Angular Observables for Spin Discrimination in Boosted Diboson Final States

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PRISMA Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

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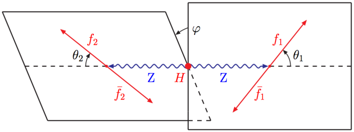
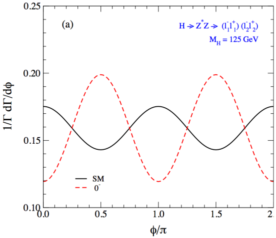
How to determine the spin of a resonance is well studied, see Higgs:



S.Choi et.al. (2002), see also: J.Dell'Aquilla,

C.Nelson (1986), A.Djouadi et.al. (1994)



Angular distributions are know analytically

see e.g.: Gao et.al. (2010), Bolognesi et.al. (2012)

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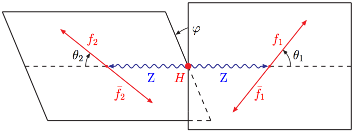

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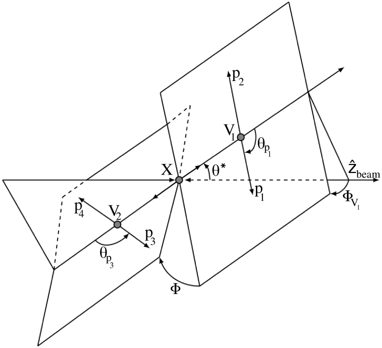

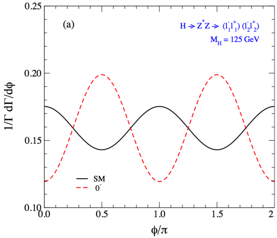

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So what is different?

Resonance masses are heavier ($\mathcal{O}(TeV)$), thus

- Very different background rates
  $\rightarrow$ other V decay channels may be sensitive
- Objects are more boosted
  $\rightarrow$ jet substructure techniques necessary for hadronic channels

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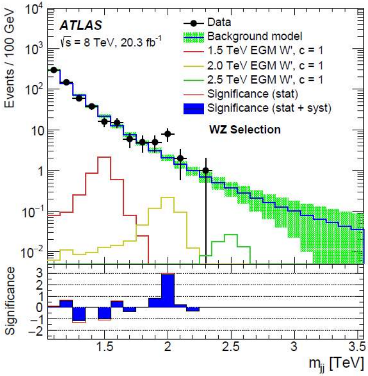


2 TeV excess taught us:

- From spin-0 to spin-2 everything seems viable
- Signal can very well show up in the hadronic channels first (higher rate than (semi-)leptonic channels)

We have to study the hadronic channel, but reconstruction difficult:

Spin discrimination still possible?

How do jet substructure techniques affect angular observables?

Can you optimize searches?

ATLAS @ 8 TeV:
Mass-drop filter

ATLAS @ 13 TeV:
Trimming + Energy correlation functions

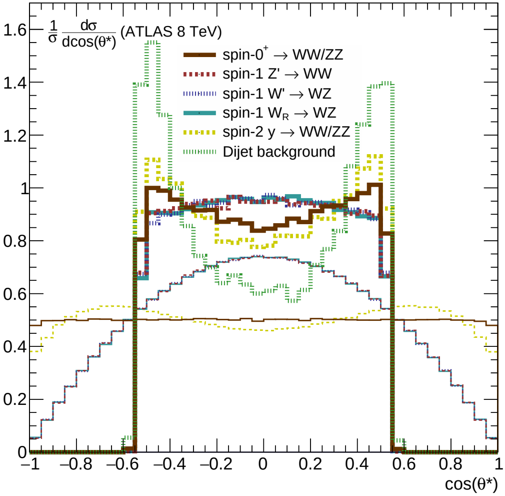
CMS @ 8+13 TeV:
Pruning + N-subjettiness

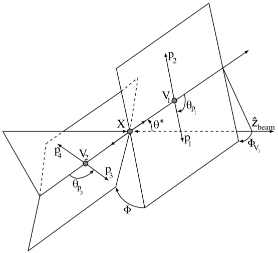
Idea of jet substrucure (simplified):

- Start with fat jet (R=0.8-1.2)
- Remove contamination from soft radiation
- Identify subjets
- To distinguish between QCD jets (1-prong) and V jets (2-prong) for example require subjets to be balanced ($y = p_{T,j2}/p_{T,j1} > y_{\text{min}}$).
  y_{min} typically 0.1-0.2

Example ATLAS @ 8 TeV: Mass-drop filter

- Select two fat jets (Cambridge/Aachen, R=1.2) with $\Delta\eta \leq 1.2$
- Jets are unclustered in reverse order
- At each step check pair of subjets for:
  - mass-drop: $\mu_i = m_i/m_0 > 1$
  - momentum balance: $y > 0.2025$
- If any criteria fails: continue unclustering harder subjet
- If criteria fulfilled: stop procedure





$\cos\theta^* = \hat{p}_{V_1}\cdot\hat{z}_{\text{beam}}$

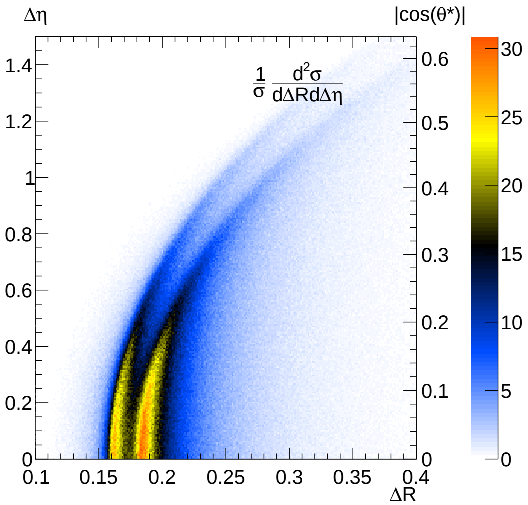
thin lines:
before analysis

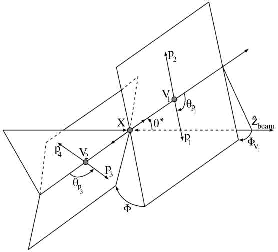
thick lines:
after analysis

Sharp edges:

$$|\cos\theta^*| = \tanh\frac{|\Delta\eta|}{2} \leq \tanh\frac{|\Delta\eta_{\text{max}}|}{2}$$

$$\text{with } \Delta\eta_{\text{max}} = 1.2\text{–}1.3$$



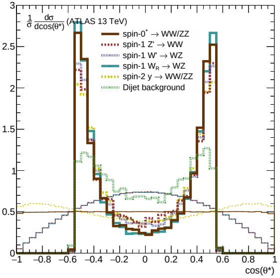


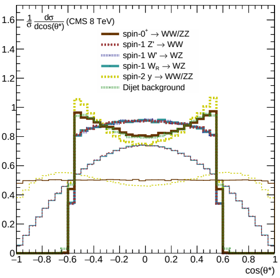
$\cos\theta^* = \hat{p}_{V_1} \cdot \hat{z}_{\text{beam}}$

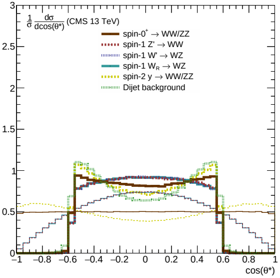
Strong correlation between ΔR separation (between subjets) and $\Delta\eta$

$+$

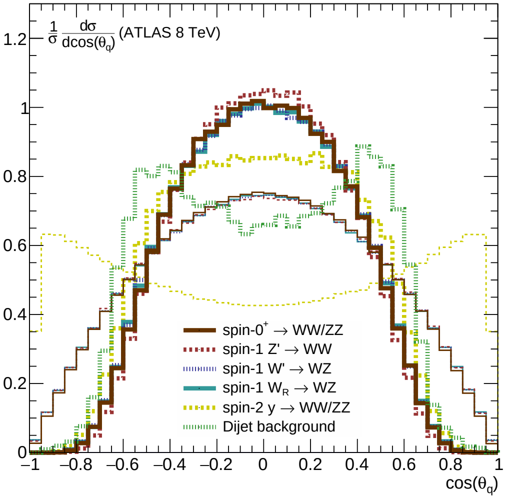
jets with small ΔR are hard to tag

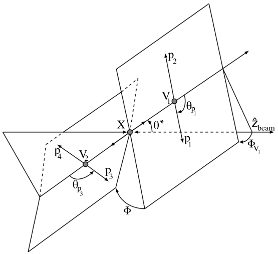






- Same features also for other diboson searches
- Note large deficiency for ATLAS 13 TeV due to large reclustering radius R=0.2!





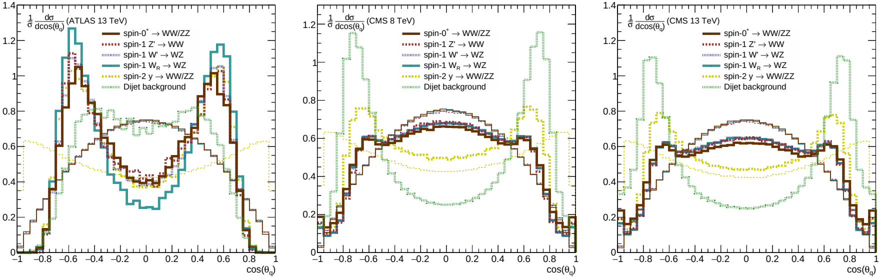
$$\cos\theta_q = -\hat{p}_q \cdot \hat{p}_{V_2}$$

thin lines:
before analysis

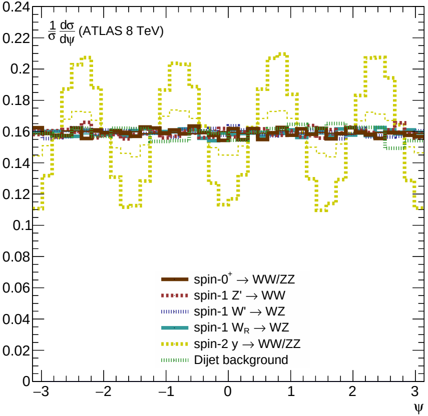
thick lines:
after analysis

Soft edges:

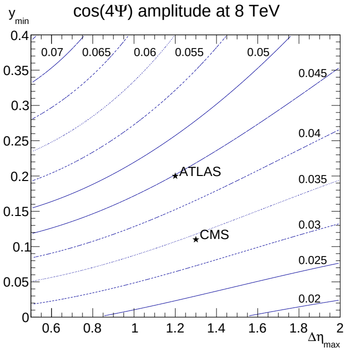
$$|\cos\theta_q| \approx \frac{1-y}{1+y} \leq \frac{1-y_{\min}}{1+y_{\min}}$$



- Again, same features also for other diboson searches!



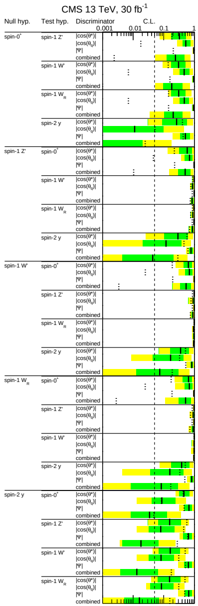
- All differential shapes expected to be flat, except for a spin-2 resonance
- Spin-2 amplitude increases after analysis cuts applied!



$$\frac{1}{\sigma^{(\text{spin-2})}} \frac{d\sigma^{(\text{spin-2})}}{d\Psi} = \frac{1}{2\pi} - \mathcal{A}(y_{\text{min}}, \Delta\eta_{\text{max}}) \cos(4\Psi) \tag{1}$$

with

$$\mathcal{A} = \frac{1}{24\pi} F_{+-} \left(1 + 4y_{\text{min}} + y_{\text{min}}^2\right)^2 (5f_{q\bar{q}} - 1)(8 + 6\cosh\Delta\eta_{\text{max}} + \cosh 2\Delta\eta_{\text{max}}) \Big/ \Big[F_{+-} \left(1 + y_{\text{min}} + y_{\text{min}}^2\right)^2 \left((5f_{q\bar{q}} + 1)(1 + 2\cosh\Delta\eta_{\text{max}}) + 2\cosh 2\Delta\eta_{\text{max}}\right) + F_{00} \left(1 + 4y_{\text{min}} + y_{\text{min}}^2\right)^2 (-15f_{q\bar{q}} + 8 + 6\cosh\Delta\eta_{\text{max}} + \cosh 2\Delta\eta_{\text{max}}) \Big] \tag{2}$$

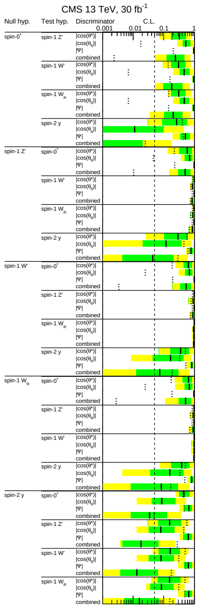


Ultimately: Test

Model A+Background

against

Model B+Background



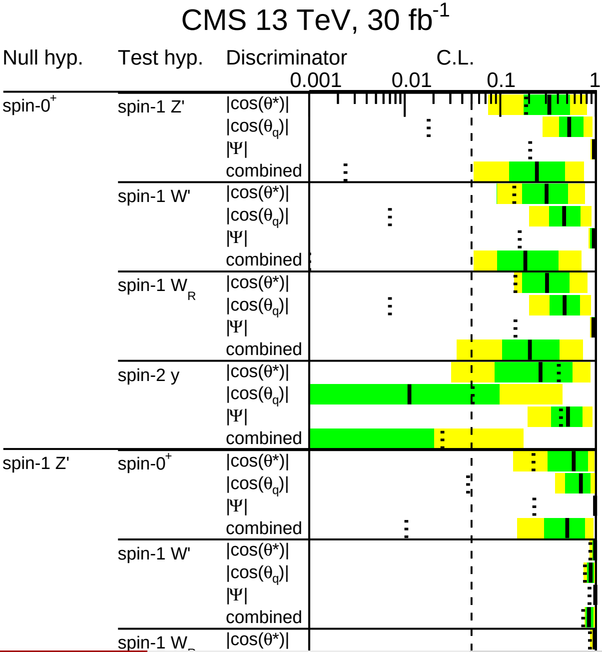
Two different scenarios:

"Rate+Shape":

In case a measurement at two different CMS energies exists (as we would have for a real 2 TeV excess) we have additional discrimination power from production rates (PDF effects)

"Shape only":

If resonance measured only at one CMS energy no discrimination due to rate can be extracted. We rely on the differential shapes.


CMS 13 TeV, 30 fb^{-1}
Null hyp.
Test hyp.
Discriminator
C.L.
0.001
0.01
0.1
1
spin-0$^+$
spin-1 Z'
spin-1 W'
spin-1 W_R
spin-2 y
spin-1 Z'
spin-0$^+$
spin-1 W'
spin-1 W_R
|cos(θ*)|
|cos($θ_q$)|
|Ψ|
combined

Summary

- High resonance masses allows us to use hadronic decay channels
- Complex analyses strategies necessary
- Jet substructure modifies differential shapes used for spin discrimination
- Searches can be optimized but even without discrimination still possible!

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Thank you!