Discriminating Higgs production mechanisms using jet energy profiles

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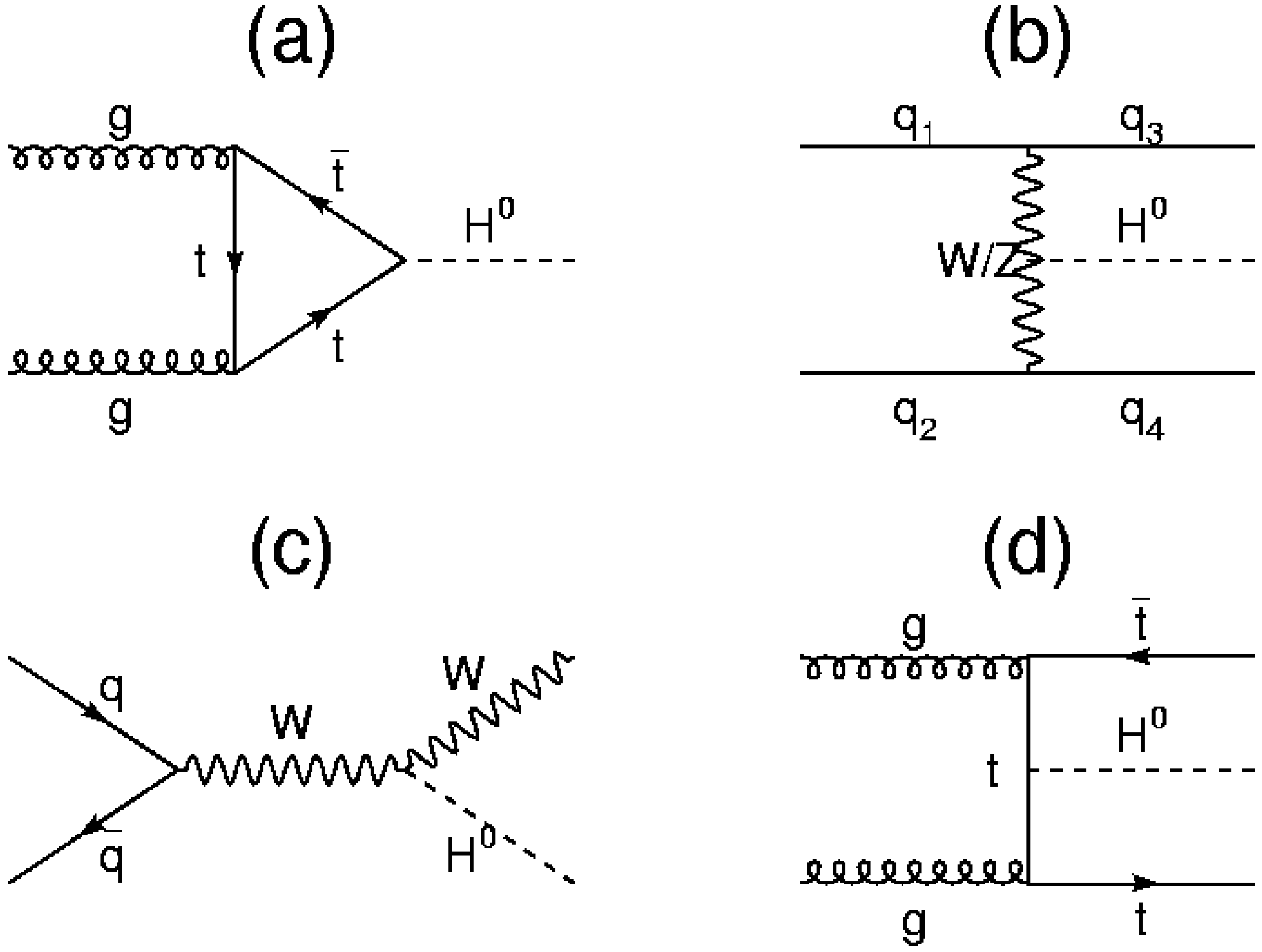
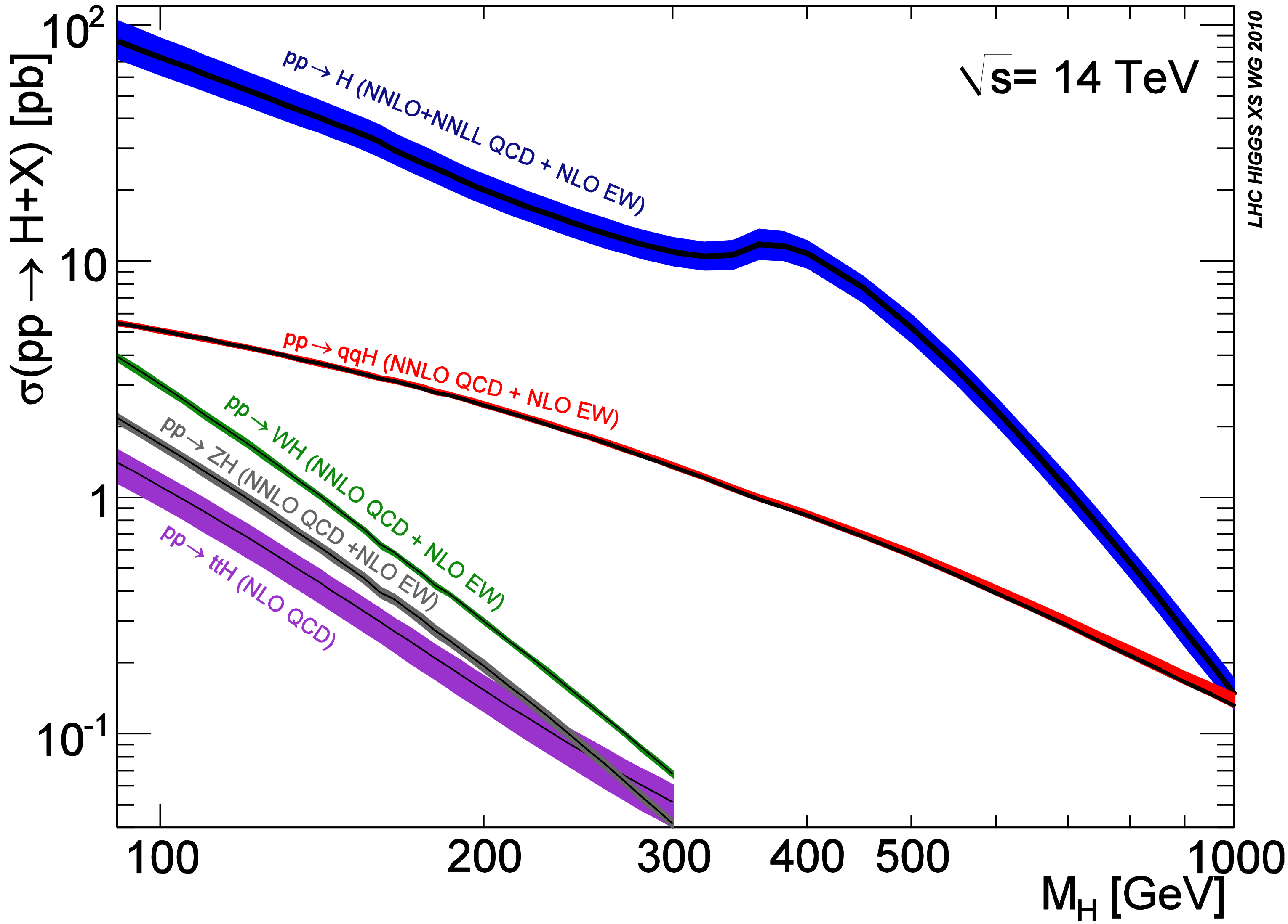
Outline

- Higgs observables
- Breaking degeneracies by separating the production mechanisms (gluon fusion and vector boson fusion)
- Kinematic discriminators
- Jet Energy Profiles
- Results

Higgs production mechanisms

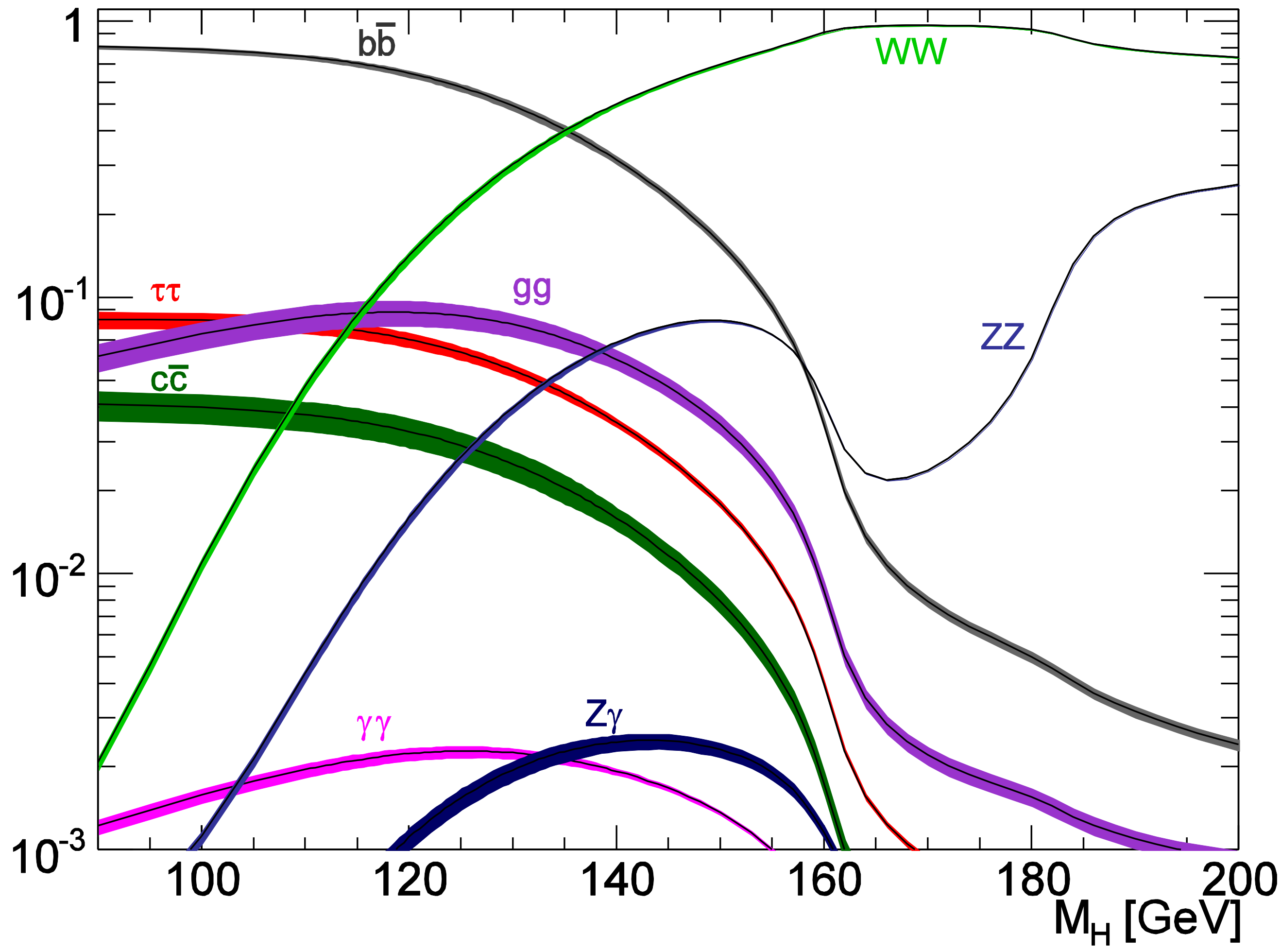


Higgs production rates at LHC



Dominated by GF and VBF

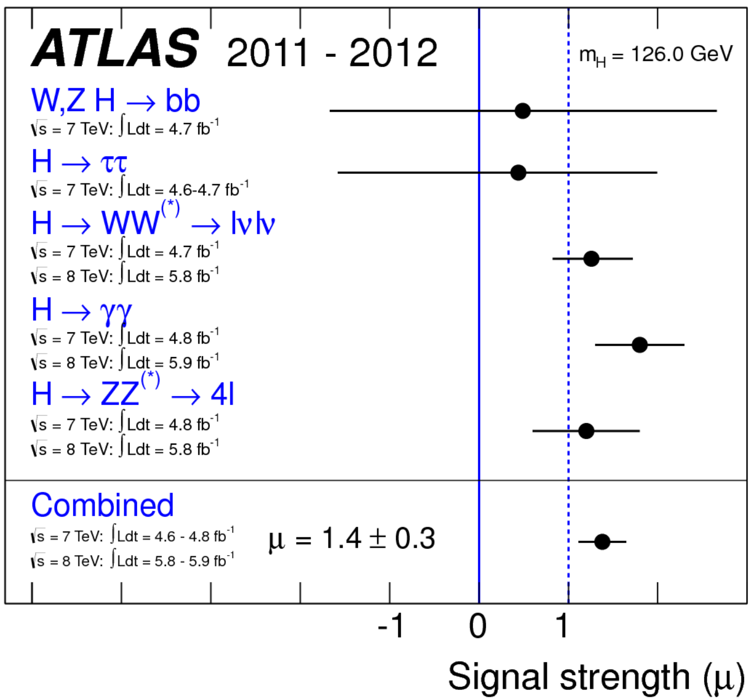
Higgs branching fractions

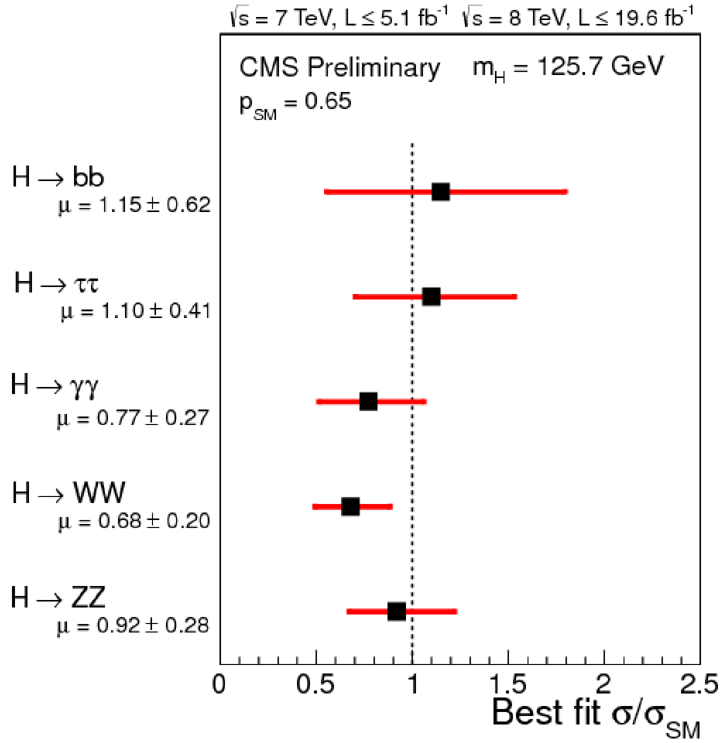


Higgs observables

$$\text{Observed rate} = \sigma_{\text{prod}} \times \frac{\Gamma(H \to XX)}{\Gamma_H}$$

Experimental results



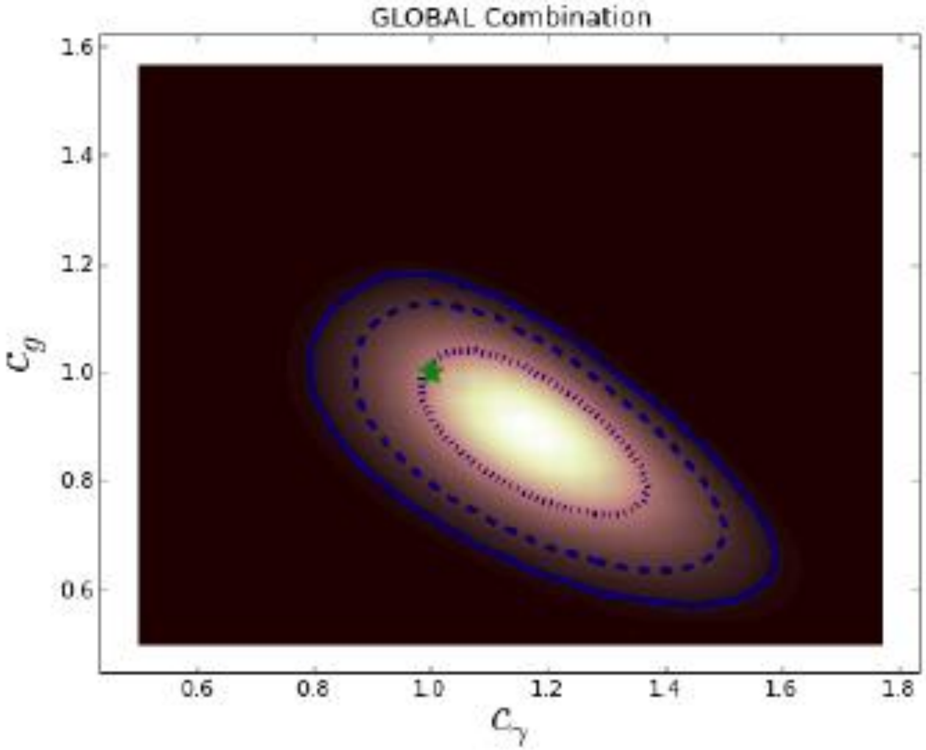


The problem

- H→ gg is sensitive to new colored particles that couple to the Higgs boson.
- H→ gg can not be directly measured because of the hadronic final state.
- H → WW is important for consistency of the unitarization of the SM at high energies.
- However there are degeneracies in g_{HWW} measurements.
- Can we break some of these degeneracies by measuring the production modes?

Gluon couplings from global fit

$$\mathcal{L}_\Delta = -\left[\frac{\alpha_s}{8\pi} c_g b_g G_{a\mu\nu} G_a^{\mu\nu} + \frac{\alpha_{em}}{8\pi} c_\gamma b_\gamma F_{\mu\nu} F^{\mu\nu}\right] \left(\frac{H}{V}\right)$$



$$c_\gamma = 1.18 \pm 0.12 \, , \; c_g = 0.88 \pm 0.11$$

Ellis, You 2013

- Global fit measurement of gluon coupling is indirect.
- Would like another handle on Higgs coupling to gluons and production mechanisms in general.

Separating Higgs production modes

Naïve approach:

a) Kinematic cuts on VBF/GF (forward jets)

b) further kinematic cuts

Kinematic separation: Rapidity gap

- Consider $pp \to H + jj$ with $H \to \gamma\gamma$
- Cuts: Large rapidity gap (CMS tight cuts)

$$\Delta\eta_{jj} > 3.5$$

$M_{jj} > 500\,\mathrm{GeV}$ $M_{jj} > 250\,\mathrm{GeV}$

Tight loose

- Even after imposing these cuts sizeable GF contamination ~ 20-30% and an O(1) background

Kinematic Separation

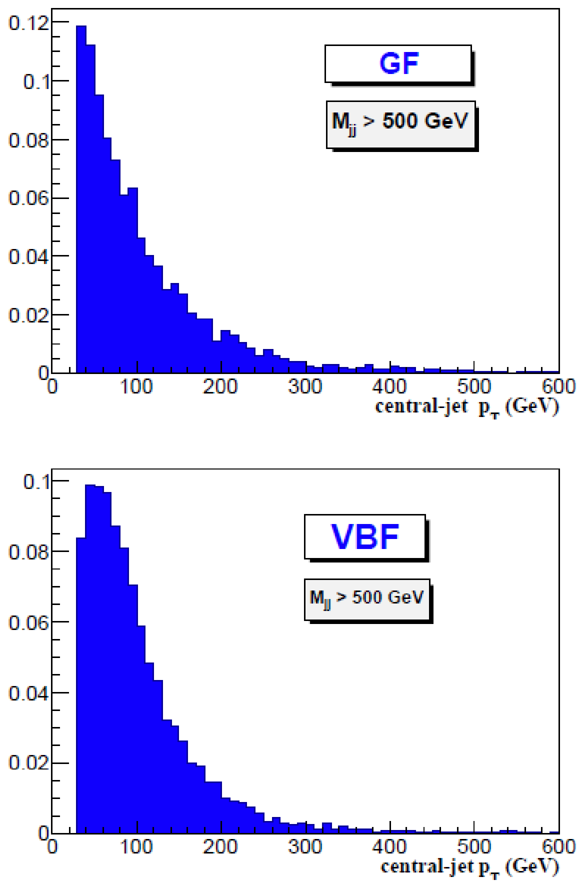


FIG. 1: Normalized p_T distribution of the central jet for GF (upper panel) and for VBF (lower panel) in $H + 2$ jets events passing the tight selection cuts with $M_{jj} > 500$ GeV.

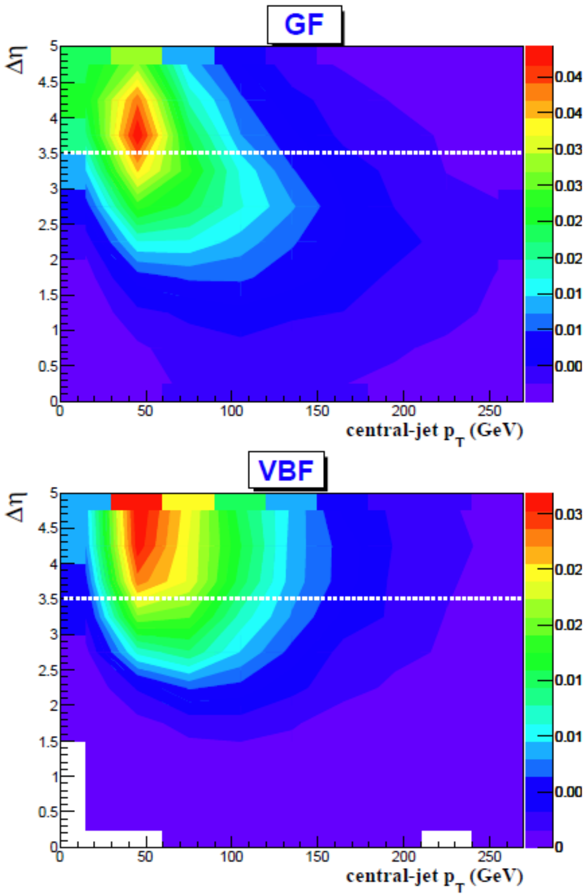


FIG. 2: p_T of the central jet vs $\Delta\eta$ of the two jets for GF (upper panel) and for VBF (lower panel) in $H+2$ jets events, when only mild cuts on jets are applied. The dotted white line shows the value of the cut on $\Delta\eta$ applied in the analysis.

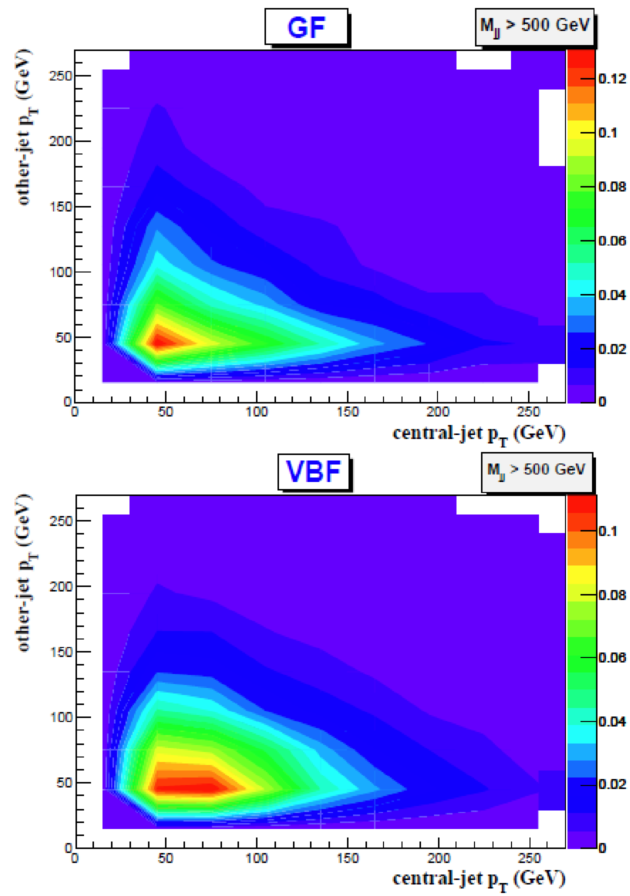


FIG. 3: p_T of the central jet vs p_T of the other jet for GF (upper panel) and for VBF (lower panel) in $H+2$ jets events passing the tight selection cuts with $M_{jj} > 500$ GeV.

Separating Higgs production modes

Naïve approach:

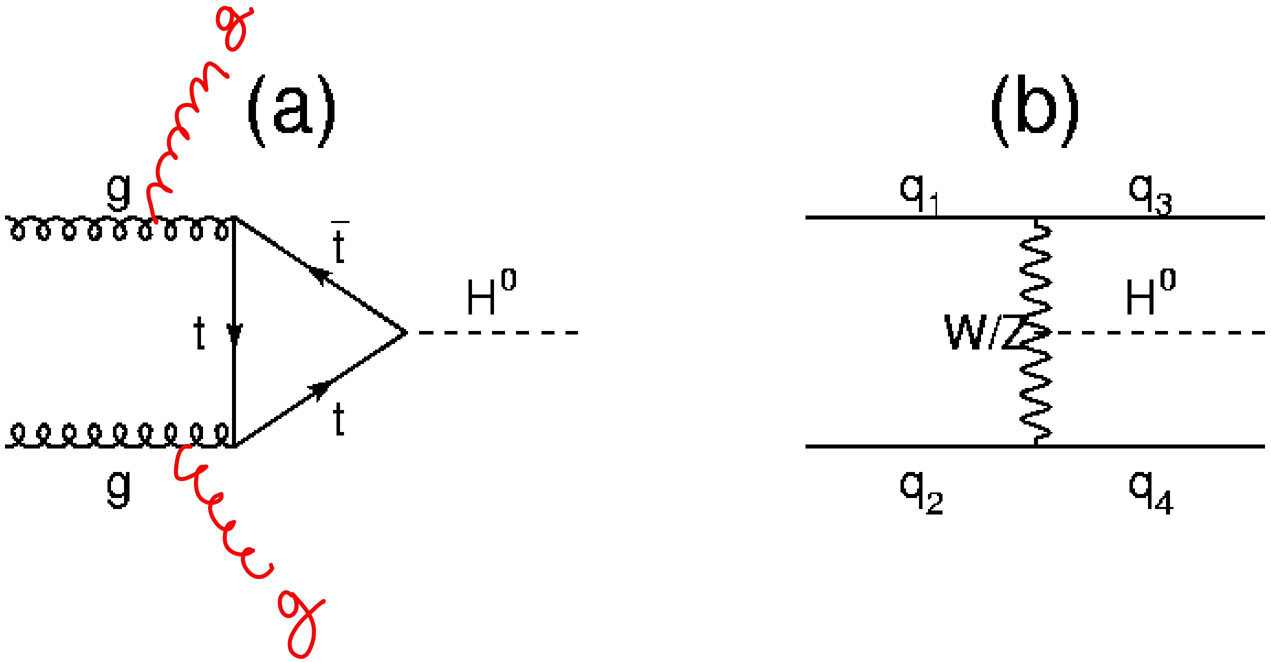
a) Kinematic cuts on VBF/GF (forward jets)

b) further kinematic cuts

Better handles:

- **Jet energy profiles: This talk**
- H + jet veto (T. Becher and M. Neubert)
- Hadronic event shapes (Englert, Spannowsky and Takeuchi)
- Matrix element method (Andersen, Englert and Spannowsky)
- Third jet veto (Cox, Forshaw, and Pilkington)

An observation



- Jets associated with GF are mostly gluon like
- Jets associated with VBF are always quark like

Any method to statistically measure ratio of quark and gluon jets efficiently could pin down the ratio of GF to VBF like events in a given Higgs sample.

Advantages of this technique

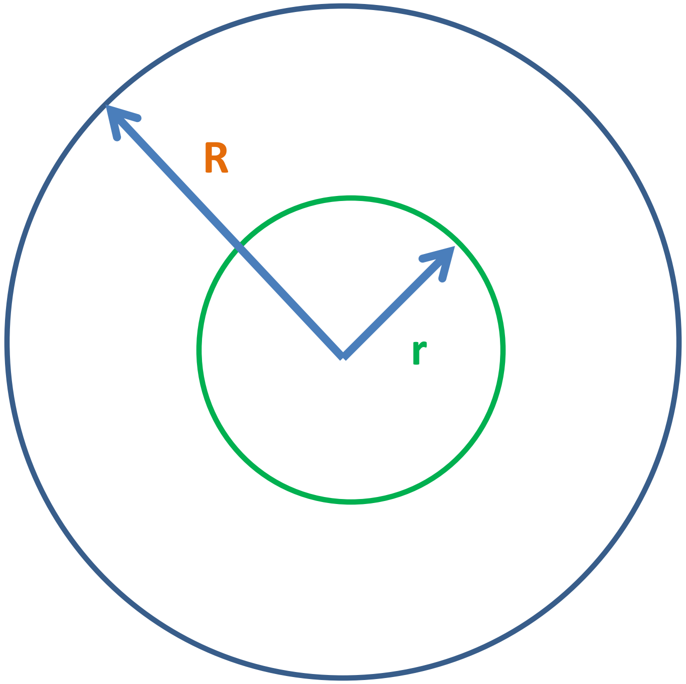
- Measurement independent of the branching fractions!

$$\text{Observed GF rate} = \sigma_{\text{GF}} \times \frac{\Gamma(H \to \gamma\gamma)}{\Gamma_H}$$

$$\text{Observed VBF rate} = \sigma_{\text{VBF}} \times \frac{\Gamma(H \to \gamma\gamma)}{\Gamma_H}$$

- Measuring ratio g_{Hgg} /g_{HWW} independently of the branching fractions
- Can be measured in many different kinematic regimes (not just with forward jets)

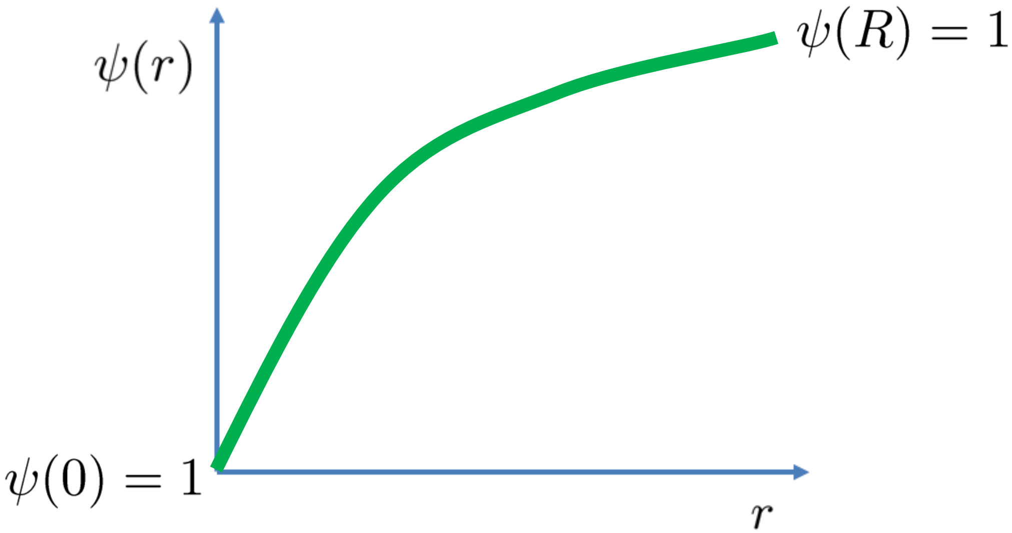
Jet energy profile



Fraction of total jet pT in a sub-cone of size r, inside a jet or size R

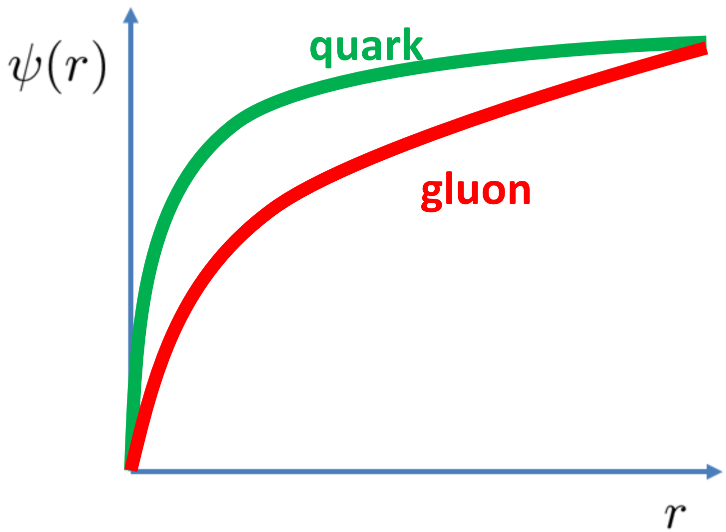
$$\Psi(r) = \frac{1}{N_J} \sum_J \frac{\sum_{r_i<r, i\in J} P_{Ti}}{\sum_{r_i<R, i\in J} P_{Ti}}$$

What to expect for the JEP



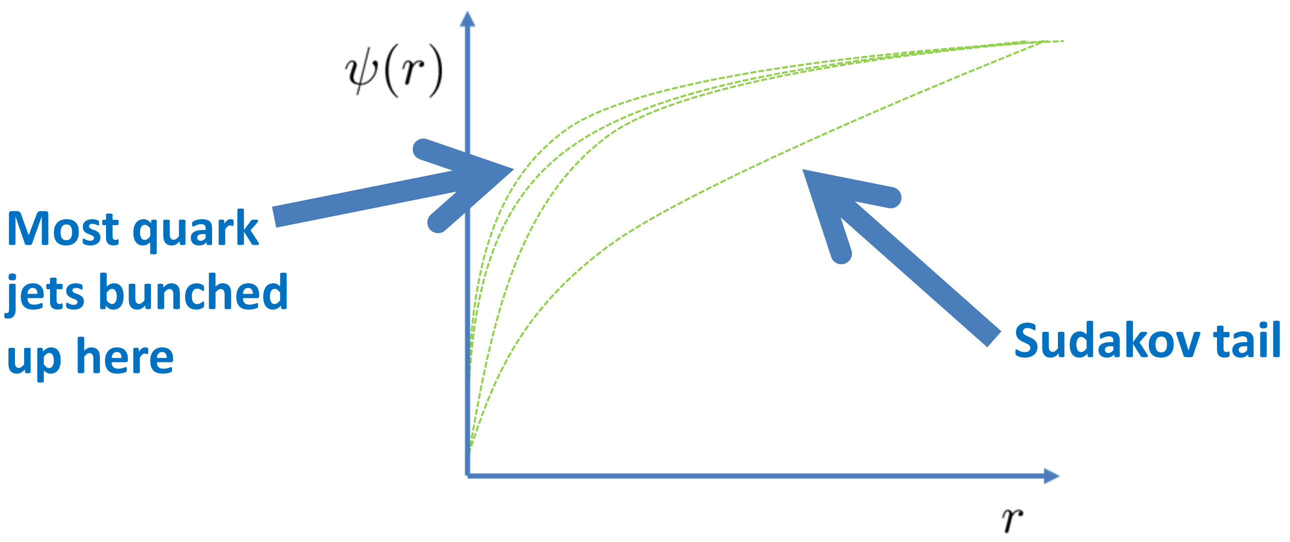
R = jet cone size during clustering (~ 0.7)

Quark vs gluon jets



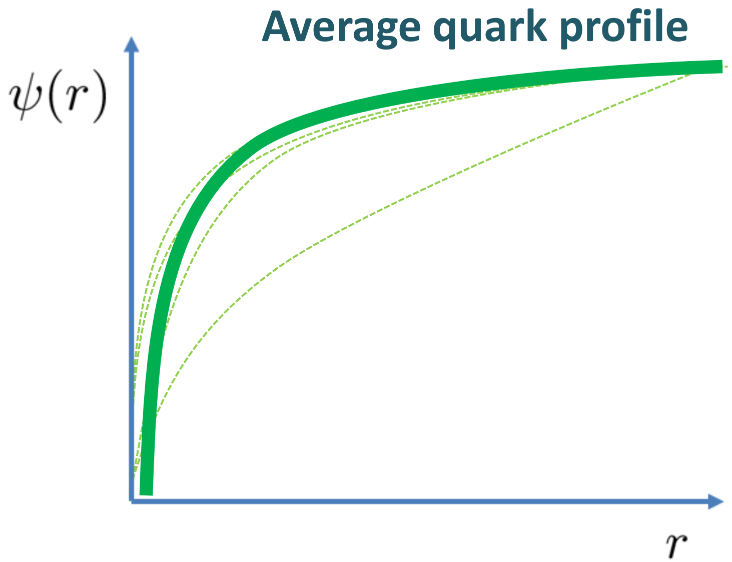
- Quark jets radiate relatively little and are narrower with a sharply rising JEP.
- Gluon jets radiate more and are broader so they have a slowly rising JEP.

Looking at a sample of (quark) jets



- For an individual quark/gluon jet the profile can fluctuate wildly.
- This fluctuation has an underlying distribution due to the underlying physics which is a Sudakov tail.
- The underlying distribution is not "gaussian" distributed about the average profile

Looking at a sample of (quark) jets

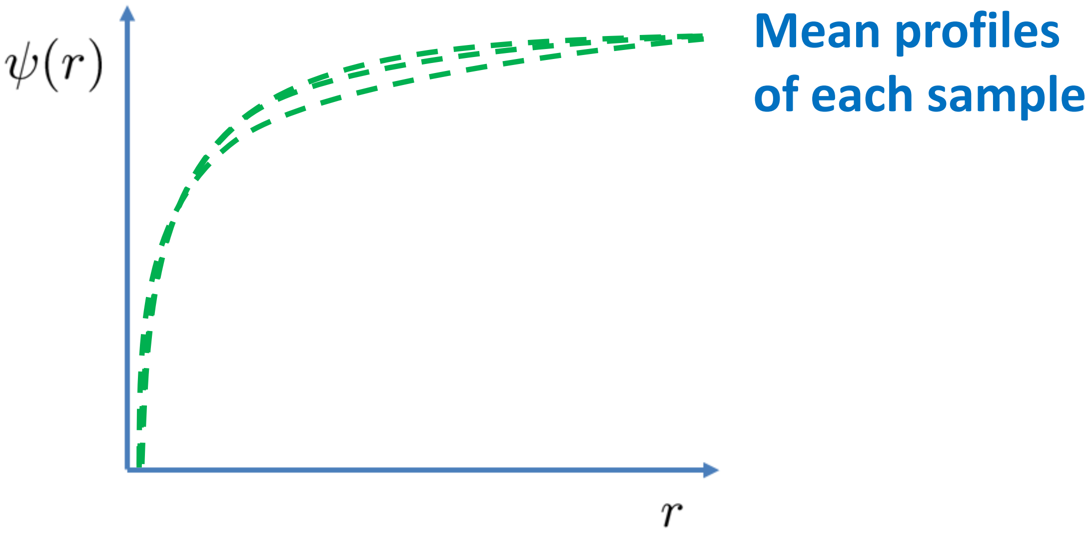


- For an individual quark/gluon jet the profile can fluctuate wildly.
- This fluctuation has an underlying distribution due to the underlying physics which is a Sudakov tail.
- The underlying distribution is not "gaussian" distributed about the average profile

A note on P_T dependence

- The average JEP has a P_T dependence, so we will have to study JEPs in narrow P_T bands at any given time.
- In what follows it is assumed that the analysis is done separately in each P_T band.

Pseudo experiments of samples

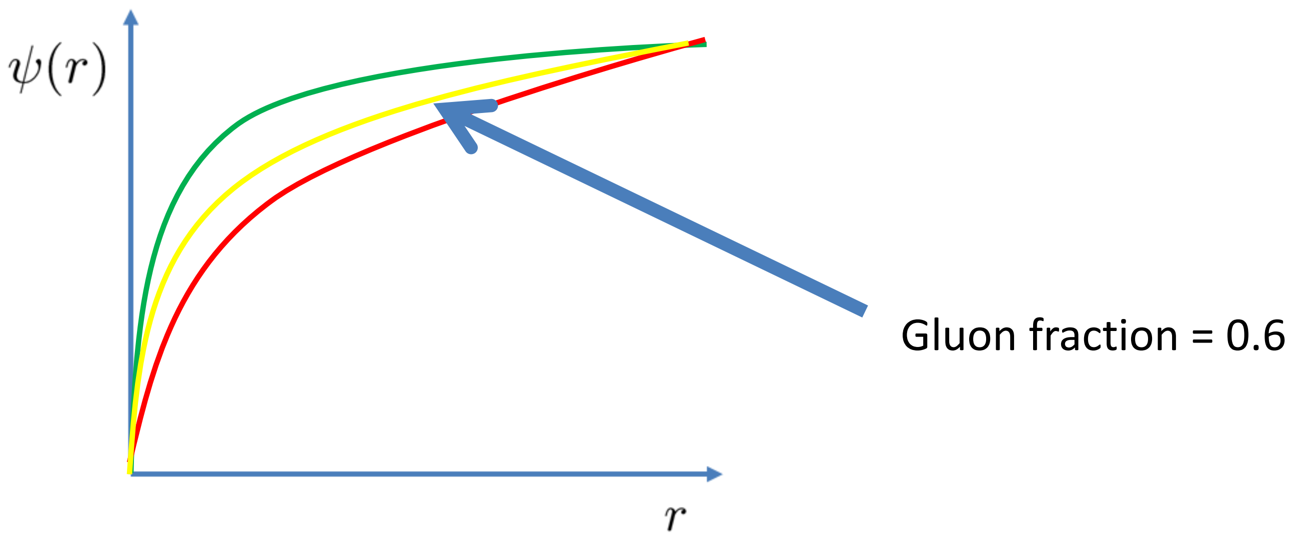


- Consider many pseudo-experiments of N_{exp} quark jets.
- The <u>average</u> profile of this sample fluctuates less wildly.
- As a rule of thumb, for > 30 events in the sample, the fluctuation in the average profile of the sample IS gaussian.

Pseudo experiments of samples

- For a given luminosity we know how many events to expect (N_{exp}). We do pseudo experiments with N_{exp} jets and take the average profile of each sample.
- The characteristic size of the fluctuation between different pseudo experiment sample average profiles is the error of the sample average JEP.

From quarks and gluons to weighted samples



- Instead of talking about samples with pure quarks or pure gluons, we can talk about samples with a specific gluon fraction.
- The average profile is just a linear weighting of the average quark and gluon profiles.

Strategy to separate VBF from GF

- Find the average profile for a SM like sample and the expected error.

  (Experimental measurement should lie within the error bars of this sample)

For comparison:

- Find the average profile for a pure VBF sample and the expected error.
- Find the average profile for a pure GF sample and the expected error.

Three ways to determine the JEP

- Experimental data (control samples of pure quark or gluon jets or known gluon fraction)
- Theoretical calculations (NLO parton splitting or LL resummation)
- Pythia (tune dependent but allows statistical fluctuations of pseudo-experiments to be estimated)

Tools available to theorists

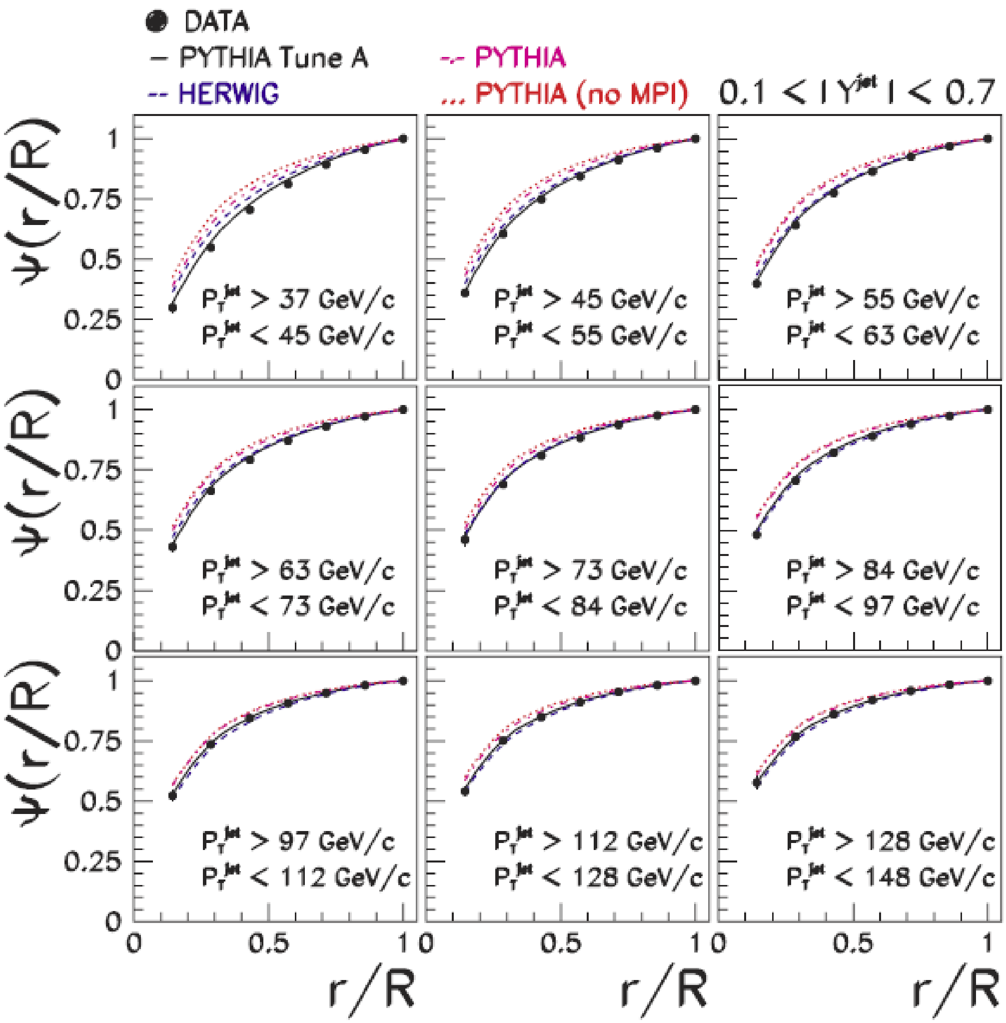
Advantages and disadvantages of each approach

All three should be used, each offers a different level of precision and each has its own limitations.

- Experiments:
  1. Smallest error for low-moderate P_T jets ~200 GeV.
  2. Suspect to systematics.
  3. No proof of factorizability (universality).
  4. Can not be extrapolated to regions where control samples are not available.
  5. Not available to theorists.
- Theory:

  NLO prediction is not finite at r = 0. LL resummation provides a nice finite formula and shows factorizability but has two problems:
  1. Undetermined constants of integration.
  2. Can not generate statistical fluctations.
- Pythia:
  1. Can generate pseudo experiments.
  2. Requires tuning.

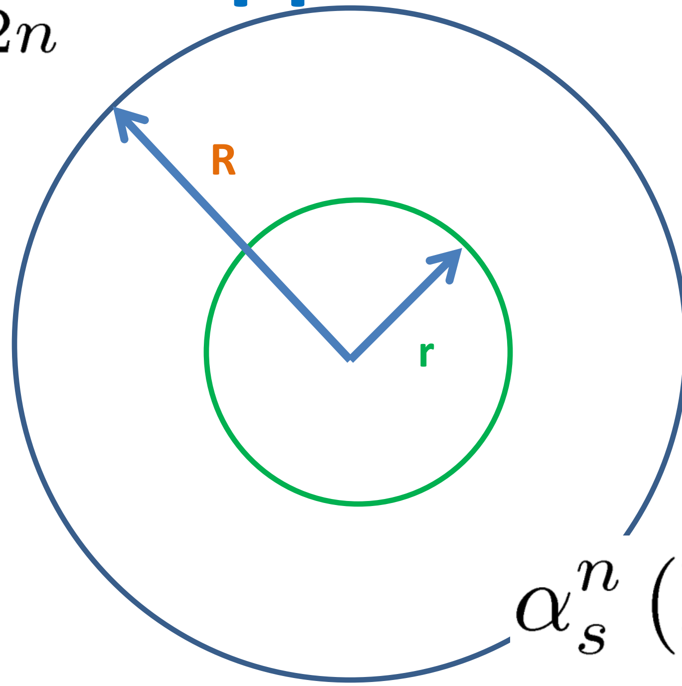
Experimental JEPs and Pythia (CDF)



170 pb^{-1}

Jet energy profile: theoretical approach

$$\alpha_s^n \left(\log(R/r)\right)^{2n}$$

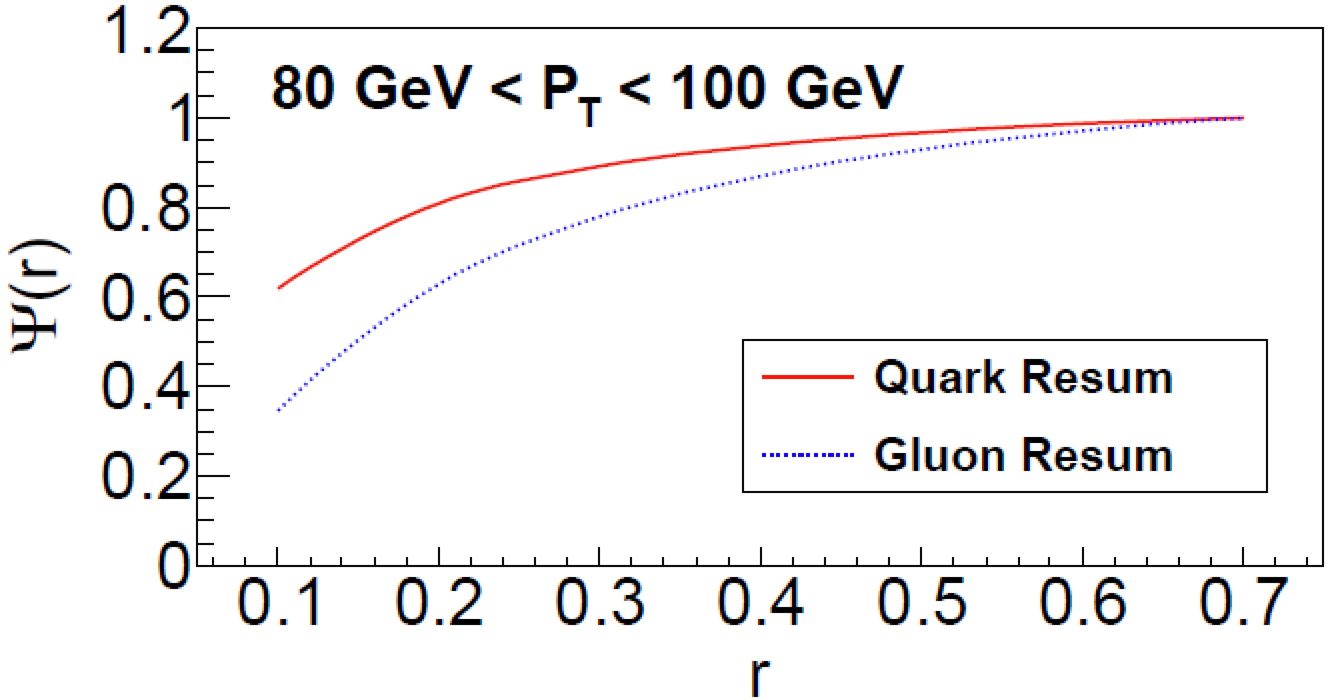


$$\alpha_s^n \left(\log(R/r)\right)^{2n-1}$$

Fraction of total jet pT in a sub-cone of size r, inside a jet or size R

$$\Psi(r) = \frac{1}{N_J} \sum_J \frac{\sum_{r_i < r, i \in J} P_{Ti}}{\sum_{r_i < R, i \in J} P_{Ti}}$$

Resummed jet energy profile for quark vs gluon jets



Li, Li, Yuan

Comparison of resummed JEPs to the data

Li, Li, Yuan

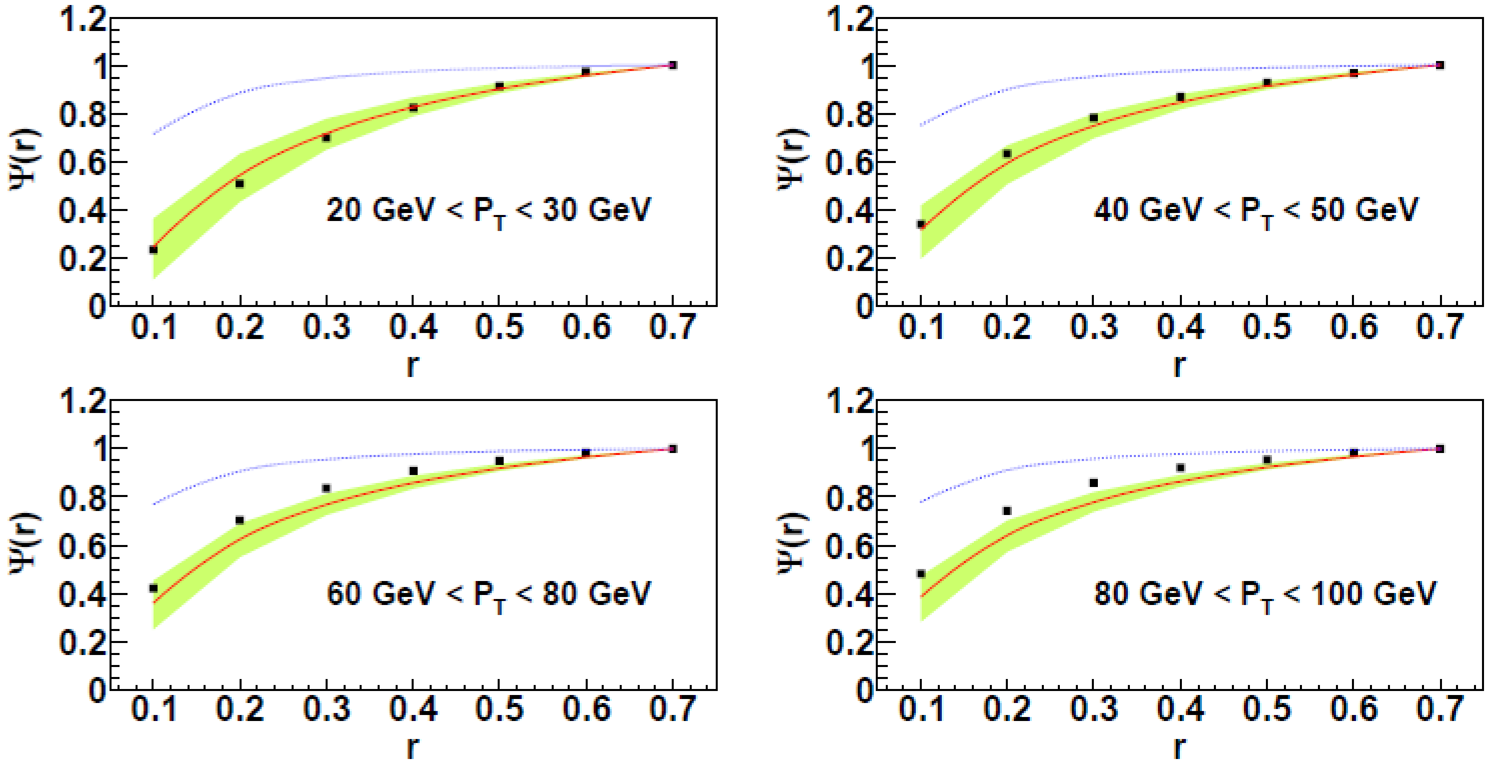


FIG. 10: Resummation predictions for the jet energy profiles with $R = 0.7$ compared to LHC CMS data in various P_T intervals. The NLO predictions denoted by the dotted curves are also displayed.

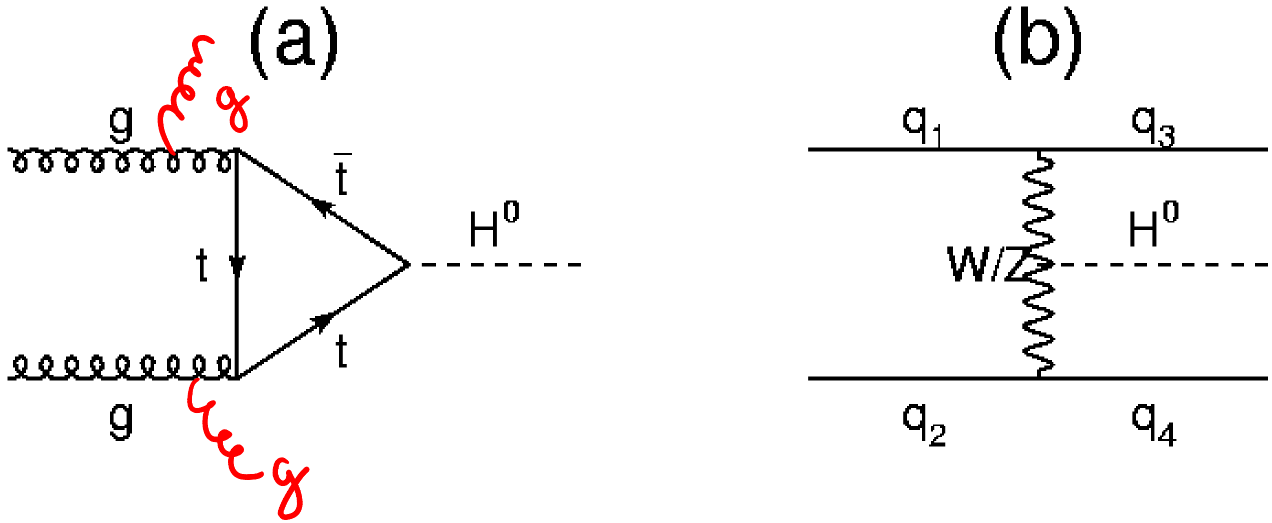
NLO: Blue line

LL: Red line

Black points: data WITH error bars

The LL resummation calculation has a constant that parameterizes the NLL contribution. Varying the constant gives the green error band.

Applying this to VBF vs GF separation



The best approach is a hybrid approach combining all three strategies to measure JEPS.

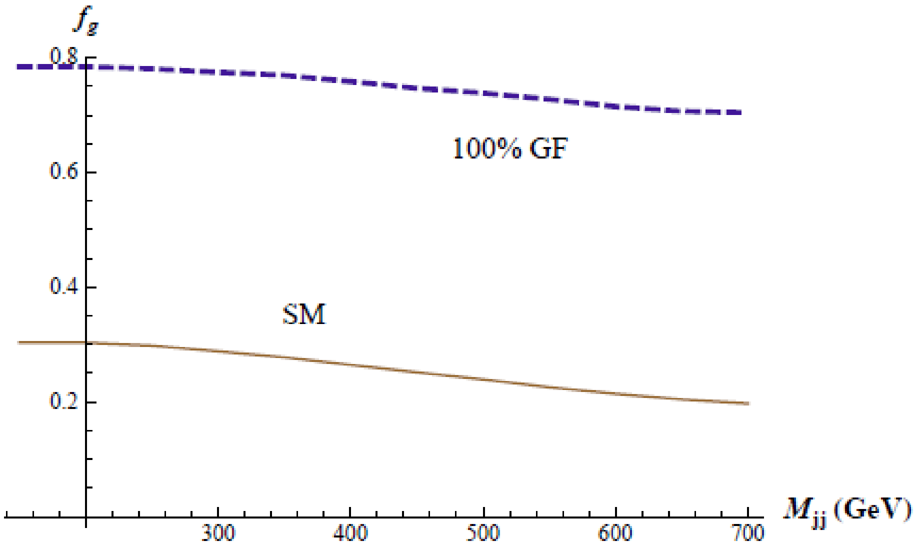
- Our choice is constrained because of lack of experimental data:
  1. We choose to use the average profile from the LL resummation calculation. The integration constants are fixed from Tevatron data and are mostly P_T independent.
  2. To estimate the error on the average profile, we conduct pseudo-experiments in (untuned) pythia and lift the error bars from the pythia JEPs and put them on the theoretical JEP.

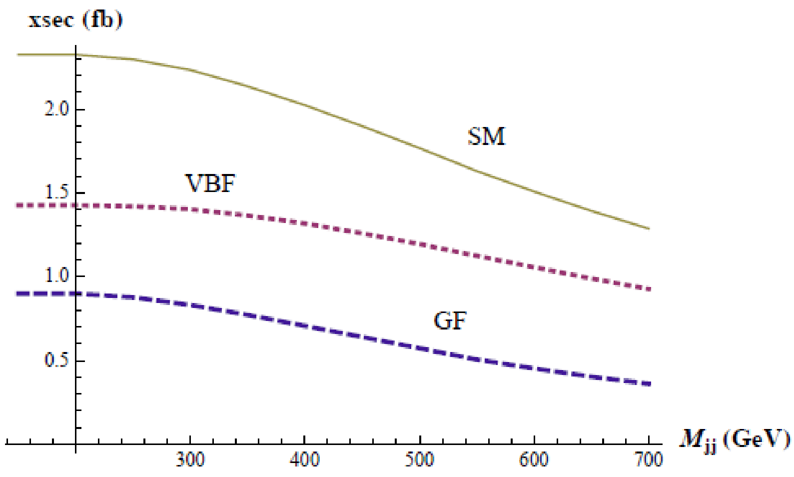
Separating VBF from GF

	$M_{jj} > 500$ GeV		$M_{jj} > 250$ GeV	
14 TeV	GF	VBF	GF	VBF
MG $\times K_f^{CMS}$	32%	68%	38%	62%
	0.57 fb	1.2 fb	0.88 fb	1.4 fb

TABLE II: SM expected cross-sections at the 14 TeV LHC, using tight cuts with $M_{jj} > 500$ GeV and with $M_{jj} > 250$ GeV.

Dijet invariant mass dependence





Strategy to separate VBF from GF

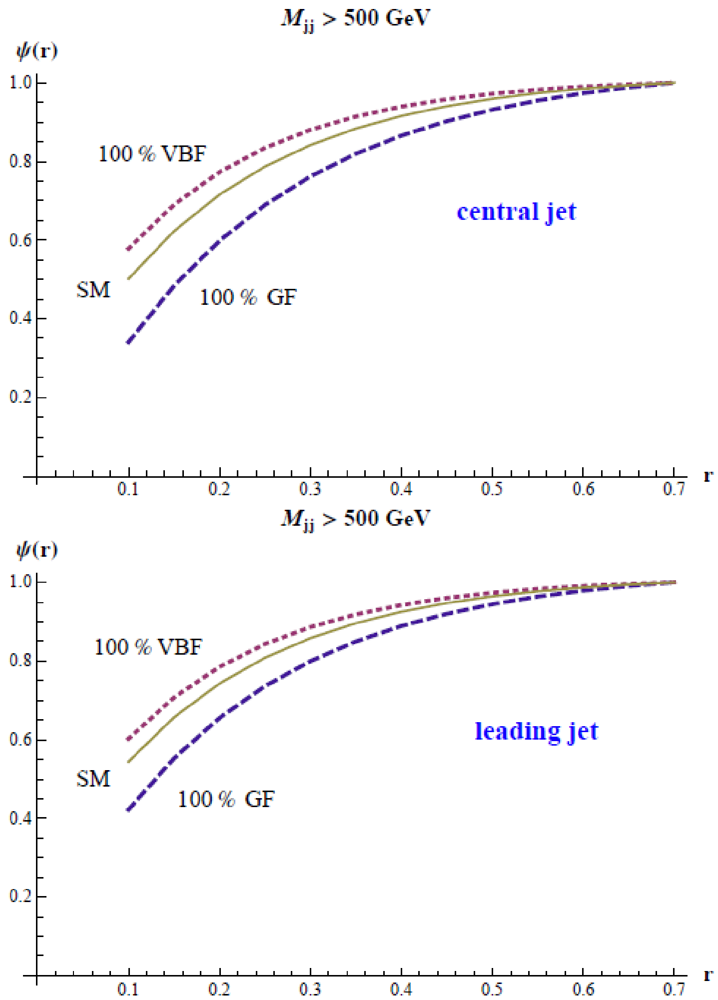
- Find the average profile for a SM like sample and the expected error.

  (Experimental measurement should lie within the error bars of this sample)

For comparison:

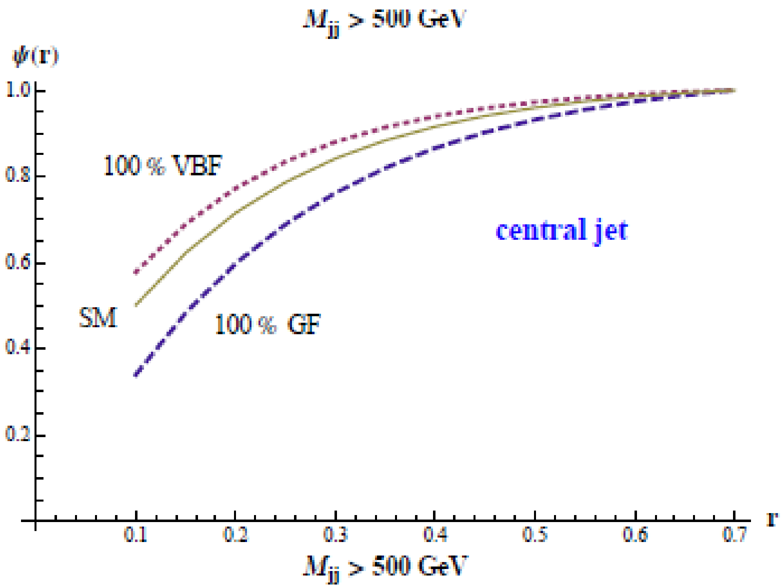
- Find the average profile for a pure VBF sample and the expected error.
- Find the average profile for a pure GF sample and the expected error.

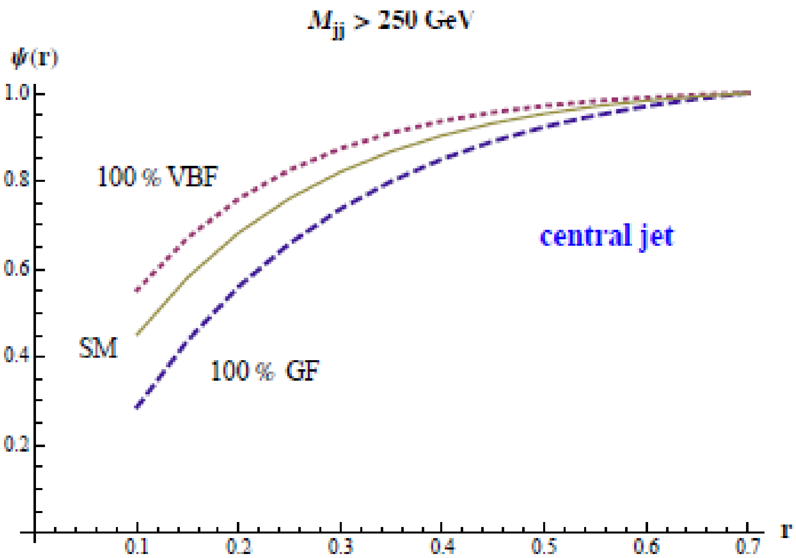
We use the central jet



- Better reconstruction
- Better separation of JEPs

Separation of profiles for different cuts





Default Pythia tune cannot be relied upon to measure the jet profile

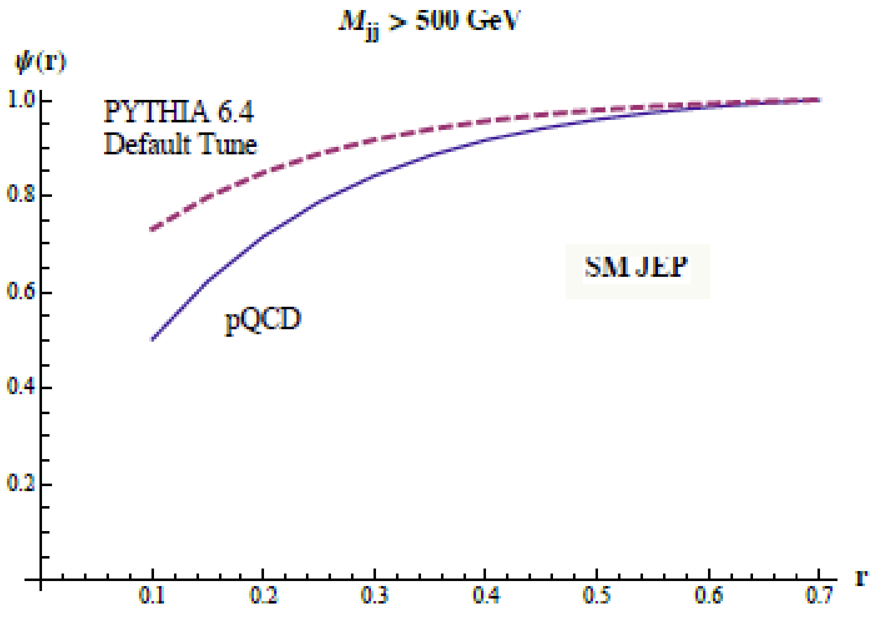
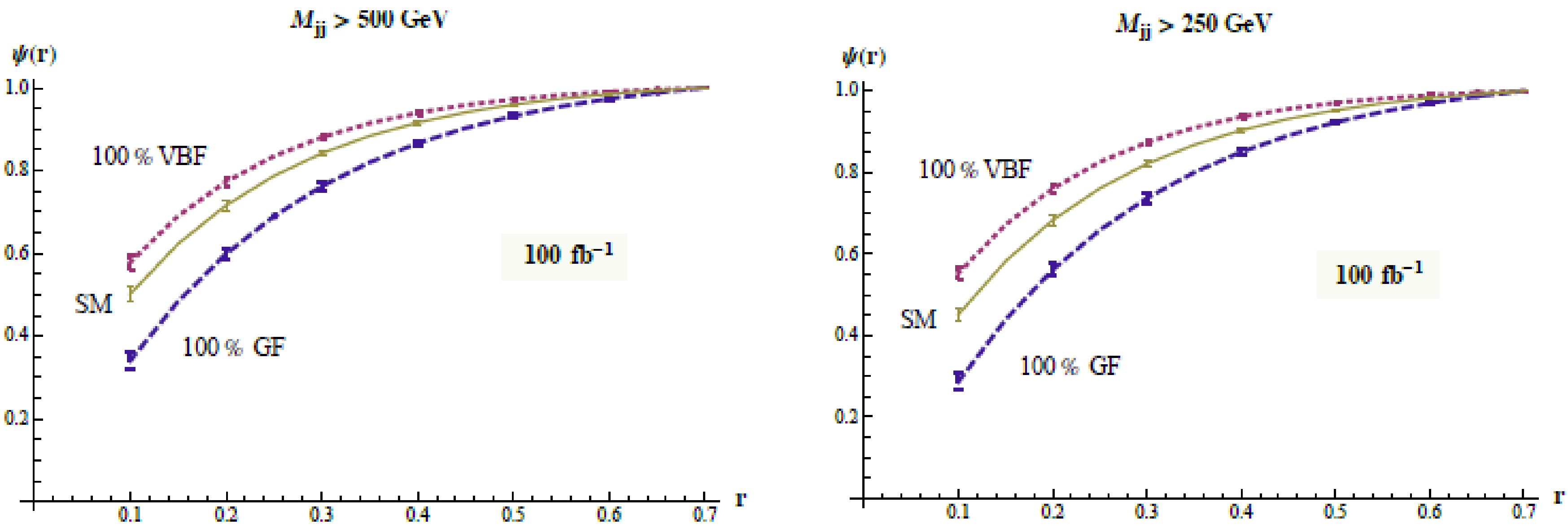


FIG. 7: Energy profile of the central jet for SM obtained by analyzing the jet substructure after Pythia v6.4 (default tune) showering, compared to the theoretical pQCD prediction using jet functions [11, 12].

Jet energy profiles with error bars from Pythia



Caution: The error bar is the monte-carlo size of the error on the mean JEP. Individual jet profiles can fluctuate far more than the size of this error bar.

Analytic approximation of JEPs

- We find the JEPs can be approximated by:

$$\psi(r) = \frac{1 - be^{-ar}}{1 - be^{-aR}}$$

- Define a one parameter linear interpolation between VBF and GF JEPs:

$$\psi_{f_V}(r) = f_V \psi_{\mathrm{VBF}}(r) + (1 - f_V)\psi_{\mathrm{GF}}(r)$$

- f_V parameterizes the VBF fraction of the sample.
- The errors on the JEPs can be translated into errors on the fitted f_V.

Measured value of f_V with errors

f_V	$M_{jj} > 500$ GeV	$M_{jj} > 250$ GeV
SM	0.68 ± 0.05	0.62 ± 0.04
VBF	1.00 ± 0.04	1.00 ± 0.03
GF	0.00 ± 0.06	0.00 ± 0.05

Compare this to the simulated cross-section:

	$M_{jj} > 500$ GeV		$M_{jj} > 250$ GeV	
14 TeV	GF	VBF	GF	VBF
$MG \times K_f^{CMS}$	32%	68%	38%	62%
	0.57 fb	1.2 fb	0.88 fb	1.4 fb

Sensitivity and Reach

	$M_{jj} > 500$ GeV		$M_{jj} > 250$ GeV	
	GF	VBF	GF	VBF
$\sigma-$level	8.7	5.0	9.7	7.6

TABLE V: Expected $\sigma-$level distinction between SM and pure GF or VBF event samples using 100 fb^{-1} of luminosity at the 14 TeV LHC.

	$M_{jj} > 500$ GeV		$M_{jj} > 250$ GeV	
5σ	GF	VBF	GF	VBF
Lum [fb^{-1}]	33	100	27	43

TABLE VI: Integrated luminosity required to distinguish SM from pure GF or VBF event samples at the 5σ level.

Lower invariant mass cut seems to be better but it also leads to increased background.

Estimating the effect of background

$$\psi_S(r) = \psi_{obs}(r) + \frac{B}{S}\left(\psi_{obs}(r) - \psi_B(r)\right)$$

- Errors scale up by a factor $\sqrt{1 + 2\frac{B}{S}}$

Sensitivity including background

	$M_{jj} > 500$ GeV		$M_{jj} > 250$ GeV	
100 fb^{-1}	GF	VBF	GF	VBF
σ level	6.4	3.6	6.4	5.0

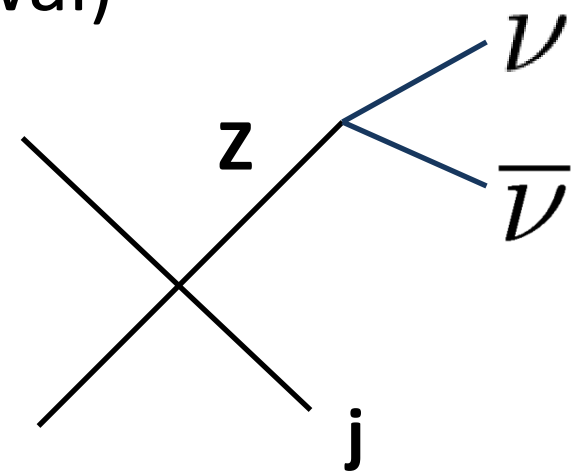
	$M_{jj} > 500$ GeV		$M_{jj} > 250$ GeV	
5σ	GF	VBF	GF	VBF
Lum [fb^{-1}]	61	190	61	100

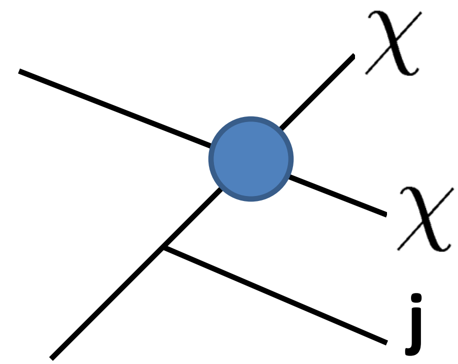
TABLE VIII: Upper Table: Expected $\sigma-$level distinction between SM and pure GF/VBF event samples using 100 fb^{-1} of luminosity at the 14 TeV LHC including the estimated effect of background. Lower Table: Integrated luminosity required to distinguish SM from pure GF/VBF event samples at the 5σ level after subtracting the background JEP.

Lower invariant mass cut is better even after including background.

Further applications of this technique

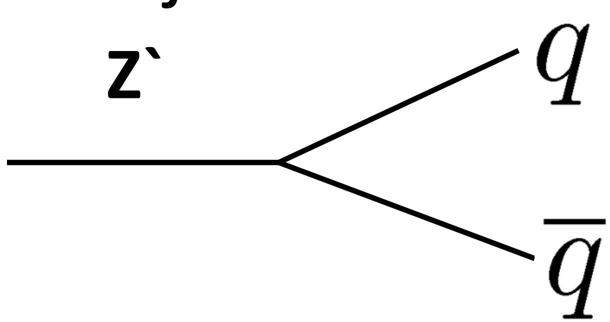
- Monojet searches (work in progress with P. Agrawal)

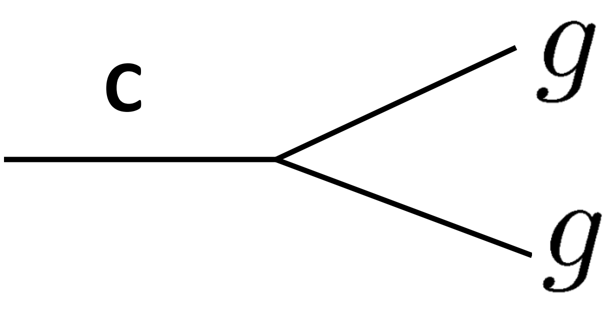




$q\bar{q} \to \chi\chi \quad gg \to \chi\chi$

- New dijet resonances





Summary and Conclusions

- New Higgs observable f_V
- Allows identification of GF and VBF fractions to within 10% with 100 fb^{-1} of data
- Probe of Higgs coupling to gluons which is sensitive to new physics
- Independent of decay branching fractions
- Should be included in global fits
- Many possible applications of JEPs to separate quarks and gluons for new physics searches

QUESTIONS, COMMENTS, SUGGESTIONS?