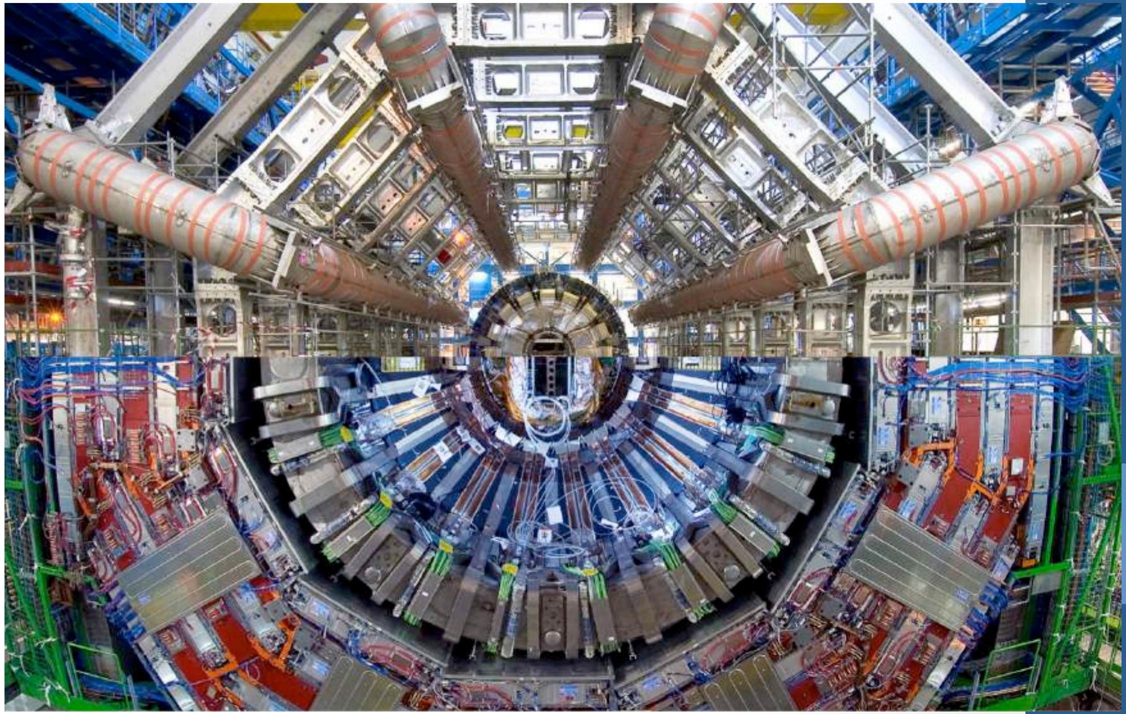
Electroweak measurements at the LHC

Gabriella Pásztor

MTA – ELTE Lendület CMS Particle and Nuclear Physics Group

Eötvös University, Budapest



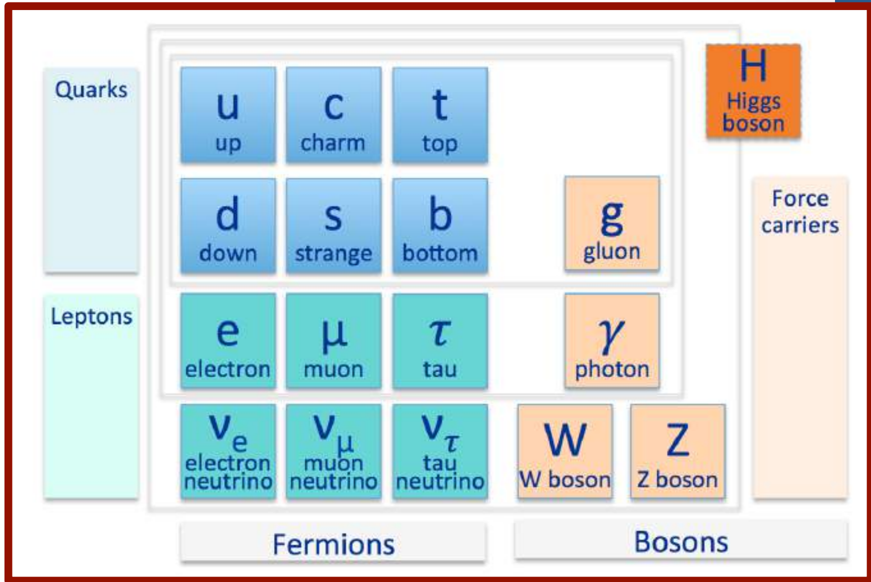
Zimányi Winter School

Wigner RCP & ELTE, Budapest

7-11 December 2015

The Standard Model and the Higgs boson

- In the **S**tandard **M**odel, the **scalar Higgs field** breaks electroweak symmetry dinamically via the Brout-Englert-Higgs mechanism making the theory renormalisable
- The field's longitudinal degrees of freedom *provide mass* to the W and Z bosons
- The elementary fermions acquire mass via Yukawa interactions
- The **Higgs boson** is the only fundamental scalar particle in the SM (while many extensions of the model predict more scalar bosons...)
- The Higgs contribution *regularizes weak* ***vector-boson scattering*** whose study thus provides a sensitive test of EWSB as well as physics beyond the SM
- Since its discovery in 2012, the LHC ATLAS and CMS collaborations proceeded to measure the **Higgs boson properties** with increasing precision



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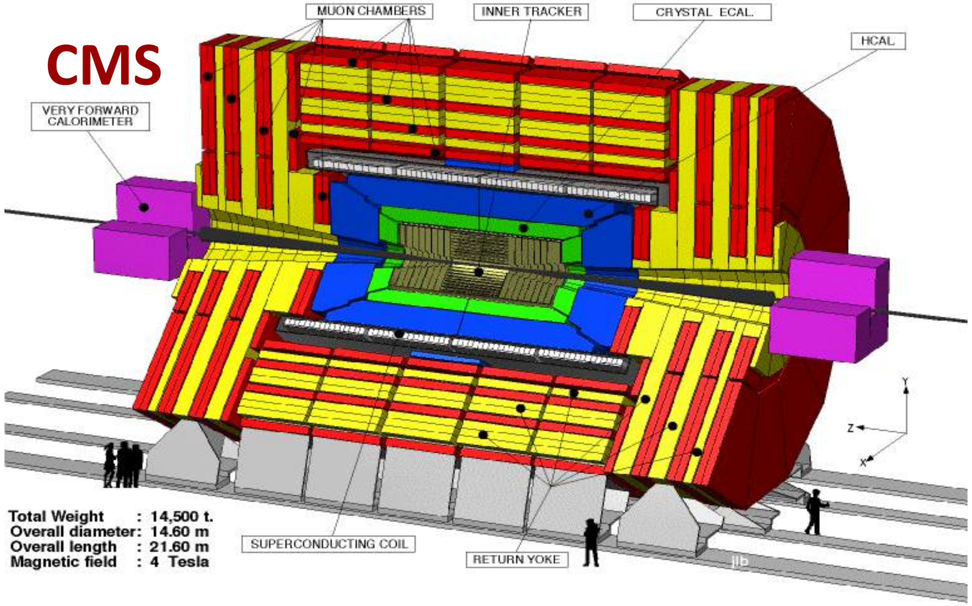
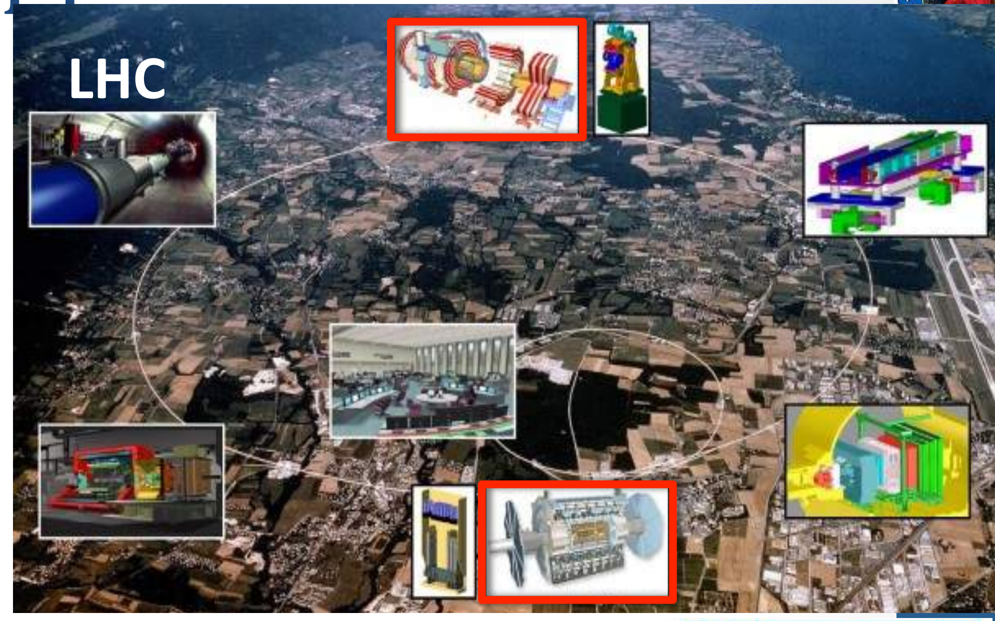
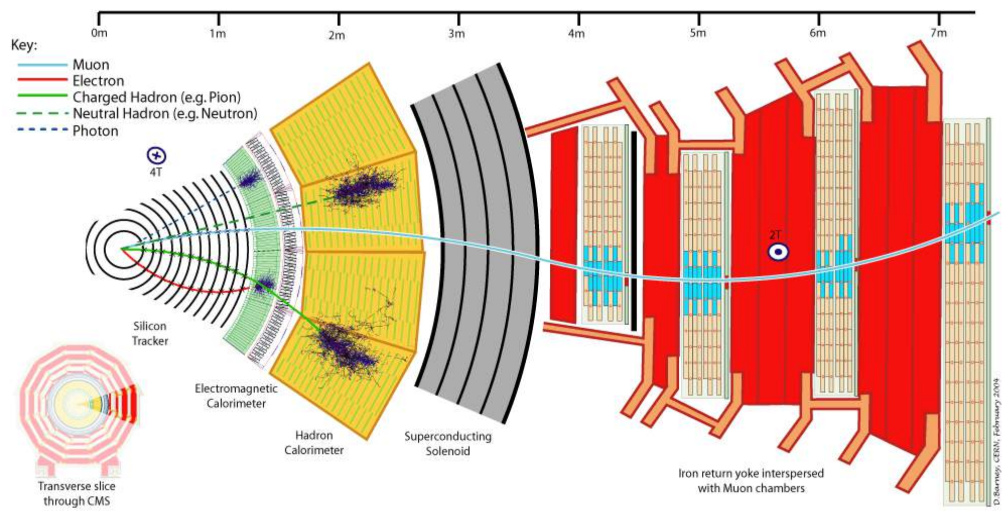
The apparatus

CMS

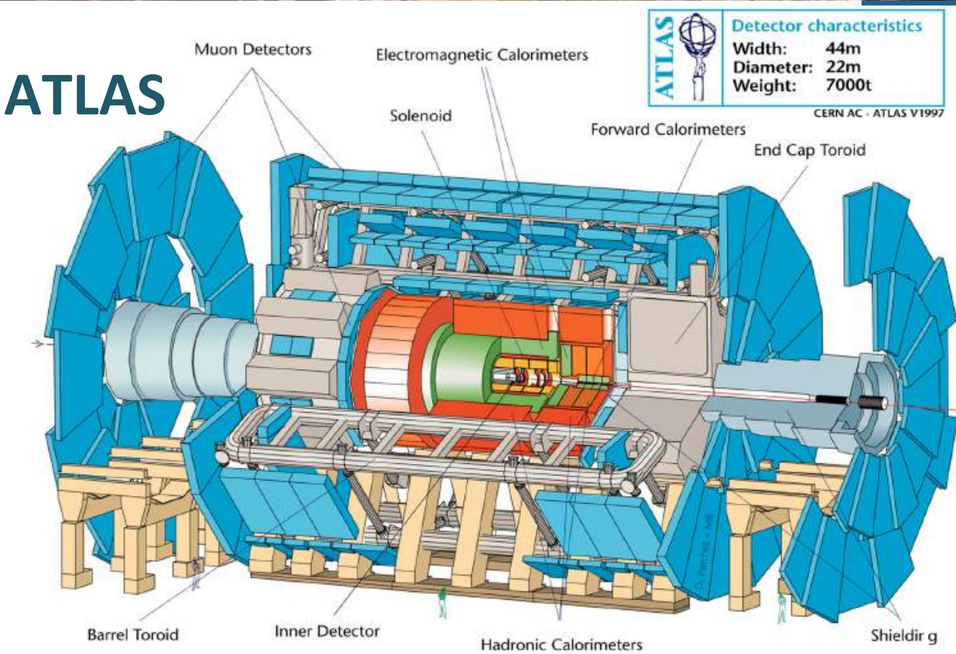


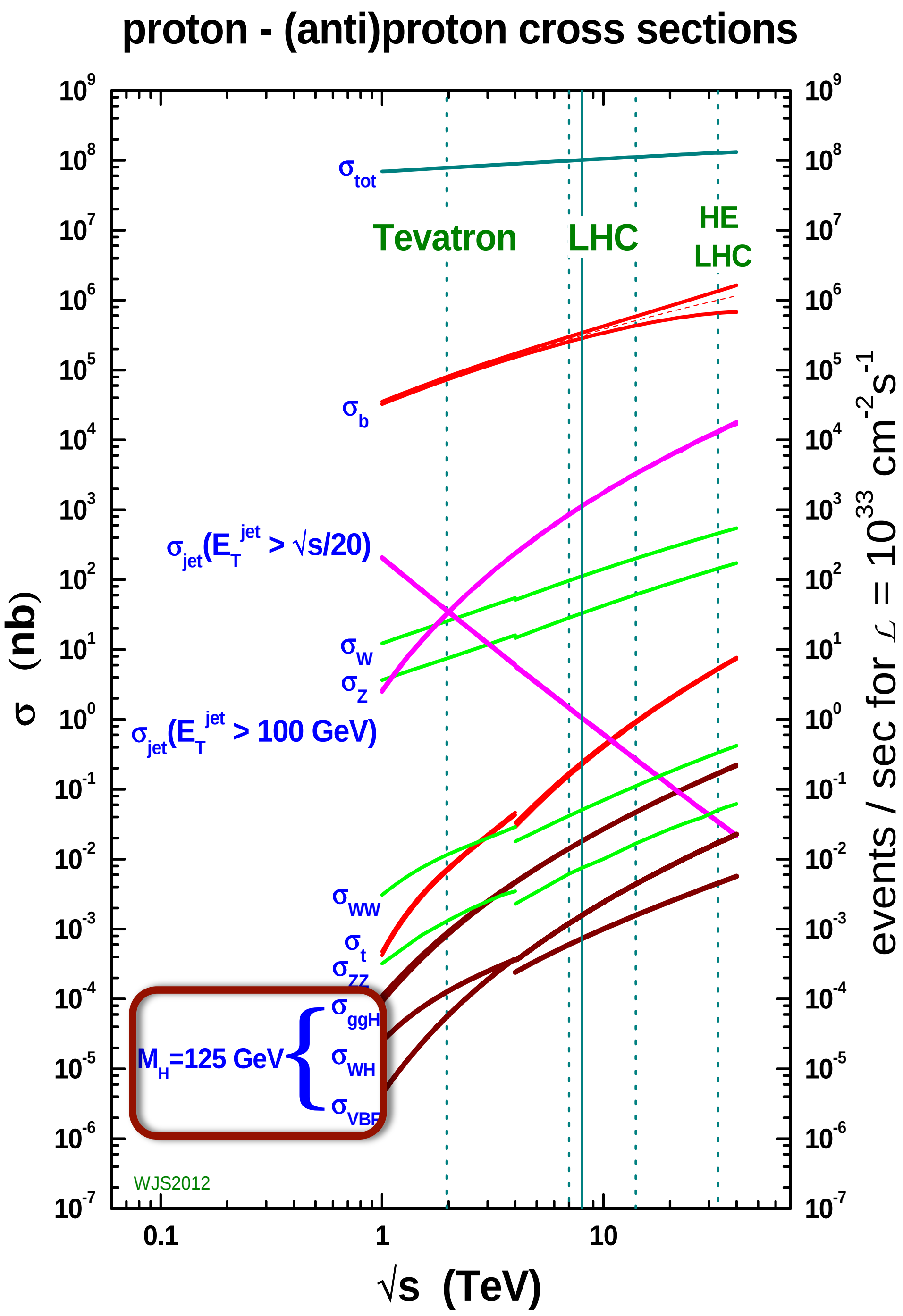
LHC





ATLAS





Challenges

- Interesting processes are very rare (~3 Higgs in 10^{10} p-p interactions)
- Select signal from huge background
- Only 1 in $4 \cdot 10^4$ events can be recorded

Excellent trigger system critical for success!

→ Both experiments execute upgrades for Run2

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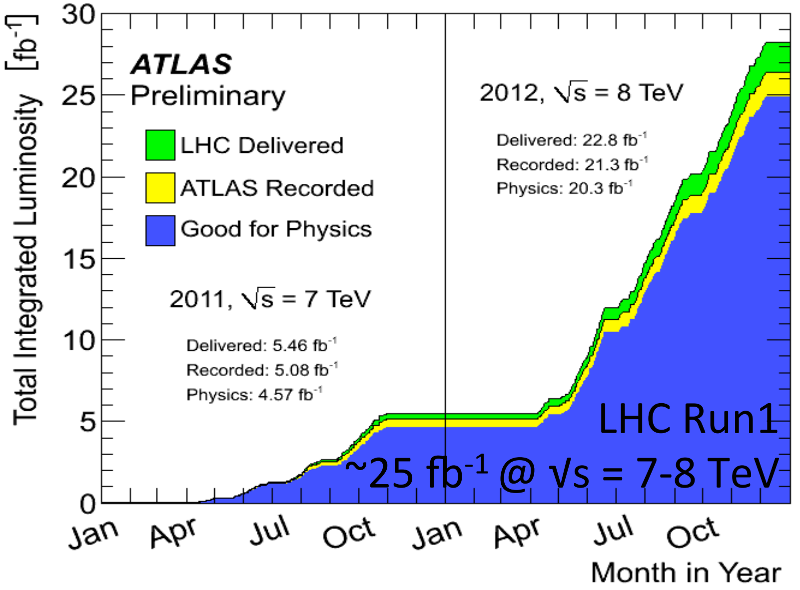
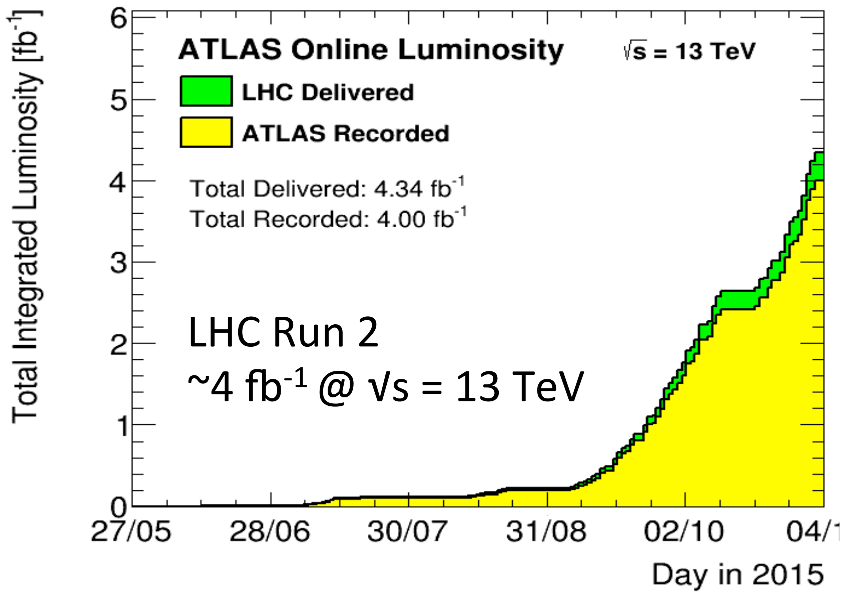
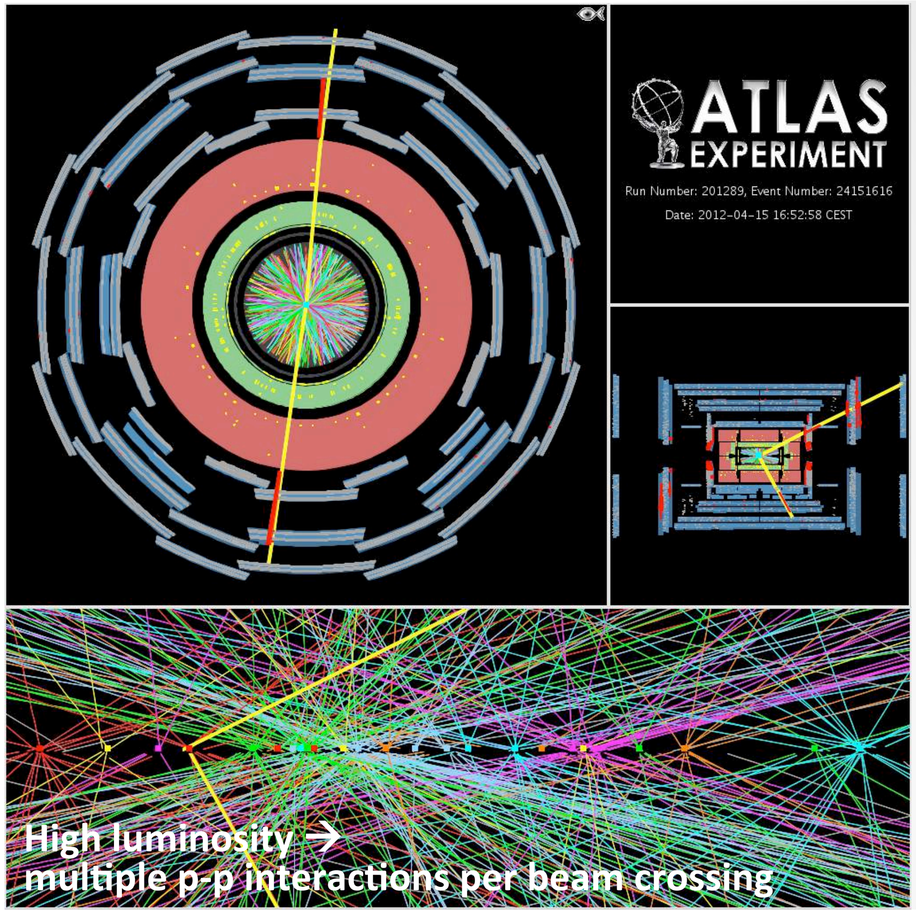
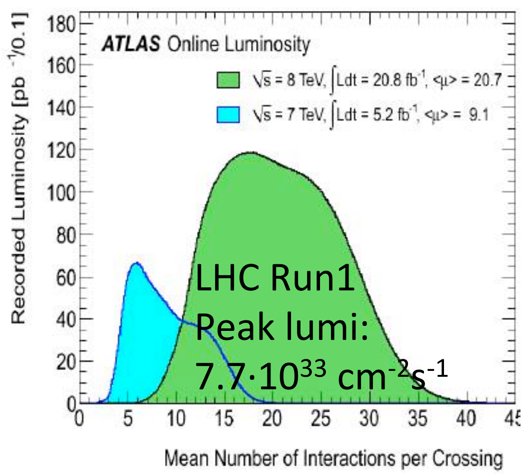
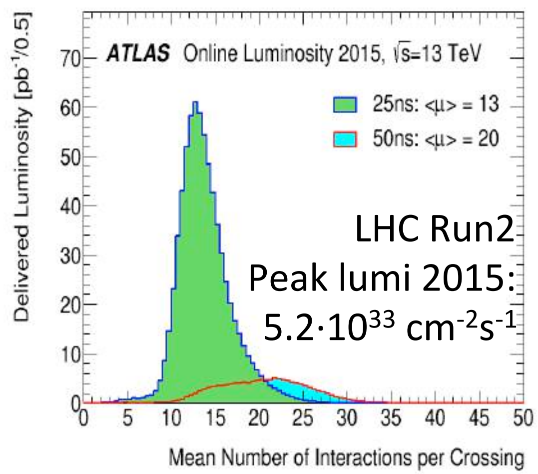
Data sample











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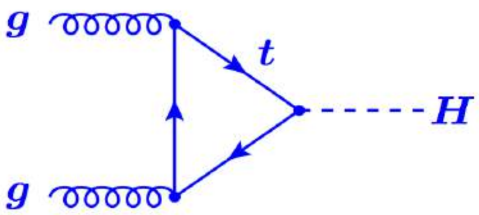
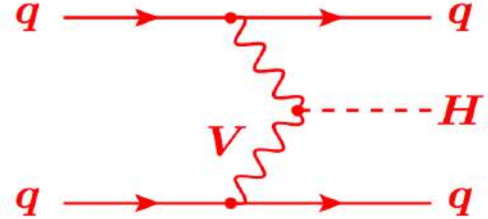
SM Higgs @ LHC

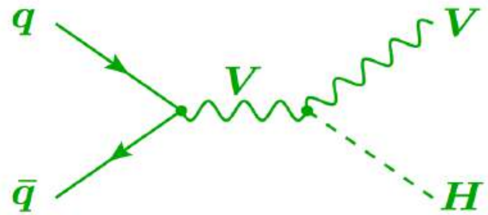
σ_{total} = 22 (51) pb @ √s = 8 (13) TeV, m_H = 125 GeV



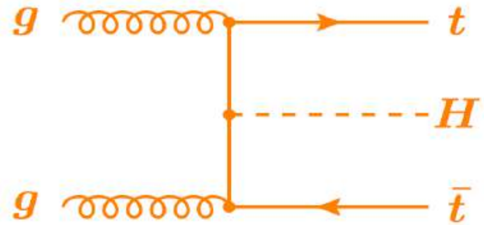
87%
ggF: dominant mode
(typically no extra
high-pT object)



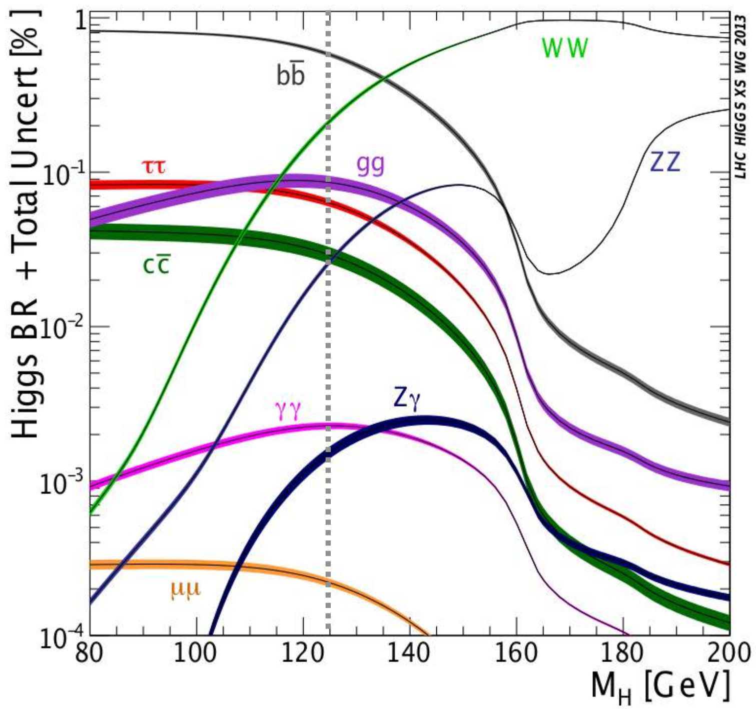
7%
VBF: tag **two forward jets**
with little hadronic
activity between



5%
VH: tag **Z and W decays**
(leptonic or hadronic)



<1%
ttH: tag **two top quarks**



H→ZZ→llll (0.012%): "Golden" channel, low stat

H→γγ (0.23%): Good resolution

H→WW→lνlν (1.0%): High stat, low resolution

H→ττ (6.3 %): Best fermionic channel

H→bb (57.5%): Dominant contribution for Γ_{total}, best for VH production

H→Zγ→llγ (0.01%)

H→μμ (0.02%)

Mass, diff. xsections

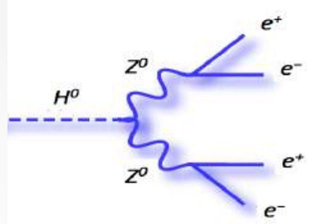
Discovery,spin

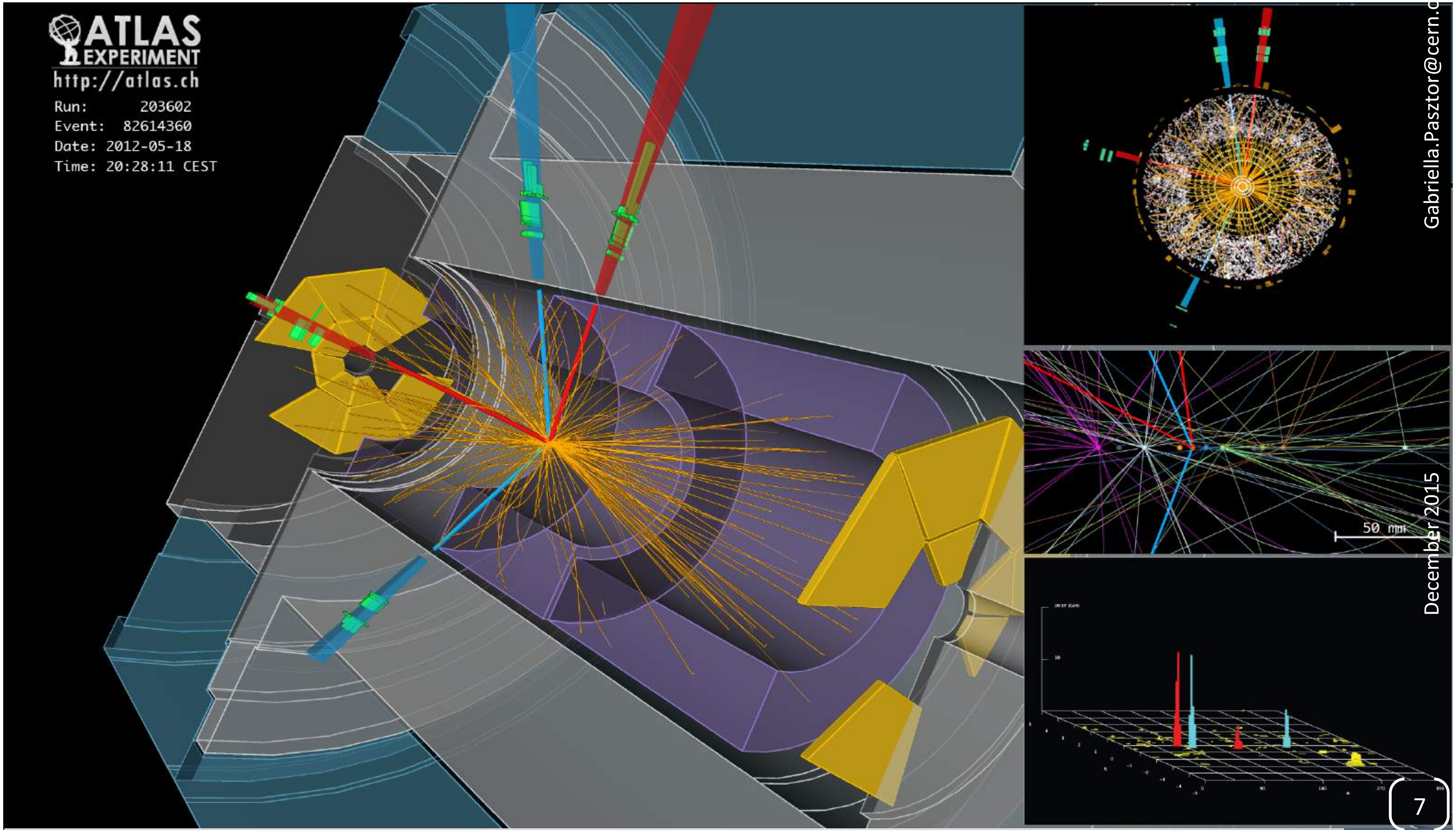
Cross-sections, couplings

Additional Higgs searches

g(Hff) ∝ $m_{fermion}$
g(HVV) ∝ m_{bozon}^2

Observing the SM Higgs

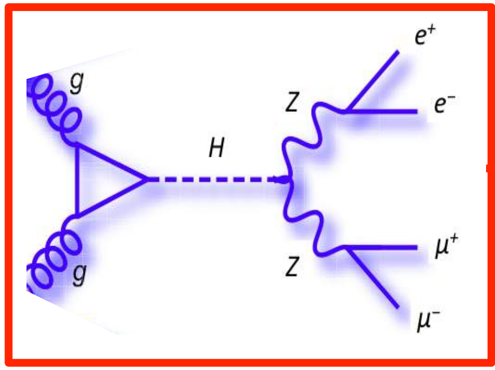




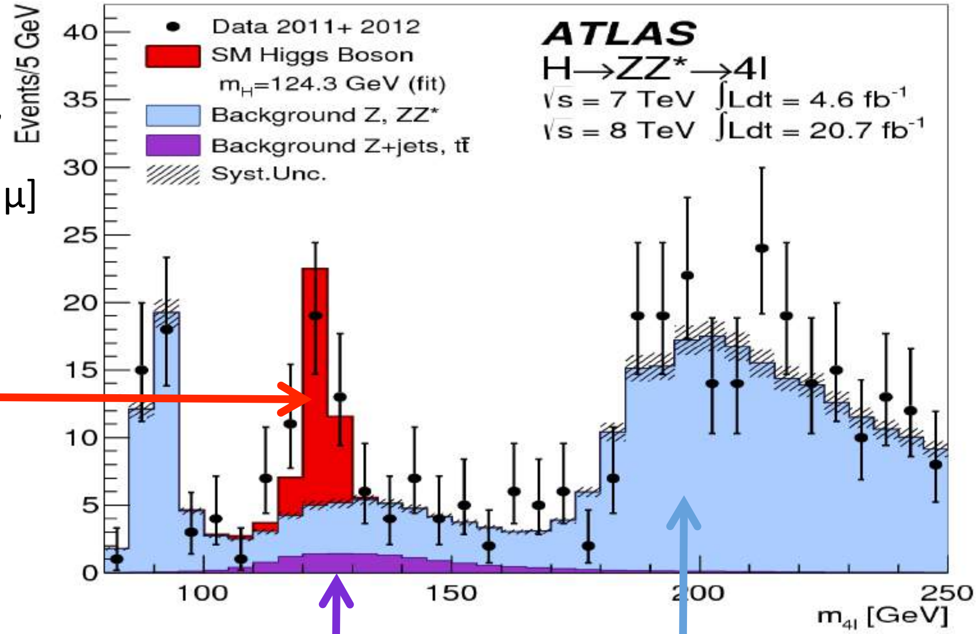
Gabriella.Pasztor@cern.ch

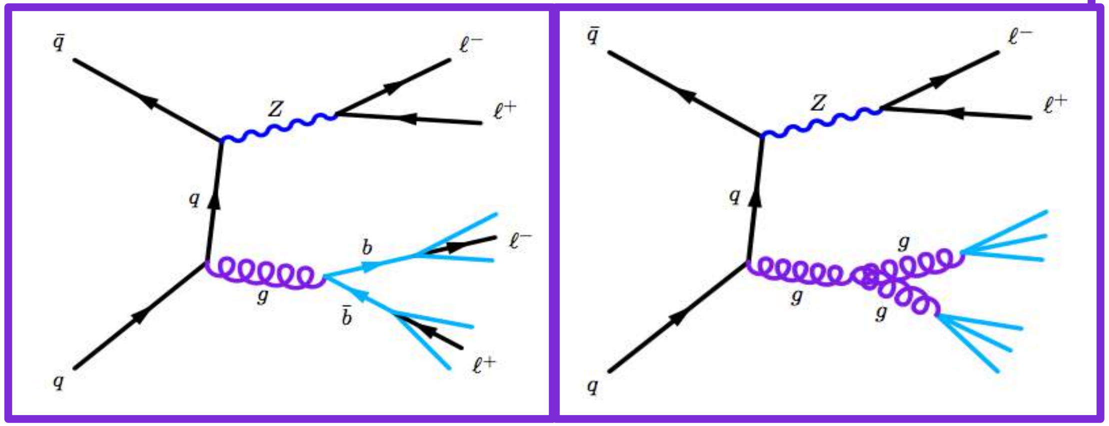
Observing the SM Higgs

Critical issues:
object reconstruction and identification efficiency, fake rate, background contributions, energy calibration [down to low p_T (~5 GeV) for e, μ]

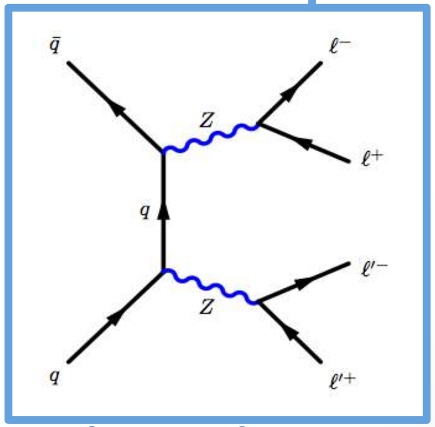


Signal (Higgs production)



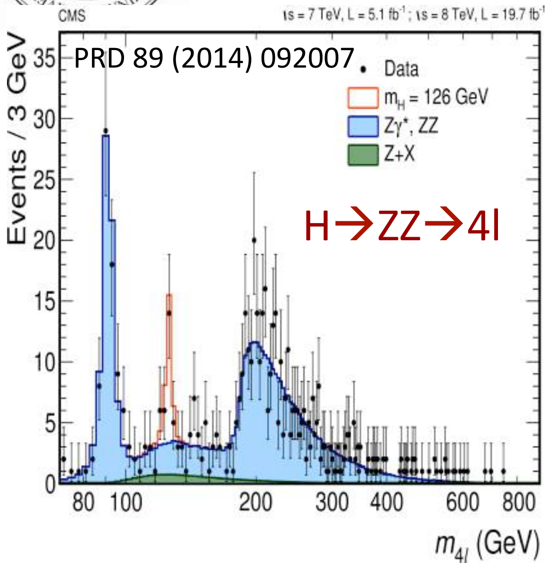


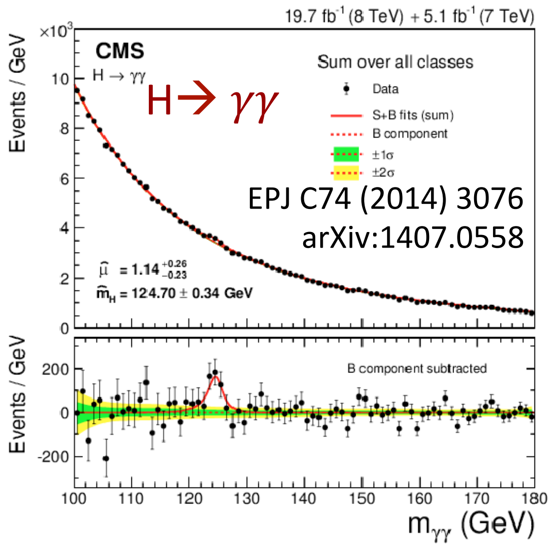
Background (reducible)



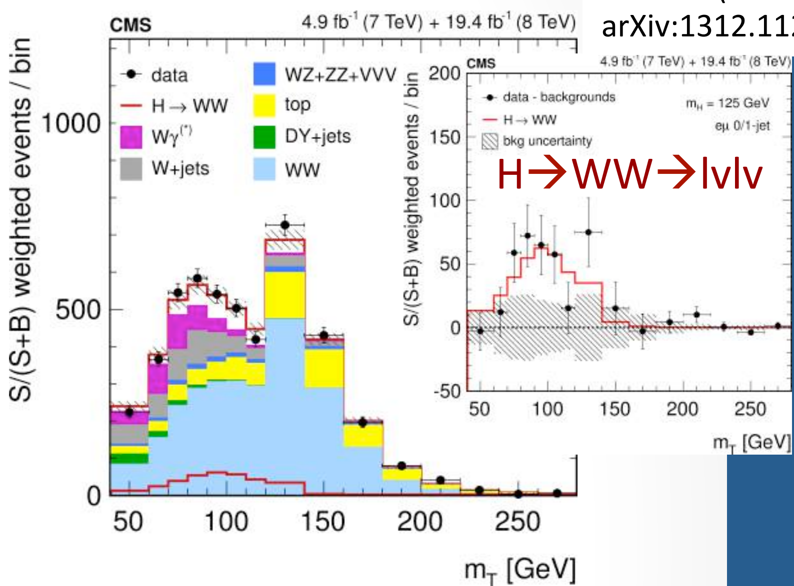
Background (identical final state)

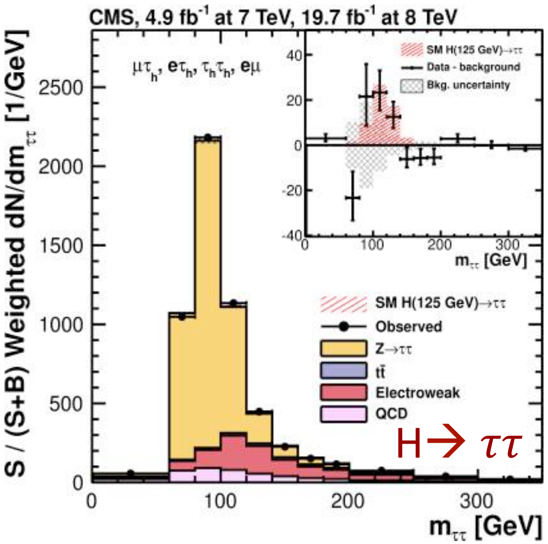
Observing the SM Higgs





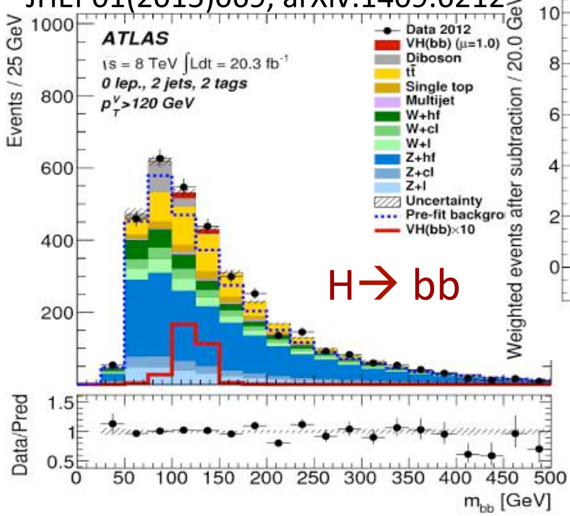
JHEP 01 (2014) 096
arXiv:1312.1129

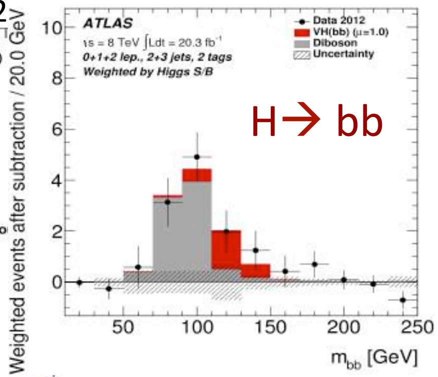




JHEP 05 (2014) 104, arXiv:1401.5041

JHEP01(2015)069, arXiv:1409.6212





- Bosonic final states drove the discovery
- Fermionic channels more challenging
- Sophisticated analysis techniques to discriminate signal against background

ATLAS-CONF-2015-044; CMS-PAS-HIG-15-002

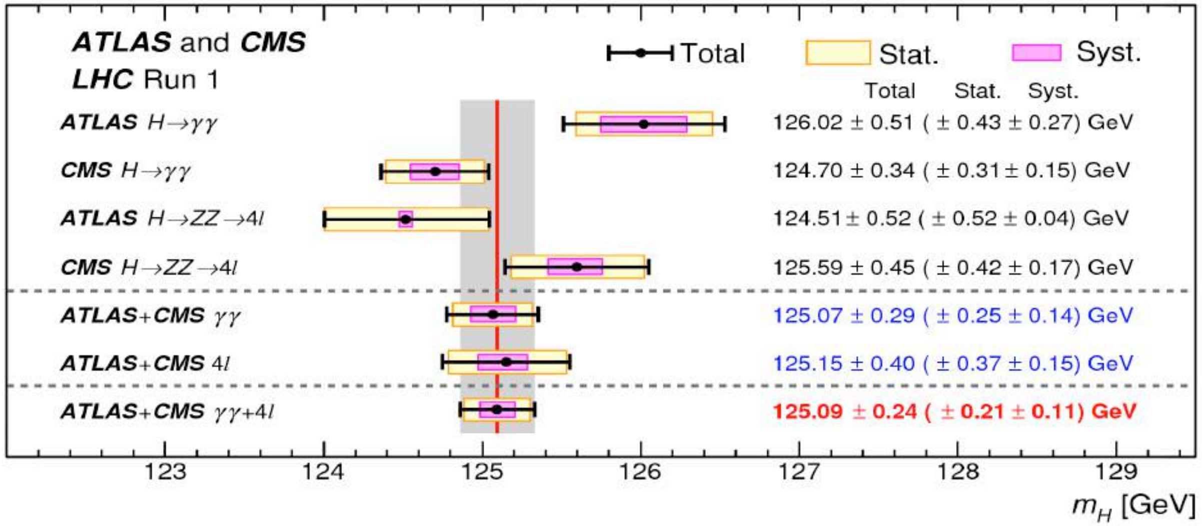
Decay channel	Measured significance (σ)	Expected significance (σ)
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

H → $\tau\tau$ observed with >5σ by ATLAS + CMS combined

Higgs mass measurement

- Higgs mass not predicted by the SM but production cross-sections and decay branching ratios are precisely predicted for a given mass
- Important input to other property measurements
  - Δm=0.2 GeV shifts BR(H→ZZ) by 2%
- Global fit to data of high resolution channels: H→ $\gamma\gamma$, H→ZZ→4l
  - m_H changes peak position and event rate (cross-section, branching ratios)
- Large improvement of precision from final Run1 calibration of EM calorimeter energy and muon momentum scales
- Measurements still statistics limited:

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$
$$= 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst) GeV}$$



arXiv:1503.07589, PRL 114 (2015) 191803

ATLAS-CONF-2015-044; CMS-PAS-HIG-15-002

Coupling measurements

- Separate different production and decay modes using their specific event characteristics
- Global fit to the events counts in the various phase-space regions taking into account (simultaneously fitting) background contributions with different assumptions for specific tests

$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \left\{\sigma_i \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}^f\right\},$$
$$= \mathcal{L}(k) \times \sum_i \sum_f \mu_i \mu^f \left\{\sigma_i^{\text{SM}} \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}_{\text{SM}}^f\right\}$$

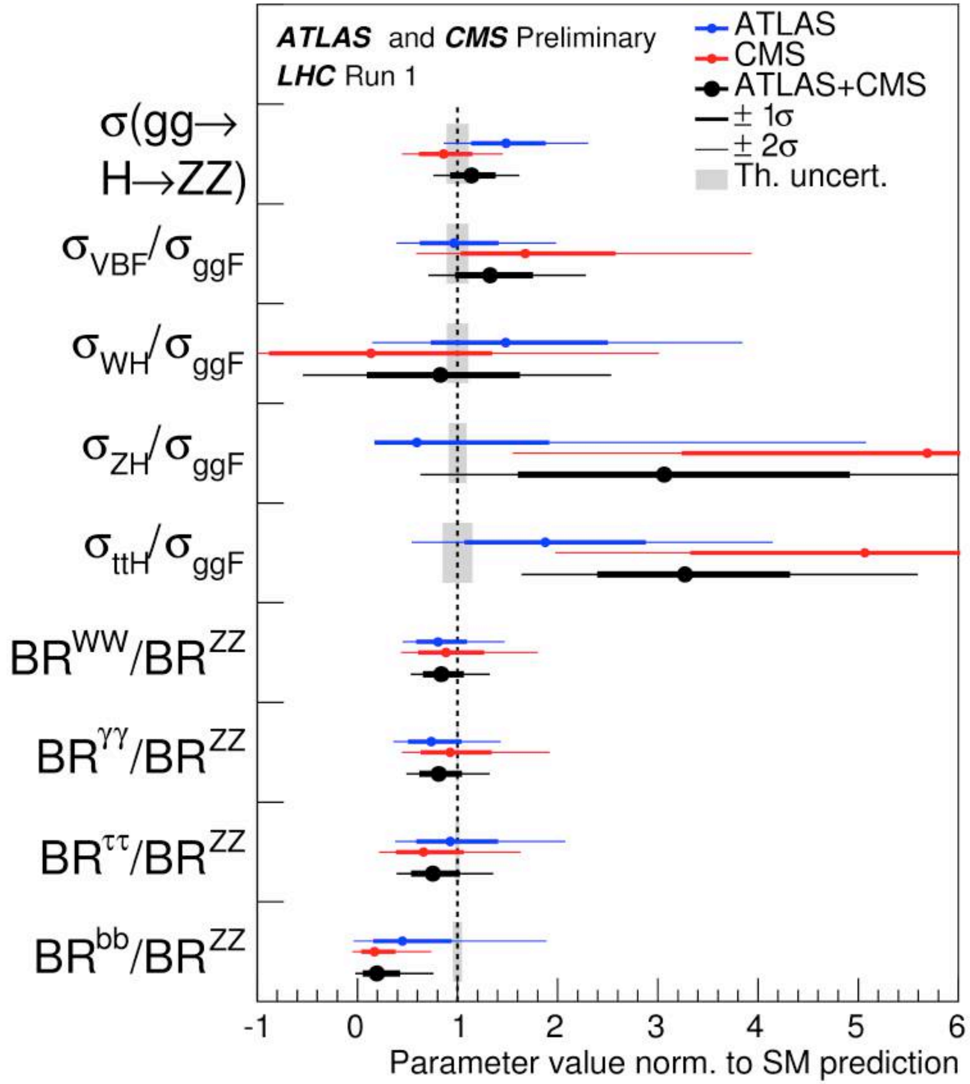
- More than 3000 nuisance parameters

- **All results assume a single SM-like Higgs boson (CP-even scalar) with the tensor structure of the SM interactions and a small width** (4 MeV in SM)
  - Inherent model dependence

Cross-sections and decay branching ratios

- Measured rates only sensitive to σ · BR
- Most general result using σ ratios and BR ratios
- Absolute normalisation to gg→H→ZZ cross-section which has the smallest systematic uncertainty
- Correlation of ratio results due to common denominator (σ_{ggF}, BR_{ZZ})
- Largest deviations for ttH cross-section and H → bb branching ratio

$$\sigma_i \cdot \mathrm{BR}^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}\right)$$

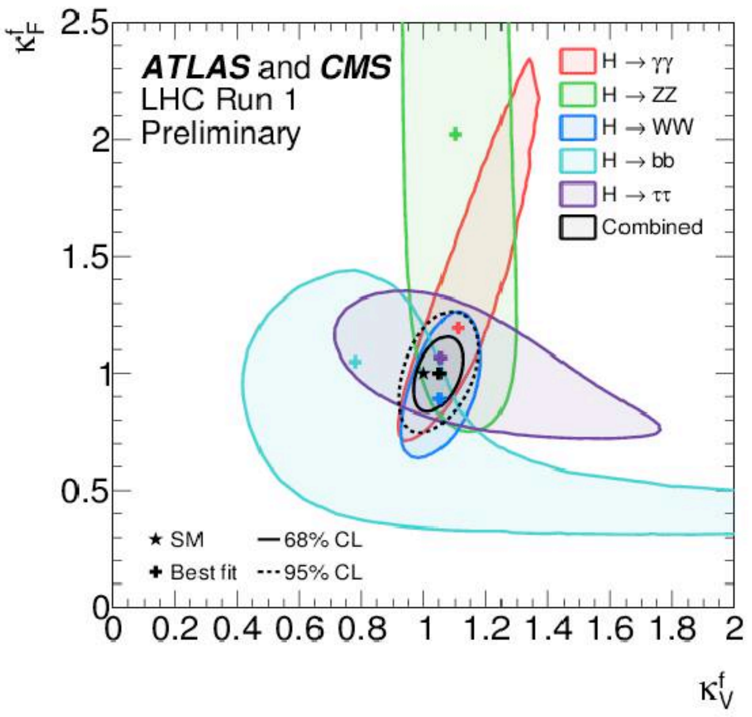


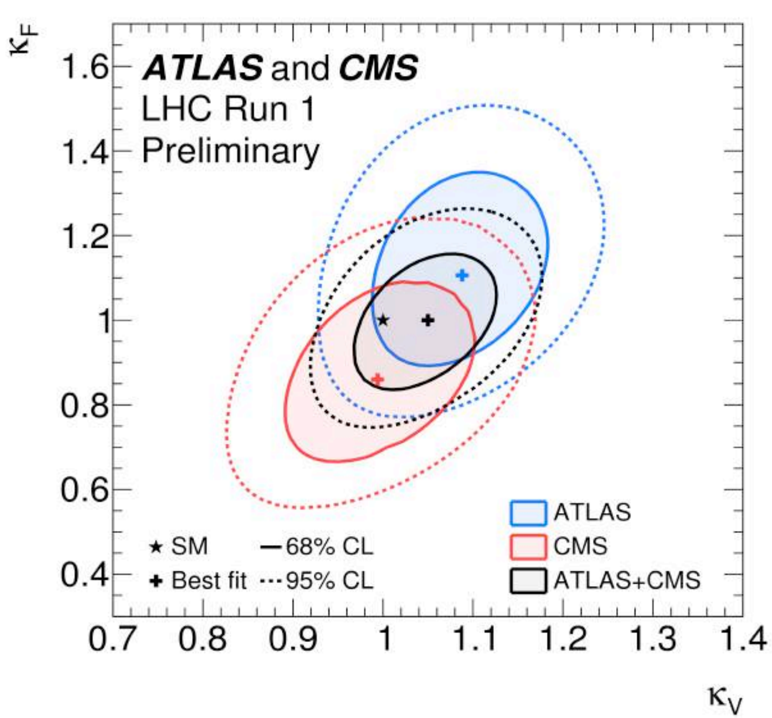
Gabriella.Pasztor@cern.ch

Couplings within the κ framework

$\kappa_i \equiv g_i / g_i^{SM}$

- Total width not well constrained at LHC
  → in most generic models only coupling strength ratios can be constrained
- Measure coupling modifiers: $g_i \equiv g_i^{SM} \times \kappa_I$
- **Minimal model**
  - All fermion couplings scale the same way: $\kappa_F \equiv \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$
  - All boson couplings scale the same way: $\kappa_V \equiv \kappa_W = \kappa_Z$
  - No non-SM contributions to the total width, $\kappa_F \cdot \kappa_V > 0$





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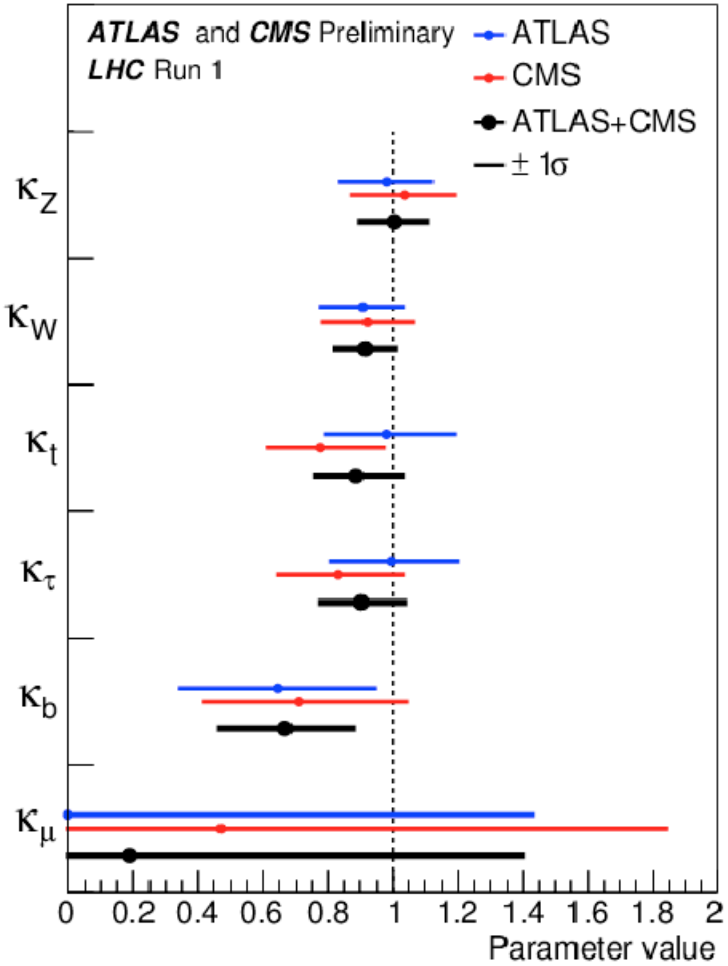
ATLAS-CONF-2015-044; CMS-PAS-HIG-15-002

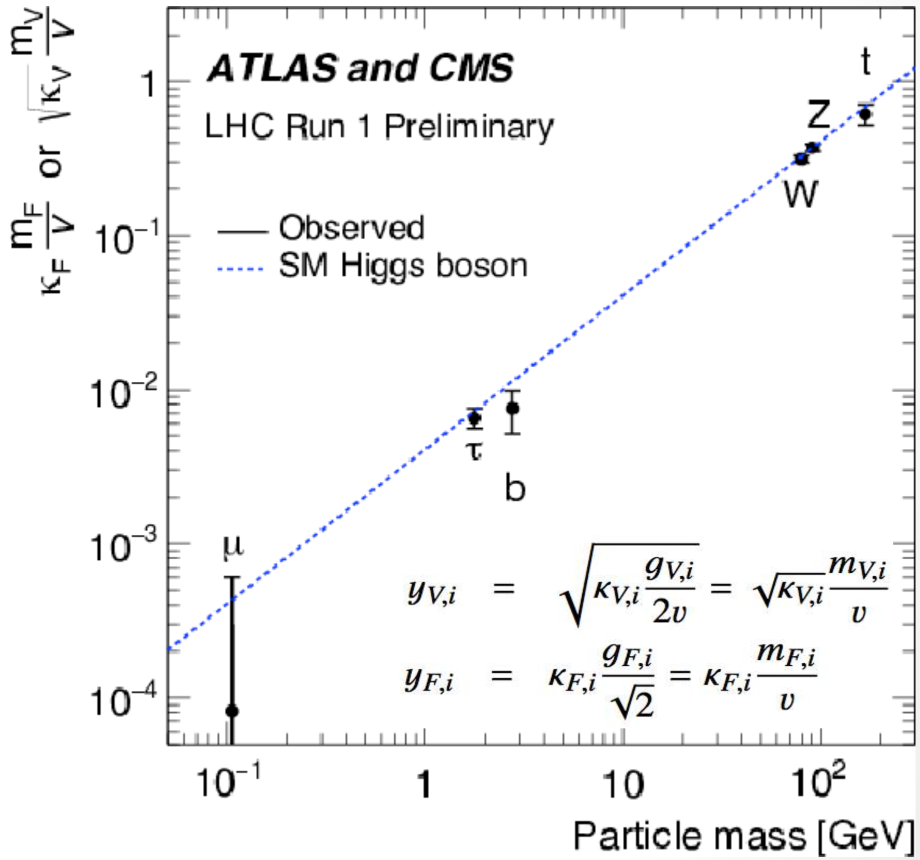
Couplings within the κ framework

No non-SM contributions to the total width

Individual coupling modifiers introduced for each SM particle



g(Hff) ∝ $m_{fermion}$
g(HVV) ∝ m_{bozon}^2



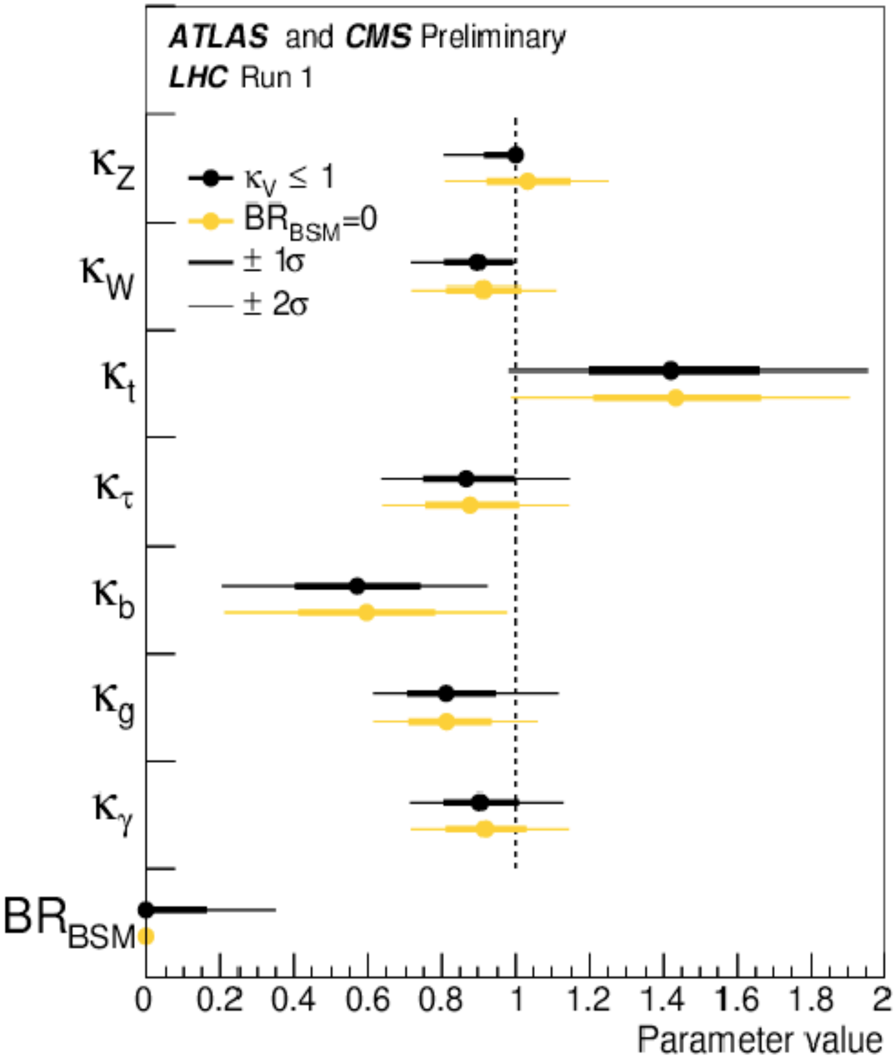
Gabriella.Pasztor@cern.ch

ATLAS-CONF-2015-044; CMS-PAS-HIG-15-002

Couplings within the κ framework

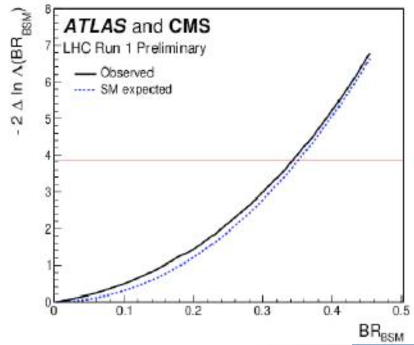
$\kappa_i \equiv g_i / g_i^{SM}$

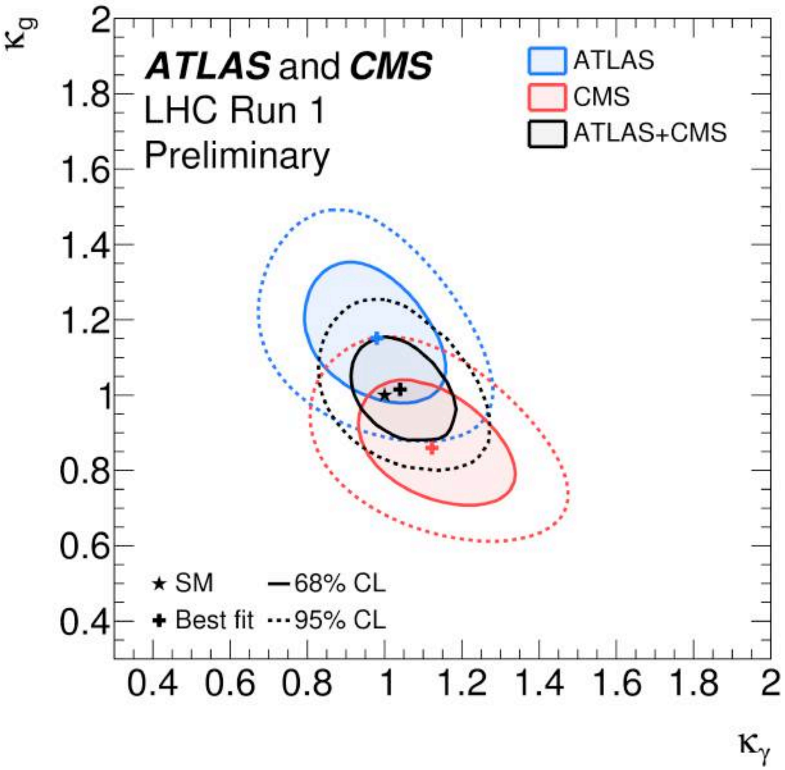
Generic models allowing physics beyond the SM



Two scenarios:

- Allowing BSM Higgs decays
- BSM contribution only in loops (gg→H, H→$\gamma\gamma$) from new heavy particles





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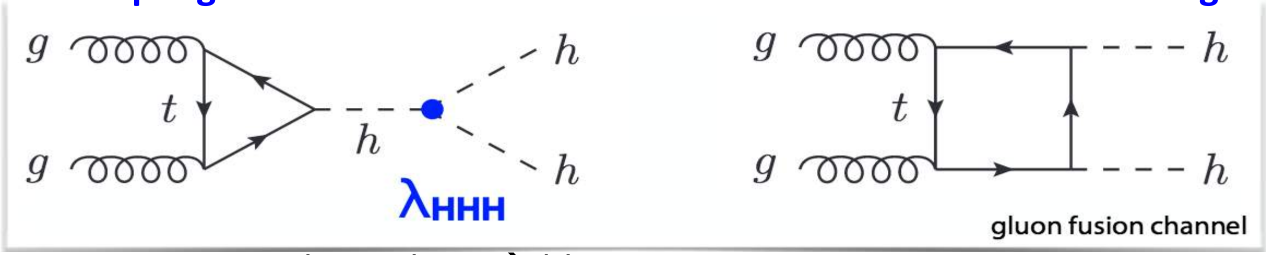
Measuring the Higgs self-coupling?

Self-coupling to be extracted from interference with non-resonant diagram



$\sigma_{SM}(gg \rightarrow hh)$

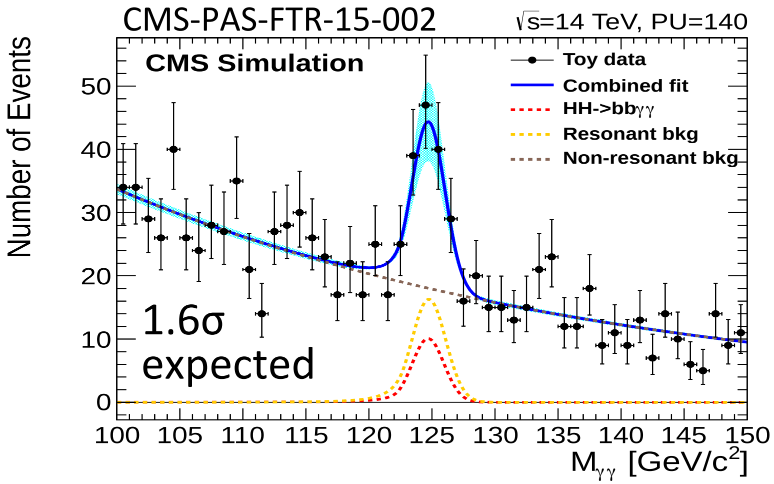
m_h = 125 GeV

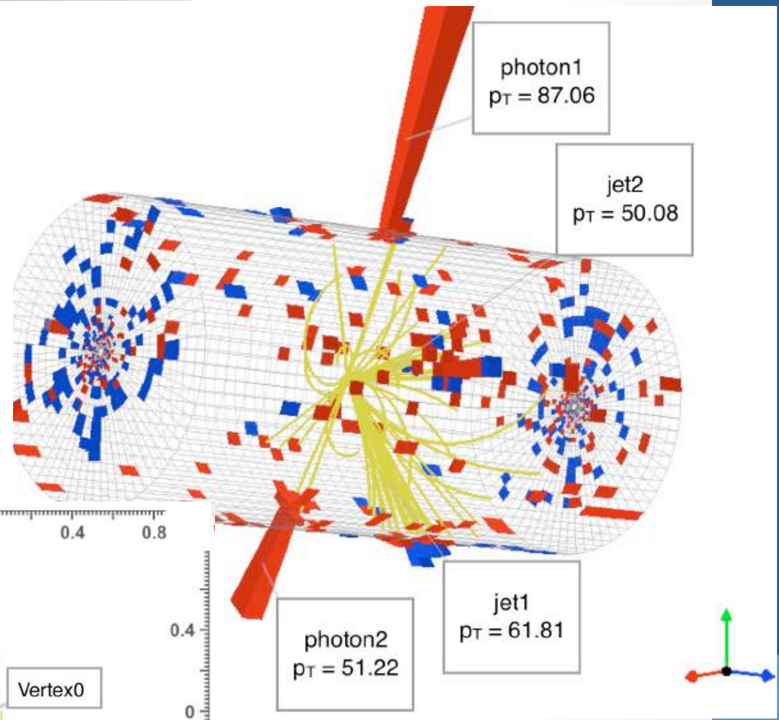
√s	σ (fb)
7 TeV	6.85
8 TeV	9.96
13 TeV	34.3
14 TeV	40.7

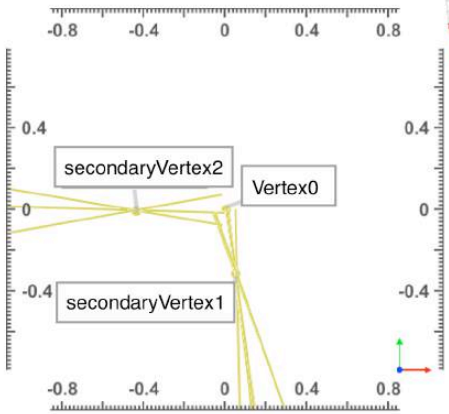
- Most promising channel: HH→ bb$\gamma\gamma$
- ATLAS @ 8 TeV search for HH → bb$\gamma\gamma$ production
  - 0.04 events from SM H → HH
  - 0.17±0.04 events from SM H+X

arXiv:1406.5053,
PRL 114 (2015) 081802

- Even at HL-LHC very challenging (need to measure rate precisely to extract λ_{HHH})
  - E.g. CMS HH→ bb$\gamma\gamma$ / bb $\tau\tau$: 1.9σ expected
  - Combine also with other channels: bb bb, bb WW







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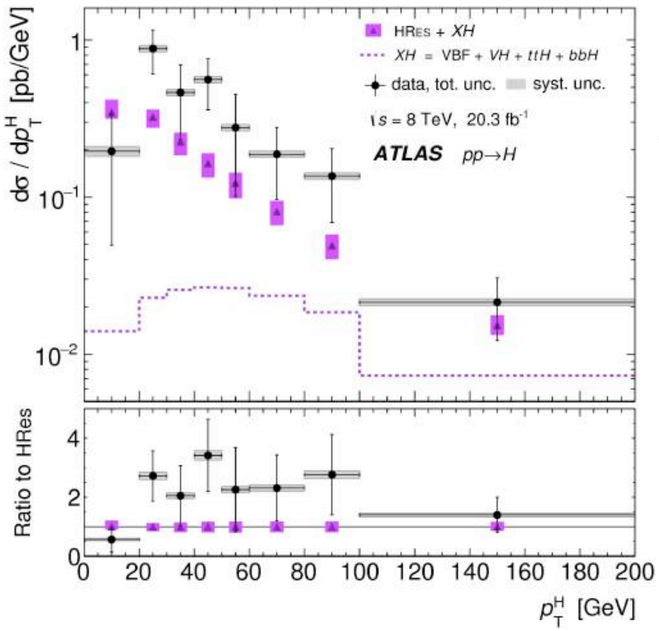
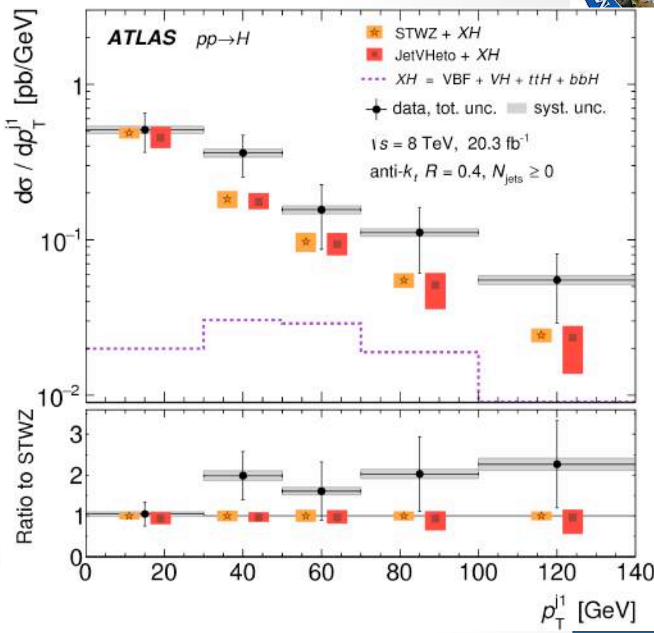
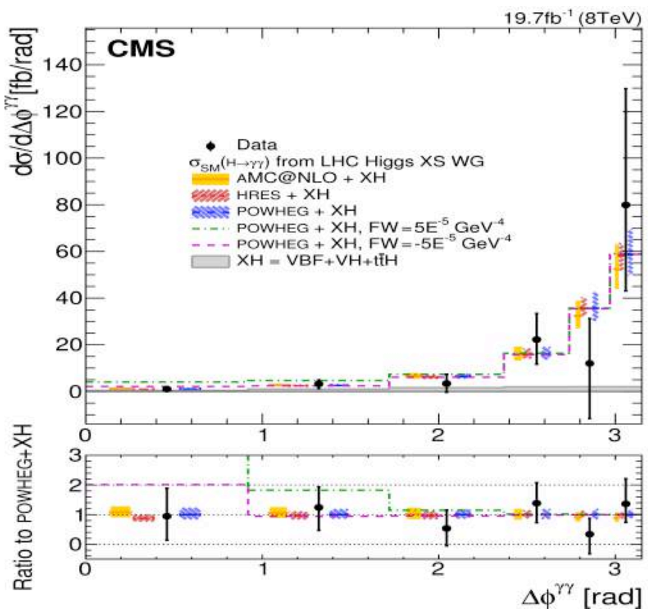
Phys. Rev. Lett. 115 (2015) 091801, arXiv:1504.05833
arXiv:1508.07819

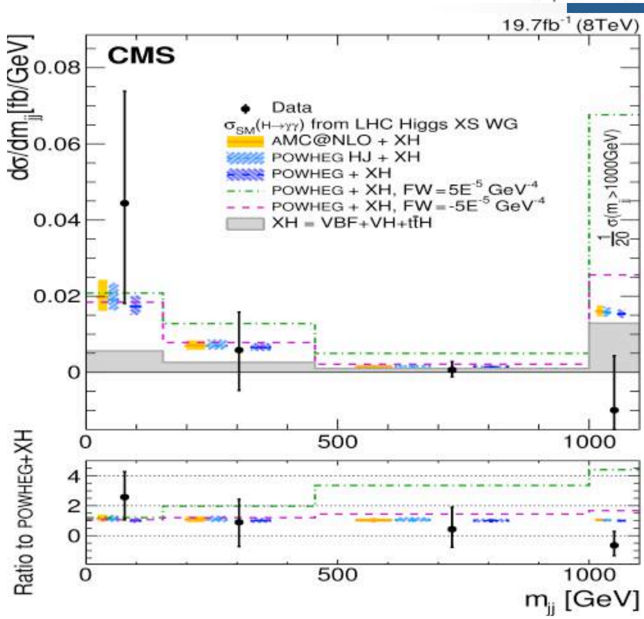
Fiducial and differential cross-sections

- Fiducial region definition motivated by experimental cuts, inclusive in production modes
- Avoids large theoretical uncertainties on extrapolation to full phase space
- Model-independent measurement of production and decay kinematics
- Allows comparison / test of compatibility with precision calculations, alternative models
- Test theoretical modelling of different Higgs boson production mechanisms
- Sensitive to BSM physics









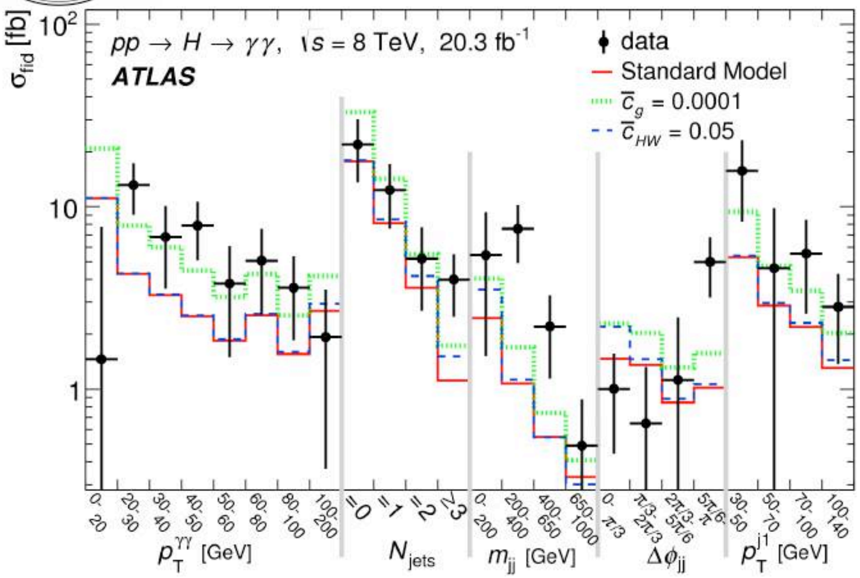
Gabriella.Pasztor@cern.ch

arXiv:1508.02507

Anomalous couplings

Using the fiducial cross-section measurements

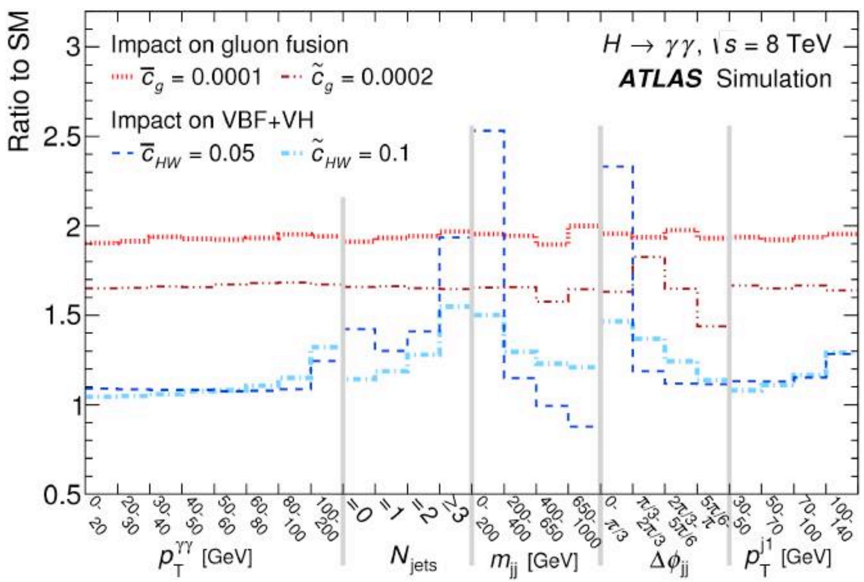
$$\mathcal{L} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB},$$

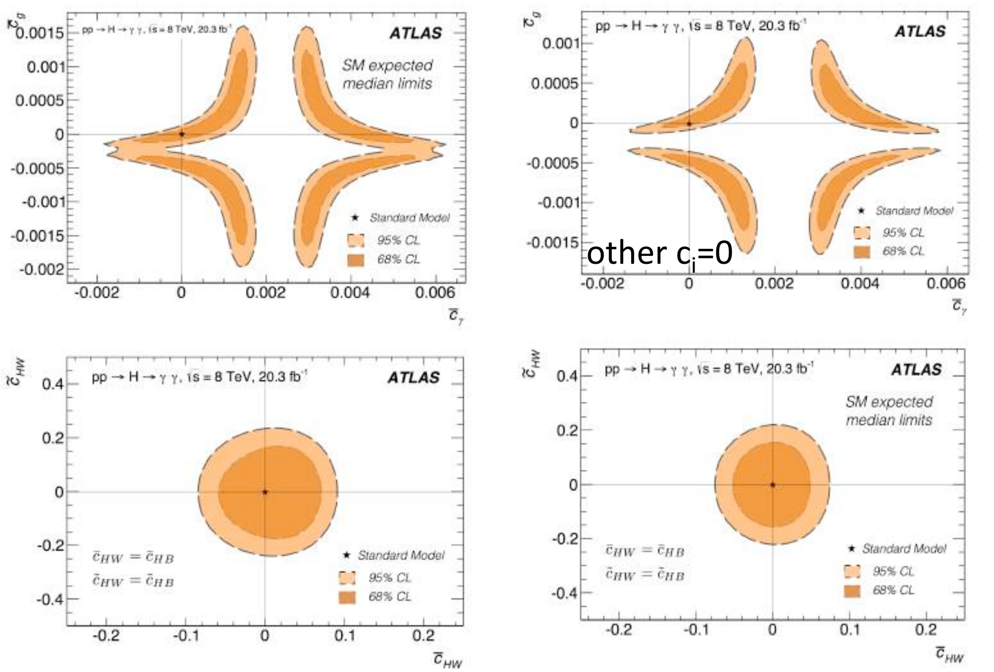


O_i and $\tilde{O}_i$ dim-6 operators describe CP-even and CP-odd interactions *with gauge bosons*

Constraints on effective Lagrangian coefficients

Coefficient	95% $1 - CL$ limit
$\bar{c}_\gamma$	$[-7.4, 5.7]\times10^{-4} \cup [3.8, 5.1]\times10^{-3}$
$\tilde{c}_\gamma$	$[-1.8, 1.8]\times10^{-3}$
$\bar{c}_g$	$[-0.7, 1.3]\times10^{-4} \cup [-5.8, -3.8]\times10^{-4}$
$\tilde{c}_g$	$[-2.4, 2.4]\times10^{-4}$
$\bar{c}_{HW}$	$[-8.6, 9.2]\times10^{-2}$
$\tilde{c}_{HW}$	$[-0.23, 0.23]$





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Many more measurements

Scrutinising the observed Higgs state

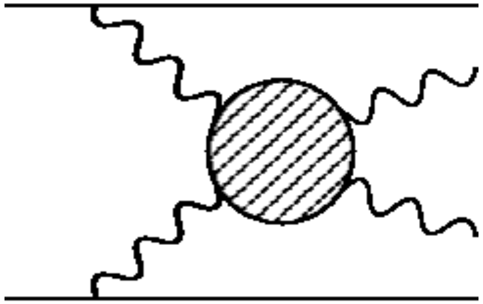
- More signal strength measurements and coupling tests with various assumptions
- Limits on new physics from coupling measurements (2HDM, …)
- Limits on rare production (tH, HH, …) and decay modes (H → μμ, ee, $Z\gamma$, $J/\psi\gamma$, … exotic e.g. invisible particles, lepton-jets, …)
- Total cross-section
- Spin-parity hypothesis tests
- Constrains on CP-odd fraction and on anomalous tensor couplings
- Constraints on Higgs width
  - Direct measurement limited by experimental resolution
  - Interferometry at high mass
- Constraints on Higgs lifetime

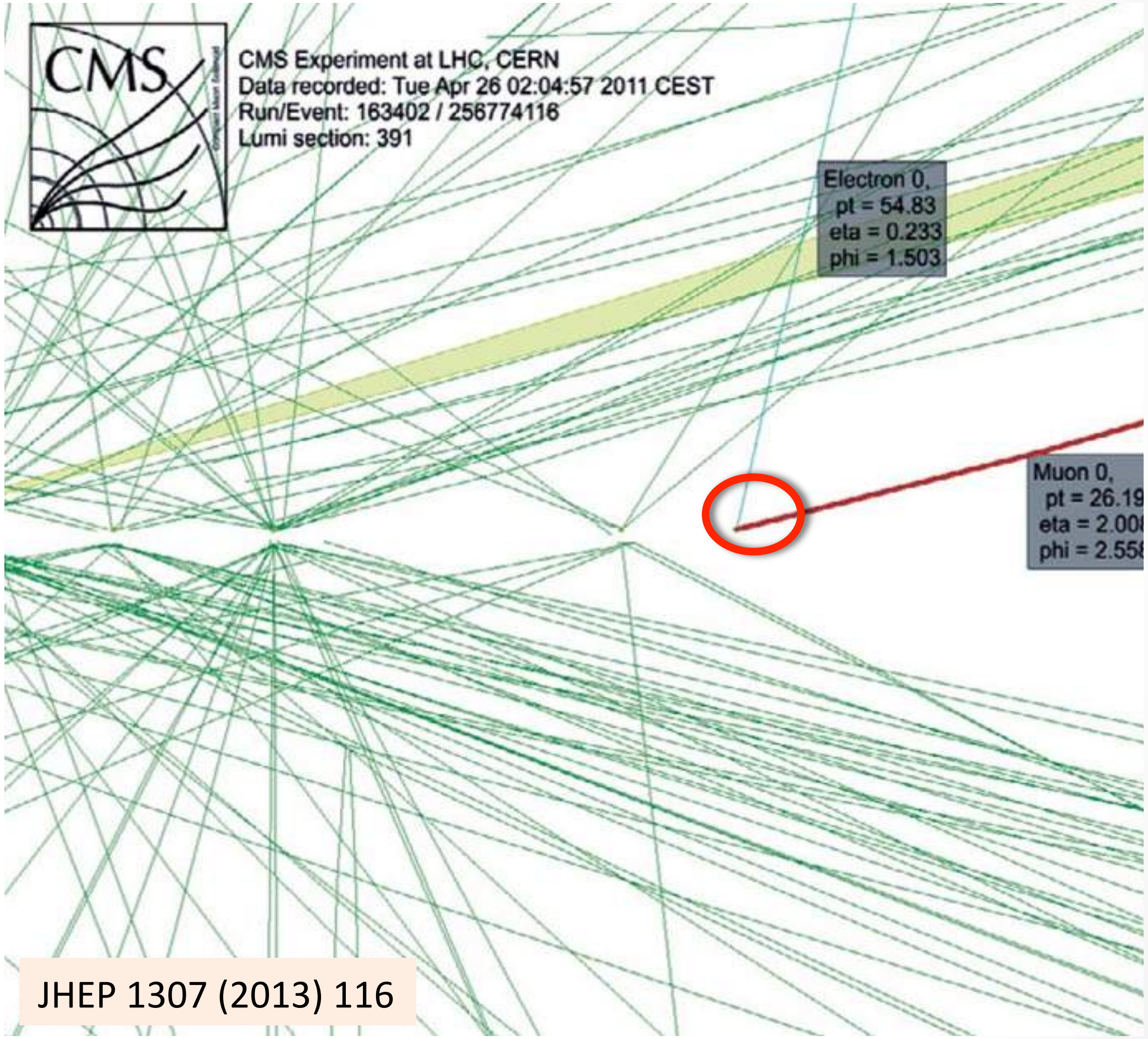
…and looking for new Higgs bosons predicted by extended models

In general, all measurements are in agreement with the SM predictions…

Gabriella.Pasztor@cern.ch

Vector-boson scattering as probe of EWSB and new physics





JHEP 1307 (2013) 116

Exclusive $\gamma\gamma \rightarrow$ WW production candidate

VV scattering: a probe of EWSB

Vector boson scattering is „intimately” connected to EWSB and new physics

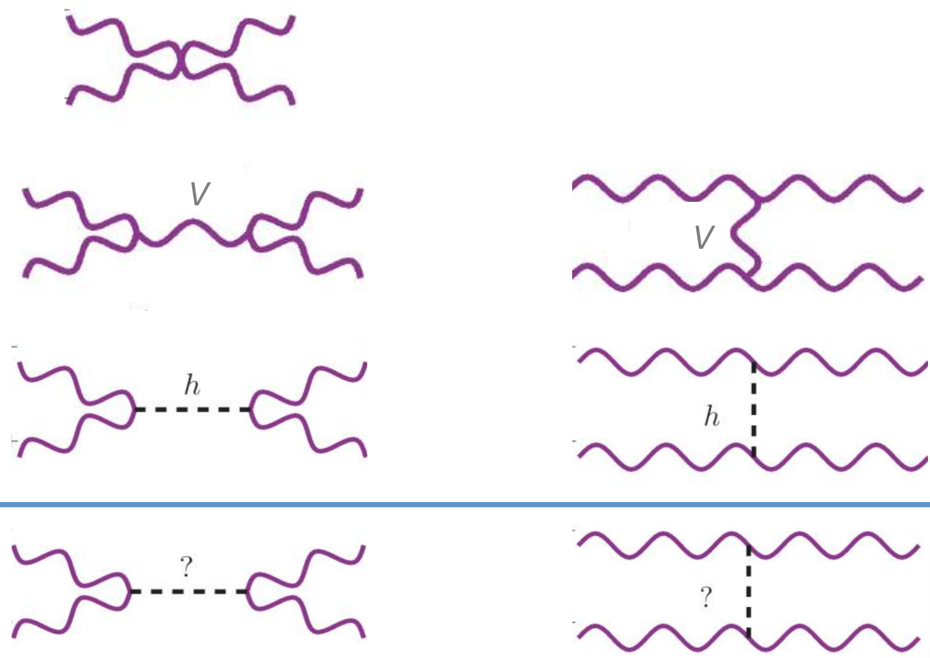
- In SM, unitarity in VV scattering is restored by Higgs exchange: $\sigma \sim O(E^2) - O(E^2) \rightarrow O(E^0)$
- If HVV coupling is not exactly the SM value, unitarity is not realized [$\sigma \sim O(E^2)$] or „delayed” until a new high-mass state enters

Even if no new physics is observed directly (finite energy reach, large backgrounds), VV scattering can reveal its existence

SM gauge bosons:

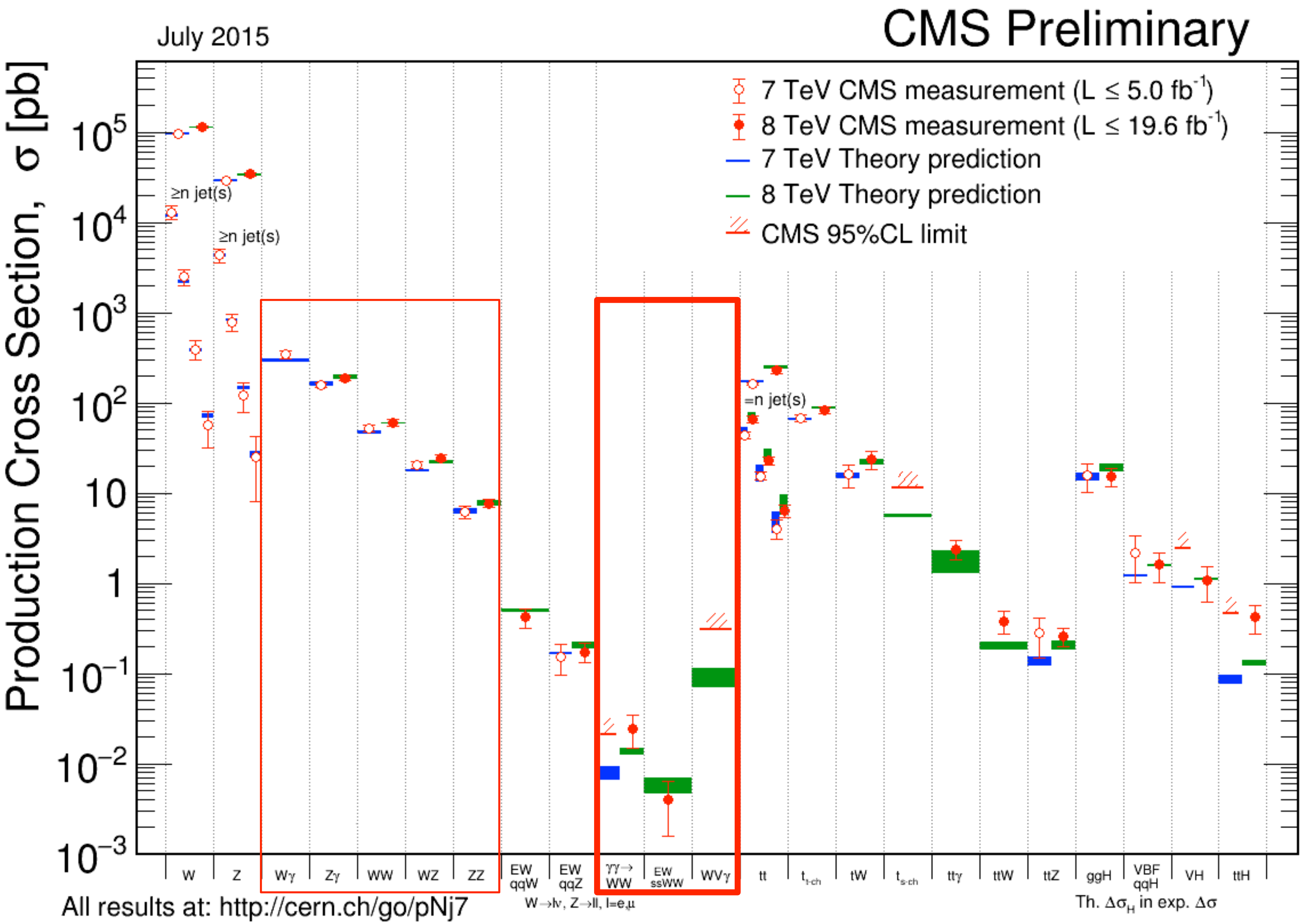
Higgs:

New scalar
(or new gauge boson):



Gabriella.Pasztor@cern.ch

Multi-boson production



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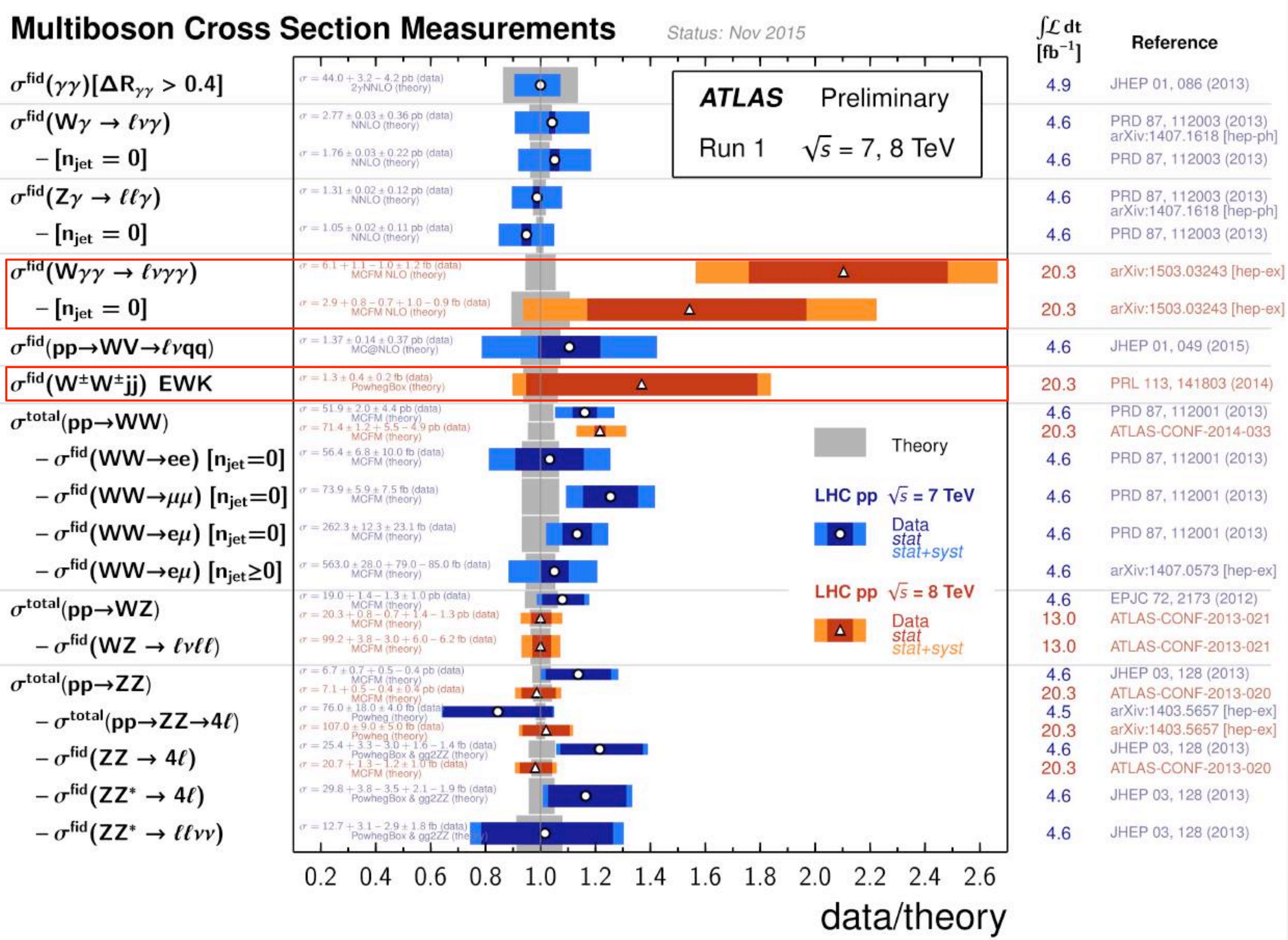
Multi-boson production



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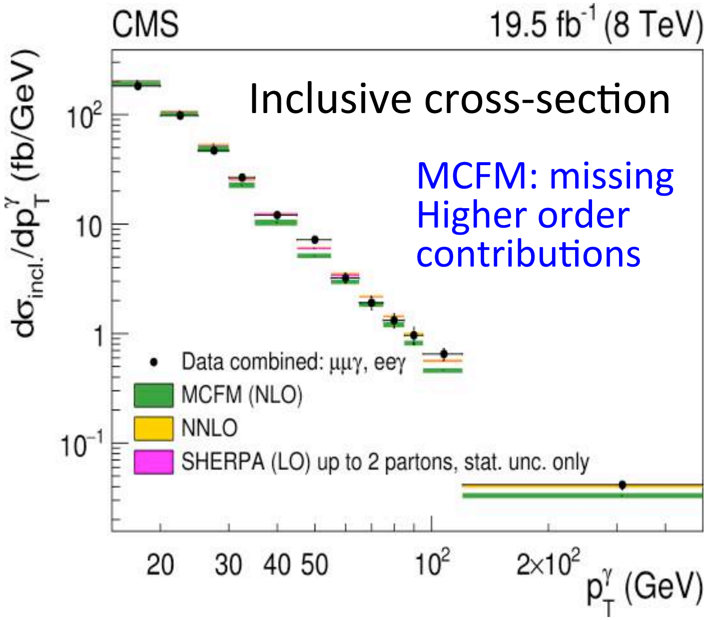
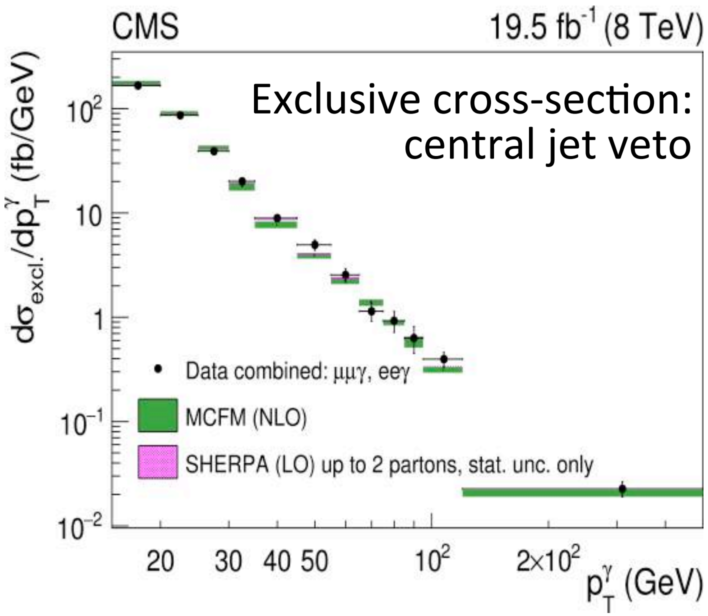
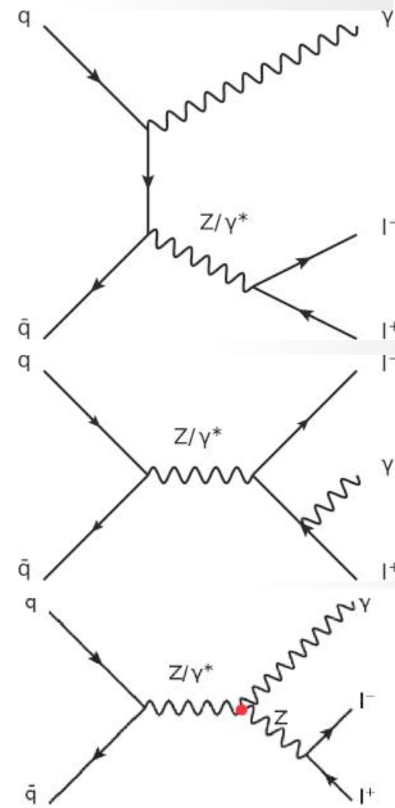
JHEP 04 (2015) 164, arXiv:1502.05664

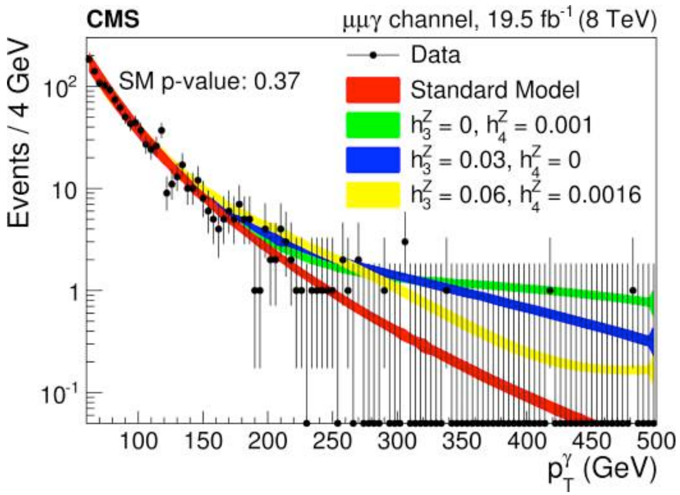
Zγ production

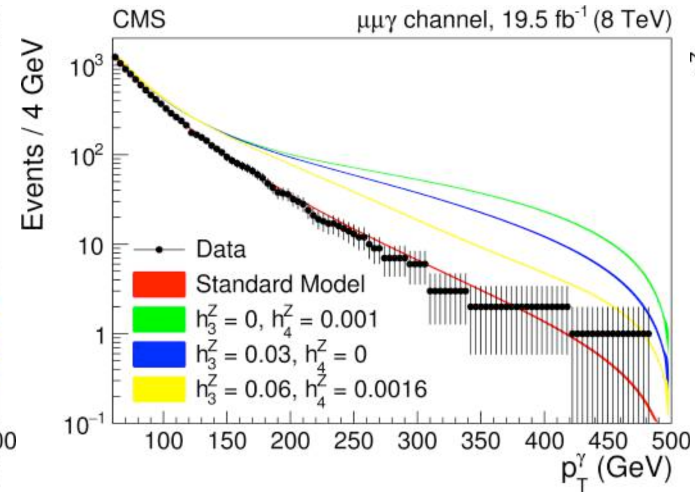


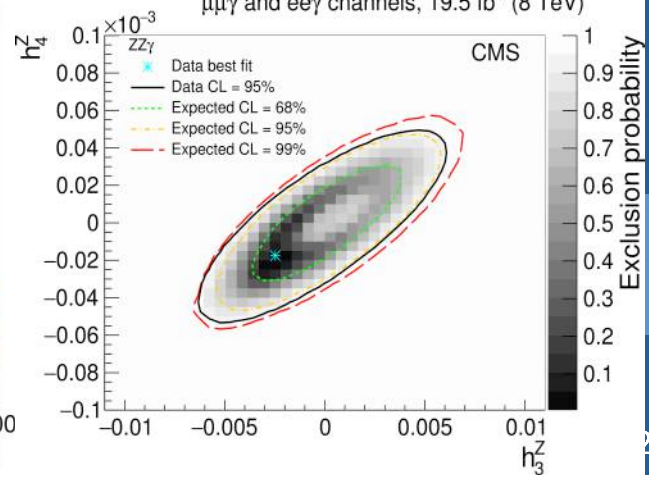




High-pT region sensitive to new physics







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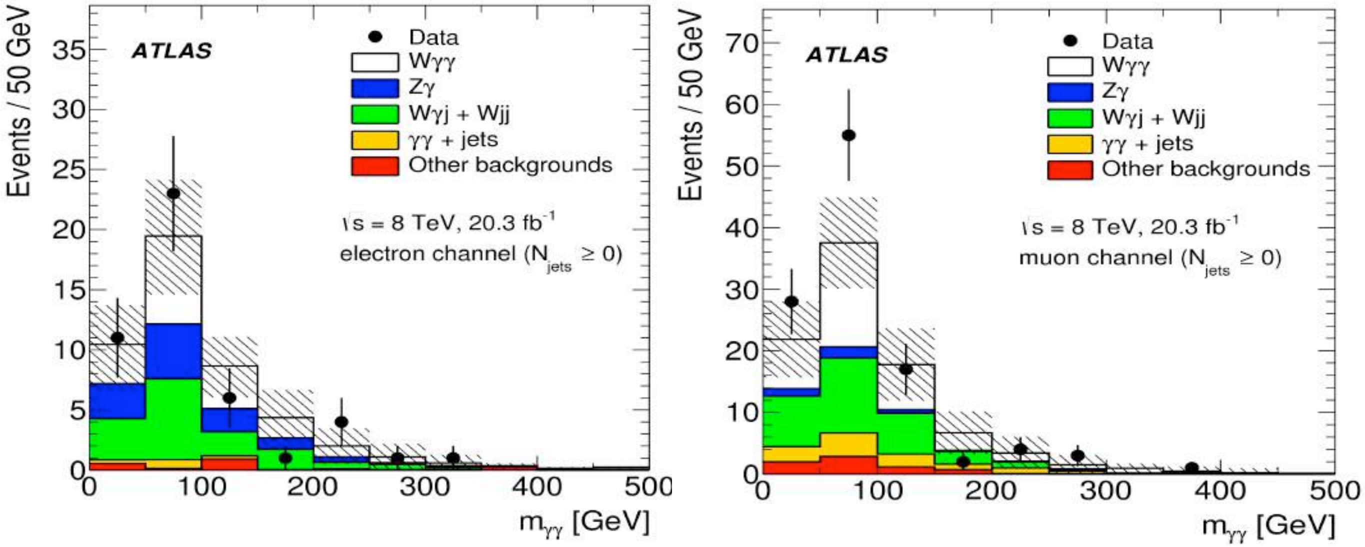
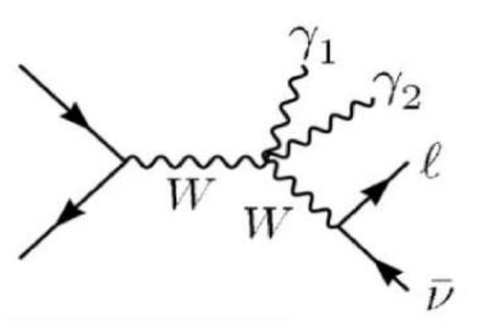
$W\gamma\gamma$ production

- First evidence for triple gauge boson production: >3σ significance





Phys. Rev. Lett. 113, 141803

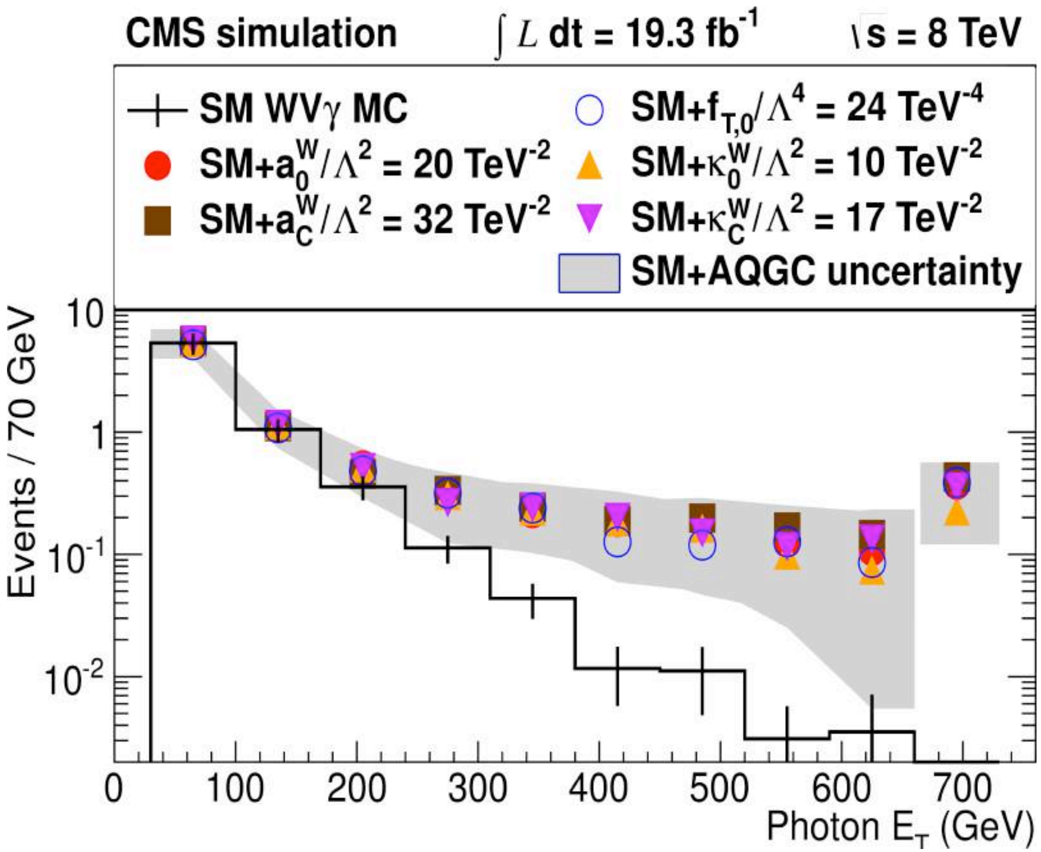
	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		NLO SM
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (syst.) ± 0.2 (lumi.)	
Exclusive ($N_{\text{jet}} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ± 0.1 (lumi.)	
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ± 0.1 (lumi.)	

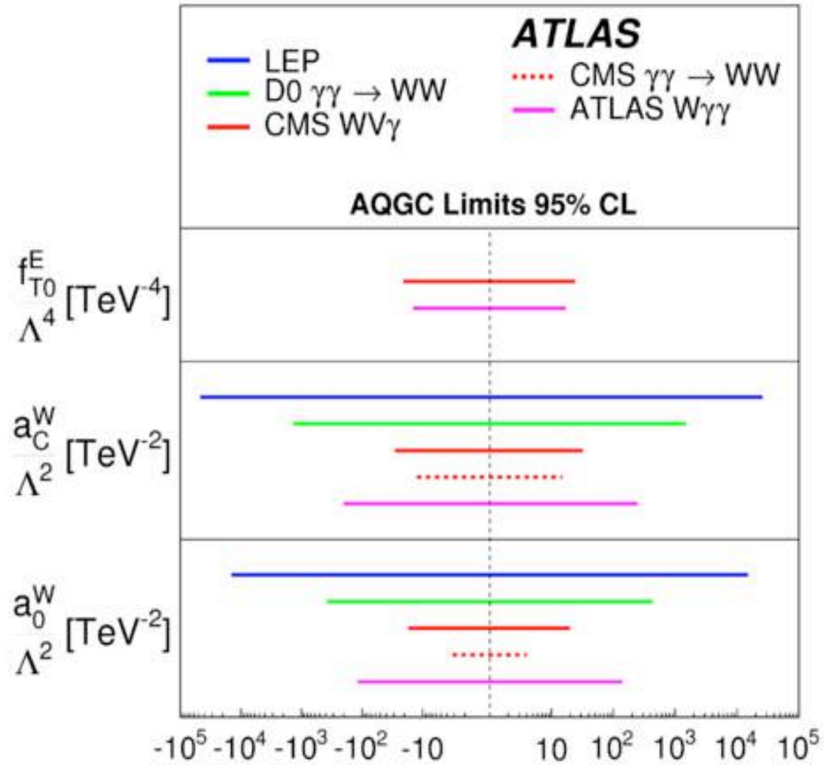
1.9σ excess in
inclusive measurement

Gabriella.Pasztor@cern.ch

Anomalous quartic couplings

- High di-photon mass region in W$V\gamma$ and W$\gamma\gamma$ sensitive to new physics
- Introduce dim-8 operators (ATLAS) as in PRD 74 (2006) 073005
  - Related to dim-6 operators (LEP, CMS) as given in arXiv:1309.7890
- Stringent constraints from CMS exclusive $\gamma\gamma$ → WW measurement



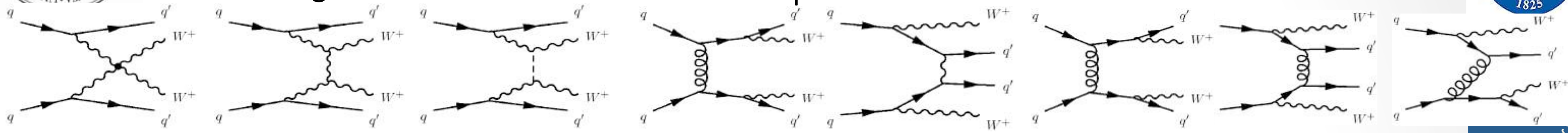


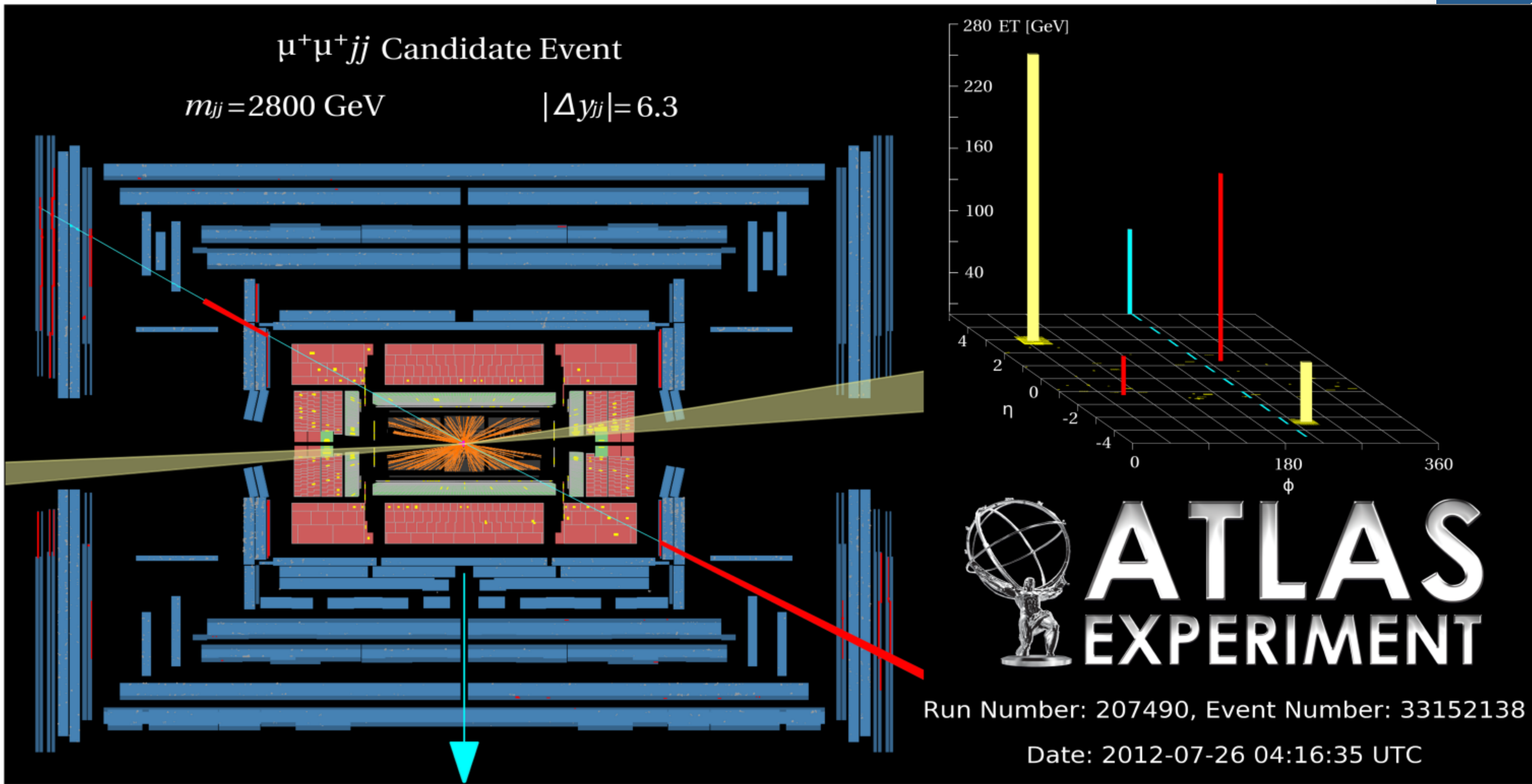
W±W±jj production

Vector-boson scattering

Other EW production

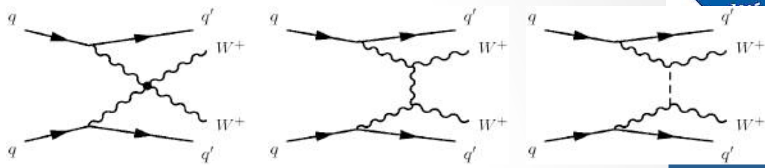
QCD production

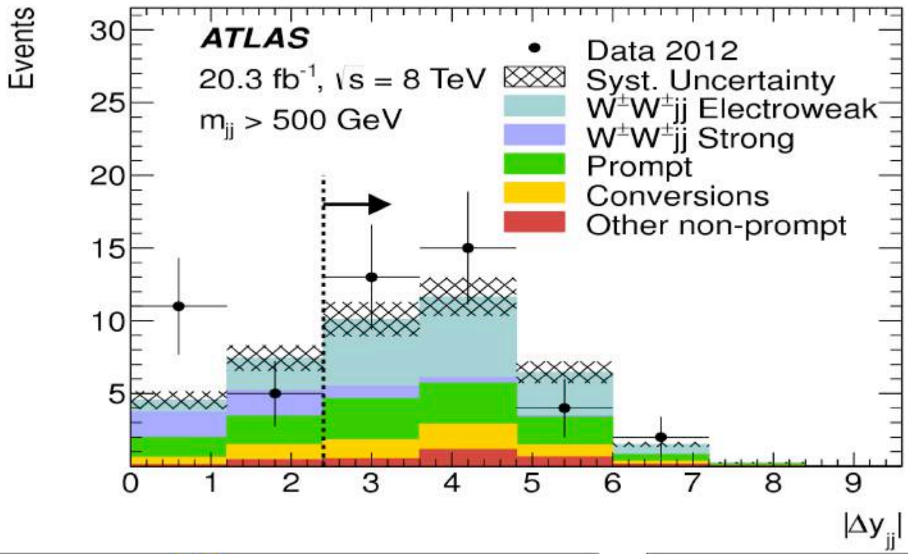




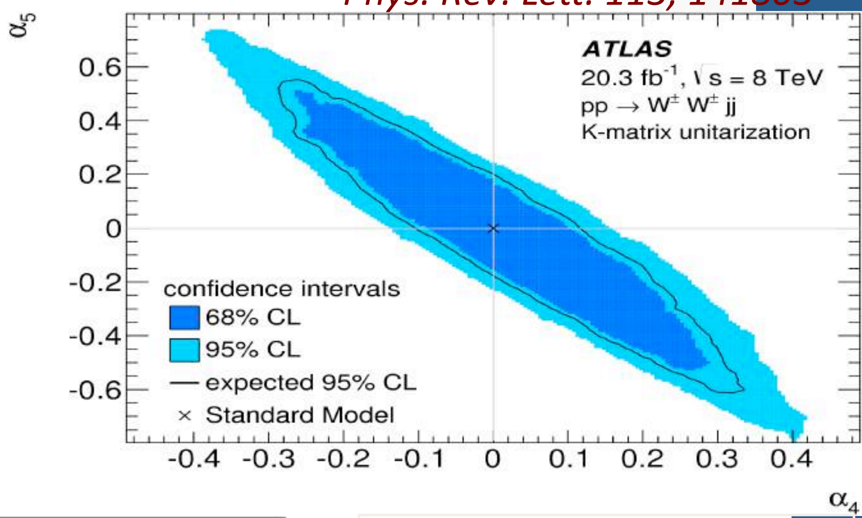
W±W±jj production

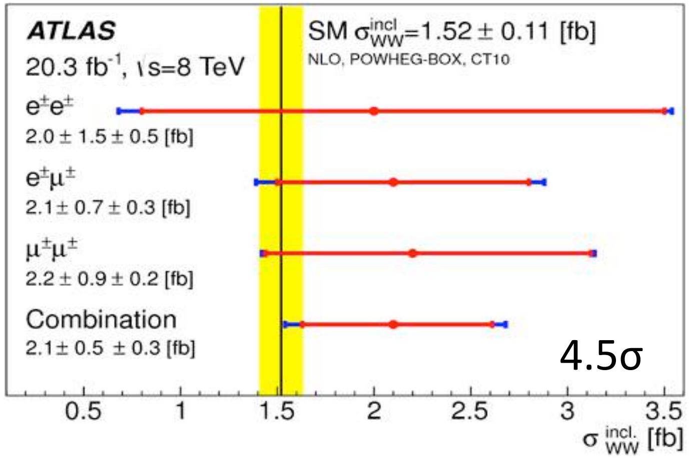
- Higgs regularises longitudinal VBS cross-section in SM
- VBS region is sensitive to new physics
- Rare process, require forward jets

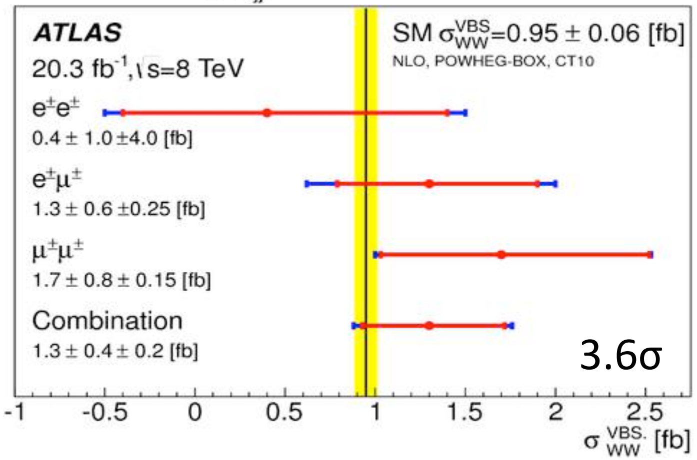




Phys. Rev. Lett. 113, 141803







$$\mathcal{L}_4^{(4)} = \alpha_4 \left[\mathrm{Tr}\left(V_\mu V_\nu\right)\right]^2$$

$$\mathcal{L}_5^{(4)} = \alpha_5 \left[\mathrm{Tr}\left(V_\mu V^\mu\right)\right]^2$$

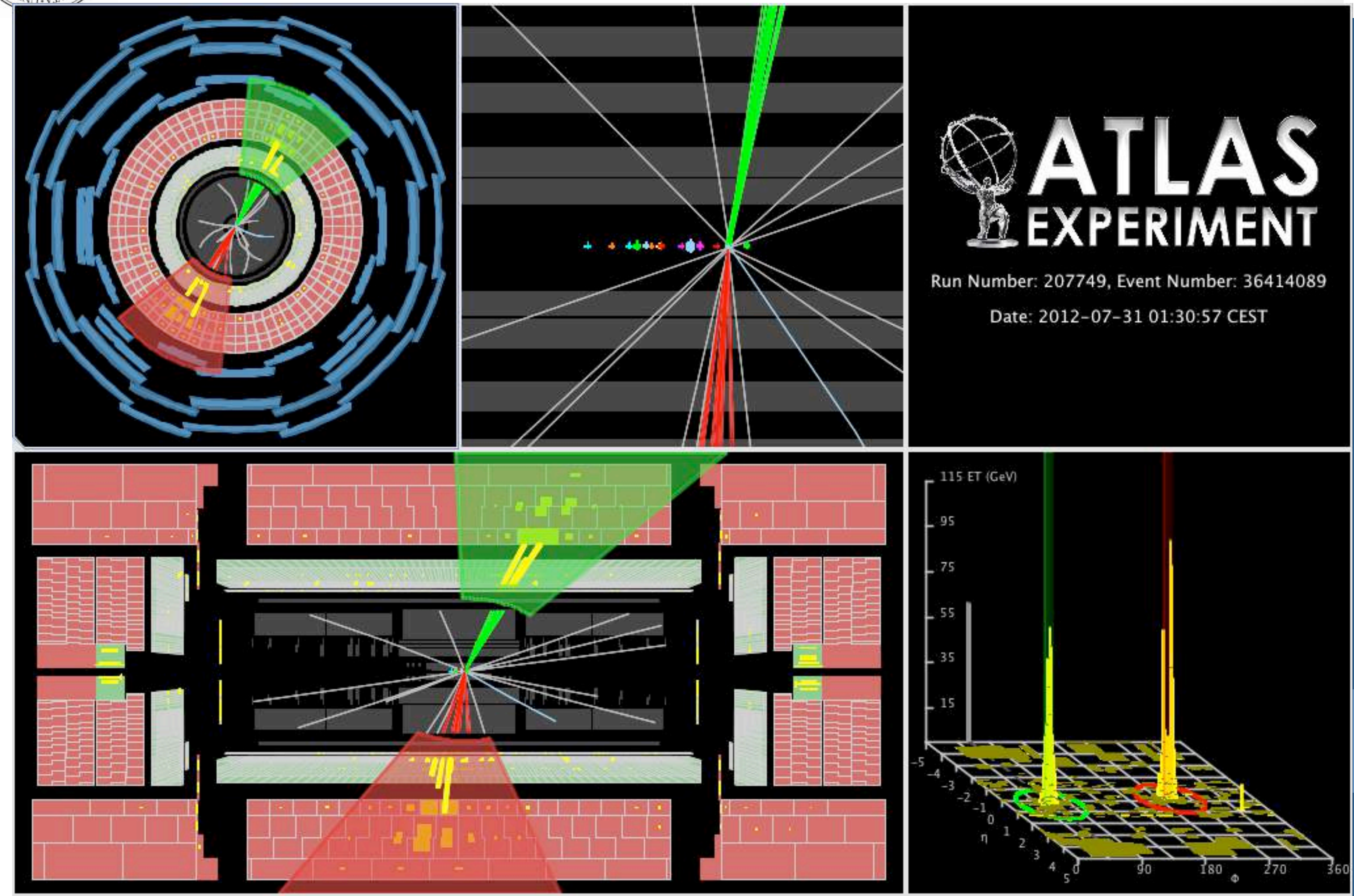
for the WWWW-Vertex:

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{8}$$

$$\alpha_4 + 2 \cdot \alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{8}$$

Gabriella.Pasztor@cern.ch

Search for heavy bosons in VV final states



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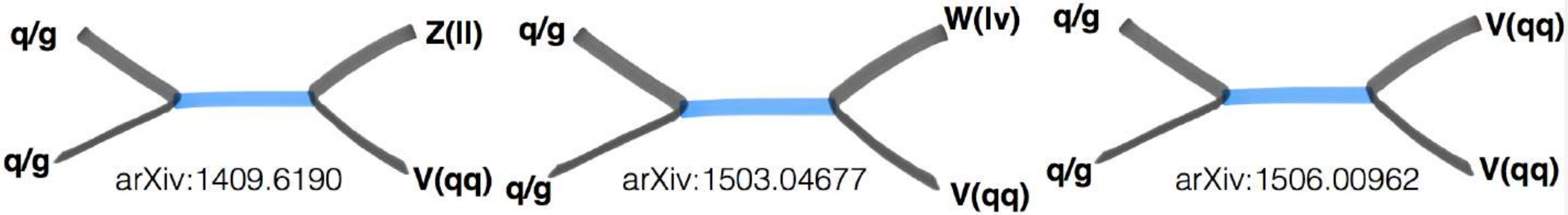
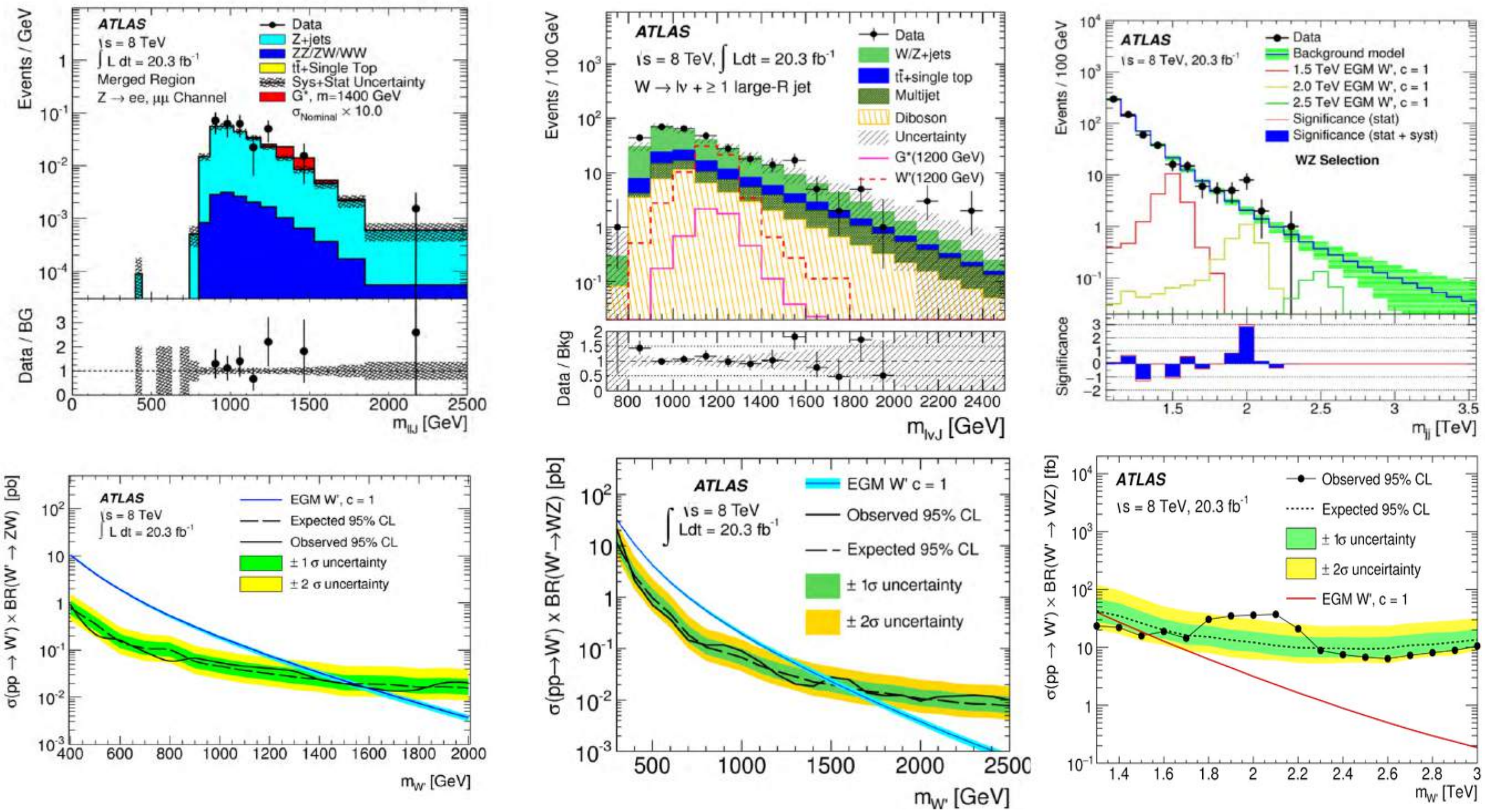
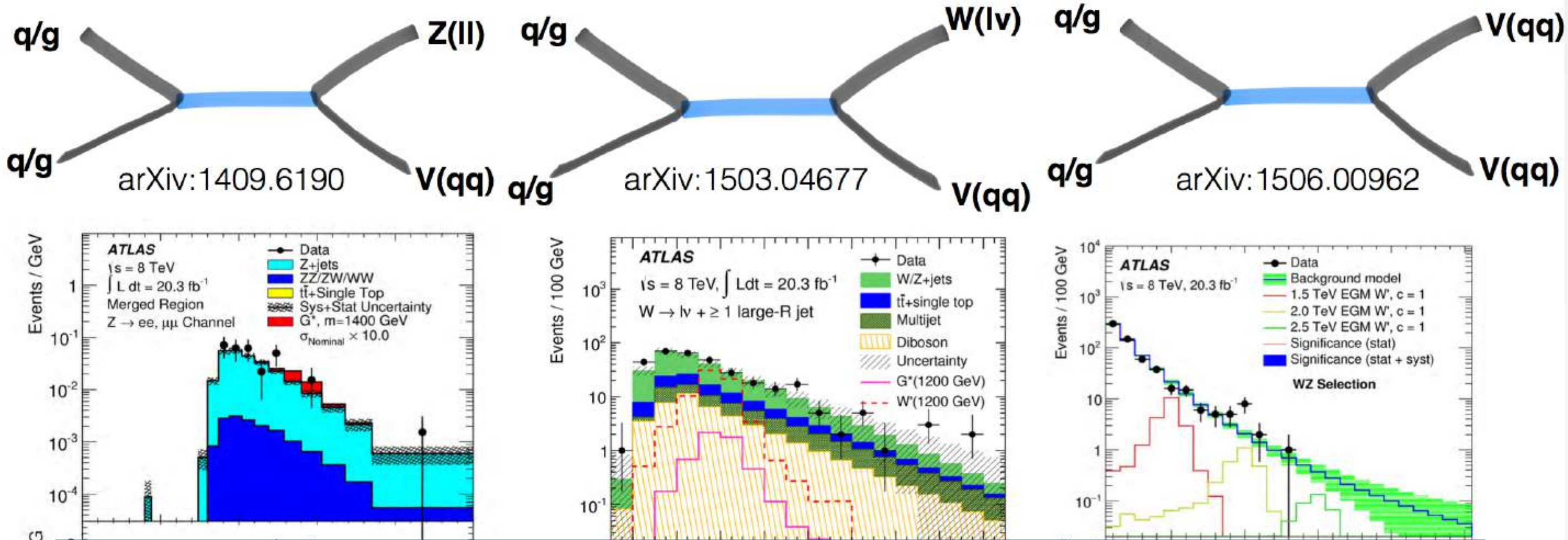
Search for heavy bosons in VV final states

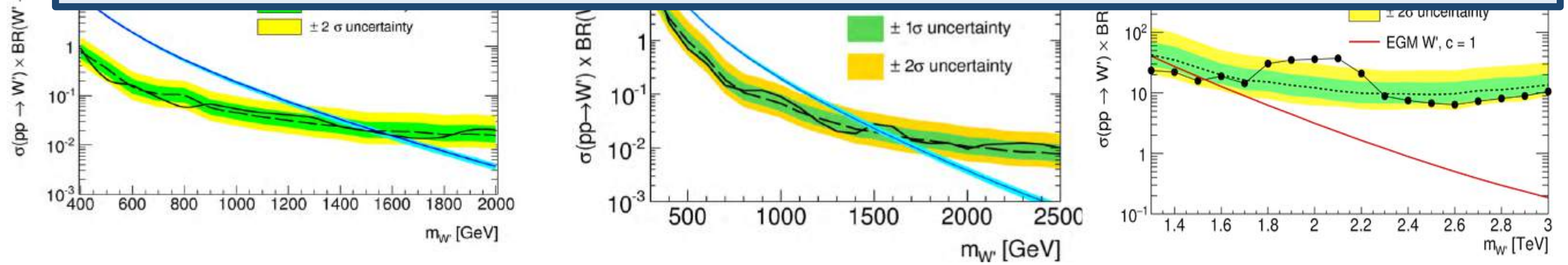




Search for heavy bosons in VV final states



- ~3.5σ excess in W'→WZ→JJ final state not confirmed by other channels
- 2.5σ excess remains after combination
- <2σ for G*→ WW / ZZ
- 3-5 fb^{-1} @ 13 TeV surpasses Run1 sensitivity
- 4 fb^{-1} data of 2015 run on disk and being analysed



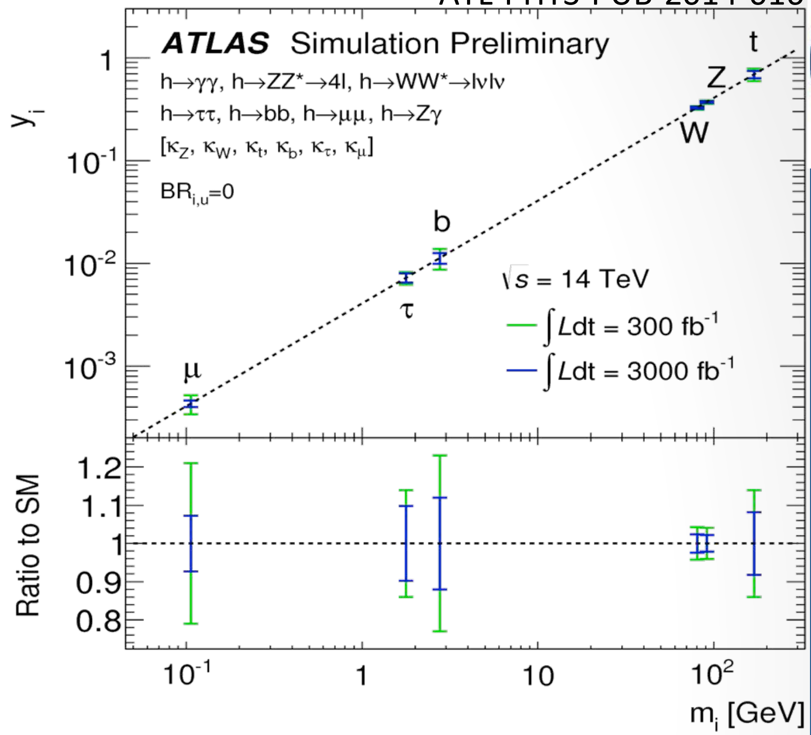
Gabriella.Pasztor@cern.ch

December 2015

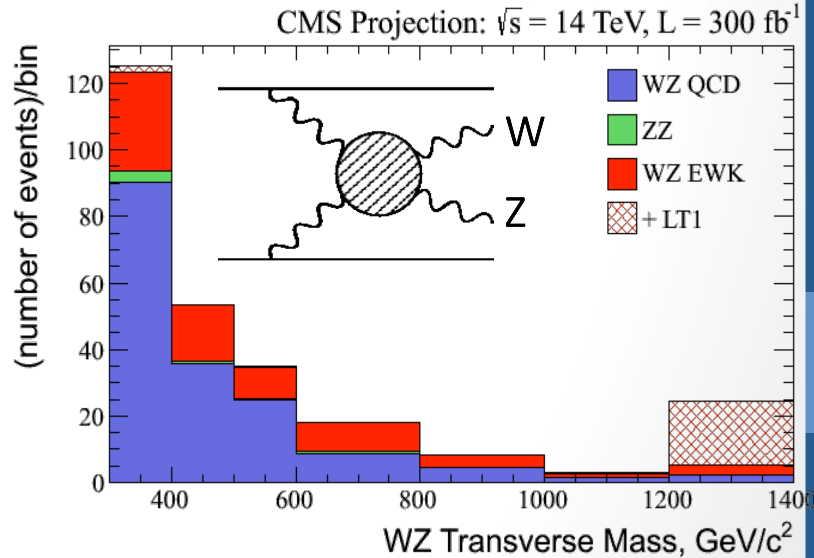
Conclusion

- LHC entered Higgs boson precision era
- 3 years after the discovery
  - Measurements still statistics dominated
  - Mass known by 0.2% precision
  - Some couplings measured with 10% uncertainty
  - Largest discrepancies for ttH production and H→bb decay (also least precise measurements)
  - Differential distributions measured
  - Spin-parity structure tested
- No sign yet for physics beyond the SM
- Run2 started with increased energy of √s=13 TeV and higher luminosity expected
  - Improved precision for EW measurements
  - Enlarged phase-space for new physics searched
- The adventure continues to discover what lies behind the now completed SM

ATL-PHYS-PUB-2014-016



CMS-PAS-FTR-13-006



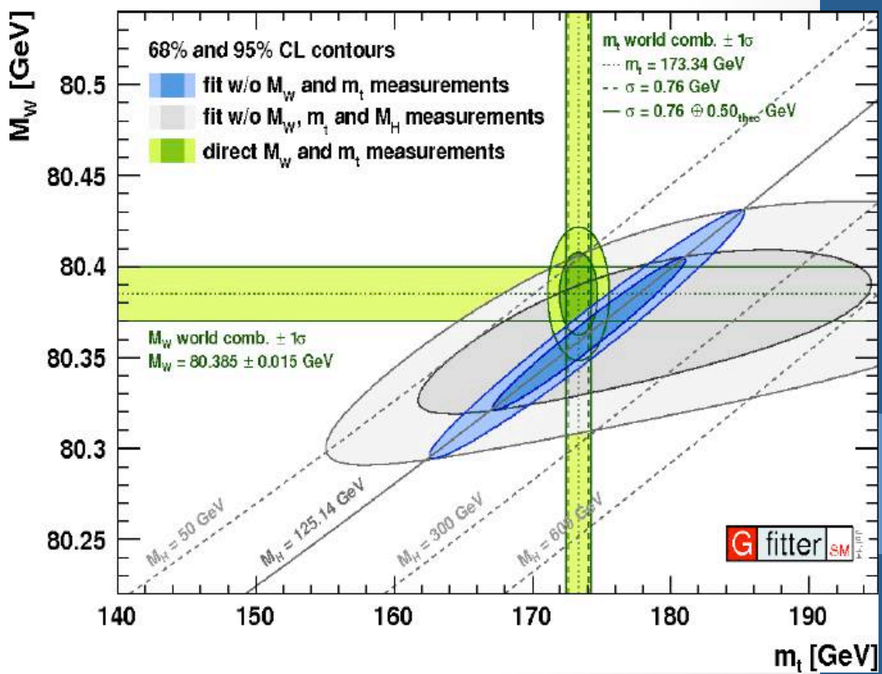
Gabriella.Pasztor@cern.ch

Backup

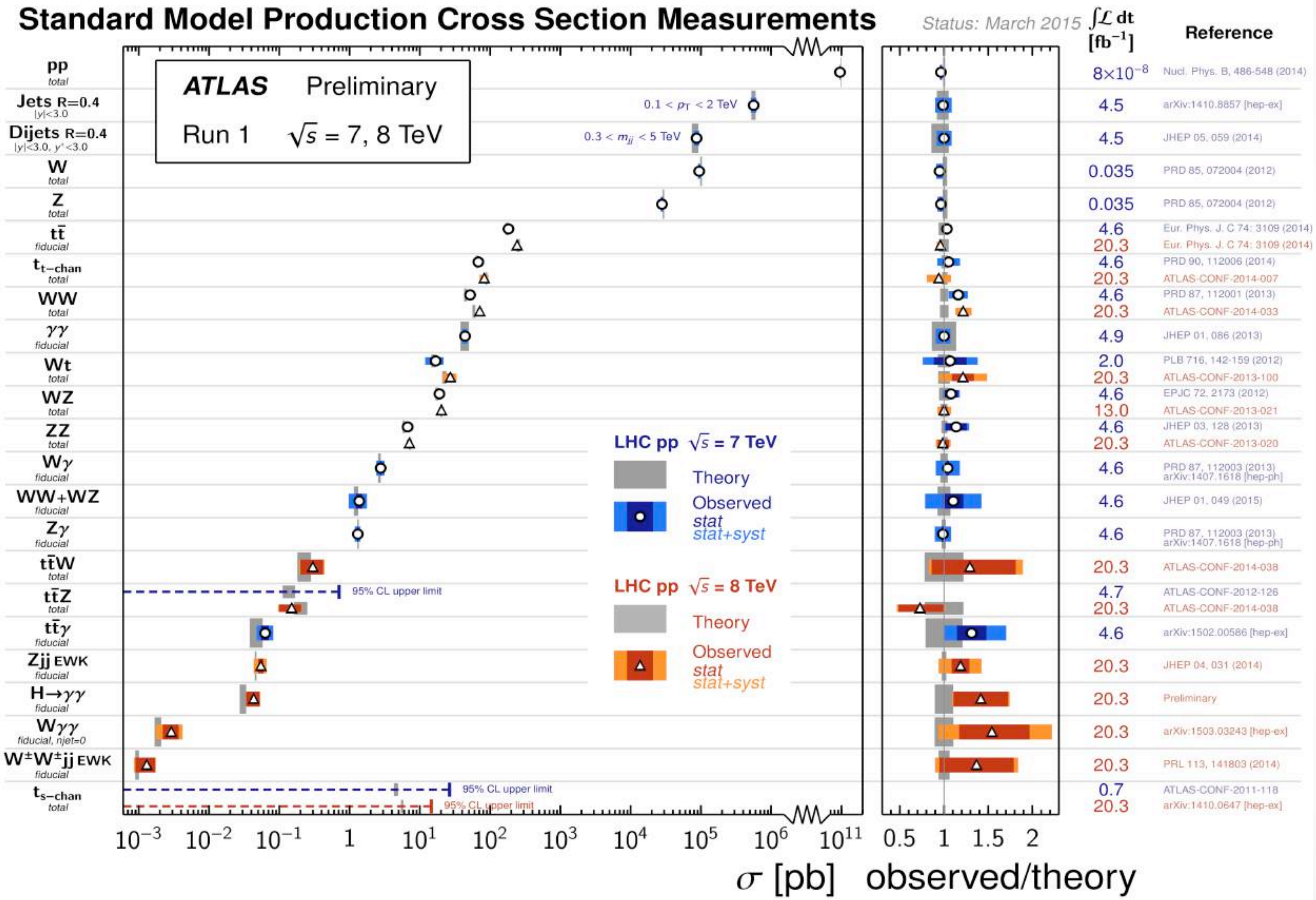
Gabriella.Pasztor@cern.ch

Higgs @ LHC

- The newly discovered Higgs boson behaves just as the SM predicts *within current theoretical and experimental precision*
- Still enormous potential to further our knowledge by studying the Higgs sector
  - *Precision measurements of Higgs properties*: are they consistent with the SM beyond the present precision?
  - Measurements of the *Higgs signal in rare or challenging channels*
  - *Search for (discovery of?) new Higgs states*: many extensions predict more than one Higgs bosons, one of them frequently SM-like



Standard Modell @ LHC

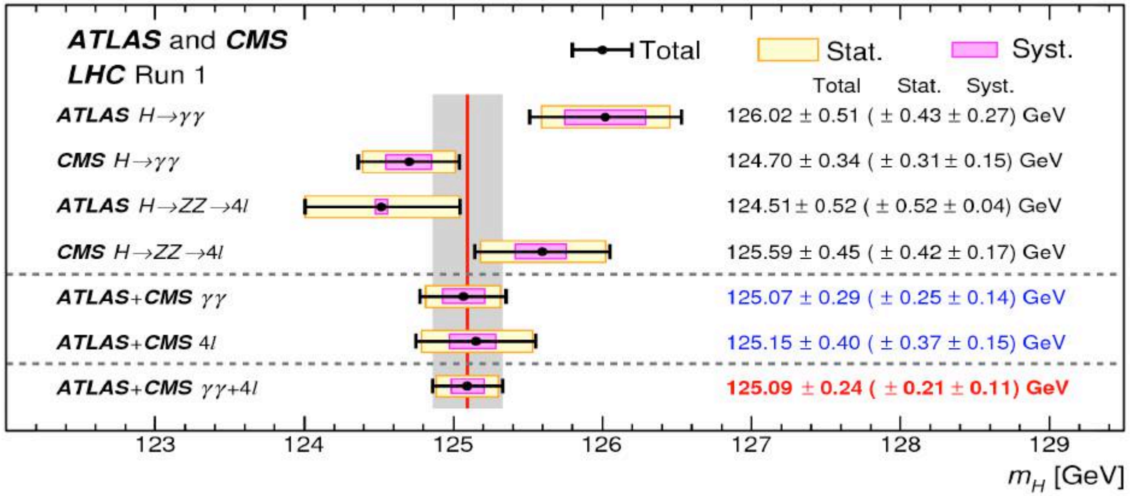


Before embarking on new discoveries… needed to establish the Standard Model at LHC energies
Excellent agreement for a wide range of processes over 14 orders in cross-section

arXiv:1503.07589, PRL 114 (2015) 191803

Higgs mass

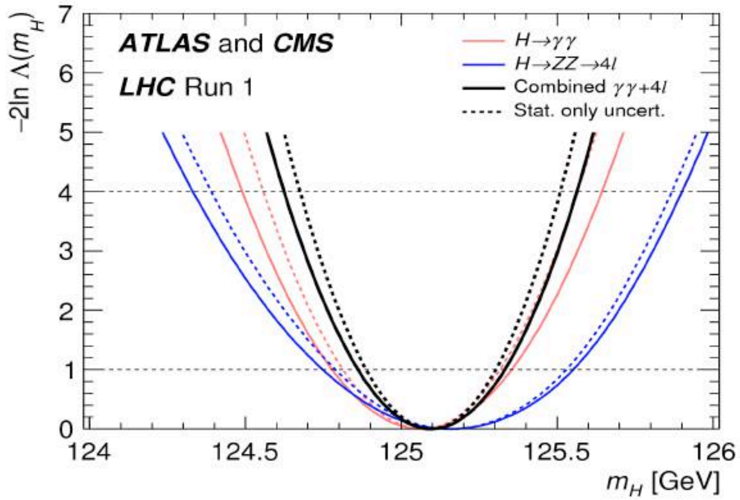
$$m_H = 125.09 \pm 0.24 \text{ GeV}$$
$$= 125.09 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst}) \text{ GeV}$$

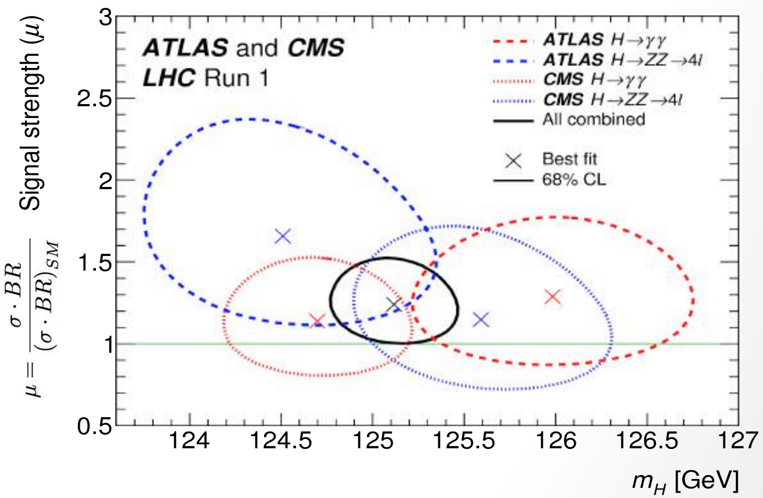


Three signal strengths parameters profiled:

$$\mu^{\gamma\gamma}_{ggF+t\bar{t}H} = 1.15^{+0.28}_{-0.25}$$
$$\mu^{\gamma\gamma}_{\text{VBF}+VH} = 1.17^{+0.58}_{-0.53}$$
$$\mu^{4\ell} = 1.40^{+0.30}_{-0.25}$$

Compatibility of four mass measurements with the combined value: 10%





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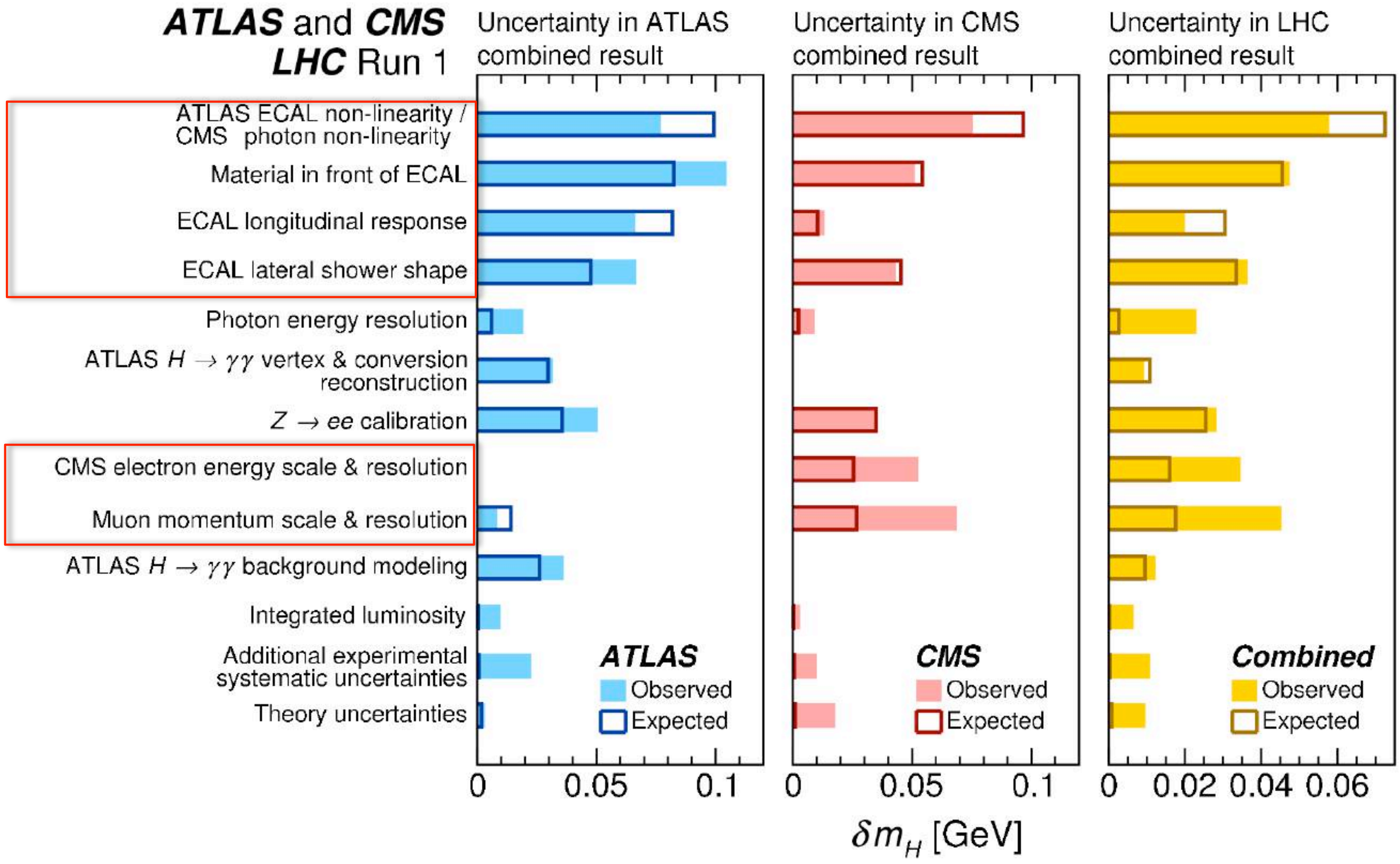
arXiv:1503.07589, PRL 114 (2015) 191803

Higgs mass uncertainties



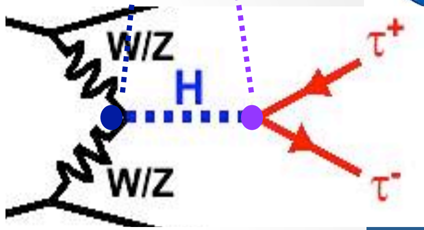
Experimental / theoretical / luminosity uncertainties treated as uncorrelated / fully correlated / partially correlated between the experiments

Gabriella.Pasztor@cern.ch

ATLAS-CONF-2015-044; CMS-PAS-HIG-15-002

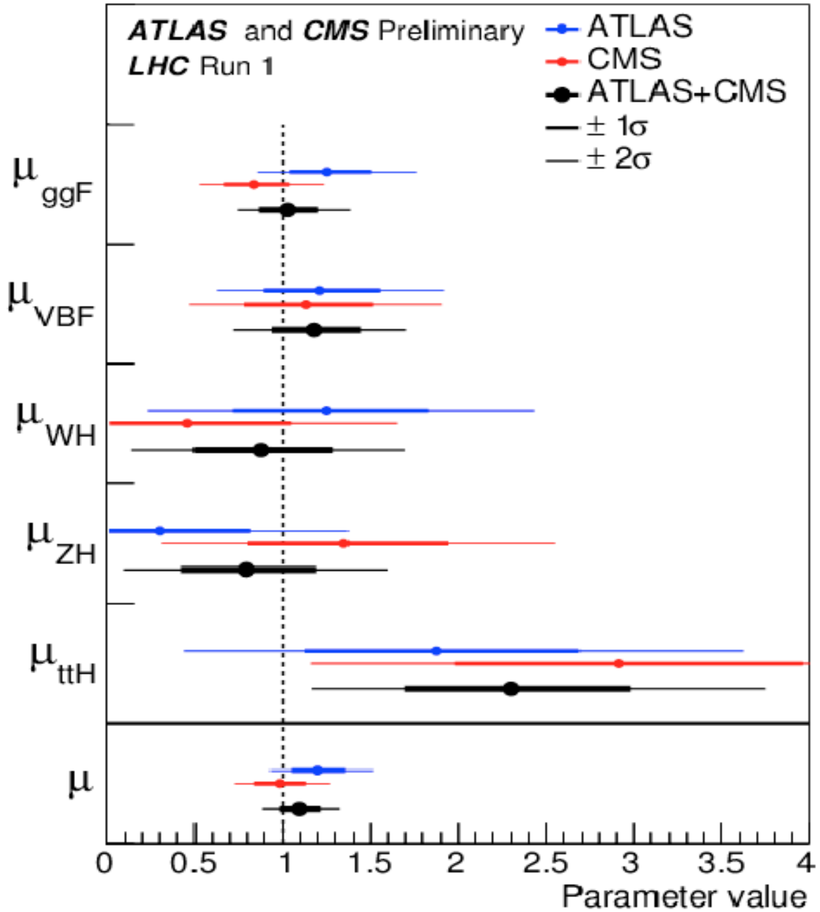
Signal strengths

$$\mu = \frac{\sigma \cdot BR}{(\sigma \cdot BR)_{SM}}$$

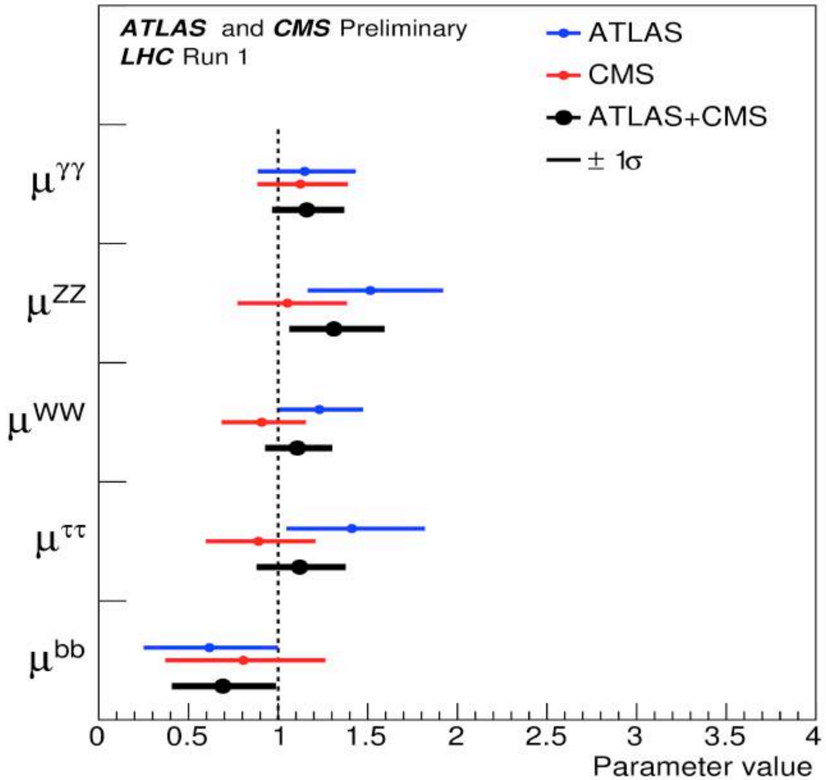


Normalized cross-section * decay branching ratio wrt SM

SM decay branching ratios assumed



SM production cross-sections assumed



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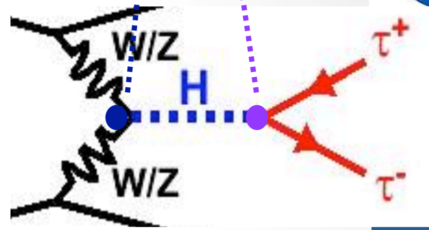
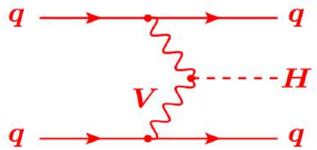
ATLAS-CONF-2015-044; CMS-PAS-HIG-15-002

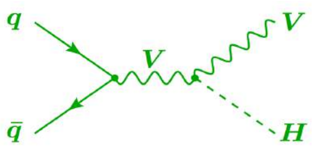
Signal strengths

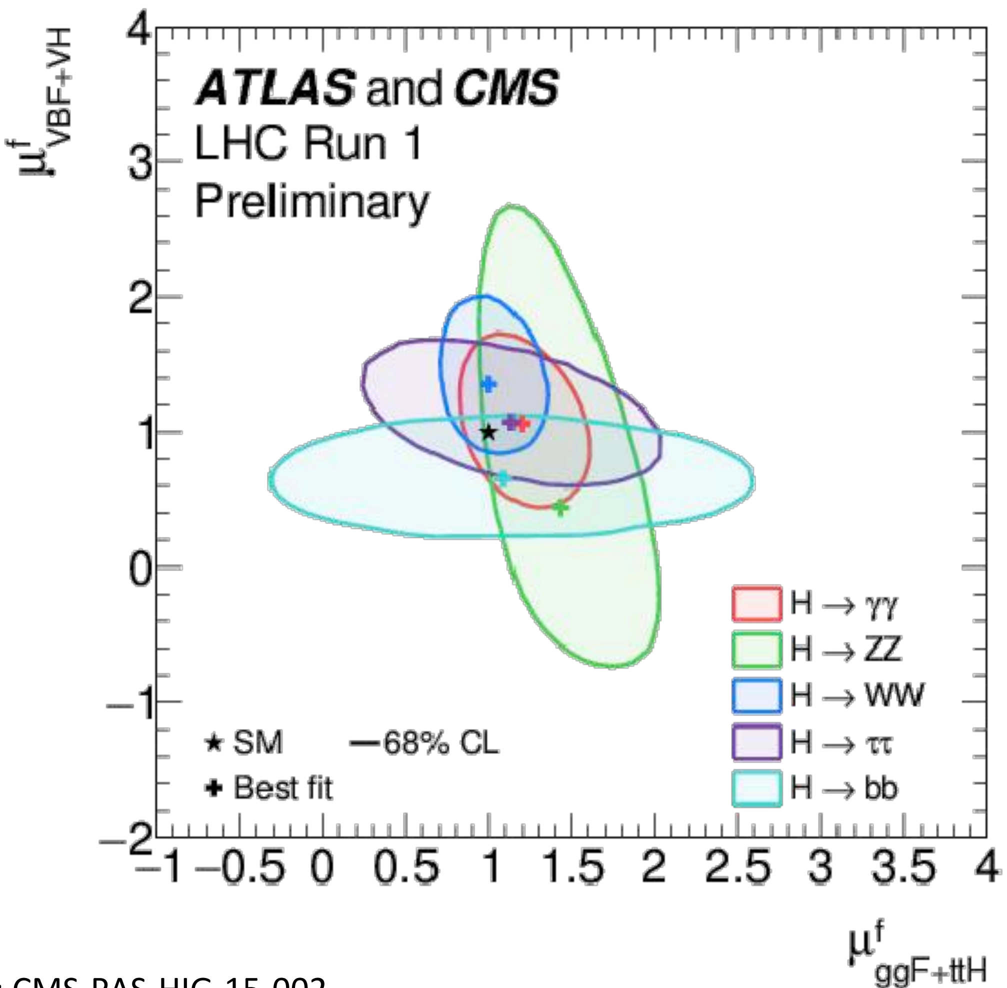
$$\mu = \frac{\sigma \cdot BR}{(\sigma \cdot BR)_{SM}}$$



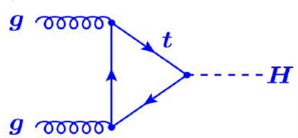
Grouping production processes via HVV (VBF+VH) and Hff (ggF+ttH) couplings together, assuming common μ for given decay mode

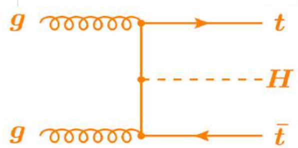






All modes give results compatible with SM





ATLAS-CONF-2015-044; CMS-PAS-HIG-15-002

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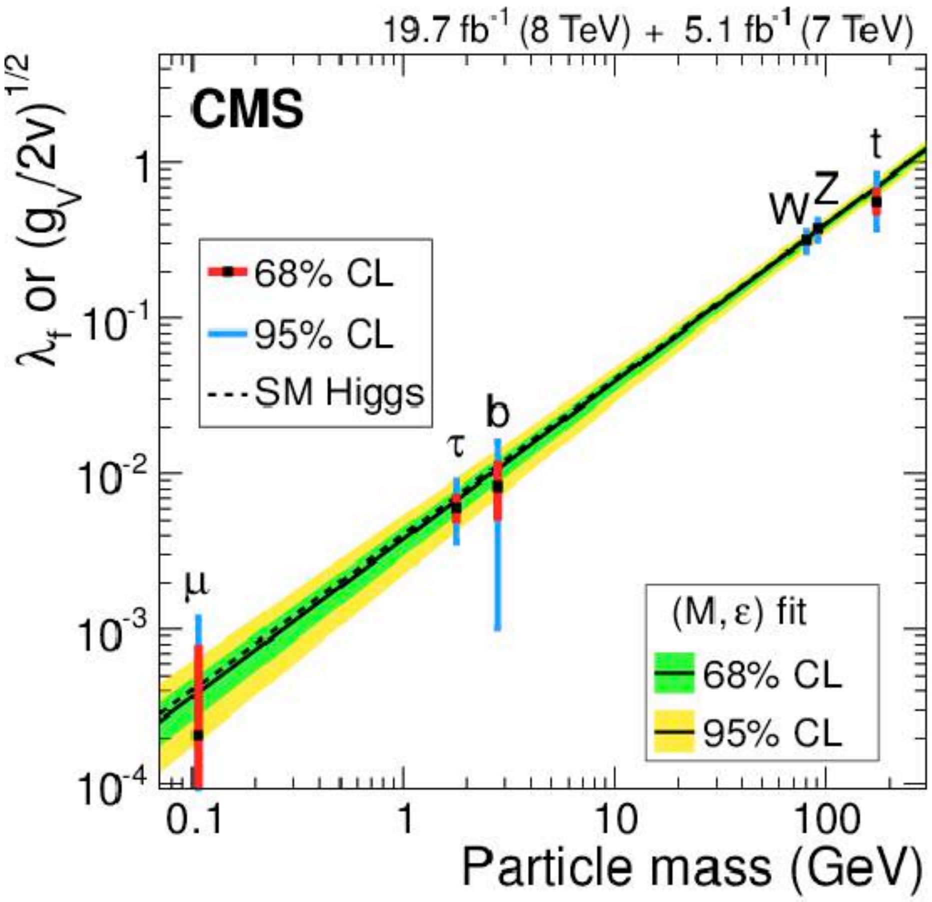
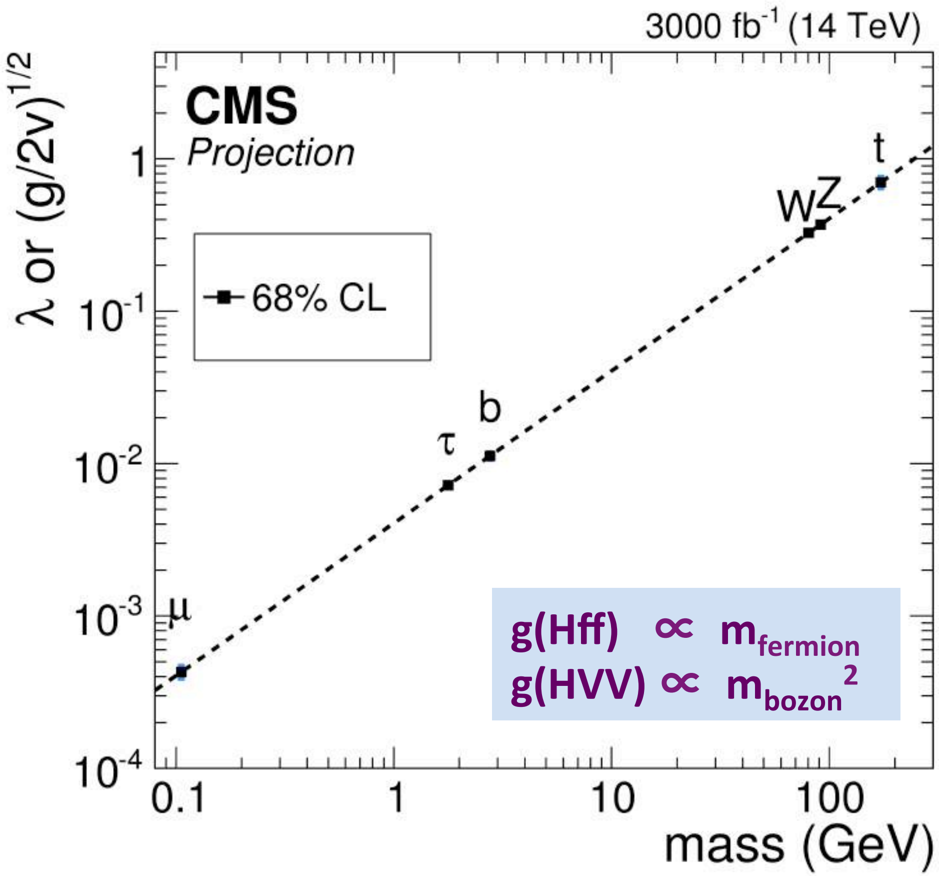
Ultimate coupling measurement precision



Today: ~10-20% precision

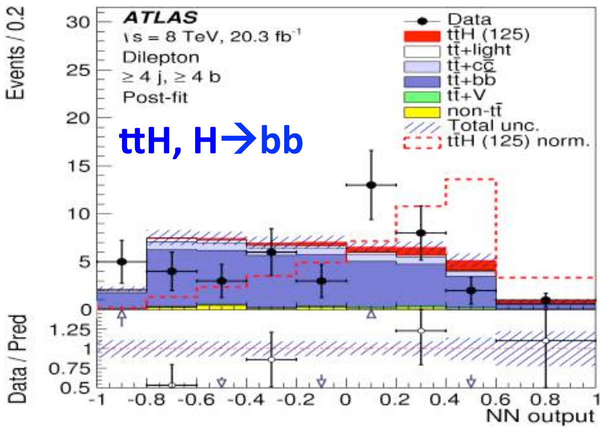


HL-LHC: O(1%) precision for most couplings

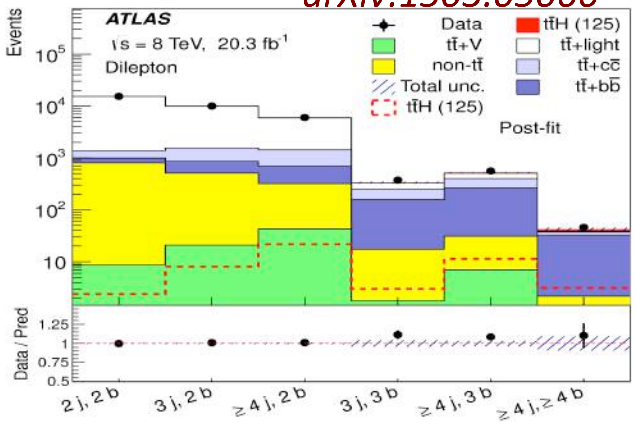
Gabriella.Pasztor@cern.ch

December 2015

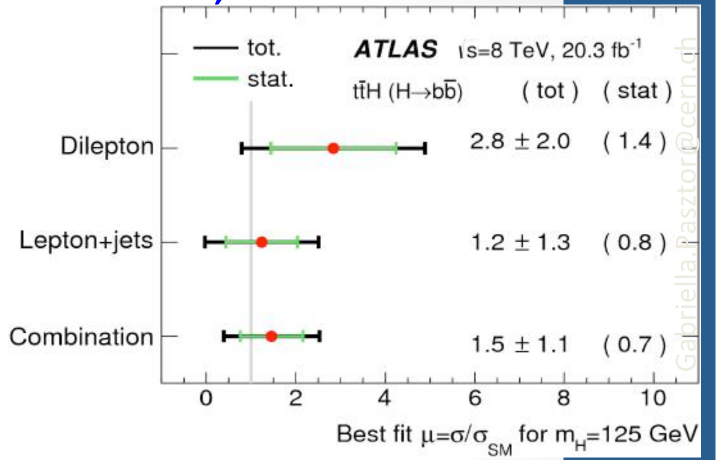
Accessing rare processes: ttH



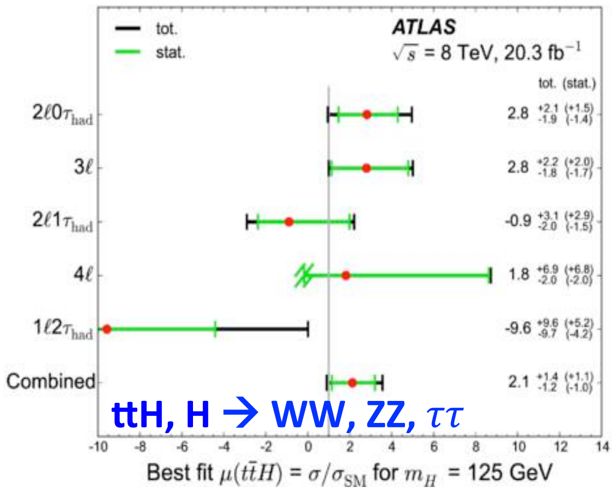
arXiv:1503.05066



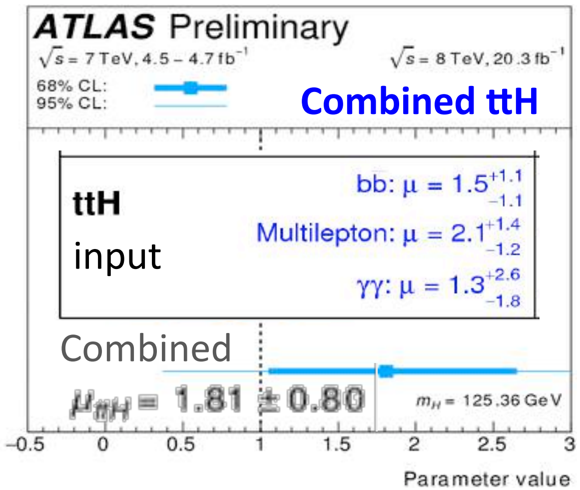
ttH, H→bb



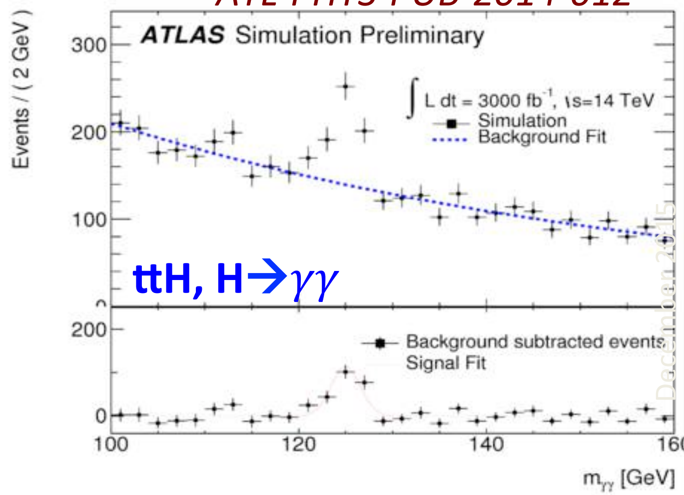
arXiv:1506.05988



ATLAS-CONF-2015-007



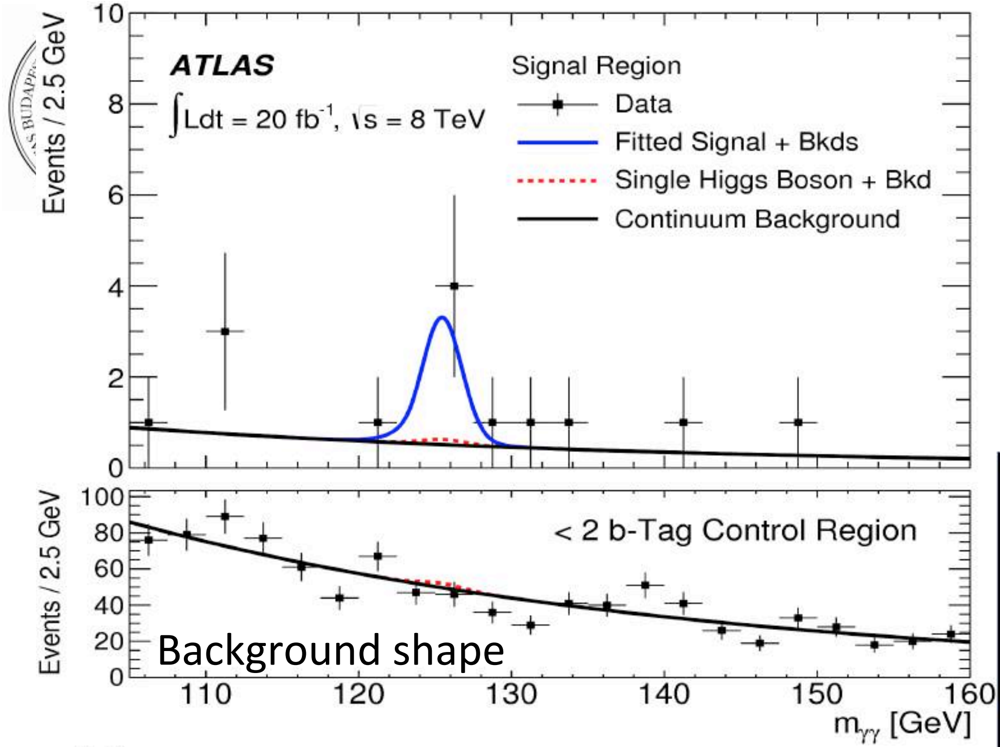
ATL-PHYS-PUB-2014-012



8.2σ at HL-LHC
Δμ/μ ~ 0.2

Important to understand SM backgrounds, such as ttZ, ttγ, …
Run2: improved s/b due to E_{cm} increase + higher statistics!

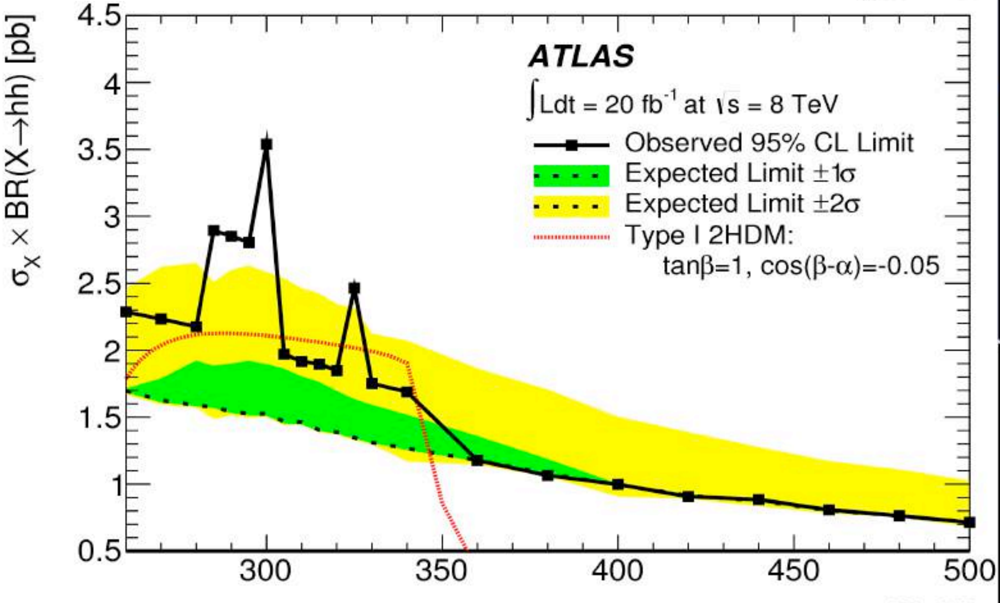
Search for HH→ bbγγ



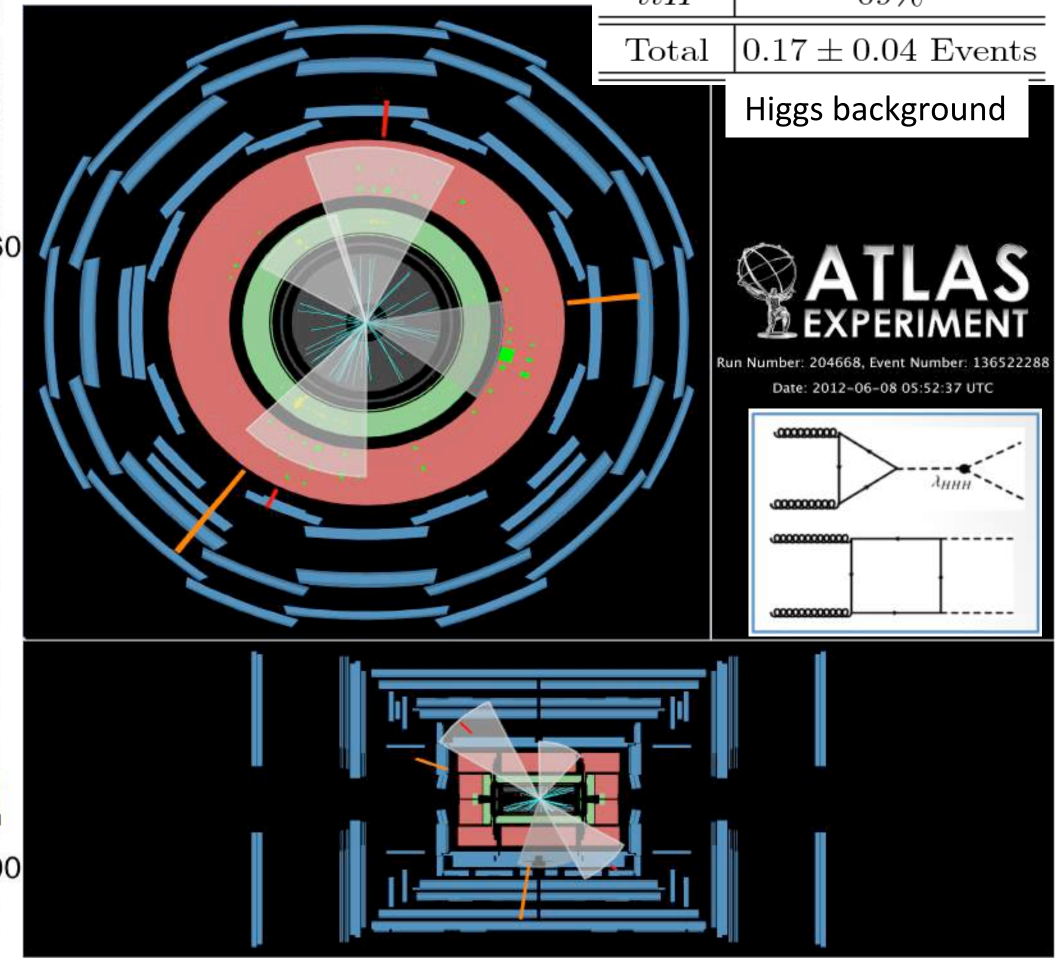
Search for (resonant and non-resonant) HH production (~ 0.04 events are expected in 8 TeV data from SM)

Process	Fraction of total
ggH	11%
qqH	2%
WH	1%
ZH	17%
$t\bar{t}H$	69%
Total	0.17 ± 0.04 Events

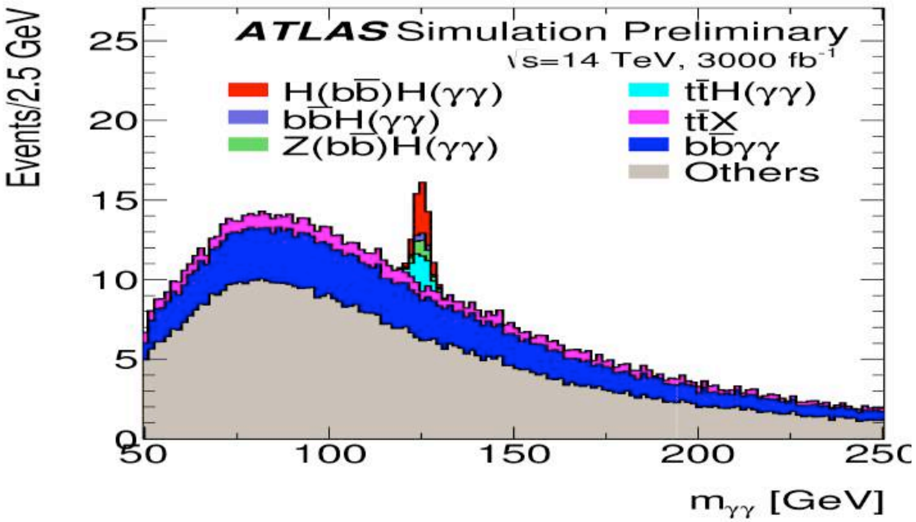
Higgs background

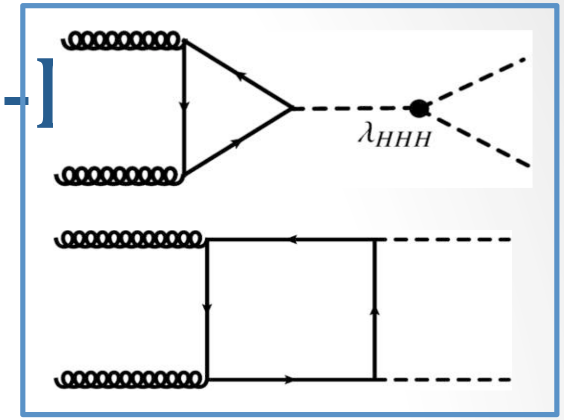


arXiv:1406.5053

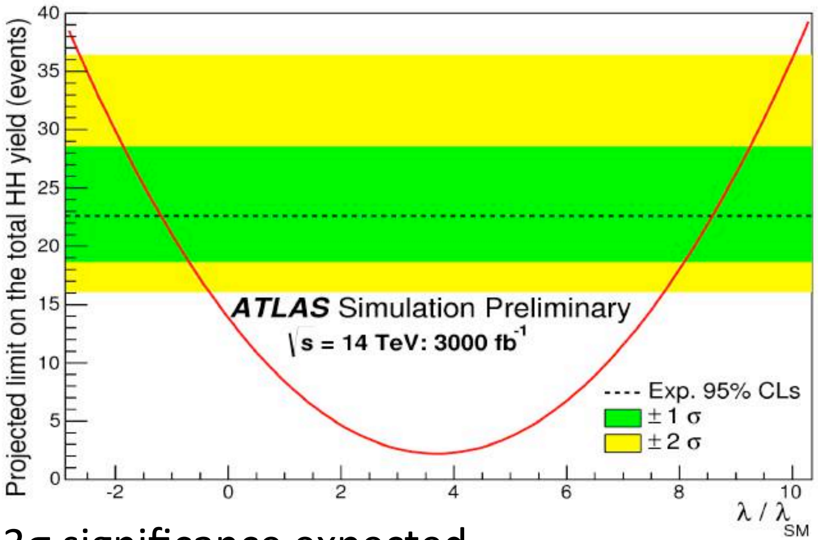


HH→ bb$\gamma\gamma$ at HL-L…



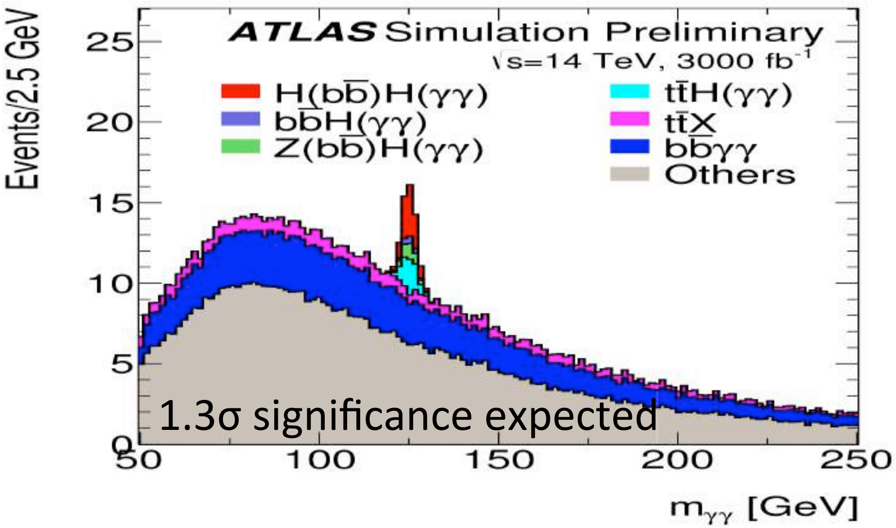


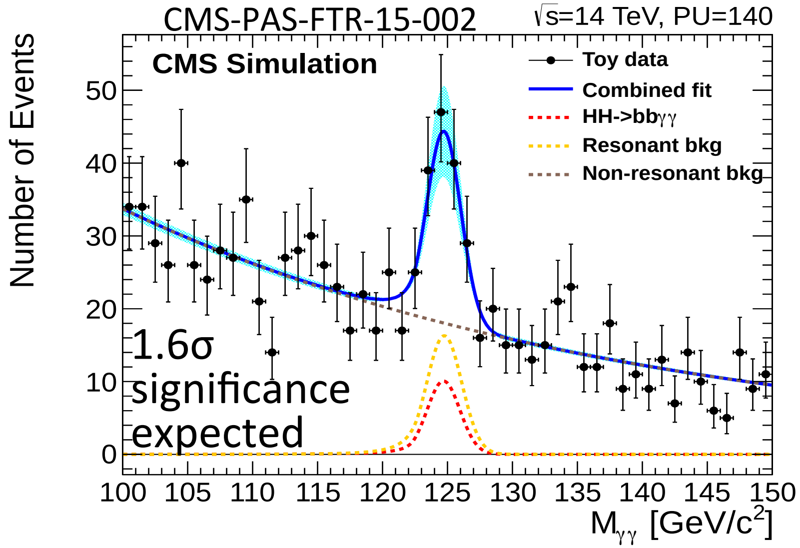
Expected yields (3000 fb^{-1}) Samples	Total	Barrel	End-cap
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=1)$	8.4±0.1	6.7±0.1	1.8±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=0)$	13.7±0.2	10.7±0.2	3.1±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=2)$	4.6±0.1	3.7±0.1	0.9±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=10)$	36.2±0.8	27.9±0.7	8.2±0.4
$b\bar{b}\gamma\gamma$	9.7±1.5	5.2±1.1	4.5±1.0
$c\bar{c}\gamma\gamma$	7.0±1.2	4.1±0.9	2.9±0.8
$b\bar{b}\gamma j$	8.4±0.4	4.3±0.2	4.1±0.2
$b\bar{b}jj$	1.3±0.2	0.9±0.1	0.4±0.1
$jj\gamma\gamma$	7.4±1.8	5.2±1.5	2.2±1.0
$t\bar{t}(\geq 1$ lepton$)$	0.2±0.1	0.1±0.1	0.1±0.1
$t\bar{t}\gamma$	3.2±2.2	1.6±1.6	1.6±1.6
$t\bar{t}H(\gamma\gamma)$	6.1±0.5	4.9±0.4	1.2±0.2
$Z(b\bar{b})H(\gamma\gamma)$	2.7±0.1	1.9±0.1	0.8±0.1
$b\bar{b}H(\gamma\gamma)$	1.2±0.1	1.0±0.1	0.3±0.1
Total Background	47.1±3.5	29.1±2.7	18.0±2.3
$S/\sqrt{B}(\lambda/\lambda_{SM}=1)$	1.2	1.2	0.4



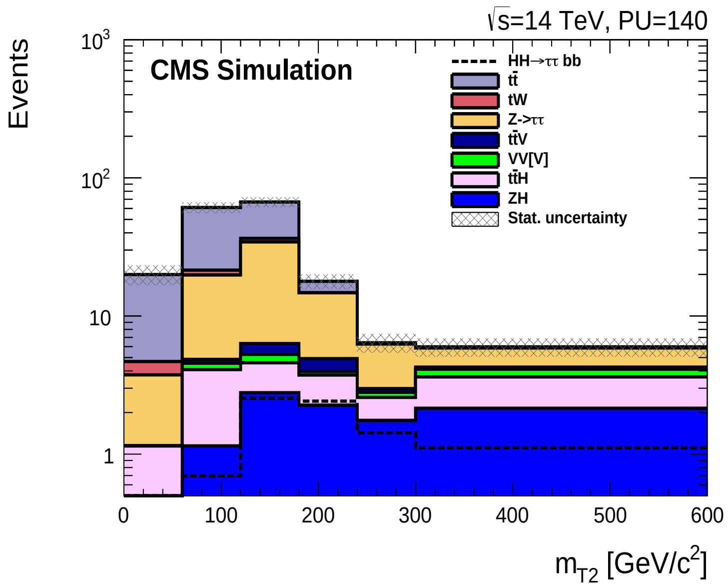
1.3σ significance expected
(CMS: 2σ, under discussion)
To be combined with other channel e.g. HH → bb $\tau\tau$, bb bb, bb WW …

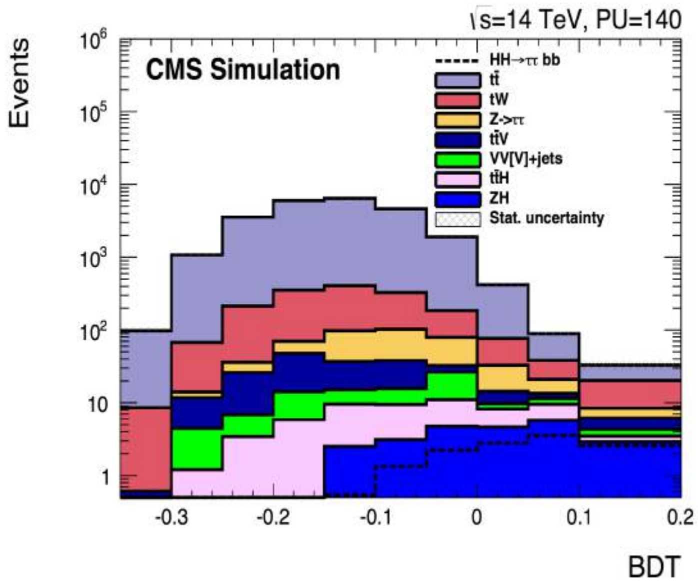
H→HH at HL-LHC





HH→ bb$\gamma\gamma$ to be combined with other channel e.g. HH → bb $\tau\tau$, bb bb, bb WW …





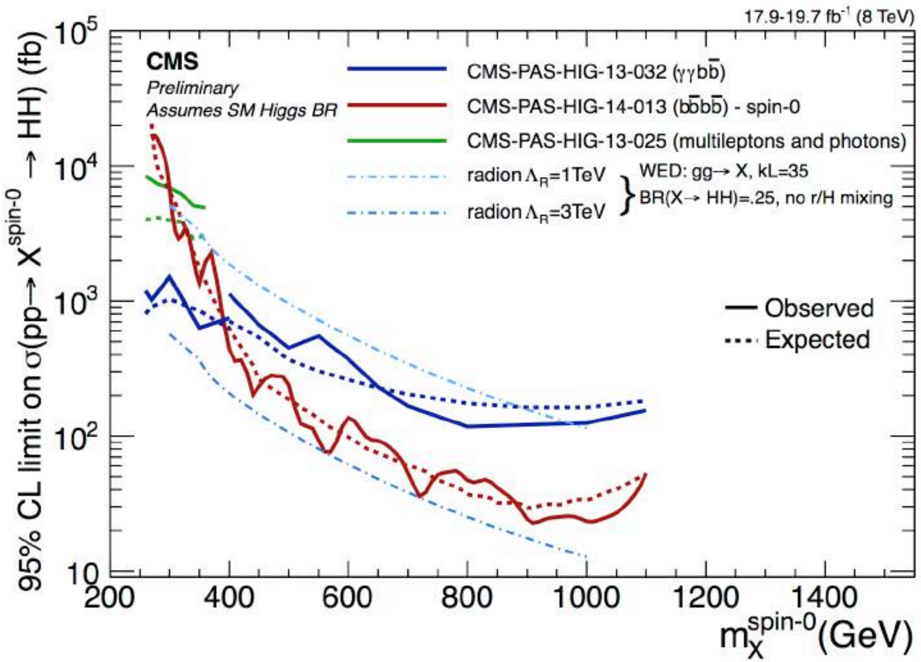
CMS HH→ bb$\gamma\gamma$ and HH → bb $\tau\tau$: 1.9σ significance expected

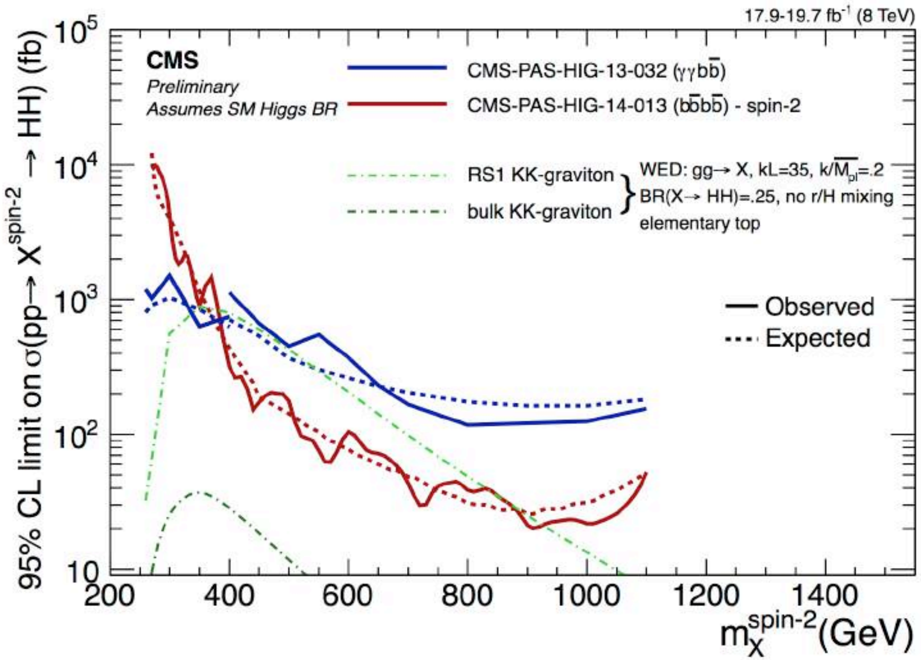
Huge challenge even at HL-LHC!!!

Gabriella.Pasztor@cern.ch

December 2015

X → HH search

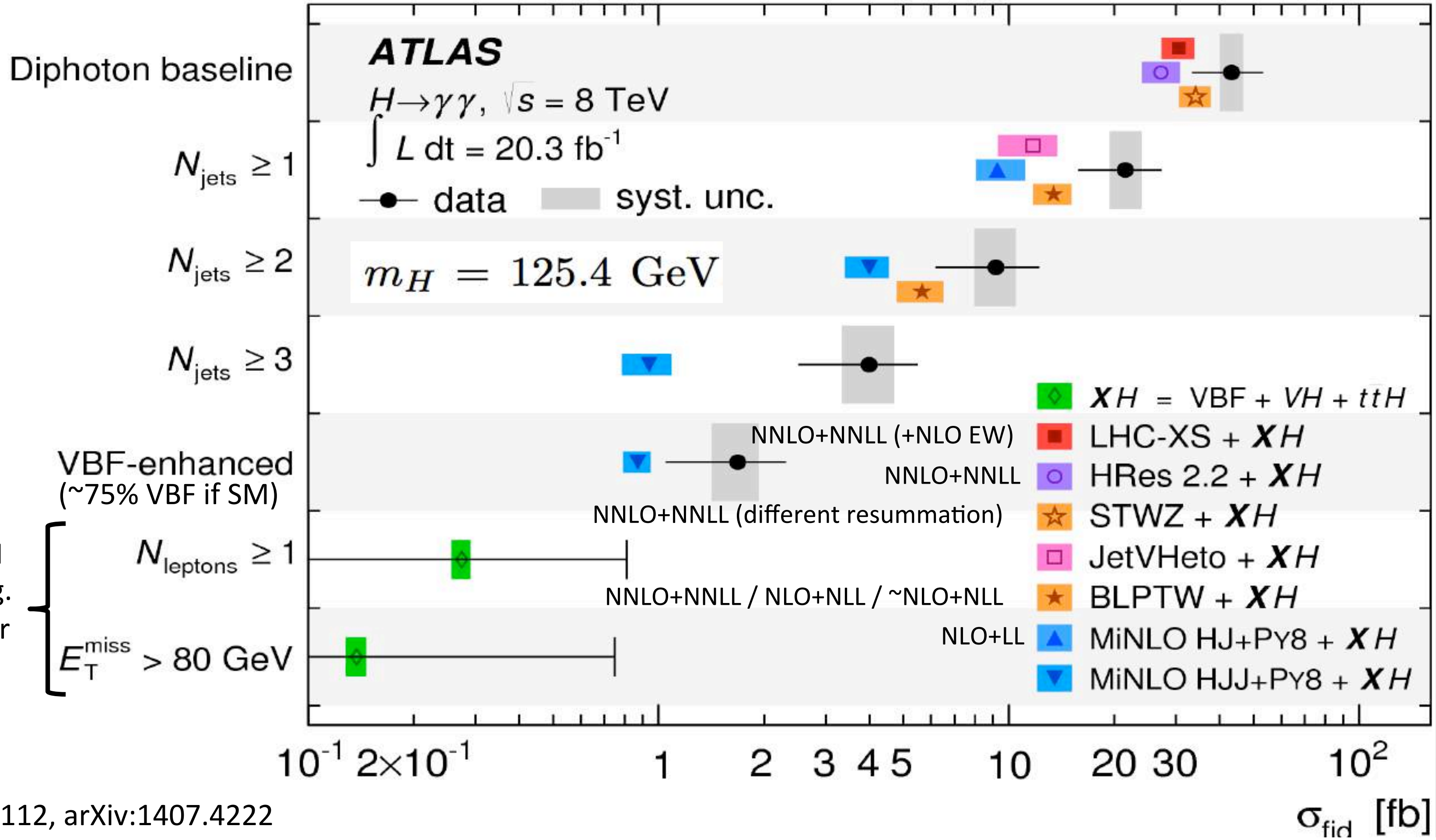




Gabriella.Pasztor@cern.ch

Fiducial cross-sections

- Fiducial region definition motivated by experimental cuts, inclusive in production modes
- Model-independent measurement of production and decay kinematics
- Allows comparison with precision calculations, alternative models
- Test theoretical modelling of different Higgs boson production mechanisms
- Sensitive to BSM physics



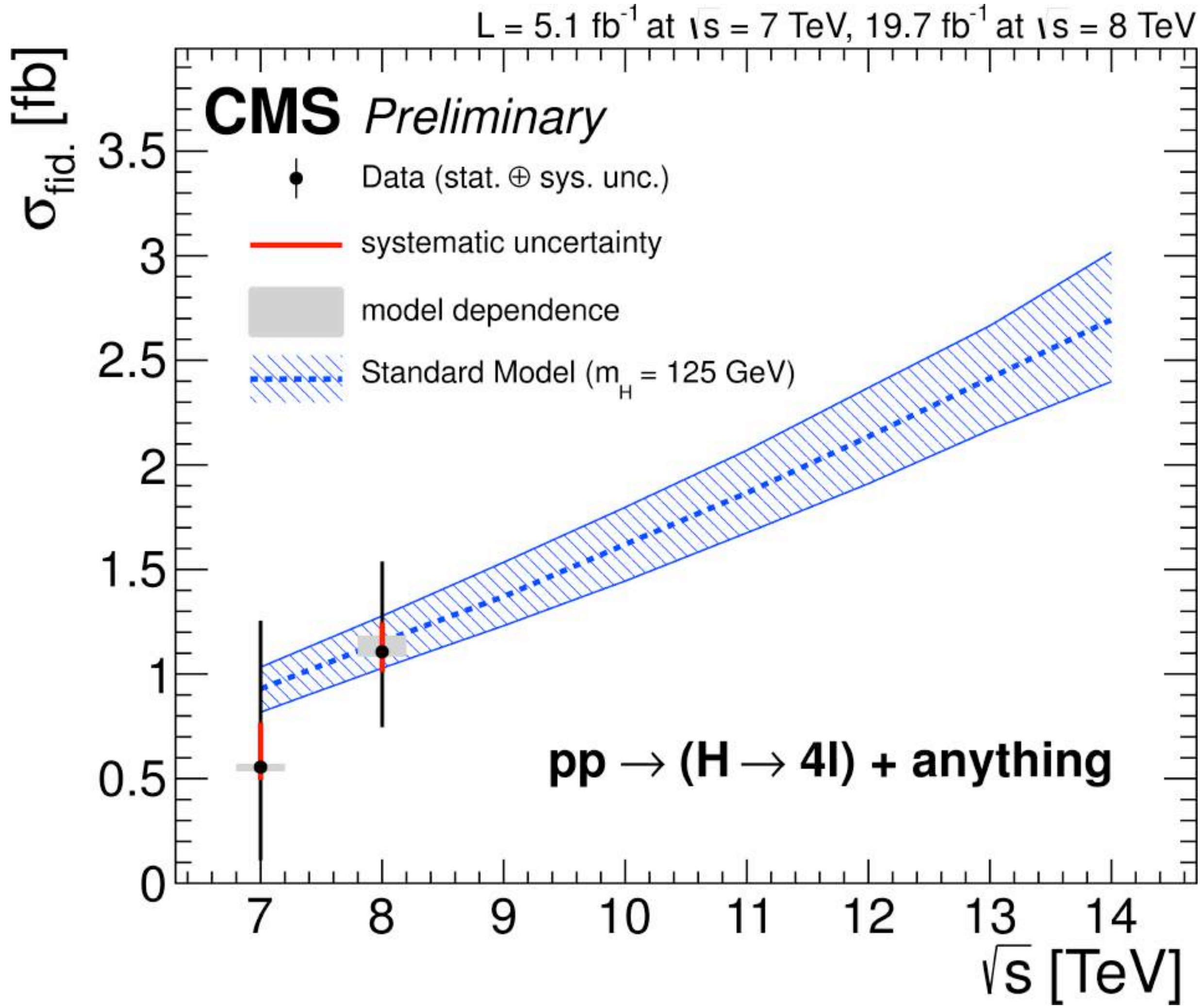
VH + ttH if SM
Constrains e.g.
H+dark matter
production

JHEP09(2014)112, arXiv:1407.4222

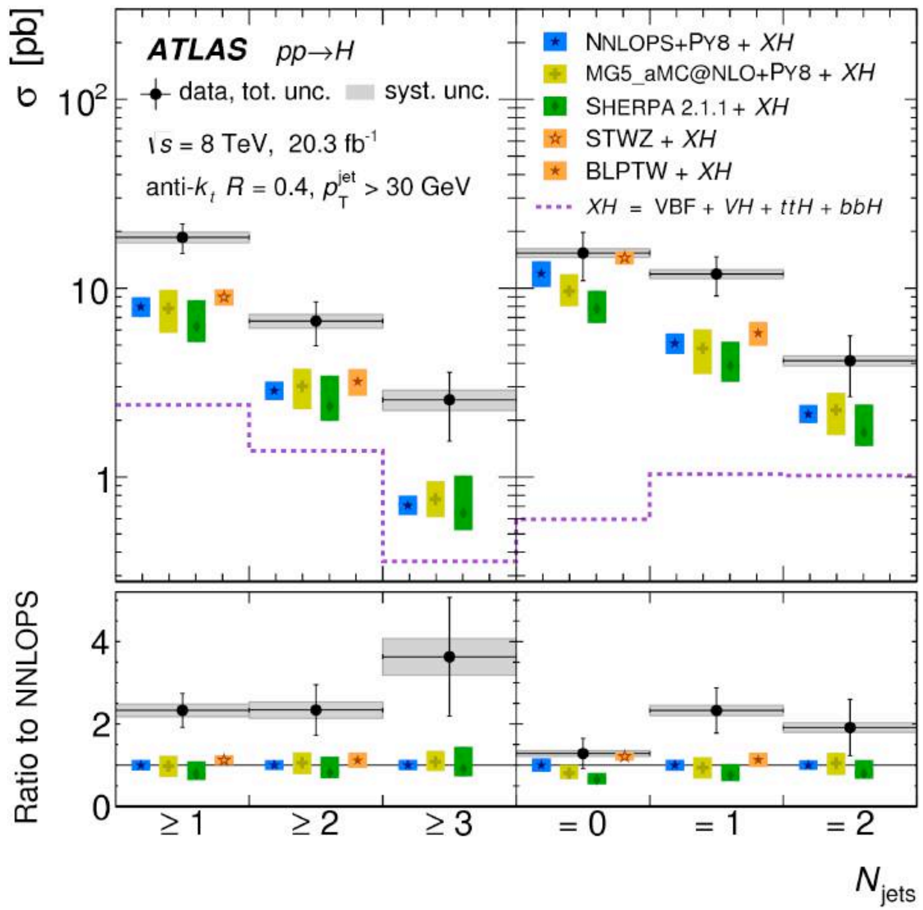
Gabriella.Pasztor@cern.ch

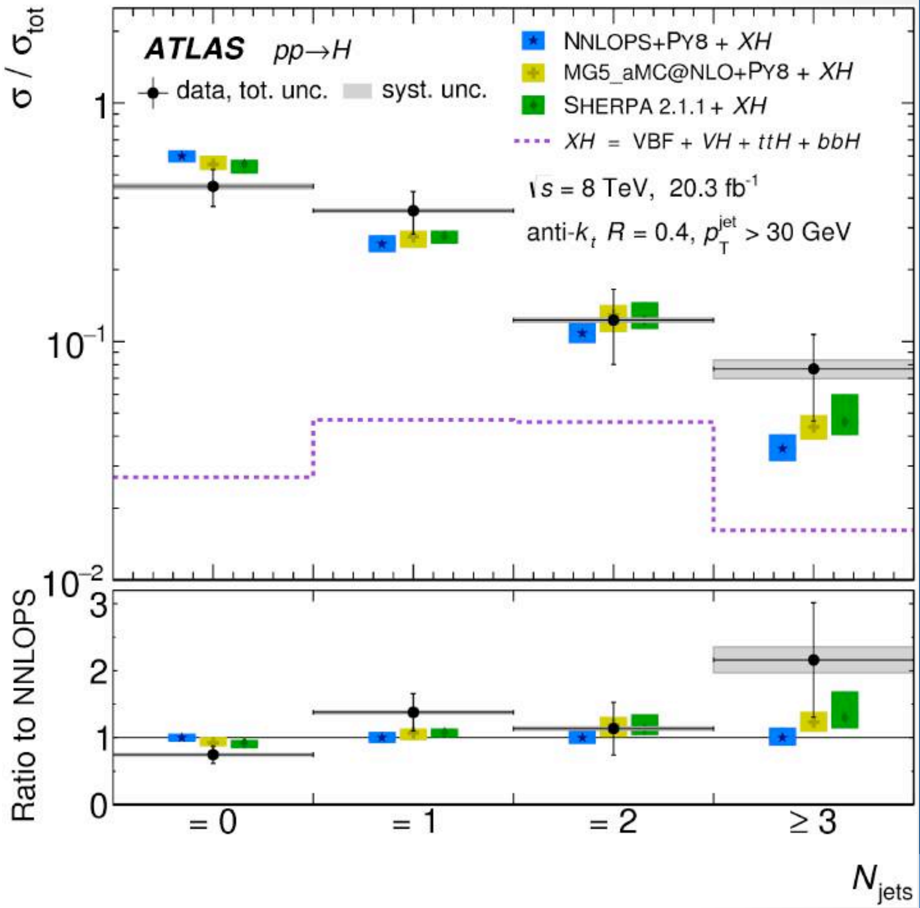
CMS-PAS-HIG-14-028

Fiducial cross-section



Fiducial cross-sections vs. N_{jets}





Phys. Rev. Lett. 115 (2015) 091801, arXiv:1504.05833

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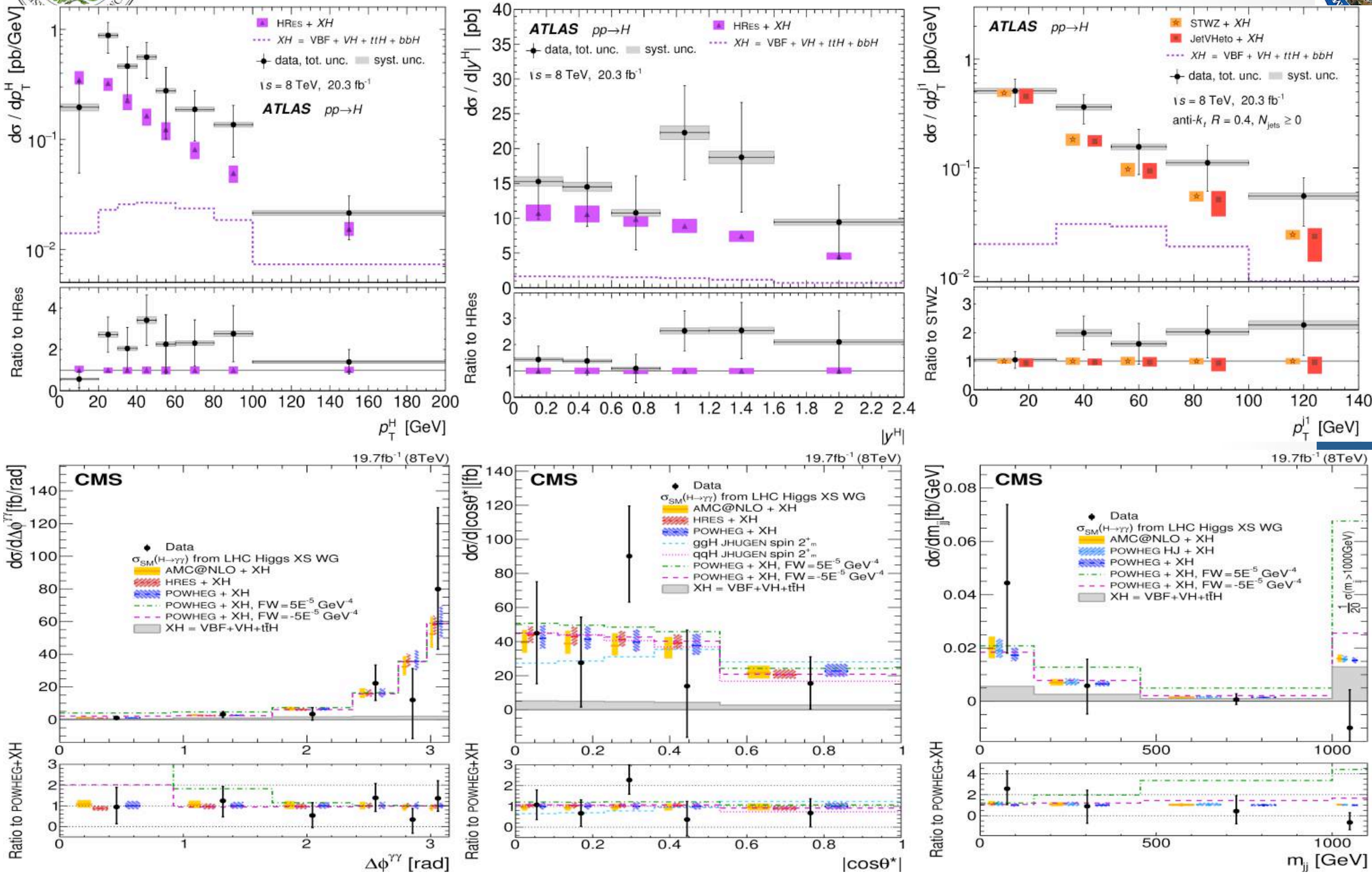
Phys. Rev. Lett. 115 (2015) 091801, arXiv:1504.05833
arXiv:1508.07819

Differential cross-sections



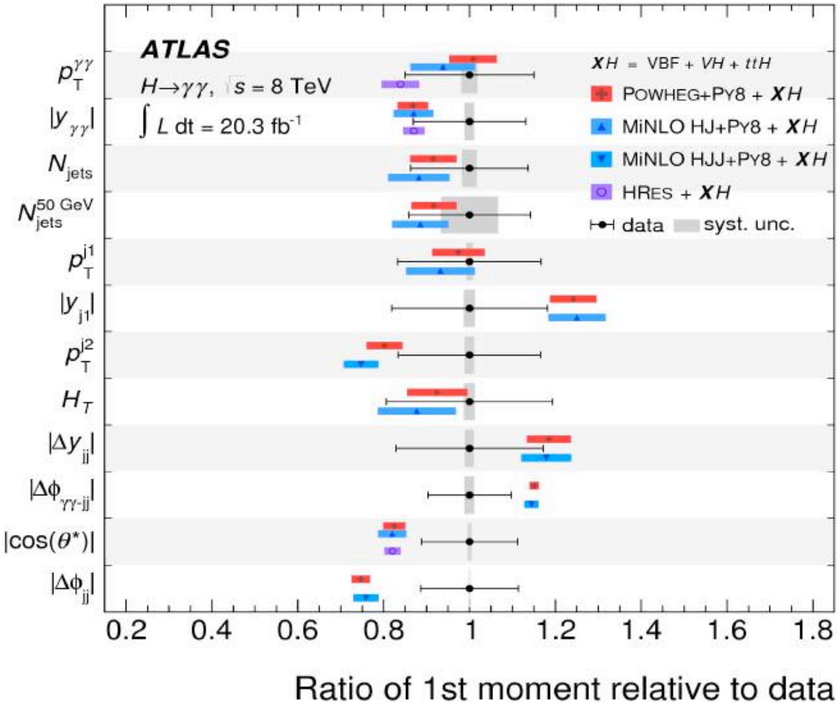
Compatibility with SM

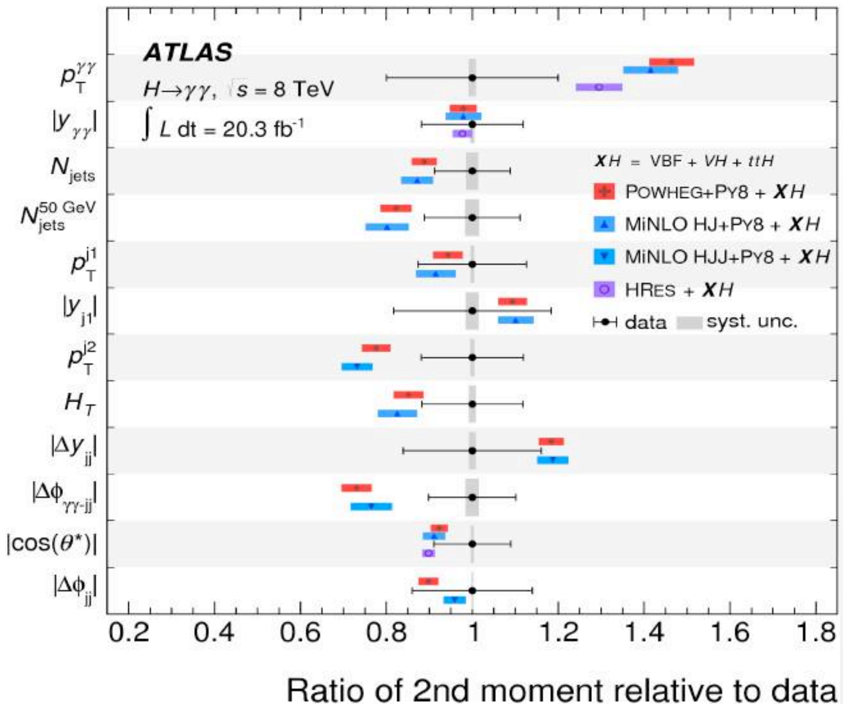
Reasonable agreement within large (statistically-dominated) uncertainties

χ^2 probability

Variable	POWHEG	MINLO HJ	MINLO HJJ	HRES
$p_T^{\gamma\gamma}$	0.12	0.10	0.09	0.12
$\lvert y_{\gamma\gamma}\rvert$	0.81	0.83	0.83	0.80
$\lvert\cos\theta^*\rvert$	0.59	0.57	0.58	0.56
N_{jets}	0.42	0.36	0.30	-
$N_{\text{jets}}^{50\text{ GeV}}$	0.33	0.33	0.30	-
H_T	0.43	0.39	0.34	-
$p_T^{j_1}$	0.84	0.82	0.79	-
$\lvert y_{j_1}\rvert$	0.64	0.58	0.51	-
$p_T^{j_2}$	0.34	0.29	0.23	-
$\lvert\Delta\phi_{jj}\rvert$	0.21	0.28	0.24	-
$\lvert\Delta y_{jj}\rvert$	0.64	0.58	0.49	-
$\lvert\Delta\phi_{\gamma\gamma,jj}\rvert$	0.45	0.46	0.42	-

JHEP09(2014)112, arXiv:1407.4222

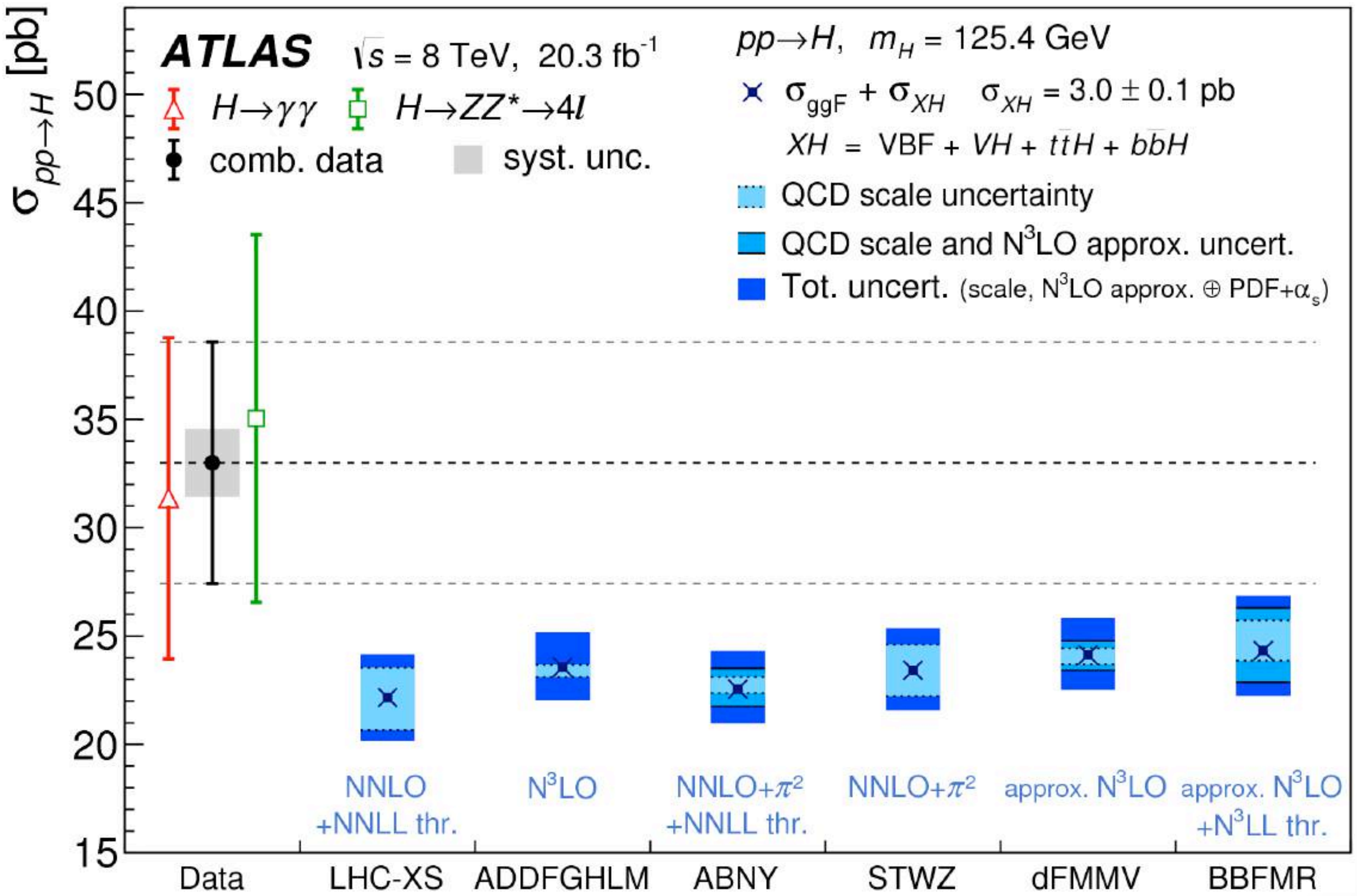




Gabriella.Pasztor@cern.ch

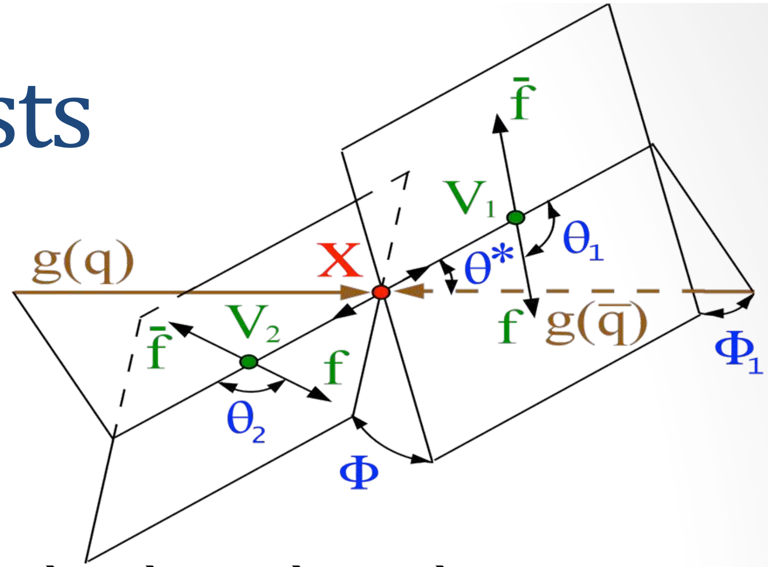
Total cross-section

- From measured fiducial cross-section, extrapolate to the full phase-space
- Aimed at measuring the dominant ggF cross-section, other modes corrected for assuming SM values

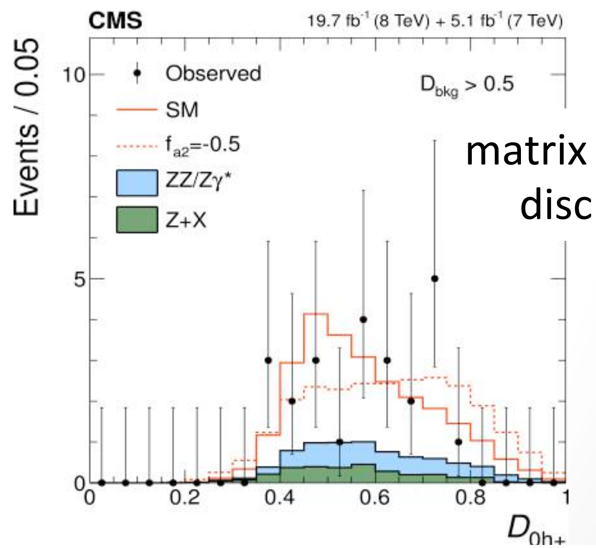


Phys. Rev. Lett. 115 (2015) 091801, arXiv:1504.05833

Spin-parity tests



- In SM, Higgs is CP-even scalar: $J^{CP} = 0^{++}$
- In BSM, often extended Higgs sector with possibility of CP-mixing
- Interactions could violate C and CP,
- thus testing only J^P
- Measurement in bosonic channels: H→$\gamma\gamma$, H→ZZ→4l, H→WW→eνμν rely mainly on angular distributions
- Observation of H→$\gamma\gamma$ excludes spin-1 hypothesis via Landau – Young theorem
- Large number of fixed spin-parity hypothesis tests assuming the resonance decay involves only one CP eigenstate
  - $J^P = 0^+, 0^-, 0^+_h$ (BSM scalar, higher-order operators), 1^+, 1^-, 2^+ (e.g. graviton-like with universal and non-universal couplings to fermions and vector bosons), 2^-
- Detailed study of the spin-0 hypothesis
  - Parametrisations with anomalous vertices (CMS) or Effective Field Theory approach (ATLAS) to test HVV couplings



matrix element discriminant

Gabriella.Pasztor@cern.ch

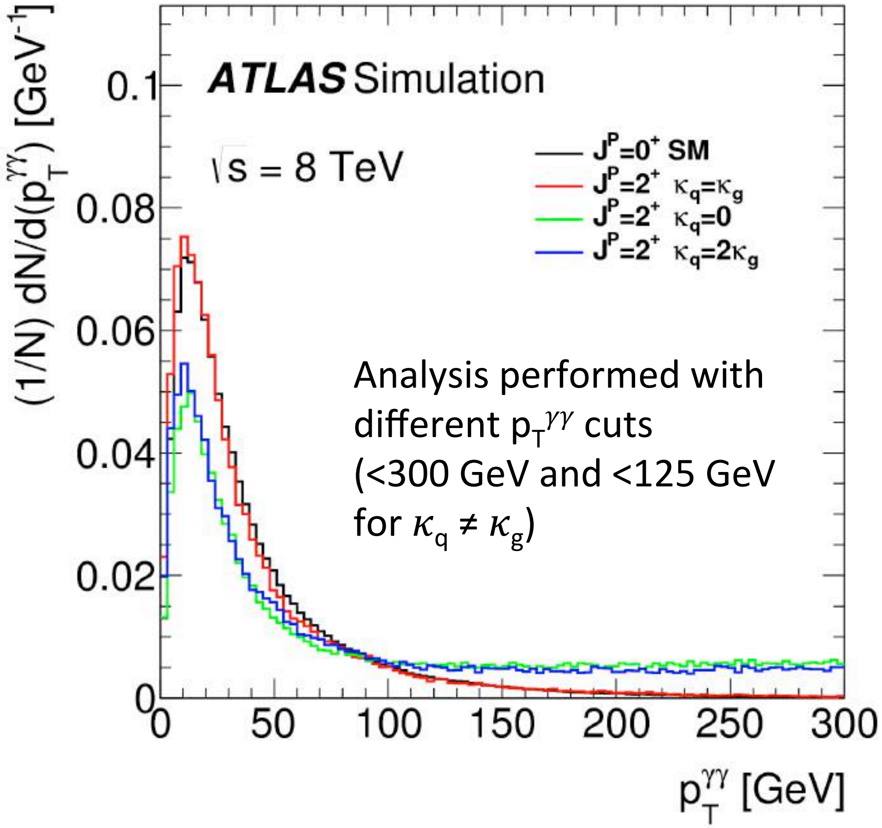
December 2015

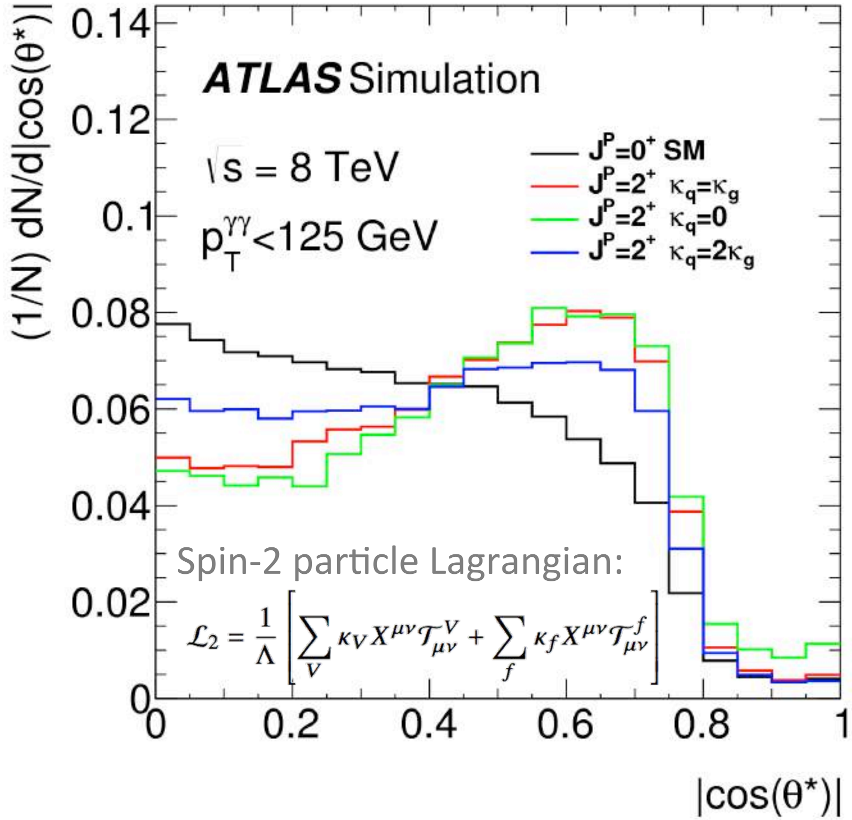
H→γγ observables

Production angle of the two photons in the Collins-Soper frame:

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma 1}p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$

arXiv:1506.05669





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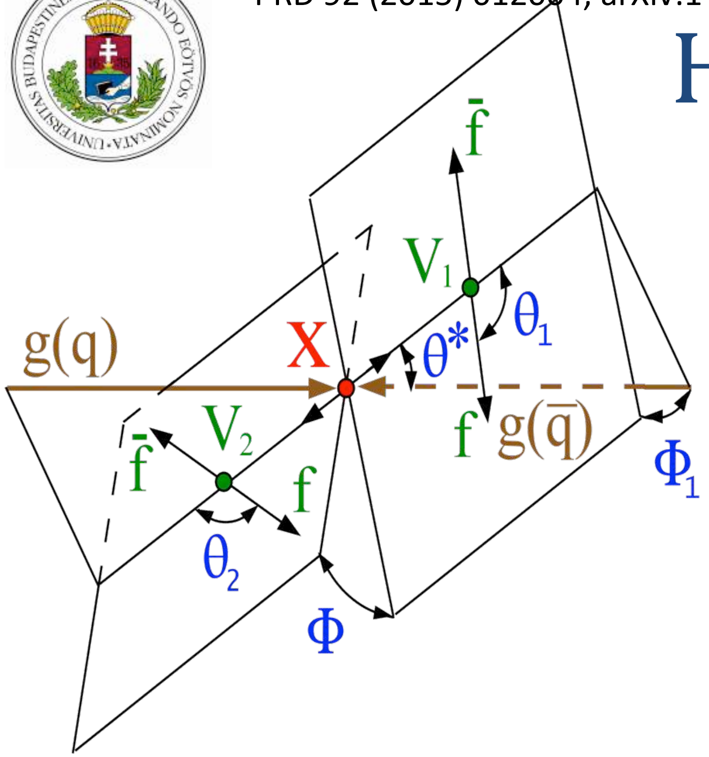
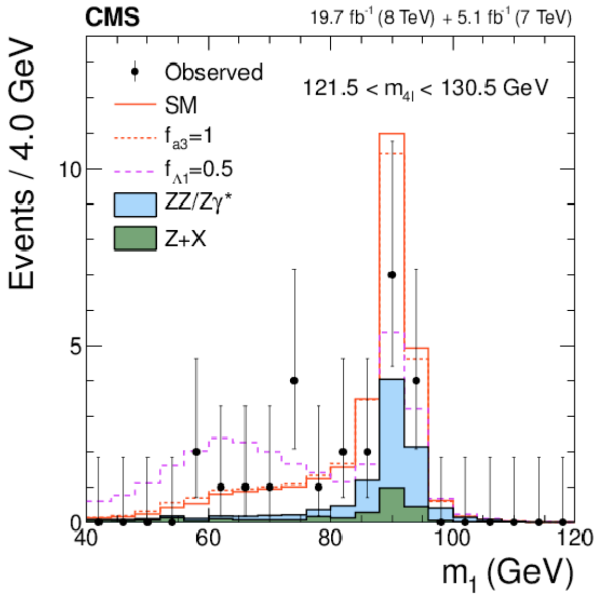
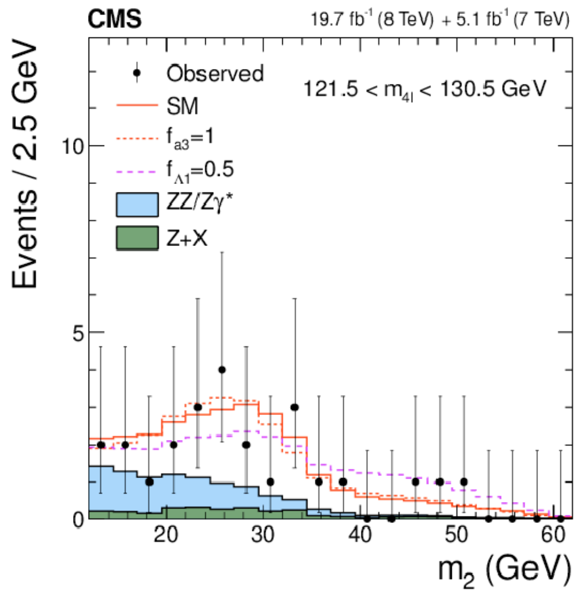
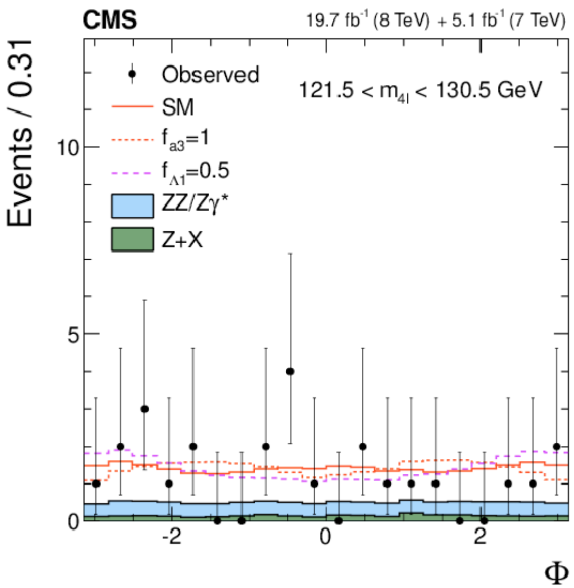
PRD 92 (2015) 012004, arXiv:1411.3441

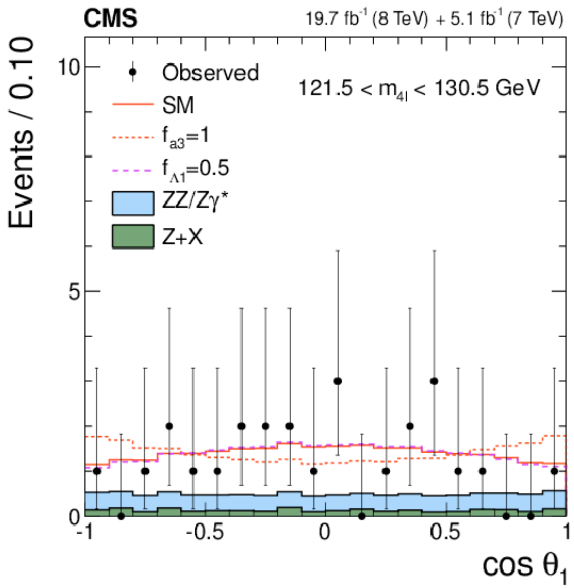
H→4l observables

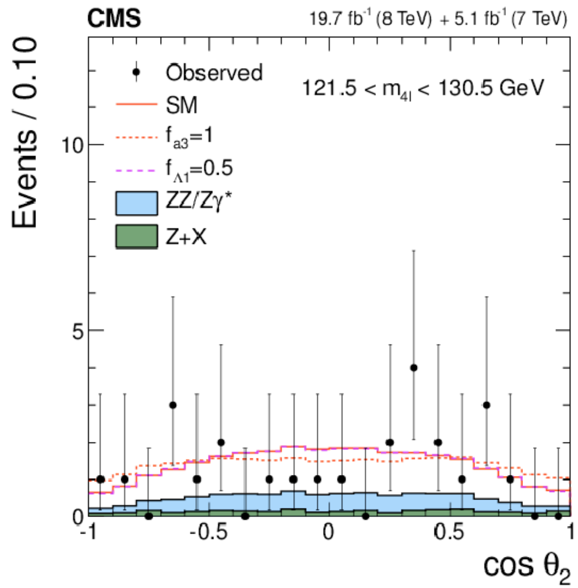










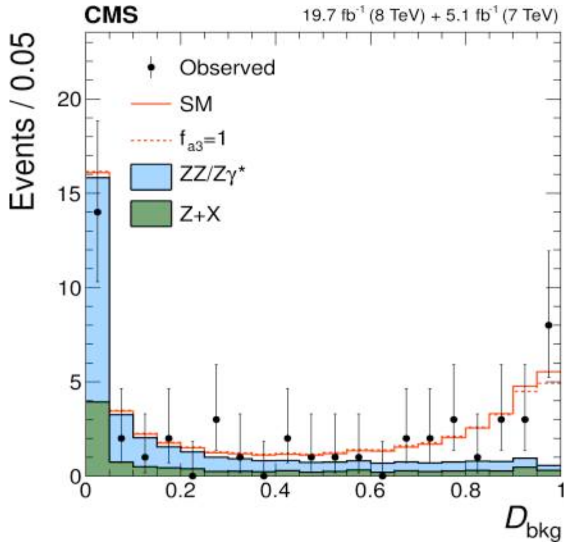


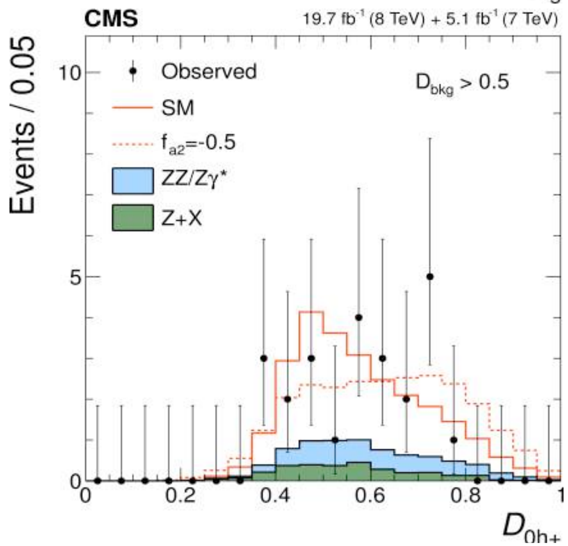
PRD 92 (2015) 012004, arXiv:1411.3441

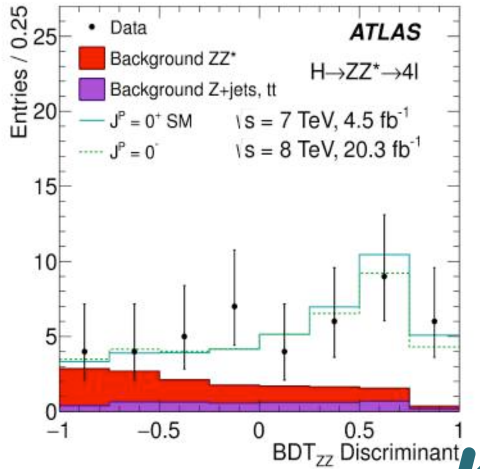
arXiv:1506.05669

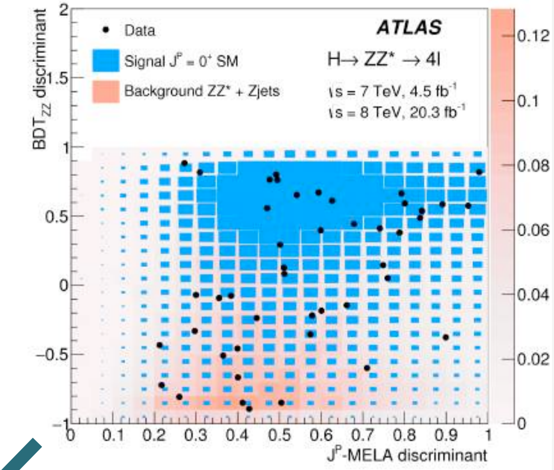
H→4l observables and hypothesis testing

Build a matrix element discriminant to separate different spin-parity hypotheses and a kinematic variable against background

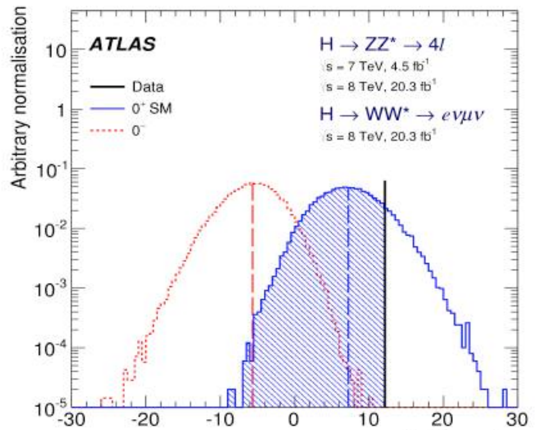




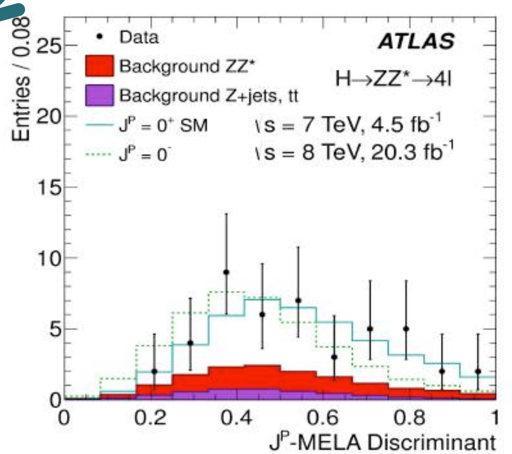




Ratio of profiled likelihoods



$$\tilde{q} = \log \frac{\mathcal{L}(J^P_{SM}, \hat{\hat{\mu}}_{J^P_{SM}}, \hat{\hat{\theta}}_{J^P_{SM}})}{\mathcal{L}(J^P_{alt}, \hat{\hat{\mu}}_{J^P_{alt}}, \hat{\hat{\theta}}_{J^P_{alt}})}$$

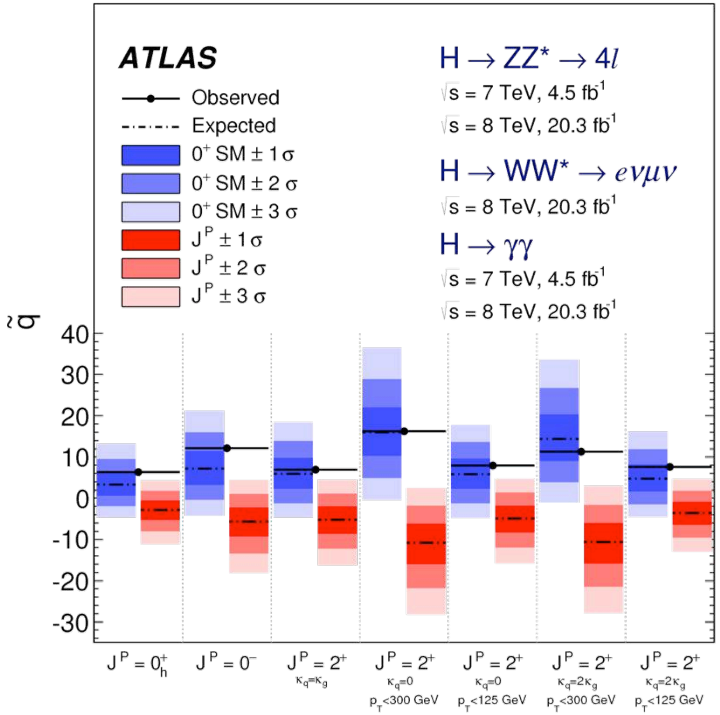


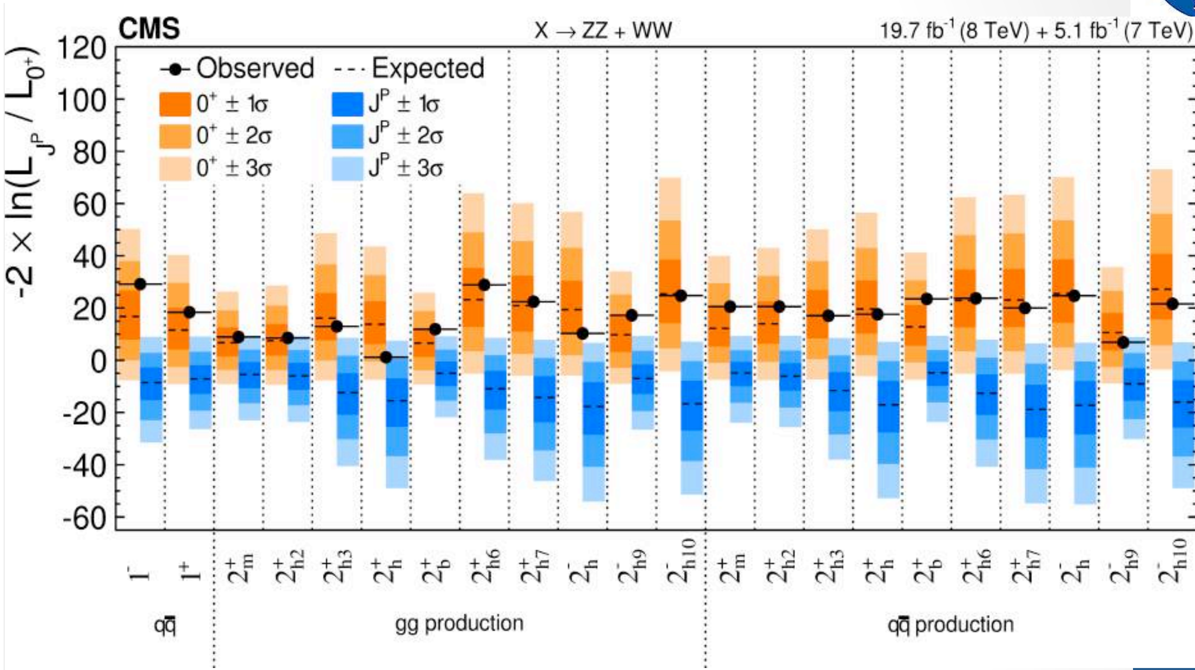
Gabriella.Pasztor@cern.ch

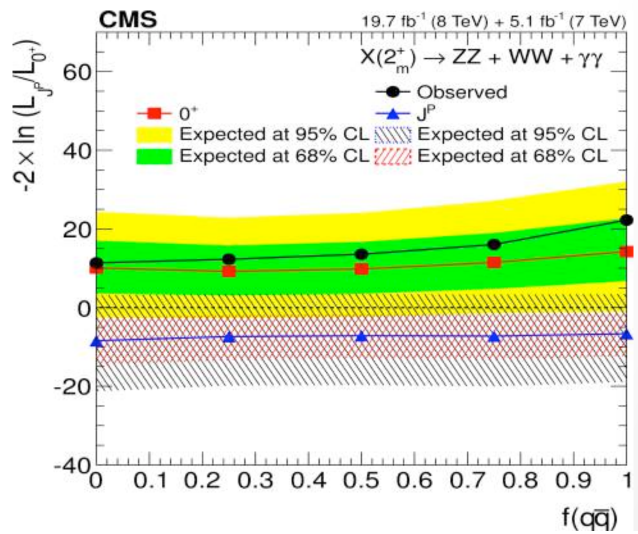
arXiv:1506.05669

PRD 92 (2015) 012004, arXiv:1411.3441

Spin-parity tests







- All tests prefer SM hypothesis
- All spin-1 and spin-2 hypotheses as well as 0^- and 0^+_h excluded with >99%CL (most with >99.9% CL)
- Graviton inspired 2^+_m state disfavoured independent of production mode (gg or qq)

Gabriella.Pasztor@cern.ch

Anomalous couplings (ATLAS)

- Test presence of BSM CP-even and CP-odd terms in spin-0 H→VV decay using effective Lagrangian: CP-odd fraction and tensor couplings constrained
- EFT approach, valid up to a scale Λ (= 1 TeV):

$$\mathcal{L}_0^V = \left\{c_\alpha \kappa_{SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W_\mu^+ W^{-\mu}\right] - \tfrac{1}{4}\tfrac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] - \tfrac{1}{2}\tfrac{1}{\Lambda}\left[c_\alpha \kappa_{HWW}W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW}W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}\right]\right\} X_0$$

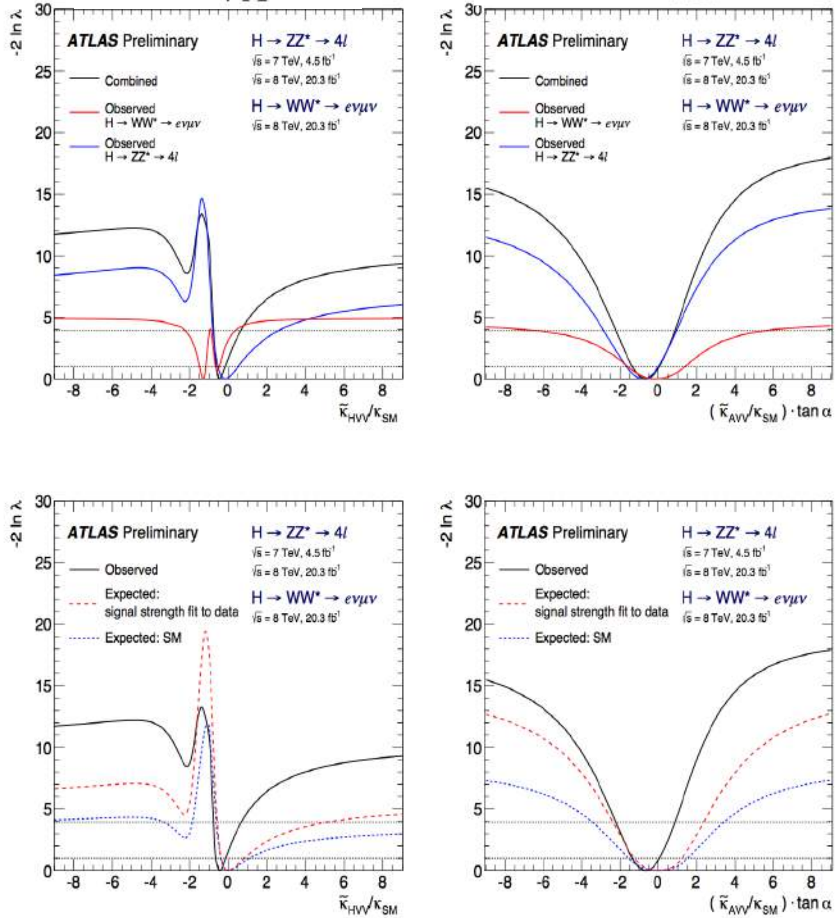
SM coupling strength: $g_{HVV} \propto m_{Z/W}^2$

α: CP-mixing angle, for α ≠ 0, π: CP-violation
(s_α = sinα, c_α = cosα)

Assume only one BSM contribution at a time

J^P	Model	Choice of tensor couplings			
		κ_{SM}	κ_{HVV}	κ_{AVV}	α
0^+	Standard Model Higgs boson	1	0	0	0
0_h^+	BSM spin-0 CP-even	0	1	0	0
0^-	BSM spin-0 CP-odd	0	0	1	$\pi/2$

$$\tilde{\kappa}_{HVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{HVV} \qquad \tilde{\kappa}_{AVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{AVV}$$



Gabriella.Pasztor@cern.ch

PRD 92 (2015) 012004, arXiv:1411.3441

Anomalous couplings (CMS)

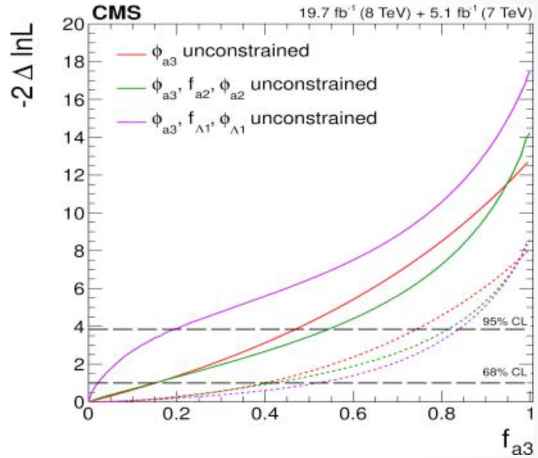
- Parametrisation with anomalous vertices:

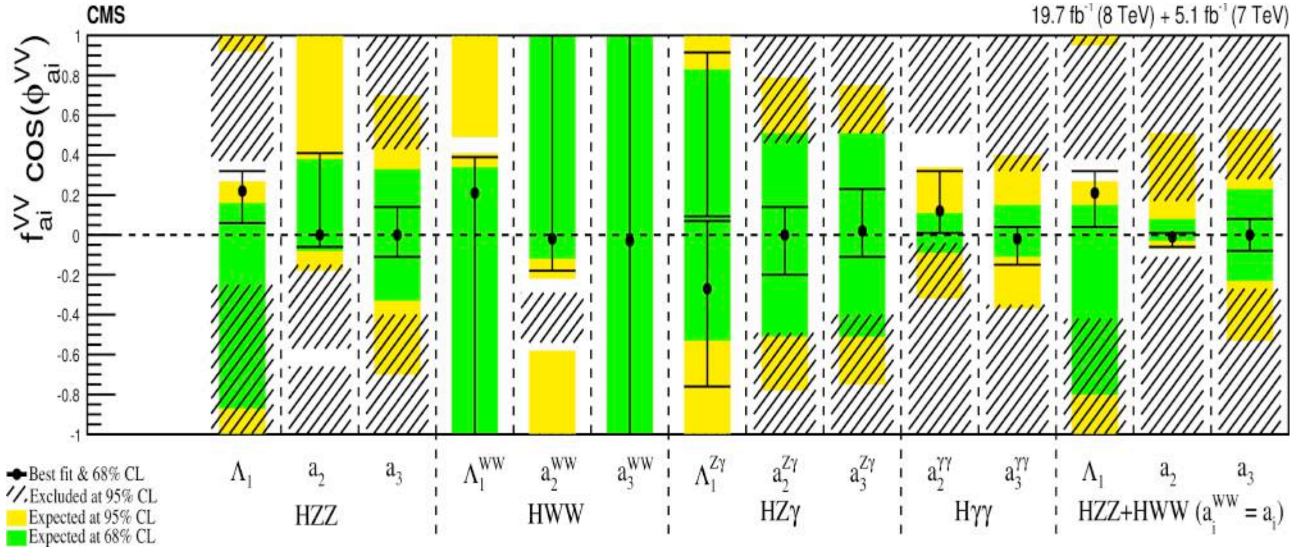
$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

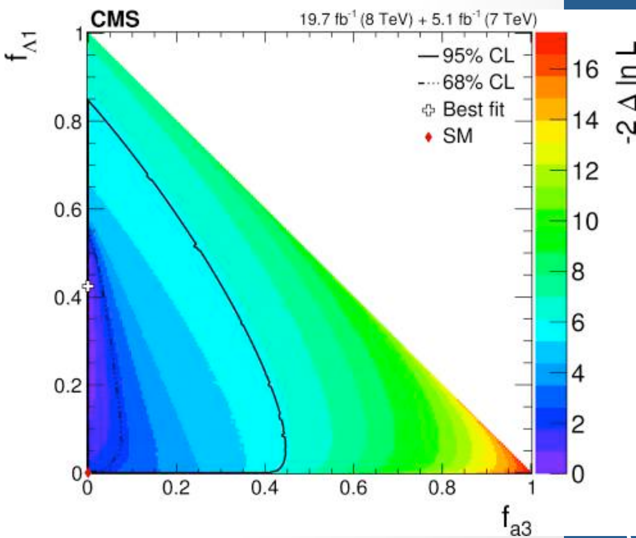
- Constrain fractional ZZ cross-sections, eg.:

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

- Pure pseudo-scalar Higgs (f_{a3}=1) excluded at 99.98% CL
- Pseudo-scalar fraction constrained: f_{a3}<0.43 (0.4) for + (-) phase







Gabriella.Pasztor@cern.ch

Beyond the SM Higgs

Standard Model
1 complex scalar doublet
1 physical Higgs boson: H

New Higgs states?

2HDM
2 complex scalar doublets
5 physical Higgs bosons: h, H, A, H^+, H^-

MSSM (Type-II 2HDM)
2 complex scalar doublets
5 physical Higgs bosons: h, H, A, H^+, H^-

NMSSM (~~μ-problem of MSSM~~)
2 complex scalar doublets + 1 singlet
7 physical Higgs bosons:
h_1, h_2, h_3, a_1, a_2, h^+, h^-

Additional SM-like Higgs
(→ high-mass searches)

New decay modes?

Fermiophobic Higgs

Invisible Higgs
e.g. decaying to neutral LSP

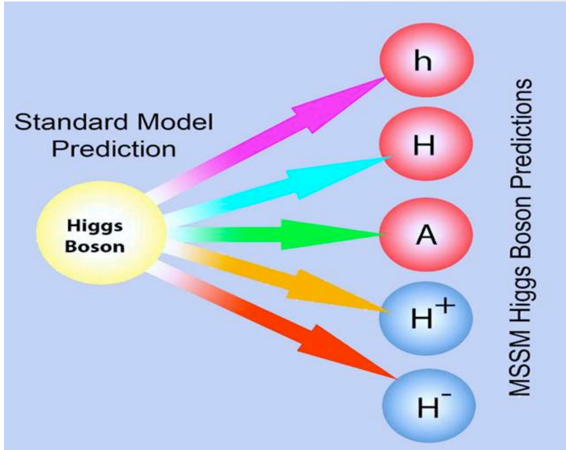
„Exotic" Higgs
e.g. decaying to lepton-jets in hidden-valley SUSY

New production modes?

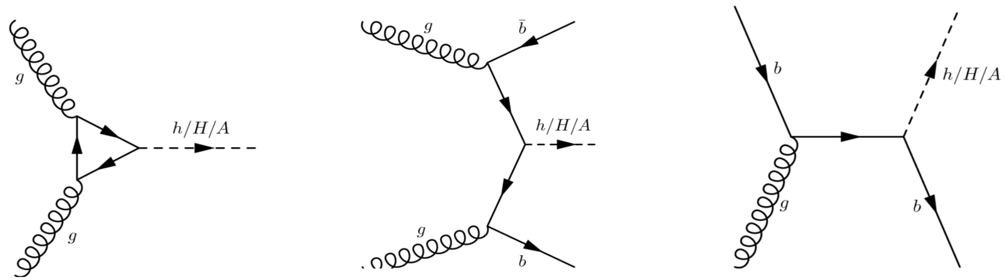
Higgs from BSM particle decays
e.g. Higgs from SUSY particle cascades

Gabriella.Pasztor@cern.ch

MSSM Higgs sector



- 2 complex scalar doublets → 5 physical Higgs bosons
- Tree-level parameters: m_A, tanβ
- Many more parameters after radiative corrections
  → **Benchmark scenarios**
- In the decoupling limit, h becomes SM-like at large m_A (>>m_Z) and the heavy partners mass-degenerate
  → Direct search for additional Higgs states important!
- Coupling to down-type fermions enhanced wrt SM especially at high tanβ
- Associated bbϕ production plays an important role



- Strongly enhanced cross-section at high tanβ
- Decays ϕ→bb, $\tau\tau$ are important also at high mass
- ϕ→bb very challenging (huge background)
- ϕ→μμ very low BR but excellent resolution (could separate H /A when degenerate)

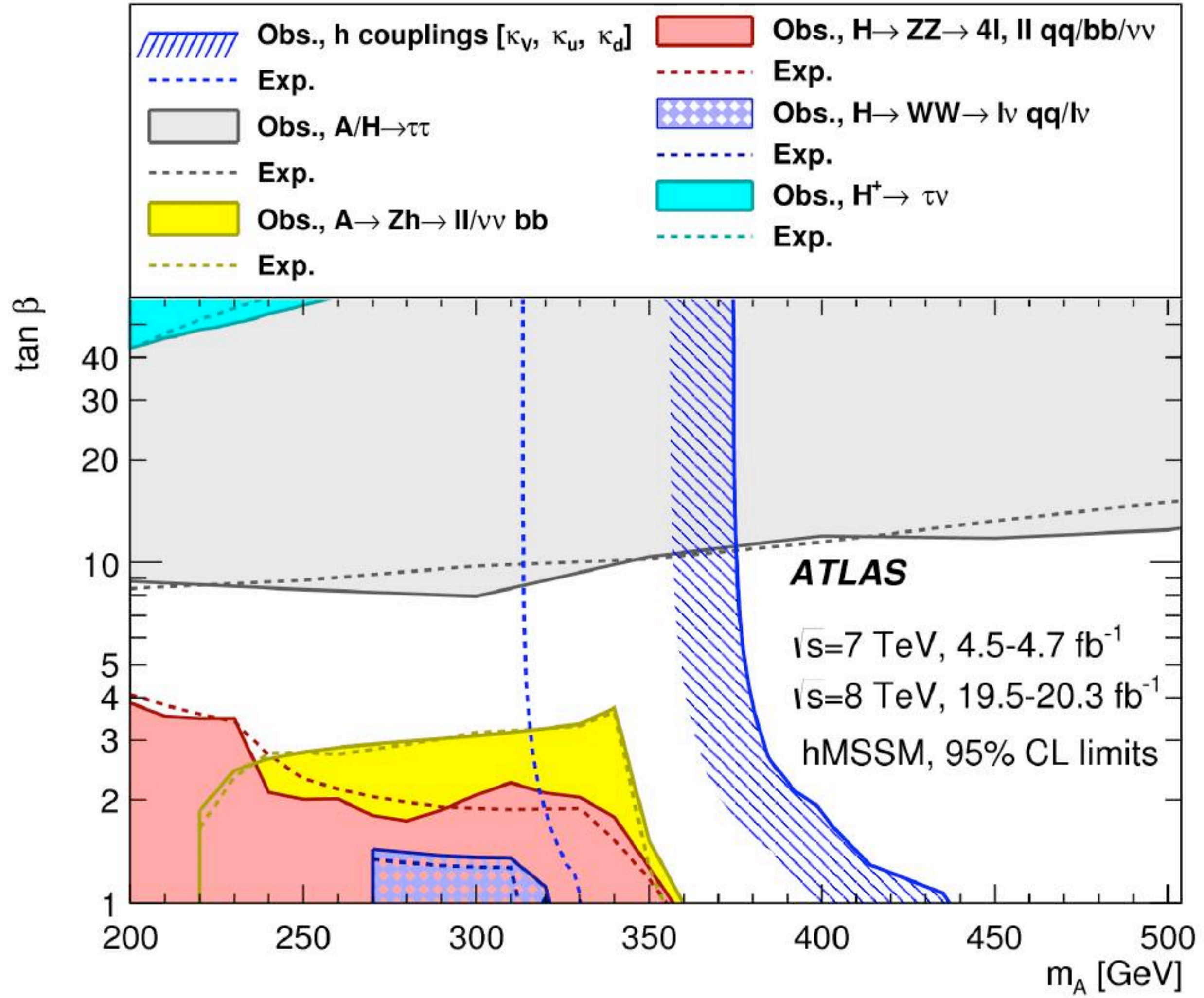
SM measurements can be reinterpreted in MSSM or other SM extensions
→ ATLAS-CONF-2014-010
→ ATL-PHYS-PUB-2014-017

Need to ensure models are compatible with observed Higgs

Gabriella.Pasztor@cern.ch

Direct and indirect limits on hMSSM

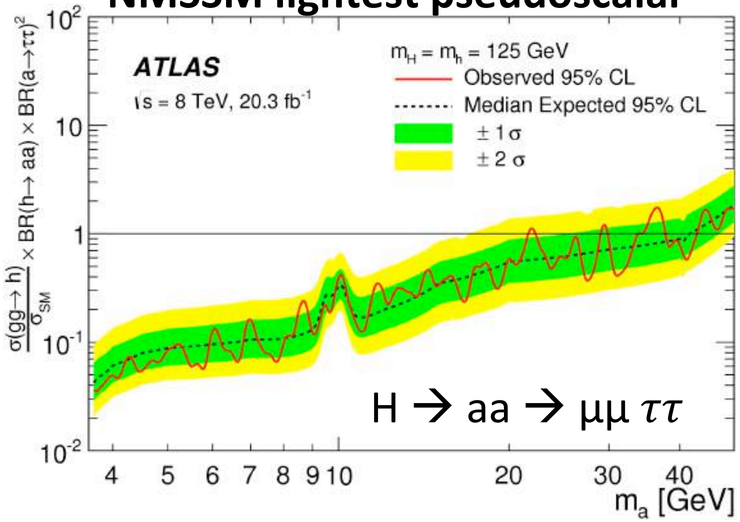
arXiv:1509.00672



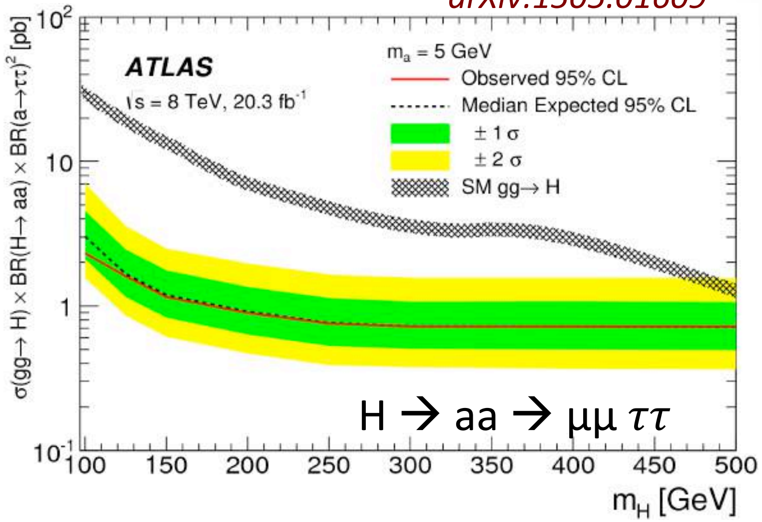
Gabriella.Pasztor@cern.ch

Searches for non-standard Higgs

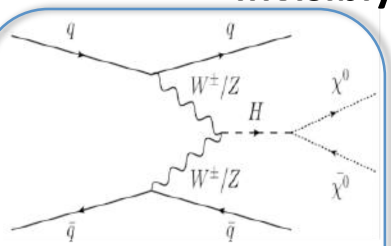
NMSSM lightest pseudoscalar



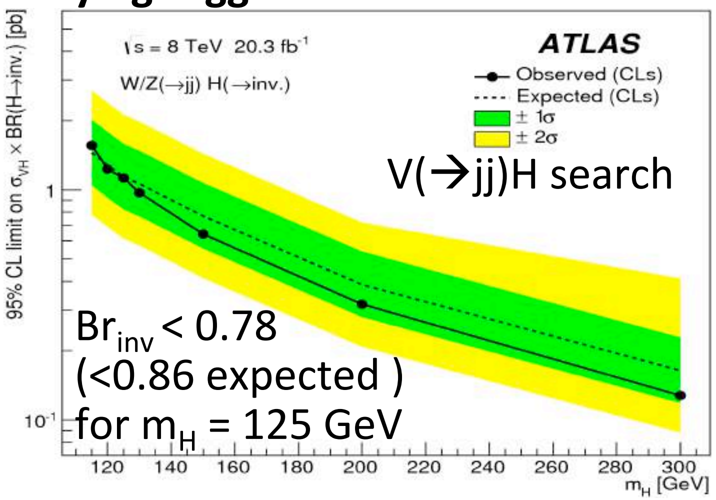
arXiv:1505.01609



Invisibly decaying Higgs

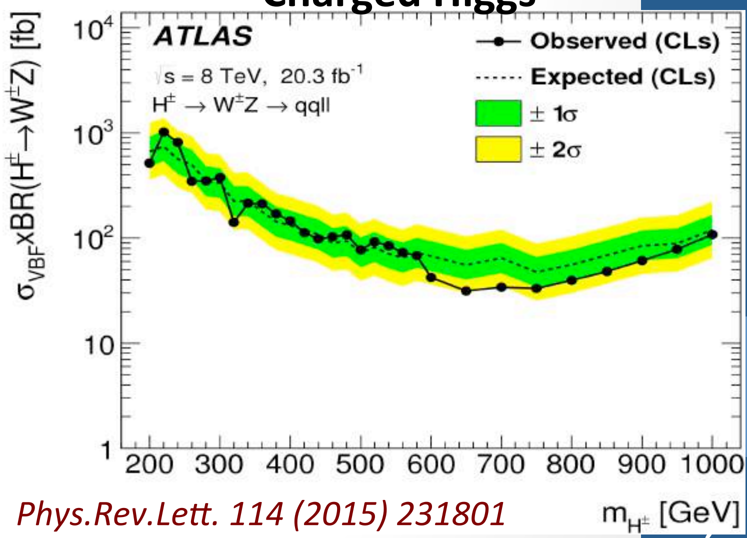


From VBF search:
$Br_{inv} < 0.29$
(<0.36 expected)
for m_H = 125 GeV



$Br_{inv} < 0.78$
(<0.86 expected)
for m_H = 125 GeV

Charged Higgs

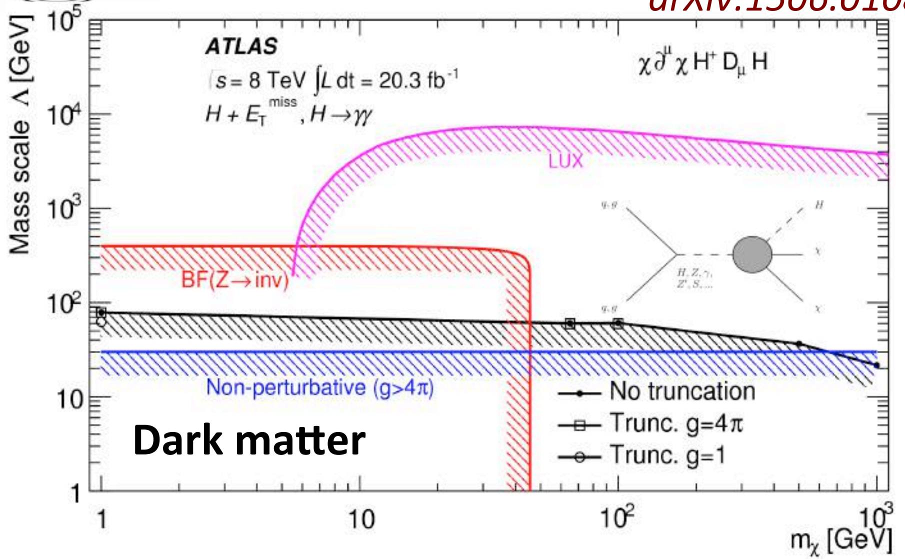


ATLAS-CONF-2015-004 *arXiv:1504.04324* *Phys.Rev.Lett. 114 (2015) 231801*

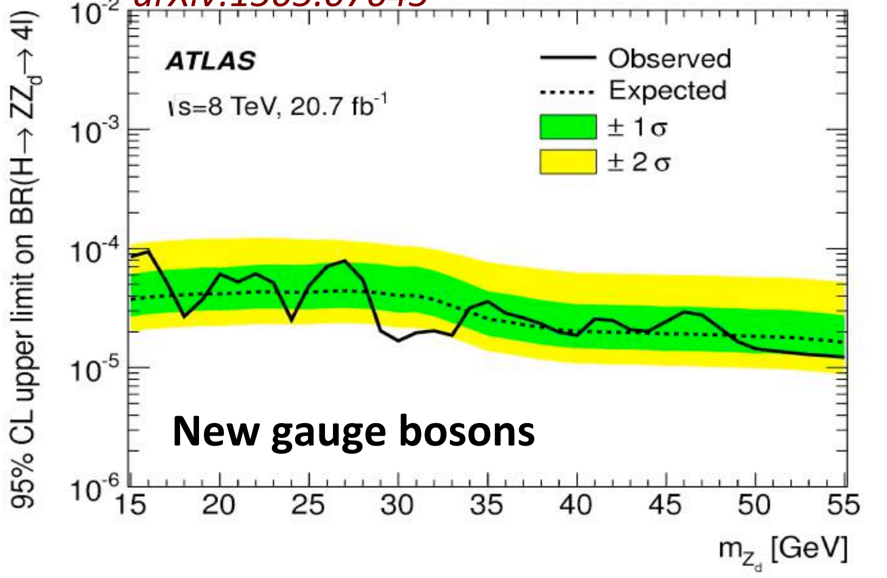
Gabriella.Pasztor@cern.ch

Searches for new physics with Higgs

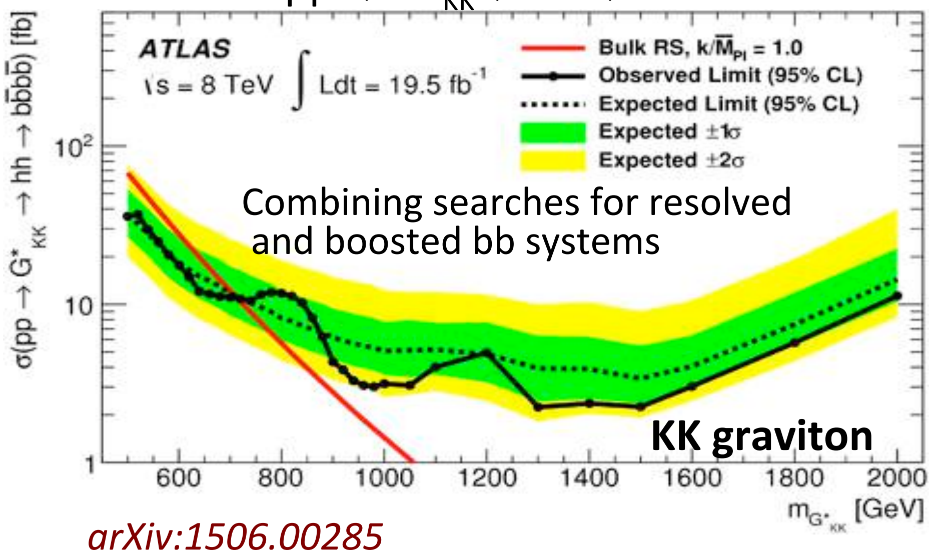
arXiv:1506.01081



arXiv:1505.07645



$pp \to G^*_{KK} \to hh \to bbbb$



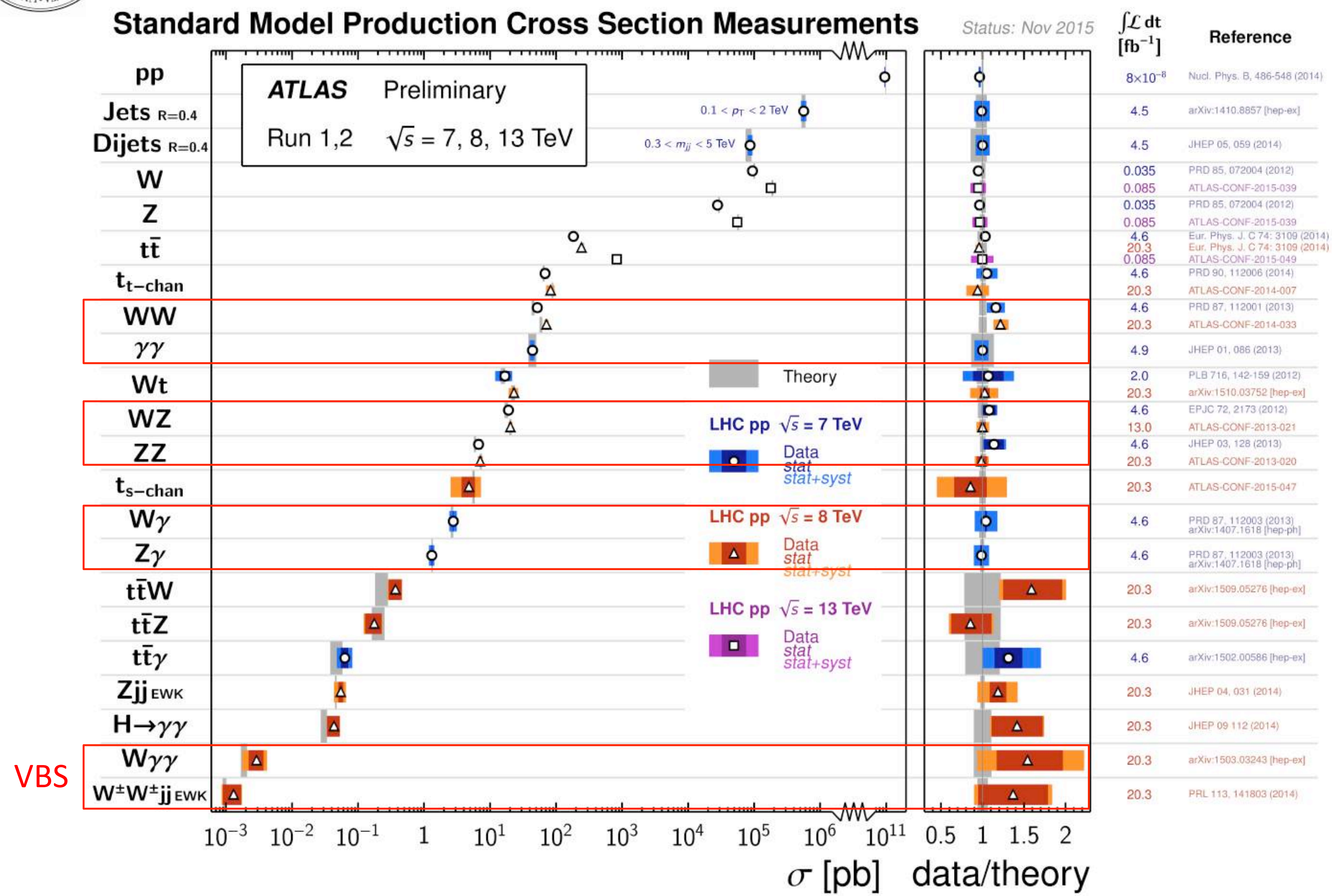
arXiv:1506.00285

Exotics Higgs production and decay: no significant access (yet?)

Window to new physics?

Gabriella.Pasztor@cern.ch

Multi-boson production



Gabriella.Pasztor@cern.ch

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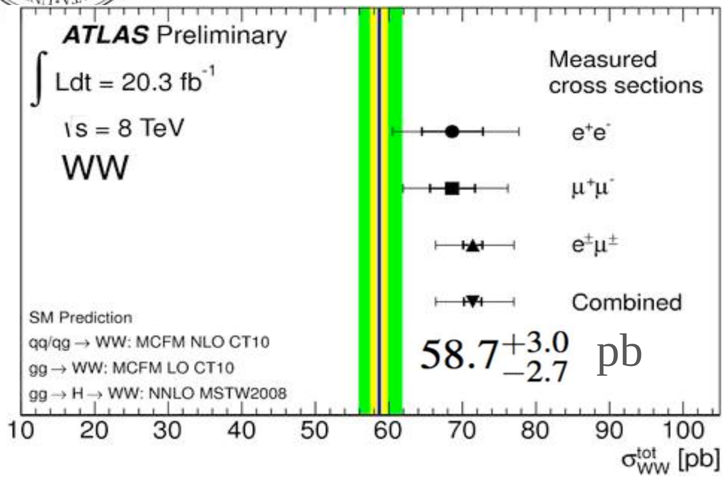
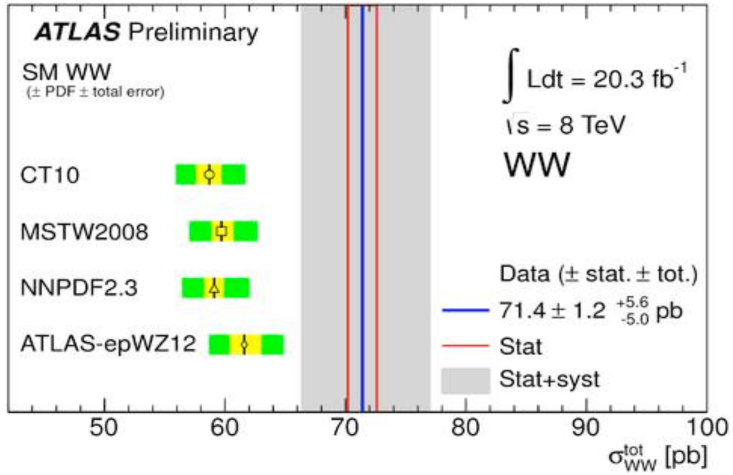
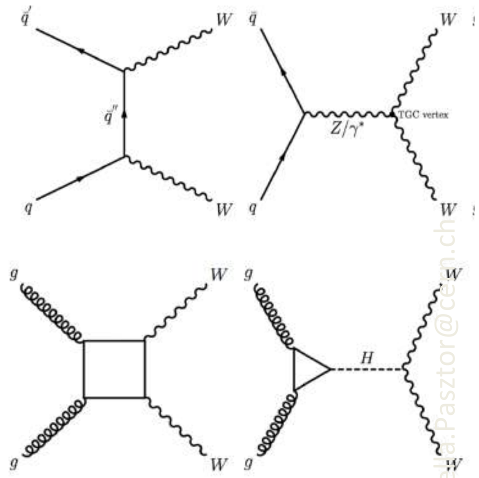
WW cross-section

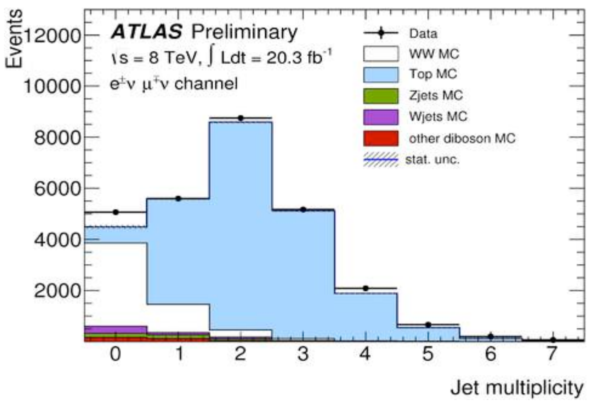
ATLAS-CONF-2014-033

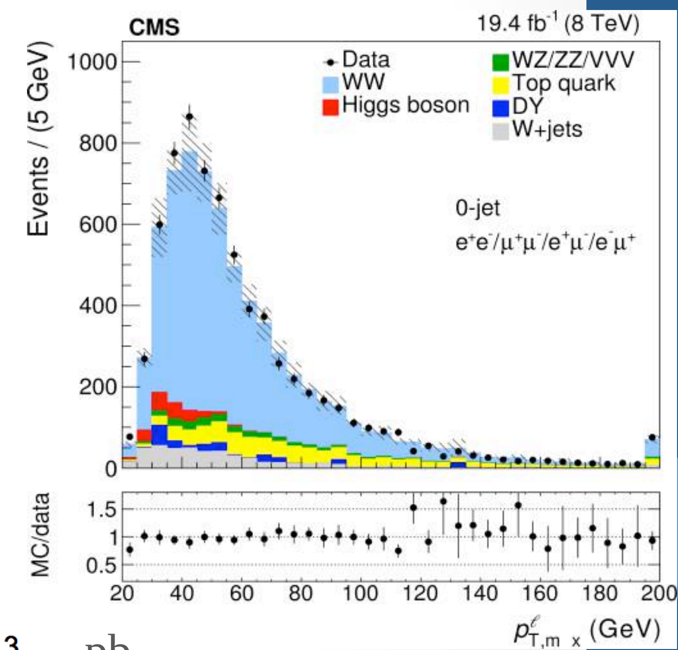






- 2.1σ excess: $\sigma_{WW}^{tot} = 71.4\ ^{+1.2}_{-1.2}(\text{stat})\ ^{+5.0}_{-4.4}(\text{syst})\ ^{+2.2}_{-2.1}(\text{lumi})$ pb,
- First (on-shell only) NNLO predicts 10% cross-section increase (PRL 113 (2014) 212001), larger than NLO scale uncertainty
- NLO EW corrections can be as large as 15% at high p_T
- Jet veto (to supress tt background) subject to large QCD uncertainty
- Recent 8 TeV CMS result agrees with NNLO prediction





60.1 ± 0.9 (stat) ± 3.2 (exp) ± 3.1(th) ± 1.6 (lumi) pb vs. $59.8^{+1.3}_{-1.1}$ pb

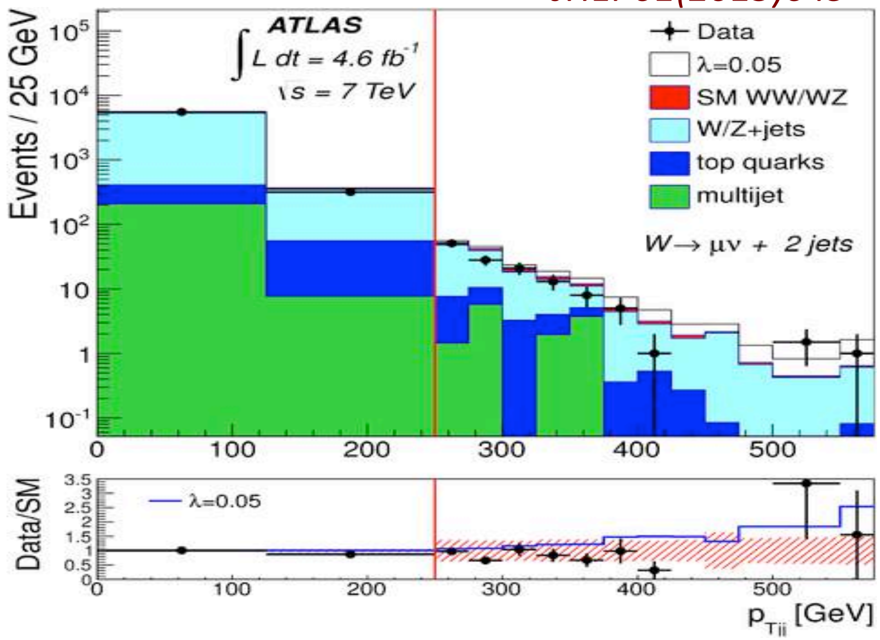
arXiv:1507.03268

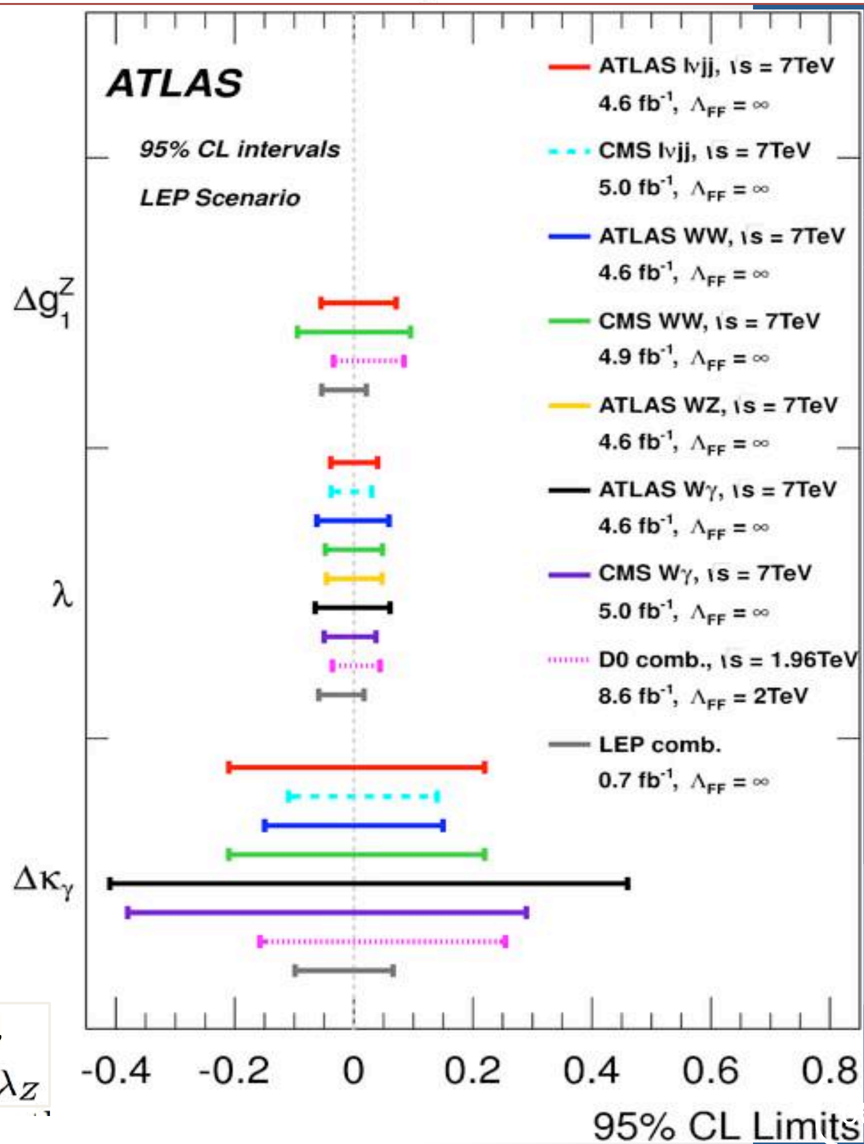
WW+WZ production

$$\mathcal{L} = ig_{WWV}\Big(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho$$
$$+ig_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) - ig_5^V \epsilon^{\mu\nu\rho\sigma}(W^+_\mu \partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma$$
$$+\tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2} W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho\Big),$$

- 2 jets+ e/μ final state: 3.4σ significance
- Observed cross-section:
  $68 \pm 7\ (\text{stat.}) \pm 19\ (\text{syst.})$ pb
  with 61.1 ± 2.2 pb expected (MC@NLO)
- Dijet transverse momentum sensitive to new physics

JHEP01(2015)049



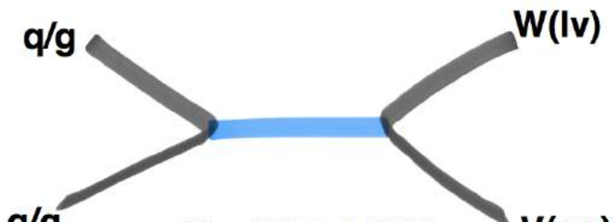


- Setting limits on aTGCs and on coefficients of dim-6 operators in an EFT

$$\Delta g_1^Z = g_1^Z - 1,\ \Delta\kappa_{\gamma,Z} = \kappa_{\gamma,Z} - 1,$$
$$\Delta g_1^Z = \Delta\kappa_Z + \tan^2\theta_W \Delta\kappa_\gamma,\ \lambda_\gamma = \lambda_Z$$

Search for heavy bosons in VV final states

arXiv:1409.6190

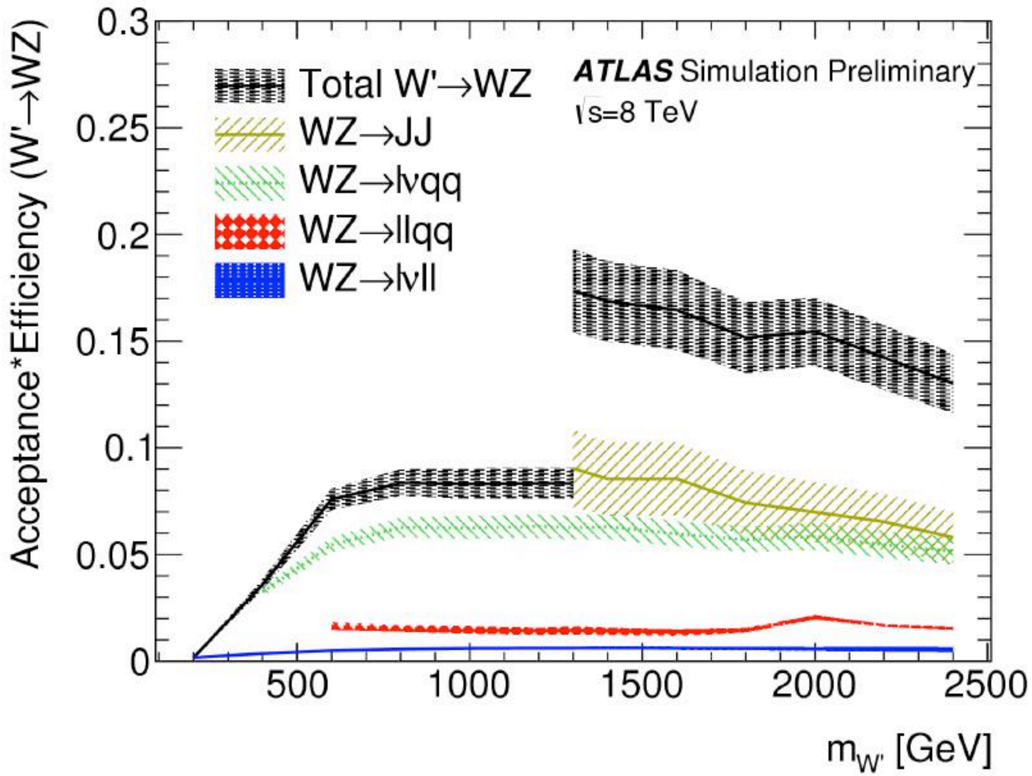


arXiv:1503.04677

arXiv:1506.00962

	W	Z
ll,lν	22%	7%
ττ, τν	11%	3%
νν		20%
qq	67%	70%

- Narrow resonance search
- Interpreted in different models
  - Extended gauge model with heavy W'
  - Randall-Sundrum model with heavy spin-2 graviton
- Fully hadronic analysis relies on jet substructure techniques



Gabriella.Pasztor@cern.ch

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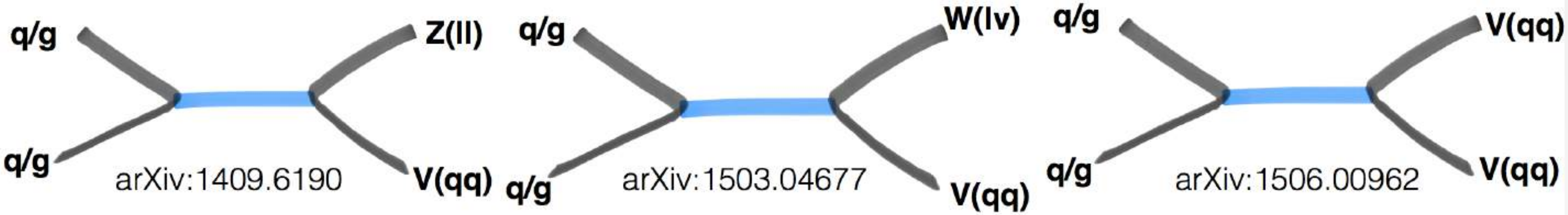
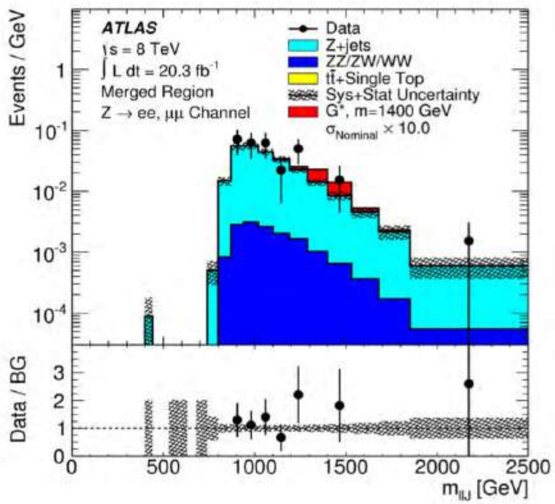
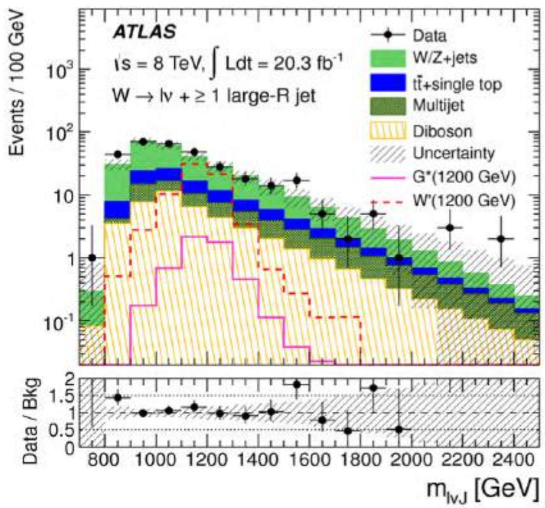
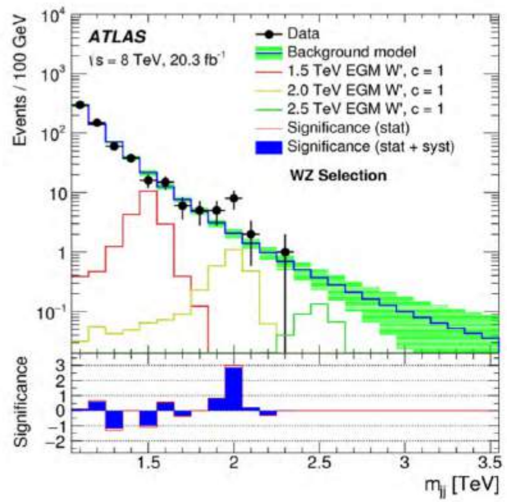
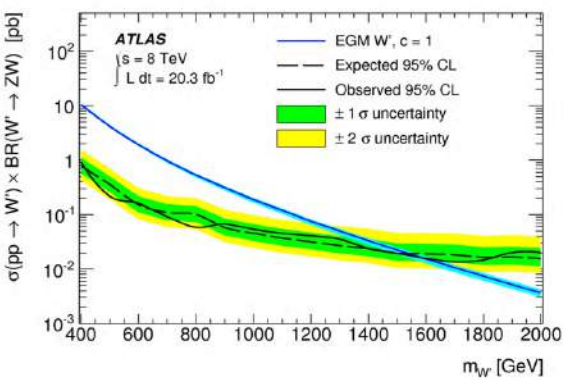
Search for heavy bosons in VV final states

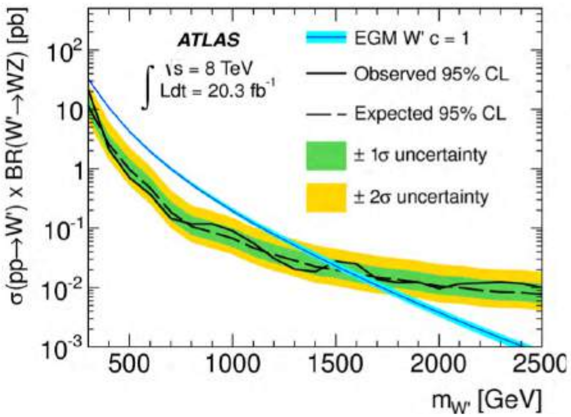


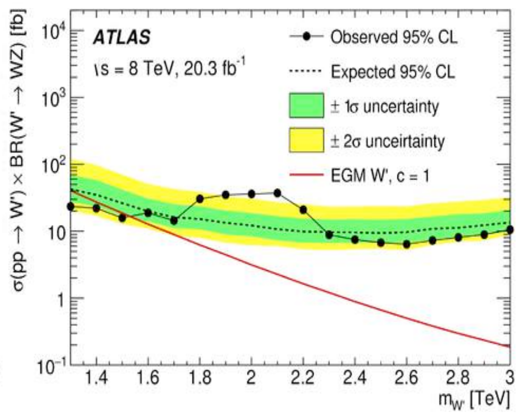








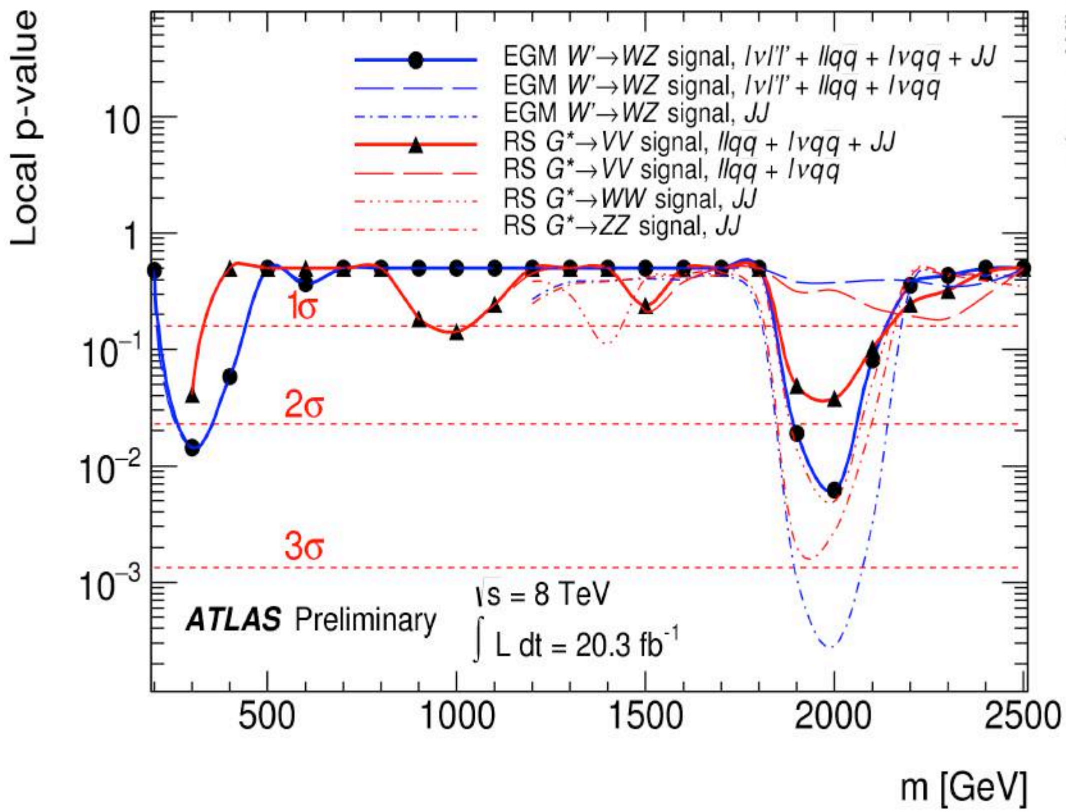


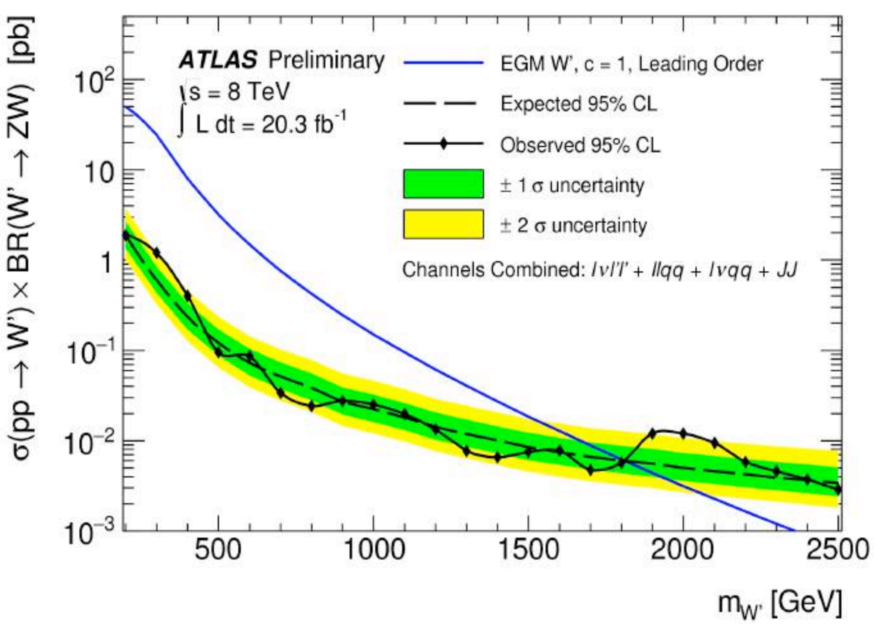


Gabriella.Pasztor@cern.ch

Search for heavy bosons in VV final states: combination

- ~3.5σ excess in W'→WZ→JJ final state not confirmed by other channels
- 2.5σ excess remains after combination
- <2σ for G*→ WW / ZZ





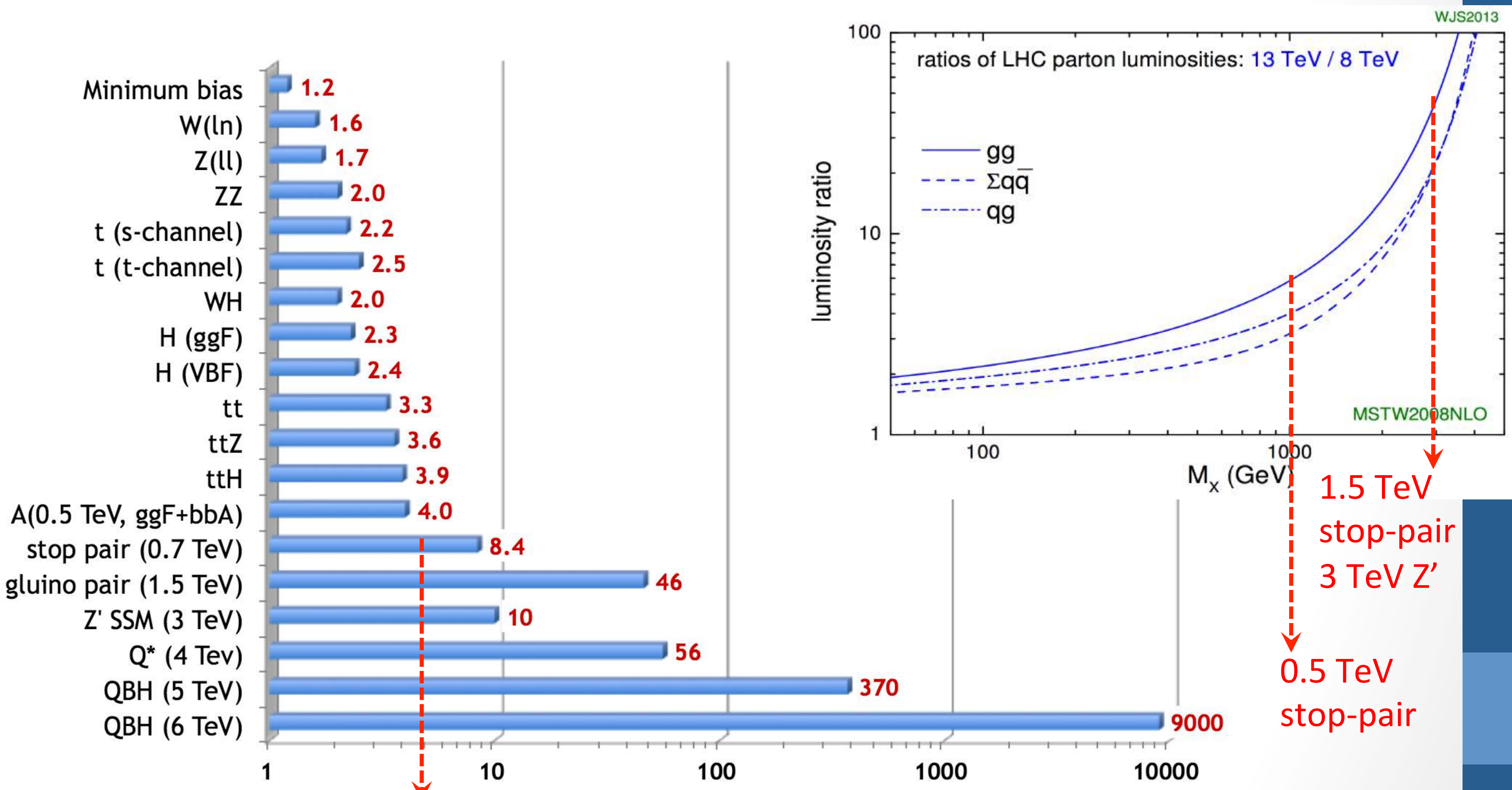
3-5 fb^{-1} @ 13 TeV surpasses Run1 sensitivity

4 fb^{-1} data of 2015 run on disk and being analysed

Gabriella.Pasztor@cern.ch

Run2 prospects

13 TeV / 8 TeV inclusive pp cross-section ratio



1.5 TeV
stop-pair
3 TeV Z'

0.5 TeV
stop-pair

~4-5 fb^{-1} equivalent to Run1 reach