Particle discrimination using jet substructures

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Outlines

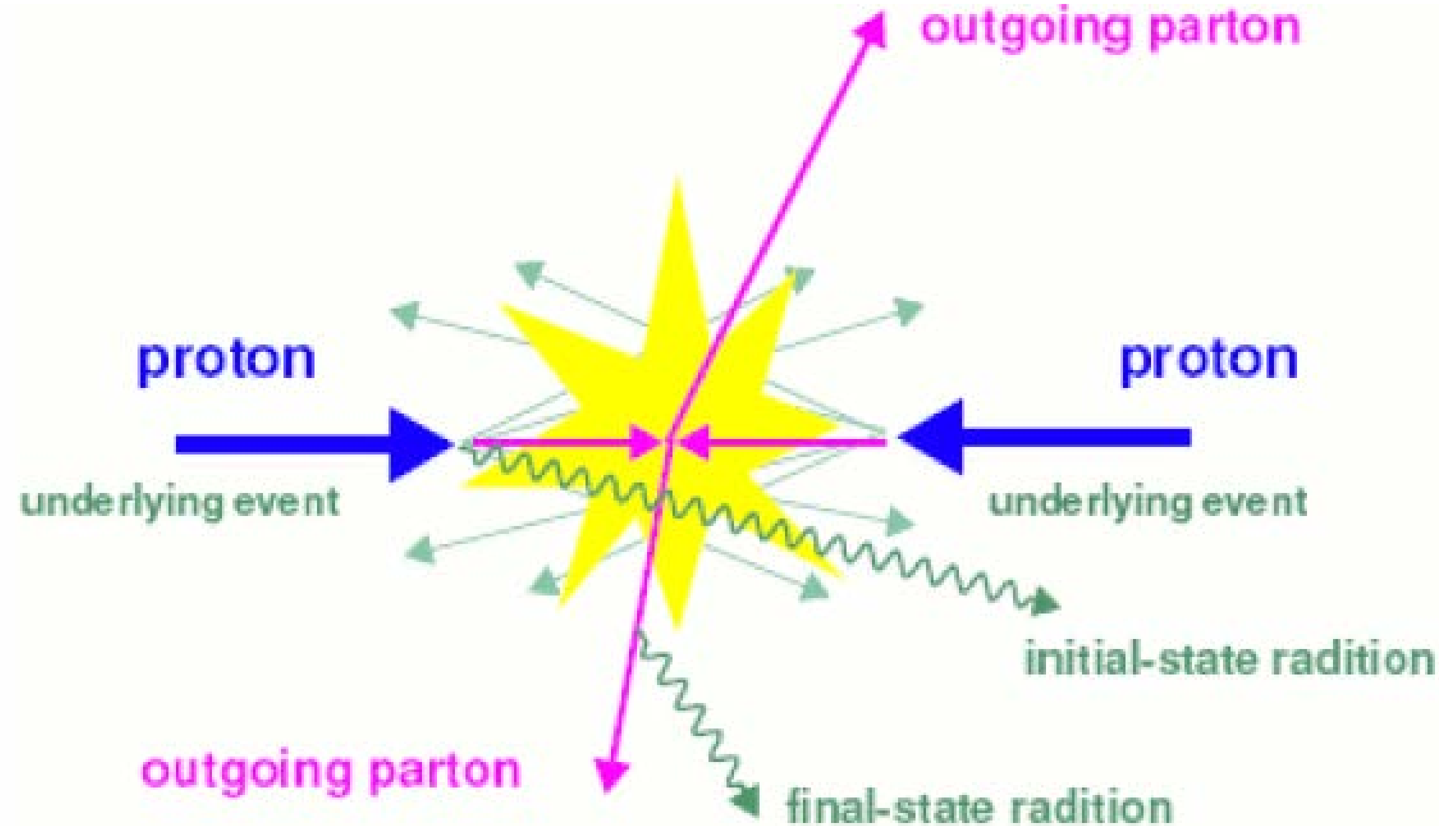
- Introduction
- Examples of jet substructures
- Higgs production mechanism
- Summary

Introduction

- Jets are abundantly produced at colliders
- Jets carry information of underlying events, hard dynamics (strong and weak), and parent particles, including particles beyond the Standard Model
- Jet substructures can be used to discriminate particles, production/decay mechanism
- Study of jets is crucial; comparison between theory and experiment is nontrivial

Underlying events

- Everything but hard scattering
- Initial-state radiation, final-state radiation, multi-parton interaction all contribute to jets

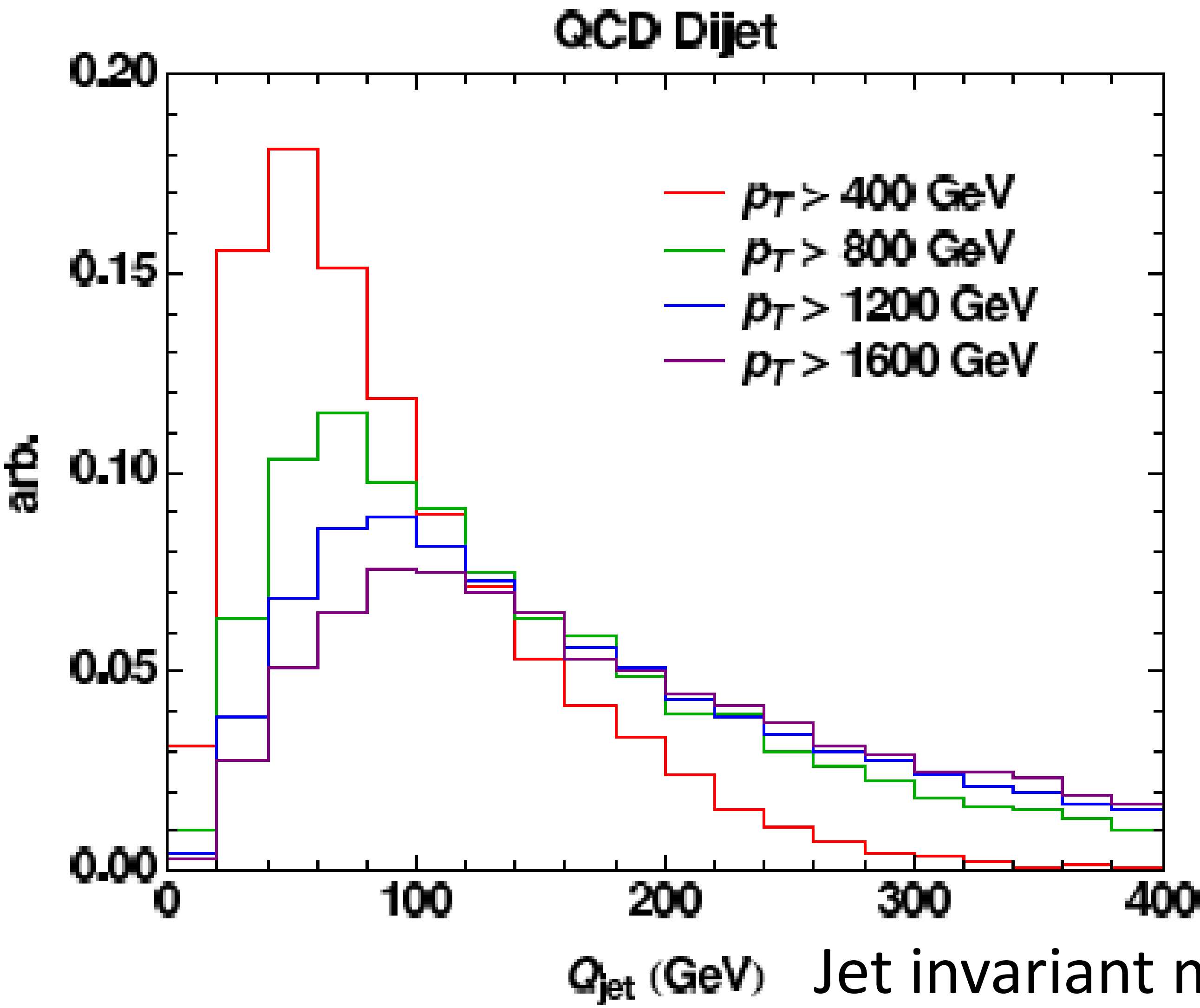


Examples of jet substructures

Boosted heavy particles

- Heavy particles (Higgs, W, Z, top, new particles) may be produced with large boost at LHC
- Decaying heavy particle with sufficient boost gives rise to a single jet
- If just measuring invariant mass, how to differentiate heavy-particle jets from ordinary QCD jets?

Fat QCD jet looks like top jet at high pT

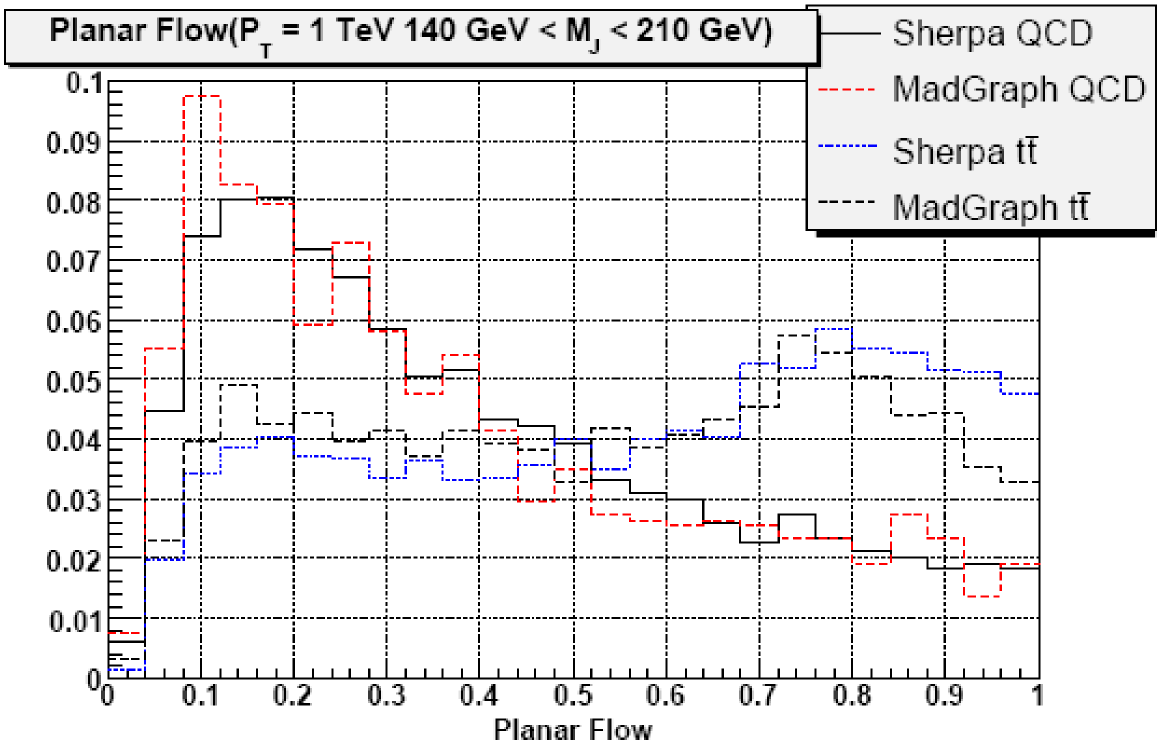


Jet invariant mass

Thaler
& Wang
0806.0023
Pythia 8.108

Planar flow

- Use jet substructures resulting from different weak and strong dynamics
- QCD jets: 1 to 2 linear flow, linear energy deposition in detector
- Top jets: 1 to 3 weak decay planar flow



Almeida et al, 0807.0234

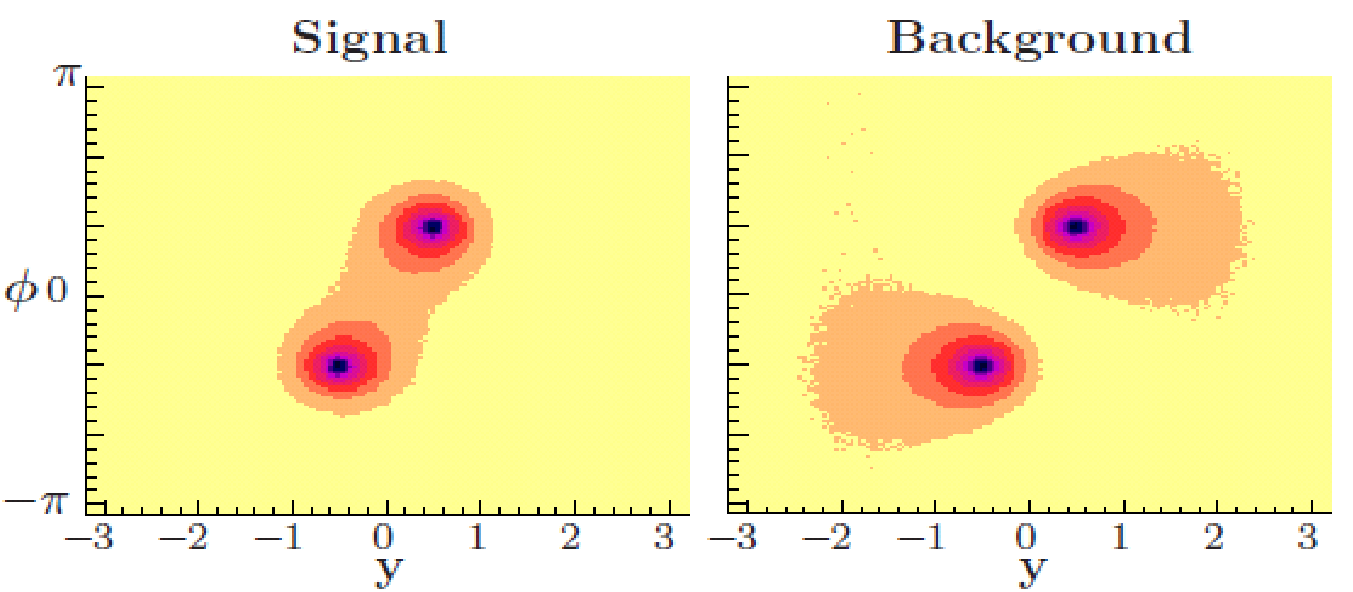
Higgs jet

- Major Higgs decay modes H -> bb with Higgs mass ~ 125 GeV
- Important background g -> bb
- Both involve 1 -> 2 splitting, planar flow does not work
- Analyzing appropriate substructures to improve identification
- For instance, color pull made of soft gluons, attributed to strong dynamics

Gallicchio, Schwartz, 2010

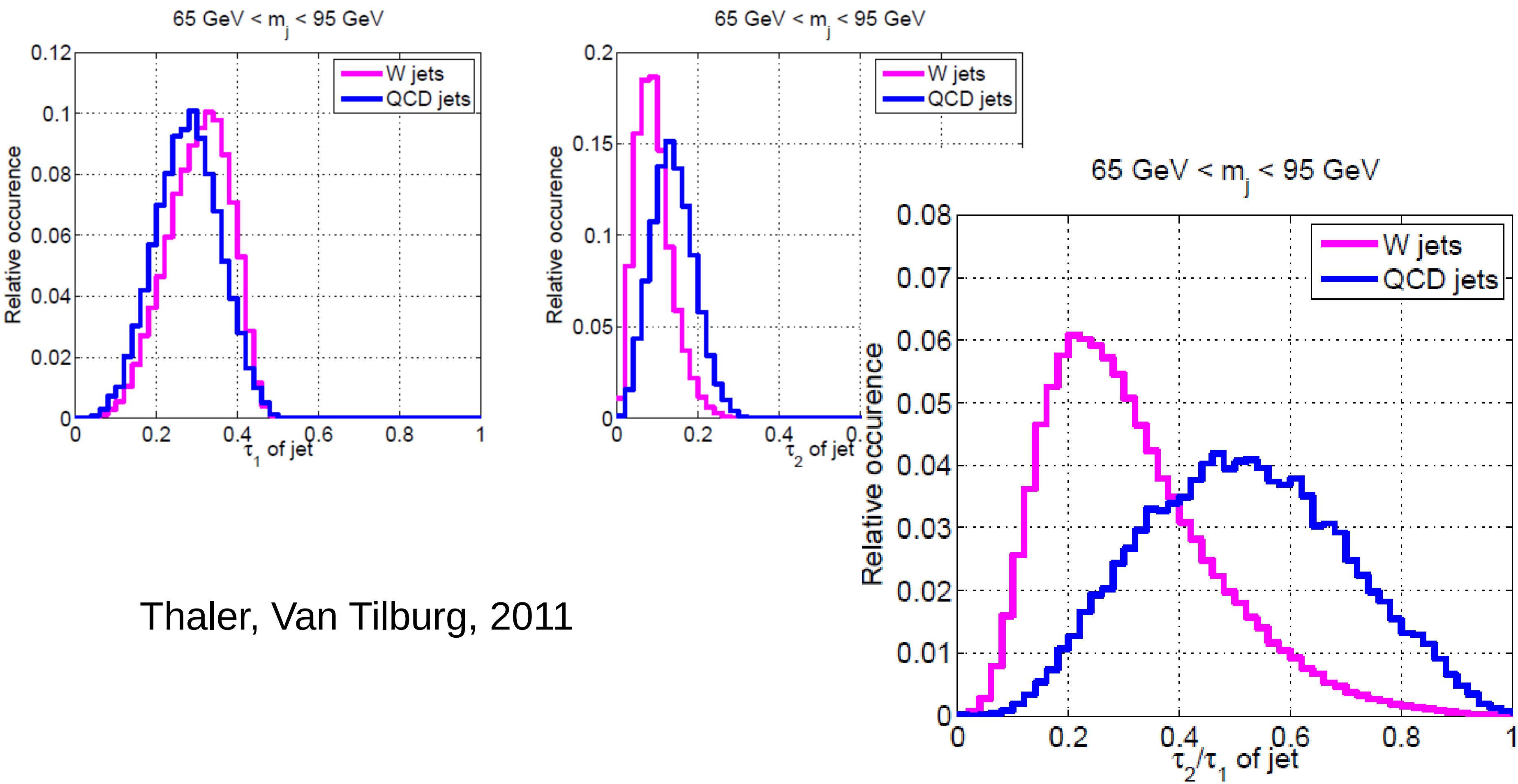
Color pull

- Higgs is colorless, bb forms a color dipole
- Soft gluons exchanged between them
- Gluon has color, b forms color dipole with other particles, such as beam particles



N-subjettiness

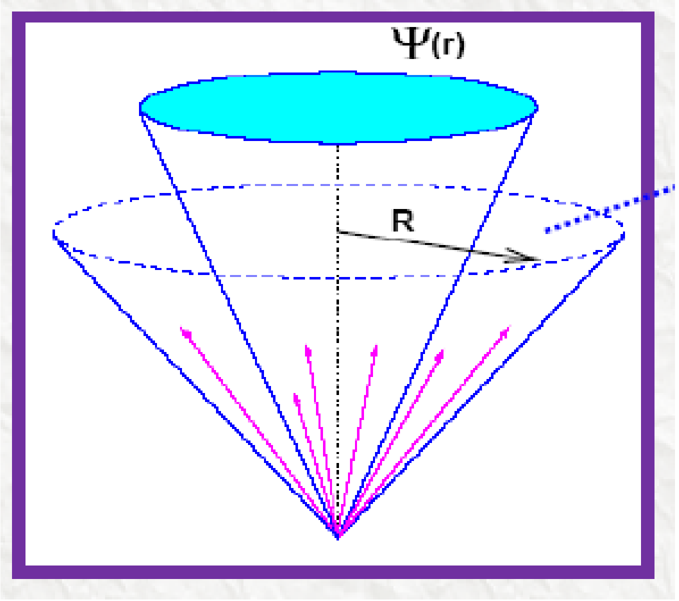
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$

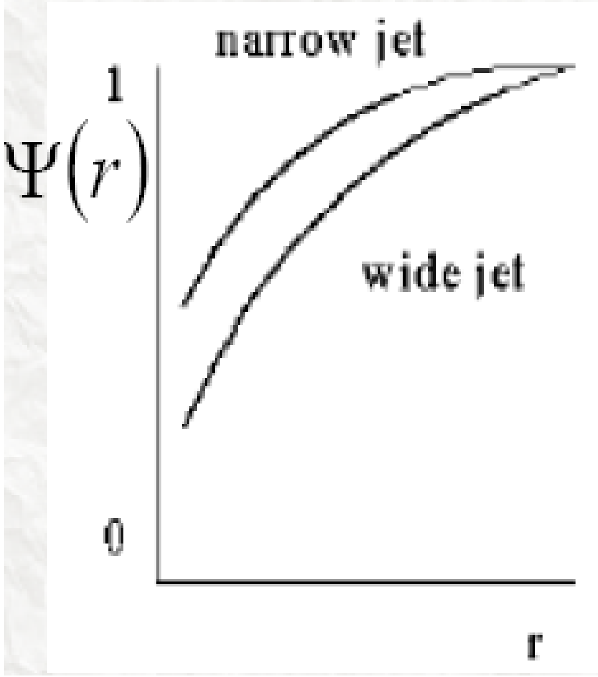


Thaler, Van Tilburg, 2011

Jet energy profile

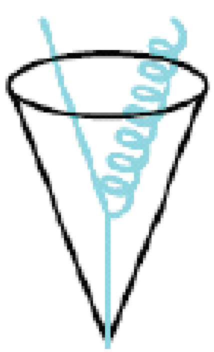
- Energy fraction in cone size of r, $\Psi(r), \Psi(R)=1$
- Quark jet is narrower than gluon jet due to smaller color factor (weaker radiations)
- Heavy particle jet energy profiles should be different

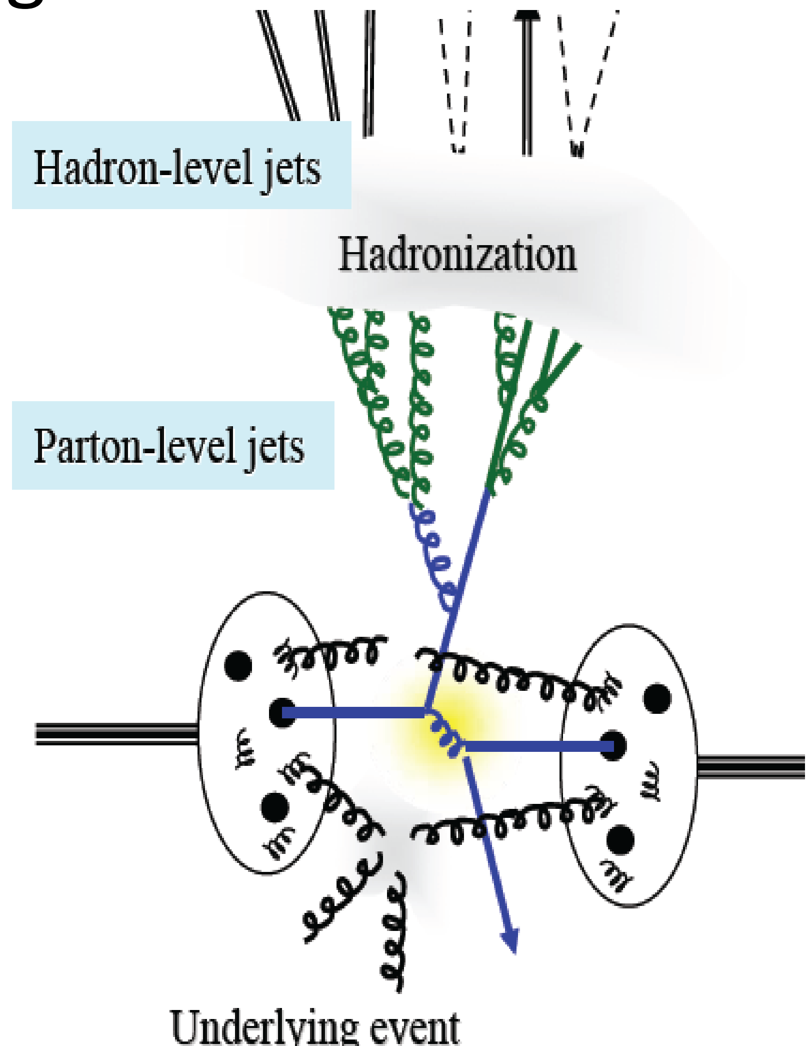




Various approaches

- Event generator: leading log radiation, hadronization, underlying events
- Fixed order: finite number of collinear/soft radiations
- Resummation: all-order collinear/soft radiations

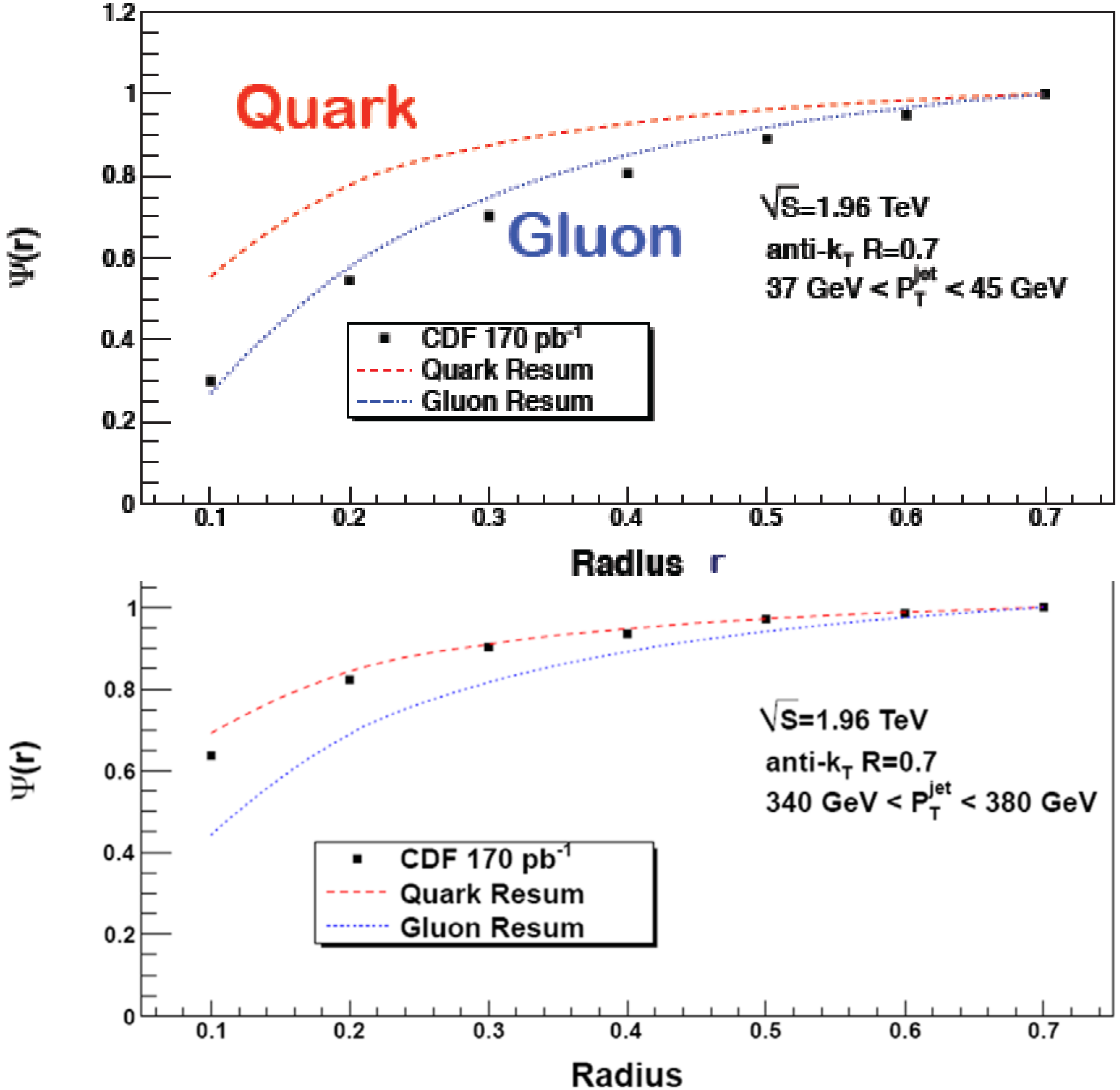




Quark and gluon jet production

- Quark jet dominates at high pT
- Sum over jet mass

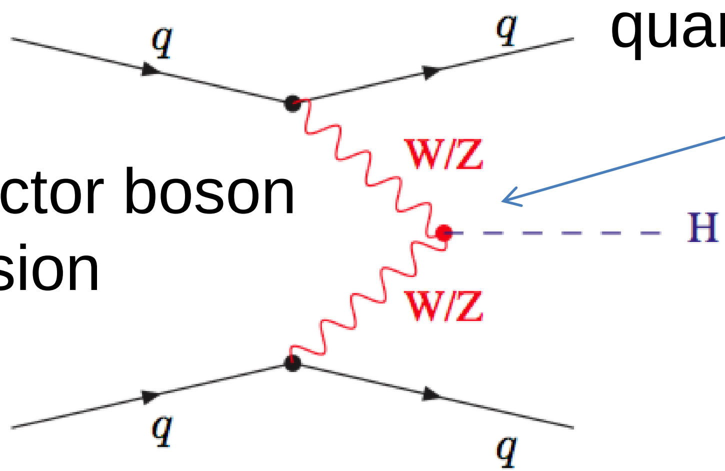
Li, Li, Yuan 2011



Higgs production mechanism

Consider pp -> H+2j

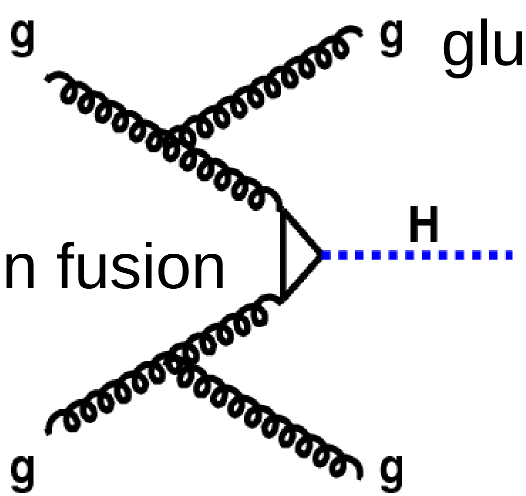
VBF vs GF



quark jet

vector boson fusion

precise measurement can
1) determine Higgs-vector-boson coupling
2) improve measurement of Higgs decays



gluon jet

gluon fusion

need to discriminate Higgs production mechanism

usually apply kinematic cuts
jets are more central in VBF due to massive vector bosons

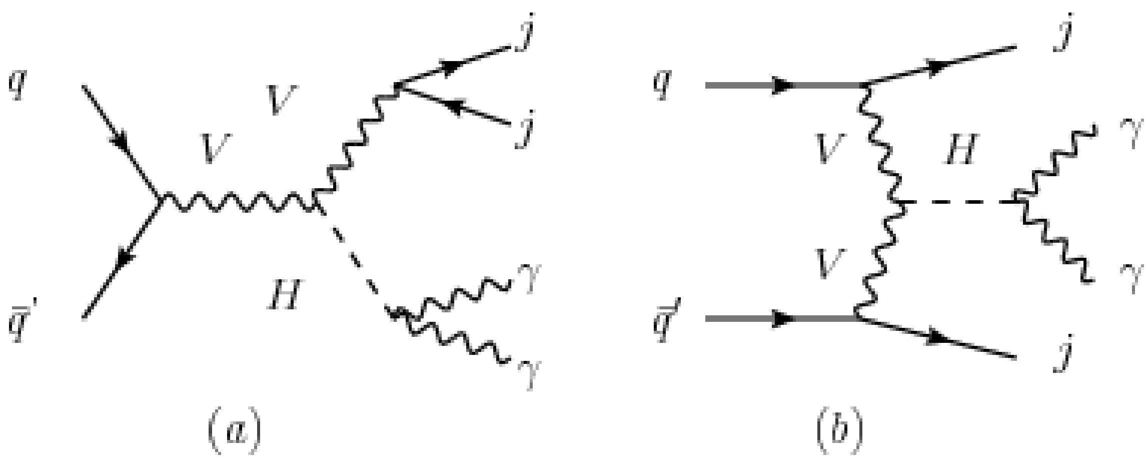
Kinematic cuts

$$p_T^{\gamma_1} > m_{\gamma\gamma}/2, \quad p_T^{\gamma_2} > m_{\gamma\gamma}/4, \quad |\eta_\gamma| < 2.5,$$

$$p_T^{j_1} > 30 \text{ GeV}, \quad p_T^{j_2} > 30 \text{ GeV}, \quad |\eta_j| < 4.7,$$

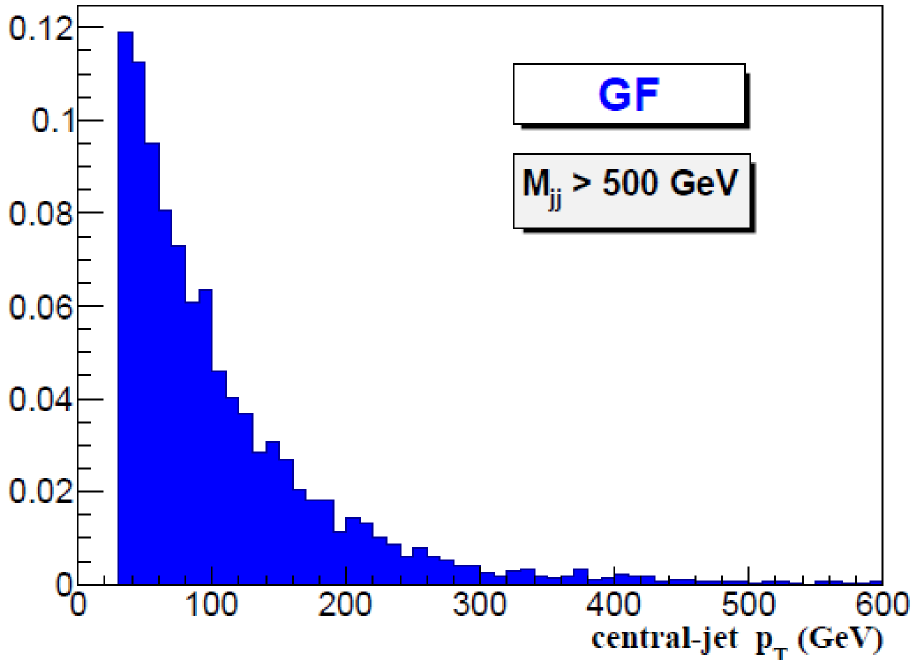
$$\Delta\eta_{jj} > 3.5, \quad M_{jj} > 500\,\text{GeV}$$

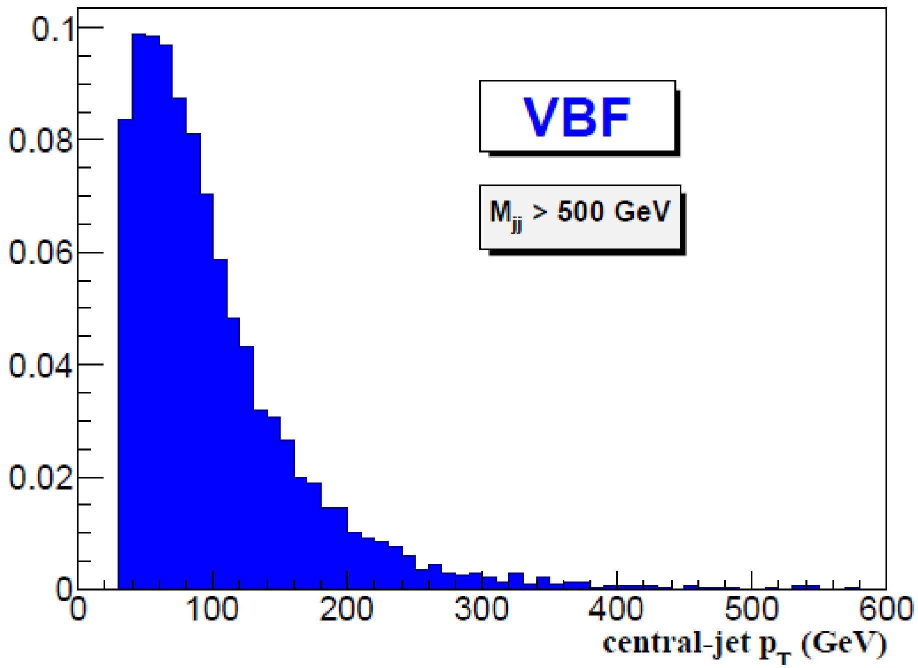
to discriminate associated production



Rentala, Vignaroli, Li, Li, Yuan 2013

Central jet pT distribution



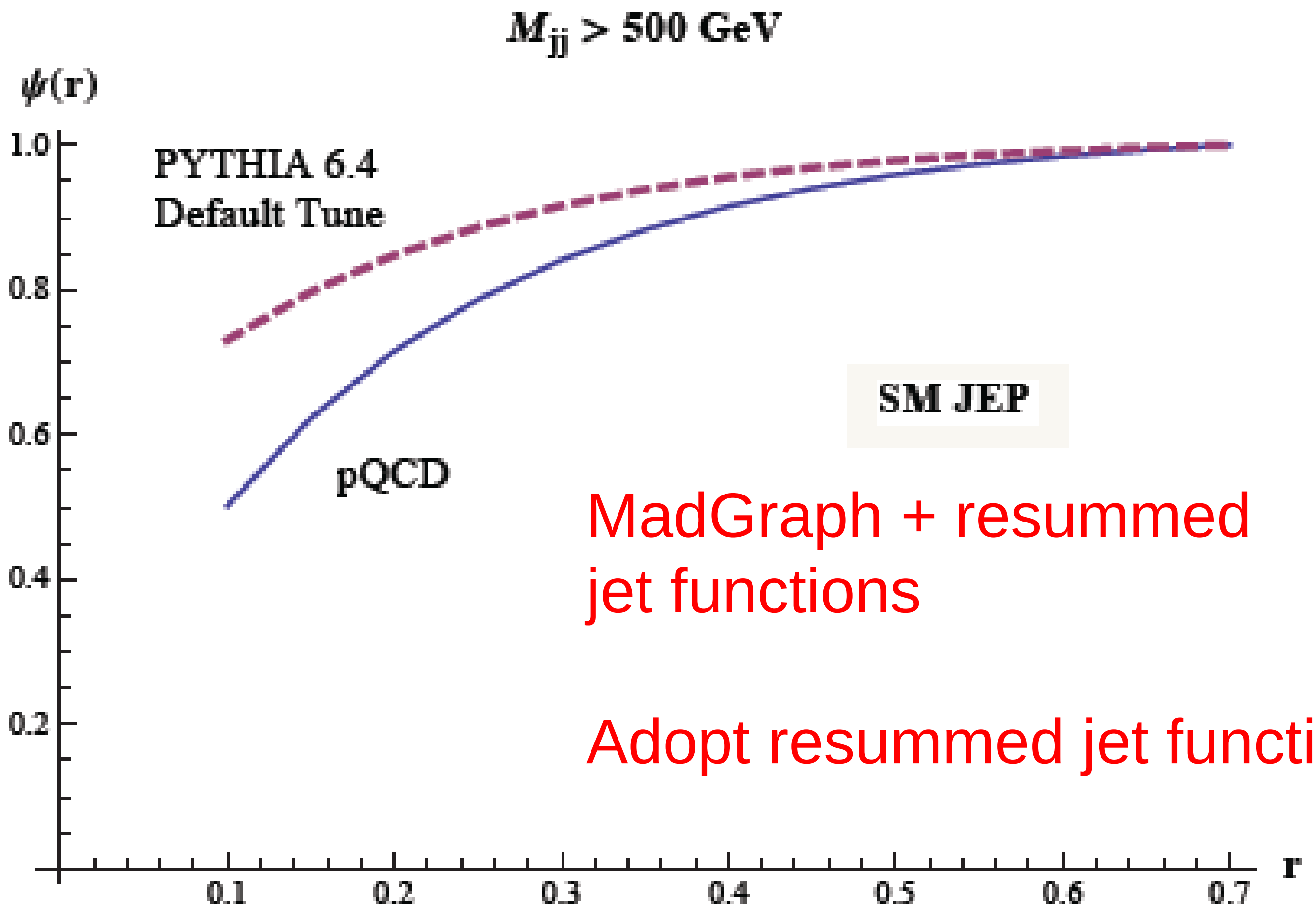


kinematic discrimination
may not be sufficient

broader distribution
more central jets in VBF

Difference between Pythia and PQCD

MadGraph + Pythia showering and hadronization
+ Spartyjet with anti-kt algorithm



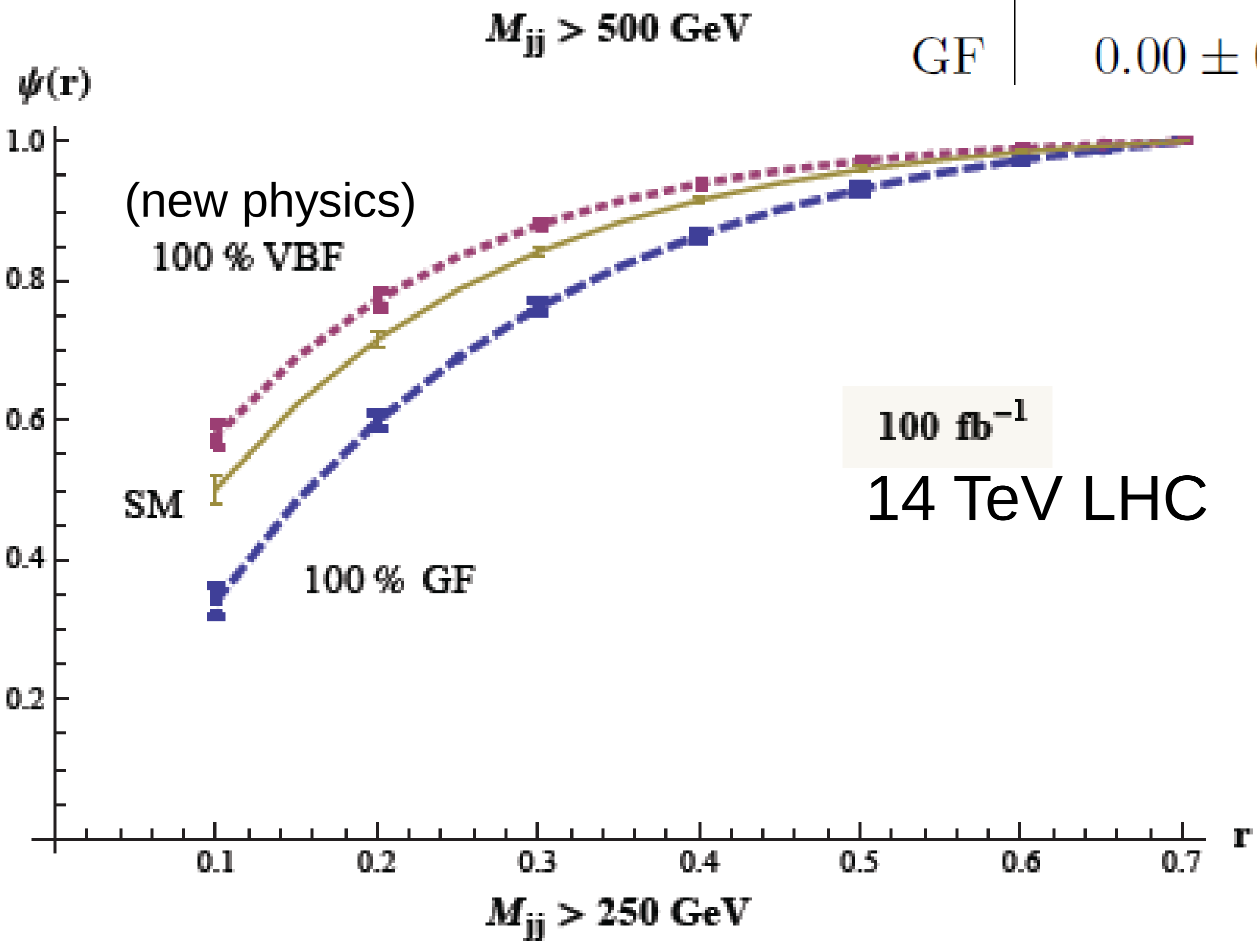
MadGraph + resummed
jet functions

Adopt resummed jet functions

1σ statistic errors from Pythia

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

f_V	$\mathrm{M_{jj}} > 500$ GeV
SM	0.68 ± 0.05
VBF	1.00 ± 0.04
GF	0.00 ± 0.06



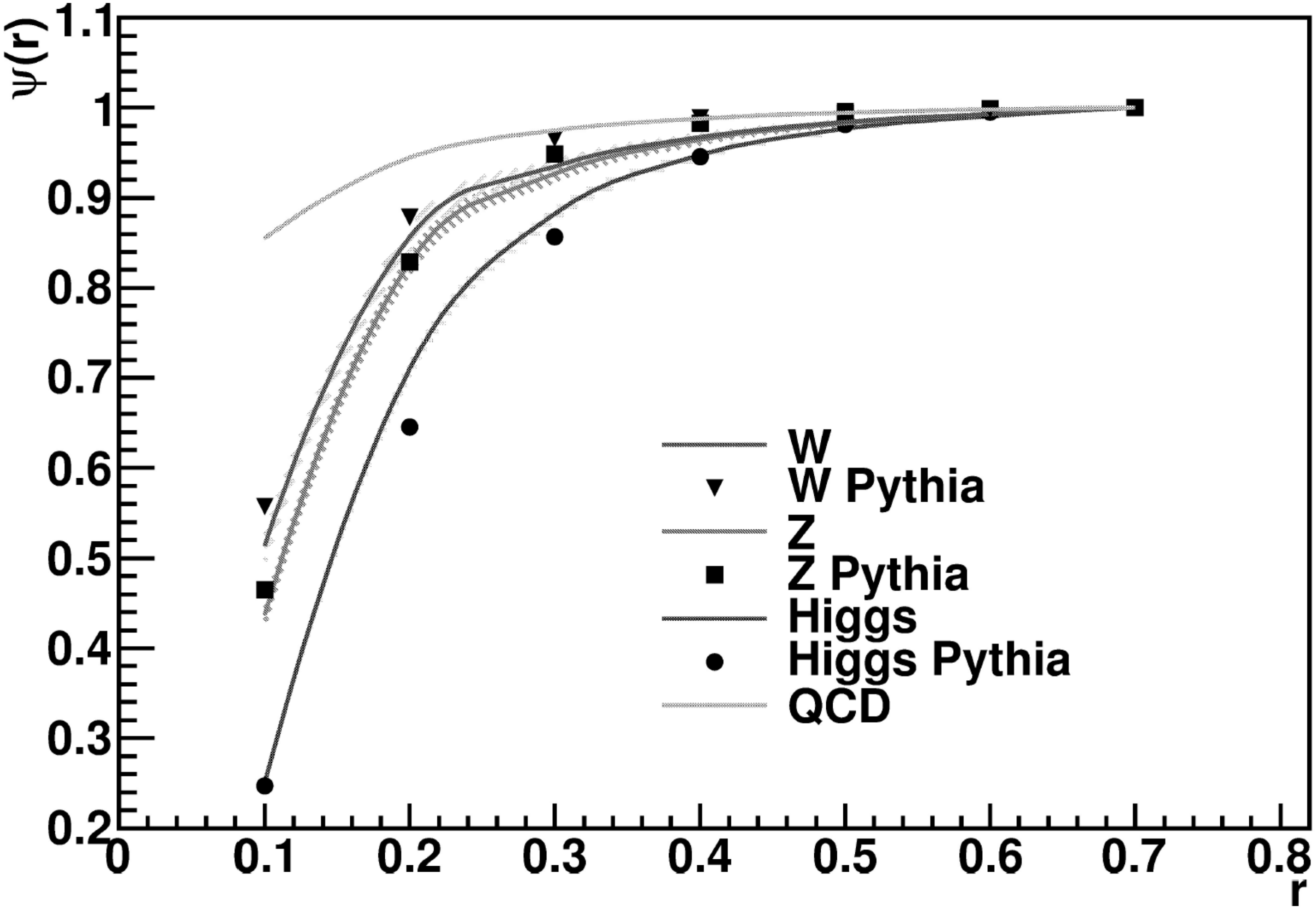
Discrimination of pure GF/VBF

- Define

$$\sigma^{VBF/GF} \equiv \frac{\left| f_V^{VBF/GF} - f_V^{SM} \right|}{\sqrt{\left(\sigma_{f_V}^{VBF/GF}\right)^2 + \left(\sigma_{f_V}^{SM}\right)^2}}.$$

- Pure VBF/GF hypothesis is ruled out at 5.0/8.7 sigma level. Considering $\gamma\gamma jj$ background, discriminating power reduce to 3.6/6.4. Much better than kinematic discrimination
- Improve new physics identification

Jet profiles of boosted EW bosons



Isaacson, Li, LI, Yuan 2016

Summary

- Jet substructures (planar flow, color pull, N-subjettiness,…) improve particle identification and production/decay mechanism
- Discrimination of quark and gluon jets is crucial
- Jet energy profile is powerful discriminator for quark and gluon jets
- Applied to discriminate Higgs production mechanism (VBF/GF), much better than kinematic discrimination