Template Overlap for Boosted Tops

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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, Soreq, Perez (in preparation)

- Publically available code:
  - ***Template Tagger v1.0.0*** - Backovic, Juknevich (arxiv:1212:2978) available online at tom.hepforge.org

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

Template Overlap Method (TOM)

See backup slides for more detail!

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

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

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):

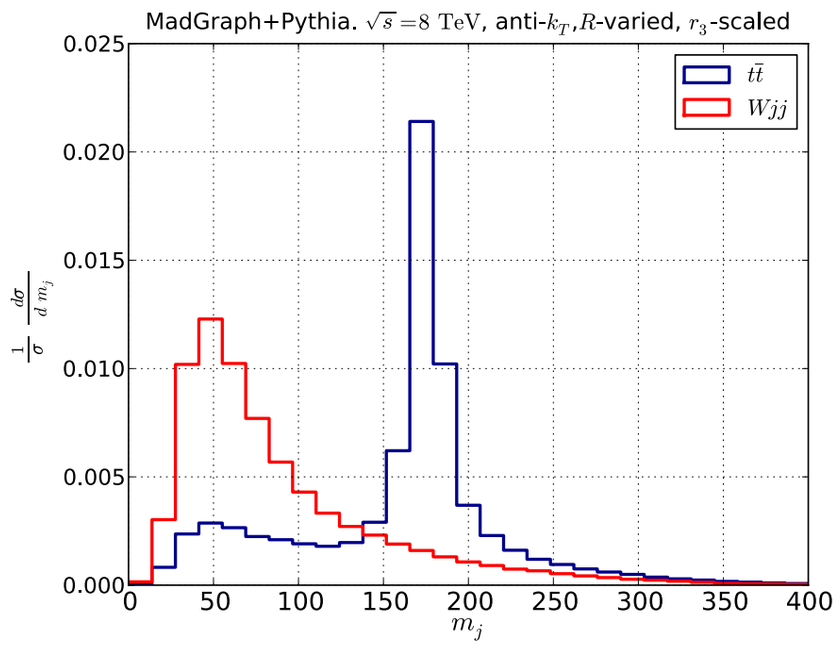
$$Ov^{(F)}(j,f) = \max_{\tau_n^{(R)}} \exp\left[-\frac{1}{2\sigma_E^2}\left(\int d\Omega \left[\frac{dE(j)}{d\Omega} - \frac{dE(f)}{d\Omega}\right] F(\Omega, f)\right)^2\right]$$

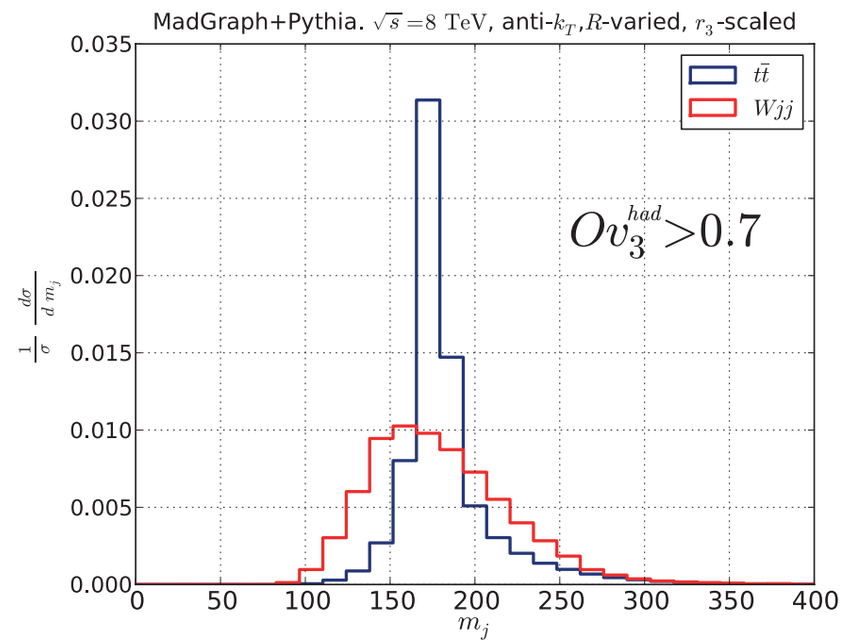
It is possible to construct other template based observables out of the peak templates! (e.g. Template Planar Flow)

Also possible to define overlap on leptonic decays of the top!

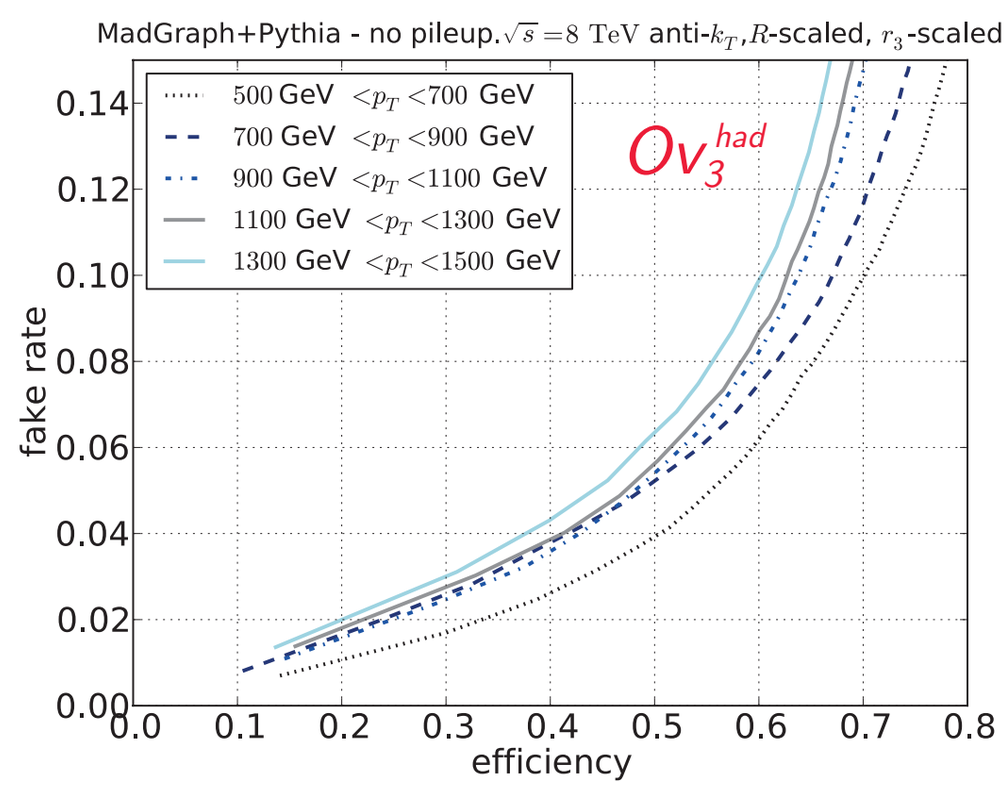
Properties of TOM

1. Intrinsic mass cut





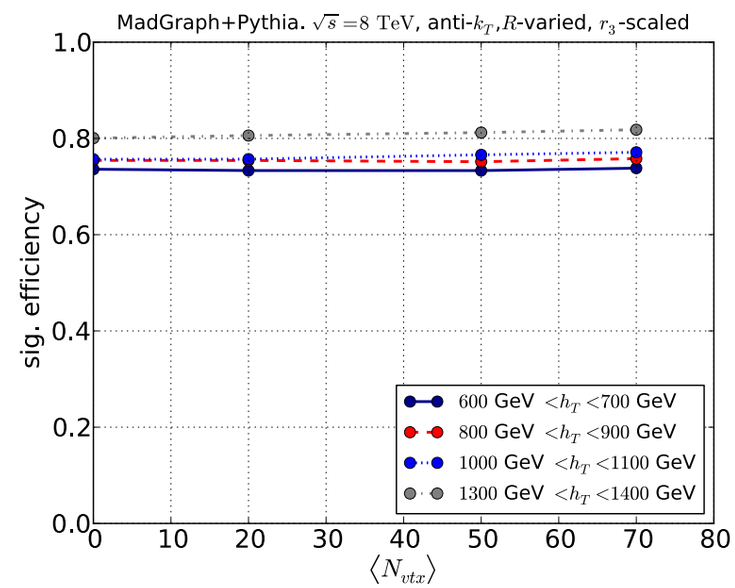
2. Good rej. pow. against Wjj at high signal efficiency (~0.6 signal efficiency)

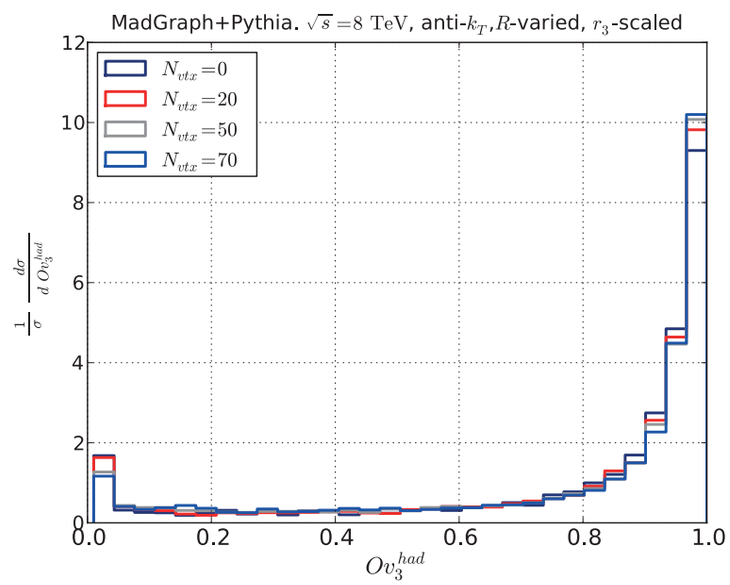


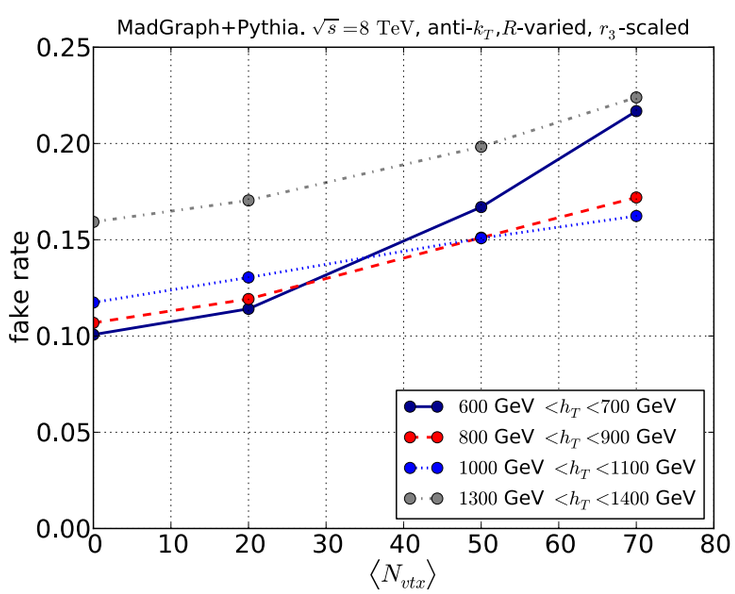
Properties of TOM

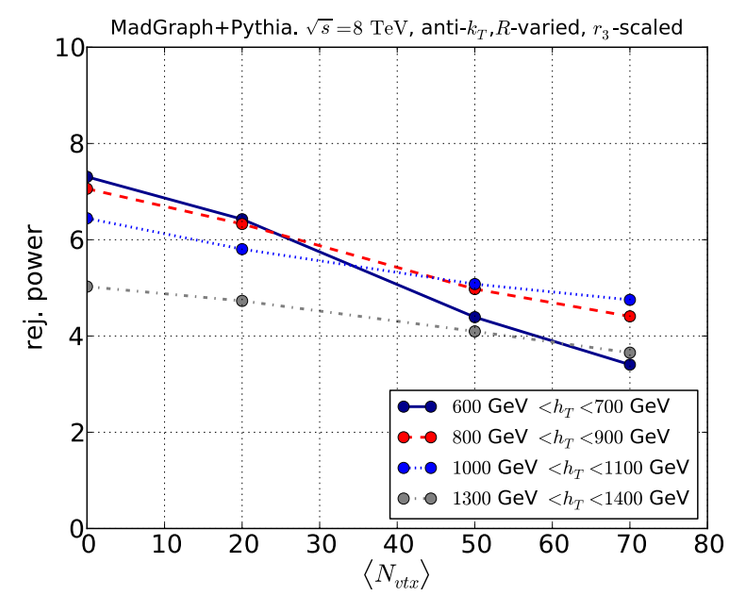
3. Weak sensitivity to pileup (up to 50 interactions per bunch crossing)

Ov > 0.6









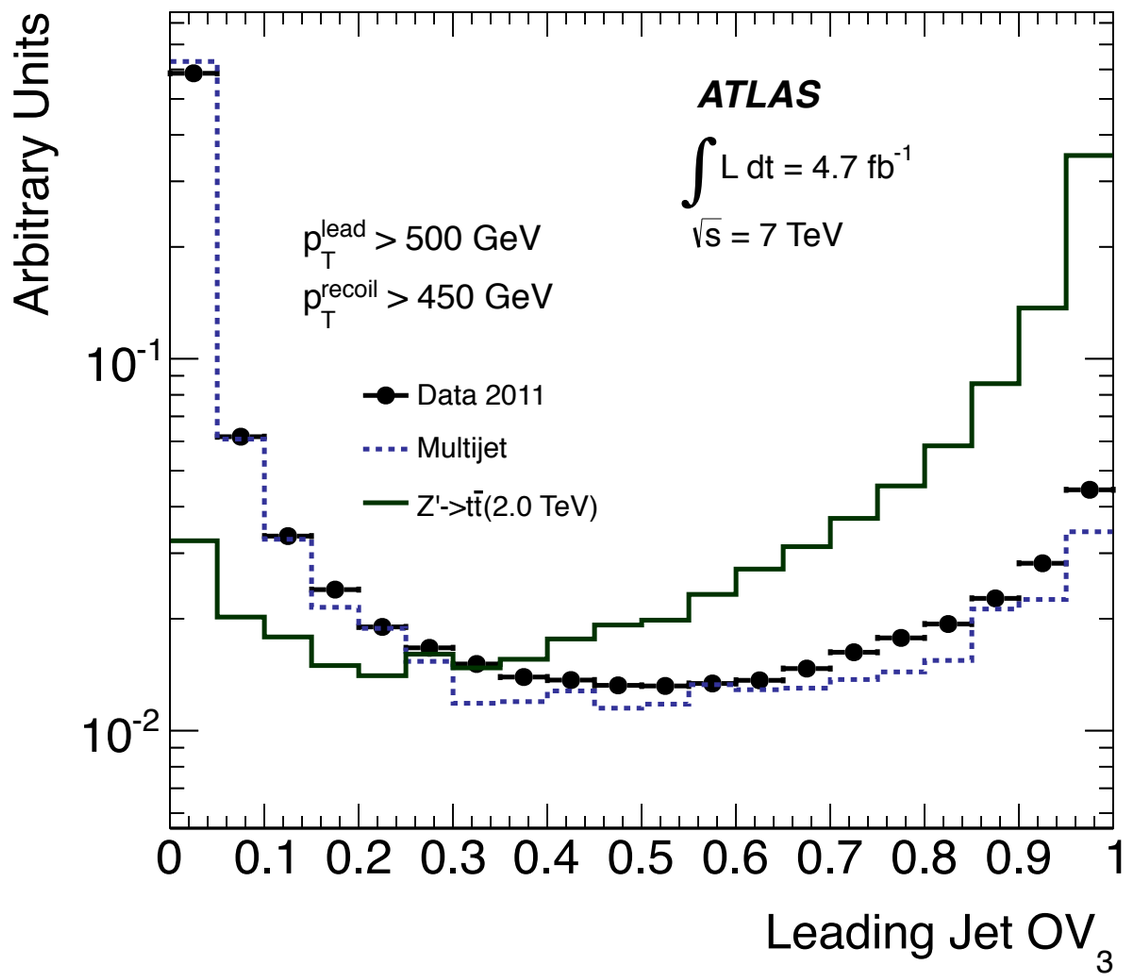
- Avoid pileup sensitive observables (jet mass, jet pT etc.)

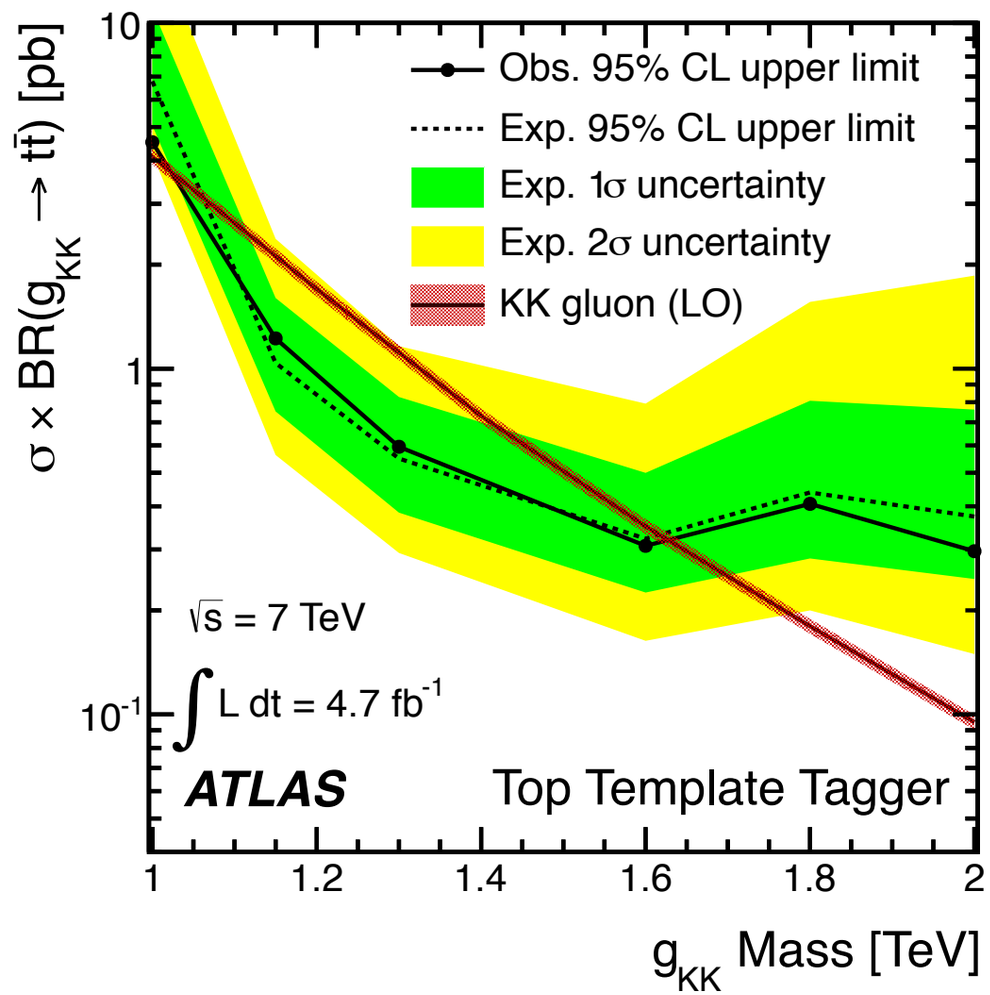
- Scale the jet cone with the pt of the to reduce pileup contamination.

- Rely on template based observables instead (template pT, Ov) and the leptonic top.

TOM: Atlas analysis

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





At the time of the publication the best limit on the kkg mass!

Boosted top resonance searches

We looked at Snowmass benchmark points for s-channel KK-gluons decaying to a pair of boosted tops at 14 TeV:

- Case 1: RH KKg, top near the TeV brane (m = 3, 5 TeV)
  Width is 0.116 x m(kkg).

- Case 2: LH KKg, bottom near the TeV brane (m = 3, 5 TeV)
  Width is 0.210 x m(kkg).

- Semi leptonic ttbar channels.

- Dominant background from SM ttbar an Wjj. di-light jet not significant after mini-ISO of the lepton.
(Use both hadronic Ov and leptonic Ov to supress the Wjj background)

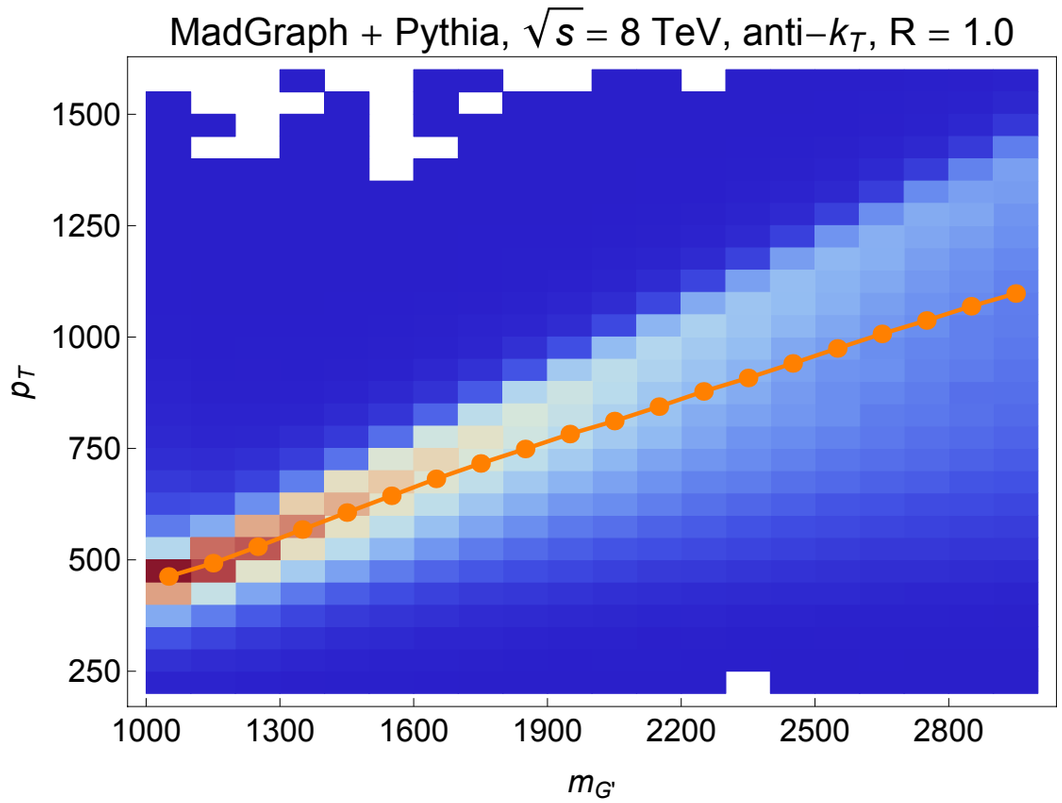
Boosted top resonance searches

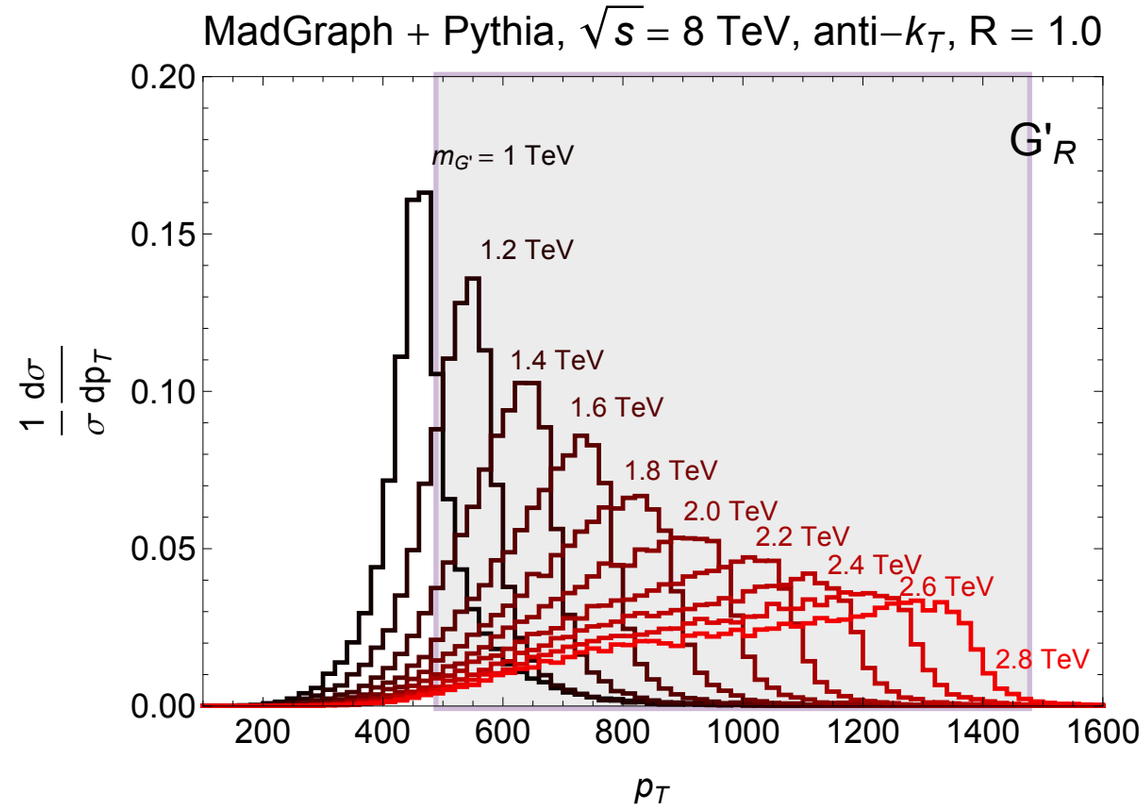
- Which pT range to consider?

- Beyond 1.5 TeV detector resolution starts becoming a problem (no jet substructure anymore).

$$R \sim 2m_t/p_T \sim 350GeV/1.5TeV = 0.23$$

- Signal events characterized by a wide top pT distribution, mostly in the highly boosted top regime (pT > 500 GeV)





PDF broadening works for us.

take jets between pT = 500 GeV and 1.5 TeV

Boosted top resonance searches

CASE 1, m = 3 TeV

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

14 TeV!

Case 1: 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}	$\sigma_{m_{KK}=3\ \mathrm{TeV}}$ (fb)	$\epsilon_{m_{KK}=3\ \mathrm{TeV}}$(fb)	S/B	$S/\sqrt{B}(300\mathrm{fb}^{-1})$
Basic Cuts	12.2	1.00	121.0	1.00	3.3	1.00	0.02	4.9
& Ov cuts	4.1	0.34	3.9	0.03	2.3	0.7	0.30	14.3

Case 1: 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}	$\sigma_{m_{KK}=3\ \mathrm{TeV}}$ (fb)	$\epsilon_{m_{KK}=3\ \mathrm{TeV}}$(fb)	S/B	$S/\sqrt{B}(300\mathrm{fb}^{-1})$
Basic Cuts	18.7	1.00	208.5	1.00	4.1	1.00	0.02	4.7
& Ov cuts	5.2	0.25	5.2	0.025	2.9	0.70	0.30	15.7

basic cuts include a pt(fat jet) > 500 GeV
pileup makes more events pass the cut.

1. **Possible to improve the sig. significance by 3-fold with jet substructure.**
2. **The searches are limited by the irreducable SM ttbar background.**
3. **High signal efficiency achievable.**
4. **50 pileup does not significantly affect the search w/ TOM (10% effect)**

Boosted top resonance searches

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CASE 2, m = 3 TeV

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

14 TeV!

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}	$\sigma_{m_{KK}=3\ \mathrm{TeV}}$ (fb)	$\epsilon_{m_{KK}=3\ \mathrm{TeV}}$(fb)	S/B	$S/\sqrt{B}(300\mathrm{fb}^{-1})$	$S/\sqrt{B}(3000\mathrm{fb}^{-1})$
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}	$\sigma_{m_{KK}=3\ \mathrm{TeV}}$ (fb)	$\epsilon_{m_{KK}=3\ \mathrm{TeV}}$(fb)	S/B	$S/\sqrt{B}(300\mathrm{fb}^{-1})$	$S/\sqrt{B}(3000\mathrm{fb}^{-1})$
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. **The searches are limited by the irreducable SM ttbar background.**
3. **High signal efficiency achievable.**
4. **50 pileup does not significantly affect the search w/ TOM (10% effect)**

Boosted top resonance searches

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CASE 1, m = 5 TeV

14 TeV!

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

Case 1: m(kkg) = 5TeV, no pileup, no b-tagging, no mass cut on the jet, mtt(template) > 3.5 TeV

Cuts	$\sigma_{t\bar{t}}$(fb)	$\epsilon_{t\bar{t}}$	σ_{wjj}(fb)	ϵ_{Wjj}	$\sigma_{m_{KK}=5\ \mathrm{TeV}}$ (fb)	$\epsilon_{m_{KK}=5\ \mathrm{TeV}}$(fb)	S/B	$S/\sqrt{B}(300\mathrm{fb}^{-1})$	$S/\sqrt{B}(3000\mathrm{fb}^{-1})$
Basic Cuts	2.5	1.00	44.6	1.00	0.18	1.00	0.004	0.4	1.4
& Ov cuts	0.6	0.33	1.3	0.03	0.12	0.70	0.07	1.5	4.8

Case 1: m(kkg) = 5TeV, 50 pileup, no b-tagging, no mass cut on the jet, mtt(template) > 3.5 TeV

Cuts	$\sigma_{t\bar{t}}$(fb)	$\epsilon_{t\bar{t}}$	σ_{wjj}(fb)	ϵ_{Wjj}	$\sigma_{m_{KK}=5\ \mathrm{TeV}}$ (fb)	$\epsilon_{m_{KK}=5\ \mathrm{TeV}}$(fb)	S/B	$S/\sqrt{B}(300\mathrm{fb}^{-1})$	$S/\sqrt{B}(3000\mathrm{fb}^{-1})$
Basic Cuts	4.2	1.00	73.0	1.00	0.18	1.00	0.002	0.4	1.1
& Ov cuts	0.9	0.27	2.0	0.027	0.12	0.69	0.041	1.3	4.1

5. **Going to higher luminosity could help to extend the reach of the resonance searches in boosted ttbar channels to m(kkg) = 5 TeV.**

Boosted top resonance searches

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CASE 2, m = 5 TeV

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

14 TeV!

Case 2: m(kkg) = 5 TeV, no pileup, no b-tagging, no mass cut on the jet, mtt(template) > 3.5 TeV

Cuts	$\sigma_{t\bar{t}}$(fb)	$\epsilon_{t\bar{t}}$	σ_{wjj}(fb)	ϵ_{Wjj}	$\sigma_{m_{KK}=5\ \mathrm{TeV}}$ (fb)	$\epsilon_{m_{KK}=5\ \mathrm{TeV}}$(fb)	S/B	$S/\sqrt{B}(300\mathrm{fb}^{-1})$	$S/\sqrt{B}(3000\mathrm{fb}^{-1})$
Basic Cuts	2.5	1.00	44.6	1.00	0.17	1.00	0.001	0.3	0.8
& Ov cuts	0.6	0.33	1.3	0.03	0.12	0.72	0.01	0.7	2.3

Case 2: m(kkg) = 5 TeV, 50 pileup, no b-tagging, no mass cut on the jet, mtt(template) > 3.5 TeV

Cuts	$\sigma_{t\bar{t}}$(fb)	$\epsilon_{t\bar{t}}$	σ_{wjj}(fb)	ϵ_{Wjj}	$\sigma_{m_{KK}=5\ \mathrm{TeV}}$ (fb)	$\epsilon_{m_{KK}=5\ \mathrm{TeV}}$(fb)	S/B	$S/\sqrt{B}(300\mathrm{fb}^{-1})$	$S/\sqrt{B}(3000\mathrm{fb}^{-1})$
Basic Cuts	4.2	1.00	73.0	1.00	0.17	1.00	7×10^{-4}	0.2	0.6
& Ov cuts	0.9	0.27	2.0	0.027	0.12	0.72	0.01	0.7	2.0

6. **But not in all cases.**

Boosted top resonance searches

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CASE 1, m = 5 TeV

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

33 TeV!

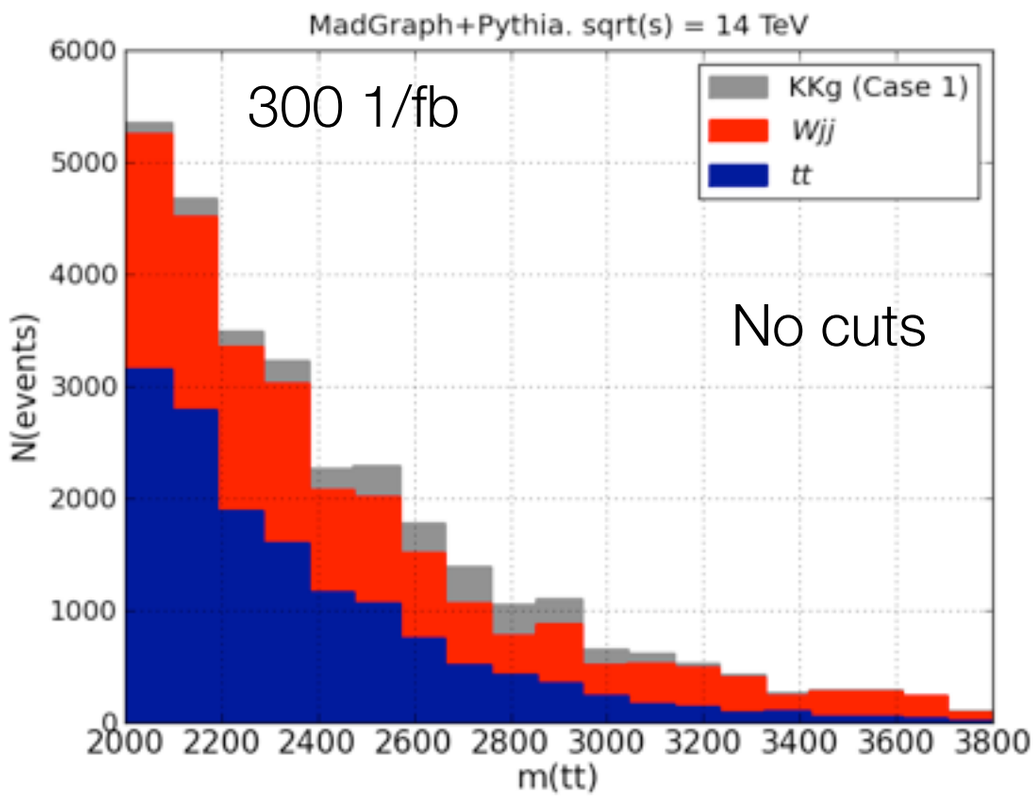
Case 1: m(kkg) = 5 TeV, no pileup, no b-tagging, no mass cut on the jet, mtt(template) > 3.5 TeV

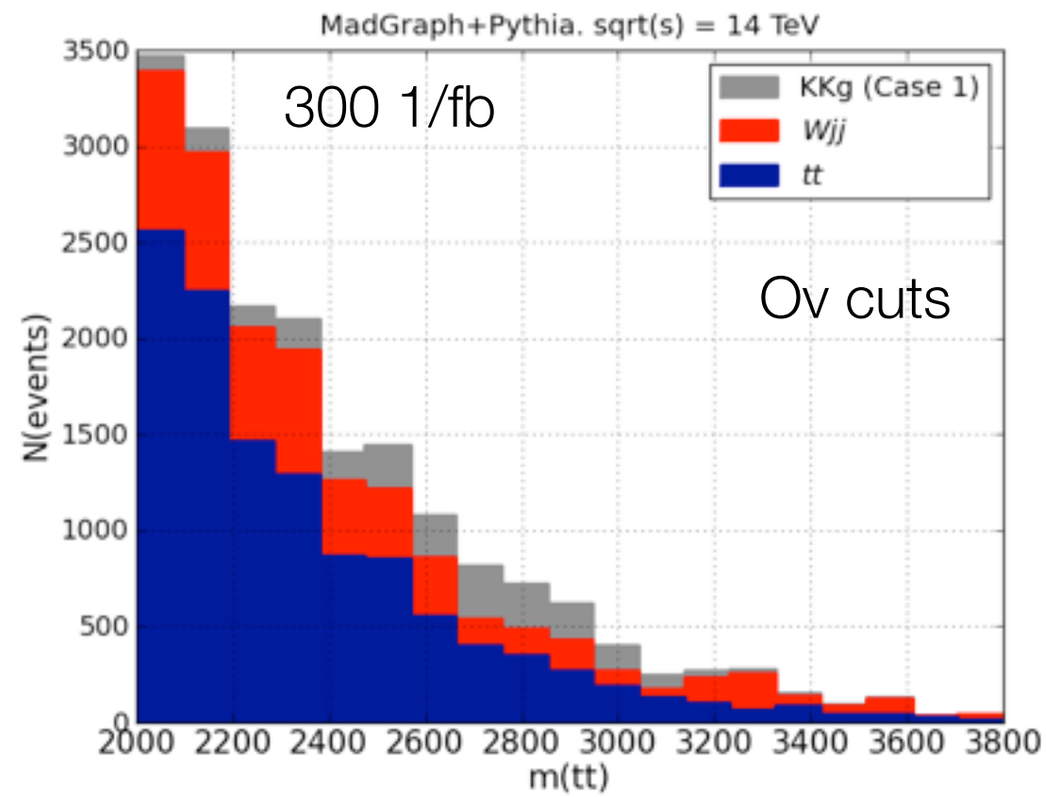
Cuts	$\sigma_{t\bar{t}}$(fb)	$\epsilon_{t\bar{t}}$	σ_{wjj}(fb)	ϵ_{Wjj}	$\sigma_{m_{KK}=5\ \mathrm{TeV}}$ (fb)	$\epsilon_{m_{KK}=5\ \mathrm{TeV}}$(fb)	S/B	$S/\sqrt{B}(300\mathrm{fb}^{-1})$	$S/\sqrt{B}(3000\mathrm{fb}^{-1})$
Basic Cuts	173.0	1.00	800.0	1.00	9.7	1.00	0.009	5.2	16.4
& Ov cuts	48.0	0.28	39.0	0.04	6.5	0.67	0.075	12.1	38.2

We are working on the rest of the 33 TeV data!

Mass resolution

Case 1: m(kkg) = 3TeV, no b-tagging, no mass cut on the jet, mtt(template) > 2.8 TeV





It remains to be seen how good of a mass resolution we can achieve. (in progress)

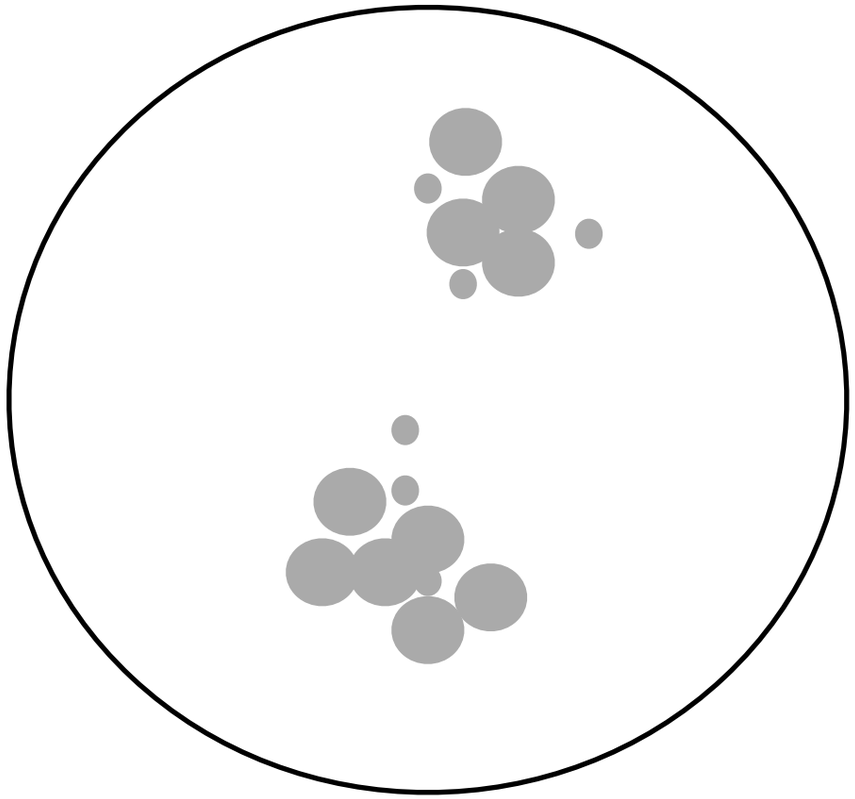
We are working on 33 TeV data!

BACKUP SLIDES

Illustrated TOM algorithm

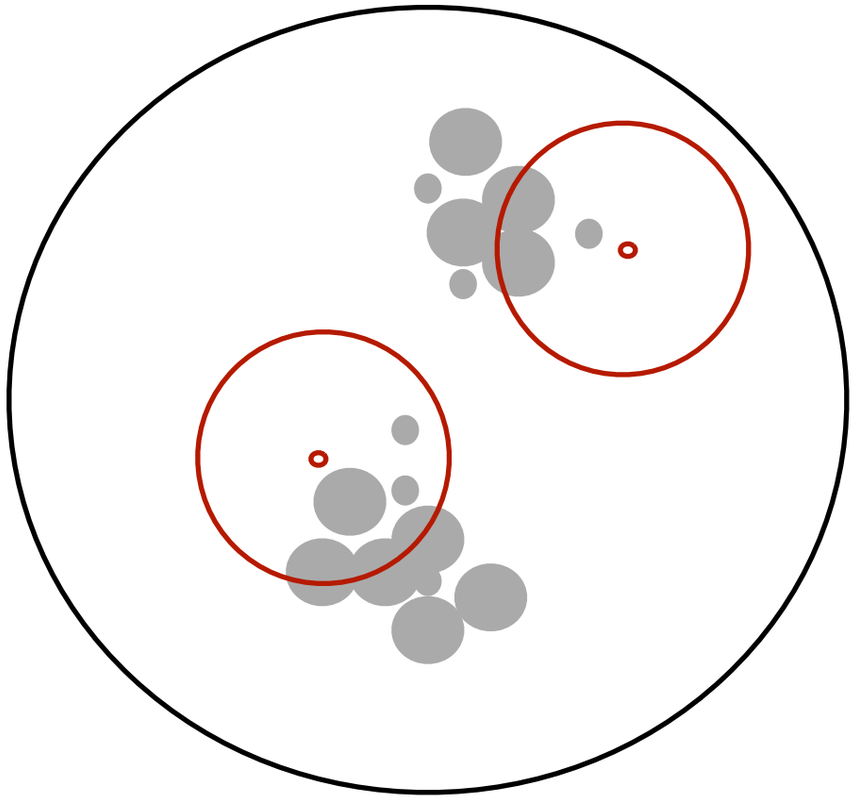
TOM: Illustration

Consider for instance a "Higgs jet"



TOM: Illustration

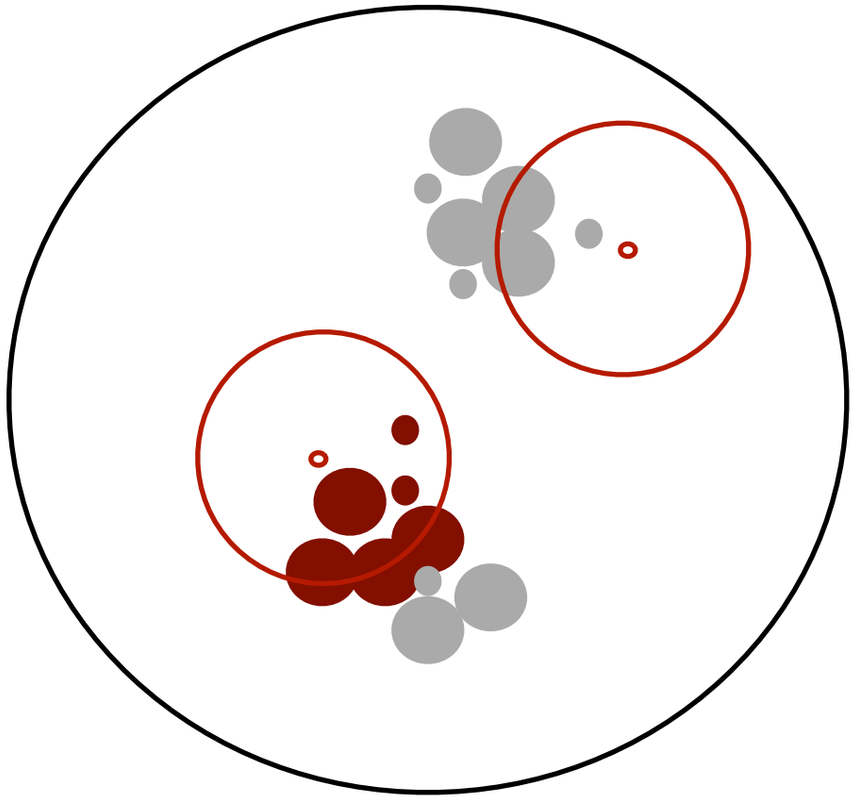
Pick one configuration out of many possible 2-body decay configurations of a boosted Higgs (Template).



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



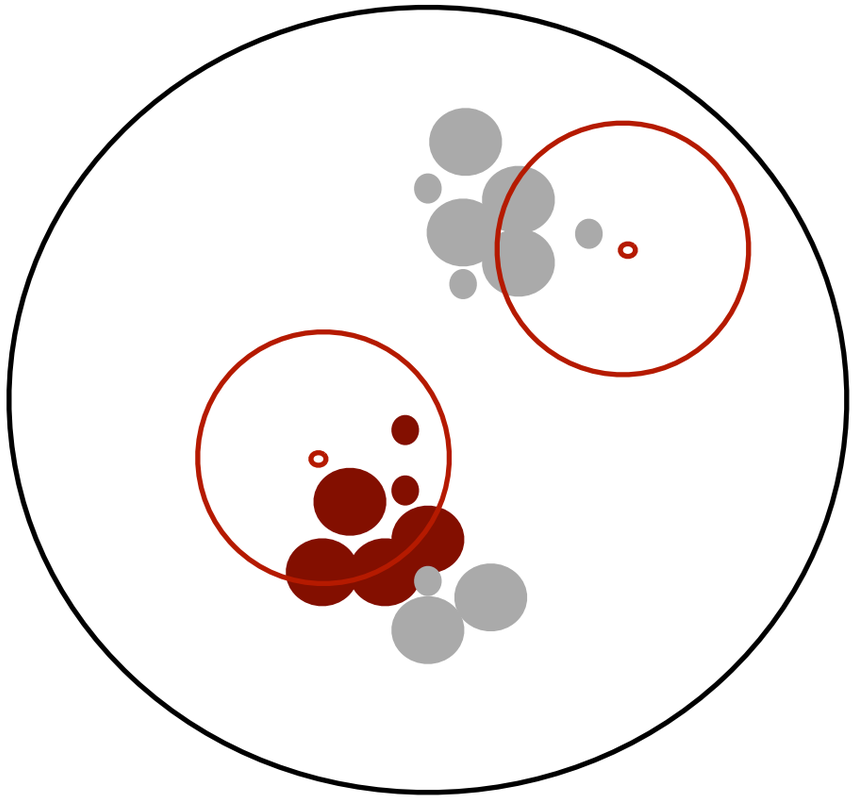
$$\sum_j E_j$$

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

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

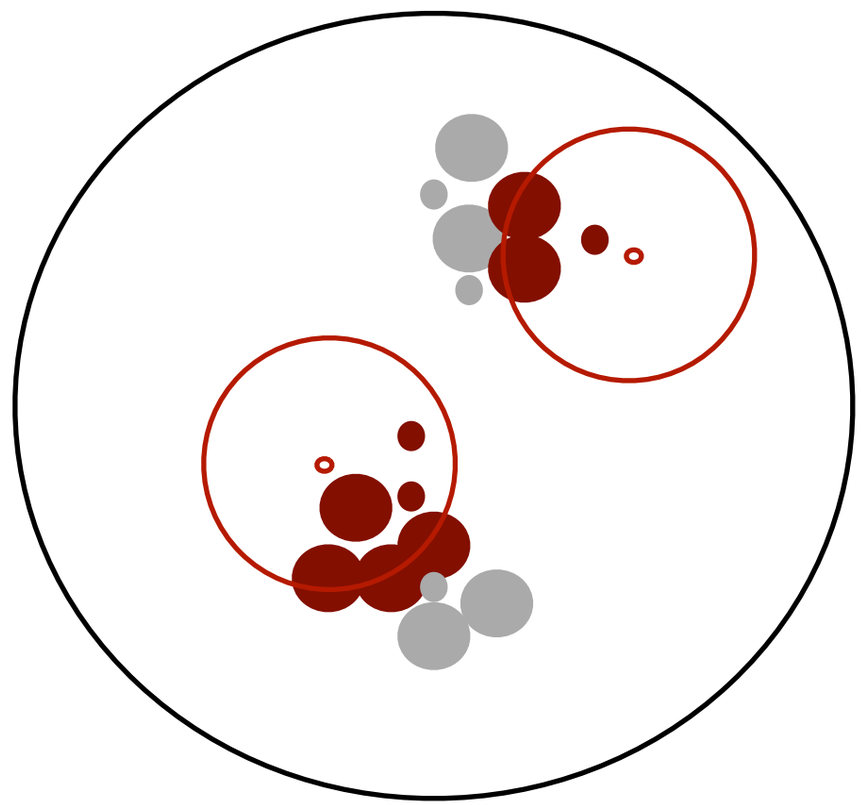


$$\sum_j E_j - E_i$$

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



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.

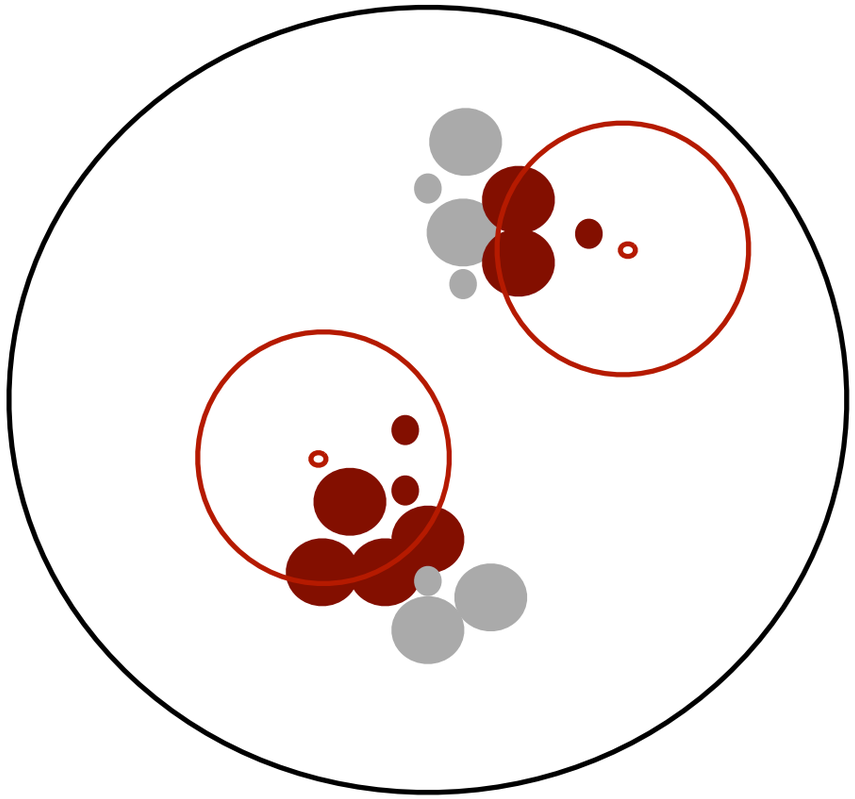
Weight needed to compensate for the template resolution of the mass, transverse momenta etc.

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

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



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.

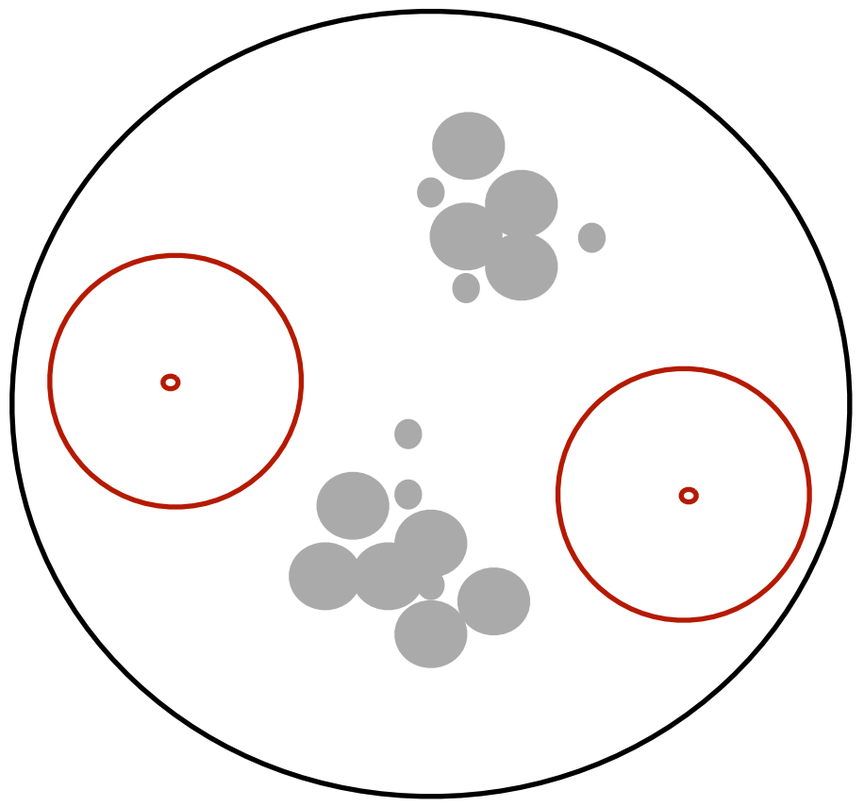
Exponentiate the sum!

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

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.

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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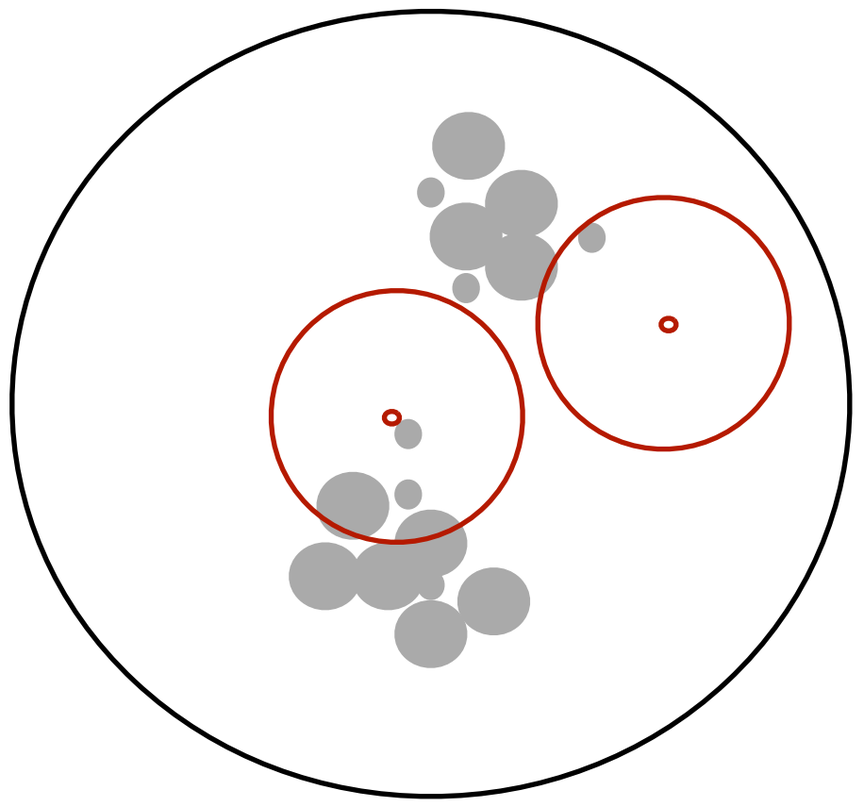


For each template, subtract the sum from the energy of the template momentum.

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

Exponentiate the sum!

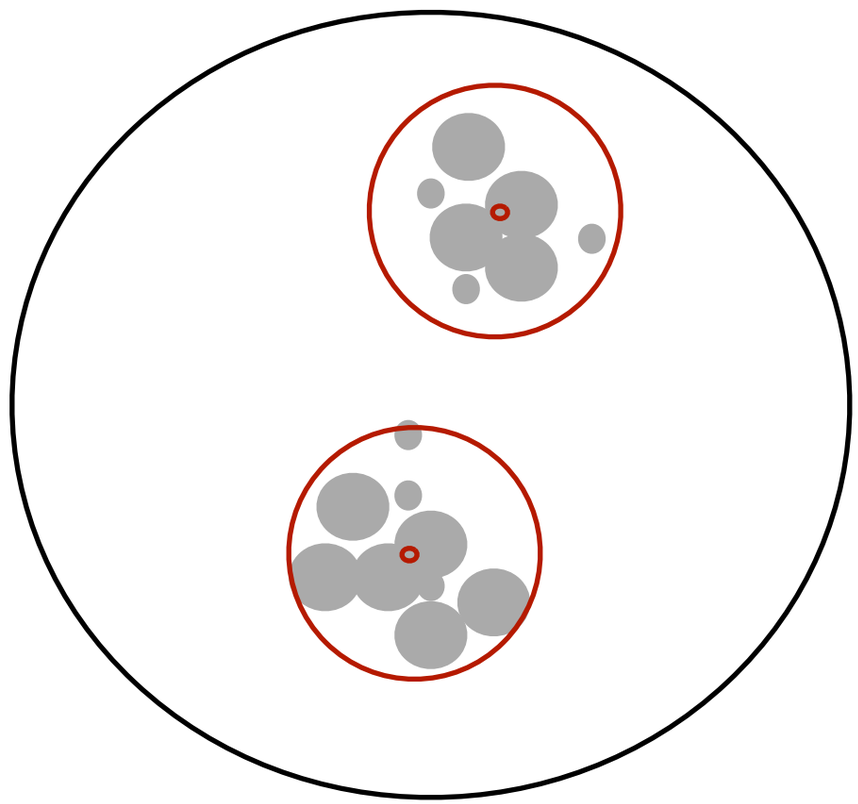
$$exp\left[-\sum_i \frac{1}{2\sigma_i^2}\left[\sum_j E_j - E_i\right]^2\right]$$

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

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.

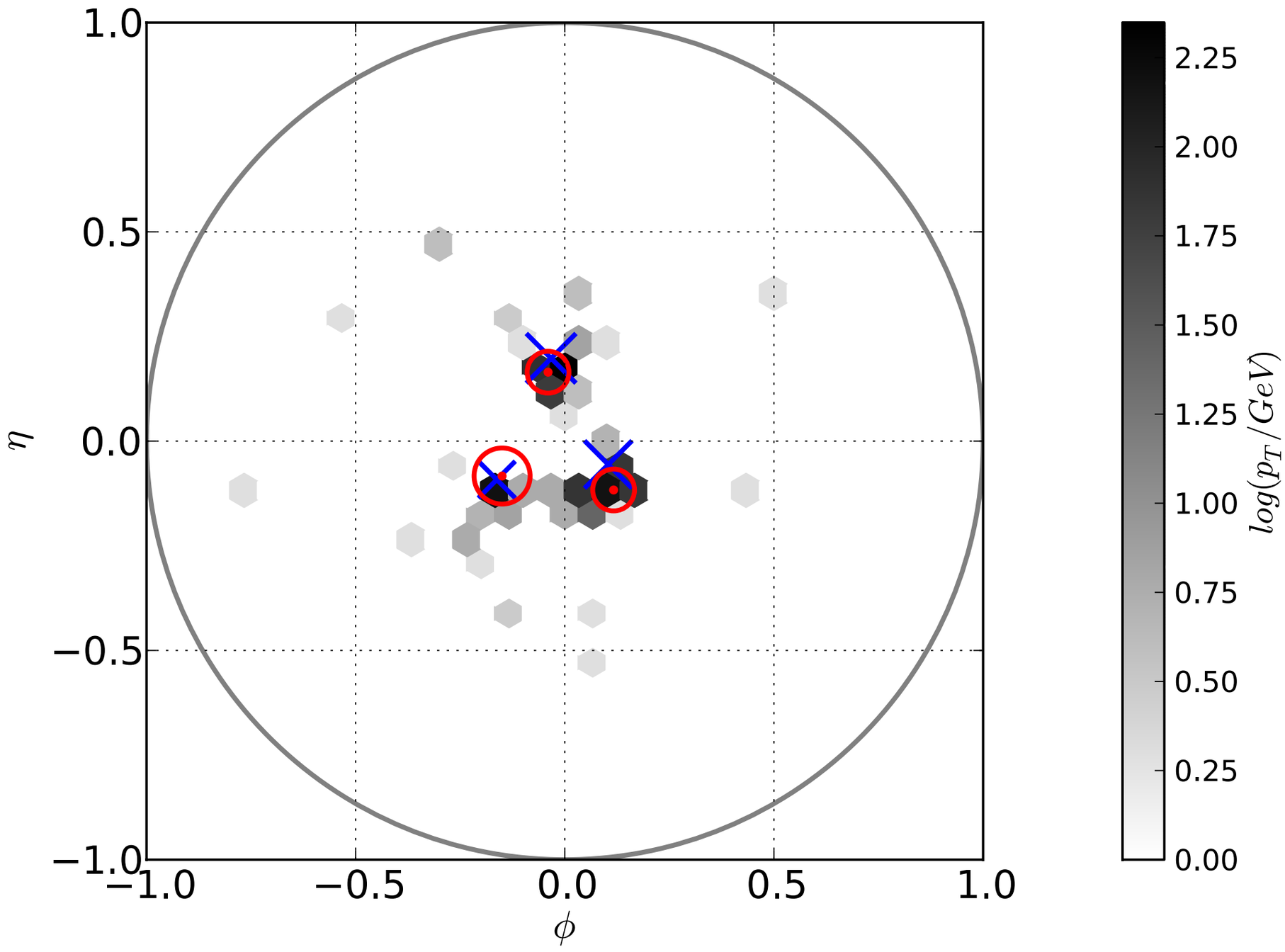
Choose the configuration which maximizes the exponential!

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

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