Measurements of the Higgs boson mass and its spin and CP properties with the ATLAS Detector

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Presented on behalf of the ATLAS Collaboration

at the International Conference on

Weak Interactions and Neutrinos 2017 – UC Irvine

Slides prepared by Stephen Sekula

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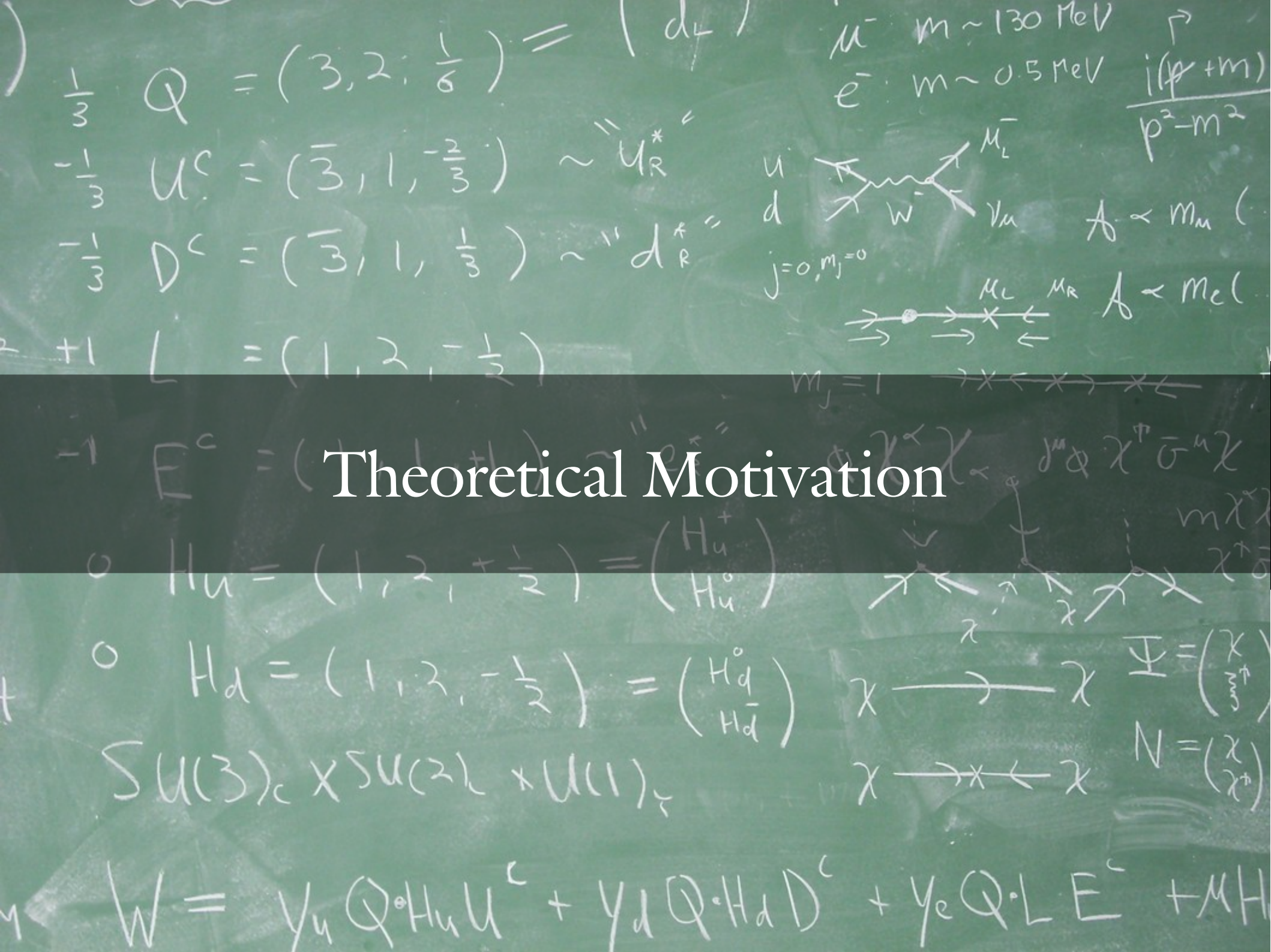
ATLAS EXPERIMENT

CERN

Programme

- Theoretical Motivation
- Higgs Mass
- Higgs Spin and Parity
- Conclusions and Outlook

Theoretical Motivation

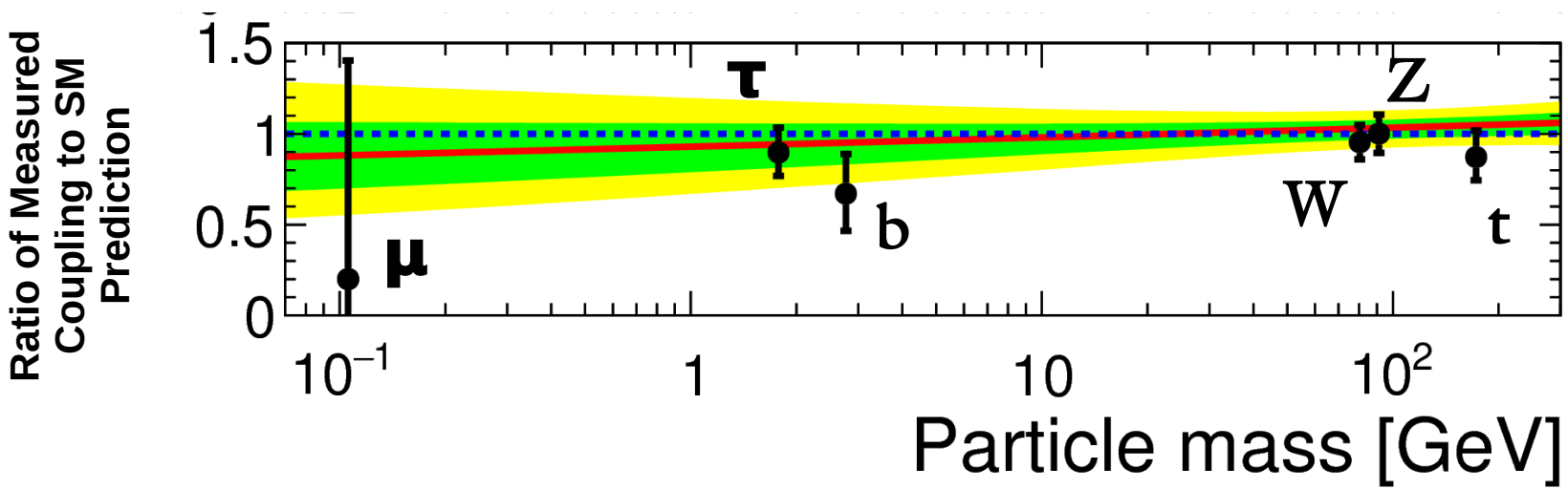


The Standard Model and the Higgs Boson

Once the mass of the Higgs boson is established, the Standard Model (SM) is *highly predictive* of other properties of the Higgs boson.

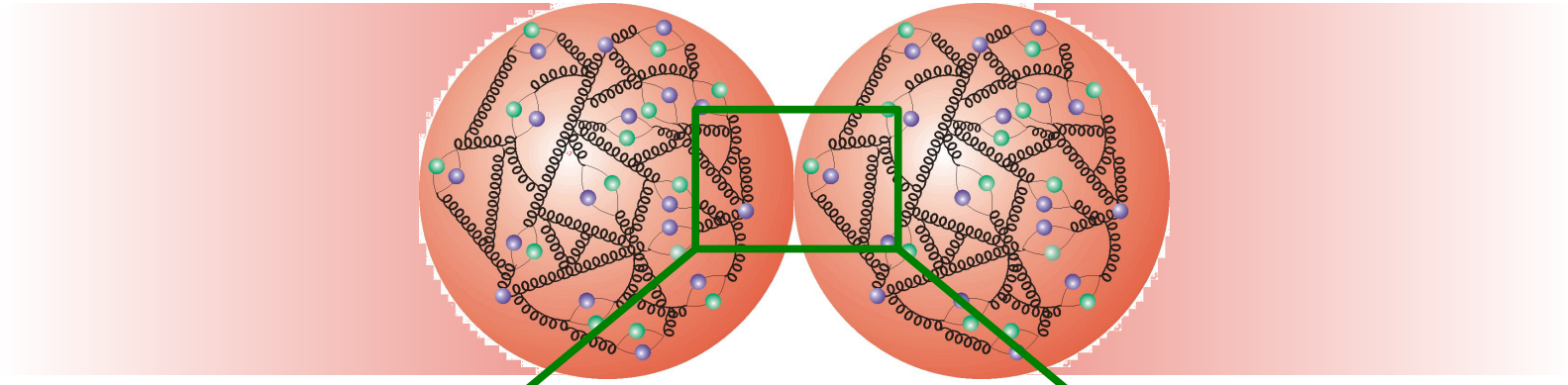
$$\Gamma_{\rm NLO}(H \to q\bar{q}) \simeq \frac{3G_\mu}{4\sqrt{2}\pi} M_H m_q^2 \left[1 + \frac{4}{3}\frac{\alpha_s}{\pi}\left(\frac{9}{4} + \frac{3}{2}\log\frac{m_q^2}{M_H^2}\right)\right]$$

Given the history of **parameter measurement within the SM** context, once you actually **find the Higgs boson** its couplings to other particles snap into view.

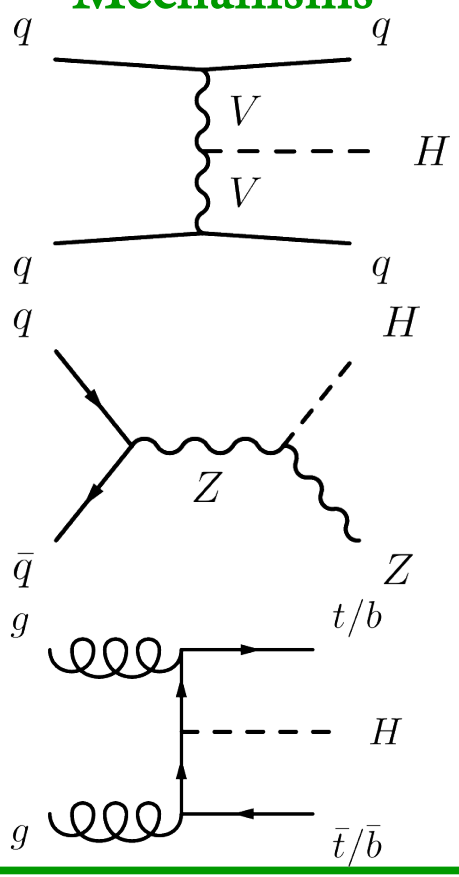


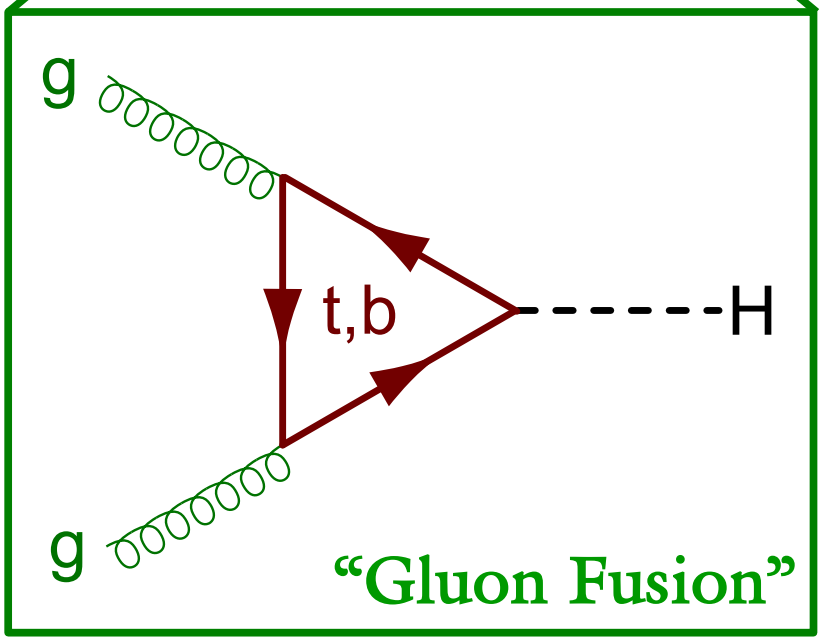
JHEP 08 (2016) 045

Higgs Production and Decay at LHC



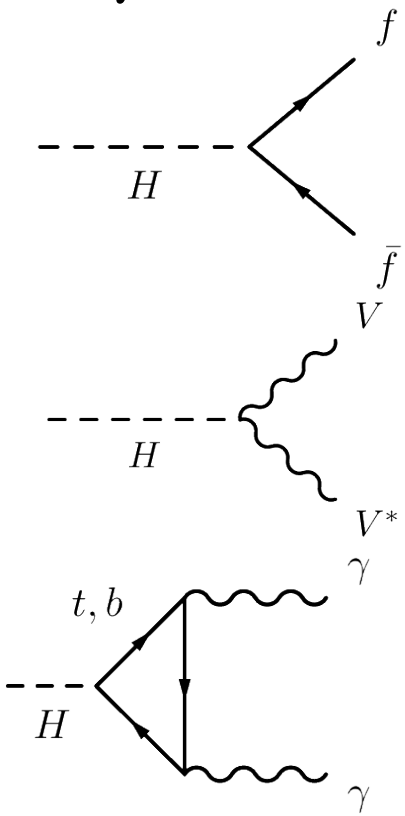
Other Production Mechanisms



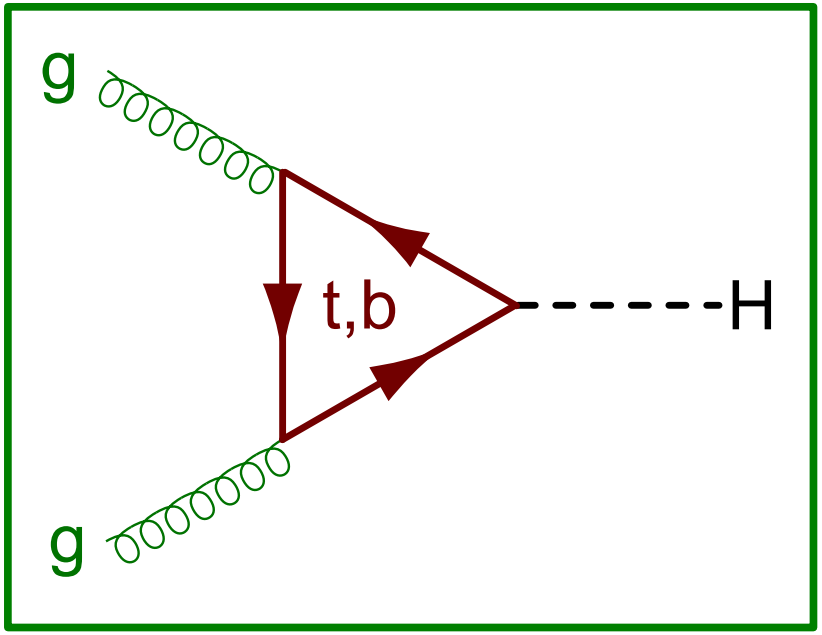


Goal: probe production and decay across many channels

Decay Mechanisms



Probing New Physics Contributions



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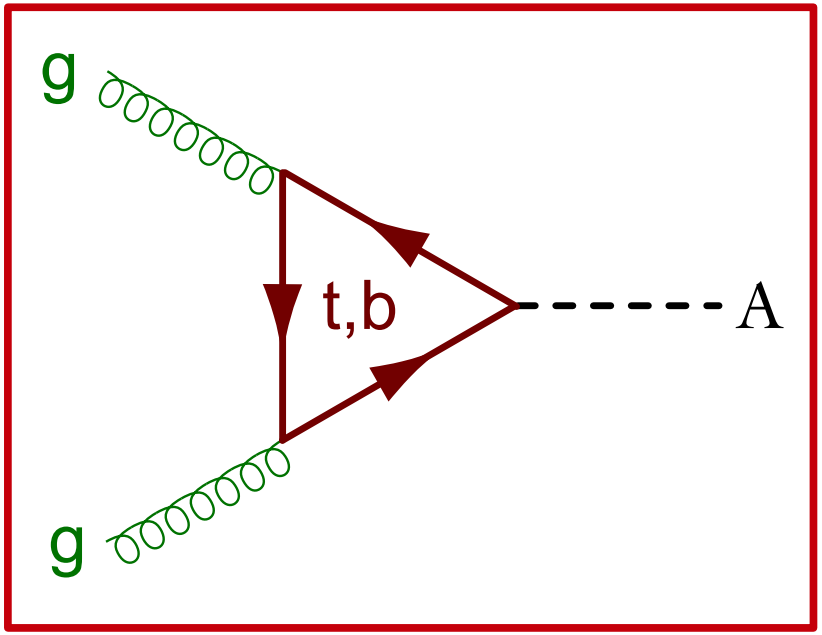


Spin-0 model: a CP-odd scalar mixes with a CP-even scalar. The mixing angle is α and the anomalous couplings to vector bosons are written κ_{HVV} and κ_{AVV}.

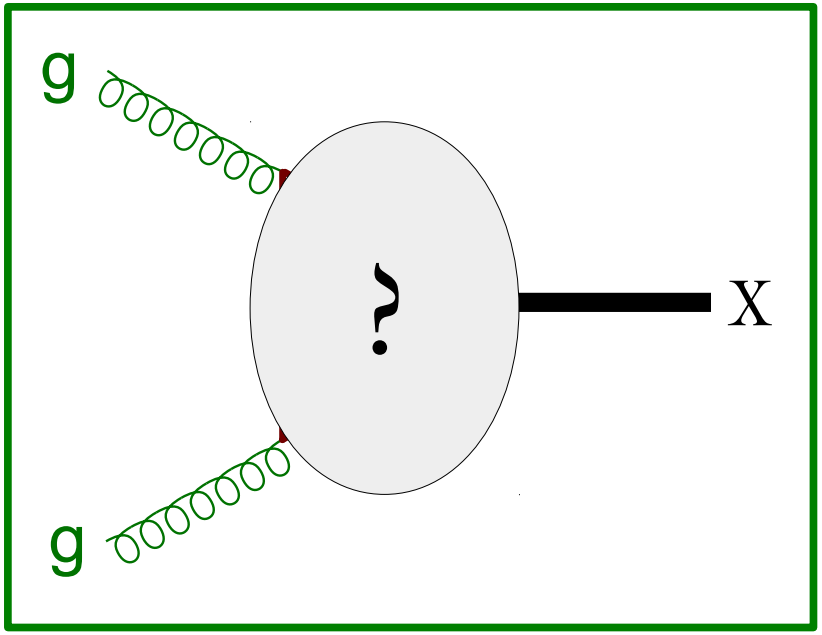
$$\mathcal{L}_0^V = \Big\{\cos(\alpha)\kappa_{SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right] - \tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] - \tfrac{1}{2}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu}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

If the SM is correct, we observe that:
$\kappa_{HVV} = \kappa_{AVV} = 0$ and $\alpha = 0$.

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

JHEP 1311 (2013) 043

Probing New Physics Contributions



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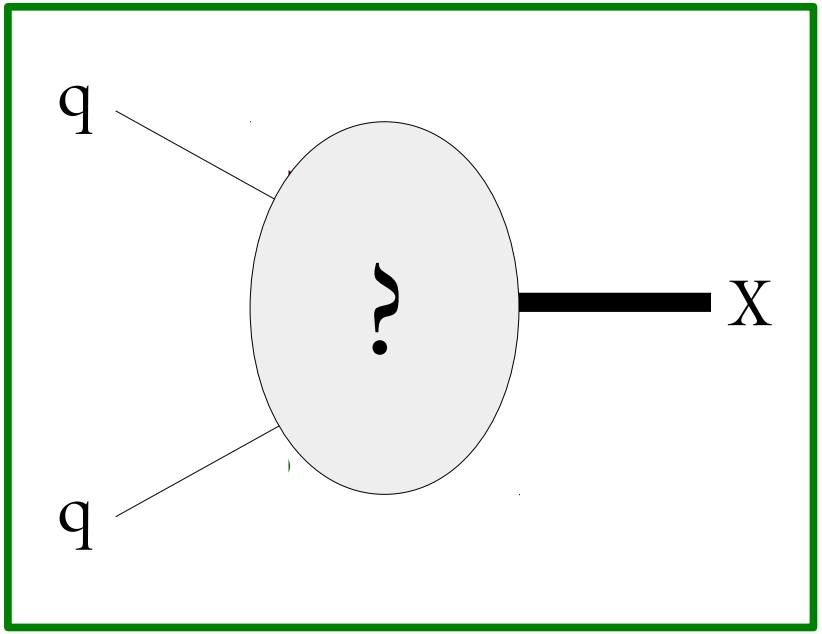

Spin-2 model: select a spin-2 model with graviton-like couplings. One then has to try different parameter spaces for quark and gluon couplings and assess their compatibility with data.

$$\mathcal{L}_2 = -\frac{1}{\Lambda}\left[\sum_V \kappa_V \mathcal{T}^V_{\mu\nu} X^{\mu\nu} + \sum_f \kappa_f \mathcal{T}^f_{\mu\nu} X^{\mu\nu}\right]$$

This model allows us to probe tensor couplings, which are expected to be zero in the SM.

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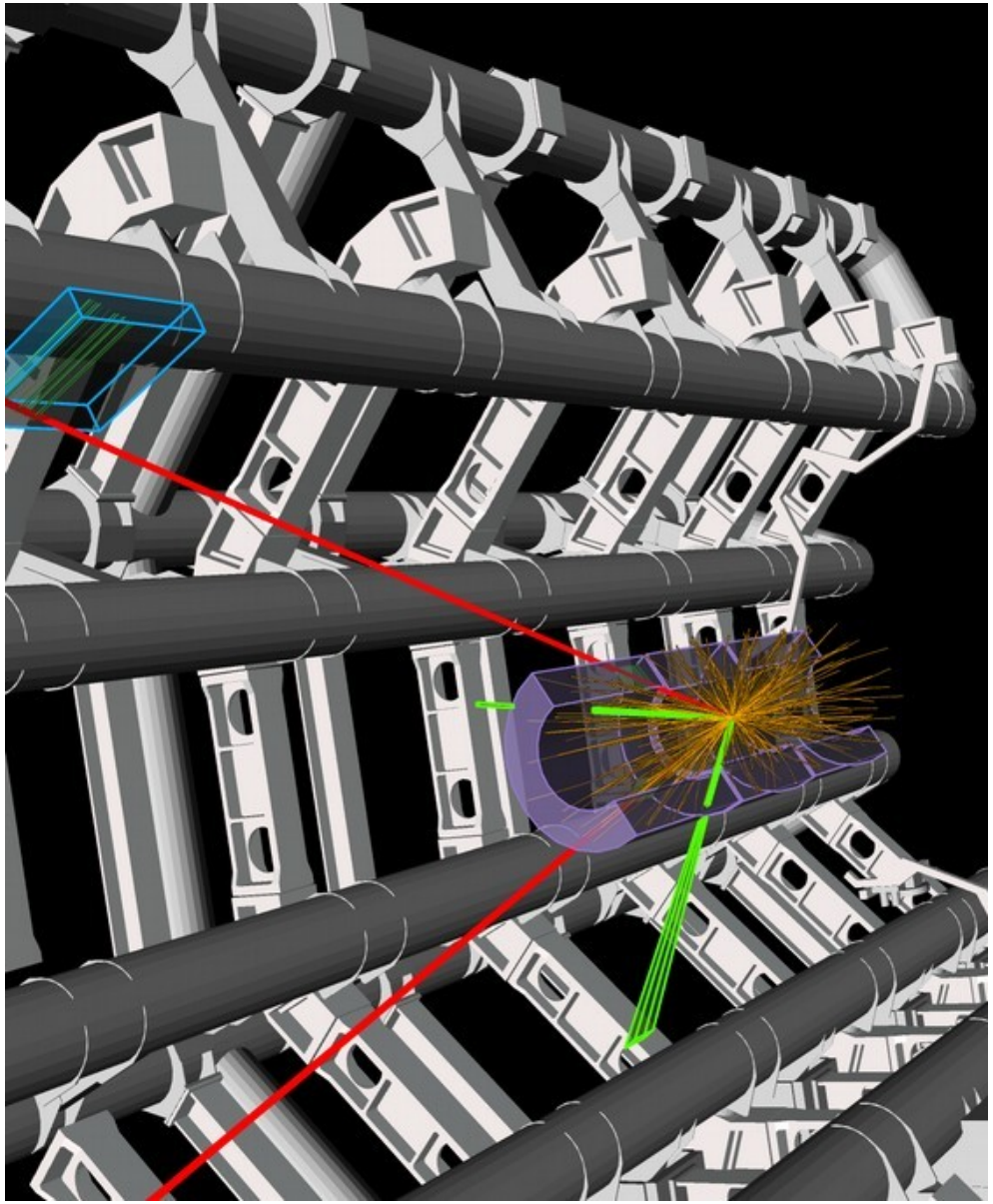
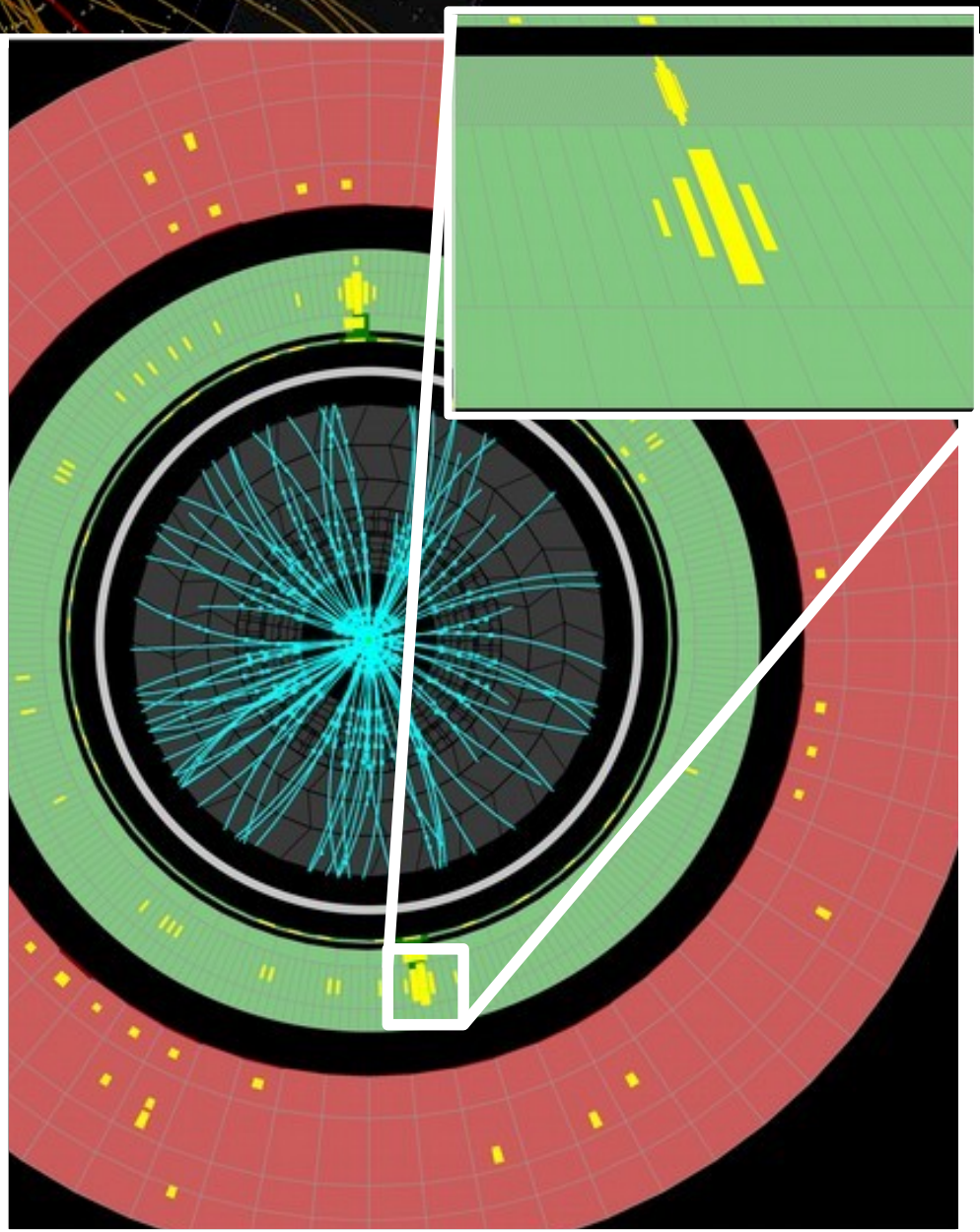
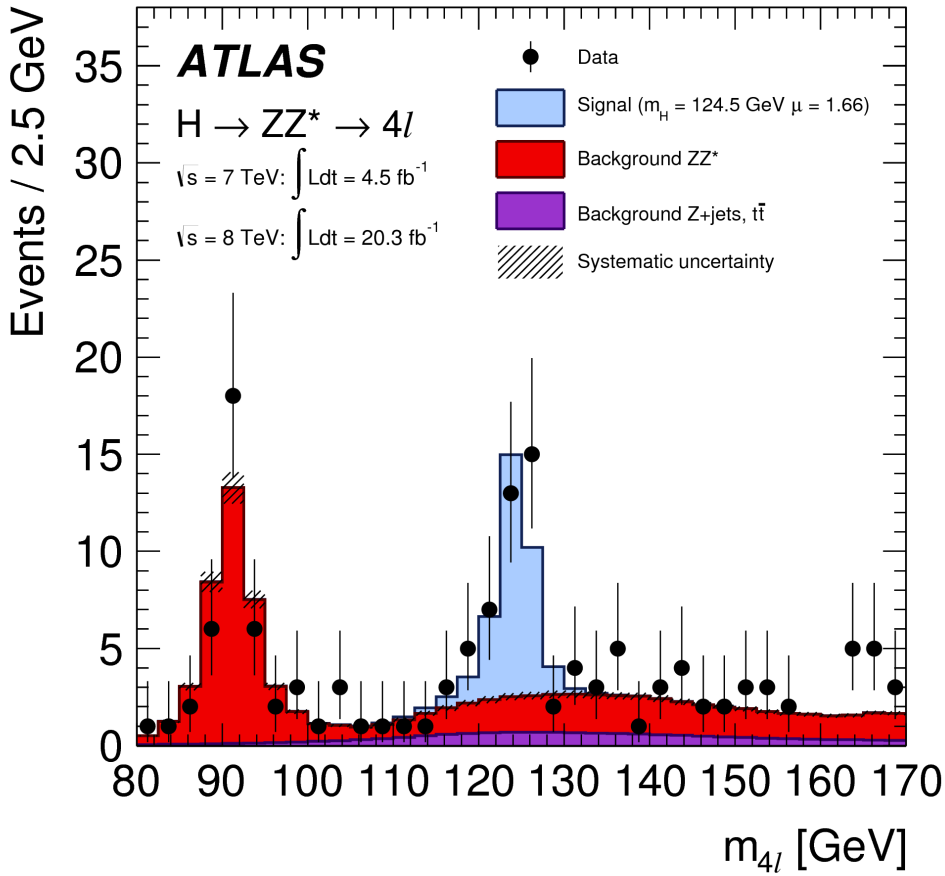
Higgs Mass

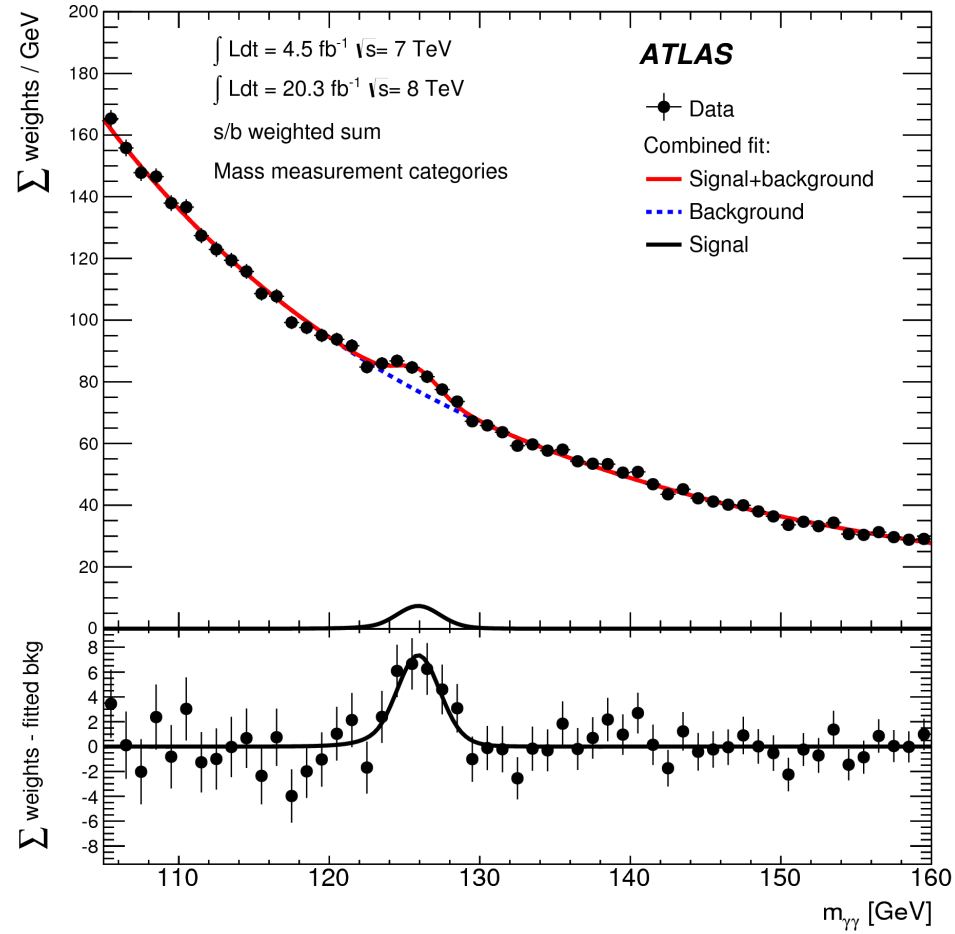
Well-Resolved Higgs Decays: ZZ* and γγ





Invariant Mass Distributions

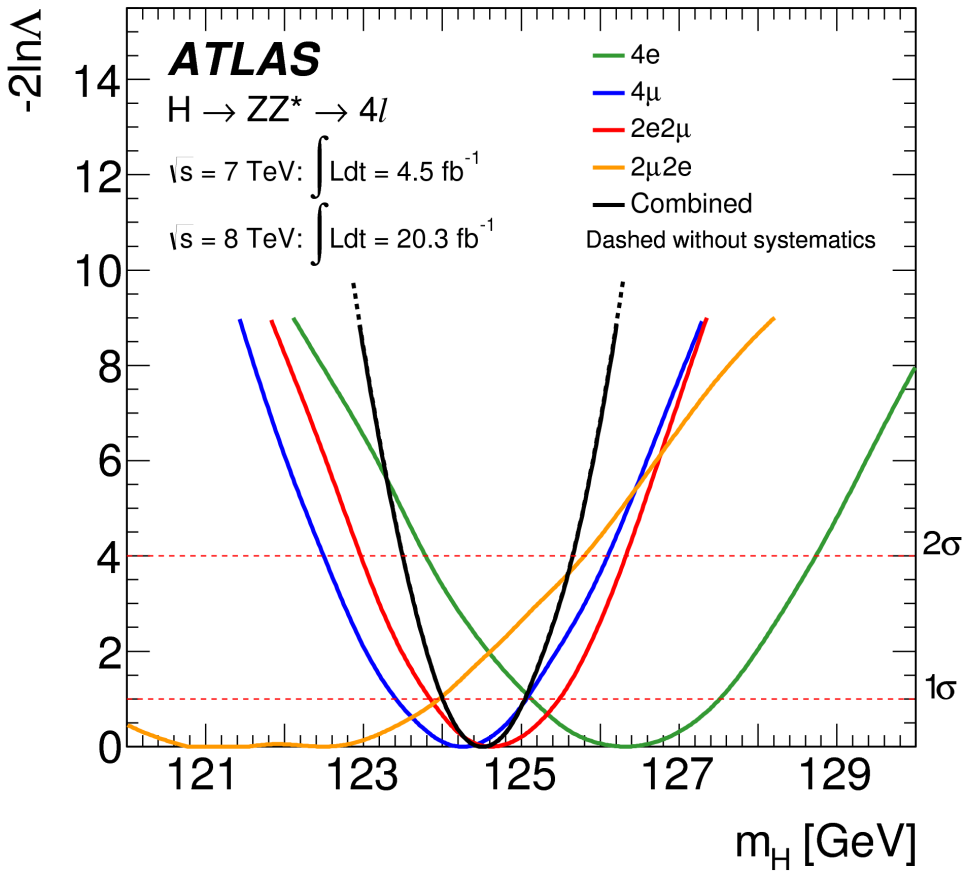




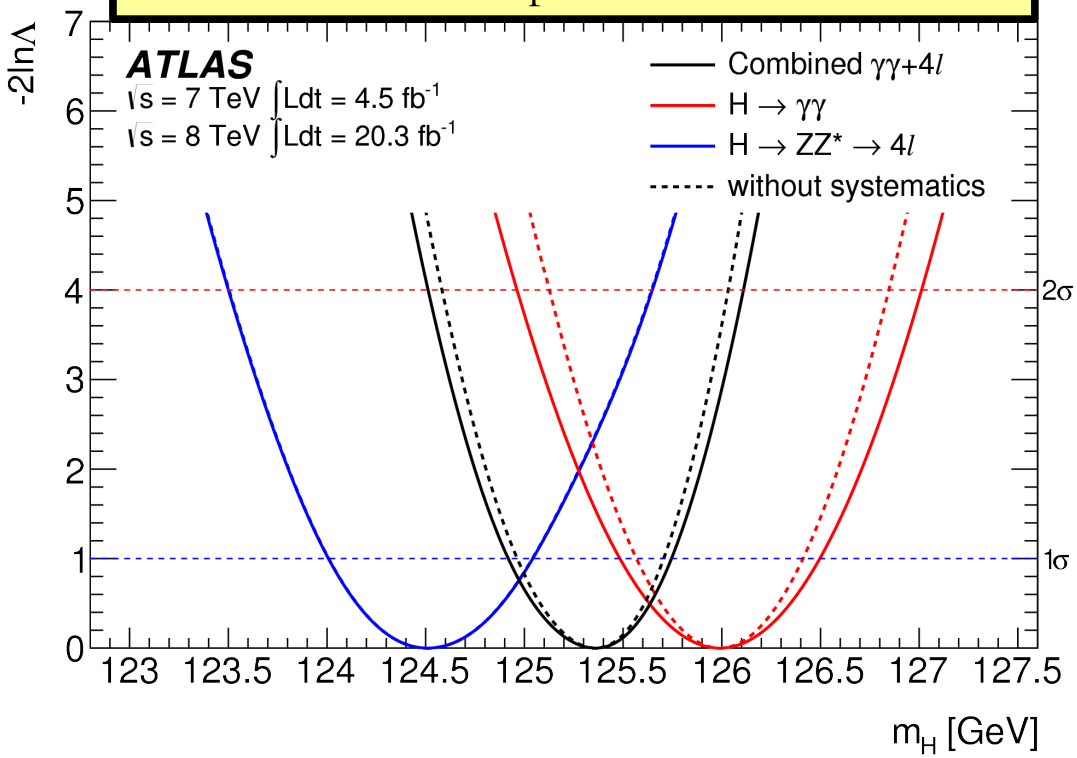
Detector resolution dominates the measurements – the natural width is expected to be almost 500x smaller than the widths seen here.

Phys. Rev. D 90, 052004

Mass Measurement – channel-by-channel



Masses compatible at 1.98σ



Channel	Mass measurement [GeV]
$H \to \gamma\gamma$	$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{syst}) = 125.98 \pm 0.50$
$H \to ZZ\text{llll}$	$124.51 \pm 0.52\,(\text{stat}) \pm 0.06\,(\text{syst}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst}) = 125.36 \pm 0.41$

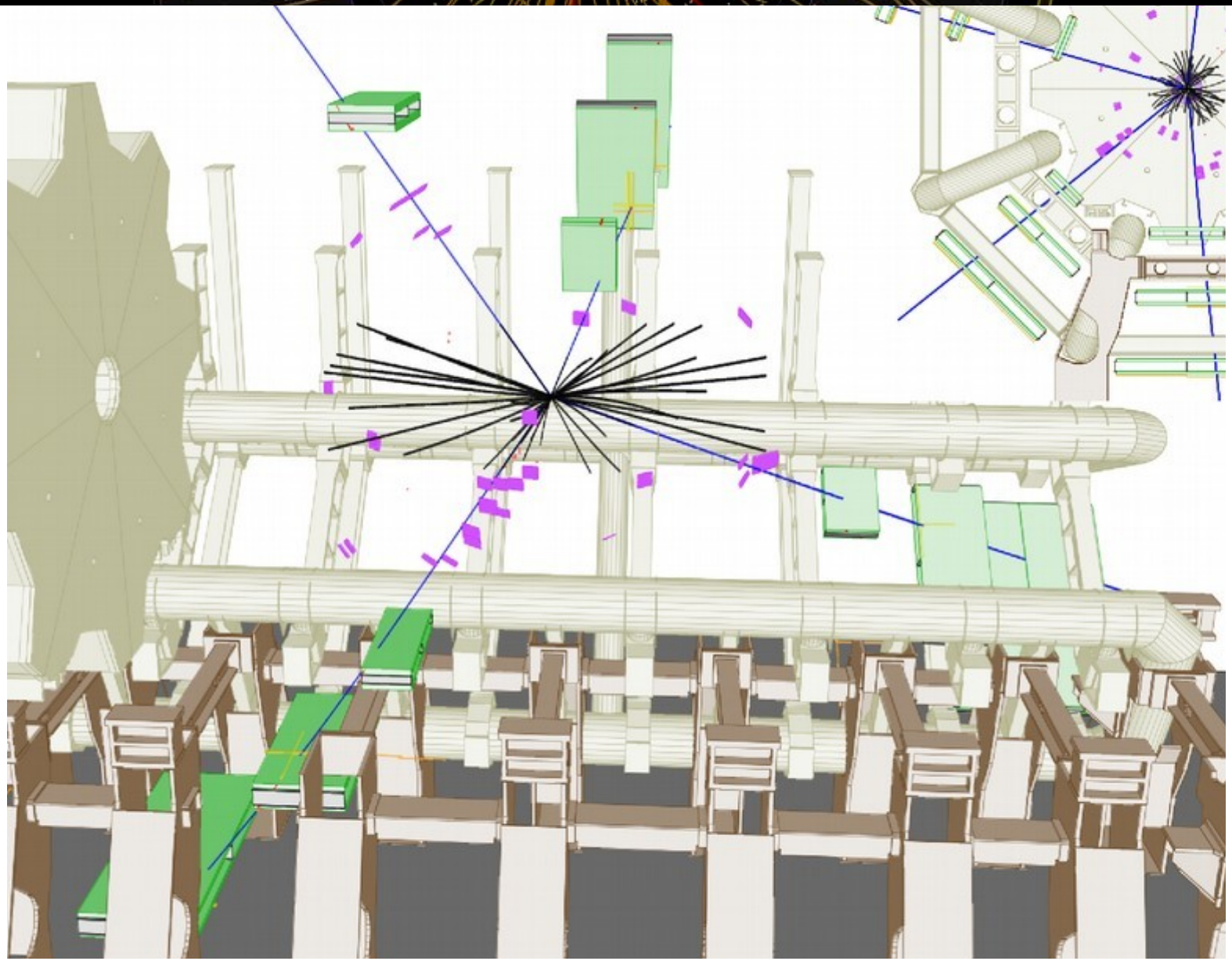
Dominant Systematic Errors:

- ZZ → 4l: Z → ee calibration
- γγ: EM Calorimeter shower modeling (material modeling, energy response, shower shape, calibration)

Phys. Rev. D 90, 052004

Higgs Spin and Parity

Angular Momentum Analysis Example: $H \rightarrow ZZ^*$ decays



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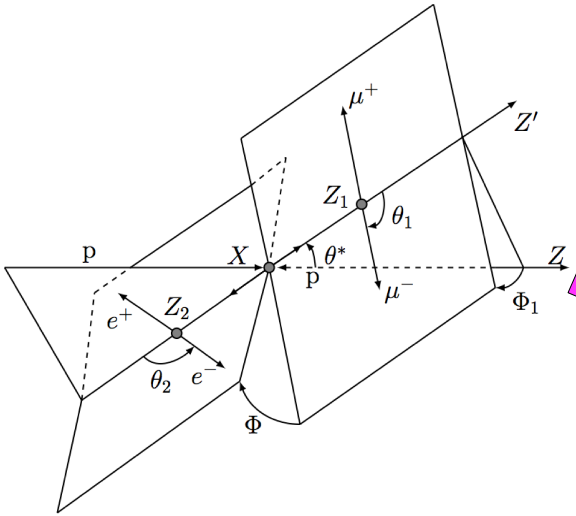

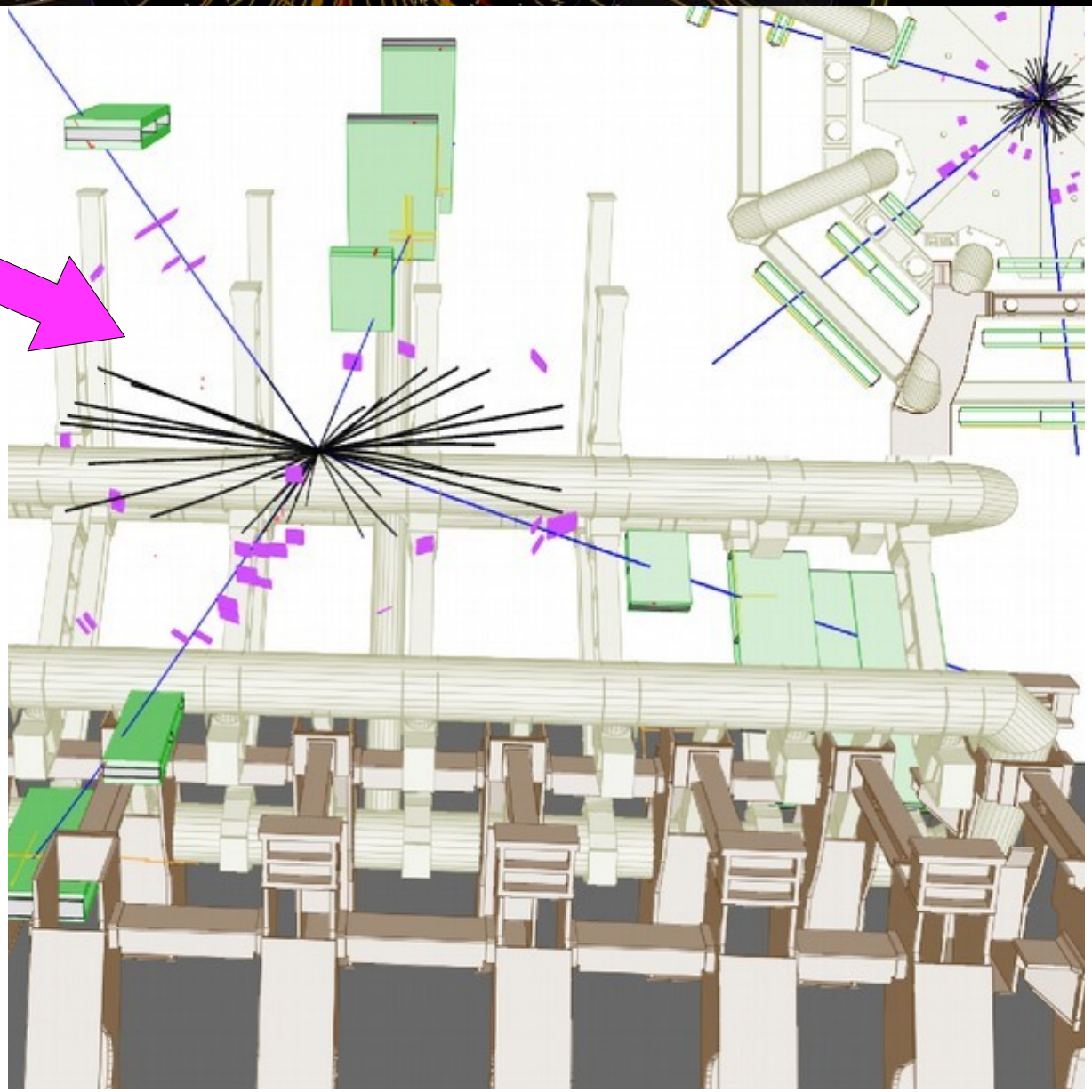

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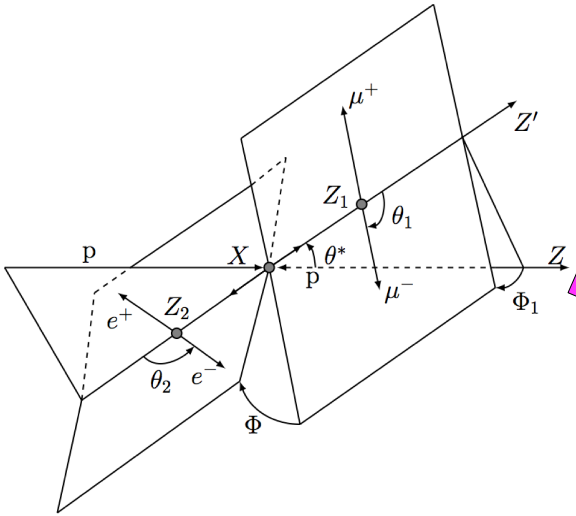

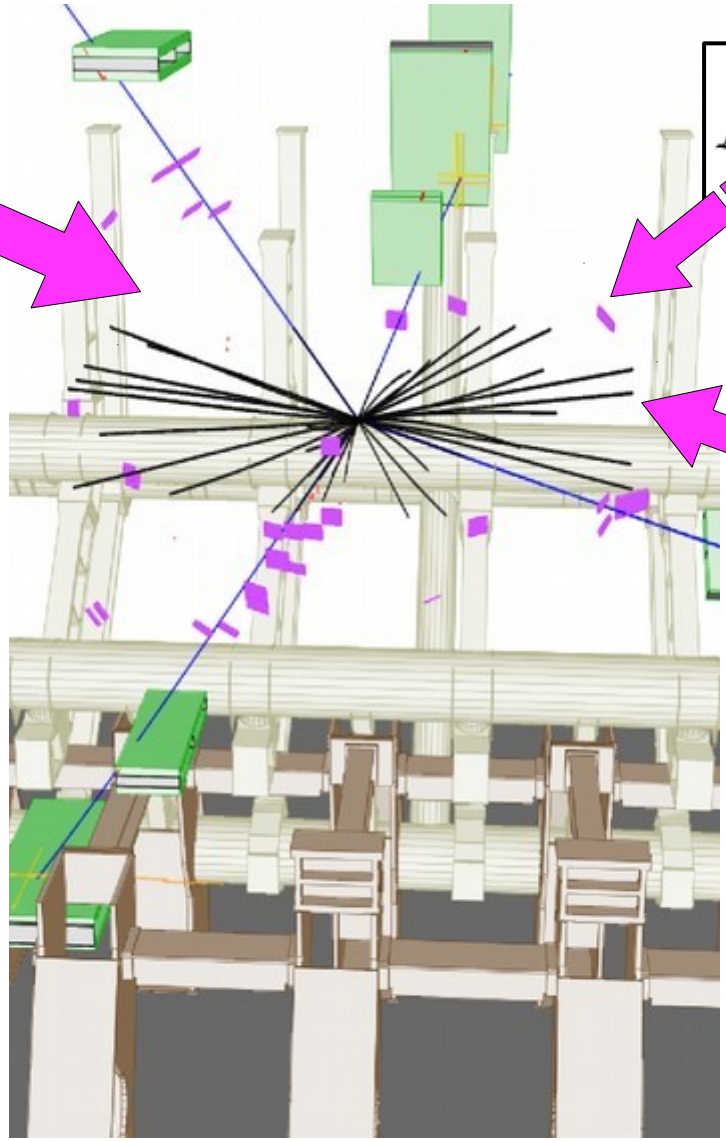

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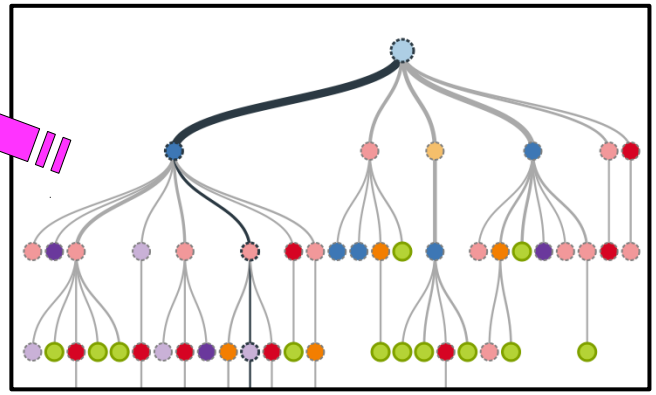
$$\mathcal{L}_2 = \frac{1}{\Lambda} \left[\sum_V \kappa_V X^{\mu\nu} \mathcal{T}^V_{\mu\nu} + \sum_f \kappa_f X^{\mu\nu} \mathcal{T}^f_{\mu\nu} \right]$$

OR



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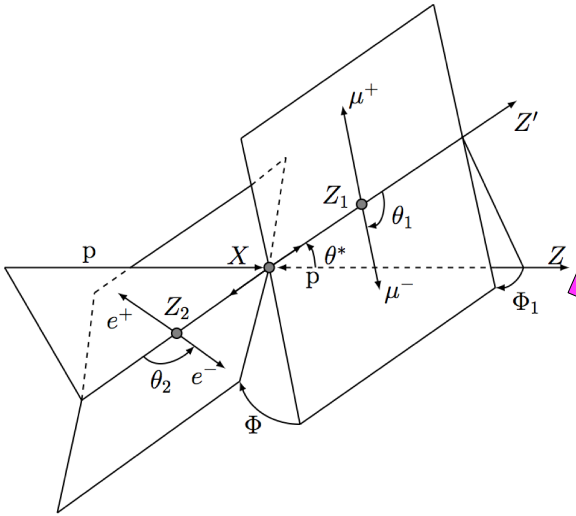

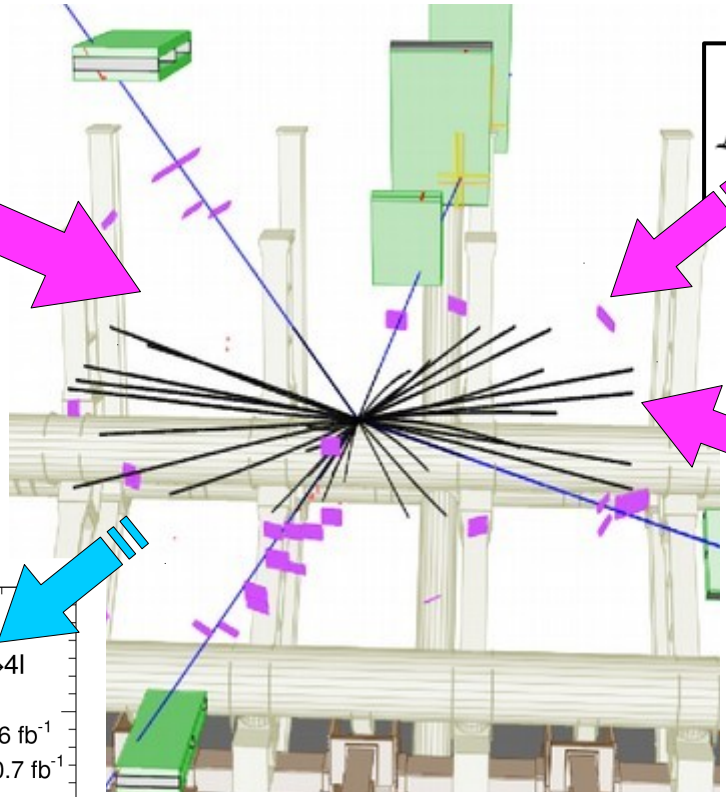

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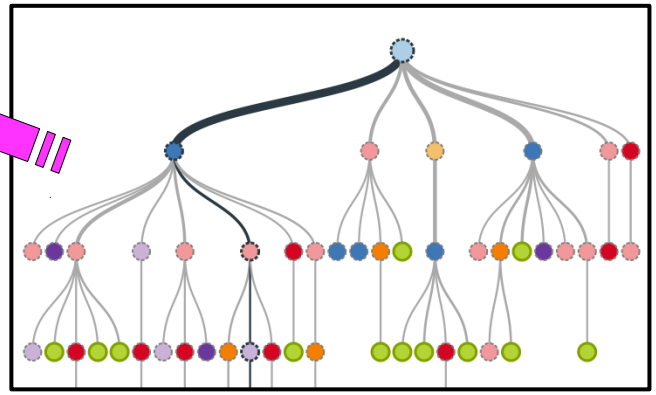

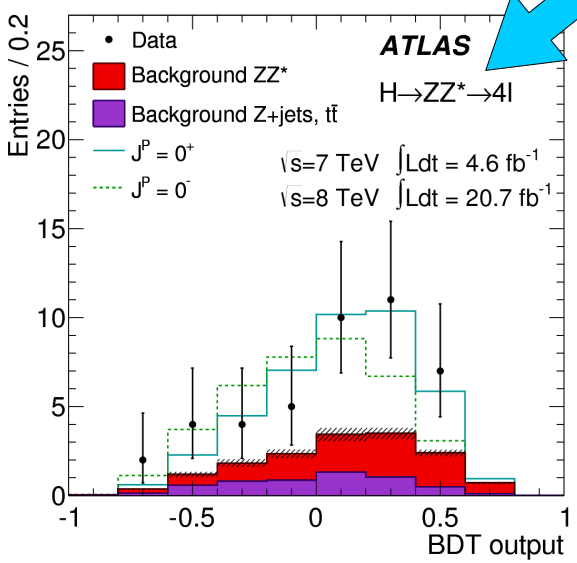

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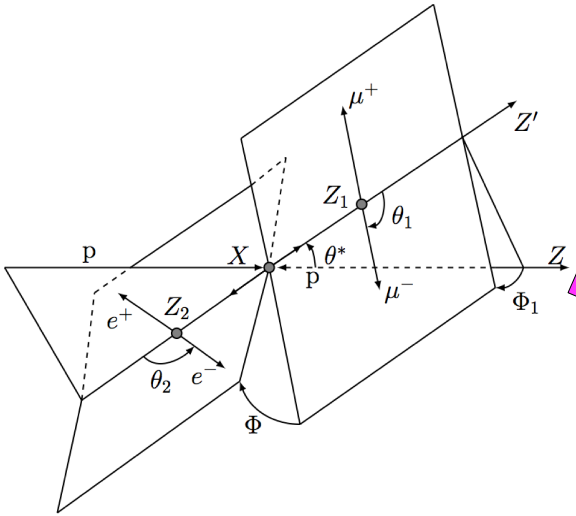

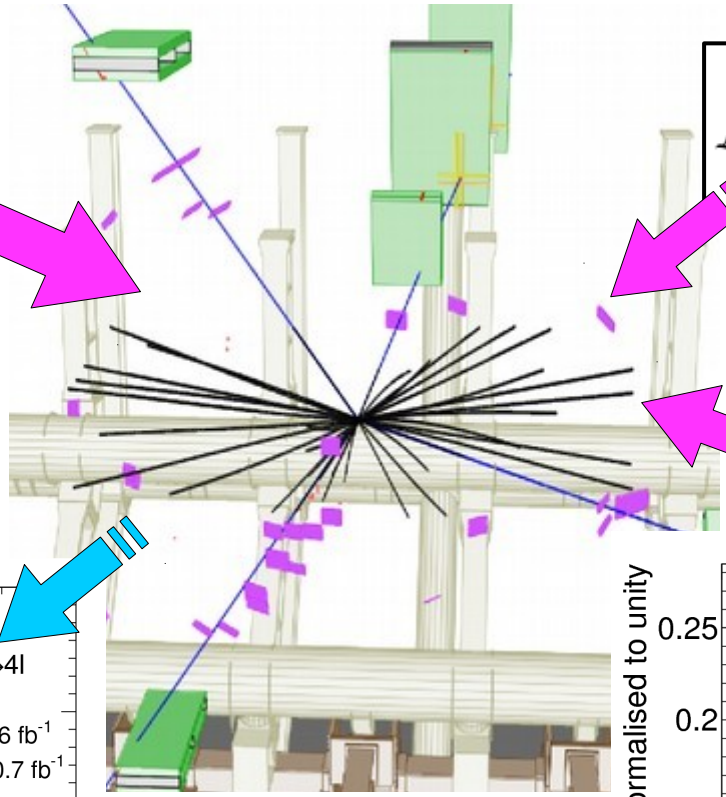

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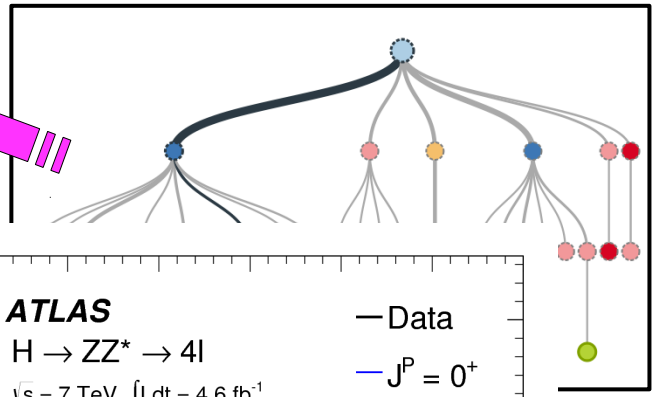
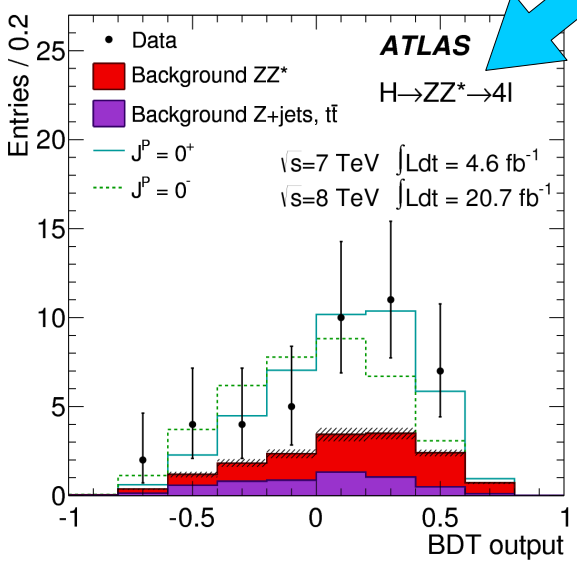
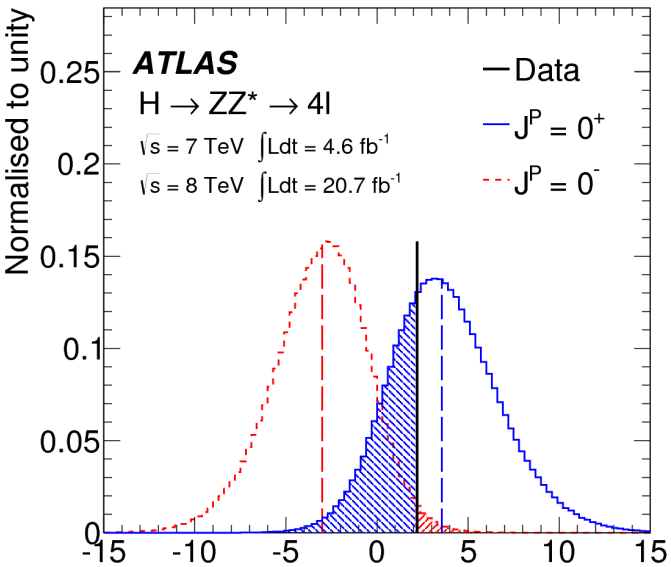


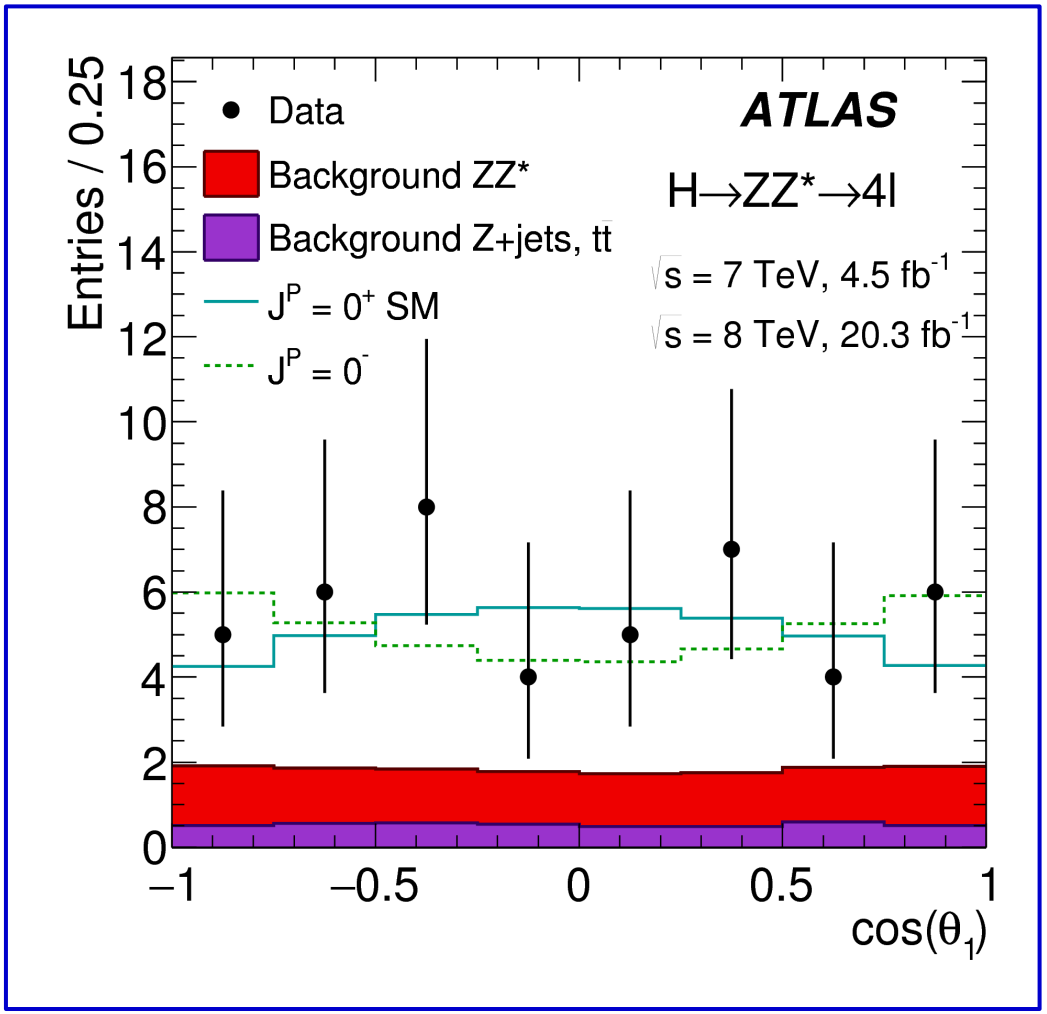




Hypothesis Discrimination: backgrounds vs. signal hypotheses

For each final state (ZZ*, WW*, and γγ) the background shapes are included and data compared to the combination of background and a pair of signal hypotheses: $J^P=0^+$ and an *alternative* (e.g. 0^-, 0^+_h, 2^+, etc).

- **ZZ* analysis**
- WW* analysis
- γγ



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- ZZ* analysis
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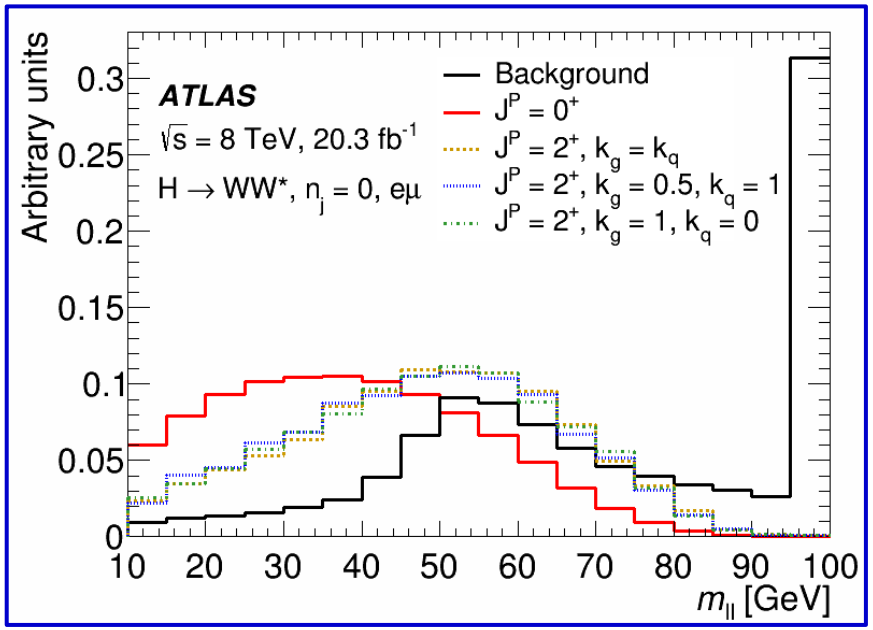

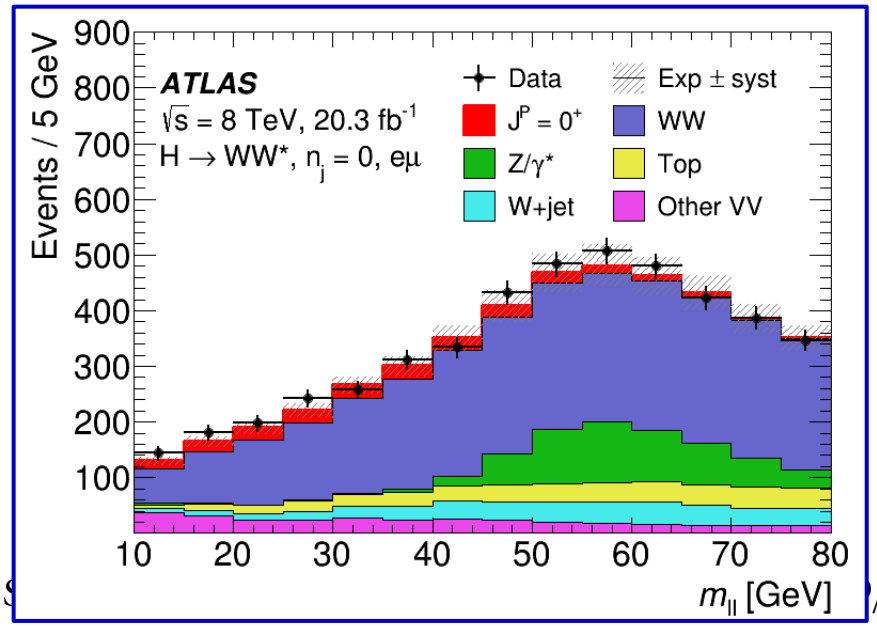

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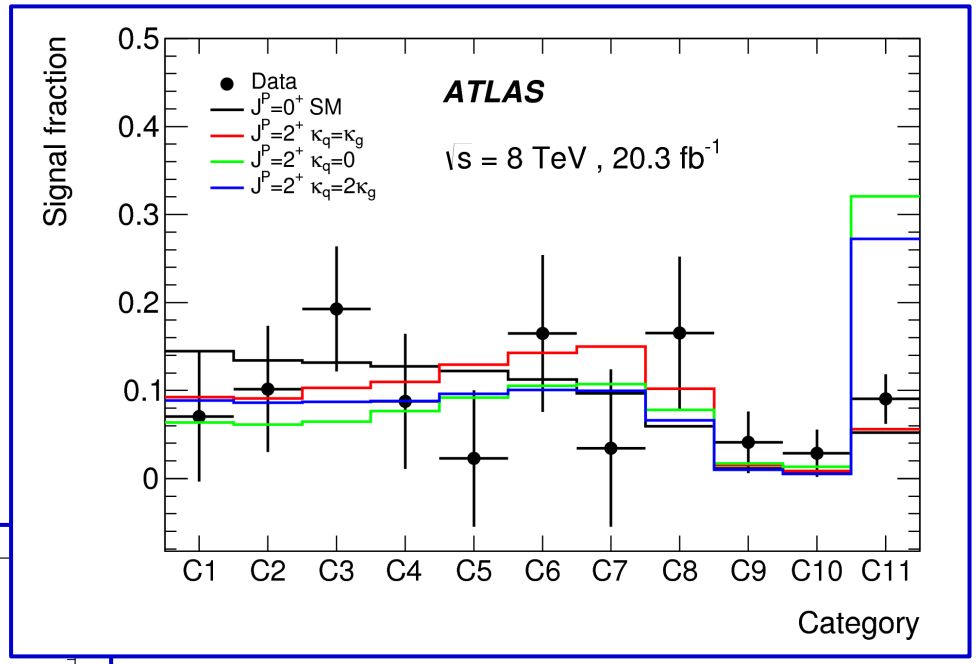
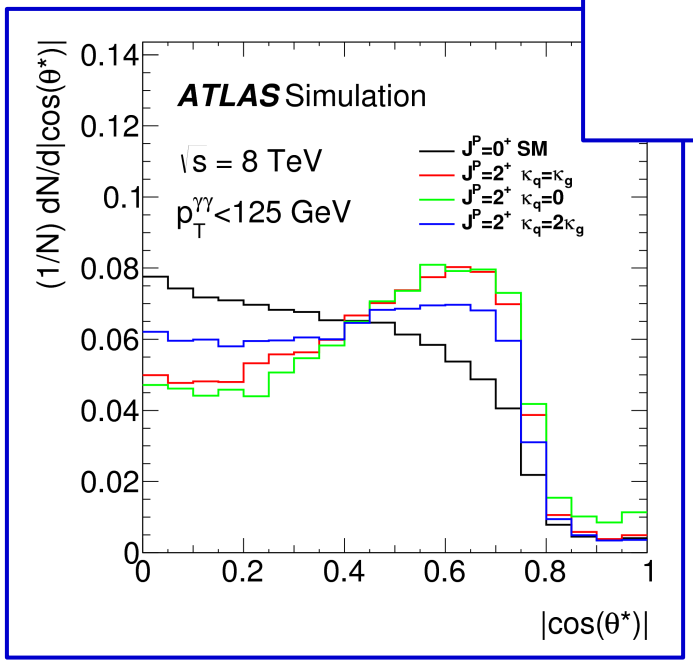


- ZZ* analysis
- WW* analysis
- **γγ analysis**

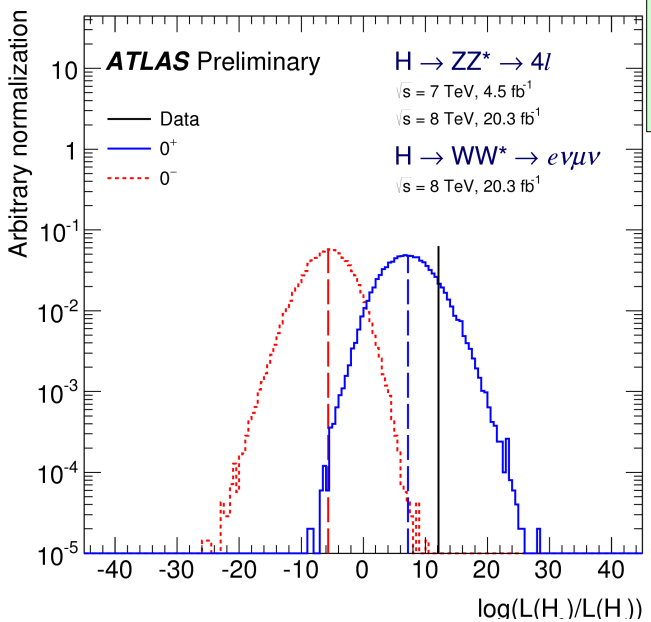


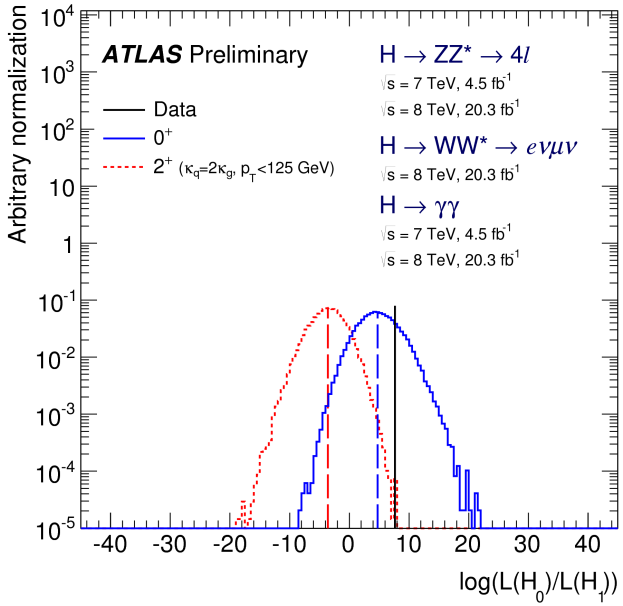
In this channel, events are categorized in ways consistent with hypothetical Higgs production mechanism. Gluon/Quark coupling alterations would then change the "fingerprints" of these categories.

ATLAS-CONF-2015-008

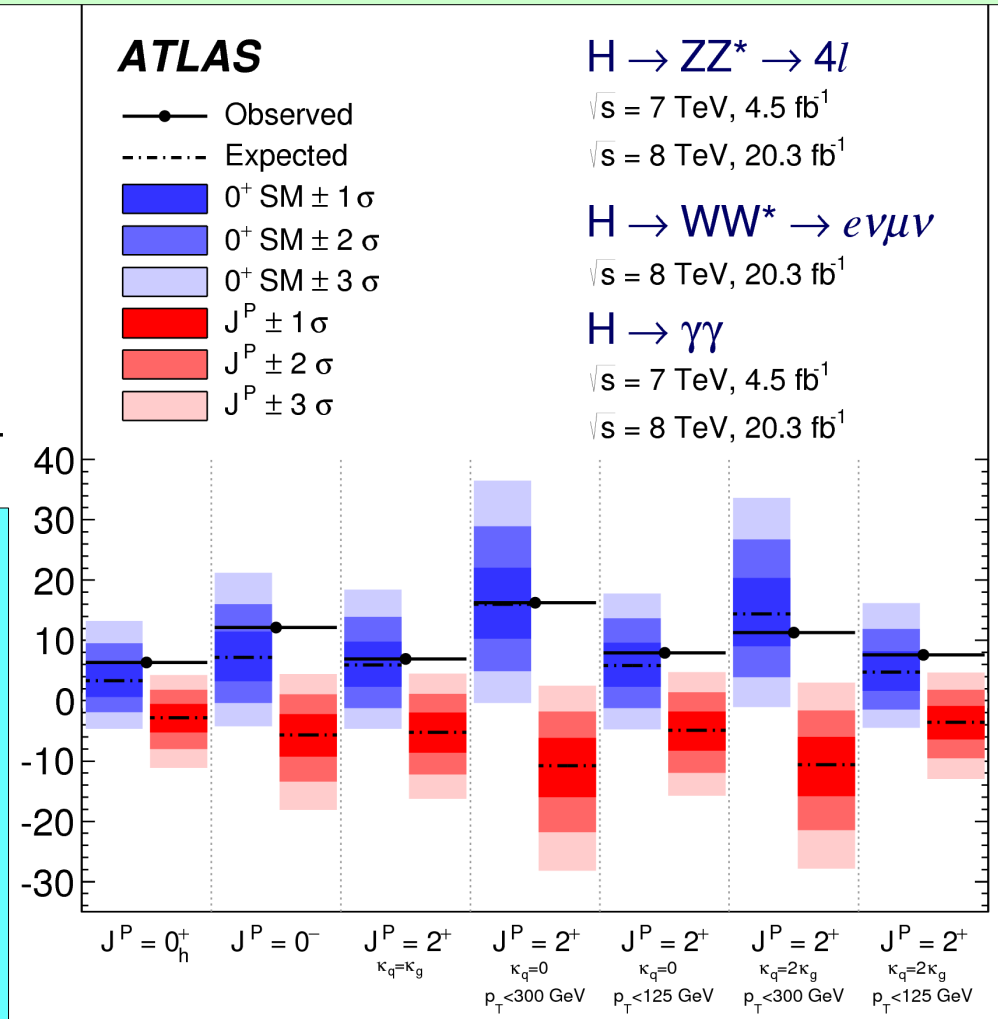
Results – pairwise hypothesis comparisons

Conclusions: in pairwise hypothesis comparisons, 0^+ is favored. This measurement is still statistics-limited.





Note: spin-2 EFT only valid up to a certain energy scale, necessitating pT cuts to make the interpretation (see right)



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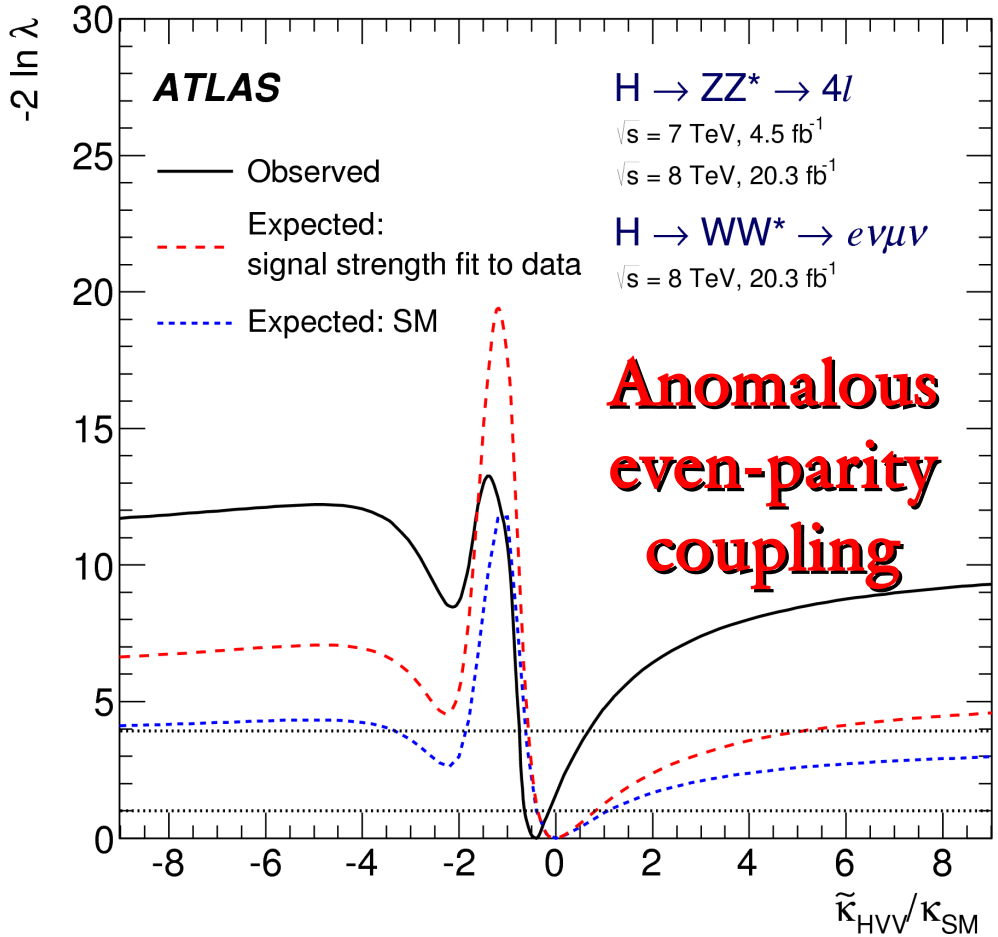
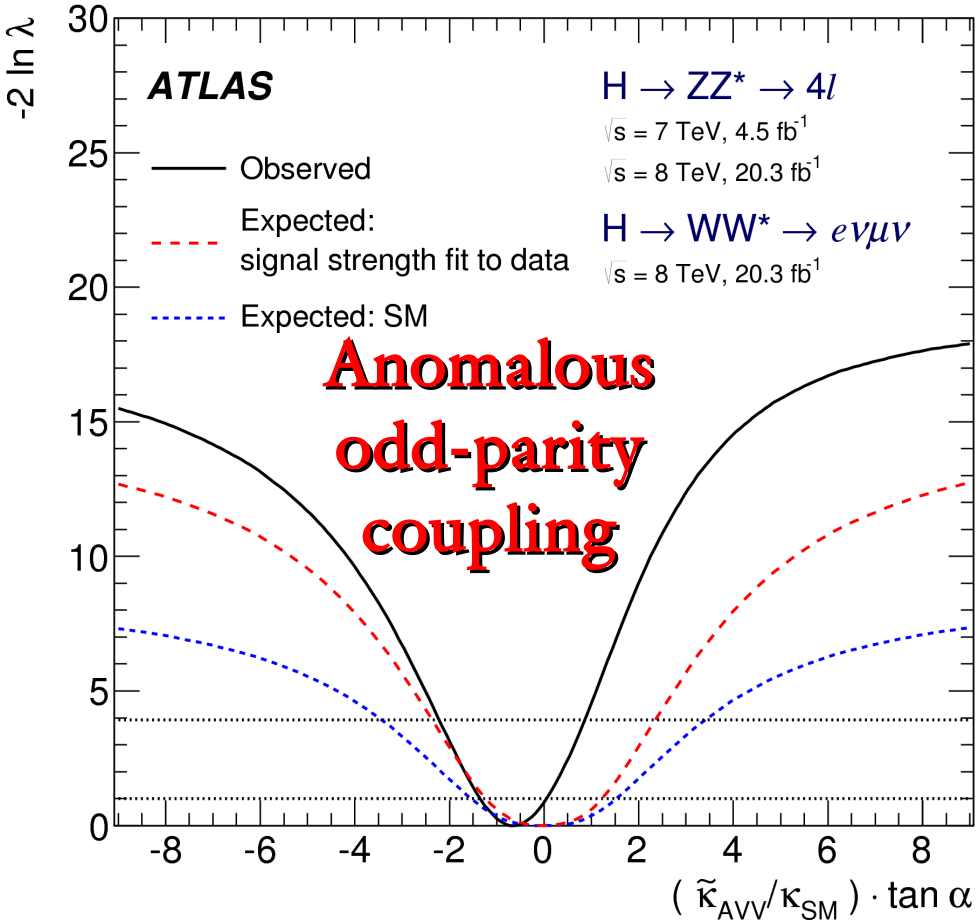
Results – Tensor Structure Analysis





Coupling ratio	Best-fit value	95% CL Exclusion Regions	
Combined	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{SM}$	−0.48	$(-\infty, -0.55] \bigcup [4.80, \infty)$	$(-\infty, -0.73] \bigcup [0.63, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$	−0.68	$(-\infty, -2.33] \bigcup [2.30, \infty)$	$(-\infty, -2.18] \bigcup [0.83, \infty)$

Conclusions: SM still favored compared to this extension.

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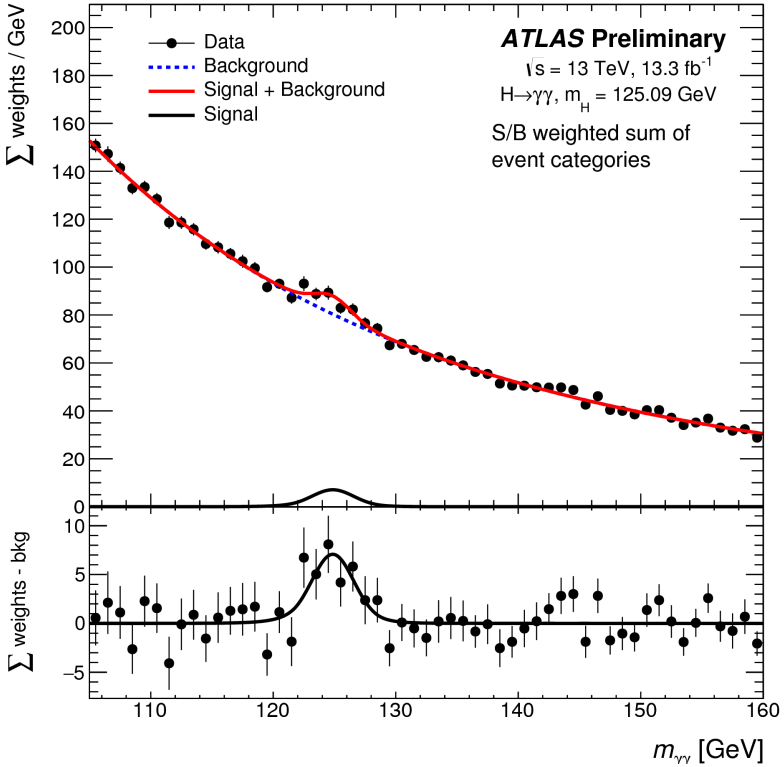
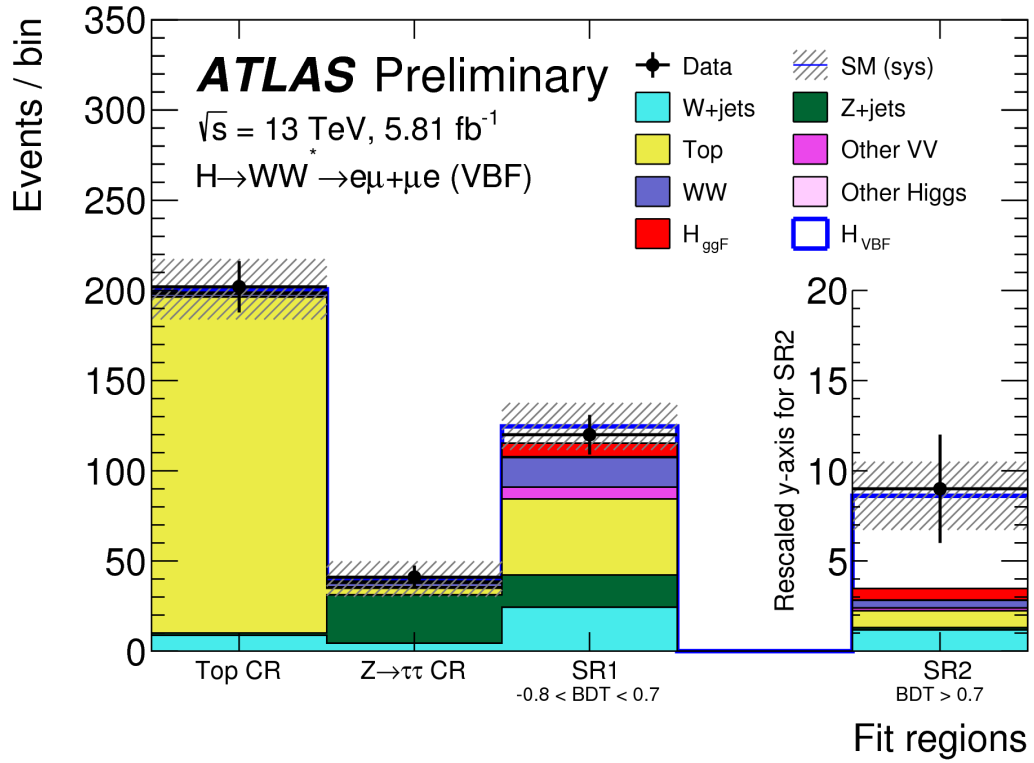
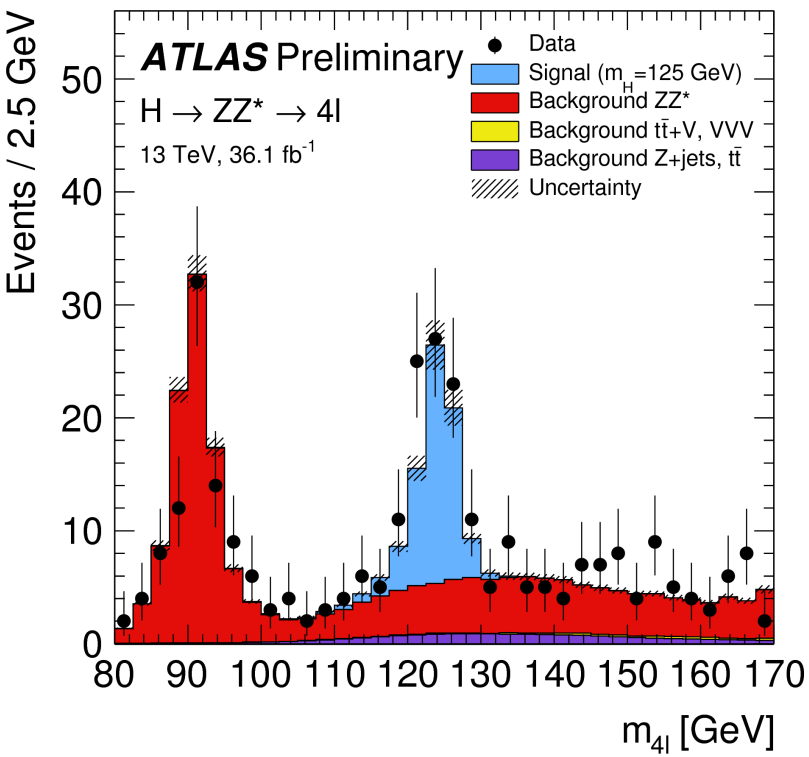
Conclusions and Outlook







Data-taking exceeded expectations in 2016. Public results from H → ZZ*,WW*, γγ overall use only a fraction of available data so far, some using Run 1 only. Watch for updates on full 2015-2016 data sets!

LHC planning to deliver 90fb^{-1} for 2017+2018.
Expect the textbooks to continue to need rewriting as ATLAS and CMS improve our knowledge of the Higgs Boson.

ATLAS-CONF-2017-032 and
ATLAS-CONF-2016-112 and
ATLAS-CONF-2016-067

Conclusions

- The 125-GeV boson is highly compatible with the Standard Model Higgs Boson
  - Mass:
    - ATLAS: $(125.36 \pm 0.37_{stat.} \pm 0.18_{syst.})$ GeV
    - ATLAS+CMS: $(125.09 \pm 0.21_{stat.} \pm 0.11_{syst.})$ GeV

Phys. Rev. Lett. 114 (2015) 191803

  - Spin and Parity
    - Favors strongly the $J^P=0^+$ hypothesis in pairwise comparisons with alternative hypotheses.
  - Couplings are another way to look at all of this. See JHEP 08 (2016) 045
- Future
  - The Higgs is "re-discovered" in Run 2. ATLAS continuing with detailed analyses of the Higgs Boson. Watch for updates.
  - LHC planning to deliver $90fb^{-1}$ more in Run 2!

Appendix

Mass Measurement - Extras

Mass Systematics – ZZ* and γγ

Systematic	Uncertainty on m_H [MeV]
LAr syst on material before presampler (barrel)	70
LAr syst on material after presampler (barrel)	20
LAr cell nonlinearity (layer 2)	60
LAr cell nonlinearity (layer 1)	30
LAr layer calibration (barrel)	50
Lateral shower shape (conv)	50
Lateral shower shape (unconv)	40
Presampler energy scale (barrel)	20
ID material model ($\|\eta\| < 1.1$)	50
$H \to \gamma\gamma$ background model (unconv rest low p_{Tt})	40
$Z \to ee$ calibration	50
Primary vertex effect on mass scale	20
Muon momentum scale	10
Remaining systematic uncertainties	70
Total	180

Mass Systematics – γγ breakdown

	Unconverted					Converted				
	Central		Rest		Transition	Central		Rest		Transition
Class	low p_{Tt}	high p_{Tt}	low p_{Tt}	high p_{Tt}		low p_{Tt}	high p_{Tt}	low p_{Tt}	high p_{Tt}	
$Z \to e^+e^-$ calibration	0.02	0.03	0.04	0.04	0.11	0.02	0.02	0.05	0.05	0.11
LAr cell nonlinearity	0.12	0.19	0.09	0.16	0.39	0.09	0.19	0.06	0.14	0.29
Layer calibration	0.13	0.16	0.11	0.13	0.13	0.07	0.10	0.05	0.07	0.07
ID material	0.06	0.06	0.08	0.08	0.10	0.05	0.05	0.06	0.06	0.06
Other material	0.07	0.08	0.14	0.15	0.35	0.04	0.04	0.07	0.08	0.20
Conversion reconstruction	0.02	0.02	0.03	0.03	0.05	0.03	0.02	0.05	0.04	0.06
Lateral shower shape	0.04	0.04	0.07	0.07	0.06	0.09	0.09	0.18	0.19	0.16
Background modeling	0.10	0.06	0.05	0.11	0.16	0.13	0.06	0.14	0.18	0.20
Vertex measurement	0.03									
Total	0.23	0.28	0.24	0.30	0.59	0.21	0.25	0.27	0.33	0.47

Systematics in γγ are subdivided into the case where the photon does or does not convert (γ → ee) in material as it traverses the ATLAS detector.

- **Converted photons** are electron pairs and can be calibrated more reliably using the Z → ee measurement. Otherwise, dominant systematics are Liquid Argon (LAr) calorimeter cell linearity (of response to energy) and the layer calibration.
- **Unconverted photons** have a larger systematic from the Z → ee calibration and otherwise are dominated by the same effects as the converted photons.

Spin-Parity Measurement - Extras

Confidence Levels – Channel-by-Channel

Tested Hypothesis	$H \to \gamma\gamma$				
	$p^{\rm alt}_{{\rm exp},\mu=1}$	$p^{\rm alt}_{{\rm exp},\mu=\hat{\mu}}$	$p^{\rm SM}_{\rm obs}$	$p^{\rm alt}_{\rm obs}$	Obs. $\mathrm{CL_s}$ (%)
$2^+(\kappa_q = \kappa_g)$	0.13	$7.5 \cdot 10^{-2}$	0.13	0.34	39
$2^+(\kappa_q = 0;\ p_{\rm T} < 300GeV)$	$4.3 \cdot 10^{-4}$	$< 3.1 \cdot 10^{-5}$	0.16	$2.9 \cdot 10^{-4}$	$3.5 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_{\rm T} < 125GeV)$	$9.4 \cdot 10^{-2}$	$5.6 \cdot 10^{-2}$	0.23	0.20	26
$2^+(\kappa_q = 2\kappa_g;\ p_{\rm T} < 300GeV)$	$9.1 \cdot 10^{-4}$	$< 3.1 \cdot 10^{-5}$	0.16	$8.6 \cdot 10^{-4}$	0.10
$2^+(\kappa_q = 2\kappa_g;\ p_{\rm T} < 125GeV)$	0.27	0.24	0.20	0.54	68
Tested Hypothesis	$H \to WW^* \to e\nu\mu\nu$				
	$p^{\rm alt}_{{\rm exp},\mu=1}$	$p^{\rm alt}_{{\rm exp},\mu=\hat{\mu}}$	$p^{\rm SM}_{\rm obs}$	$p^{\rm alt}_{\rm obs}$	Obs. $\mathrm{CL_s}$ (%)
0^+_h	0.31	0.29	0.91	$2.7 \cdot 10^{-2}$	29
0^-	$6.4 \cdot 10^{-2}$	$3.2 \cdot 10^{-2}$	0.65	$1.2 \cdot 10^{-2}$	3.5
$2^+(\kappa_q = \kappa_g)$	$6.4 \cdot 10^{-2}$	$3.3 \cdot 10^{-2}$	0.25	0.12	16
$2^+(\kappa_q = 0;\ p_{\rm T} < 300GeV)$	$1.5 \cdot 10^{-2}$	$4.0 \cdot 10^{-3}$	0.55	$3.0 \cdot 10^{-3}$	0.6
$2^+(\kappa_q = 0;\ p_{\rm T} < 125GeV)$	$5.6 \cdot 10^{-2}$	$2.9 \cdot 10^{-2}$	0.42	$4.4 \cdot 10^{-2}$	7.5
$2^+(\kappa_q = 2\kappa_g;\ p_{\rm T} < 300GeV)$	$1.5 \cdot 10^{-2}$	$4.0 \cdot 10^{-3}$	0.52	$3.0 \cdot 10^{-3}$	0.7
$2^+(\kappa_q = 2\kappa_g;\ p_{\rm T} < 125GeV)$	$4.4 \cdot 10^{-2}$	$2.2 \cdot 10^{-2}$	0.69	$7.0 \cdot 10^{-3}$	2.2
Tested Hypothesis	$H \to ZZ^* \to 4\ell$				
	$p^{\rm alt}_{{\rm exp},\mu=1}$	$p^{\rm alt}_{{\rm exp},\mu=\hat{\mu}}$	$p^{\rm SM}_{\rm obs}$	$p^{\rm alt}_{\rm obs}$	Obs. $\mathrm{CL_s}$ (%)
0^+_h	$3.2 \cdot 10^{-2}$	$5.2 \cdot 10^{-3}$	0.80	$3.6 \cdot 10^{-4}$	0.18
0^-	$8.0 \cdot 10^{-3}$	$3.6 \cdot 10^{-4}$	0.88	$1.2 \cdot 10^{-5}$	$1.0 \cdot 10^{-2}$
$2^+(\kappa_q = \kappa_g)$	$3.3 \cdot 10^{-2}$	$5.7 \cdot 10^{-4}$	0.91	$3.6 \cdot 10^{-5}$	$4.0 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_{\rm T} < 300GeV)$	$3.9 \cdot 10^{-2}$	$9.0 \cdot 10^{-3}$	0.95	$2.7 \cdot 10^{-5}$	$5.4 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_{\rm T} < 125GeV)$	$4.6 \cdot 10^{-2}$	$1.1 \cdot 10^{-2}$	0.93	$3.0 \cdot 10^{-5}$	$4.3 \cdot 10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_{\rm T} < 300GeV)$	$4.6 \cdot 10^{-2}$	$1.1 \cdot 10^{-2}$	0.66	$3.3 \cdot 10^{-3}$	0.97
$2^+(\kappa_q = 2\kappa_g;\ p_{\rm T} < 125GeV)$	$5.0 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	0.88	$3.2 \cdot 10^{-4}$	0.27

Confidence Levels – Combined

Tested Hypothesis	$p^{\text{alt}}_{\text{exp},\mu=1}$	$p^{\text{alt}}_{\text{exp},\mu=\hat{\mu}}$	$p^{\text{SM}}_{\text{obs}}$	$p^{\text{alt}}_{\text{obs}}$	Obs. CL_s (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
$2^+(\kappa_q = \kappa_g)$	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_\text{T} < 300GeV)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-5}$	$< 6.5 \cdot 10^{-3}$
$2^+(\kappa_q = 0;\ p_\text{T} < 125GeV)$	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_\text{T} < 300GeV)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-5}$	$< 4.3 \cdot 10^{-3}$
$2^+(\kappa_q = 2\kappa_g;\ p_\text{T} < 125GeV)$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$