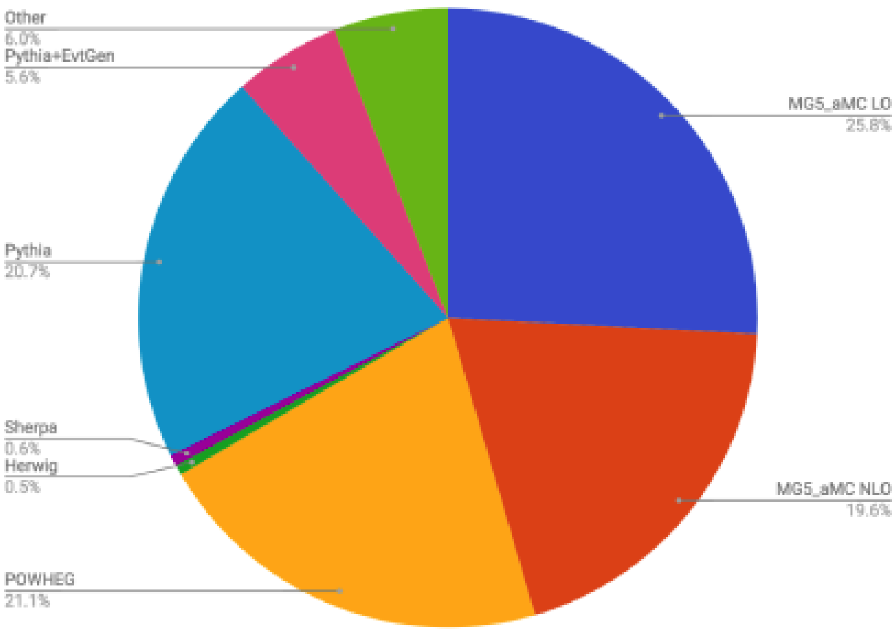
→ NLO/multi-leg/merged MC generators needed for high accuracy predictions for the LHC

Matrix Element Generation

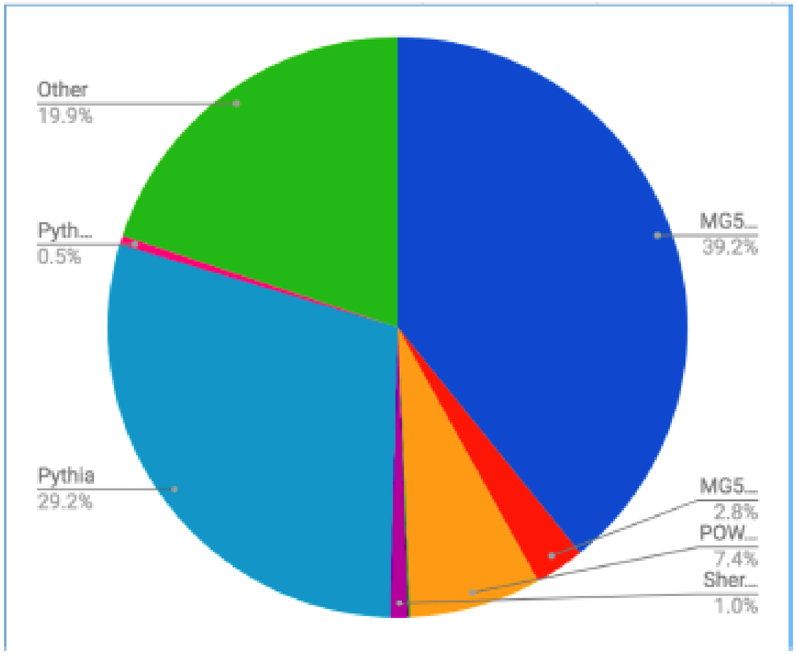


- Multi-leg LO and NLO consistently matched to the parton shower
- LO: Most commonly used in CMS: MG5_aMC@NLO+Pythia8 with MLM matching
  - Most complex process up to 4 additional jets
- NLO:
  - Most commonly used in CMS: MG5_aMC+Pythia8 with FxFx merging
    - Most complex process up to 2 additional jets at NLO.
  - And POWHEG

Standard Setups for CMS Monte Carlo at Run II



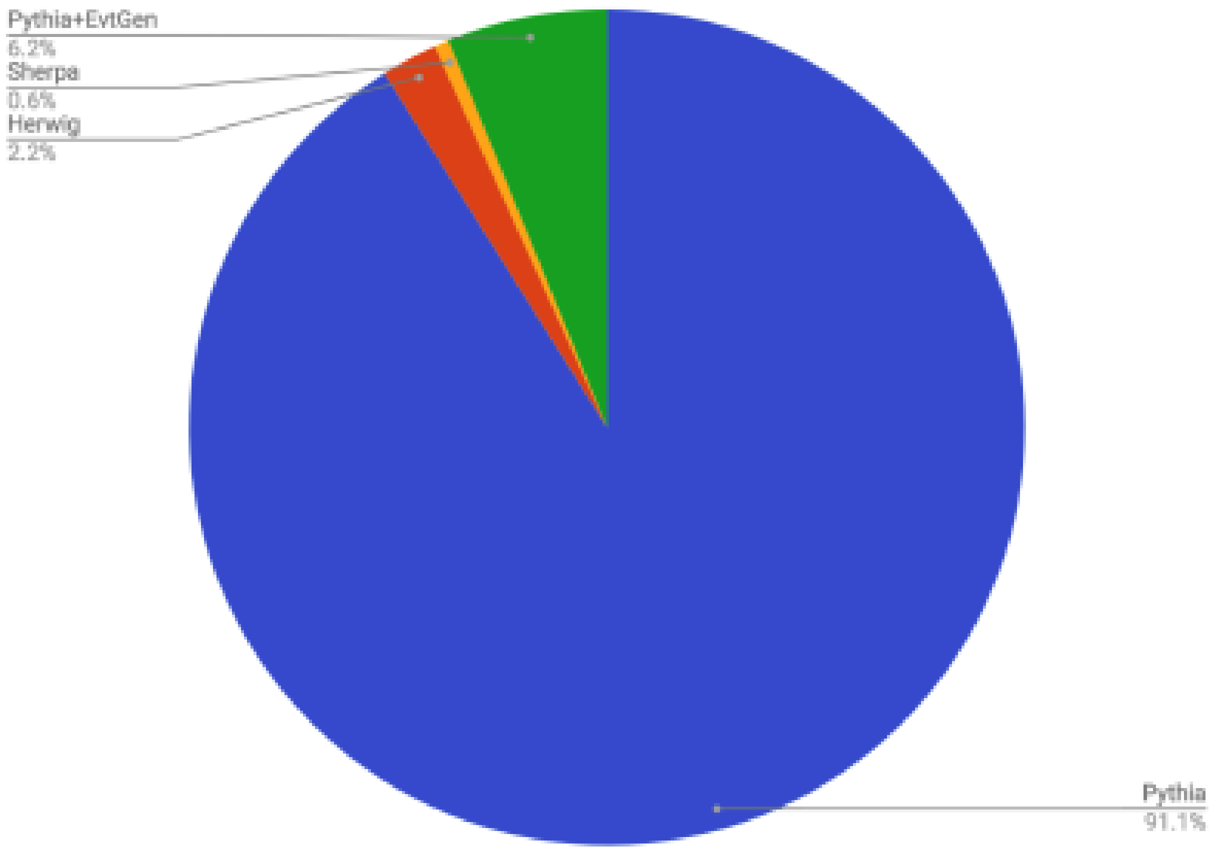
Percentage of events from different generators



Percentage of samples from different generators

→ *Approximate and based on 2016 MC campaign*

Standard Setups for CMS Monte Carlo at Run II – parton shower



→ *Percentage of events from different generators*
→ *Approximate and based on 2016 MC campaign*

CMS Software

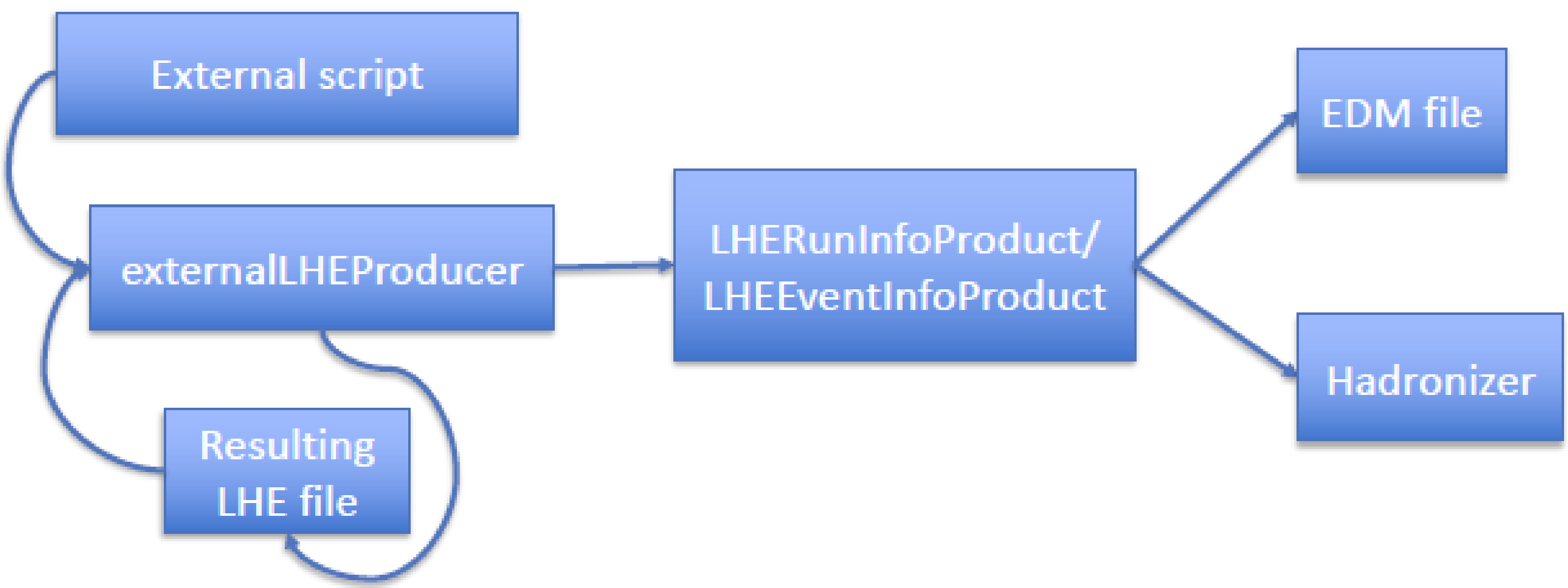
- Modular C++ application used for event generation, detector simulation, reconstruction and analysis
- Steered with python-based configuration files
- Input/output: root-based EDM files
  - Store run-,lumi-section-, and event-level data
- Links directly to « externals »
  - Externally maintained fortran, python, C, C++, ... codes (e.g. parton shower codes Pythia, Herwig, ...)
  - External code versions locked to CMSSW release

CMS Central Monte Carlo Sample Production

- Python-based tools for submission of CMSSW jobs to grid resources
- Similar mechanism available for users to submit analysis jobs
- CMSSW + externals available on worker nodes through CVMFS (CERN Virtual Machine File System)
  - distributed disk system for providing code and libraries to interactive nodes and grid worldwide.

Central Production of LHE Events

- MG5_aMC, Powheg, … not compatible with our computing model, i.e. they can't be called from CMSSW.
  - Solution: C++ CMSSW externalLHEProducer module



Gridpacks

- Pre-generated and compiled code with initial phase space integration results stored in a tarball (with fixed model/run parameters).
- Contribution from each subprocess is calculated with high precision in the creation of the gridpack. Then the gridpack jobs *randomly include subprocesses based on their relative contributions* to the total cross section.
- Once the gridpack has been generated the number of events and the random number seed are the only input variables.
- Placed in CVMFS and accessed by remote jobs
- Gridpack location – a parameter of the externalLHEProducer module

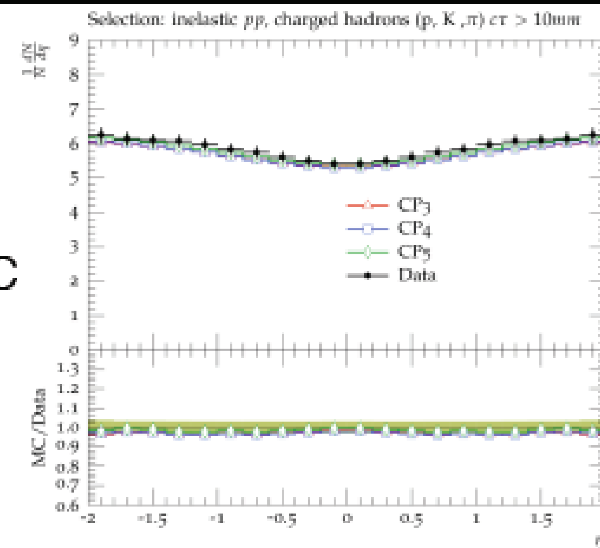
```
process.externalLHEProducer = cms.EDProducer("ExternalLHEProducer",
    args = cms.vstring('/cvmfs/cms.cern.ch/phys_generator/gridpacks/slc6_amd64_gcc481/14TeV/madgraph/V5_2.4
.2/ttGamma_Dilept_5f_ckm_LO/v1/ttGamma_Dilept_5f_ckm_LO_tarball.tar.xz','false', 'slc6_amd64_gcc481','CMSSW
_7_1_28'),
    nEvents = cms.untracked.uint32(10),
    numberOfParameters = cms.uint32(4),
    outputFile = cms.string('cmsgrid_final.lhe'),
    scriptName = cms.FileInPath('GeneratorInterface/LHEInterface/data/run_generic_tarball_cvmfs.sh')
)
```

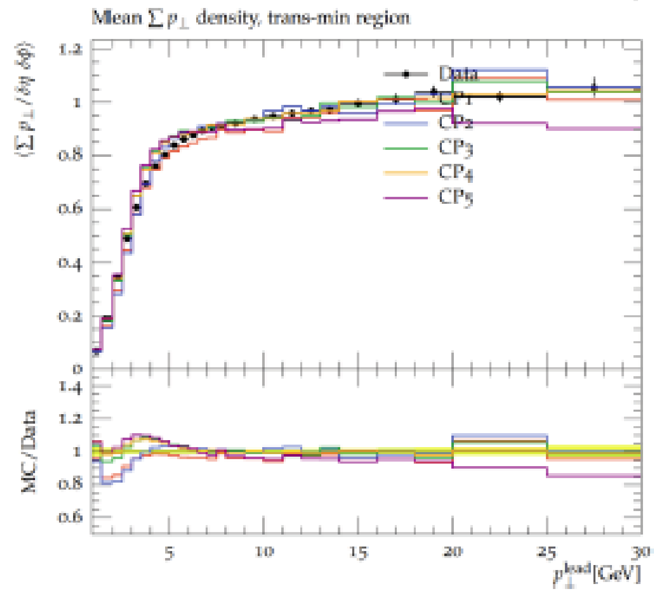
(Approximate) CPU Time

- Multi-leg LO
  - up to ~10s/gen-evt
  - ~10% matching efficiency → 100s/full-sim-evt
- Multi-leg NLO
  - up to ~30s/gen-evt
  - ~30% matching efficiency → 100s/full-sim-evt
  - Large fraction of negative weights of up to ~40% → larger samples!

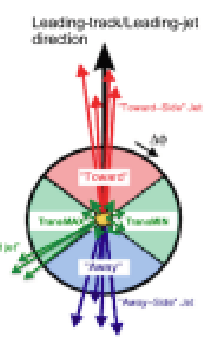
MC Tuning in CMS

- CMS produces and uses custom tunes for most MC samples
  - Professor, Rivet, and MCPlots used extensively to aid this process
- New tune for Pythia 8 produced and used for 2017 MC
  - First CMS tune with 13 TeV LHC data
  - Test the effect of using different PDF orders of NNPDF sets in Pythia8 among other parameter variations
  - Some public results available, paper very soon
- Similar agreement obtained in min. bias and UE distributions from higher-order PDFs with LO PDF
  - ➡ Result with NNLO PDF taken as central tune





For UE tuning



Kenneth Long

CP1: NNPDF3.1 LO (alpha_s 0.130)
CP2: NNPDF3.1 LO (alpha_s 0.130)
CP3: NNPDF3.1 NLO (alpha_s 0.118)
CP4: NNPDF3.1 NNLO (alpha_s 0.118)
CP5: NNPDF3.1 NNLO (alpha_s 0.118)

α_S = 0.013 for MPI, ISR, and FSR vs. tuned
ISR emissions ordered by rapidity

Current Simulation Frontier

Wishlist

Feature / Generator	ME scale & PDF weights	NLO merging	NNLO QCD corrections	NLO EWK corrections	PS weights	Alternative shower model	Alternative hadronisation model
Powheg	YES	YES: (MiNLO. No NLO+LO)	YES: ME via RW	SOME	n/a	n/a	n/a
Sherpa2.3	YES	YES: NLO+LO	YES: ME via qT subtraction	YES: approx NLO	YES	YES: DIRE	YES: Lund (untuned)
MG5_aMC	YES	YES (UNLOPS NLO+LO)	NO	YES: approx NLO	n/a	n/a	n/a
Pythia8	n/a	n/a	n/a	n/a	YES: Only for inclusive LO/ NLO	YES: DIRE (only inclusive LO/ NLO)	NO
Herwig7	NO	YES: Matchbox (NLO+LO)	NO?	NO?	YES	YES: ang-ord vs dipole (only for LO/NLO incl.)	NO
Geneva	YES: NPs	NO	YES: NNLO ME + NNLL PS	NO?	n/a	n/a	n/a

7 Josh McFayden | MCnet | 11/4/2018

$$N_{eff} = \frac{(\sum_i w_i)^2}{\sum w_i^2} = N(1-2f)^2$$

Aside | Negative event weights

- Any development here would be much appreciated…

- We cannot afford to run full simulation on samples with negative weight fraction >25%
  - Starting to become a deal-breaker

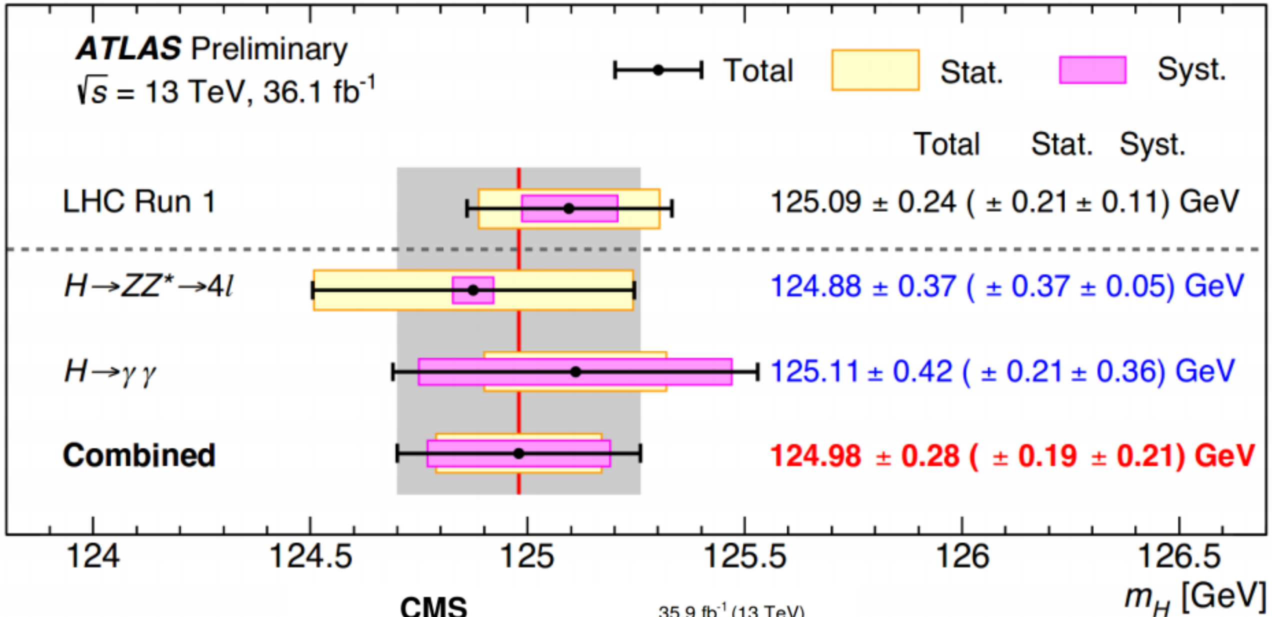
- Also has knock-on effects
  - For e.g. huge W/Z samples for high precision analyses we cannot currently use MC@NLO-like matching schemes.

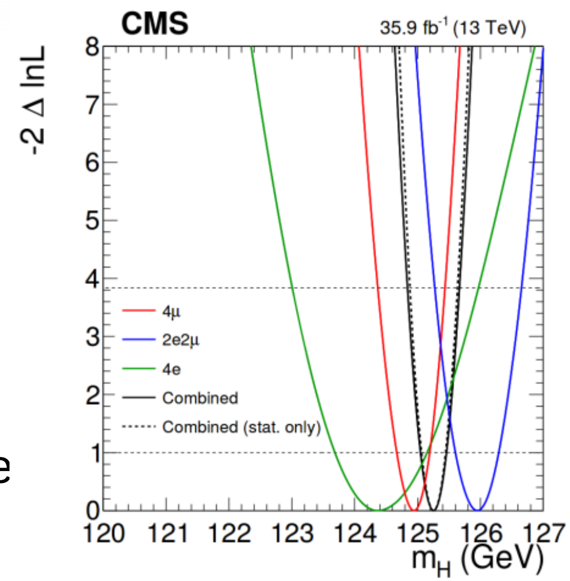
Sample	DSID	Fraction of events with neg. weights [%]
Sherpa (lepton+jets)	364345	20.5
Sherpa (lepton+jets)	364346	20.4
Sherpa (dilepton)	364347	20.4
Sherpa ttbb (lepton+jets, CSSKIN, 4FS)	410329	24.4
Sherpa ttbb (lepton+jets, CMMPS, 4FS)	410335	25.7
aMC@NLO+Py8 (lepton+jets)	410441	23.7
aMC@NLO+Py8 (dilepton)	410442	23.7
aMC@NLO+Py8 (FxFx, 70 GeV)	410452	28.4
aMC@NLO+H++ (4FS, ttbb)	410245	37.2
Powheg+Herwig7 (lepton+jets)	410557	0.4
Powheg+Herwig7 (dilepton)	410558	0.4

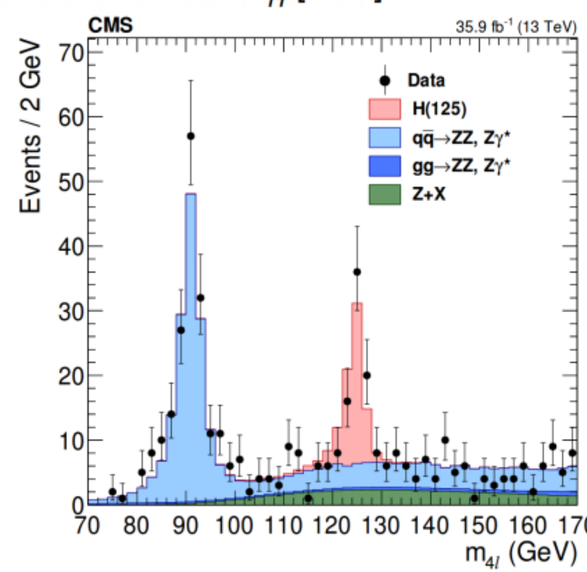
SM and BSM Higgs

Higgs Mass

ATLAS-CONF-2017-046; JHEP11(2017)047







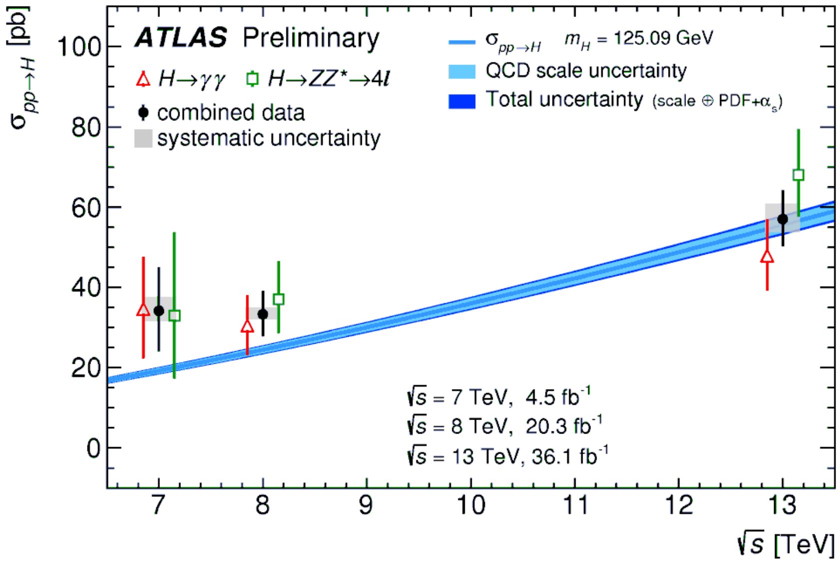
12% more precise compared to Run 1 ATLAS+CMS combination

Dominant systematic uncertainty comes from the lepton energy scale

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

ATLAS Combination (ZZ and γ γ)

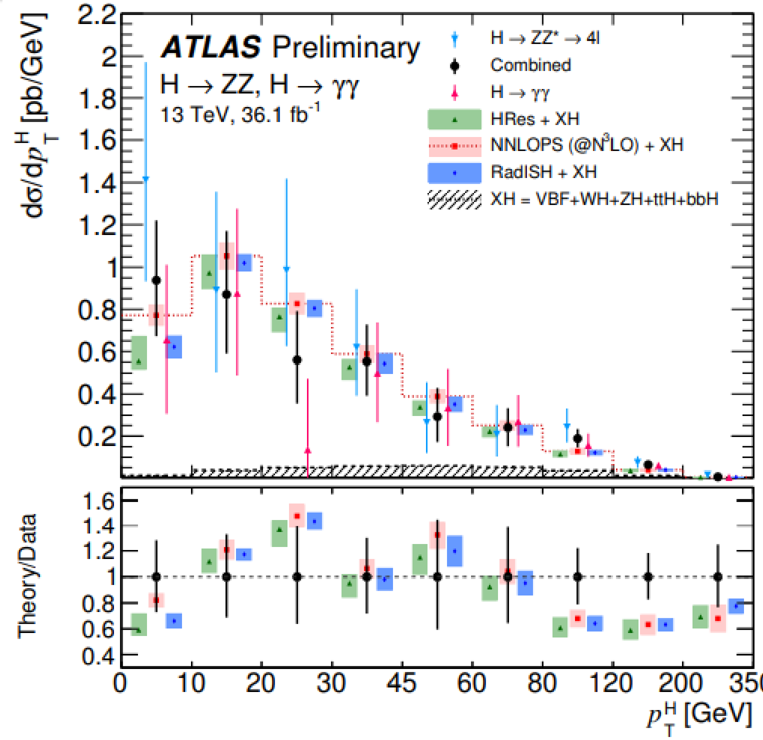
ATLAS-CONF-2018-002
ATLAS-CONF-2017-047

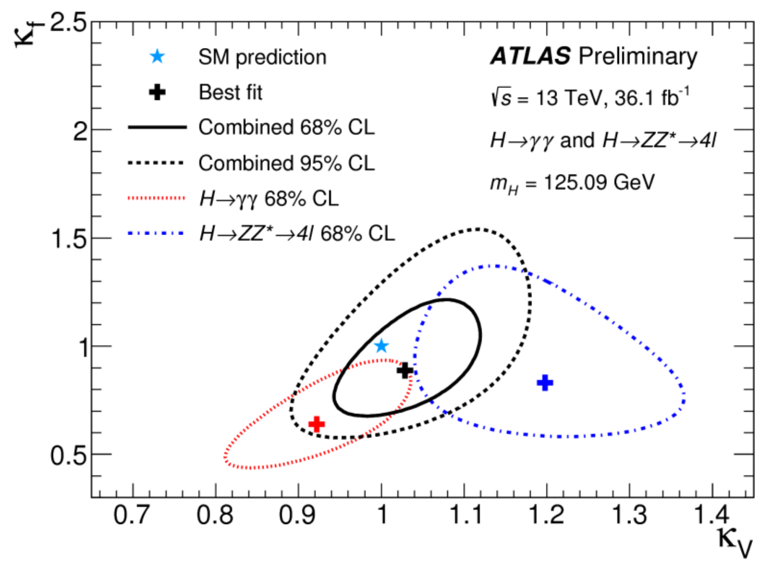


$H \to \gamma\gamma$ decay channel	$47.9^{+9.1}_{-8.6}$ pb
$H \to ZZ^* \to 4\ell$ channel	68^{+11}_{-10} pb
combined measurement	$57.0^{+6.0}_{-5.9}$ (stat.) $^{+4.0}_{-3.3}$ (syst.) pb

SM prediction of 55.6±2.5 pb

Process	Accuracy	Fraction [%]
ggF	N^{3}LO, NLO EW corrections [36–49]	87.4
VBF	NLO, NLO EW corrections [50–52] with approximate NNLO QCD corrections [53]	6.8
VH	NNLO [54, 55], NLO EW corrections [56]	4.1
$t\bar{t}H$	NLO [57–60]	0.9
$b\bar{b}H$	five-flavour: NNLO, four-flavour: NLO [61]	0.9





CMS Big Combination

CMS-PAS-HIG-17-031

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

$H \to \gamma\gamma$, Section 2.1				
$\gamma\gamma$	Untagged	74-91% ggH	4	≈1-2%
	VBF	51-80% VBF	3	
	VH hadronic	25% WH, 15% ZH	1	
	WH leptonic	64-83% WH	2	
	ZH leptonic	98% ZH	1	
	VH p_T^{miss}	59% VH	1	
	ttH	80-89% ttH, ≈8% tH	2	
$H \to ZZ^{(*)} \to 4\ell$, Section 2.2				
4μ, $2e2\mu/2\mu 2e$, $4e$	Untagged	≈95% ggH	3	≈1-2%
	VBF 1, 2-jet	≈11-47% VBF	6	
	VH hadronic	≈13% WH, ≈10% ZH	3	
	VH leptonic	≈46% WH	3	
	VH p_T^{miss}	≈56% ZH	3	
	ttH	≈71% ttH	3	
$H \to WW^{(*)} \to \ell\nu\ell\nu$, Section 2.3				
$e\mu/\mu e$	ggH 0, 1, 2-jet	≈55-92% ggH, up to ≈15% $H \to \tau\tau$	17	≈20%
	VBF 2-jet	≈47% VBF, up to ≈25% $H \to \tau\tau$	2	
$ee+\mu\mu$	ggH 0, 1-jet	≈84-94% ggH	6	
$e\mu$+jj	VH 2-jet	22% VH, 21% $H \to \tau\tau$	1	
3ℓ	WH leptonic	≈80% WH, up to 19% $H \to \tau\tau$	2	
4ℓ	ZH leptonic	85-90% ZH, up to 14% $H \to \tau\tau$	2	
$H \to \tau\tau$, Section 2.4				
$e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$	0-jet	≈70-98% ggH, 29% $H \to WW$ in $e\mu$	4	≈10-20%
	VBF	≈35-60% VBF, 42% $H \to WW$ in $e\mu$	4	
	Boosted	≈48-83% ggH, 43% $H \to WW$ in $e\mu$	4	

New HIG-16-042

5.9σ PLB 779 (2018) 283

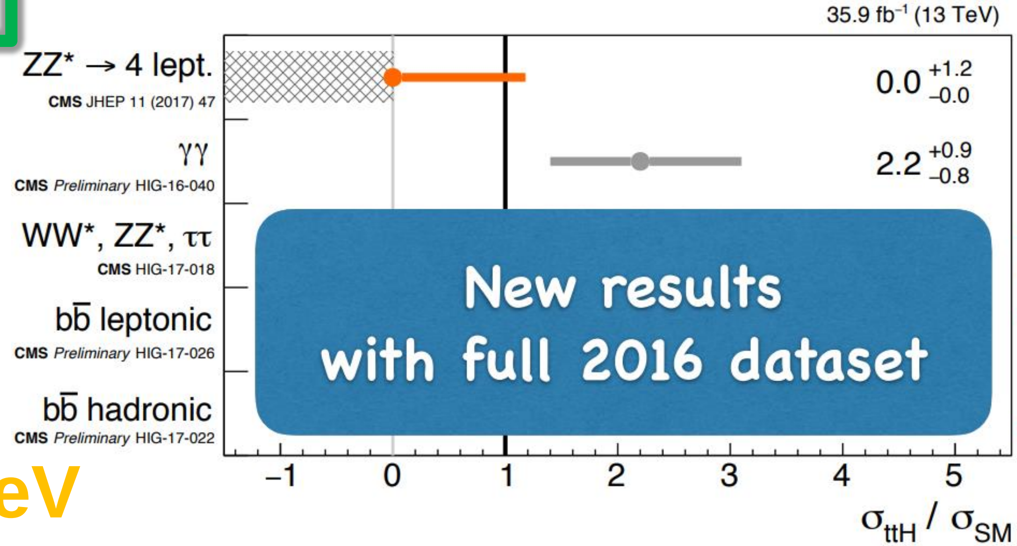
CMS Big Combination

CMS-PAS-HIG-17-031

VH production with H → bb, Section 2.5		3.8σ arXiv:1709.07497		
Z(νν)bb	ZH leptonic	≈100% VH, 85% ZH	1	≈10%
W(ℓν)bb	WH leptonic	≈100% VH, ≈97% WH	2	
Z(ℓℓ)bb	Low p_T(V) ZH leptonic	≈100% ZH, of which ≈20% ggZH	2	
	High p_T(V) ZH leptonic	≈100% ZH, of which ≈36% ggZH	2	
Boosted H Production with H → bb, Section 2.6				
H → bb	p_T(H) bins	PRL 120 (2018) 071802 ≈72-79% ggH	6	≈10%
ttH production with H → leptons, Section 2.7				
H → WW, ττ, ZZ	2ℓss	WW/ττ ≈ 4.5, ≈5% tH	10	New HIG-17-018
	3ℓ	WW : ττ : ZZ ≈ 15 : 4 : 1, ≈5% tH	4	
	4ℓ	WW : ττ : ZZ ≈ 6 : 1 : 1, ≈3% tH	1	
	1ℓ+2τ_h	96% ttH with H → ττ, ≈6% tH	1	
	2ℓss+1τ_h	ττ : WW ≈ 5 : 4, ≈5% tH	2	
	3ℓ+1τ_h	ττ : WW : ZZ ≈ 11 : 7 : 1, ≈3% tH	1	
ttH production with H → bb, Section 2.8				
H → bb	$t\bar{t}$ → jets	≈83-97% ttH with H → bb	6	New HIG-17-022/026
	$t\bar{t}$ → 1ℓ+jets	≈65-95% ttH with H → bb, up to 20% H → WW	18	
	$t\bar{t}$ → 2ℓ+jets	≈84-96% ttH with H → bb	3	
H → μμ, Section 2.9				
μμ	S/B bins	56-96% ggH, 1-42% VBF	15	≈1-2%
Search for invisible H decays, Section 2.10				
H → inv.	VBF	52% VBF, 48% ggH	1	Br<0.24 HIG-17-023
	ggH + ≥ 1 jet	80% ggH, 9% VBF	1	
	VH hadronic	54% VH, 39% ggH	1	
	ZH leptonic	≈100% ZH, of which 21% ggZH	1	

CMS ttH

HIG-17-018,022,026



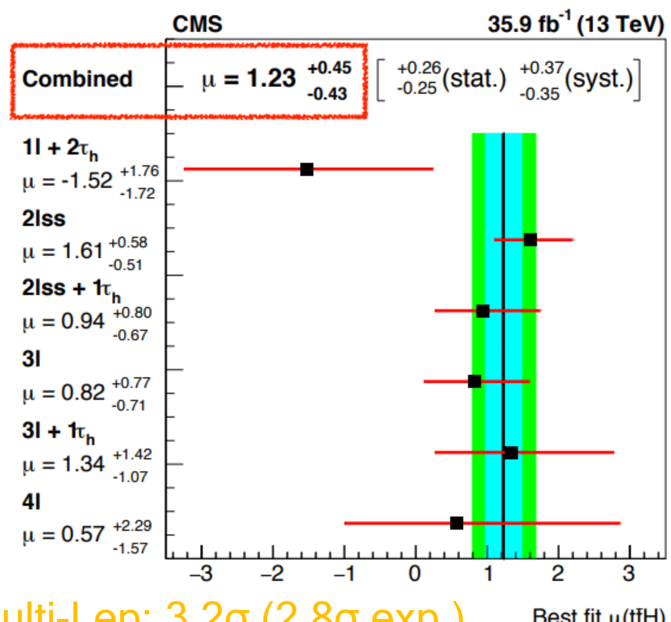
New combination of leptonic channels

New measurements shown today for the first time

7+8+13TeV

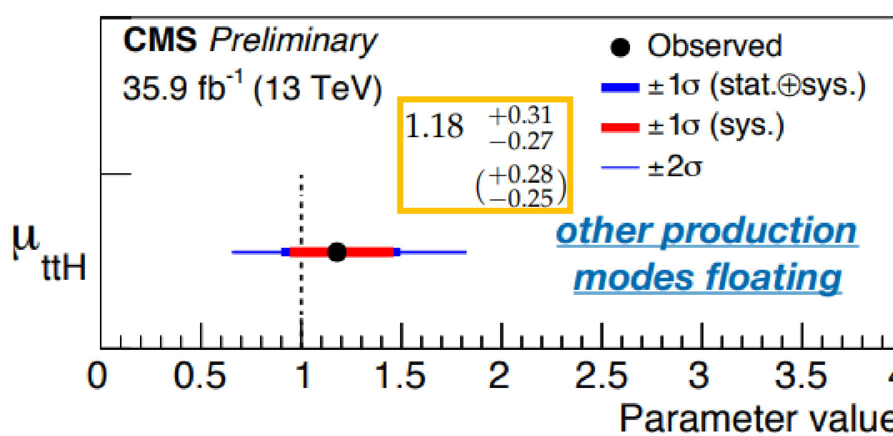
>5σ

- Event categorization in lepton flavor, charge and b-jet multiplicity
- Multivariate analysis and Matrix Element method, DNN for Hbb(1lep)



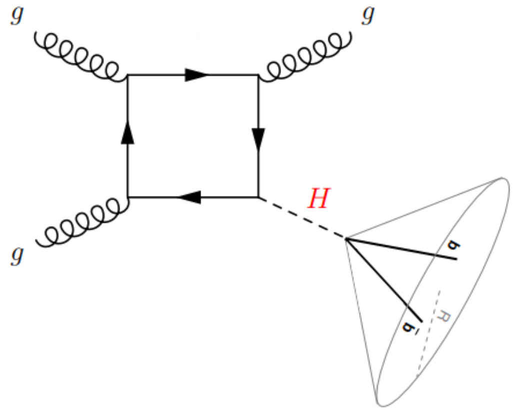
Multi-Lep: 3.2σ (2.8σ exp.)

- All ttH analyses combined with other Higgs measurements in global fits



CMS Boosted H(bb)

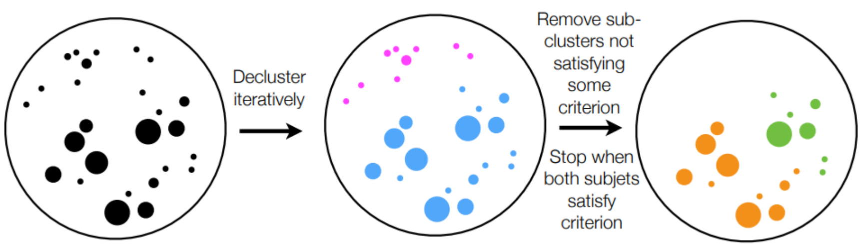
Phys. Rev. Lett. 120, 071802 (2018)



Huge QCD Bkg

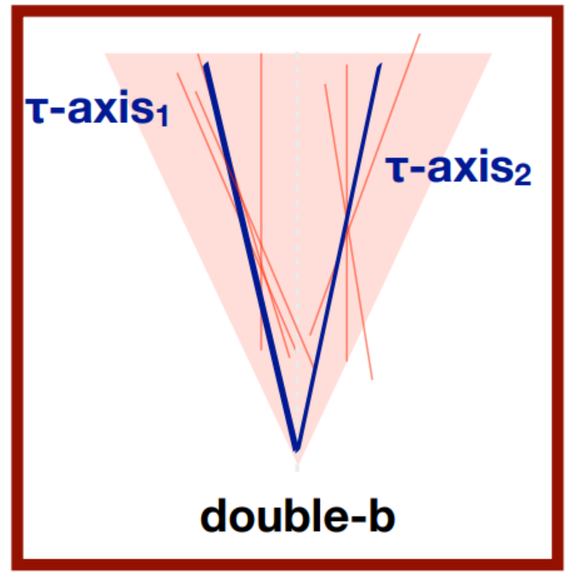
Fat Jet, with PT>450GeV

- Dedicated algorithm to remove pile -up effects (PUPPI)
- Grooming (soft -drop mass) removes soft radiation
- Generalized energy correlation functions are sensitive to N-point correlations within a jet



Soft Drop Condition: $$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

CMS: $z_{cut} = 0.1$, $\beta = 0$



- Identifies two b hadron decay chains in the same fat jet
- Does not define subjects, but uses N-subjettiness axes

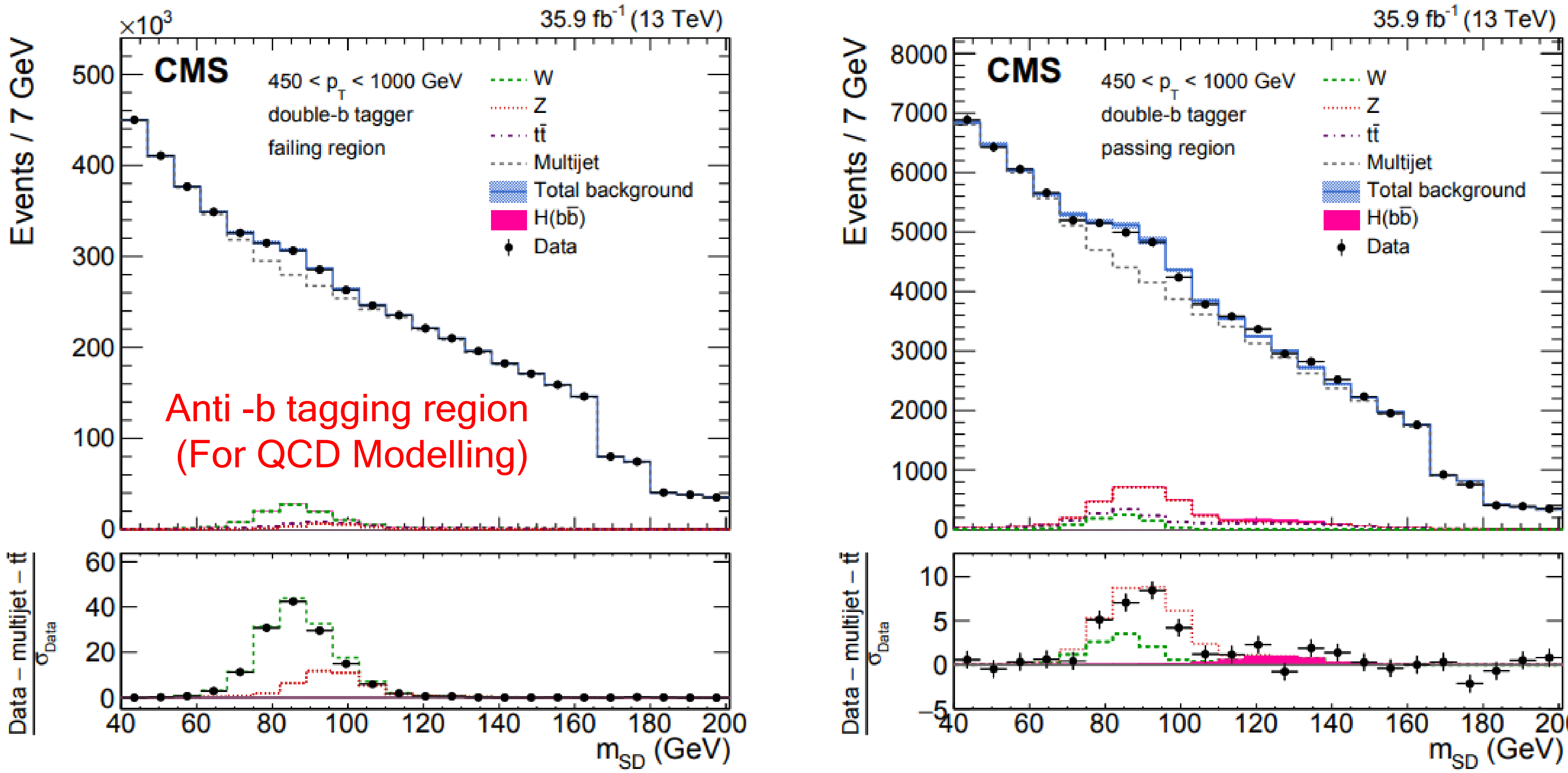
$$_1e_2^{\beta} = \sum_{1 \le i < j \le n_J} z_i z_j \Delta R_{ij}^{\beta}$$

$$N_2^{\beta} = \frac{_2e_3^{\beta}}{(_1e_2^{\beta})^2} \qquad \beta = 1$$

$$_2e_3^{\beta} = \sum_{1 \le i < j < k \le n_J} z_i z_j z_k \min\{\Delta R_{ij}^{\beta} \Delta R_{ik}^{\beta}, \Delta R_{ij}^{\beta} \Delta R_{jk}^{\beta}, \Delta R_{ik}^{\beta} \Delta R_{jk}^{\beta}\}$$

CMS Boosted H(bb)

Phys. Rev. Lett. 120, 071802 (2018)



measured visible cross sections for p_T > 450 GeV:

$\sigma_H = 74^{+51}_{-49}$ fb

$\sigma_Z = 0.85^{+0.26}_{-0.21}$ pb

observed Z(bb) significance:

5.1σ, $\mu_Z = 0.78^{+0.23}_{-0.19}$

observed H(bb) significance:

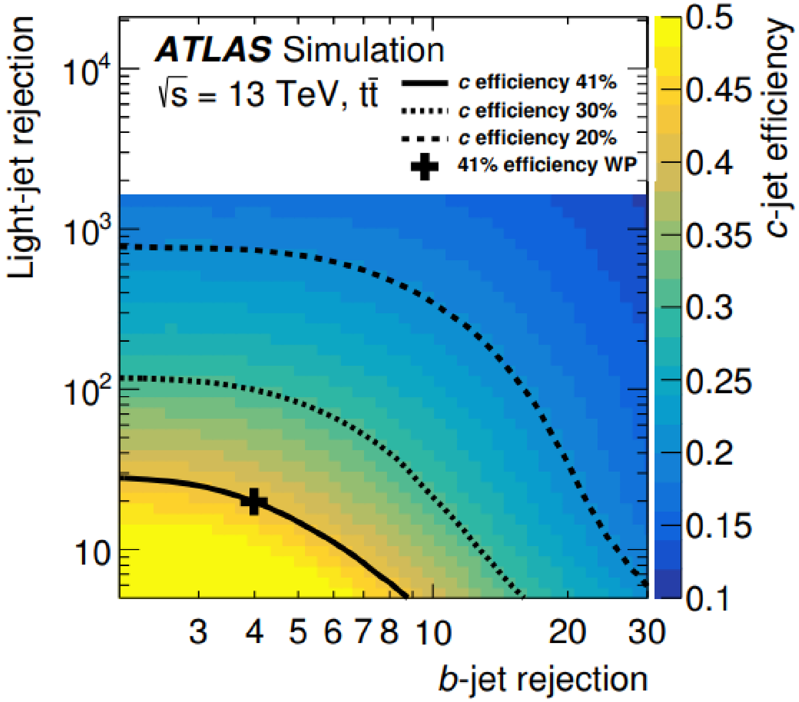
1.5σ, $\mu_H = 2.3^{+1.8}_{-1.6}$

ATLAS H(cc)

arXiv:1802.04329

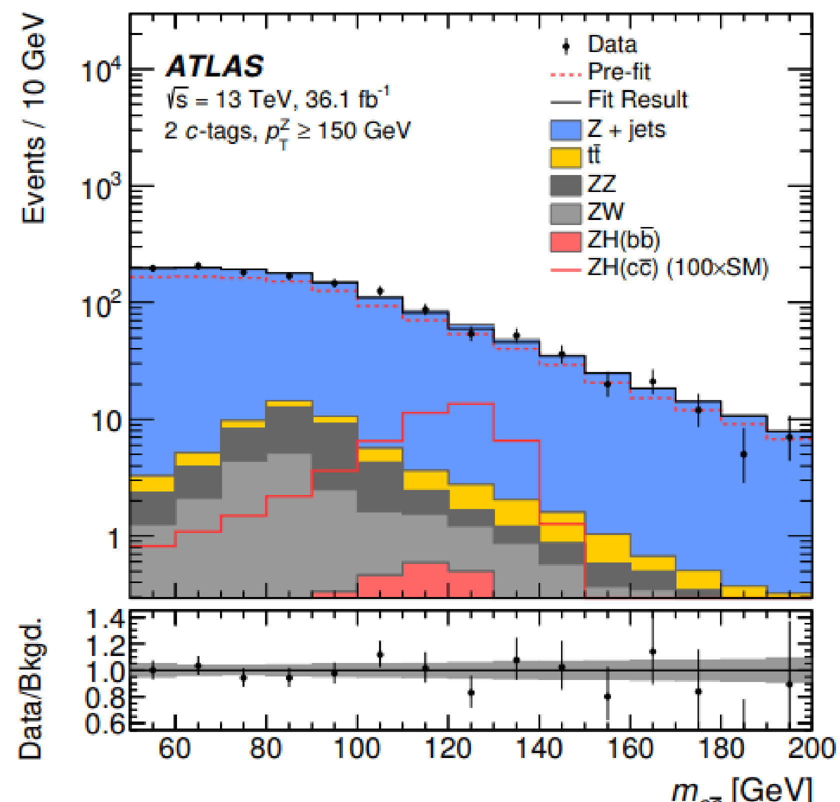
Dedicated MVA discriminants similar to b-tagger:

- Separate c-jets from light-jets and c-jets from b-jets
- Challenges of short τc , low track multiplicity in c-hadron decays
- Both 1 c-tag and 2 c-tag events are used to keep efficiency high



Validation: $\mu_{ZV} = 0.6^{+0.5}_{-0.4}$
(1.4σ observed, 2.2σ expected)

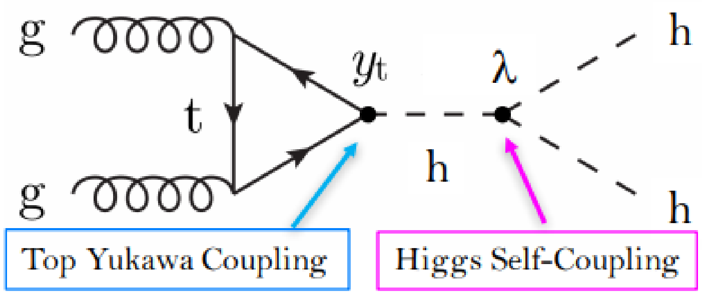
Cut-based event selection with fit to m_{cc}

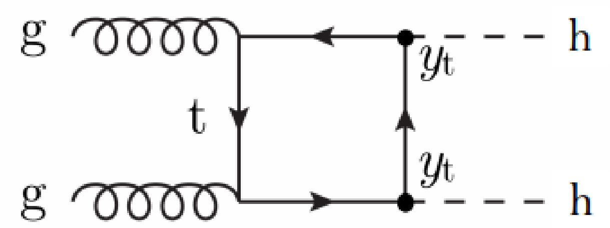


Observed upper limit of 2.7 pb on $\sigma(ZH) \times B(H \to c\bar{c})$
(SM predicts 26 fb at 13 TeV)

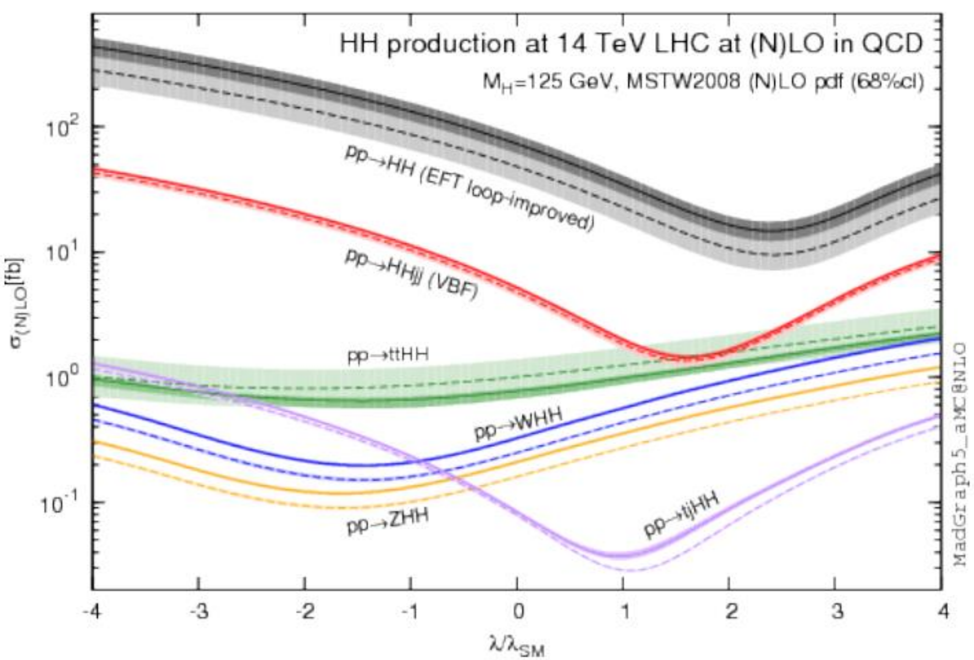
HH: Higgs Self Couplings and Resonant search

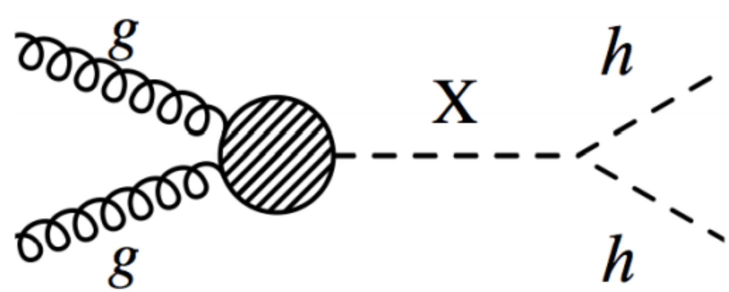
$$\lambda_{SM} = \frac{m_h^2}{2v^2}$$





- Probing Higgs Self-coupling and potential
- Small xsec ~30fb at 13 TeV
- Many different channels: bbbb, bbγγ, bbτ τ,bbww……
- Also sensitive to heavy resonance: Radion, Graviton, heavy scalar

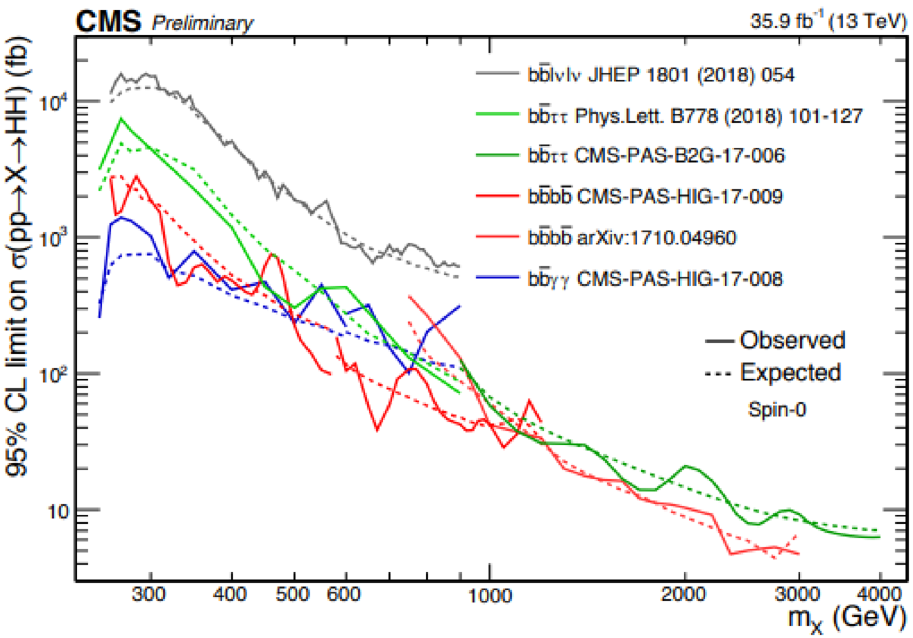


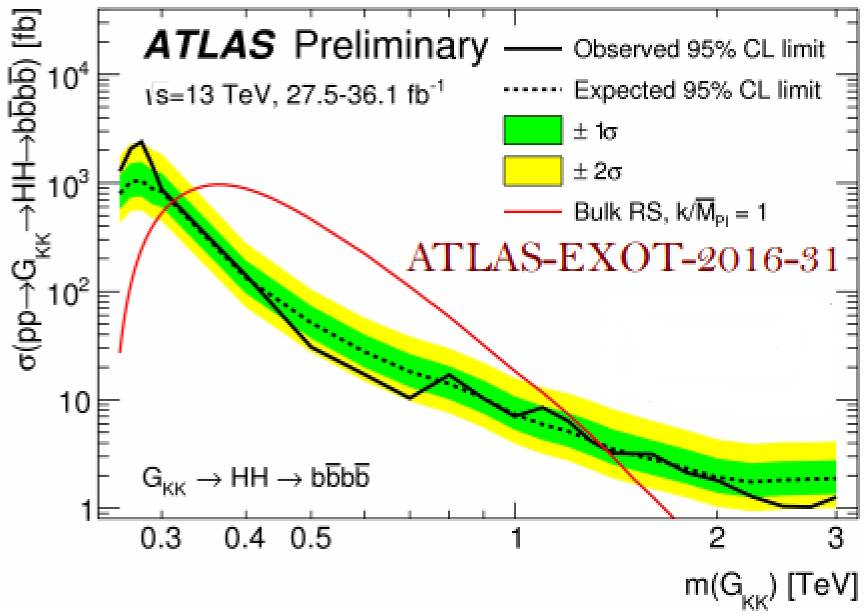


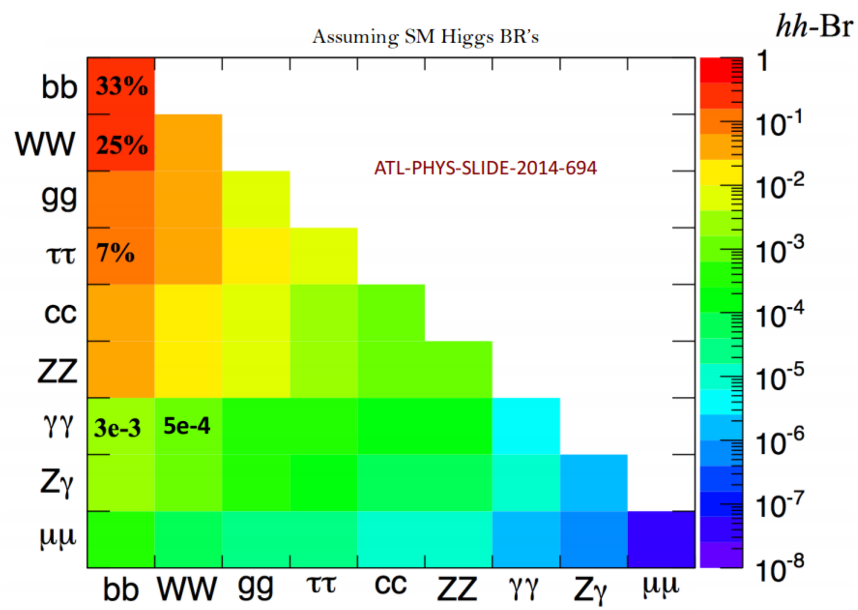
Cross sections up to O(pb) possible

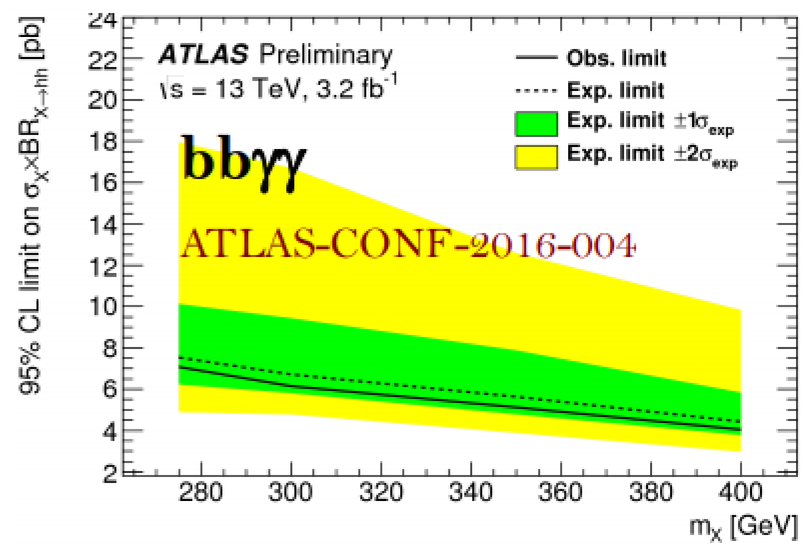
HH Resonance

ATLAS-EXOT-2016-31, ATLAS-CONF-2016-004,071
CMS-PAS-HIG-17-008



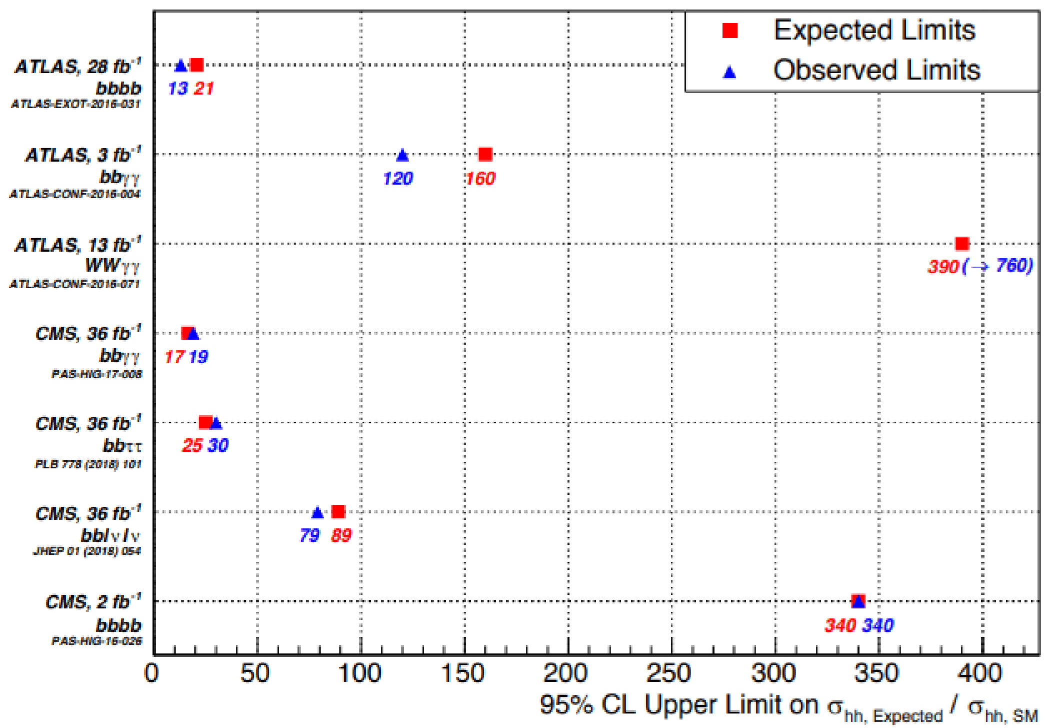


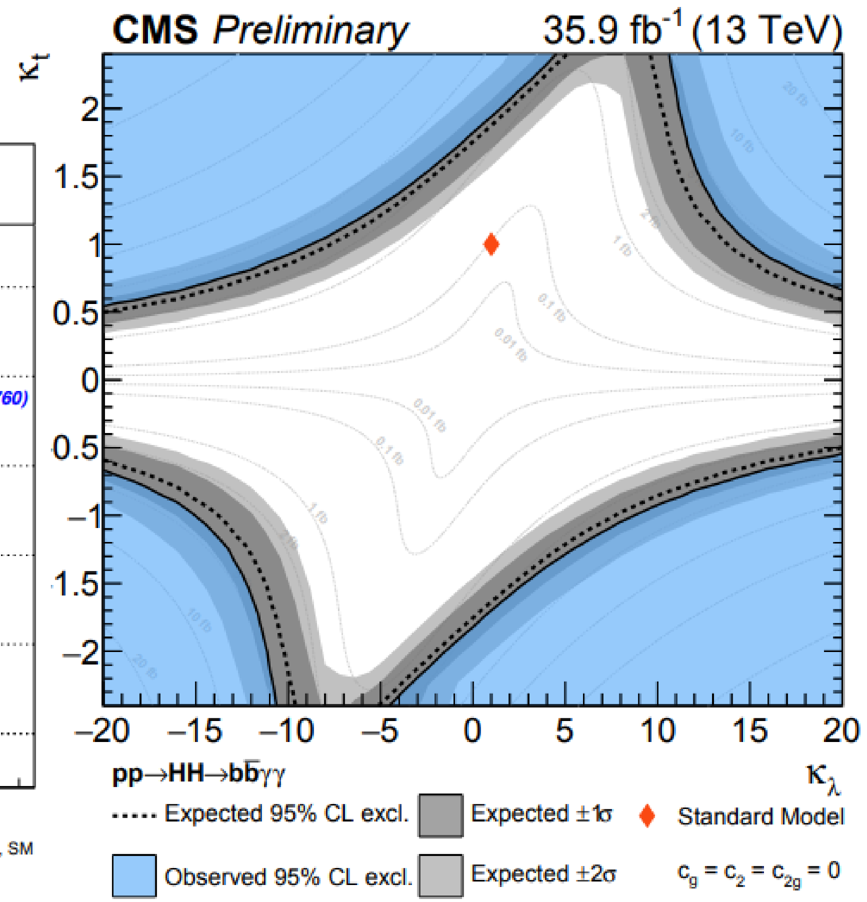




HH Non-Resonance

CMS-PAS-HIG-17-008





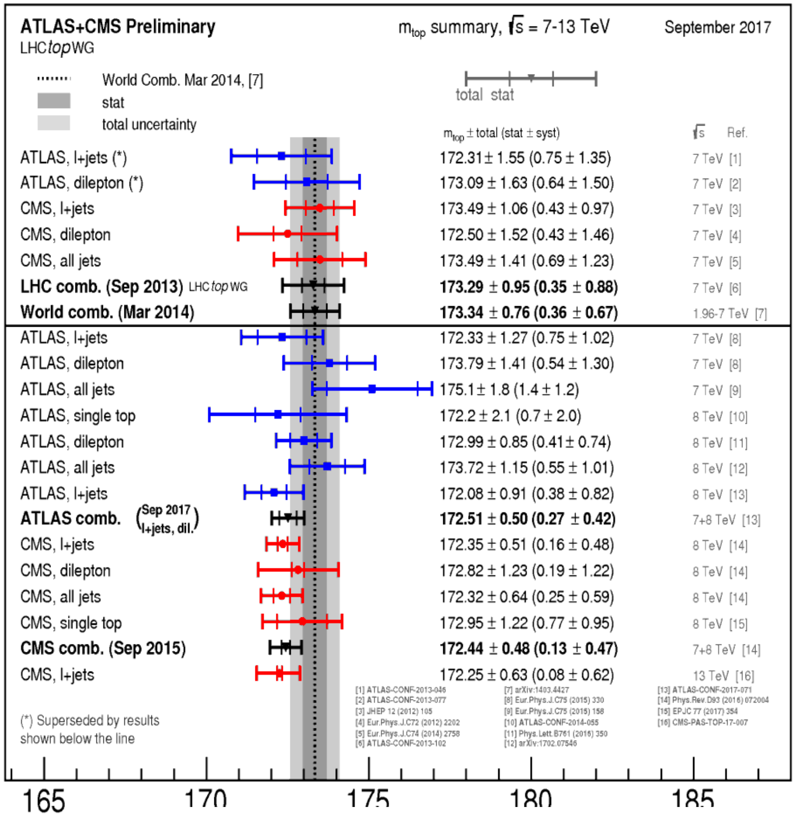
- Non resonance xsec limit :
  ~40@Run1 → ~10@Run2 X σ(SM)
- Limit on Higgs Self-coupling, assuming all others SM-like
  $\kappa_\lambda > -8.82$ and $\kappa_\lambda < 15.04$

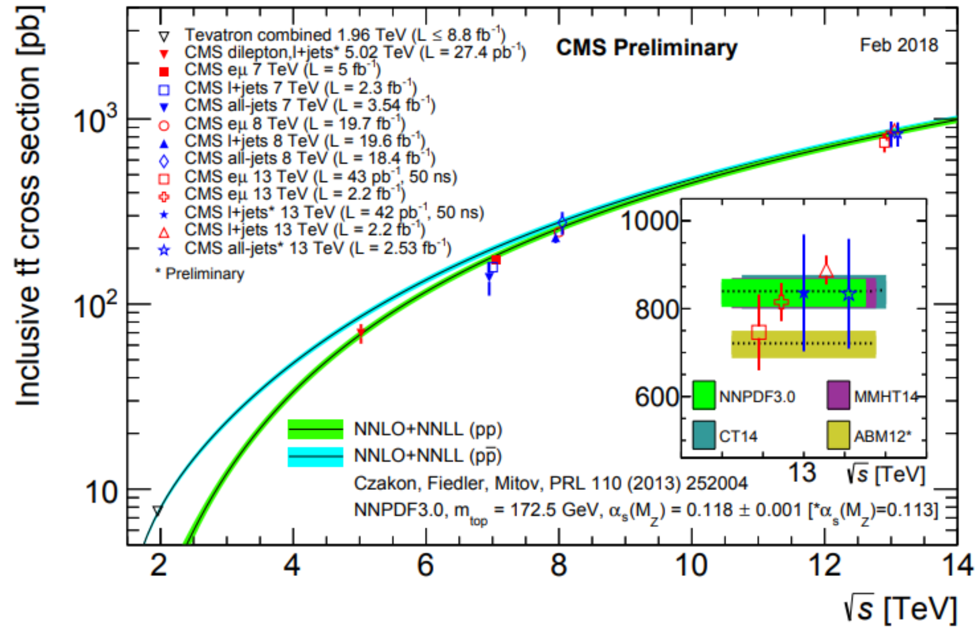
$$\Delta\mathcal{L} = \kappa_\lambda\,\lambda_{SM} v\,\mathrm{H}^3 - \frac{m_t}{v}\left(v + \kappa_t\,\mathrm{H} + \frac{c_2}{v}\,\mathrm{H}^2\right)\left(\bar{t}_L t_R + h.c.\right) + \frac{1}{4}\frac{\alpha_s}{3\pi v}\left(c_g\,\mathrm{H} - \frac{c_{2g}}{2v}\,\mathrm{H}^2\right) G^{\mu\nu}G_{\mu\nu}$$

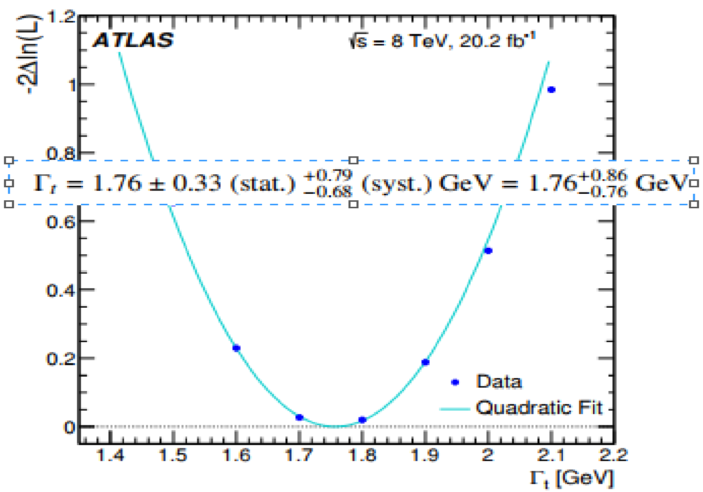
SM and TOP

Top Physics

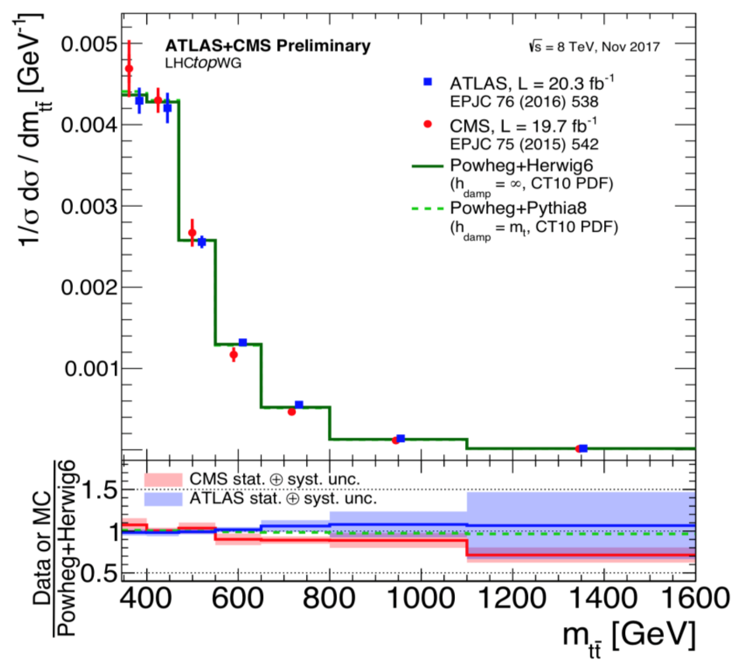
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults







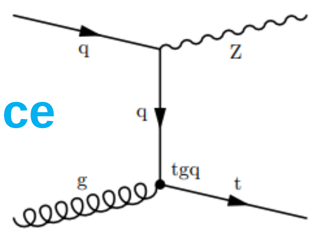
$$\Gamma_t = 1.76 \pm 0.33\ (\text{stat.})\ ^{+0.79}_{-0.68}\ (\text{syst.})\ \text{GeV} = 1.76^{+0.86}_{-0.76}\ \text{GeV}$$



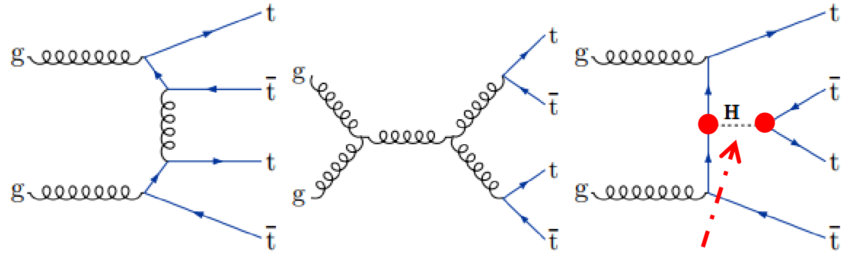
Top Highlights

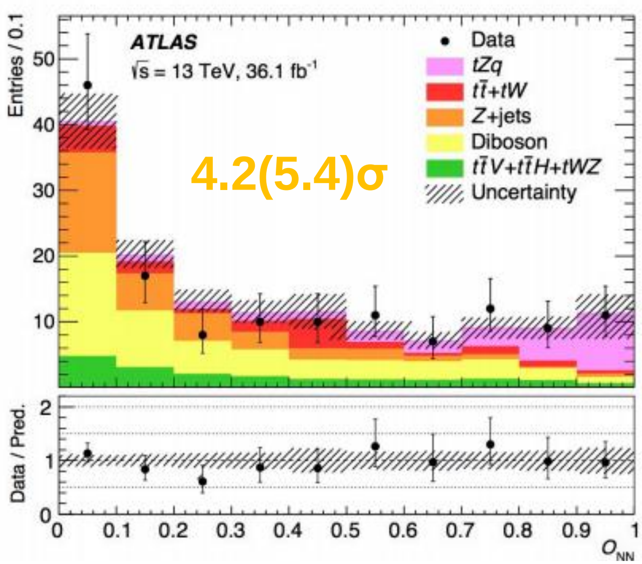
arXiv:1710.03659; arXiv:1709.07411; PLB779 (2018) 3585; JHEP 07(2017) 003; EPJC78 (2018) 140

tZq evidence

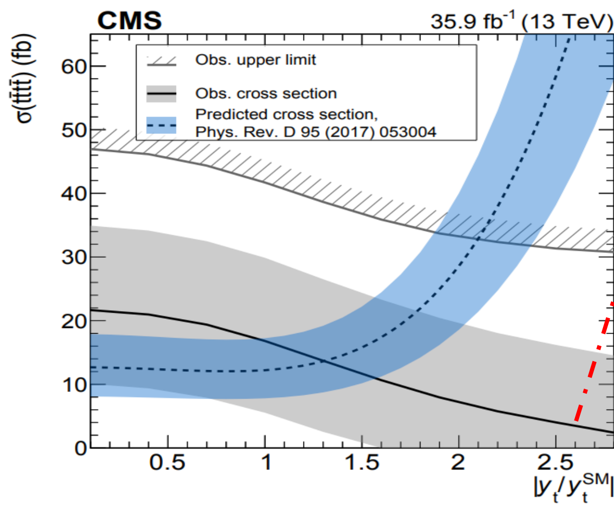


4-top

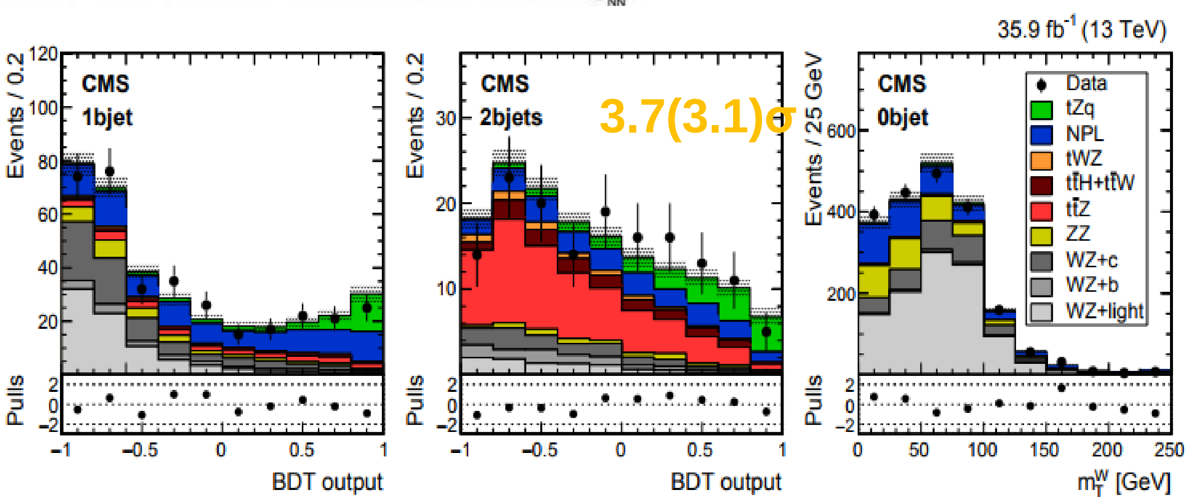




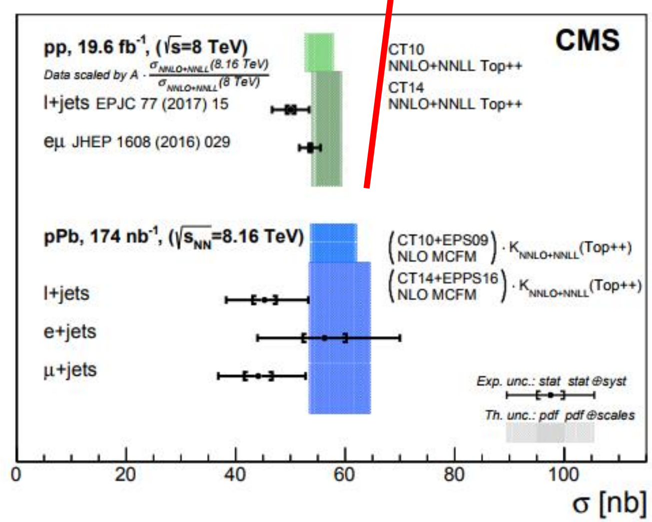
4.2(5.4)σ



First observation of top quark production in proton-nucleus collisions



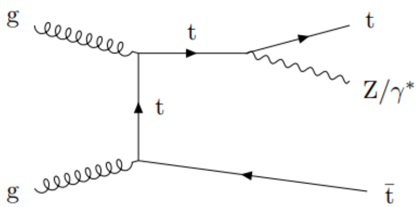
3.7(3.1)σ



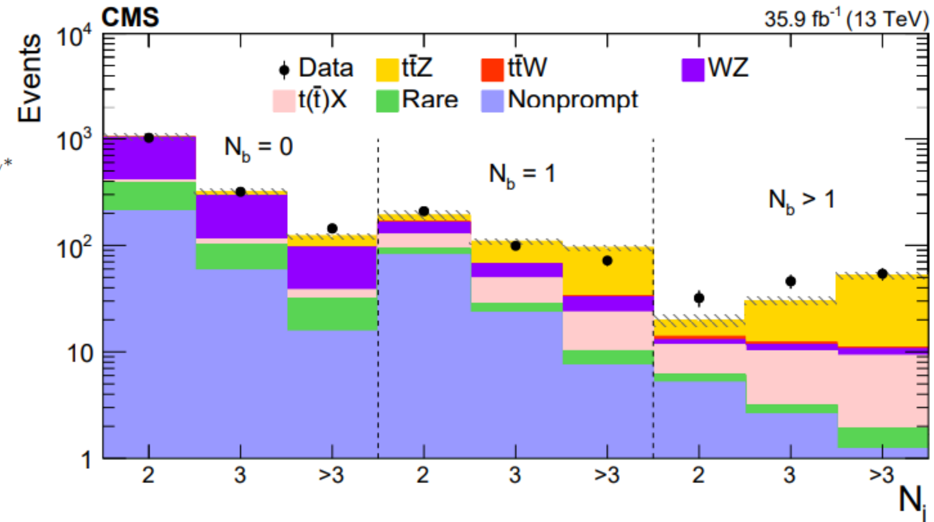
Top Highlights

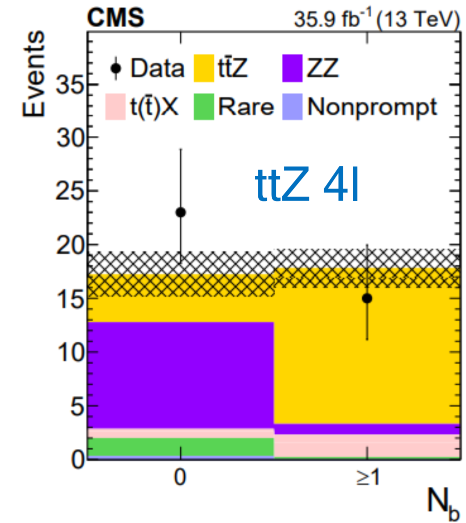
Eur. Phys. J. C77 (2017) 40, arXiv:1711.02547

ttZ 3l

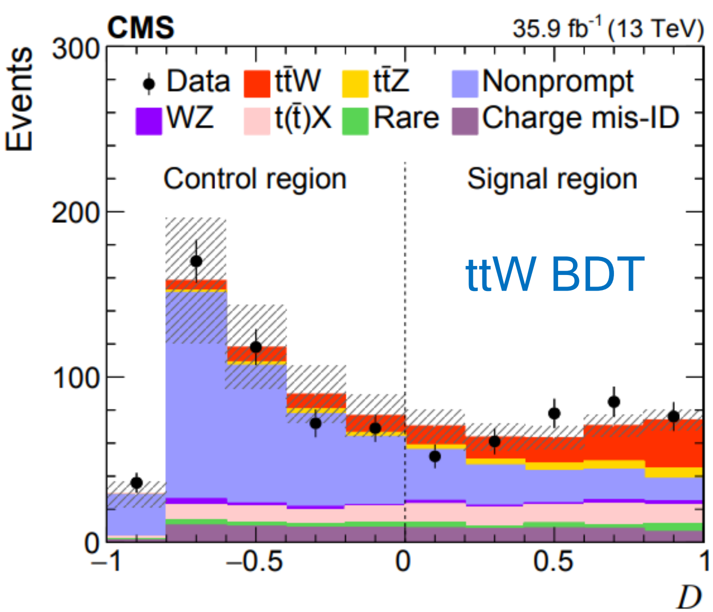


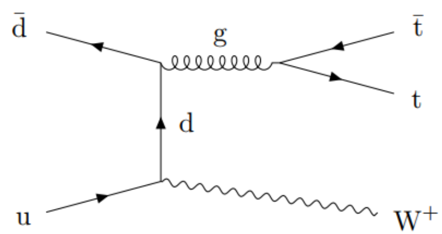
$\sigma^{SM} = 0.839 \pm 0.101$ pb



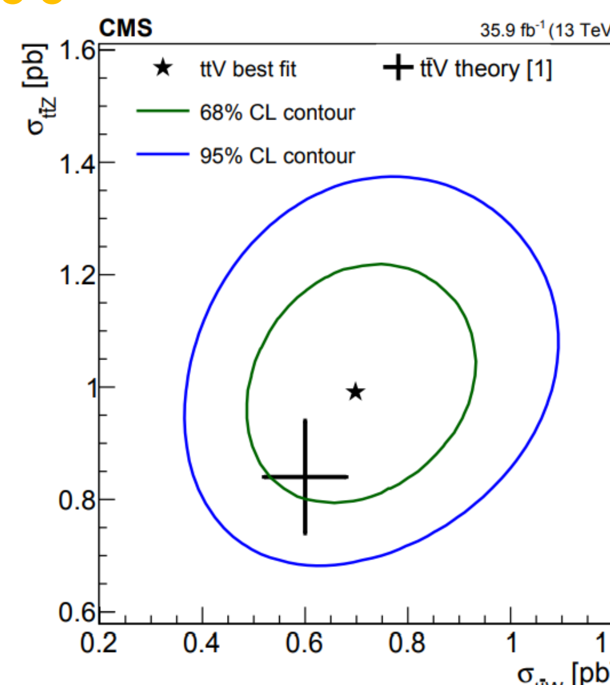


Observed significances above 5 σ



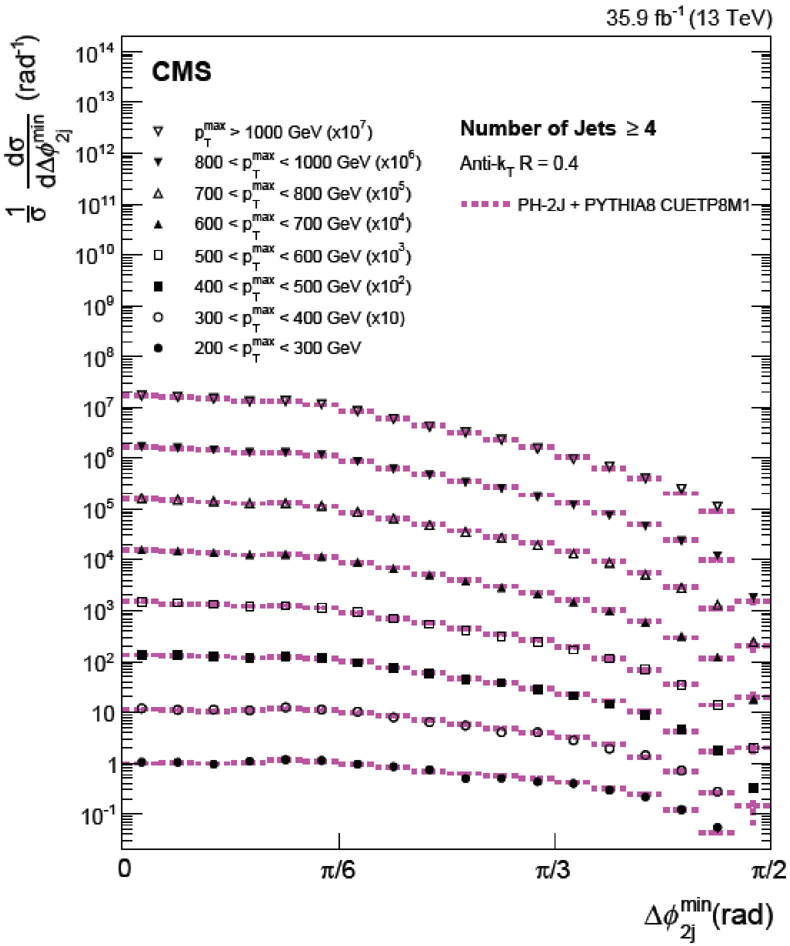


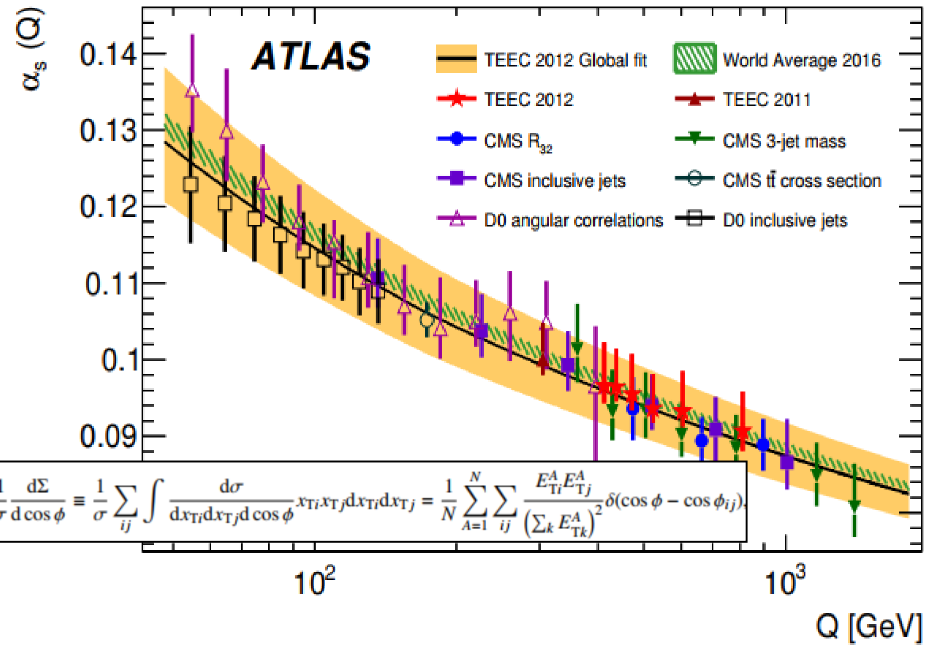
$\sigma^{SM} = 0.628 \pm 0.082$ pb



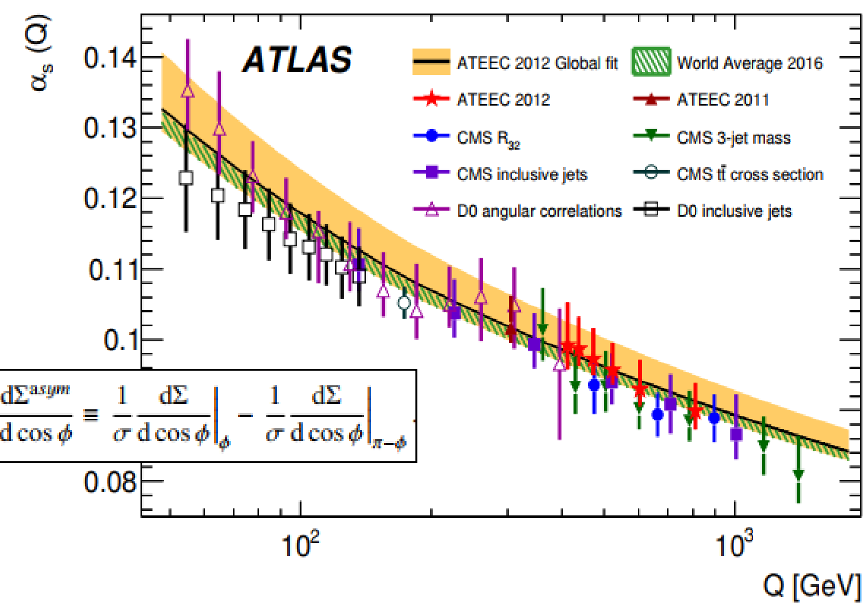
Multijets and α_s

arXiv:1707.02562; EPJC 77 (2017) 746; arXiv:1712.05471





$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{Ti}dx_{Tj}d\cos\phi}x_{Ti}x_{Tj}dx_{Ti}dx_{Tj} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{Ti}E^A_{Tj}}{\left(\sum_k E^A_{Tk}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

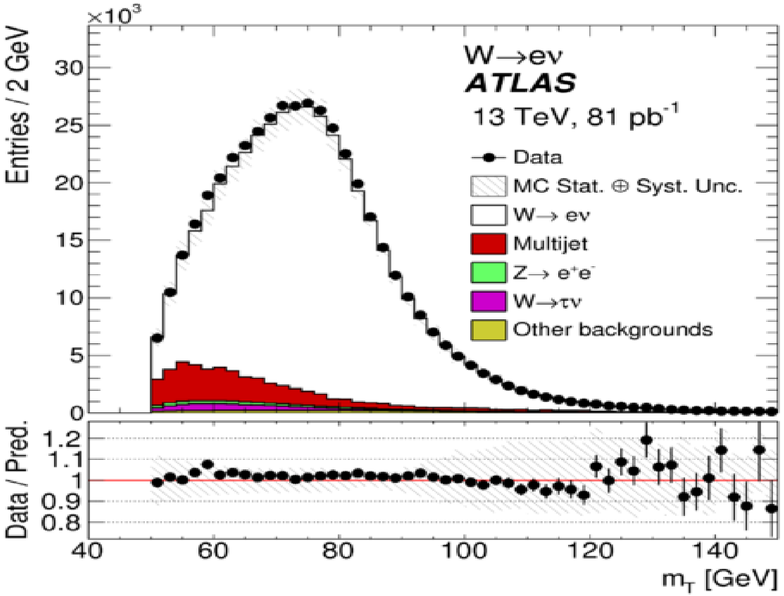


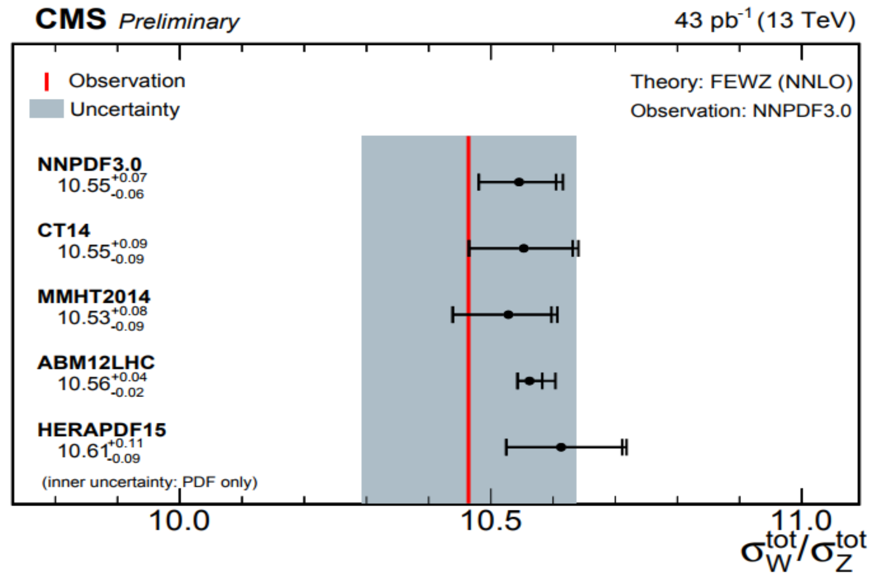
$$\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d\cos\phi} \equiv \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$

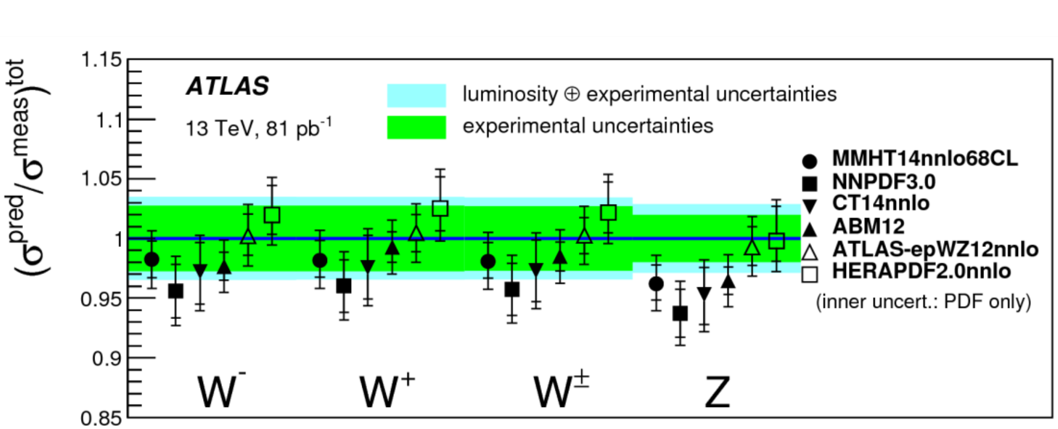
Jets correlations in multi-jet topology

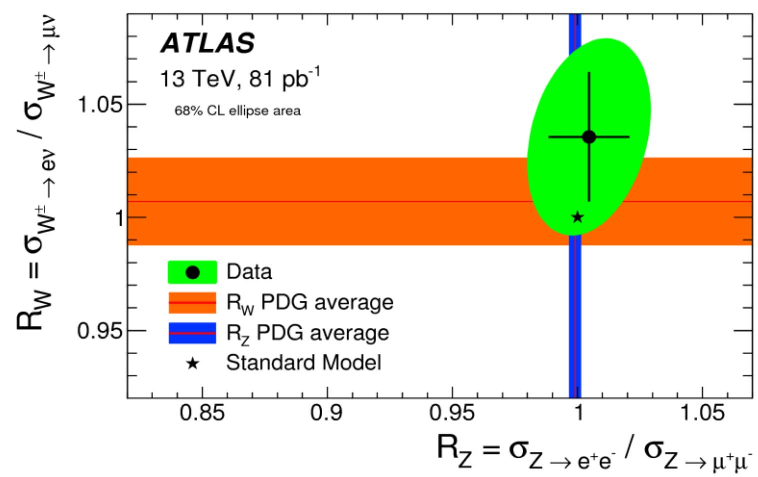
W/Z Xsecs 13TeV

PLB 759 (2016) 601; CMS-PAS-SMP-15-004, CMS-PAS-SMP-15-011









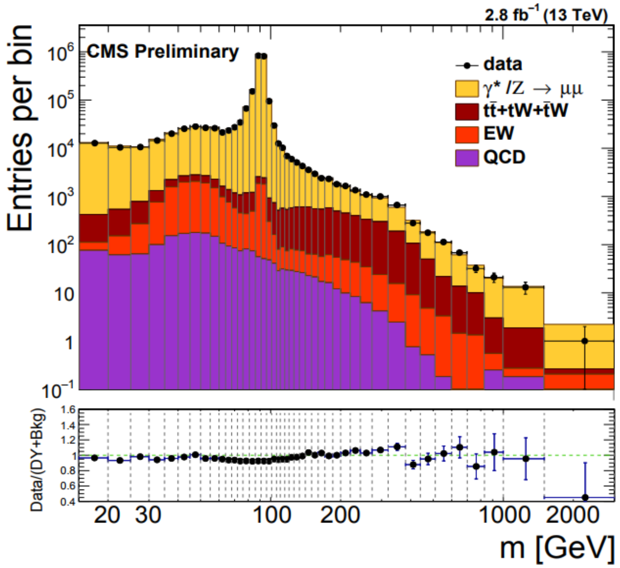
Good agreement with NNLO predictions. Sensitive to PDF.

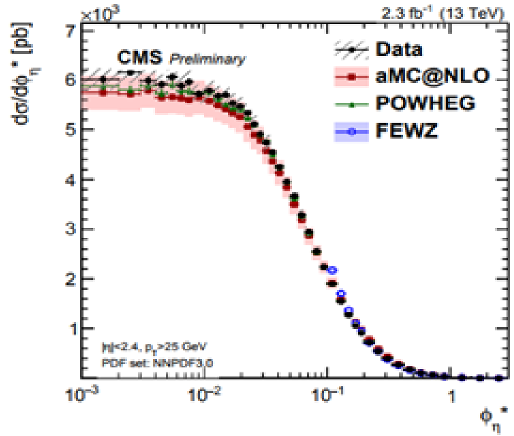
Stat unc. negligible. Sys largely cancelled in ratio. Lepton Universality also checked

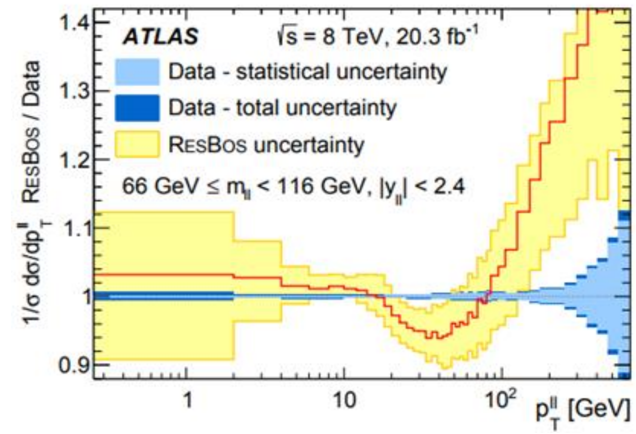
W/Z 1/2/3D

$M_{\mu\mu}, p_{Tz}, p_{T\mu}, y^{\mu\mu}, \Phi_{\eta}^{*}$

JHEP 12 (2017) 059; CMS-PAS-SMP-15-011; CMS-PAS-SMP-16-009



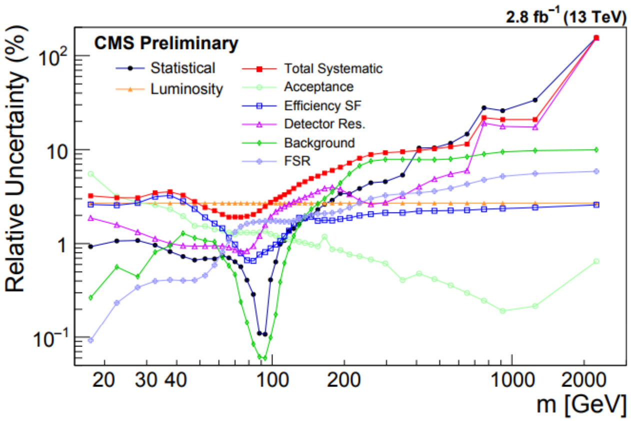


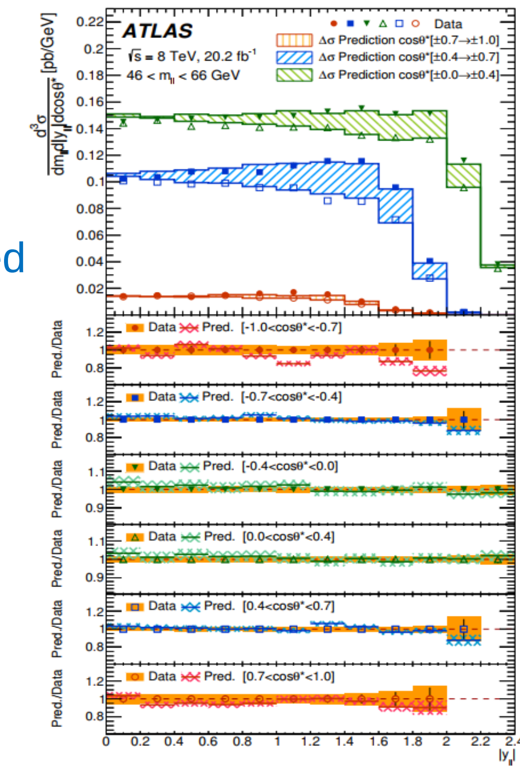


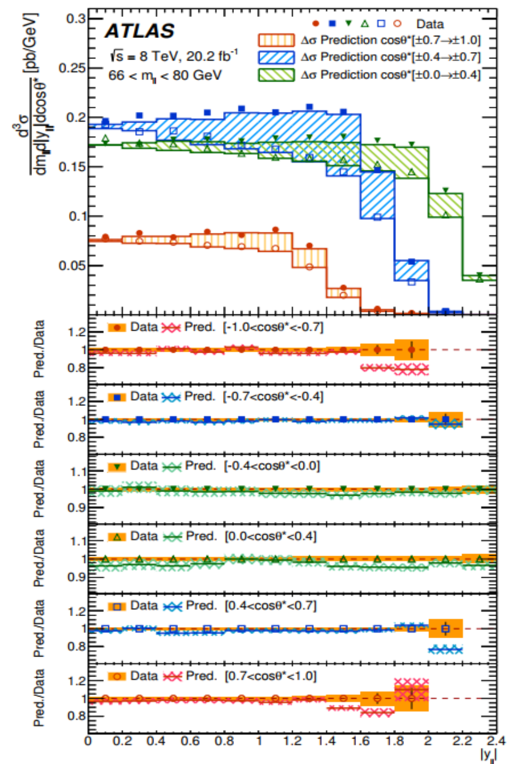
[15,3000]GeV, 43 bins

Stat unc. In very high mass bin

Pre- and Post-FSR both provided







3D

POWHEG including NNLO QCD +NLO EWK K factors

Angular Distributions and AFB

ATLAS JHEP 08 (2016) 159 8TeV 20.3/fb
CMS PLB 750 (2015) 154 8TeV 19.7/fb
CMS EPJC 76 (2016) 325 8TeV 19.7/fb
LHCb JHEP 1511(2015) 190 7+8TeV 3/fb

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}$$

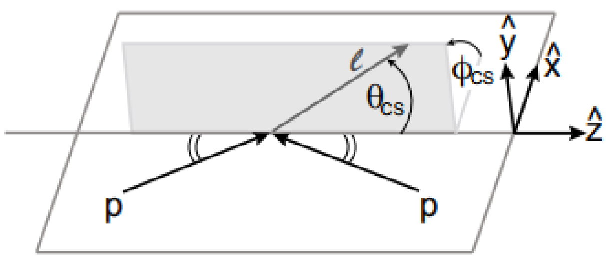
$$\Big\{(1+\cos^2\theta) + \frac{1}{2} A_0(1-3\cos^2\theta) + A_1\ \sin 2\theta\ \cos\phi$$
$$+\frac{1}{2} A_2\ \sin^2\theta\ \cos 2\phi + A_3\ \sin\theta\ \cos\phi + A_4\ \cos\theta$$
$$+A_5\ \sin^2\theta\ \sin 2\phi + A_6\ \sin 2\theta\ \sin\phi + A_7\ \sin\theta\ \sin\phi\Big\}.$$

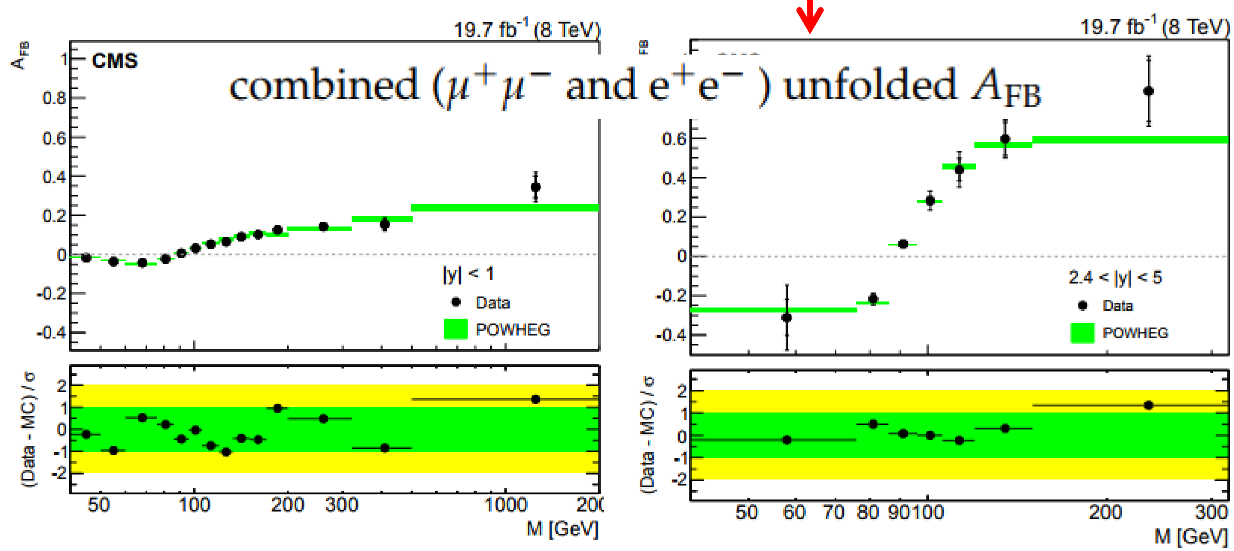
A_4 is the only non-zero at LO
A_{0-3} become non-zero at NLO
$A_0 - A_2 = 0$ Lam-Tung relation (valid at O(α_s))
A_{5-7} appear at NNLO

integrating over ϕ yields:

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta} = \frac{3}{8}\frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_4\cos\theta\Big\}.$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$





combined ($\mu^+\mu^-$ and e^+e^-) unfolded A_{FB}

$$\cos\theta^*_{CS} = \frac{2(P_1^+P_2^- - P_1^-P_2^+)}{\sqrt{Q^2(Q^2+Q_T^2)}},$$

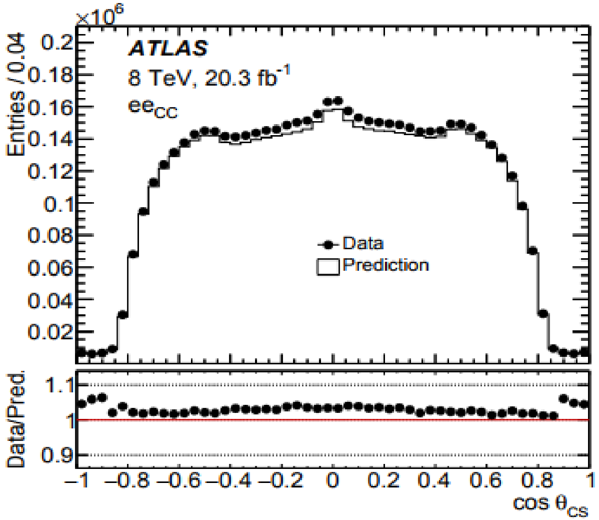
$$\cos\theta^*_{CS} \rightarrow \frac{|Q_z|}{Q_z}\cos\theta^*_{CS},$$

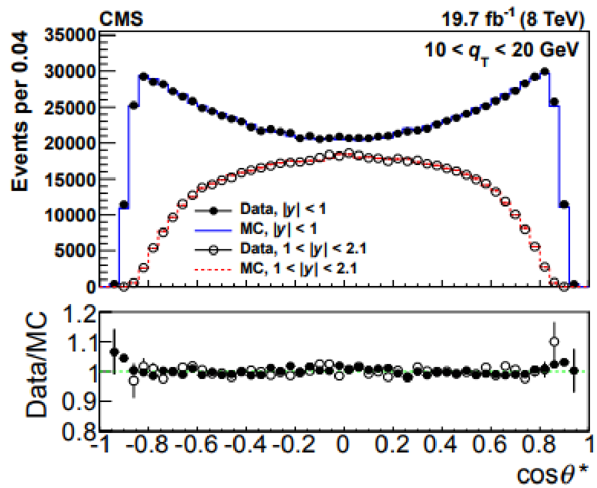
Dilution effect is smaller at high |y|

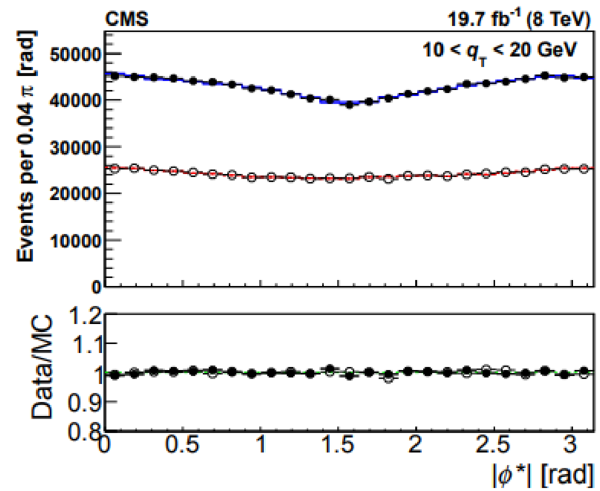
8/4.3M |y|<2.4 $\mu\mu/ee$ events;
0.5M 2.4<|y|<5 ee events

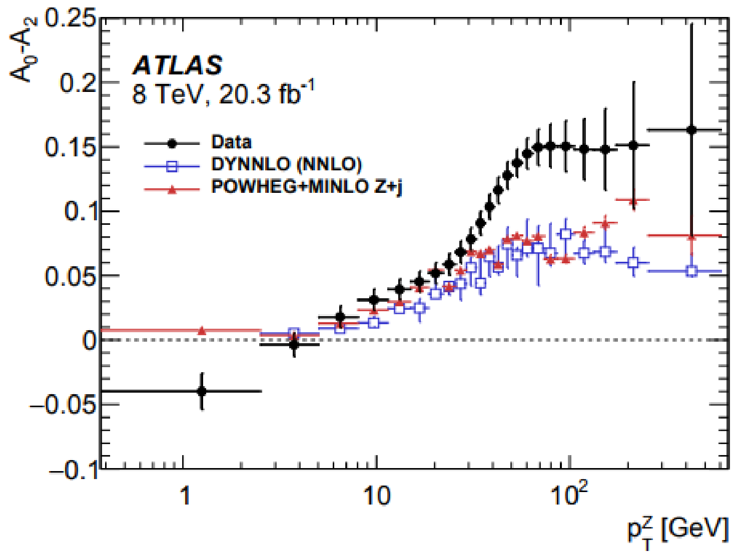
Angular Coefficients

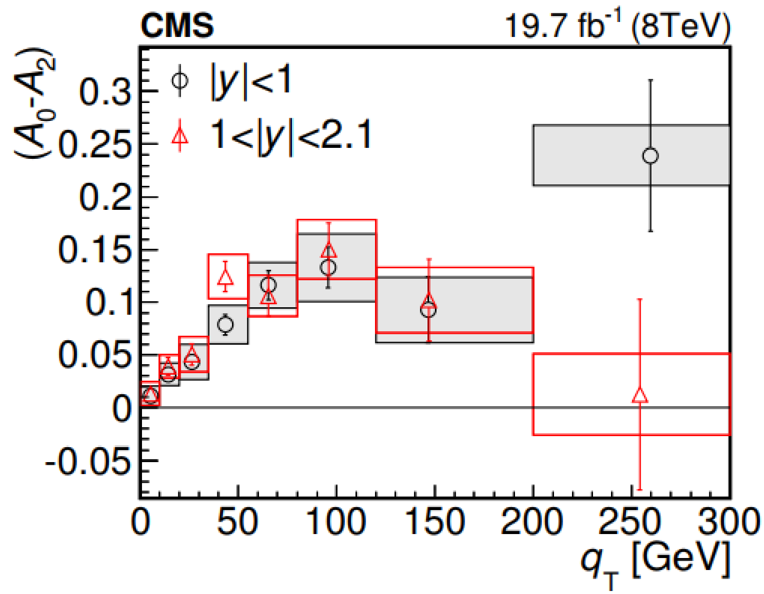
Template fit to extract the A_i coefficients









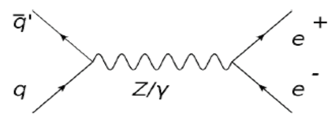


Lam-Tung relation violated as expected. High p^Z_T no good descriptions by models

Effective Mixing Angle

CMS-PAS-SMP-16-007; JHEP 09 (2015) 049

LEP, SLD 3σ tension



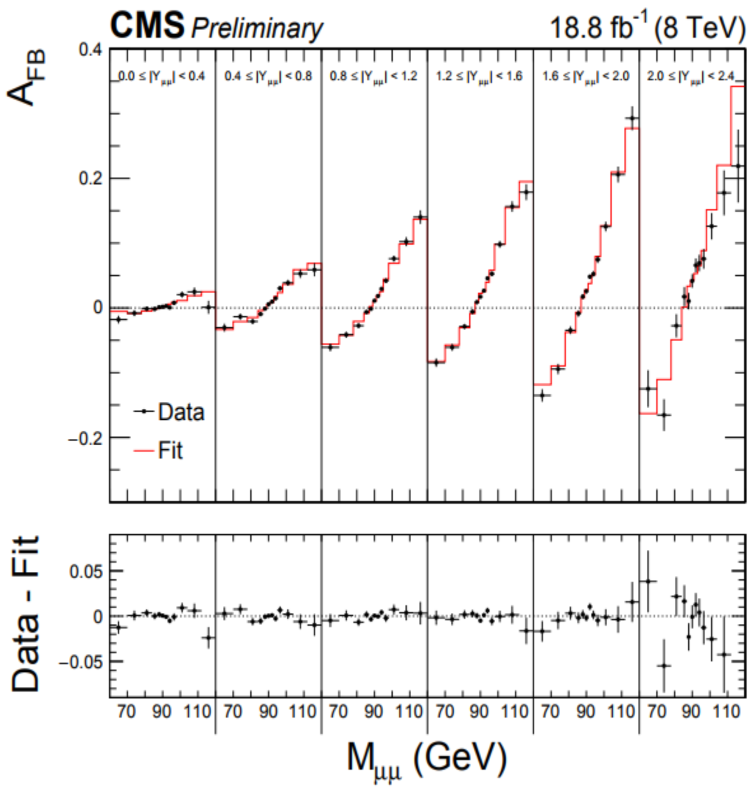
The axial and vector neutral currents interfere

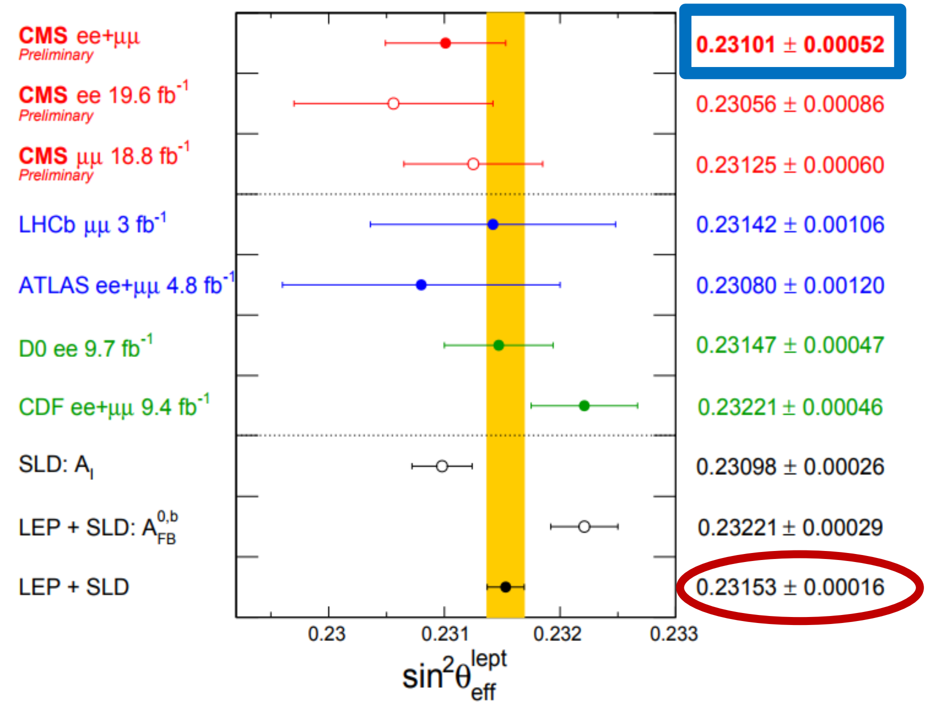
Weak neutral current strength related to $\sin^2\theta_{eff}$

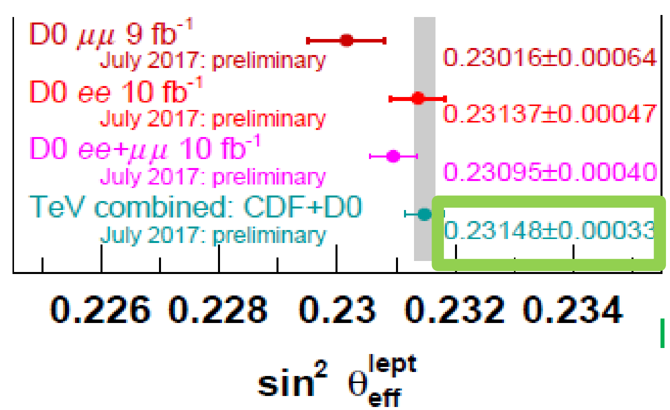
$\sin^2\theta_W = \sin^2\theta_W^{on\text{-}shell} = 1 - M_w^2 / M_z^2$

$\sin^2\theta_{eff}^{lept} = \mathrm{Re}[\kappa_l(M_Z^2, \sin^2\theta_W)]\sin^2\theta_W$

↳ ≈1.037



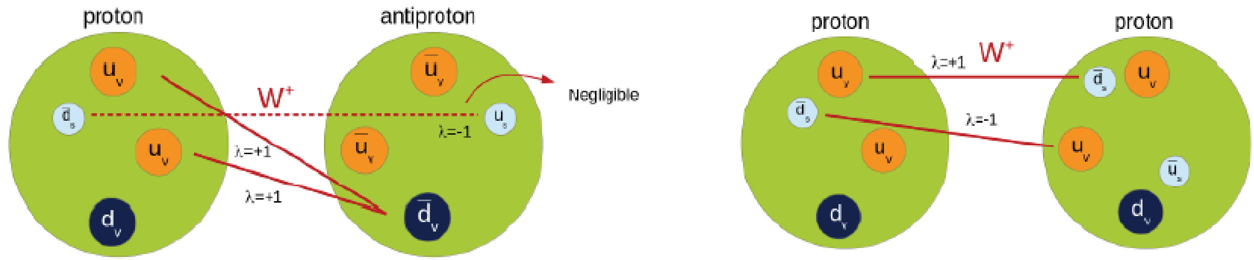




Inference on Mw:

W Mass

Eur. Phys. J. C 78 (2018) 110 ; CMS-PAS-SMP-14-007



- W^+/W^- production is asymmetric —> charge-dependent analysis
- Second generation quark PDFs play a larger role at the LHC *(25% of the W-boson production is induced by at least one second generation quark s or c).*
- The W polarisation is determined by the difference between the u,d valence and sea densities

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y)P_i(\cos\theta, \phi)\right]$$

Breit-Wigner

NNLO pQCD

Parton Shower

Decay channel	$W \to e\nu$	$W \to \mu\nu$
Kinematic distributions	p_T^ℓ, m_T	p_T^ℓ, m_T
Charge categories	W^+, W^-	W^+, W^-
$\lvert\eta_\ell\rvert$ categories	[0, 0.6], [0.6, 1.2], [1.8, 2.4]	[0, 0.8], [0.8, 1.4], [1.4, 2.0], [2.0, 2.4]

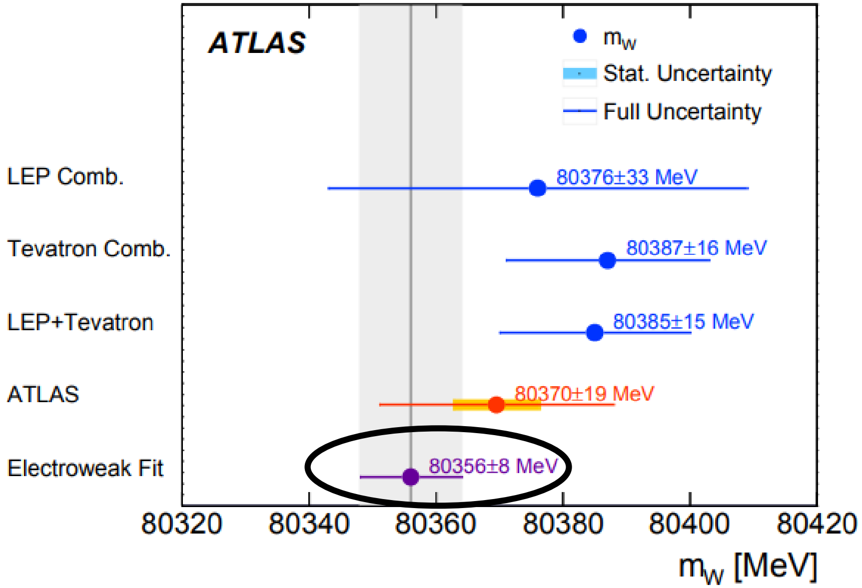
Py8 AZ Tune by Z data, extrapolated to W. It describe W/Z PT better than resummed predictions (DYRES, ResBos, CuTe and POWHEG MiNLO+PY8).

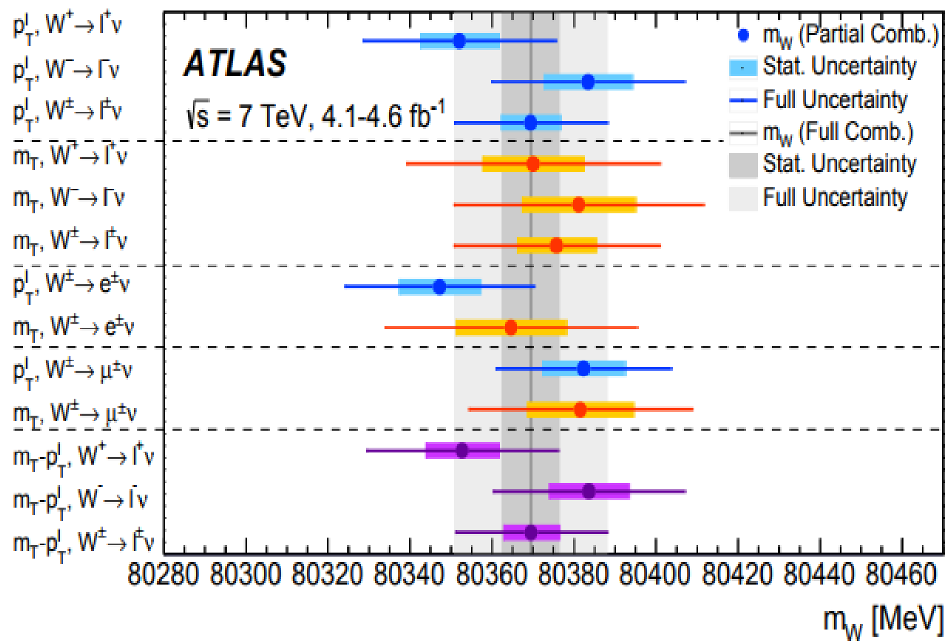
DYNNLO for A_i modelling, constrained by previous measurements.

Template fit on Jacobian edges of p^l_T and m_T

W Mass

Eur. Phys. J. C 78 (2018) 110





Huge effort to control systematics; Uncertainty comparable with previous best measurement from CDF; Dominated by Modelling.

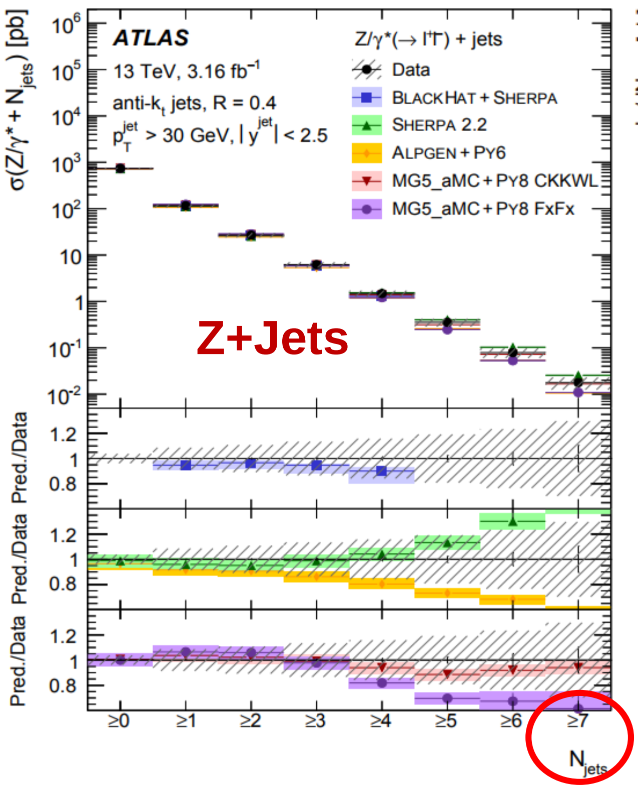
Combination Weights:
pTl 86%   mu 57% $W^{+/-}$: 52%/48%

$$
\begin{aligned}
m_W &= 80369.5 \pm 6.8\,\text{MeV(stat.)} \pm 10.6\,\text{MeV(exp. syst.)} \pm 13.6\,\text{MeV(mod. syst.)} \\
&= 80369.5 \pm 18.5\,\text{MeV},
\end{aligned}
$$

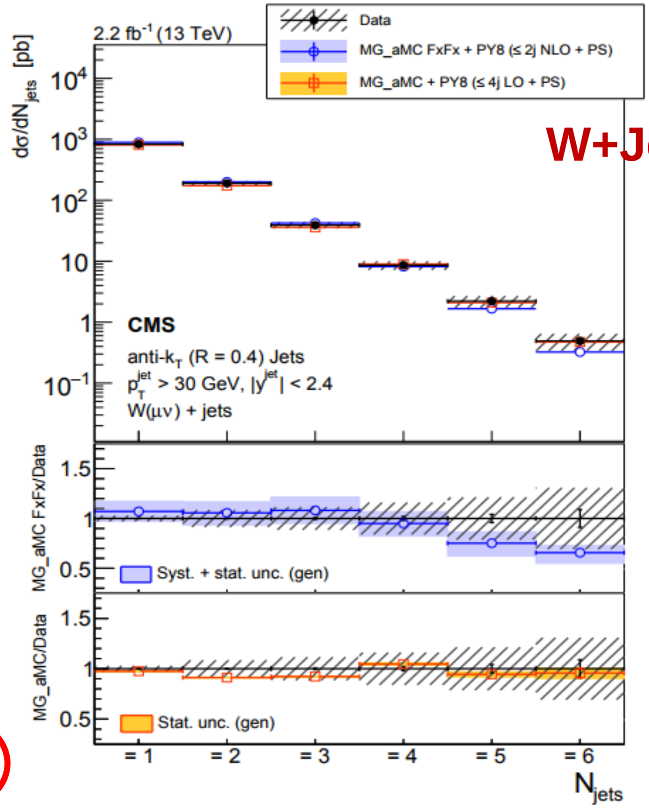
Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, W^+, e-μ	80352.7	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4	7/13
m_T-p_T^ℓ, W^-, e-μ	80383.6	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4	15/13
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

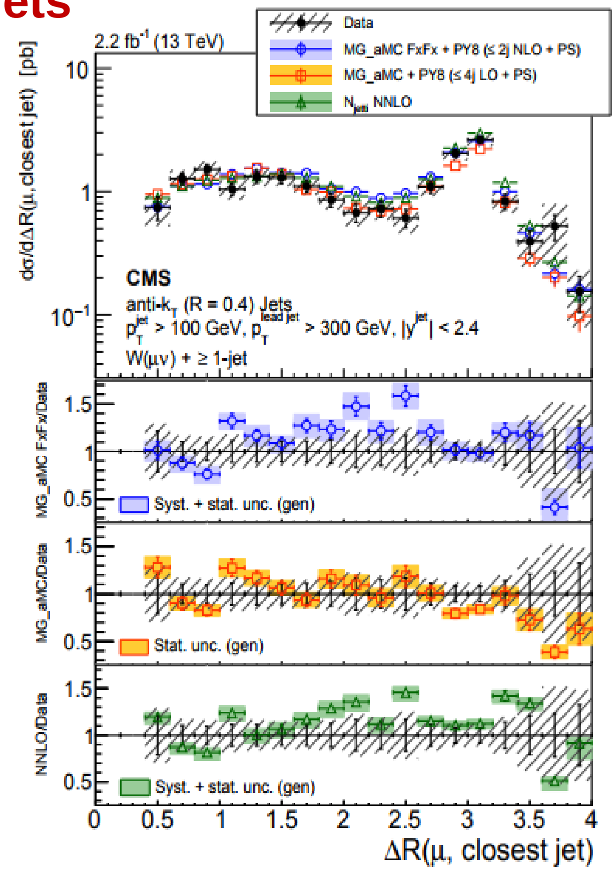
W/Z+Jets 13TeV

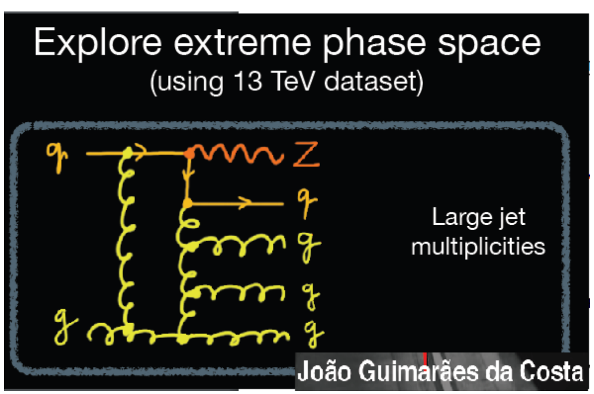
EPJC77 (2017) 361 13TeV; PRD 96 (2017) 072005; CMS-PAS-SMP-15-010



W+Jets







Unfolded distributions in good agreement within uncertainties. A bit worse at high jet multiplicity mainly due to jet here are modelled only by PS

$\Delta R(\mu, closest\ jet)$ sensitive to EWK emission of W bosons, best described by NNLO

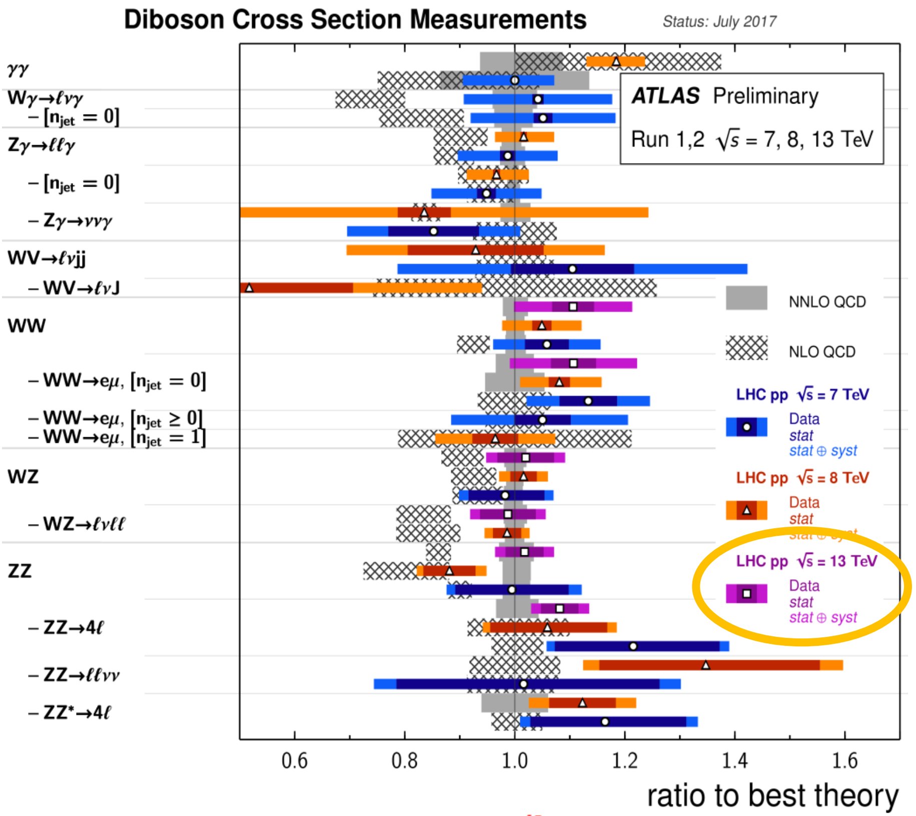
Multi-Boson Productions

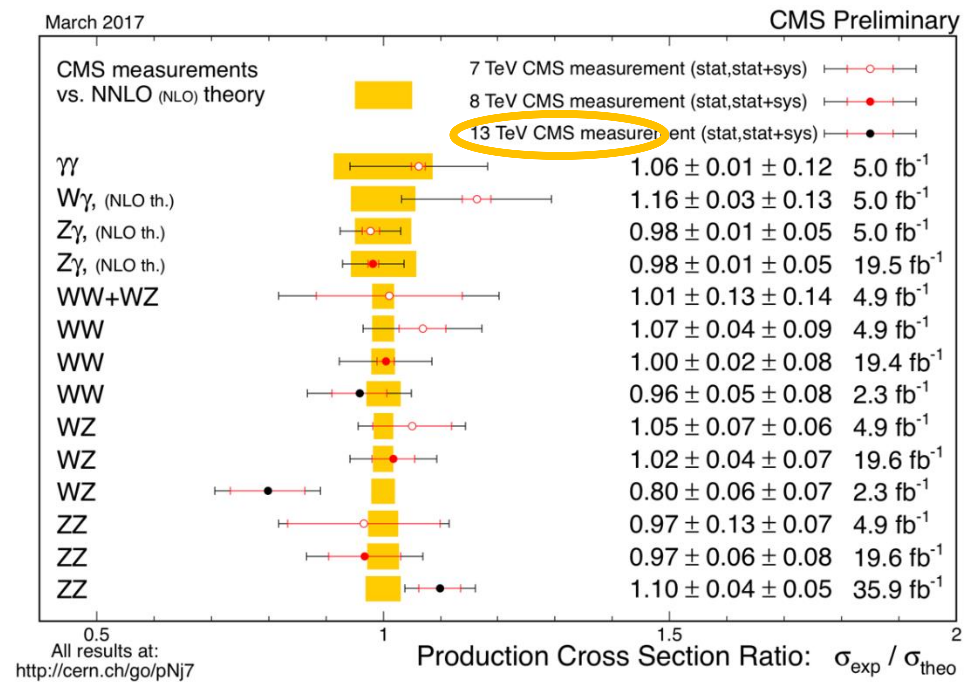
Crucial test of the SM:

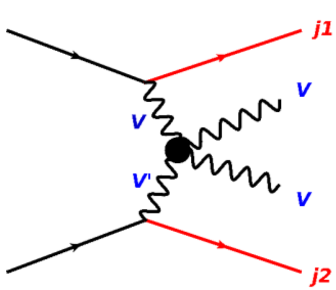
- on the non-Abelian gauge symmetry part of the SM
- sensitive to NLO EW, NLO/NNLO QCD, resummation

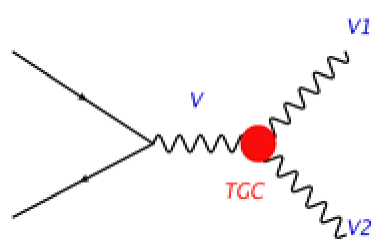
Important backgrounds to Higgs and new physics searches

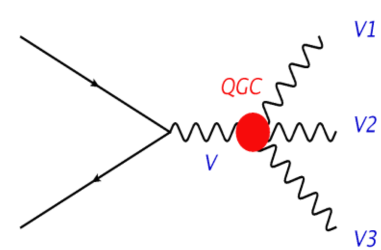
Sensitive to anomalous Triple (Quartic) Gauge Couplings





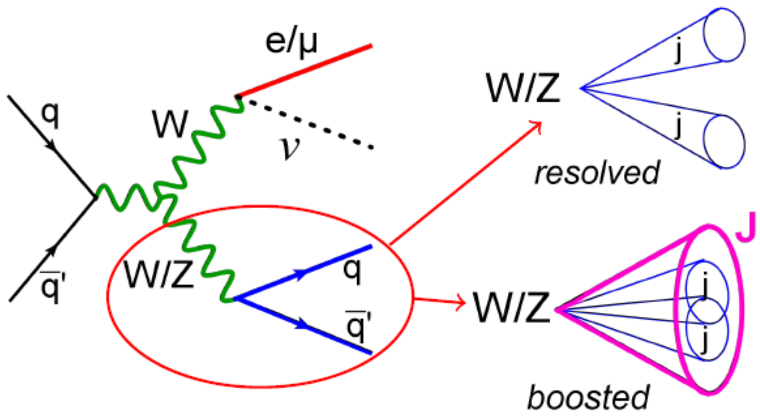


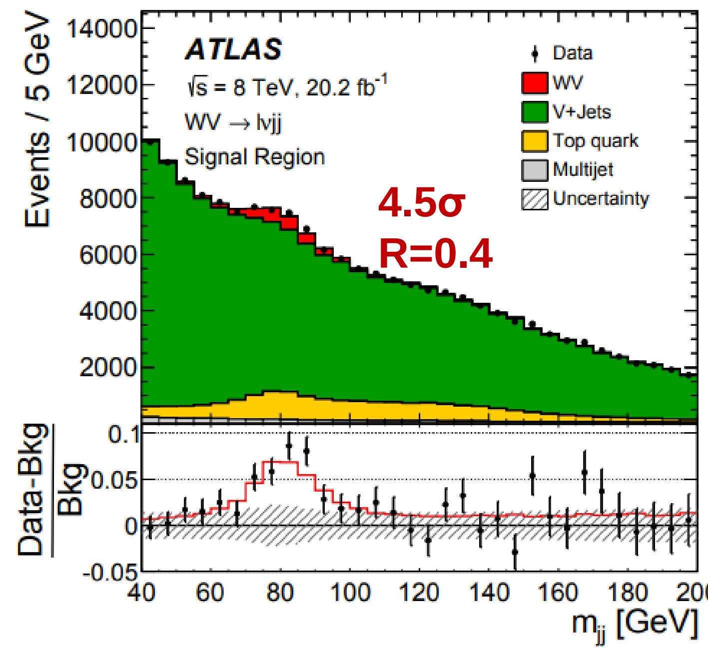


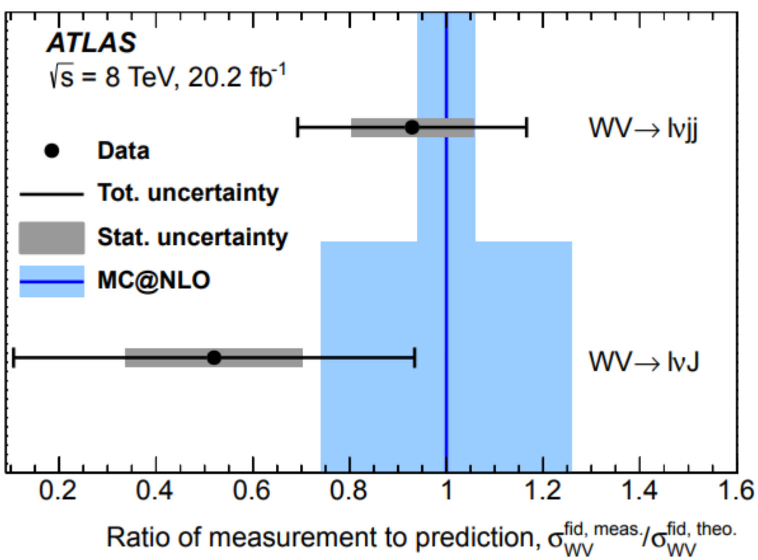


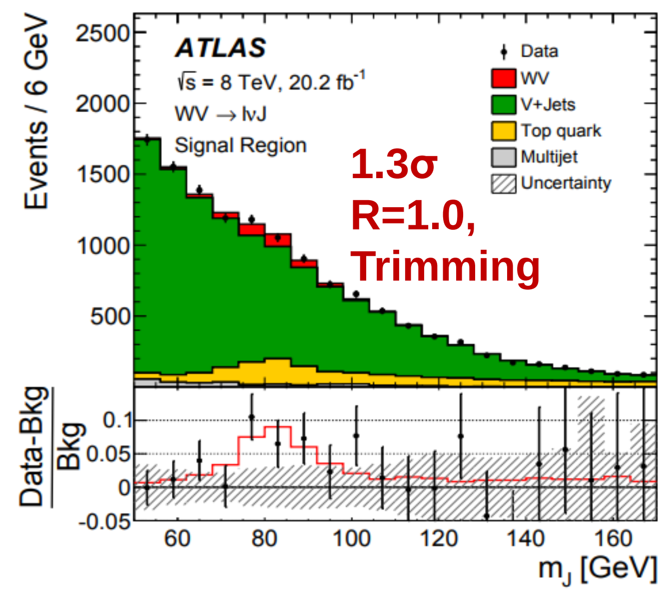
WV

EPJC 77 (2017) 563 8TeV; PLB 772 (2017) 21; CMS-PAS-SMP-16-012



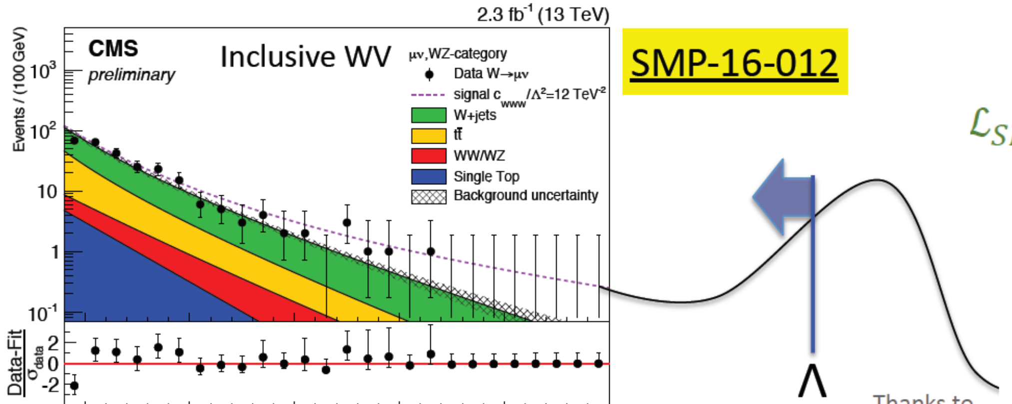






Partially overlapping, no combination

aTGC

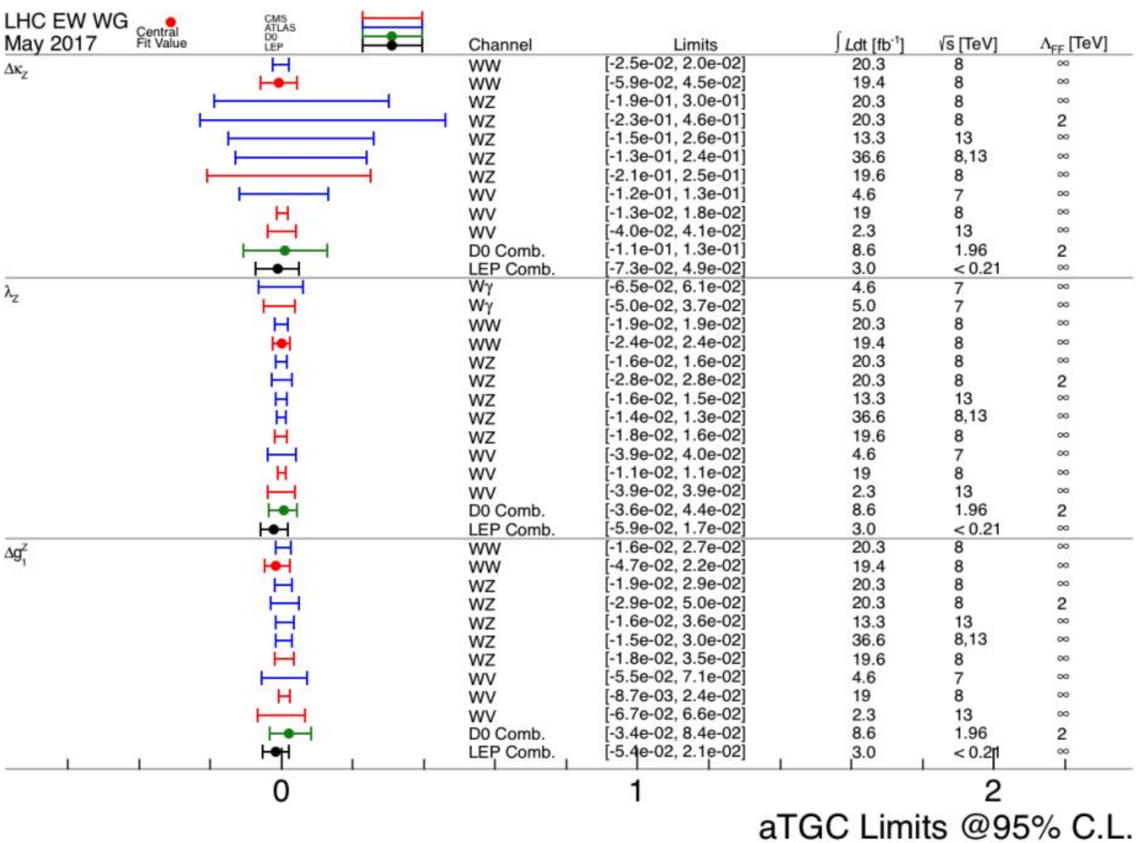


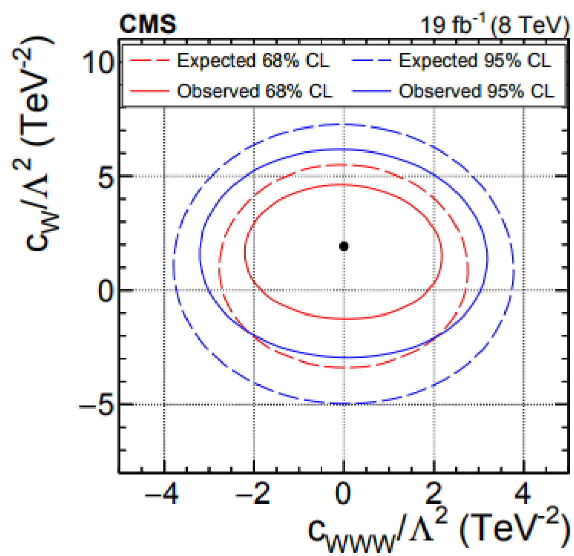
SMP-16-012

$$\mathcal{L}_{SM} \rightarrow \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_i \frac{c_i^n}{\Lambda^n} \mathcal{O}_i^{n+4}$$

Thanks to Senka Duric for the drawing

Effective operators or EFT approach





Dim6 operators

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SummaryPlots

VBS Discovery

Phys. Rev. Lett. 120, 081801 (2018)

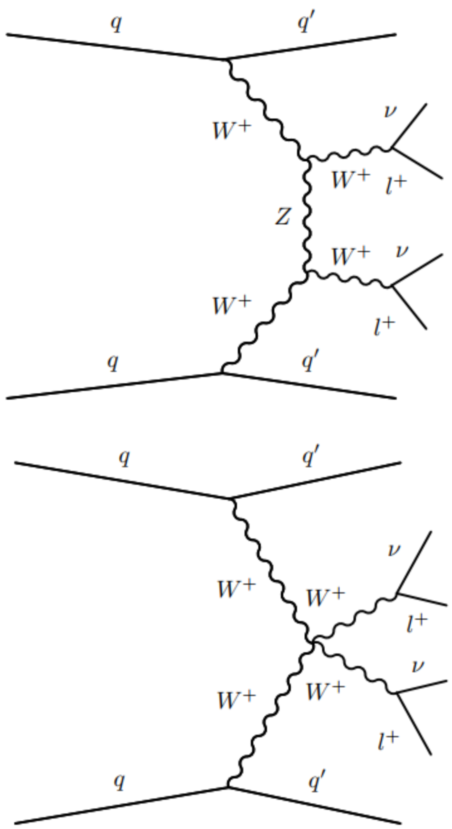
- **Run 1 CMS 1.9σ, ATLAS 3.6σ**
- **Event selection:**
  - Two same-sign lepton with P_T>25(20) GeV
  - 3rd lepton veto: pT>10 GeV (18 for tau)
  - M_{ll}>20 GeV, $|m_{ll}-m_Z|$> 15 GeV, E_T^{miss} > 40 GeV
  - **mjj>500 GeV, $|\Delta\eta_{jj}|$>2.5, $max(z^*_l)$ <0.75**
- **Background:**
  - Non-prompt leptons / WZ

Signal extracted from a 2D fit on m_{jj} and m_{ll}

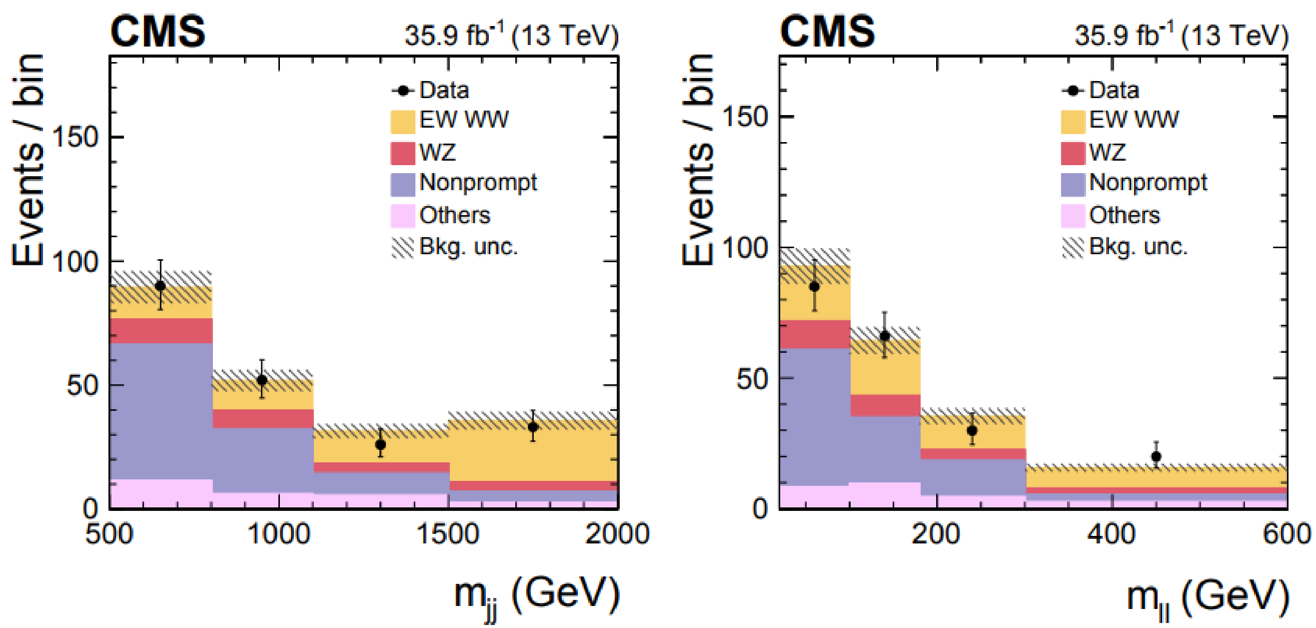
Observed (expected) significance: **5.5 (5.7) σ**

Constraints are set on aQGC and doubly charged Higgs

$$\sigma_{\text{fid}}(W^{\pm}W^{\pm}jj) = 3.83 \pm 0.66\,(\text{stat}) \pm 0.35\,(\text{syst})\,\text{fb}$$

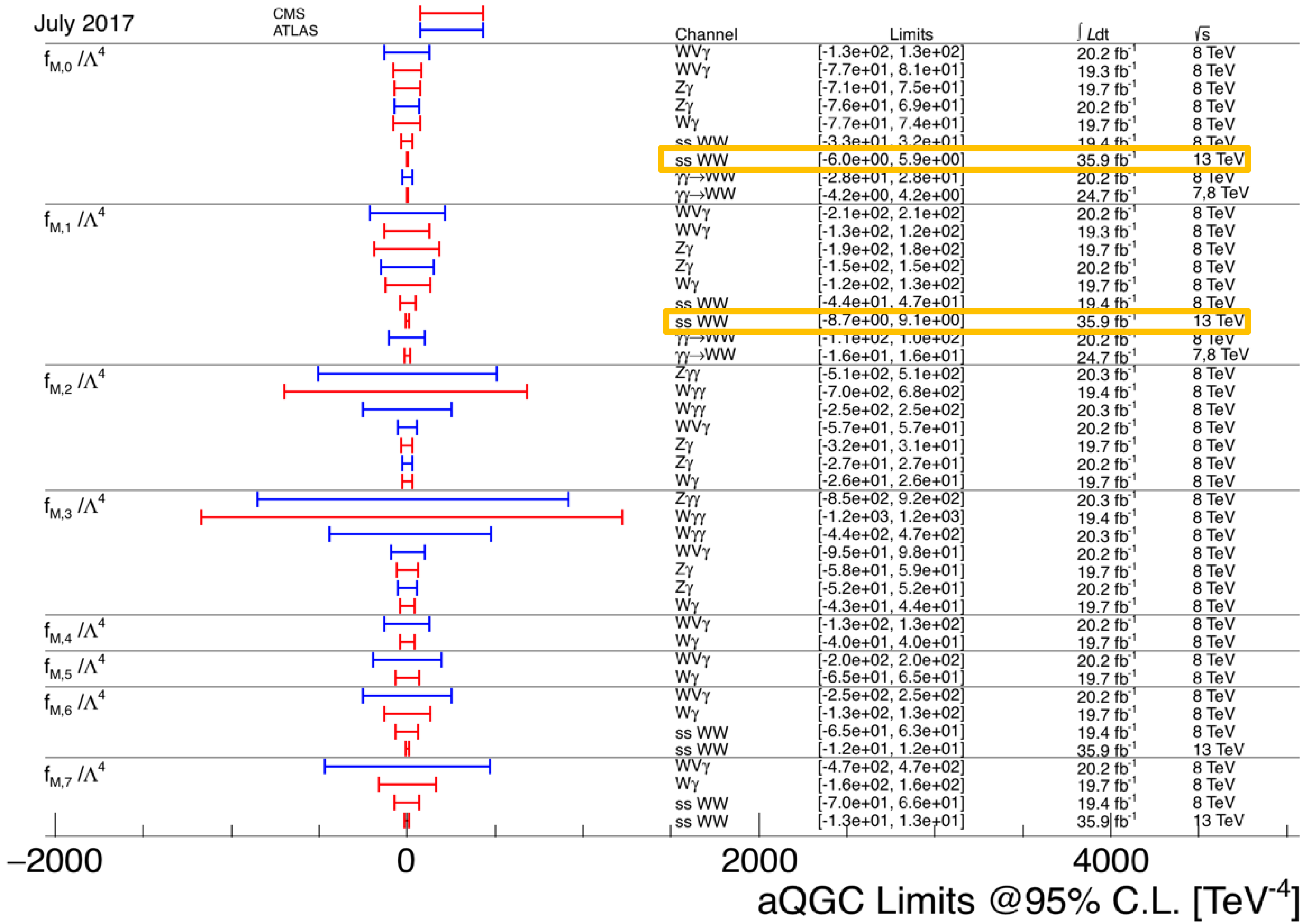


The interference between the EW and QCD processes is found to be a few percent in the signal region and considered as systematic uncertainty



aQGC

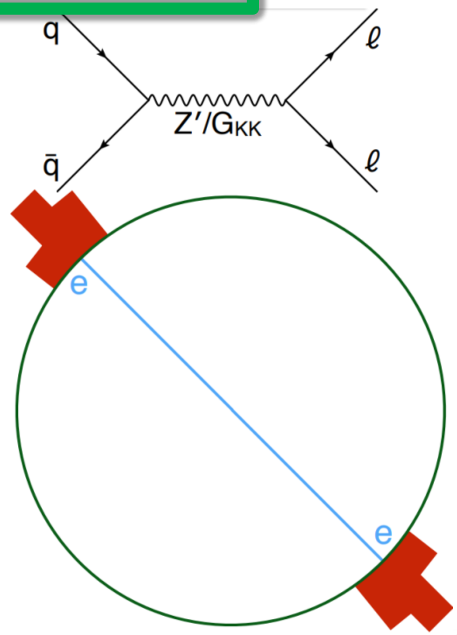
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

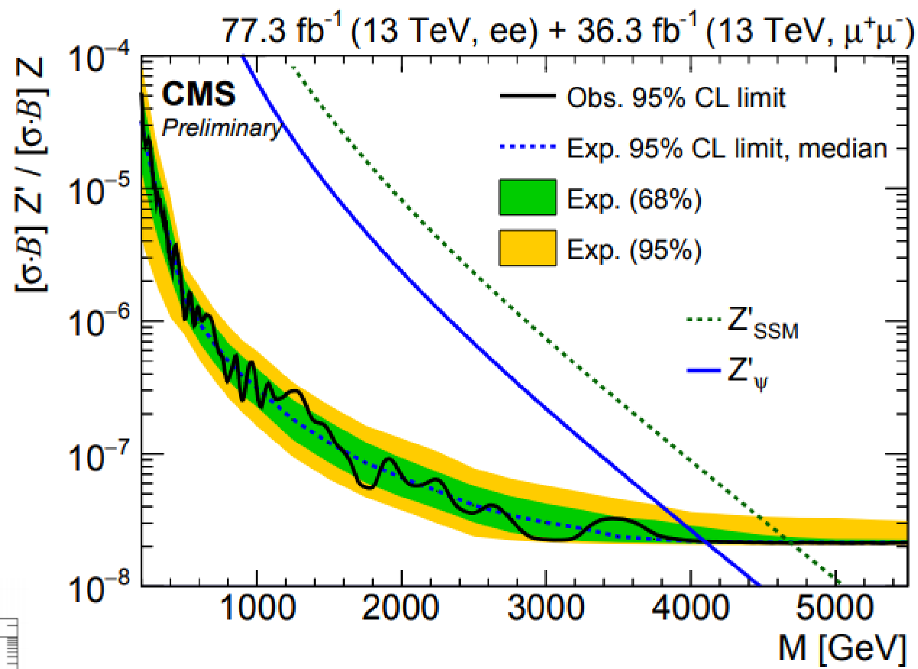


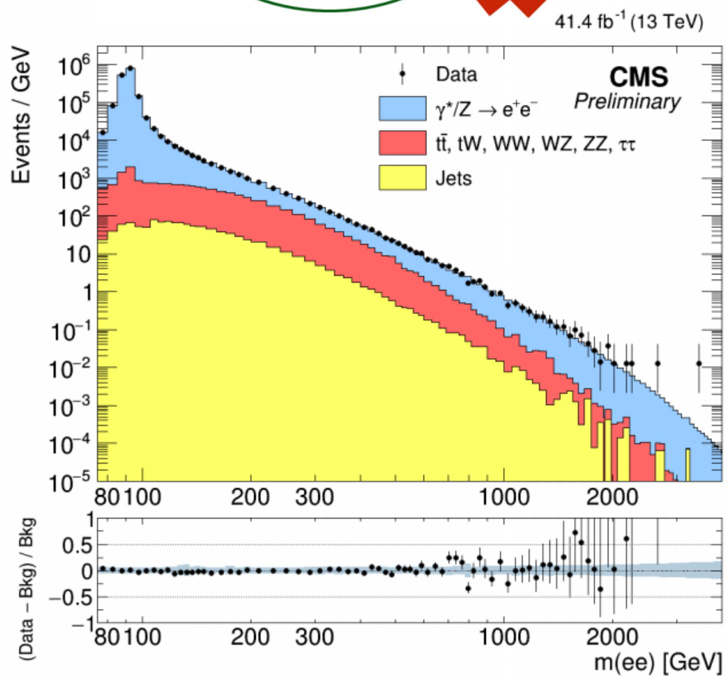
NEW Physics

Di-lepton

CMS-PAS-EXO-18-006 2016(ee+μμ)+2017(ee)!





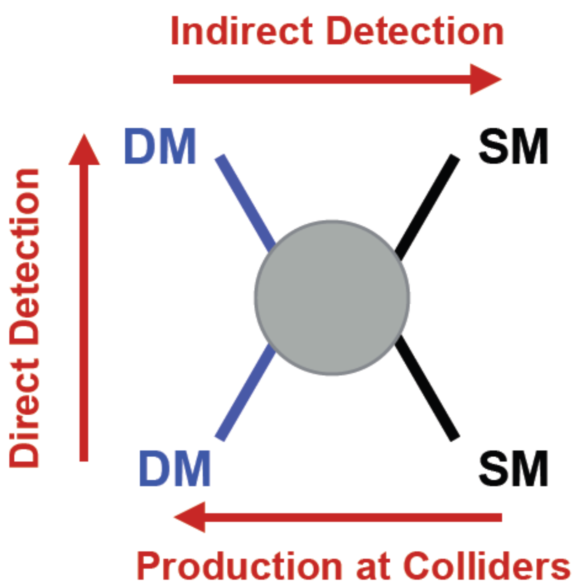


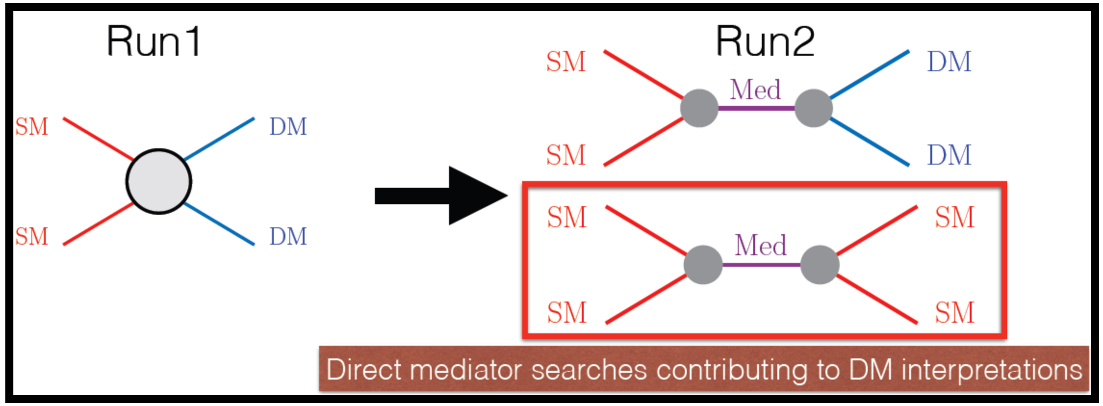
Channel	Model	Obs. limit [TeV]	Exp. limit [TeV]
ee (2017)	Z'_{SSM}	4.10	4.15
	Z'_{ψ}	3.35	3.55
ee (2016 and 2017) + $\mu\mu$ (2016)	Z'_{SSM}	4.7	4.7
	Z'_{ψ}	4.1	4.1

Dark Matter

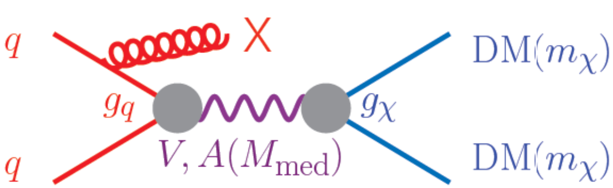
JHEP 01 (2018) 126; PRL 119, 181804 (2017); Phys. Lett. B 776 (2017) 318; arXiv:1801.08427; Phys. Rev. D 97, 032009 (2018); EXO-17-014

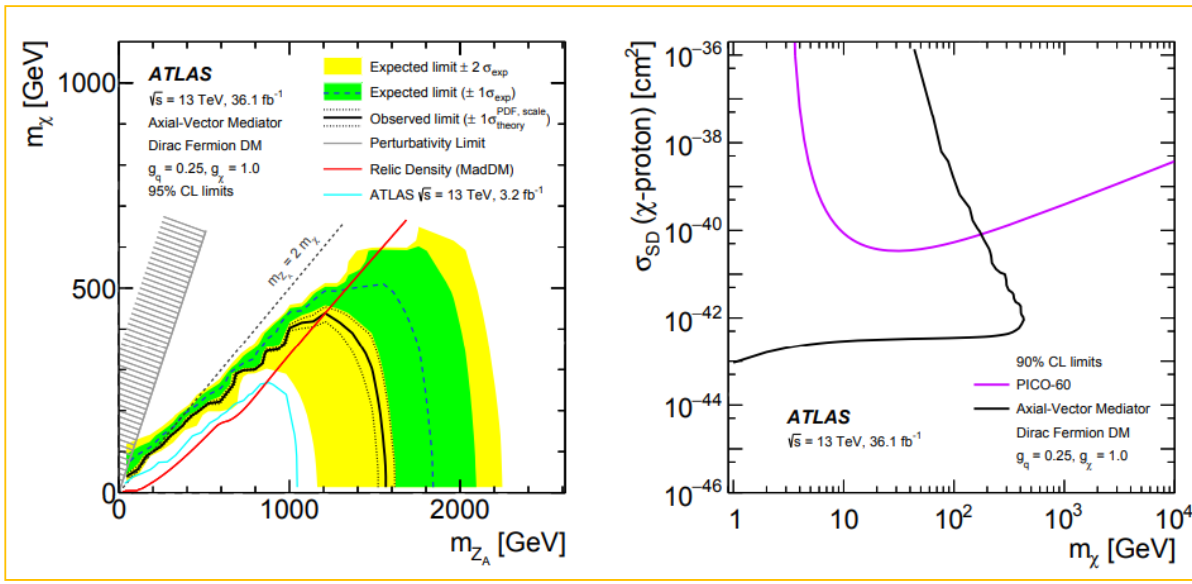
ATLAS/CMS DM Forum: arxiv:1507.00966





E_T^{miss}+X a.k.a. Mono-X
- X from ISR jet, b, t, γ, W, Z





ATLAS Mono-Jet, in this particular model, results compared with PICO-60

Heavy Flavor

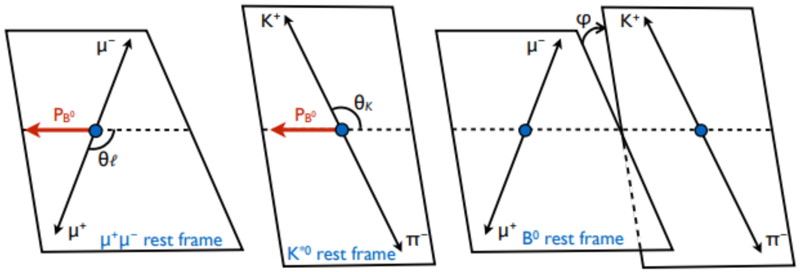
B→Kμμ

arXiv:1710.02846

S-wave and S&P-wave interference

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_K\, d\phi} = \frac{9}{8\pi}\left\{\frac{2}{3}\left[(F_S + A_S\cos\theta_K)(1-\cos^2\theta_l) + A_S^5\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\right] + (1-F_S)\left[2F_L\cos^2\theta_K(1-\cos^2\theta_l) + \frac{1}{2}(1-F_L)(1-\cos^2\theta_K)(1+\cos^2\theta_l) + \frac{1}{2}P_1(1-F_L)(1-\cos^2\theta_K)(1-\cos^2\theta_l)\cos 2\phi + 2P_5'\cos\theta_K\sqrt{F_L(1-F_L)}\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\right\}$$

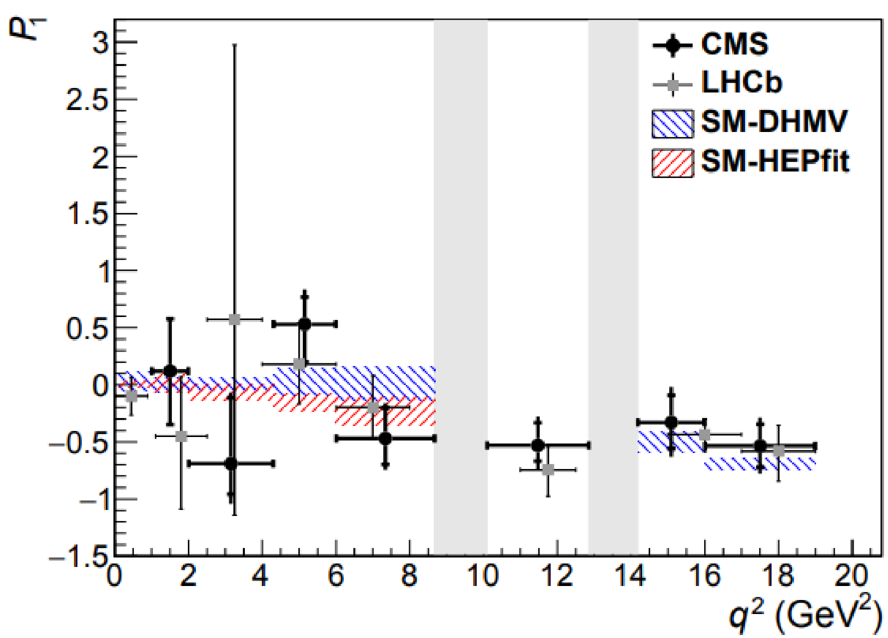
P-wave

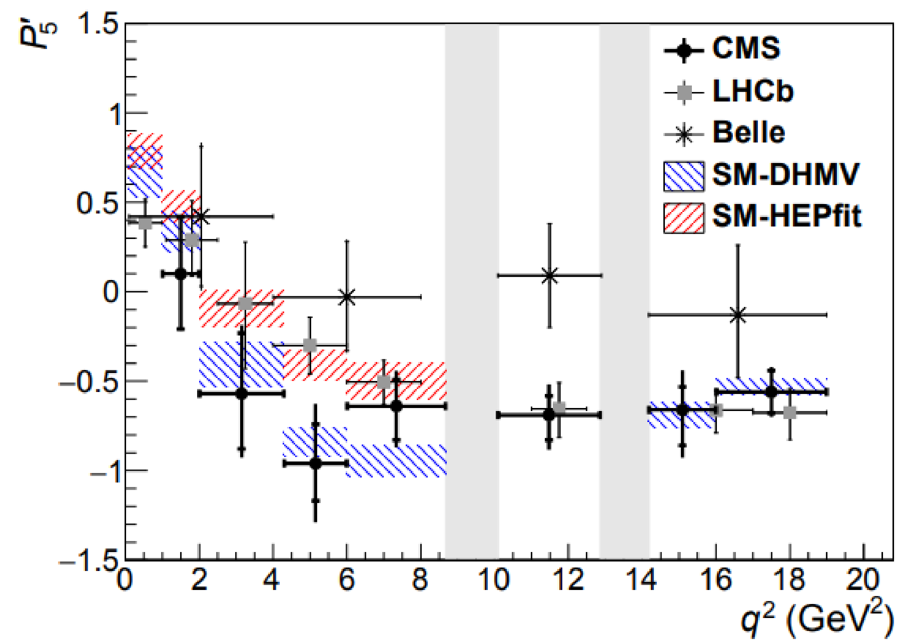


P5' chosen to decrease theo unc.

Same interesting pattern, but CMS more SM-like

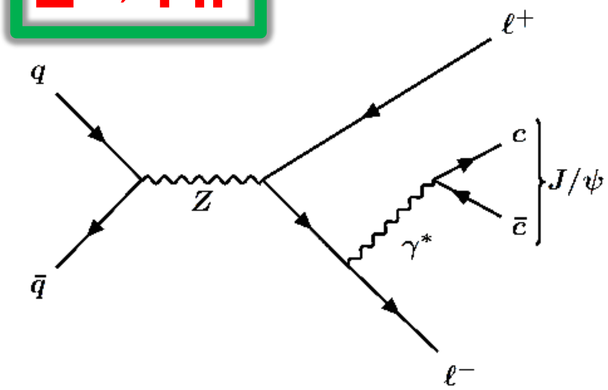
- SM-DHMV: *JHEP 01 (2013) 048, JHEP 05 (2013) 137*
- SM-HEPfit: *JHEP 06 (2016) 116, arXiv:1611.04338*





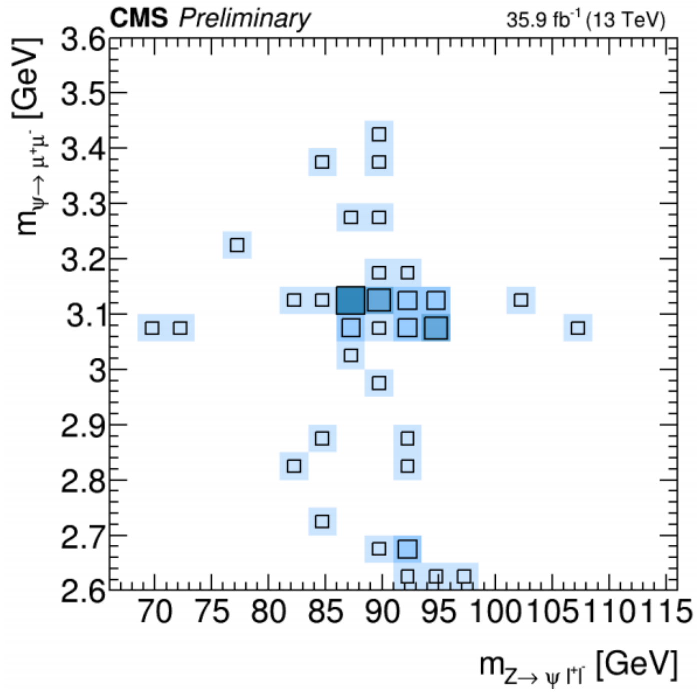
Z→ΨII

CMS-PAS-BPH-16-001



Signal events

Z→ψμμ	Z→ψee
13.0 ± 3.9	11.2 ± 3.4



2D extended maximum likelihood unbinned fit

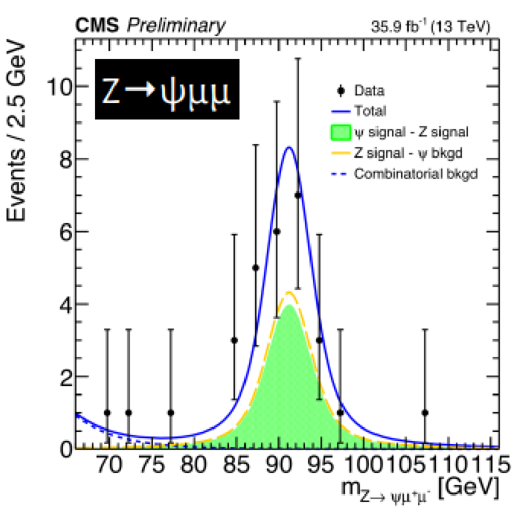
Signal significance of Z→ψℓℓ

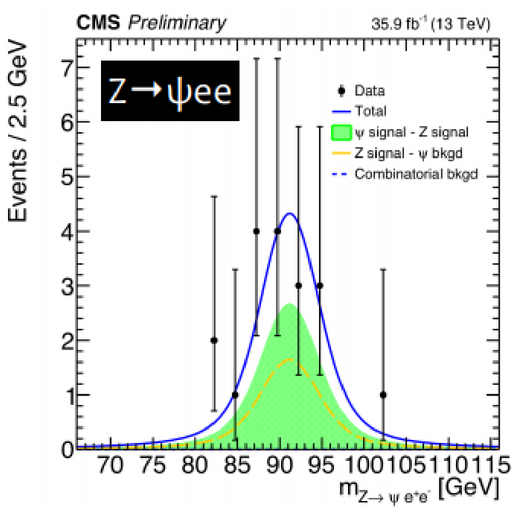
- ψμμ at 4.0σ
- ψee at 4.3σ
- combined significance: **5.7σ**

Z→μμμμ (reference channel)

- 250 ± 20 events

ψ(2S) feed-down to J/ψ removed



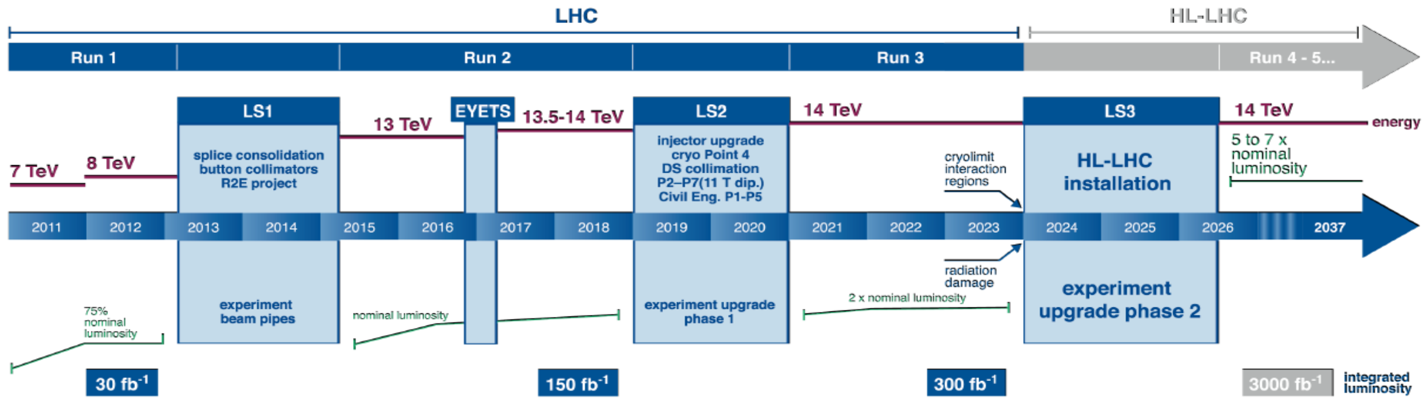


$$\frac{\mathcal{B}(Z \to J/\psi\, \ell^+\ell^-)}{\mathcal{B}(Z \to \mu^+\mu^-\mu^+\mu^-)} = 0.70 \pm 0.18\,(\text{stat}) \pm 0.05\,(\text{syst}).$$

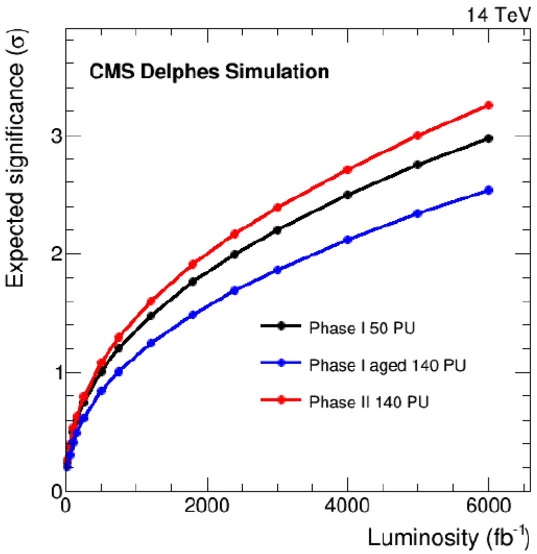
- use B(Z→μμμμ) from PDG
- **CMS:** B(Z→J/ψℓℓ) ≈ 8 x 10^{-7}
- **Theory:** B(Z→J/ψℓℓ) = (6.7 ± 0.7) × 10^{-7} **and** 7.7 × 10^{-7}

Future

Summary



ATLAS-PHYS-PUB-2013-006;
CMS-PAS-FTR-13-006;
CERN-LHCC-2015-010



CMS Same-Sign WW
Longitudinal VBS

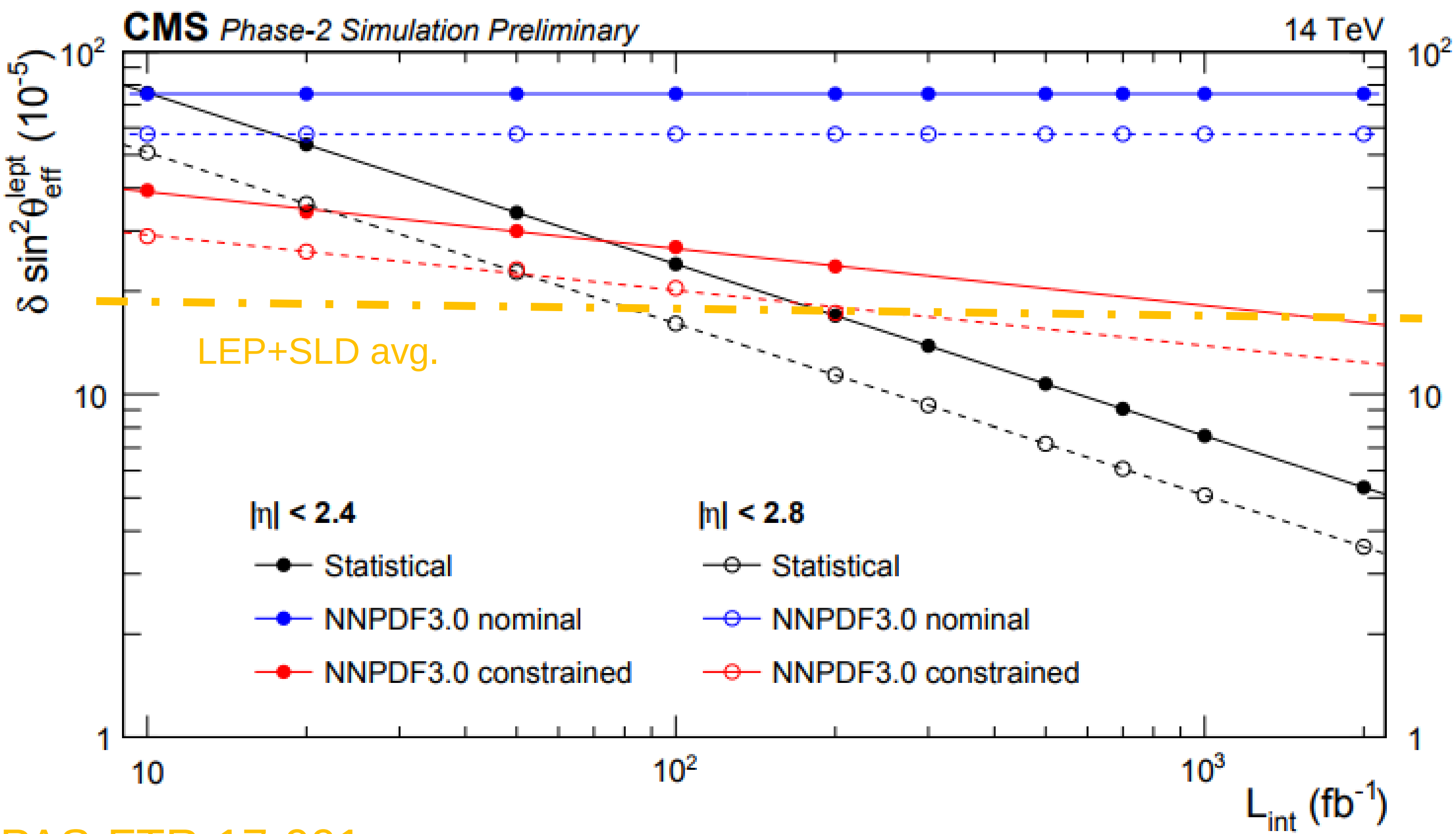
- **Outstanding performance of the LHC!**
- **Extensive and Excellent Studies from LHC with 7, 8 and 13 TeV data**

- **More Precise measurements on Higgs, Top, SM..**
- **First measurement of W boson mass from LHC**
- **First observation of VBS and VVV**
- **Stringent limits on New Physics from the LHC**

- **We are still at the beginning, ~2% of HL-LHC expected data analyzed!**
- **New ideas and technique are crucial**

SM Precision

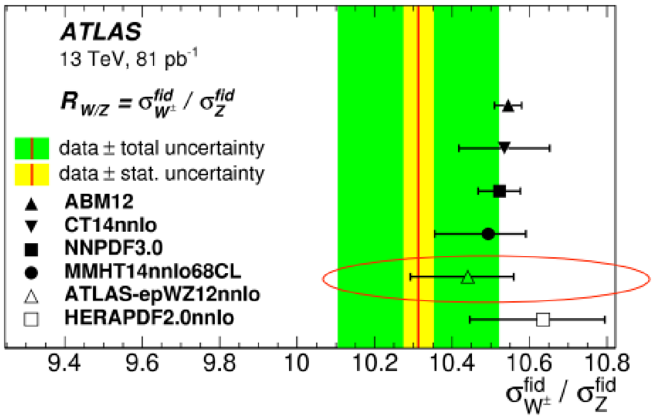
LHC Electroweak WG meeting: December 13-14, 2017



CMS-PAS-FTR-17-001

- Dilution is worse, but detector will have larger acceptance for leptons: |η| < 2.8
- Not a detailed simulation
- Only PDF systematic uncertainty considered
- Negligible statistical uncertainty

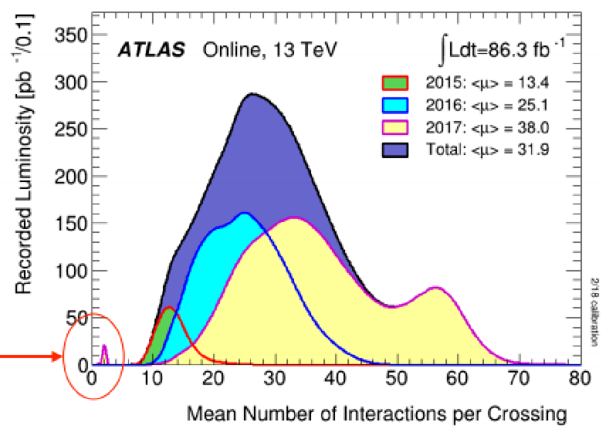
SM Precision



Extract and use new PDF sets from the data.

Future

ATL-PHYS-PUB-2017-021

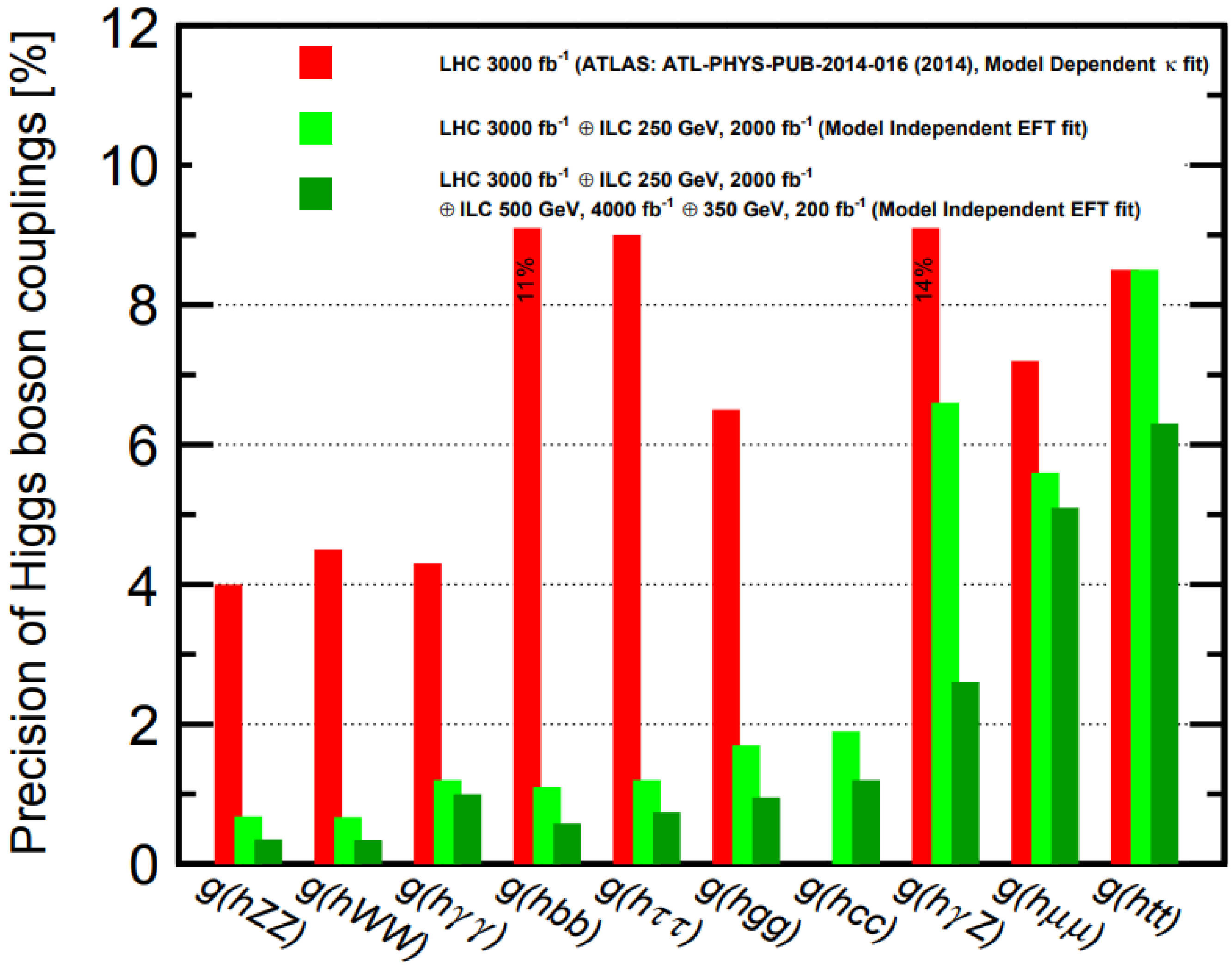


Level luminosity to low pileup values

- ATLAS pTW measurement 31pb-1 at 7 TeV from 2010 with error >2.5% on coarse bins.
- Recent low-μ runs taken by ATLAS: ~150/pb at 13 TeV: 1.75M W, 220k Z ~270/pb at 5 TeV: 1.3M W, 150k Z
- Possibility to measure directly pTW/pTZ at low pTW which is crucial to improve ΔmW!
- Measurement of pTW ~ 1% uncertainty & 5 GeV binning at low pTW, with low-μ data.
- Low-μ necessary for good recoil resolution.

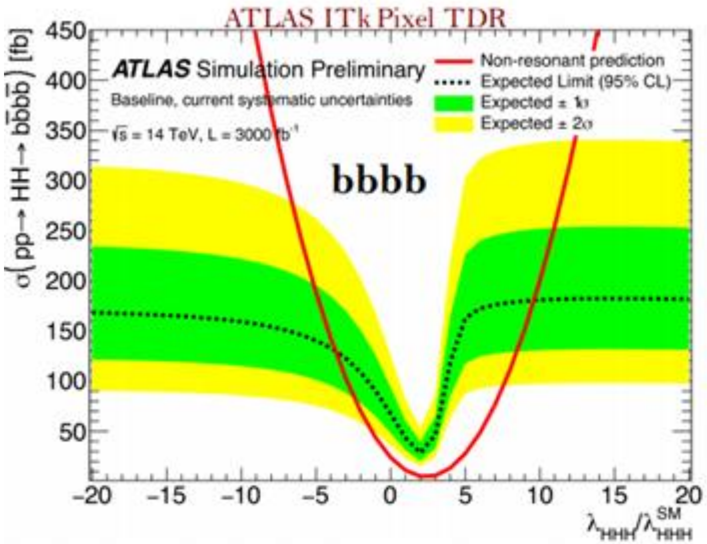
Higgs Precision

Driving force for physics at HL-LHC and motivation for e^+e^- Higgs Factory



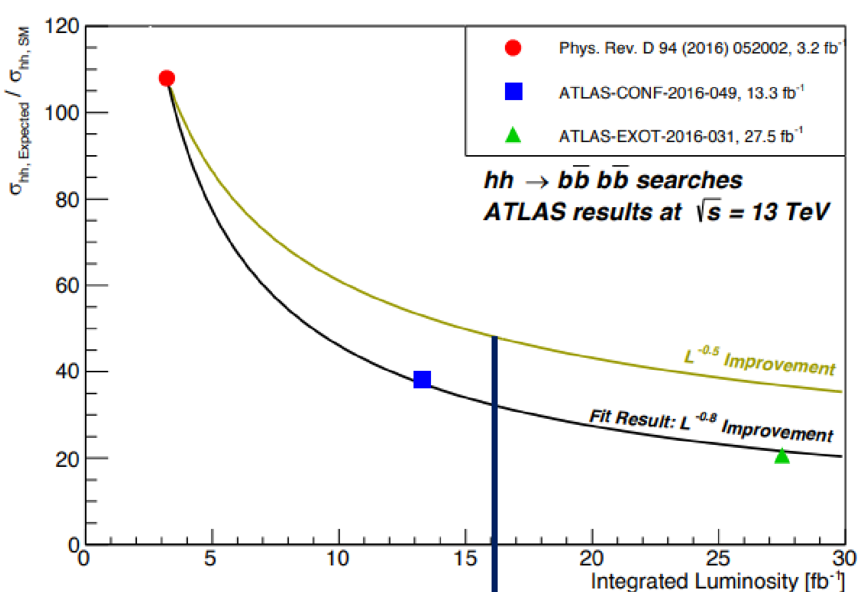
arXiv:1710.07621

Higgs Self-Coupling

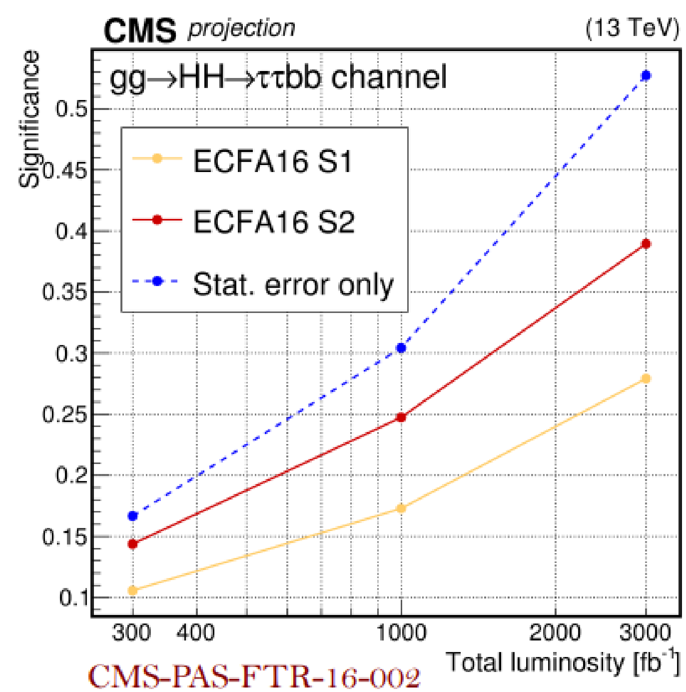


$hh \to 4b$ extrapolation on upper limit on $\frac{\sigma}{\sigma_{SM}}$	Run II (120 fb^{-1})	Run II+III (450 fb^{-1})	HL-LHC 3000 fb^{-1}
HL-LHC Prospects Studies (using current systematics)	-	-	~3.7
$L^{-0.5}$ improvement on 27.5 fb^{-1} result	~10	~5.2	~2
$L^{-0.8}$ improvement on 27.5 fb^{-1} result	~6.5	~2.2	<1

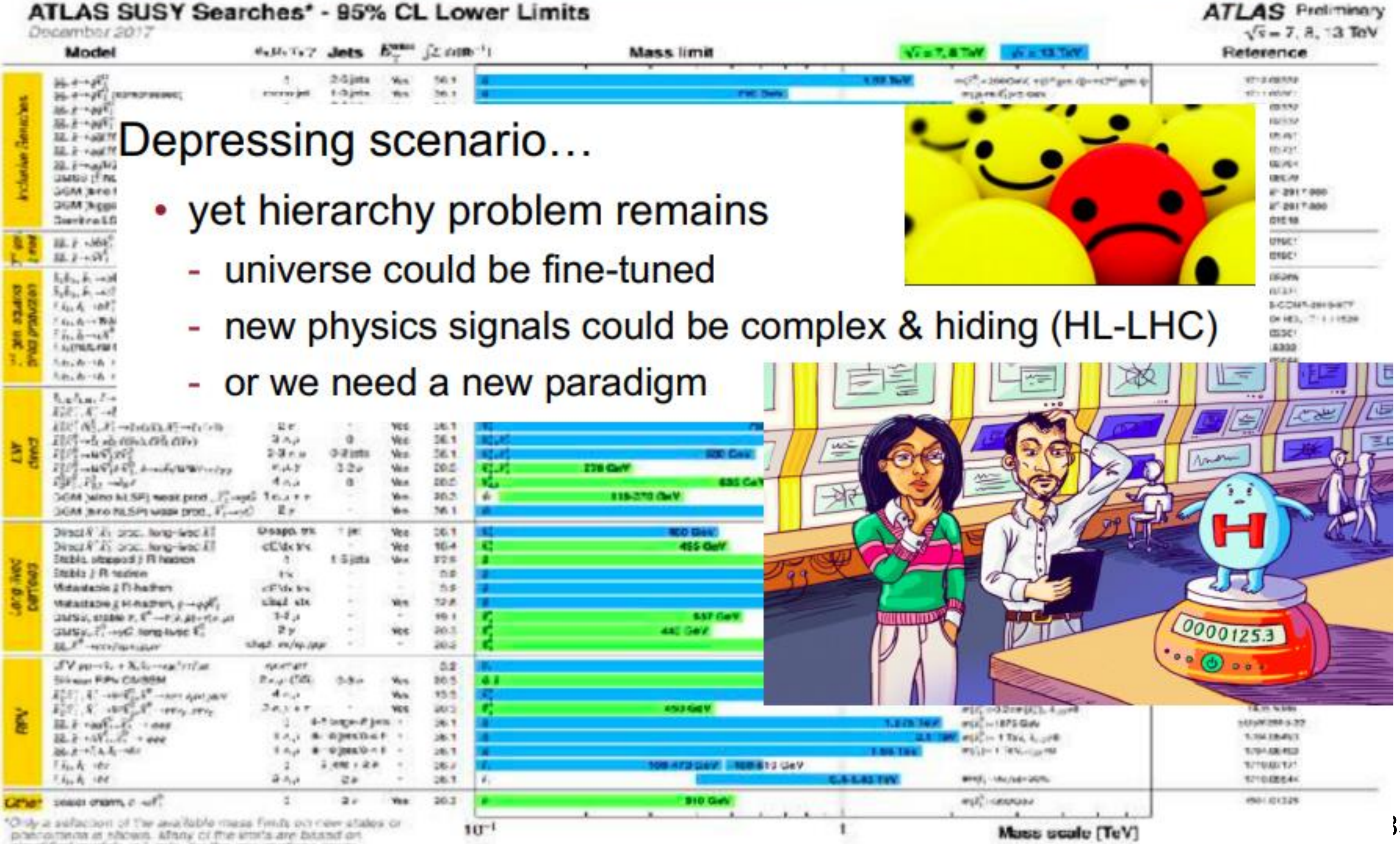
https://indico.in2p3.fr/event/16579/contributions/60820/attachments/47219/59316/Kagan_hh_MoriondEW2018.pdf



Improved jet and b-tagging performance and calibration…



New particles & interactions: direct production

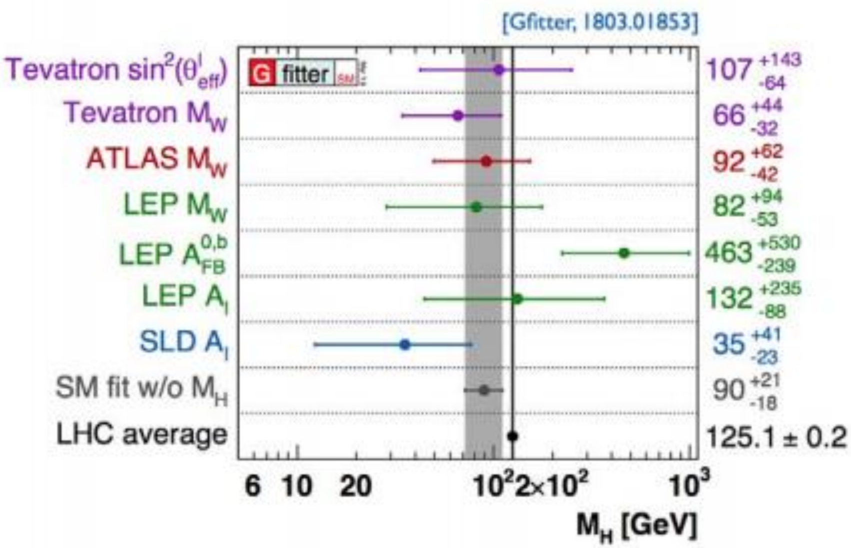


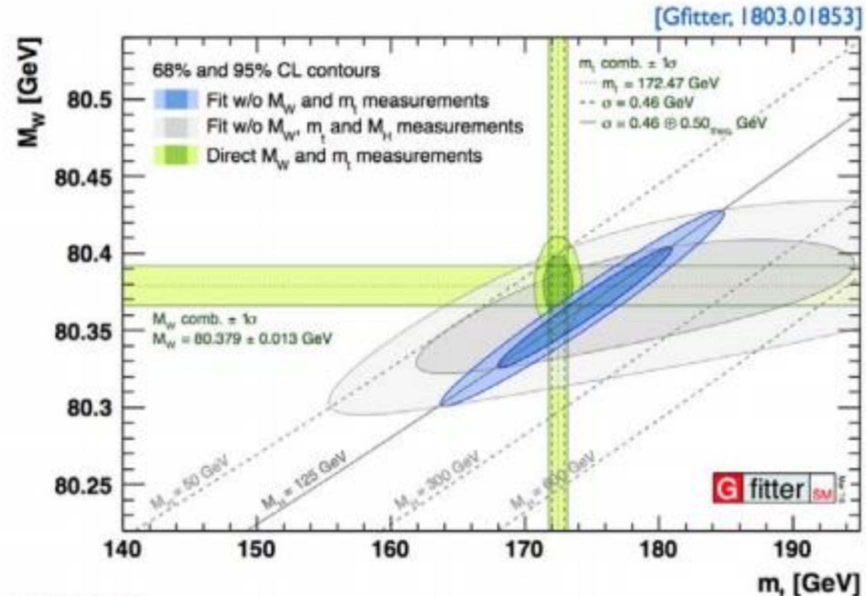
Depressing scenario…

- yet hierarchy problem remains
  - universe could be fine-tuned
  - new physics signals could be complex & hiding (HL-LHC)
  - or we need a new paradigm

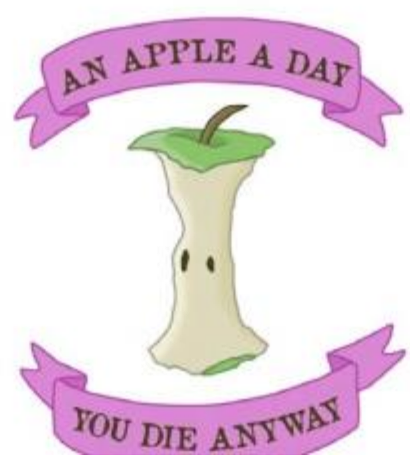
Backup

SM FIT: "Incredibly Healthy"



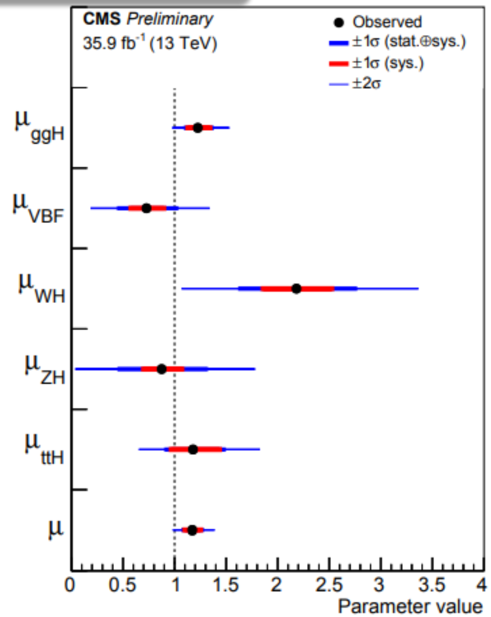


[Kogler]

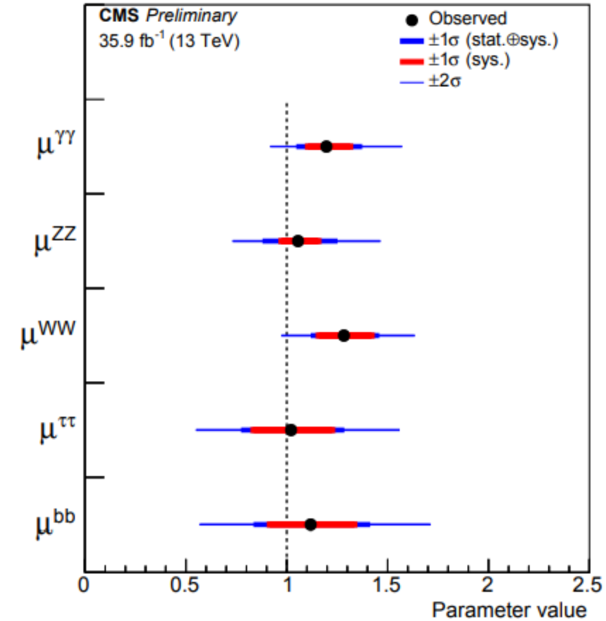


CMS Combination

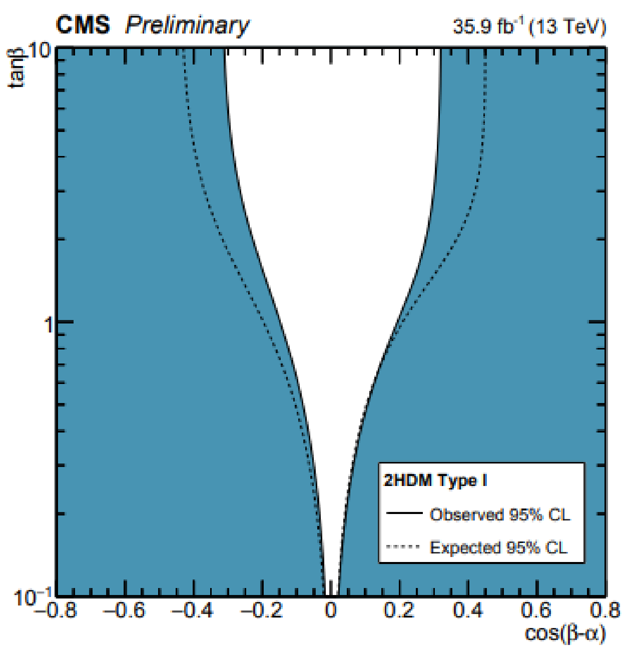
Productions

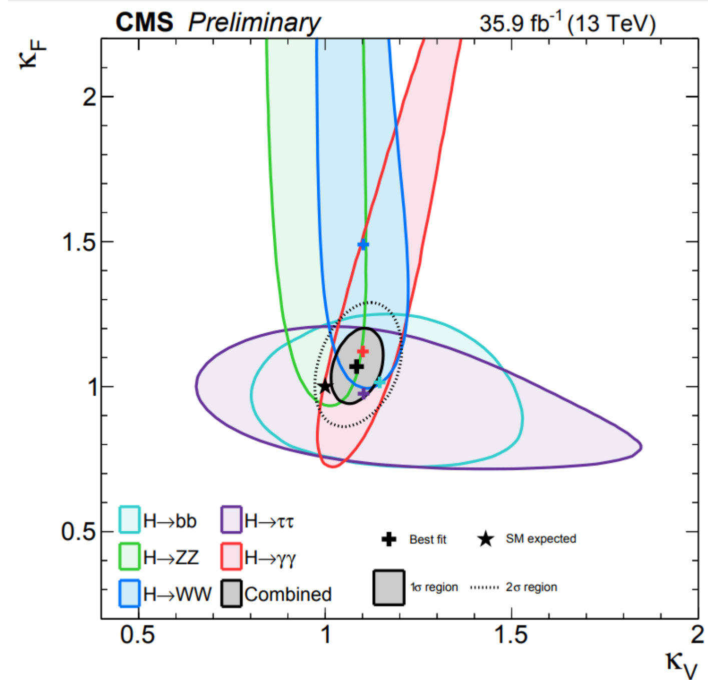


Decays



2HDM I

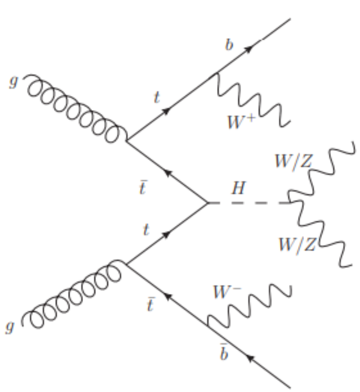


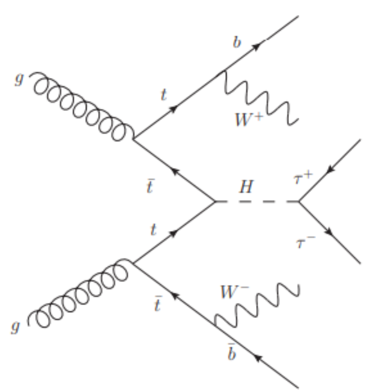


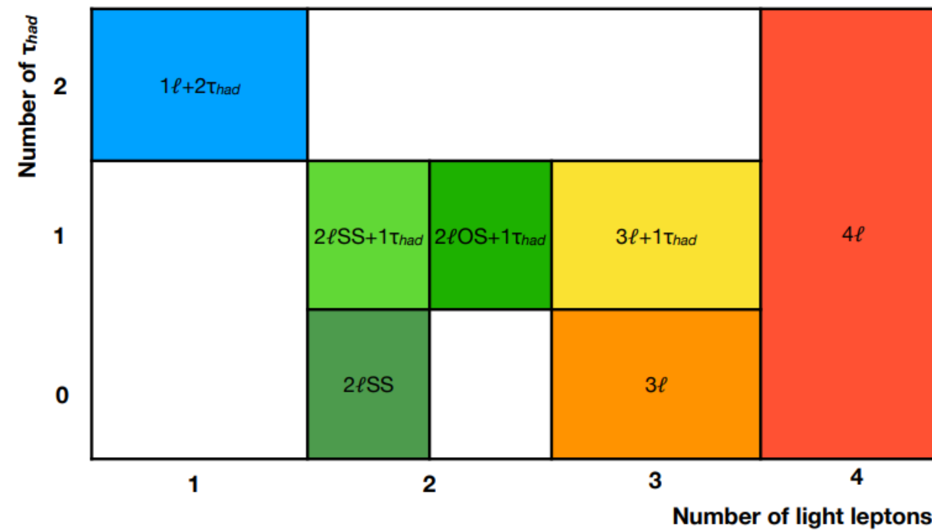
ATLAS ttH

arXiv:1712.08891

Channel	Best-fit μ		Significance	
	Observed	Expected	Observed	Expected
Multilepton	$1.6\ ^{+0.5}_{-0.4}$	$1.0\ ^{+0.4}_{-0.4}$	4.1σ	2.8σ
$H \to b\bar{b}$	$0.8\ ^{+0.6}_{-0.6}$	$1.0\ ^{+0.6}_{-0.6}$	1.4σ	1.6σ
$H \to \gamma\gamma$	$0.6\ ^{+0.7}_{-0.6}$	$1.0\ ^{+0.8}_{-0.6}$	0.9σ	1.7σ
$H \to 4\ell$	< 1.9	$1.0\ ^{+3.2}_{-1.0}$	—	0.6σ
Combined	$1.2\ ^{+0.3}_{-0.3}$	$1.0\ ^{+0.3}_{-0.3}$	4.2σ	3.8σ



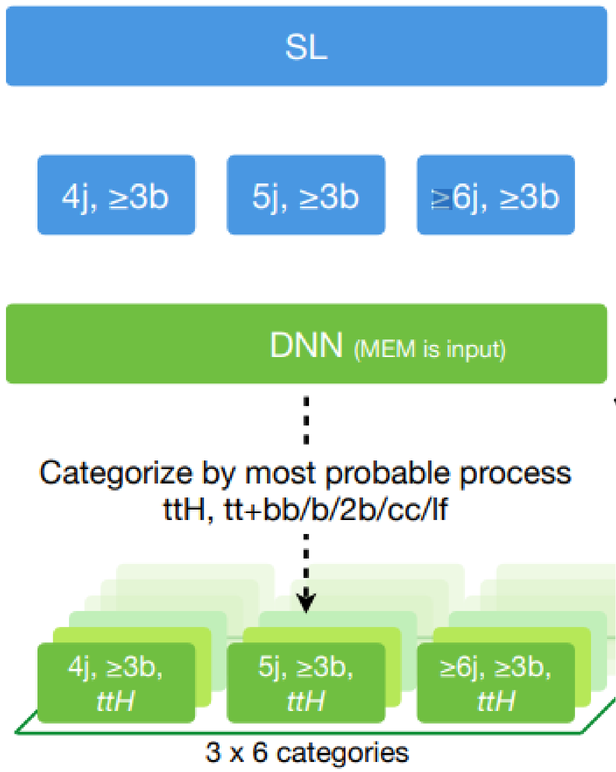




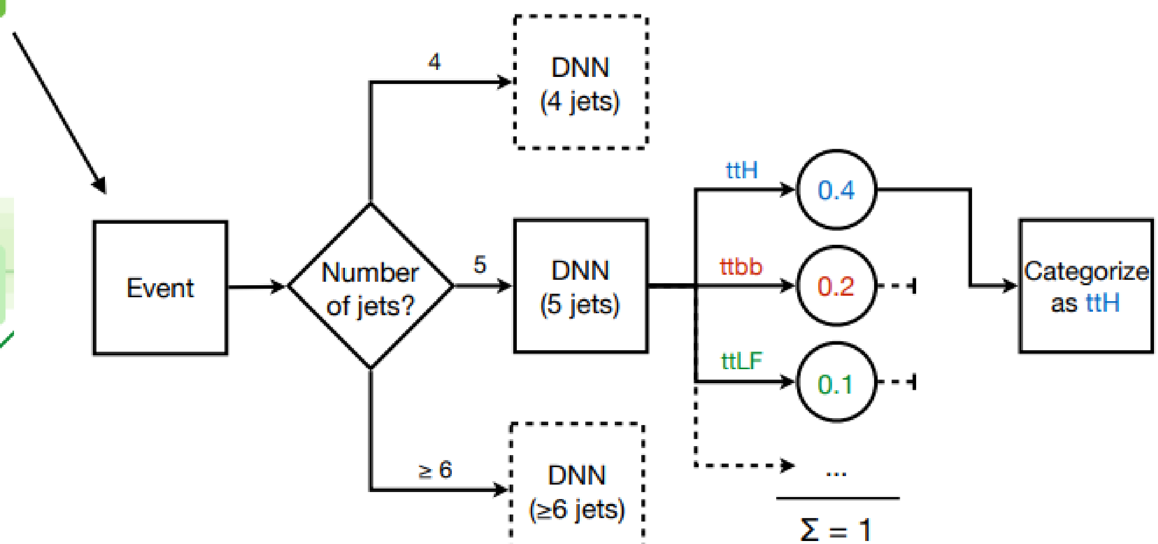
NEW RESULT

bb, 1ℓ analysis

CMS PAS HIG-17-026



- Categories based on jet multiplicity: **4j, 5j, ≥6j**
- **Deep neural network** in each category with BDT input variables + MEM discriminant
- Multi-classifier output representing “probability” of a certain physics process hypothesis



$\lvert\eta_\ell\rvert$ range	0–0.8	0.8–1.4	1.4–2.0	2.0–2.4	Inclusive
$W^+ \to \mu^+\nu$	1 283 332	1 063 131	1 377 773	885 582	4 609 818
$W^- \to \mu^-\bar{\nu}$	1 001 592	769 876	916 163	547 329	3 234 960
$\lvert\eta_\ell\rvert$ range	0–0.6	0.6–1.2		1.8–2.4	Inclusive
$W^+ \to e^+\nu$	1 233 960	1 207 136		956 620	3 397 716
$W^- \to e^-\bar{\nu}$	969 170	908 327		610 028	2 487 525

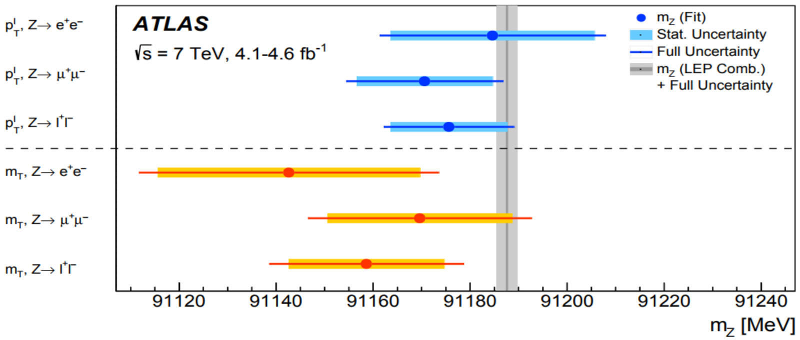
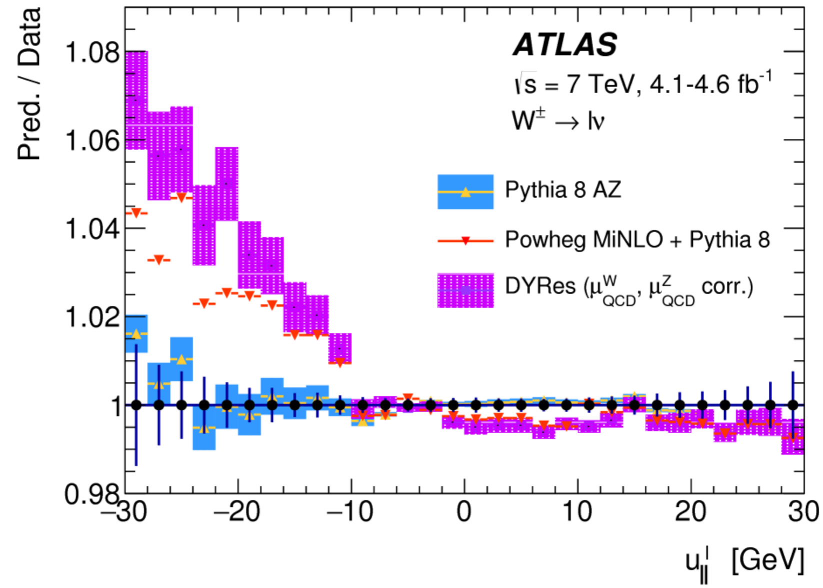


Figure 16: Summary of the m_Z determinations from the p_T^ℓ and m_T distributions in the muon and electron decay channels. The LEP combined value of m_Z, which is used as input for the detector calibration, is also indicated. The horizontal and vertical bands show the uncertainties of the m_Z determinations and of the LEP combined value, respectively.



The measurements of m_W in the various categories are combined accounting for statistical and systematic uncertainties and their correlations. The statistical correlation of the m_W values determined from the p_T^ℓ and m_T distributions is evaluated with the bootstrap method [113], and is approximately 50% for all measurement categories.

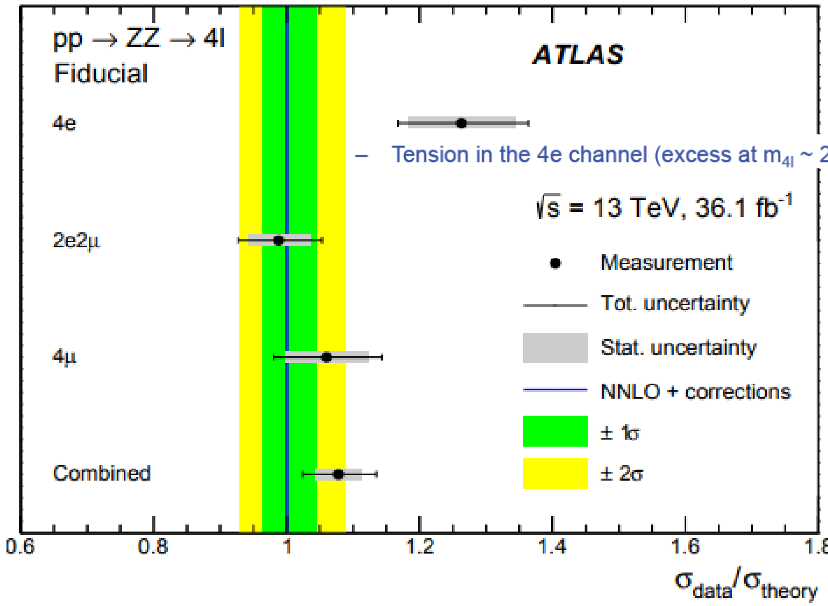
bution of the W boson. Several measurement combinations are performed, using the best linear unbiased estimate (BLUE) method [114, 115]. The results of the combinations are verified with the HERAverager program [116], which gives very close results.

Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

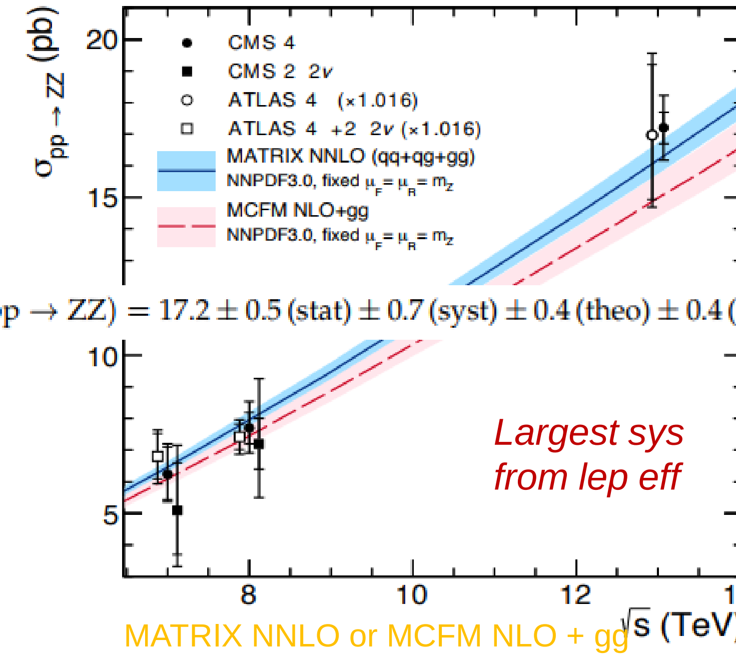
$$m_{W^+} - m_{W^-} = -29.2 \pm 12.8\,\text{MeV(stat.)} \pm 7.0\,\text{MeV(exp. syst.)} \pm 23.9\,\text{MeV(mod. syst.)}$$
$$= -29.2 \pm 28.0\,\text{MeV},$$

ZZ@13TeV

ATLAS arXiv:1709.07703 13TeV 36.1/fb; CMS arXiv:1709.08601 35.9/fb



– Tension in the 4e channel (excess at m_{4l} ~ 250 GeV)

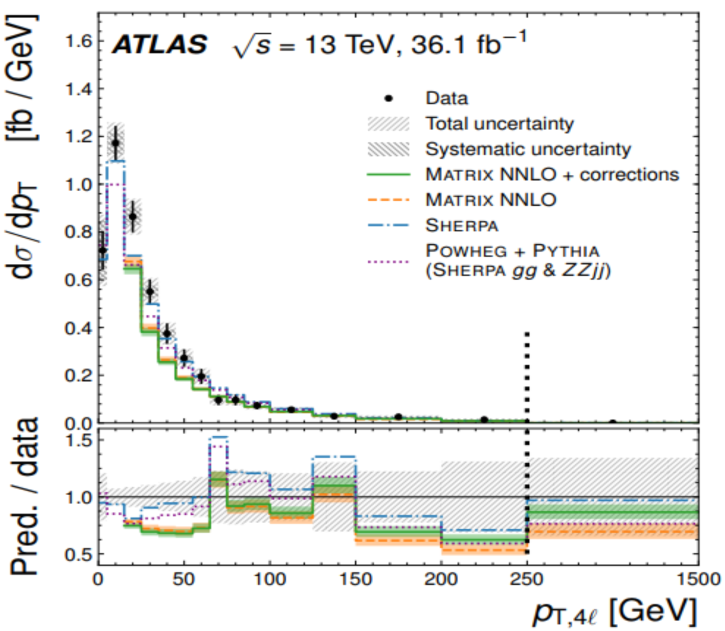


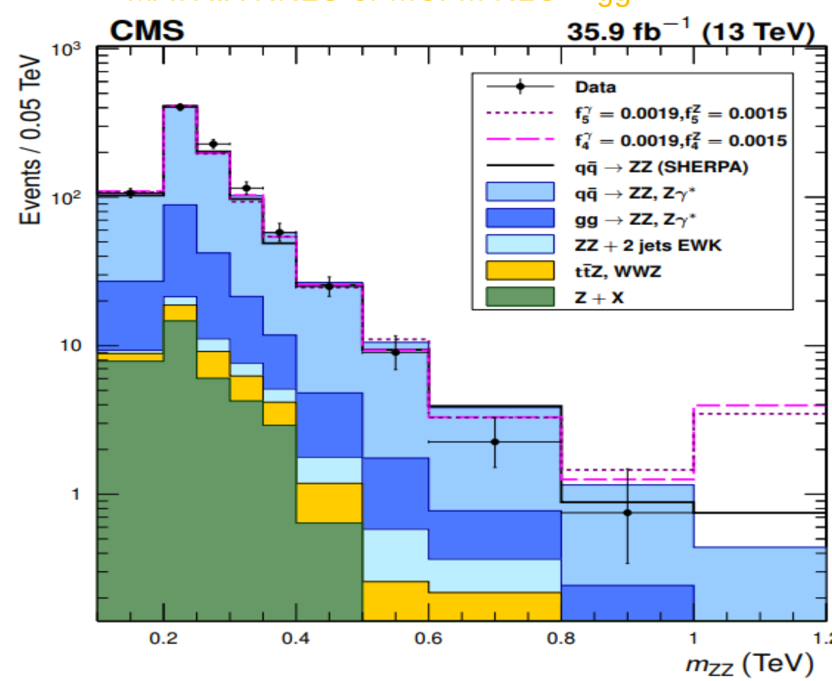
$$\sigma(pp \to ZZ) = 17.2 \pm 0.5\,(\mathrm{stat}) \pm 0.7\,(\mathrm{syst}) \pm 0.4\,(\mathrm{theo}) \pm 0.4\,(\mathrm{lumi})\,\mathrm{pb}.$$

Largest sys from lep eff

NNLO QCD+NLO QCD gg-induced + NLO EWK + EWK ZZjj

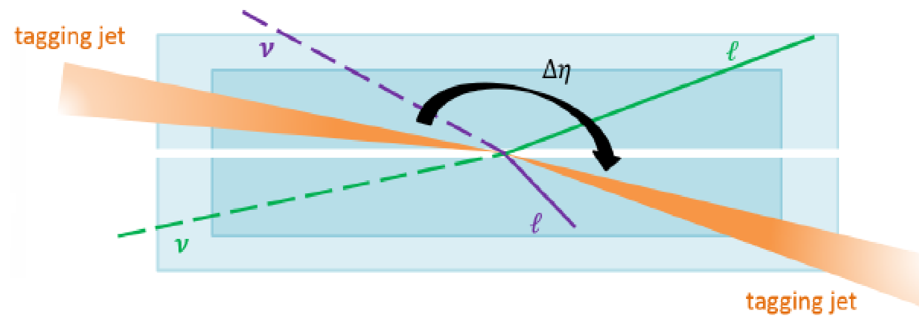
MATRIX NNLO or MCFM NLO + gg





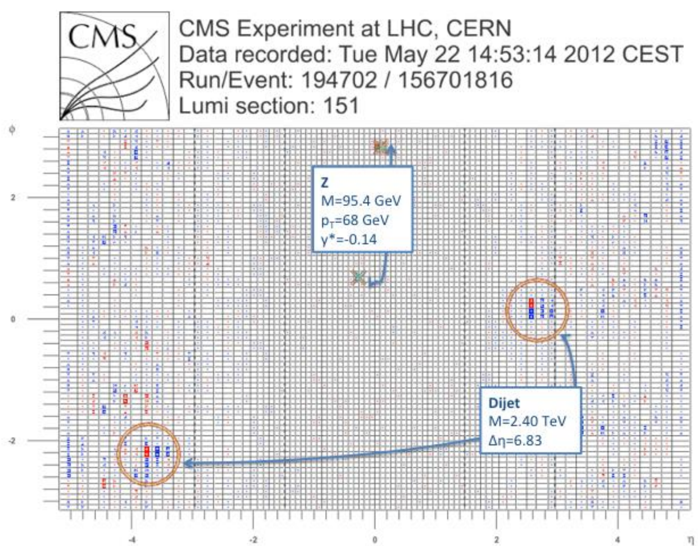
VBF/VBS

IHEP, PKU

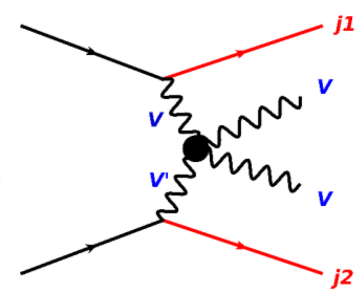


- **VBF Higgs established at >5σ**
- **VBF/VBS SM processes**
  1. Rare & Novel processes to be discovered
  2. pure EWK activity with less QCD emission,
  3. VV scattering sensitive to UV completeness
  4. High Tail enhancements: to probe aGCs

- **Two VBF Tagged Jets:**
  Large M_{jj} and $|\Delta\eta_{jj}|$
  More quark-like
- **Lower central hadronic activity:**



CMS
VBF Z+2jets
M_{jj}=2.4TeV,
$|\Delta\eta_{jj}|$=6.83



$$p_{\mathrm{T}}^{\text{balance}} = \frac{\left|\vec{p}_{\mathrm{T}}^{\ell_1} + \vec{p}_{\mathrm{T}}^{\ell_2} + \vec{p}_{\mathrm{T}}^{j_1} + \vec{p}_{\mathrm{T}}^{j_2}\right|}{\left|\vec{p}_{\mathrm{T}}^{\ell_1}\right| + \left|\vec{p}_{\mathrm{T}}^{\ell_2}\right| + \left|\vec{p}_{\mathrm{T}}^{j_1}\right| + \left|\vec{p}_{\mathrm{T}}^{j_2}\right|}$$

$$Rp_{\mathrm{T}}^{\text{hard}} = \frac{|\mathbf{p}_{\mathrm{Tj_1}} + \mathbf{p}_{\mathrm{Tj_2}} + \mathbf{p}_{\mathrm{TZ}}|}{|\mathbf{p}_{\mathrm{Tj_1}}| + |\mathbf{p}_{\mathrm{Tj_2}}| + |\mathbf{p}_{\mathrm{TZ}}|}$$

$$y^* = y_{\mathrm{Z}} - \frac{1}{2}(y_{\mathrm{j1}} + y_{\mathrm{j2}})$$

Zeppenfeld Variable

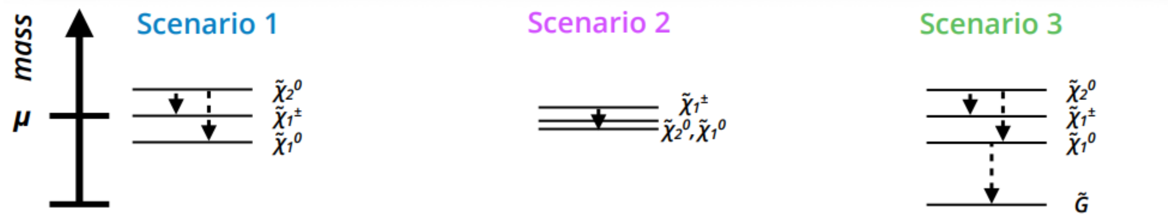
$$|y_{W\gamma} - (y_{j1} + y_{j2})/2.0|$$

$$|\Delta\phi_{W\gamma,dijet}|$$

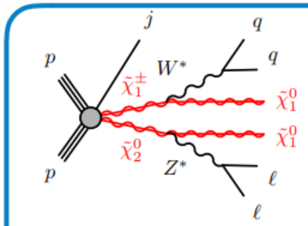
aQGCs *WWWW/WWγγ/WWZγ/ZZZγ/ZZγγ/Zγγγ*
Dimension 6 LEP style a_0^c, a_0^W; Whizard Parametrization α_4, α_5
or Dimension 8 operators $\boldsymbol{L_{S0,S1}}$, $\boldsymbol{L_{M0-7}}$, $\boldsymbol{L_{T0-9}}$

SUSY: Higgsino

https://indico.in2p3.fr/event/16579/contributions/60896 https://indico.in2p3.fr/event/16579/contributions/60827
https://indico.in2p3.fr/event/16579/contributions/60829 https://indico.in2p3.fr/event/16579/contributions/60897

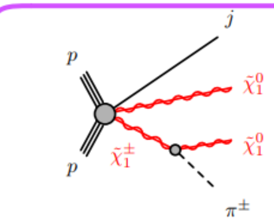


Scenario 1	Scenario 2	Scenario 3
$\Delta m(\tilde\chi_2^0,\tilde\chi_1^\pm,\tilde\chi_1^0)$ ~ a few GeV	$\Delta m(\tilde\chi_2^0,\tilde\chi_1^\pm,\tilde\chi_1^0)$ ~ 300 MeV	$\Delta m(\tilde\chi_2^0,\tilde\chi_1^\pm,\tilde\chi_1^0)$ ~ a few GeV



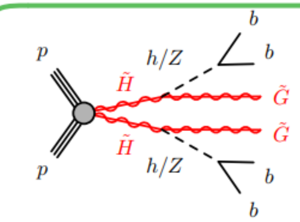
- Decays via *off-shell W/Z*
- Soft-leptons + jets

arxiv:1712.08119



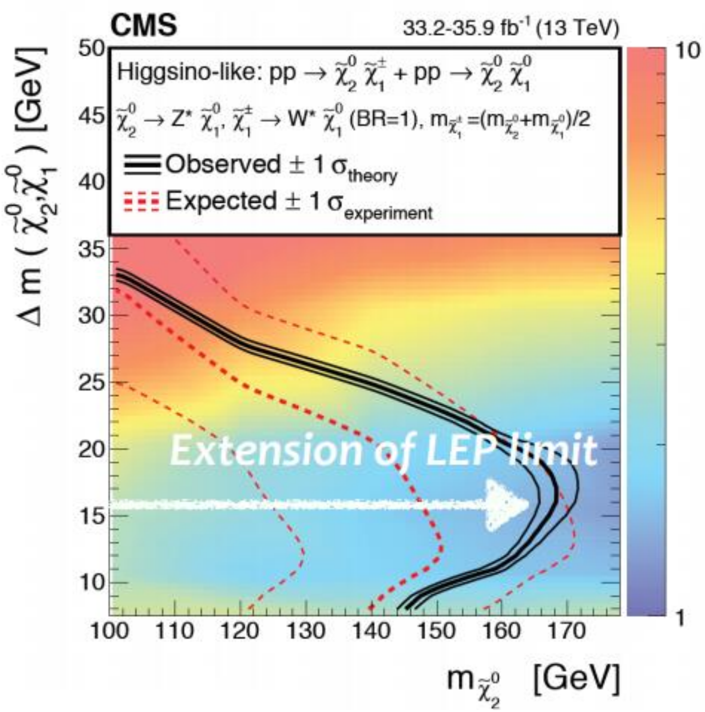
- Extremely compressed
- Disappearing tracks

arxiv:1712.02118
ATL-PHYS-PUB-2017-019

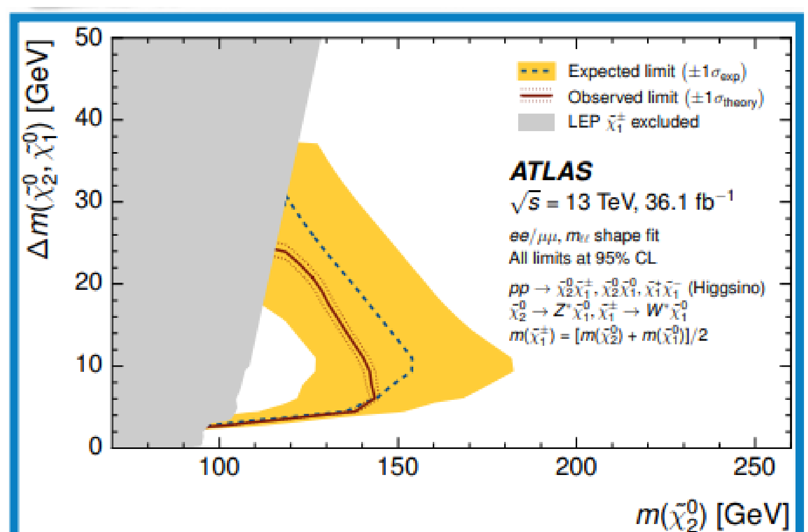


- Decays via *on-shell h/Z*
- ≥3*b*-jets

ATLAS-CONF-2017-081

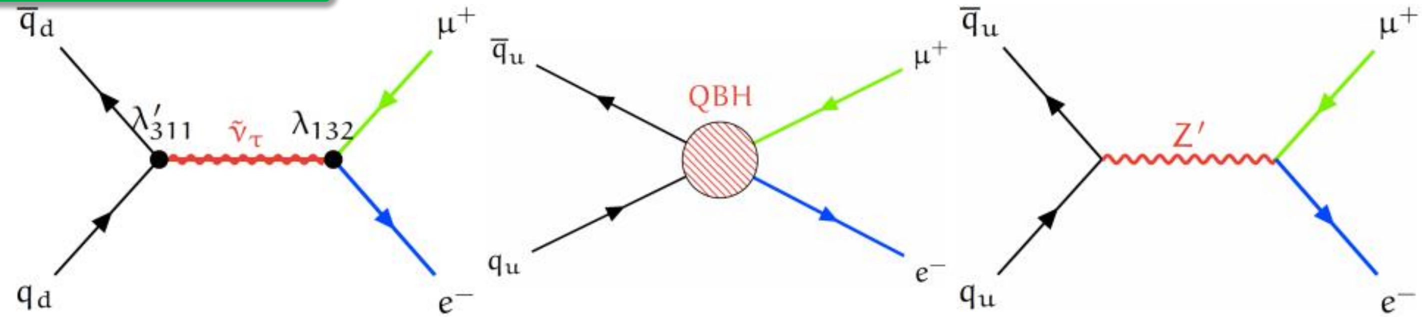


arXiv 1801.01846



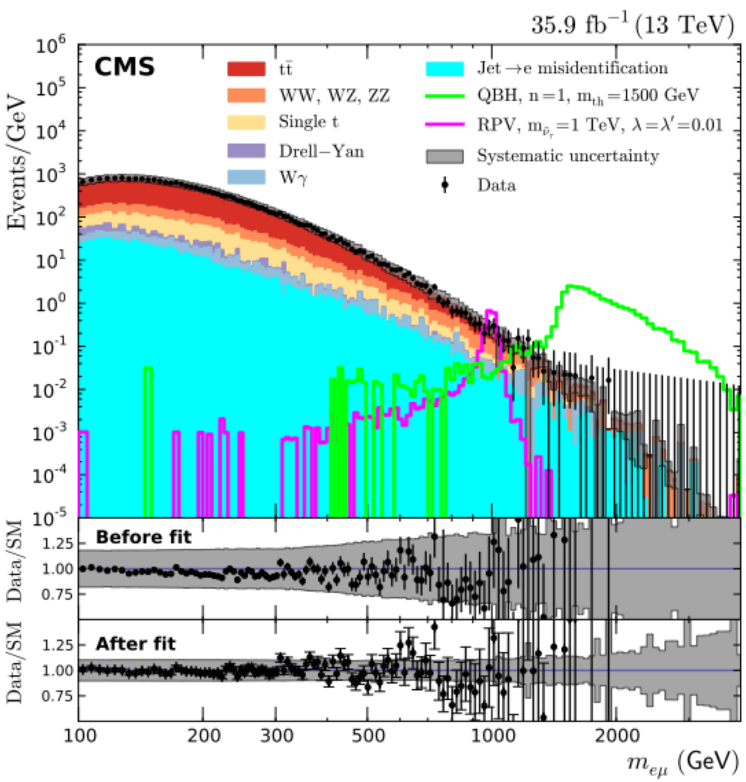
LFV resonance

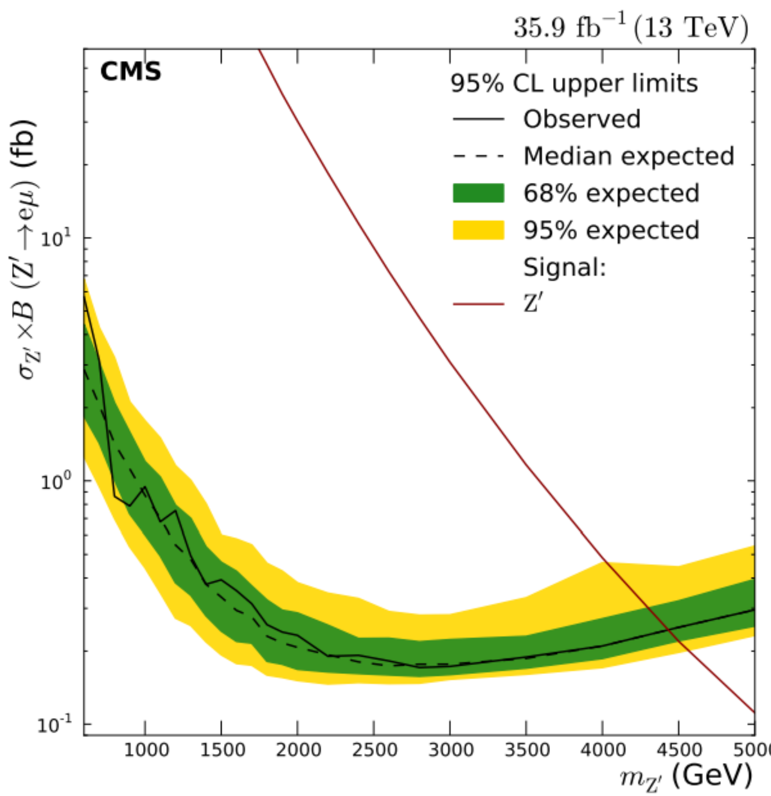
arXiv:1802.01122



Backgrounds containing misidentified electron and muons：W+γ is taken from simulation; W+Jets and QCD mutlijet from data-driven; Electron mis-identification rate measured in control region

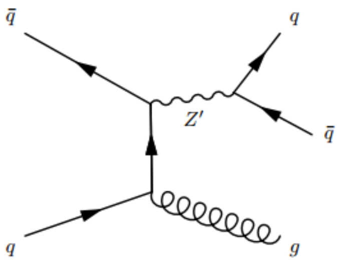
Largest uncertainty is the shape variation in the $t\bar{t}$ from renormalization and factorization scale variation

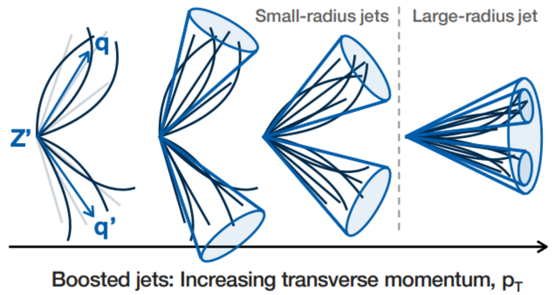


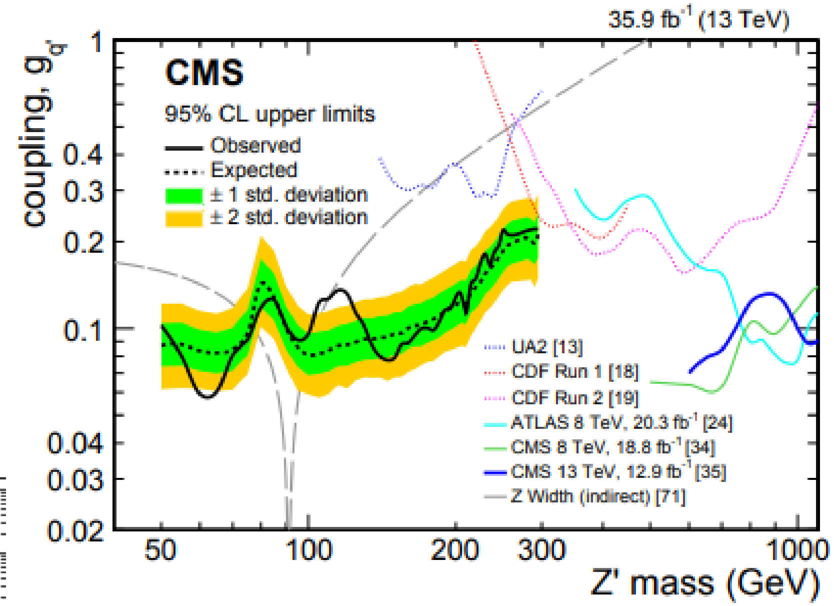


Boosted Dijet + ISR jet or γ (ATLAS)

arXiv:1801.08769; JHEP 1801 (2018) 097

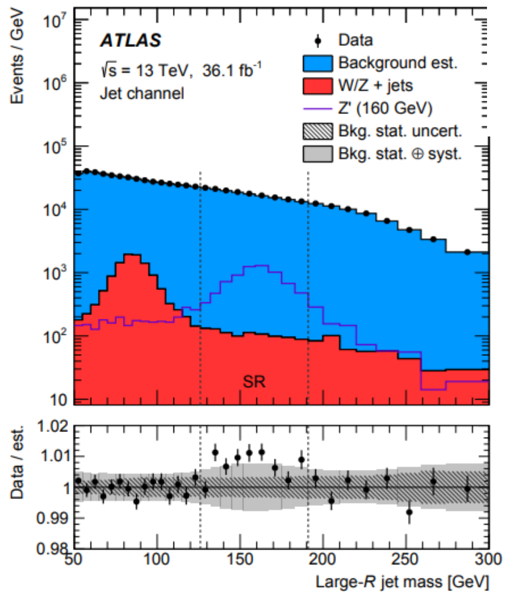


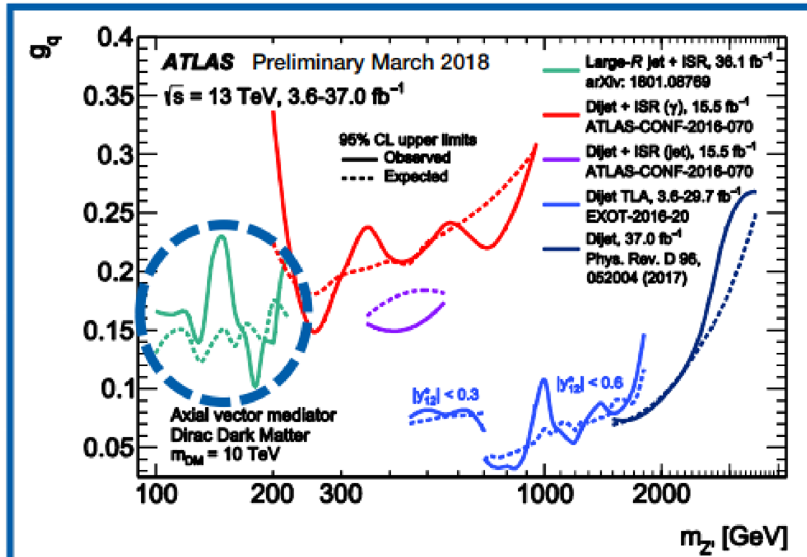




ATLAS: Trimming
CMS: Soft-drop

- **Challenge**: Substructure cut (τ_{21}) sculpts m_J distribution, used for data-driven background estimate.
- τ_{21} de-correlated from m_J by subtracting linear fit from kinematic dependence → τ_{21}^{DDT}.
- Data-driven background estimate using transfer factor on τ_{21}^{DDT} "pass"/"fail" regions.
- Search validated on W/Z peak, $\hat{\mu}$ consistent with 1.



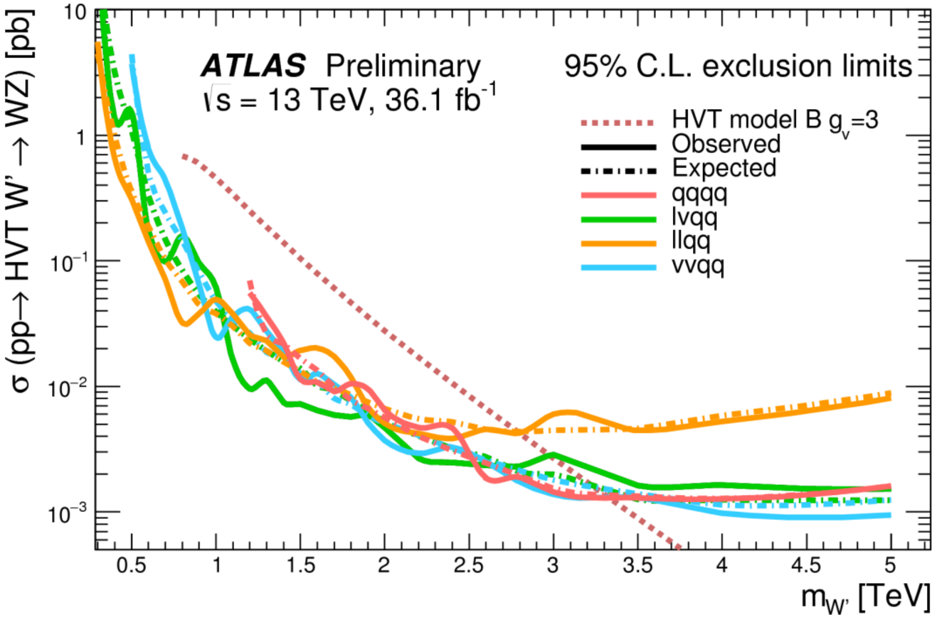


CMS did similar but uses a DDT version of

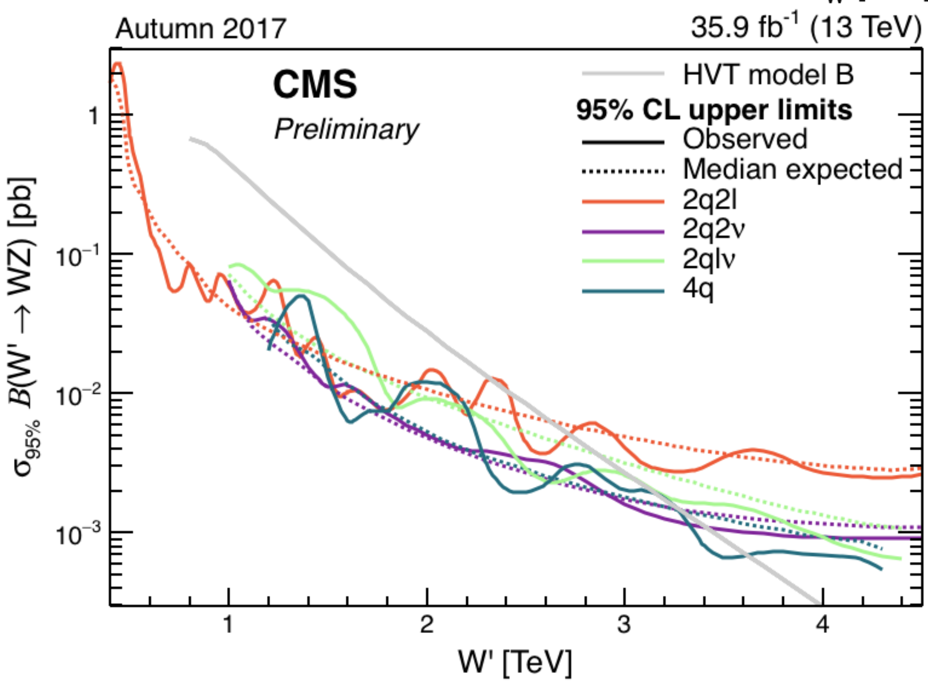
$$N_2^{\beta} = \frac{{}_2e_3^{\beta}}{({}_1e_2^{\beta})^2} \qquad \beta = 1$$

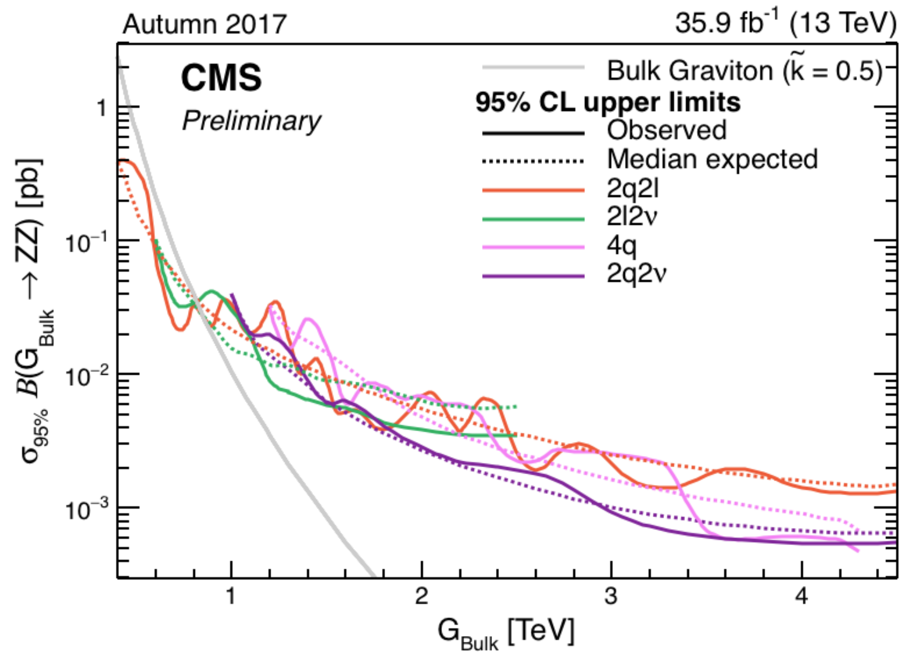
VV resonances

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2GDibosons



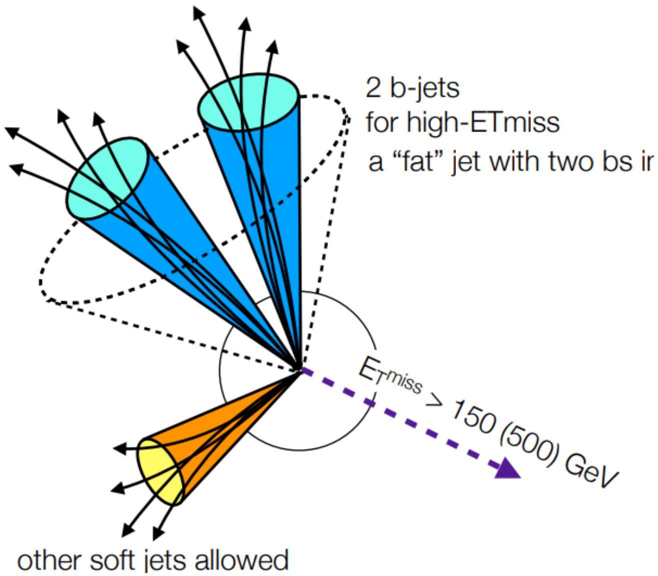
- Search for di-boson resonances in HVT and Bulk Graviton models;
- Extensive usage of Jet-subtructure and boosted b tagging technique;
- Comparable results between limits from ATLAS and CMS

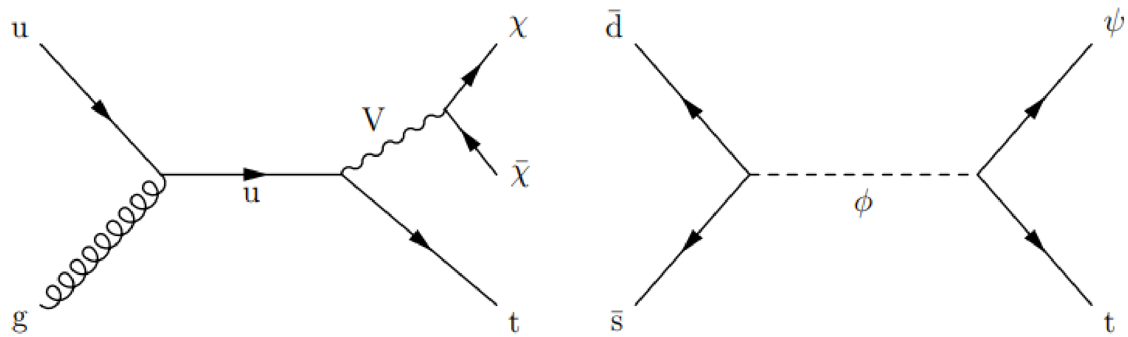


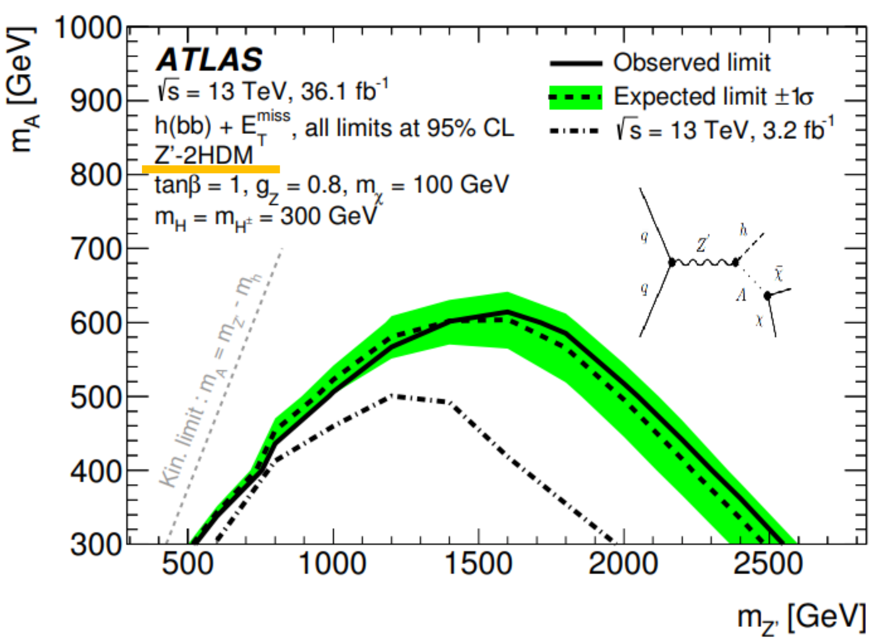


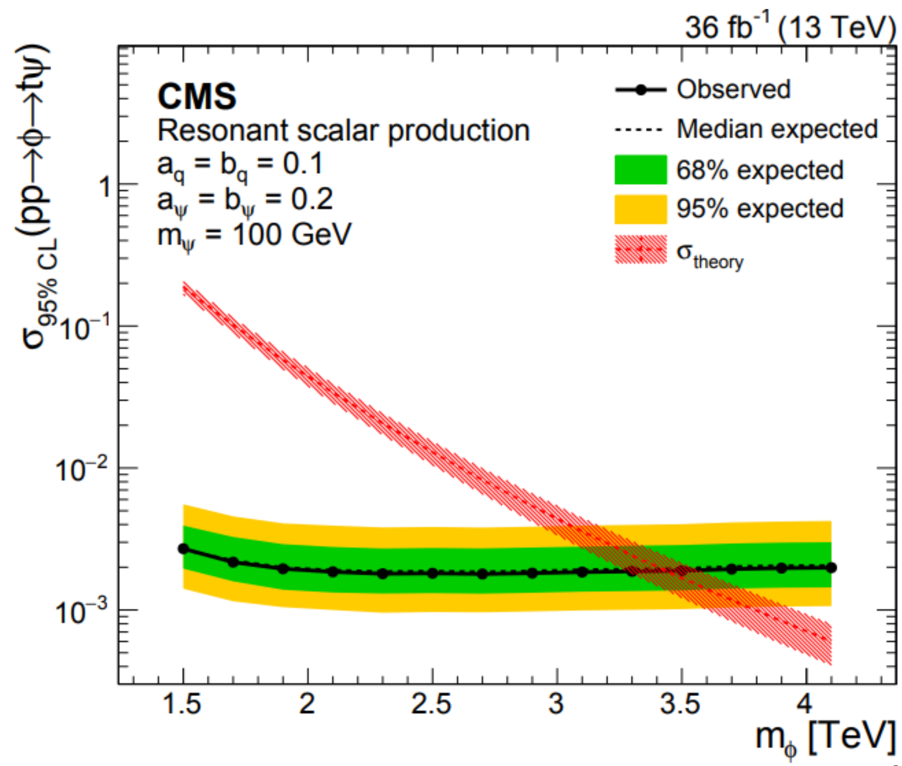
Dark Matter

JHEP 01 (2018) 126; PRL 119, 181804 (2017); Phys. Lett. B 776 (2017) 318; arXiv:1801.08427; Phys. Rev. D 97, 032009 (2018); EXO-17-014

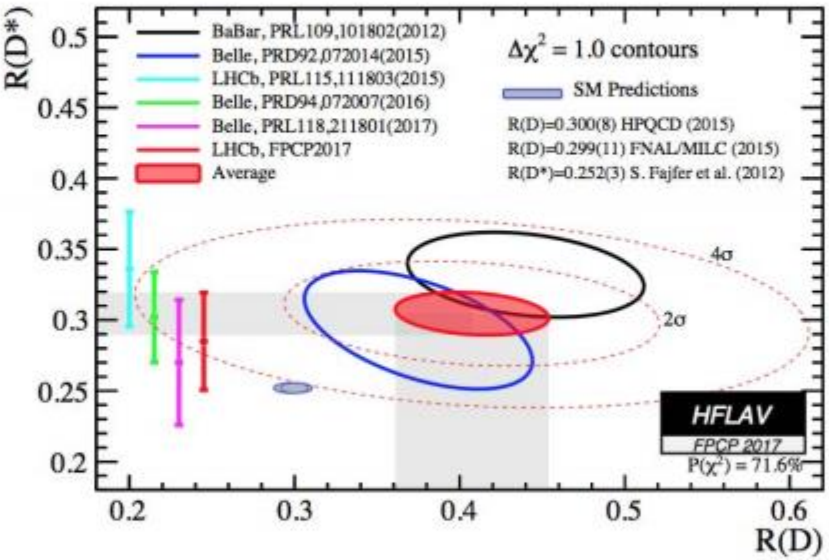


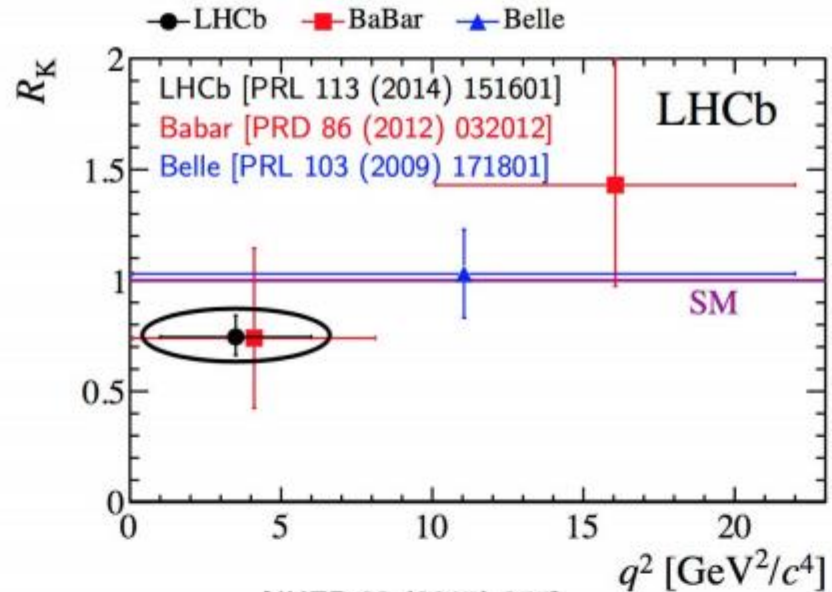


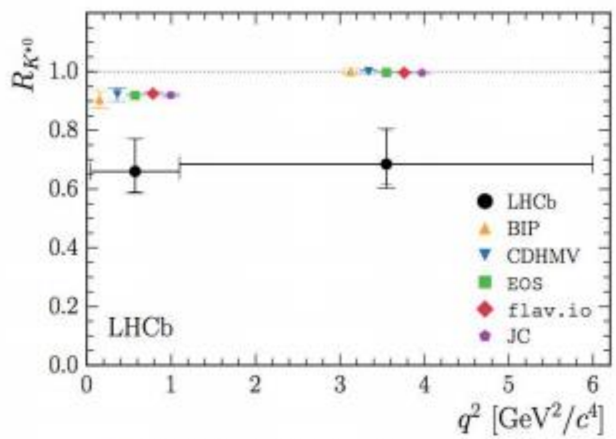




Lepton Flavour Universality in B decays

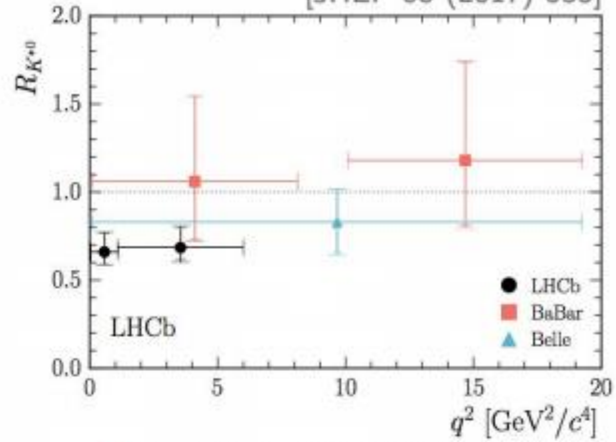






- BIP [EPJC 76 (2016) 440]
- CDHMV [JHEP 04 (2017) 016]
- EOS [PRD 95 (2017) 035029]
- flav.io [EPJC 77 (2017) 377]
- JC [PRD 93 (2016) 014028]

[JHEP 08 (2017) 055]



- Babar [PRD 86 (2012) 032012]
- Belle [PRL 103 (2009) 171801]

New results eagerly awaited

[Langenbruch]

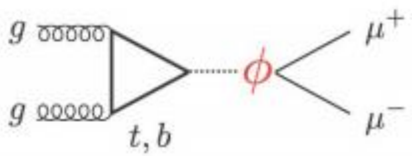
LHCb: light bosons and dark photons searches

New

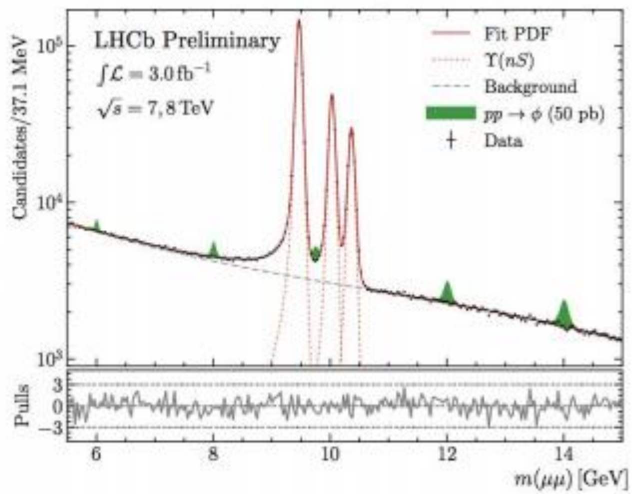
[Borsato]

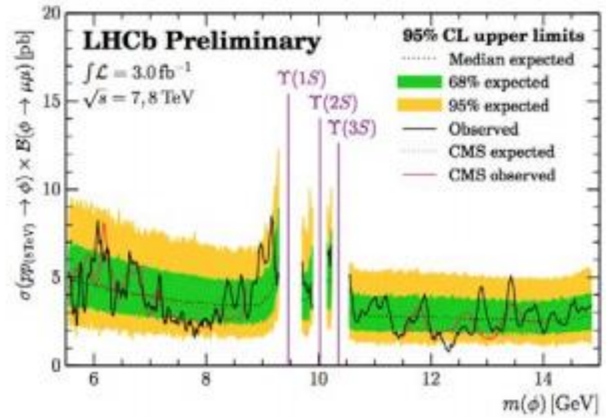
LHCb-PAPER-2018-008 in preparation

Light Boson



First limits 8.7-11.5 GeV





Dark Photon