Higgs Hunting with the Template Overlap Method

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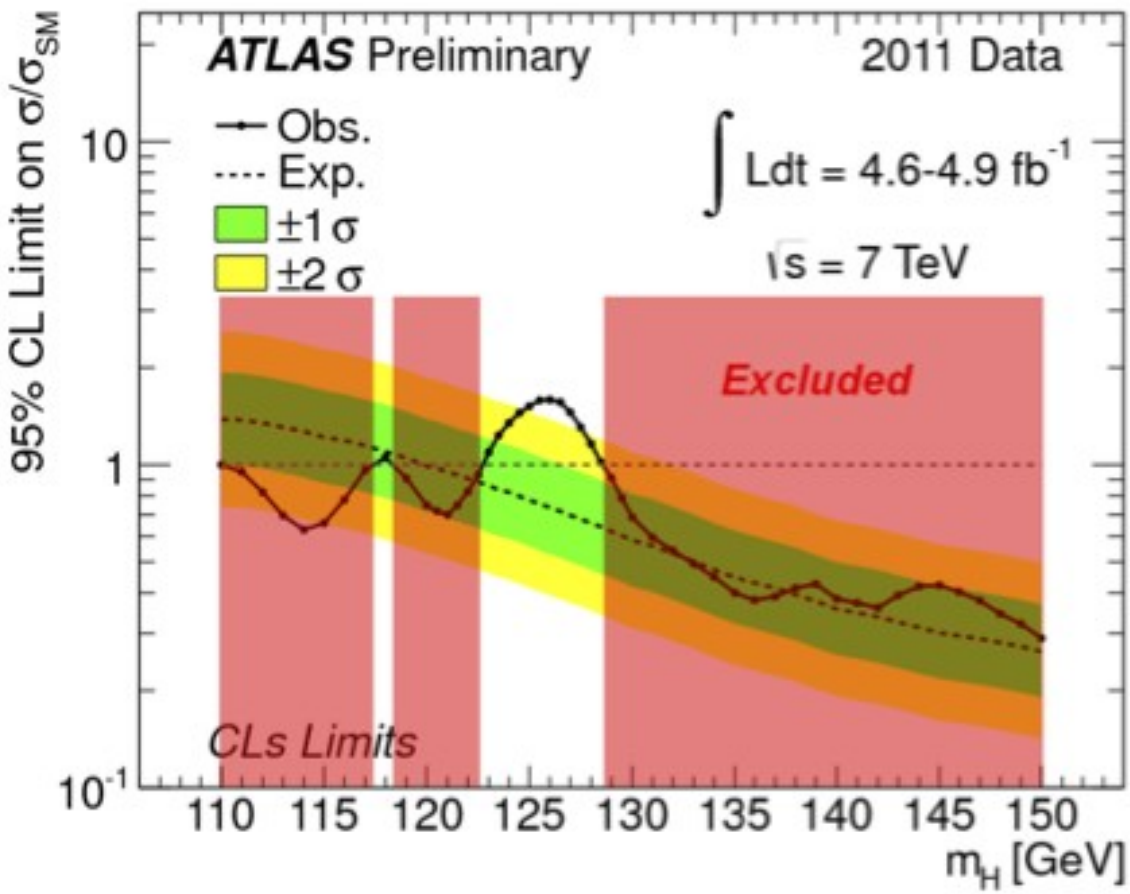
- Implications of LHC results for TeV-scale physics
- March 2012

Based on:

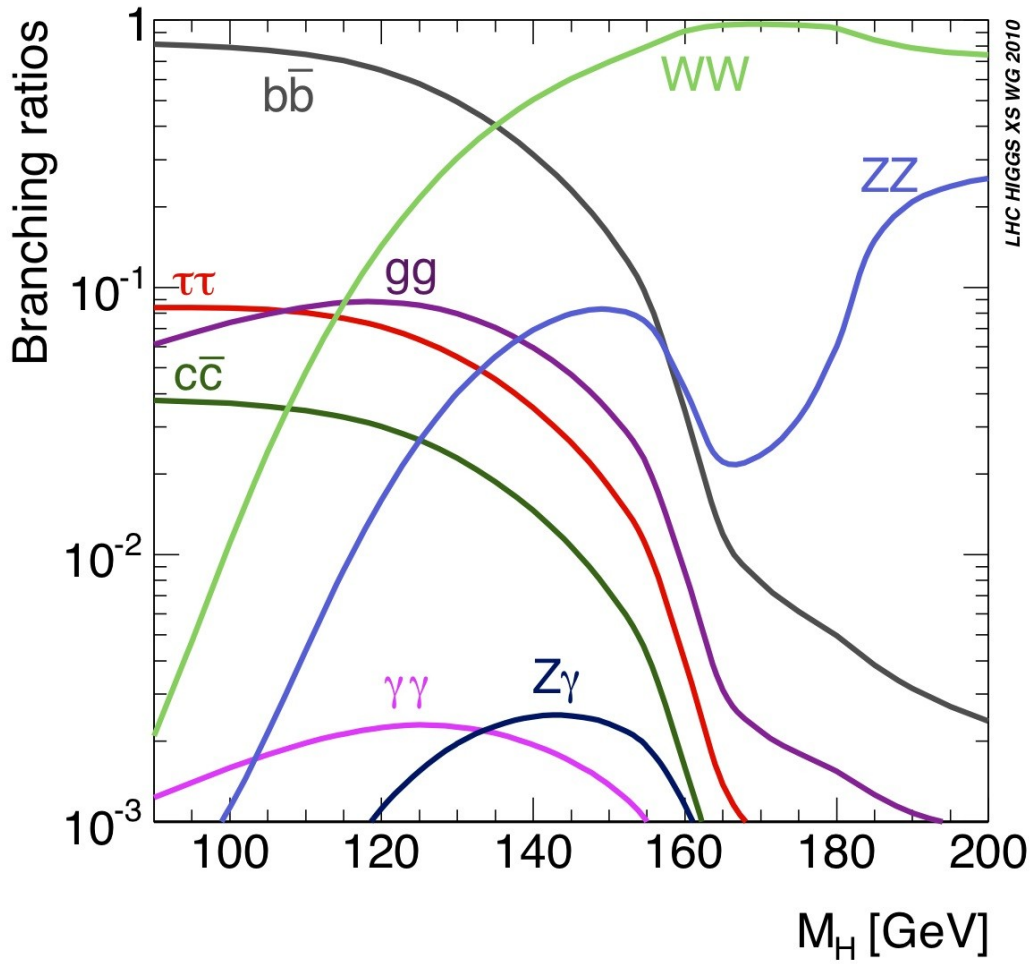
L. Almeida, O. Erdogan, JJ, S.J. Lee, G. Perez and G. Sterman, ``Three-particle templates for boosted Higgs,'' arXiv:1112.1957 [hep-ph].
M. Backovic, JJ, G. Perez and J. Winter, in preparation.

Current status of Higgs searches



Favors light Standard Model Higgs

LHC Higgs searches in 115-130 GeV

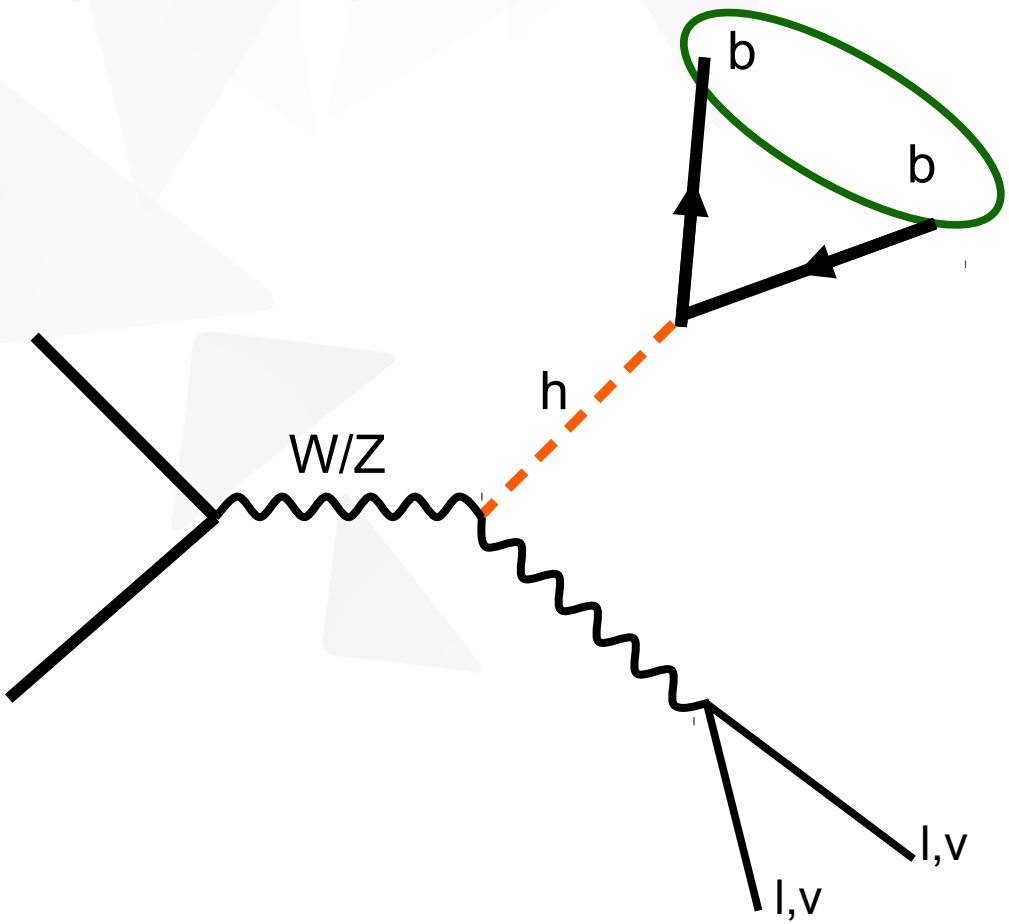


H decay to bb is dominant decay mode for low mass H
However, the background is huge in the gg ⟶ H channel

Search for boosted Higgs

Butterworth, Davison, Rubin, Salam (2008)

- Look for associated WH and ZH production
- Use the leptonic decay mode of the W/Z to suppress QCD bkg



$$h \to b\bar{b}$$

$$\Delta R \sim 2m_H / p_T$$

$$p_T^j = 200\,\mathrm{GeV}$$

$$\Rightarrow \Delta R \sim 1.2$$

Typical jet size

$$\Delta R \sim 1.2$$

But... QCD is our enemy

- The signal is not easily separated from the background
- Even such exotic states will coexist with substantial tail of the mass distribution of light parton QCD jets.
  - collinear splittings => easy to get several “hard” partons emitted into a small solid angle
  - jet mass ~ sqrt(α_s)*p_T*R ~ 100 GeV
  - Size too large compared to ΔR => messed-up jet-mass measurements
- Thus, it will generaly be necessary to use jet substructure systematically to identify the states that initiated the jets
  - Provide with an additional tool to separate signal from background
  - Keep the interesting radiation; eliminate the junk: pileup/UE

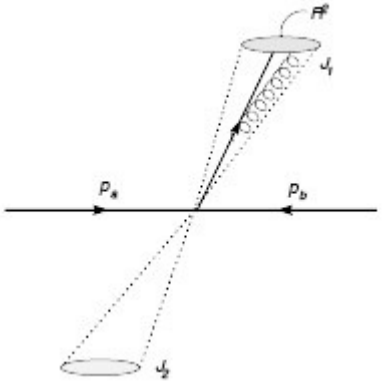
Substructure, basic approaches

Not an exhaustive list

- Filtering
  - Butterworth, Cox, Forshaw;
  - Thaler, Wang;
  - Kaplan, Rehermann, Schwartz, Tweedie;...
  - Butterworth, Davison, Rubin, Salam;
  - Plehn, Salam, Spannowsky;
  - Ellis, Vermilion, Walsh;
  - Krohn, Thaler,Wang;...
- Moments — Almeida, Lee, Perez, Sterman, Sung, Virzi Gur-Ari,Papucci, Perez;...
- Template Overlap Method — Almeida, Lee, GP, Sterman & Sung (10).

Substructure, two-pronged decays

- To LO, there are only two variables
  - Mass
  - Energy ratio or angle (i.e. angularity)



- QCD

$$\frac{d^2\sigma}{dm_J^2 d\theta} \propto \alpha_s \frac{C_F}{m_J^2} \frac{1}{\theta}\Bigg|_{R>\theta>\frac{m_J}{E_J}}$$

- Higgs

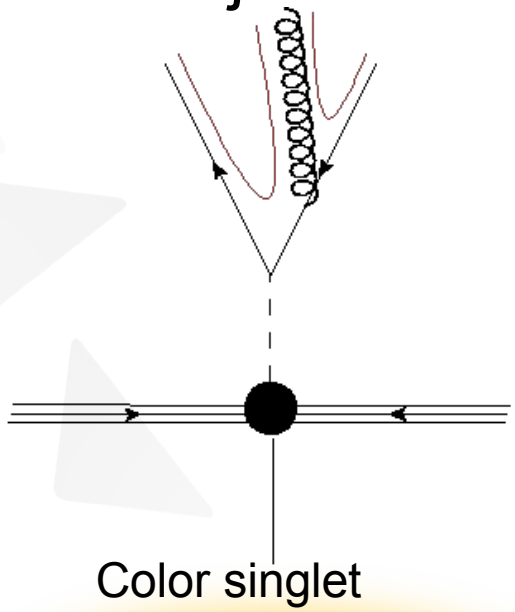
$$\frac{d^2\sigma}{dm_J^2 d\theta} \propto \delta(m_J^2 - m_H^2) \frac{1}{\theta^3}\Bigg|_{R>\theta>\frac{m_J}{E_J}}$$

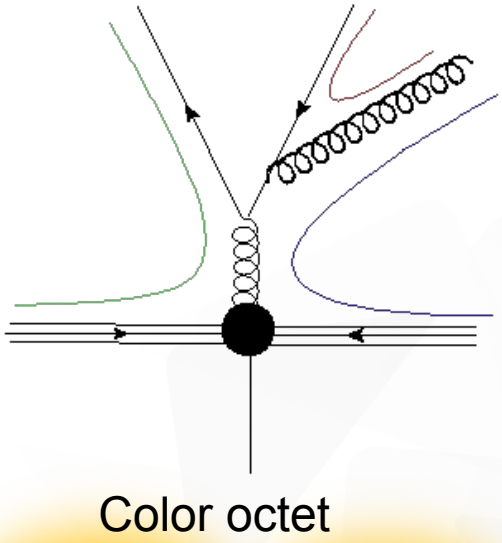
Only quantitative difference, very similar distributions

How to go ahead?

Sung;Gallicchio, Schwartz

- Additional difference between H->bb and g->bb
  - H is color singlet: b's must have same color and are color connected together
  - g is color octet: b's have different color and are connected to beam or other jets

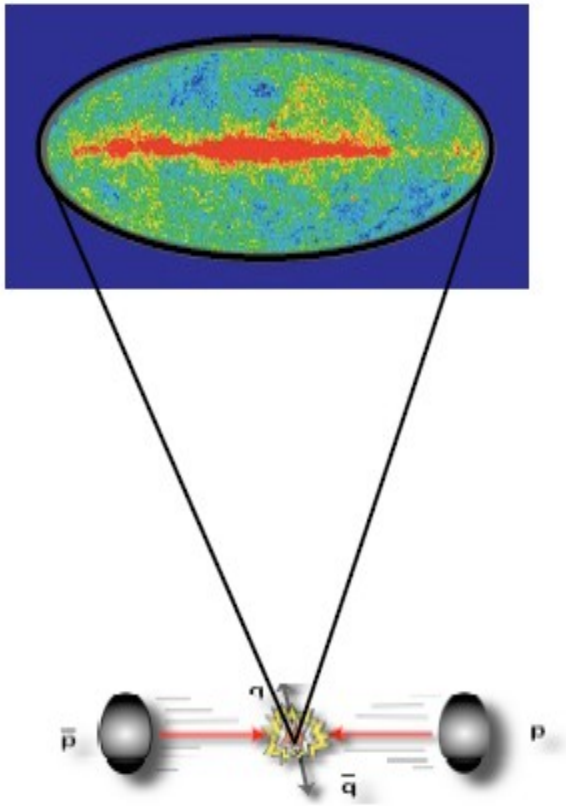




Need to understand the energy flow inside jet
jet shapes or jet substructure

- Find observable correlated with parton shower and hadronization
- Capture leading gluon radiation
- Toss away the junk: UE/pileup

- We can characterize the signal via spikes of energy, that we can calculate in pQCD.



Template Overlap Method

2-body template => LO, $h \to b\bar{b}$.

3-body template => extra gluon, $h \to b\bar{b}g$.

Template Overlap Method

L. Almeida, S. Lee, G. Perez,
G. Sterman, & I. Sung '10

- Functional measure for the quantitative comparison of the energy flow of observed jets at high-pT with the flow of selected sets (the templates) of partonic states

$$\langle j|f\rangle = \mathscr{F}\left[\frac{dE(j)}{d\Omega}, \frac{dE(f)}{d\Omega}\right]$$

- Our templates will be sets of partonic momenta $f = \{p_1, p_2, \ldots, p_n\}$

$$\sum_{i=1}^{N} p_i = P, \; P^2 = M^2$$

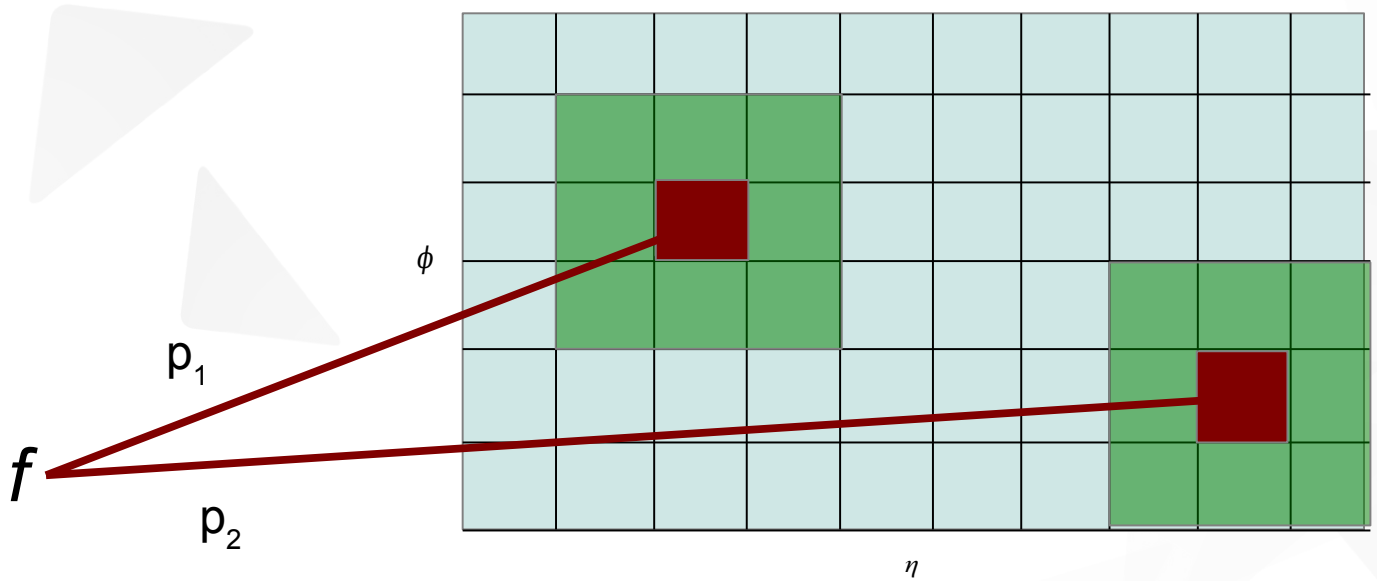
- For a given jet j, we determine the template state f[j] for which the measure is maximized:

$$Ov(j, f) = \max_{\{f\}} \mathcal{F}(j, f)$$

Example

- We compute the overlap between data state j and N-body template f from the sum of the energy in the nine cells of state j surrounding and including the cells of template f

$$Ov_N(j,f) = \max_{\tau_N^{(R)}} \quad \exp\left[- \sum_{a=1}^{N} \frac{1}{2\sigma_a^2} \left(\sum_{k=i_a-1}^{i_a+1} \sum_{l=j_a-1}^{j_a+1} E(k,l) - E(i_a,j_a)^{(f)} \right)^2 \right]$$



The observables: Implementation

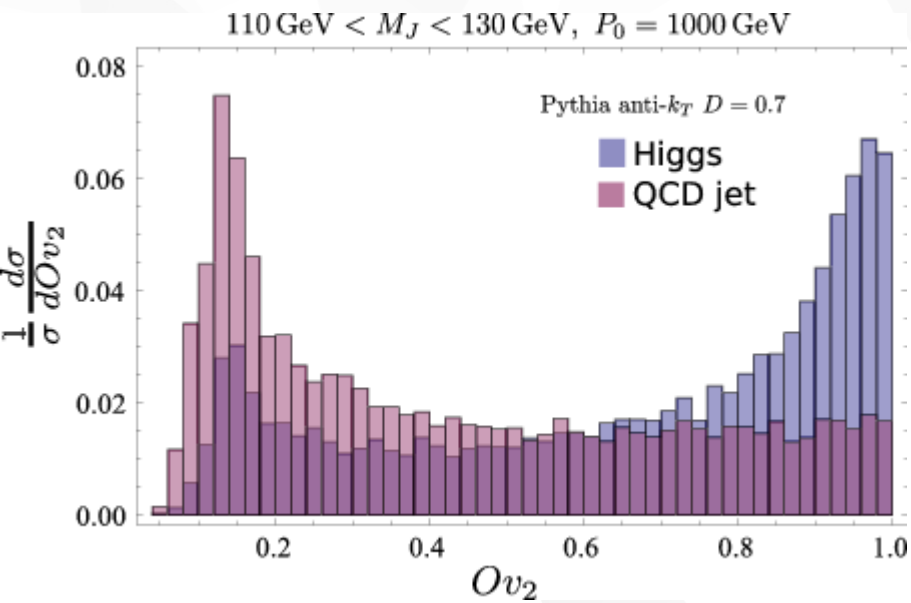
- Build antikT jets with large cone sizes (1.0, 1.2 and 1.4)
- Pre-selection based on the “classic” variables:
  - MET, lepton pT, Jet pT, Jet mass, ... b-tag
- For given *j*, find $Ov(j,f) = \max_{\{f\}} F(j,f)$
- Use the best matched templates *f*[*j*] to calculate additional parameters: planar flow (Pf), angularity (tau_{-2}), ...
- Use the separation power of the new variables (Ov_2 Ov_3 pf and angularity) to further suppress QCD background

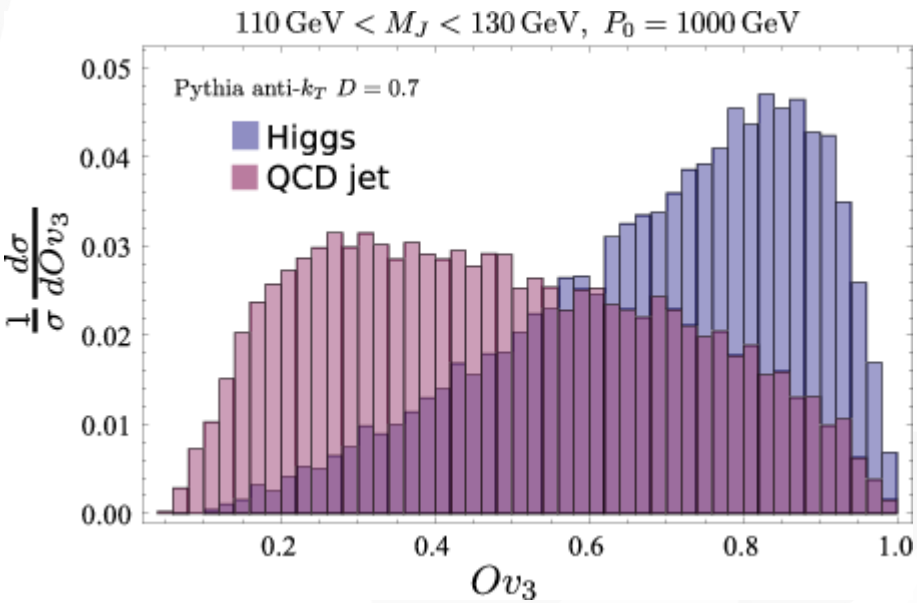
First look at the overlap observables

L. Almeida, O. Erdogan, JJ, S. Lee,
G. Perez, & G. Sterman (1112:1957)

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

$$|f\rangle = |h\rangle^{(\mathrm{NLO})} = |p_1, p_2, p_3\rangle$$





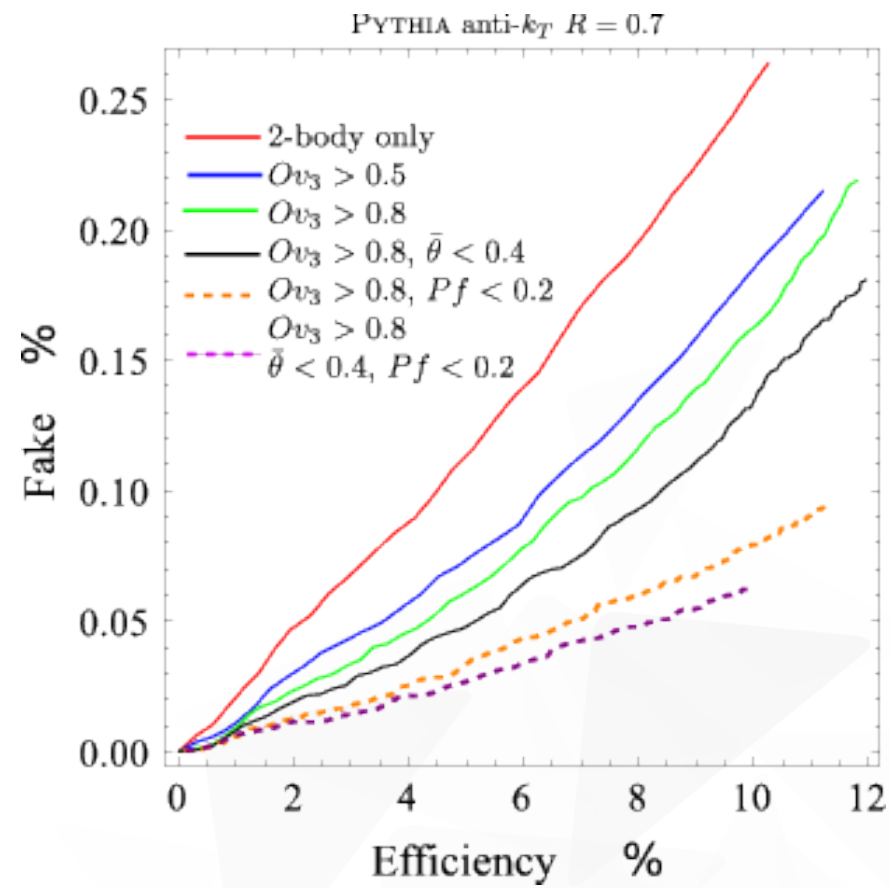
Histograms of template overlap Ov with Higgs jets and QCD jets from Pythia 8, for $R = 0.5$, 950 GeV$\leq P_0 \leq$1050 GeV, 110 GeV$\leq m_J \leq$130 GeV and m_{higgs} = 120 GeV using 2-body templates (Left) and 3-body templates (Right).

Can use best matched template to compute other shapes: angularities, Pf,...

Template Overlap works well for TeV jets

L. Almeida, O. Erdogan, JJ, S. Lee,
G. Perez, & G. Sterman (1112:1957)

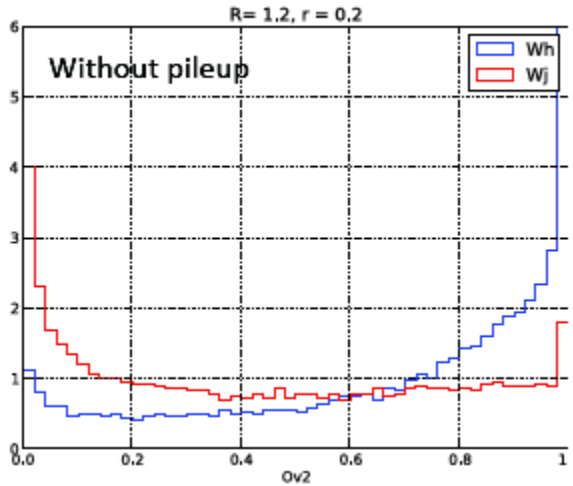
Rejection rates of ~100
Before b-tagging possible
With efficiency of 10%



Can we do the same (or better) for moderate pT?

M. Backovic, JJ, G. Perez and J. Winter, in preparation.

$p_T \sim 200\,\mathrm{GeV}$



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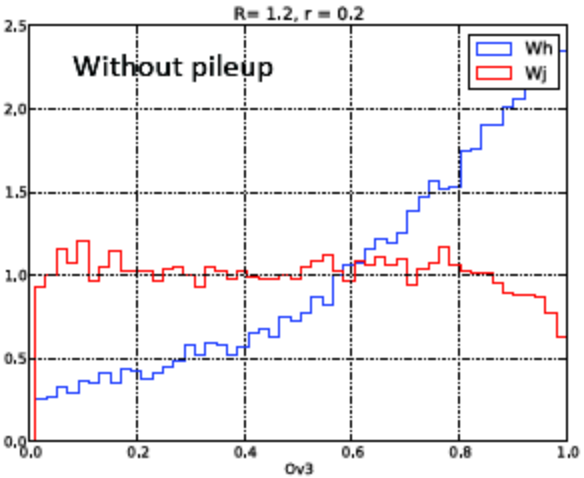
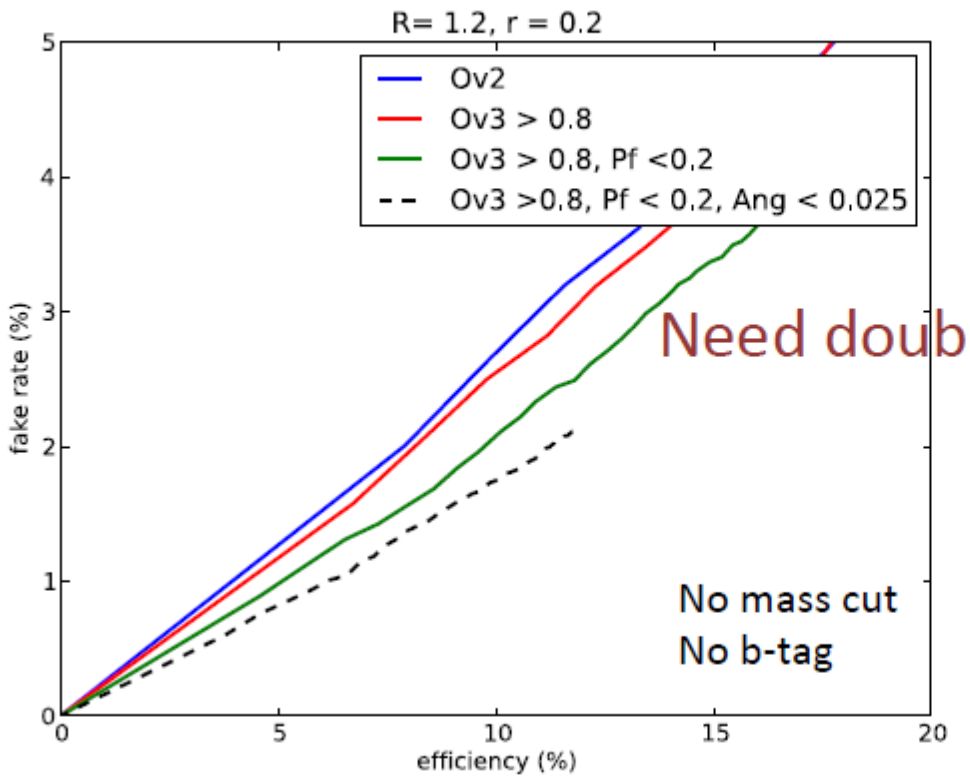


Clear separation
Of signal and background
still present

Rejection power before pileup



For 10 % efficiency rejection Factor of ~ 5.

Total rejection factor:

Need double b tag

15 - *mass cut*
x 40 - *b-tagging*
x 5 - *template+pf*

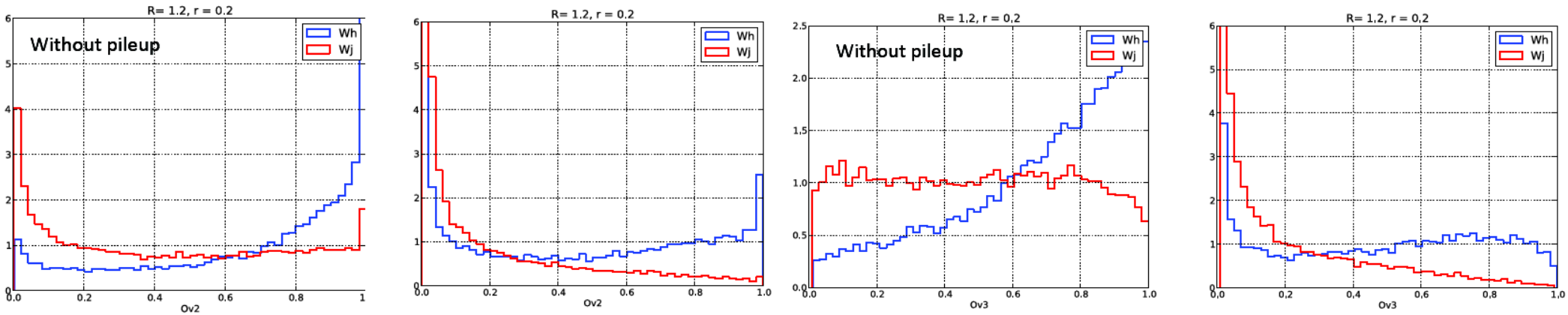
= 3000

Not using other variables such as partonic angle, angularity or planar-flow ...

Pileup effects

Two-Body Overlap w/pileup

Three-Body Overlap w/pileup



Pileup

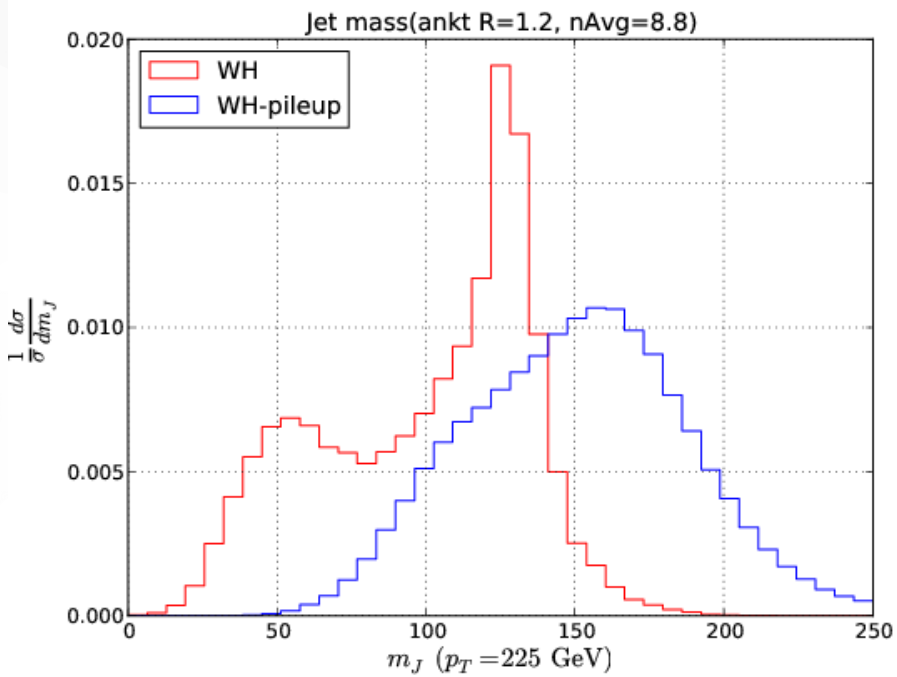
As expected, pileup pushes both distributions towards lower values of maximum overlap.

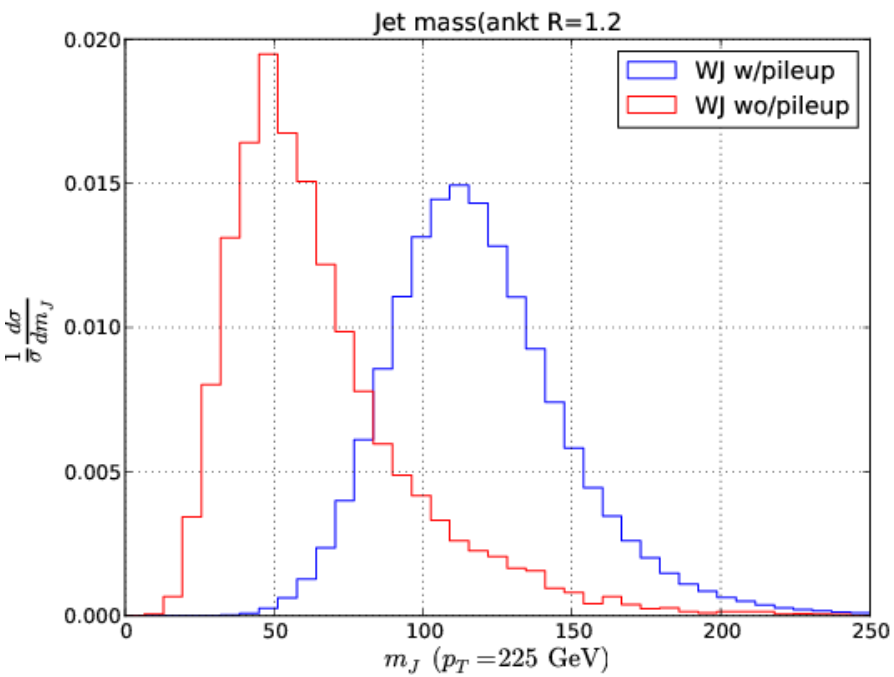
Pileup

Pythia8, 2.5 Low pileup

- Pile up yields lots of soft incoherent deposition
- Does not affect the spiky hard part of the signal

Impact of 8.8 nvtx pileup mass





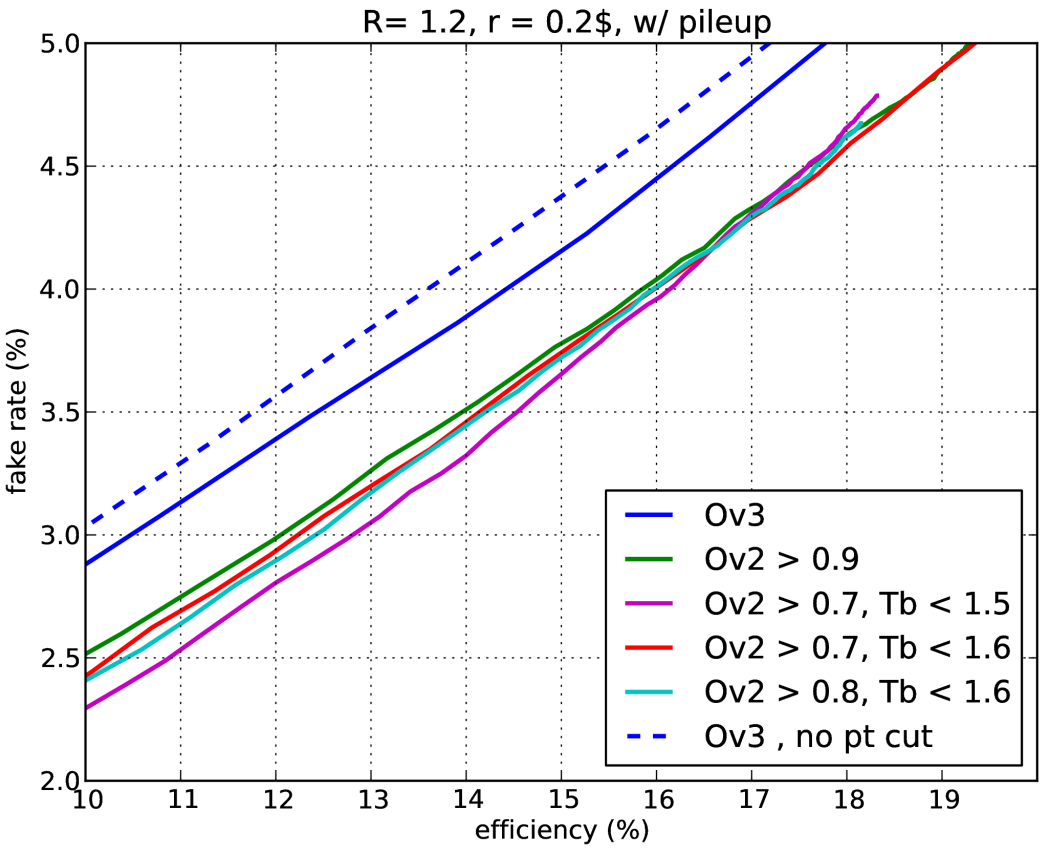
Pileup effects: revisiting the template Ov dist.

The template overlap method looks for spikes of energy inside the large jet

Pile up yields lots of soft incoherent deposition

Does not affect the spiky hard part of the signal

Rejection power without mass cut



Summary

- The template overlap method may provide separation of boosted Higgs from boosted QCD jets
- The study was initiated and the needed tools are in place
- The method seems robust against pileup effects

...and plans

- Optimize the method (templates for different pT / eta bins...)
- Perform a complete VH H→bb analysis
  - Refine the selection, include also b-tagging
  - Estimate the background
  - ATLAS affiliated Template Overlap “Task Force” formed at the Weizmann Institute.

Stay tuned...

Backup slides

Moving down to pT of 200 GeV

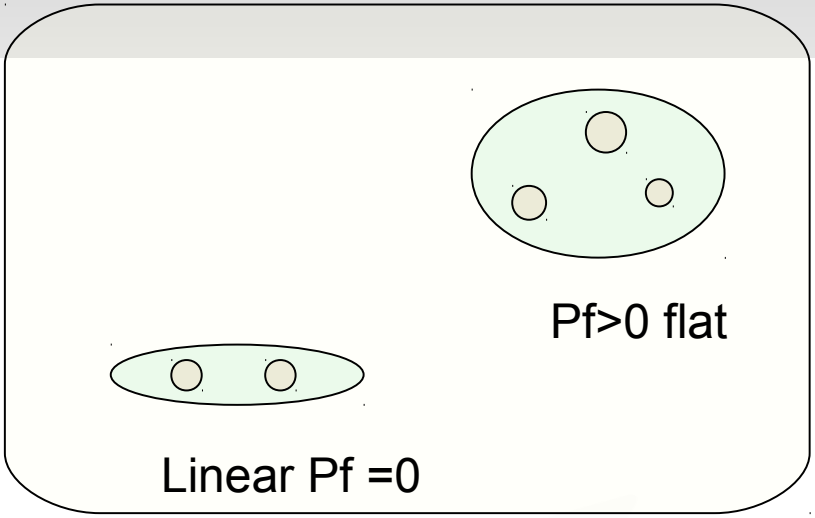
	Wj+Zj	$Wb\bar{b} + Zb\bar{b}$	Wh+Zh
K (NLO Γ)	2.5	1.5*	1.6
σ (m_j cut, w/ K fact.)	1.2 pb	6.12 fb	3.2 fb

Signal and background cross sections using Pythia and MCFM. The K factors were obtained using MCFM (no invariant mass cut). The two different cases of MCFM calculation refer to the Higgs width evaluation at *LO* and *NLO*. Notice the 25 - 30 per-cent difference in the numerical values for the signal cross section at NLO. The K factor on the other hand does not seem to depend on the higgs width. The invariant mass cut and the K factor were applied in the Pythia calculation in column 6. Column 7 is the pythia calculation with the K factor applied, but with no invariant mass cut on the jet.

Planar Flow

Thaler & Wang, 08
Almeida, Lee, Perez, Sterman, Sung & Virzi, 09

Top decays often feature a triangular structure, transverse to the boost axis

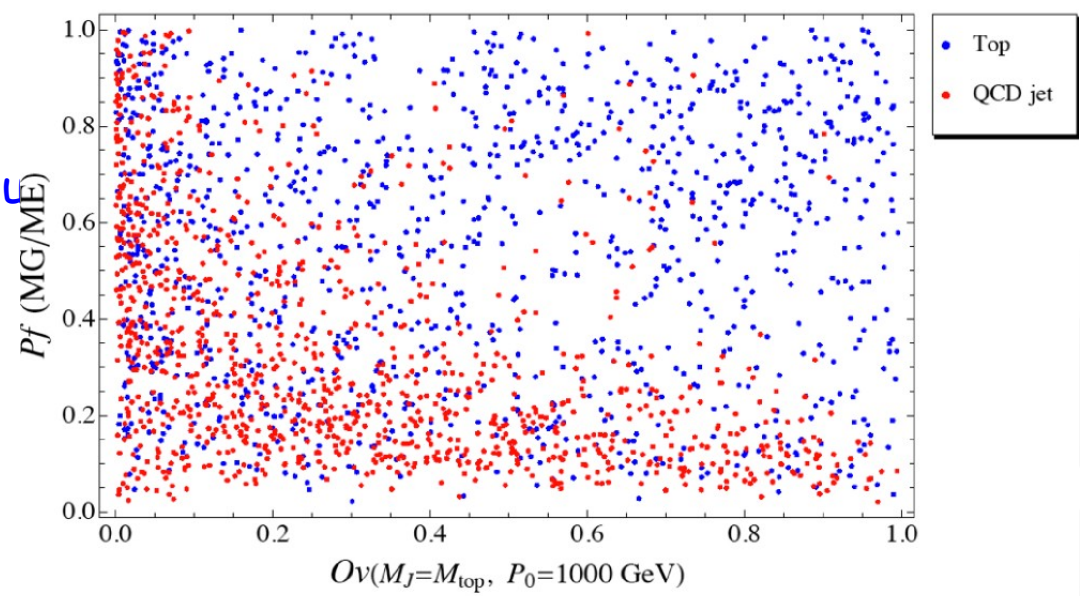


Planar flow: measures the planarity of the energy flow within a jet

$$I_\omega^{kl} = \frac{1}{m_J} \sum_i \omega_i \frac{p_{i,k}}{\omega_i} \frac{p_{i,l}}{\omega_i}$$

$$\mathrm{Pf} = \frac{4 \det I_\omega}{(\mathrm{tr} I_\omega)^2}$$

Planar-flow jet shapes can be used to distingu between many 3-jet events with large template overlap

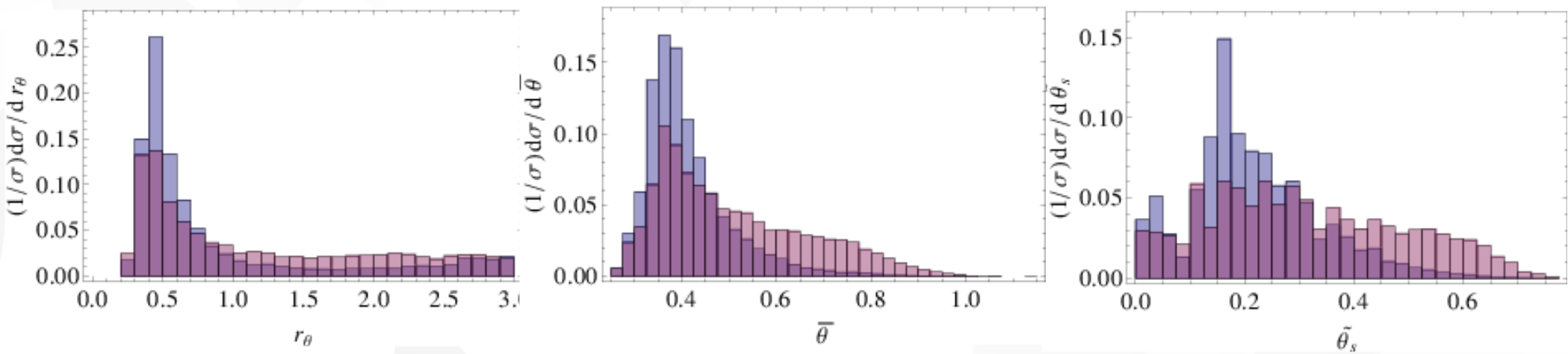


Best matched template dist.

- We can analyze angular distributions of template partons

Max. Ov: *f*[*j*]

Kinematical variables |*f*> ⟷ Jets |*j*>



$$r_\theta = \min\{\theta_{13}/\theta_{12}, \theta_{23}/\theta_{12}\}$$

$$\bar{\theta} = \sum_i \sin\theta_{iJ}$$

$$\theta_s = \min\{\theta_{iJ}\}$$