Jet substructures of boosted heavy bosons

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Outlines

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- Jet factorization
- Jet energy profile
- Summary

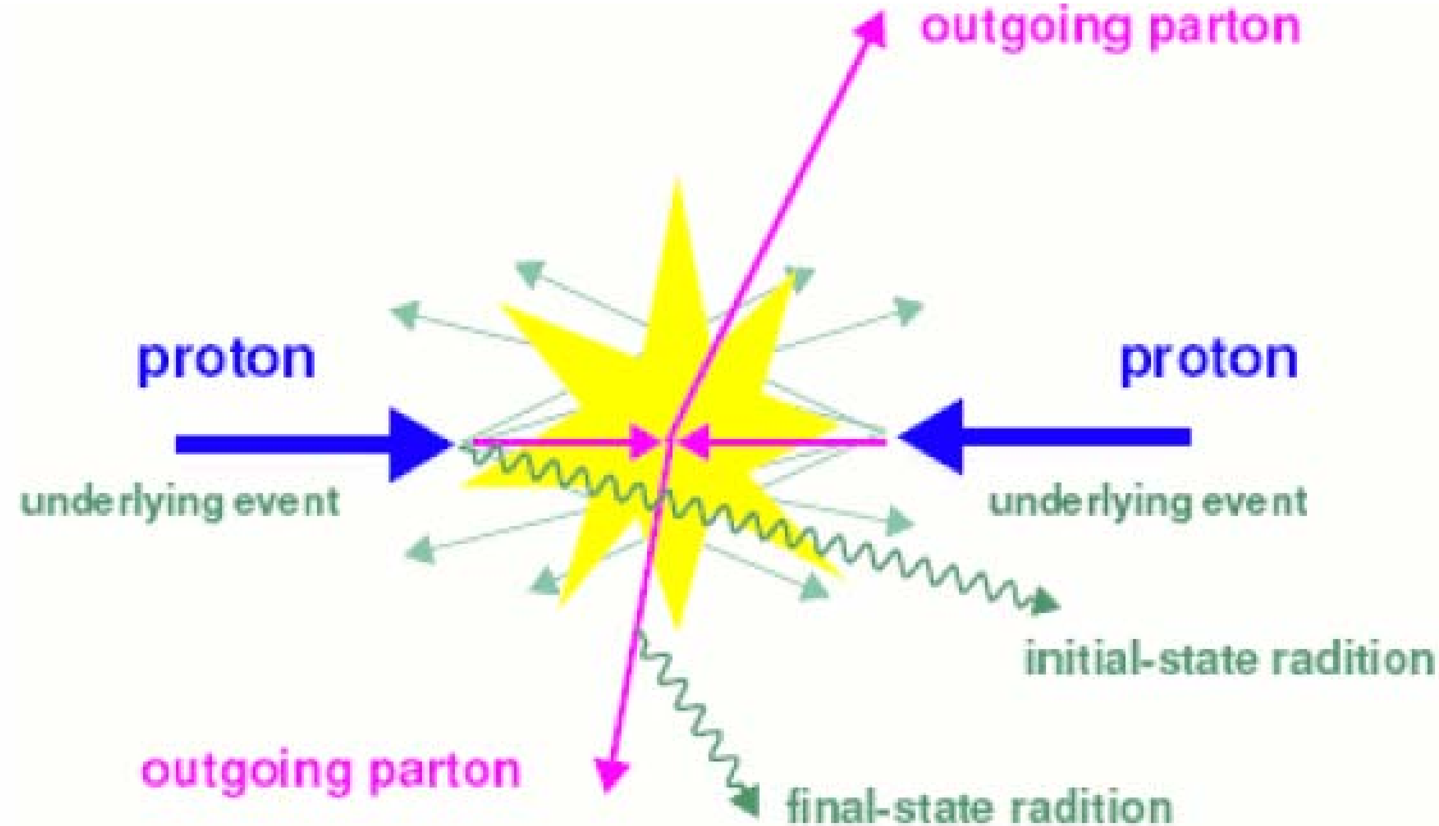
Introduction

Jets

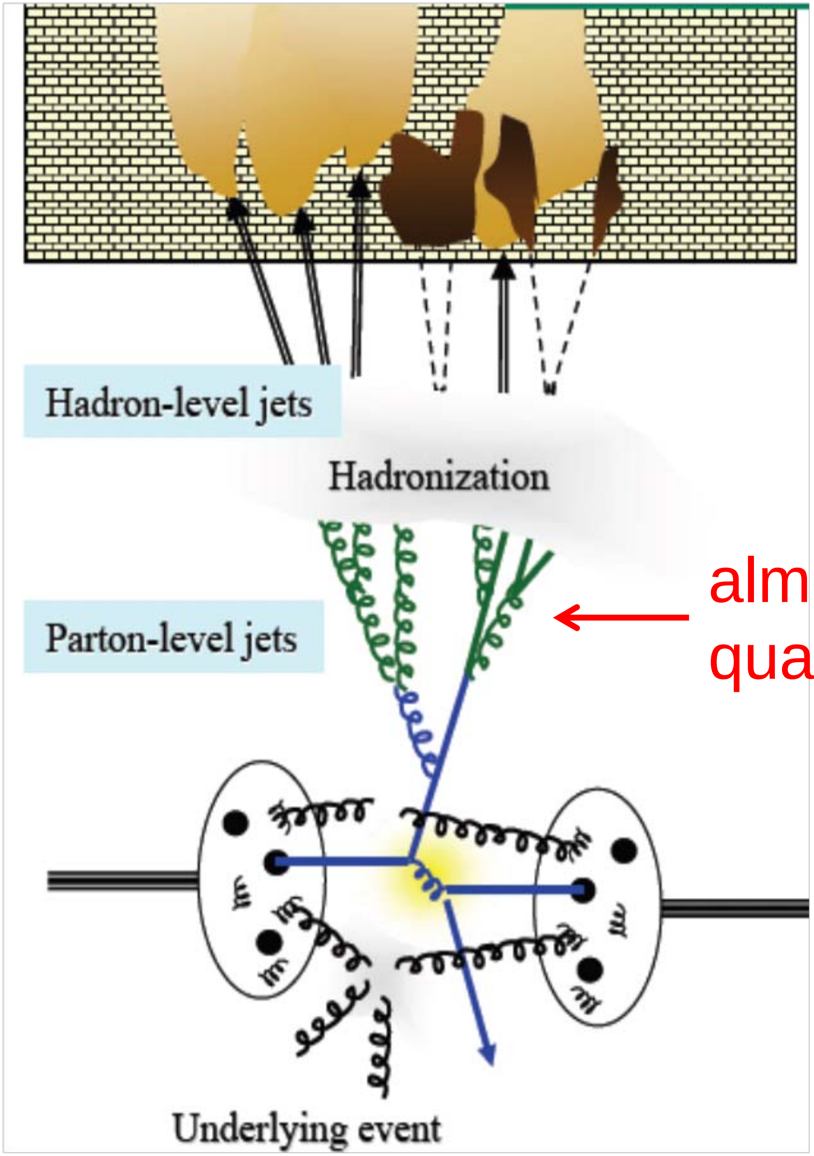
- Jets are abundantly produced at colliders
- Jets carry information of underlying events, hard dynamics (strong and weak), and parent particles, including particles beyond the Standard Model
- Study of jets is crucial; comparison between theory and experiment is nontrivial
- Usually use event generators
- How much can be done in PQCD?

Underlying events

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



Cascades in collider

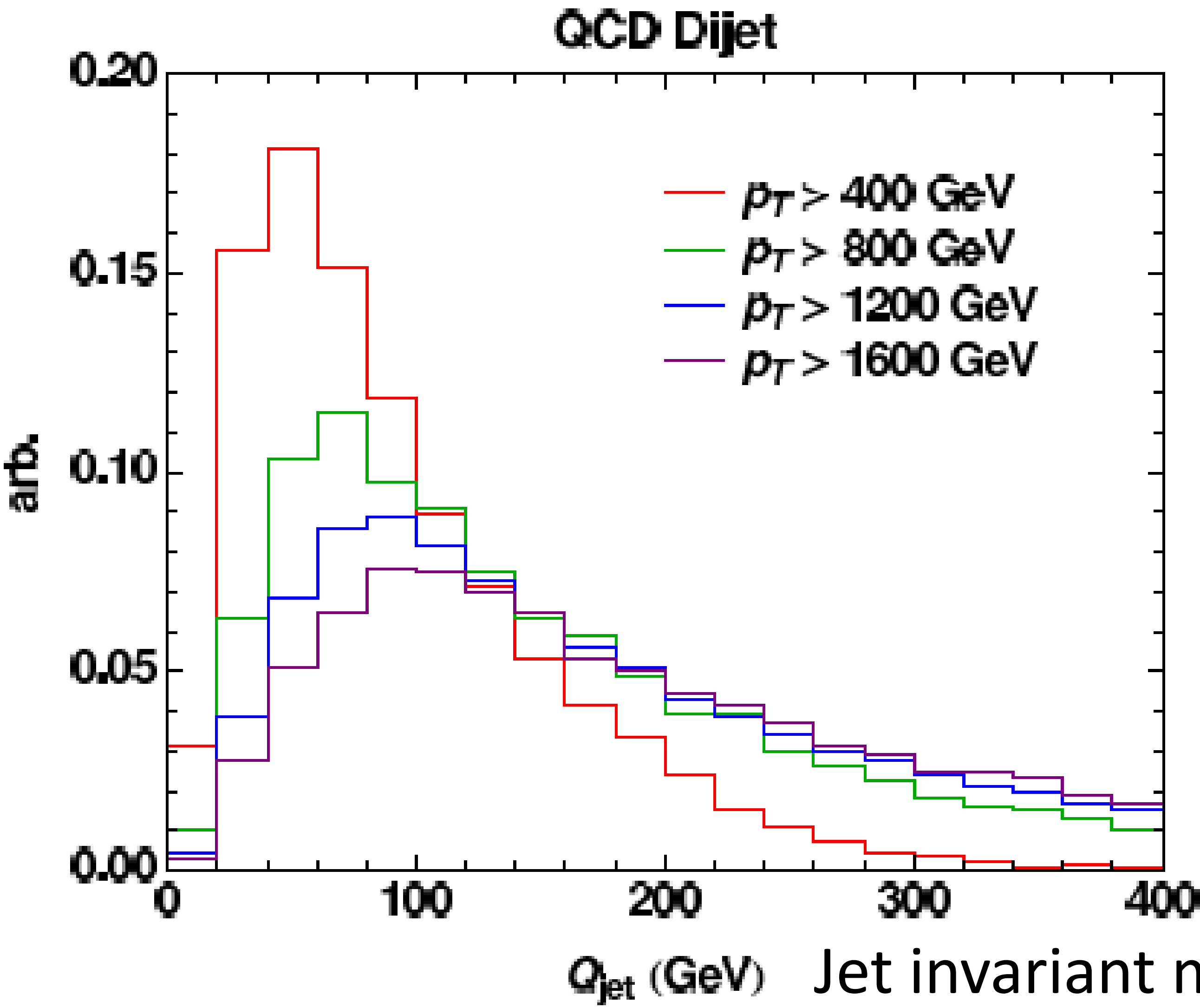


almost parallel
quarks, gluons

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?
- Use different jet substructures resulting from different weak and strong dynamics

Fat high pT QCD jet fakes heavy-particle jet

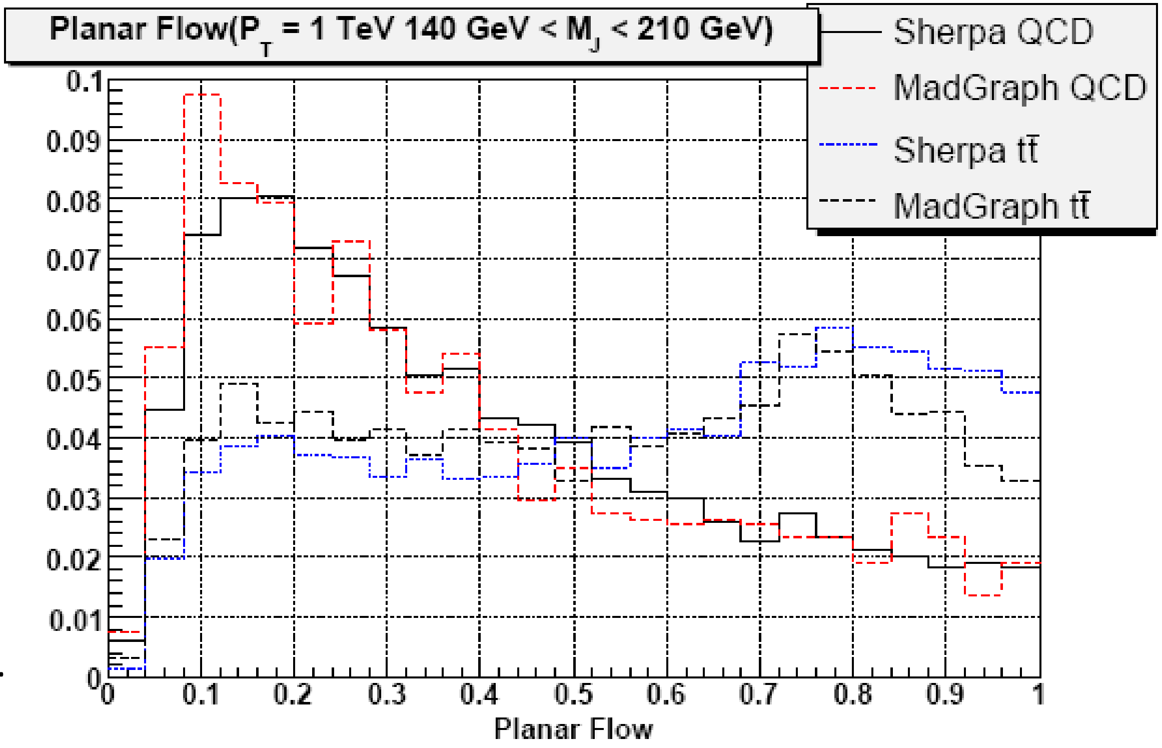


Jet invariant mass

Thaler
& Wang
0806.0023
Pythia 8.108

Planar flow

- Make use of differences in jet internal structure in addition to standard event selection criteria
- Example: planar flow
- QCD jets: 1 to 2 linear flow, linear energy deposition in detector
- Top jets: 1 to 3 planar flow



Almeida et al, 0807.0234

Trilinear Higgs coupling

Thus far the results from the LHC indicate that the couplings of the Higgs boson to other particles are consistent with the Standard Model.

But the ultimate test as to whether this particle is the SM Higgs boson will be the trilinear Higgs coupling that appears in Higgs pair production.

$E_{\mathrm{c.m.}}$	8 TeV	14 TeV	33 TeV	100 TeV
σ_{NNLO}	9.76 fb	40.2 fb	243 fb	1638 fb
Scale [%]	$+9.0-9.8$	$+8.0-8.7$	$+7.0-7.4$	$+5.9-5.8$
PDF [%]	$+6.0-6.1$	$+4.0-4.0$	$+2.5-2.6$	$+2.3-2.6$
PDF + α_S [%]	$+9.3-8.8$	$+7.2-7.1$	$+6.0-6.0$	$+5.8-6.0$

Higgs jets can be produced

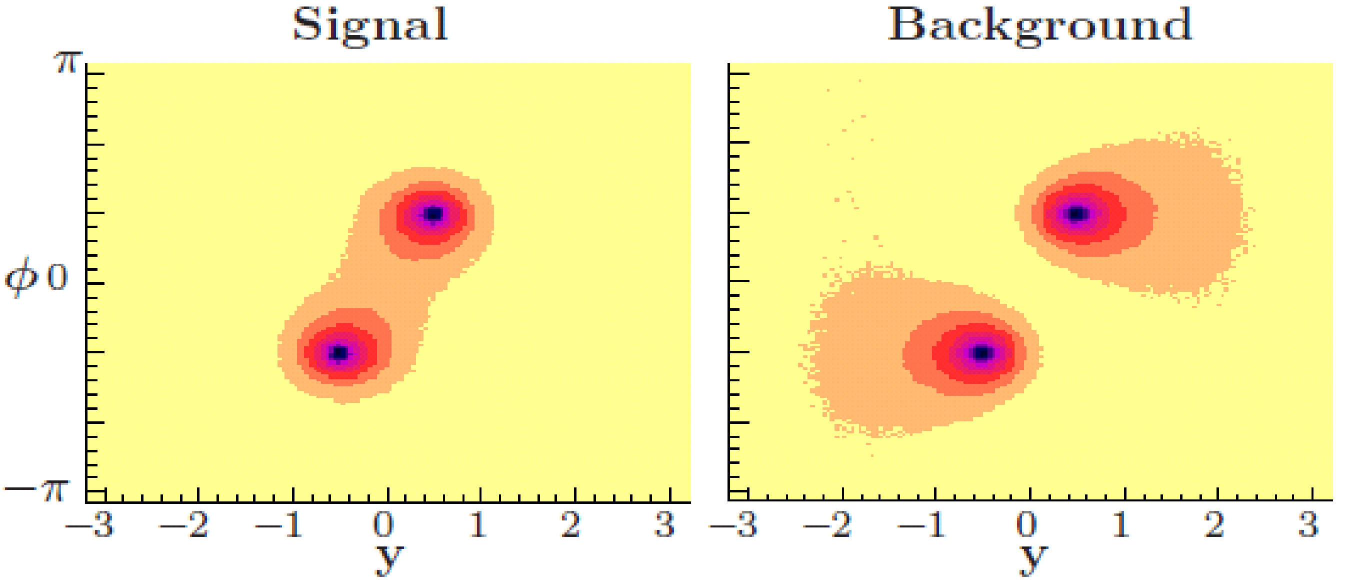
de Florian, Mazzitelli 2013

Higgs jet

- One of major Higgs decay modes H -> bb with Higgs mass ~ 125 GeV
- Important background g -> bb
- Both involve 1 -> 2 splitting
- Analyzing substructure of Higgs jet improves its identification Gallicchio, Schwartz, 2010
- For instance, color pull made of soft gluons, attributed to strong dynamics
- Top jet substructure is attributed to weak dynamics

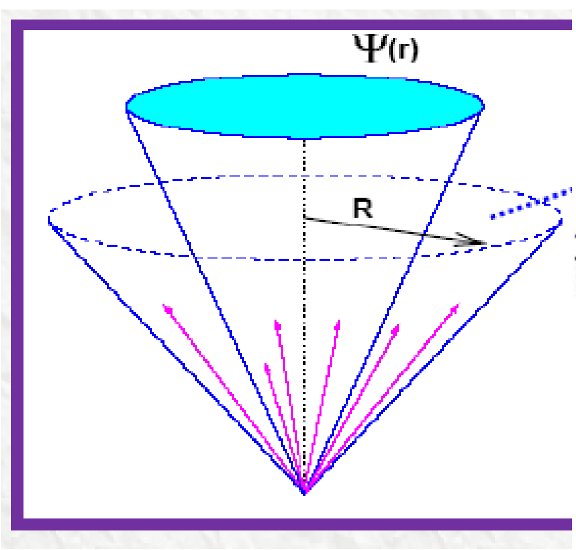
Color pull

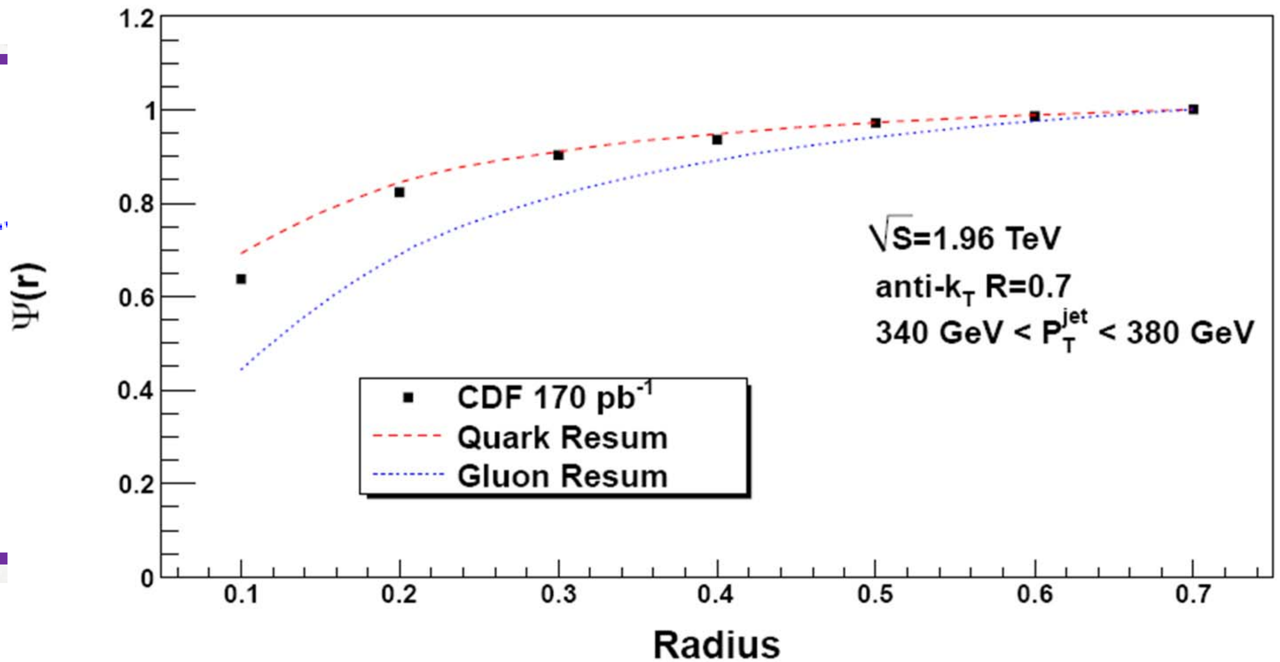
- Higgs is colorless, bb forms a color dipole
- Soft gluons exchanged between them
- Gluon has color, b forms color dipole with other particles, such as beam particles



Energy profile

- We propose to measure 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)



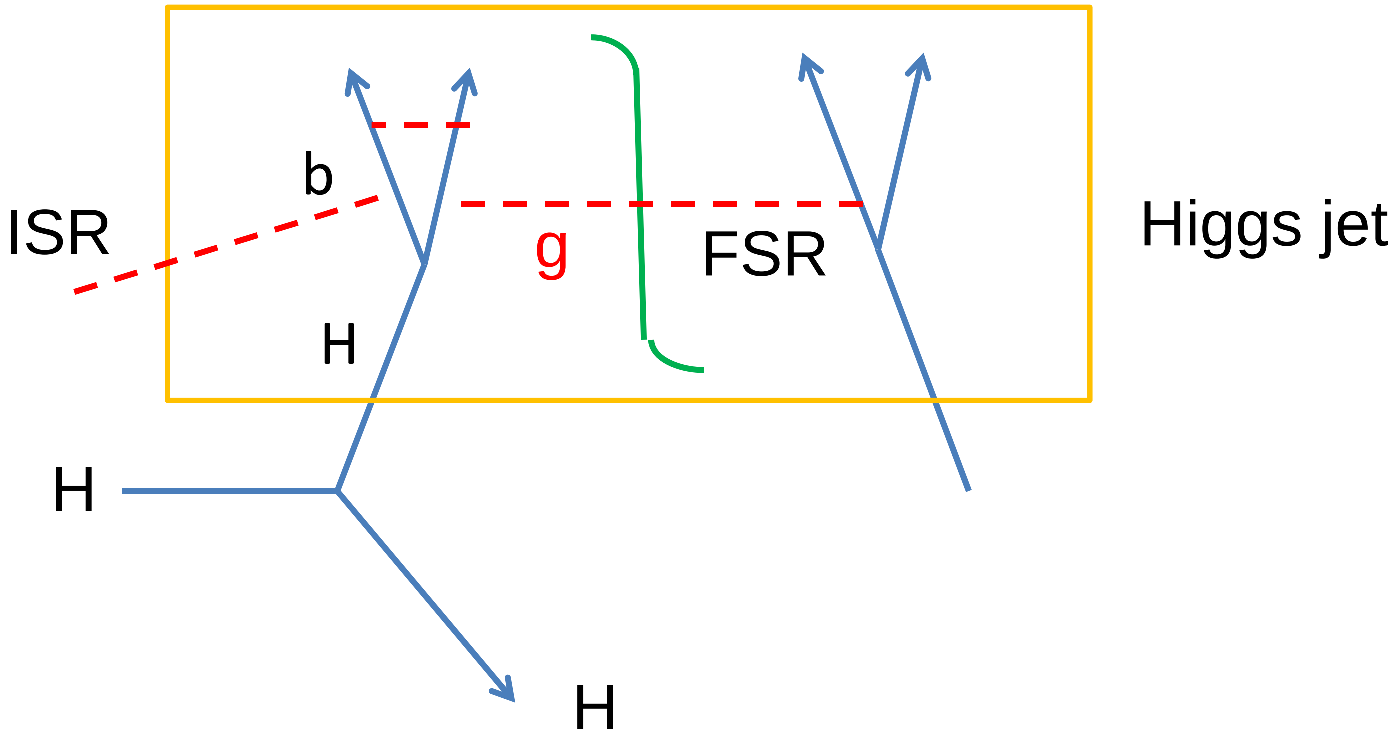


Jet factorization

Achieved by eikonalization and Ward identity

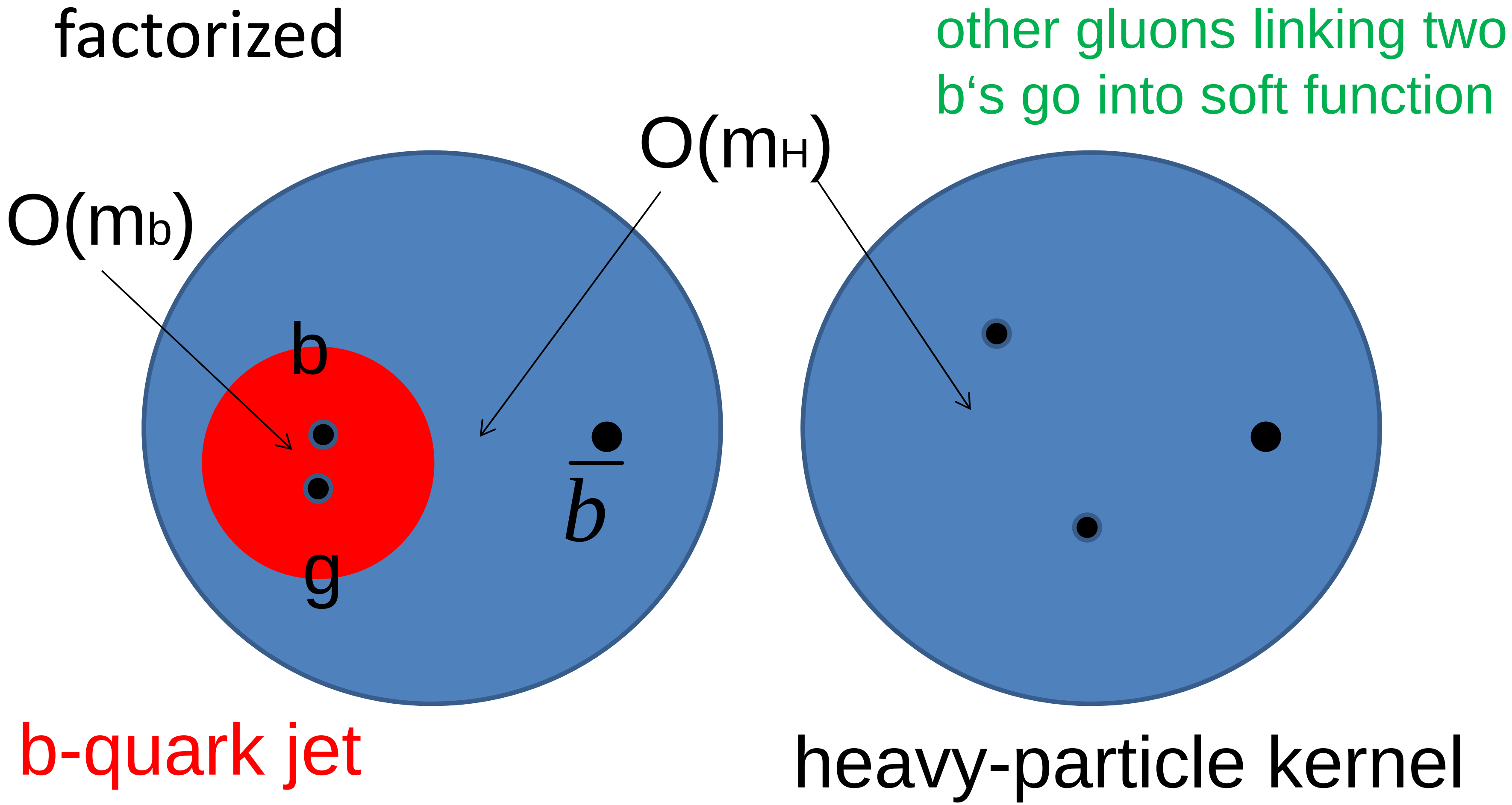
Factorization at jet energy E

- Factorize heavy Higgs jet first from collision process at jet energy scale E



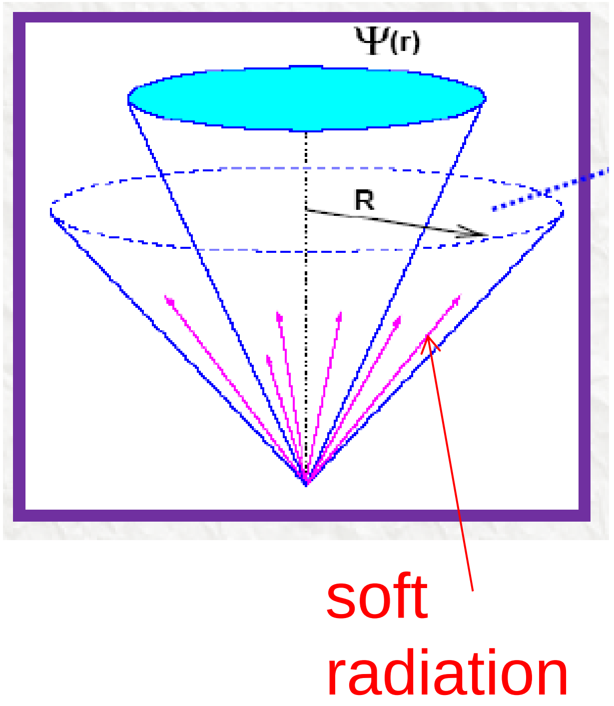
Scale hierarchy $E \gg m_H \gg m_b$

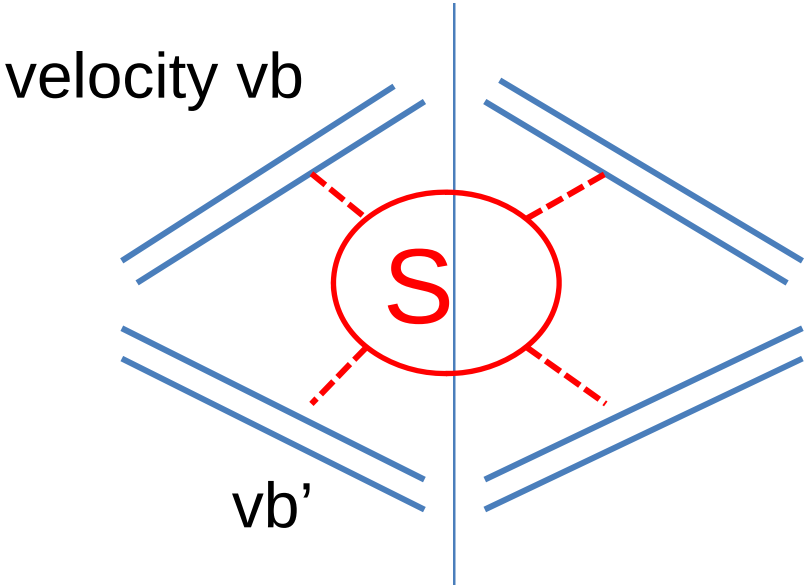
- The two lower scales m_H and m_b characterize different dynamics, which can be further factorized



Soft function

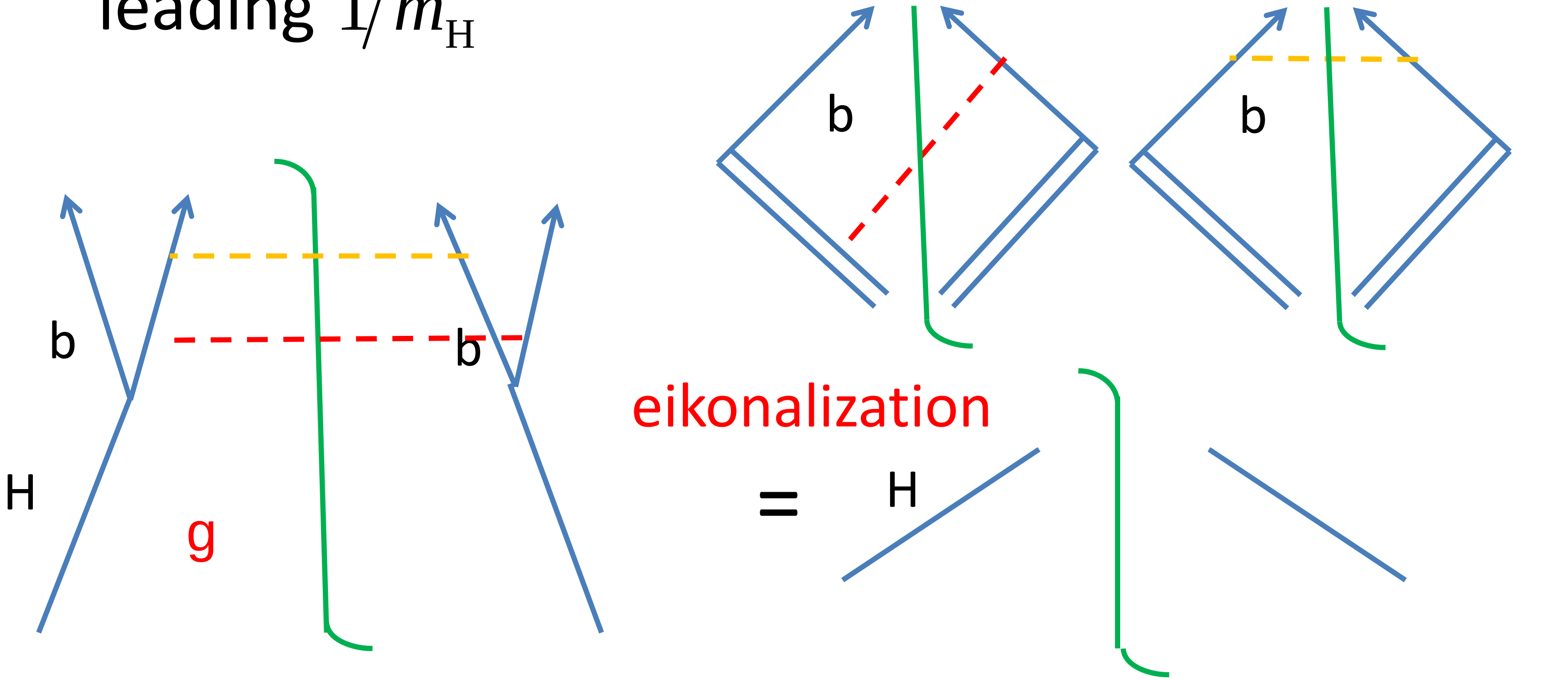
- Soft radiation around two b jets plays important role
- Feynman diagrams
- Calculated as jet function





Factorization into two sub-jets

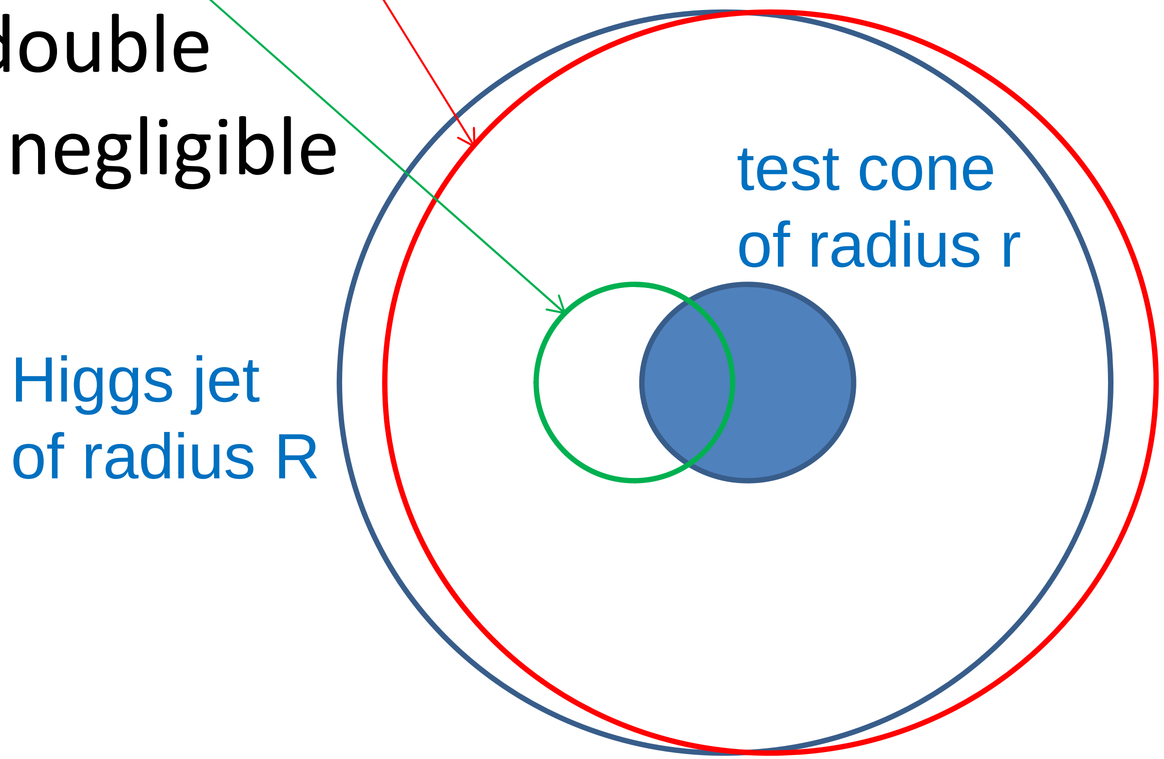
- Then factorize two b-jets from the Higgs jet at leading $1/m_{\mathrm{H}}$



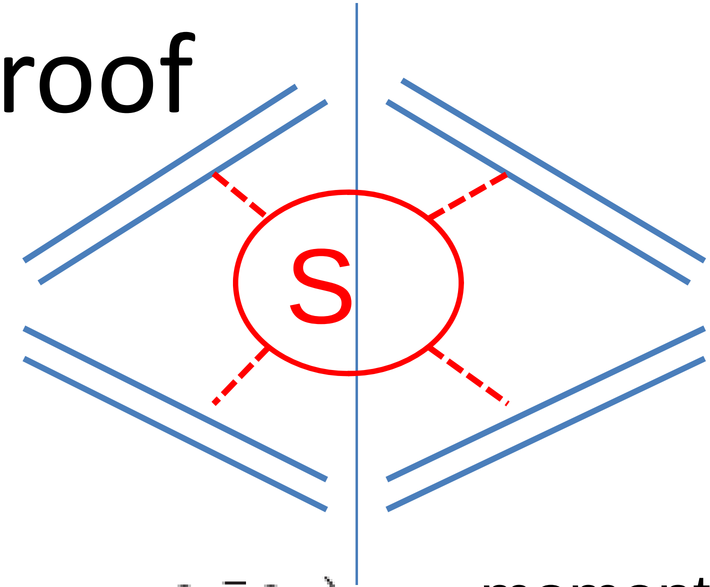
$$J_{\mathrm{H}} = H \otimes J_1 \otimes J_2 \otimes S$$

Simpler factorization

- Absorb soft radiation into one of b-jets to form a fat b-jet of radius R
- Another is a thin b-jet of radius r
- At small r, double counting is negligible



One-loop proof



- Soft contribution from eikonalized b quarks

b quark velocities

$$S^{(1)} = \frac{\alpha_s C_F}{\pi (R E_{J_H})^2} \ln \frac{\bar{\xi}_{J_1}^2 \bar{\xi}_{J_2}^2}{4(\bar{\xi}_{J_1} \cdot \bar{\xi}_{J_2})^2} \left(\frac{1}{\epsilon} + \ln \frac{4\pi \mu_f^2 \bar{N}^2}{R^4 E_{J_H}^2 e^{\gamma_E}} \right)$$

moment $N \exp(\gamma_E)$

- Collinear subtraction from fat b

$$S^{(1)} - S^{(1)}_{n_{J_2}} =$$

$4(\bar{\xi}_{J_2} \cdot n_{J_2})^2 / n_{J_2}^2 = R^2$ final condition of jet resummation

$$\frac{\alpha_s C_F}{\pi (R E_{J_H})^2} \ln \frac{\bar{\xi}_{J_1}^2 (\bar{\xi}_{J_2} \cdot n_{J_2})^2}{(\bar{\xi}_{J_1} \cdot \bar{\xi}_{J_2})^2 n_{J_2}^2} \left(\frac{1}{\epsilon} + \ln \frac{4\pi \mu_f^2 \bar{N}^2}{R^4 E_{J_H}^2 e^{\gamma_E}} \right)$$

Merge soft and collinear objects

- At last, collinear subtraction from thin b

$$S^{(1)} - S^{(1)}_{n_{J_1}} - S^{(1)}_{n_{J_2}} = \frac{\alpha_s C_F}{\pi (R E_{J_H})^2} \ln \frac{\xi^2_{J_1} R^2}{4(\bar{\xi}_{J_1} \cdot \bar{\xi}_{J_2})^2} \ln \frac{R^4}{R_1^4}$$

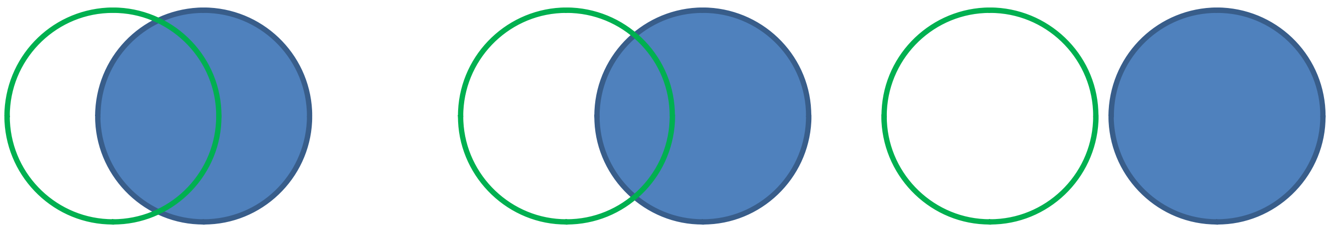
same argument as $S^{(1)} - S^{(1)}_{n_{J_2}}$

- Thin b jet contributes only overall normalization, so its final condition of jet resummation is arbitrary
- Independent of N, $S(\omega, R, \mu_f^2) \propto \delta(\omega)$ soft function drops from factorization

Jet energy profile

Merging criterion

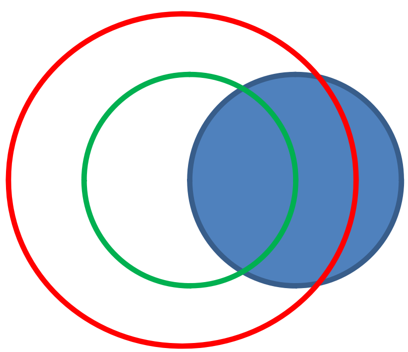
- As integrated over polar angles of b-jets, how distant can they be still merged into test cone?
- If merged, whole energy of thin b-jet and whole energy in test cone of fat b-jet contribute to Higgs jet profile



- d=r r < d < 2r d>2r
- yes ? No

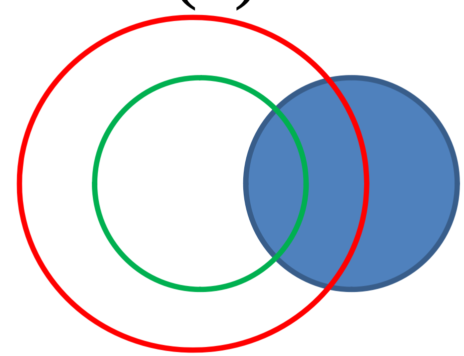
Idea of factorization

- Partons of thin b-jet or in test cone of fat b-jet, if satisfying merging criterion, are assigned into jet energy function $J^E(r)$
- Partons, not satisfying merging criterion, are assigned into a hard kernel $H^E(r)$



$d < 1.5r$

$J_2^E(R,r)$



$d > 1.5r$

$H^E(R,r)$

Factorization formula for profile

- Merging criterion is a matter of factorization scheme
- Choose d=2r to minimize $H^E(r)$
- Factorization formula

$$J_H^E(m_{J_H}^2, E_{J_H}, R, r, \mu^2) = \frac{1}{E_{J_H}} \Pi_{i=1,2} \int dm_{J_i}^2 dE_{J_i} d^2\hat{n}_{J_i} \int d\omega S(\omega, R, \mu_f^2)$$
$$\times \sum_{i \neq j} J_i^E(m_{J_i}^2, E_{J_i}, R_i, r_i, \mu_f^2) J_j(m_{J_j}^2, E_{J_j}, R_j, \mu_f^2) H^{(0)}(P_{J_1}, P_{J_2}, R, \mu^2, \mu_f^2)$$
$$\times \delta(m_{J_H}^2 - P_{J_1} \cdot P_{J_H} - P_{J_2} \cdot P_{J_H} - \omega) \delta(E_{J_H} - E_{J_1} - E_{J_2}) \delta^{(2)}(\hat{n}_{J_H} - \hat{n}_{J_1+J_2})$$

- Applicable to W and Z boson jets

Heavy-particle kernel

- Adopt LO kernel from Higgs propagator

$$H^{(0)} = \frac{1}{2\pi^3}\left(\frac{m_b}{v}\right)^2 \frac{(P^0_{J_1}P^0_{J_2})^2}{(P^2_{J_H}-m^2_H)^2+\Gamma^2_H m^2_H}(\bar{\xi}_{J_1}\cdot\bar{\xi}_{J_2})$$

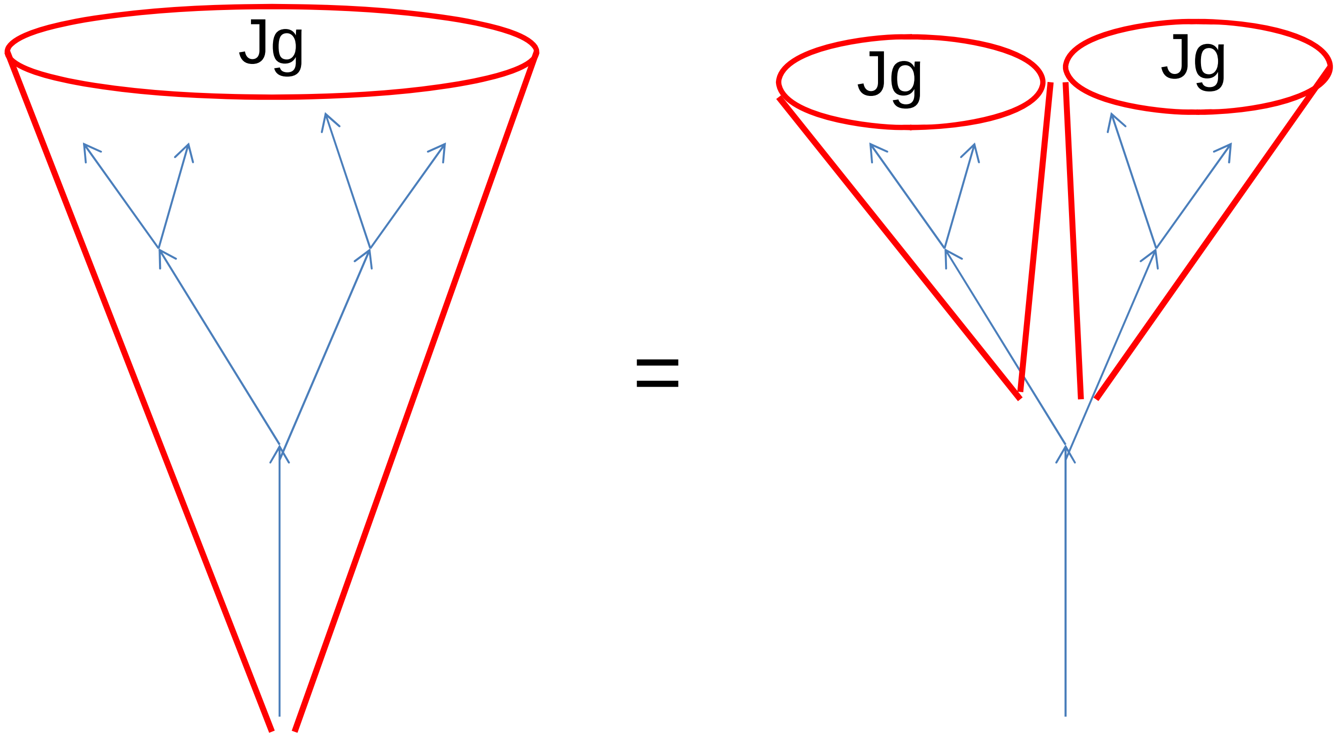
$$\uparrow$$

$$\delta(m^2_{J_H}-P_{J_1}\cdot P_{J_H}-P_{J_2}\cdot P_{J_H}-\omega)$$

- Due to gluon radiation, b- jet spreads into dead cone around Higgs jet axis

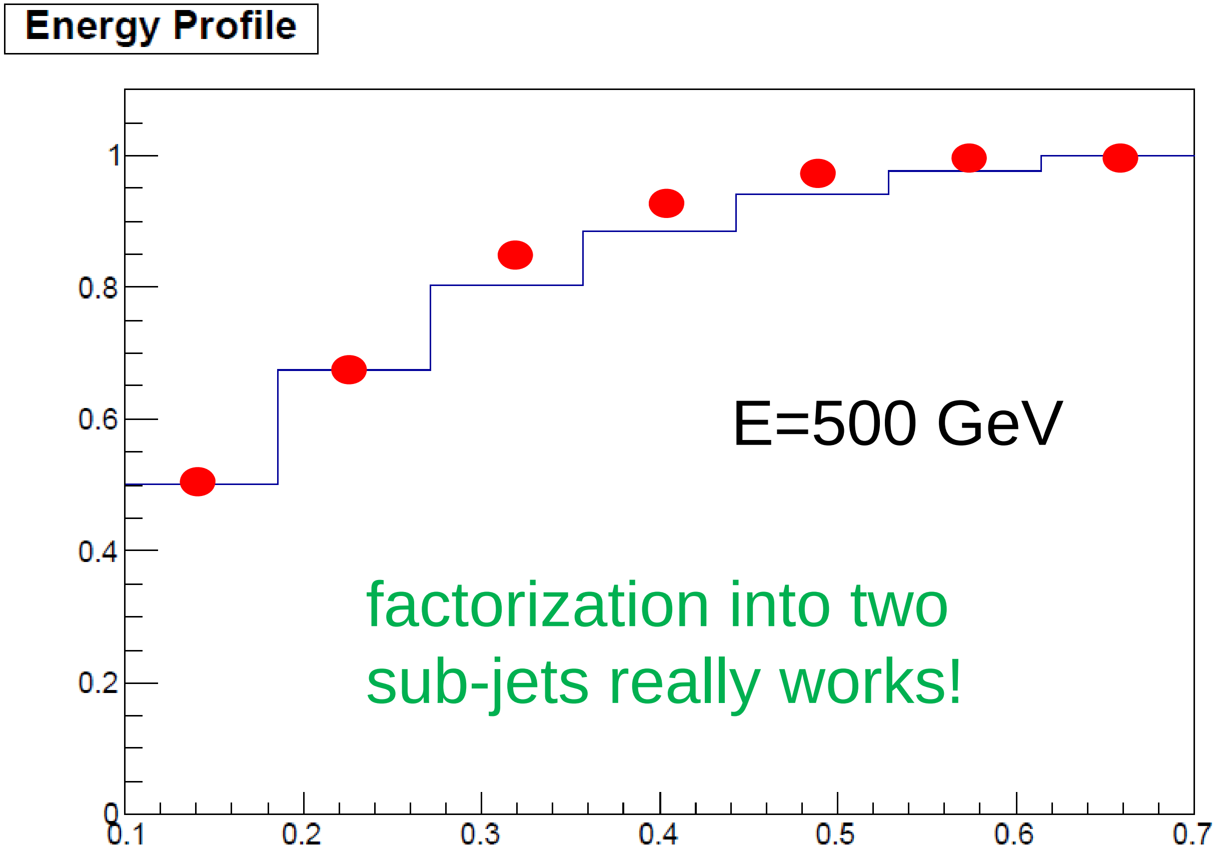
Test by gluon jet profile

- LHS: an original gluon jet
- RHS: Factorization into two sub-jets

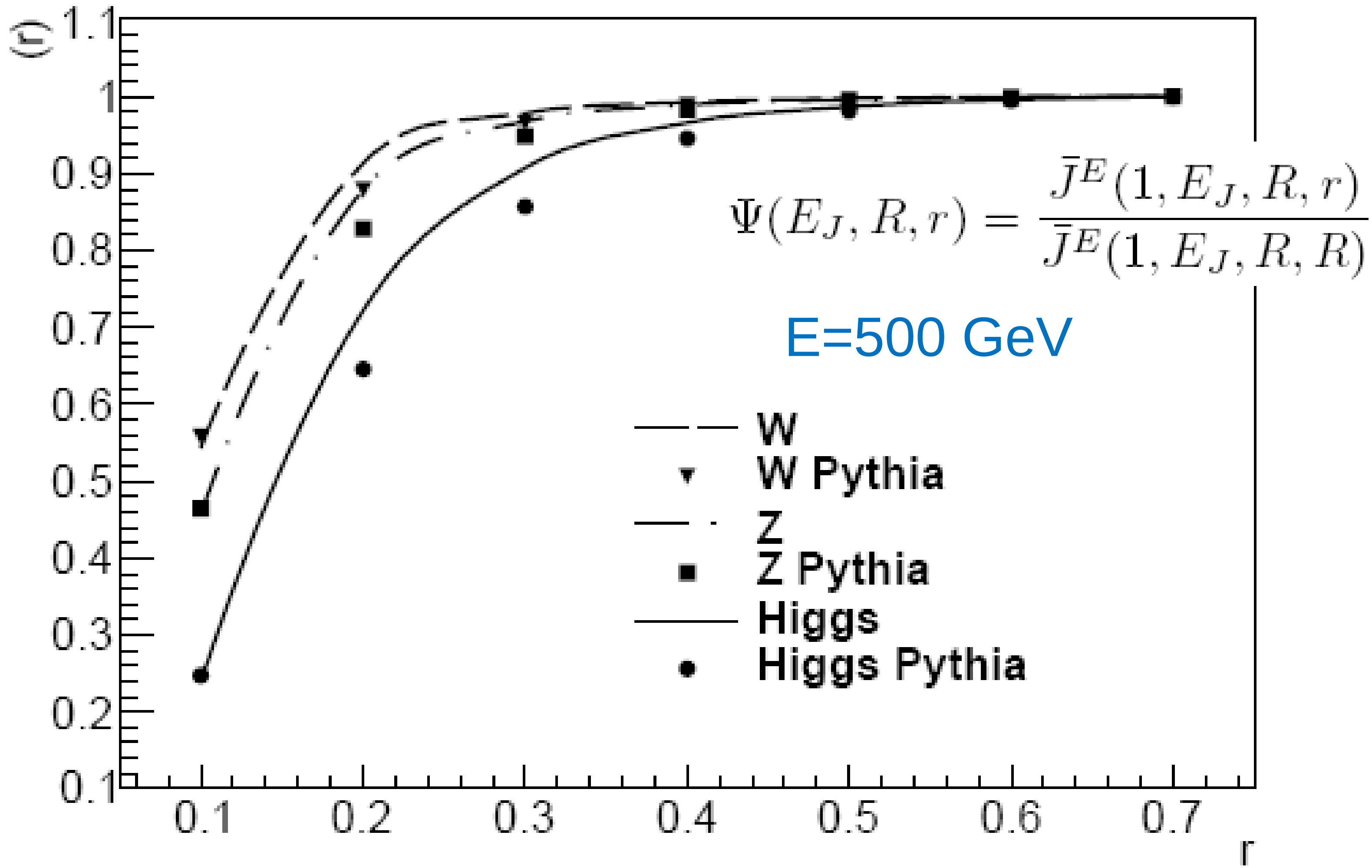


Fat jet factorization works!

- Energy profile from factorization into two sub-jets coincides with profile of gluon jet



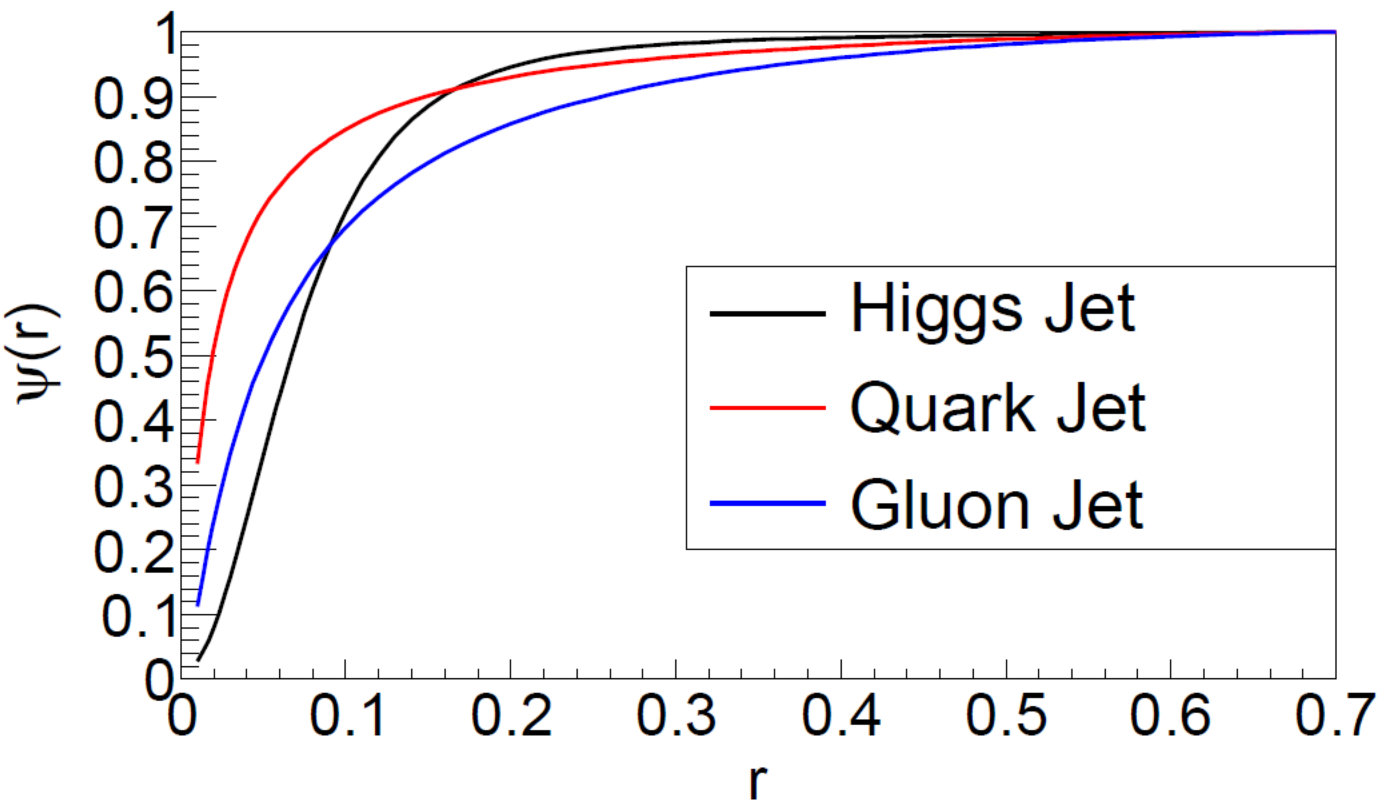
Heavy-boson jet profiles



light-quark jet input from resummation, Li et al, 2013

Comparison with QCD jets

- Dead cone effect, so Higgs jet profile is lower at small r. It increases faster with r due to energetic b- jets



Summary

- Jet substructures improve particle identification
- QCD factorization and resummation provide reliable prediction, and independent check
- Factorization of a fat jet into several sub-jets works well (checked via gluon jet profile)
- Application to heavy boson jet profiles successful, showing moderated dead cone by soft gluons and fast increase due to pencil-like b jets