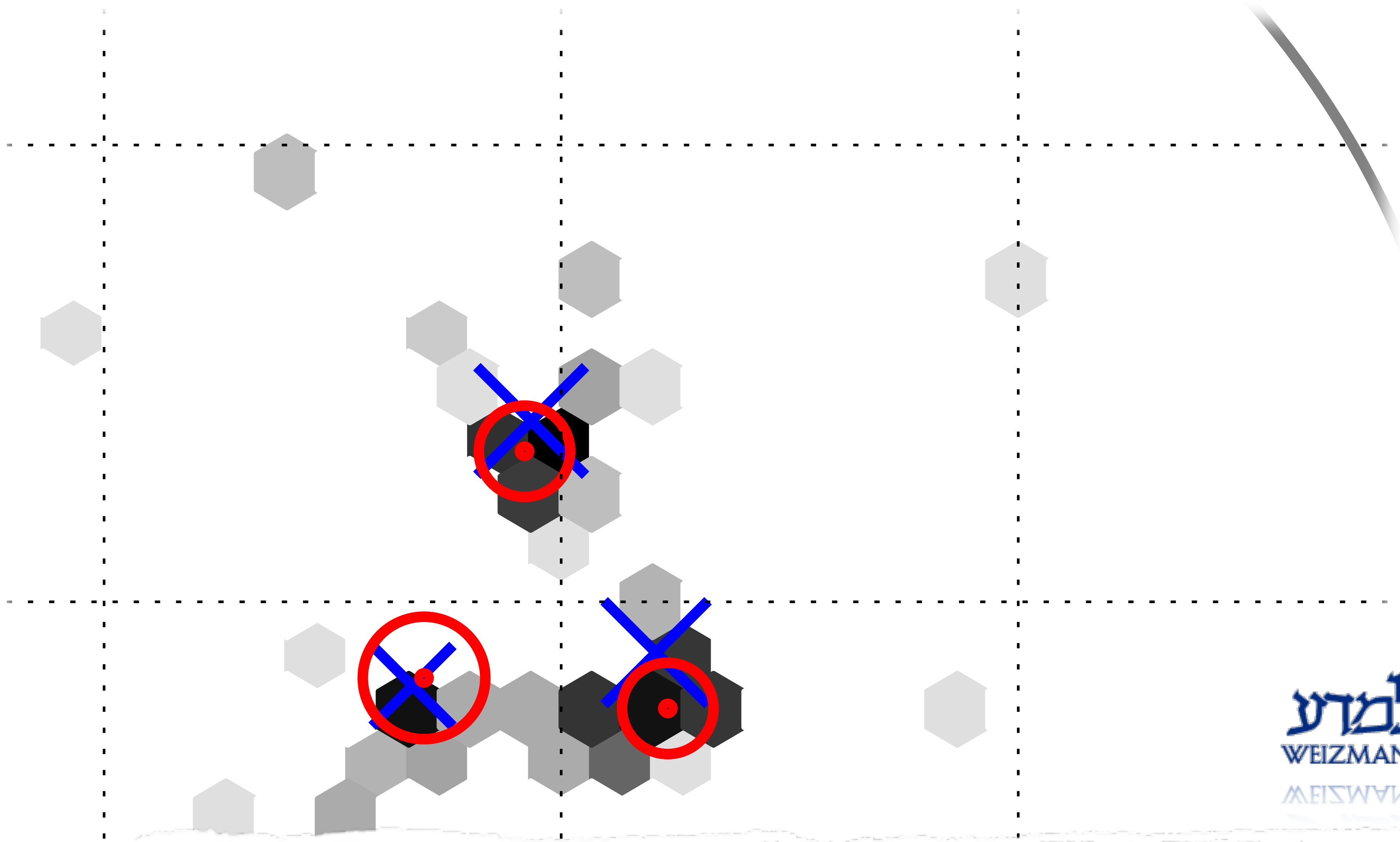

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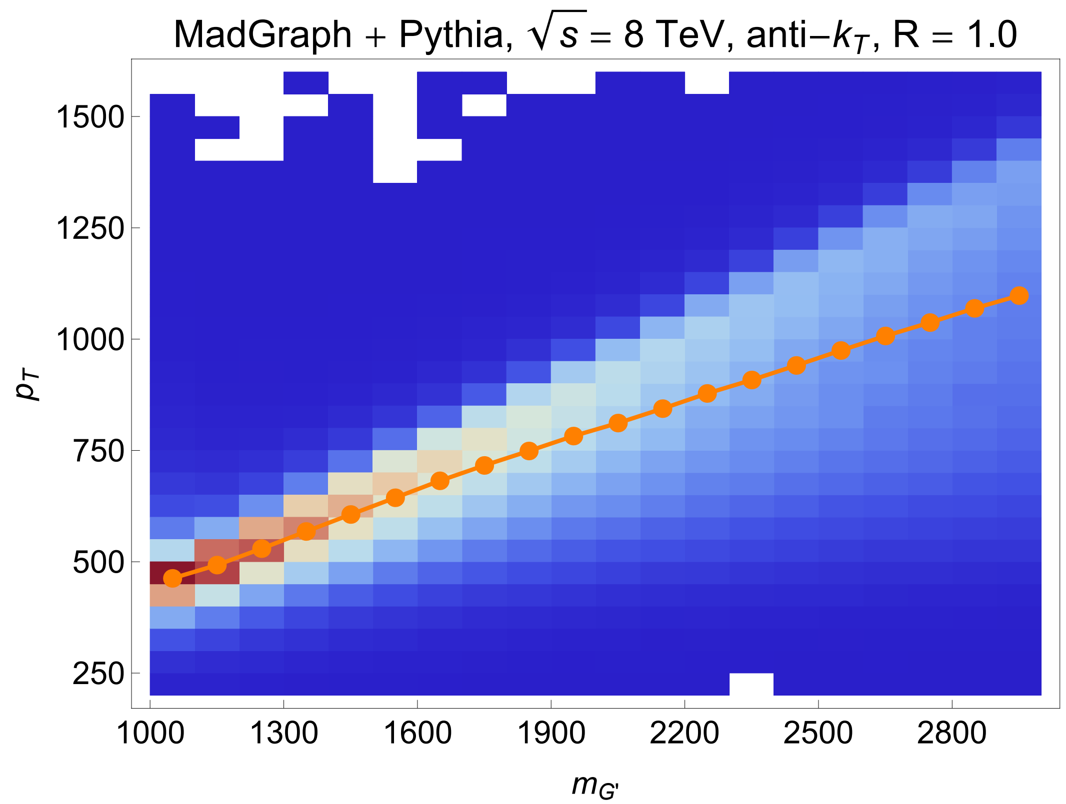
Measuring Boosted Semi Leptonic $t\bar{t}$ events.

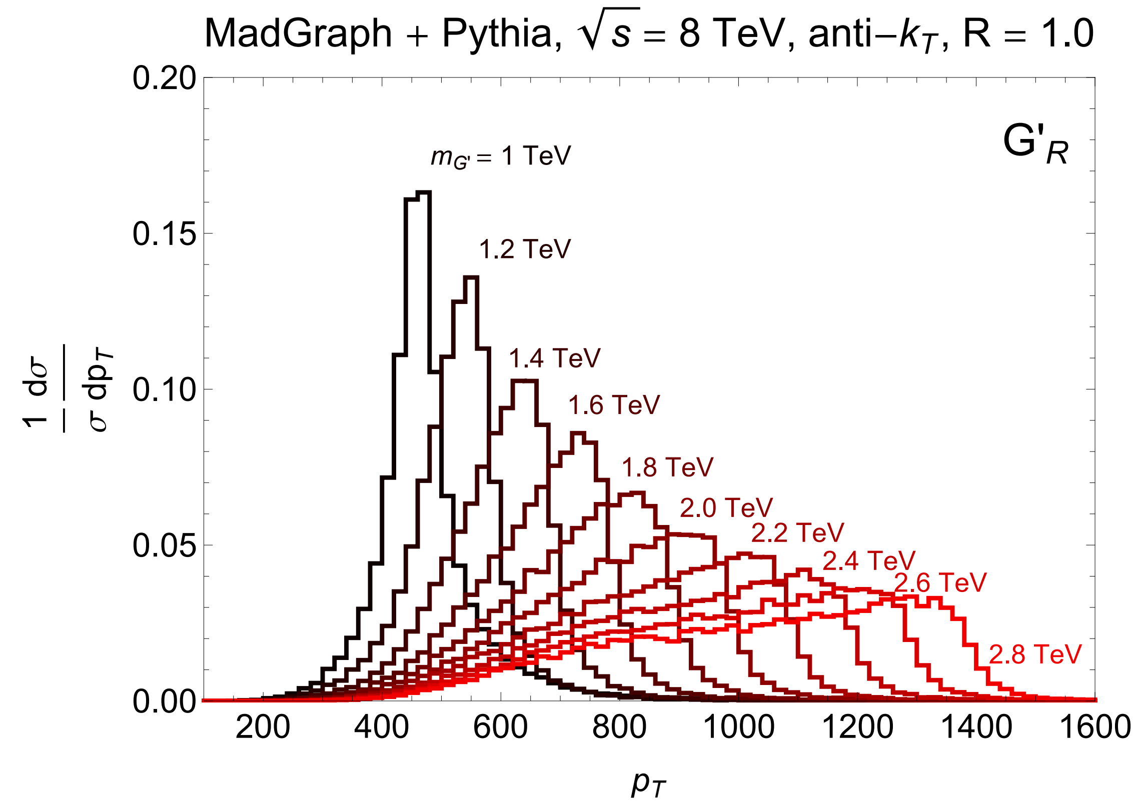
Mihailo Backovic (WIS) w/ Ofir Gabizon (WIS), Jose Juknevich (WIS) Yotam Soreq (WIS) and Gilad Perez (WIS & CERN)

Boosted Tops

1. Measuring the differential top cross sections (e.g. tail of the transverse momentum distribution).

2. Search for NP (e.g. tt resonances):





- Ultra-highly boosted jets (p_T > 1 TeV) become more important at higher masses. (e.g. about 50% of events with $m_{g'}$ = 2.8 TeV give top jets with p_T > 1 TeV).

- So far most resonance searches used **fully hadronic** di-top channel.

Boosted Tops

1. Measuring the differential top cross sections (i.e. tail of the transverse momentum distribution).

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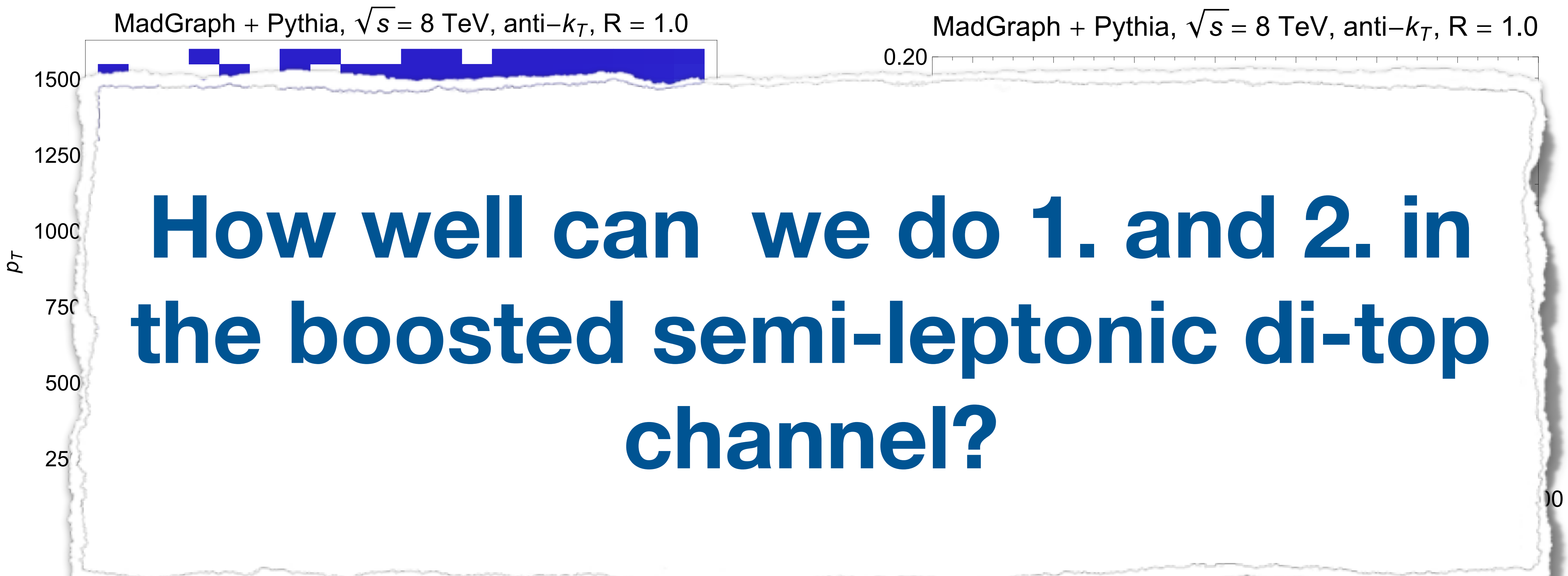

How well can we do 1. and 2. in the boosted semi-leptonic di-top channel?

- Ultra-highly boosted jets (p_T > 1 TeV) become more important at higher masses. (e.g. about 50% of events with $m_{g'}$ = 2.8 TeV give top jets with p_T > 1 TeV).

- So far most resonance searches used **fully hadronic** di-top channel.

Template Overlap Method (TOM)

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- A jet substructure algorithm to tag heavy, boosted jets against the background.

- First introduced by **Almeida, Lee, Perez, Sterman and Sung** (Phys.Rev. D82 (2010) 054034)

- Subsequent pheno studies:
    - ***Highly boosted Higgs study*** - Almeida, Erdogan, Juknevich, Lee, Perez, Sterman (Phys.Rev. D85 (2012) 114046).
    - ***Boosted Higgs study*** - Backovic, Juknevich, Perez (arXiv:1212.2977)
    - ***Semi-leptonic Top study*** **- Backovic, Juknevich, Gabizon, Soreq, Perez (arXiv:1311.2962)**

- Publically available code:
    - ***Template Tagger v1.0.0 (http://tom.hepforge.org/)***- Backovic, Juknevich (arXiv:1212:2978)
    - Also available through ATHENA.

- ATLAS study:
    - ***Search for resonances in ttbar events*** - (JHEP 1301 (2013) 116)

Template Overlap Method (TOM)

Templates: Sets of “n” four-momenta which satisfy the kinematic constraints of the decay products of a boosted massive jet:

“template momenta”

$$\sum_{i=1}^{n} p_i = P\,, \qquad P^2 = M^2 \;\; etc.$$

top 4-mom.

top mass

e.g. the decay of a boosted top also requires two template momenta to reconstruct the W boson.

** We generate templates at fixed transverse momentum in several bins (significantly improves computation time.)
** Template pT bin matched to the fat jet pT.

Not a unique definition!

Template Overlap Method (TOM)

Peak Template Overlap: Functional measure of how well the energy distribution of the jet matches the parton-like model for the decay of a massive particle (Template):

template resolution (typically E(f)/3)

j - jet “constituent”

$$Ov^{(F)}(i,j) = max_{TS}\, exp\left[-\sum_f \frac{1}{2\sigma_f^2}\left(\sum_j (E_j - E_f)F(f,j)\right)^2\right]$$

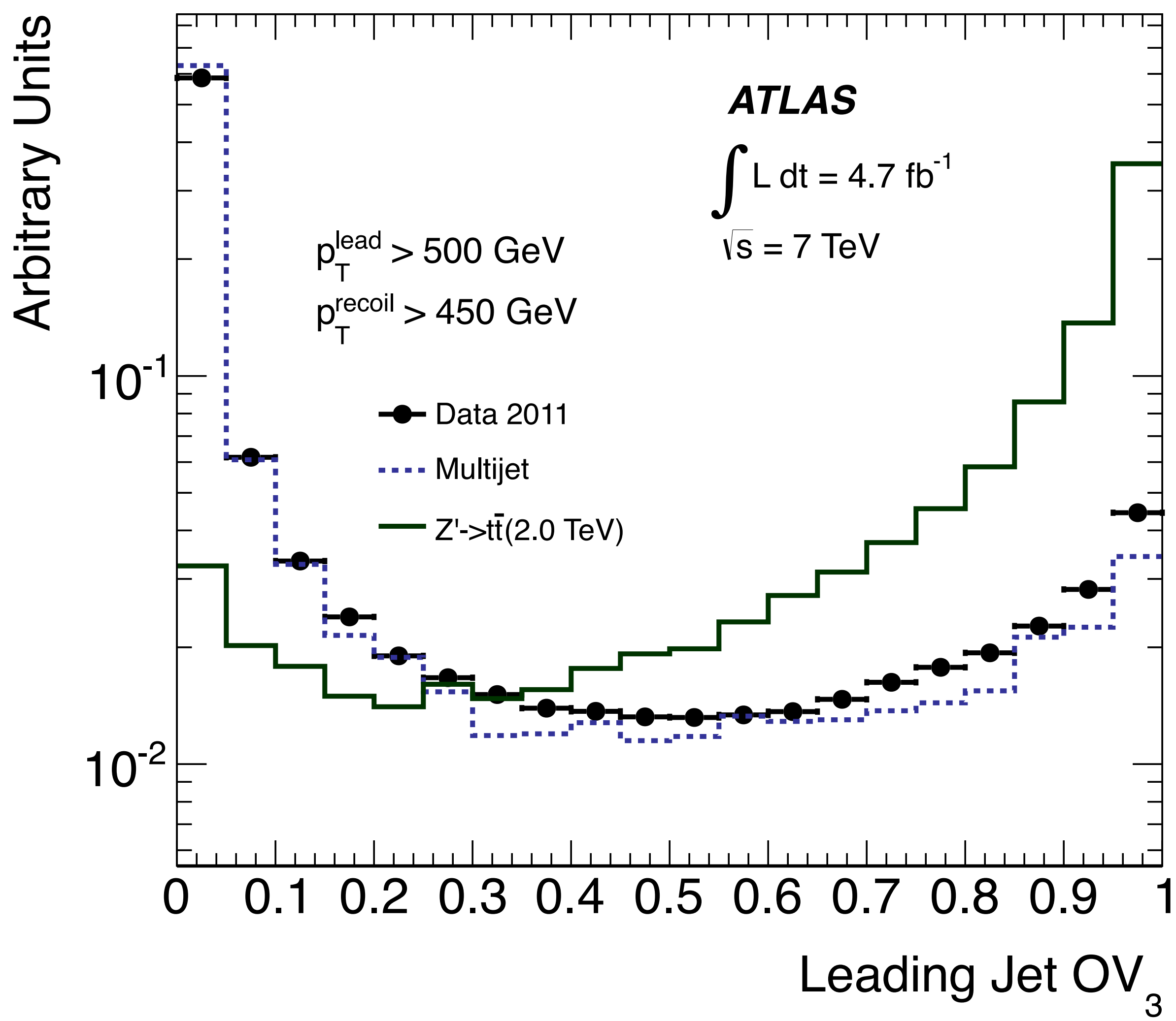
TS - template “space”

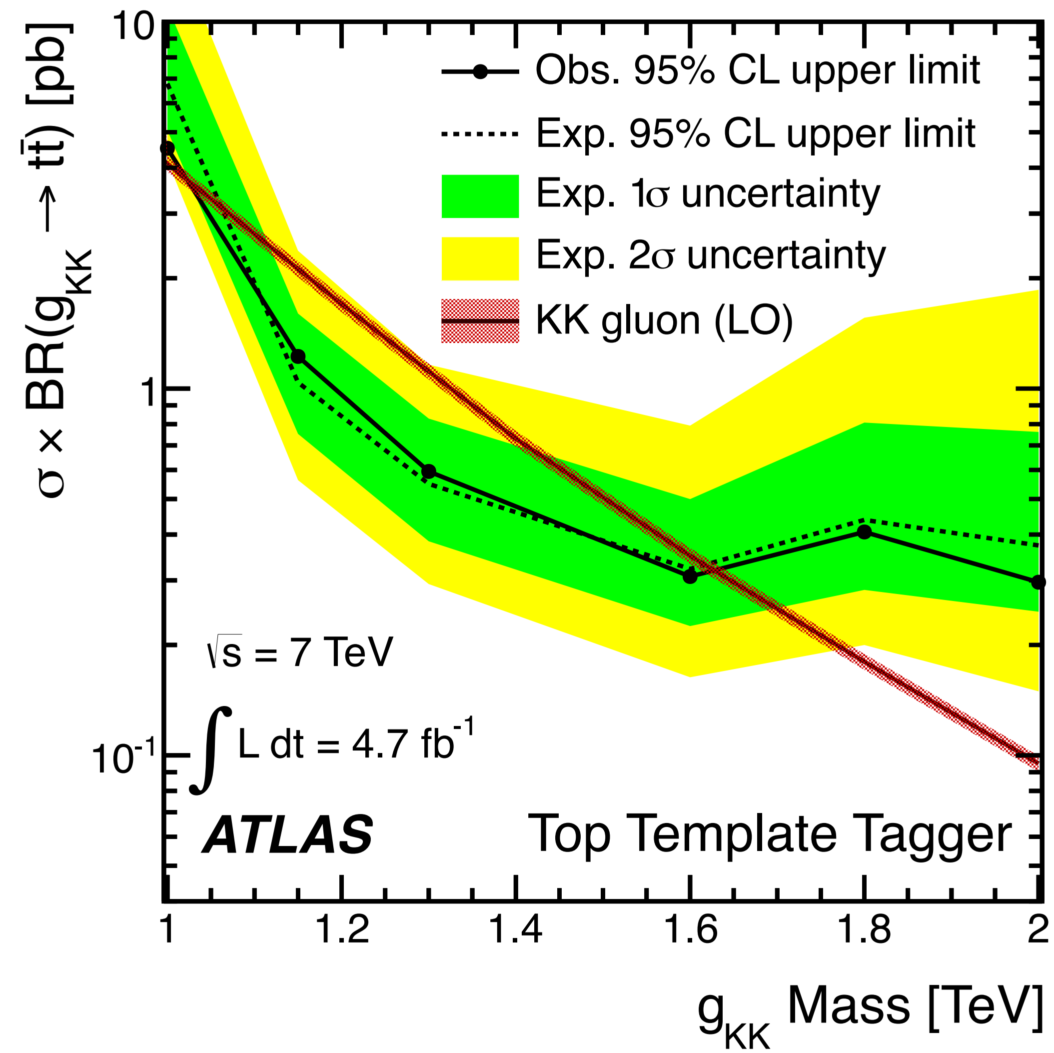
f - template momentum

The kernel F restricts the angular region around each template momentum

Hadronic TOM: Atlas analysis

- A 7 TeV search for heavy ttbar resonances JHEP 1301(2013) 116:





Future analyses should look even better (improvements in the method and new observables).

TOM w/ missing energy

It is possible to define Template Overlap for a leptonically decaying top:

$$Ov_3^l = \max_{\{f\}} \left[\underbrace{\exp \frac{-1}{\sigma_b^2} \left(\epsilon\, k_{T,b} - \sum_{i \in j} p_{T,i}\, F(\hat{n}_i, \hat{n}_a) \right)^2}_{\text{b quark}} \underbrace{\exp \frac{-1}{\sigma_l^2} \left(\epsilon_l\, k_{T,l} - p_{T,l} \right)^2}_{\text{lepton}} \underbrace{\exp \frac{-1}{\sigma_\nu^2} \left(\epsilon_\nu\, k_{T,\nu} - \not{E}_T F'(\phi_\nu, \phi_{\not{E}_T}) \right)^2}_{\text{neutrino}} \right]$$

Three main differences from the fully hadronic decays:

1. We only take into account the transverse component of the missing energy.

2. We "anchor" the template at the lepton instead of the jet axis.

3. We keep track of the identities of individual template momenta.

Properties of Template Overlap

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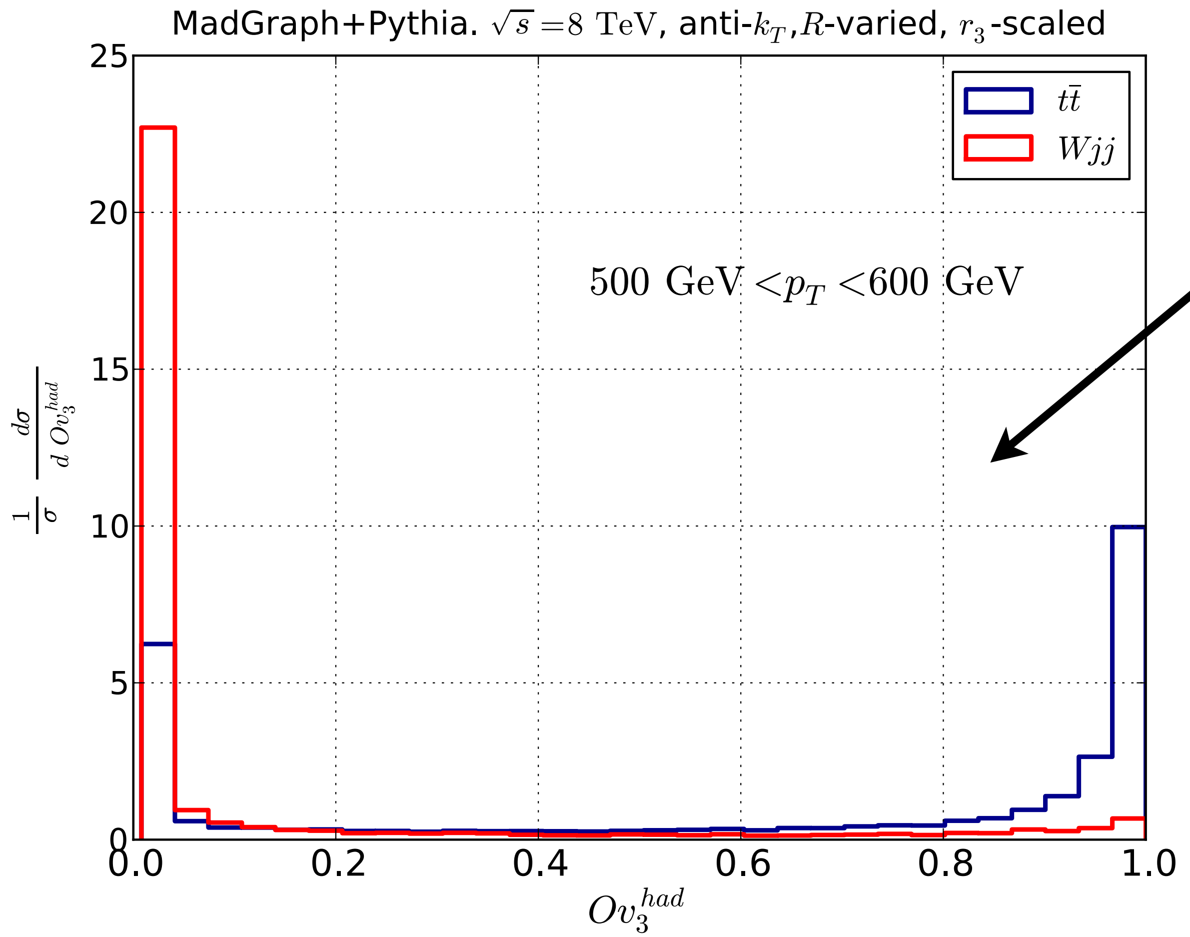
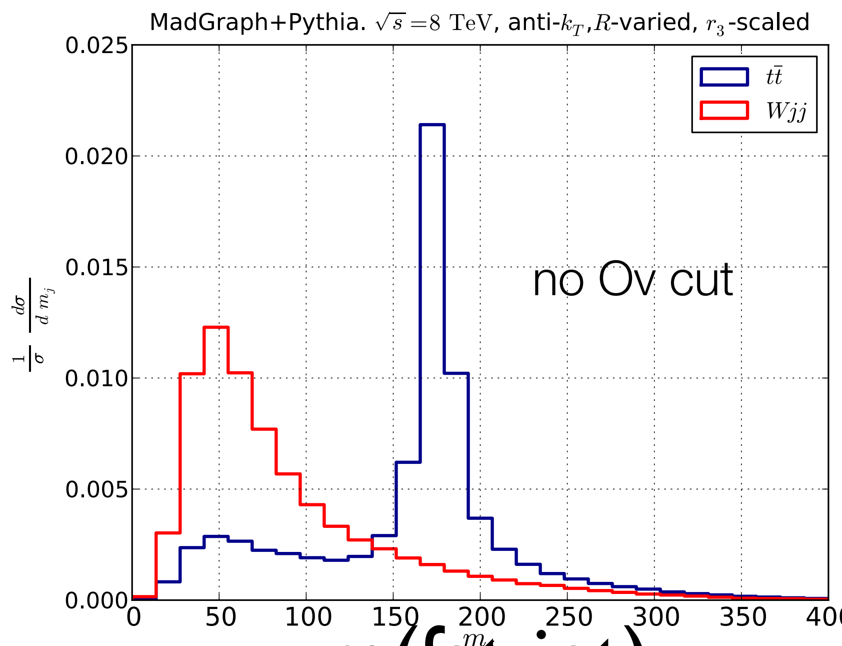
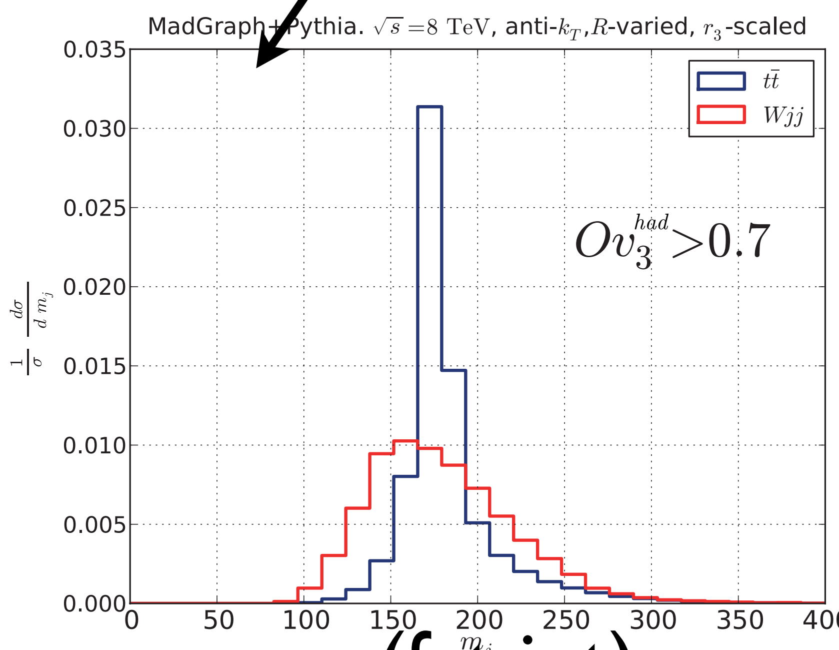


Expect signal event distribution to peak at 1, background at 0.

Templates incorporate a cut on the fat-jet mass! (**We will come back to this when discussing pileup**).

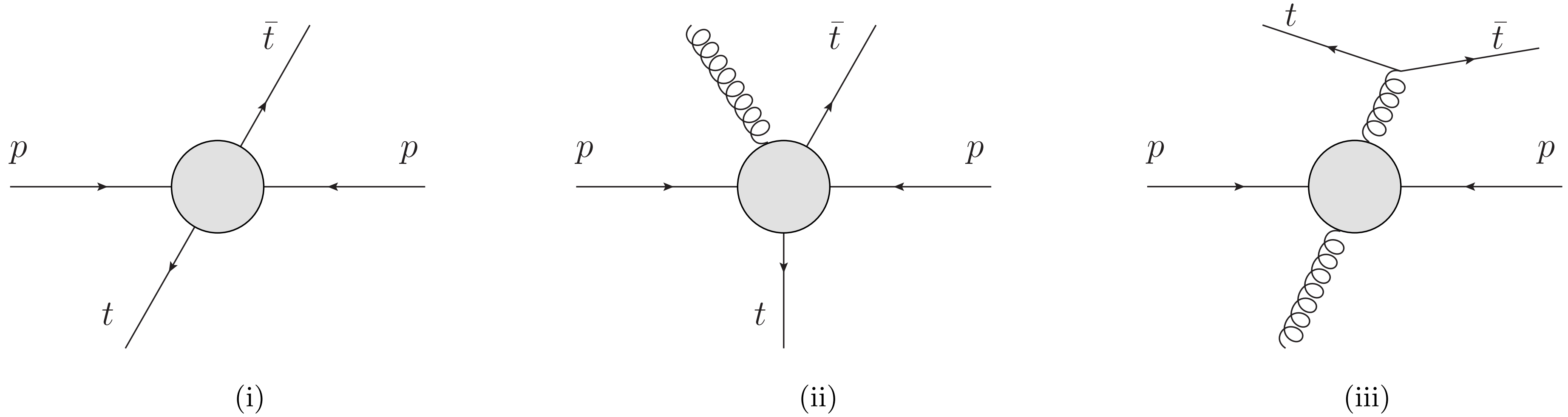


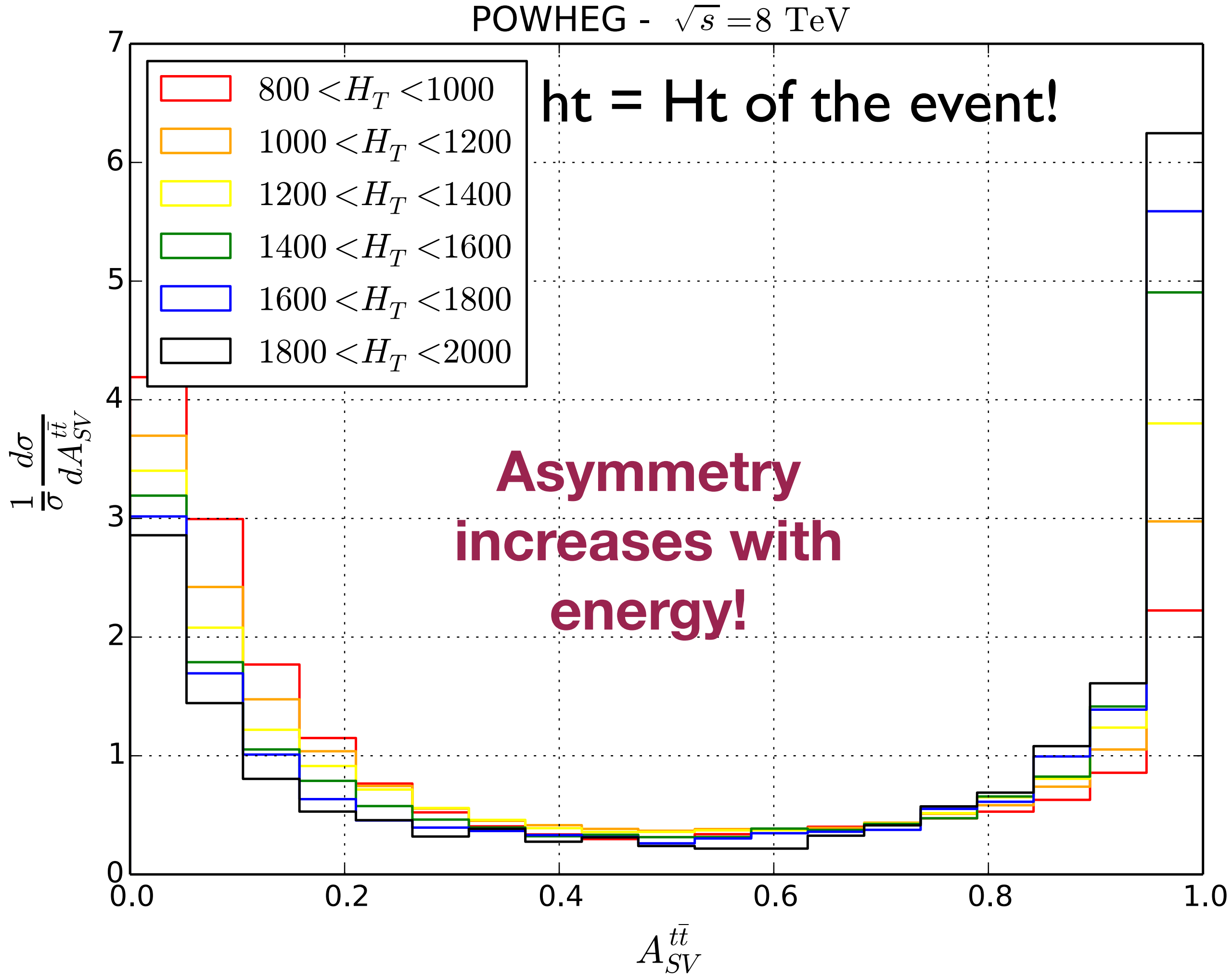
m(fat jet)



m(fat jet)

Higher order effects become significant at high energies. (**Tops are not necessarily back to back**)





$$A_{t\bar{t}}^{T} \equiv \frac{|\vec{p}_T^{\,t} + \vec{p}_T^{\,\bar{t}}|}{p_T^t + p_T^{\bar{t}}}$$

defined from truth level tops!

1. Measuring Top Differential Distributions

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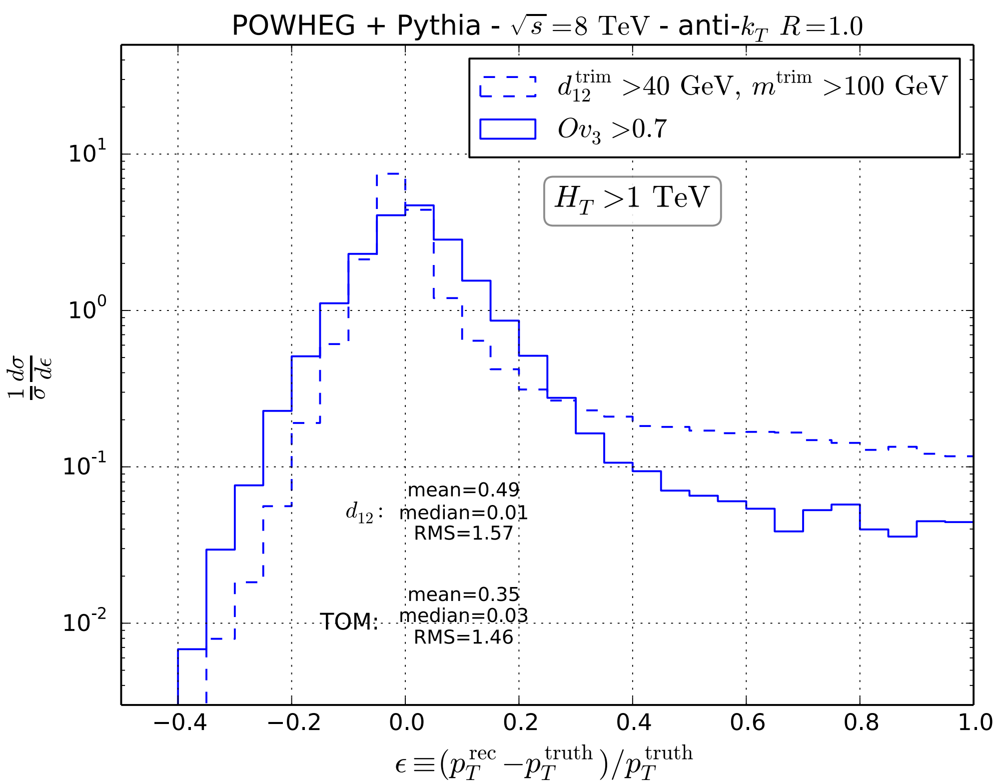
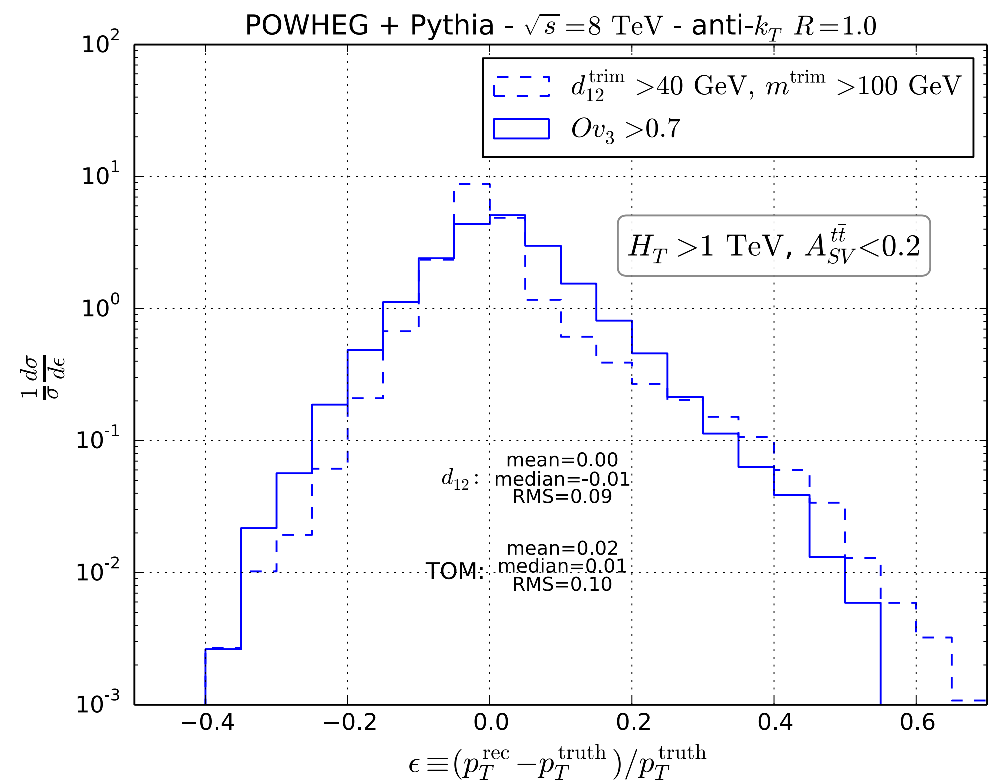
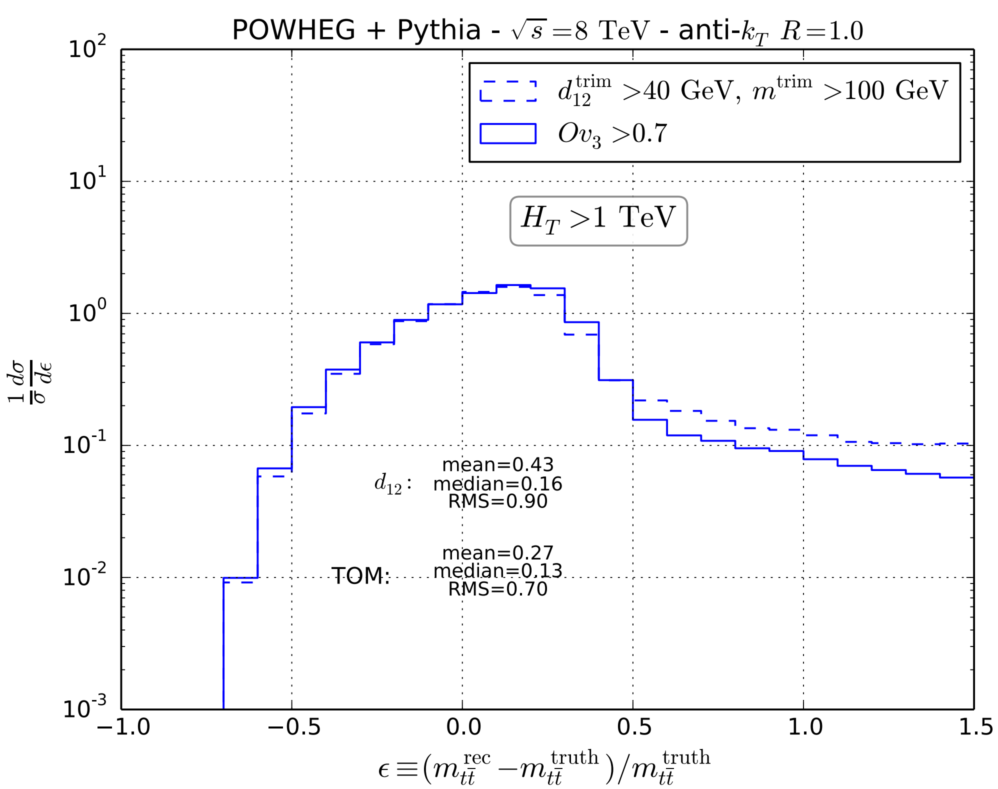
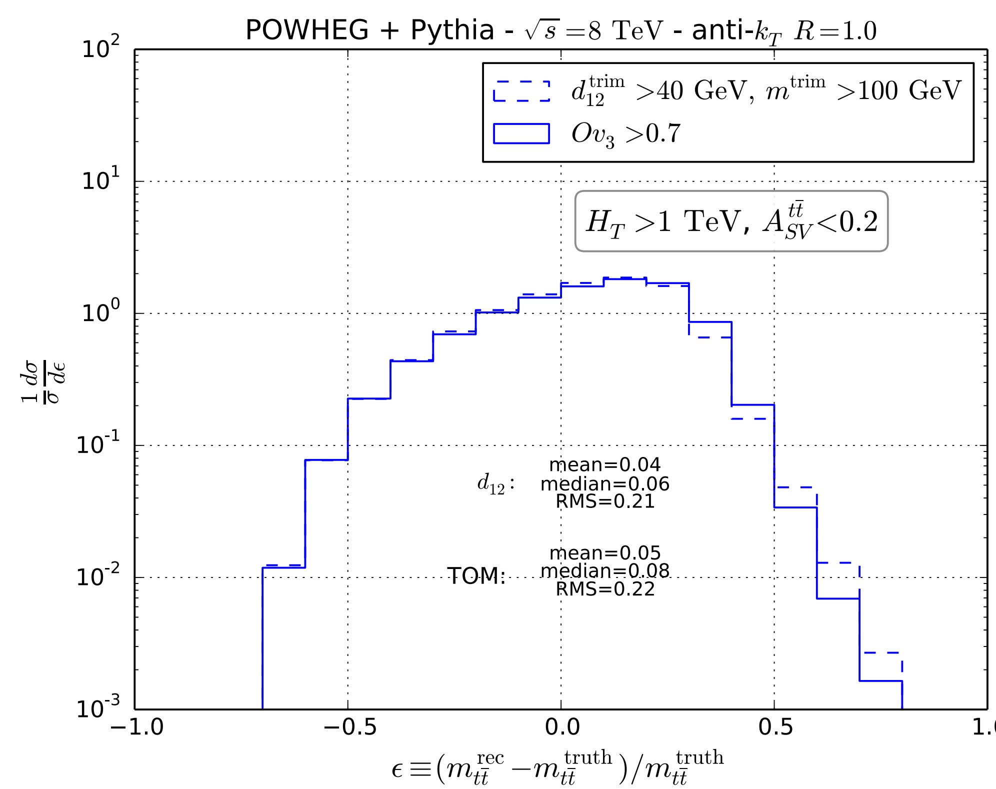
All Events



Symmetric events only

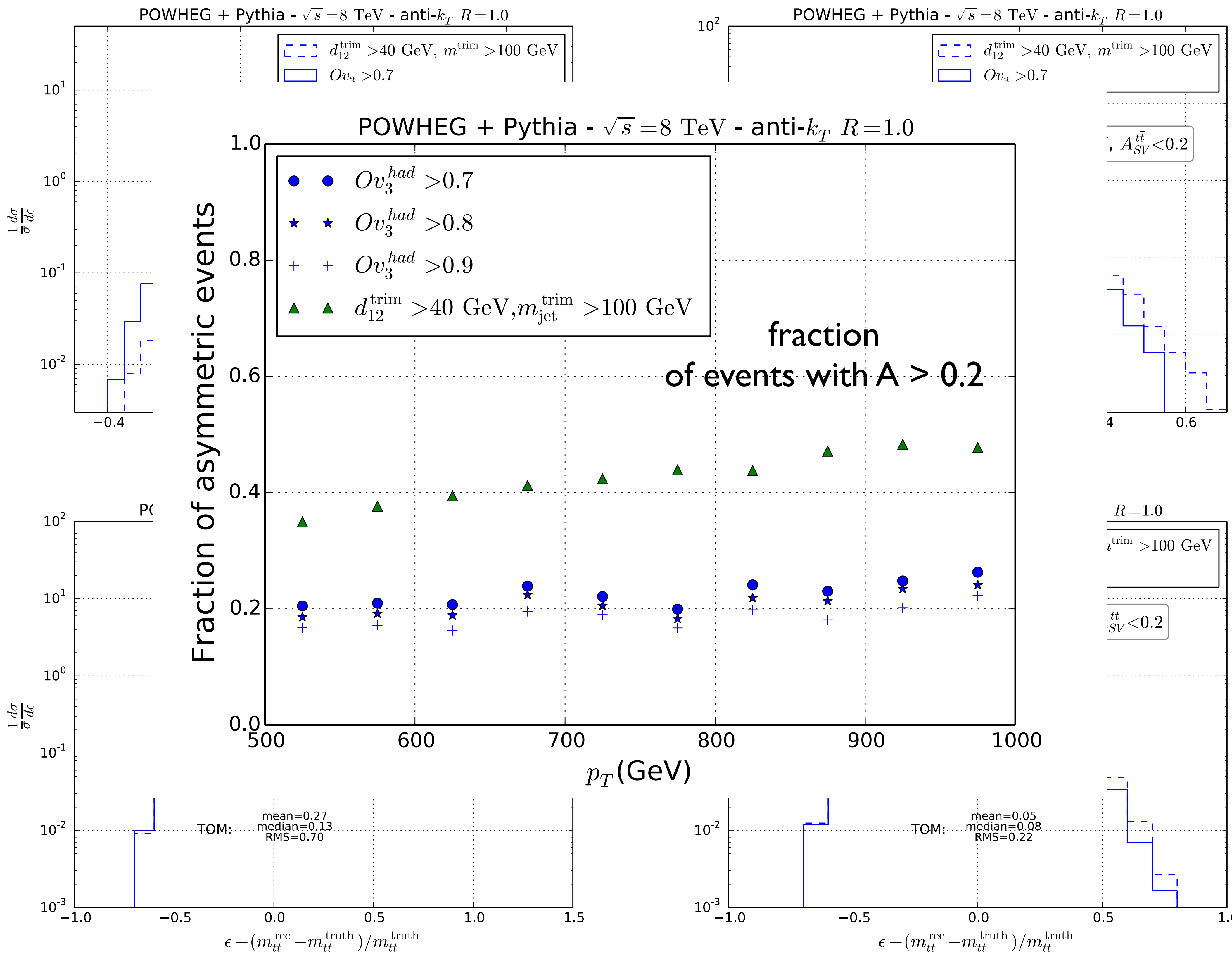






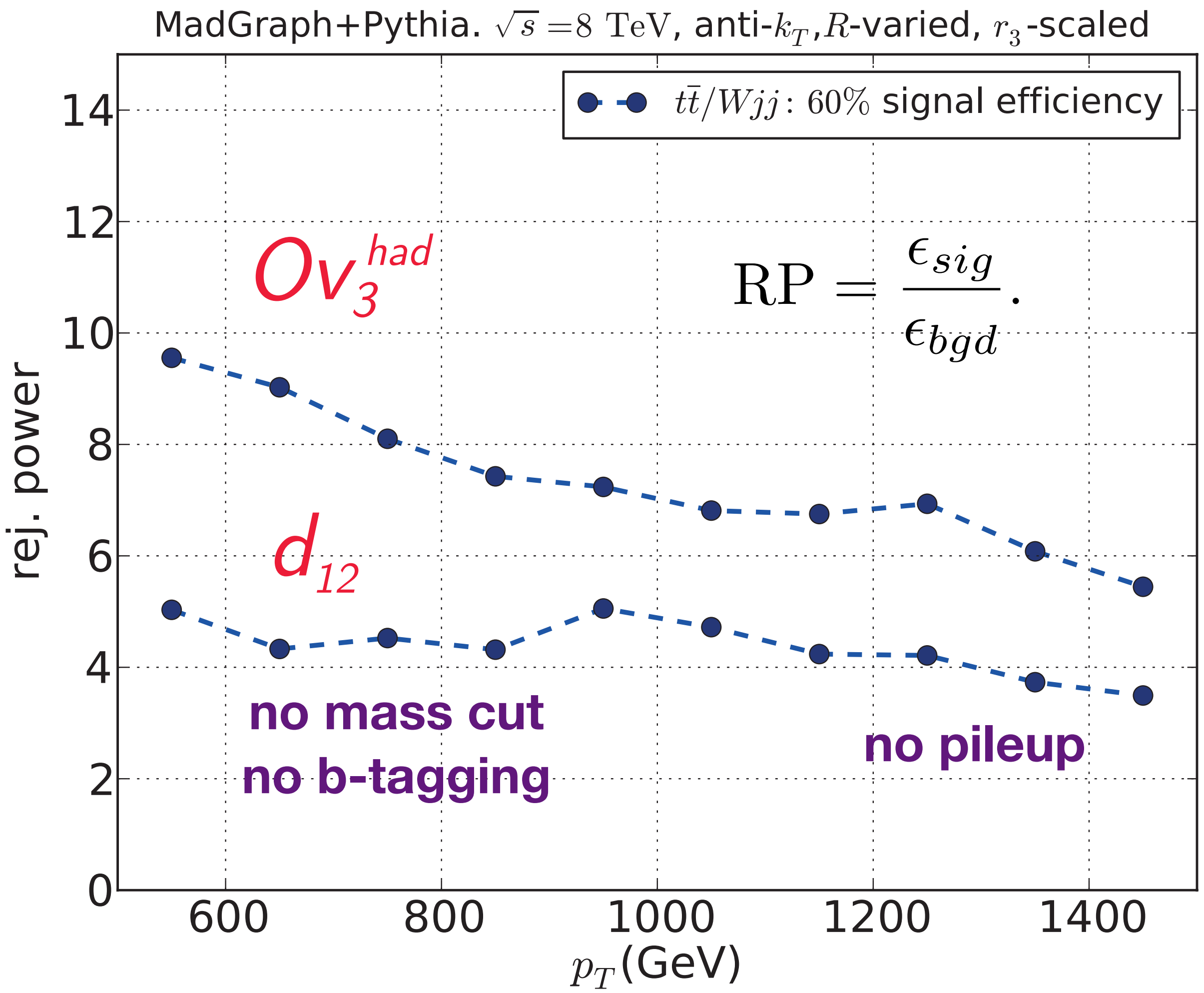
All Events

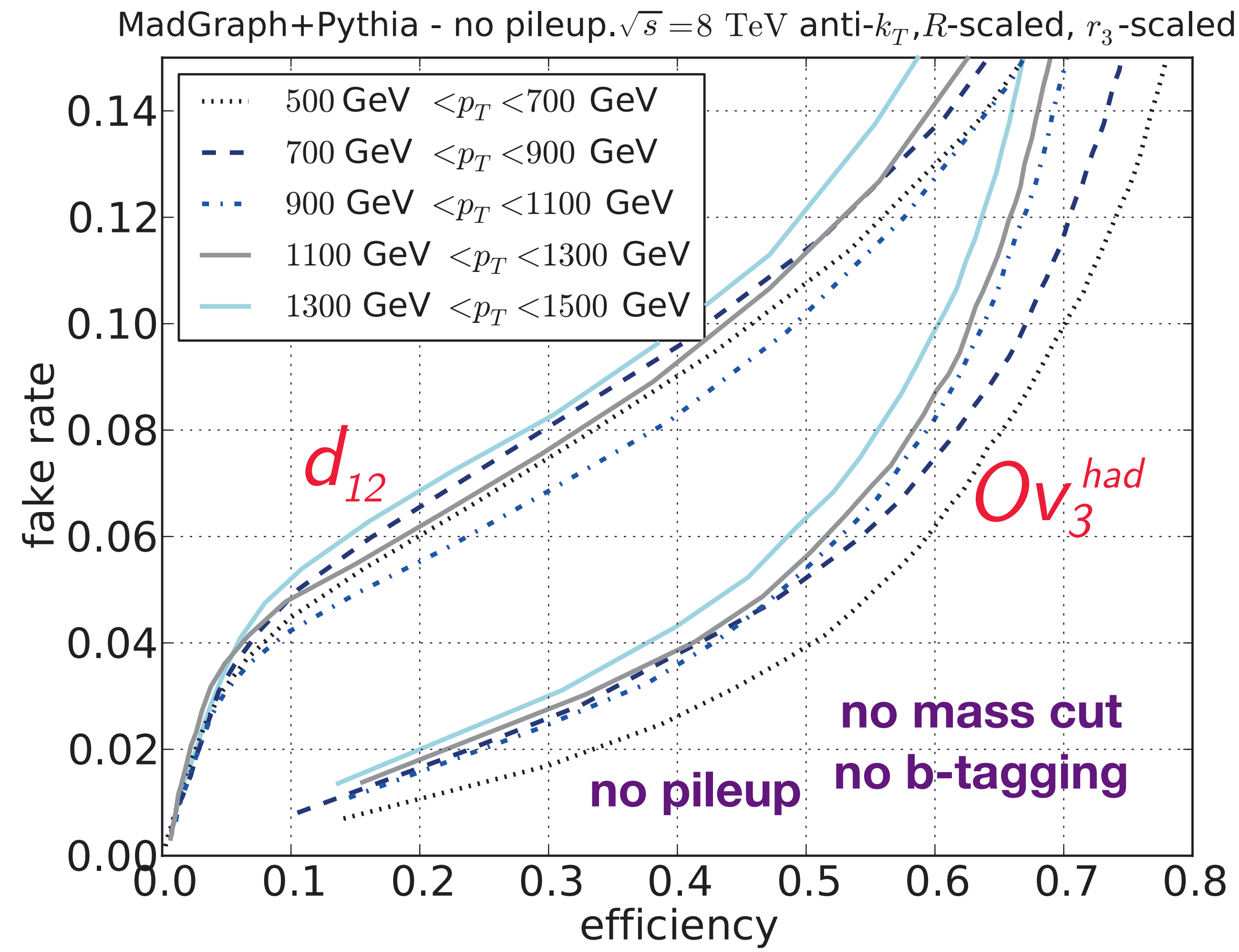
Symmetric events only



TOM Background Rejection Power

W+jets main background for high di-top mass





$$\text{efficiency} \equiv \frac{\sigma(t\bar{t})^{cuts}}{\sigma(t\bar{t})^{BC}}, \qquad \frac{\sigma(Wjj)^{cuts}}{\sigma(Wjj)^{BC}} \equiv \text{fake rate}$$

Hadronic Top

TOM Background Rejection Power

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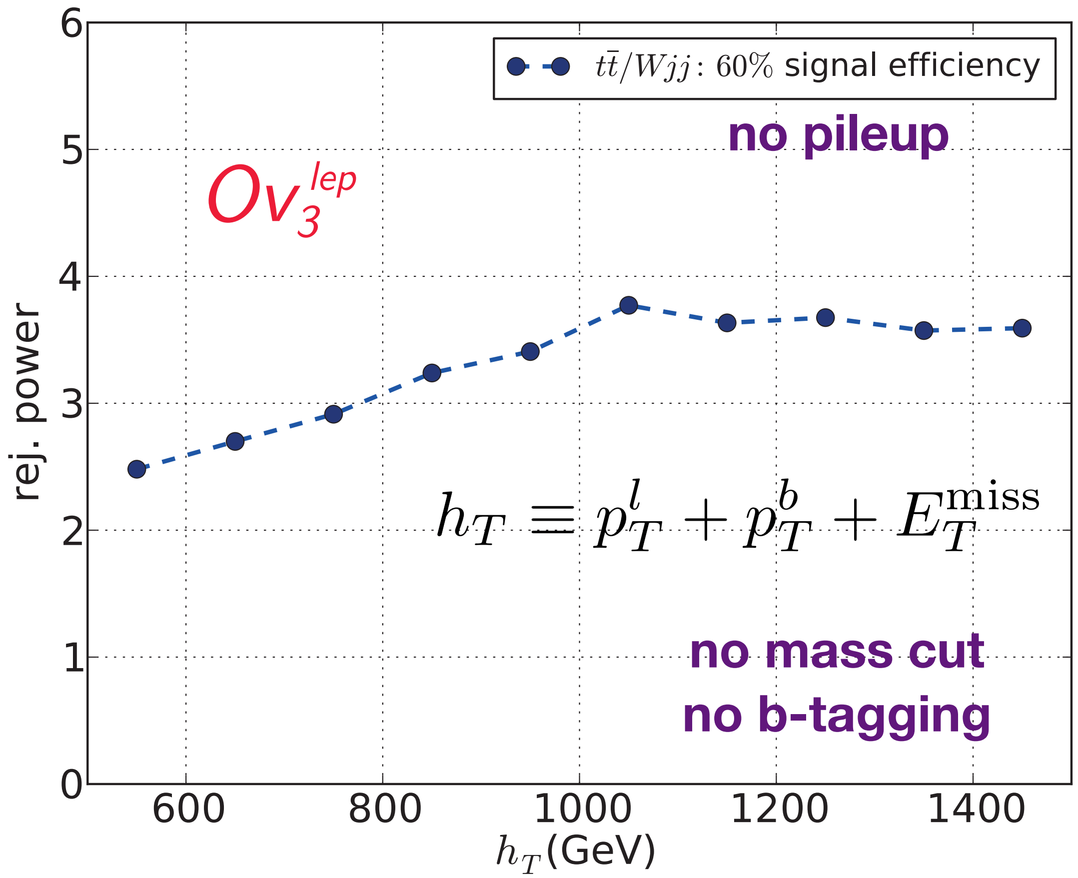
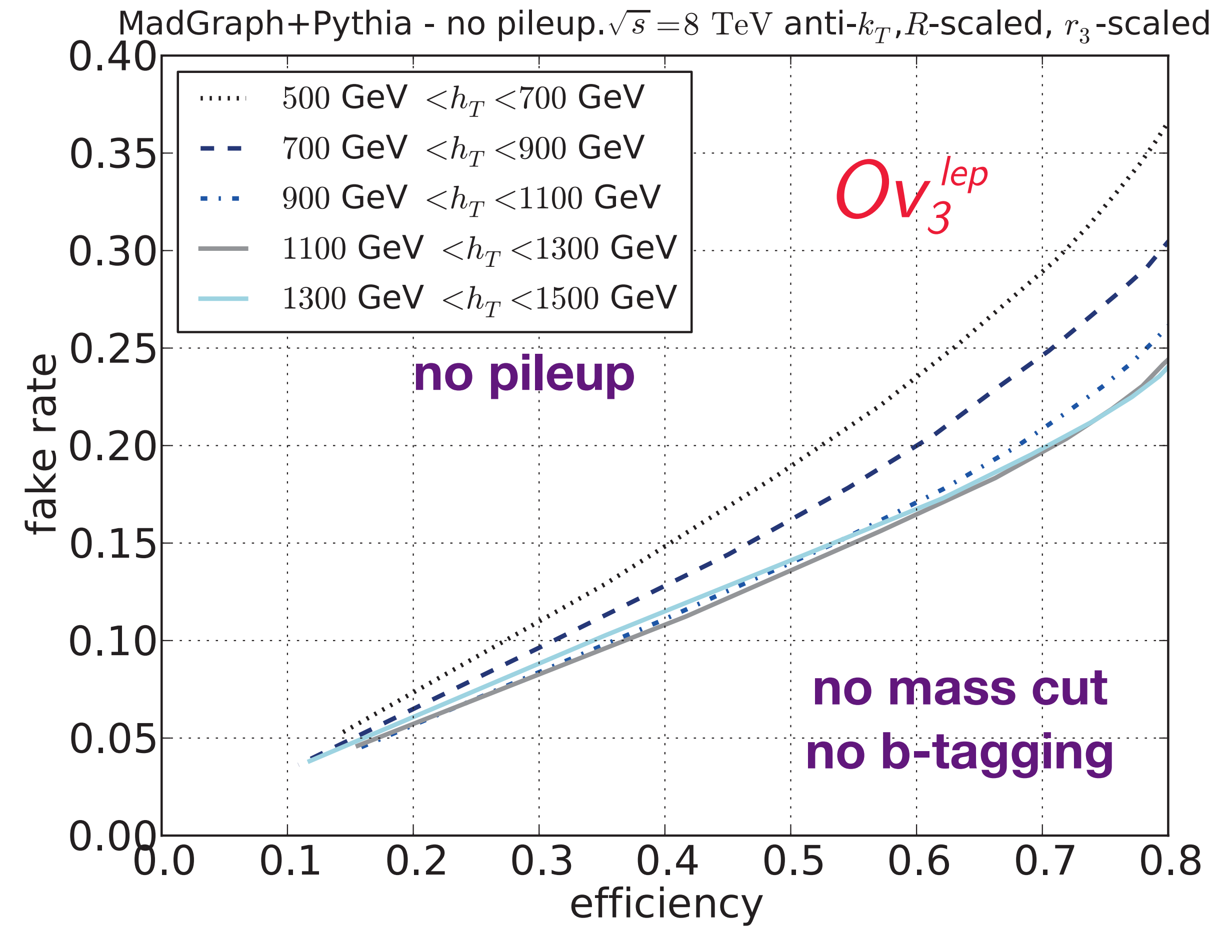
Rejection power of the leptonic top lower due to the background object already containing a W.





Leptonic overlap can compensate for "lack" of b-tagging at high transverse momentum

h_T	$\epsilon_{\rm sig}$	b-tag rejection	Ov_3^{lep} RP
700 - 900 GeV	0.5	4.5	3.2
900 - 1100 GeV	0.5	4.5	3.9
1100 - 1300 GeV	0.5	4.5	4.0
1300 - 1500 GeV	0.5	4.5	4.2

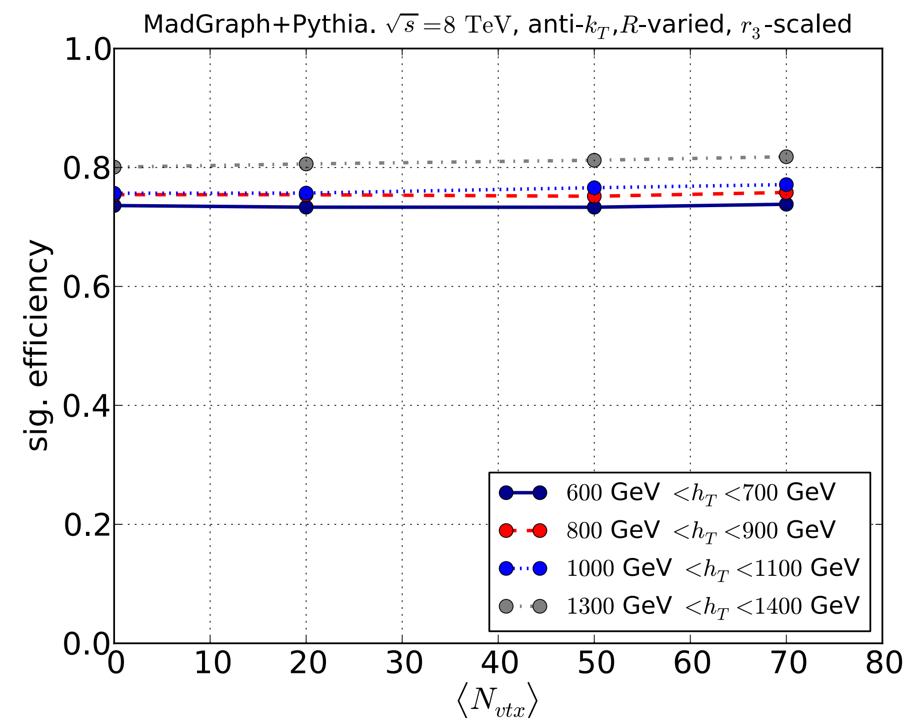
$\epsilon_b = 0.5\,, \quad \epsilon_c = 0.3\,, \quad \epsilon_l = 0.1$

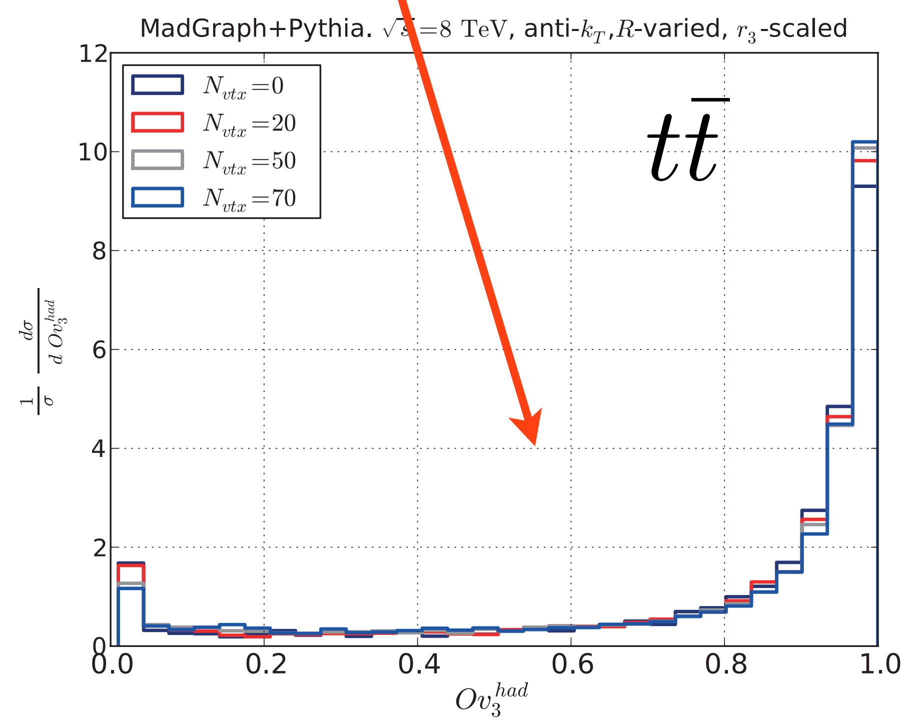
Leptonic Top

TOM & Pileup

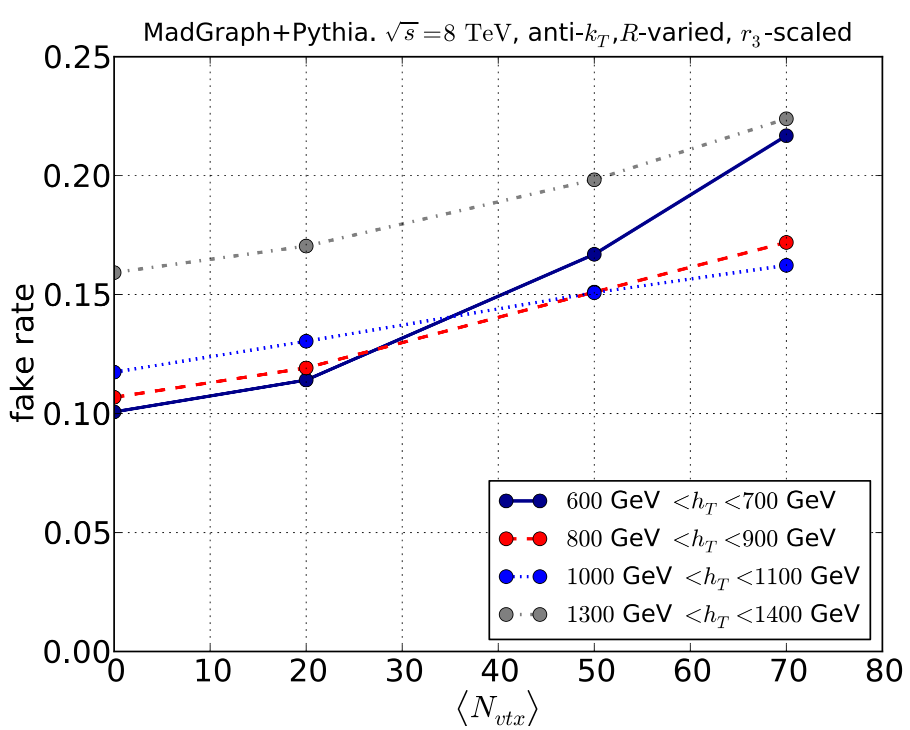
$$Ov_3^{\rm had} > 0.6$$

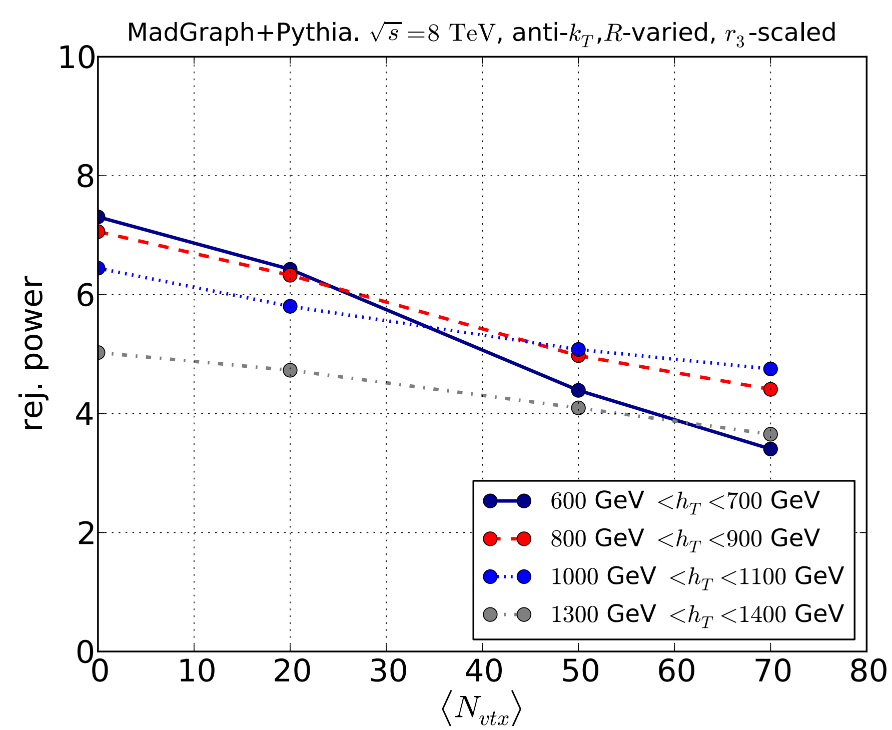
Very little effect on the signal!
Templates are tagging the "prongs".





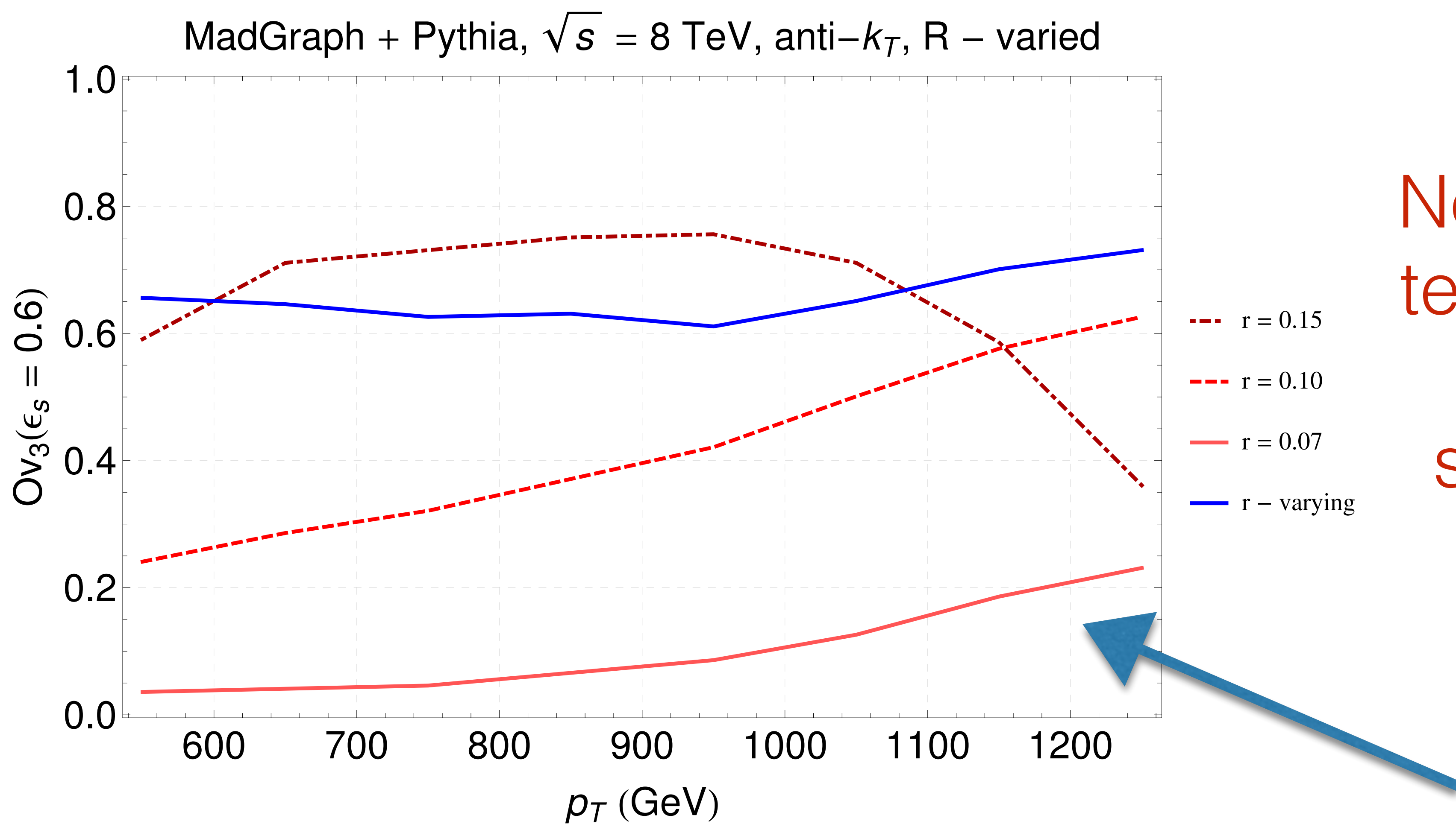
At < 50 interactions per bunch crossing no pileup correction (subtraction) necessary!





Hadronic Top

Can you use fixed template subcones for a wide range of fat jet p_T?



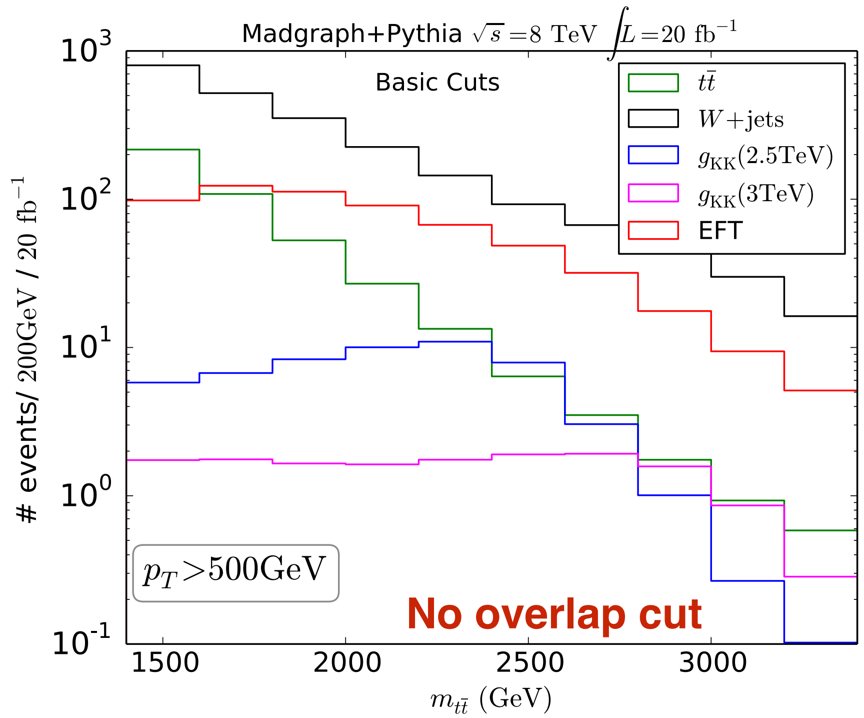
No single fixed value of template sub cone size can give you fixed signal efficiency for a fixed overlap cut!

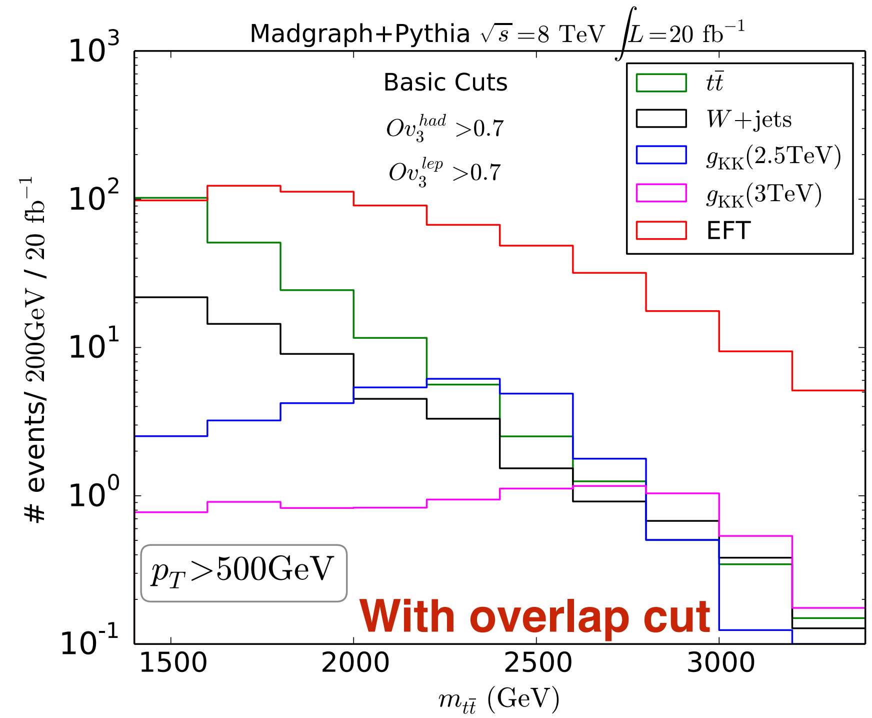
"Varying" means $$r_a(p_T) = 0.041 + \frac{12.1}{p_{T,\,a}} - \frac{122.1}{p_{T,\,a}^2}\,,$$

Many more technical details (MET resolution, adequate number of templates…) in **arXiv:1311.2962**.

Boosted top resonance searches

RS KK gluon search at 8 TeV (m_{kk} =2.5, 3 TeV & EFT)



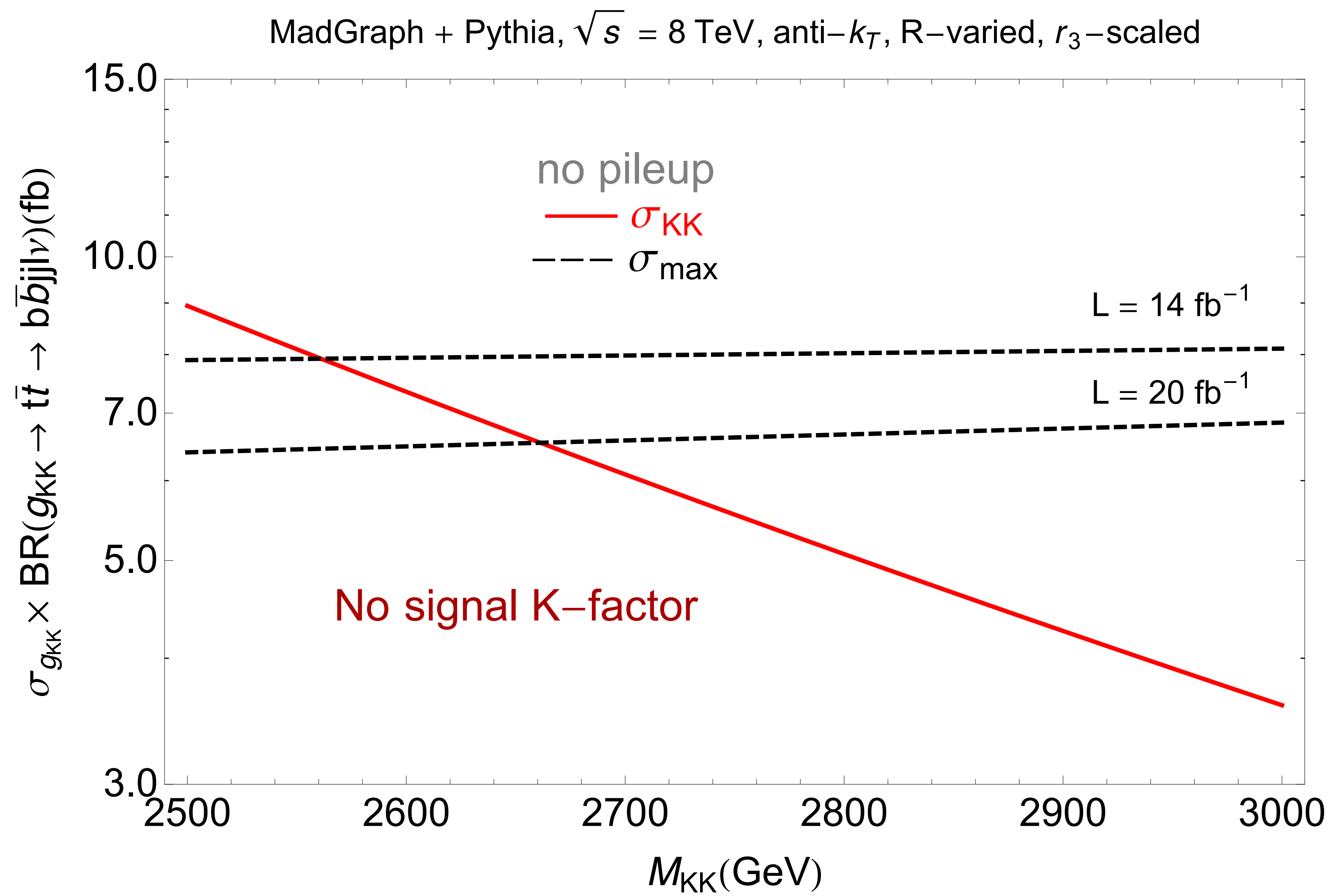


Model	M_{KK} = 2.5 TeV		M_{KK} = 3.0 TeV		EFT	
$m_{t\bar{t}}^{min}$	2125 GeV		2550 GeV		2000 GeV	
Ov_3^{min}	0	0.7	0	0.7	0	0.7
$\sigma_{t\bar{t}}$ (fb)	1.8	0.75	0.43	0.14	2.7	1.1
σ_{W+jets} (fb)	30	0.51	13	0.15	38	0.67
σ_S (fb)	1.4	0.82	0.46	0.16	13.0	12.0
S/B	0.04	0.65	0.04	0.55	0.3	6.8
$S/\sqrt{B}\,(14.3\,\text{fb}^{-1})$	0.9	2.8	0.5	1.1	7.7	34
$S/\sqrt{B}\,(20.0\,\text{fb}^{-1})$	1.1	3.3	0.6	1.3	9.1	40

Template Overlap improves S/B by a factor of O(10), significance by a factor of 2-3.

Efficiency of Ov cut for SM do-tops is lower than the signal due to SM di-tops containing more “asymmetric” top events.

Mass exclusion reach:



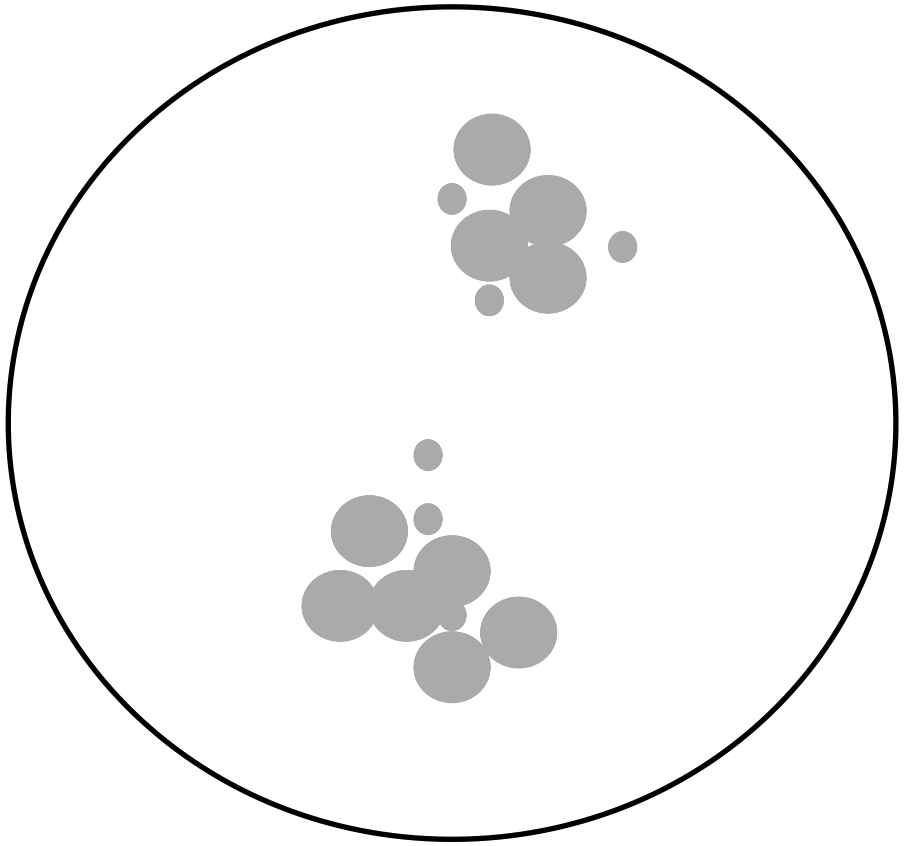
The plot includes background K-factors **but not the signal K-factor**

We also have projections for 14, 33 TeV (see arXiv:1309.7847)

THANK YOU!

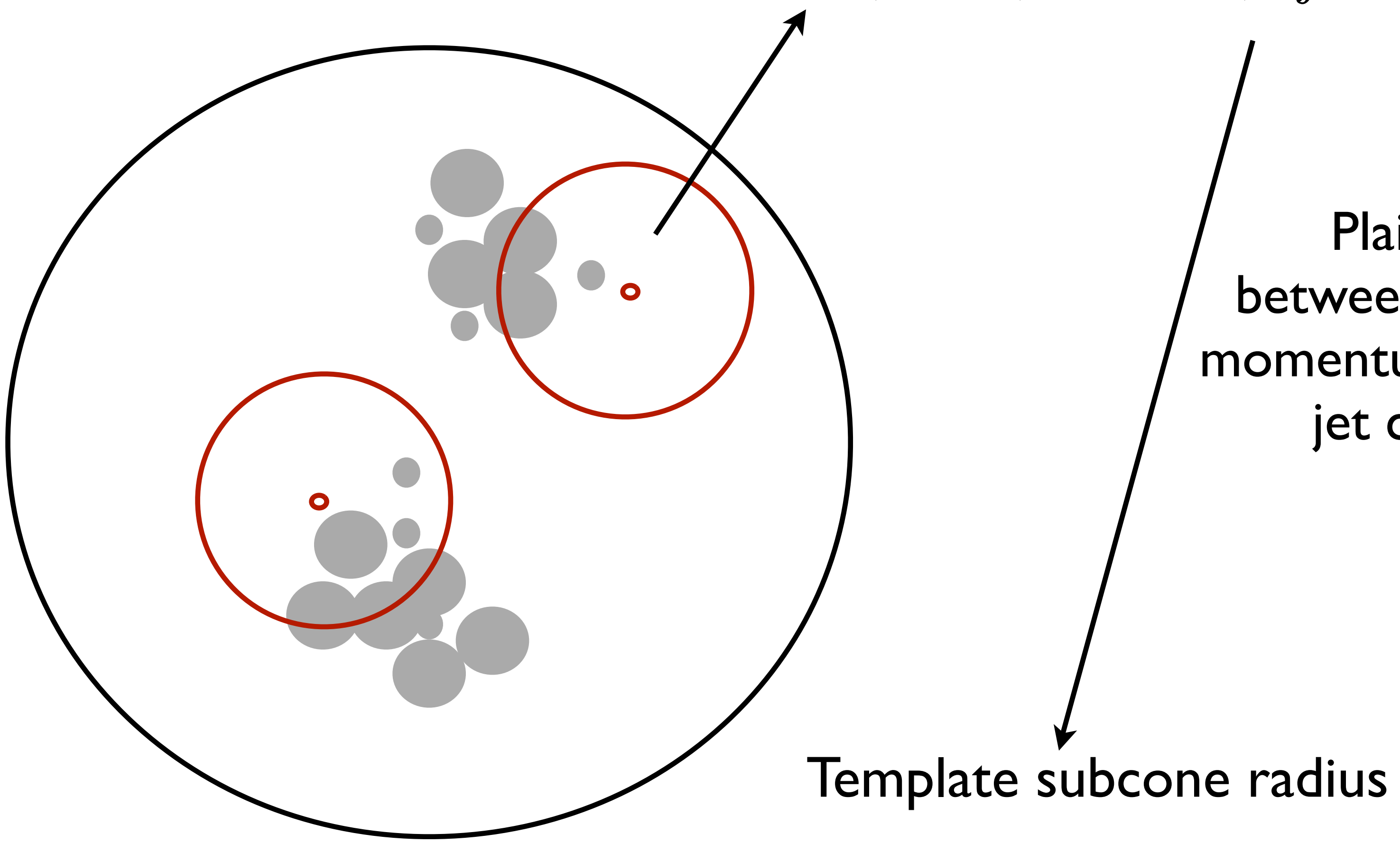
TOM: Illustration

Consider for instance a "Higgs jet"



Pick one configuration out of many possible 2-body decay configurations of a boosted Higgs (Template).

$$F(f, j) = \theta(r_f - \Delta r_{fj})$$

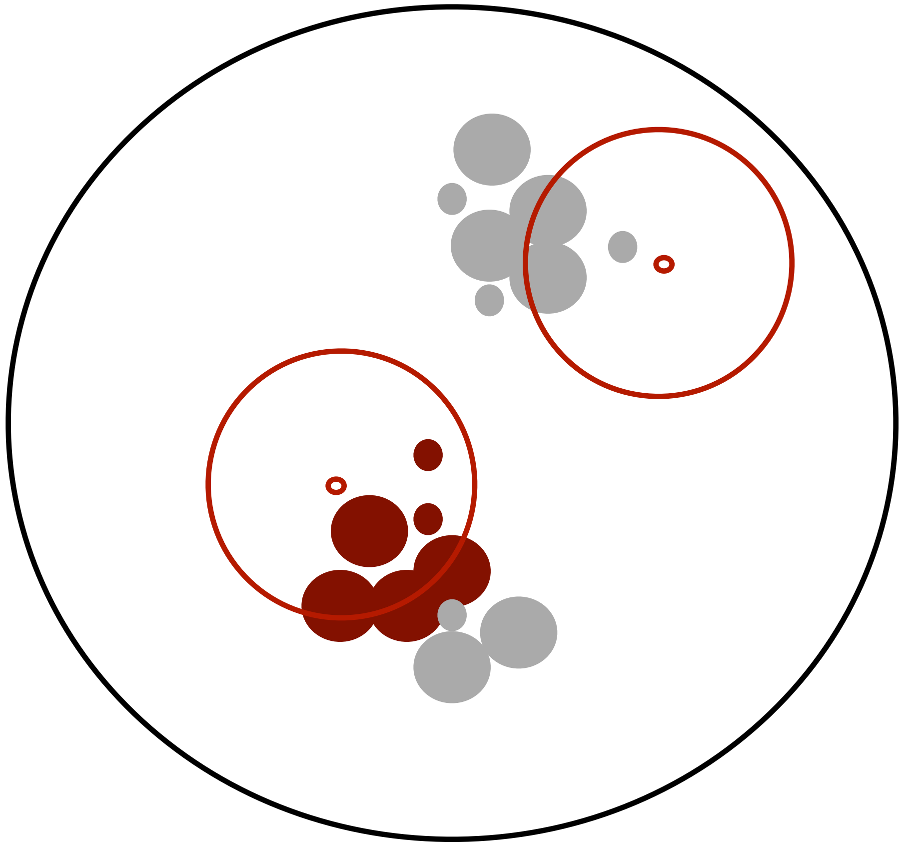


Plain distance between the template momentum f and the i-th jet constituent.

Template subcone radius

Pick one configuration out of many possible 2-body decay configurations of a boosted Higgs (Template).

For each template momentum, add up the energy deposited inside the cone of radius r around the template momentum



$$\sum_j E_j$$

Pick one configuration out of many possible 2-body decay configurations of a boosted Higgs (Template).

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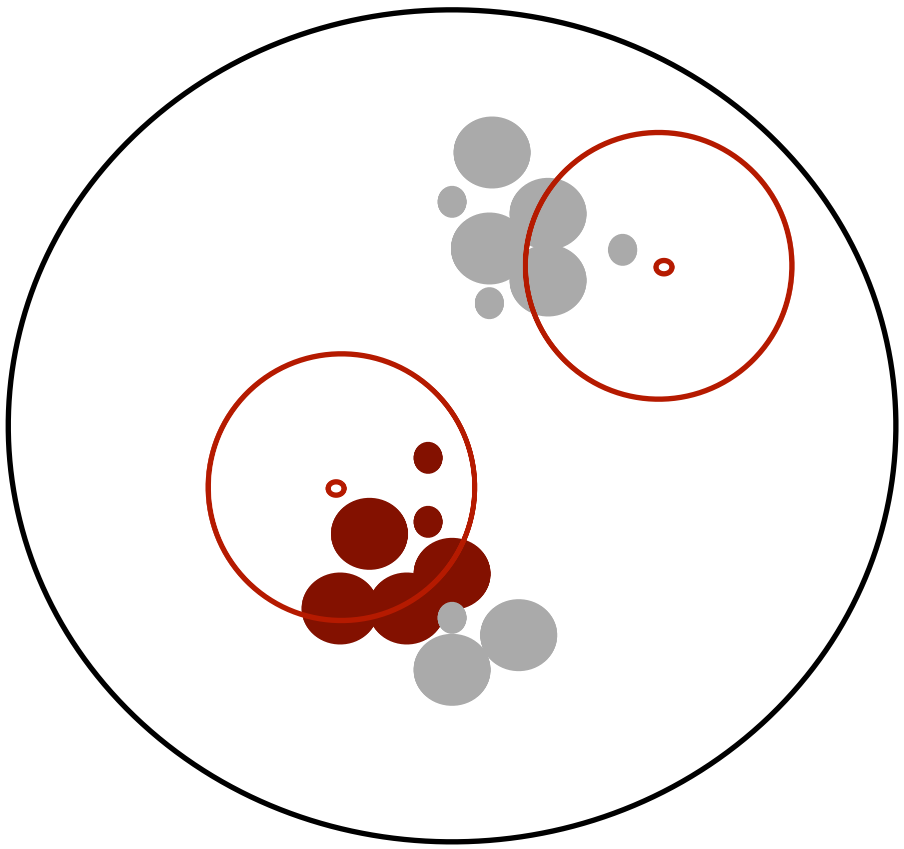


For each template, subtract the sum from the energy of the template momentum.

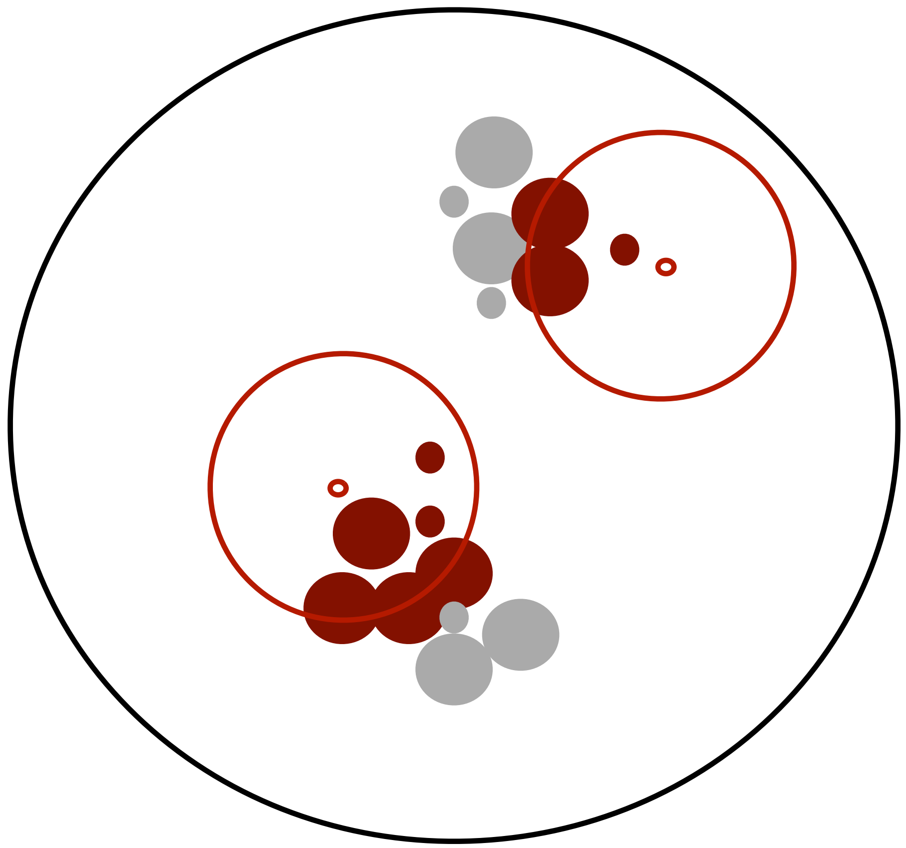
$$\sum_j E_j - E_i$$

TOM: Illustration

Pick one configuration out of many possible 2-body decay configurations of a boosted Higgs (Template).

For each template momentum, add up the energy deposited inside the cone of radius r around the template momentum

Weight needed to compensate for the template resolution of the mass, transverse momenta etc.



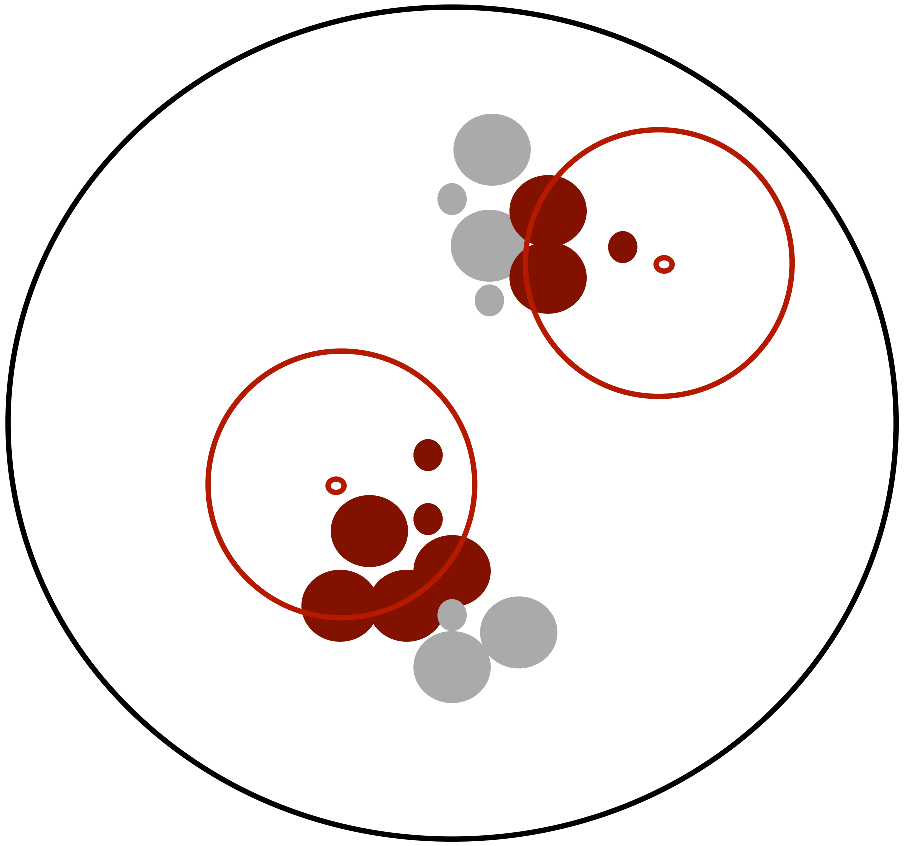
For each template, subtract the sum from the energy of the template momentum.

Repeat for all other template momenta and sum over the number of momenta in the template.

$$\sum_i \frac{1}{2\sigma_i^2}\left[\sum_j E_j - E_i\right]^2$$

Pick one configuration out of many possible 2-body decay configurations of a boosted Higgs (Template).

For each template momentum, add up the energy deposited inside the cone of radius r around the template momentum



For each template, subtract the sum from the energy of the template momentum.

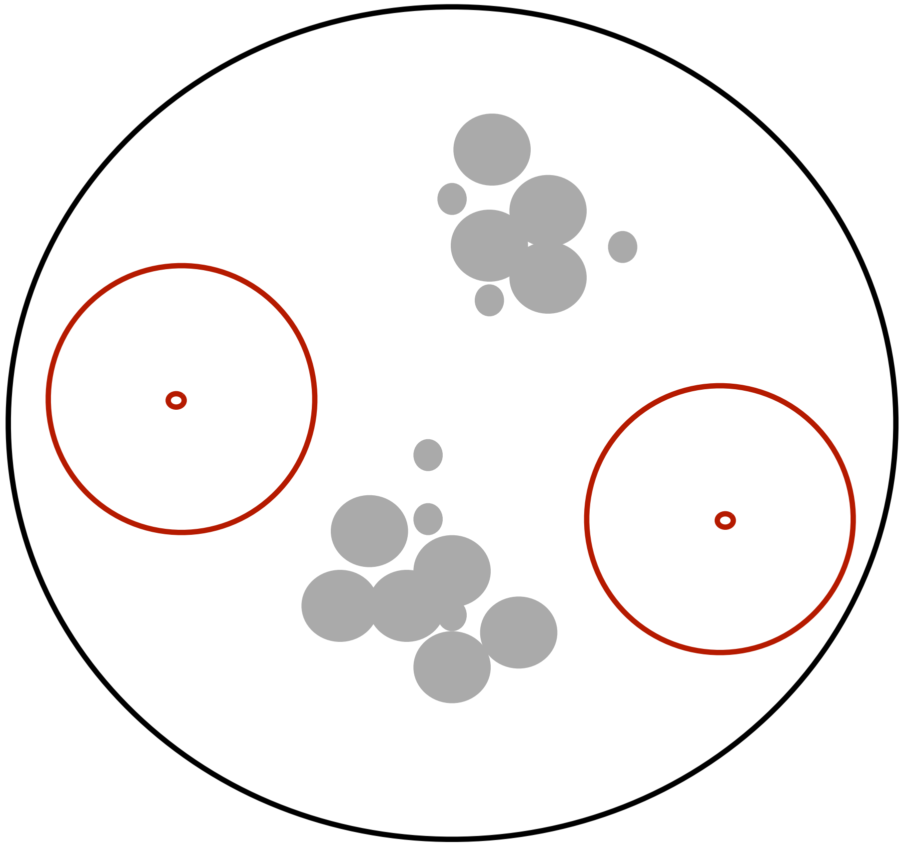
Repeat for all other template momenta and sum over the number of momenta in the template.

Exponentiate the sum!

$$exp\left[-\sum_i \frac{1}{2\sigma_i^2}\left[\sum_j E_j - E_i\right]^2\right]$$

Repeat the algorithm for many possible template configurations

For each template momentum, add up the energy deposited inside the cone of radius r around the template momentum



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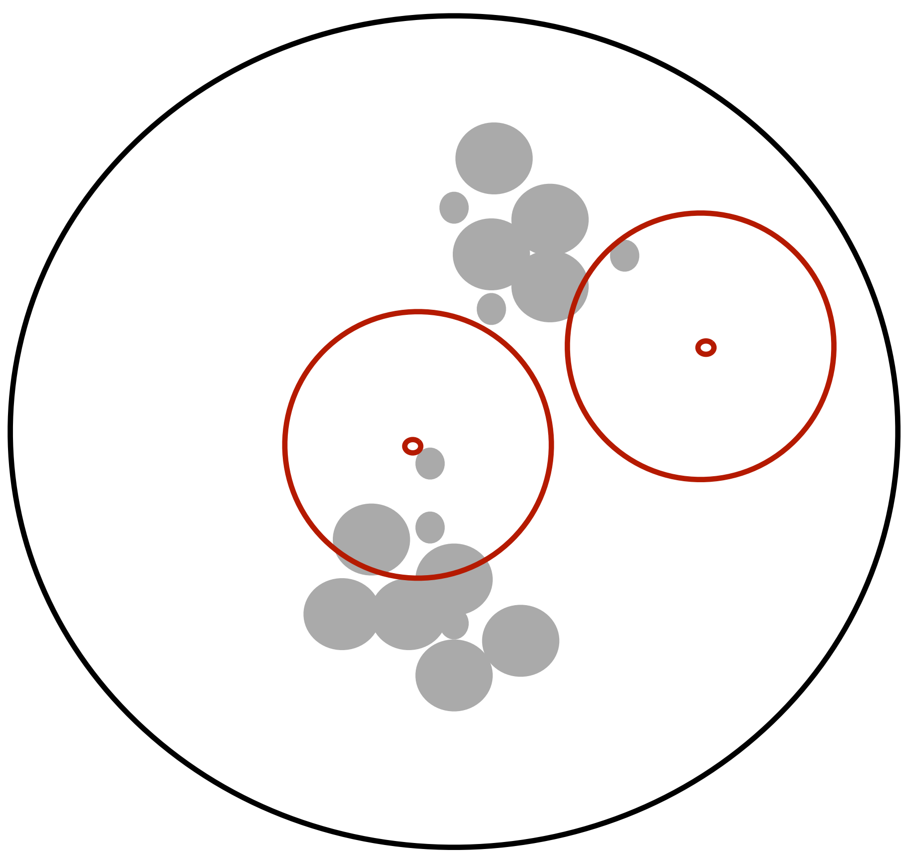
Exponentiate the sum!



For each template, subtract the sum from the energy of the template momentum.

Repeat for all other template momenta and sum over the number of momenta in the template.

$$exp\left[-\sum_i \frac{1}{2\sigma_i^2}\left[\sum_j E_j - E_i\right]^2\right]$$

TOM: Illustration

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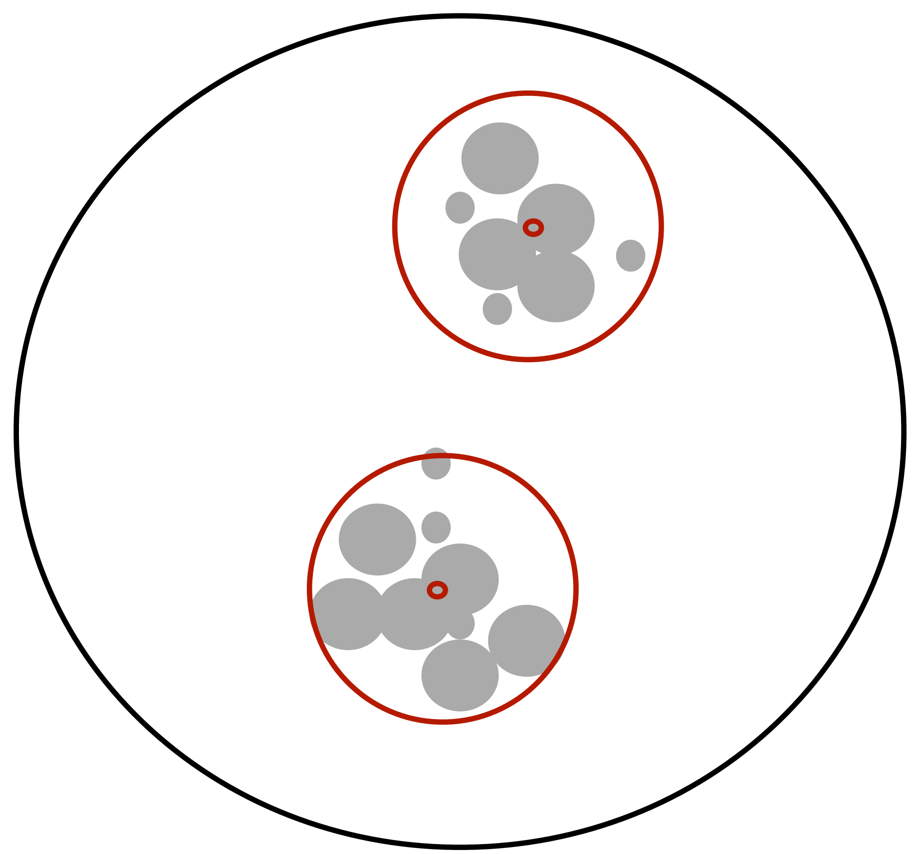
Repeat the algorithm for many possible template configurations

Result: Ov AND template which maximizes overlap.

For each template momentum, add up the energy deposited inside the cone of radius r around the template momentum



For each template, subtract the sum from the energy of the template momentum.

Repeat for all other template momenta and sum over the number of momenta in the template.

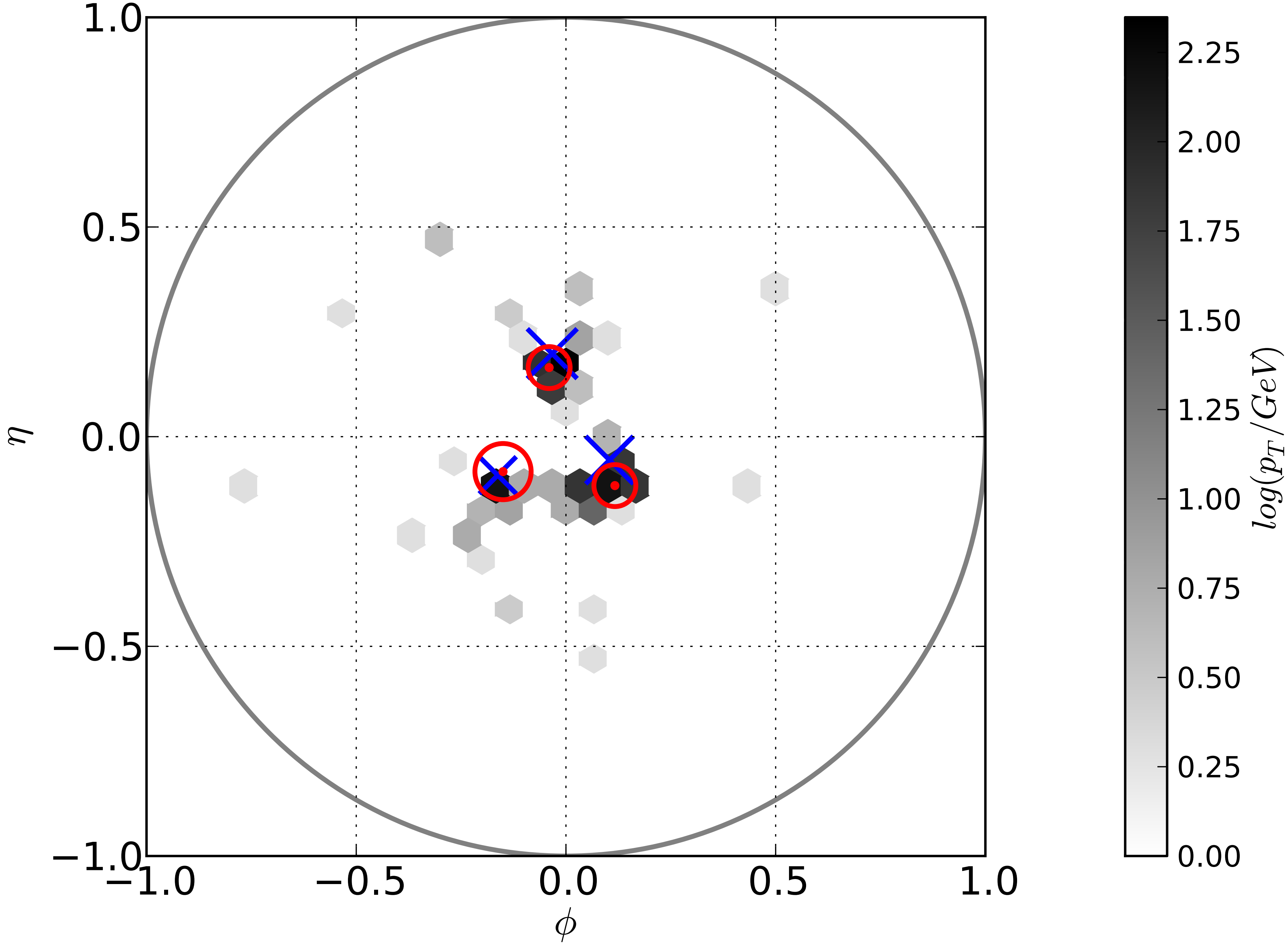
Choose the configuration which maximizes the exponential!

$$Ov = max_{(TS)}\left\{ exp\left[-\sum_i \frac{1}{2\sigma_i^2}\left[\sum_j E_j - E_i\right]^2\right]\right\}$$

TOM: Example

Typical boosted top jet:

Blue - positions of parton level top decay products.
Gray - Calorimeter energy depositions.
Red - Peak template positions.



Overlap info:
$Ov_3 = 0.91$

Event info:
$p_T = 1021.91\ GeV$
$m = 212.39\ GeV$

Partonic info:
$p_{T1} = 421.80\ GeV$
$p_{T2} = 385.85\ GeV$
$p_{T3} = 233.45\ GeV$

Template info:
$p^t_{T1} = 414.24\ GeV$
$p^t_{T2} = 401.14\ GeV$
$p^t_{T3} = 215.18\ GeV$