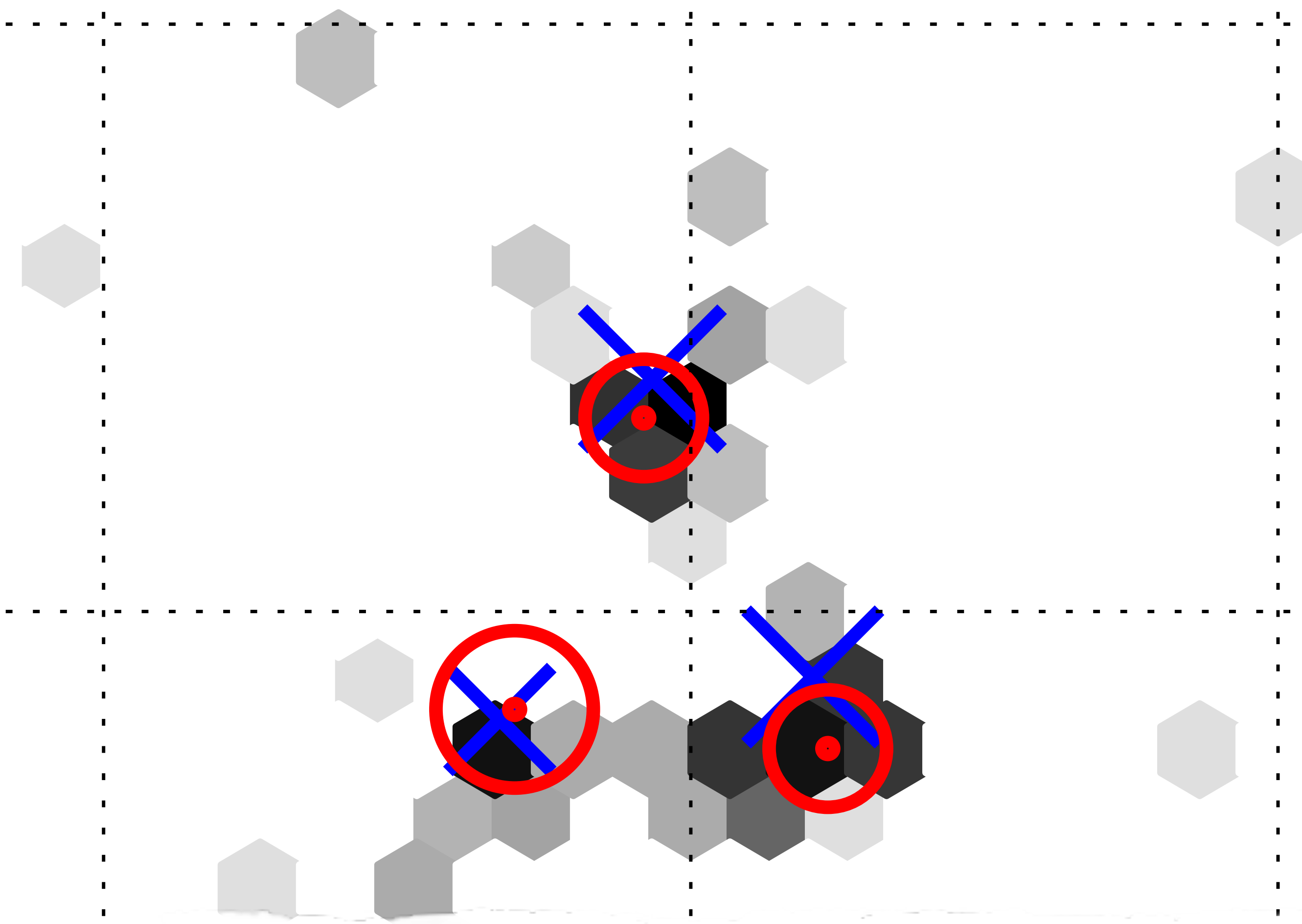

Template Tagger v.1.0

a C++ implementation of the Template Overlap Method for Jet Substructure

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

Template Overlap Method (TOM)

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- A jet substructure algorithm to tag heavy, boosted jets against the background. (see Matteo's talk for some alternatives)

- 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).
    - ***Highly boosted Higgs study*** - Backovic, Juknevich, Perez (arXiv:1212.2977)
    - ***Semi-leptonic Top study*** - Backovic, Juknevich, Lee, Soreq, Perez (in preparation)

- Publically available code:
    - ***Template Tagger v1.0.0*** - Backovic, Juknevich (arxiv:1212:2978)

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

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

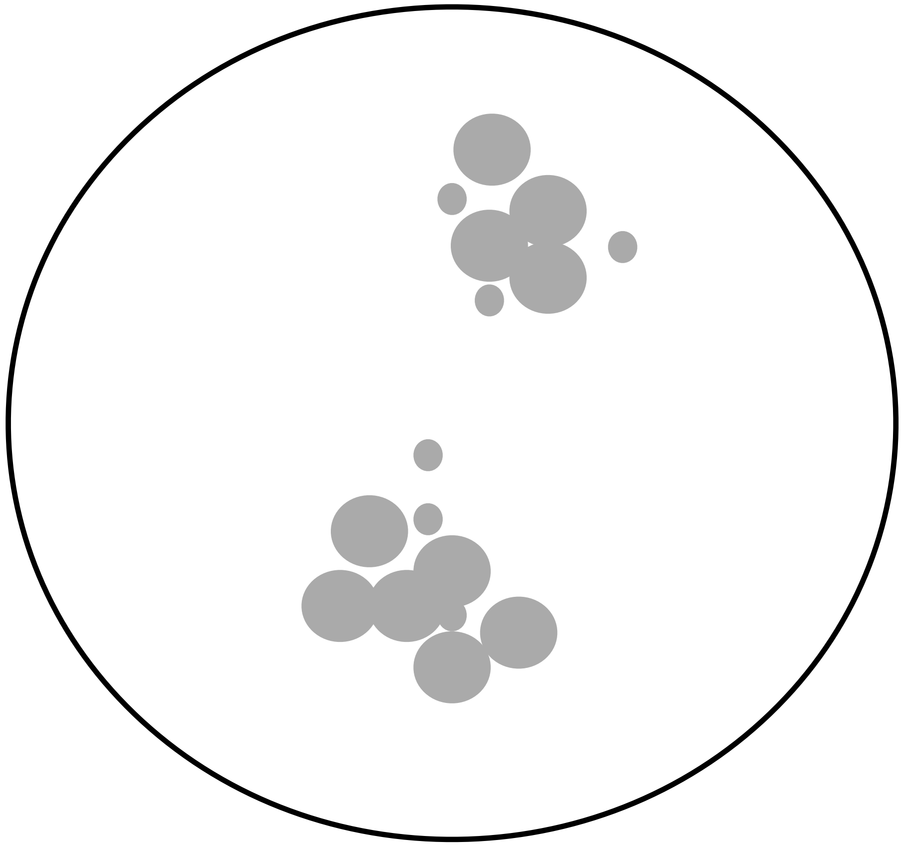
$$\sum_{i=1}^{n} p_i = P\,, \qquad P^2 = M^2 \quad \textit{etc.}$$

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

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):

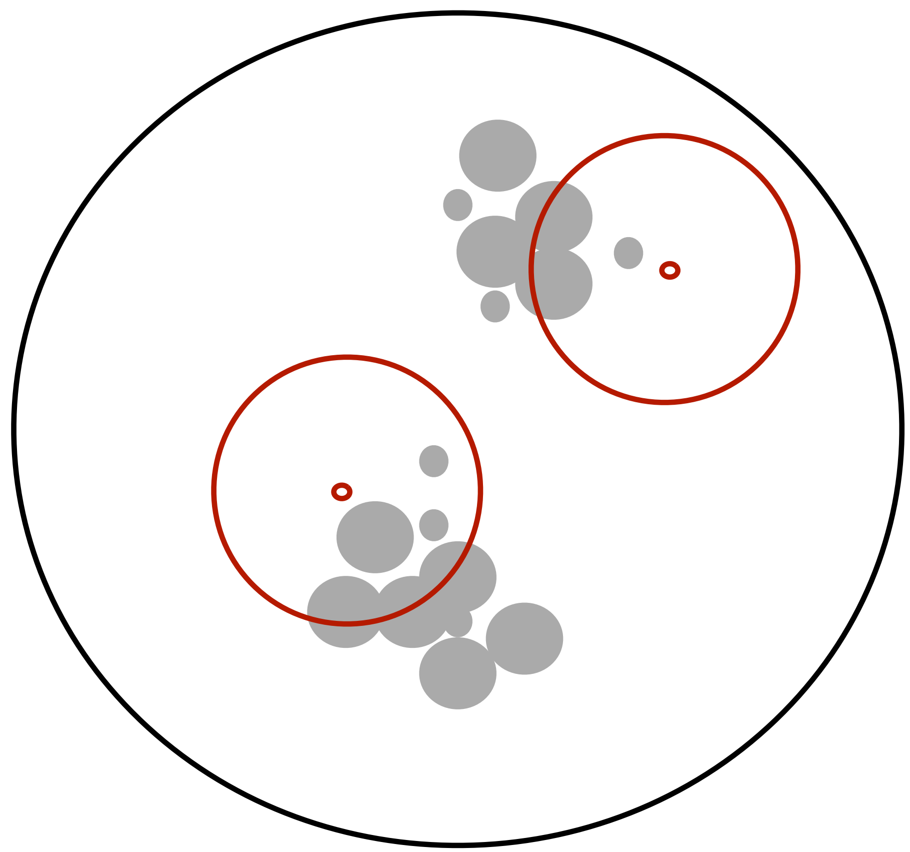
$$Ov^{(F)}(j,f) = \max_{\tau_n^{(R)}} \exp\left[-\frac{1}{2\sigma_E^2} \left(\int d\Omega \, \left[\frac{dE(j)}{d\Omega} - \frac{dE(f)}{d\Omega} \right] F(\Omega, f) \right)^2 \right]$$

Consider for instance a “Higgs jet”



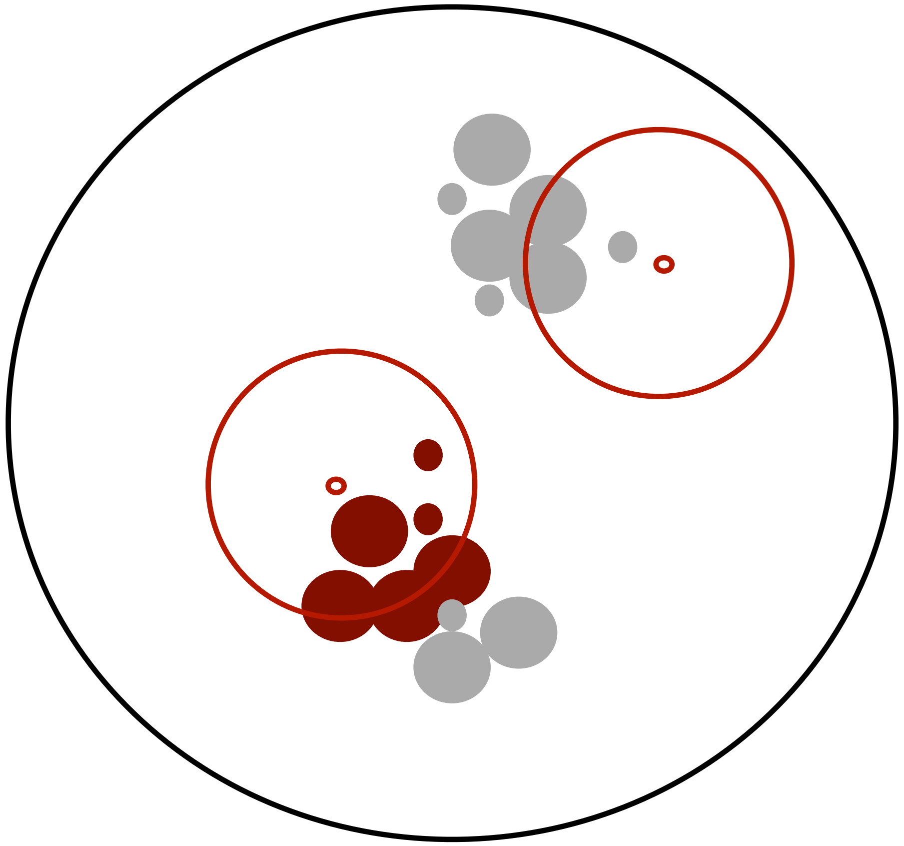
TOM: Illustration

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



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

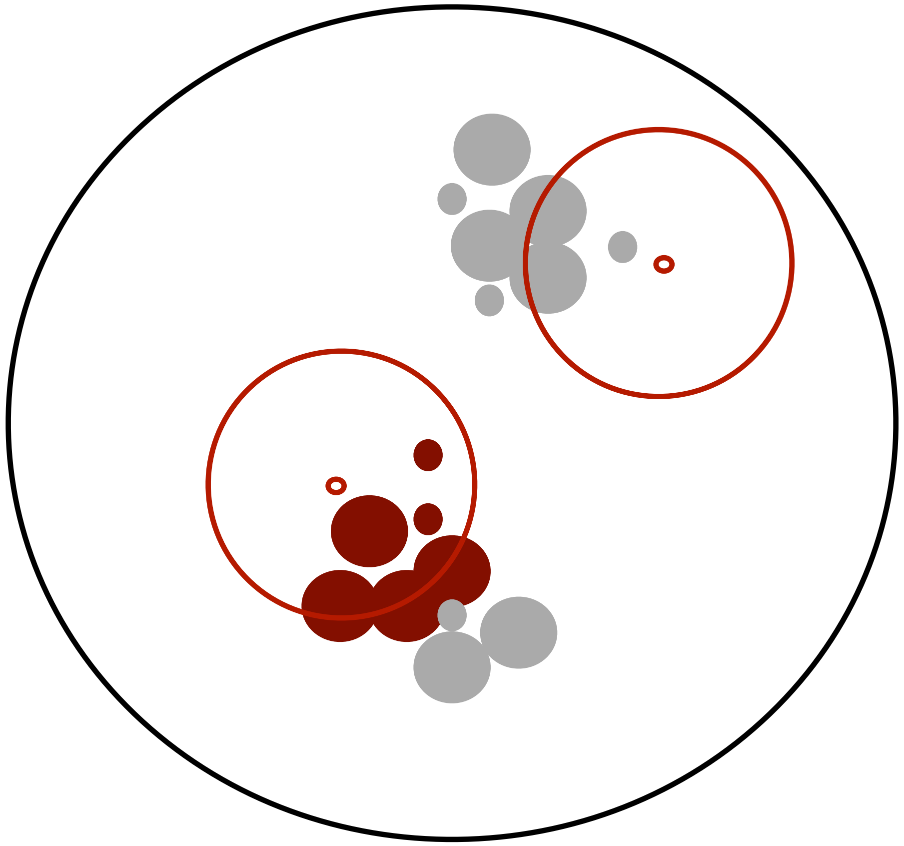
For each template momentum, add up the energy deposited inside the cone of radius r around the template momentum



$$\sum_j E_j$$

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

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



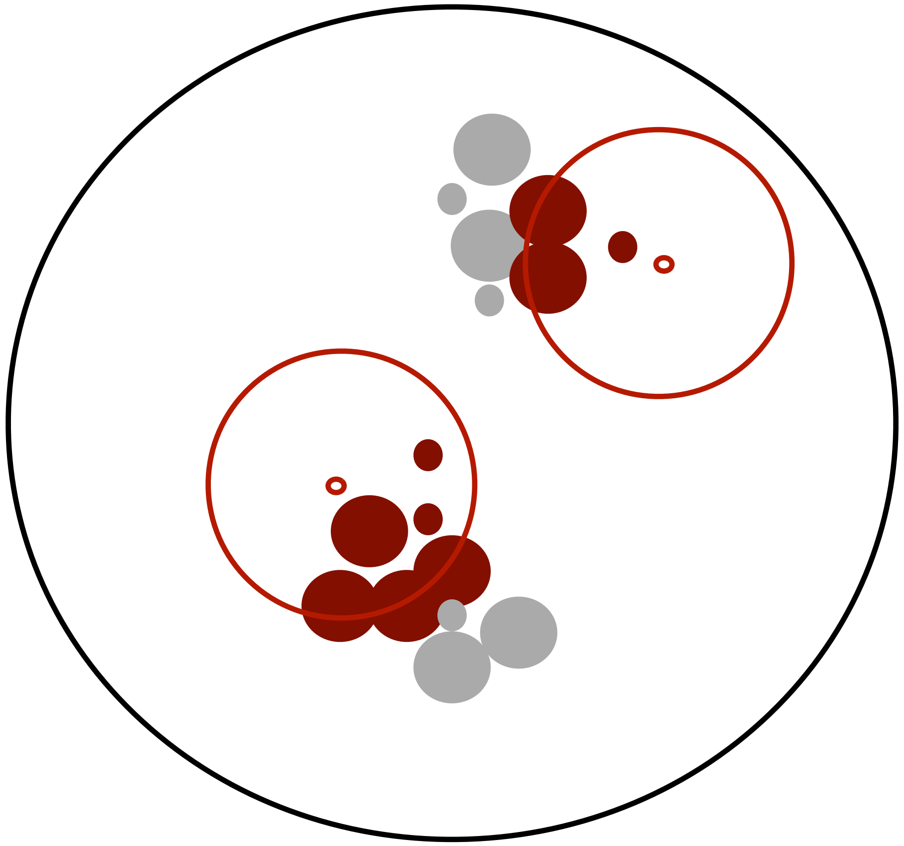
For each template, subtract the sum from the energy of the template momentum.

$$\sum_j E_j - E_i$$

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

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



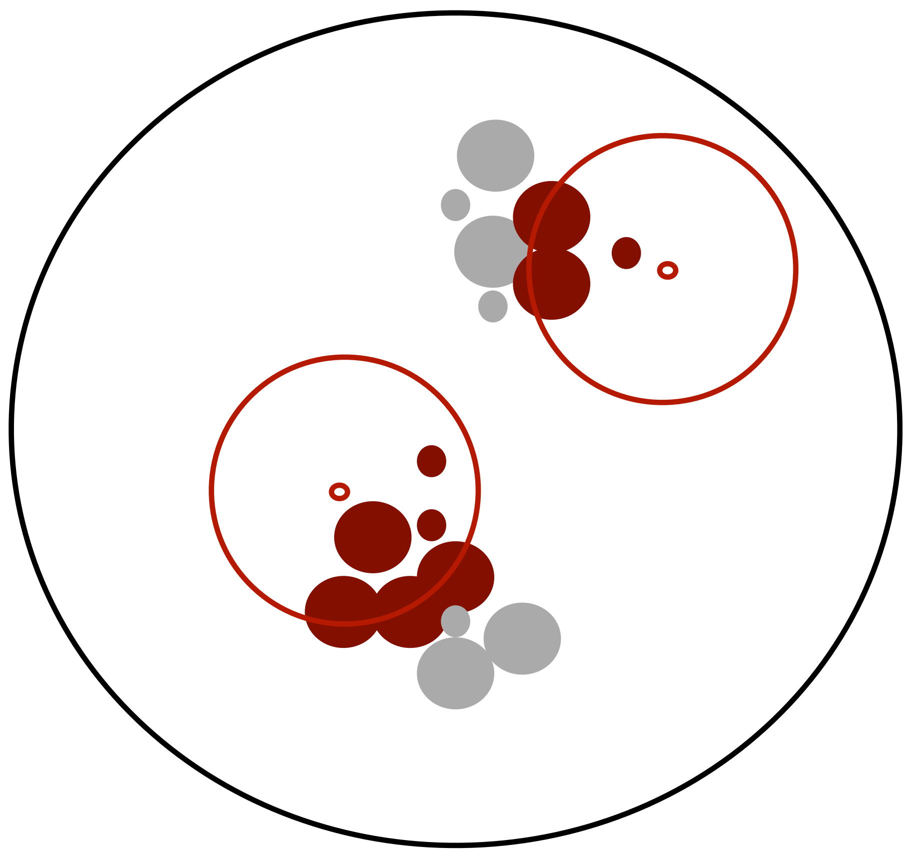
Repeat for all other template momenta and sum over the number of momenta in the template.

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

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

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!

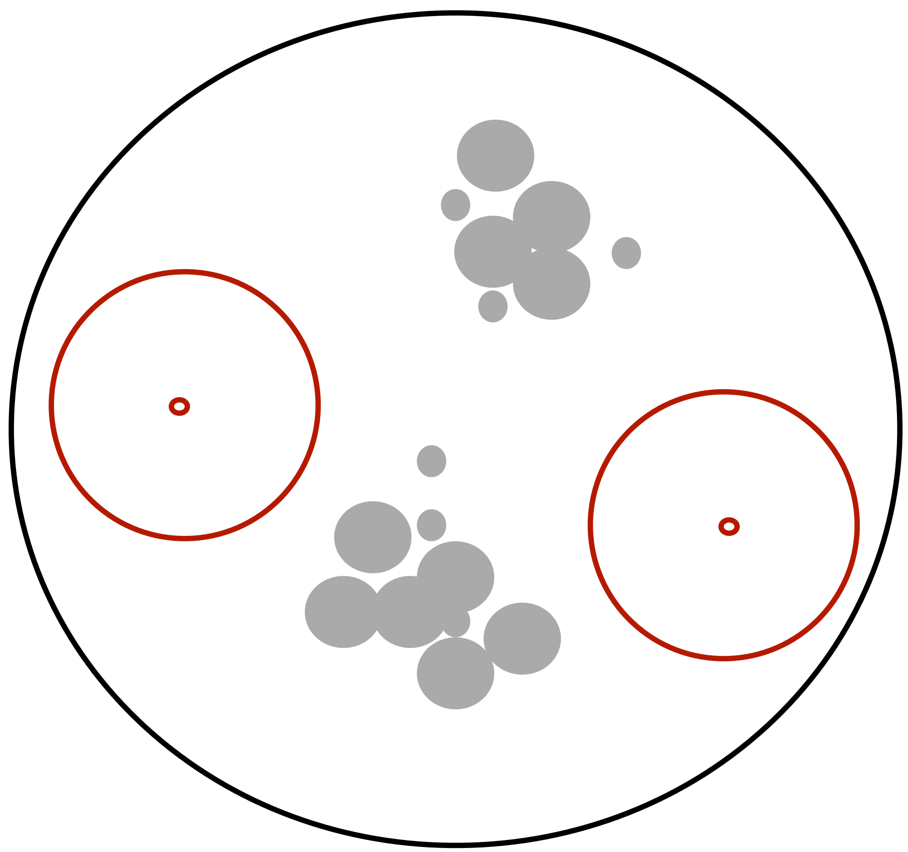
$$exp\left[-\sum_i \frac{1}{2\sigma_i^2}\left[\sum_j E_j - E_i\right]^2\right]$$

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

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.

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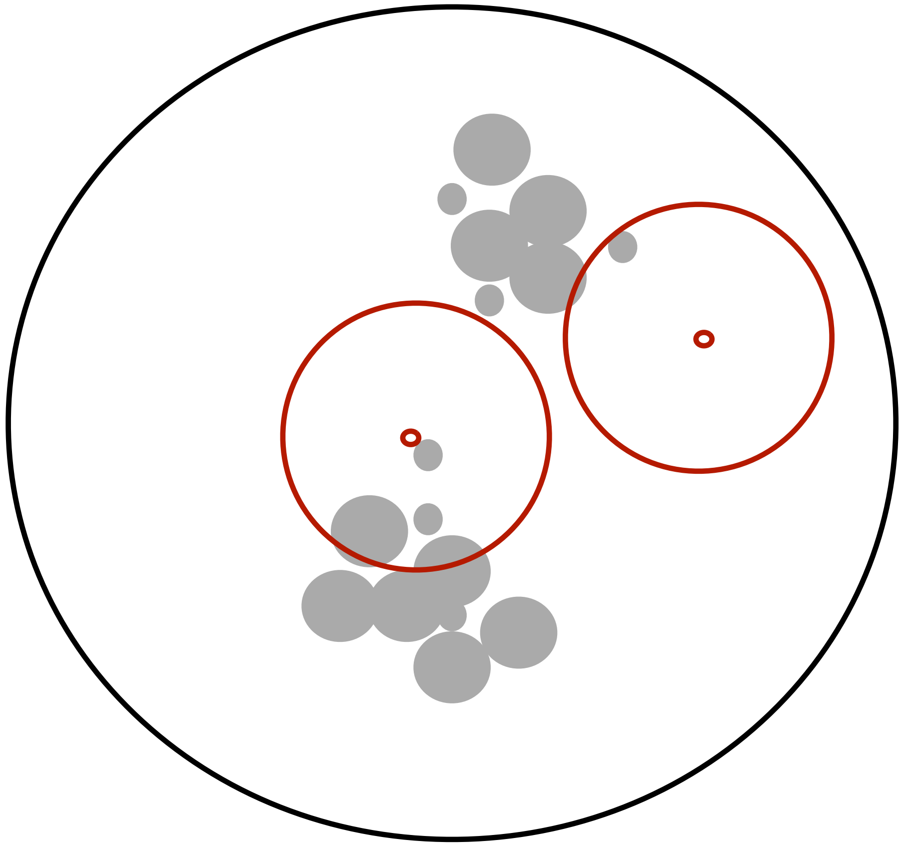


Repeat for all other template momenta and sum over the number of momenta in the template.

Exponentiate the sum!

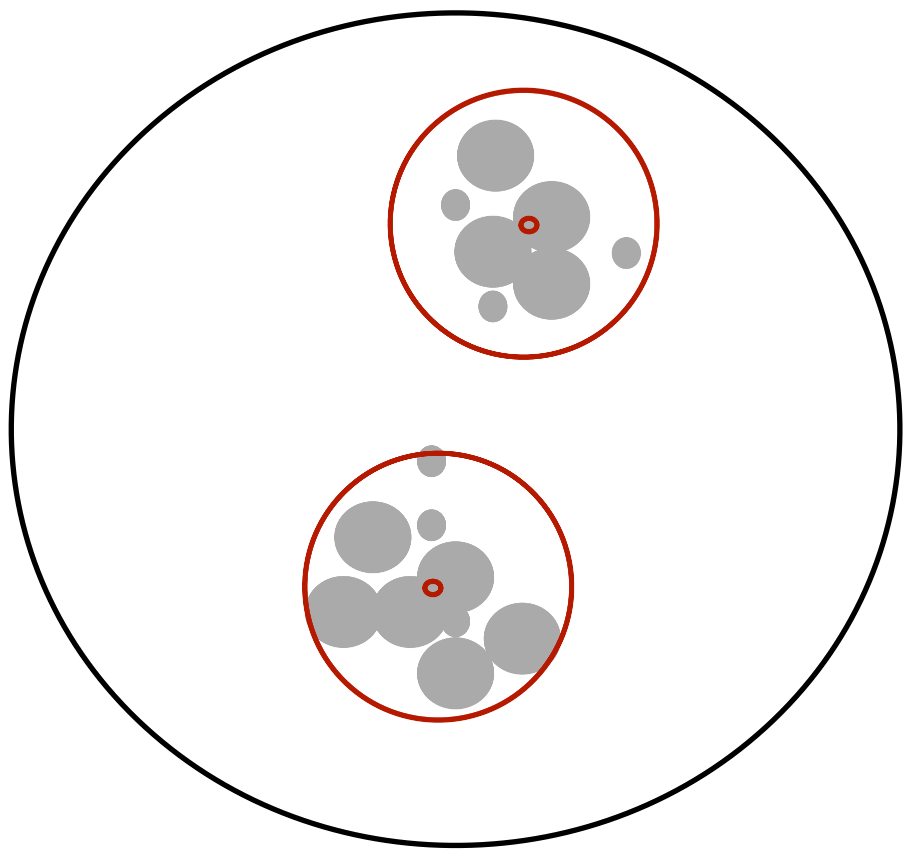
$$exp\left[-\sum_i \frac{1}{2\sigma_i^2}\left[\sum_j E_j - E_i\right]^2\right]$$

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

Choose the configuration which maximizes the exponential!

Result: Ov AND template which maximizes overlap.



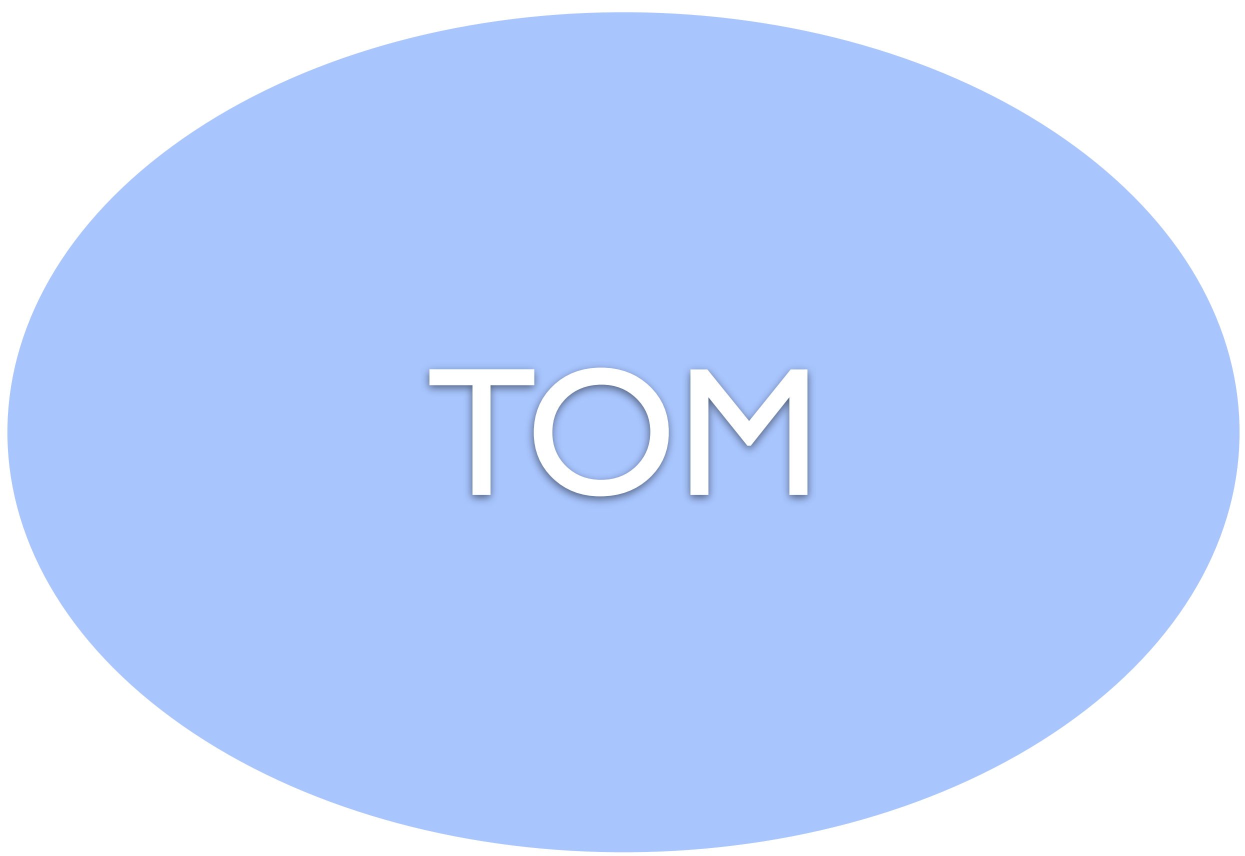
For each template, subtract the sum from the energy of the template momentum.

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

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

TOM today

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



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.

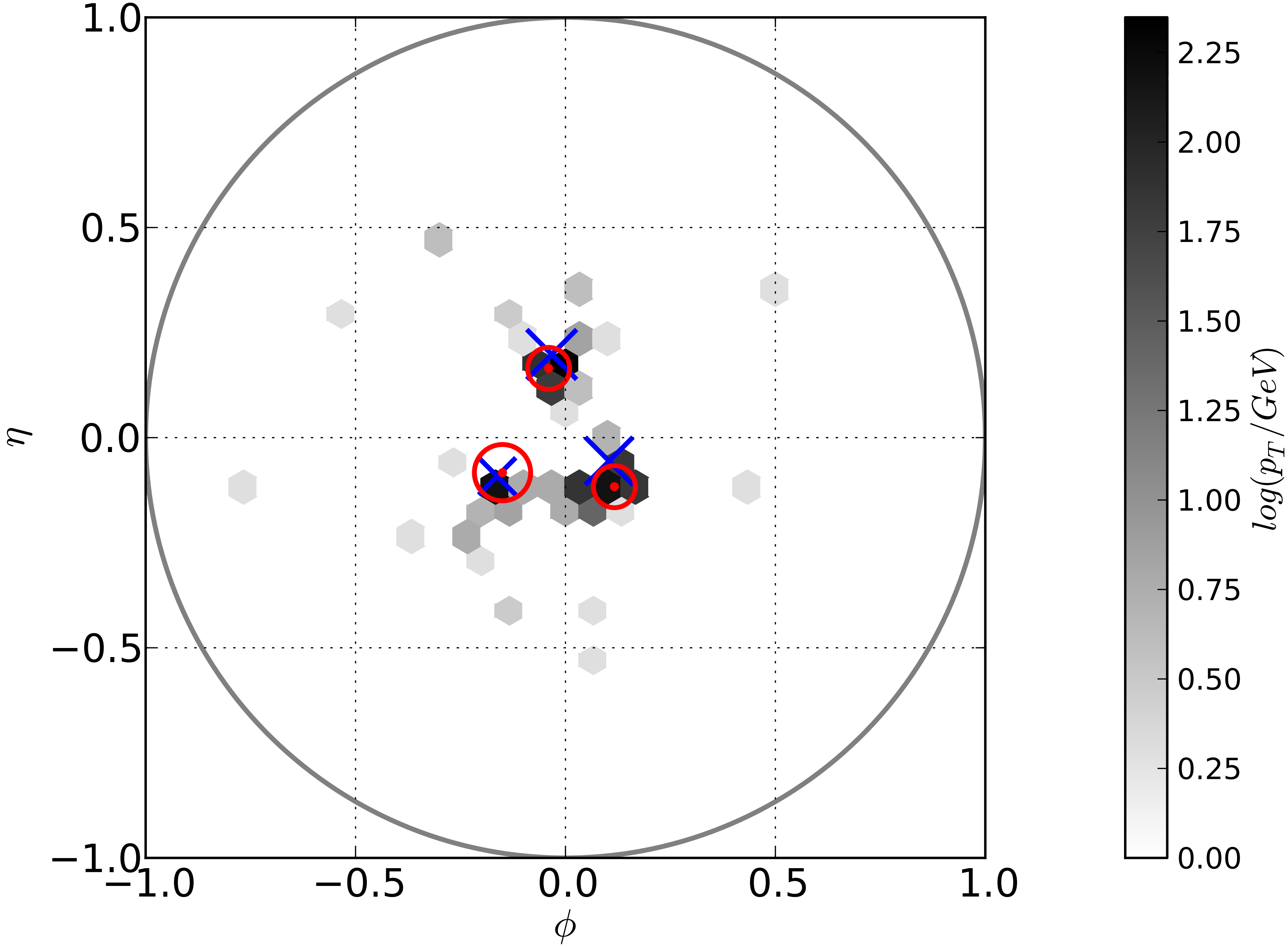
Leptonic Top Template.

Everything in red introduced in arXiv:1212.2977

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

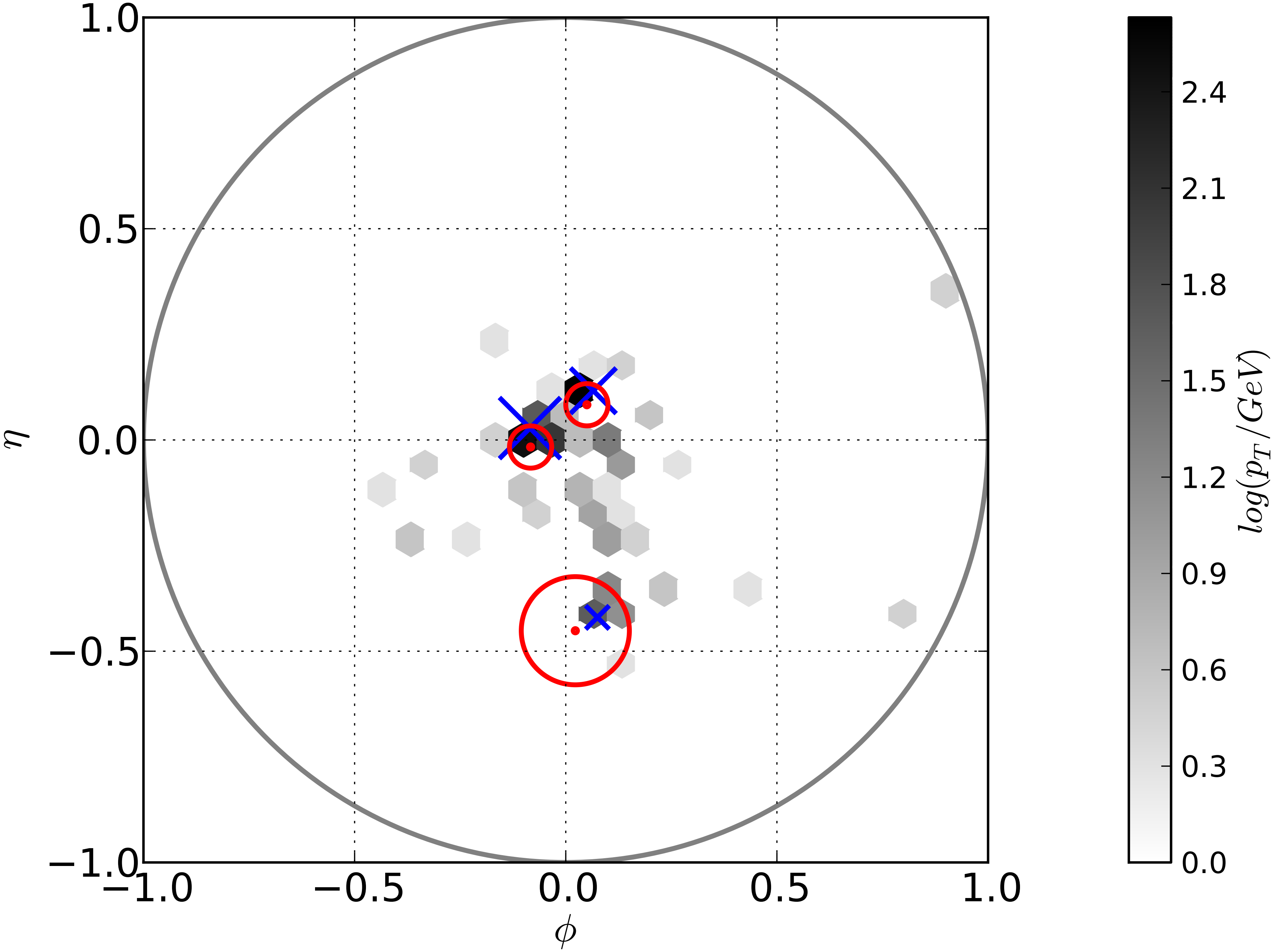
Partonic info:
$p_{T1} = 421.80\ GeV$
$p_{T2} = 385.85\ GeV$
$p_{T3} = 233.45\ GeV$

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

TOM: Example

Typical boosted top jet:

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



Overlap info:
$Ov_3 = 0.60$

Event info:
$p_T = 1104.60\ GeV$
$m = 204.65\ GeV$

Partonic info:
$p_{T1} = 627.57\ GeV$
$p_{T2} = 349.72\ GeV$
$p_{T3} = 93.56\ GeV$

Template info:
$p^t_{T1} = 598.91\ GeV$
$p^t_{T2} = 384.95\ GeV$
$p^t_{T3} = 93.25\ GeV$

מכון ויצמן למדע
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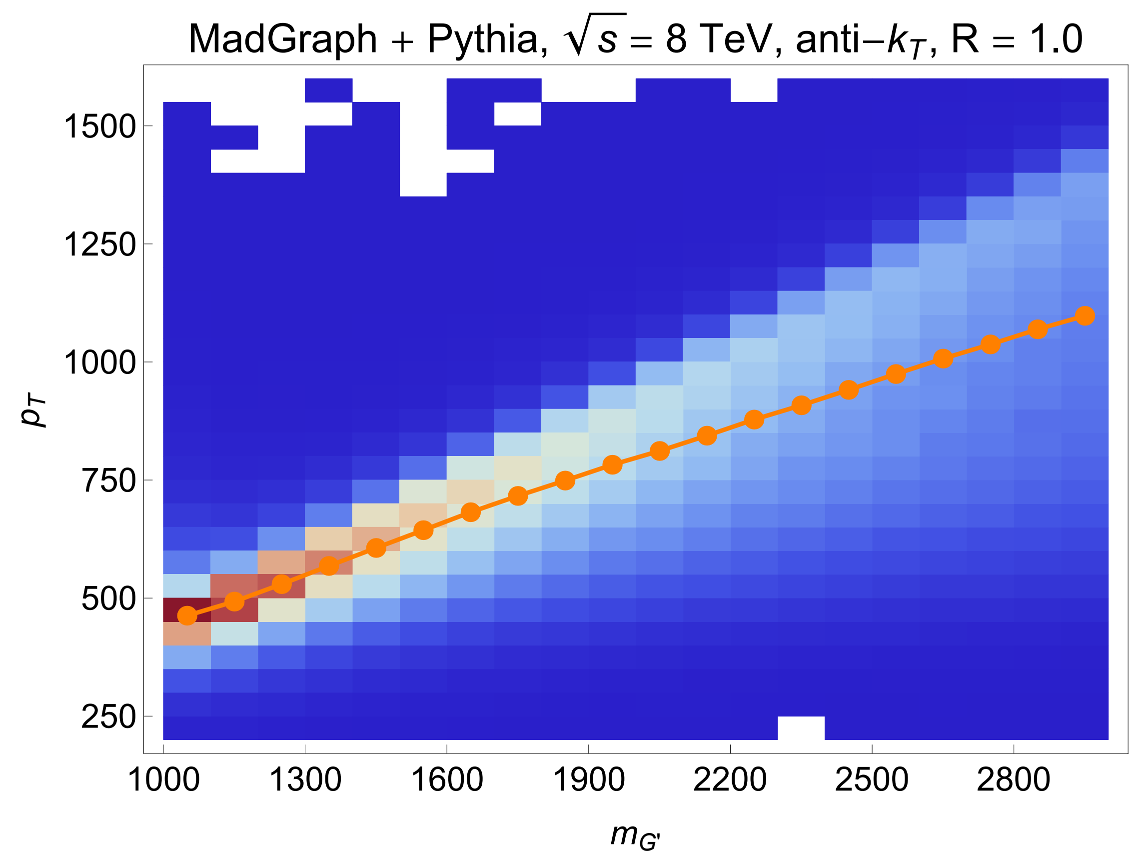
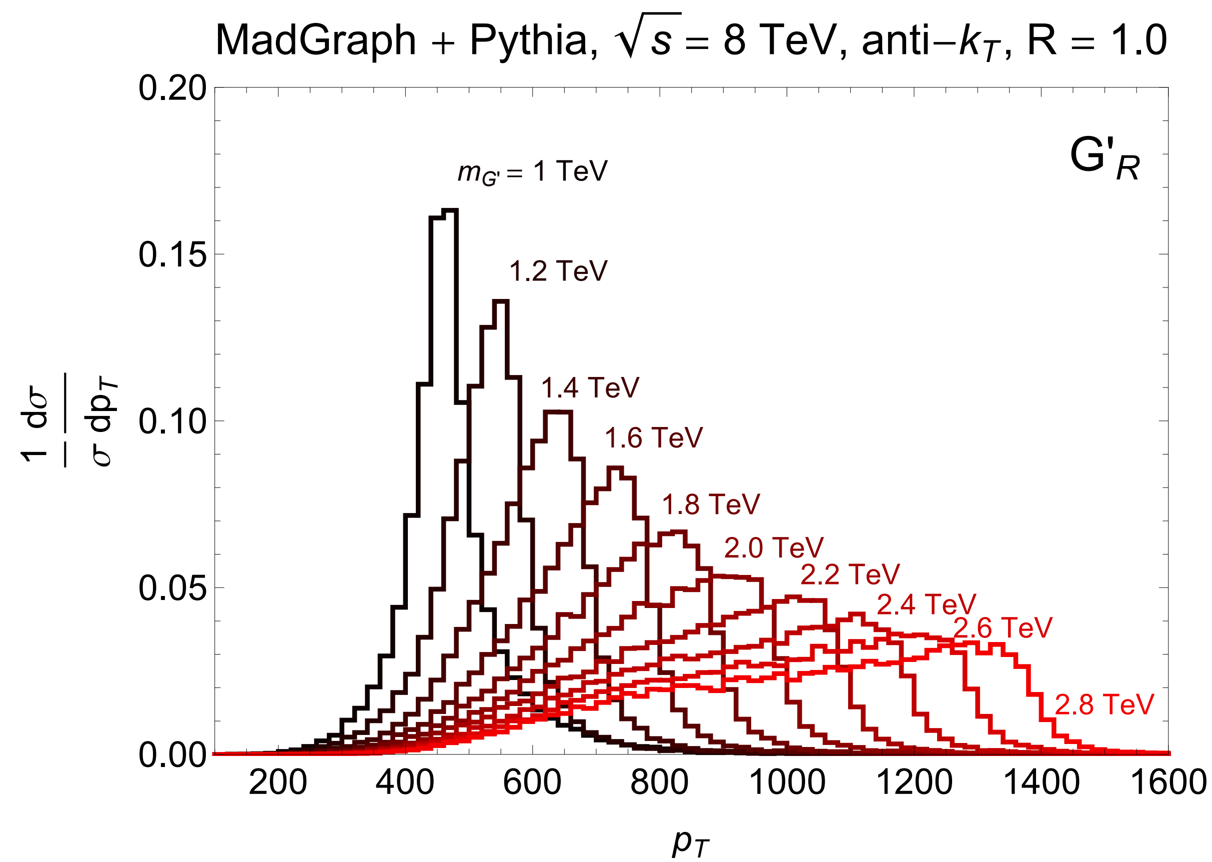
Search for tt resonances:



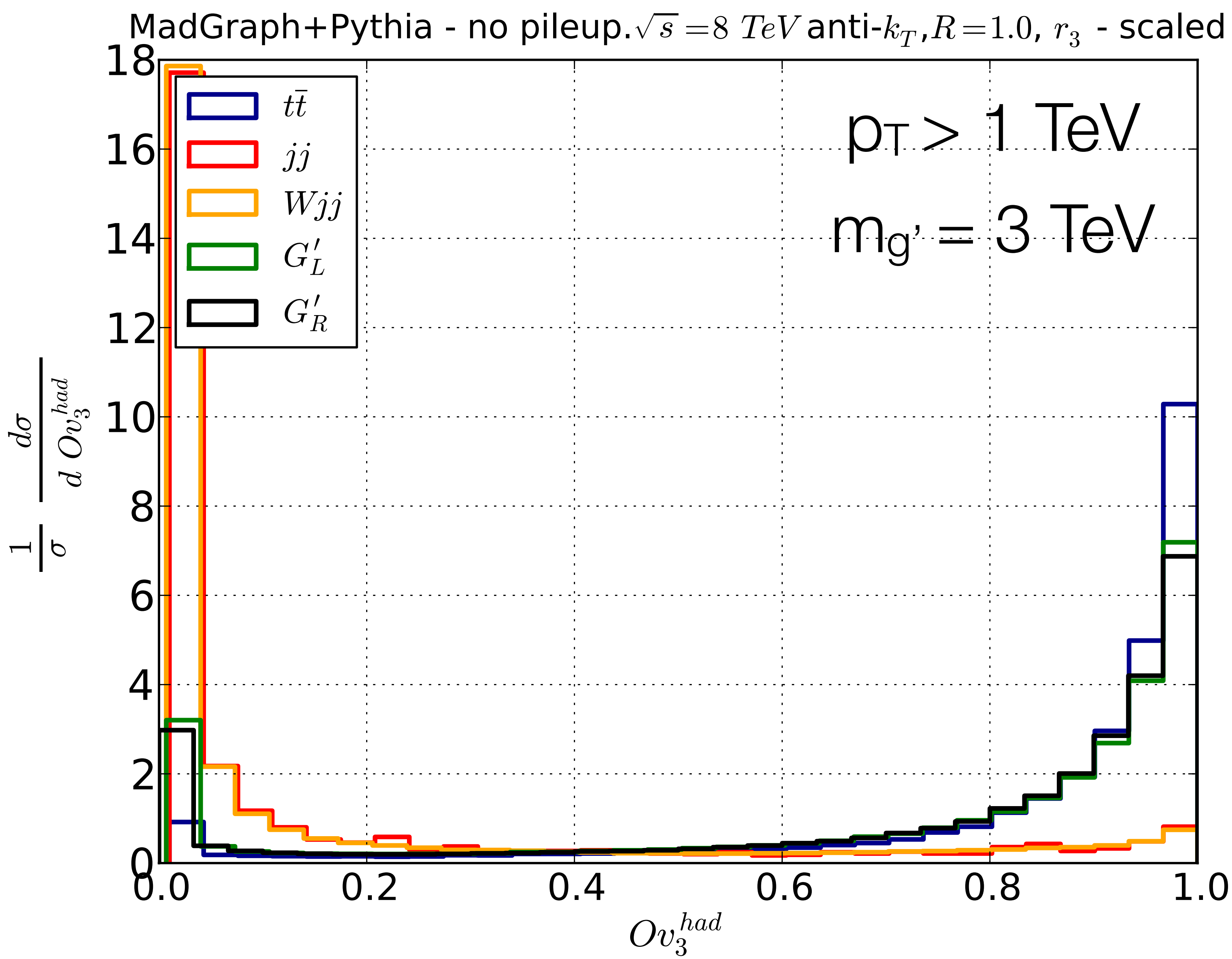


- Ultra-highly boosted jets (p_T > 1 TeV) become more important at higher masses. (e.g. about 50% of events with $m_{g'}$ = 2.8 TeV give top jets with p_T > 1 TeV).

- Most jet substructure methods ability to tag the boosted jets decreases with p_T of the boosted jet.

TOM: Example

Semi-leptonic t-tbar events (in progress):

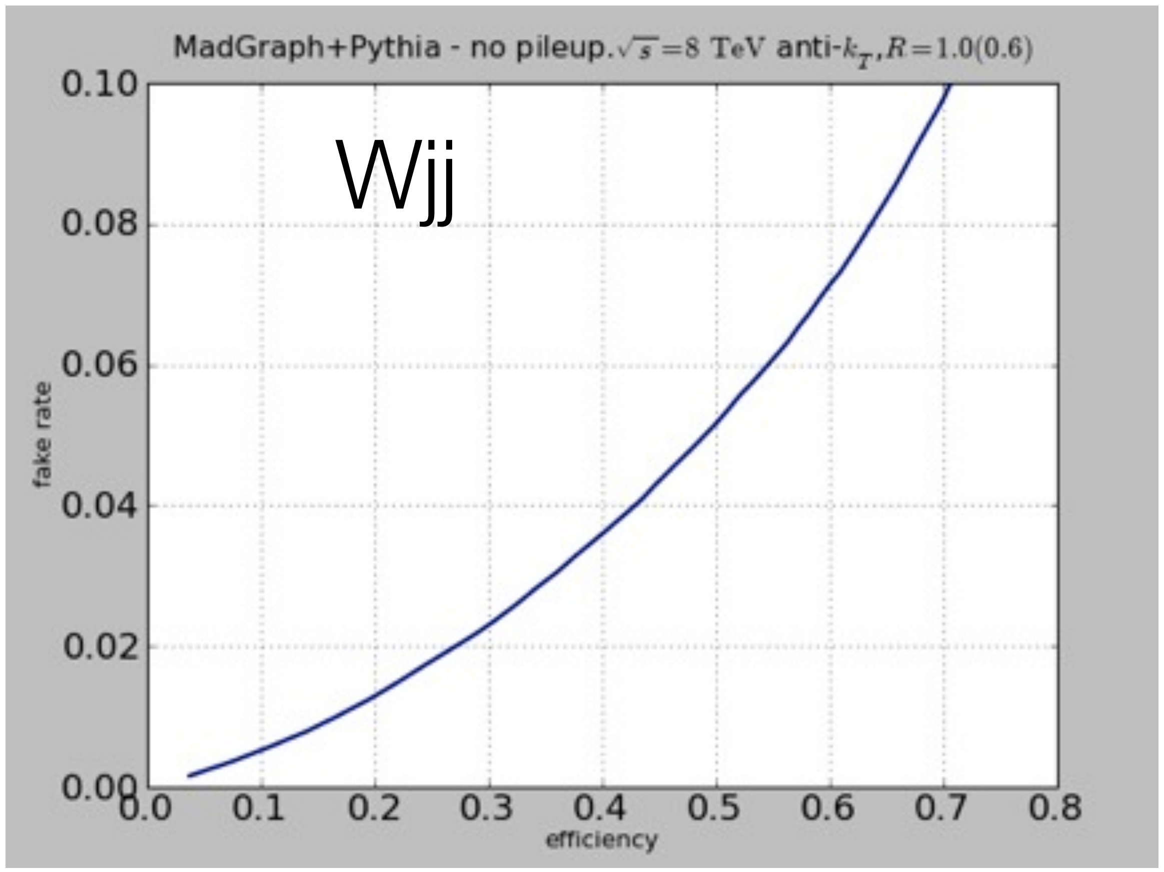


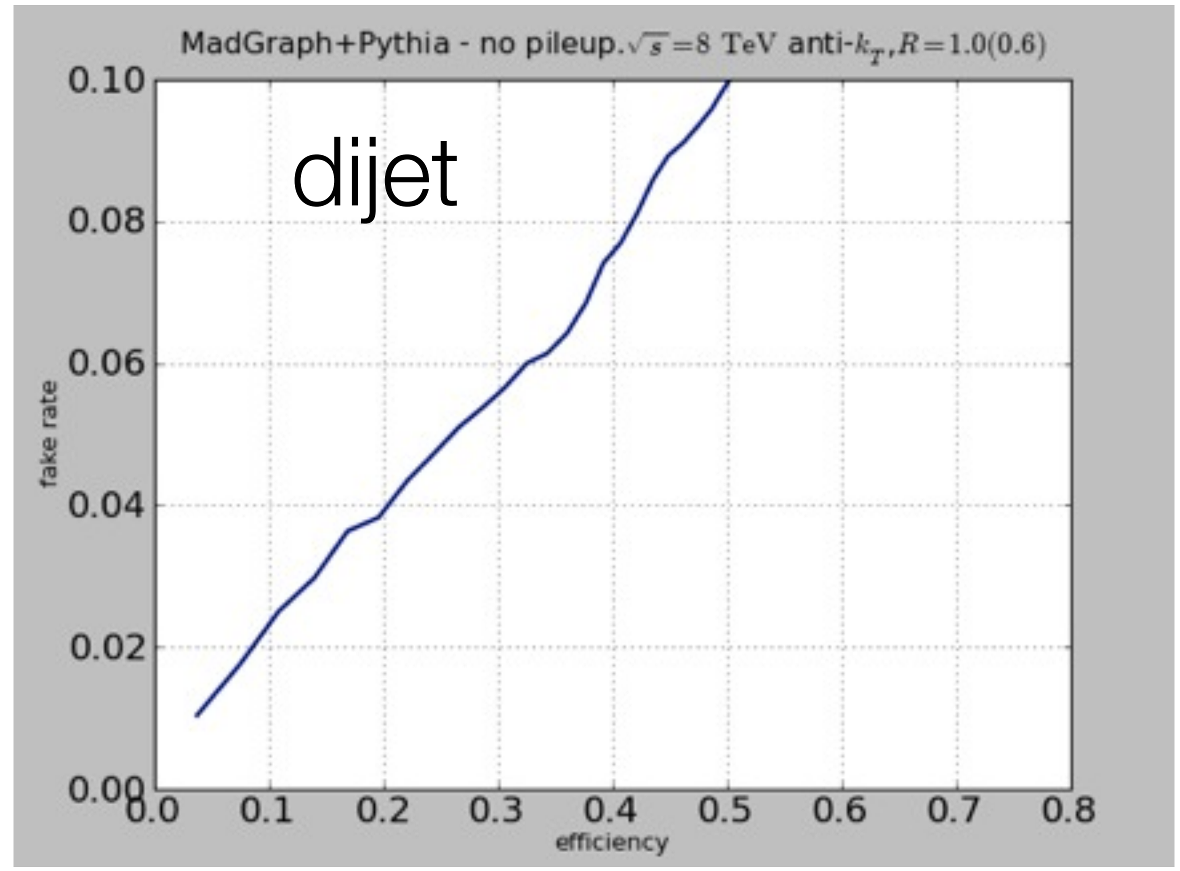
We are also developing TOM for the leptonic top decays.

Rejection rate for dijets and Wjj ($p_T > 1$ TeV):

no b-tagging
no mass cut

Cut on Ov_3 runs along the lines

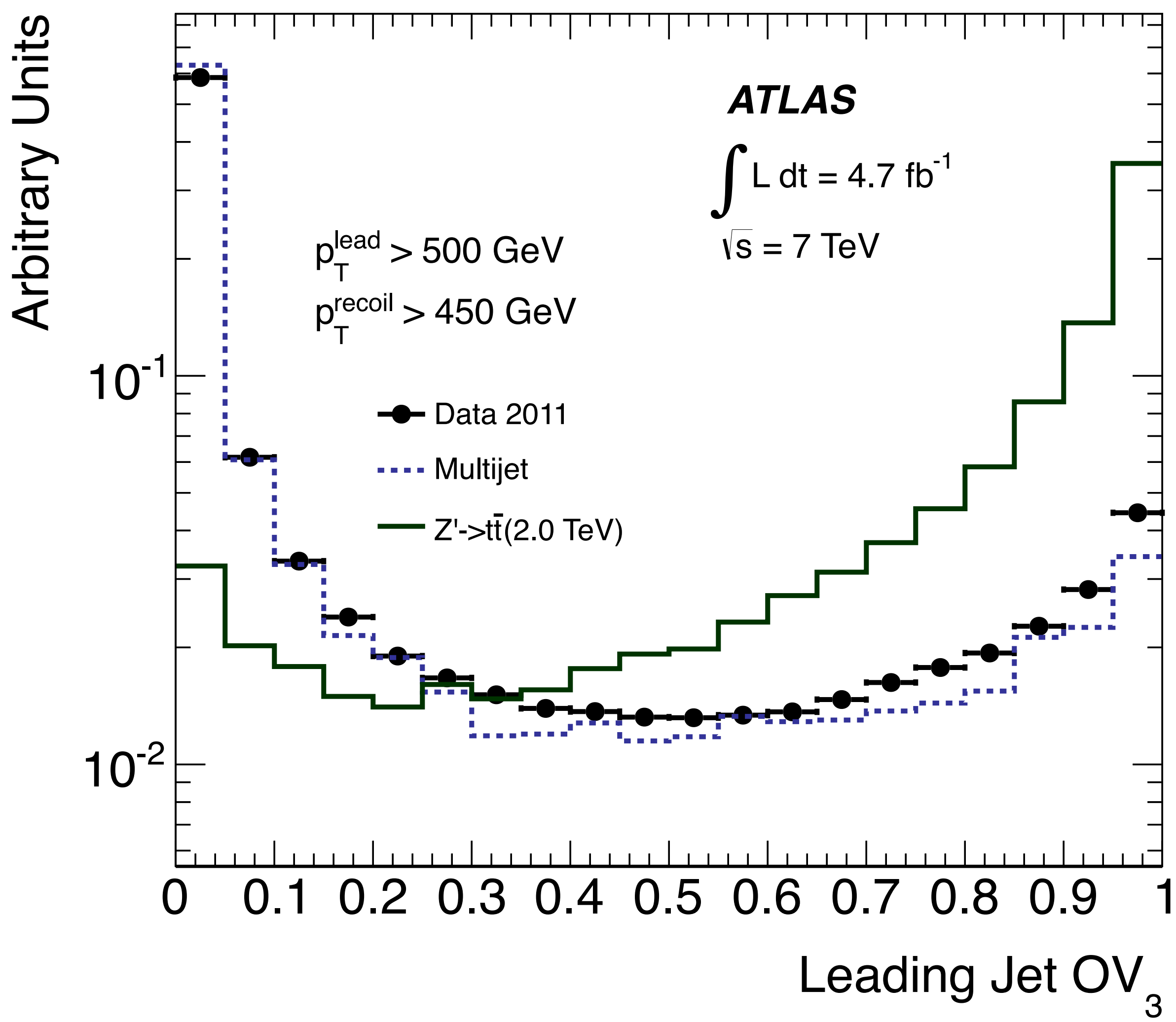


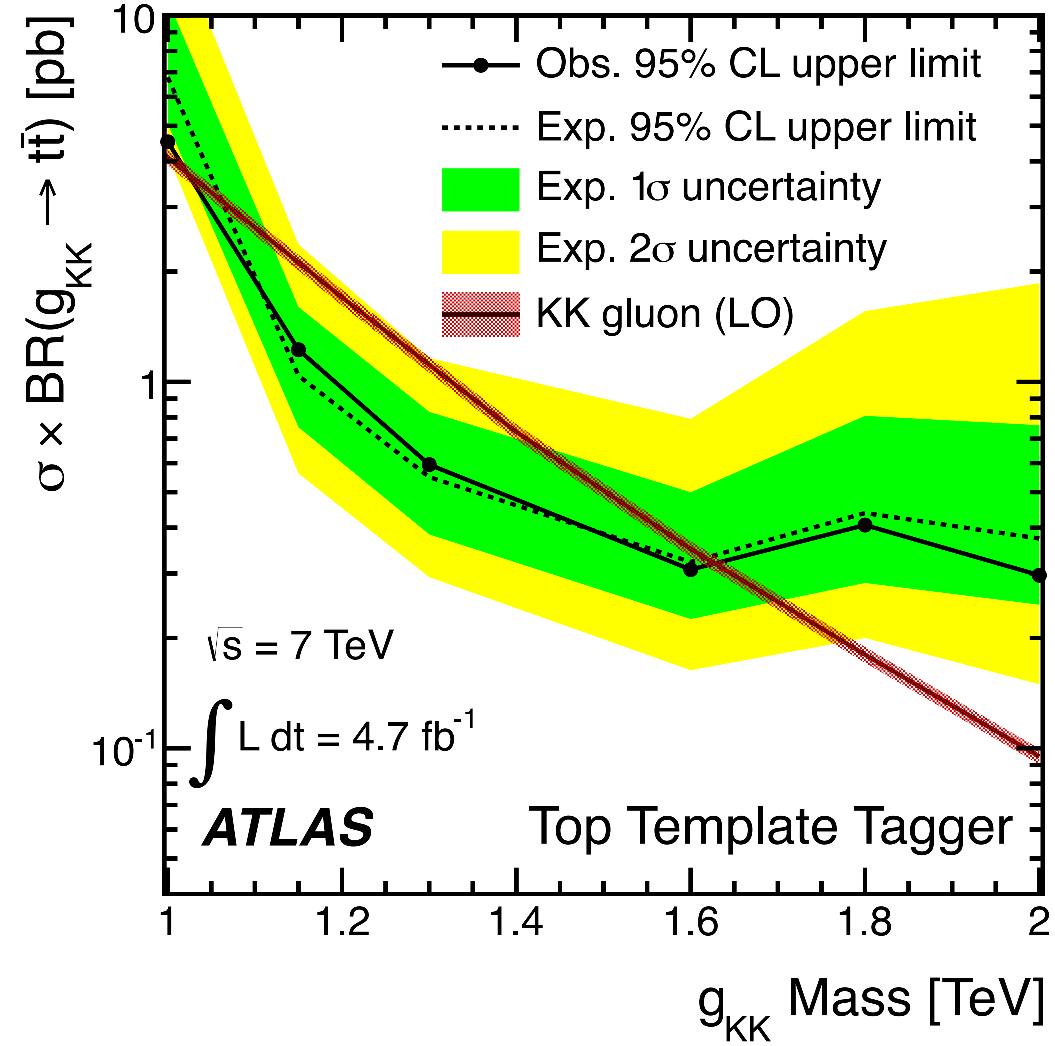


Wjj main background. Very good rejection rate (a factor of 10 for 50% efficiency).

TOM: Atlas analysis

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



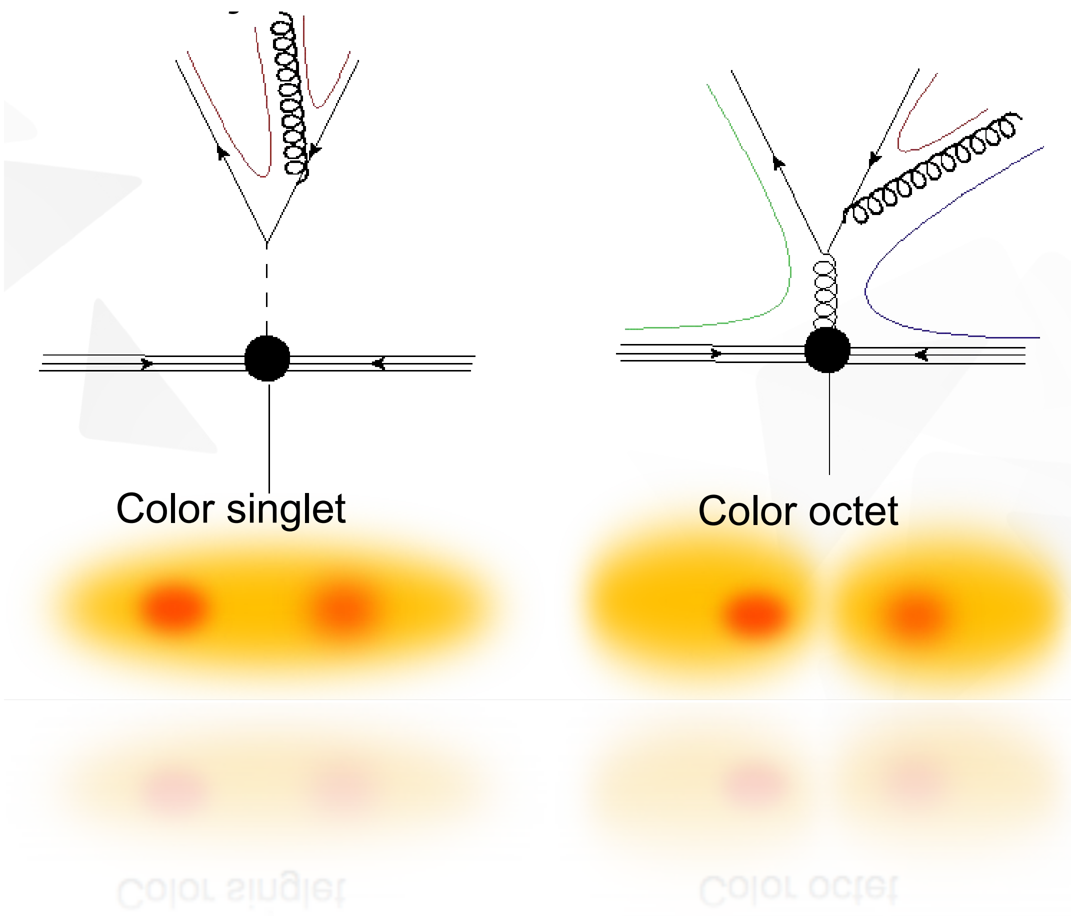


Future analyses should look even better as TOM works better at higher transverse momentum + improvements in the new code.

TOM: Example - Boosted Higgs

-Different radiation patters expected due to color connections
- e.q. gluon is a color octet -> b quarks are color connected to the beam and have different color

- Higgs is a color singlet - b quarks have the same color and are color connected

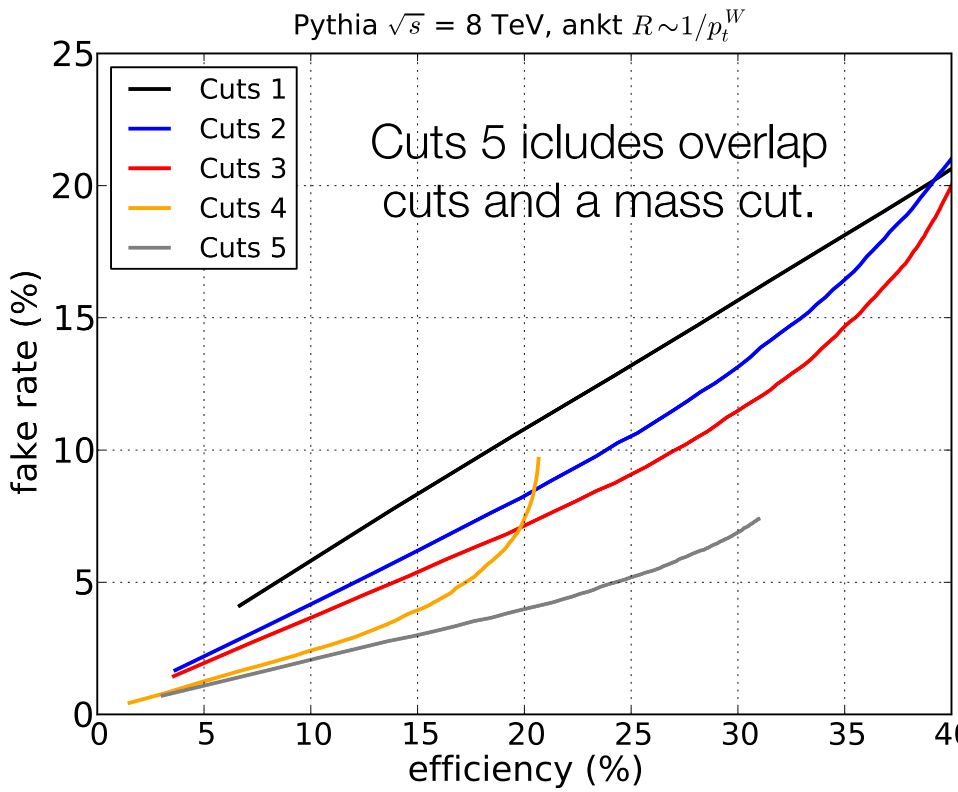


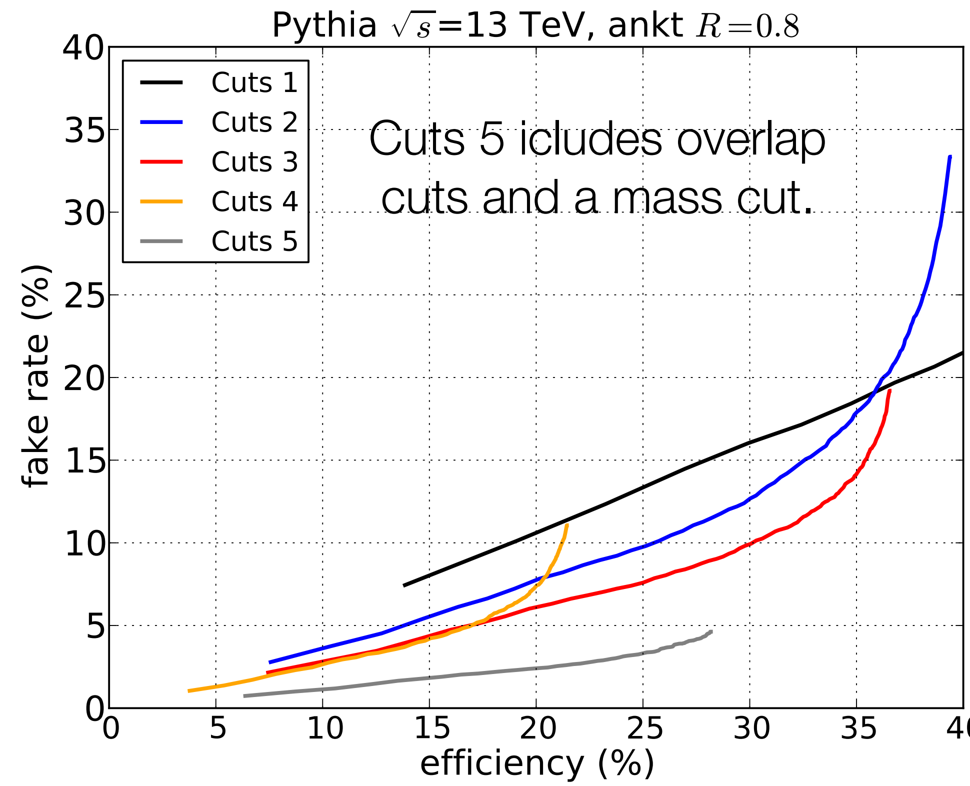
Use both 2-body and 3-body templates to characterize the Higgs.

Phys.Rev. D85 (2012) 114046

arxiv:1212:2978

Boosted Higgs Search (arXiv: 1212:2977)





Before overlap analysis, no mass cut (MCFM):

fb	$t\bar{t}$	$Wb\bar{b}$	Wh	S/B
$\sigma(\sqrt{s} = 8\ \text{TeV},\ p_T^W > 300\ \text{GeV})$	565.0	56.0	1.6	
$\sigma(\sqrt{s} = 8\ \text{TeV},\ \text{Basic Cuts})$	2.0	2.5	0.2	0.05
$\sigma(\sqrt{s} = 13\ \text{TeV},\ p_T^W > 350\ \text{GeV})$	956.0	47.0	1.2	
$\sigma(\sqrt{s} = 13\ \text{TeV},\ \text{Basic Cuts})$	3.0	1.7	0.3	0.06

Tiny signal

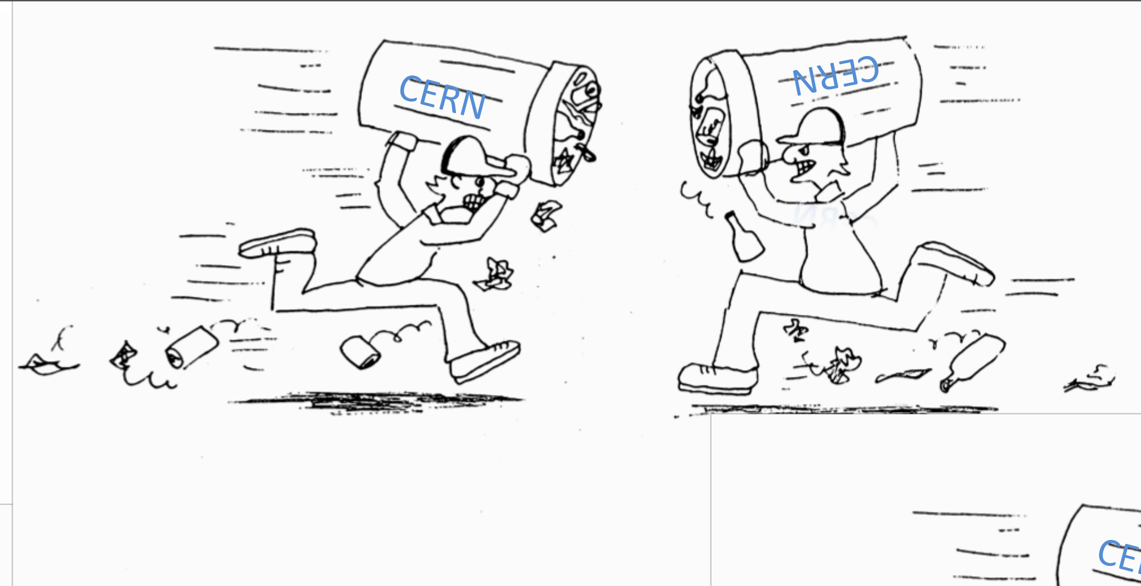
$$\text{RP} \equiv \frac{\epsilon_s}{\epsilon_f} \qquad \epsilon_s \equiv \frac{\sigma_{Wh}^{cuts}}{\sigma_{Wh}^{BC}}$$

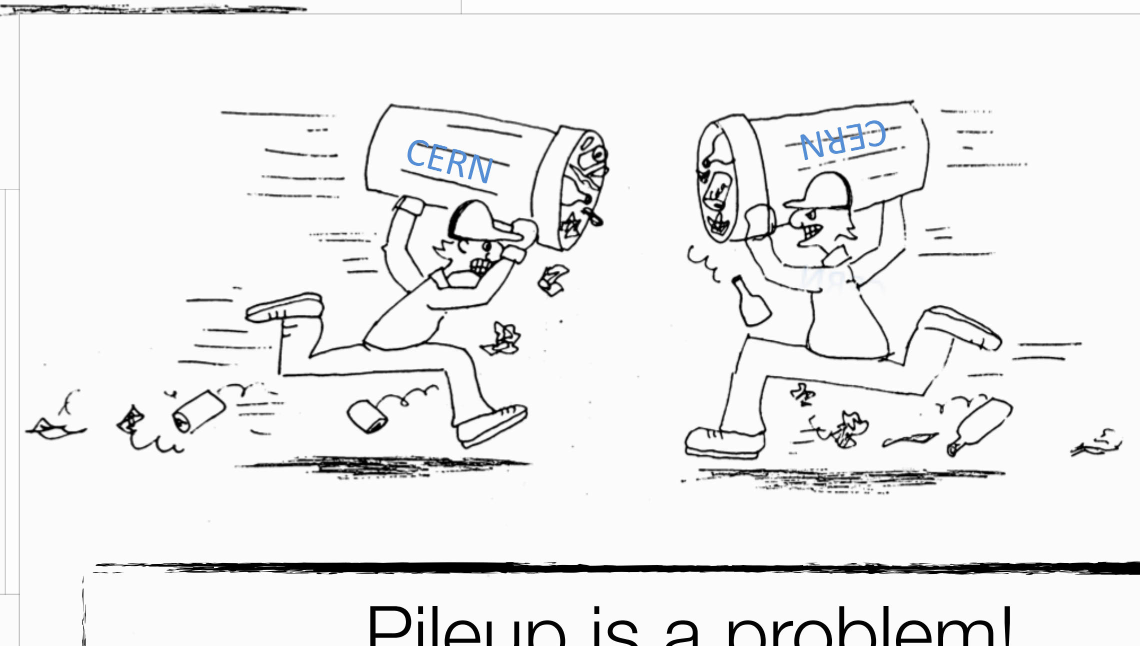
All RPs relative to the Basic Selection Cuts including a double b-tag.

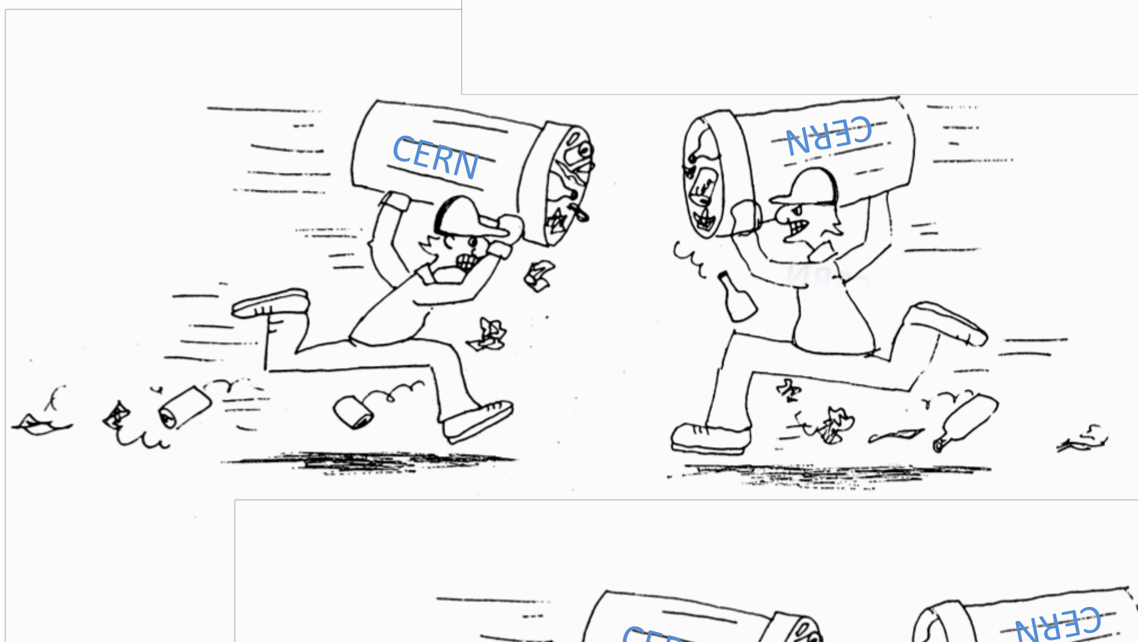
Good rejection power at 13 TeV, but signal efficiency too low.

Need about 250 fb^{-1} of data to see a 3 sigma signal.

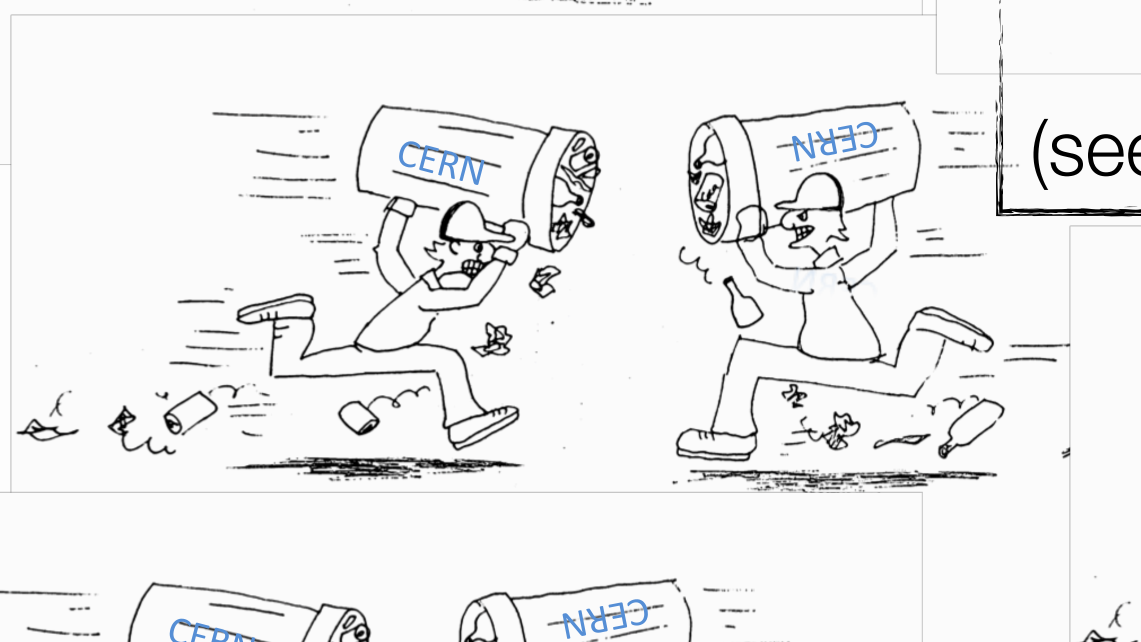
Mihailo Backovic, MC4BSM 2013

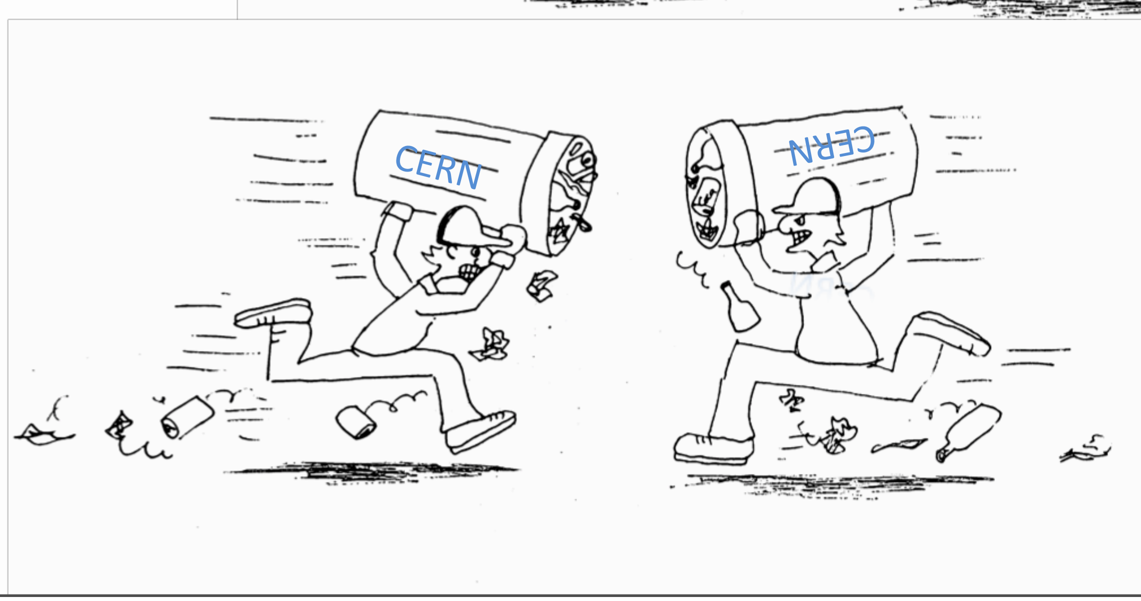


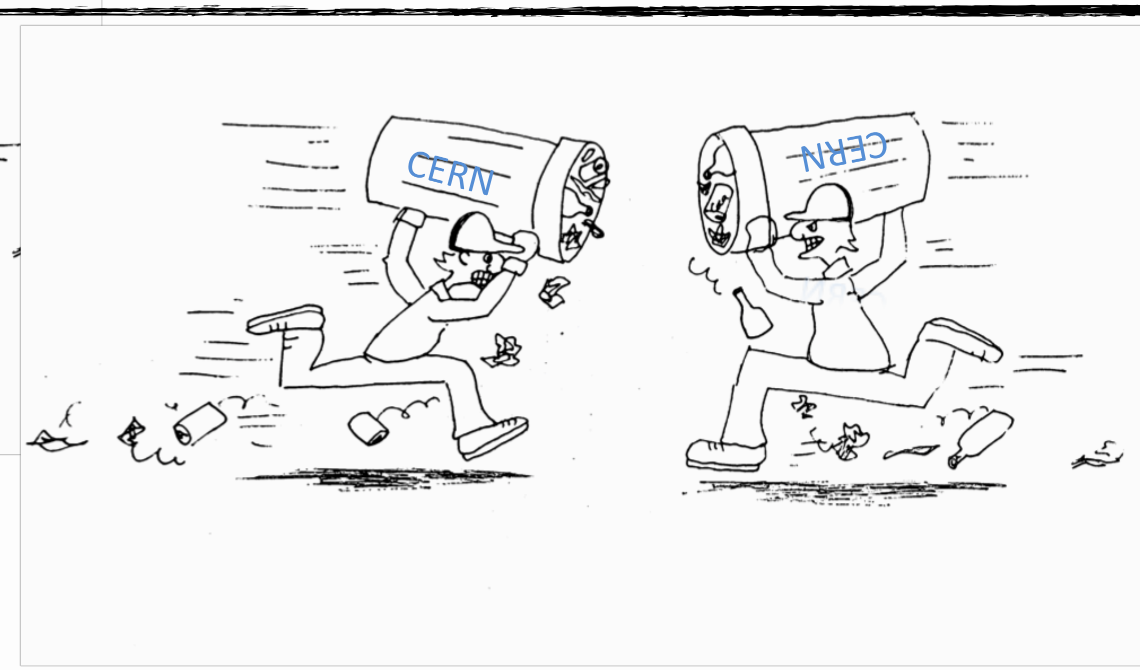




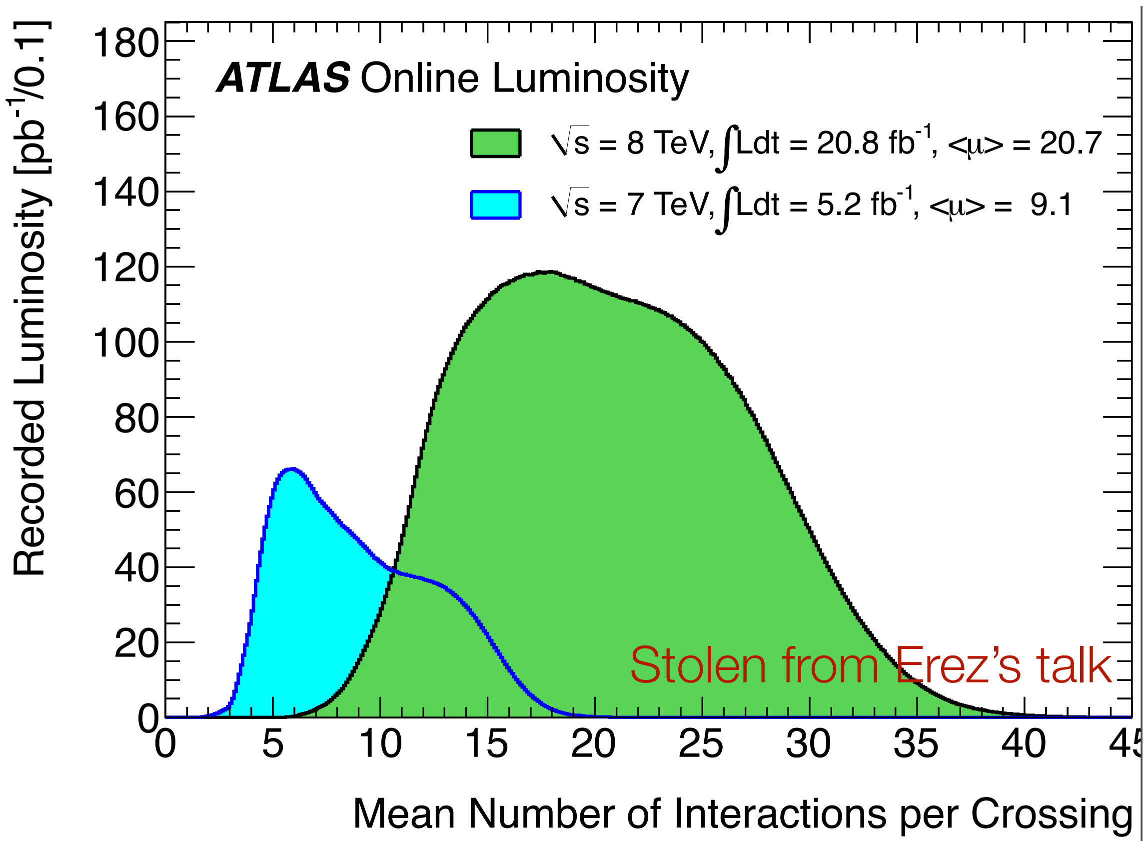
Pileup is a problem!
(see also talks by Erez and Matteo)

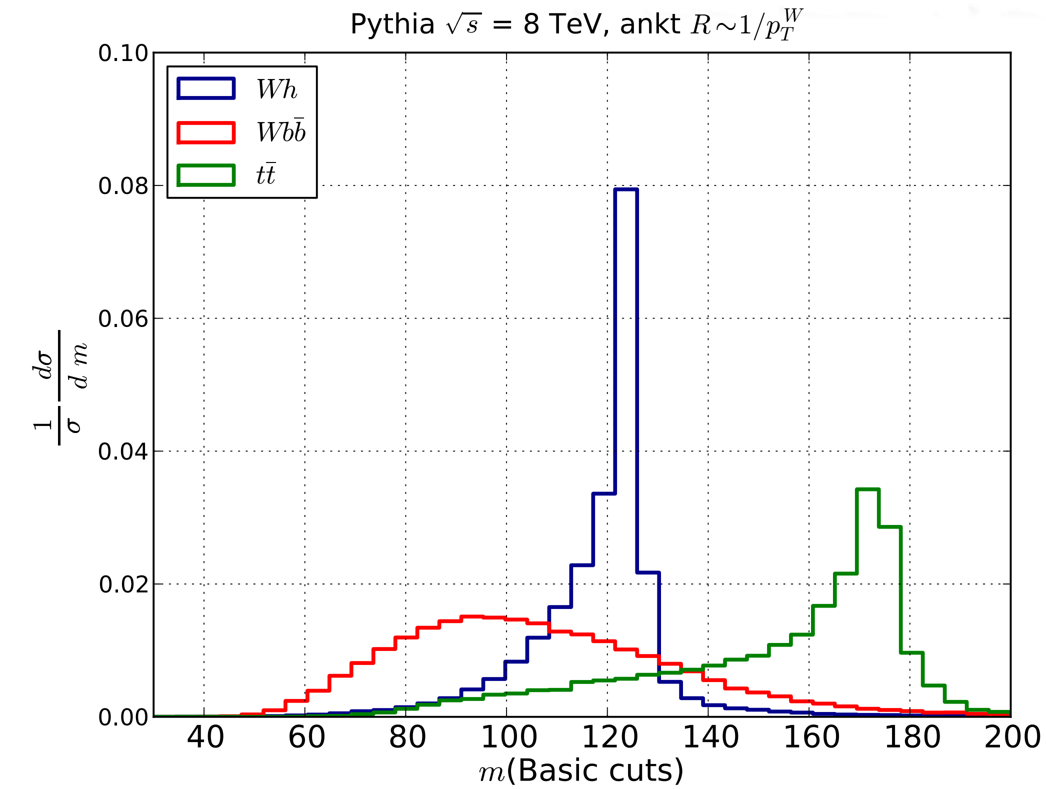


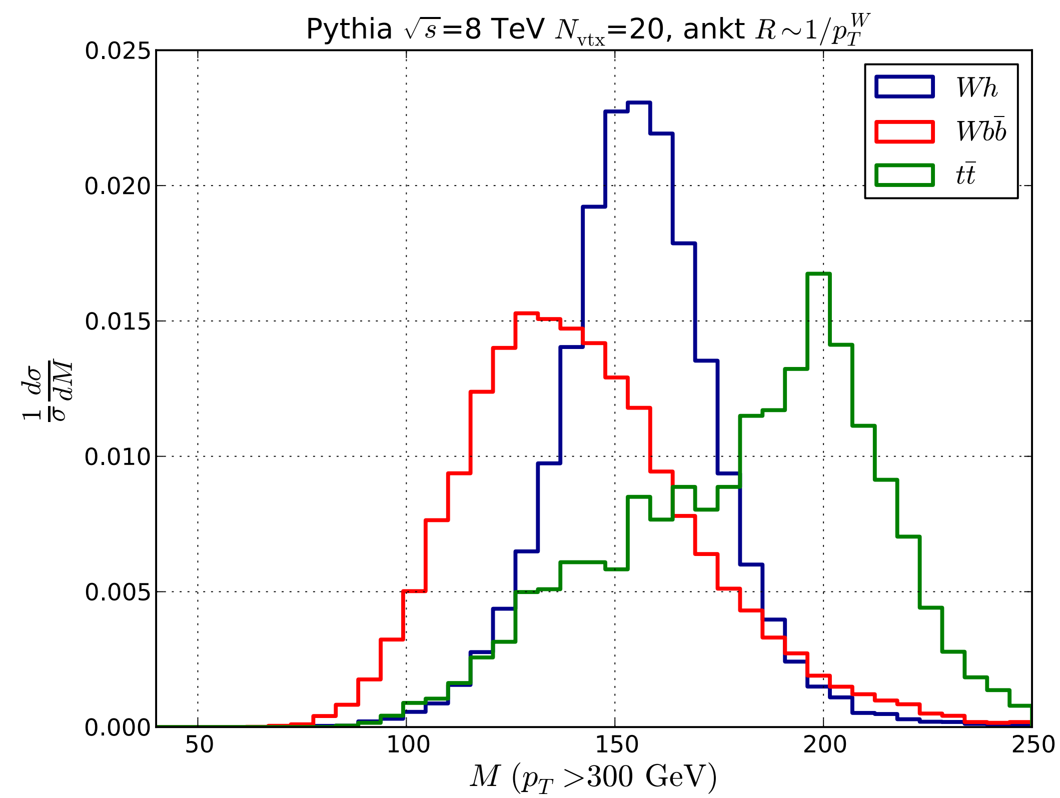




Effects of pileup







kinematic distributions not only shifted but become wider as well.

TOM & Pileup

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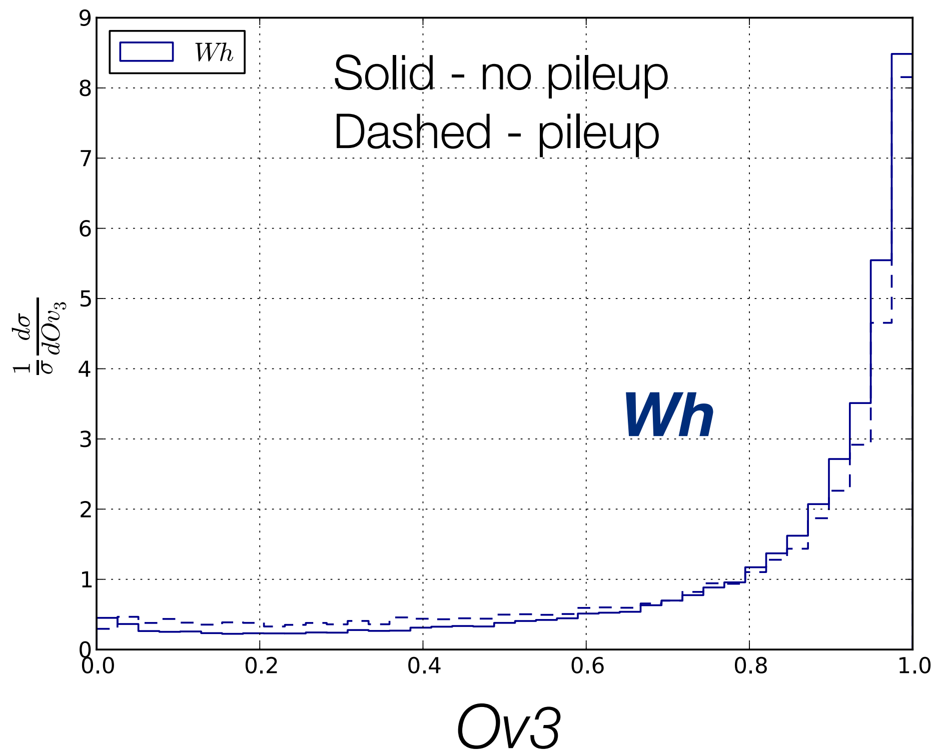
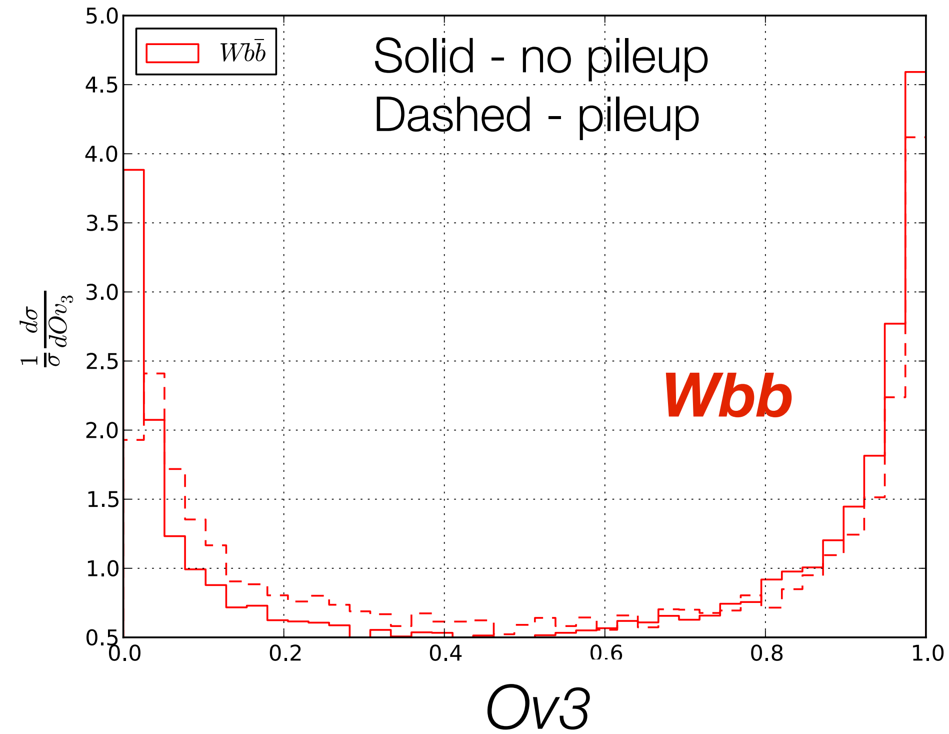
TOM is very weakly sensitive to pileup even in a high pileup environment characteristic of the LHC 8 TeV run!

- Example: 8 TeV boosted Higgs analysis with **$\langle N_{vtx} \rangle = 20$!**





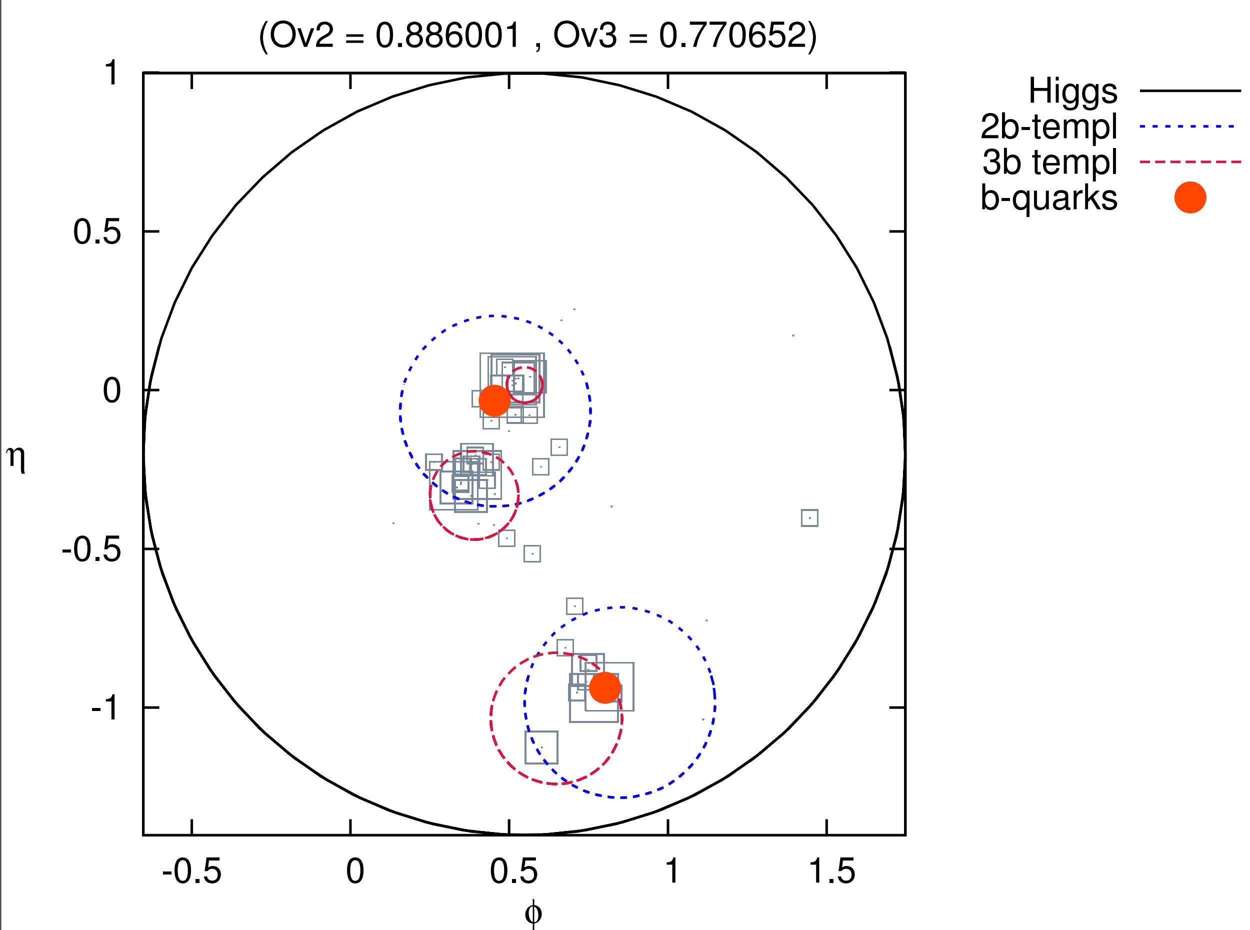
For fat jets: $\delta p_T^{pileup} \sim R^2$

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

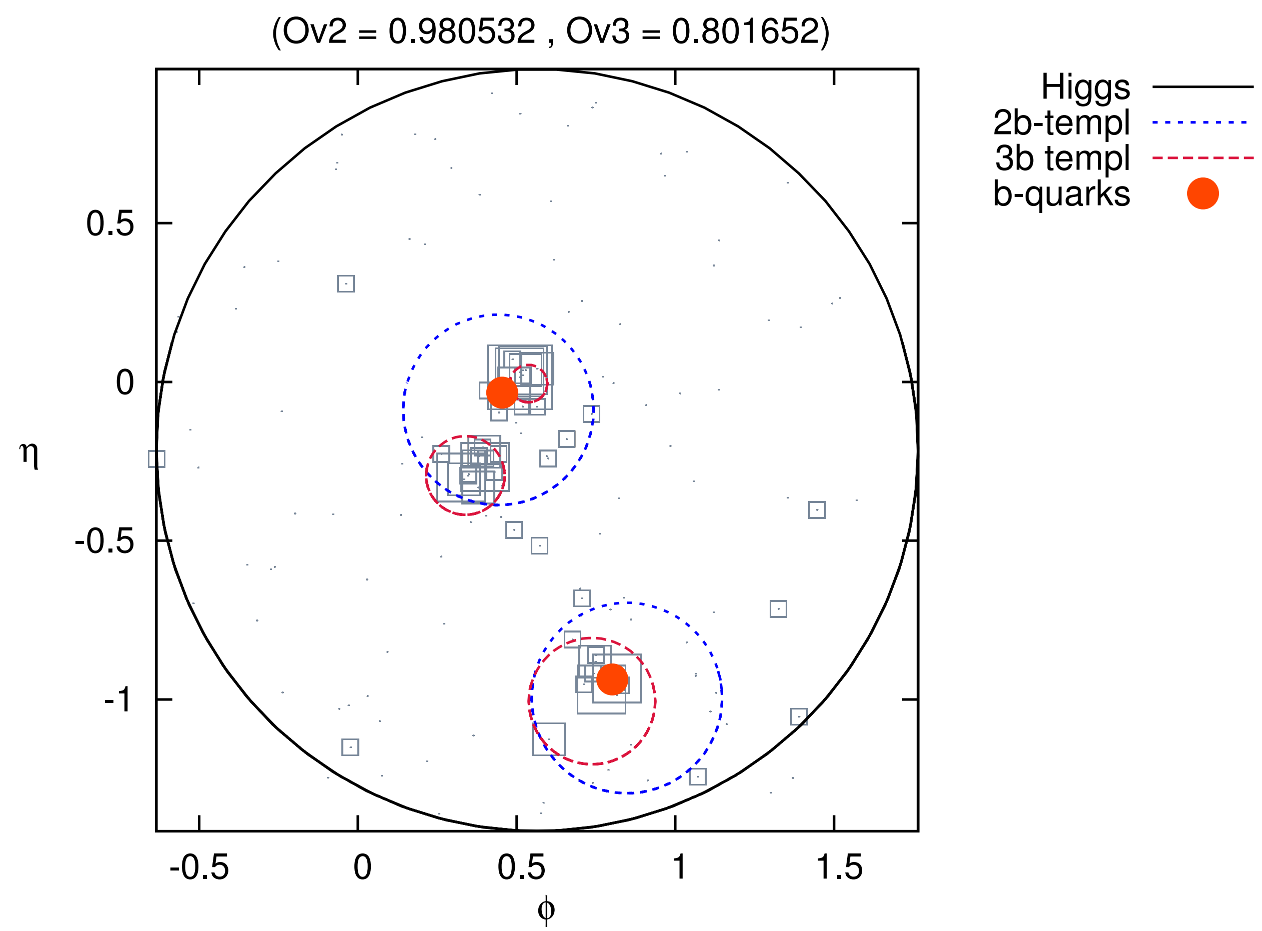
Pileup contribution to a template relative to the fat jet

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

Example boosted Higgs event:



No pileup



Pileup ($\langle N_{vtx} \rangle = 20$)

Template Tagger Code

- C++ implementation of TOM

- Open source, can be downloaded from http://tom.hepforge.org/

- Basic Structure:

  matching.hh: Contains the code which performs TOM.

  TemplateBuilder.hh: Code for template generation.

  TemplateTagger.hh: Fastjet plugin.

- The code is user friendly, examples included in the tar-ball.

- Manual on the arXiv: 1212.2978