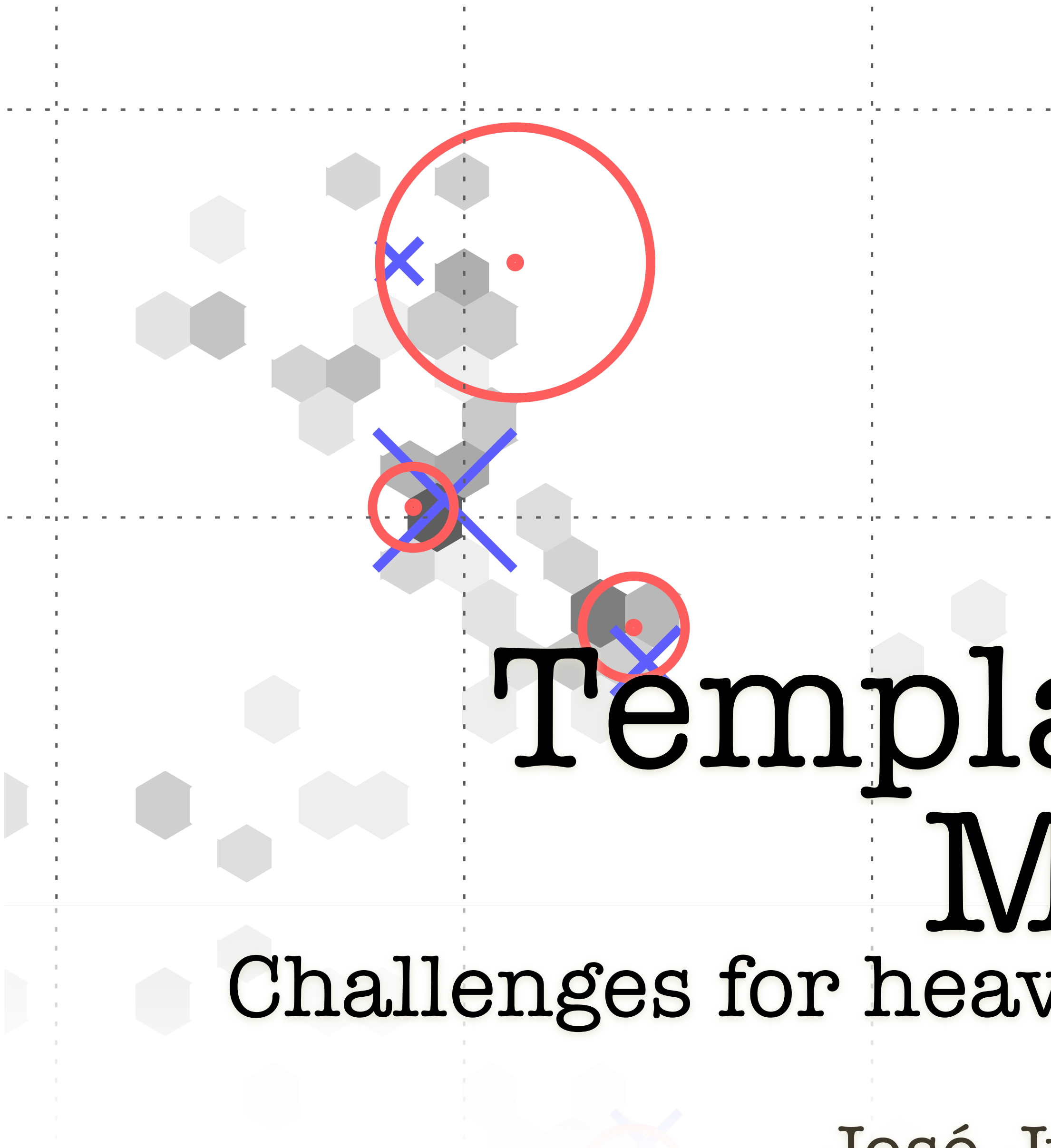


Template Overlap Method

Challenges for heavy gluon searches at the LHC

José Juknevich (SISSA)

with Backovic, Gabizon, Perez, Soreq, JHEP04(2014)176

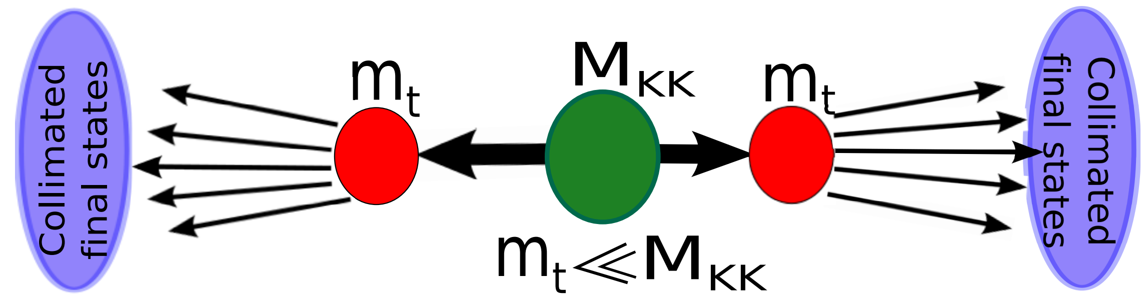
and Chala, Perez, Santiago, to appear

22 May ‘14

MC4BSM

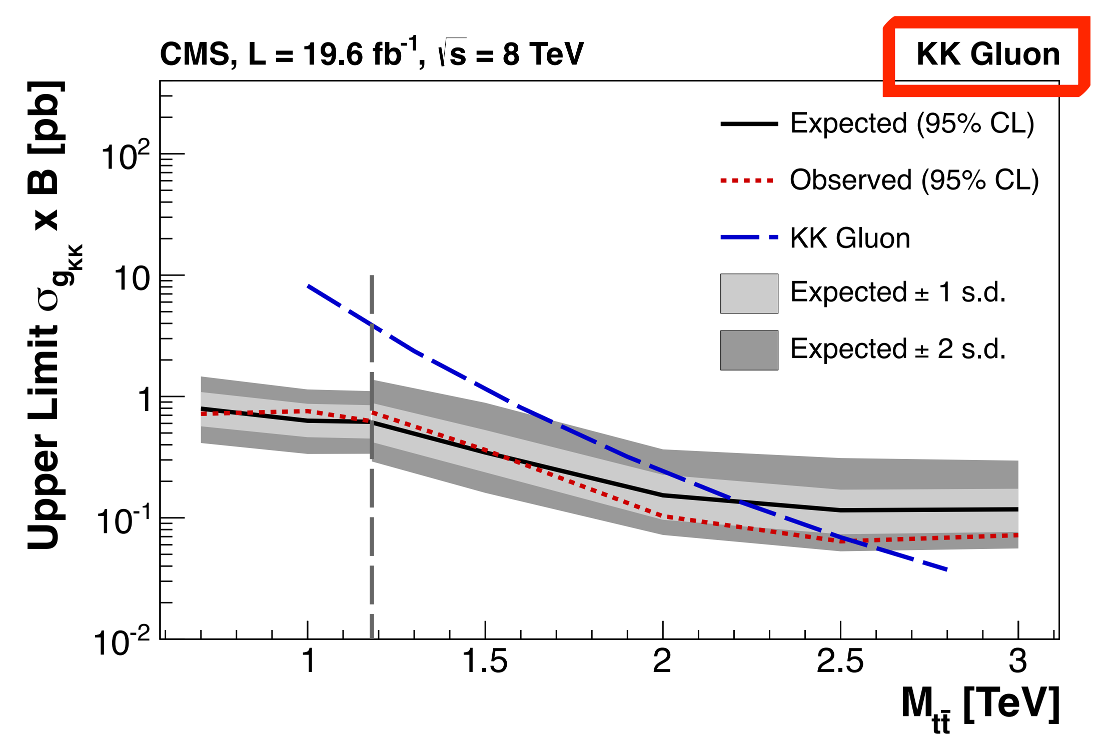
Introduction

- Strong dynamics models (composite Higgs, Randall-Sundrum,…) predict heavy Kaluza-Klein (KK) resonances with large couplings to tops (EWPT: $m_{KK} \gtrsim 3$ TeV)



- With the high collision energy, we enter the boosted regime:
  - Collimated states
  - Special jet substructure techniques needed [See M. Cacciari and B. Tweedie's talks]

CMS-B2G-13-001



Heavy gluons now excluded up to 2.5 TeV!

- Future directions:
  - Keep pushing bound: boosted searches
  - NP could be lighter but hidden

Outline

- Boosted searches: Template Overlap Method
- The elusive gluon
- Conclusions

Template Overlap Method

A general jet substructure algorithm to tag heavy, boosted jets against light quark and gluon jets

- First introduced by Almeida, Lee, Perez, Sterman and Sung (Phys. Rev. D82 (2010) 054034)
- Subsequent phenomenological studies:
  - **Ultra boosted Higgs study** - Almeida, Erdogan, JJ, Lee, Perez, Sterman (Phys. Rev. D85 (2012) 114046)
  - **Midly boosted Higgs** - Backovic, JJ, Perez (JHEP07(2013)114)
  - **Semileptonic top** - Backovic, Gabizon, JJ, Perez, Soreq (JHEP04(2014)176)
- Publicly available code
  - **TemplateTagger v1.0.0** - Backovic, JJ (COMPHY 5223)
- ATLAS study
  - **Search for resonances in ttbar events** (JHEP 1301 (2013) 116)

Template Overlap Method

- **Templates:** Sets of boosted partonic decays built from fixed-order signal distributions

template momenta

Anzatz:

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

+ extra constraints
e.g. top decay requires
two vectors to reconstruct
W decay

total momentum
of the resonance

resonance mass

Not a unique definition!

Template Overlap Method

- **Overlap function:** Functional measure of how well the energy distribution of the jet matches our model for the signal (template)

kernel function
e.g. step function (cones), gaussian, etc.

resolution
e.g. E(f)/3

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

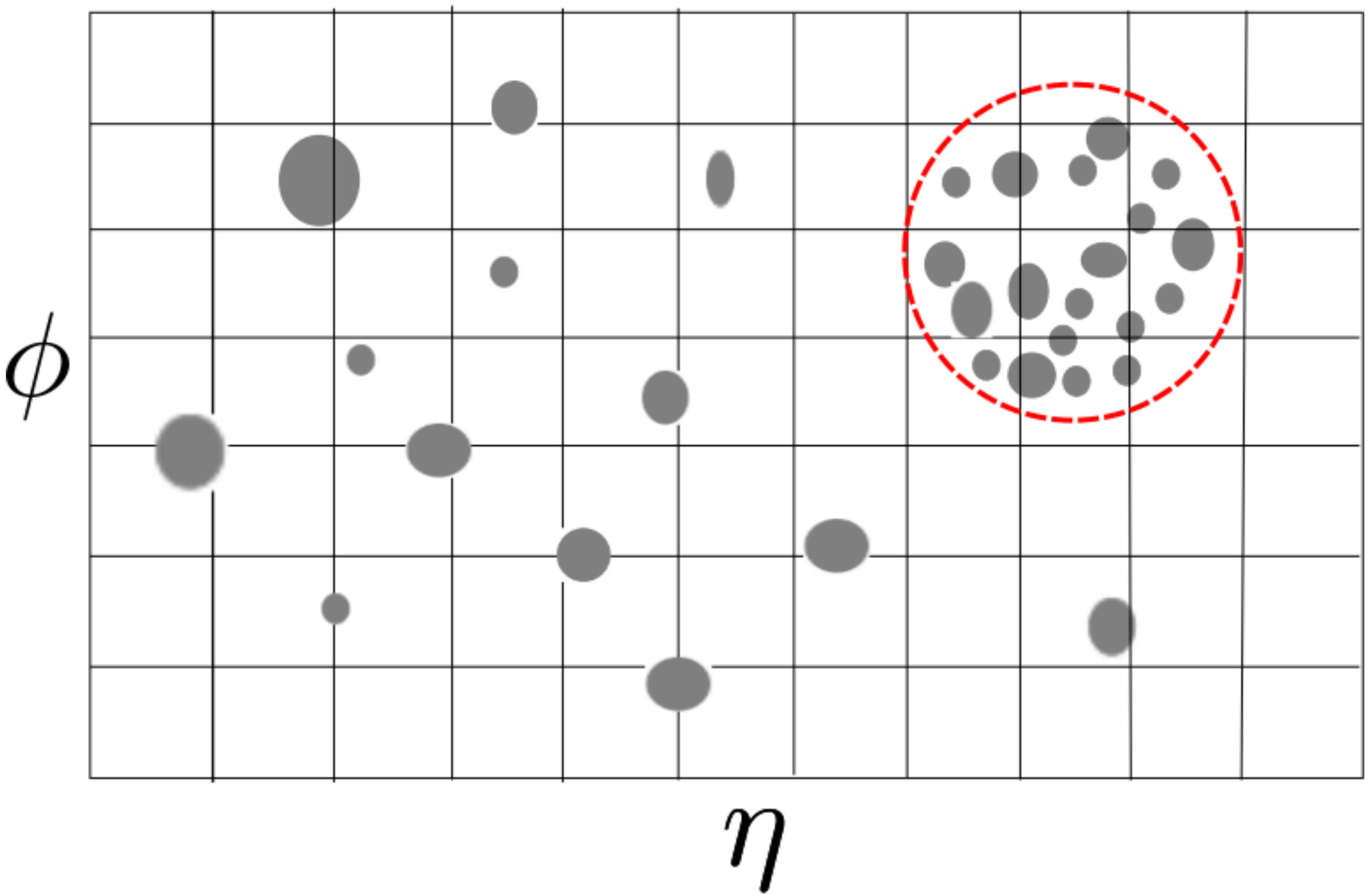
maximization over template phase space

Jet energy distribution

Template distribution

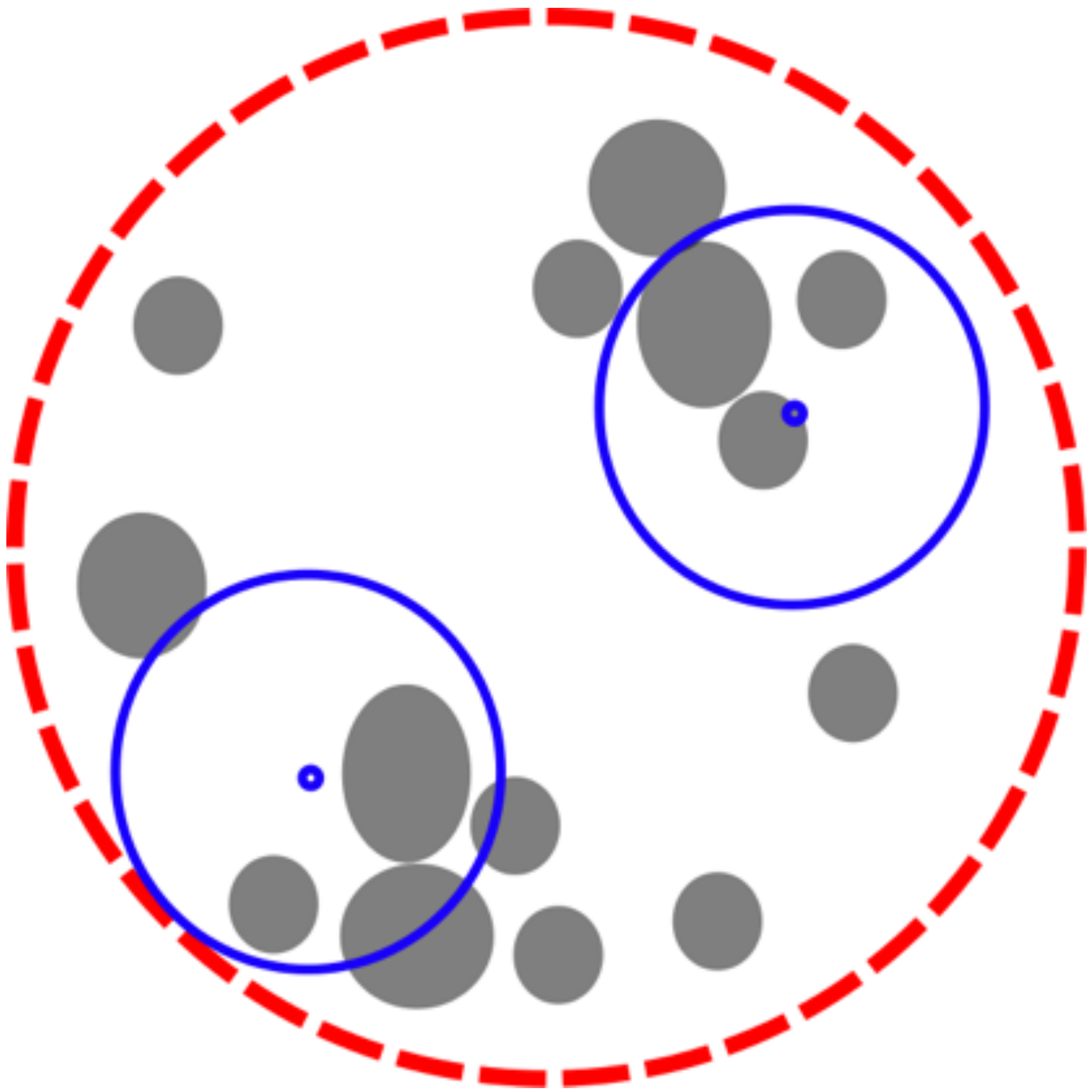
How does TOM work?

Consider for instance an event with a "Higgs jet"



Locate leading jet by using jet algorithm, e.g. anti-kT R=1.0

How does TOM work?

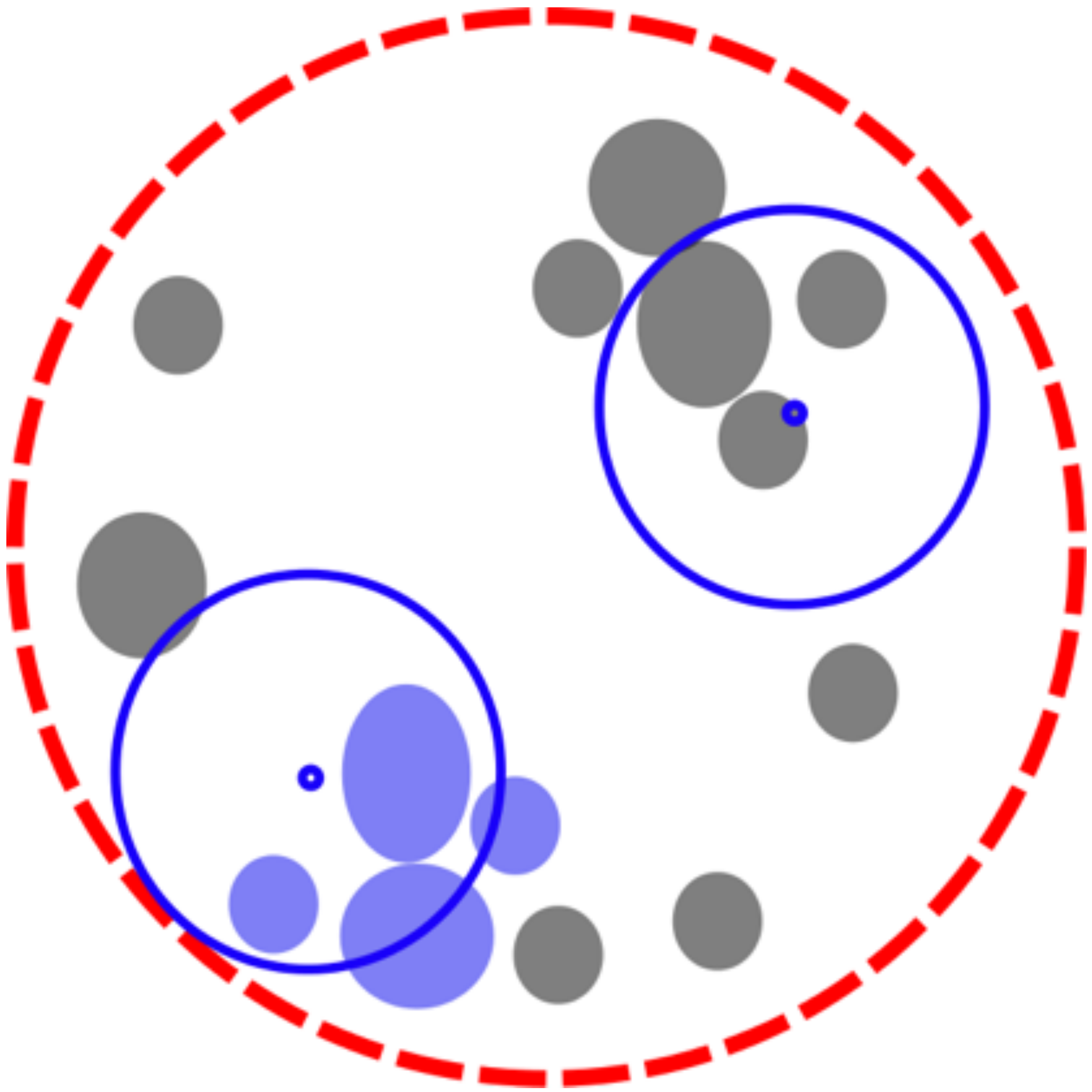


1. Pick out one configuration out of many possible 2-body decays of a boosted Higgs

e.g. using a kernel that picks out cones around template partons

$$|f\rangle = |h\rangle^{(\mathrm{LO})} = |p_1, p_2\rangle$$
$$(P_J - p_1)^2 = 0$$

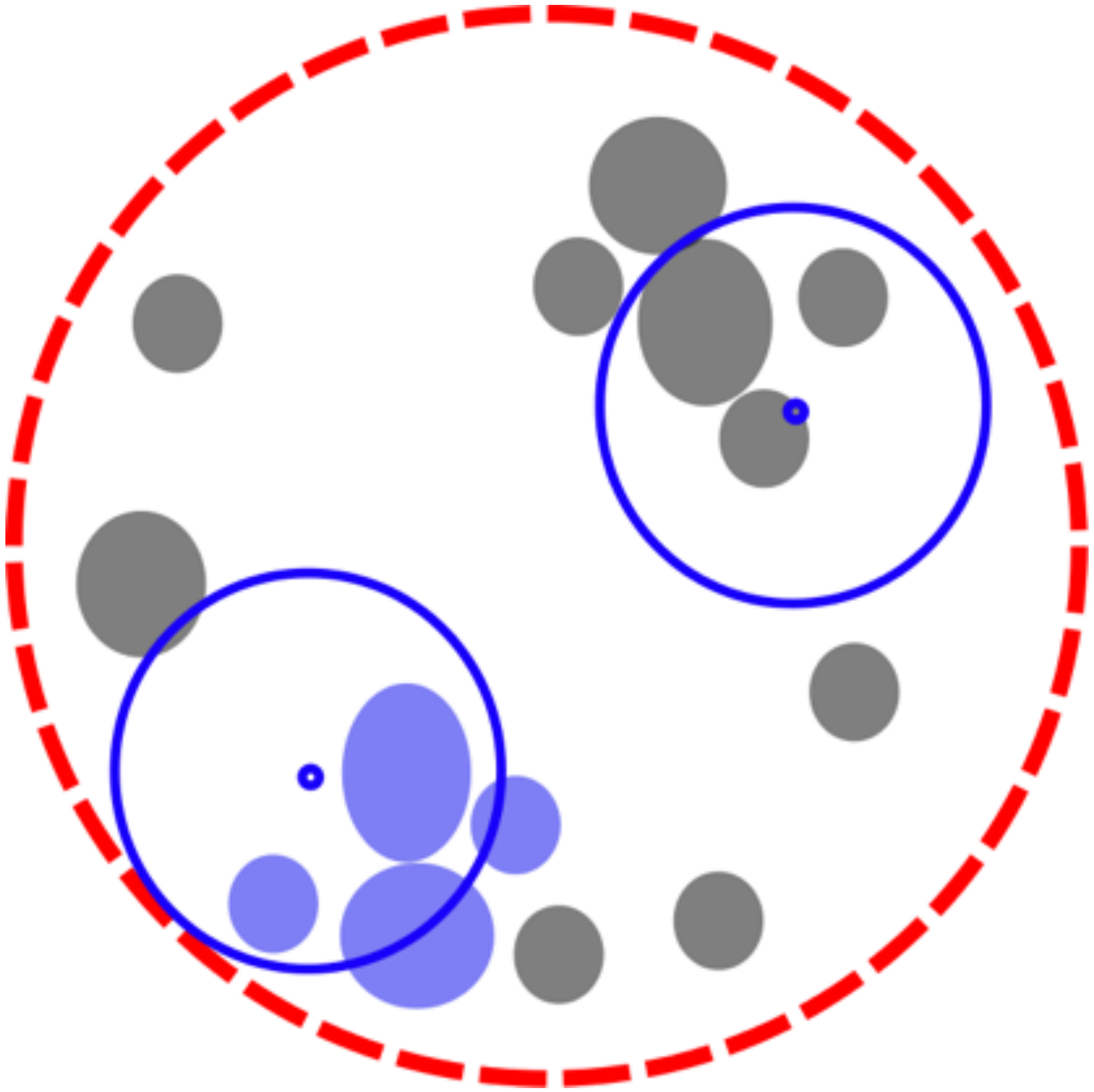
How does TOM work?



1. Pick out one configuration out of many possible 2-body decays of a boosted Higgs
2. For each template particle, add up the energy deposited within the template subcone…

$$\sum_j p_{T,j}$$

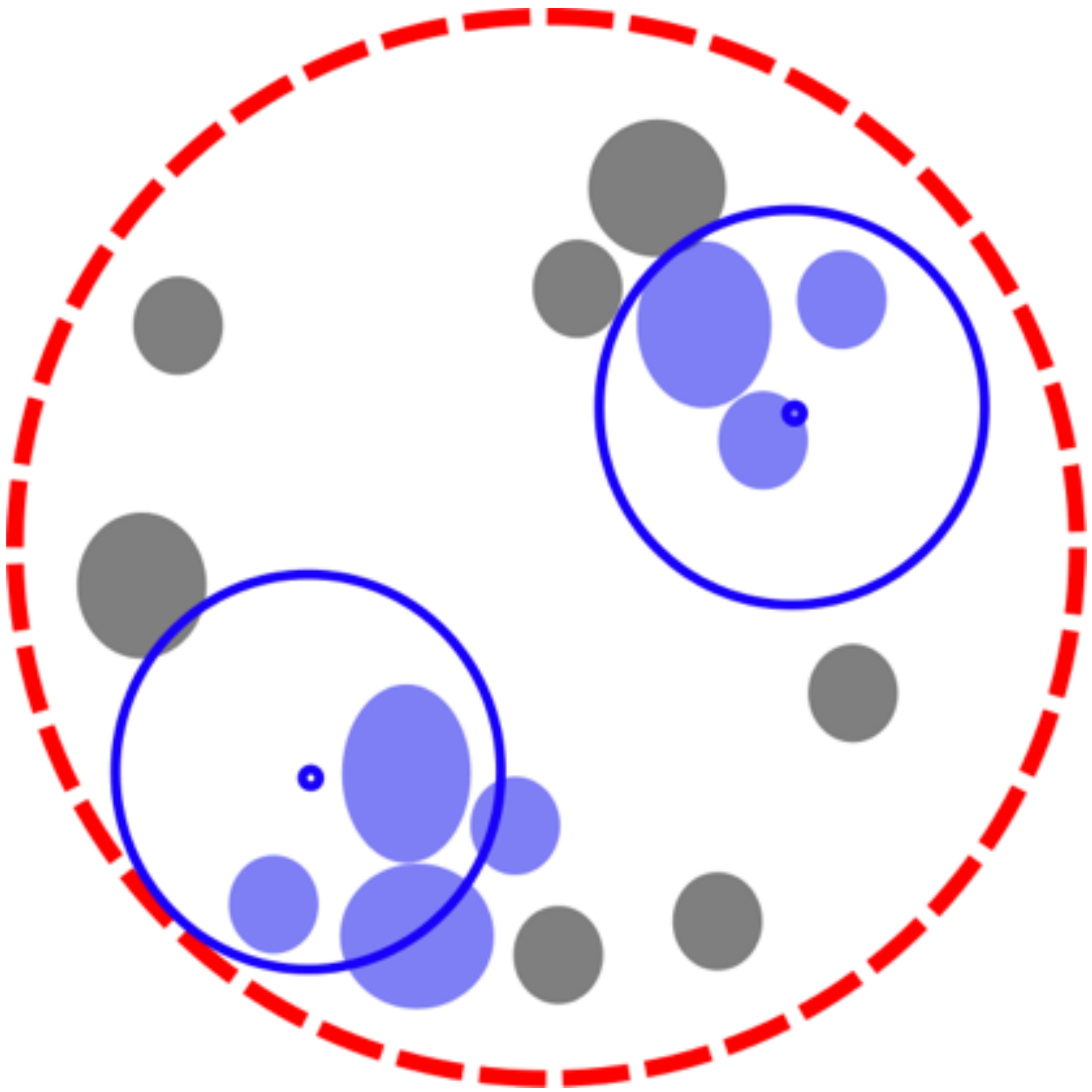
How does TOM work?



1. Pick out one configuration out of many possible 2-body decays of a boosted Higgs
2. For each template particle, add up the energy deposited within the template subcone…
3. …and subtract the template energy

$$\sum_j p_{T,j} - p_{T,a}$$

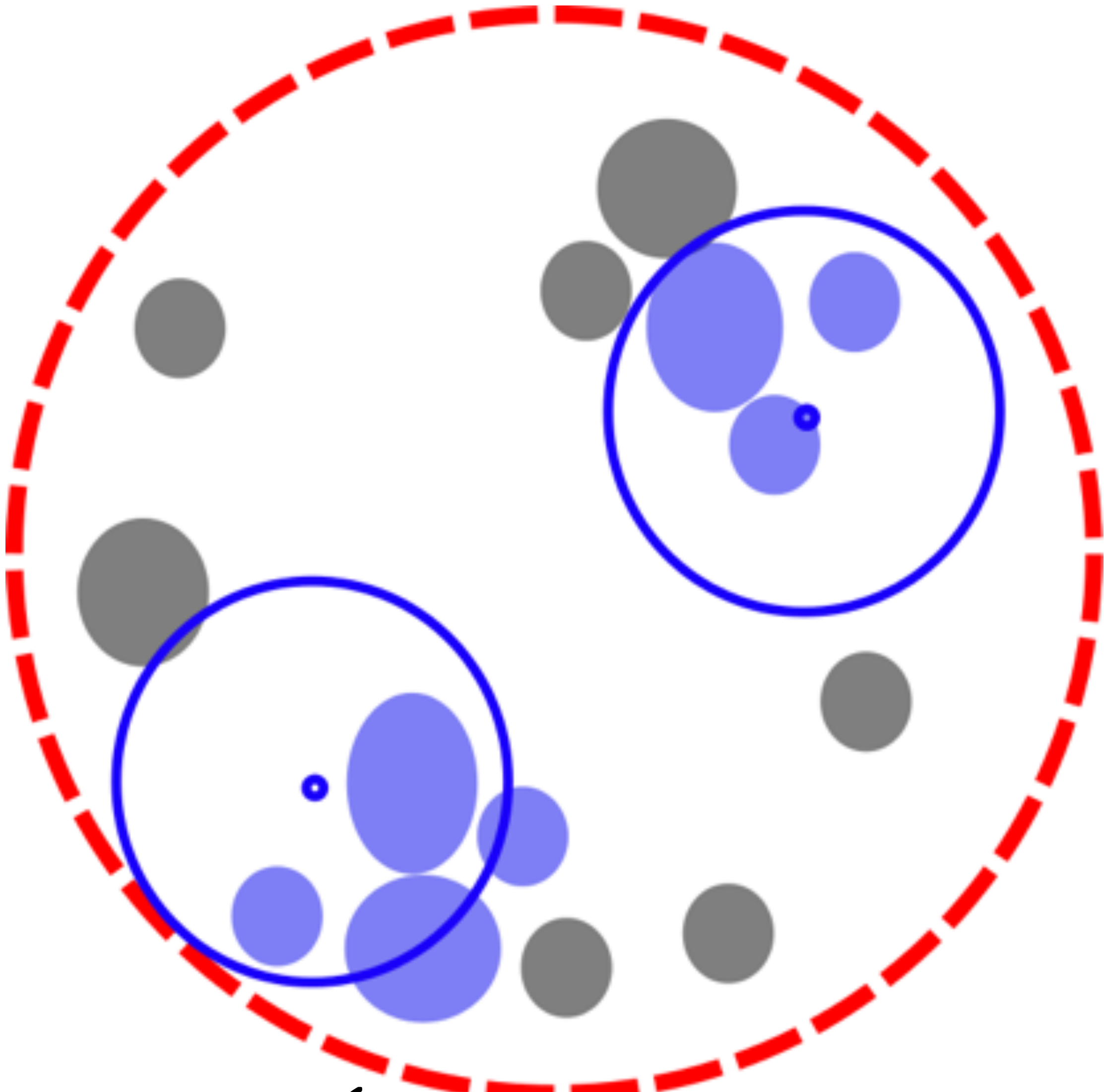
How does TOM work?



1. Pick out one configuration out of many possible 2-body decays of a boosted Higgs
2. For each template particle, add up the energy deposited within the template subcone…
3. …and subtract the template energy
4. Repeat for all other template particles and sum

$$\sum_a \frac{1}{2\sigma_a^2}\left[\sum_j p_{T,j} - p_{T,a}\right]^2$$

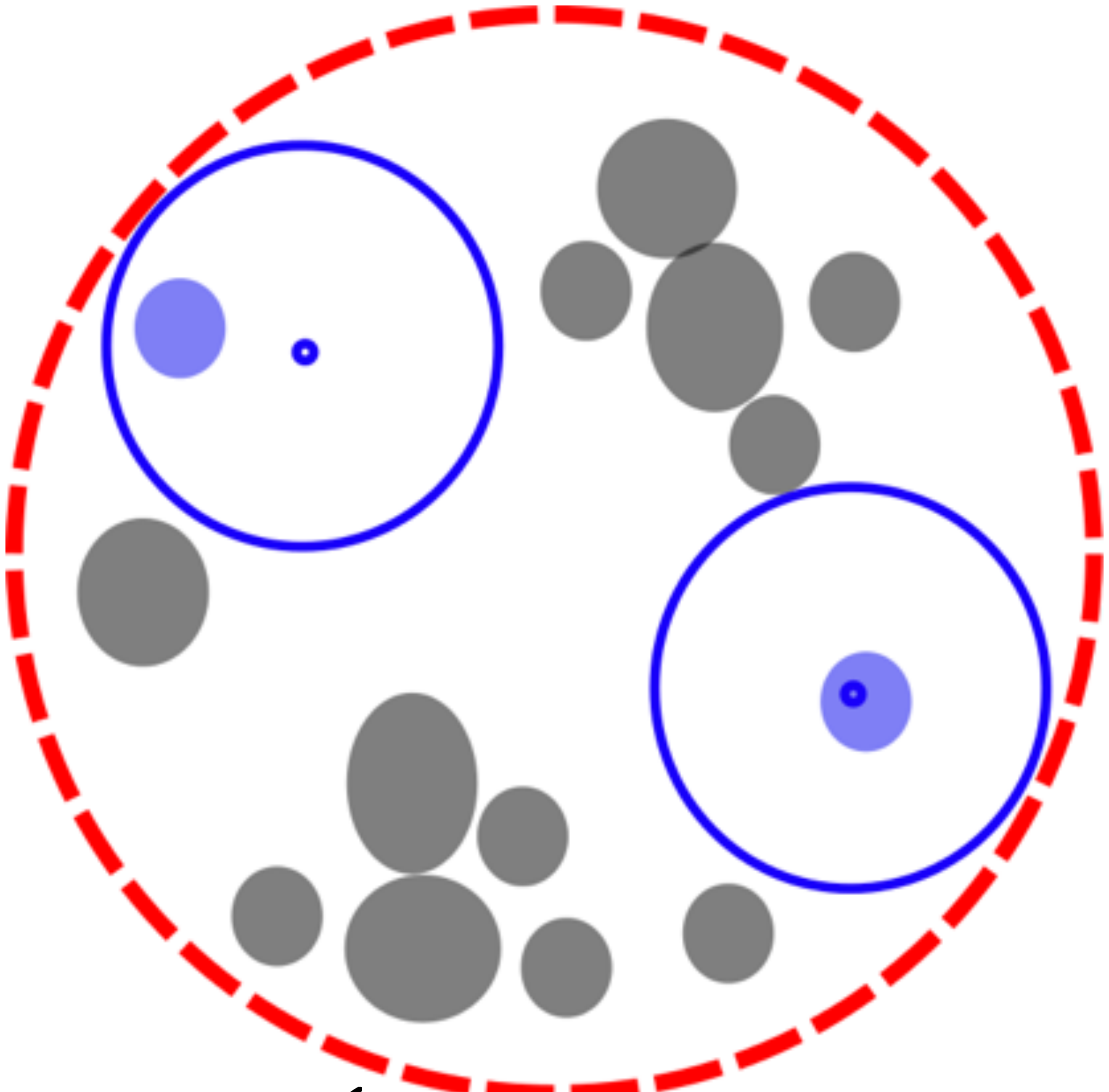
How does TOM work?



1. Pick out one configuration out of many possible 2-body decays of a boosted Higgs
2. For each template particle, add up the energy deposited within the template subcone…
3. …and subtract the template energy
4. Repeat for all other template particles and sum
5. Exponentiate the sum!

$$\exp\left\{-\sum_a \frac{1}{2\sigma_a^2}\left[\sum_j p_{T,j} - p_{T,a}\right]^2\right\}$$

How does TOM work?



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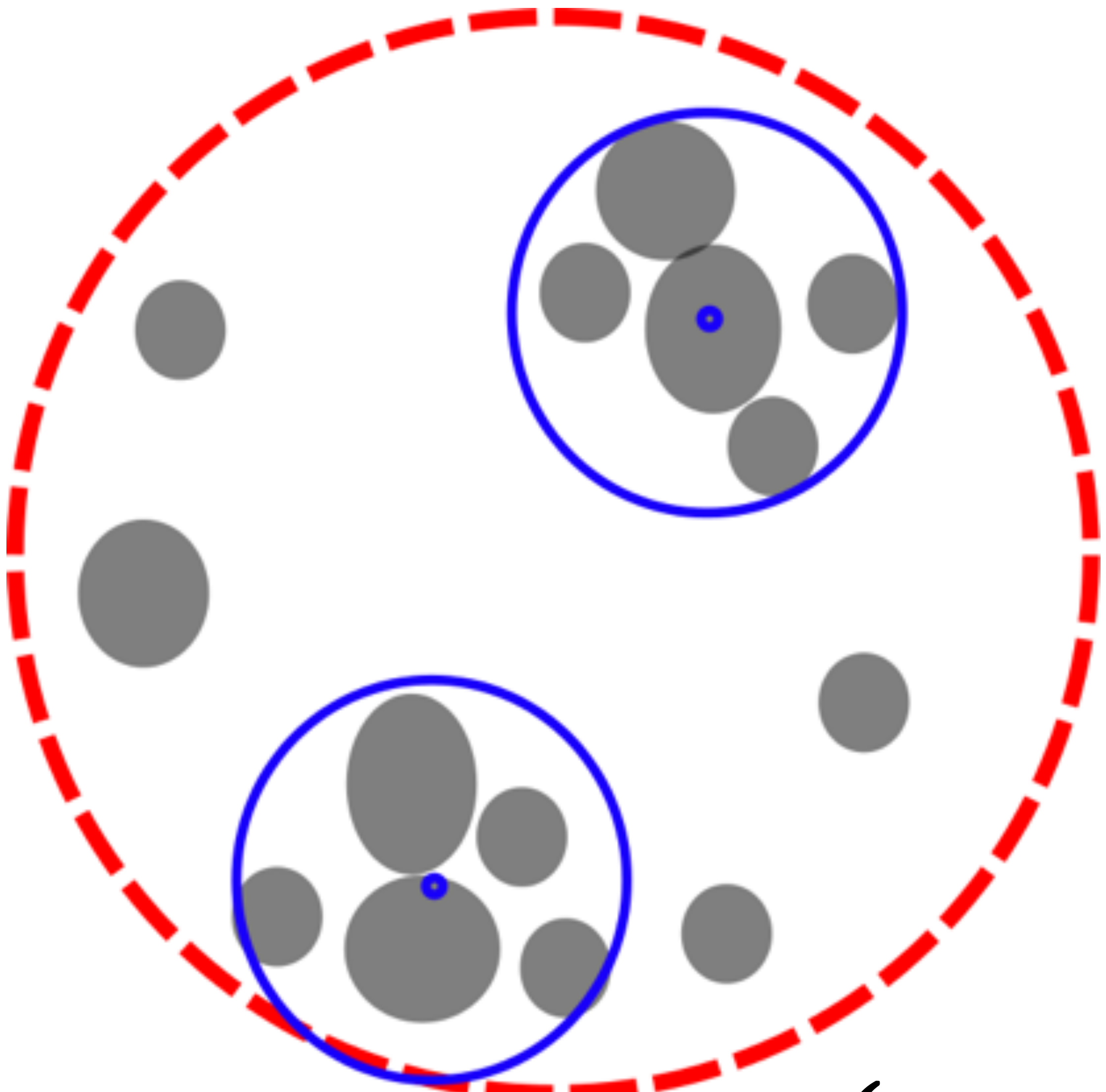
4. Repeat for all other template particles and sum
5. Exponentiate the sum!
6. Repeat 1-5 for many possible template configurations

$$\exp\left\{-\sum_a \frac{1}{2\sigma_a^2}\left[\sum_j p_{T,j} - p_{T,a}\right]^2\right\}$$

How does TOM work?

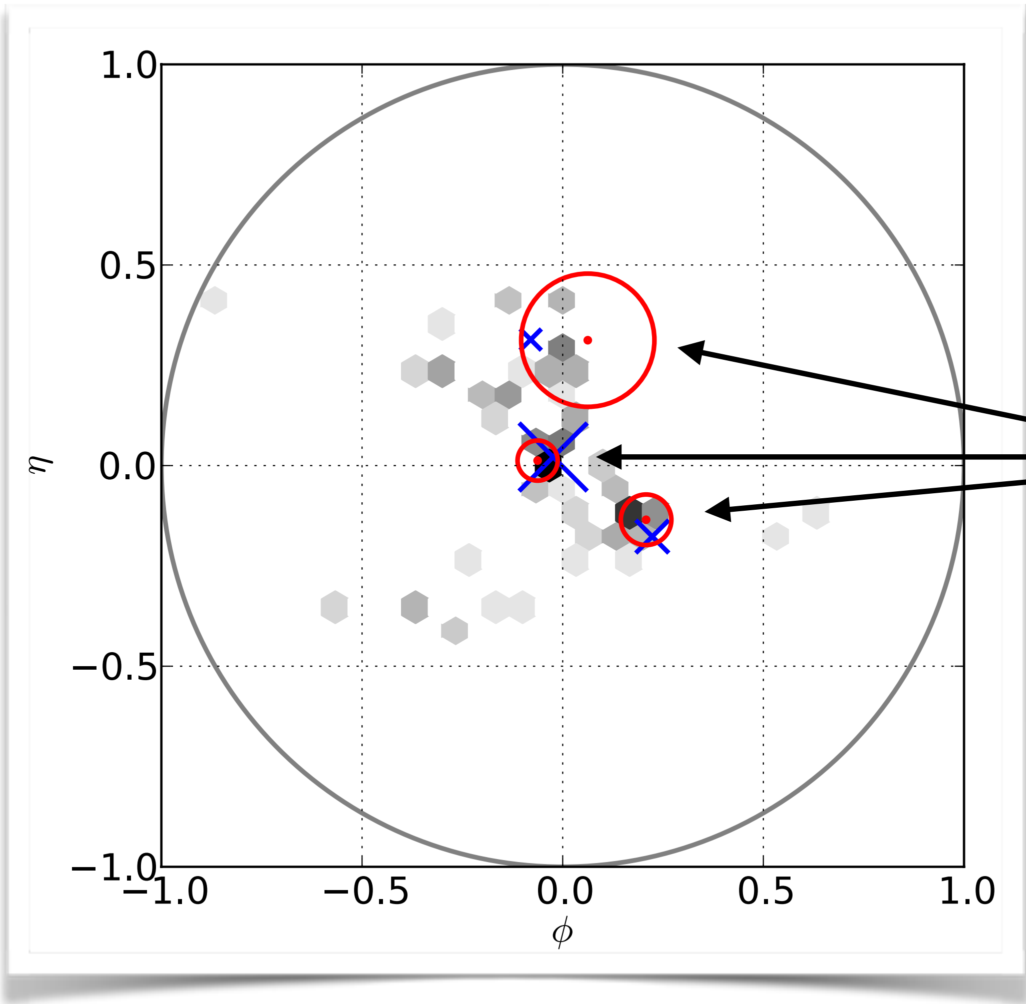


1. Pick out one configuration out of many possible 2-body decays of a boosted Higgs
2. For each template particle, add up the energy deposited within the template subcone…
3. …and subtract the template energy
4. Repeat for all other template particles and sum
5. Exponentiate the sum!
6. Repeat 1-5 for many possible template configurations
7. Choose the configuration with the best match to the given jet

$$Ov = \max_{\{F\}} \exp\left\{-\sum_a \frac{1}{2\sigma_a^2}\left[\sum_j p_{T,j} - p_{T,a}\right]^2\right\}$$

TOM vs. pileup

TOM properly tags the spiky energy depositions



Templates are sensitive ***only*** to energy deposition inside the template subcones

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

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

Pileup contribution to a template relative to the fat jet

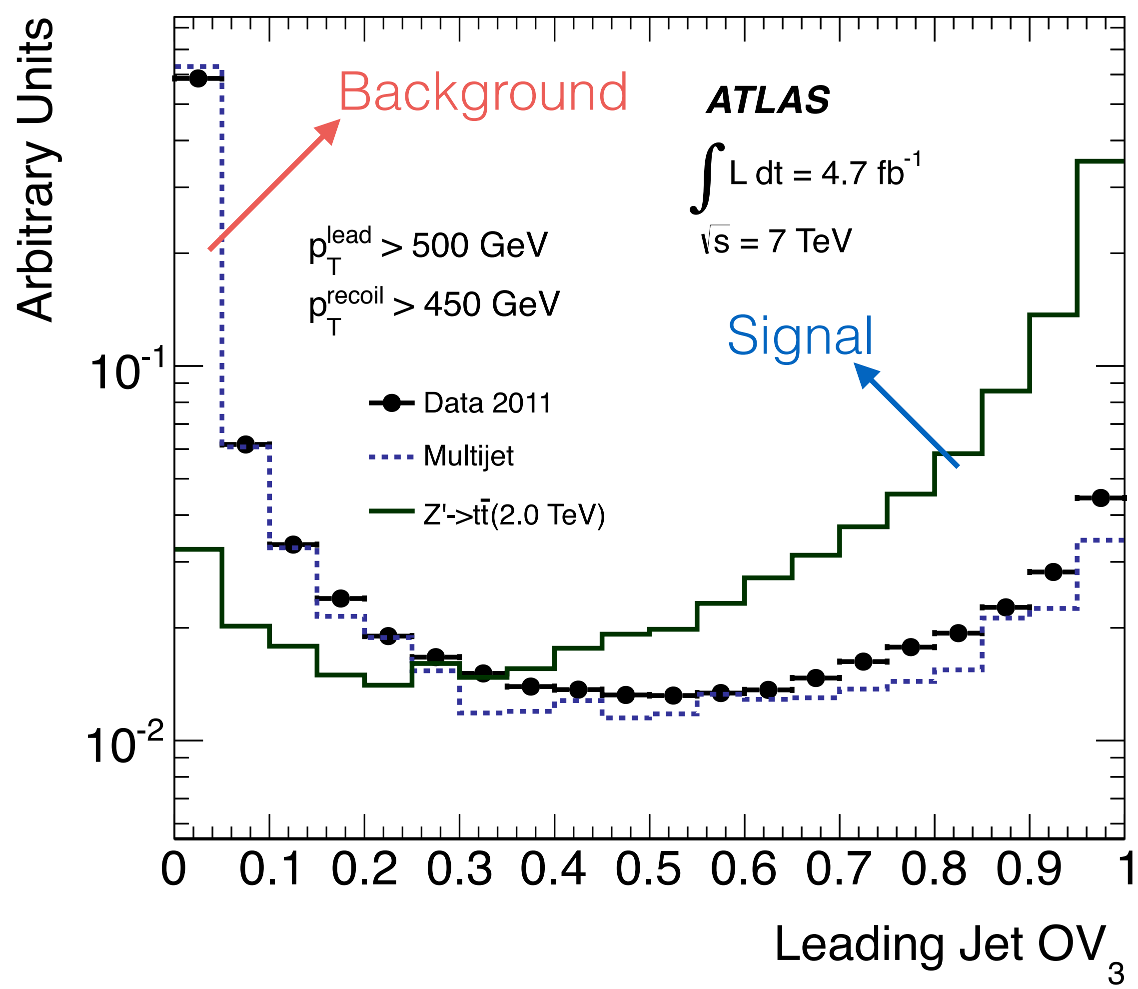
e.g. $n_{temp} \times r^2/R^2 \sim n_{temp} \times 0.1^2/1.0^2 = 0.01 \times n_{temp}$

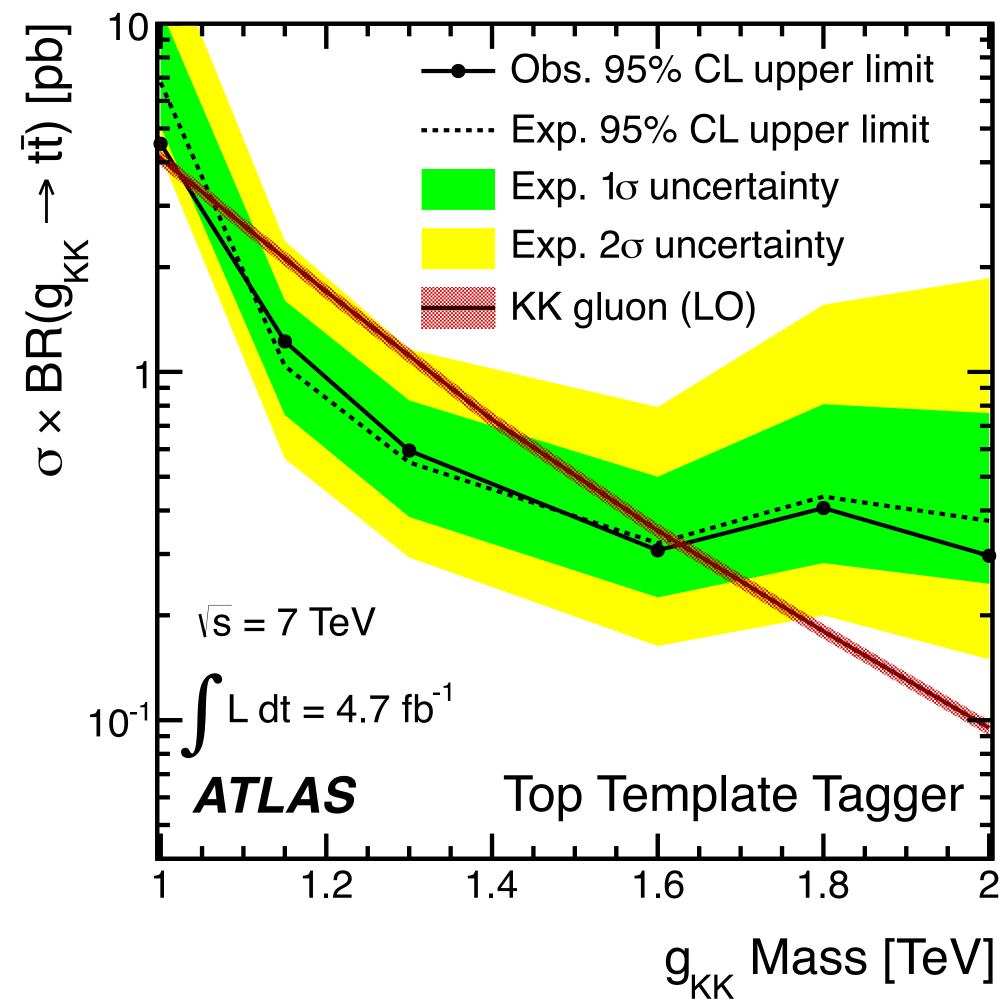
TOM @ ATLAS

(JHEP 1301 (2013) 116)

- An ATLAS study validated TOM at the 7 TeV LHC in the fully hadronic $t\bar{t}$ channel

- The results were also used to set an useful bound on Randall-Sundrum Kaluza-Klein gluon mass





TOM with missing energy

Backovic, Gabizon, JJ, Perez, Soreq, JHEP04(2014)176

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

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

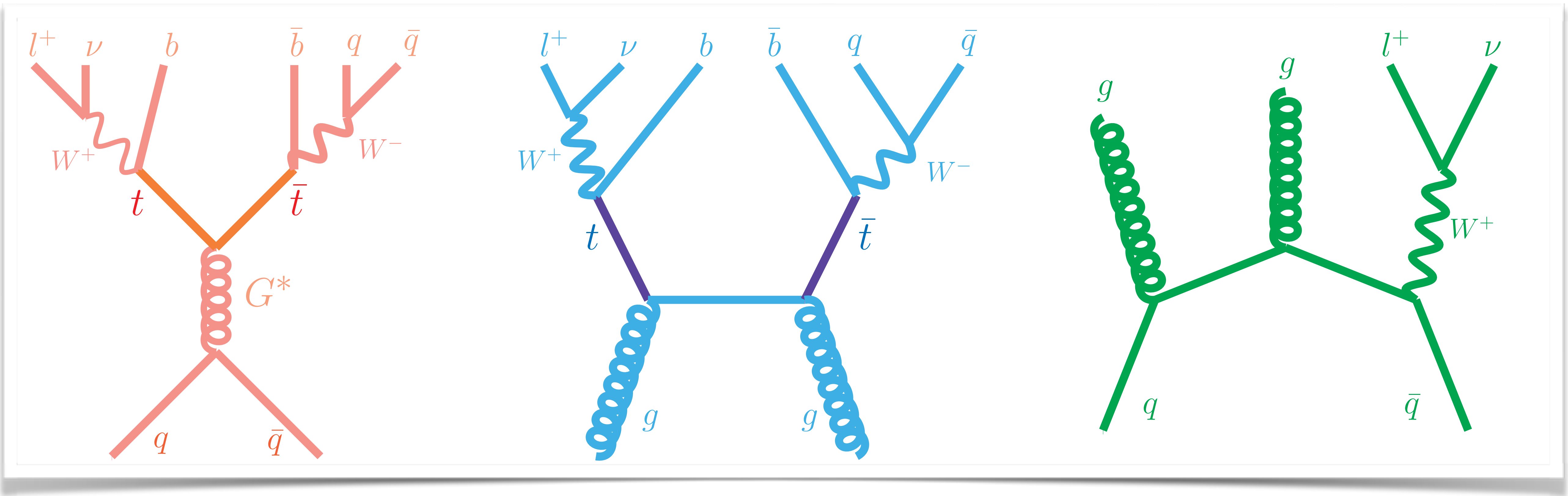
1. Only transverse component of the missing energy vector is included

2. Potential improvement in rejection and alternative to *b*-tagging!

Application of TOM

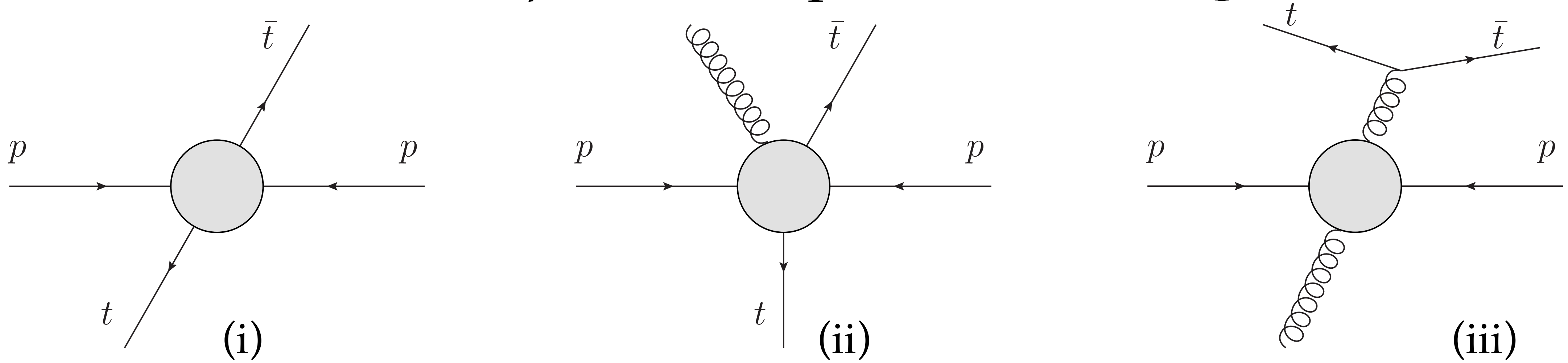
semi-leptonic KKG → $t\bar{t}$

signal | $t\bar{t}$ | W+jets



A close-up of high pT $t\bar{t}$ events

High energy events involve richer topologies, resulting in an imbalance between the p_T of the top and the antitop



- Asymmetric events (ii) and (iii) are of great importance to measure the SM top differential distributions

- On the other hand, an interesting NP signal like $pp \rightarrow KKG \rightarrow t\bar{t}$ would typically give rise to back-to-back $t\bar{t}$ pairs

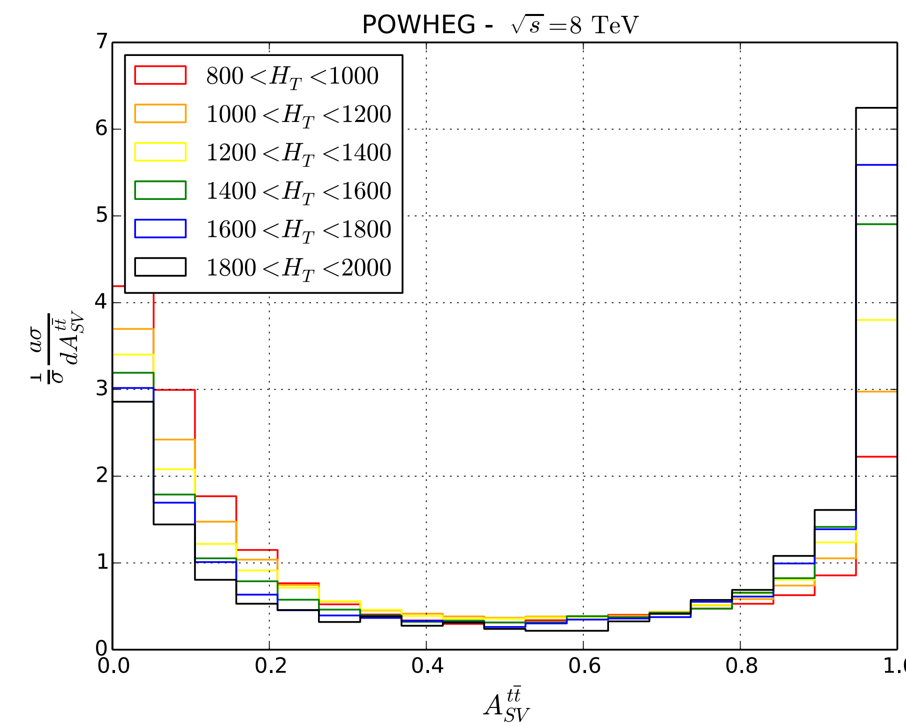
Tagging high pT $t\bar{t}$ events

Backovic, Gabizon, JJ, Perez, Soreq, JHEP04(2014)176

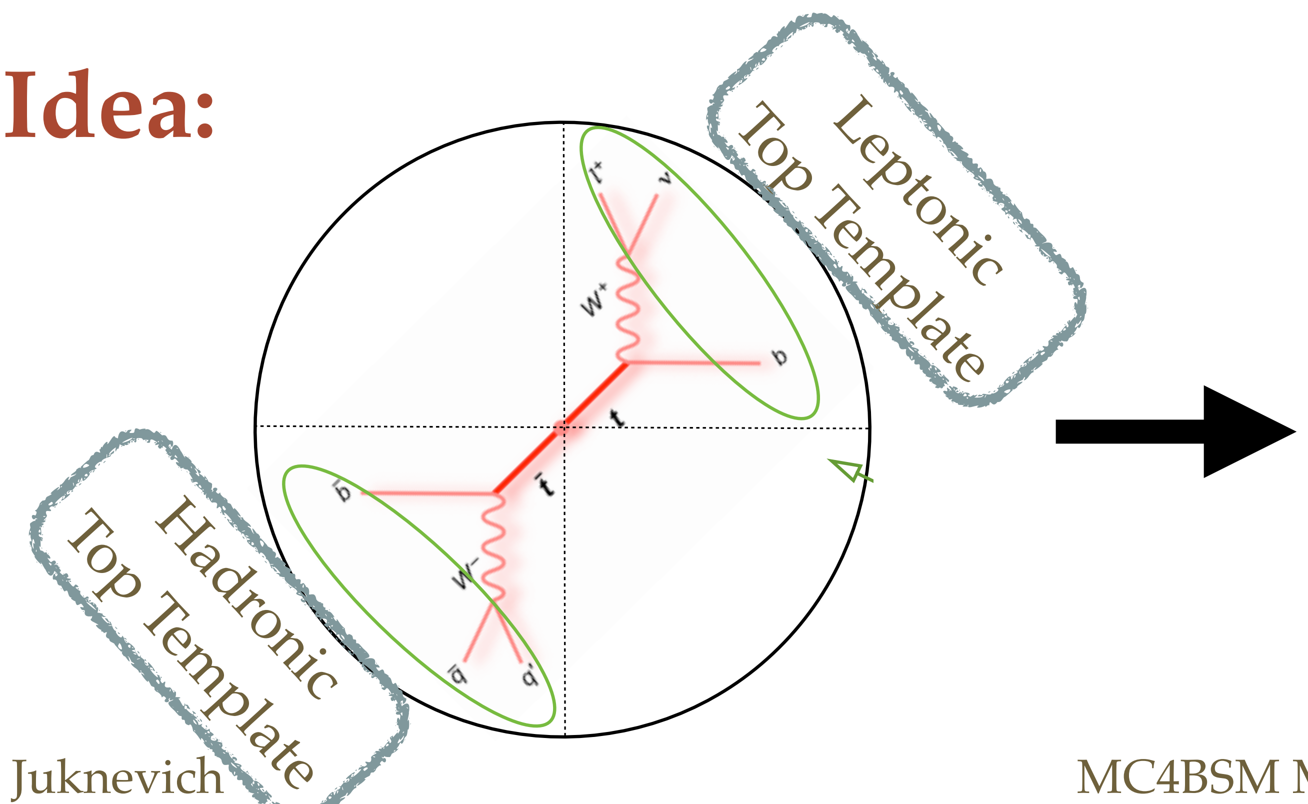
We define an asymmetry to quantify p_T imbalance

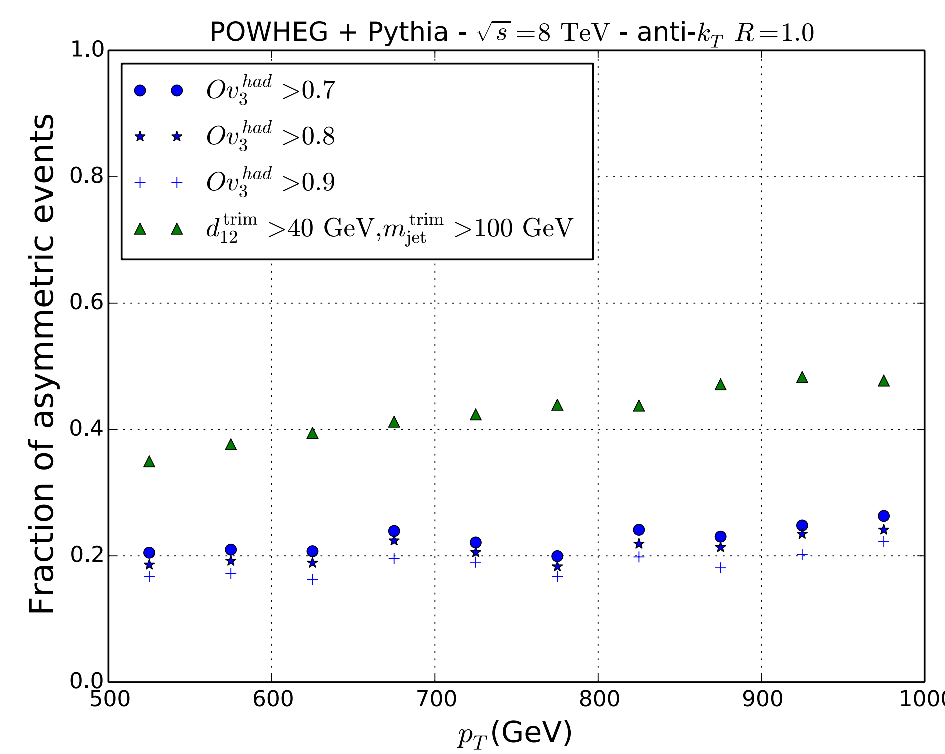
$$A_{t\bar{t}}^{\mathrm{SV}} = \frac{|\vec{p_T}^{\,t} + \vec{p_T}^{\,\bar{t}}|}{|p_T^t| + |p_T^{\bar{t}}|} \, ,$$

$$H_T^t = p_T^b + p_T^l + p_T^{miss}$$



Idea:



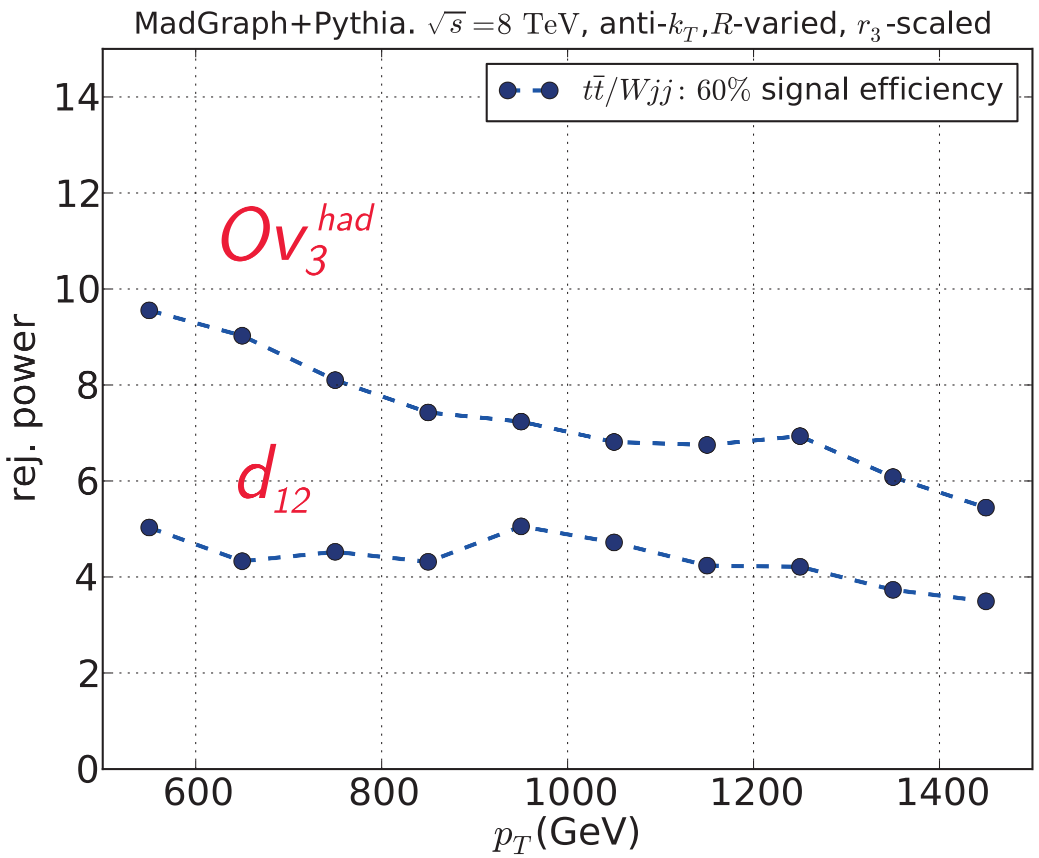


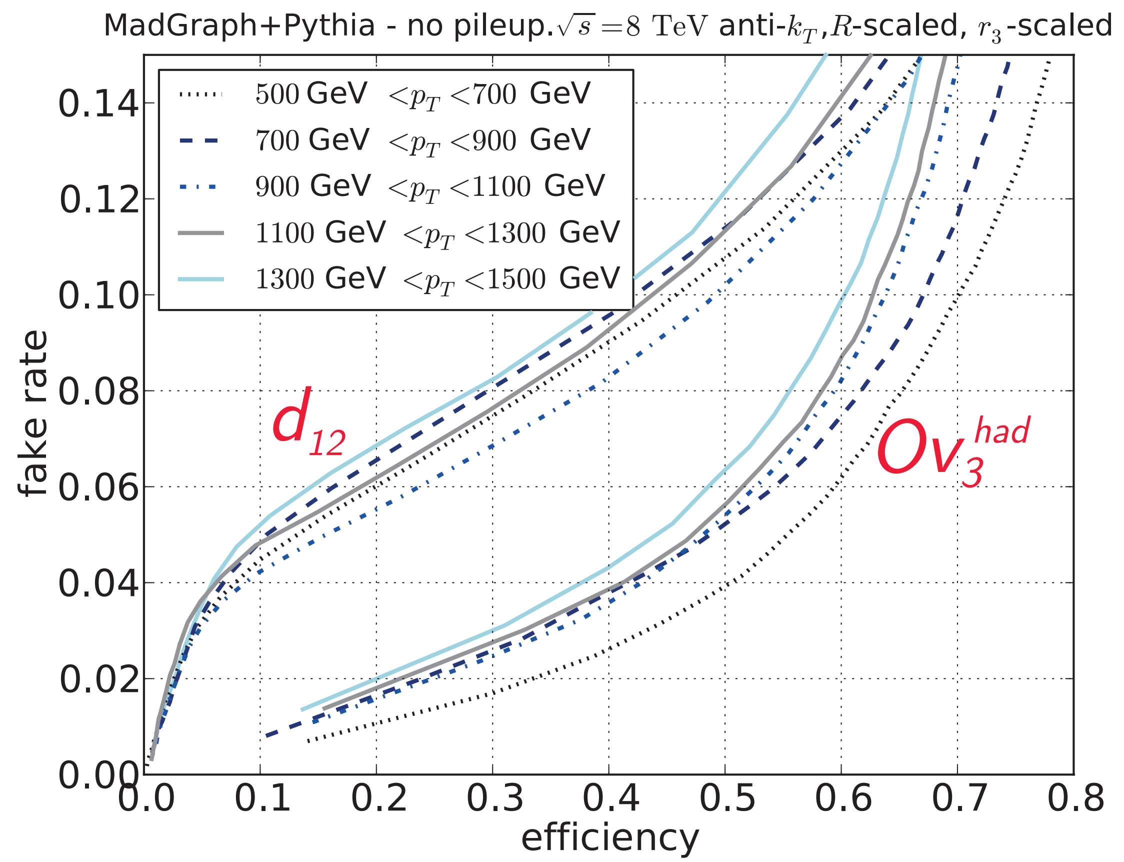
TOM background rejection

- Basic Cuts (BC)

$$p_T^{j\,R} > 500 \text{ GeV} \qquad \not{E}_T > 40 \text{ GeV}$$
$$N_\ell^{\text{out}}(p_T^\ell > 25 \text{ GeV}) = 1 \qquad N_j^{\text{out}}(p_T^j > 25 \text{ GeV}) \geq 1$$
$$\Delta\phi_{j\ell} > 2.3 \qquad |\eta_{j,\ell}| < 2.5\,,$$

+ One lepton with mini-ISO >0.95, at least one r=0.4 anti-kT jet within R=1.5 from the lepton

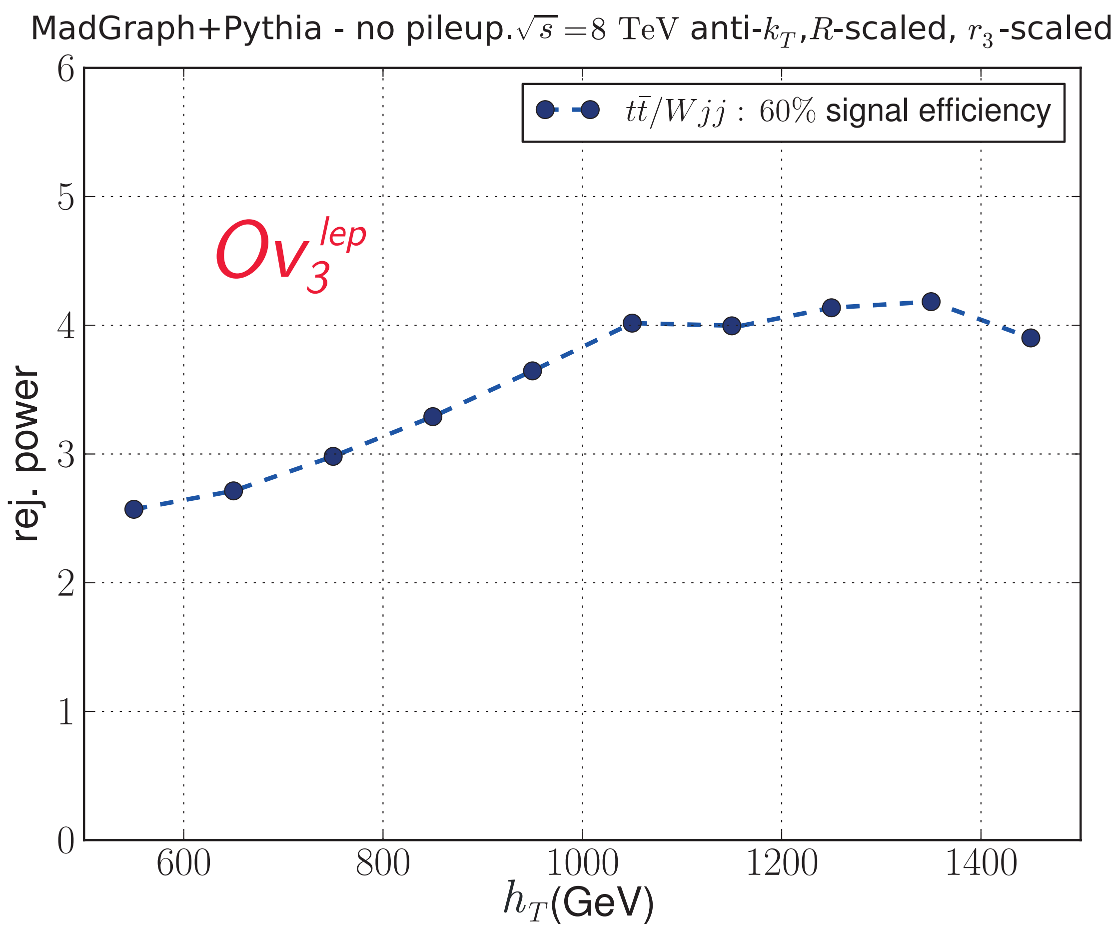


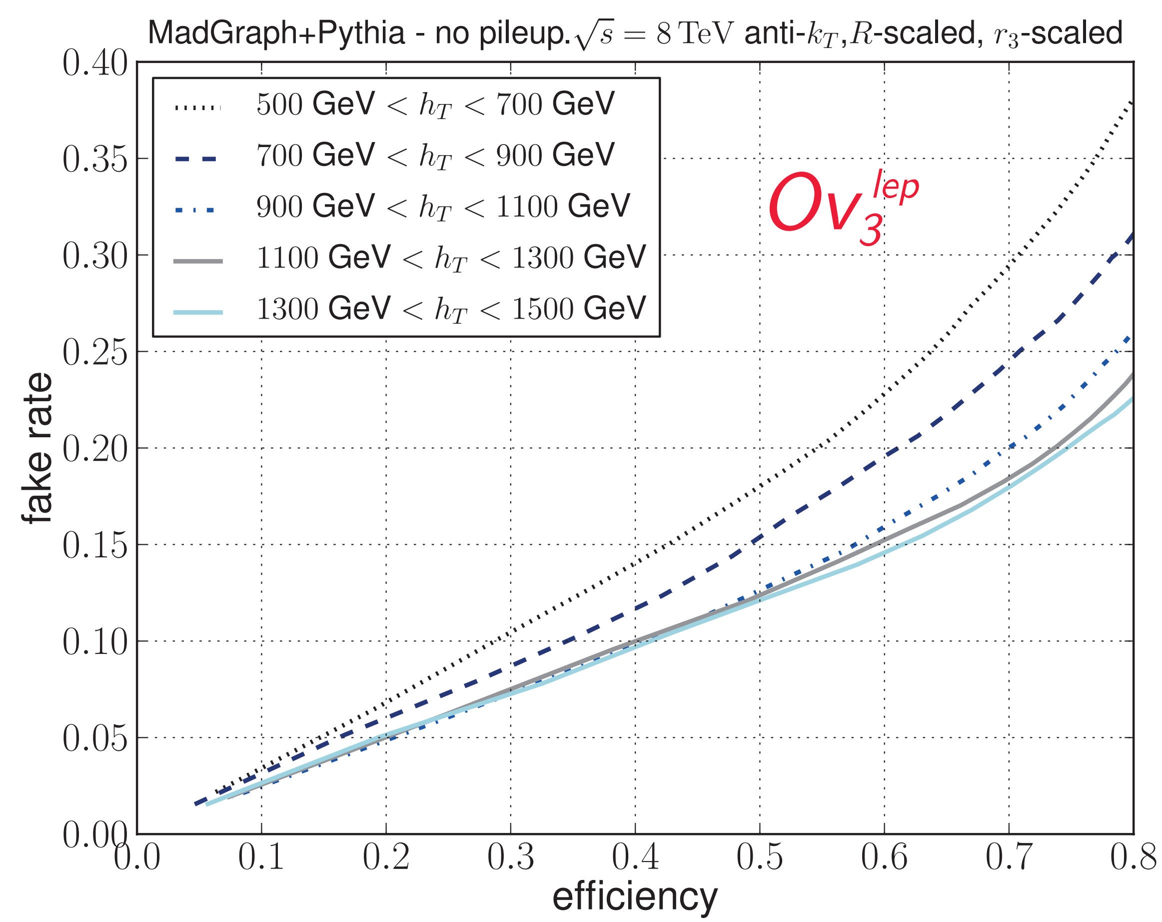


$$\text{RP} = \frac{\epsilon_{\text{sig}}}{\epsilon_{\text{bgd}}} \qquad \text{Efficiency} = \frac{\sigma(t\bar{t})^{\text{cuts}}}{\sigma(t\bar{t})^{\text{BC}}} \qquad \text{Fake} = \frac{\sigma(Wjj)^{\text{cuts}}}{\sigma(Wjj)^{\text{BC}}}$$

TOM background rejection

- Rejection power of the leptonic top tagger lower due to background already containing a W boson





$$H_T^t = p_T^b + p_T^l + p_T^{miss}$$

Alternative to b-tagging at high p_T

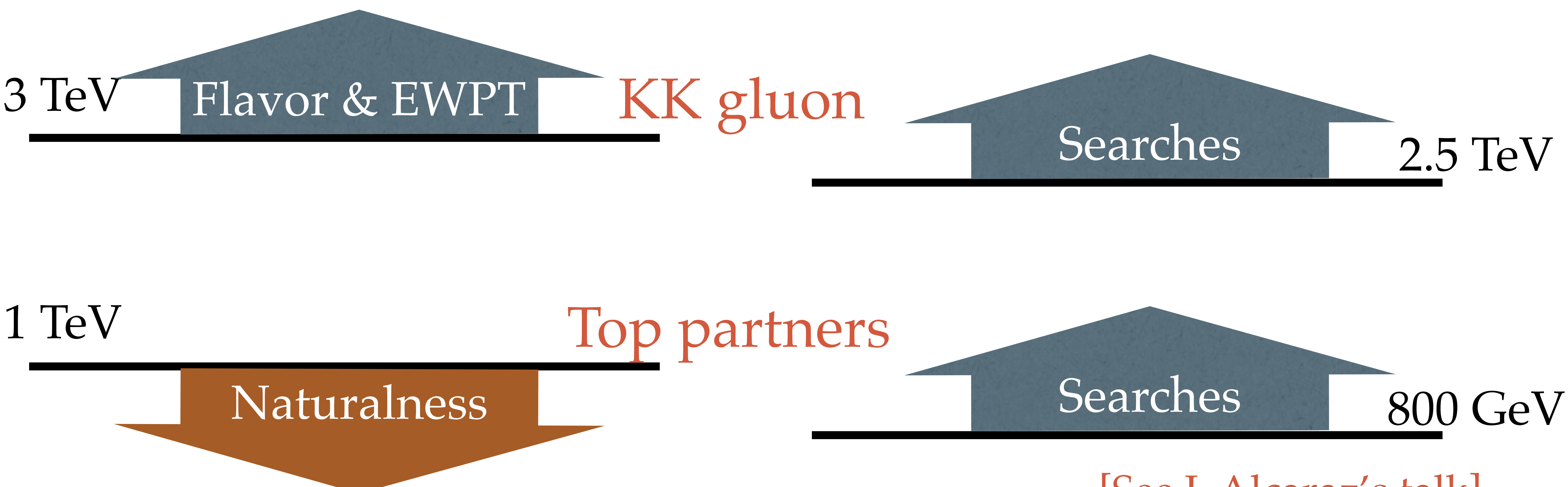
The elusive gluon

Chala, JJ, Perez & Santiago, to appear.

Do we search for the right thing?

- The KK gluon (G^*) is part of the composite sector, it has enhanced couplings to composite objects (t,T)

[See A. Wulzer's talk]



[See J. Alcaraz's talk]

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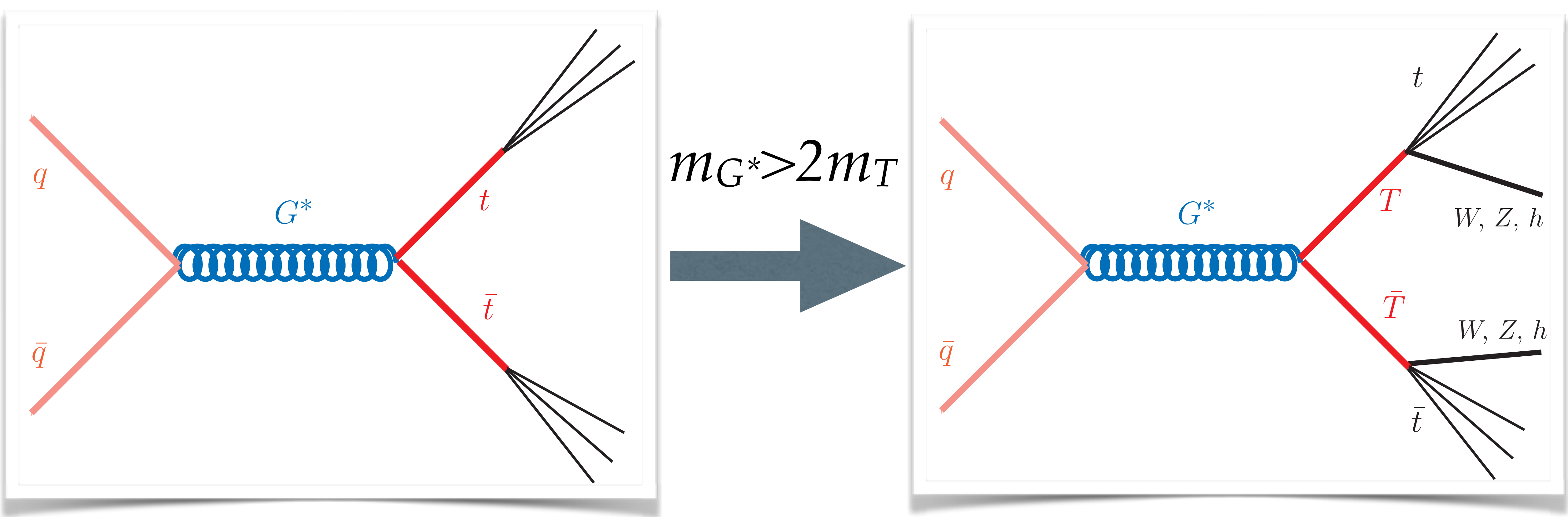


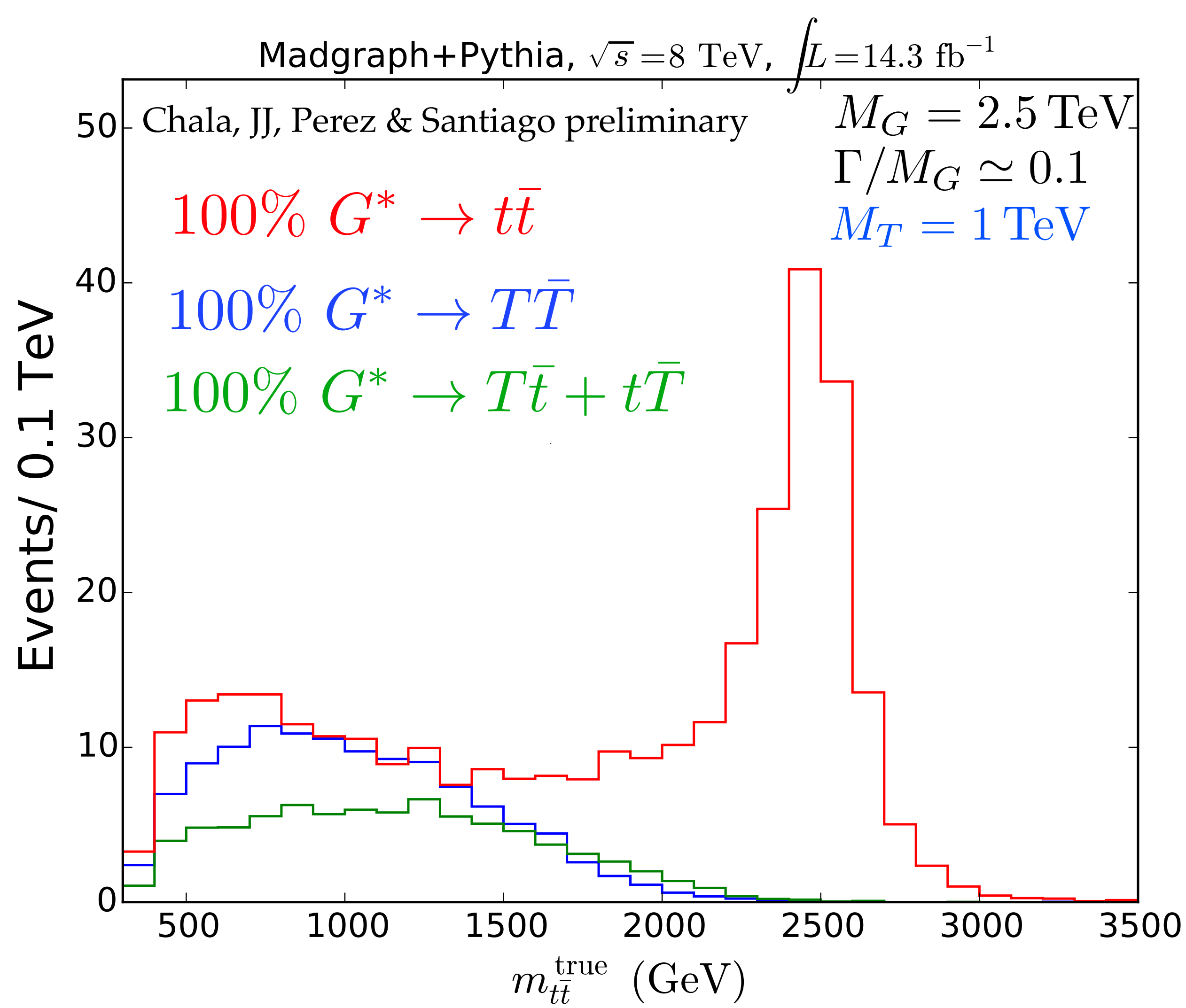
Implications for G* pheno'

Chala, JJ, Perez & Santiago, to appear.

- T decays to t+$W/Z/h$, but we search only for tops
  ➥observed spectrum becomes softer

Let us see it step by step

Partonic $t\bar{t}$ invariant mass



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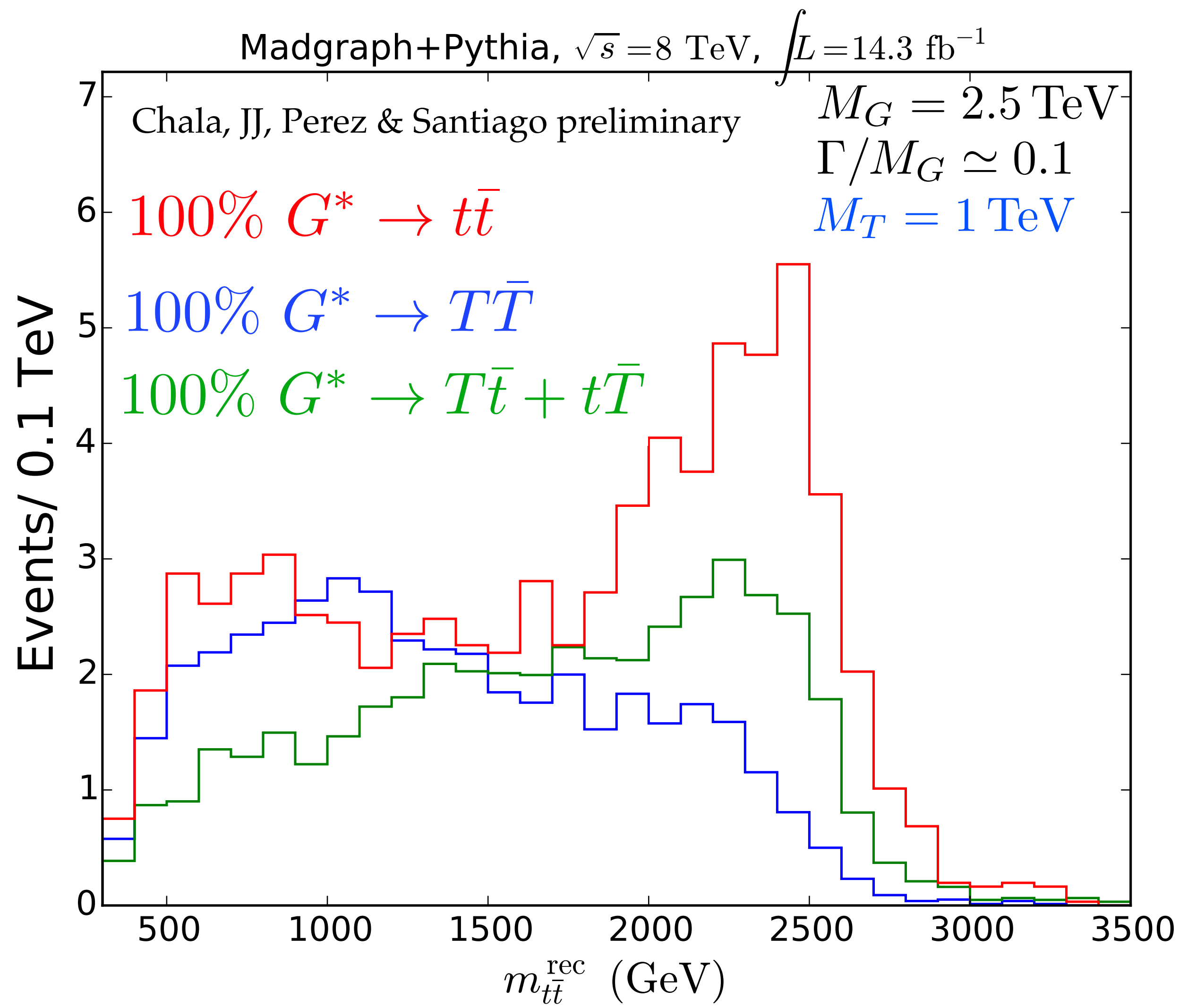
Reconstructed $t\bar{t}$ invariant mass



ATLAS reconstruction
ATLAS-CONF-2013-052

Implications for G* pheno'

Chala, JJ, Perez & Santiago, to appear.

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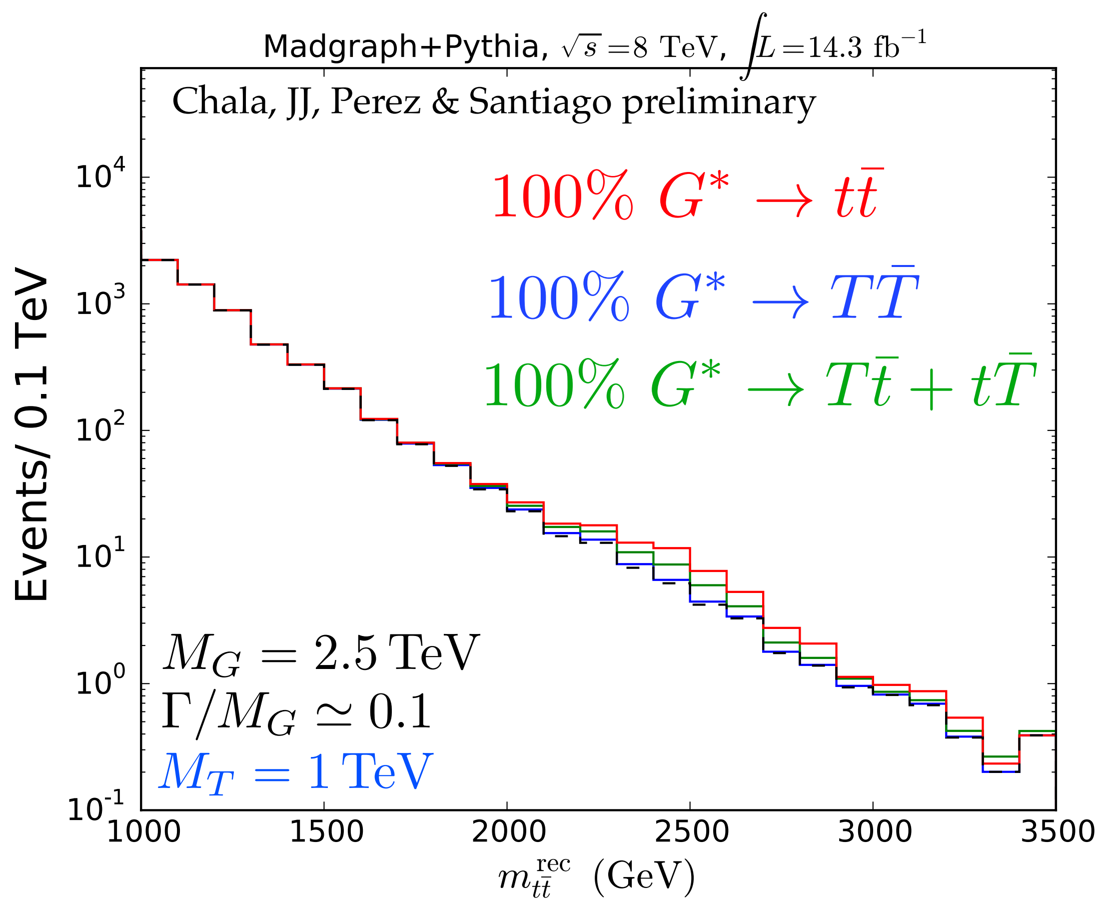
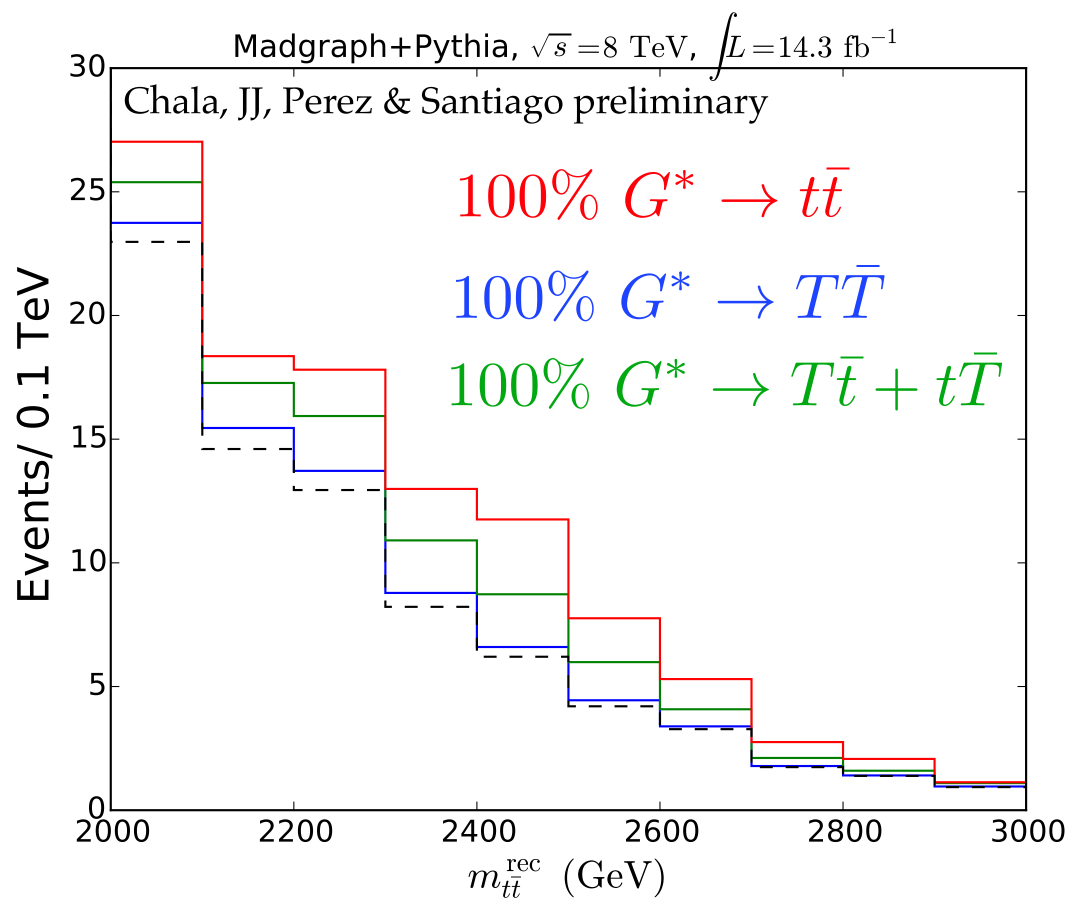
Let us see it step by step

adding SM $t\bar{t}$ reconstructed invariant mass





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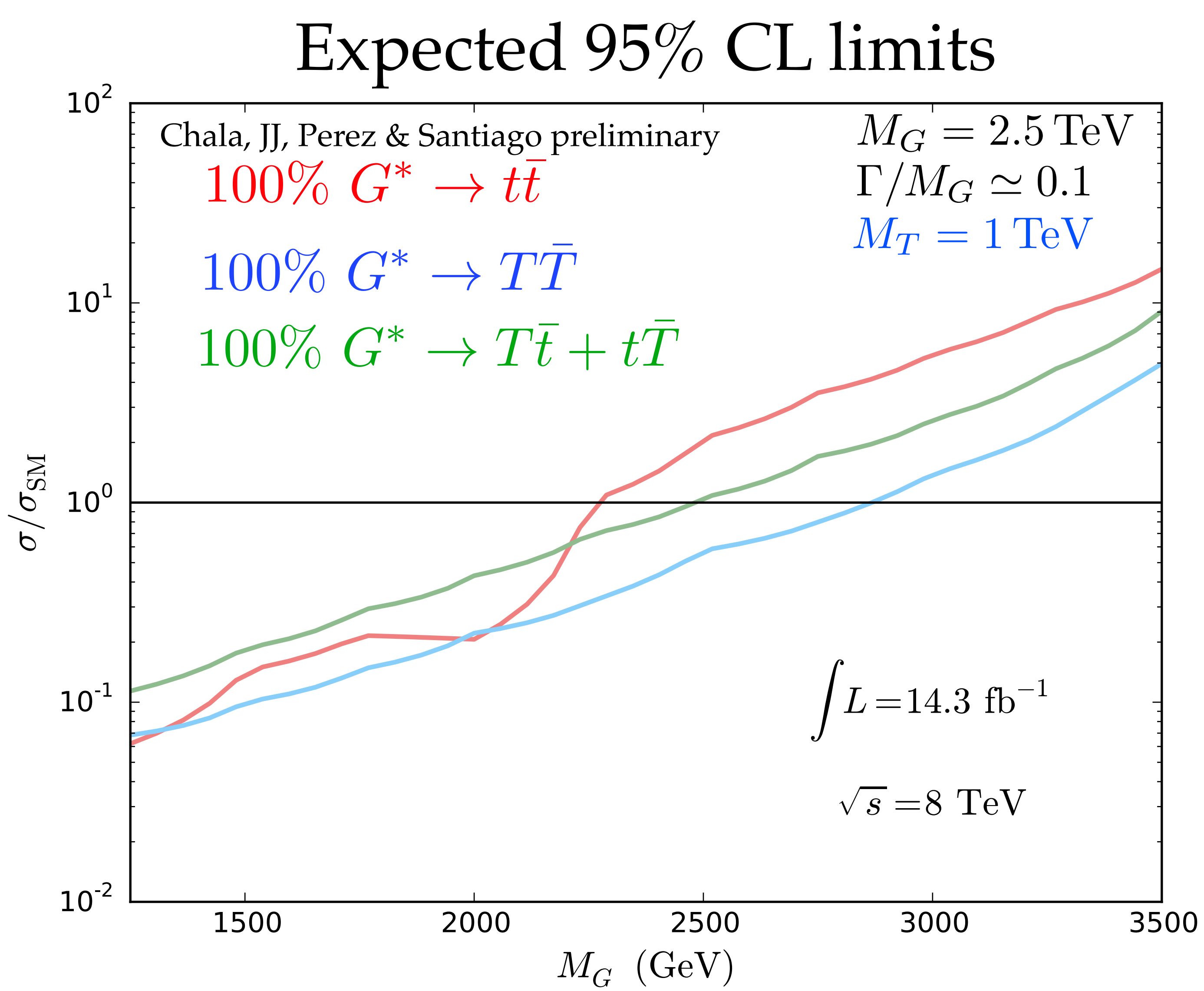


Summary

- Template Overlap is flexible enough to work with a variety of resonances and channels

- High-energy effects: boosted jet regime offers richer kinematics.

- TemplateTagger 2.0: currently being tested by ATLAS
  http://tom.hepforge.org

- Several models not yet adopted by experimental collaborations, besides the RS one: asks for a better tailored analyses.

- Thanks for your attention!

Searches for top-philic NP with TOM

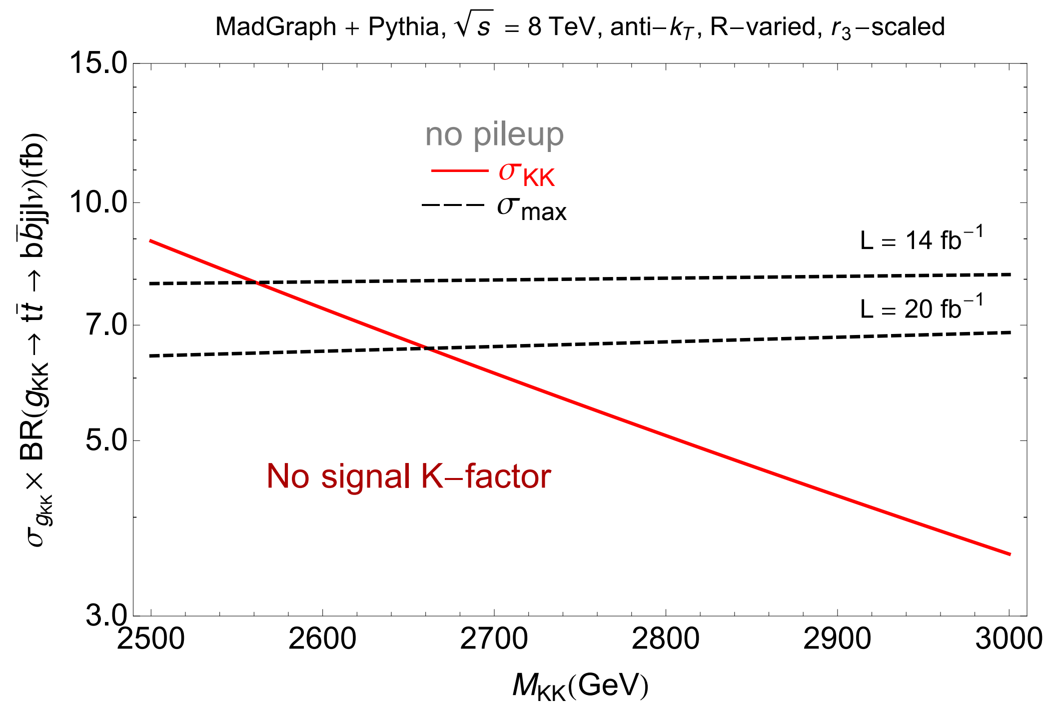
KK gluons from the bulk Randall-Sundrum model

$$g_L^{q\bar{q}} = -\frac{1}{5} g_s \,, \qquad g_R^{q\bar{q}} = -\tfrac{1}{5} g_s \,,$$
$$g_L^{b\bar{b}} = g_s \,, \qquad g_R^{b\bar{b}} = -\tfrac{1}{5} g_s \,,$$
$$g_L^{t\bar{t}} = g_s \,, \qquad g_R^{t\bar{t}} = 4 g_s \,,$$

$$\Gamma_{\mathrm{KK}} / M_{\mathrm{KK}} = 15\%$$

Only LO (+MLM) study!

Model	$M_{\mathrm{KK}} = 2.5$ TeV		$M_{\mathrm{KK}} = 3.0$ 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
$\sigma_{W+\mathrm{jets}}$ (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
$S/\sqrt{B}\,(14.3\,\mathrm{fb}^{-1})$	0.9	2.8	0.5	1.1	7.7	34
$S/\sqrt{B}\,(20.0\,\mathrm{fb}^{-1})$	1.1	3.3	0.6	1.3	9.1	40



- Improvement of S/B from 0.04 to 0.6
- 3 sigma after 20 fb
- Expected reach to improve in full NLO samples; asymmetry works in our favor!

Explicit model: MCH45

De Simone, Matsedonskyi, Rattazzi, Wulzer JHEP (13)

$$\Psi = \frac{1}{\sqrt{2}}\begin{pmatrix} i(B - X_{5/3}) \\ B + X_{5/3} \\ i(T + X_{2/3}) \\ X_{2/3} - T \end{pmatrix}$$

Resonances
in **4** of SO(4)

SM in **5** of SO(5)

$$(Q_L^5)_I = \frac{1}{\sqrt{2}}\begin{pmatrix} ib_L \\ b_L \\ it_L \\ -t_L \\ 0 \end{pmatrix}$$

t_R composite

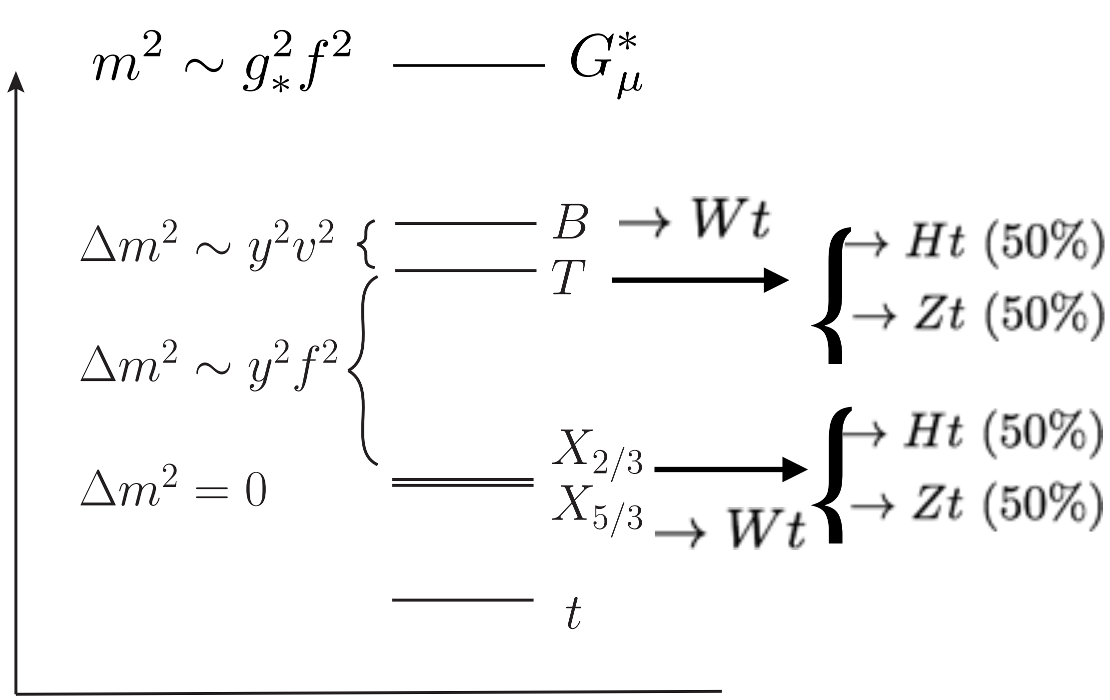
$$\begin{aligned}\mathscr{L}^{\mathbf{M4}_5} = \; & i\,\bar{q}_L \not{D}\, q_L + i\,\bar{t}_R \not{D}\, t_R + i\,\bar{\Psi}(\not{D} + i\not{e})\Psi - M_\Psi \bar{\Psi}\Psi \\ & + \left[i\,c_1\,(\bar{\Psi}_R)_i\,\gamma^\mu d^i_\mu\, t_R + y f\,(\overline{Q}^{\mathbf{5}}_L)^I U_{I\,i}\,\Psi^i_R + y\,c_2 f\,(\overline{Q}^{\mathbf{5}}_L)^I U_{I\,5}\, t_R + \text{h.c.}\right]\end{aligned}$$

$$s_h = \sin(h/f)$$

Goldstone matrix
Unitary gauge

$$U = \begin{pmatrix} 1_{3\times 3} & 0 & 0 \\ 0 & c_h & s_h \\ 0 & -s_h & c_h \end{pmatrix}$$

Typical spectrum



But this is very
model dependent
(very sensitive to
parameters)