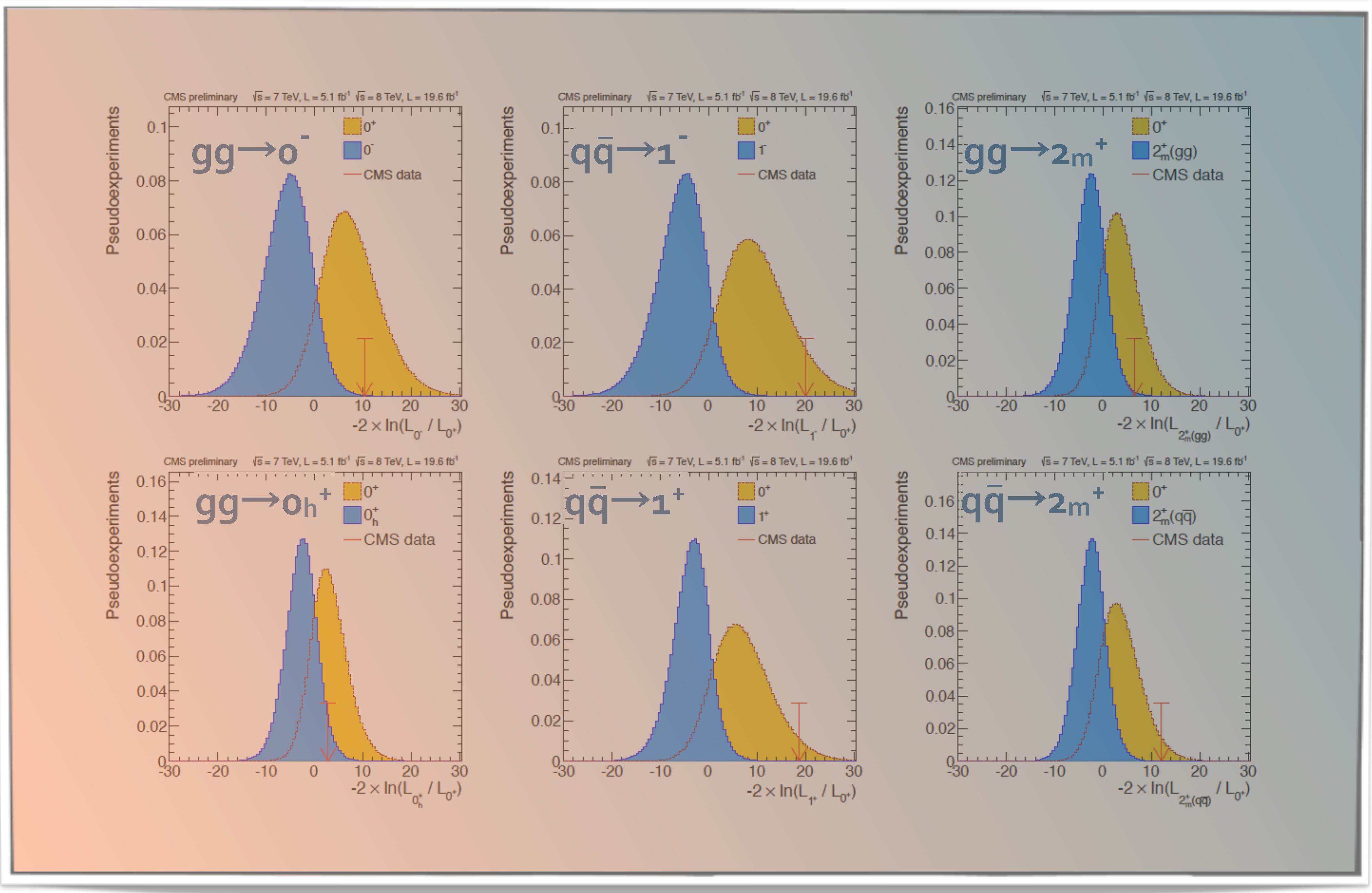
Higgs Boson – Spin and Parity



Higgs Boson – Spin and Parity

Spin 0:

$$A(X \to V_1 V_2) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} m_H^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta \right)$$

Spin 2:

$$A(X \to V_1 V_2) = \Lambda^{-1} e_1^{*\mu}\, e_2^{*\nu} \Bigg[c_1\, (q_1 q_2) t_{\mu\nu} + c_2\, g_{\mu\nu} t_{\alpha\beta} \tilde{q}^\alpha \tilde{q}^\beta +$$

$$+ c_3\, \frac{q_{2\mu} q_{1\nu}}{m_X^2} t_{\alpha\beta} \tilde{q}^\alpha \tilde{q}^\beta + 2c_{41}\, q_{1\nu} q_2^\alpha t_{\mu\alpha} + 2c_{42}\, q_{2\mu} q_1^\alpha t_{\nu\alpha} +$$

$$+ \; c_5 t_{\alpha\beta} \frac{\tilde{q}^\alpha \tilde{q}^\beta}{m_X^2} \epsilon_{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma + c_6 t^{\alpha\beta} \tilde{q}_\beta \epsilon_{\mu\nu\alpha\rho} q^\rho +$$

$$+ \frac{c_7 t^{\alpha\beta} \tilde{q}_\beta}{m_X^2} \left(\epsilon_{\alpha\mu\rho\sigma} q^\rho \tilde{q}^\sigma q_\nu + \epsilon_{\alpha\nu\rho\sigma} q^\rho \tilde{q}^\sigma q_\mu \right) \Bigg]$$

Higgs Boson – Spin and Parity

Spin 0:

$$A(H_{J=0} \rightarrow V_1 V_2) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} M_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta \right)$$

SM
CP-even

CP-even

CP-odd

For X ➛ ZZ, WW:

SM Higgs ($J^P = 0^+$): $a_1 \neq 0$, $a_2 = a_3 = 0$

Pseudoscalar ($J^P = 0^-$): $a_3 \neq 0$, $a_1 = a_2 = 0$

General amplitude can be separated in various helicity amplitudes …
Helicity amplitudes are used to characterize event kinematics …

[Computation of helicity amplitude via polarization vectors, ε(±,0)]
[For generic X ➛ VV decay: 9 possible amplitudes A_{jk} with j,k = ±1,0]

Higgs Boson – Spin and Parity

Spin 0:

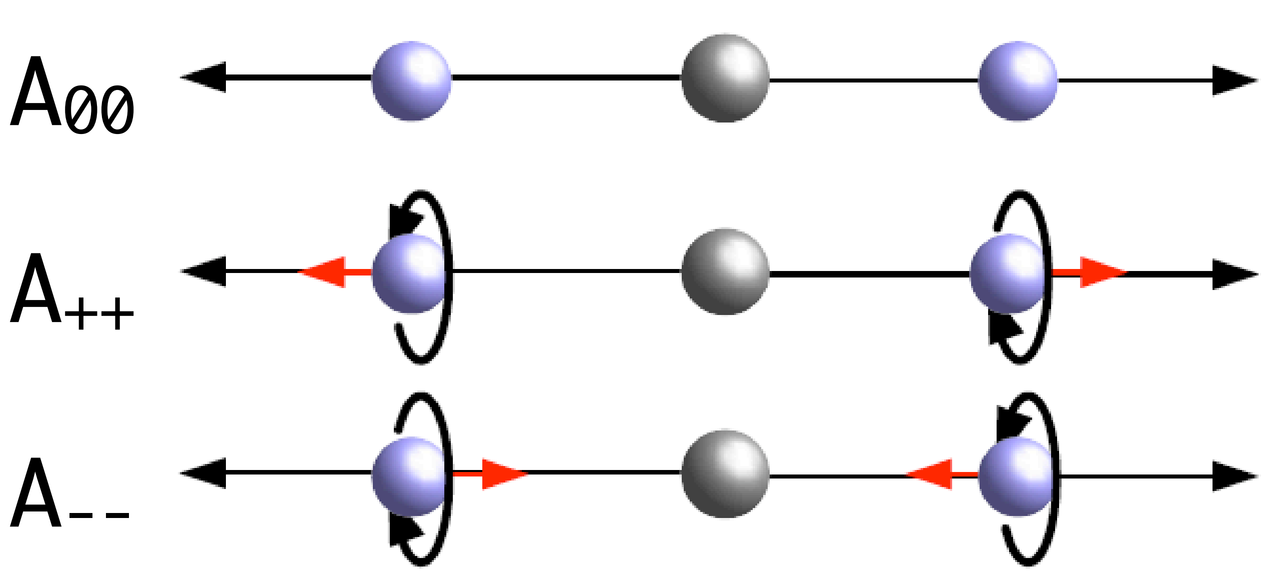
$$A(H_{J=0} \rightarrow V_1 V_2) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} M_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta \right)$$

SM
CP-even

CP-even

CP-odd

Three allowed amplitudes for spin 0:
[A_{00}, A_{++}, A_{--}]



Yields different angular distributions

Angular distribution

parametrized by helicity amplitudes

$$
\begin{aligned}
F^J_{00}(\theta^*) \times \Big\{ & 4\, f_{00}\, \sin^2\theta_1 \sin^2\theta_2 + (f_{++} + f_{--}) \left((1+\cos^2\theta_1)(1+\cos^2\theta_2) + 4R_1R_2\cos\theta_1\cos\theta_2\right) \\
& - 2\,(f_{++} - f_{--}) \left(R_1\cos\theta_1(1+\cos^2\theta_2) + R_2(1+\cos^2\theta_1)\cos\theta_2\right) \\
& + 4\sqrt{f_{++}f_{00}}\,(R_1 - \cos\theta_1)\sin\theta_1(R_2 - \cos\theta_2)\sin\theta_2\cos(\Phi + \phi_{++}) \\
& + 4\sqrt{f_{--}f_{00}}\,(R_1 + \cos\theta_1)\sin\theta_1(R_2 + \cos\theta_2)\sin\theta_2\cos(\Phi - \phi_{--}) \\
& + 2\sqrt{f_{++}f_{--}}\,\sin^2\theta_1\sin^2\theta_2\cos(2\Phi + \phi_{++} - \phi_{--})\Big\}
\end{aligned}
$$

$J_z = 0$

$$
\begin{aligned}
+4F^J_{11}(\theta^*) \times \Big\{ & (f_{+0} + f_{0-})(1 - \cos^2\theta_1\cos^2\theta_2) - (f_{+0} - f_{0-})(R_1\cos\theta_1\sin^2\theta_2 + R_2\sin^2\theta_1\cos\theta_2) \\
& + 2\sqrt{f_{+0}f_{0-}}\,\sin\theta_1\sin\theta_2(R_1R_2 - \cos\theta_1\cos\theta_2)\cos(\Phi + \phi_{+0} - \phi_{0-})\Big\} \\
+(-1)^J \times 4F^J_{-11}(\theta^*) \times \Big\{ & (f_{+0} + f_{0-})(R_1R_2 + \cos\theta_1\cos\theta_2) - (f_{+0} - f_{0-})(R_1\cos\theta_2 + R_2\cos\theta_1) \\
& + 2\sqrt{f_{+0}f_{0-}}\,\sin\theta_1\sin\theta_2\cos(\Phi + \phi_{+0} - \phi_{0-})\Big\}\sin\theta_1\sin\theta_2\cos(2\Psi)
\end{aligned}
$$

$J_z = \pm 1$

$$
\begin{aligned}
&+2F^J_{22}(\theta^*) \times f_{+-}\Big\{(1+\cos^2\theta_1)(1+\cos^2\theta_2) - 4R_1R_2\cos\theta_1\cos\theta_2\Big\} \\
&+(-1)^J \times 2F^J_{-22}(\theta^*) \times f_{+-}\sin^2\theta_1\sin^2\theta_2\cos(4\Psi)
\end{aligned}
$$

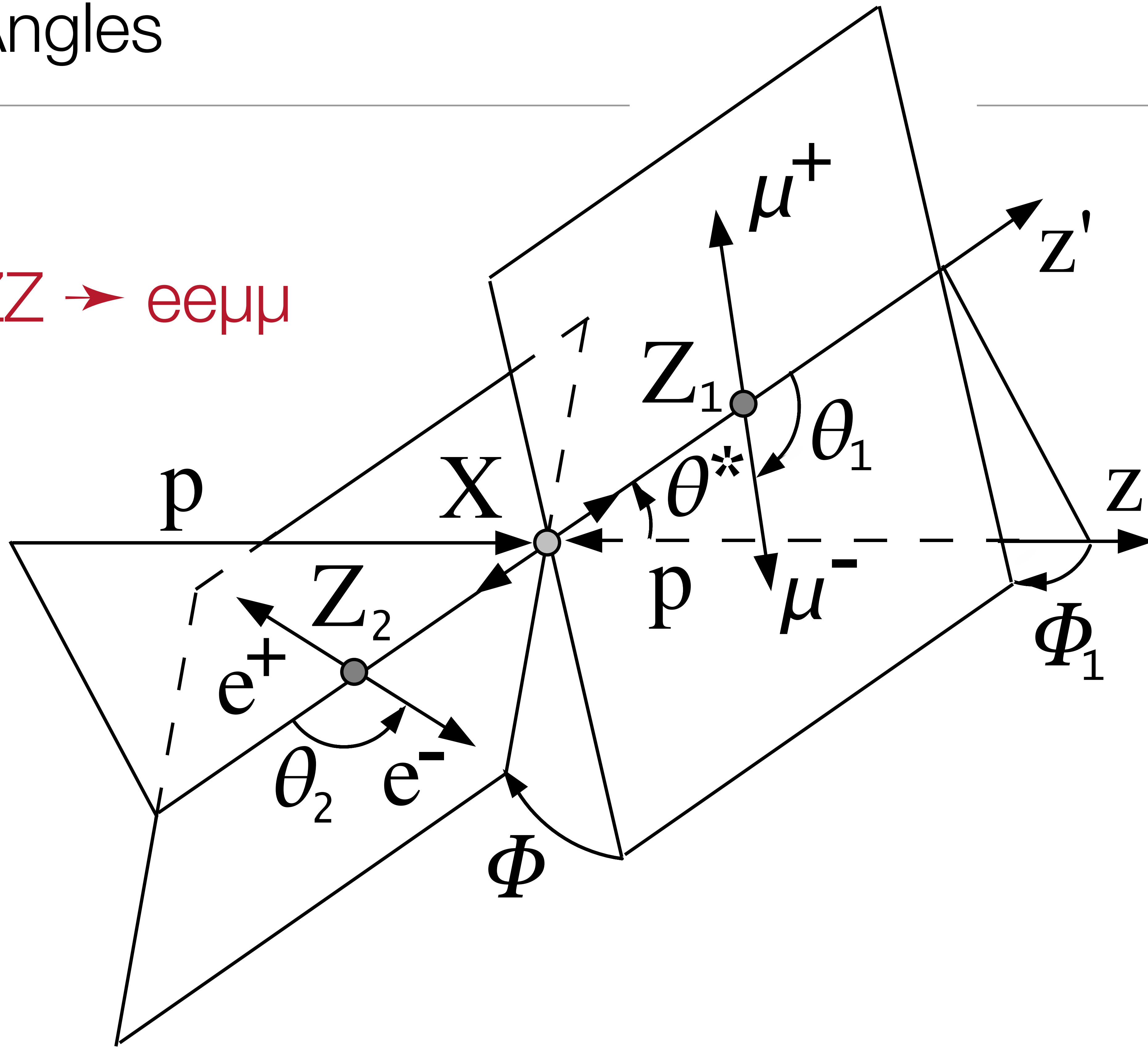
$J_z = \pm 2$

+ interference terms

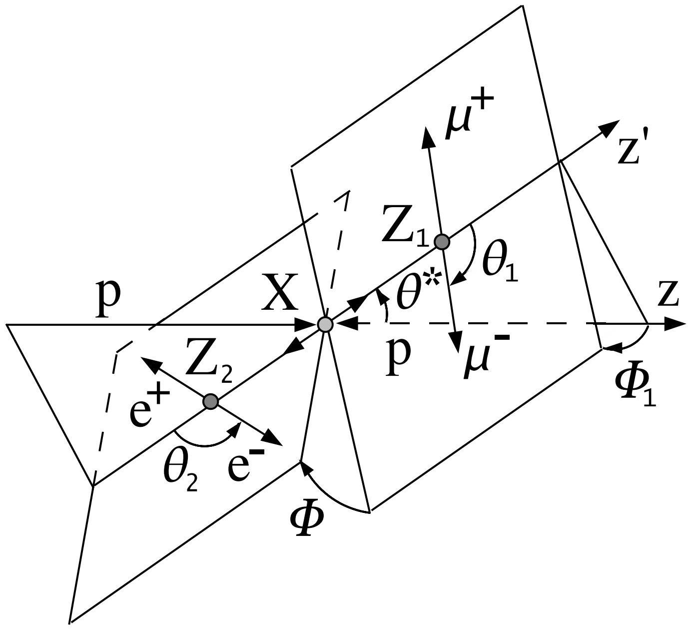
from N.Tran et al.

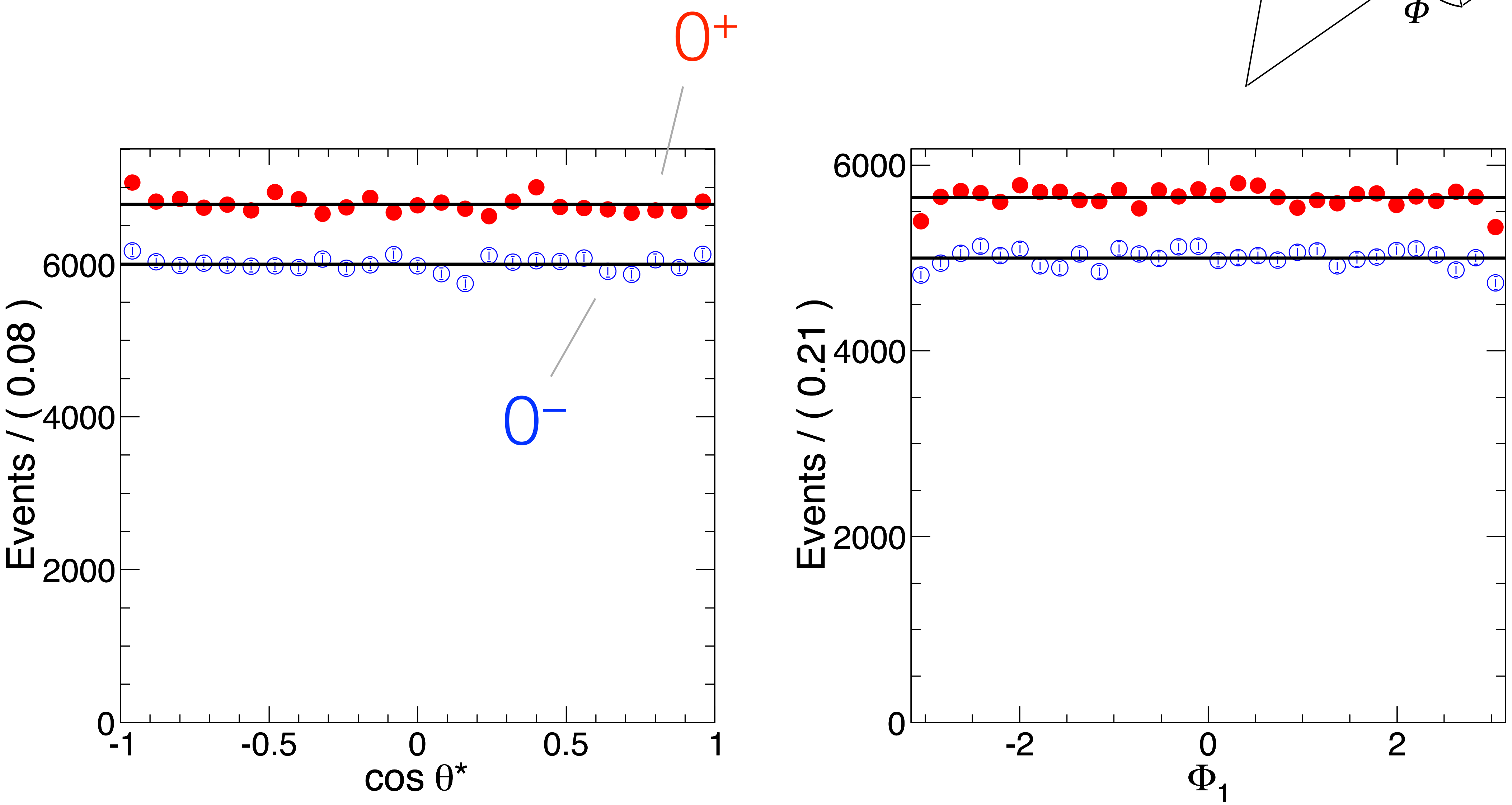
Decay Angles

X ➛ ZZ ➛ eeμμ



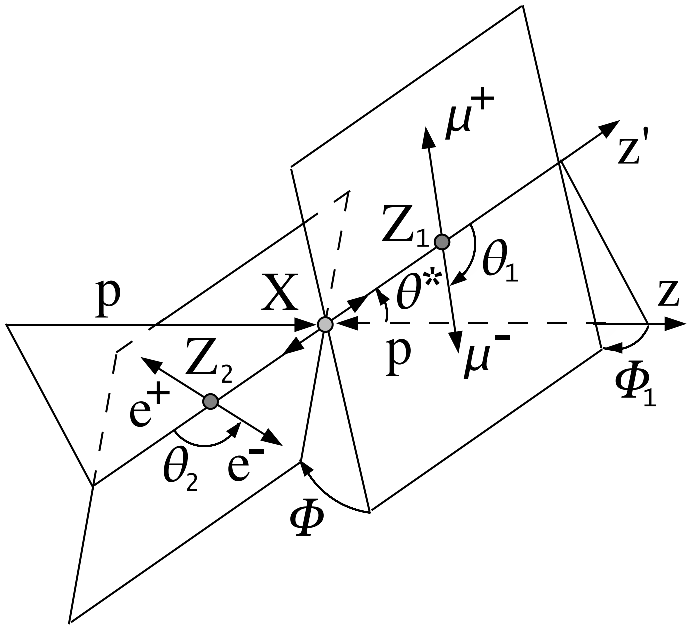
Angular Distributions – Expectation

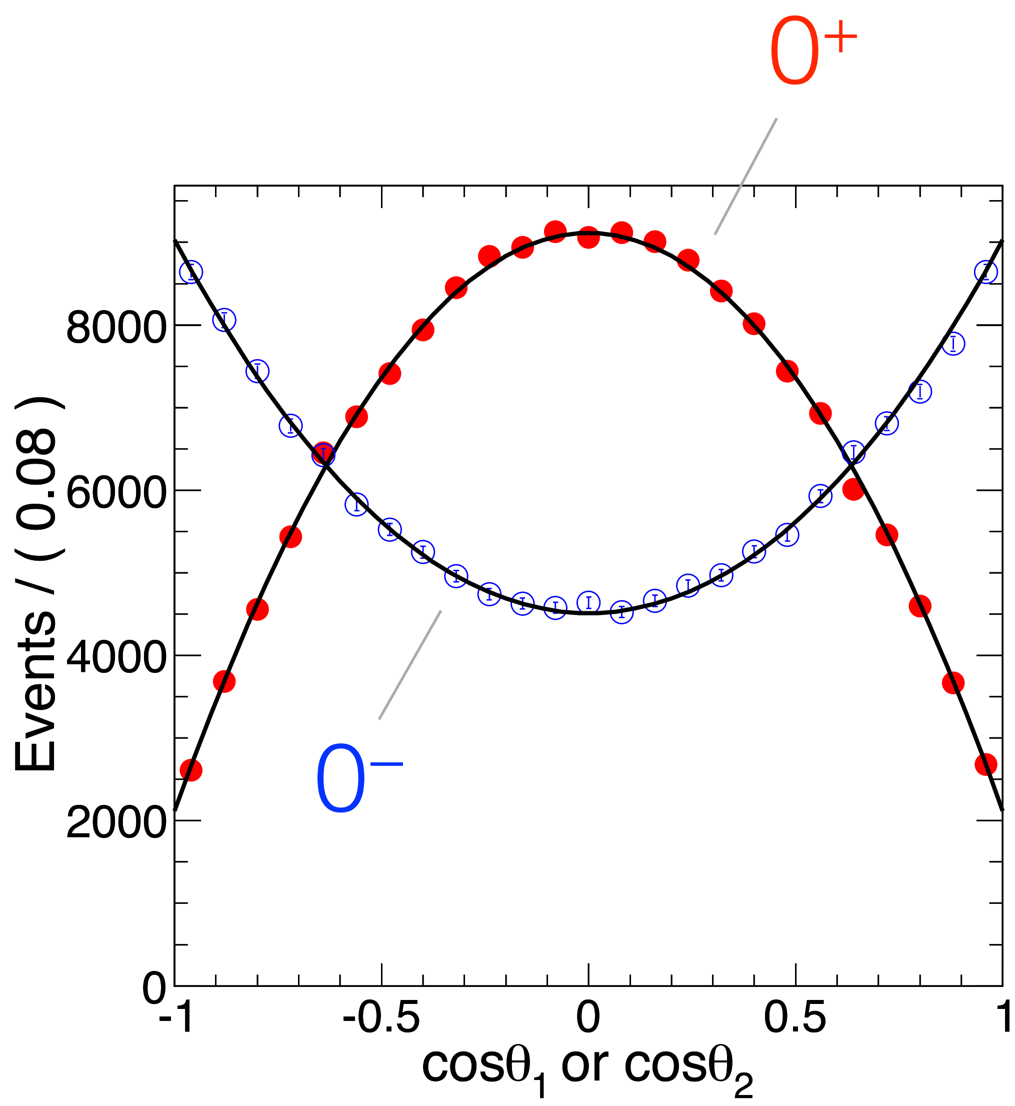


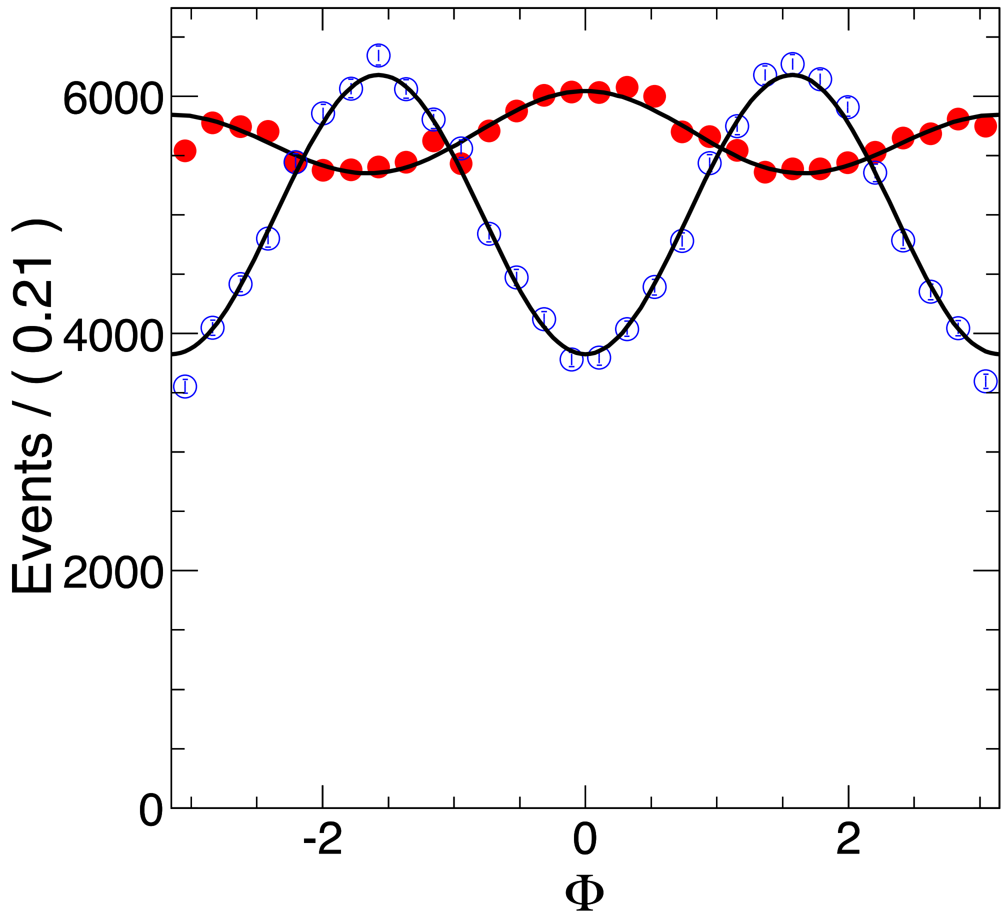


Spin 0; θ* and Φ$_1$ …

Angular Distributions – Expectation

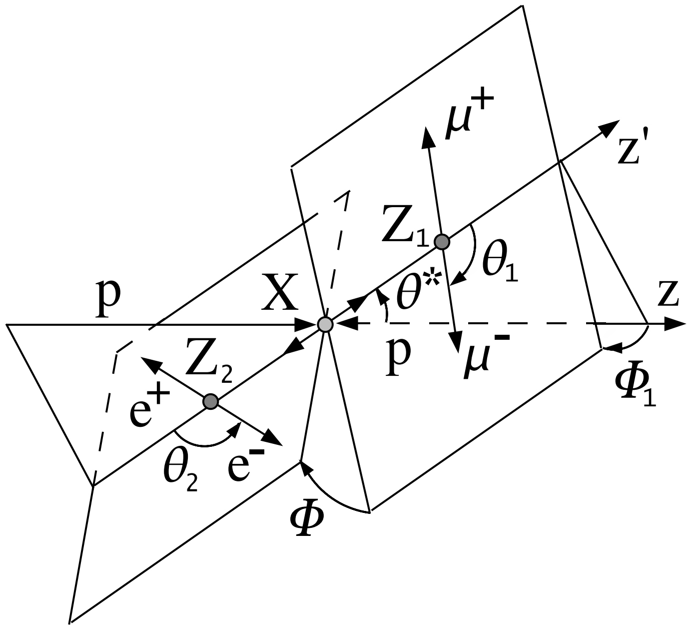


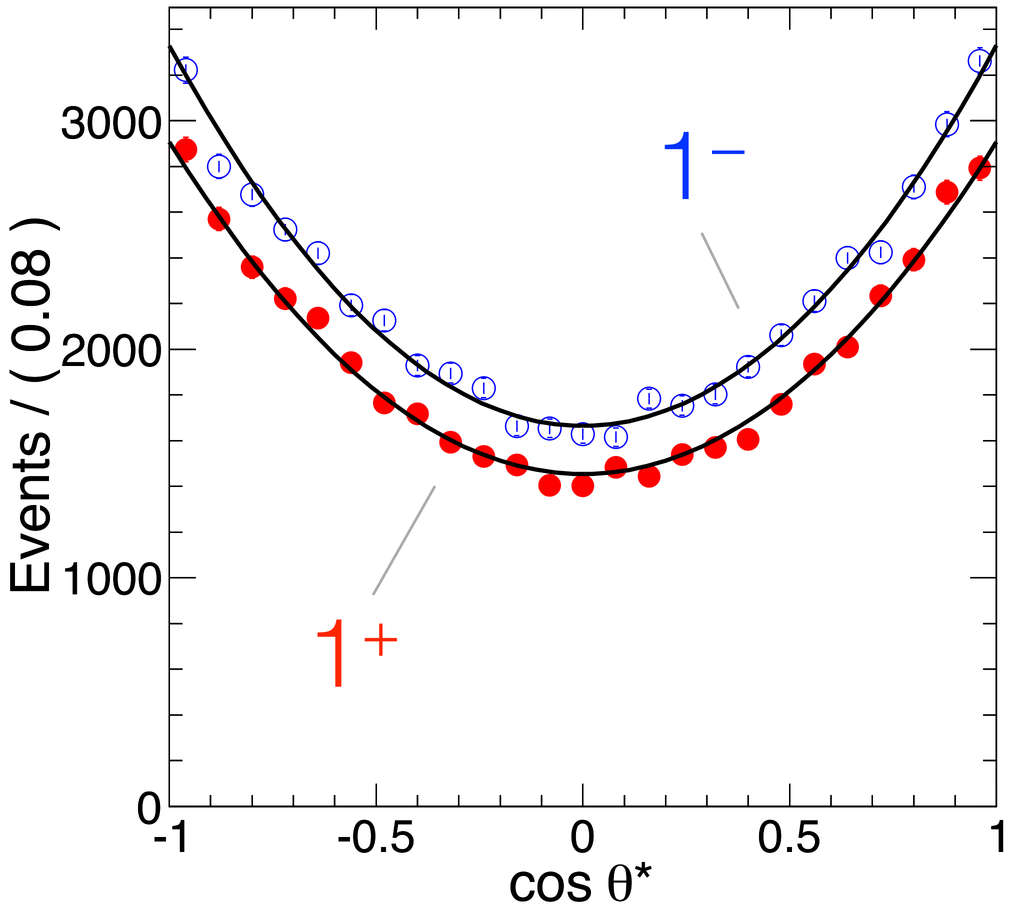


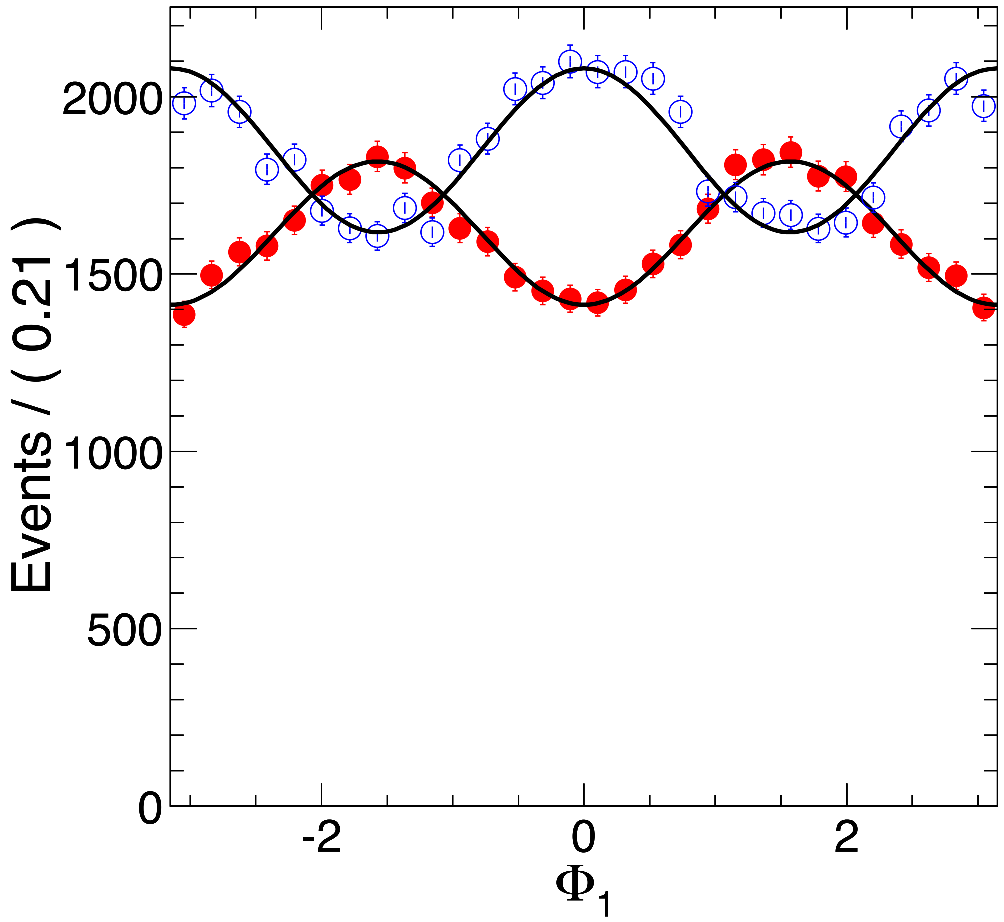


Spin 0; $\theta_{1,2}$ and Φ …

Angular Distributions – Expectation

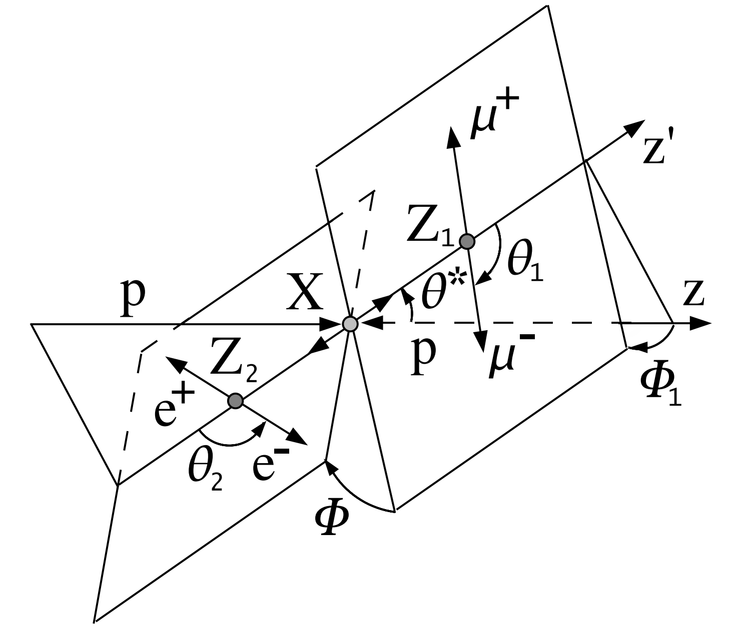


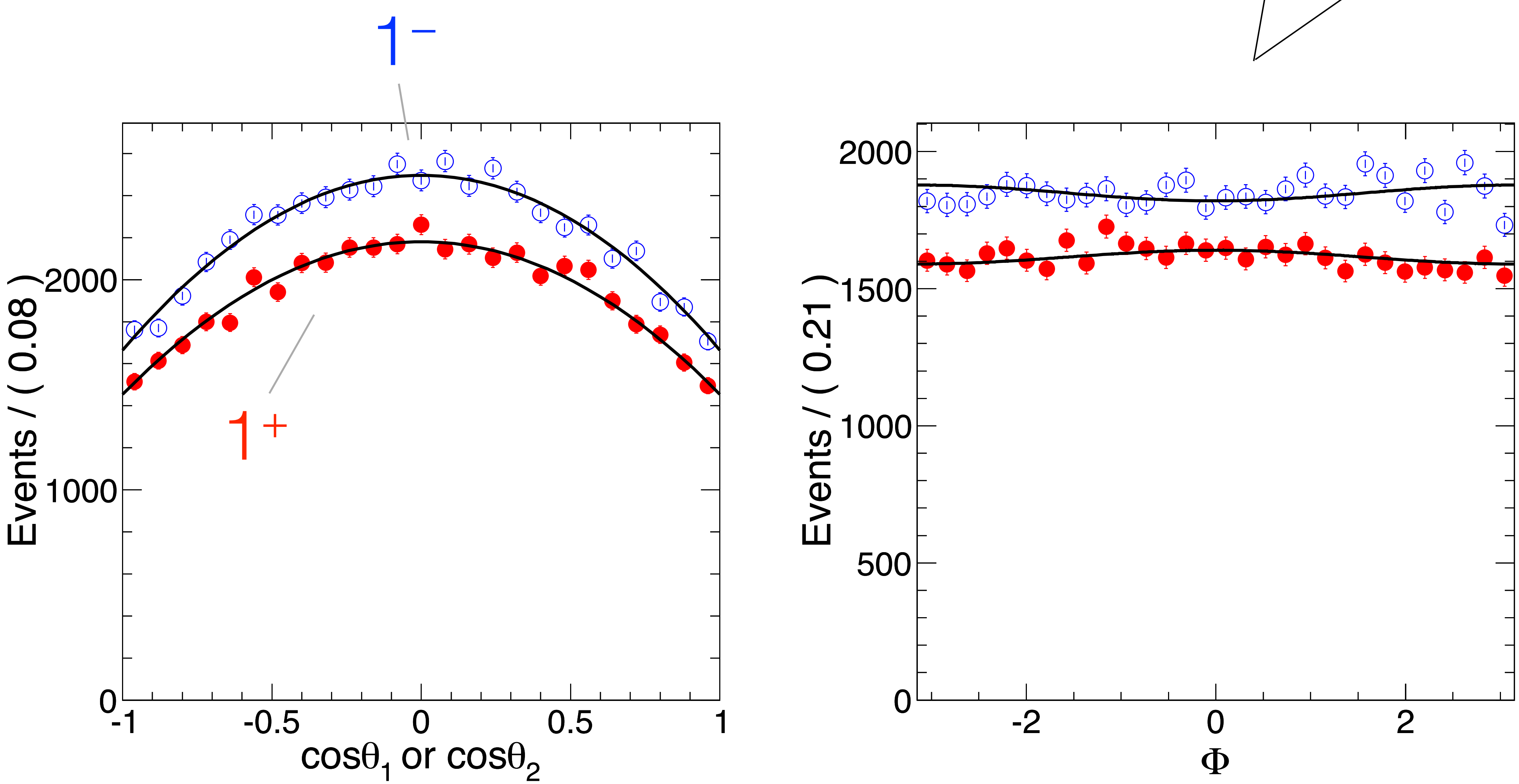




Spin 0; θ* and Φ_1 …

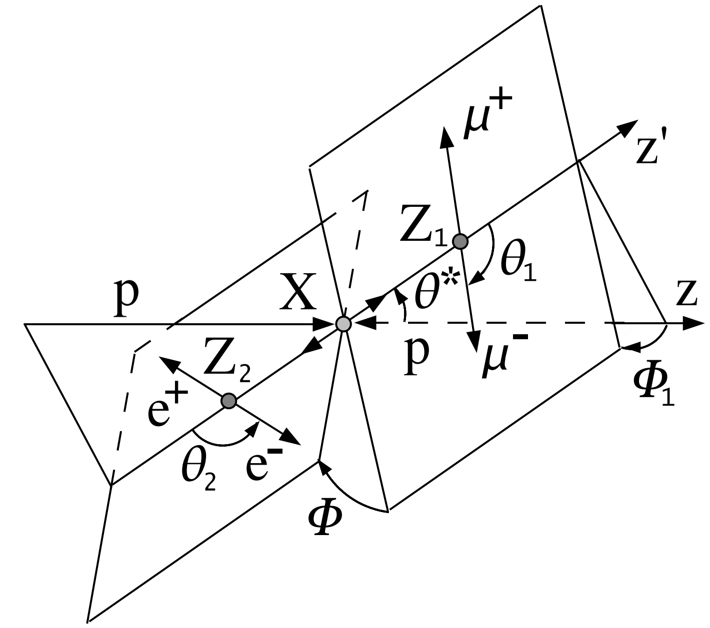
Angular Distributions – Expectation





Spin 1; $\theta_{1,2}$ and Φ …

Angular Distributions – Expectation

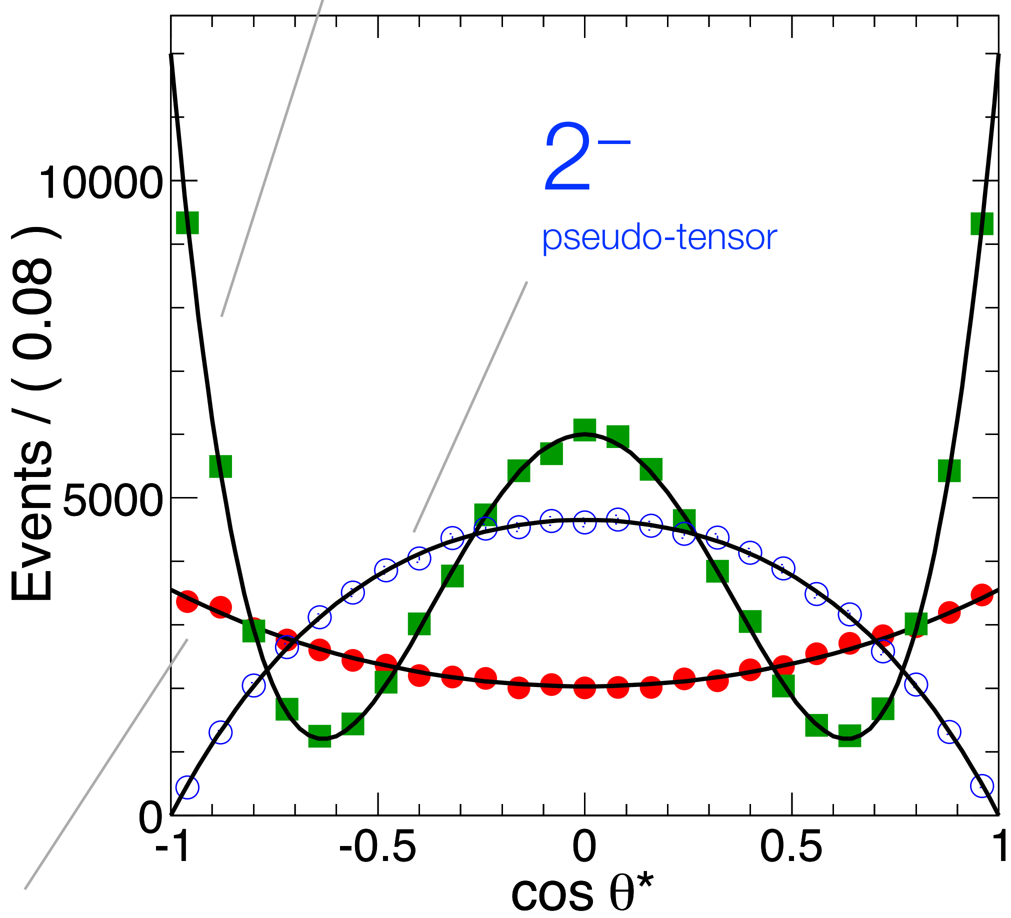


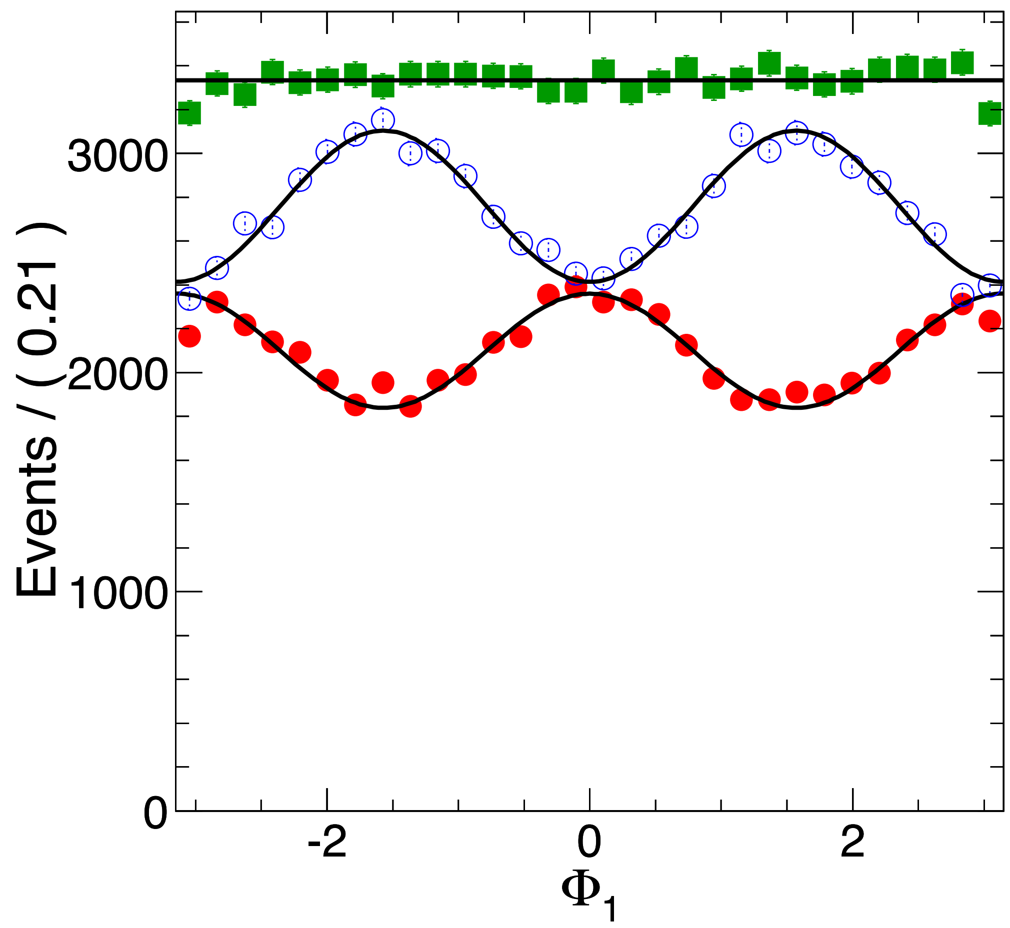
2+

gravition-like tensor longitudinally polarized and J_Z = 0 contribution

2−

pseudo-tensor



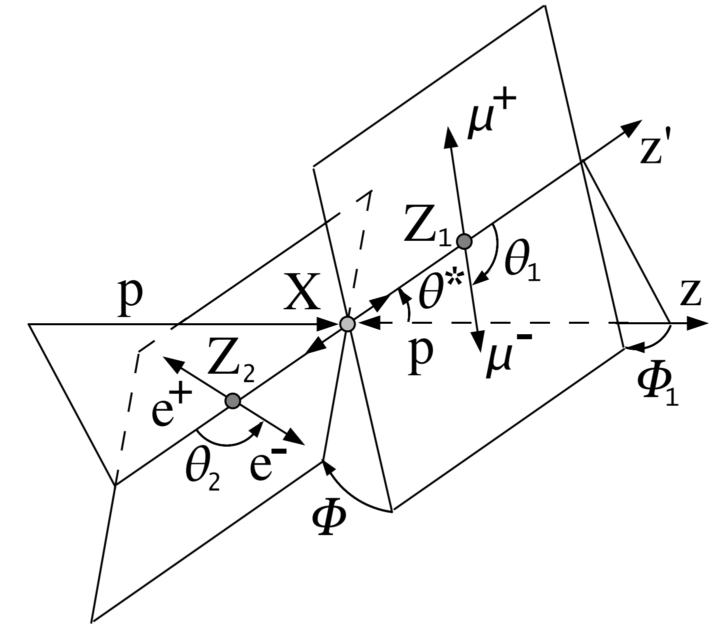


2+

gravition-like tensor with minimal couplings

Spin 0; θ* and Φ_1 …

Angular Distributions – Expectation

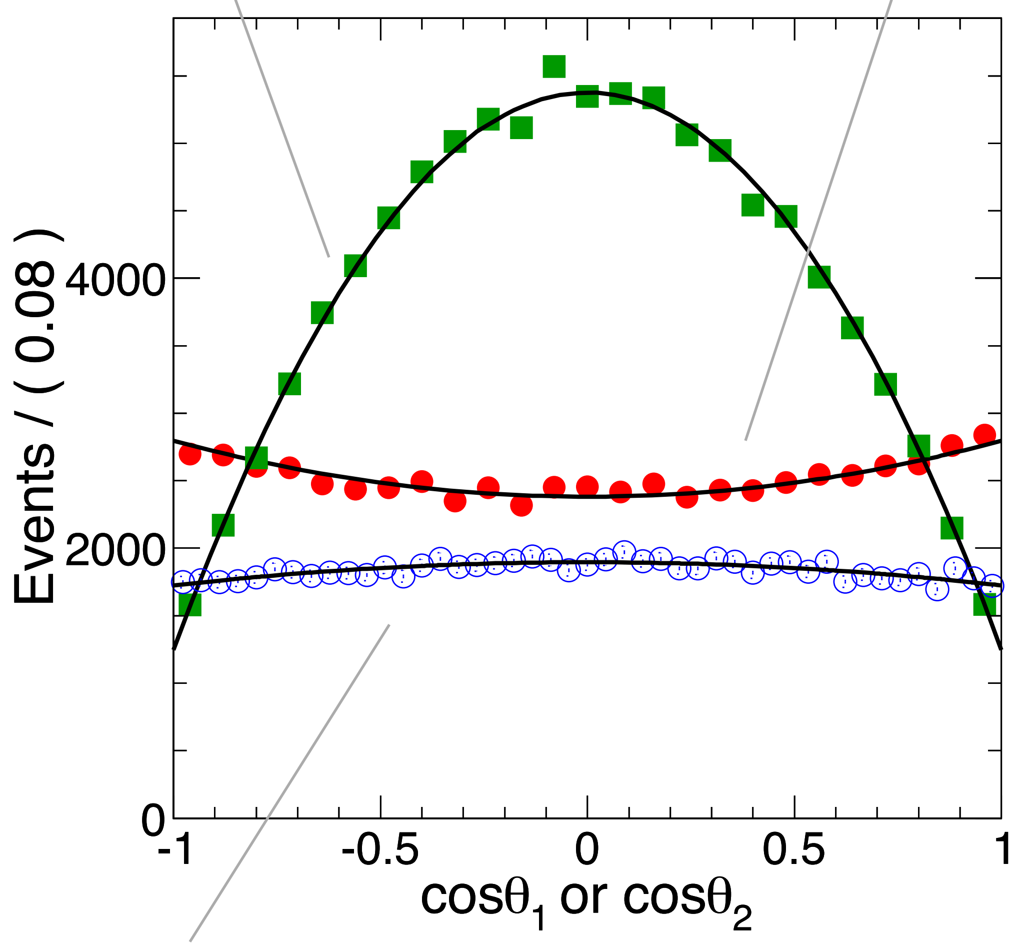


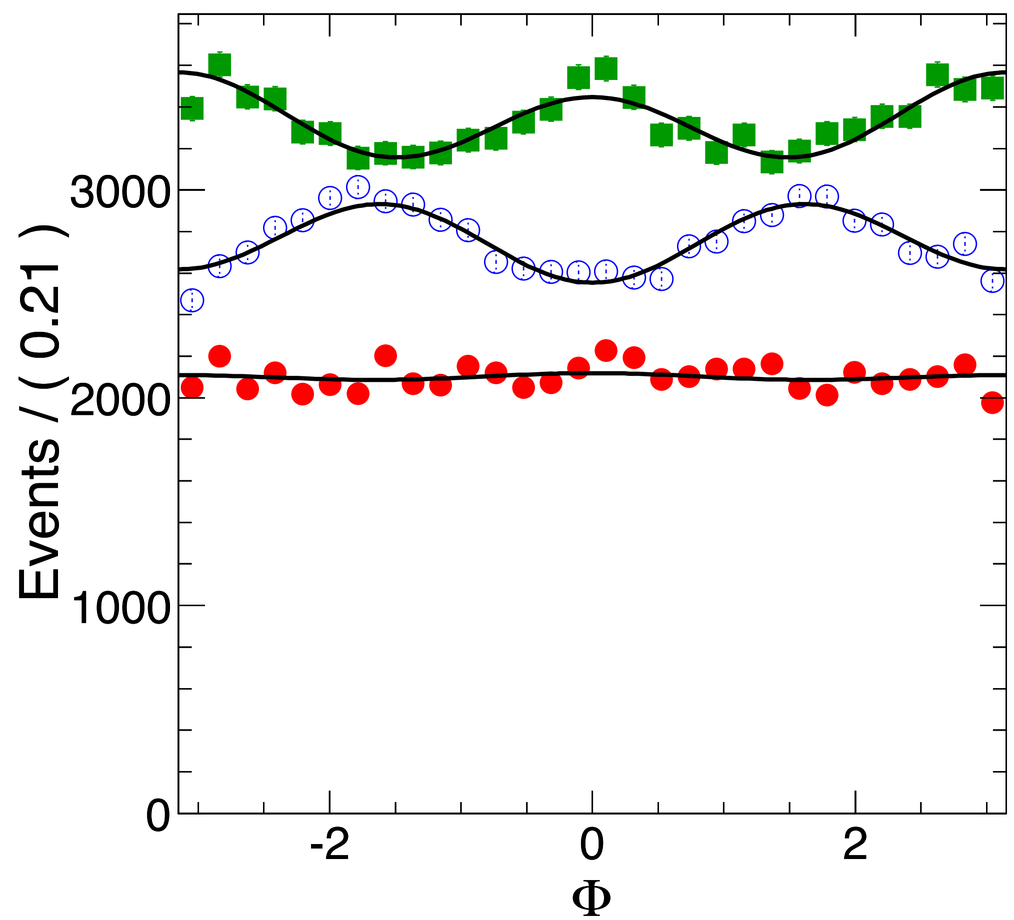
2^+

gravition-like tensor longitudinally polarized and $J_Z = 0$ contribution

2^+

gravition-like tensor with minimal couplings





2^-

pseudo-tensor

Spin 1; $\theta_{1,2}$ and Φ …

Higgs Spin and Parity – Analysis

H ➛ ZZ analysis

CMS-HIG-12-04
[12.2 fb^{-1} at 8 TeV & 5.1 fb^{-1} at 7 TeV]

ATLAS-CONF-2013-013
[20.7 fb^{-1} at 8 TeV & 4.8 fb^{-1} at 7 TeV]

H ➛ WW analysis

ATLAS-CONF-2013-031
[20.7 fb^{-1} at 8 TeV]

H ➛ γγ analysis

CMS-PAS-HIG-13-016
[19.6 fb^{-1} at 8 TeV & 5.1 fb^{-1} at 7 TeV]

ATLAS-CONF-2013-029
[20.7 fb^{-1} at 8 TeV]

Combination

CERN-PH-EP-2013-102 [Phys. Lett B]
ATLAS-CONF-2013-040

	ZZ^*	WW^*	γγ
0^-	✔	–	–
$1^+,1^-$	✔	✔	–
2^+	✔	✔	✔

H ➛ ZZ analysis

Full reconstruction of 4 decay products
5 decay angles to characterize decay kinematics

H ➛ WW analysis

Only leptonic decays; partial event reconstruction

H ➛ γγ analysis

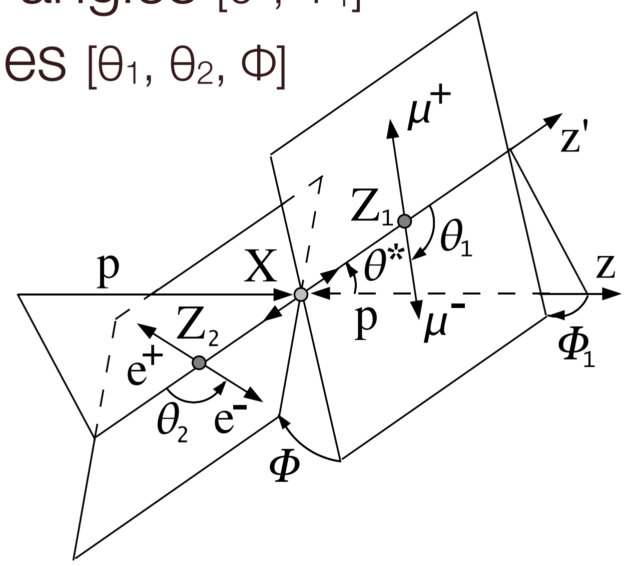
Sensitivity through polar angular distribution
Only one decay angle to characterize decay kinematics

e.g. CMS
[arXiv:1212.6639]

CMS-Analysis [H ➛ ZZ ➛ 4 leptons]

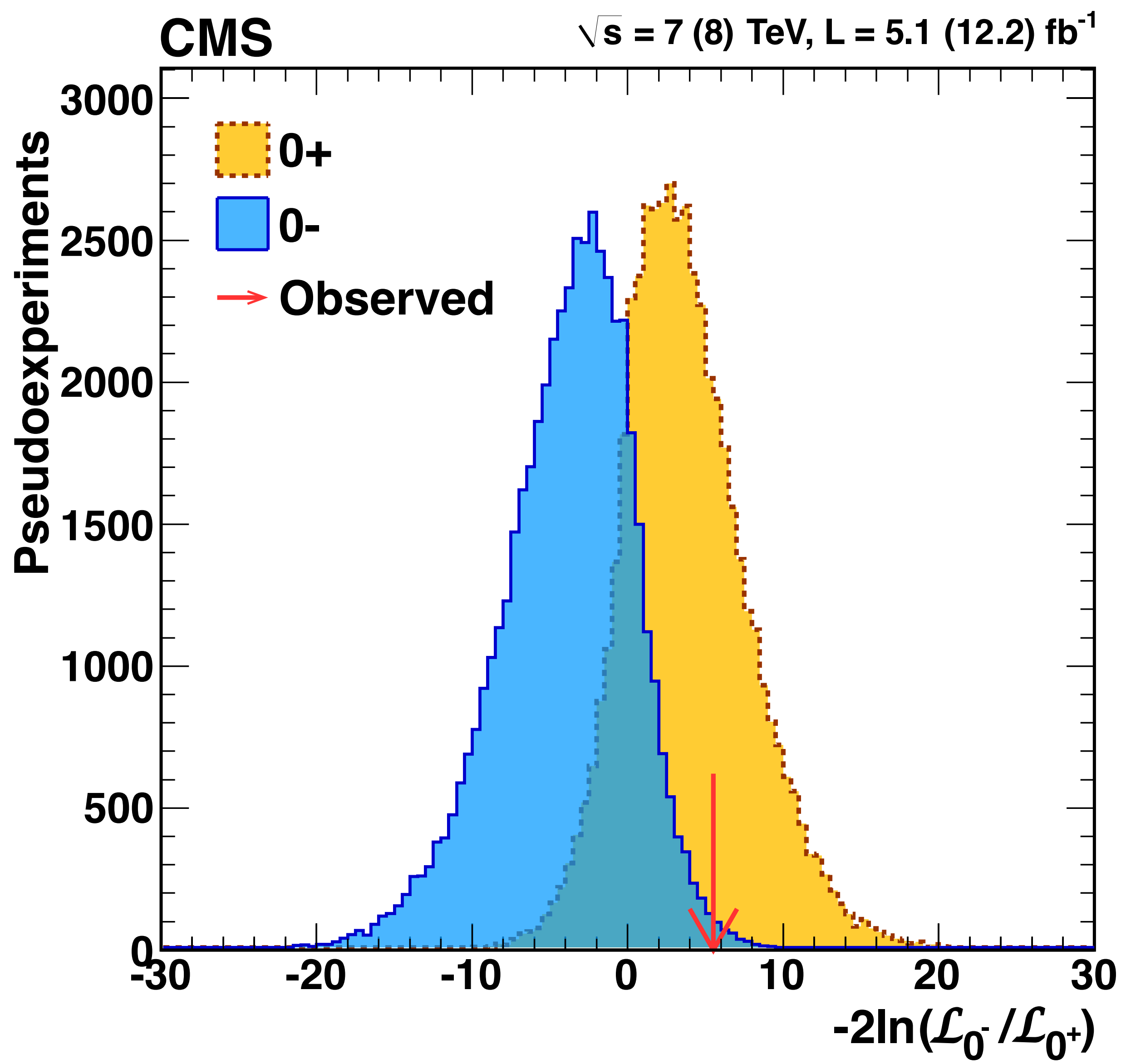
Description of 4-lepton events by a set of 8 variables:

- 3 masses [m_{4l}, m_{Z1}, m_{Z2}]
- 2 production angles [θ^*, Φ_1]
- 3 decay angles [θ_1, θ_2, Φ]



The PDF of these 8 variables can be calculated for a particular model …

In principle: use 8-dimensional fit …



Limited statistics: Combine the non-m_{4l} variables into kinematic discriminants …

CMS – Matrix Element Likelihood Analysis

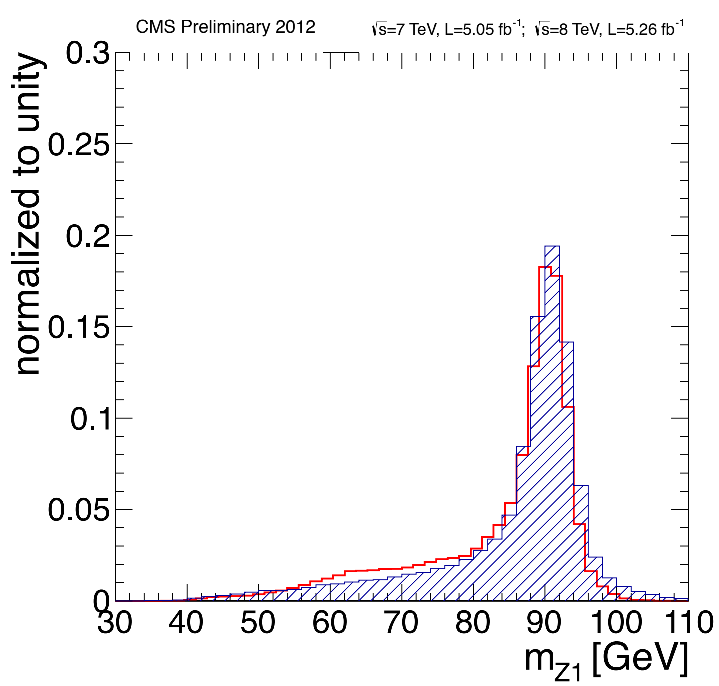
H ➛ ZZ ➛ 4 lepton CMS Analysis …
Use of MELA/K_D observable …

Kinematic discriminant K_D using the probability density in the di-lepton masses and angular variables …

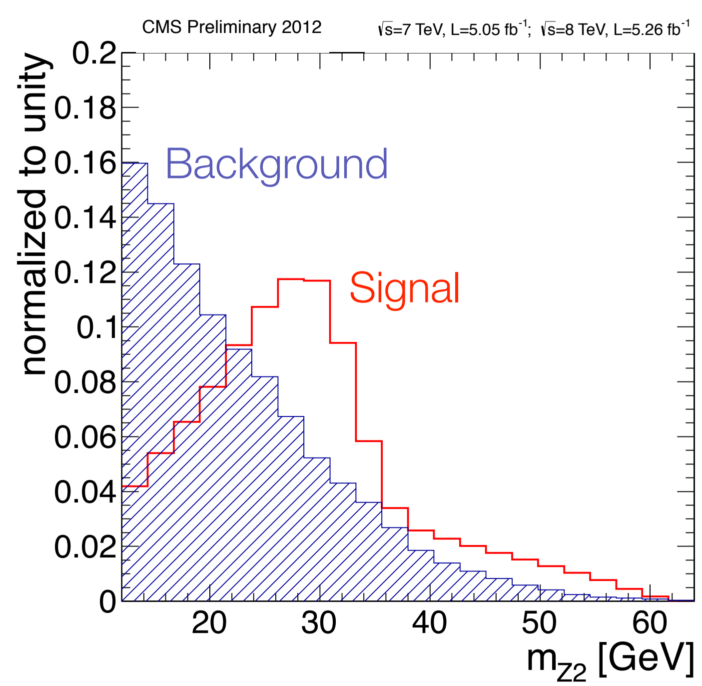
$$K_D \equiv \frac{\mathcal{P}_{\text{sig}}}{\mathcal{P}_{\text{sig}} + \mathcal{P}_{\text{bkg}}} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

with
$$\vec{\Omega} = \{\theta^*, \Phi_1, \theta_1, \theta_2, \Phi\}$$

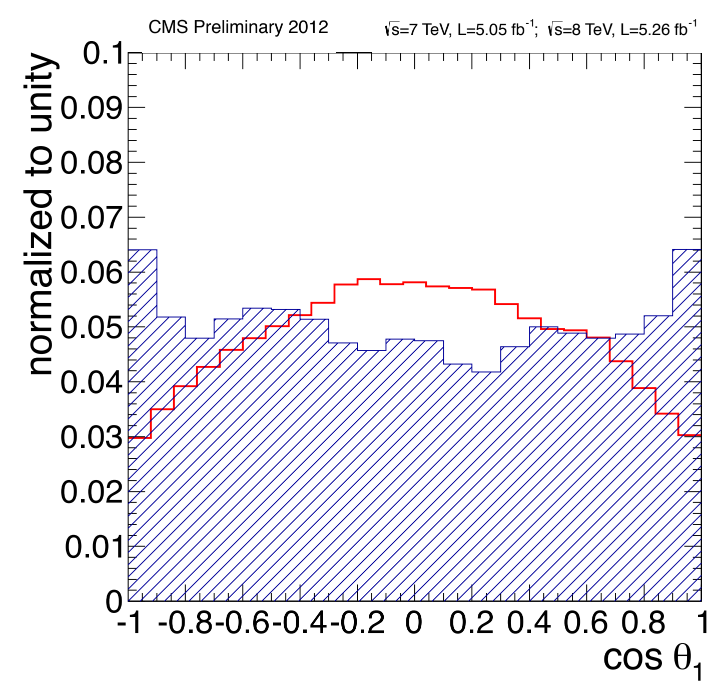
Invariant mass of on-shell Z boson



Invariant mass of off-shell Z boson



Distribution of cos θ_1



CMS – Matrix Element Likelihood Analysis

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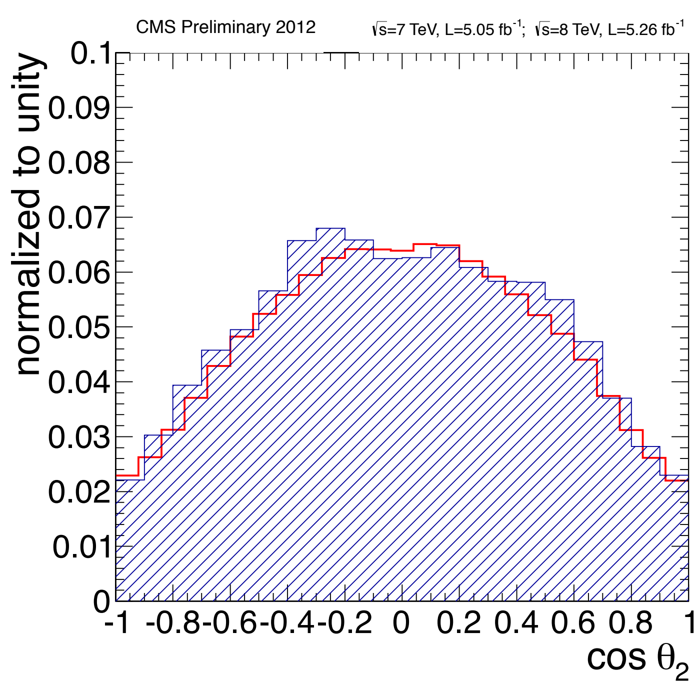
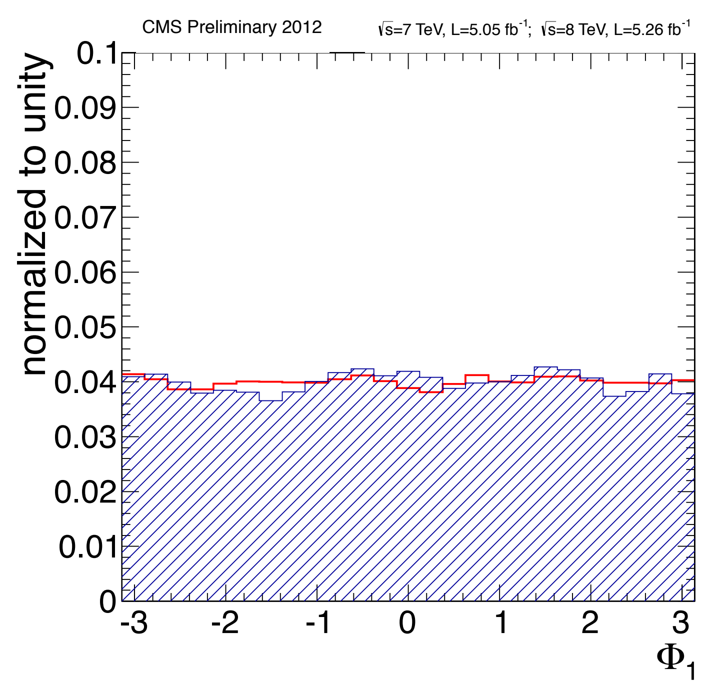
with
$$\vec{\Omega} = \{\theta^*, \Phi_1, \theta_1, \theta_2, \Phi\}$$

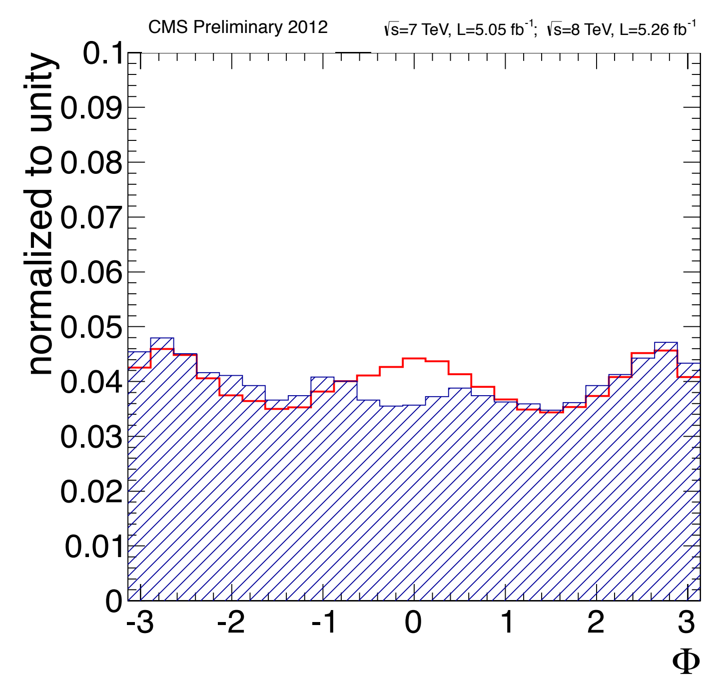
Distribution of $\cos\theta_2$



Distribution of $\cos\Phi_1$



Distribution of $\cos\Phi$



CMS – Matrix Element Likelihood Analysis

H ➛ ZZ ➛ 4 lepton CMS Analysis …
Use of MELA/K_D observable …

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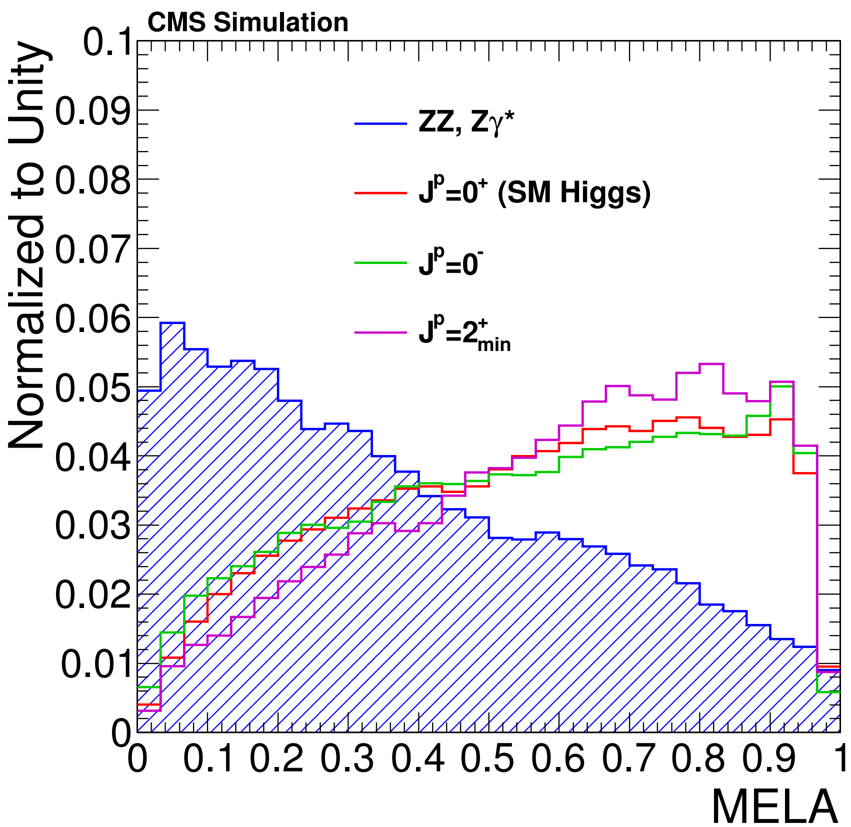
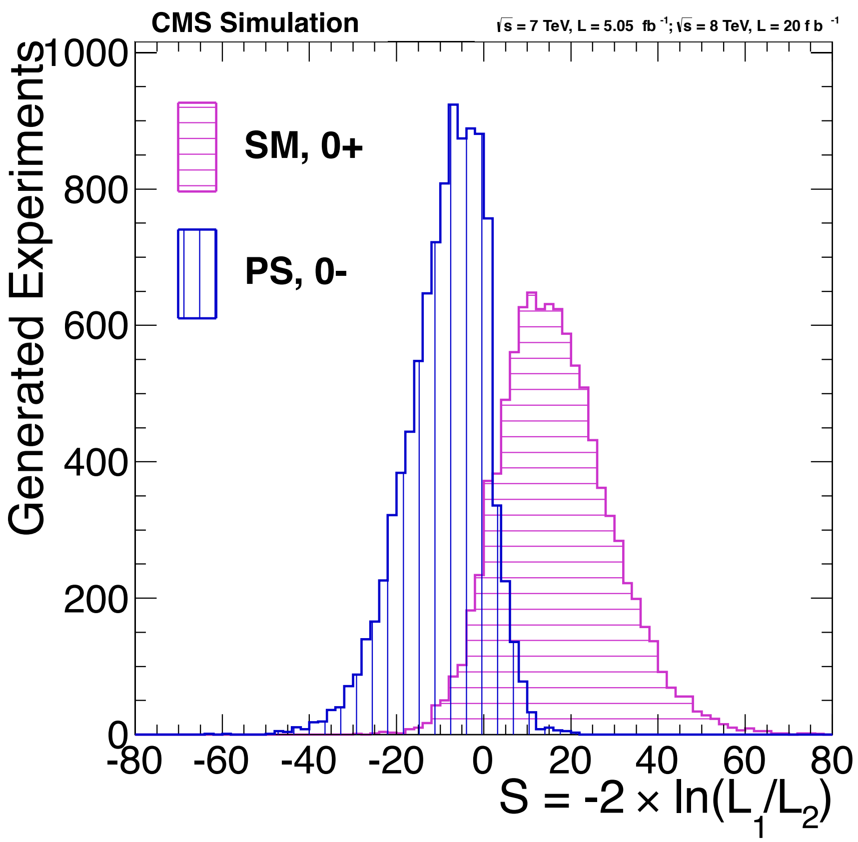
$$K_D \equiv \frac{\mathcal{P}_{\rm sig}}{\mathcal{P}_{\rm sig} + \mathcal{P}_{\rm bkg}} = \left[1 + \frac{\mathcal{P}_{\rm bkg}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\rm sig}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

with

$$\vec{\Omega} = \{\theta^*, \Phi_1, \theta_1, \theta_2, \Phi\}$$





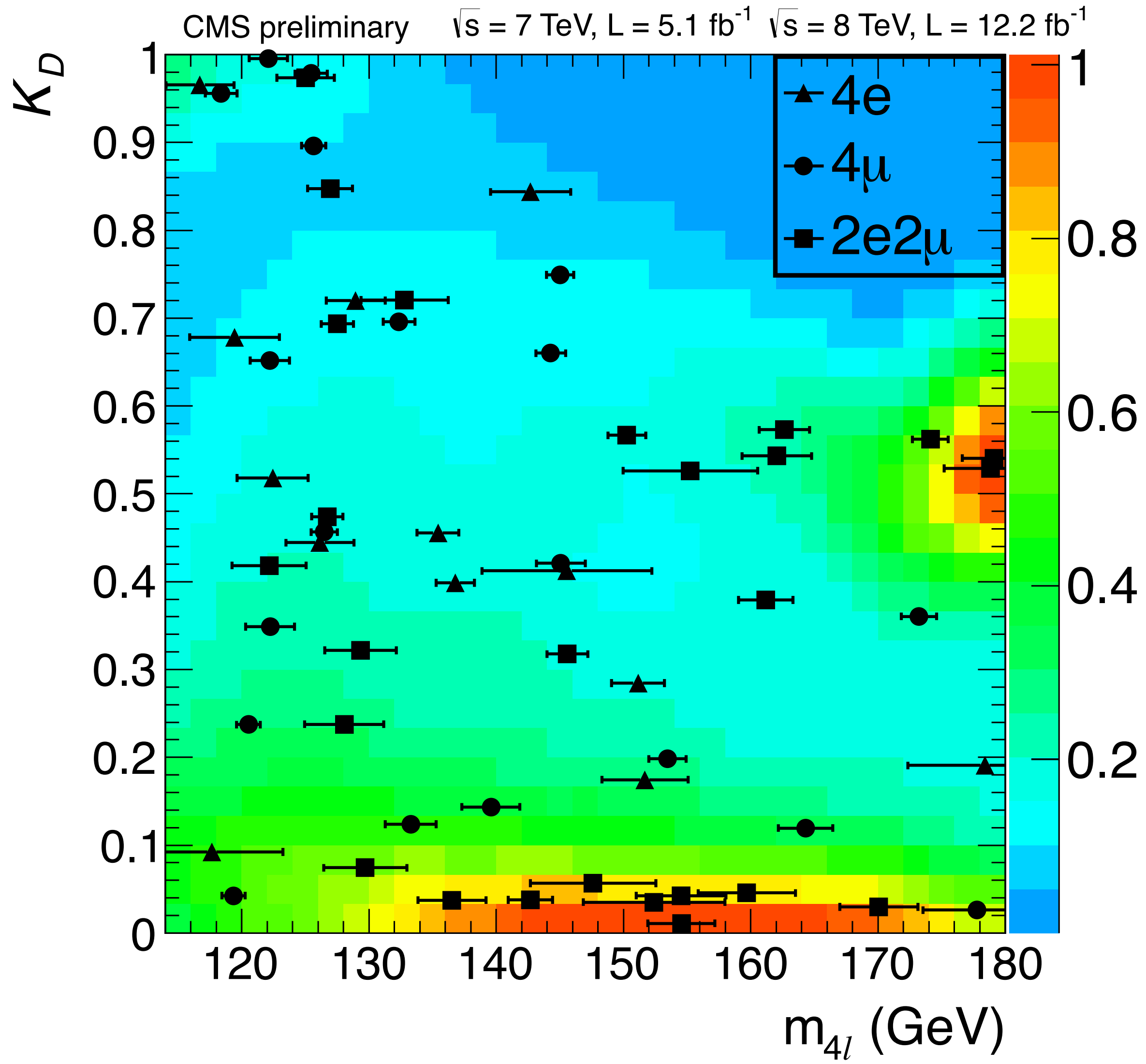
Projected separation of

$J^P = 0^+$ (purple) and
$J^P = 0^-$ (blue) resonances …

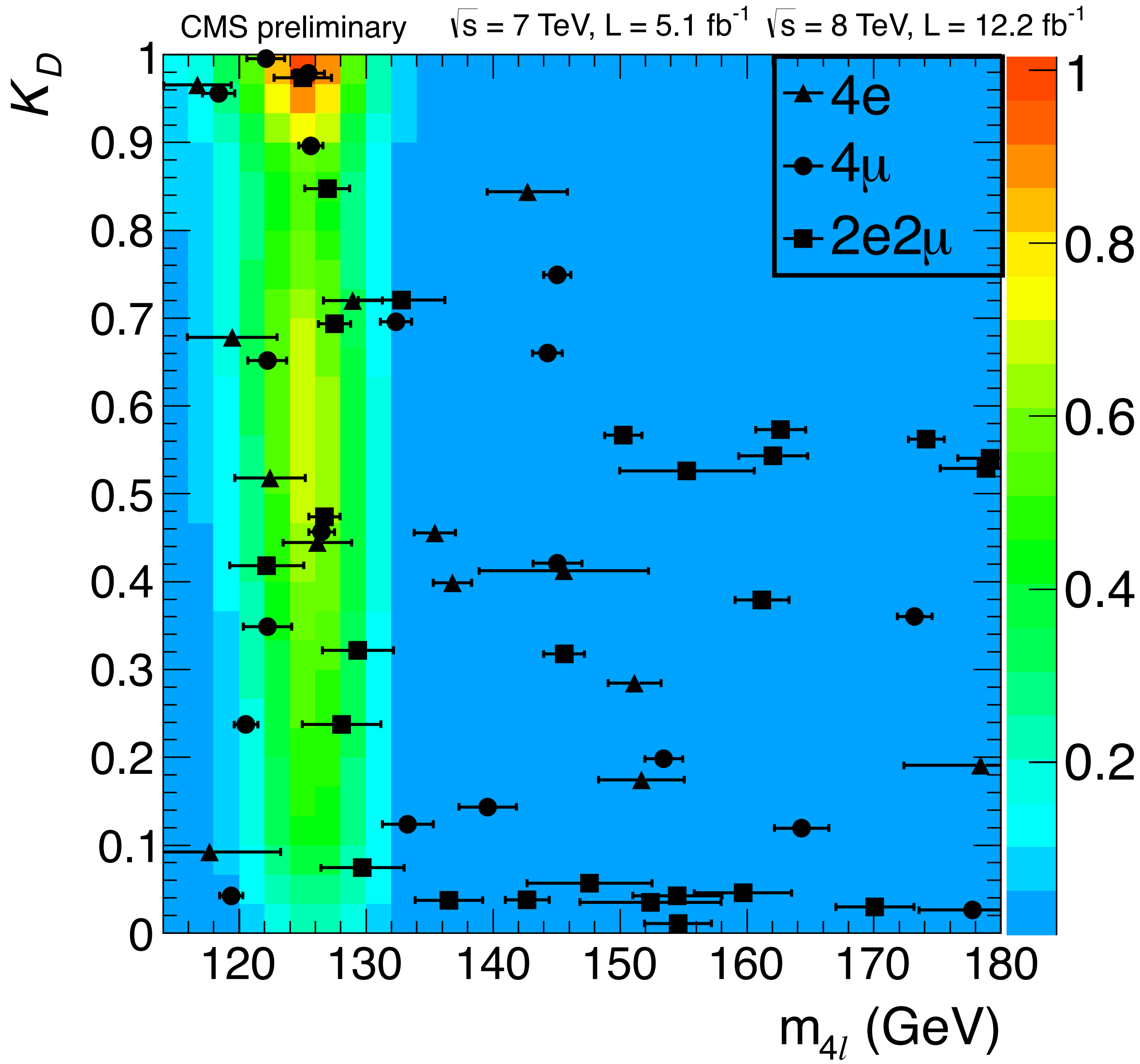
… with 20 fb^{-1} of 8 TeV data.

CMS – Data vs. Expectation

Background expectation



Signal expectation
[m_H = 126 GeV]



CMS – Distinguishing SM from other Models …

$$\text{MELA} \equiv \frac{\mathcal{P}_{\text{sig}}}{\mathcal{P}_{\text{sig}} + \mathcal{P}_{\text{bkg}}} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_{Z_1}, m_{zZ_2}, \vec{\Omega} \mid m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_{Z_1}, m_{zZ_2}, \vec{\Omega} \mid m_{4\ell})}\right]^{-1}$$

$$\text{superMELA} \equiv \frac{\mathcal{P}_{\text{sig}}}{\mathcal{P}_{\text{sig}} + \mathcal{P}_{\text{bkg}}} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_{Z_1}, m_{zZ_2}, \vec{\Omega} \mid m_{4\ell})\ \mathcal{P}_{\text{bkg}}(m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_{Z_1}, m_{zZ_2}, \vec{\Omega} \mid m_{4\ell})\ \mathcal{P}_{\text{sig}}(m_{4\ell})}\right]^{-1}$$

Define analogously:
[analogous to superMELA]

$$\mathcal{D}_{12} = \frac{\mathcal{P}_1}{\mathcal{P}_1 + \mathcal{P}_2}$$

$\mathcal{P}_1$: J^P hypothesis 1

$\mathcal{P}_2$: J^P hypothesis 2 or bkg. hypothesis

$\mathcal{D}_{\text{SB}}$: Discriminator for SM vs. background

$\mathcal{D}_{\text{PS}}$: Discriminator for Pseudoscalar ($J^P = 0^-$) vs. SM

$\mathcal{D}_{\text{GS}}$: Discriminator for Spin-2 Tensor ($J^P = 2^+$) vs. SM

CMS – Distinguishing SM from other Models …

Two-dimensional unbinned likelihood fit …

$$\mathcal{L} = \prod_{i=1}^{N} p(\vec{x}_i, \vec{a})$$

N : number of events
p : probability from model prediction

x_i : set of observables for event i
a : model parameters

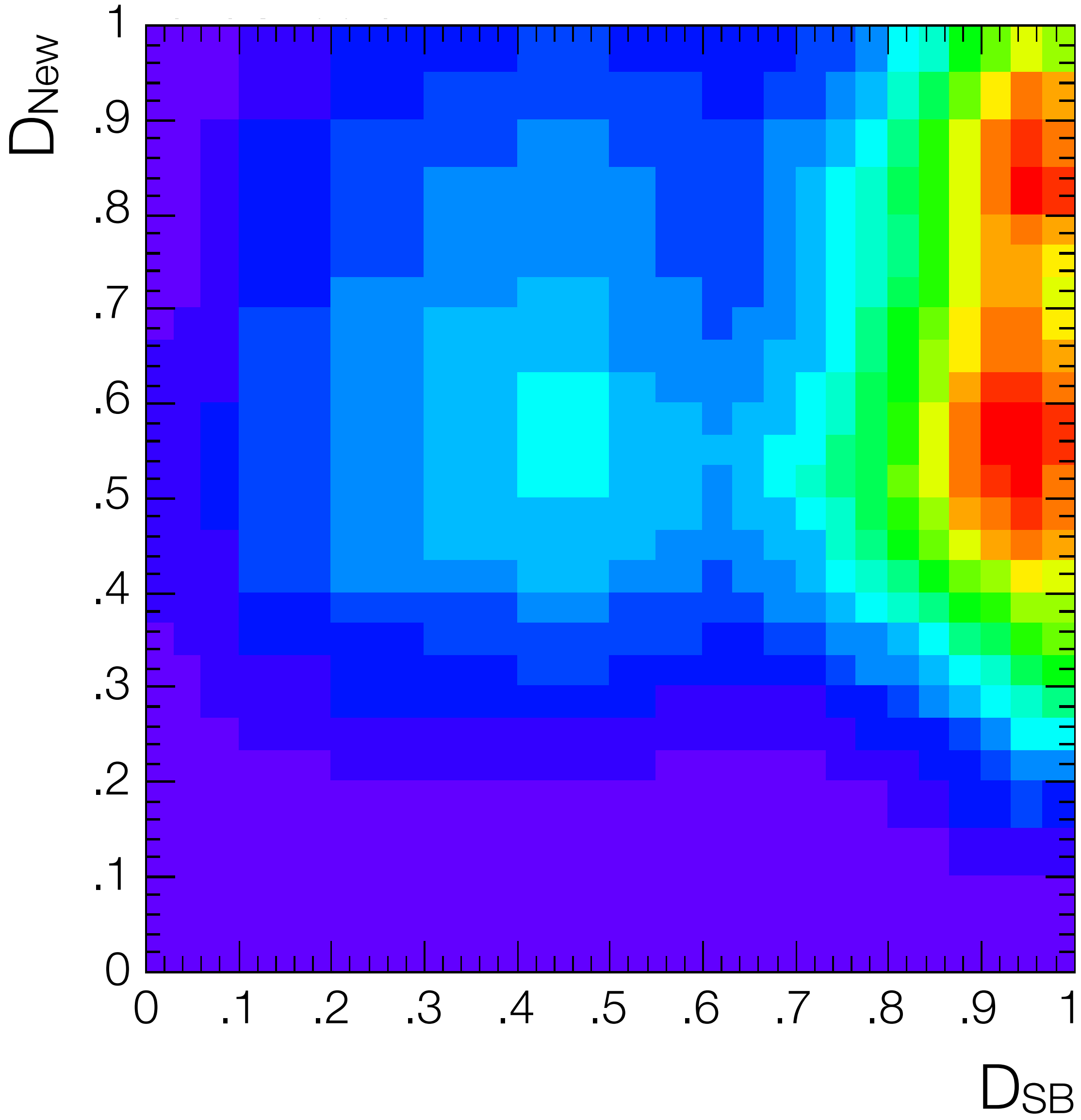
Discriminants:

$$\mathcal{D}_{\rm New} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + \mathcal{P}_{\rm New}} \qquad \mathcal{D}_{\rm SB} = \frac{\mathcal{P}_{\rm sig}}{\mathcal{P}_{\rm sig} + \mathcal{P}_{\rm bgr}}$$

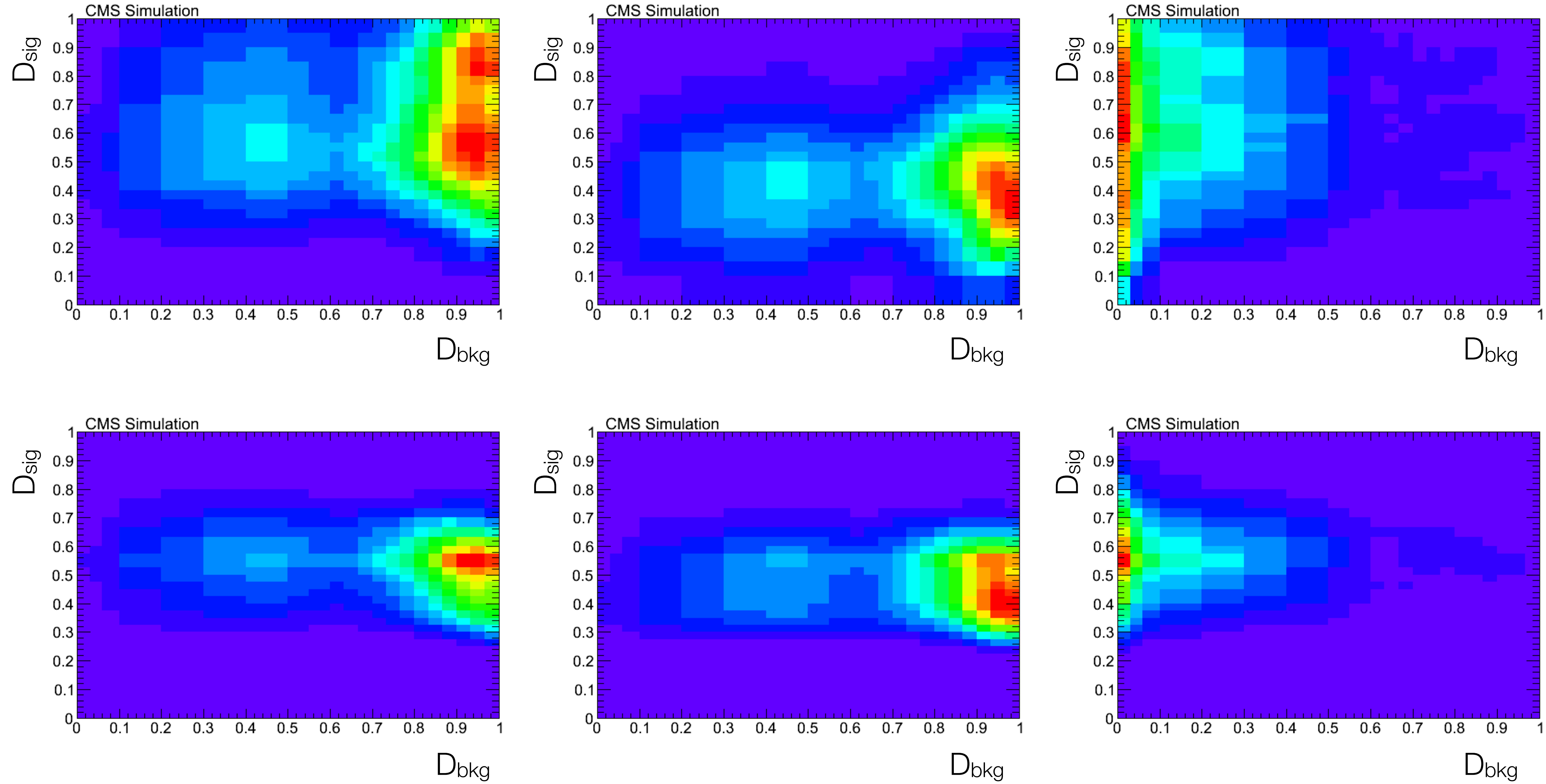
Likelihood ratio:

$$q = -2\ln\frac{\mathcal{L}_{\rm New1}}{\mathcal{L}_{\rm New2}}$$

Two-dimensional template



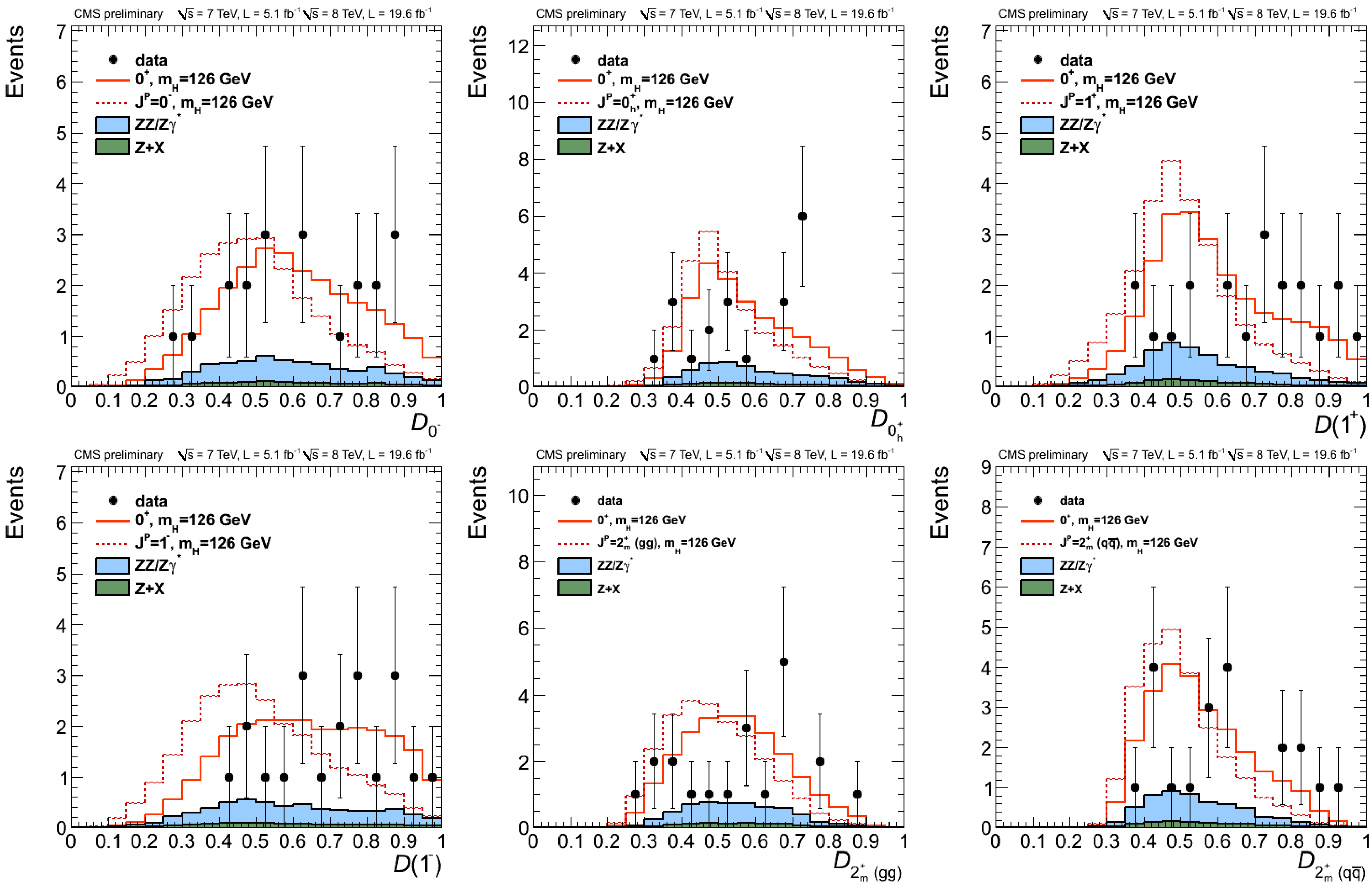
CMS – Templates for Hypothesis Testing



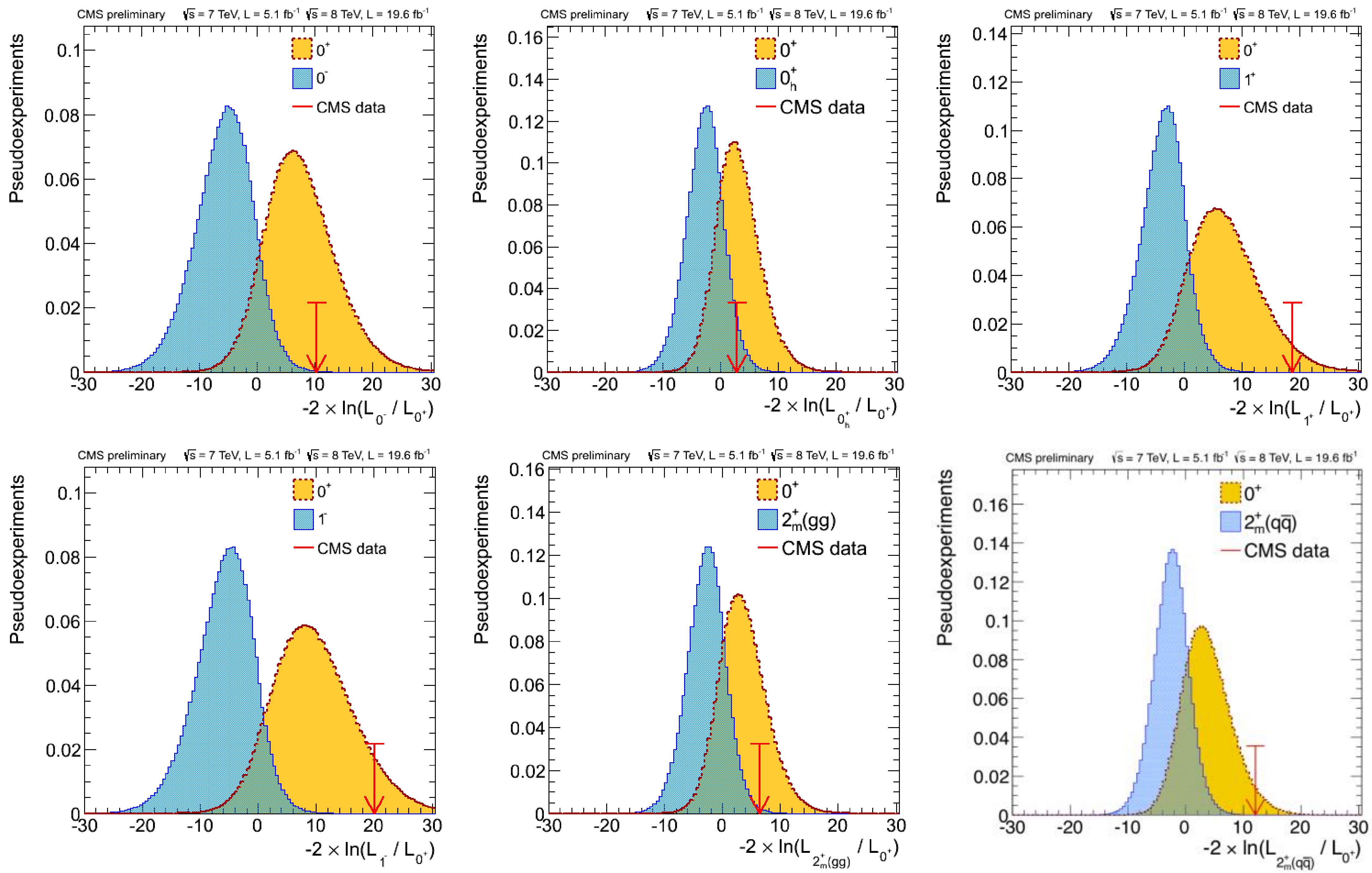
CMS – Alternative Models

0^+ : SM Higgs with minimal coupling
0^- : pure pseudoscalar
0^+_h : higher dimension operators (in decay amplitude)
1^- : vector
1^+ : axial vector
2^+_{gg} : graviton with minimal coupling
2^+_{qq} : graviton with minimal coupling

CMS – D_{sig} distributions for D_{bkg} > 0.5



CMS – Profiled Log-Likelihood Distributions



CMS – Results of Spin-Parity Analysis

J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_S
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0^+_h	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
2^+_{mqq}	$qq \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$qq \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	>4.0σ	<0.1%
1^+	$qq \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	>4.0σ	<0.1%

Separation of alternative models from the SM. The expected separation is quoted for two scenarios, when the signal strength is pre-determined from the fit to data and when events are generated with SM expectation for the signal yield (μ = 1). The observed separation quotes the difference between the observation and the expected average of the 0^+ model or the J^P model expressed in standard deviations, and corresponds to the scenario where the signal strength is pre-determined from the fit to data. The last column quotes CL_S criterion for the J^P model.

The studied pseudo-scalar, spin-1 and spin-2 models are excluded at 95% CL or higher

ATLAS – Statistical Treatment

Same for all analyses [0^+ vs. 1^+ …]

Use likelihood function with ε giving the fraction of a spin-0 component …
[ε = 0: spin = 2; ε = 1: spin = 0; signal strength μ: nuisance parameter …]

Bkgr.

$$\mathcal{L}(\epsilon,\mu,\vec{\theta}) = \prod_i^{N_{bins}} P\left(N_i \,|\, \mu\left(\epsilon S_{0^+,i}(\vec{\theta}) + (1-\epsilon) S_{2^+,i}(\vec{\theta})\right) + b_i(\vec{\theta})\right) \times \prod_j^{N_{sys}} \mathcal{A}(\tilde{\theta}_j|\theta_j)$$

Spin 0

Spin 2

Test statistic q:

$$q = \log \frac{\mathcal{L}(H_{0^+})}{\mathcal{L}(H_{2^+_m})} = \log \frac{\mathcal{L}(\epsilon = 1, \hat{\hat{\mu}}_{\epsilon=1}, \hat{\hat{\theta}}_{\epsilon=1})}{\mathcal{L}(\epsilon = 0, \hat{\hat{\mu}}_{\epsilon=0}, \hat{\hat{\theta}}_{\epsilon=0})}$$

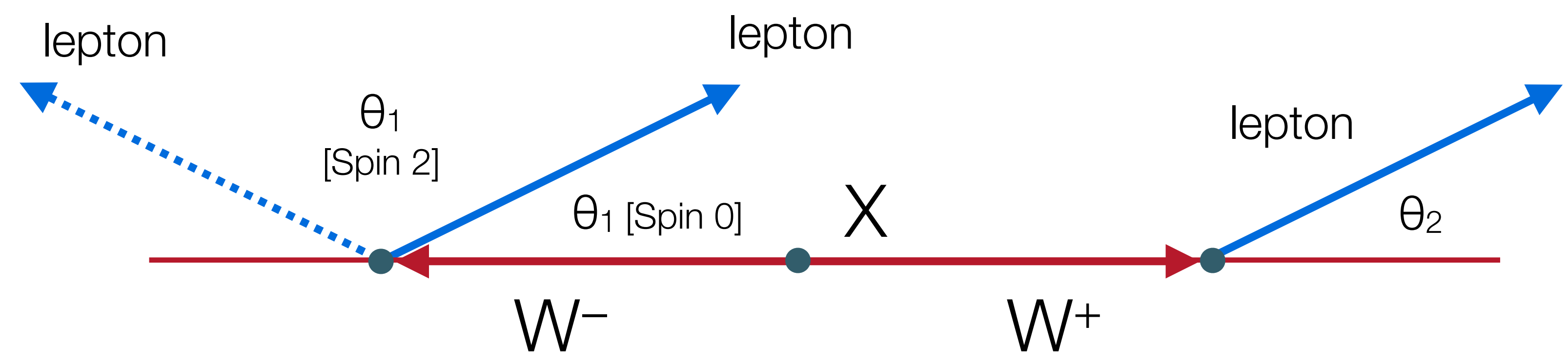
Results given in terms of p_0-values and as normalized CL_S …

Confidence level for exclusion of $J^P = 2^+$

$$\mathrm{CL_S}(J^P = 2^+) = \frac{p_0(J^P = 2^+)}{1 - p_0(J^P = 0^+)}$$

ATLAS

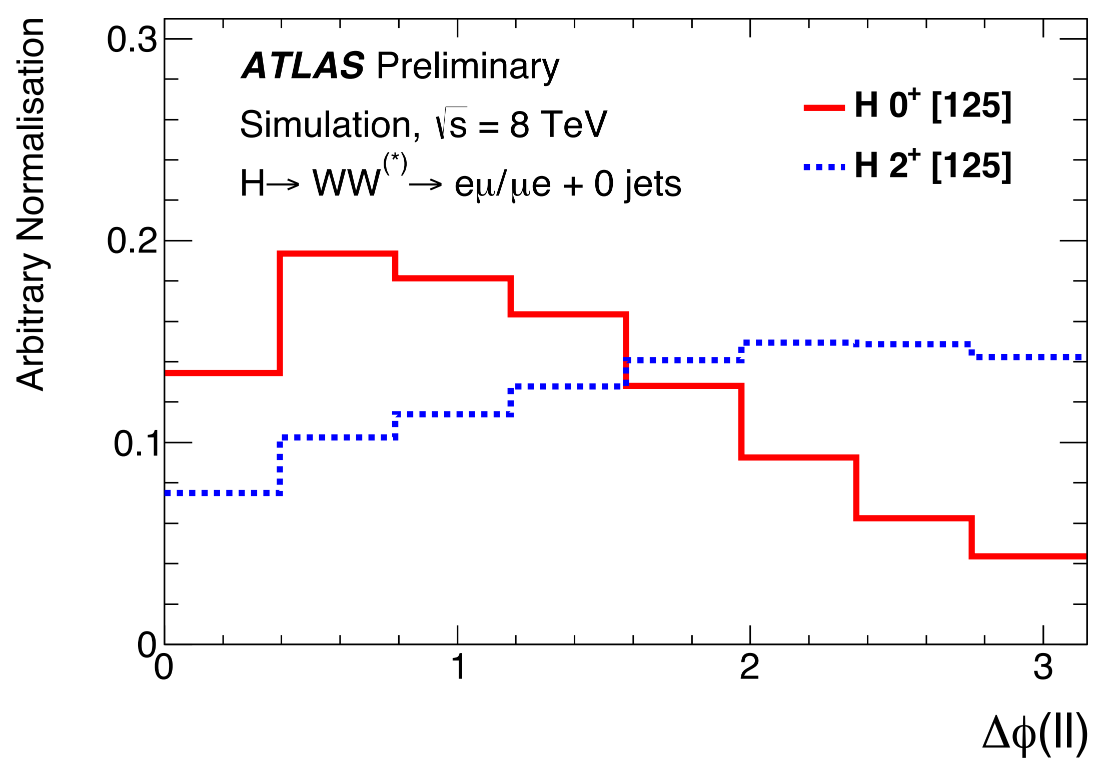
H ➝ WW ➝ lvlv



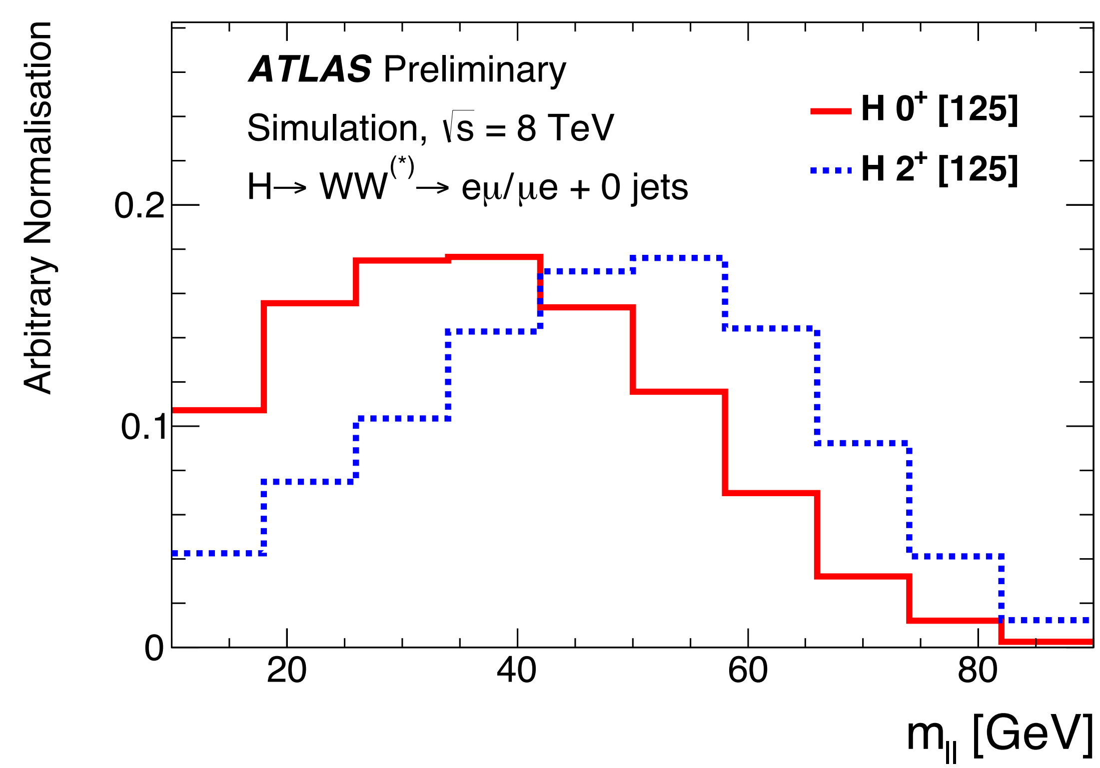
Spin correlations between the two W bosons, and hence the final leptons, depend on the spin assignment of the decaying resonance X …

Kinematic distributions for the di-lepton pair discriminate between different spin hypotheses …

Azimuth between leptons



Lepton invariant mass



ATLAS

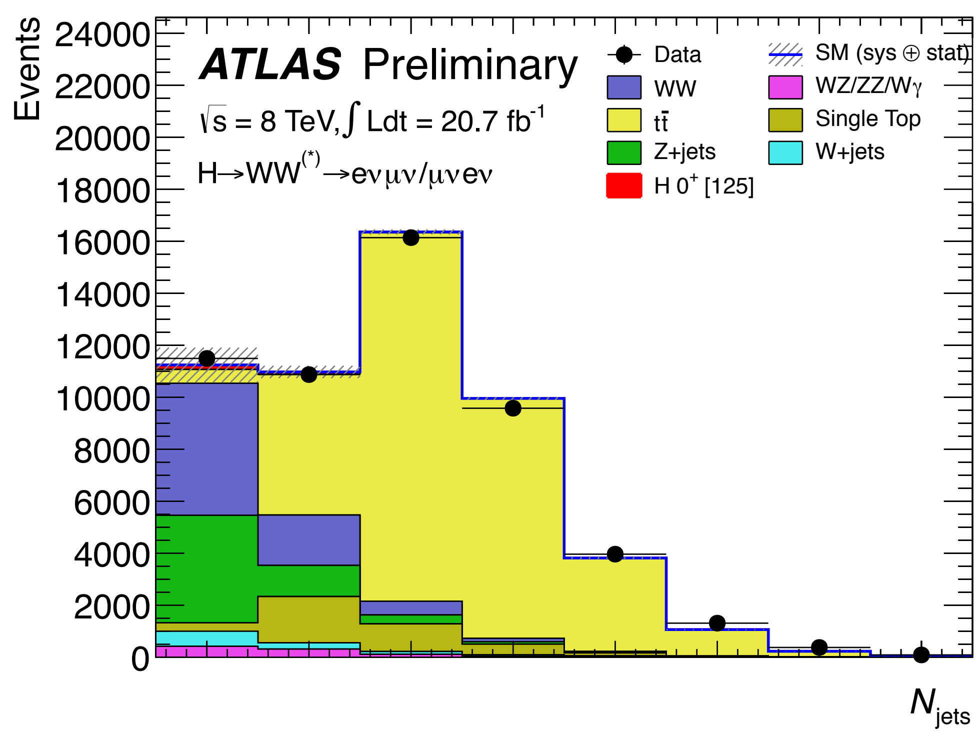
H ➛ WW ➛ lvlv

Variable	Spin analysis	Rate analysis [5]
common $e\mu/\mu e$ lepton selection		
$E_{\mathrm{T,rel}}^{\mathrm{miss}}$	> 20 GeV	> 25 GeV
N_{jets}	0 jets	0, 1, ≥ 2 jet selections
$p_{\mathrm{T}}^{\ell\ell}$	> 20 GeV	> 30 GeV
$m_{\ell\ell}$	< 80 GeV	< 50 GeV
$\Delta\phi_{\ell\ell}$	< 2.8	< 1.8

Preselection:

Re-use criteria from well-established rate measurement but:

- loosen selection cuts
- looking only at the eμ/0-jet final state



Selection via BDT …

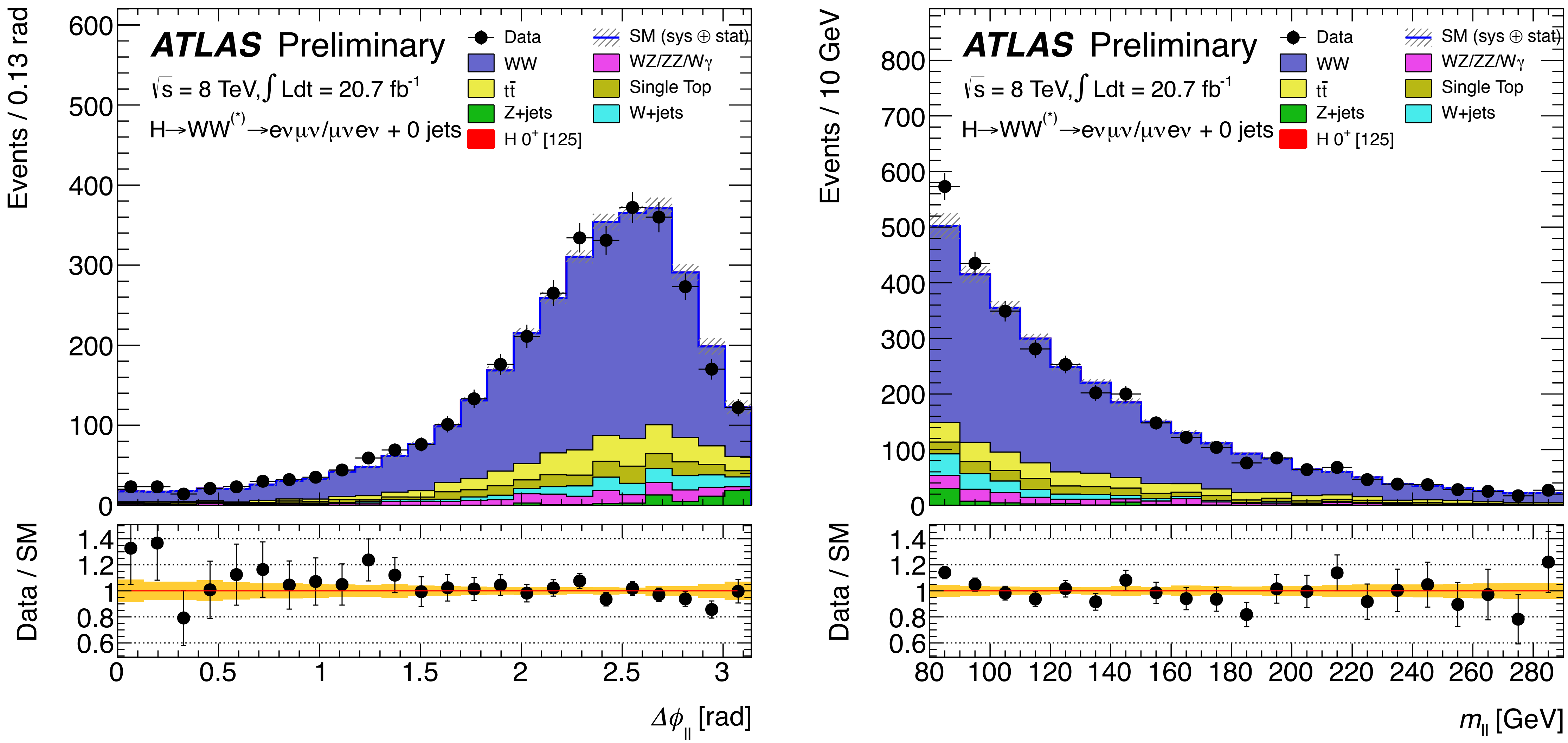
Input variables:

- m_{ll} : di-lepton invariant mass
- $p_{T,ll}$: di-lepton transverse momentum
- $\Delta\phi_{ll}$: di-lepton angular difference
- m_T : transverse mass of system

ATLAS

H ➛ WW ➛ lvlv

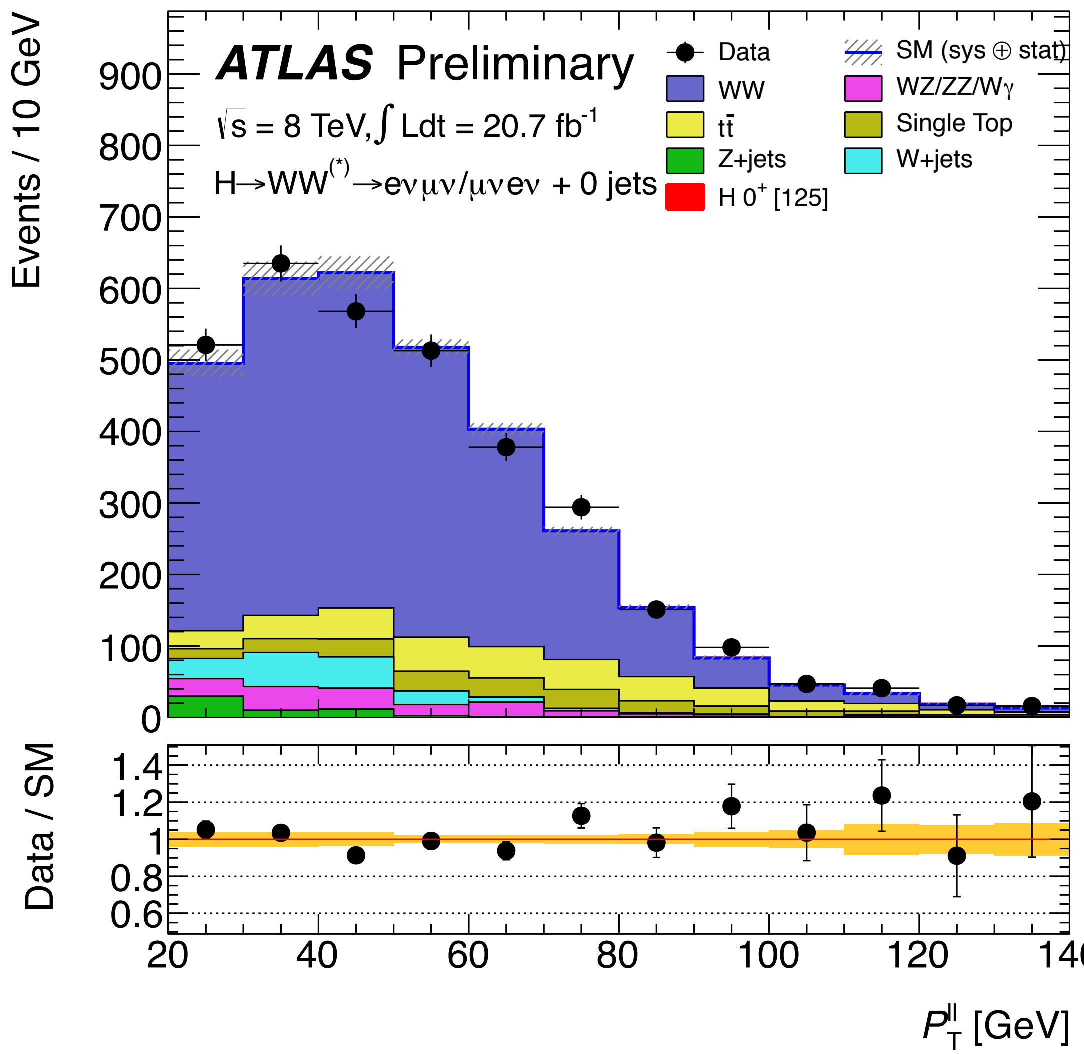
BDT Input Variables in Control Region

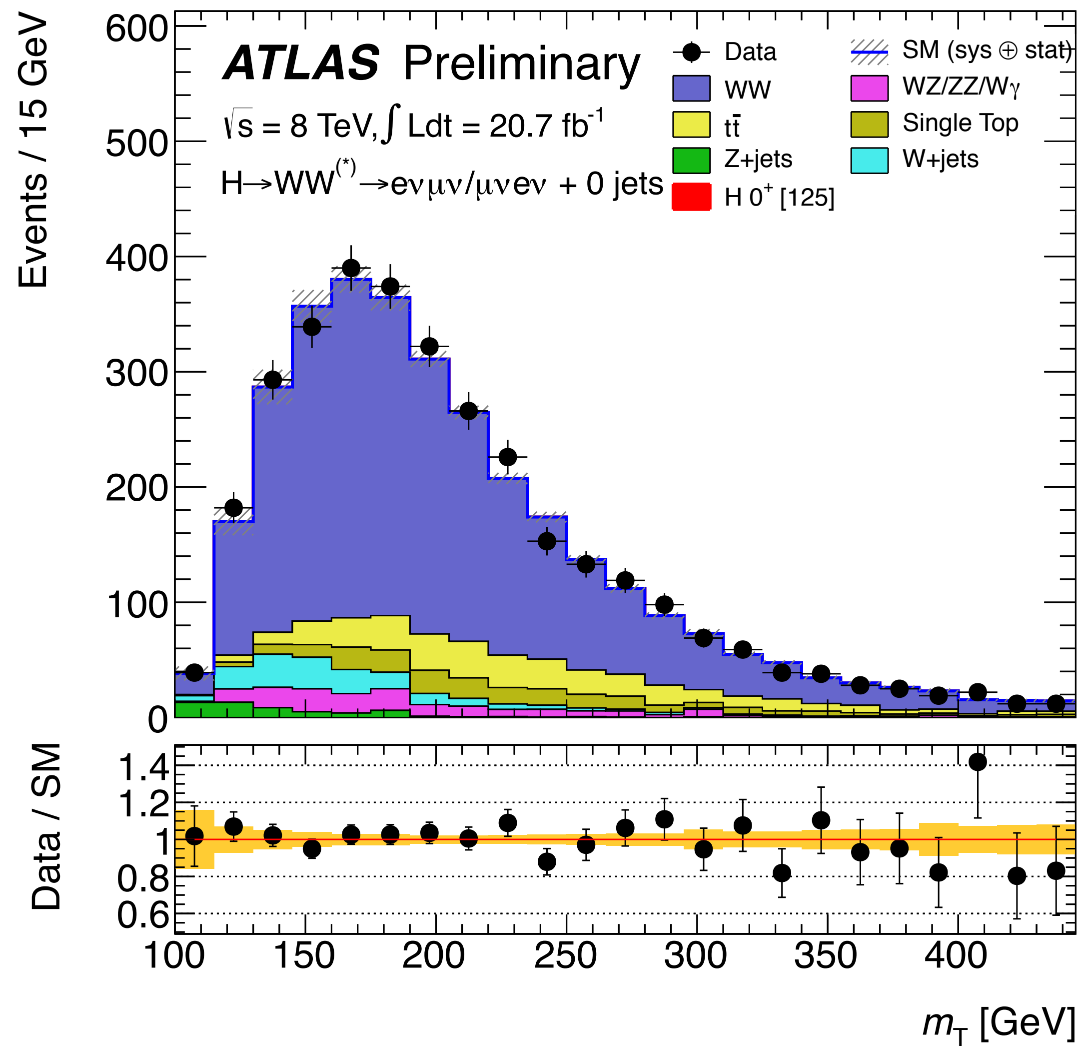


ATLAS

H ➛ WW ➛ lvlv

BDT Input Variables in Control Region

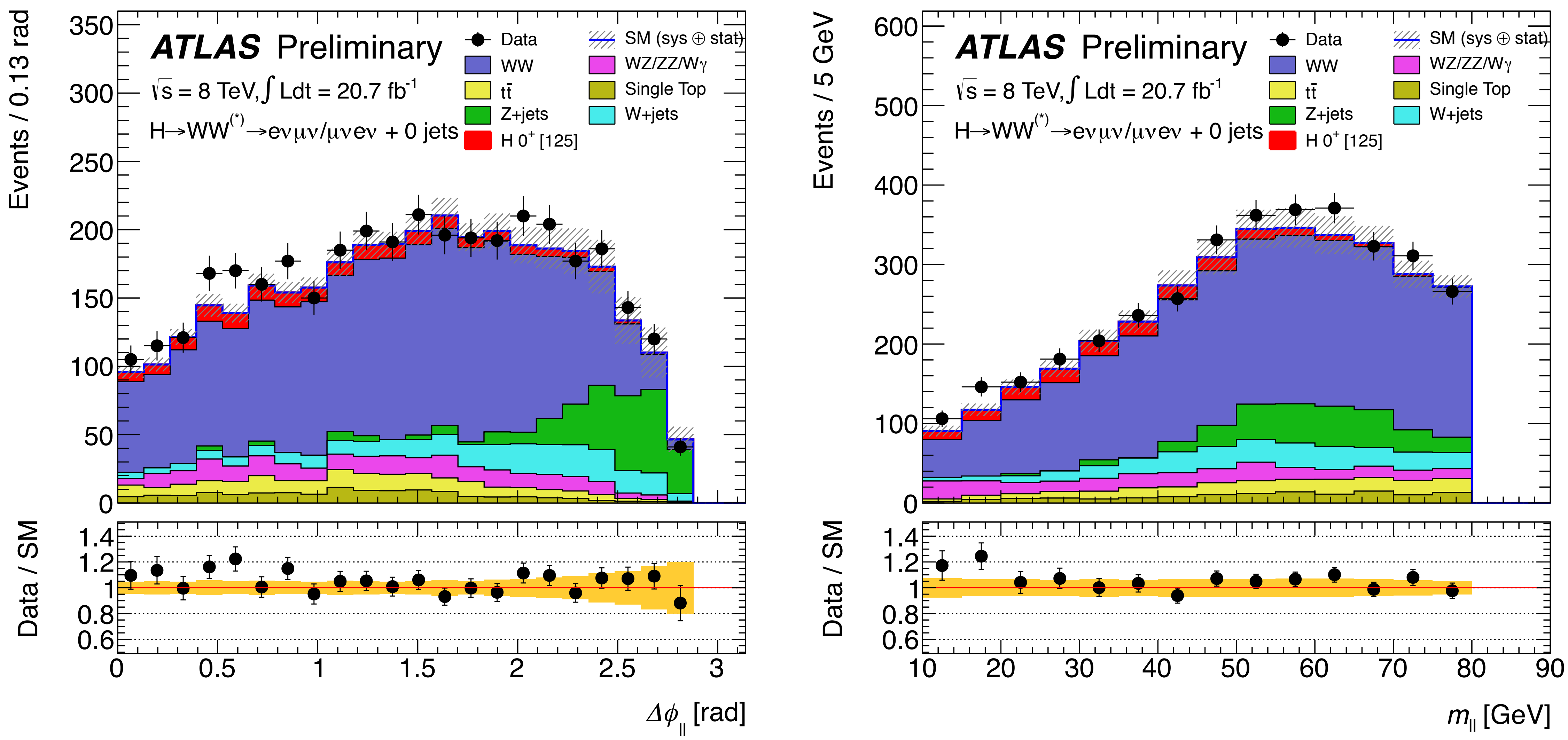




ATLAS

H ➤ WW ➤ lνlν

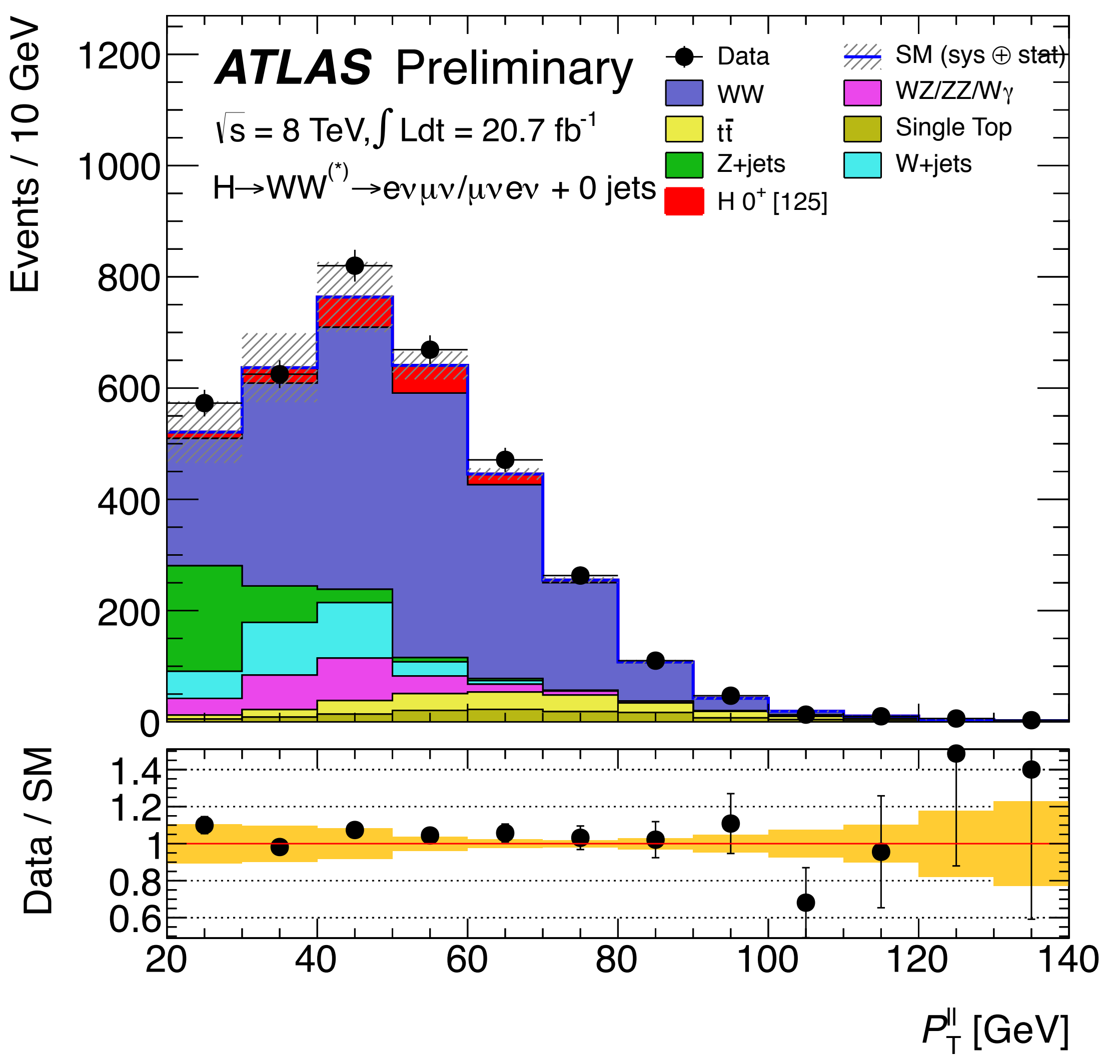
BDT Input Variables in Signal Region

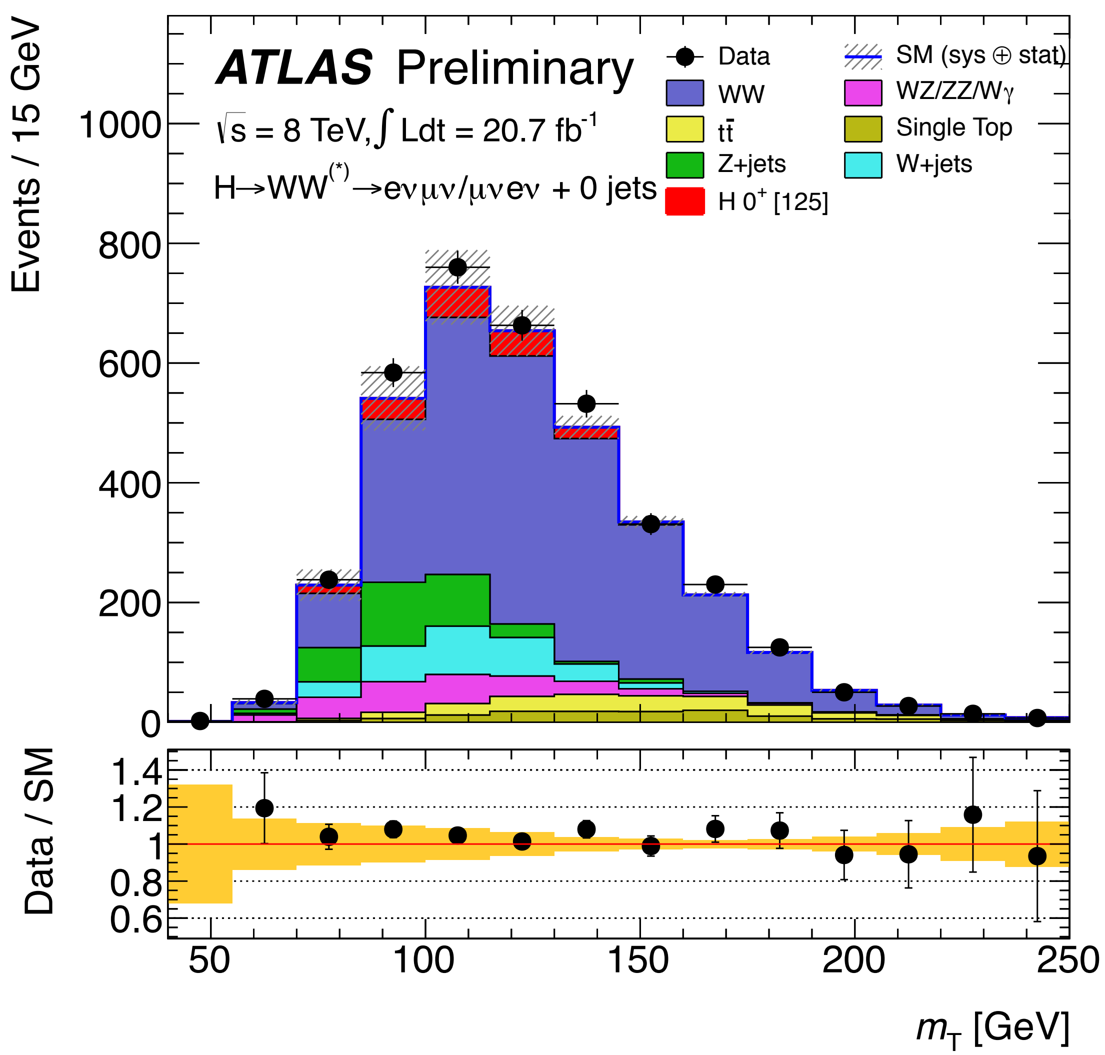


ATLAS

H ➤ WW ➤ lνlν

BDT Input Variables in Signal Region



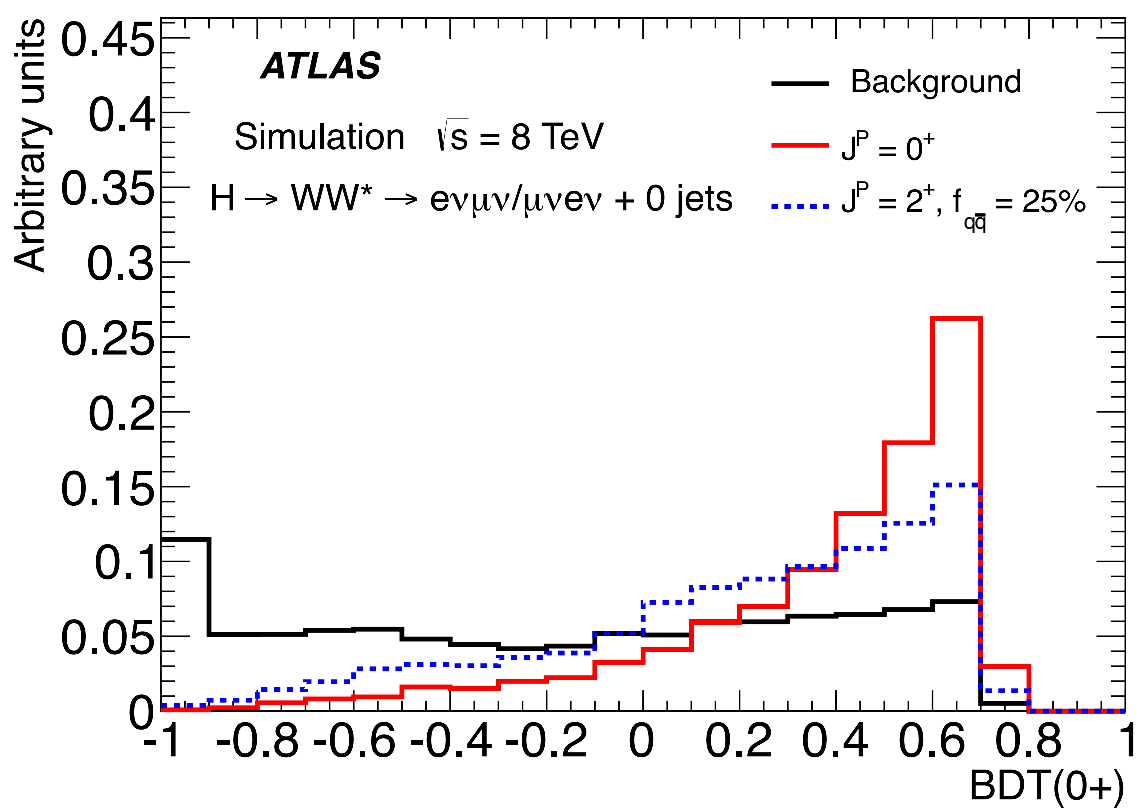


ATLAS

H ➤ WW ➤ lνlν

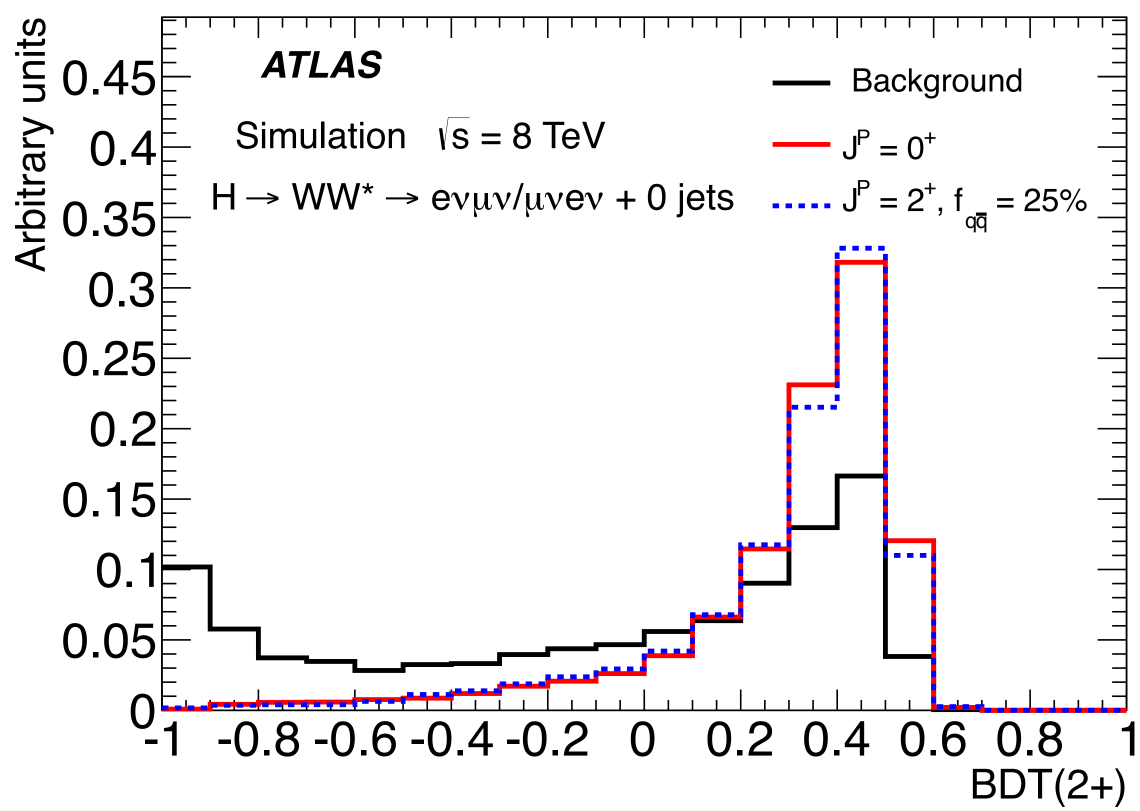
BDT 0

[Trained using 0^+ sample as signal]



BDT 2

[Trained using 2^+ sample as signal]



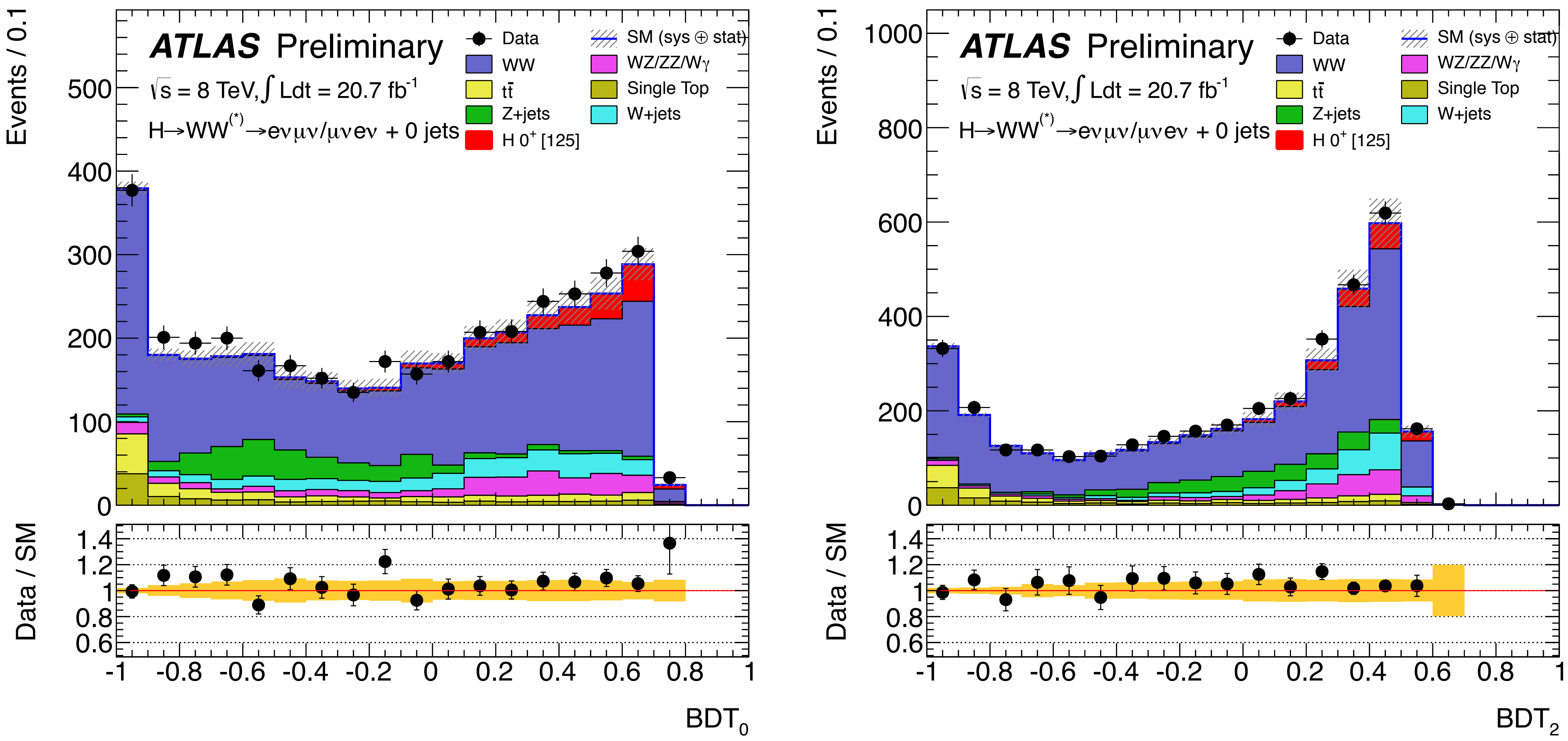
Use both BDTs in 2-dimensional fit …

ATLAS

H ➛ WW ➛ lvlv

Spin 0

BDT Output in Signal Region

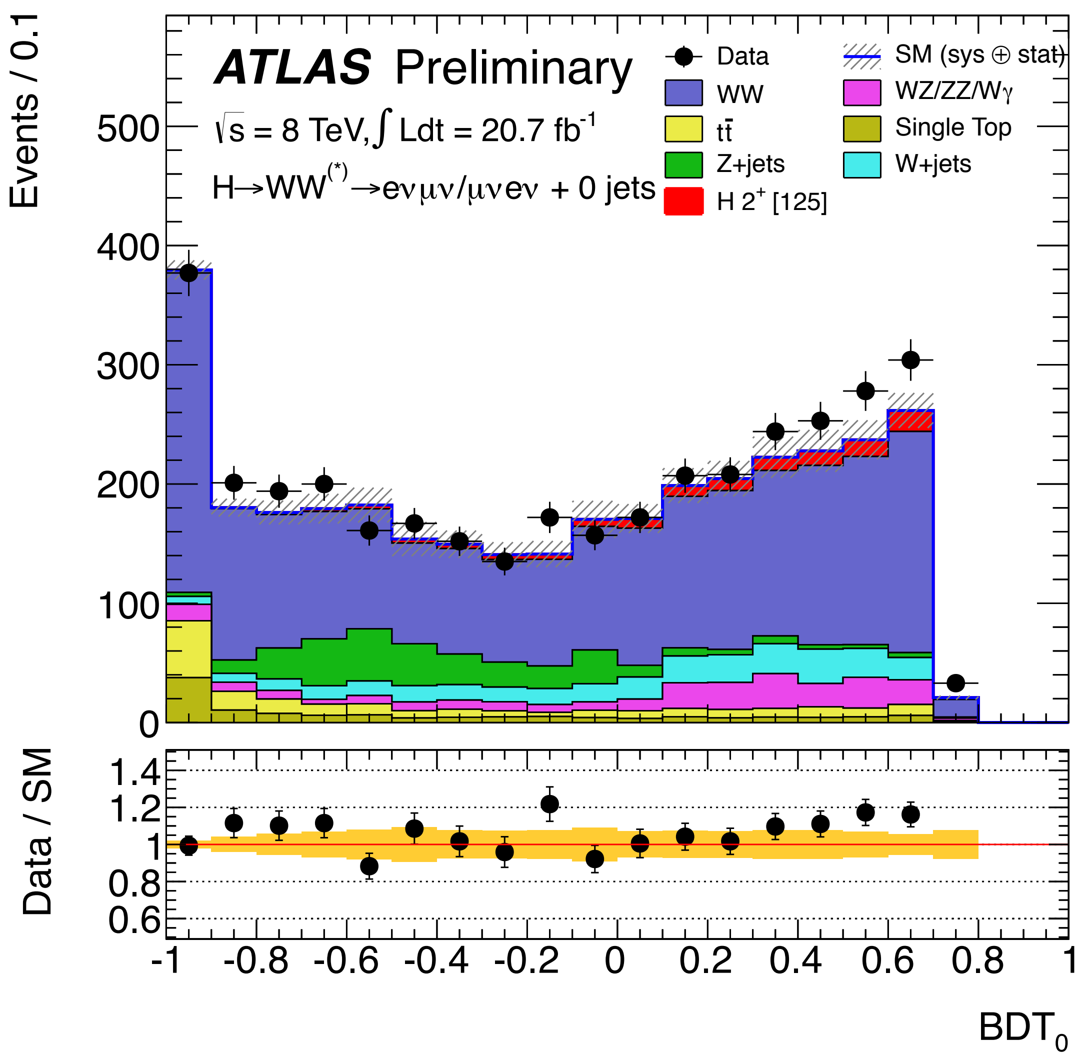


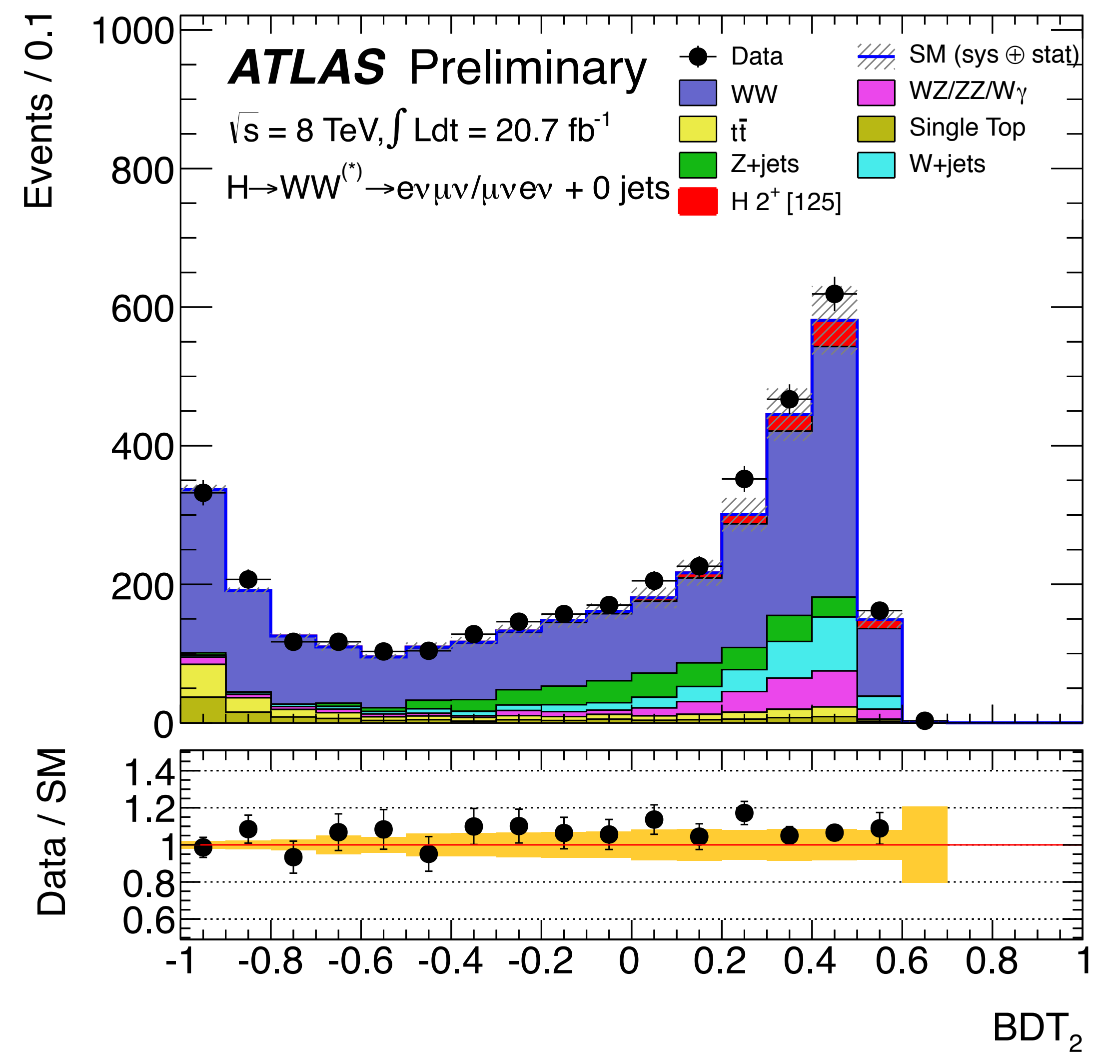
ATLAS

H ➤ WW ➤ lvlv

Spin 1

BDT Output in Signal Region

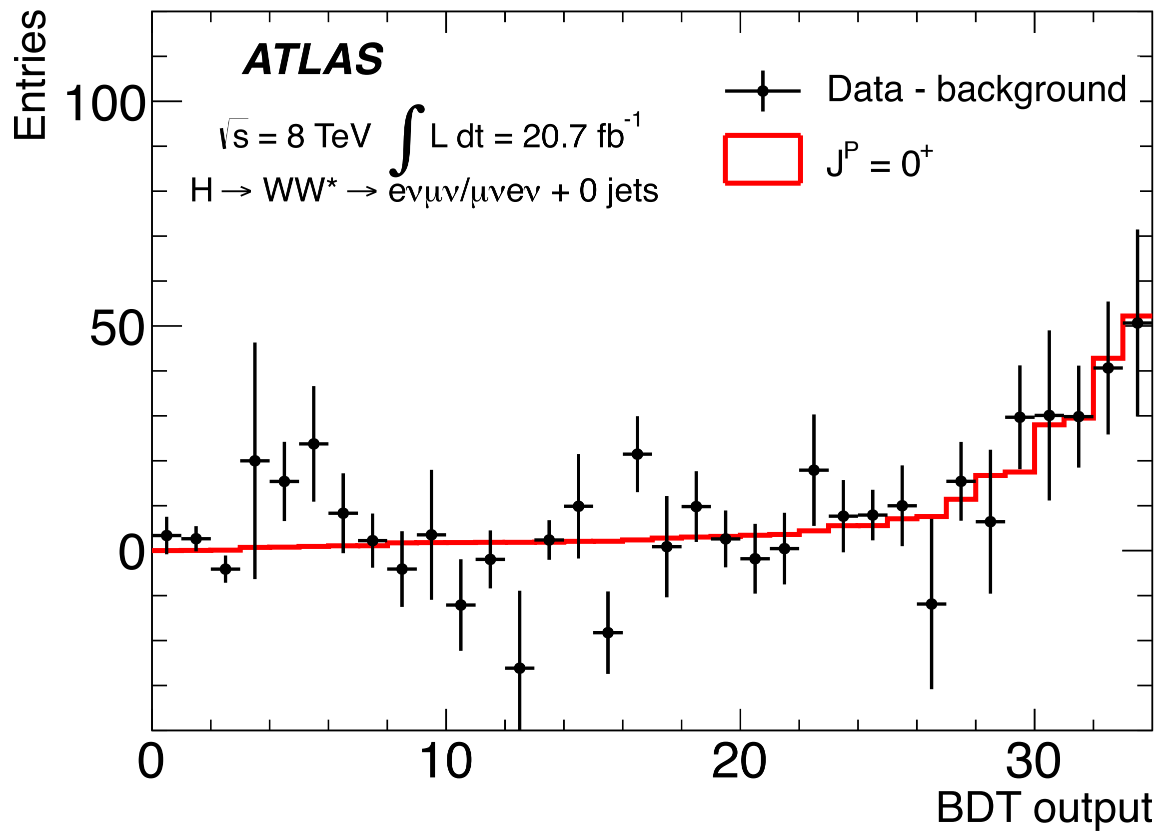




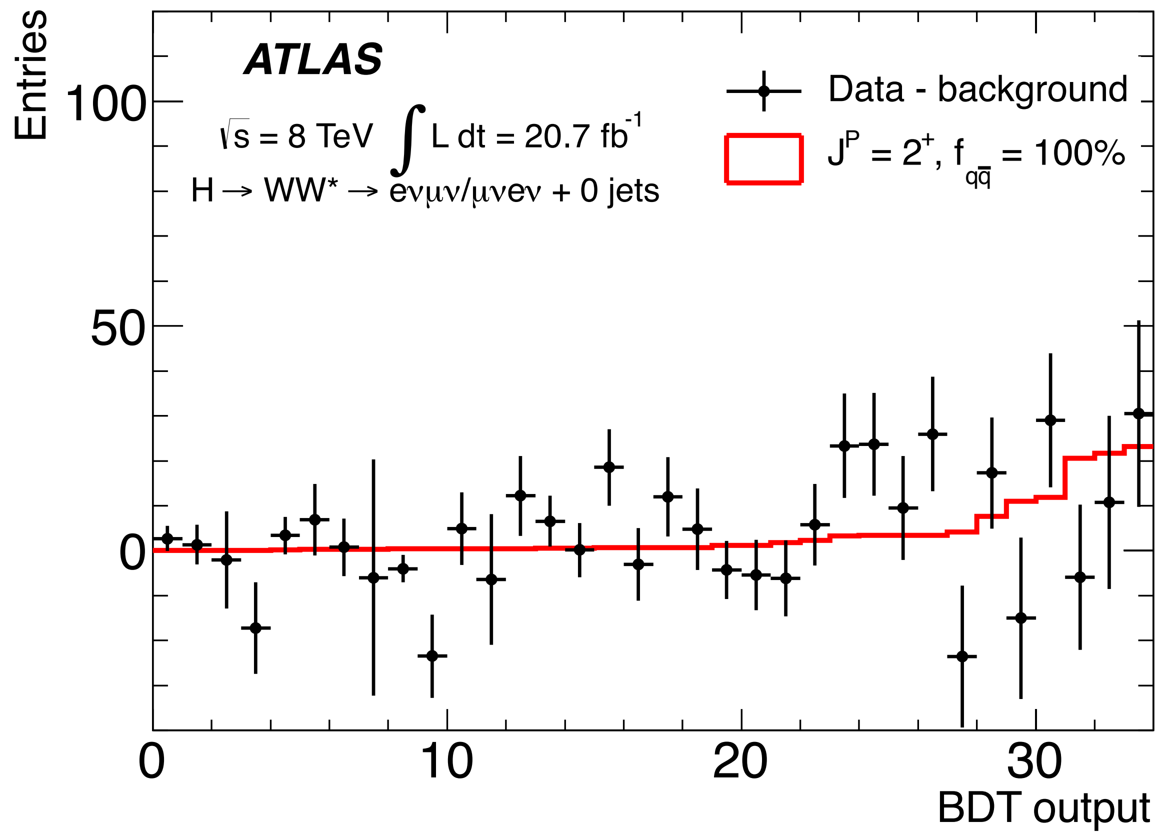
ATLAS

H ➤ WW ➤ lνlν

Use 2-dimensional log-likelihood fit to get test statistic q and determination of CL_S …



Re-mapped 1D-classifier ($J^P = 0^+$)

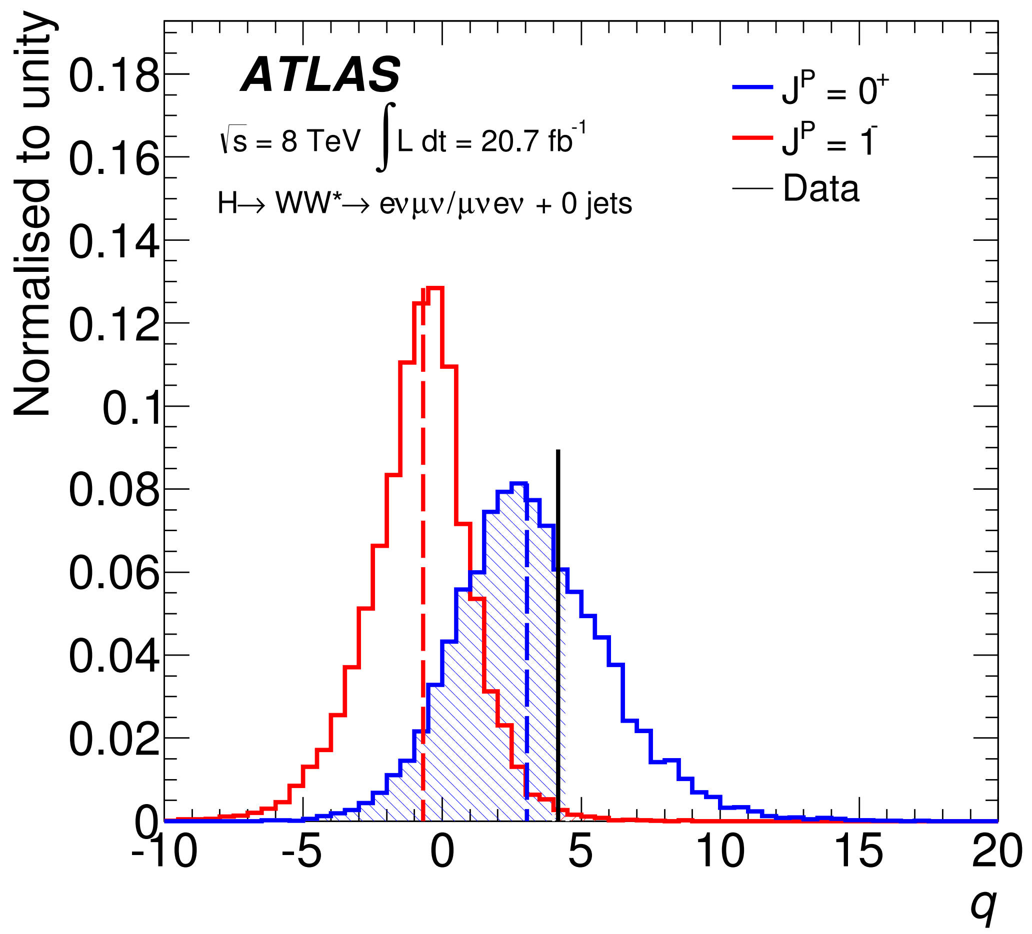


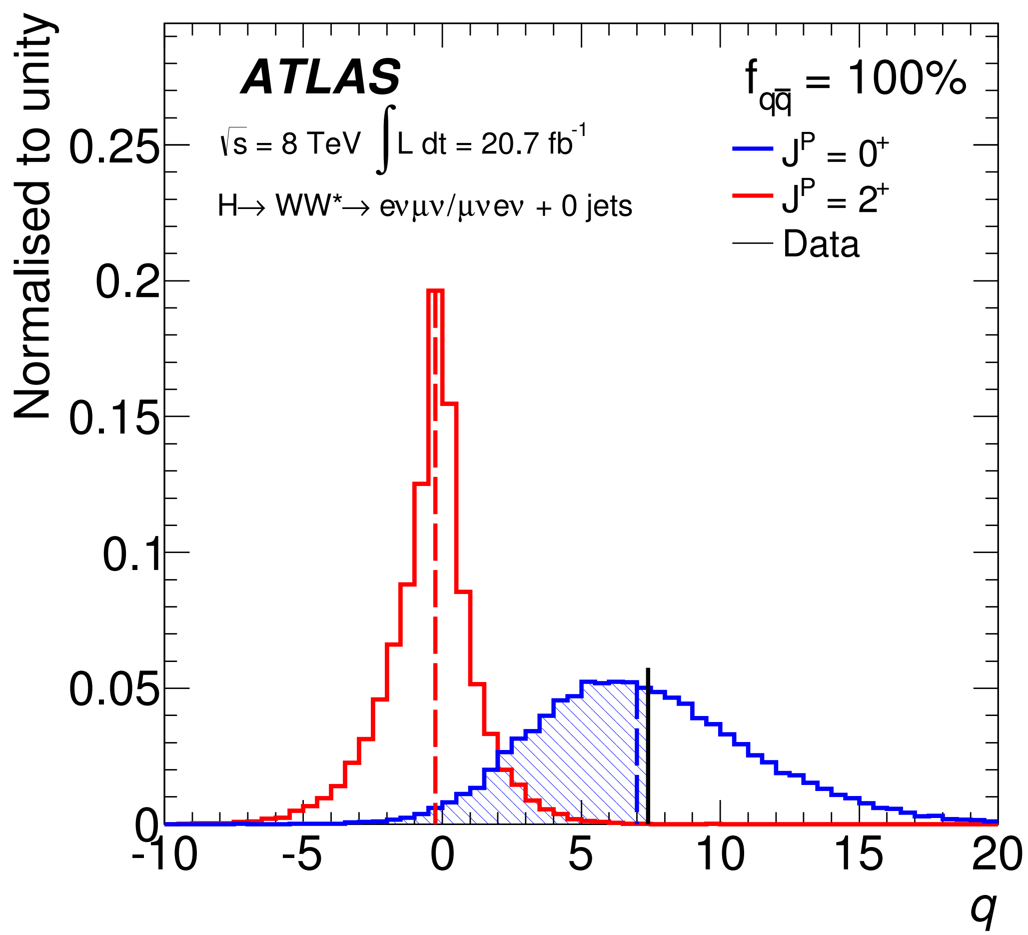
Re-mapped 1D-classifier ($J^P = 2^+$)

ATLAS

H ➛ WW ➛ lνlν

Use 2-dimensional log-likelihood fit to get test statistic q and determination of CL_S …





ATLAS

H ➛ WW ➛ lνlν

Use 2-dimensional log-likelihood fit to get test statistic q and determination of CL_S …

$H \rightarrow WW^*$

$f_{q\bar{q}}$	2^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.013	$3.6 \cdot 10^{-4}$	0.541	$1.7 \cdot 10^{-4}$	$3.6 \cdot 10^{-4}$
75%	0.028	0.003	0.586	0.001	0.003
50%	0.042	0.009	0.616	0.003	0.008
25%	0.048	0.019	0.622	0.008	0.020
0%	0.086	0.054	0.731	0.013	0.048

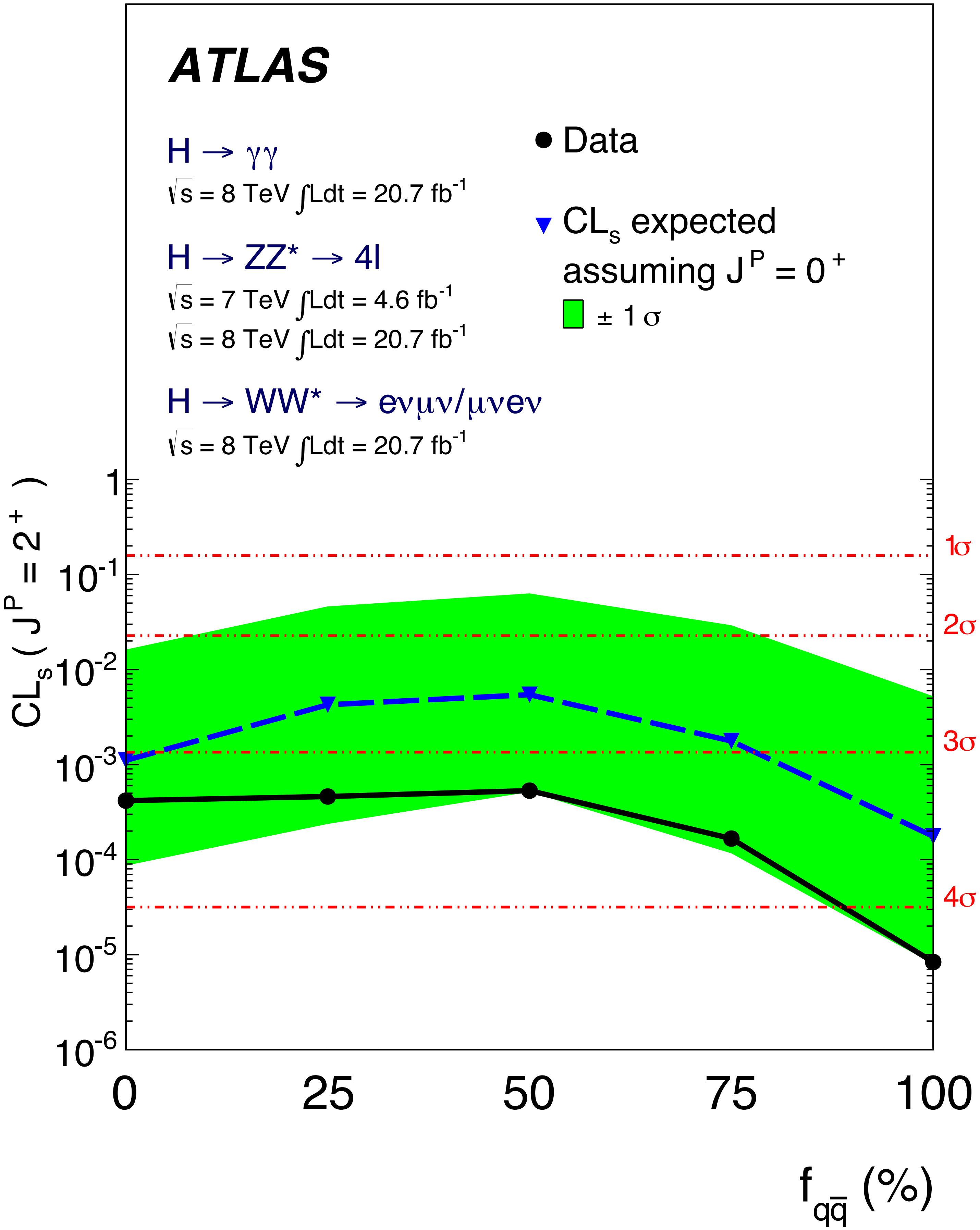
Excess easier to reconcile with a spin 0 signal! Spin 2 looks too flat.

Sensitivities between 2σ and 3σ according to fraction f_{qq}.

[f_{qq} = fraction of quark anti-quark annihilation …]

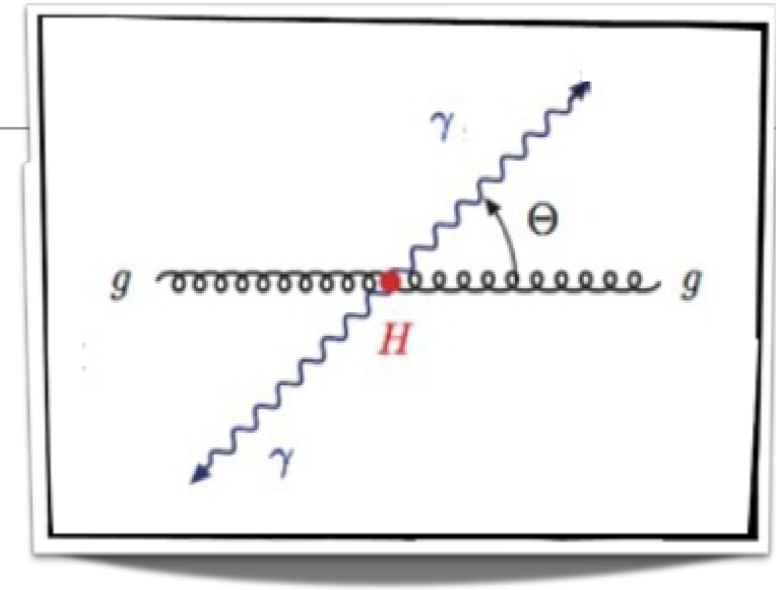
ATLAS

H ➛ WW ➛ lνlν



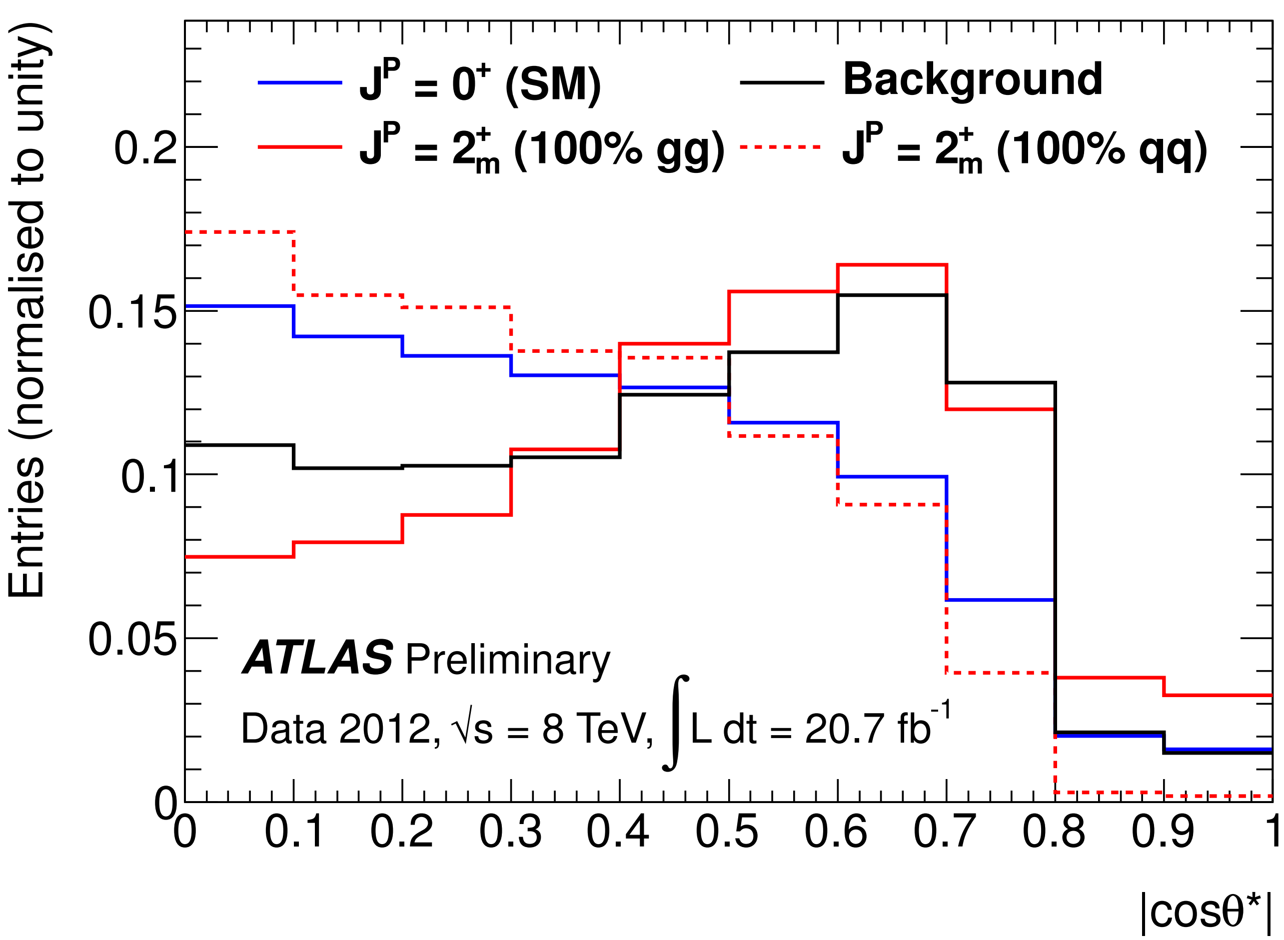
Expected and observed confidence level for $J^P = 2^+$ …

ATLAS – Higgs ➛ γγ



Discriminating variable:
distribution of the polar angle θ …

Best discrimination power …
Impact of ISR minimal …



Topological differences
before acceptance cuts:

Spin 0: Isotropic decay
Spin 2: distribution depends on the qq-fraction, f_{qq}

➛ 100% qq: $dN \sim 1 + \cos^4\theta^* + 6\cos^2\theta^*$
100% gg: $dN \sim 1 - \cos^4\theta^*$

ATLAS – Higgs ➛ γγ

Event selection:

- two photons, ET > 35, 25 GeV …
- di-photon inv. mass: $105 < m_{\gamma\gamma} < 160$

  120 - 130 GeV : signal region
  105 - 122 GeV : sideband
  130 - 160 GeV : sideband

Minimal correlations between $m_{\gamma\gamma}$ and $\cos\theta^*$: $\frac{p_T^{\gamma_1}}{m_{\gamma\gamma}} > 0.35$, $\frac{p_T^{\gamma_2}}{m_{\gamma\gamma}} > 0.25$

Likelihood:

$$-\ln\mathcal{L} = (n_S + n_B) - \sum_{\text{events}} \ln\left[n_S \cdot f_S(|\cos\theta^*|) \cdot f_S(m_{\gamma\gamma}) + n_B \cdot f_B(|\cos\theta^*|) \cdot f_B(m_{\gamma\gamma})\right]$$

polar angle pdf
[different for spin 0 and 2]

signal
mass pdf

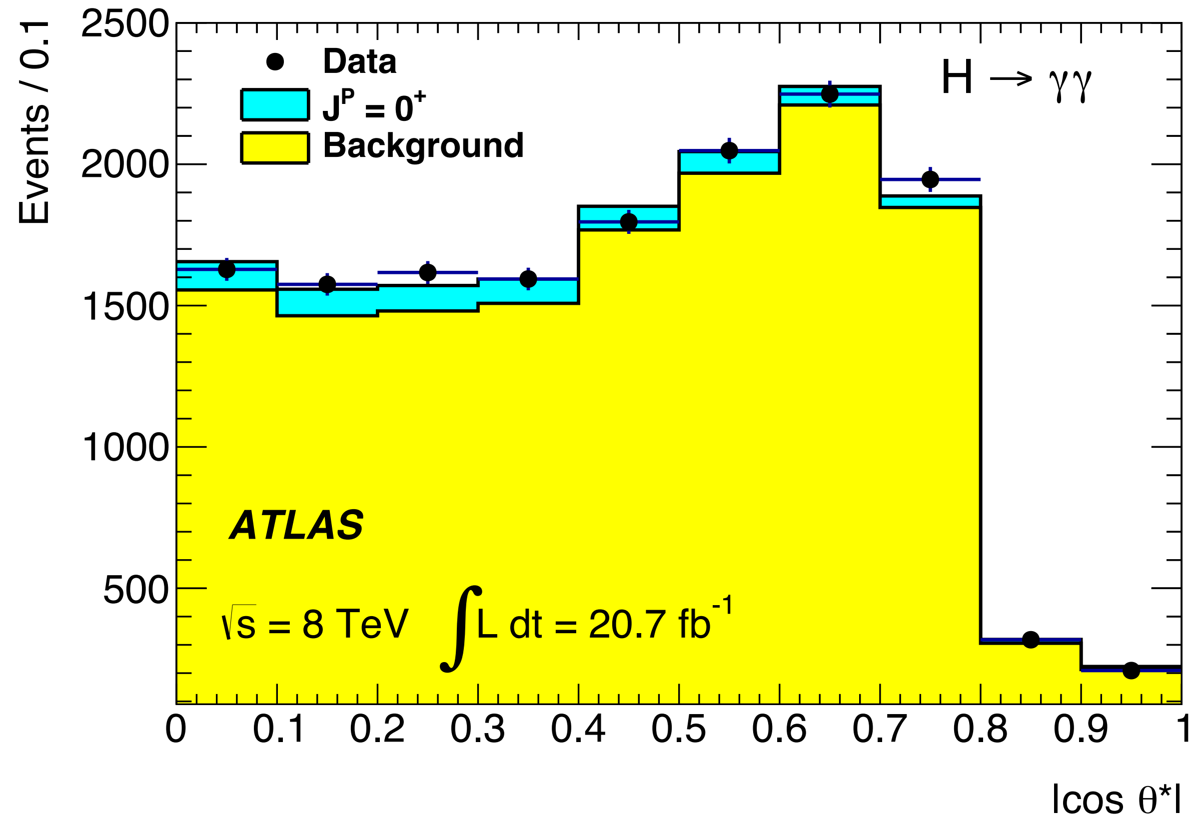
from
sidebands

background
mass pdf
[5th degree poly.]

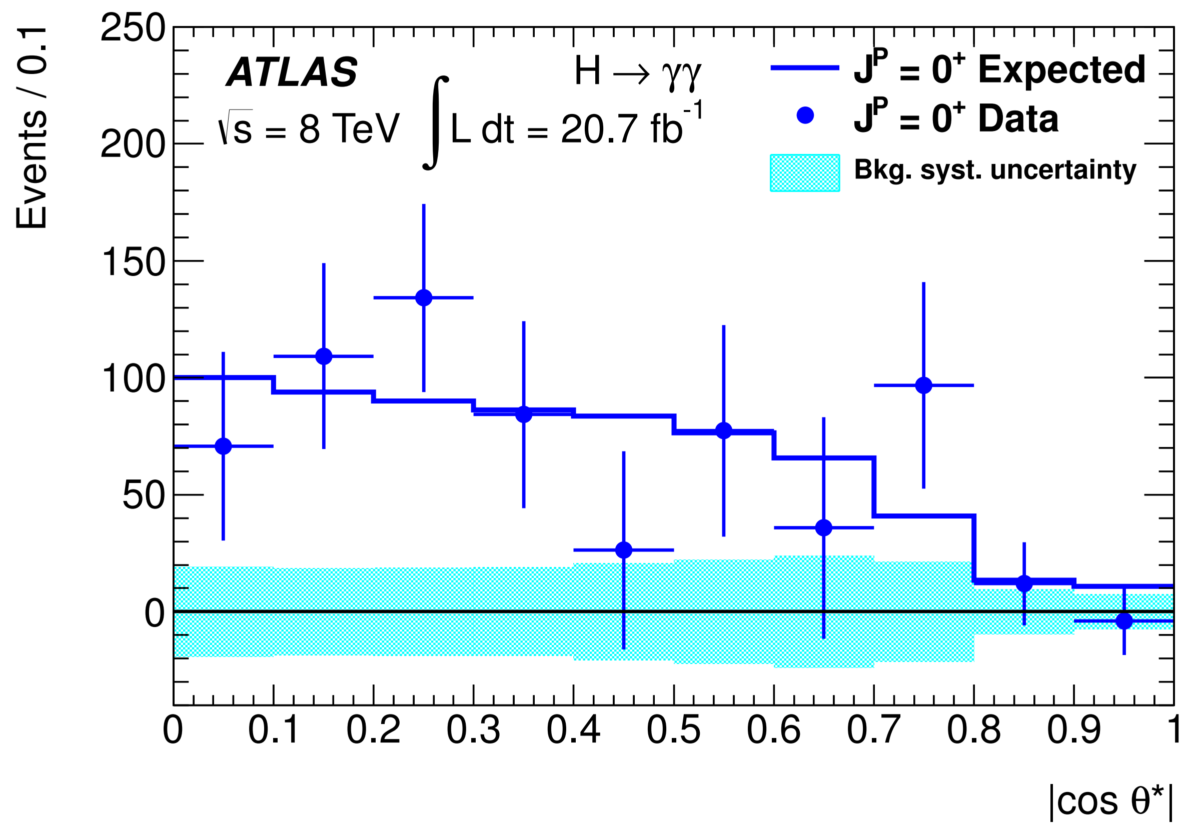
ATLAS – Higgs ➛ γγ

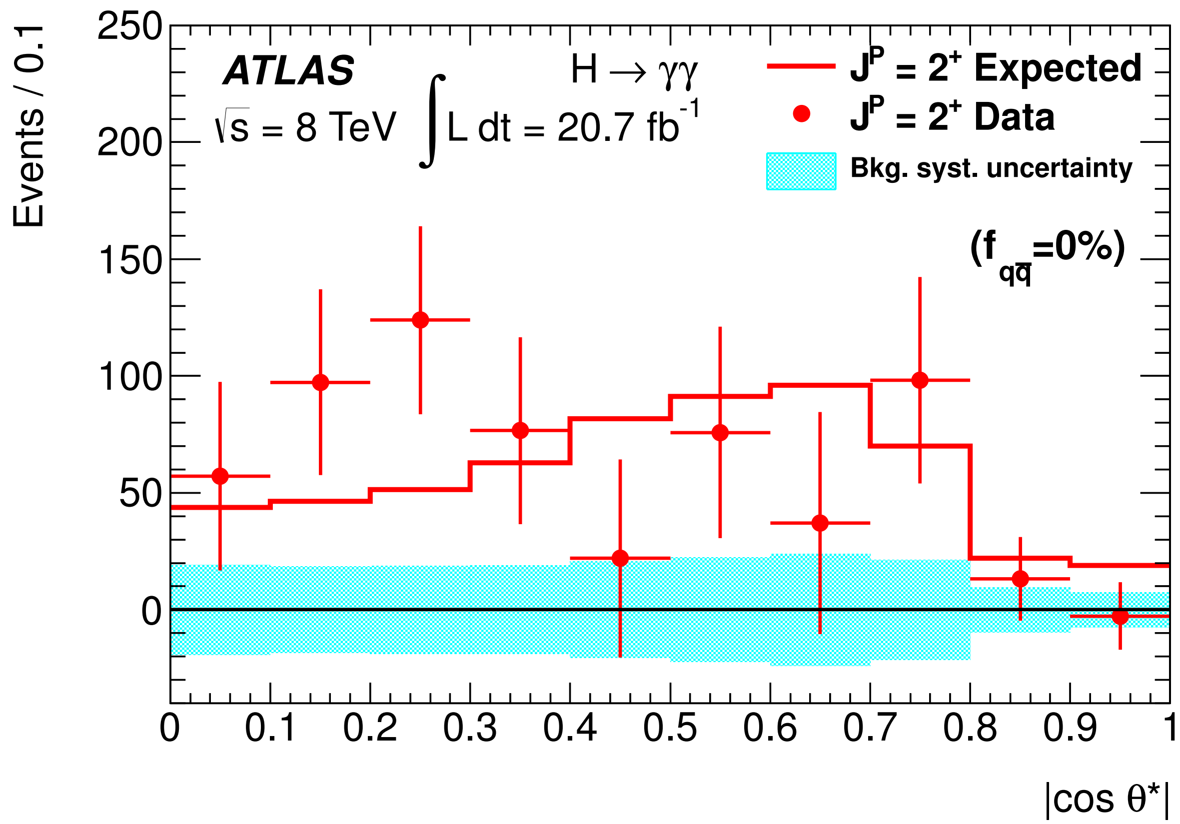
Perform
Likelihood fit to
cos θ* distribution …

Number of events in signal region
[after fit]

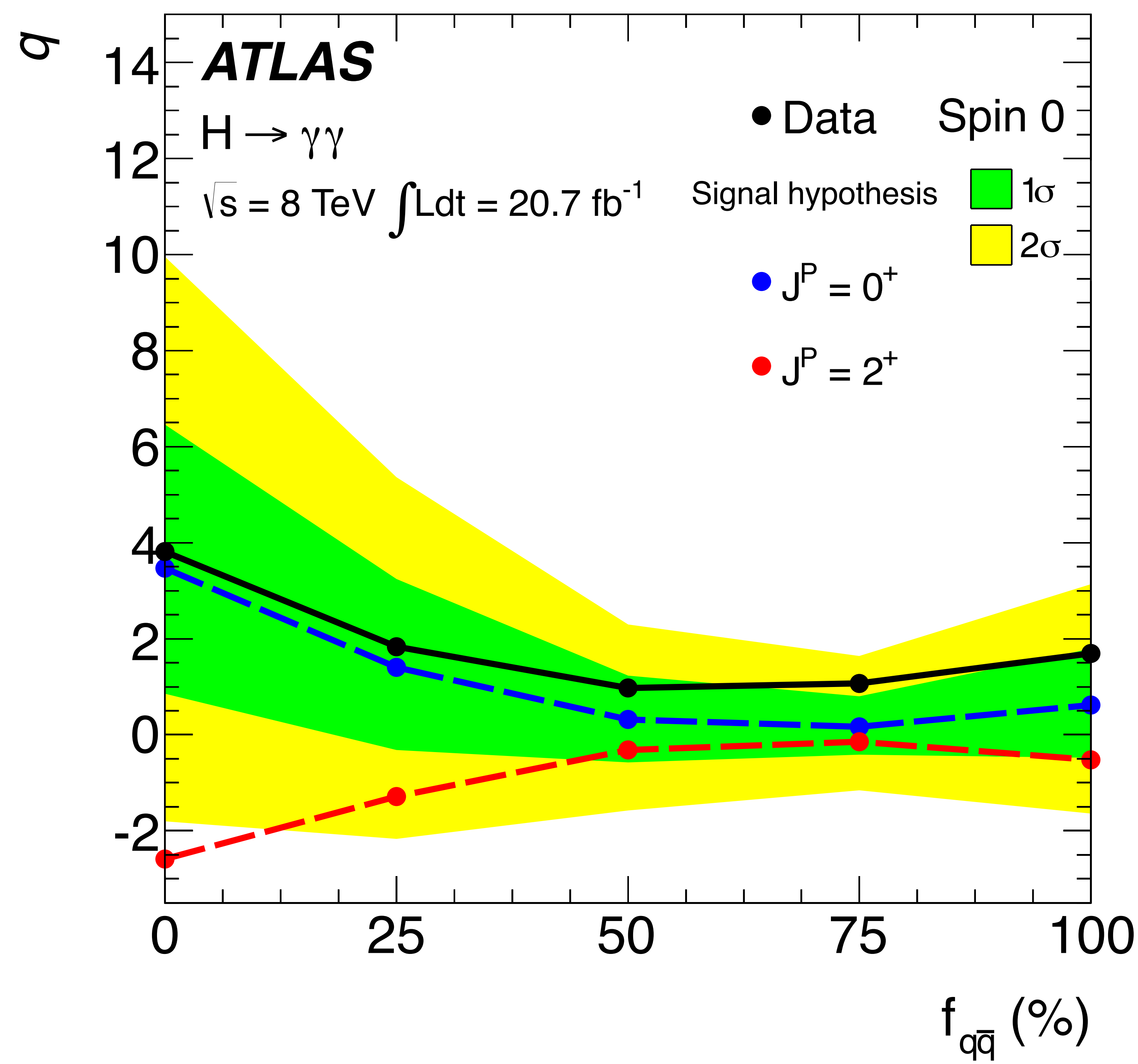


Background subtracted data
within signal region





ATLAS – Higgs ➛ γγ



Observed values
of the test statistic q …

ATLAS – Higgs Spin & Parity …

$H \to \gamma\gamma$

$f_{q\bar{q}}$	2+ assumed Exp. $p_0(J^P = 0^+)$	0+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.148	0.135	0.798	0.025	0.124
75%	0.319	0.305	0.902	0.033	0.337
50%	0.198	0.187	0.708	0.076	0.260
25%	0.052	0.039	0.609	0.021	0.054
0%	0.012	0.005	0.588	0.003	0.007

$H \to ZZ^*$

$f_{q\bar{q}}$	2+ assumed assumed Exp. $p_0(J^P = 0^+)$	0+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.102	0.082	0.962	0.001	0.026
75%	0.117	0.099	0.923	0.003	0.039
50%	0.129	0.113	0.943	0.002	0.035
25%	0.125	0.107	0.944	0.002	0.036
0%	0.099	0.092	0.532	0.079	0.169

$H \to WW^*$

$f_{q\bar{q}}$	2+ assumed Exp. $p_0(J^P = 0^+)$	0+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.013	$3.6 \cdot 10^{-4}$	0.541	$1.7 \cdot 10^{-4}$	$3.6 \cdot 10^{-4}$
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25%	0.048	0.019	0.622	0.008	0.020
0%	0.086	0.054	0.731	0.013	0.048

ATLAS – Higgs Spin & Parity …

Combined confidence levels for alternative spin-parity hypotheses …