Dissecting `multi' photon resonances at the LHC

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Workshop on the physics of HL-LHC, and perspectives at HE-LHC
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(with Ben Allanach and Disha Bhatia)

Eur.Phys.J. C77 (2017) no.9, 595
and YR contributions

Conventional di-photon searches

Three possibilities

Beyond Minimal models

Seven possibilities

Multi-photon → `Di'-photon

Photons to photon jets

Give up isolation

Substructure and kinematics to distinguish cases

Using a statistical discriminant

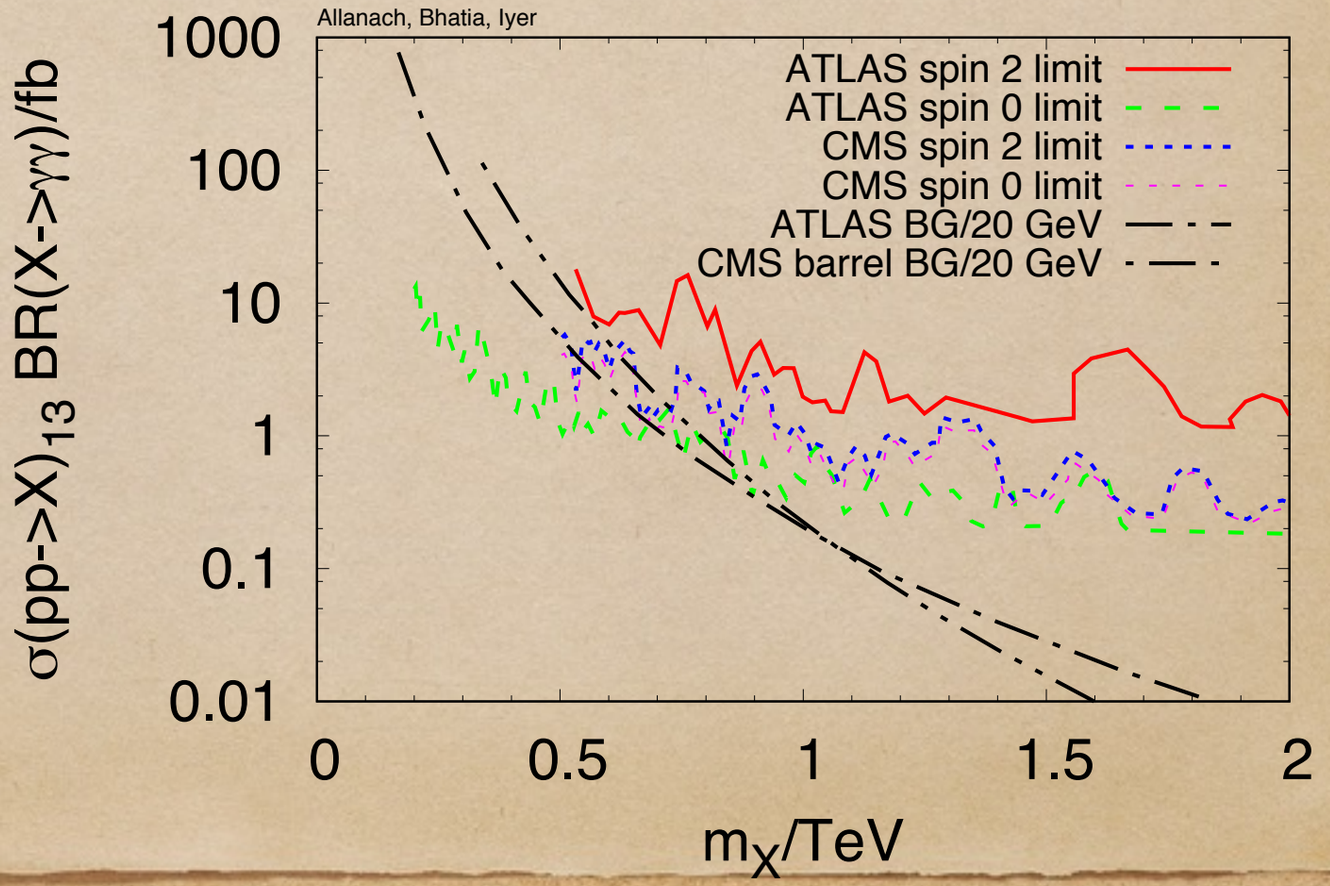
The discovery of scalar with Higgs like properties at the LHC have fuelled searches for NP

Typical final states include combinations jets, photons/electrons, missing energy

The observation/validations of Higgs in the di-photon had lead to
increased sensitivity in this channel.

Typical search for new resonance
X in Di-photon mode
is by assuming

$$pp \to X + x \to \gamma\gamma + x,$$



What are the models that can lead to such final states

Consider effective theory with SM + X

X=Spin-0 eg. MSSM, Extra-Dimensions, 2HDM etc.

X=Spin-2 eg. Extra-Dimensions (RS or UED)

$$\mathcal{L}^{int}_{X=\text{spin }0} = -\eta_{GX}\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu a}X - \eta_{\gamma X}\frac{1}{4}F_{\mu\nu}F^{\mu\nu}X,$$

$$\mathcal{L}^{int}_{X=\text{spin }2} = -\eta_{T\psi X}T^{\alpha\beta}_{fermion}X_{\alpha\beta} - \eta_{TGX}T^{\alpha\beta}_{gluon}X_{\alpha\beta} - \eta_{T\gamma X}T^{\alpha\beta}_{photon}X_{\alpha\beta}.$$

Spin-1 Not possible

Landau Yang Theorem!

But do we believe what we see? Maybe not!

Consider effective theory with SM + X + n

For simplicity assume n to be a scalar and X couples to a pair of n

$$\mathcal{L}^{int}_{X=\text{spin }0,n} = -\frac{1}{2} A_{Xnn} X n n, \qquad \mathcal{L}^{int}_{X=\text{spin }2,n} = -\eta_{TnX} X_{\alpha\beta} T^{\alpha\beta}_{n},$$

n can decay into a pair of photons through the following lagrangian

$$\mathcal{L}^{int}_{n\gamma\gamma} = -\frac{1}{4} \eta_{n\gamma\gamma} F_{\mu\nu} F^{\mu\nu} n.$$

Thus there are two possibilities for X to decay now

$X_{0,2} \to \gamma\gamma$

$X_{0,2} \to n\ n \to \gamma\gamma\gamma\gamma$

Now Spin-1 also comes to the party!

$$\mathcal{L}^{int}_{X=\text{spin }1,n} = -(\lambda_{\bar{q}Xq}\bar{q}_R\gamma_\mu X^\mu q_R + \lambda_{\bar{Q}XQ}\bar{Q}_L\gamma_\mu X^\mu Q_L + H.c.) - \frac{1}{4}\eta_{nX\gamma} n\tilde{X}_{\mu\nu}F^{\mu\nu},$$

Now Spin-1 also comes to the party!

$$X_1 \to n\gamma \to \gamma\gamma\gamma$$

Search for Spin-1 one resonance decaying into a three photon final state exist

The opening angle between the photons from n is given as

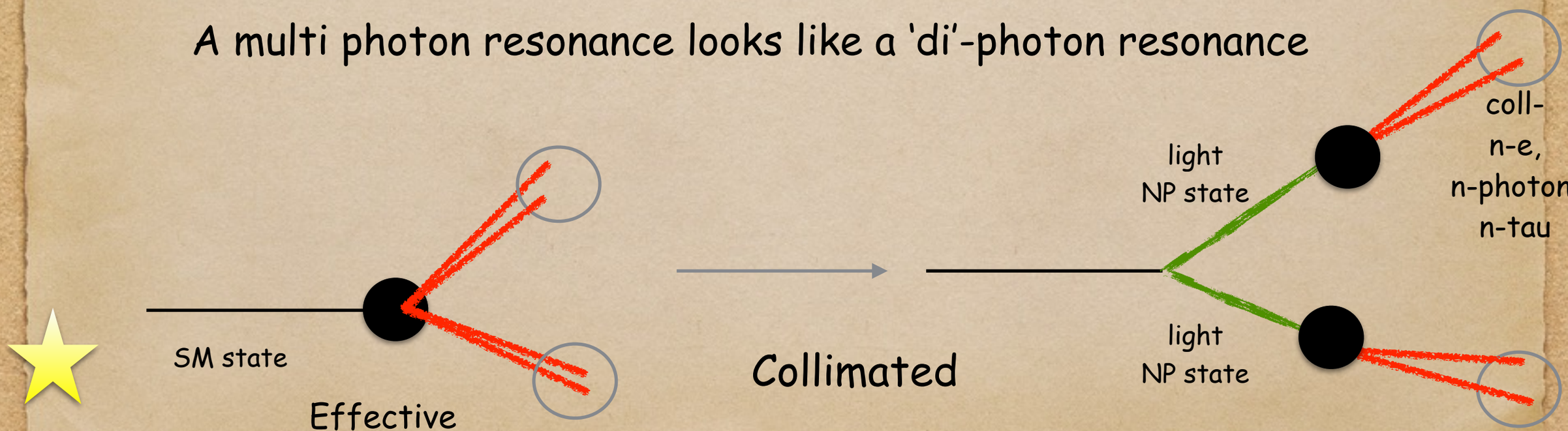
$$\Delta R = \frac{m_n}{\sqrt{z(1-z)}p_T(n)},$$

But what if the mass on n is very small such that

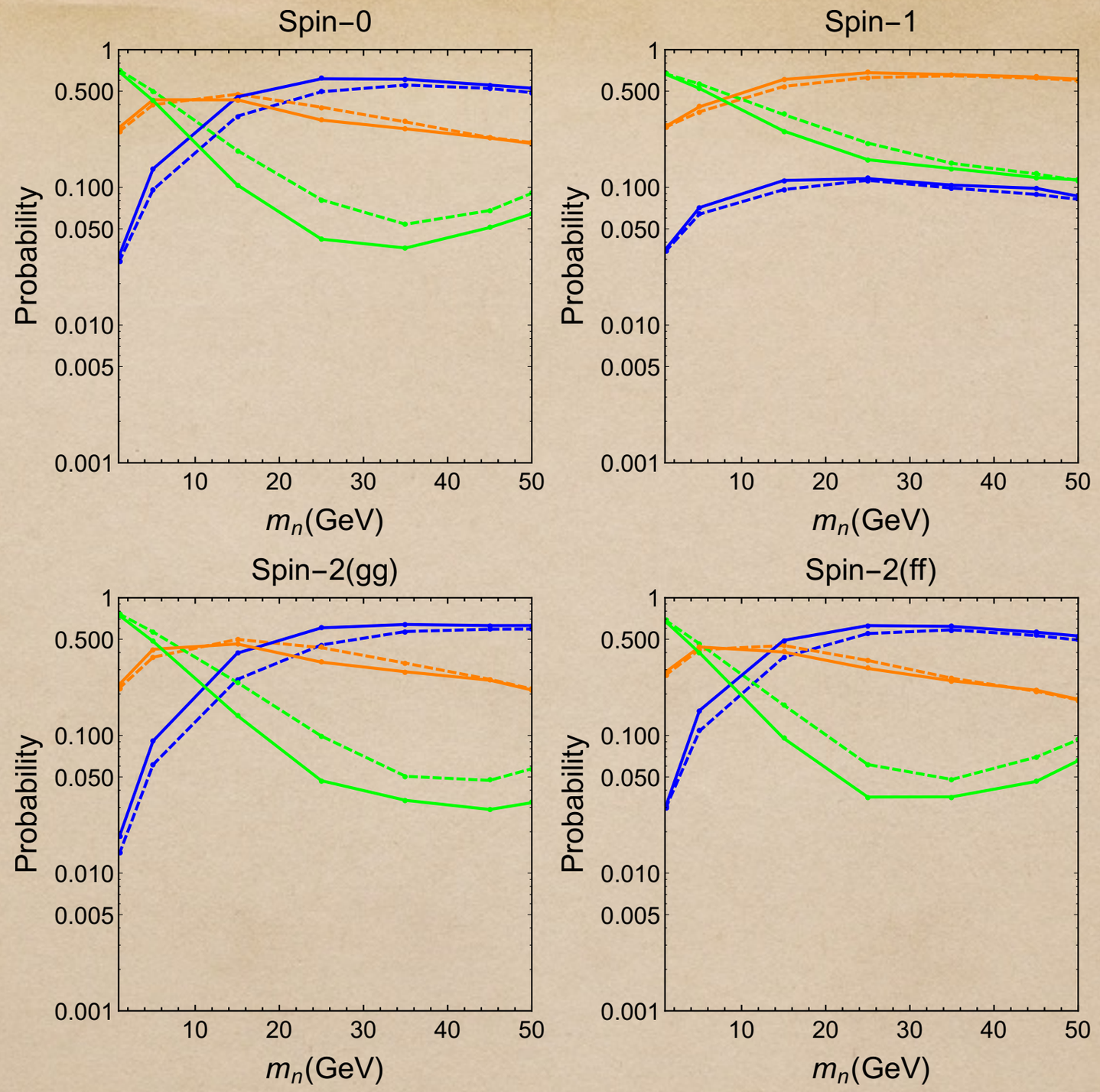
$$m_n/M_X \to 0, \xrightarrow{\text{then}} \Delta R \to 0$$

The photons from n are highly collinear

A multi photon resonance looks like a 'di'-photon resonance

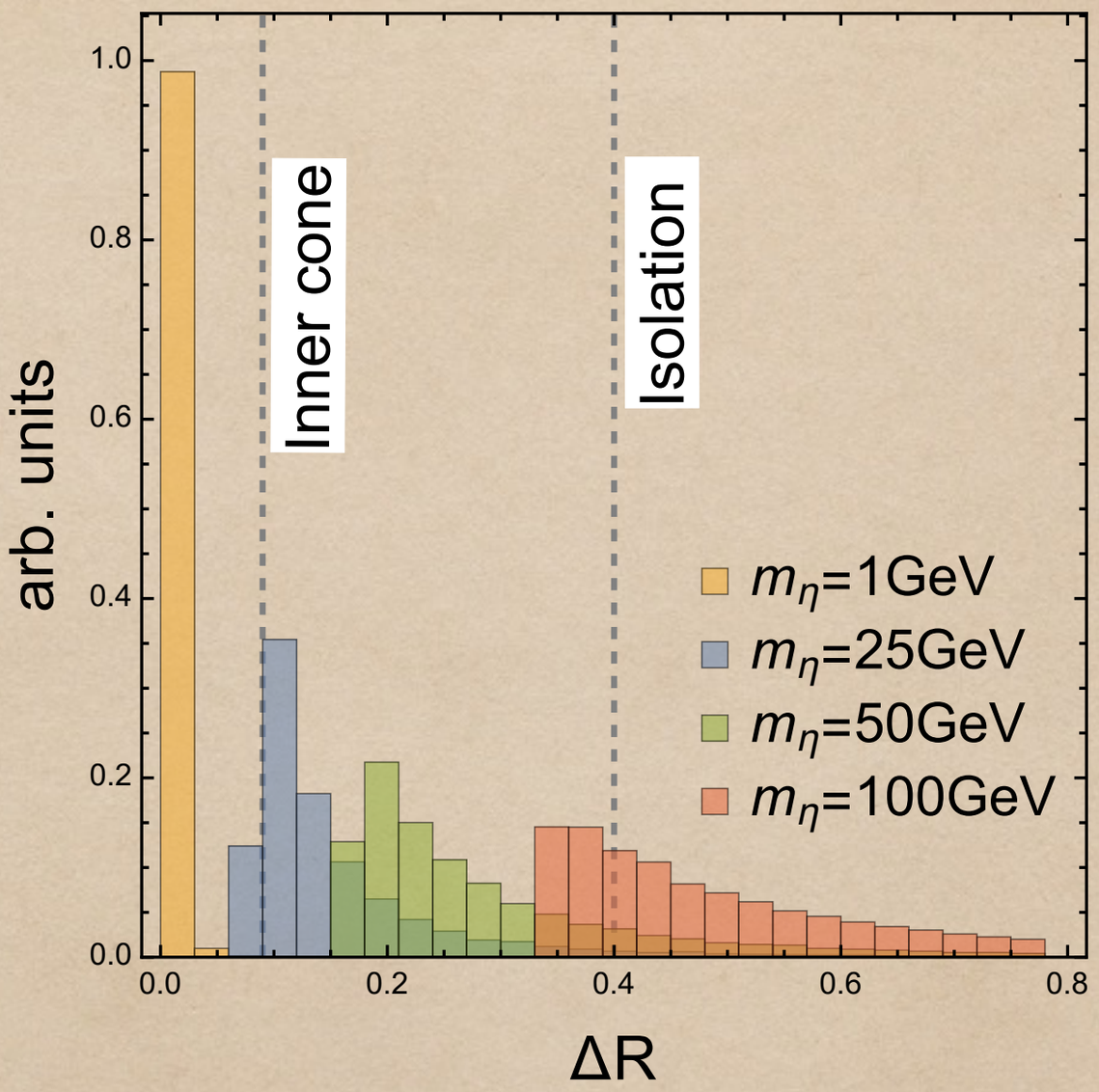


They look like 2 e, 2 photon, 2 tau final state



Isolation may kill signal if mass in intermediate range

FIG. 2: Probabilities of detecting different numbers of isolated, resolved photons for a 1200 GeV $X \to$ multi-photon decay as a function of m_n, the mass of the intermediate particle. We show the probabilities for 0 (blue), 1 (orange) or 2 (green) photons for each X produced. The probabilities for detecting 3 or 4 isolated, resolved photons for the signal are very small for this range of m_n and are not shown. Solid lines correspond to CMS, and dashed lines to ATLAS.

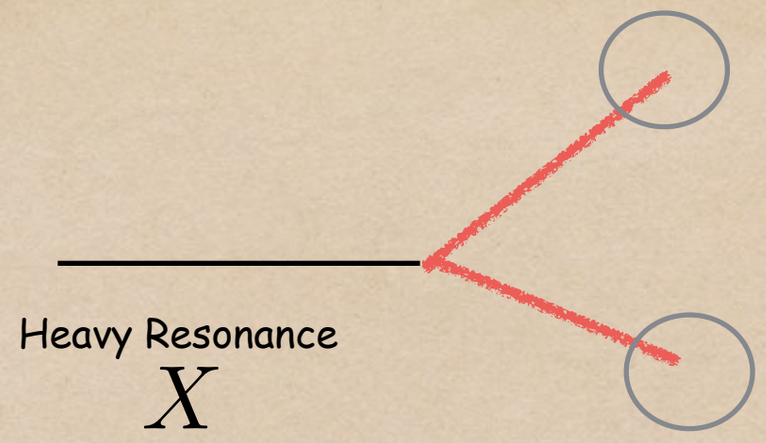


Isolation may kill signal if mass in intermediate range

FIG. 3: ΔR distribution for photon pairs originating from $n \to \gamma\gamma$ for different values of m_n. Photon pairs to the left hand side of the 'ECAL Prescription' line are considered to be one photon, whereas those between the ECAL prescription and the 'Isolation' line are rejected because of the photon isolation criteria.

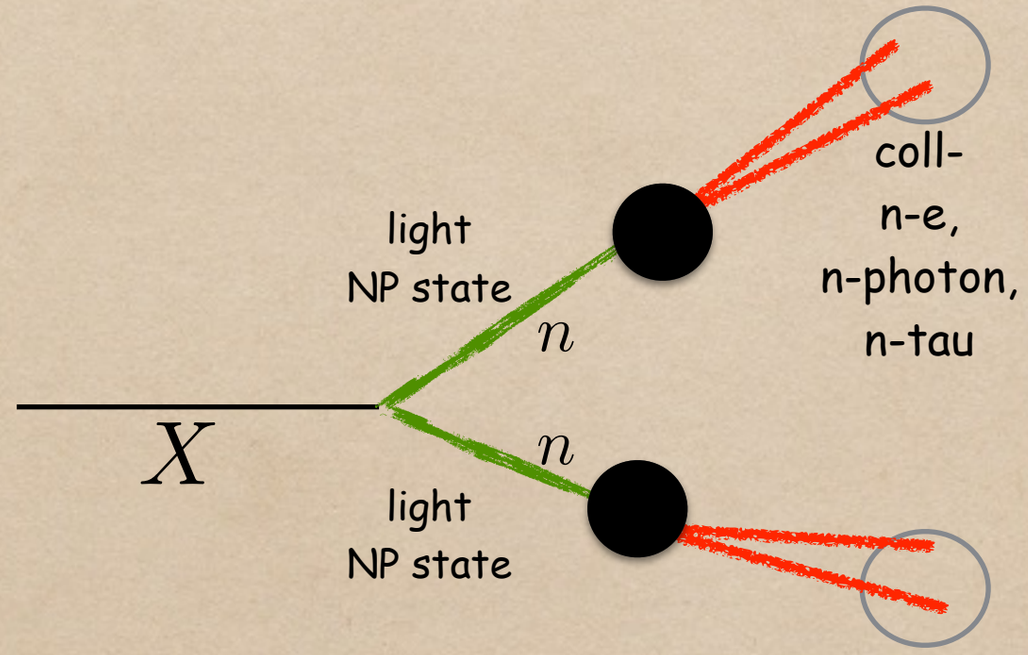
Possible `di'-photon final states

1.



Two photons

2.



Looks like Two photons

They look like 2 e, 2 photon, 2 tau final state

Possible `di'-photon final states

Model	Process
$S2$	$pp \to S \to \gamma\gamma$
$S4$	$pp \to S \to nn \to \gamma\gamma + \gamma\gamma$
$V3$	$pp \to Z' \to n\gamma \to \gamma + \gamma\gamma$
$G2_{ff}$	$q\bar{q} \to G \to \gamma\gamma$
$G2_{gg}$	$gg \to G \to \gamma\gamma$
$G4_{gg}$	$gg \to G \to nn \to \gamma\gamma + \gamma\gamma$
$G4_{ff}$	$\bar{q}q \to G \to nn \to \gamma\gamma + \gamma\gamma$

Move from photons to photon jets

Photon jets

Give up isolation

E-cal

H-cal

-Calorimetric four-vectors
-Track four-vectors
-Cluster them using anti-kt 0.4, pT=100 GeV

` jets'

QCD,tau,e, photon all fall under jets nomenclature

Track four vectors are scaled by an arbitrary small number to avoid over counting

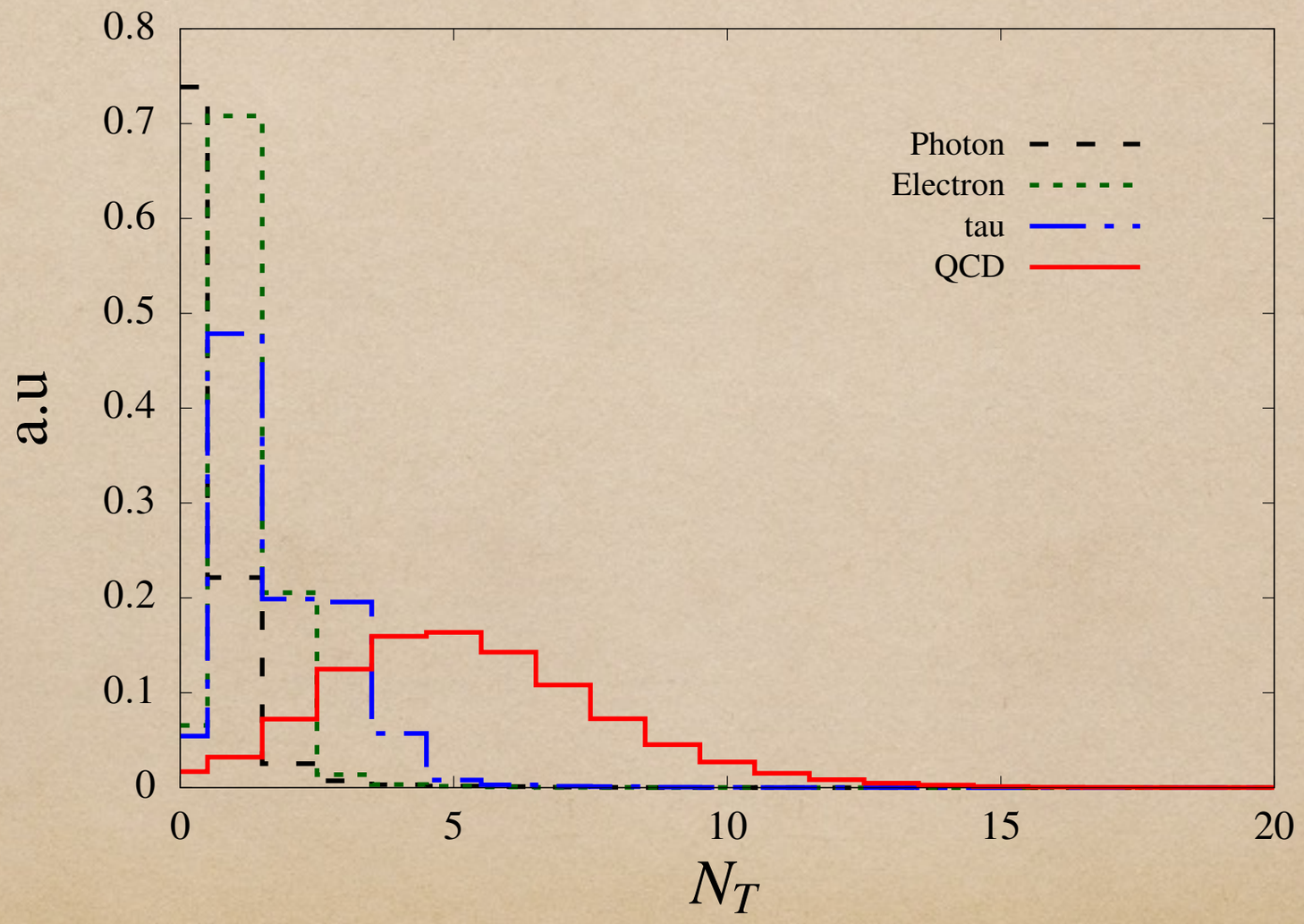
Different samples can be distinguished by studying the properties of jets:-JET SUBSTRUCTURE

How to get rid of QCD

Chakraborty, Iyer, Roy '17
1707.07084

tracks

Select jets with zero tracks



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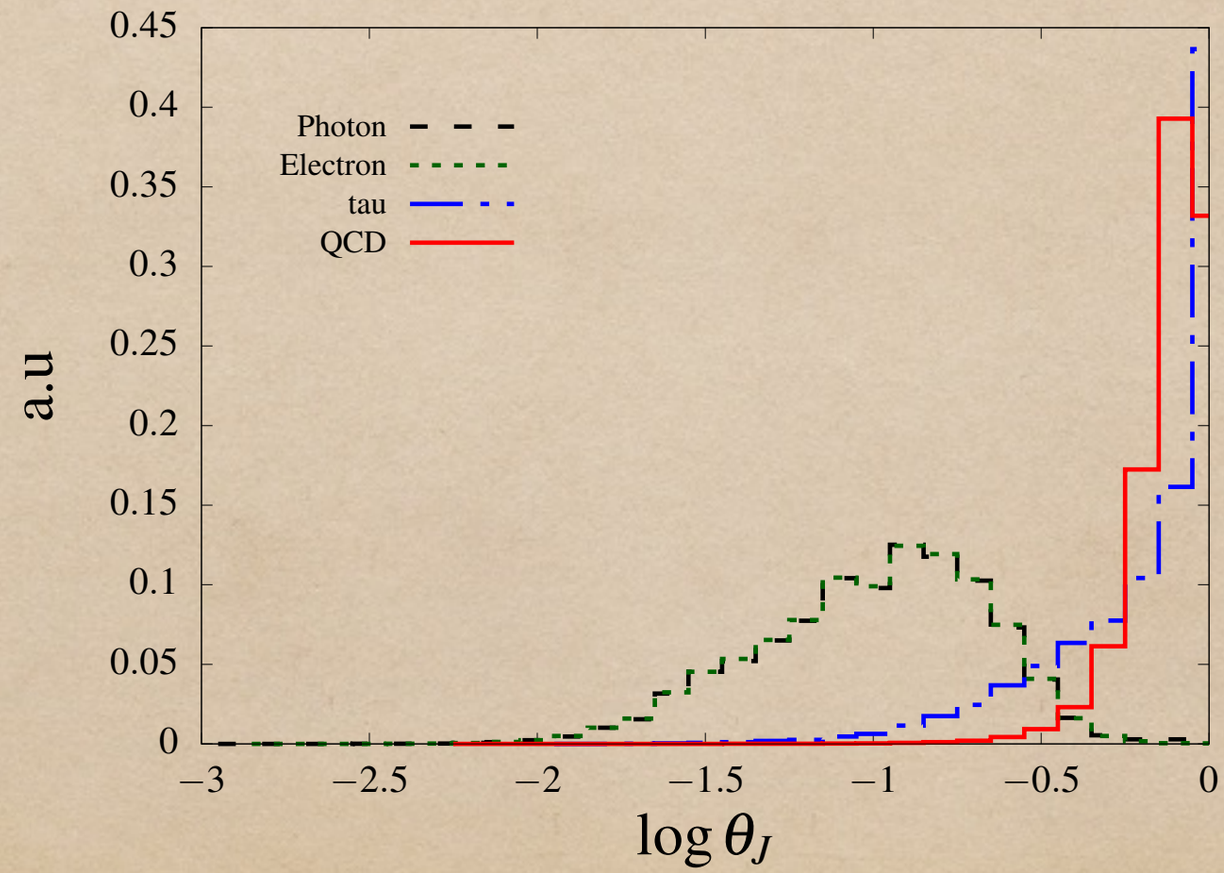
Hadronic Energy fraction

$$\theta_J = \frac{1}{E_J} \sum_{i \in H_{cal} \in J} E_i$$



Select jets with very small hadron content

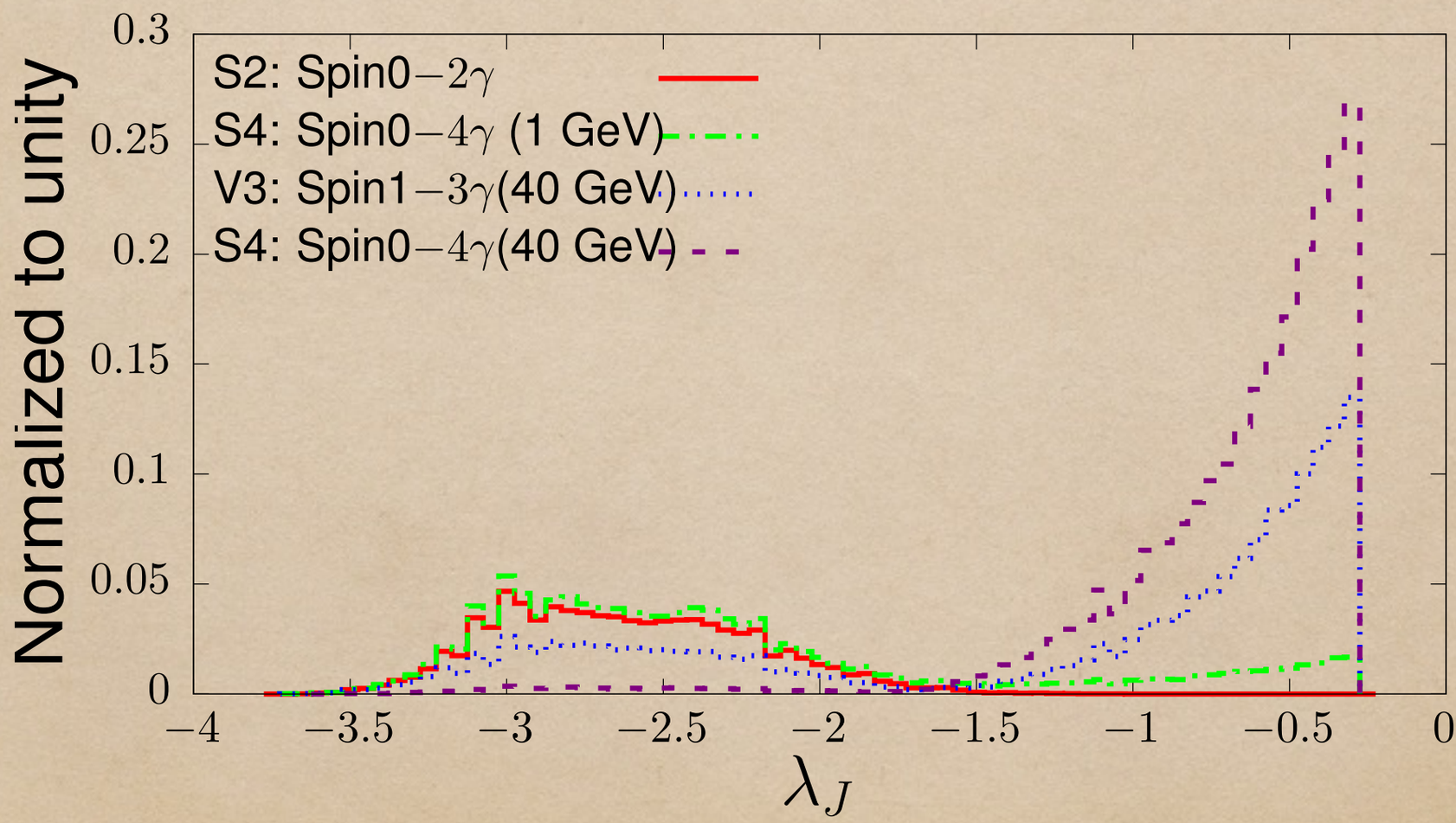
$$Log[\theta_J] < -0.5$$

Light or Heavy intermediate mass-
Jet Substructure

Light or Heavy mass-Jet Substructure

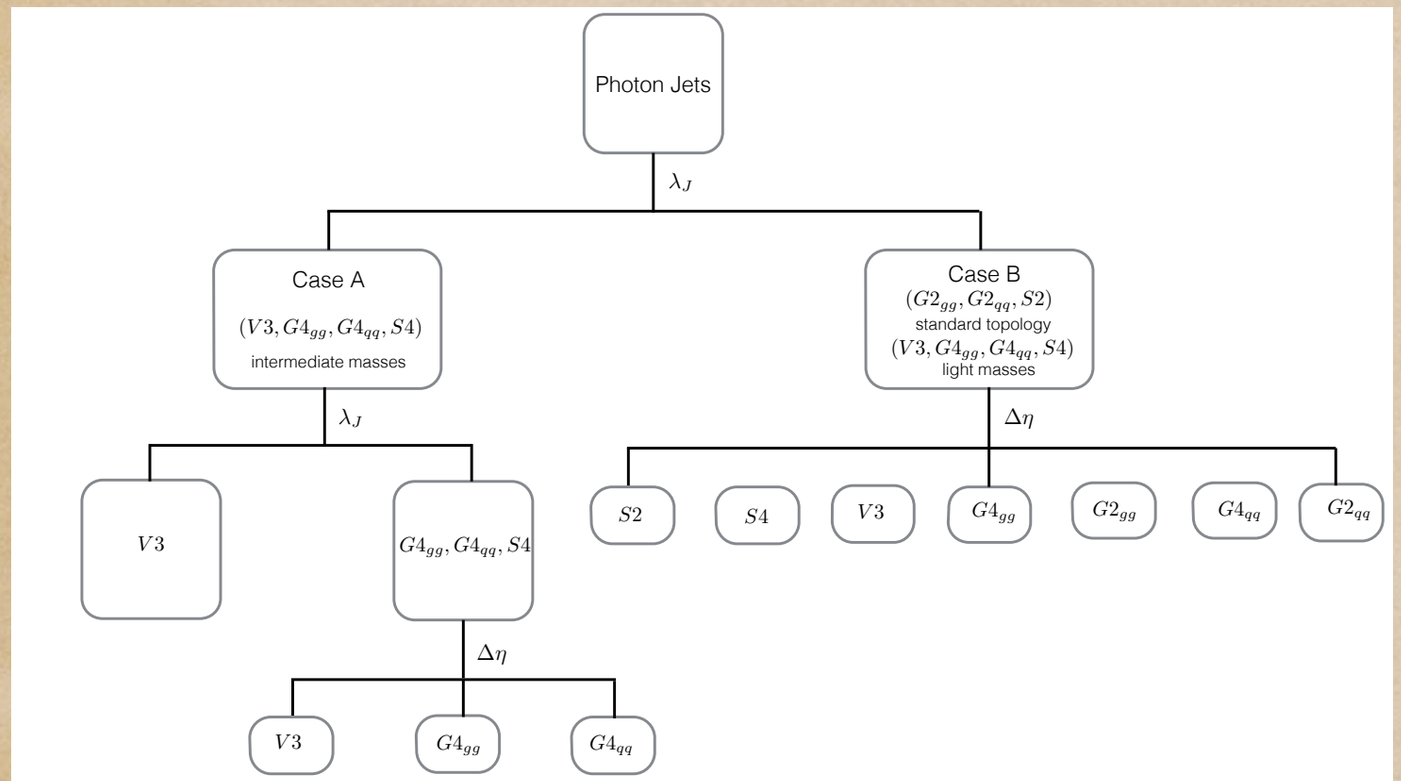
$$\lambda_J = \log\left(1 - \frac{p_{T_L}}{p_{T_J}}\right)$$

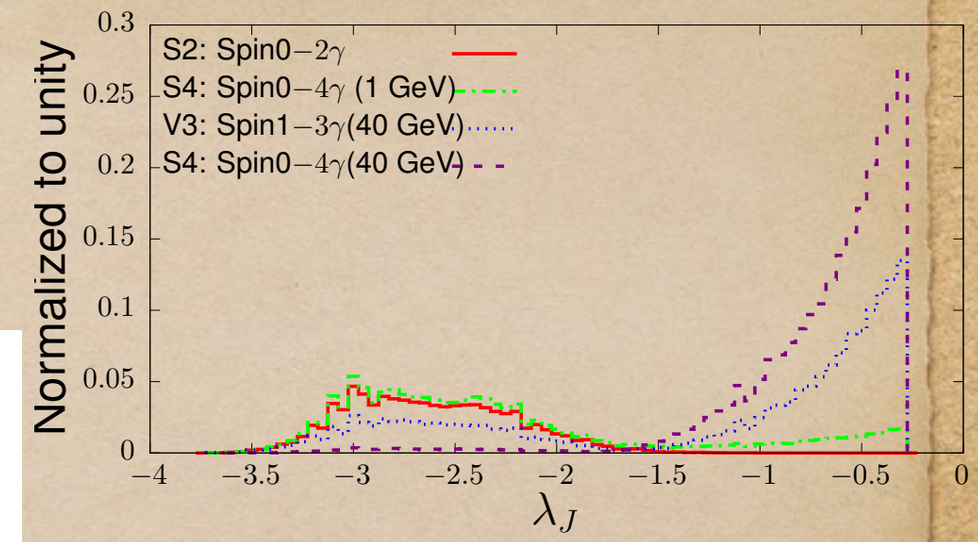
Measures the fraction of pT carried by the leading subjet of a given jet



Analysis Strategy

Using λ_J we decide between Case A and Case B.





How to quantify the analysis?

Case A: Non-standard topology with slightly heavier mass of n

Case B: Non-standard topology with very light mass of n or the standard topology

Pairwise discrimination of cases

There are several possibilities for the spin of X

A quantifying measure is required to estimate the number of events required to distinguish any two given possibilities

Model	Process
$S2$	$pp \to S \to \gamma\gamma$
$S4$	$pp \to S \to nn \to \gamma\gamma + \gamma\gamma$
$V3$	$pp \to Z' \to n\gamma \to \gamma + \gamma\gamma$
$G2_{ff}$	$q\bar{q} \to G \to \gamma\gamma$
$G2_{gg}$	$gg \to G \to \gamma\gamma$
$G4_{gg}$	$gg \to G \to nn \to \gamma\gamma + \gamma\gamma$
$G4_{ff}$	$\bar{q}q \to G \to nn \to \gamma\gamma + \gamma\gamma$

Consider two hypothesis: H_S and H_T

H_T is assumed to be the `True' Hypothesis

The number of events required to disfavour another spin Hypothesis say H_S Can be estimated by solving the following equation

$$\frac{1}{R} = \frac{p(H_S|N \text{ events from } H_T)}{p(H_T|N \text{ events from } H_T)}$$

Here we require R=20

H_S is disfavoured over H_T at a 20:1 odds

Using Baye's theorem and taking expectation over many draws

we get

$$\log\left(\frac{1}{R}\right) = \sum_{i=1}^{K}\left[\mu_j^{(T)}\log\frac{\mu_j^{(S)}}{\mu_j^{(T)}} + \mu_j^{(T)} - \mu_j^{(S)}\right].$$

The terms on the RHS are proportional to the luminosity as

$$\mu_j^{(X)} = \mathcal{L}\sigma_{tot}^{(X)}\epsilon_j^{(X)},$$

Assuming equal cross section for S and T and using $N_R = \mathcal{L}\sigma_{tot}$

$$N_R = \frac{\log R}{\sum_{j=1}^{K}\left[\epsilon_j^{(T)}\log\frac{\epsilon_j^{(T)}}{\epsilon_j^{(S)}} + \epsilon_j^{(S)} - \epsilon_j^{(T)}\right]}.$$

If two Hypothesis are exactly the same $N_R \to \infty$

$H_T > 1.5$ TeV

effective Background cross-sections are very small

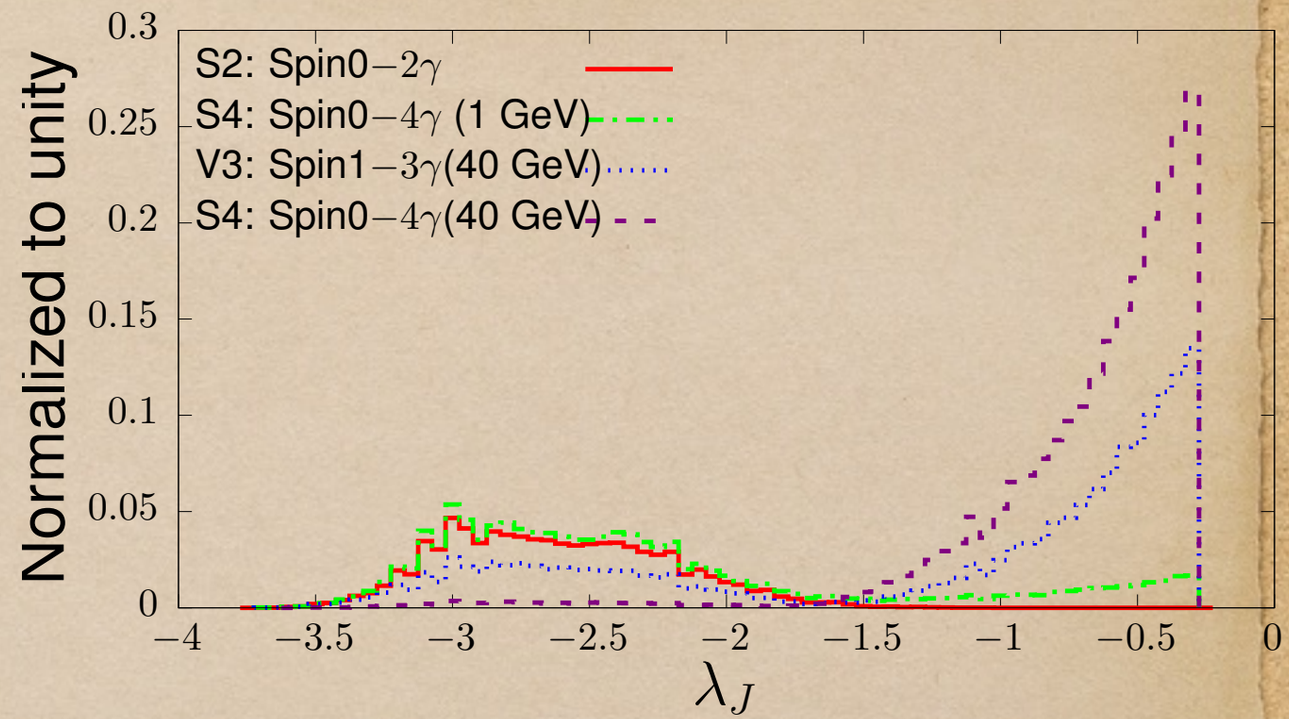
	ϵ_{BG}
jj	$< 10^{-6}$
ja	$\sim 10^{-5}$
aa	$\sim 10^{-2}$

Case A or Case B

Substructure is used to determine between the two cases

$$m_n = 10 \text{ and } m_n = 100\ GeV$$

are chose as the two hypothesis



Since the two distributions are characterized by different peaks

3-4 events are sufficient to segregate them

All scenarios are characterised by a minimum acceptance efficiency of 55%

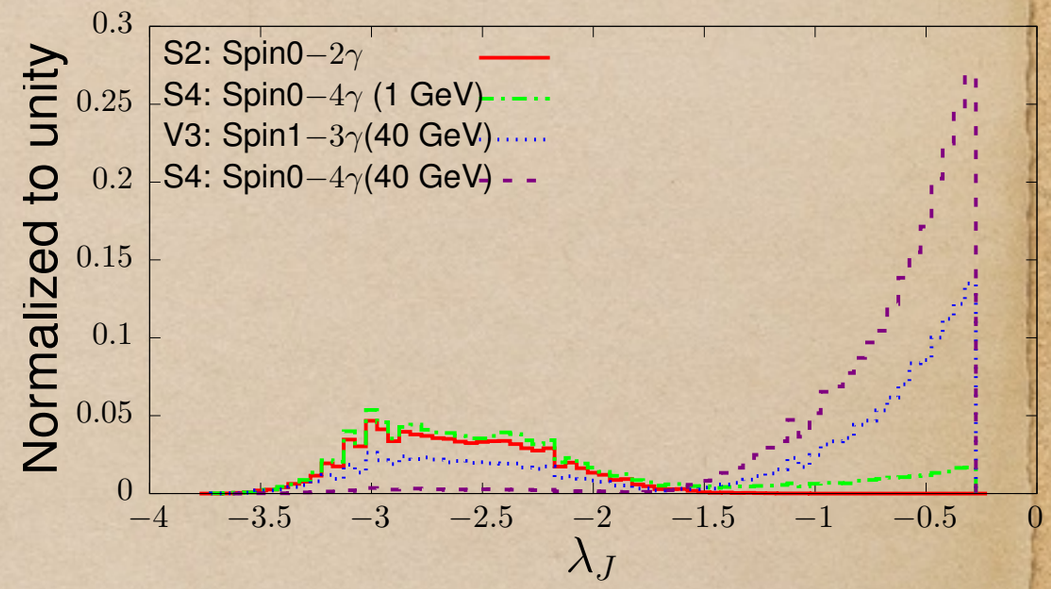
Assuming cs of 0.5 fb and the two cases can be distinguished within $20\ fb^{-1}$

Assume the tests point towards case A

Its the simpler of the two cases with just 4 possibilities:S4, G4gg, G4qq,V3

V3 has a double bump structure
owing to the
distinct nature of topology

λ_J can be used to separate it from the other cases with 20 signal events



To separate the other three cases we use $\Delta\eta$ between the leading jets

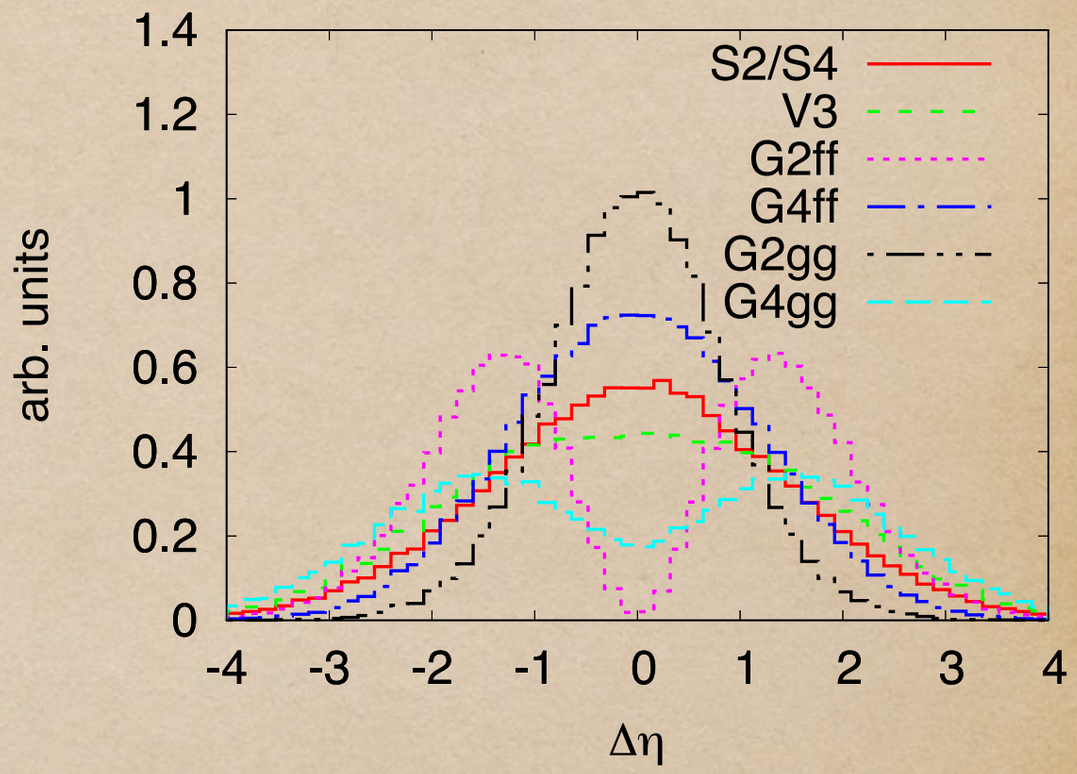
N_R	Ecm	$S4$	$G4_{gg}$	$G4_{ff}$
$S4$	14 TeV	∞	23	12
	27 TeV	∞	17	8
$G4_{gg}$	14 TeV	34	∞	5
	27 TeV	24	∞	3
$G4_{ff}$	14 TeV	18	5	∞
	27 TeV	11	4	∞

Assume the tests point towards case B (light masses or collimated topology)

All spins have same substructure so λ_J is not useful

$\Delta\eta$ between the leading jets is the only possibility

N_R	Ecm	$S2$	$S4$	$V3$	$G2_{gg}$	$G4_{gg}$	$G2_{ff}$	$G4_{ff}$
$S2$	14 TeV	∞	19270	198	25	13	85	12
	27 TeV	∞	8676	269	26	16	92	14
$S4$	14 TeV	19256	∞	202	25	13	81	13
	27 TeV	8713	∞	311	28	15	83	14
$V3$	14 TeV	186	190	∞	55	7	30	19
	27 TeV	261	299	∞	51	10	40	20
$G2_{gg}$	14 TeV	28	28	66	∞	4	11	35
	27 TeV	31	33	63	∞	5	13	41
$G4_{gg}$	14 TeV	21	21	12	6	∞	47	4
	27 TeV	26	25	16	7	∞	55	5
$G2_{ff}$	14 TeV	101	97	37	11	33	∞	8
	27 TeV	103	93	46	12	39	∞	9
$G4_{ff}$	14 TeV	18	18	26	36	4	12	∞
	27 TeV	19	20	29	41	5	13	∞



Conclusions

We offer a model independent analysis to pinpoint the possible origin of any new physics signal

The results obtained for model discrimination can be applied to any model by scaling appropriately with BR

Can be extended to di-electron, di-tau with similar results.

Substructure is a very efficient tool to hunt for new physics

Substructure can also be used to develop a trigger to uniquely identify the `di'-objects separate from the SM

Chakraborty, Iyer, Roy '17
1707.07084
Nucl.Phys. B932 (2018) 439-470

End

Backup

$$\frac{1}{R} = \frac{p(H_S|N \text{ events from } H_T)}{p(H_T|N \text{ events from } H_T)}$$

N events from H_T are characterized by one (or set of) observables o_i

By Baye's theorem

$$\frac{1}{R} = \frac{p(H_S)}{p(H_T)} \frac{p(N \text{ events from } H_T|H_S)}{p(N \text{ events from } H_T|H_T)} = \frac{p(H_S)}{p(H_T)} \frac{\prod_{i=1}^{N} p(o_i^{(T)}|H_S)}{\prod_{i=1}^{N} p(o_i^{(T)}|H_T)}.$$

Binned data in the o distribution $\{n_j^{(T)}\}$ (for $j \in \{1, 2, \ldots, K\}$,

will be poisson distributed as

$$p(n_j|H_X) = \text{Pois}(n_j|\mu_j^{(X)}),$$

where $X \in \{S, T\}$ and $\text{Pois}(n|\mu) = \frac{\mu^n e^{-\mu}}{n!}$

Substituting this above we get

$$\log\left(\frac{1}{R}\right) = \log\left(\frac{p(H_S)}{p(H_T)}\right) + \sum_{j=1}^{K}\left[n_j^{(T)} \log\frac{\mu_j^{(S)}}{\mu_j^{(T)}} + \mu_j^{(T)} - \mu_j^{(S)}\right],$$

Taking expectation over many draws

$$\langle n_j^{(T)} \rangle = \mu_j^{(T)} \quad \text{we get}$$

$$\log\left(\frac{1}{R}\right) = \sum_{i=1}^{K}\left[\mu_j^{(T)} \log \frac{\mu_j^{(S)}}{\mu_j^{(T)}} + \mu_j^{(T)} - \mu_j^{(S)}\right].$$

The terms on the RHS are proportional to the luminosity as

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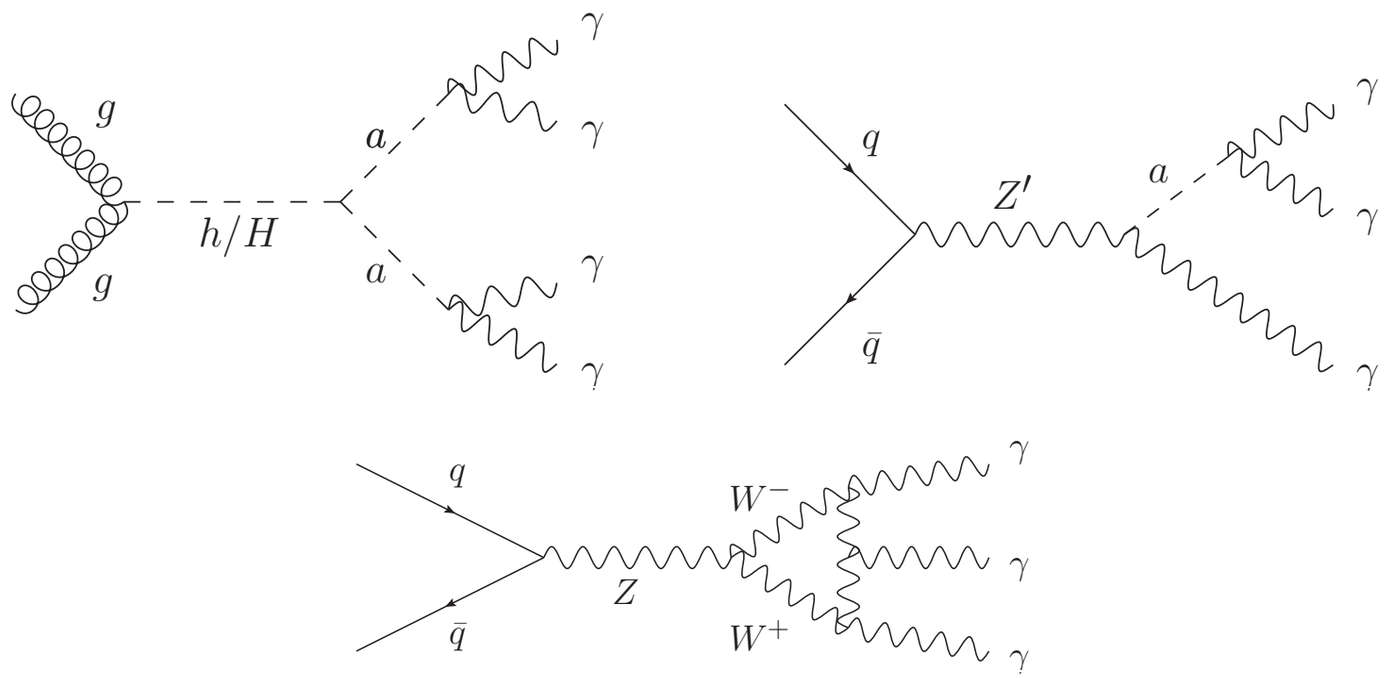
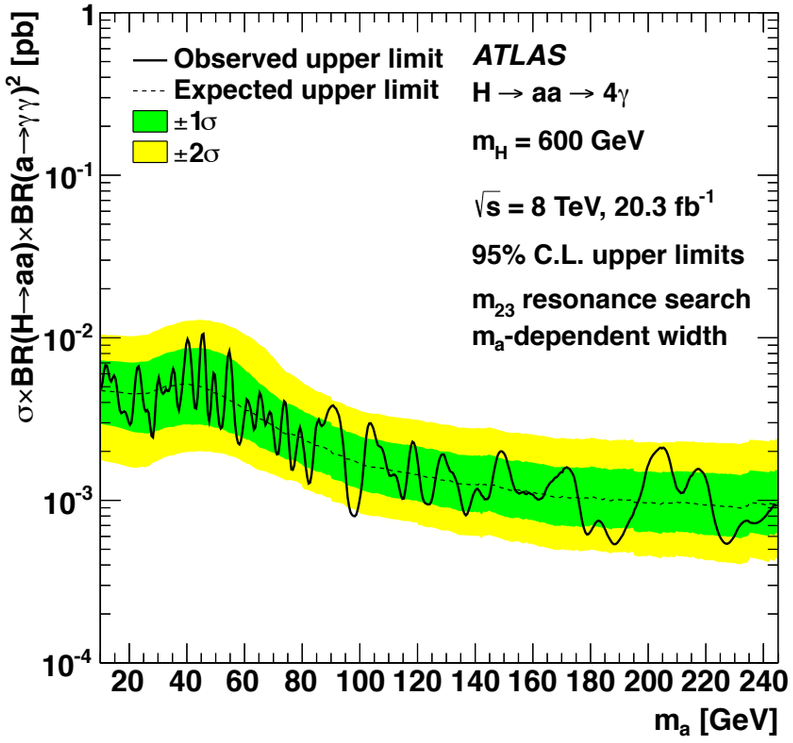
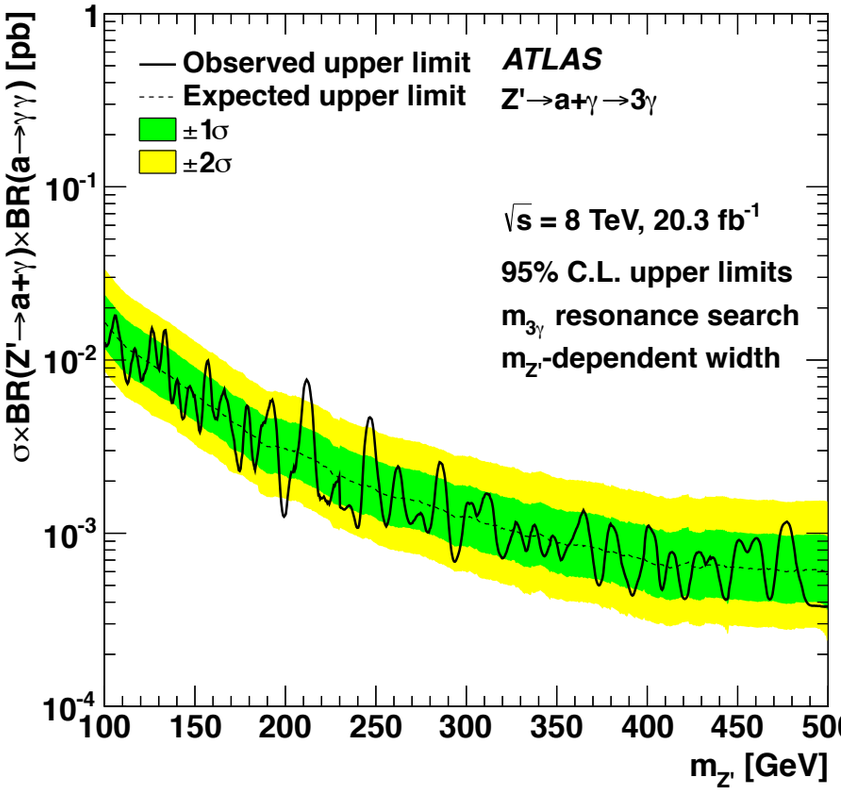
$$N_R = \frac{\log R}{\sum_{j=1}^{K}\left[\epsilon_j^{(T)} \log \frac{\epsilon_j^{(T)}}{\epsilon_j^{(S)}} + \epsilon_j^{(S)} - \epsilon_j^{(T)}\right]}.$$

If two Hypothesis are exactly the same $N_R \to \infty$







$$100 < m_{Z'} < 1000,\ 40 < m_n < 100$$

$$36 < \sigma \times B.R. < 320\ fb$$

Event selection

- We relax the isolation criteria and re-analyse the events by constructing photon jets.

- The invariant mass $m_{j_1 j_2}$ of the two leading photon jets for each events are required to lie around $m_{\gamma\gamma}^{(0)}$: we require $1100 < m_{j_1 j_2}/\text{GeV} < 1300$.

- Photon jets from pions are eliminated by requiring that leading jet to have no tracks ($n_T = 0$) and by requiring $Log[\theta_J] < -0.5$. We also take into account the photon conversion factor. This depends on whether the photon converts before or after exiting the pixel detector. This conversion probability is a function of the number of radiation lengths (a) a photon passes through before it escapes the first pixel detector and is given by [22]

$$P(\eta) = 1 - \exp(-\frac{7}{9}a(\eta)). \tag{19}$$

  We approximate this by an η independent conversion probability $P(\eta) = 0.2$.

- The substructure of each jet is analysed using λ_J to determine whether it is in Case A or B.

Disclaimer: Only a possibility!!

Case about S2 and S4

Under delta eta, S2 and S4 (1 GeV) case are nearly identical

Is there any way of telling them apart? One possibility is to look at detector smear effects on the substructure

With S4 (1 GeV) sometime the two photons hit adjacent cells near the edge

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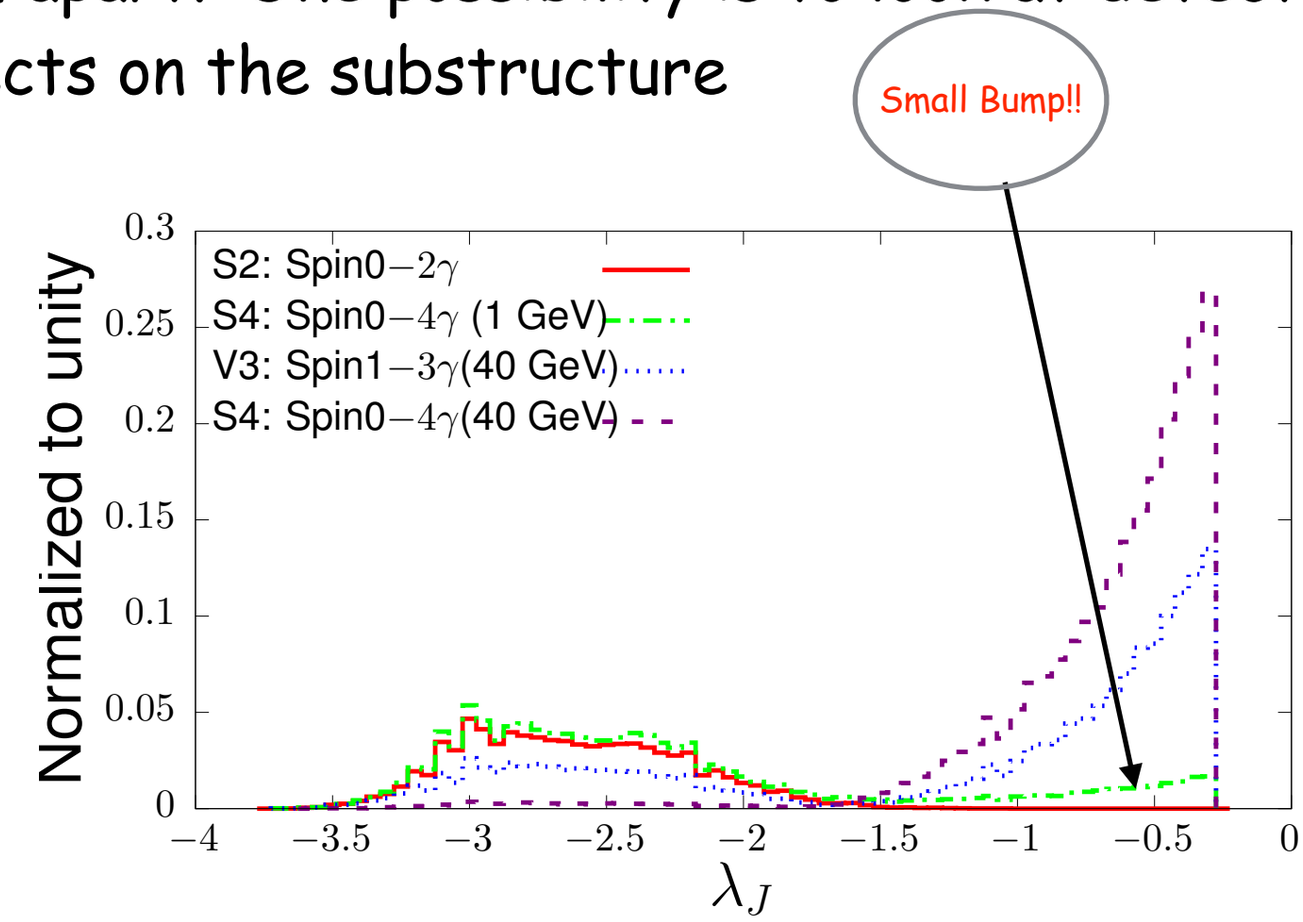
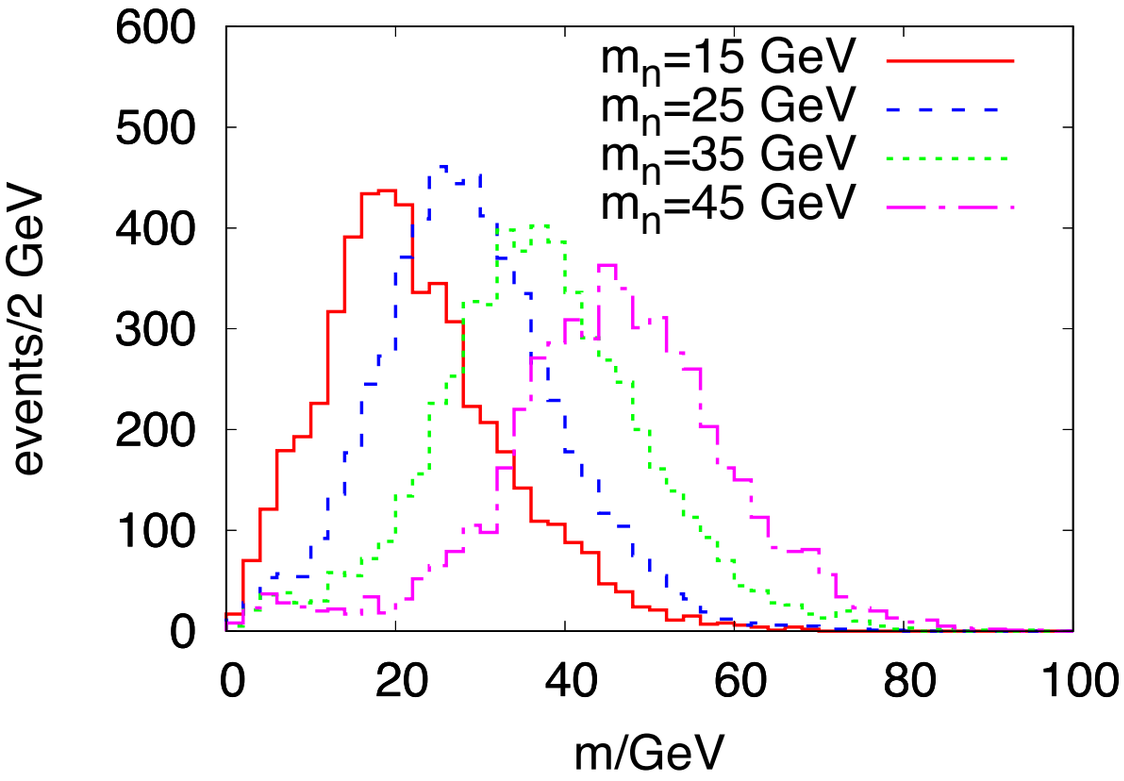


This may result in enhanced smearing in the surrounding cells and may give effect of the jet having a substructure—Needs to confirmed further

Mass of the intermediate state

A naive implementation is by simply computing the mass of the leading jet

One can then use the techniques discussed earlier to get an estimate of the masses

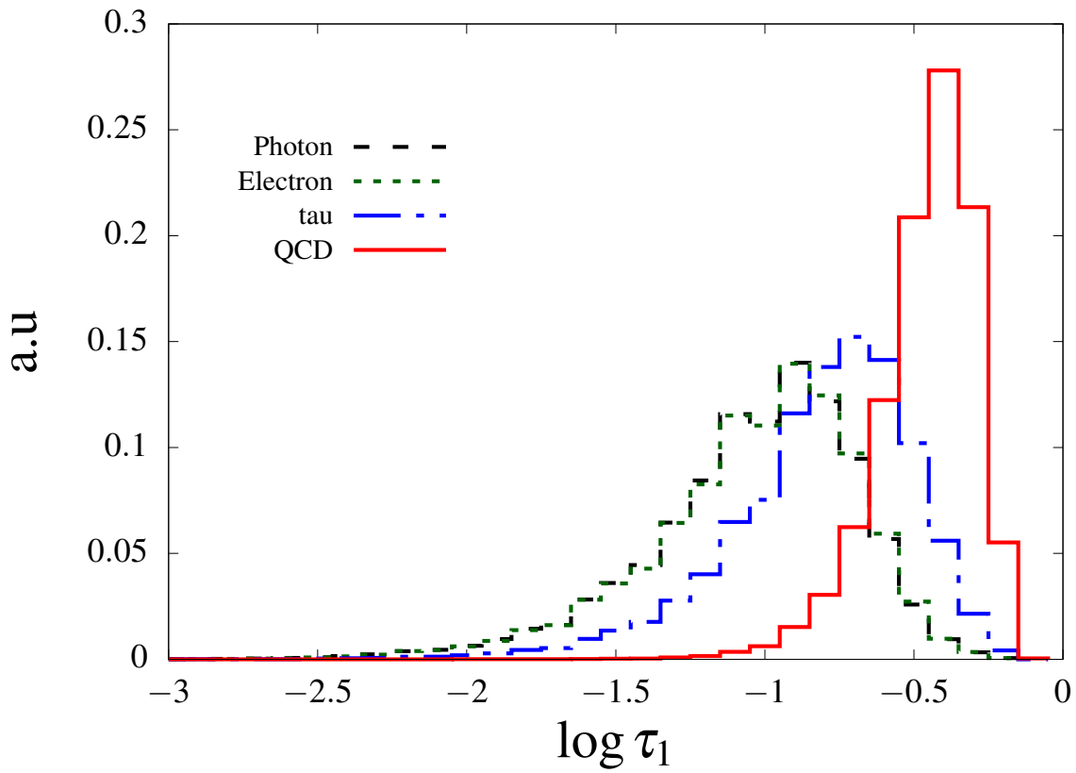


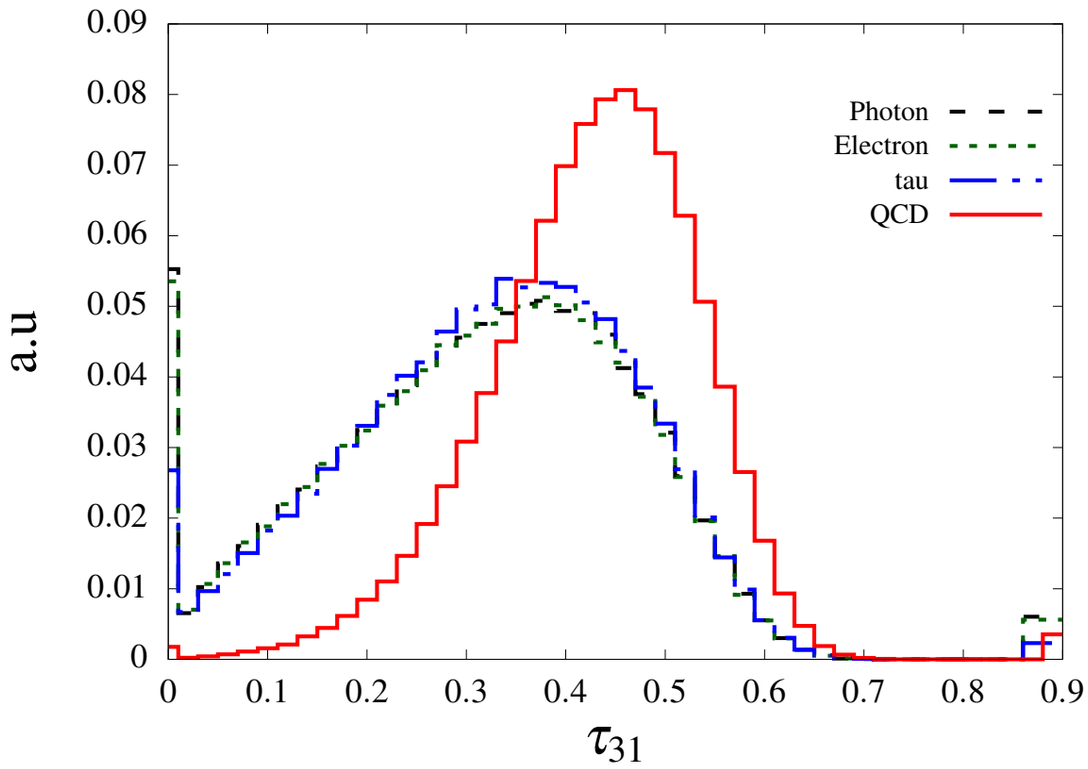
A much more sophisticated technique would involve extracting the subjects and and estimating the invariant mass of the leading subjets for each event

Other substructure variables that can be used

N-Subjettiness

$$\tau_N = \frac{\sum_k p_{T_k} \times \min\left(\Delta R_{1k}, \Delta R_{2k} \ldots \Delta R_{Nk}\right)}{\sum p_{T_k} \times R}$$





Other substructure variables that can be used

Energy-correlations functions

$$\mathrm{ECF}(N,\beta) = \sum_{i_1<i_2<\ldots<i_N\in J} \left(\prod_{a=1}^{N} p_{Ti_a}\right) \left(\prod_{b=1}^{N-1}\prod_{c=b+1}^{N} R_{i_b i_c}\right)^{\beta} ,$$

$$\mathrm{ECF}(0,\beta) = 1,$$

$$\mathrm{ECF}(1,\beta) = \sum_{i\in J} p_{Ti},$$

$$\mathrm{ECF}(2,\beta) = \sum_{i<j\in J} p_{Ti}\,p_{Tj}(R_{ij})^{\beta},$$

$$\mathrm{ECF}(3,\beta) = \sum_{i<j<k\in J} p_{Ti}\,p_{Tj}\,p_{Tk}\,(R_{ij}R_{ik}R_{jk})^{\beta} ,$$

$$\mathrm{ECF}(4,\beta) = \sum_{i<j<k<\ell\in J} p_{Ti}\,p_{Tj}\,p_{Tk}\,p_{T\ell}\,(R_{ij}R_{ik}R_{i\ell}R_{jk}R_{j\ell}R_{k\ell})^{\beta} .$$

$$r_N^{(\beta)} \equiv \frac{\mathrm{ECF}(N+1,\beta)}{\mathrm{ECF}(N,\beta)}, \qquad C_N^{(\beta)} \equiv \frac{r_N^{(\beta)}}{r_{N-1}^{(\beta)}} = \frac{\mathrm{ECF}(N+1,\beta)\,\mathrm{ECF}(N-1,\beta)}{\mathrm{ECF}(N,\beta)^2} ,$$

Similar to N-Subjettiness