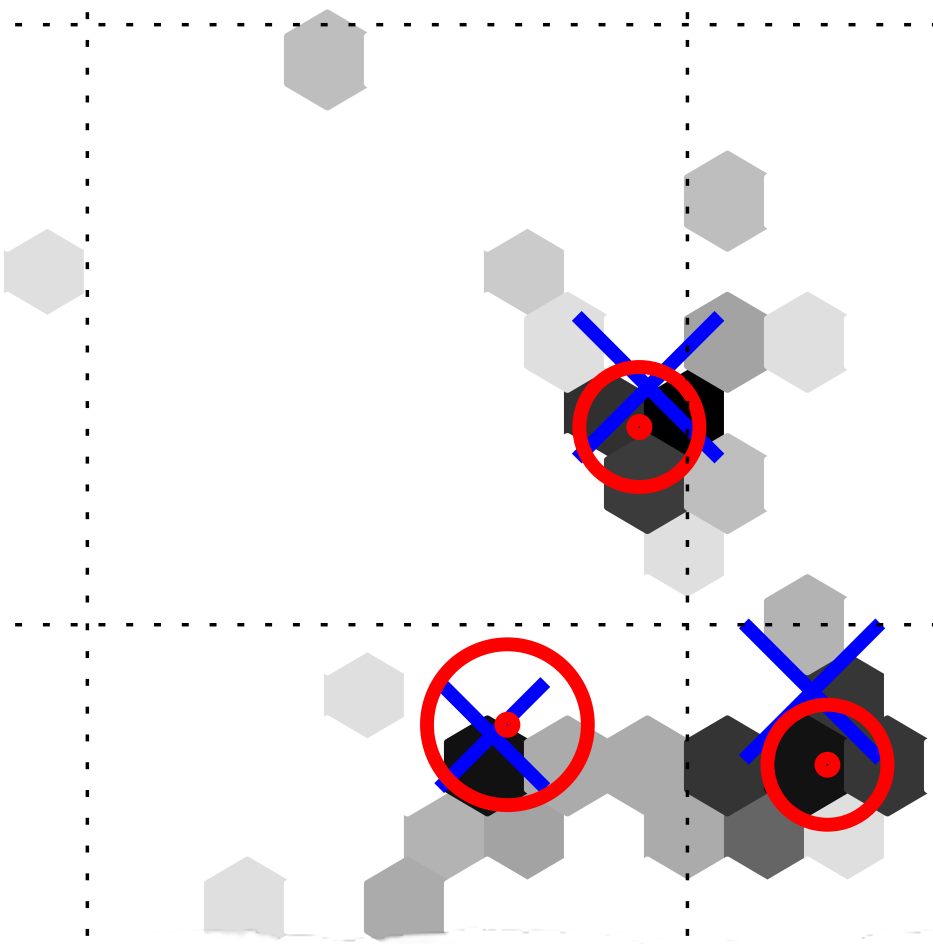

Template Overlap Method

Recent Developments in **Boosted Top Tagging**

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

Template Overlap Method (TOM)

- 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, Soreq, Perez (in preparation)

- 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)

TOM was born at Stony-Brook
but grew up at Weizmann.

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Over time, many improvements were made on the original formulation of TOM.

TOM

Sequential template generation for adequate phase space coverage

Formulation in terms of longitudinally boost-invariant quantities.

Dynamical, event-by-event template subcone radius determination.

Pileup insensitive template selection criteria.

Introduction of new template based observables (Template Planar Flow, Template Stretch ...).

Template b-tagging.

Leptonic Top Template.

Everything in red introduced in arXiv:1212.2977

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!

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 jet (Template):

template resolution (typically E(f)/3)

j - jet “constituent”

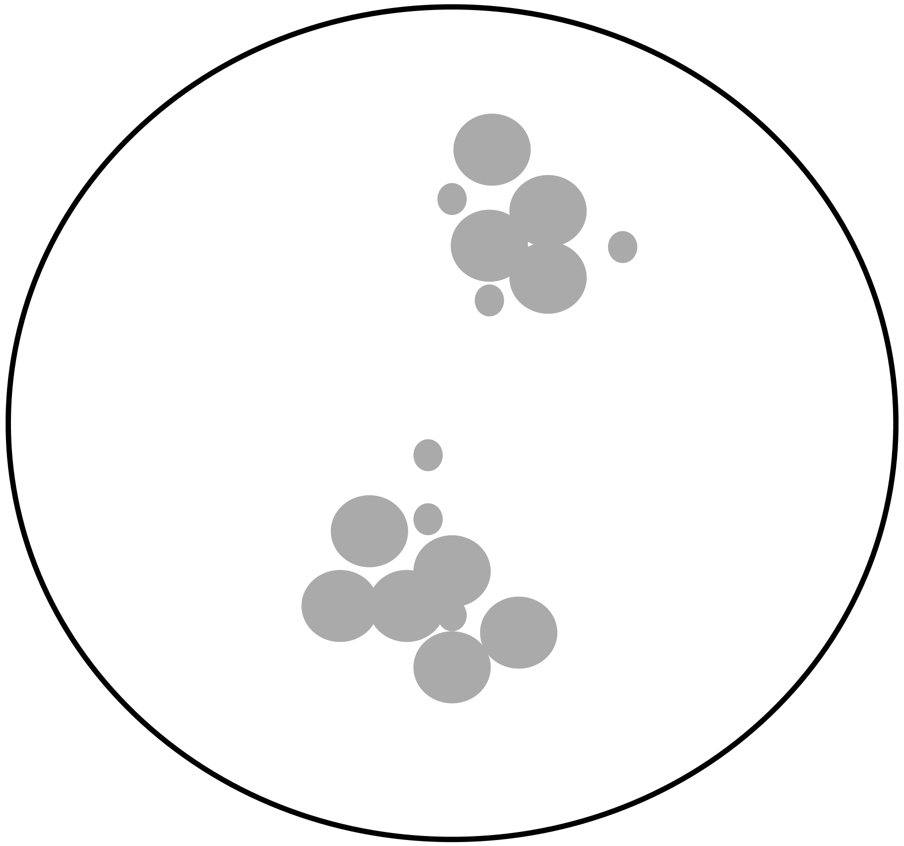
$$Ov^{(F)}(i,j) = max_{TS}\, exp\left[-\sum_f \frac{1}{2\sigma_f^2}\left(\sum_j (E_j - E_f)F(f,j)\right)^2\right]$$

TS - template “space”

f - template momentum

The kernel F restricts the angular region around each template momentum

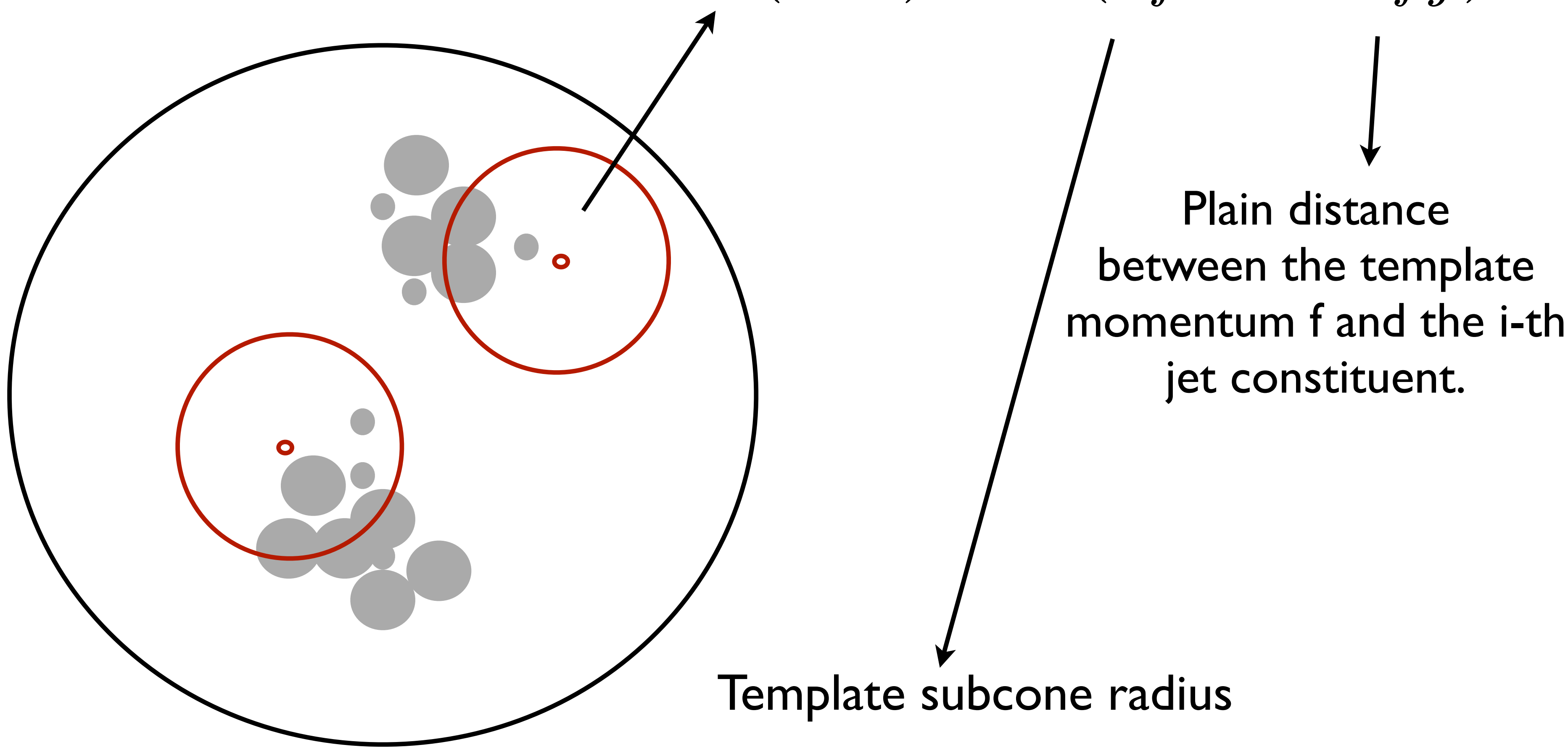
Consider for instance a "Higgs jet"



TOM: Illustration

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

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



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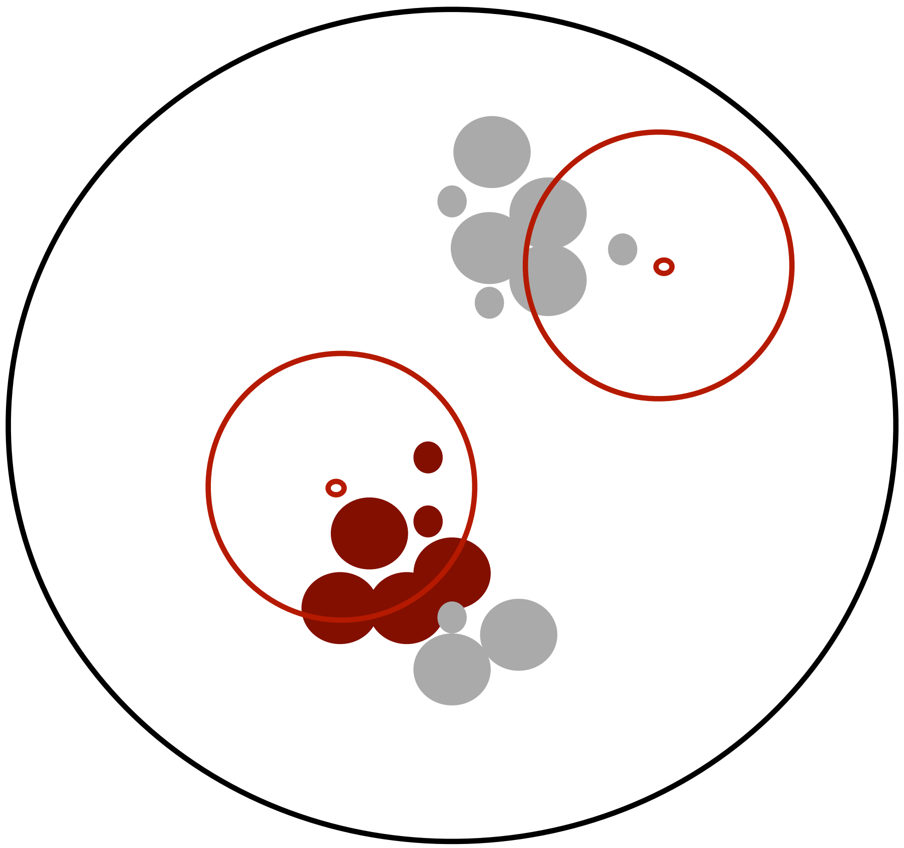
Pick one configuration out of many possible 2-body decay configurations of a boosted Higgs (Template).

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



$$\sum_j E_j$$

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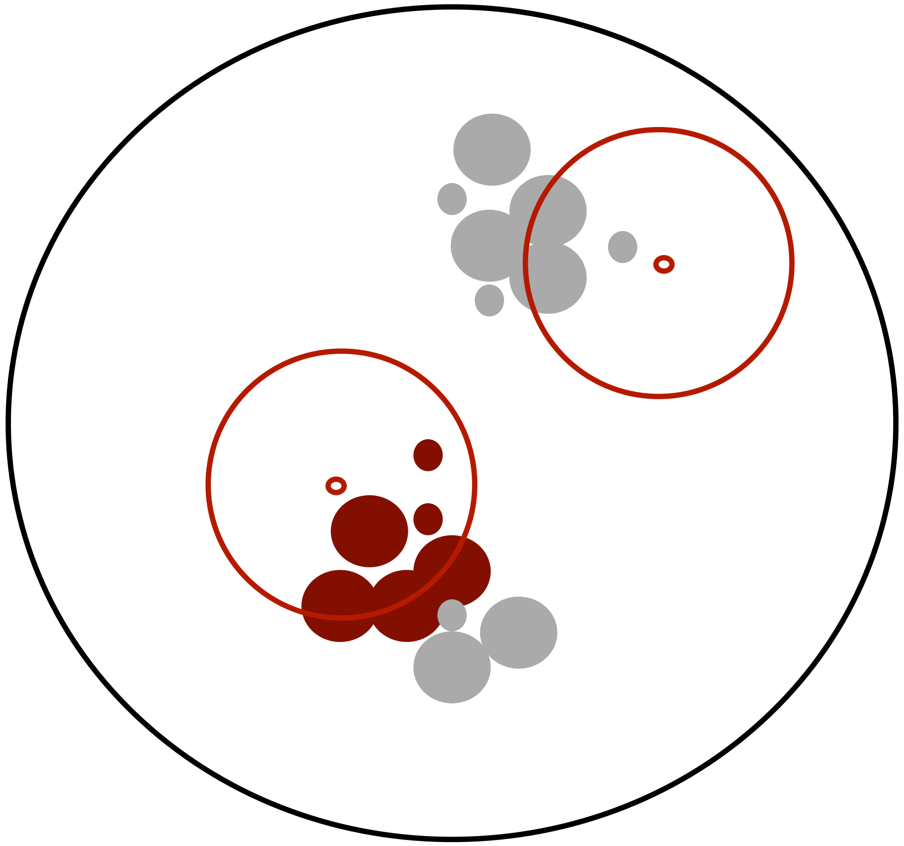
Pick one configuration out of many possible 2-body decay configurations of a boosted Higgs (Template).

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



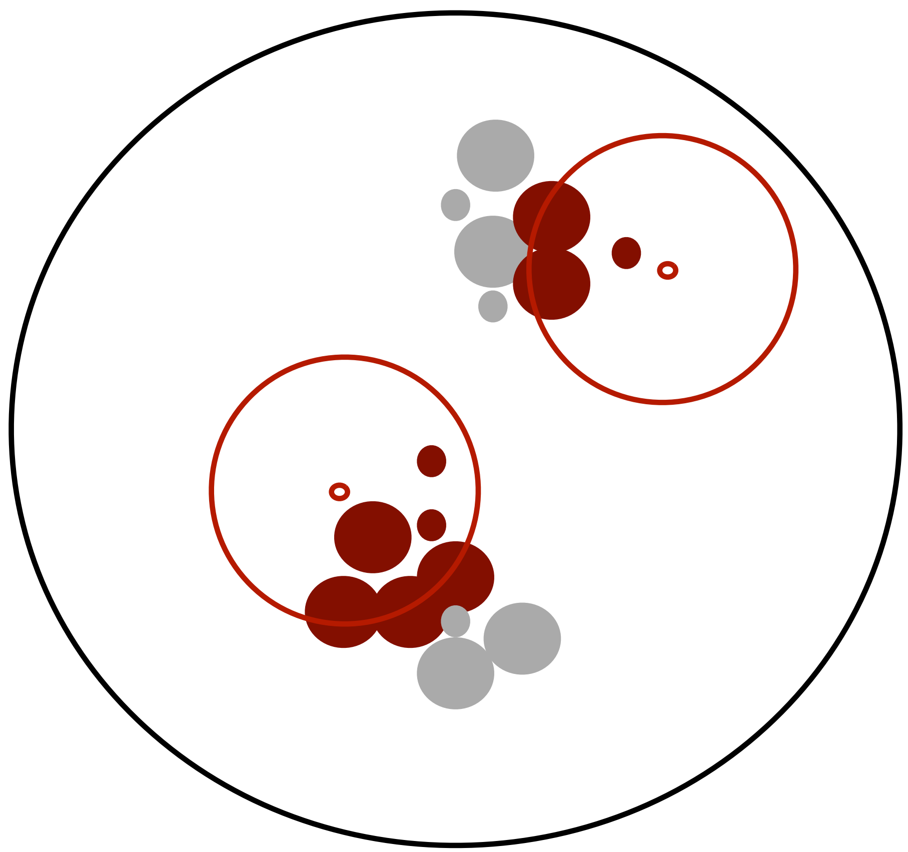
For each template, subtract the sum from the energy of the template momentum.

$$\sum_j E_j - E_i$$

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.



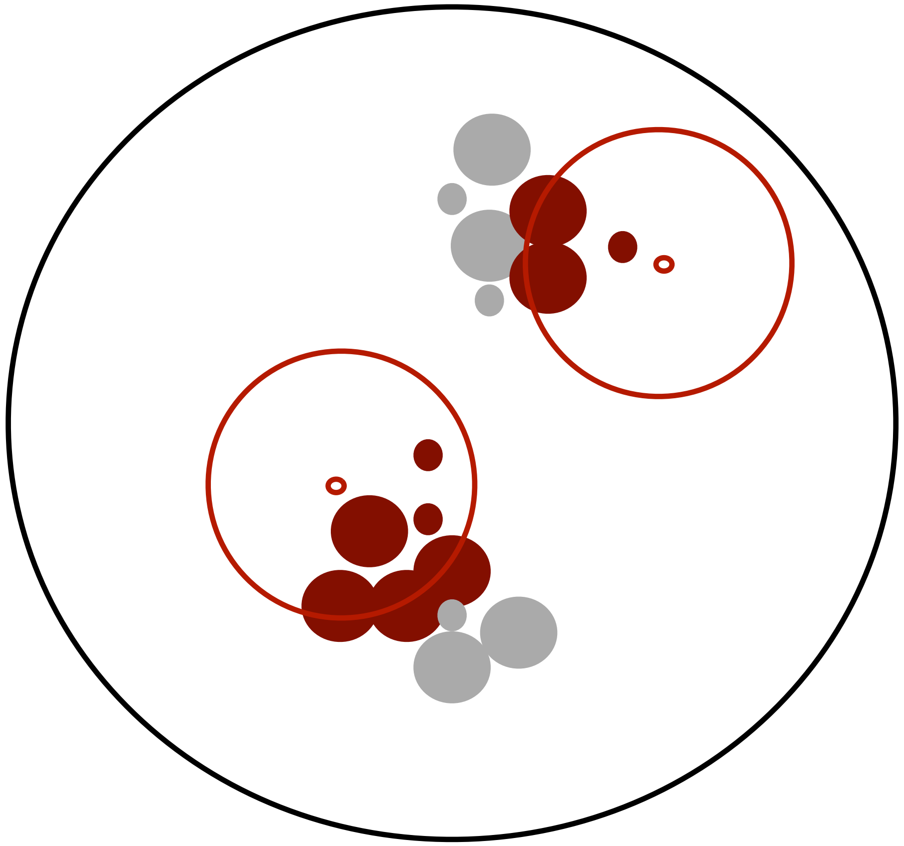
For each template, subtract the sum from the energy of the template momentum.

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!

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

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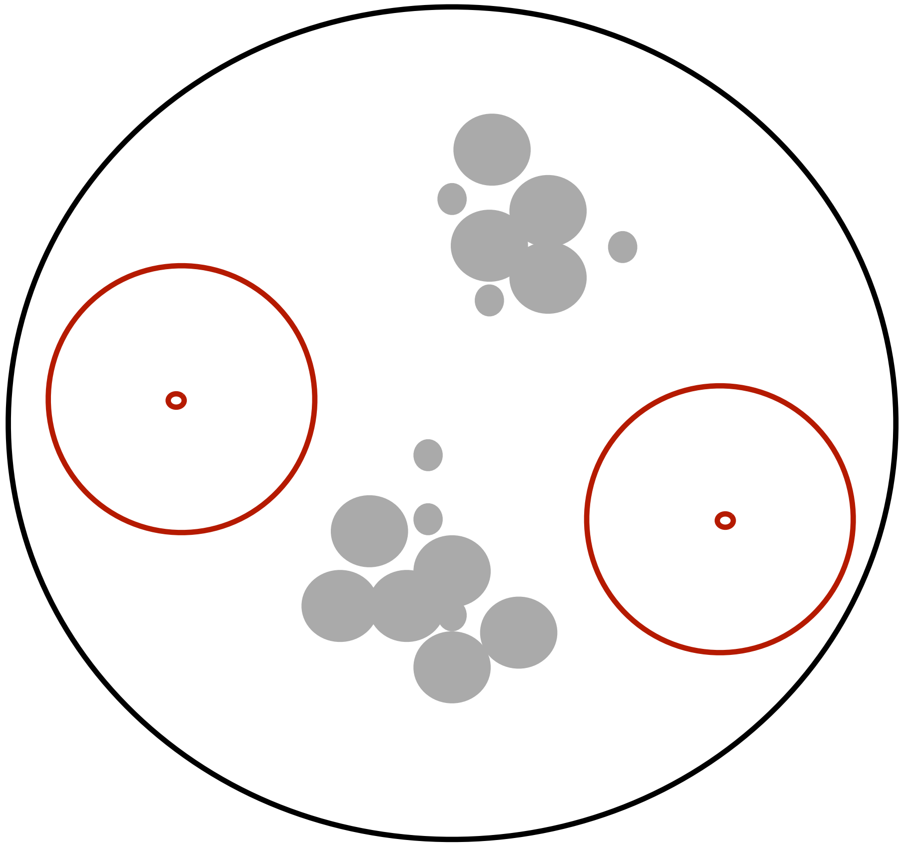
Repeat the algorithm for many possible template configurations

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



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

Exponentiate the sum!

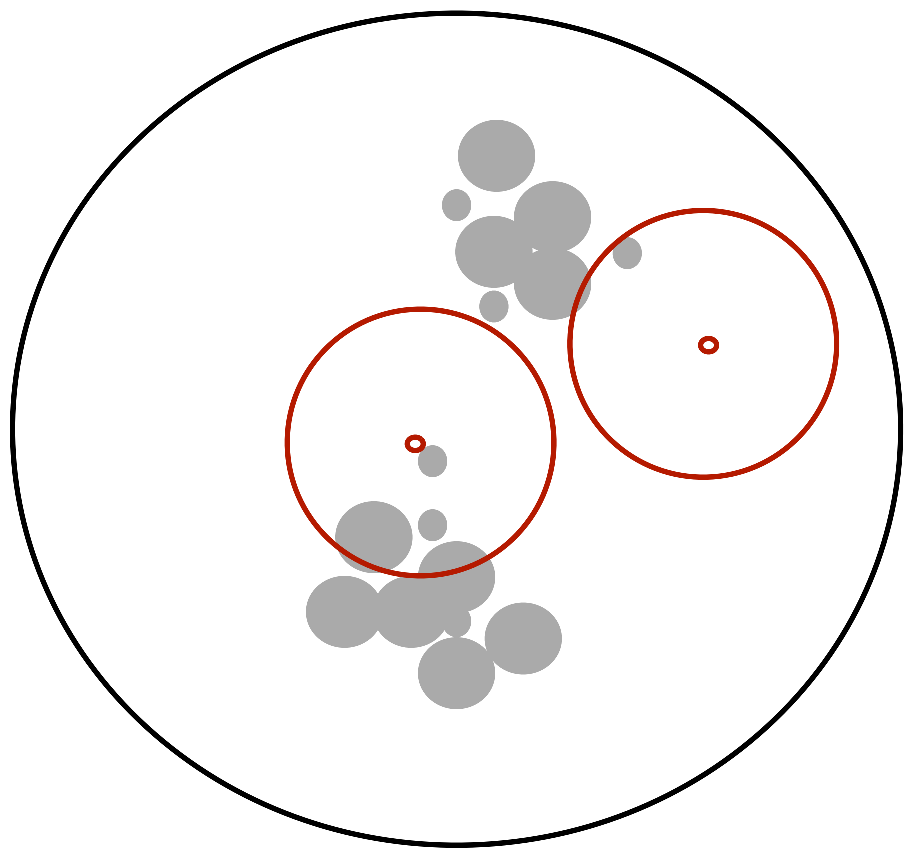
$$exp\left[-\sum_i \frac{1}{2\sigma_i^2}\left[\sum_j E_j - E_i\right]^2\right]$$

TOM: Illustration

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

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.

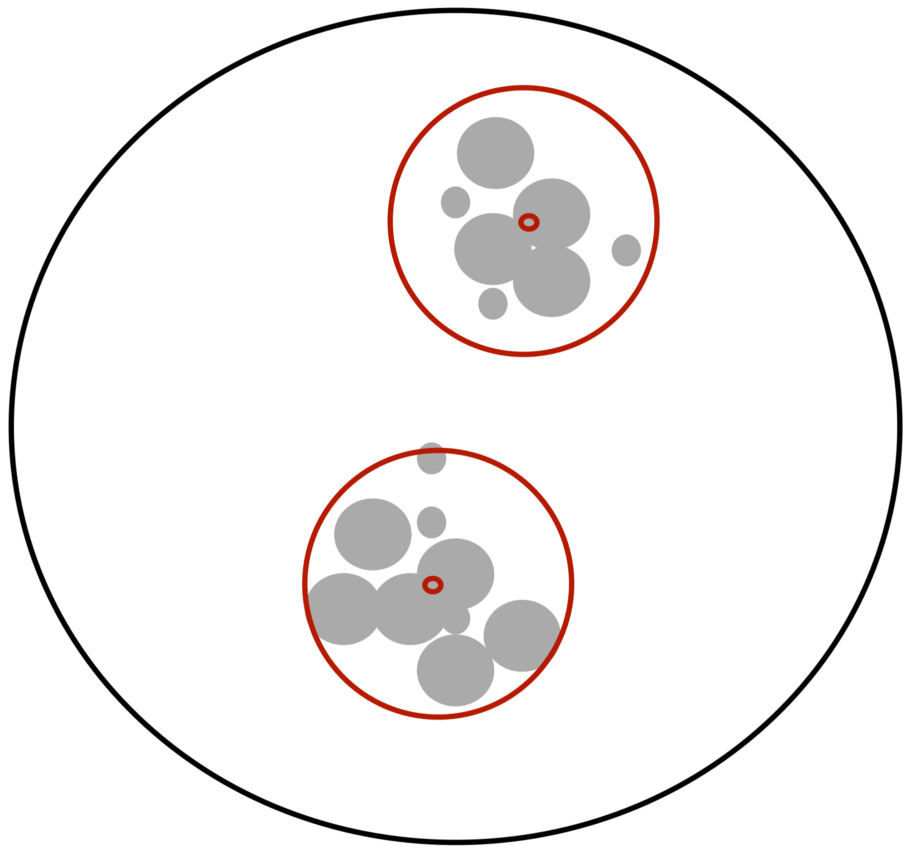
$$exp\left[-\sum_i \frac{1}{2\sigma_i^2}\left[\sum_j E_j - E_i\right]^2\right]$$

TOM: Illustration

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!

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

Properties of Template Overlap

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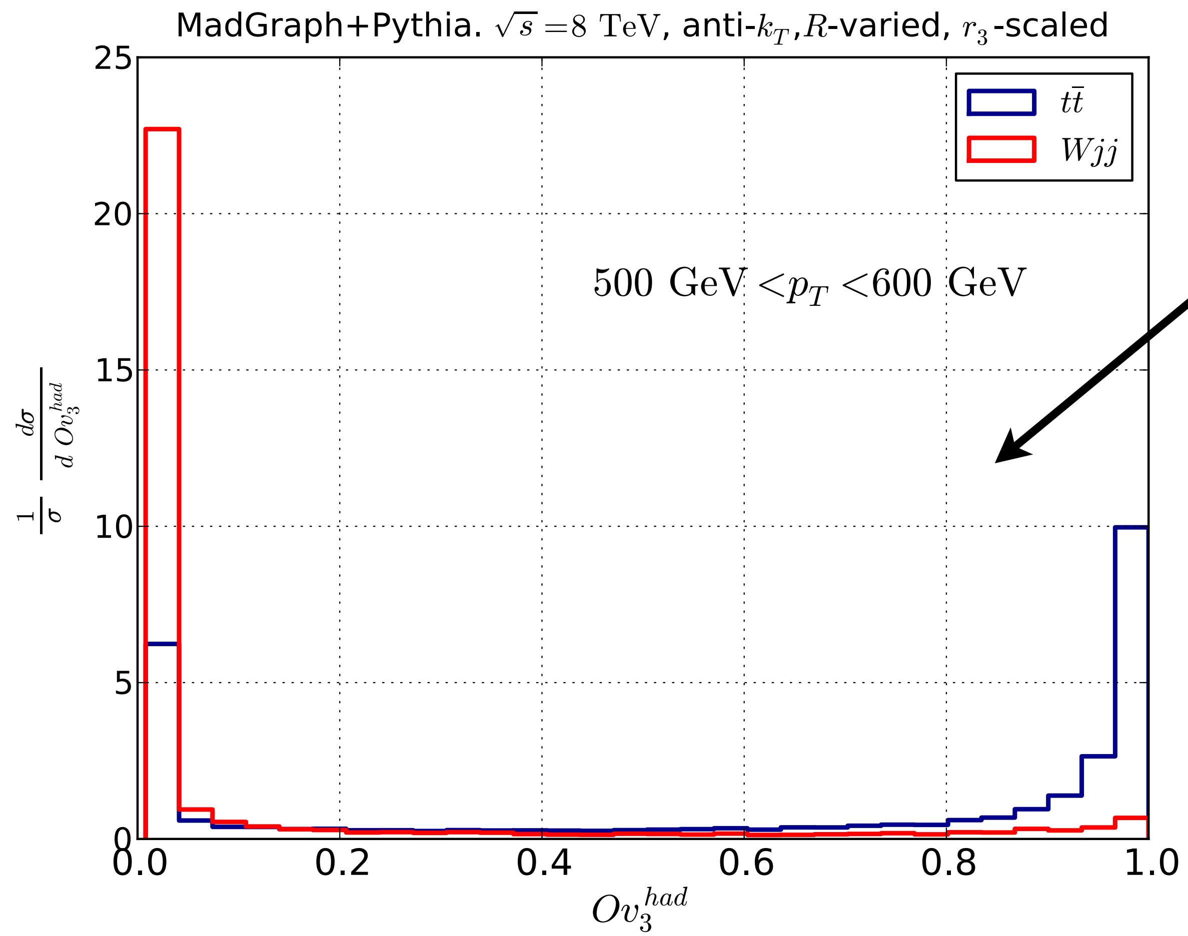
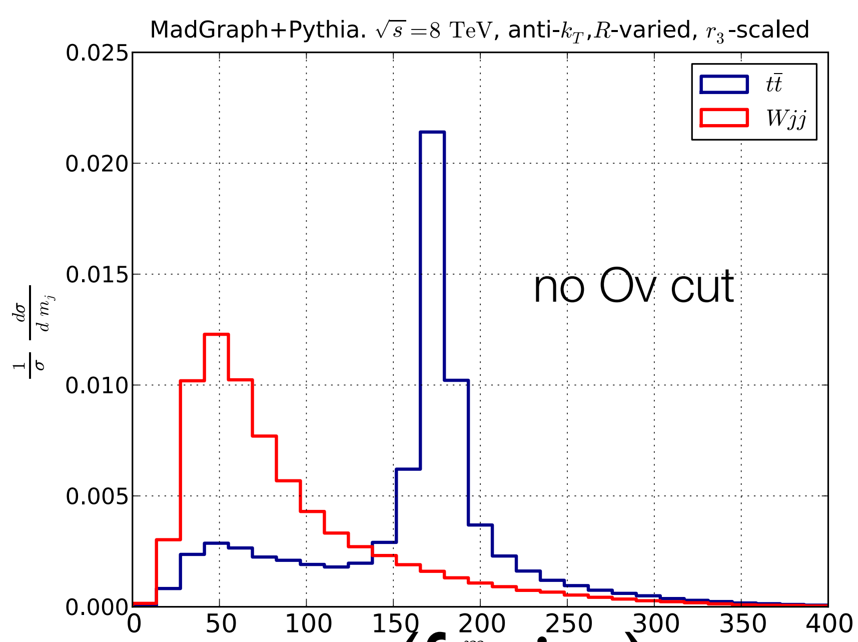
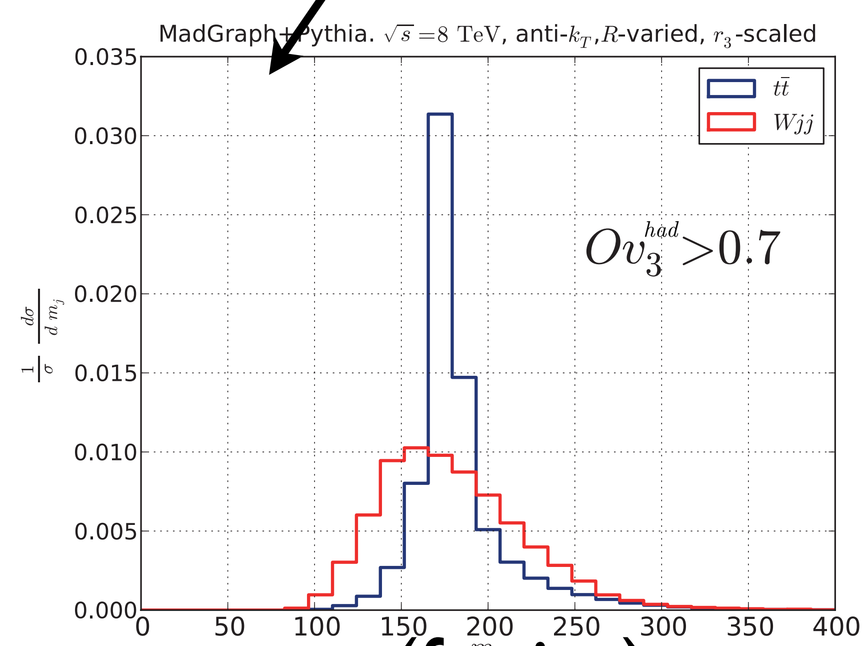


Expect signal event distribution to peak at 1, background at 0.

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



m(fat jet)



m(fat jet)

TOM w/ missing energy

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

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

<u>Three main differences from the fully hadronic decays</u>:

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.

TOM at the LHC: ATLAS analysis

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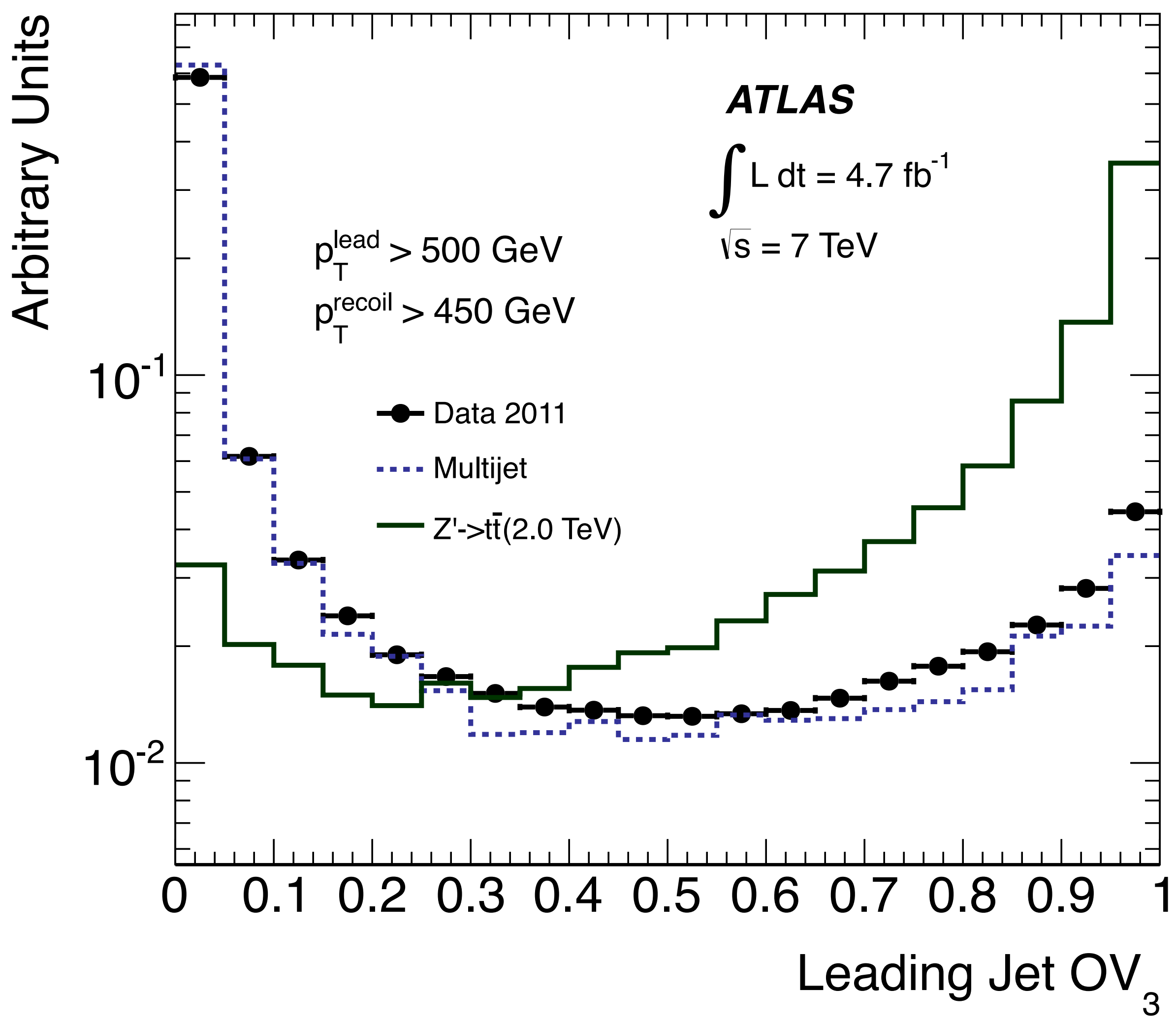
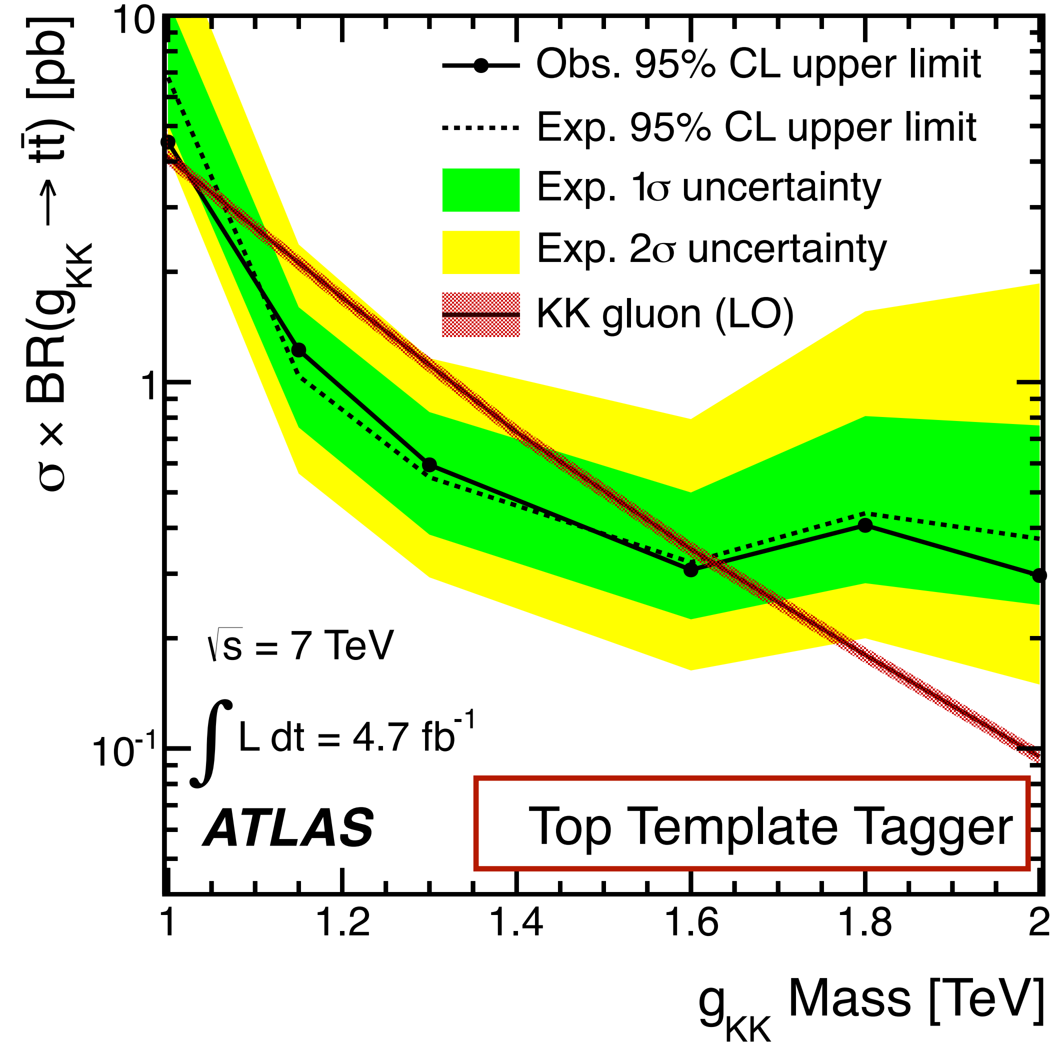
- A 7 TeV search for heavy ttbar resonances recently published: JHEP 1301(2013) 116 - **See Pekka's talk for more details.**





First measurement of the Ov3 distribution.
At the time, the most stringent limit on the mass of KKg (long surpassed by the current CMS and ATLAS measurements).

Some things we need to know about boosted jet taggers in the light of the LHC:

1. How much can the tagger help in resolving the differential distributions of jet parameters?

2. What is the effect of higher order processes on the distributions of tagger observables? (i.e. tops in a di-top event are not always back to back)

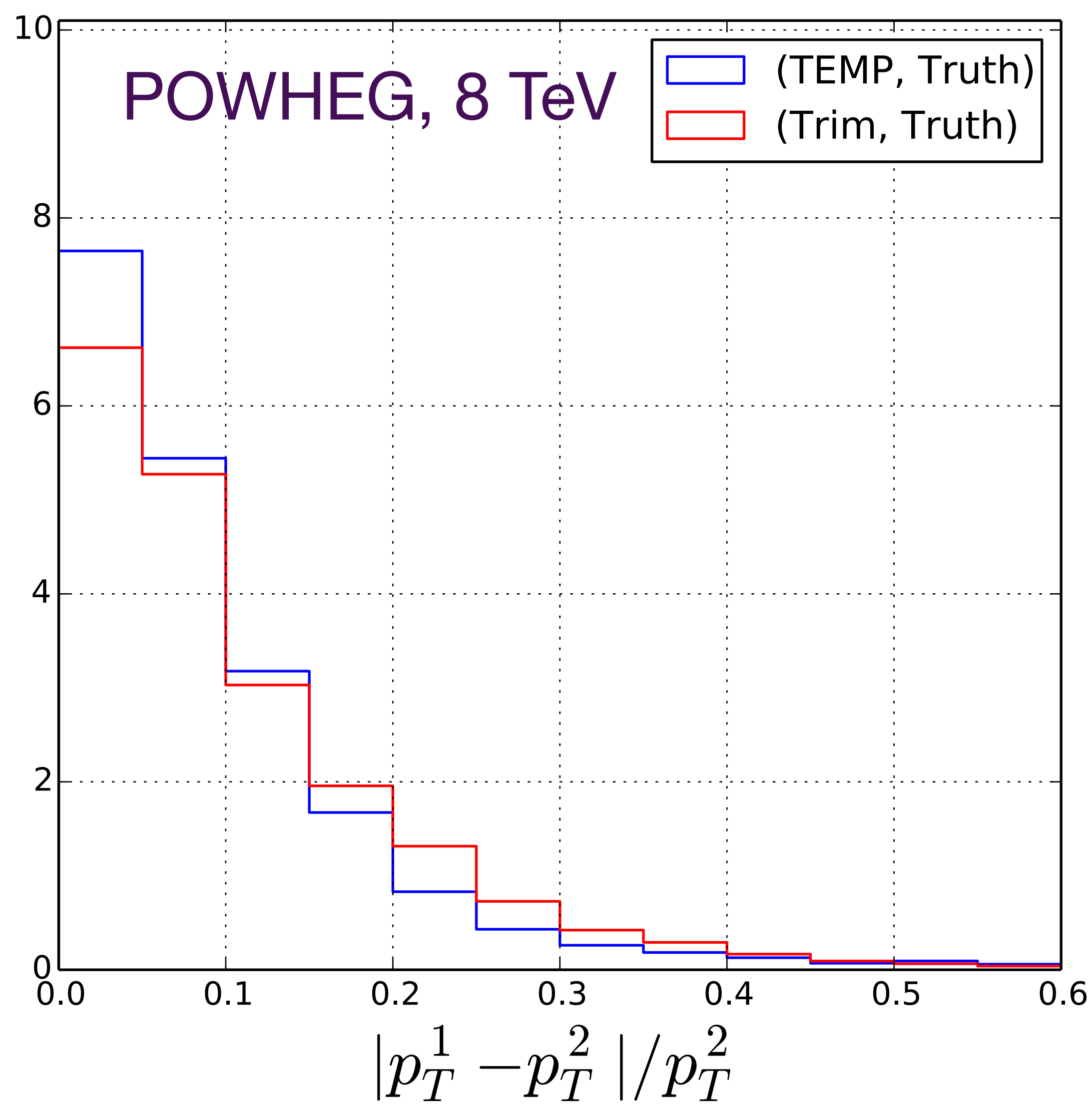
3. How well can the tagger discriminate between signal and background? (over a broad range of transverse momentum ,mass etc.)

4. How susceptible to pileup is the tagger?

Let's look at these questions in the context of the Template Overlap Method...

Differential Distributions with TOM

Question: How well does TOM resolve the transverse momentum of the top?



trimming parameter

Red - Trimmed jet with

$$t = 0.05, \quad d_{12} > 40.0\text{GeV}$$

Splitting scale at the last step of jet clustering

$$\sqrt{d_{12}} = \min(p_{T,i}, p_{T,j}) \times \delta R_{i,j};$$
$$\delta R_{i,j} = \sqrt{d\phi_{i,j}^2 + dy_{i,j}^2},$$

Blue - Template with

$$Ov_3 > 0.7$$

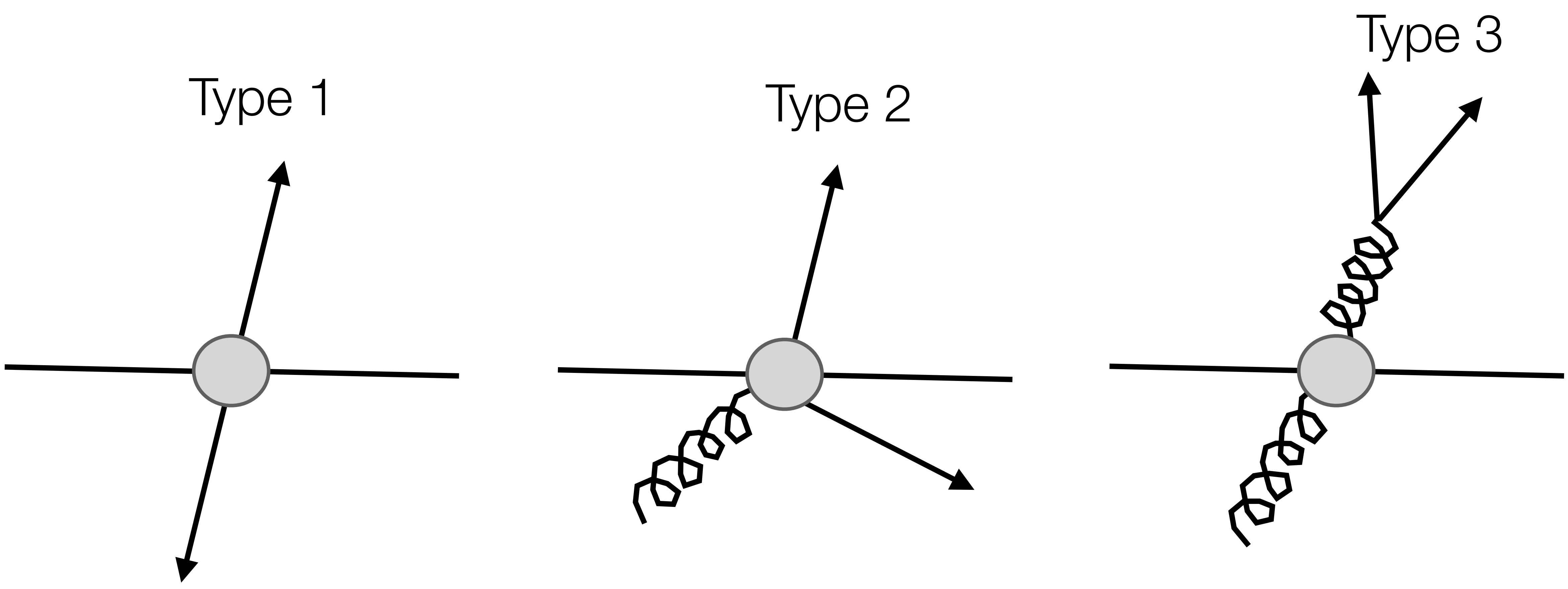
p_T^2 - transverse momentum of the truth level top.

p_T^1 - transverse momentum of the peak template or trimmed jet.

We are currently doing the calculation at various levels of pileup.

- Boosted jet regime offers many possibilities for the kinematic configurations of the final states.

- **Question**: How often are the tops back to back?



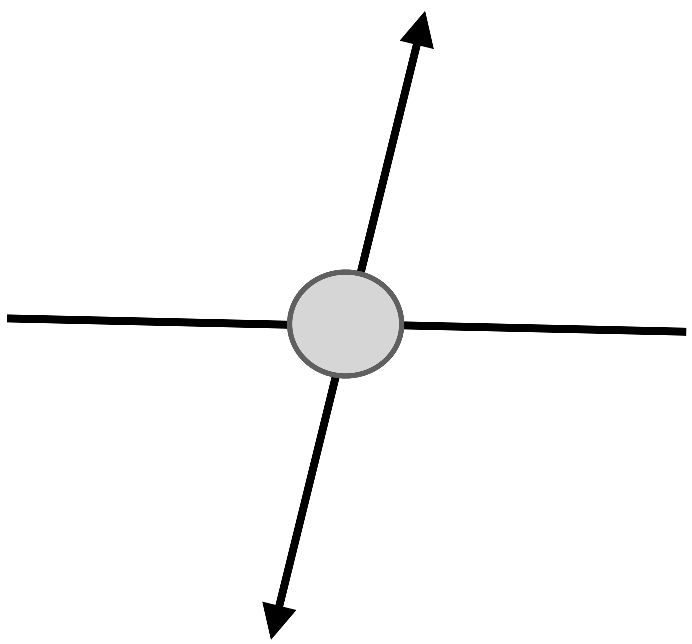
- **Question**: Are Type 2 and Type 3 a problem for TOM?

High Energy Effects

- Boosted jet regime offers rich kinematic configurations of the final states.

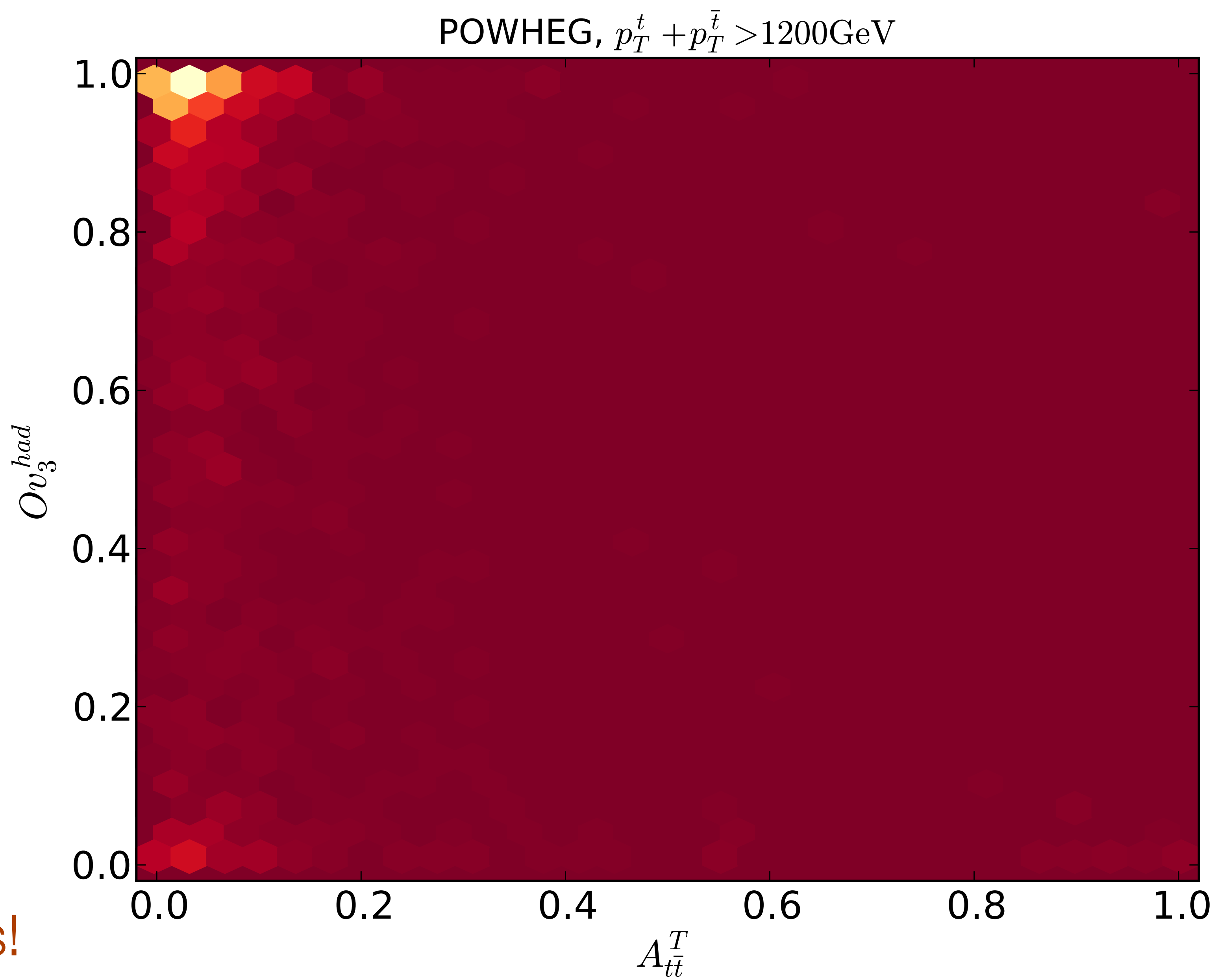
- **Question**: How often are the tops back to back?

Type 1



$$A^T_{t\bar{t}} \equiv \frac{|\vec{p}^{\,t}_T + \vec{p}^{\,\bar{t}}_T|}{p^t_T + p^{\bar{t}}_T}$$

defined from truth level tops!



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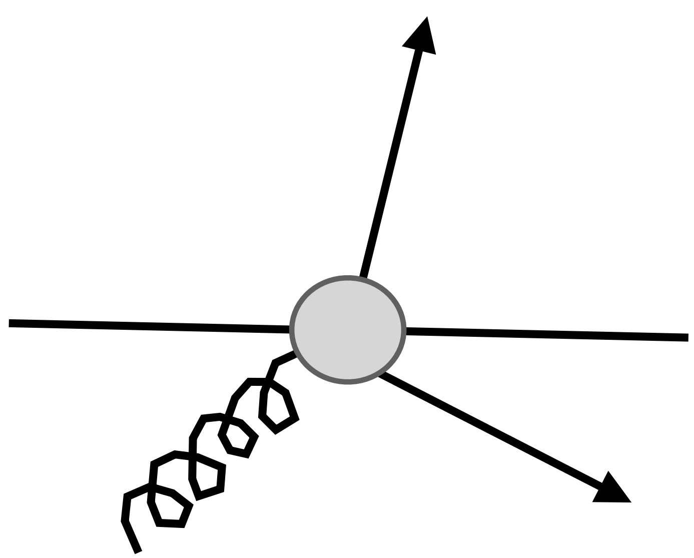

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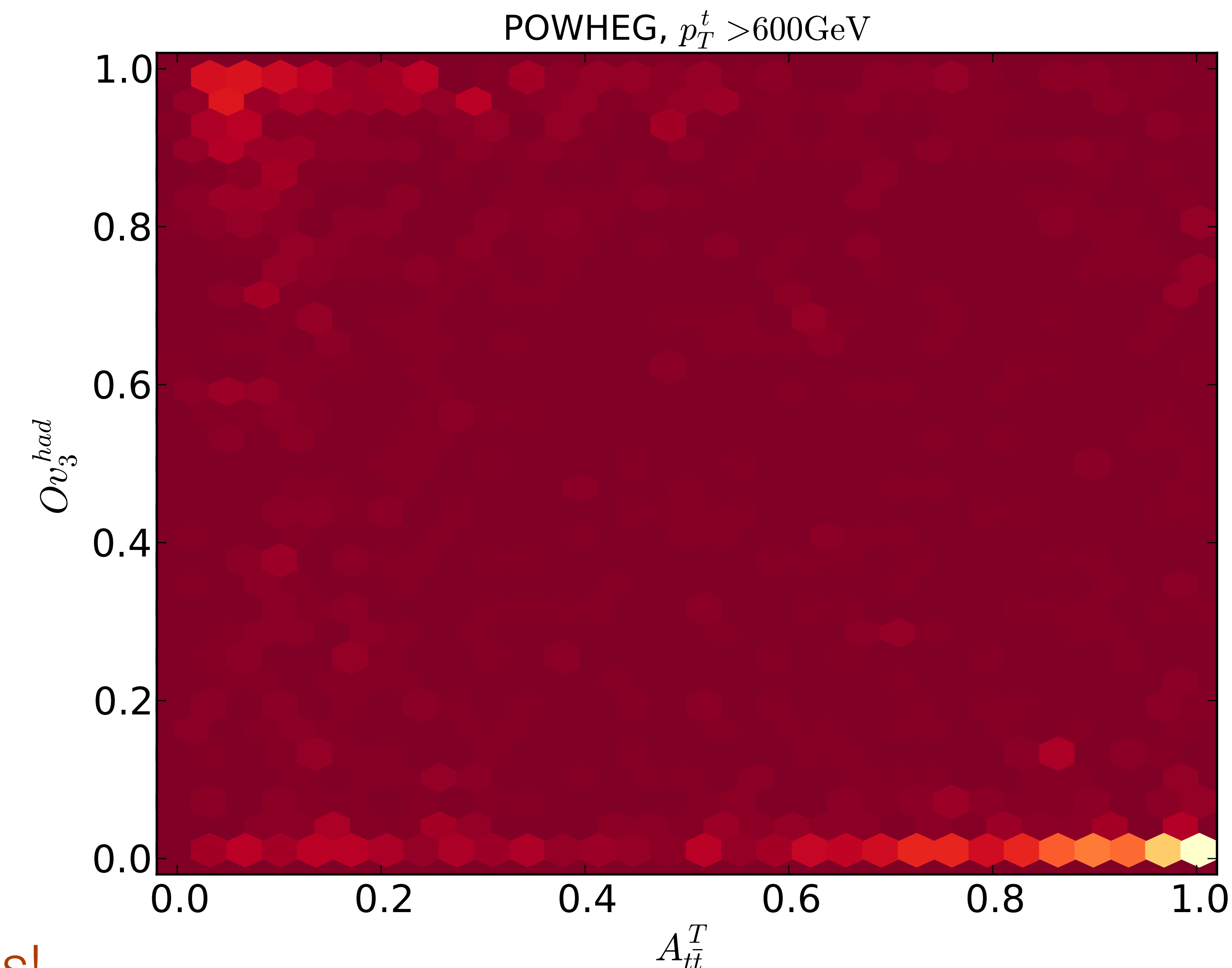

High Energy Effects

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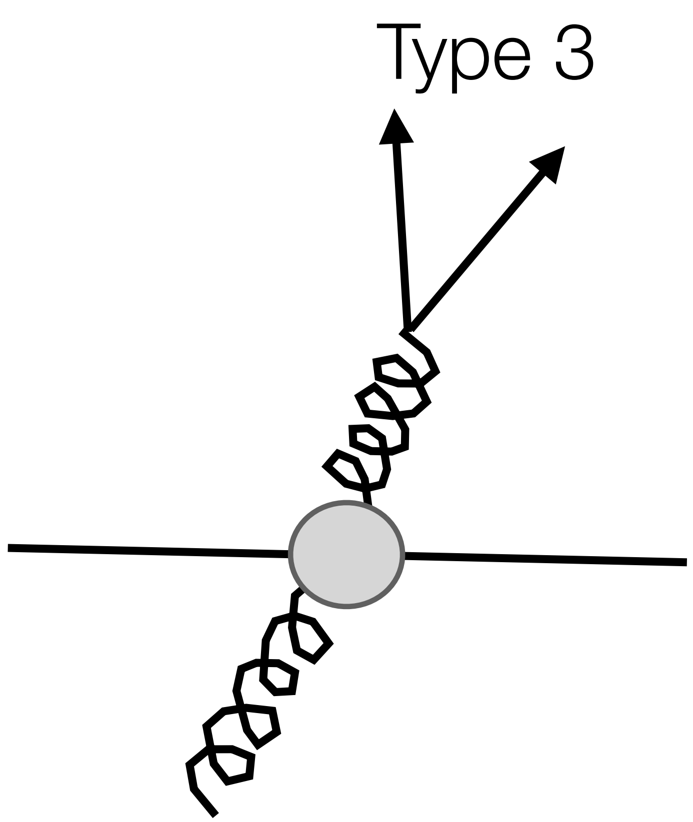

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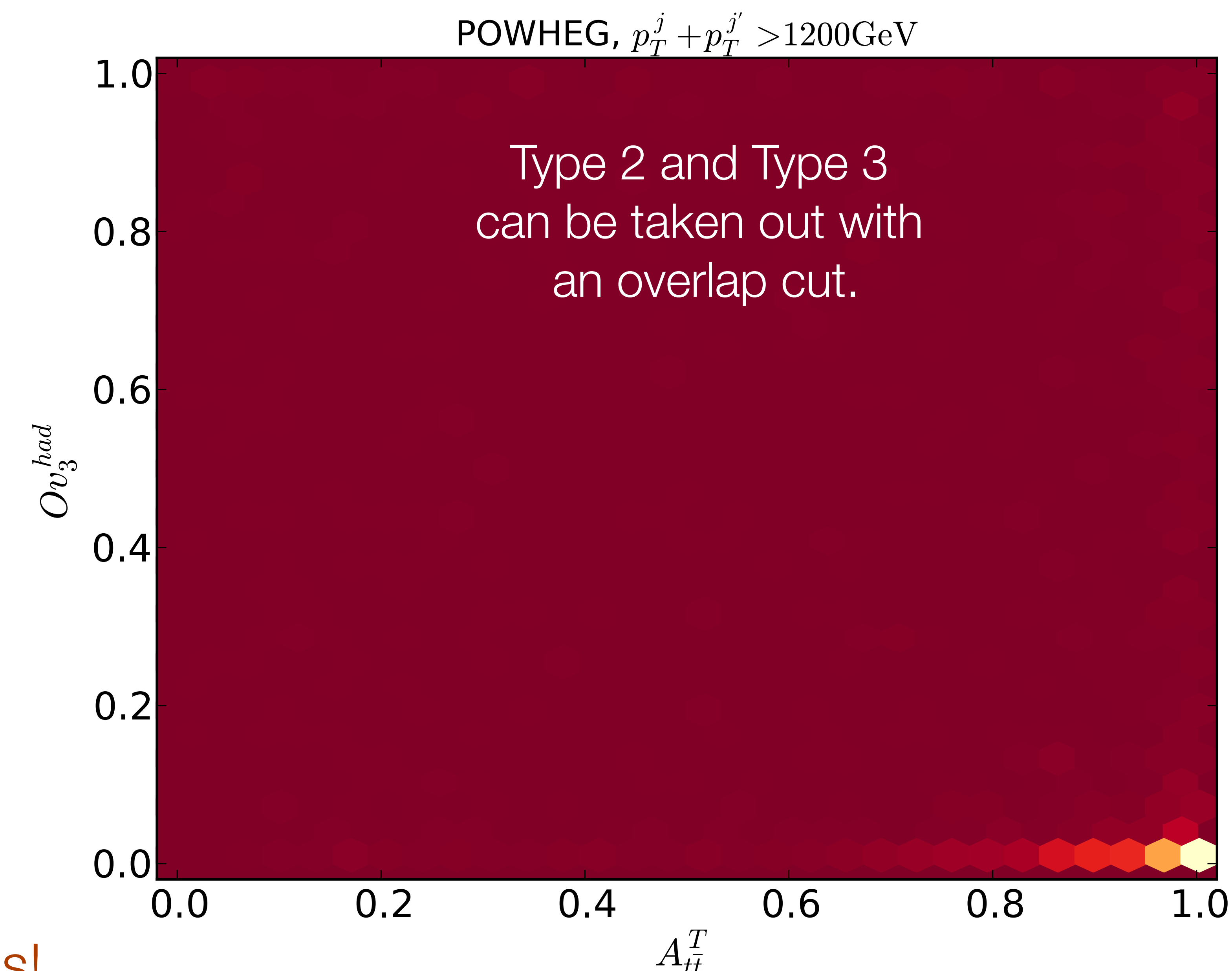

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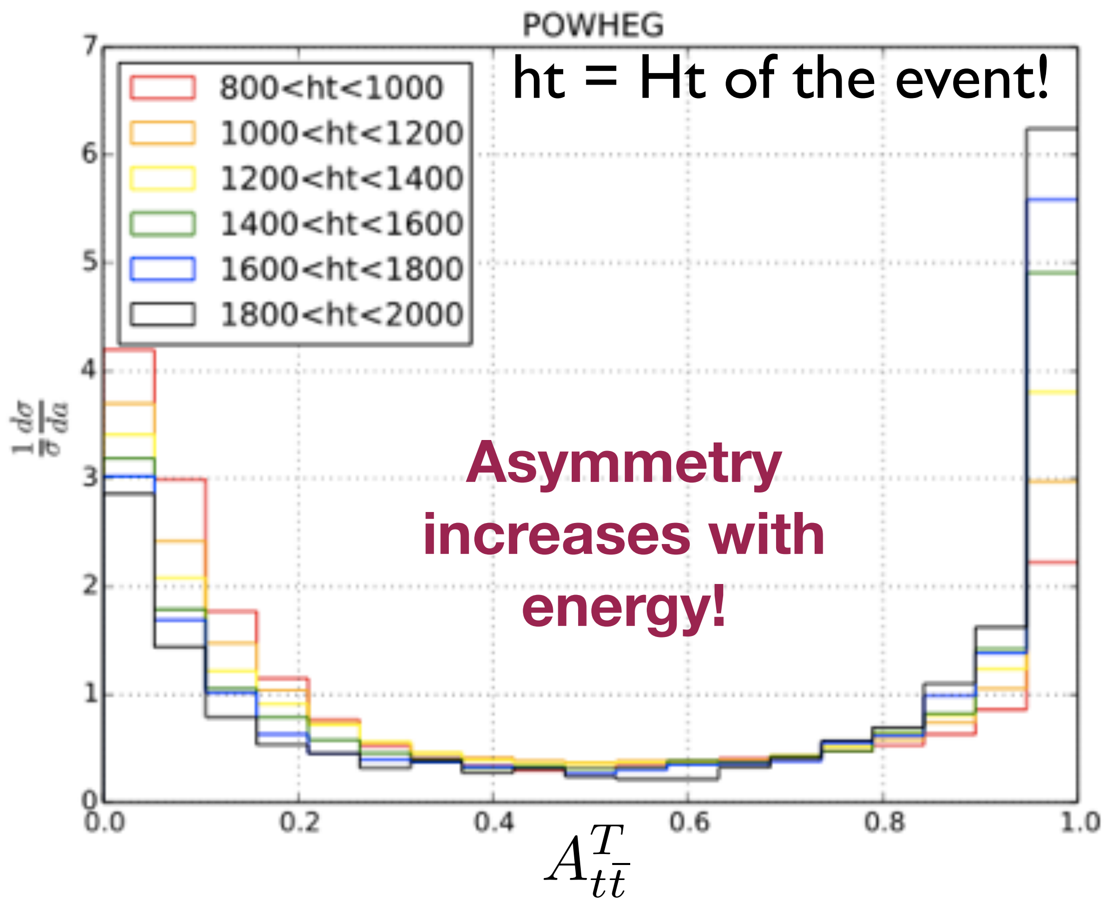
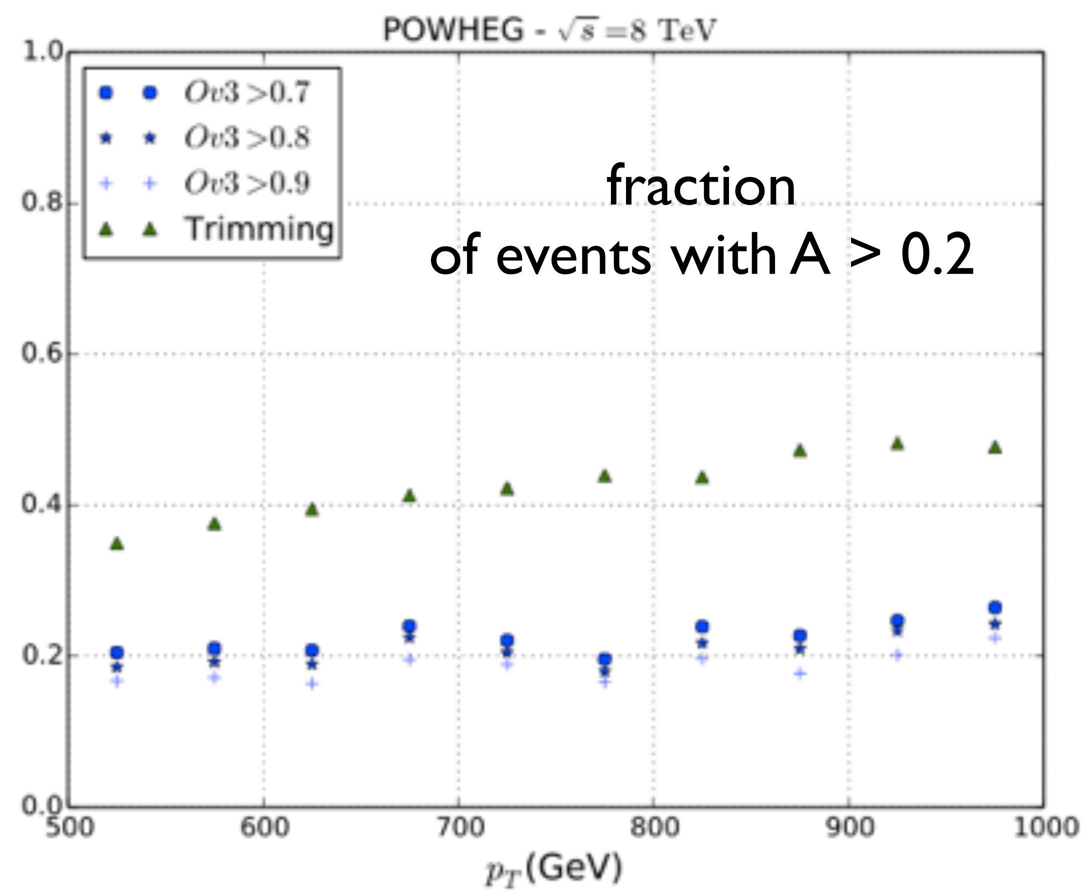
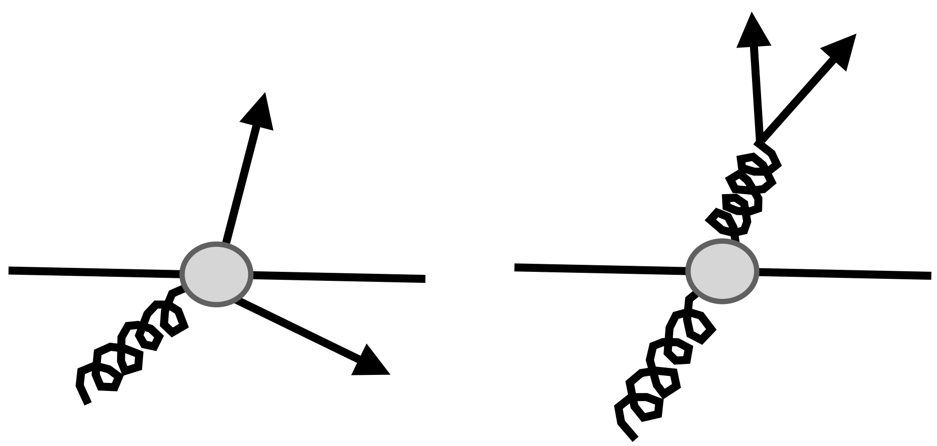
High Energy Effects







Templates perform much better at removing asymmetric events that d12+Trimming!

The fraction of asymmetric events in case of d12+Trimming increases with energy!

Asymmetric events are also a background to di-top resonance searches!

Mihailo Backovic, BOOST2013

TOM Background Rejection Power

- We looked at boosted (pT > 500 GeV) semi-leptonic di-top events.
- Main background comes from Wjj (dijets insignificant after mini-ISO).

$p_T^{j\,R} > 500$ GeV $\quad \not{E}_T > 40$ GeV

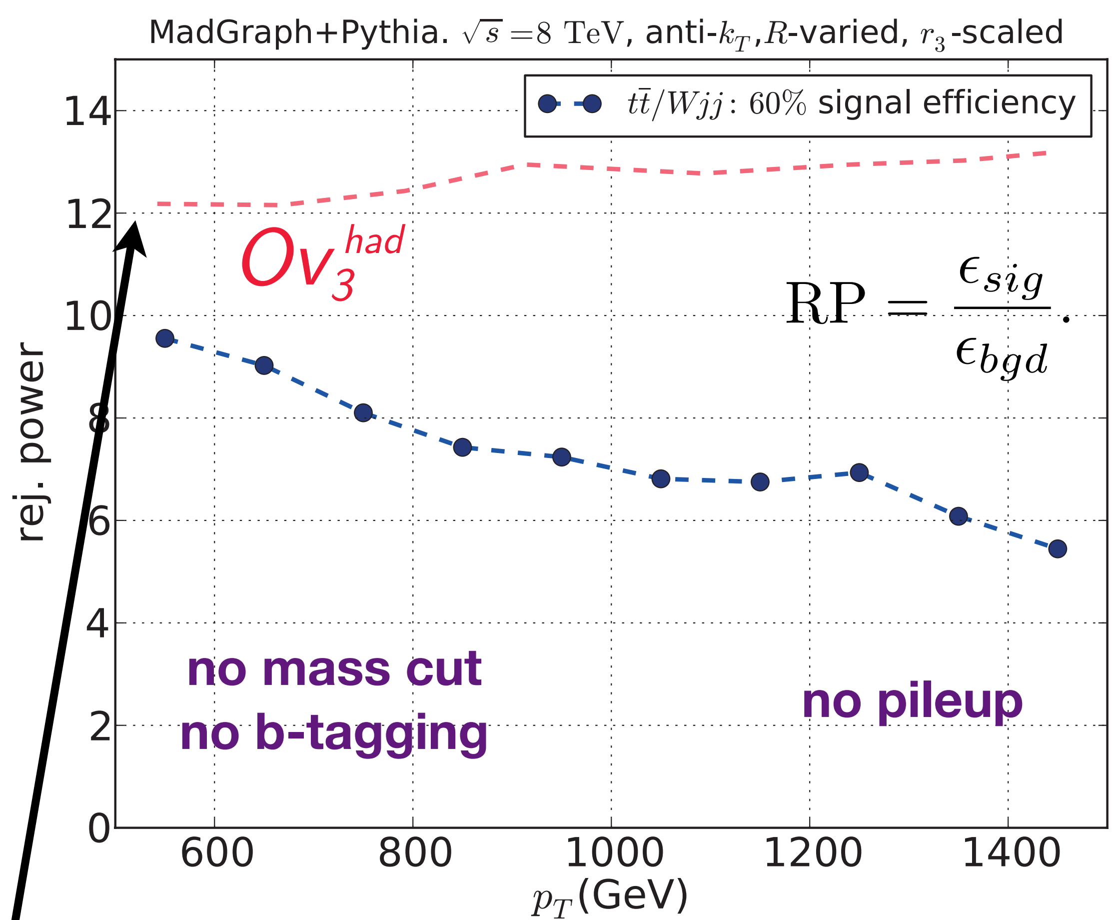
$N_l^{out}(p_T^l > 25 \text{ GeV}) = 1 \quad N_j^{out}(p_T^j > 25 \text{ GeV}) \geq 1$

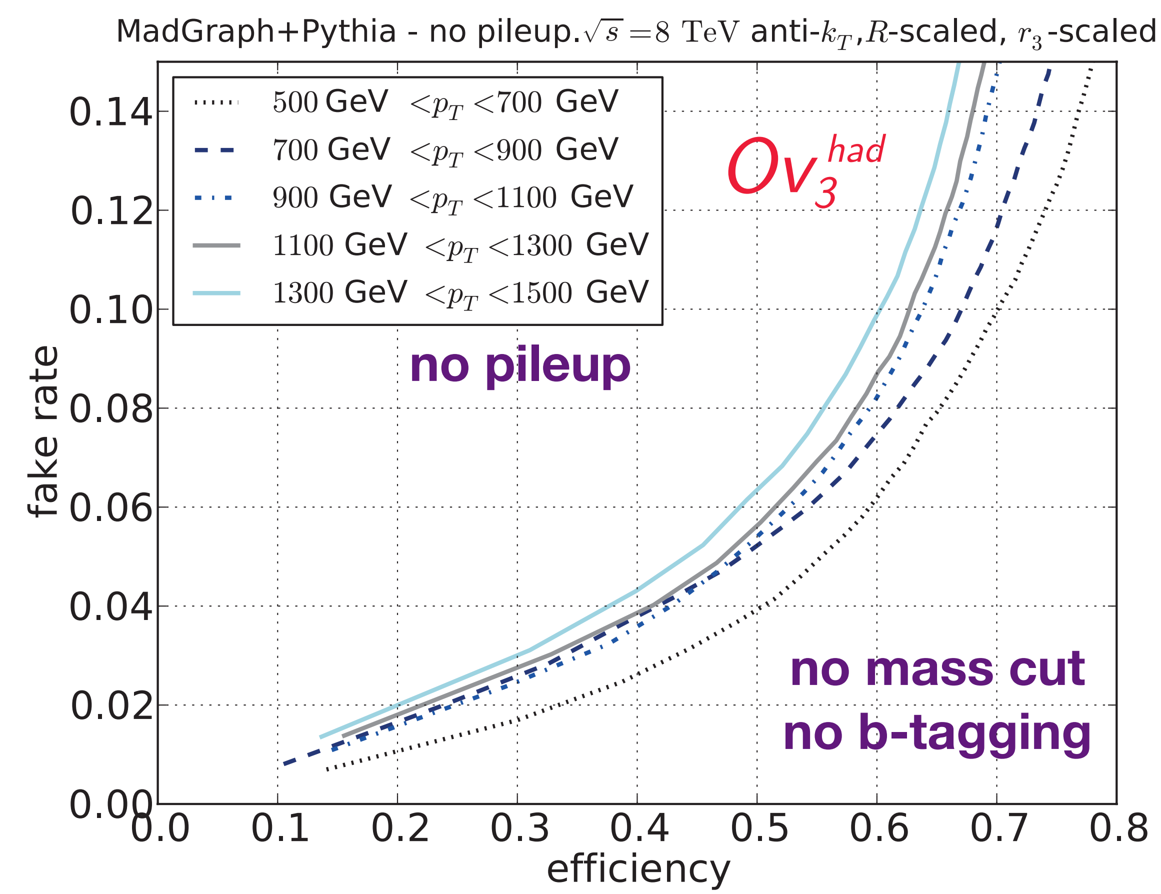
$\Delta\phi_{jl} > 2.3 \quad \eta_{j,l} < 2.5$

+

"Leptonic Top" is in the event:
One lepton with mini-ISO > 0.95
At least one r =0.4 anti-kT jet within R=1.5 from the lepton.

Basic Cuts (BC)

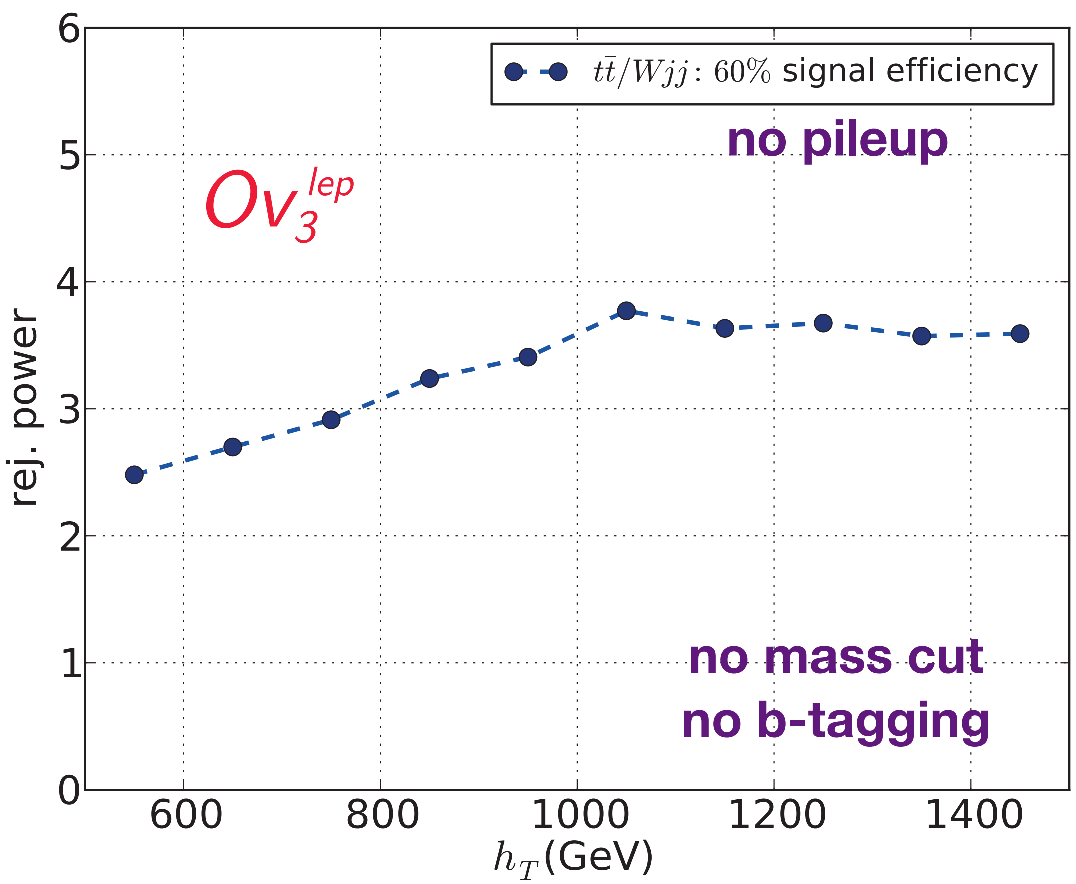


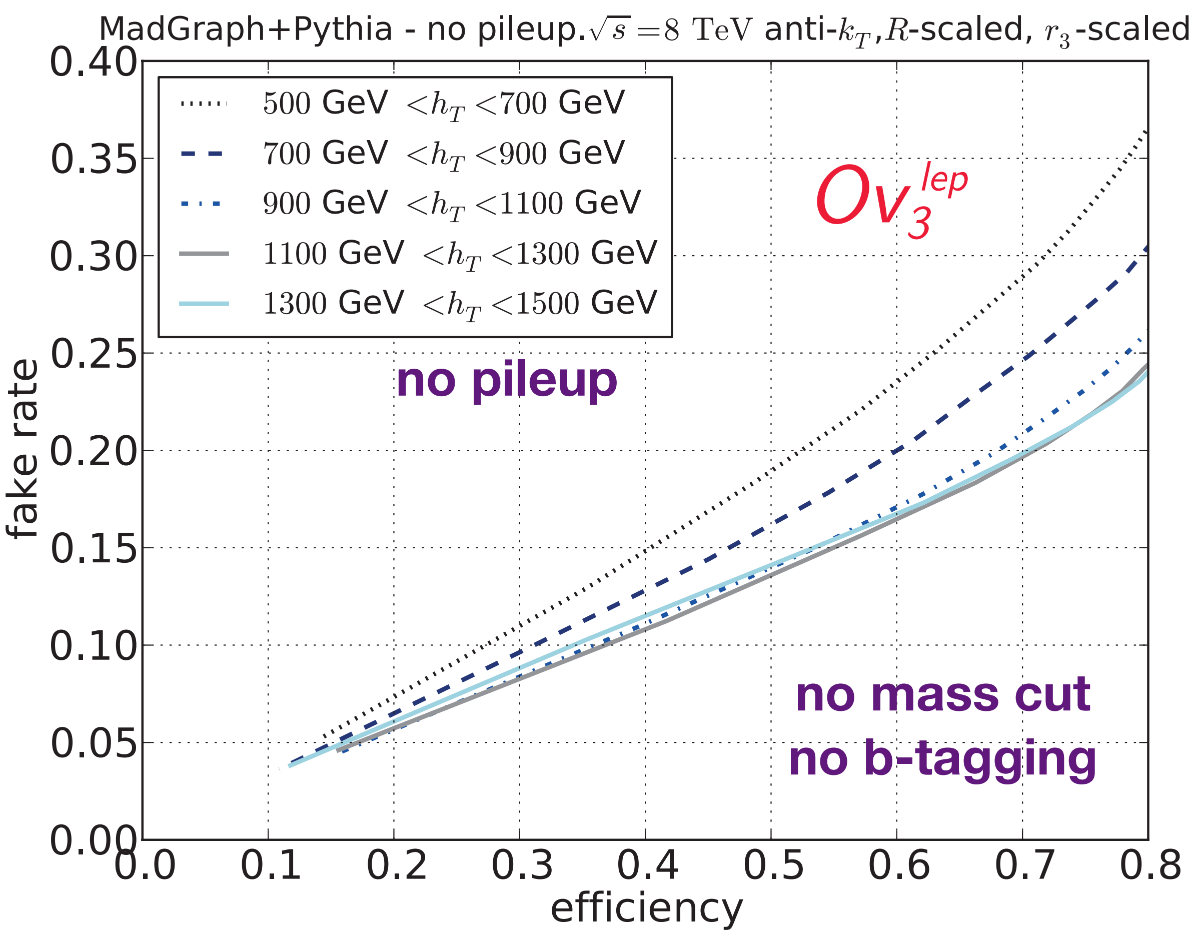


Red - Only symmetric events!

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

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

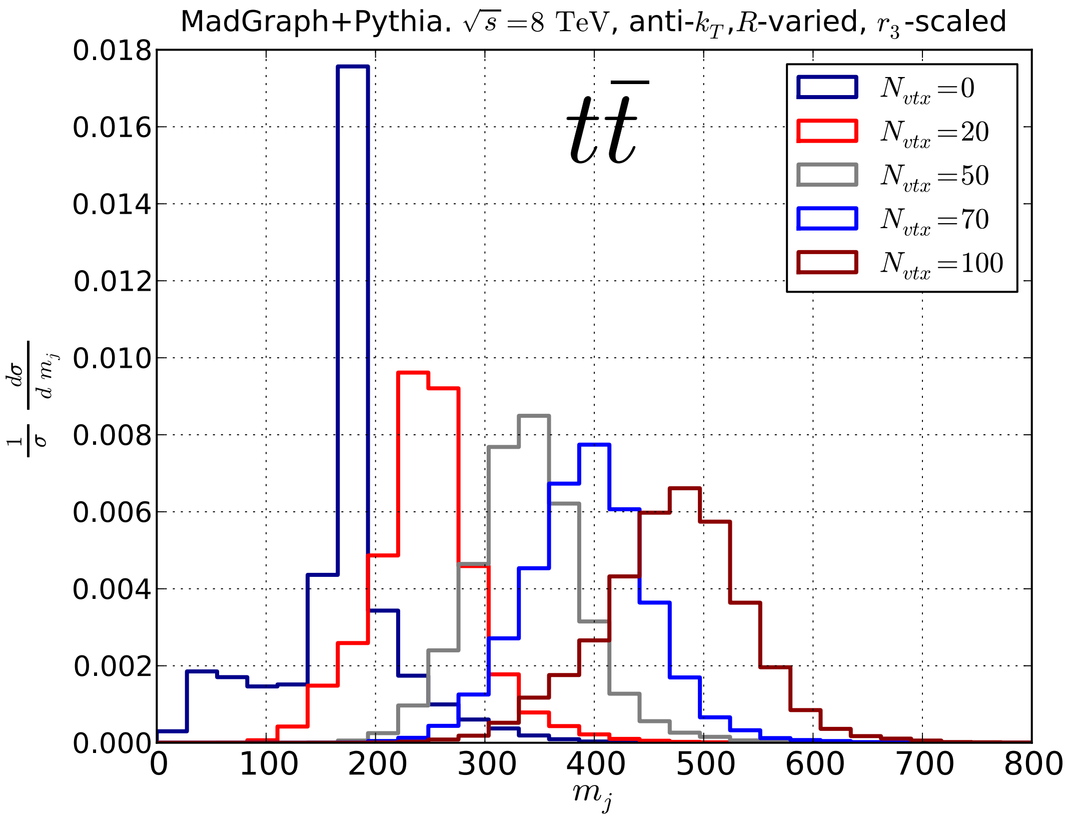


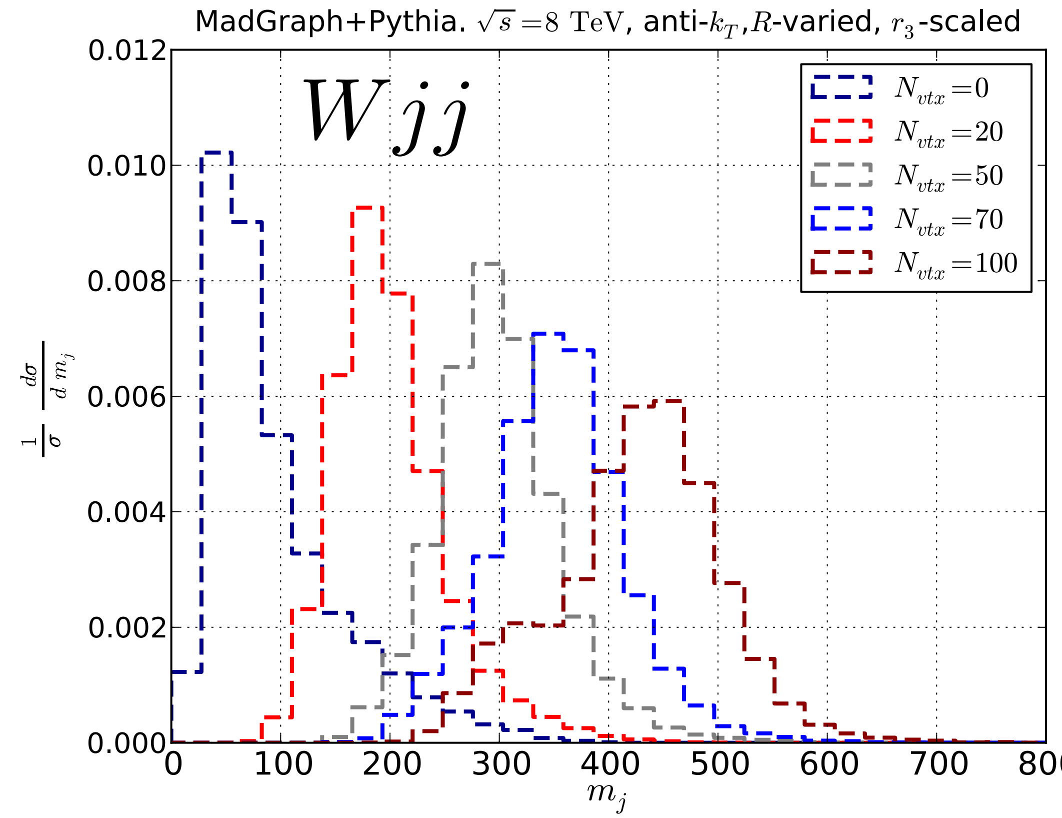


Rejection power lower than for hadronic tops because background already contains a W!

$$h_T \equiv p_T^l + p_T^b + E_T^{\mathrm{miss}}$$

Pileup in TOM framework



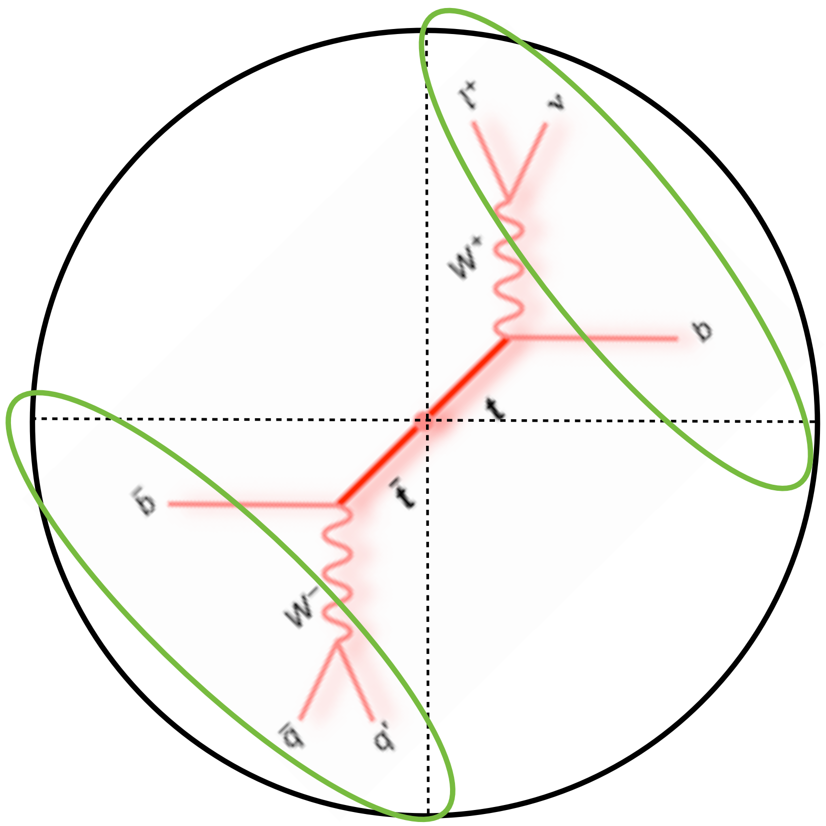


Problem: What is the true fat jet p_T in a high pileup environment?

Problem: How do you determine which template p_T bin to use or which p_T to boost templates to?

Pileup in TOM framework

Solution: Use a less sensitive pileup observable which is correlated with the hadronic top p_T.



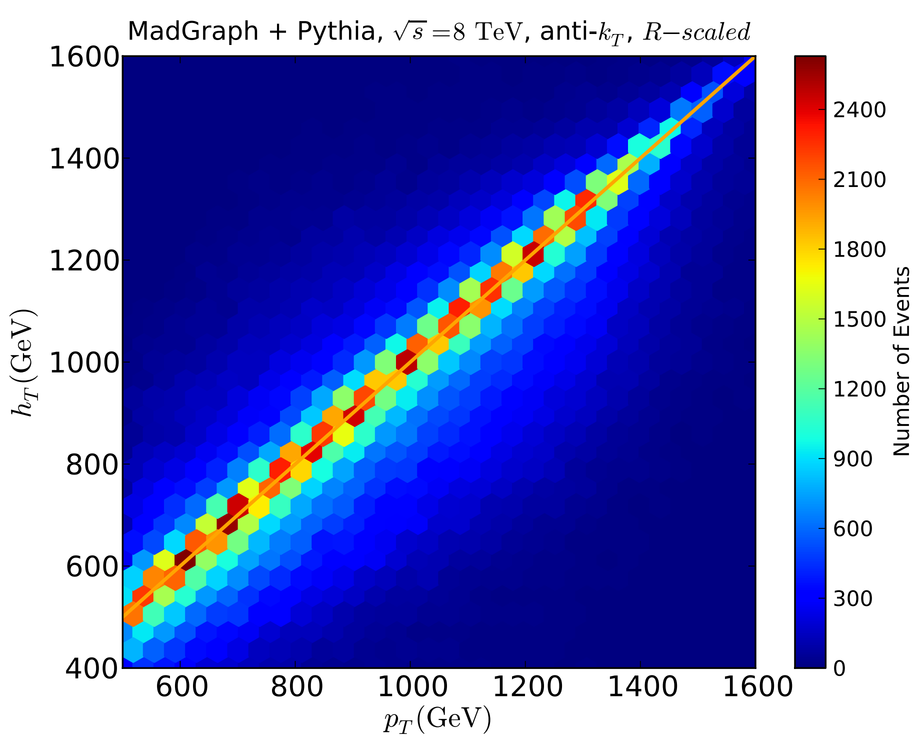
"Interesting" top and anti-top are back to back in the transverse plane:

$$p_T^t = p_T^{\bar{t}}$$

Proposal: Use

$$h_T \equiv p_T^l + p_T^b + E_T^{\text{miss}}$$

Pick the fat jet cone and the template transverse momentum based on hT.



$$R = \begin{cases} 1.0, & 500 \text{ GeV} < h_T \leq 700 \text{ GeV} \\ 0.8, & 700 \text{ GeV} < h_T \leq 900 \text{ GeV} \\ 0.6, & 900 \text{ GeV} < h_T \end{cases}$$

Pileup in TOM framework

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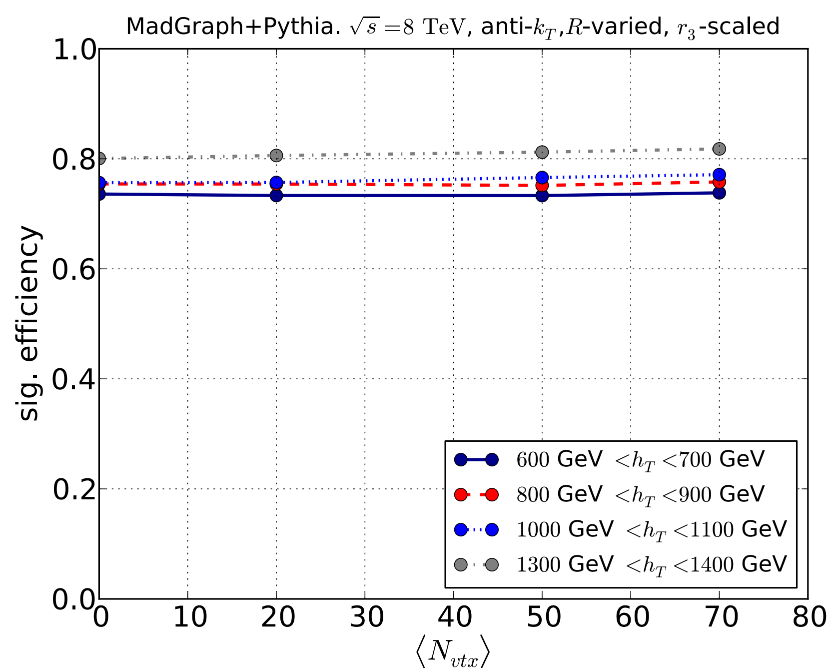
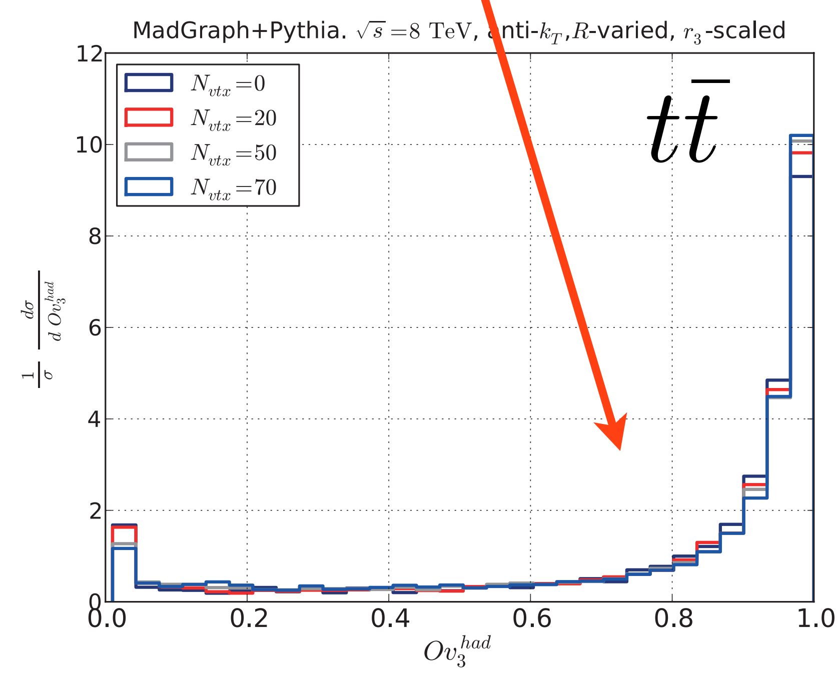
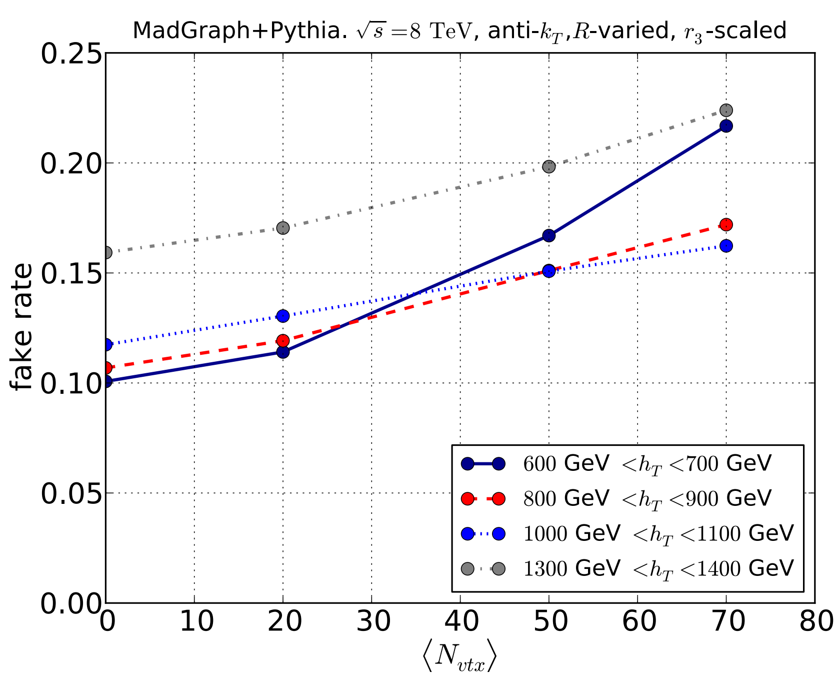
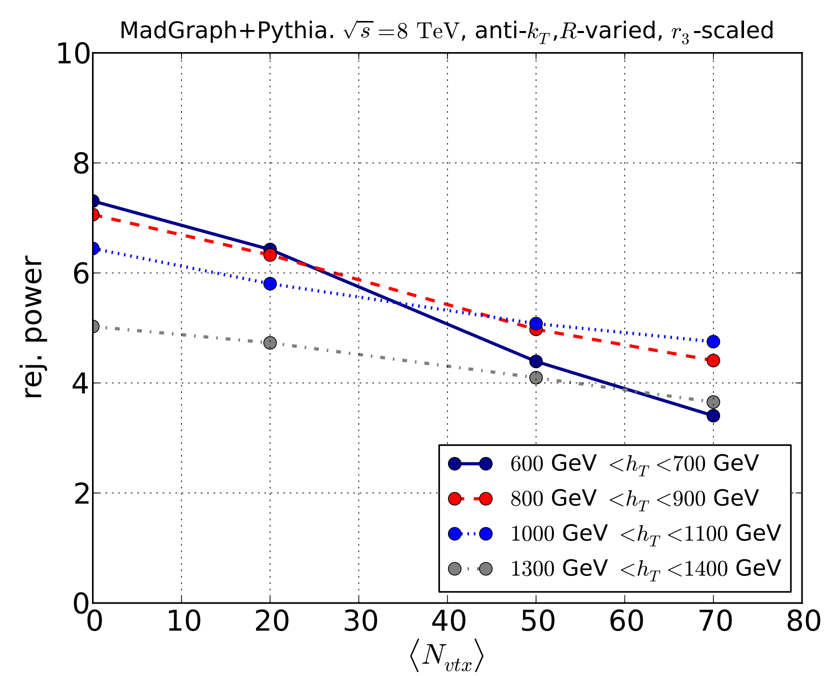
$$Ov_3^{\text{had}} > 0.6$$

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



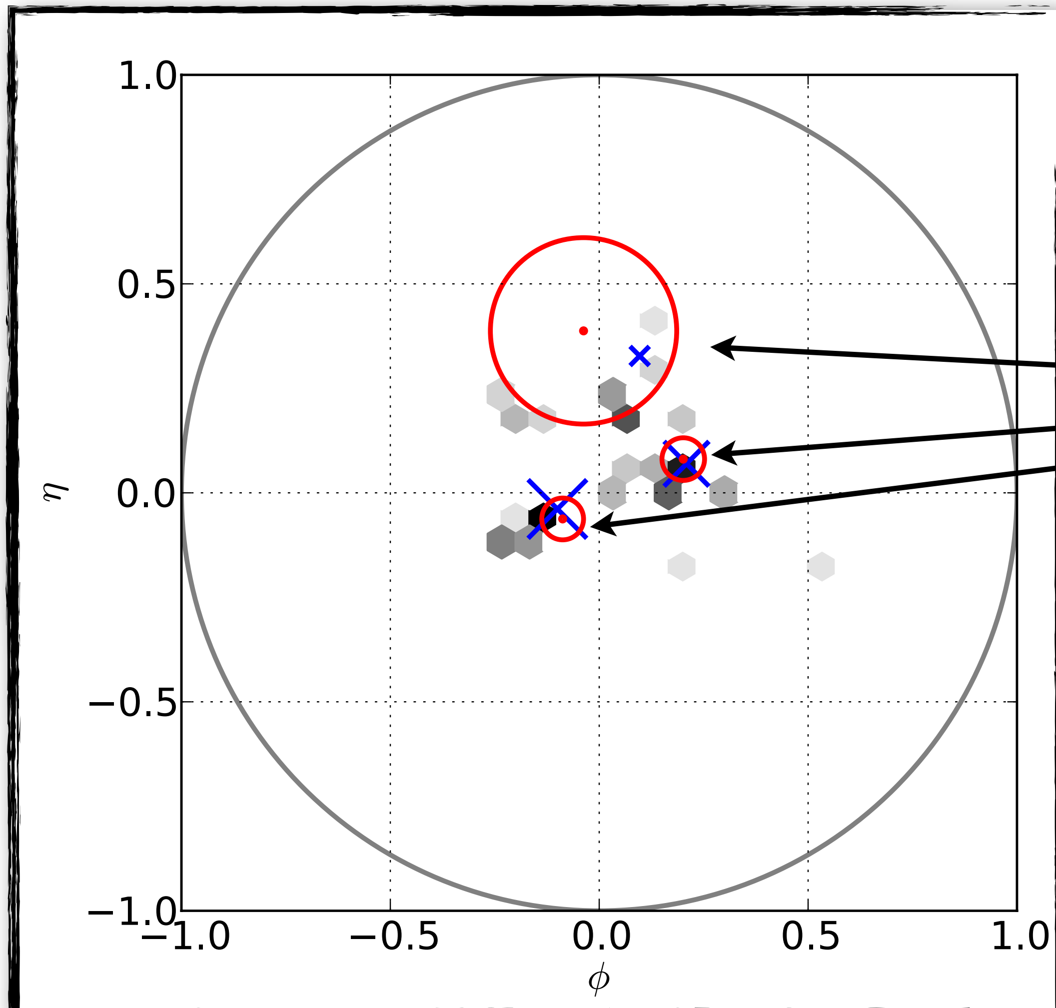






At < 50 interactions per bunch crossing no pileup subtraction necessary!

Why is TOM weakly susceptible to pileup?



Templates are sensitive ***only*** to the energy deposition inside the template sub-cones.

For fat jets: $\delta p_T^{pileup} \sim R^2$

For templates: $\delta p_T^{pileup} \sim r^2$

Pileup contribution to a template relative to the fat jet

e.g.: $n_{temp} \times r^2/R^2 \sim n_{temp} \times 0.1^2/1.0^2 = 0.01 \times n_{temp}$

Boosted top resonance searches

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LH KKg, b near the TeV brane (m = 3 TeV ,Width is 0.210 x m(kkg)

14 TeV!

Ov cuts = Ov3 > 0.5, tPf + Ov3 > 1.0, Ov3l > 0.5

Case 2: m(kkg) = 3TeV, no pileup, no b-tagging, no mass cut on the jet, mtt(template) > 2.8 TeV

Cuts	$\sigma_{t\bar{t}}$(fb)	$\epsilon_{t\bar{t}}$	σ_{wjj}(fb)	ϵ_{Wjj}	$\sigma_{m_{KK}=3\text{ TeV}}$ (fb)	$\epsilon_{m_{KK}=3\text{ TeV}}$(fb)	S/B	$S/\sqrt{B}$(300fb^{-1})	$S/\sqrt{B}$(3000fb^{-1})
Basic Cuts	12.2	1.00	121.0	1.00	1.38	1.00	0.01	2.1	6.6
& Ov cuts	4.1	0.34	3.9	0.03	1.02	0.74	0.13	6.3	19.8

Case 2: m(kkg) = 3TeV, 50 pileup, no b-tagging, no mass cut on the jet, mtt(template) > 2.8 TeV

Cuts	$\sigma_{t\bar{t}}$(fb)	$\epsilon_{t\bar{t}}$	σ_{wjj}(fb)	ϵ_{Wjj}	$\sigma_{m_{KK}=3\text{ TeV}}$ (fb)	$\epsilon_{m_{KK}=3\text{ TeV}}$(fb)	S/B	$S/\sqrt{B}$(300fb^{-1})	$S/\sqrt{B}$(3000fb^{-1})
Basic Cuts	18.7	1.00	208.5	1.00	1.6	1.00	0.007	1.8	5.8
& Ov cuts	5.2	0.25	5.2	0.025	1.2	0.74	0.11	6.3	20.0

1. **Possible to improve the sig. significance by 3-fold with jet substructure.**
2. **High signal efficiency achievable.**
3. **50 pileup does not significantly affect the search w/ TOM (~10% effect)**
4. **Asymmetry works in our favor!**

THANK YOU!

Time it takes to analyze 1 event with TOM.