Jet substructures of boosted heavy particles

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Presented at QCD Study Group

Apr. 03, 2016

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Outlines

- Introduction
- Higgs Jet factorization
- Higgs Jet energy profiles
- Boosted hadronic tops
- Top jet energy profiles
- Summary

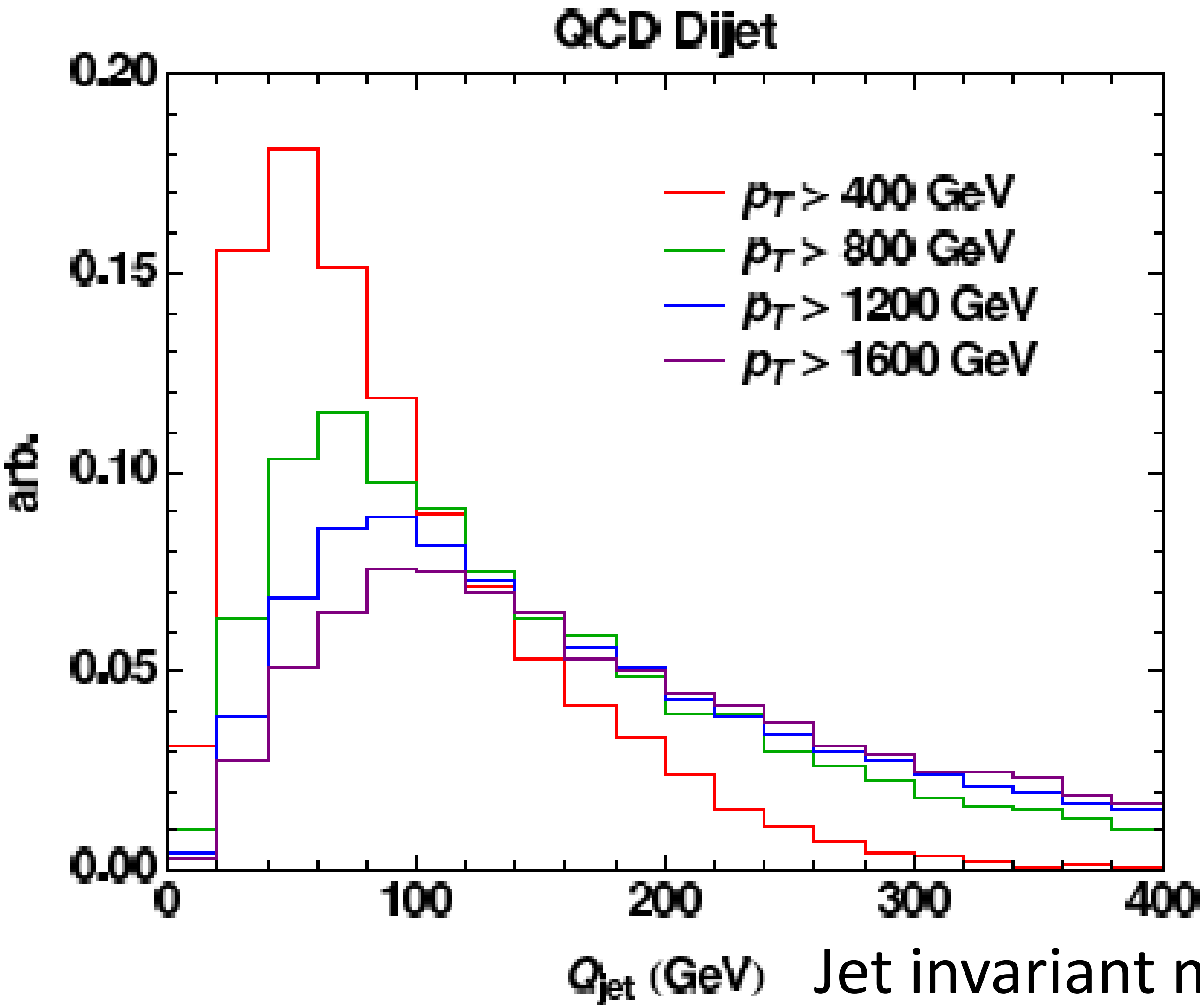
Introduction

- 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
- Study of jets is crucial; comparison between theory and experiment is nontrivial
- Usually use event generators
- Do it in PQCD---factorization & resummation

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

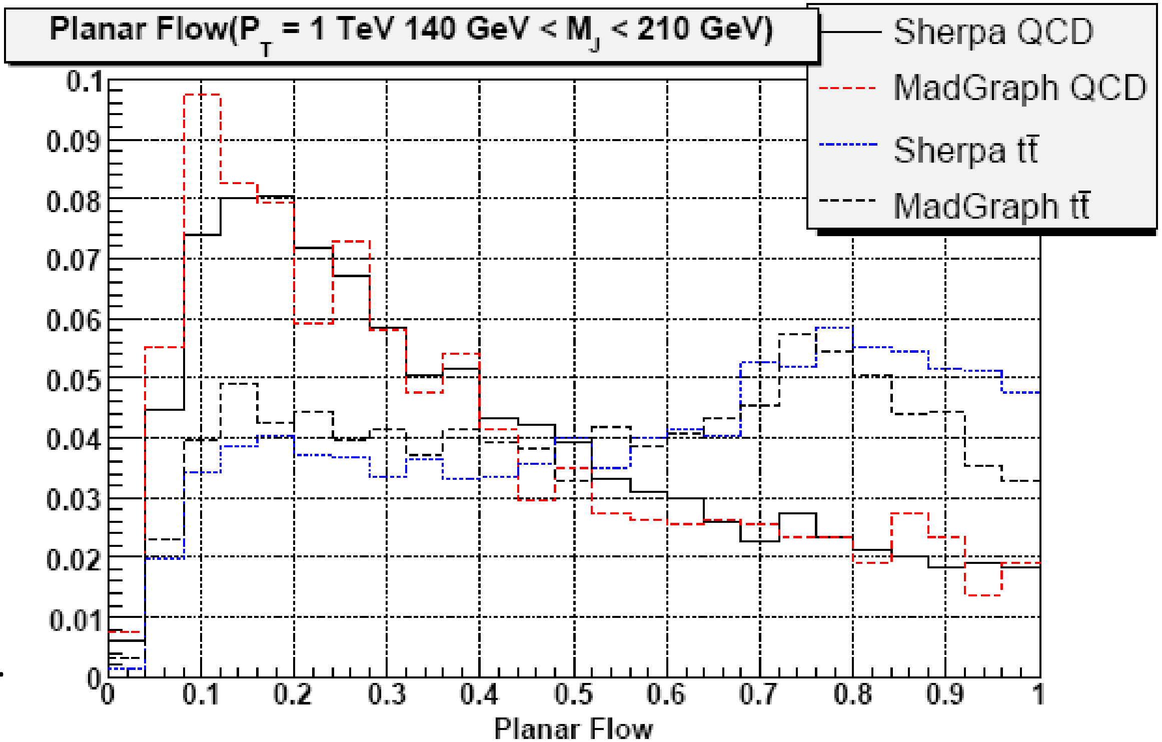


Jet invariant mass

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

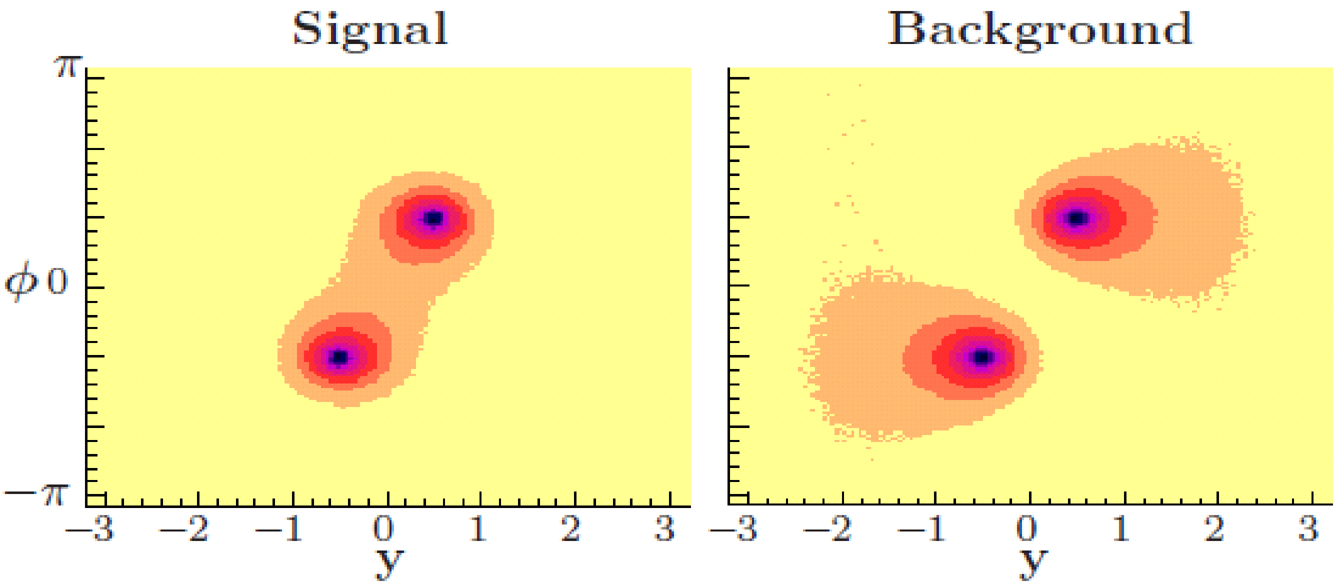
Higgs jet

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

Gallicchio, Schwartz, 2010

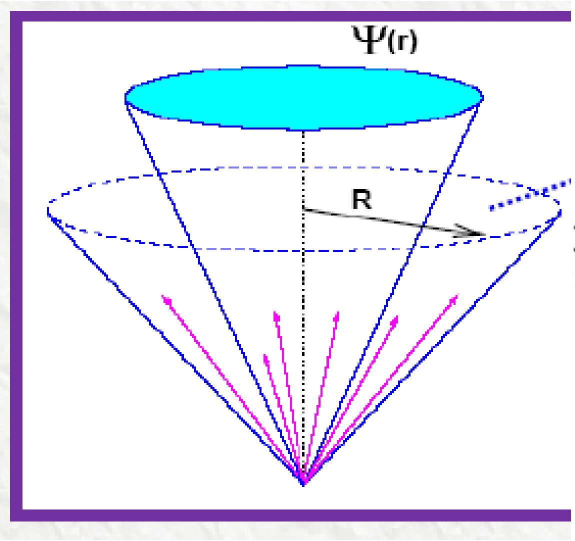
Color pull

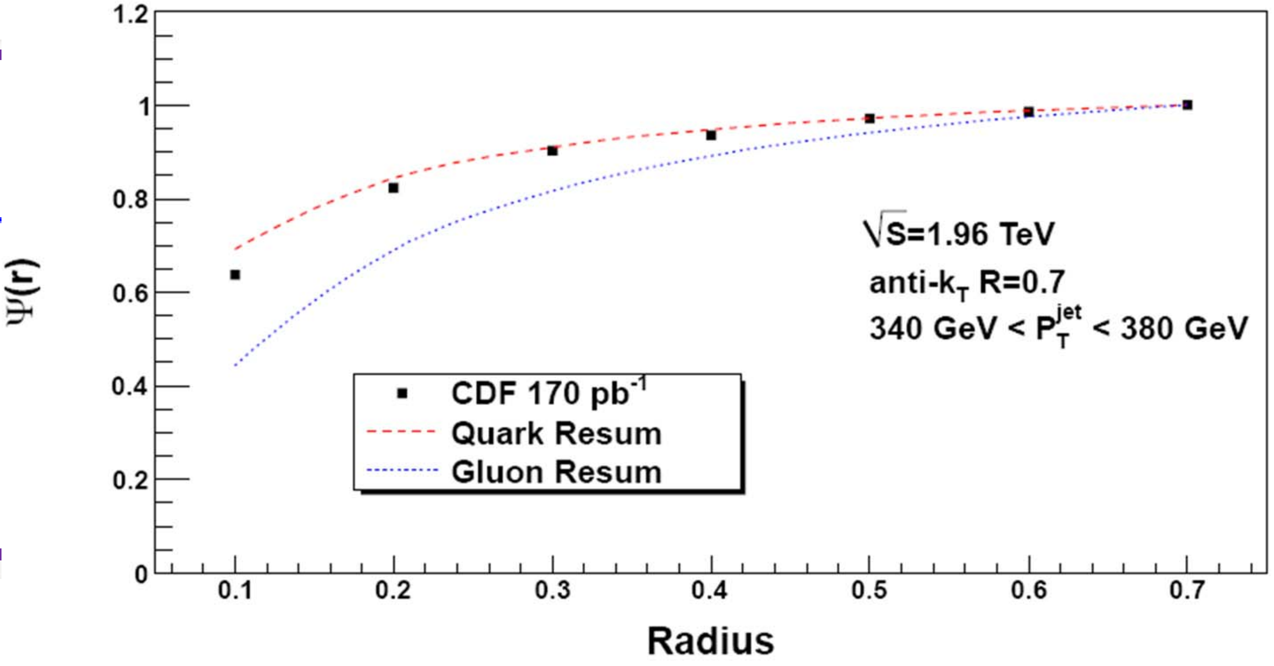
- Higgs is colorless, bb forms a color dipole
- Soft gluons exchanged between them
- Gluon has color, b forms color dipole with other particles, such as beam particles



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)



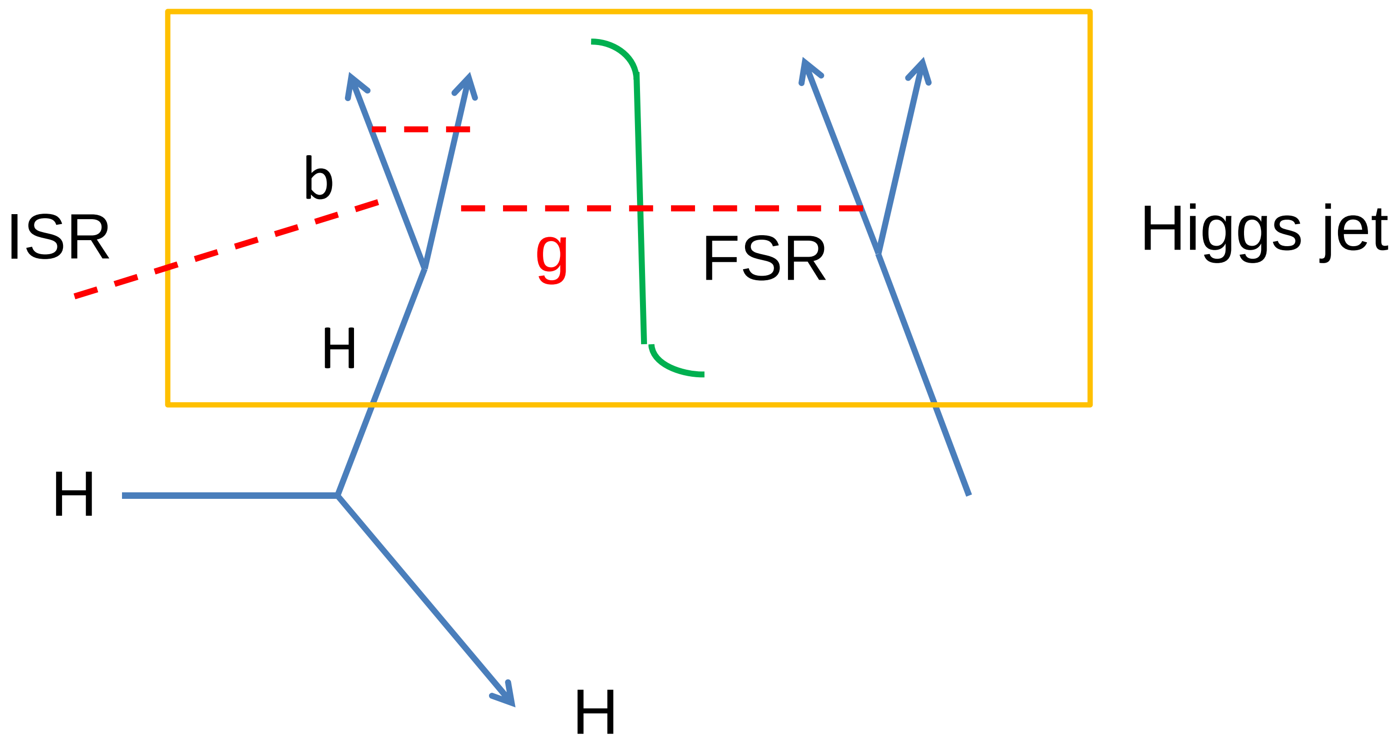


Higgs Jet factorization

See also Zhao’s talk

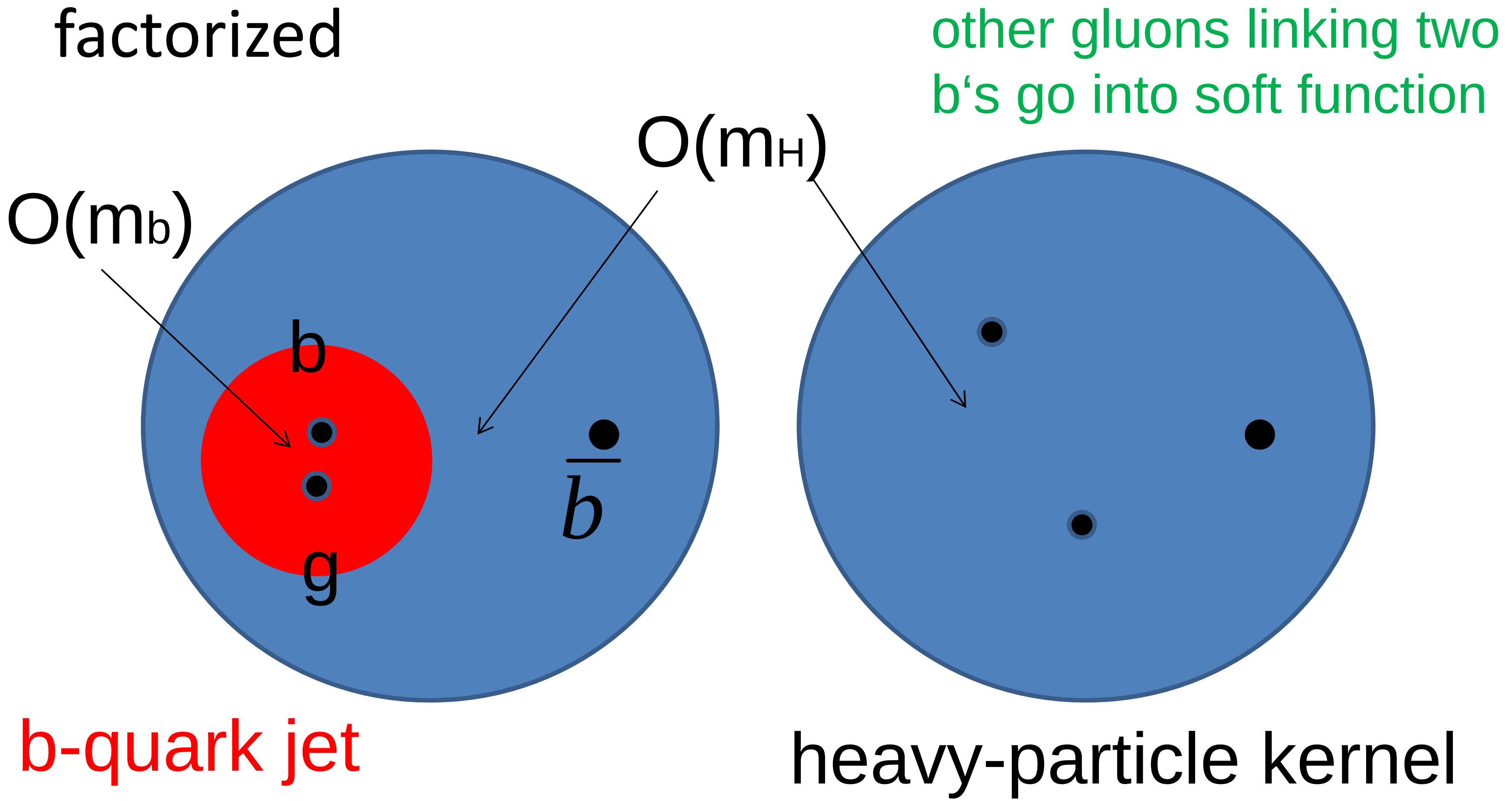
Factorization at jet energy E

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



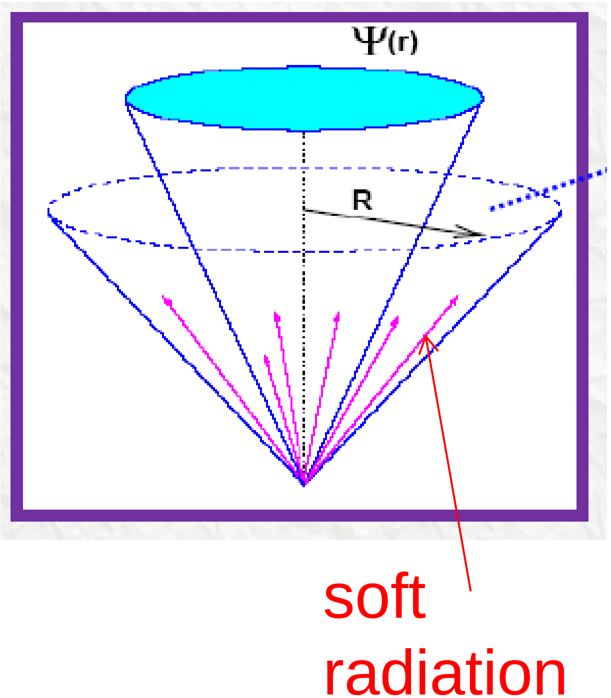
Scale hierarchy $E \gg m_H \gg m_b$

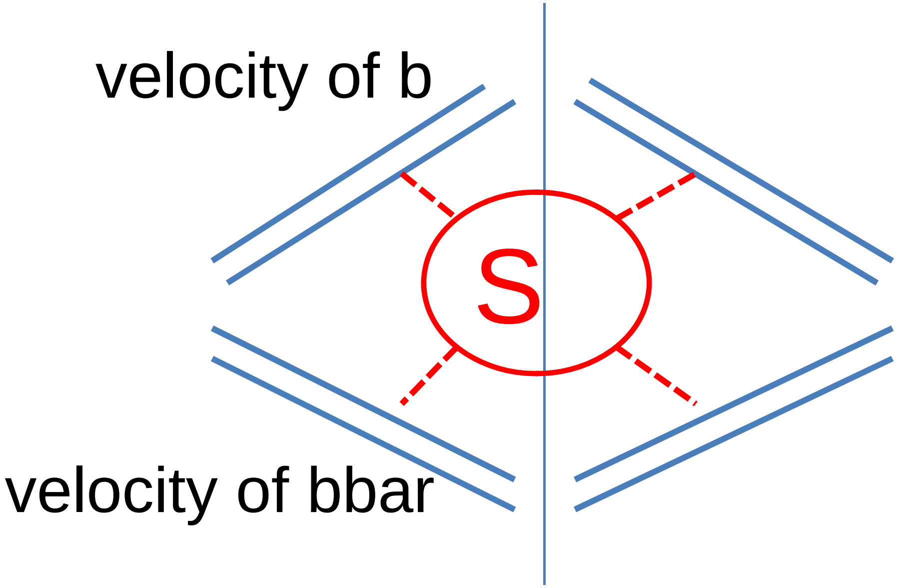
- The two lower scales m_H and m_b characterize different dynamics, which can be further factorized



Soft function

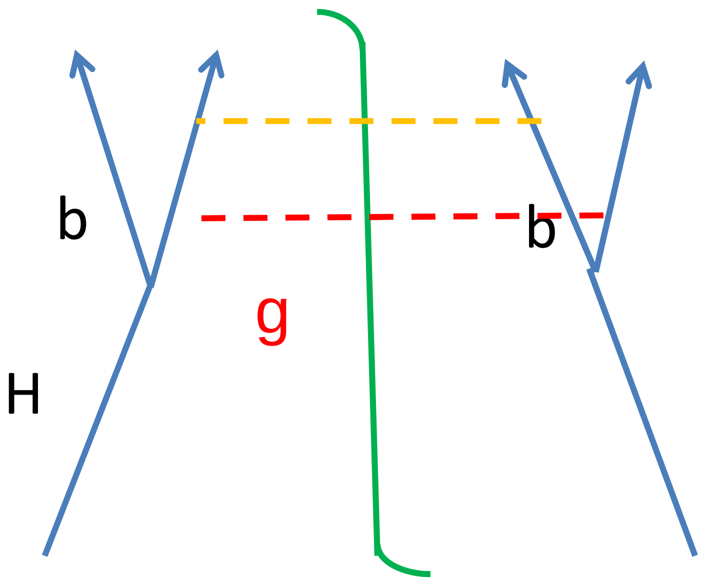
- Soft radiation around two b jets plays important role
- Feynman diagrams
- Calculated as jet function

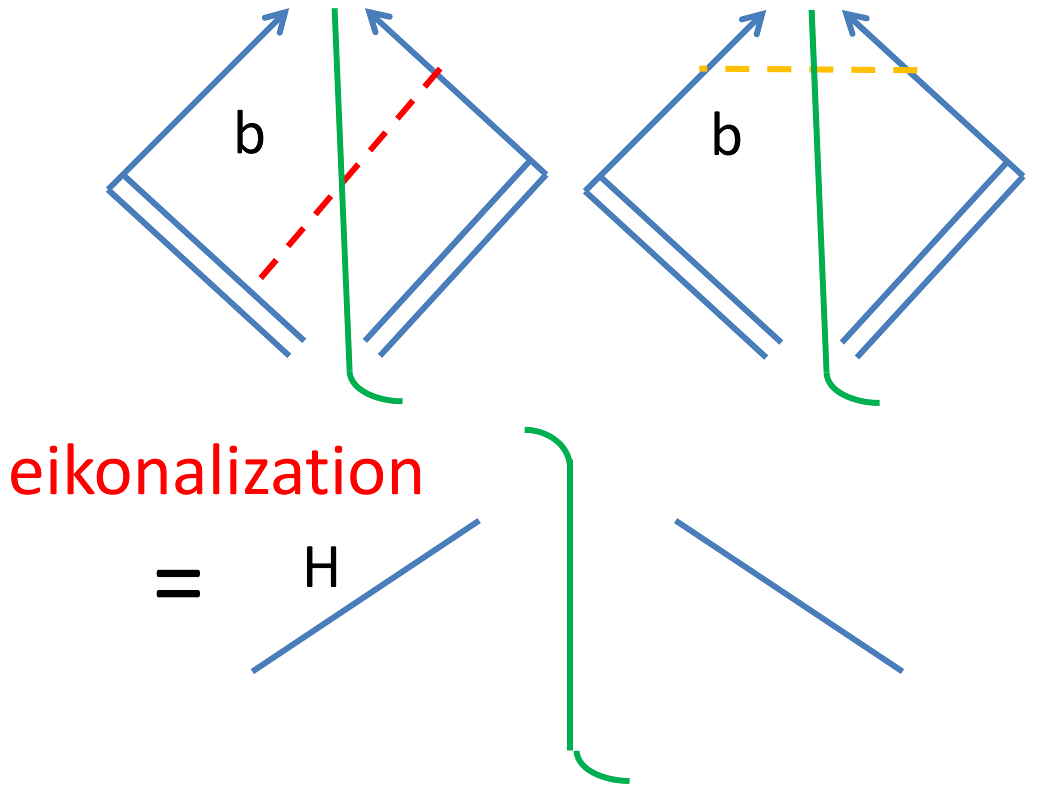




Factorization into two sub-jets

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

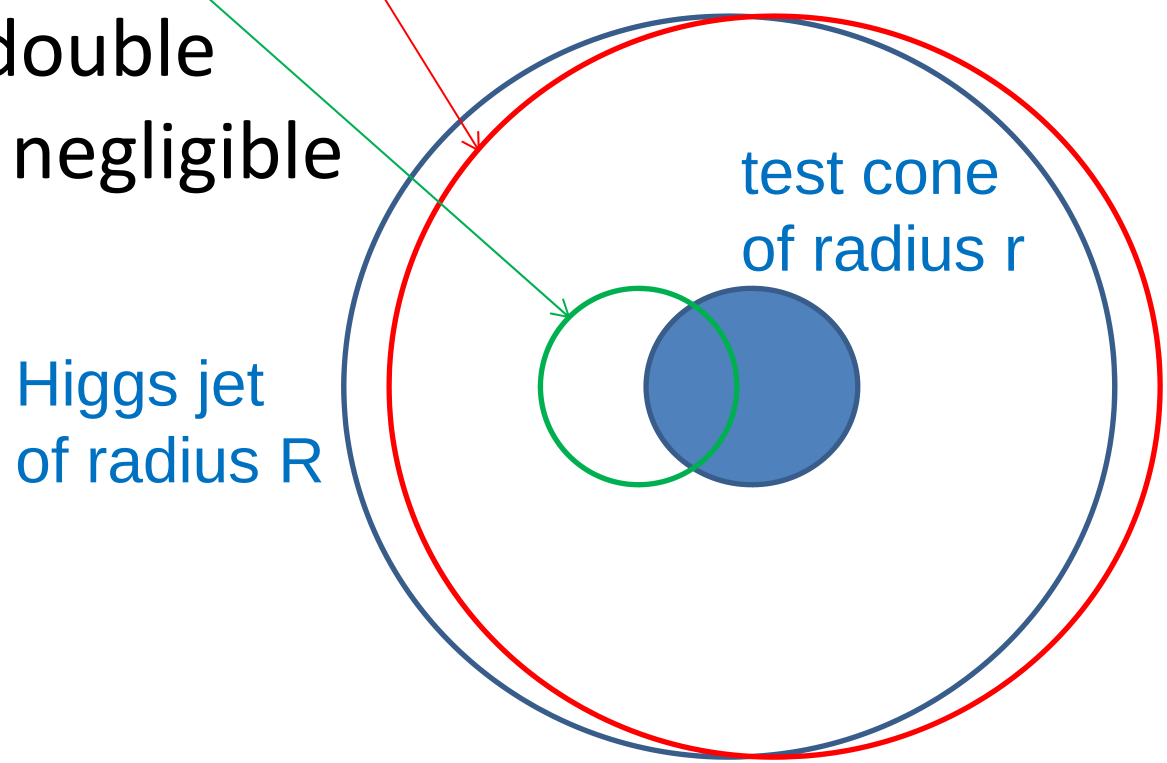




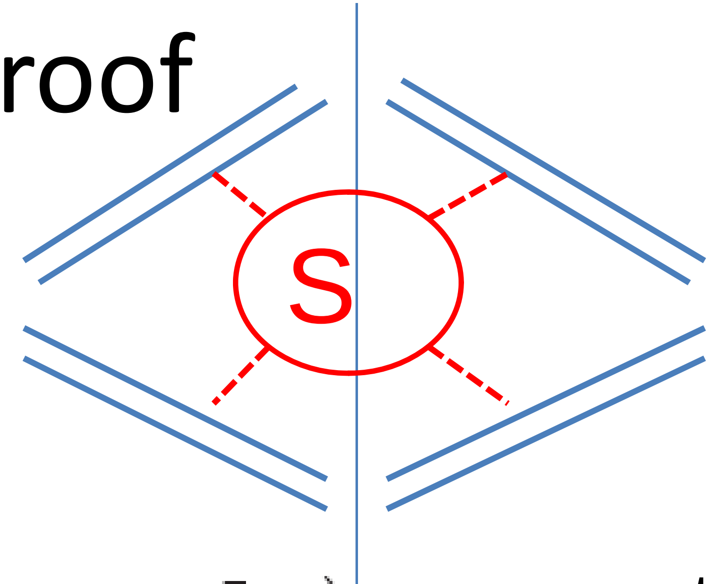
$$J_{\mathrm{H}} = H \otimes J_1 \otimes J_2 \otimes S$$

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

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

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

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

Merge soft and collinear objects

- At last, collinear subtraction from thin b
- Thin b jet contributes only overall normalization, so its final condition of jet resummation is arbitrary

$$\boxed{S^{(1)} - S^{(1)}_{n_{J_1}} - S^{(1)}_{n_{J_2}} \approx 0}$$

$$\propto \ln \frac{r^2 R^2}{(\bar{\xi}_{J1} \cdot \bar{\xi}_{J2})^2} \longleftarrow \boxed{(\bar{\xi}_{J_1} \cdot \bar{\xi}_{J_2})^2 \sim (m_H / E_{J_H})^4 \sim O(r^2)}$$

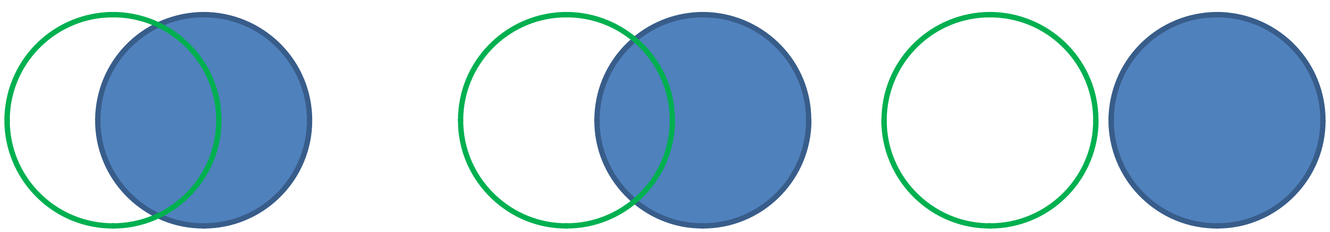
$$R \sim O(1)$$

- In this special scheme, $\boxed{S(\omega, R, \mu_f^2) \approx \delta(\omega)}$ soft function drops from factorization

Higgs Jet energy profiles

Merging criterion

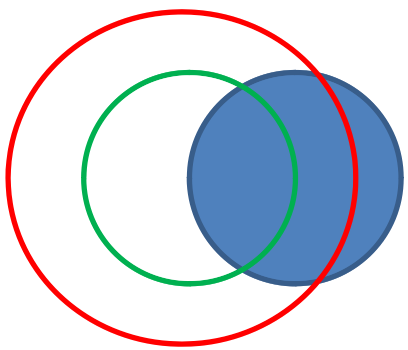
- As integrated over polar angles of b-jets, how distant can they be still merged into test cone?
- If merged, whole energy of thin b-jet and whole energy in test cone of fat b-jet contribute to Higgs jet profile

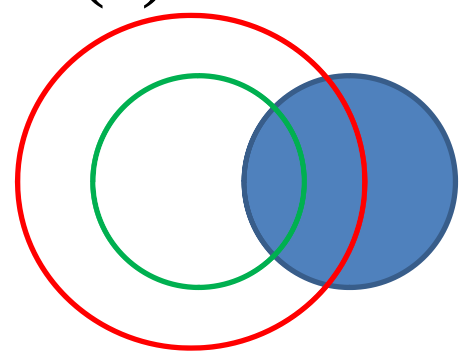


- d=r r < d < 2r d>2r
- Yes ? No

Merging vs. 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 $H^E(r)$





for example, $d < 1.5r$ $\qquad$ $d > 1.5r$

$J_2^E(R,r)$ $\qquad$ $H^E(R,r)$

Factorization formula for profile

- Merging criterion is a matter of factorization scheme
- Choose d=2r to minimize H^E , cone algorithm
- Factorization formula

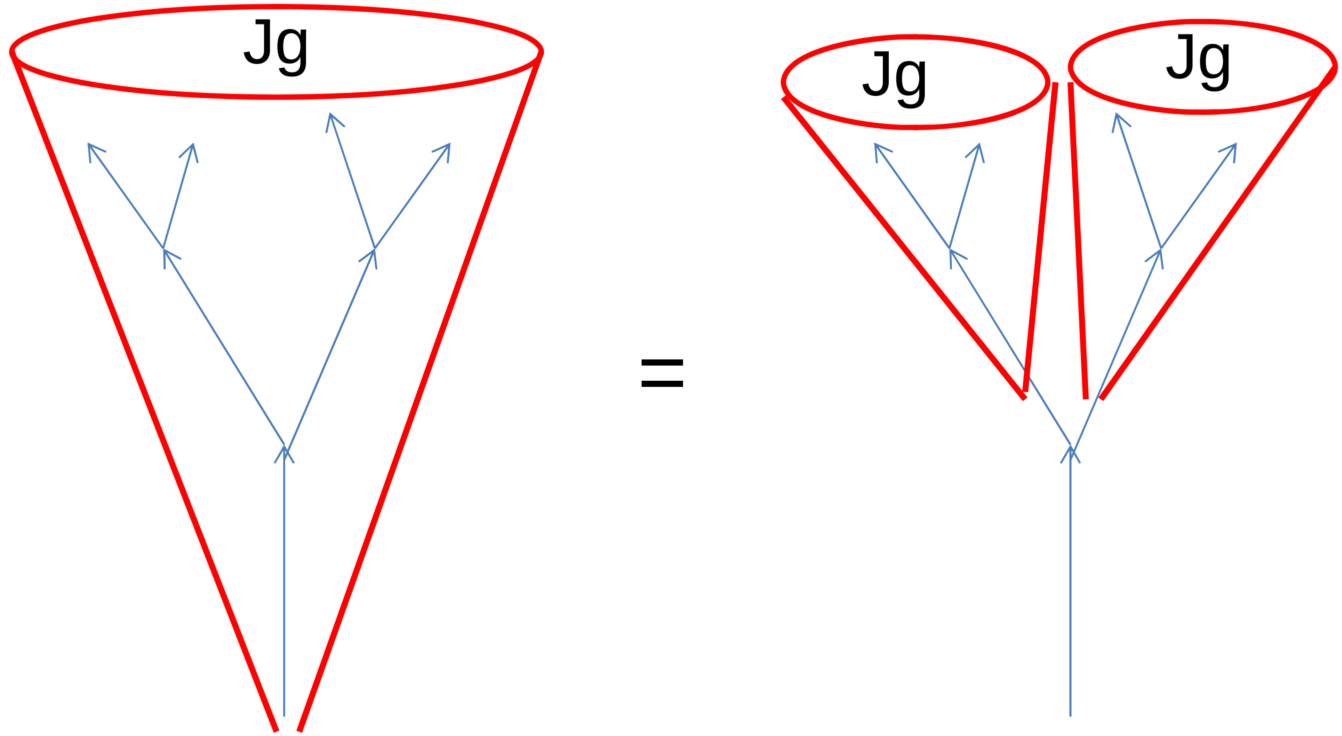
$$\delta(\omega)$$

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

- Applicable to W and Z boson jets

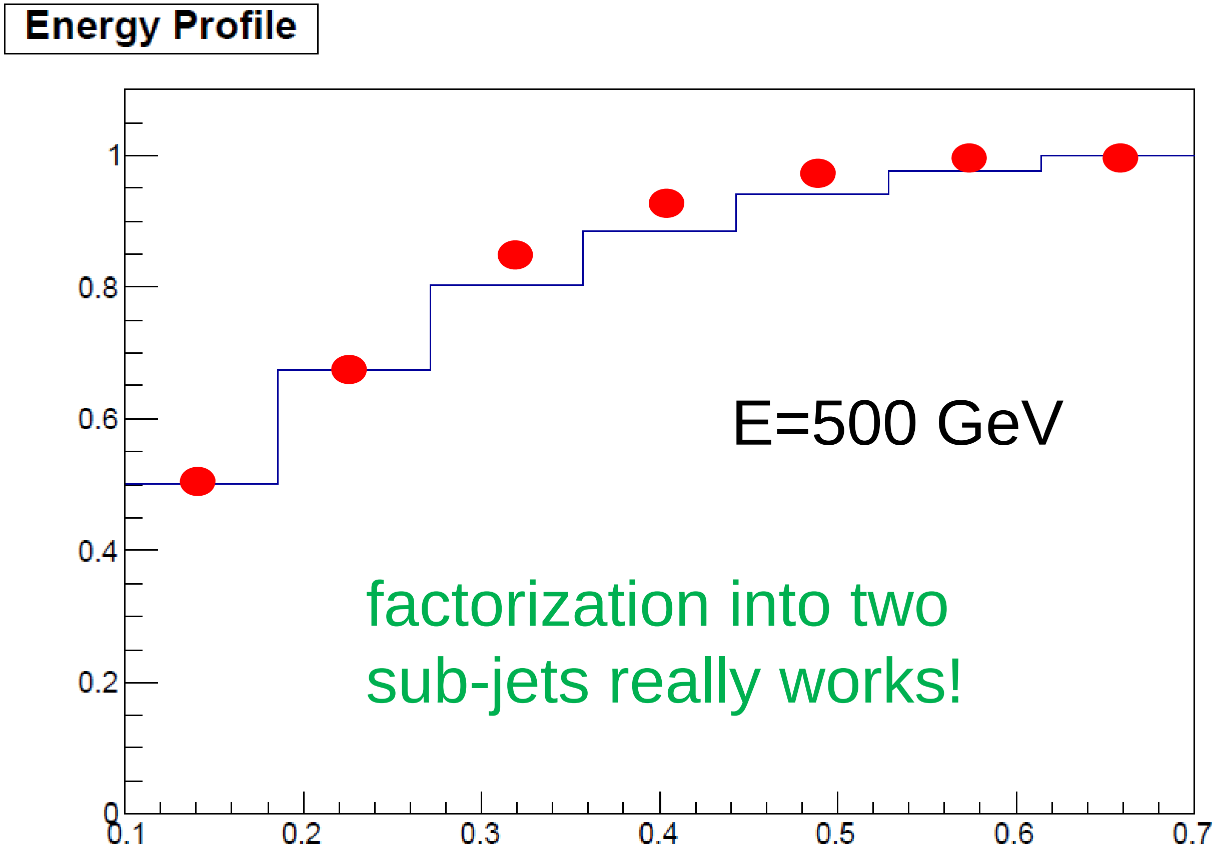
Test by gluon jet profile

- 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-particle kernel

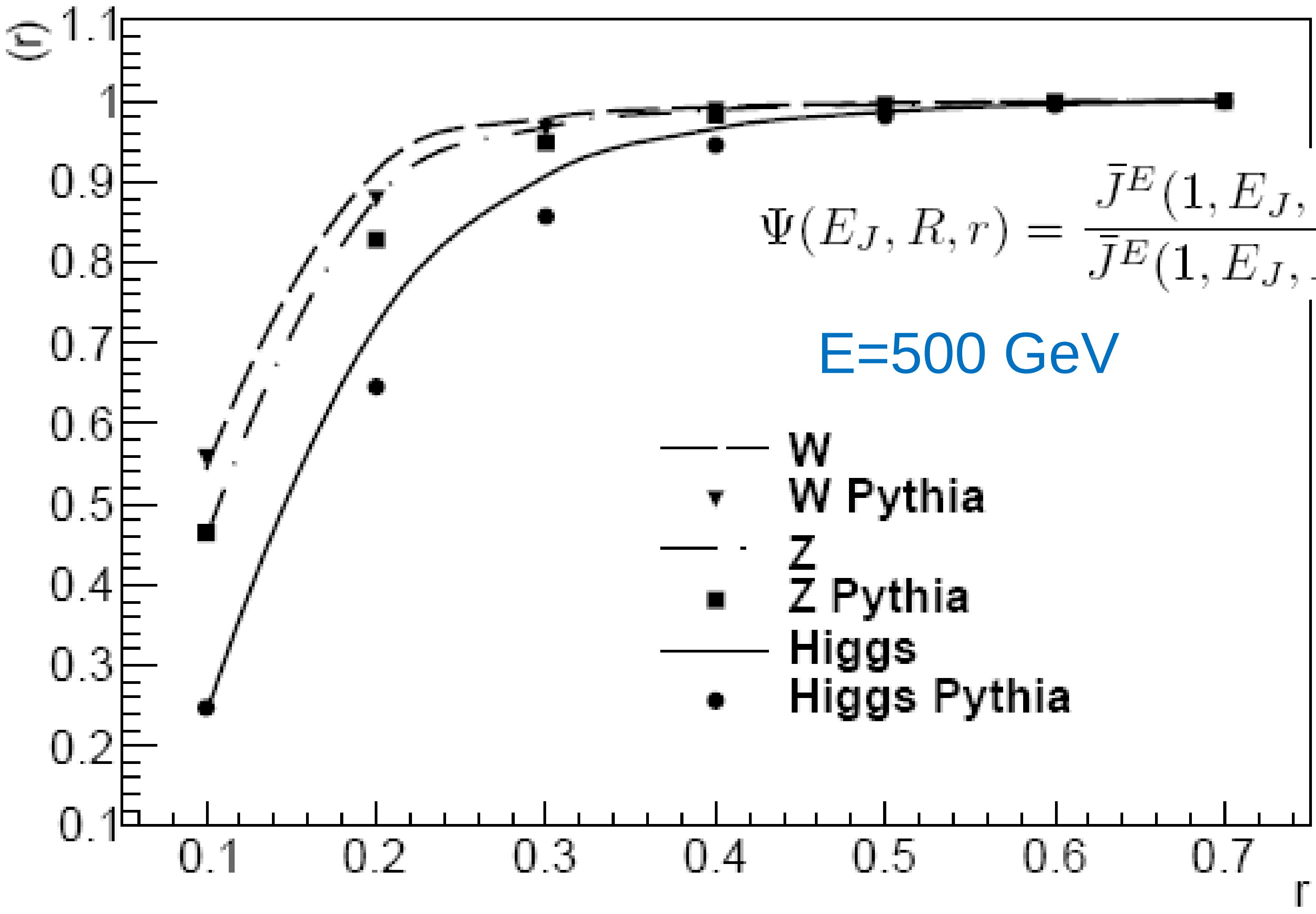
- Adopt LO kernel from Higgs propagator

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

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

- Larger $m^2_{J_H}$ can contribute to test cone
- Due to gluon radiation, b- jet spreads into dead cone around Higgs jet axis

Heavy-boson jet profiles

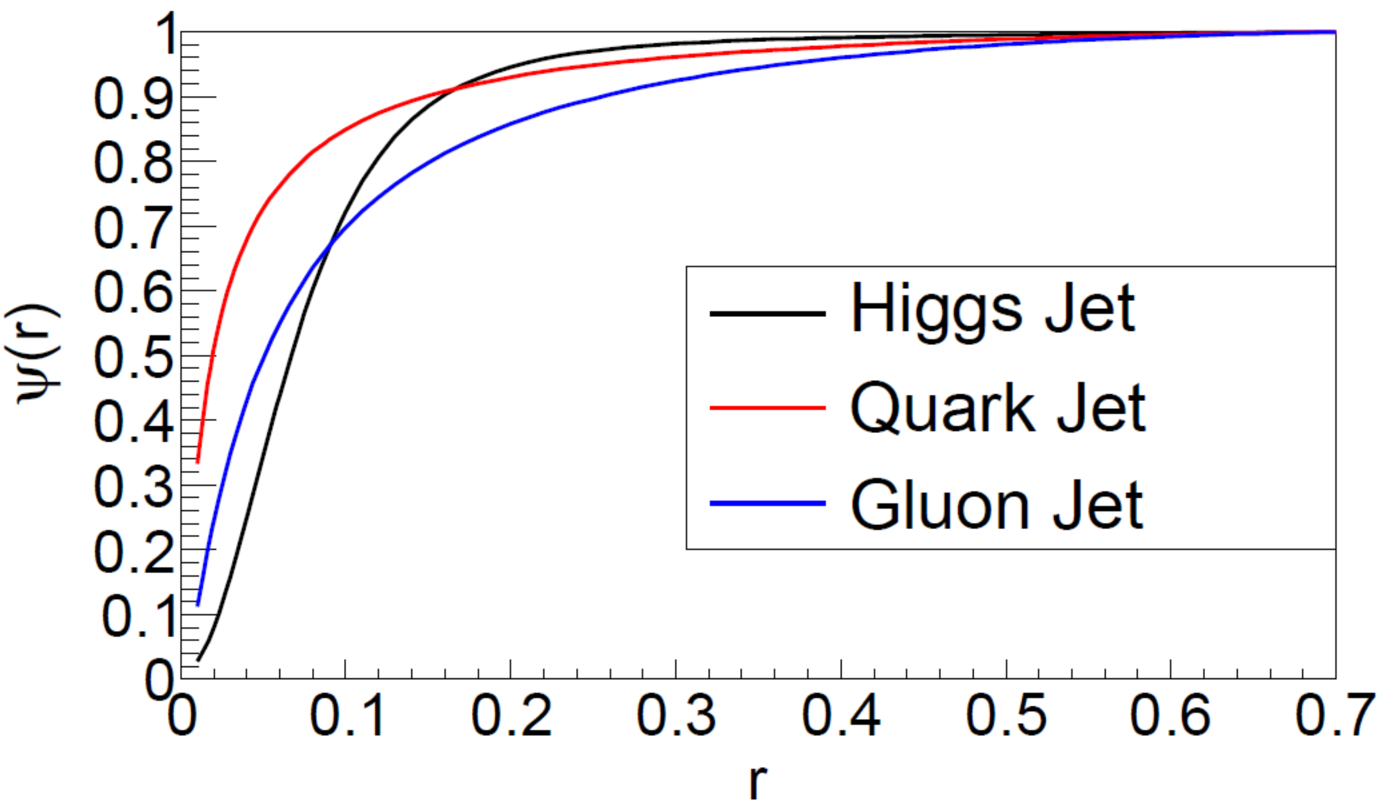


$$\Psi(E_J, R, r) = \frac{\bar{J}^E(1, E_J, R, r)}{\bar{J}^E(1, E_J, R, R)}$$

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

Comparison with QCD jets

- Higgs jet profile is lower at small r due to Higgs mass. It increases faster with r due to energetic b- jets



Kitadono, Li,1511.08675

Boosted hadronic tops

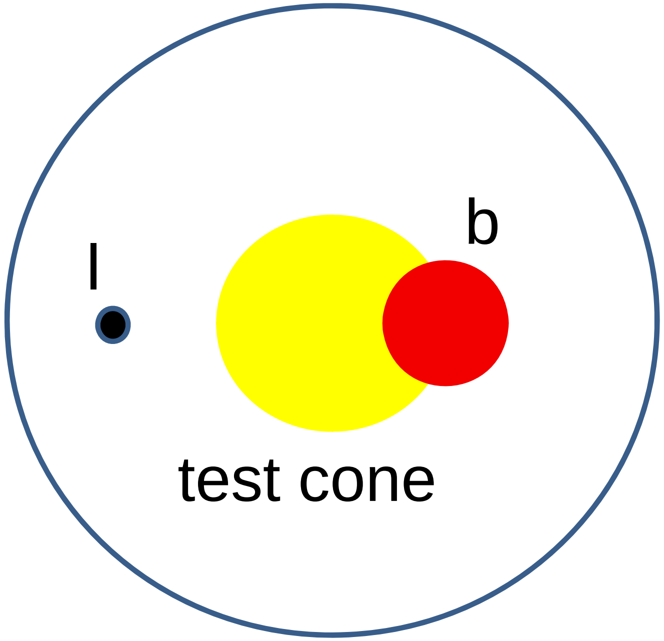
See also Yoshio’s talk

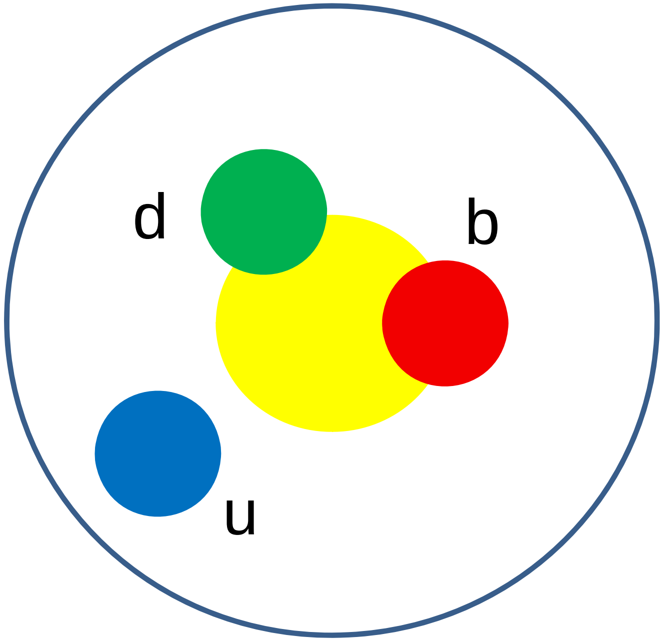
Difficulty 1

- Three-body kinematics in t -> bud
- In semileptonic decay neutrino kinematics is integrated out, basically two-body

$$k_l \sin\theta_l = k_b \sin\theta_b$$

complicated angular relation

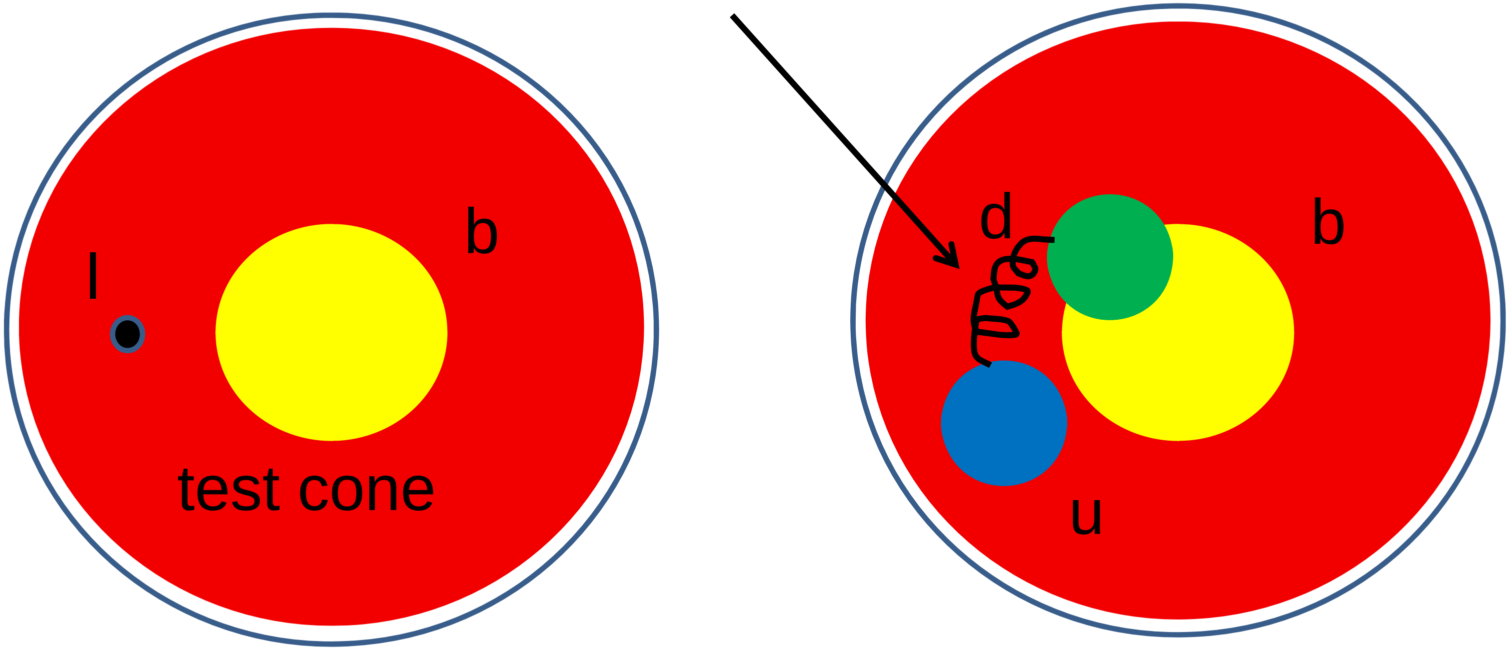




Difficulty 2

- Treatment of soft gluons
- Consider a fat b jet, which absorbs soft gluons in semileptonic case

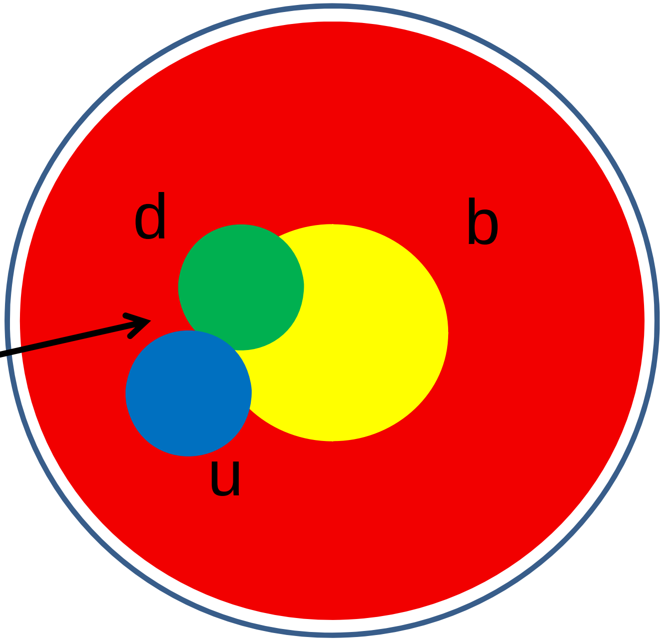
still need soft function
to absorb soft gluons



Difficulty 3

- Jet merging
- No jet merging issue in semileptonic case
- When subjets overlap, how to count their contribution to test cone?
- Ambiguity to define subjet radii

counted as single jet
or two jets?



Sequential factorization

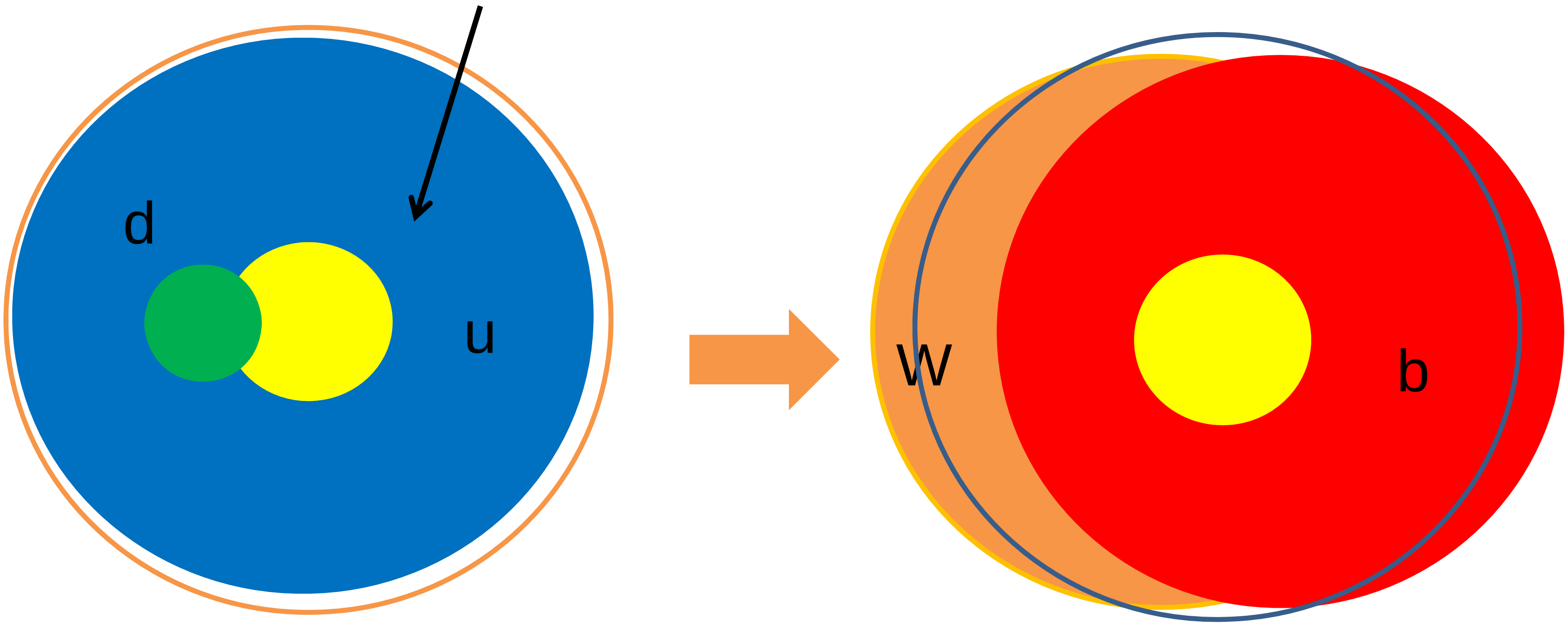
- Factorization of top jet into fat W-boson jet, fat bottom jet, and top decay kernel
- Fat bottom jet obeys universality for leptonic (Kitadono, Li, 2014) and hadronic tops
- Factorization of fat W-boson jet into fat light-quark jet, thin light-quark jet and W decay kernel (Isaacson, Li, Li, Yuan, 2015)
- At each step of factorization, handle only two-body kinematics

No soft function

- Construct W-boson jet

contain soft gluons

then construct top jet

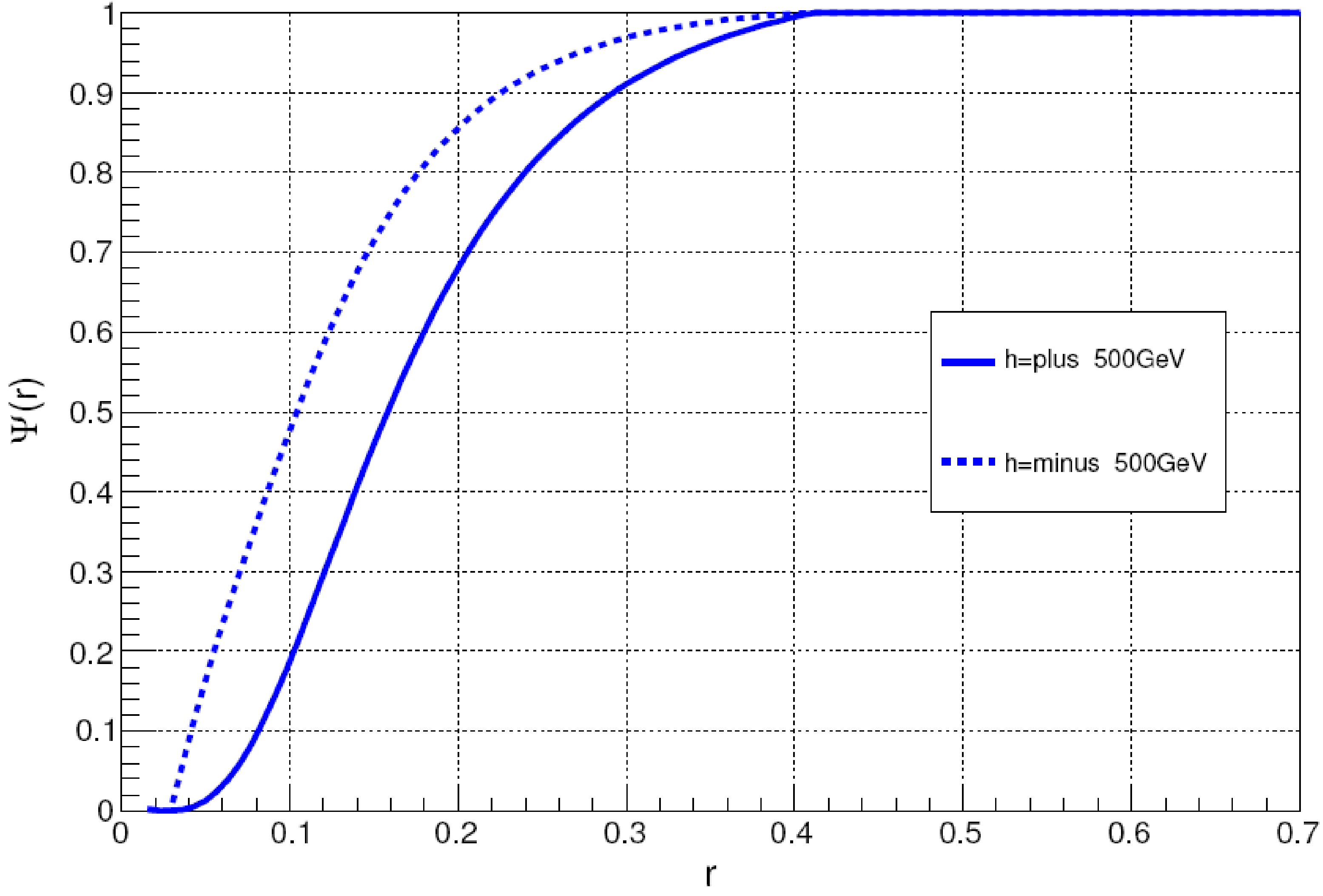


soft gluon exchanges between
b quark and color-singlet W boson
are suppressed

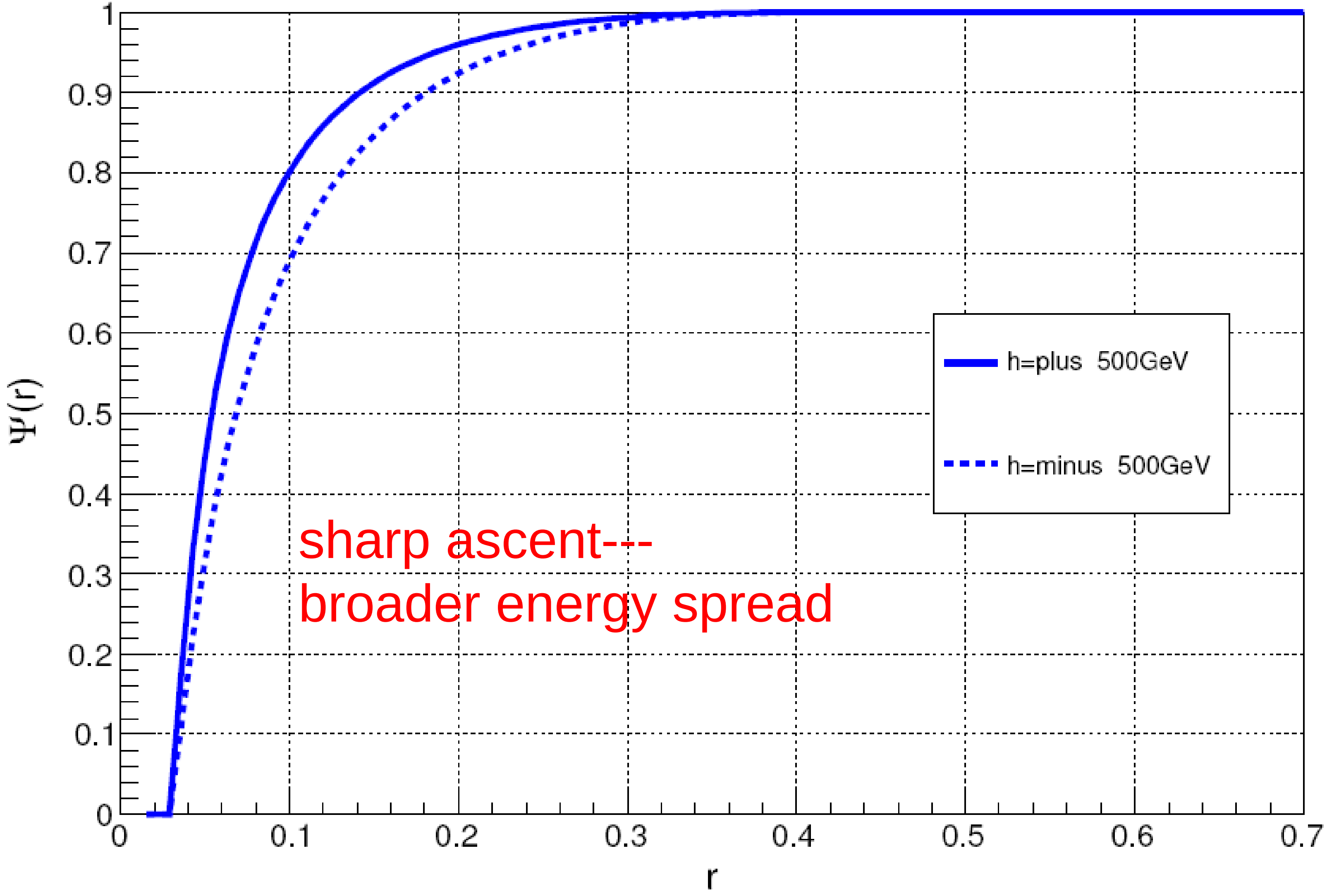
No jet merging

- Up (fat) and down (thin) jets completely overlap, no jet merging issue
- W-boson (fat) jet and bottom (fat) jet completely overlap, no jet merging issue
- Fat jet has radius R (top jet radius), and thin jet has radius r (test cone radius, focusing on energy profile at small r)
- No ambiguity to define jet radii
- Double counting of soft gluons is negligible at small r

Top jet energy profiles

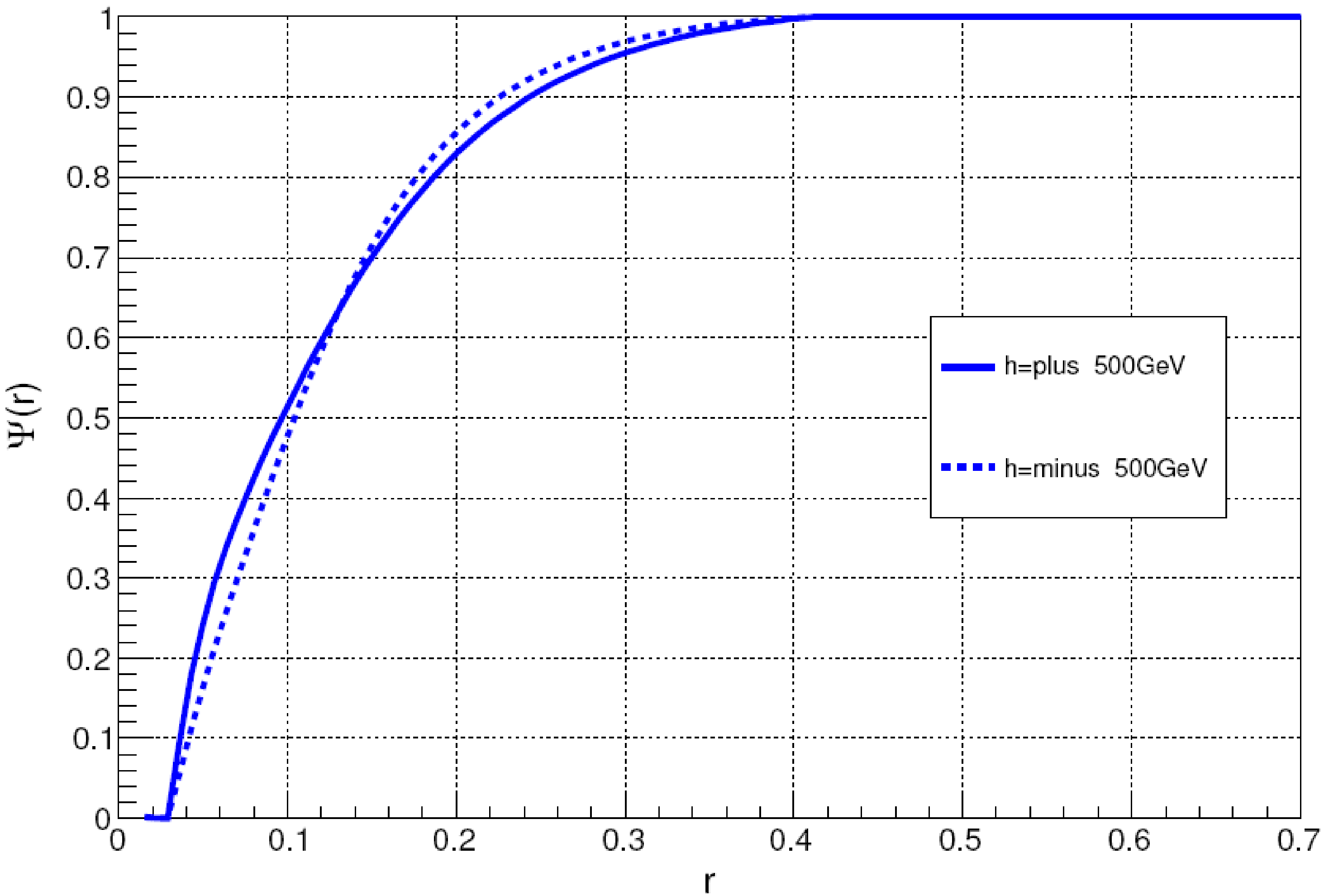


bottom jet contributes more to left-handed top
similar to energy profiles of leptonic top jet



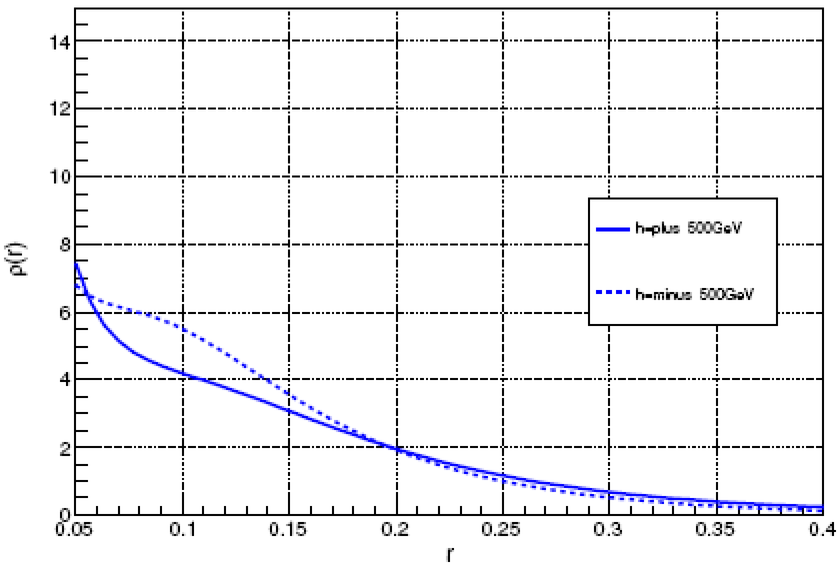
W jet shows obvious dead-cone effect, and contributes more to right-handed top

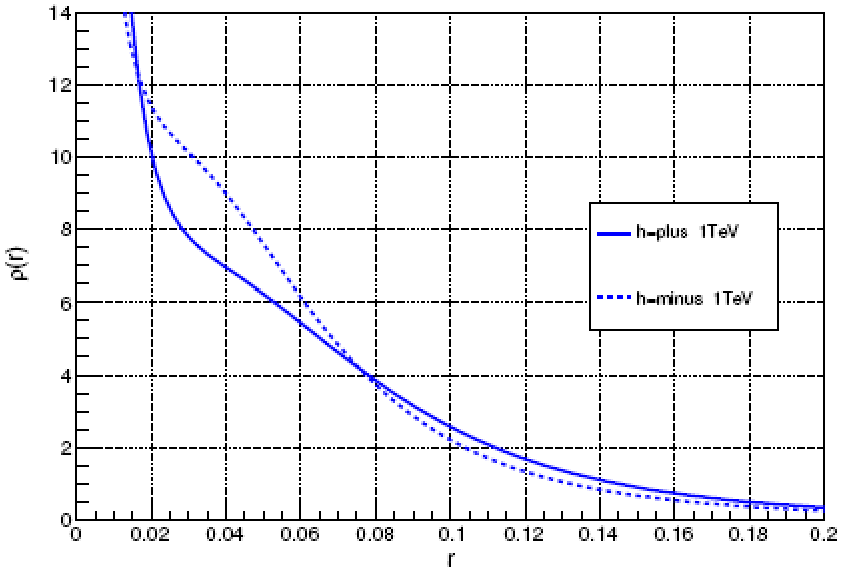
Energy profiles of hadronic top jet



due to compensation of b and W jet contributions, energy profile is not a useful discriminator

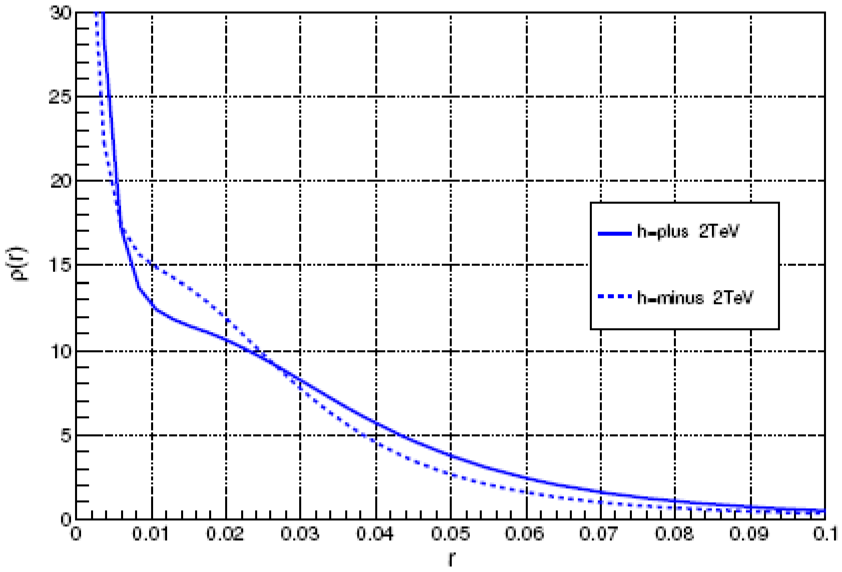
Differential energy profiles





interplay between b and W jet contribution leads to different differential profiles

maybe difficult to measure them at very small r



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 (confirmed 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

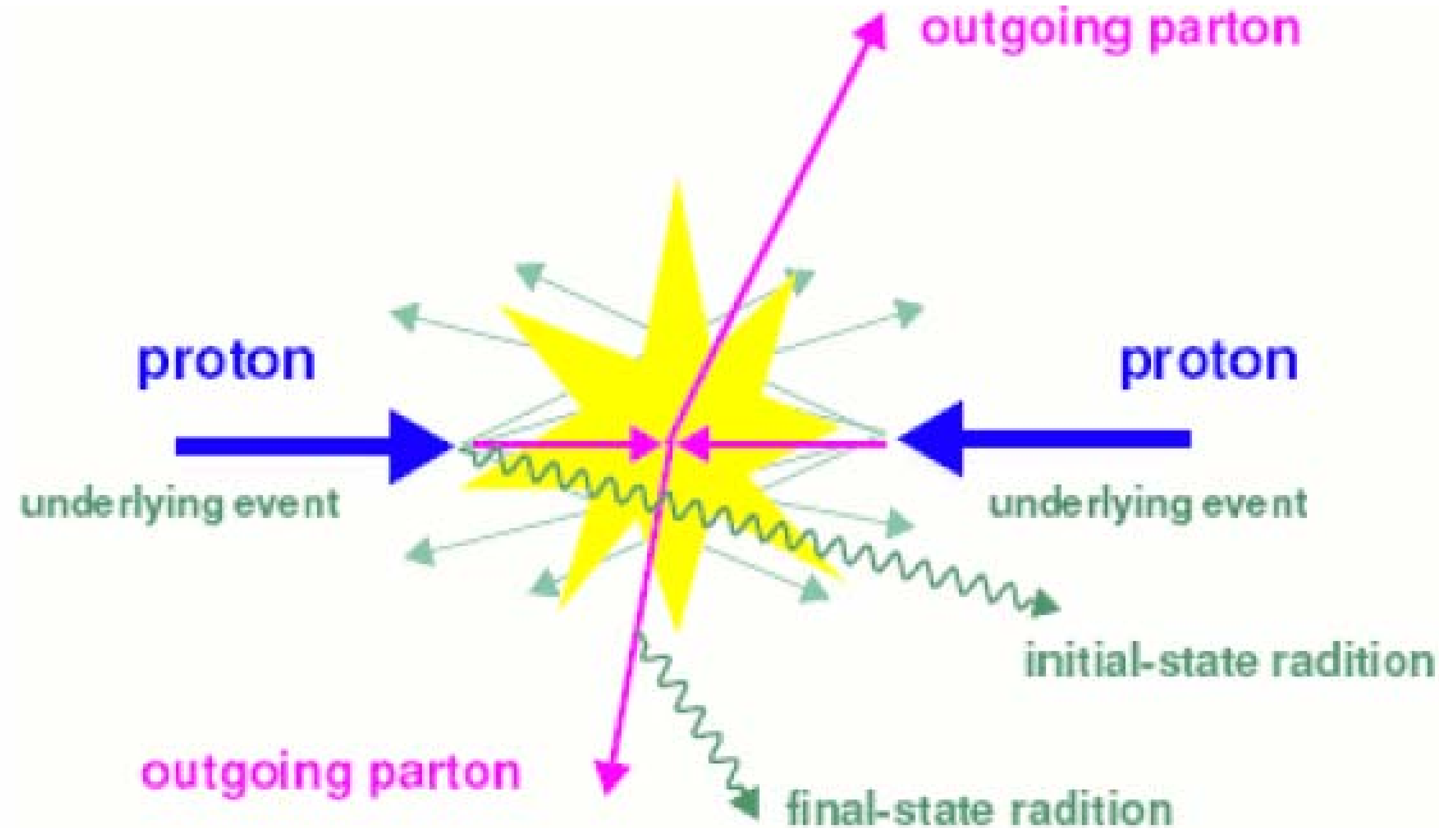
Summary

- Extension to boosted hadronic tops
- Differential energy profile, instead of energy profile, is a useful discriminator for helicity of a boosted hadronic top
- Right-handed top jet shows quick descent with r
- Difference appears at very small r. Maybe difficult to measure
- Consider track jets measured by EM calorimeter?

Back-up slides

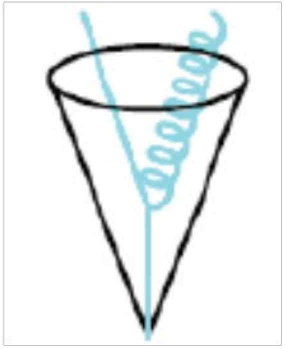
Underlying events

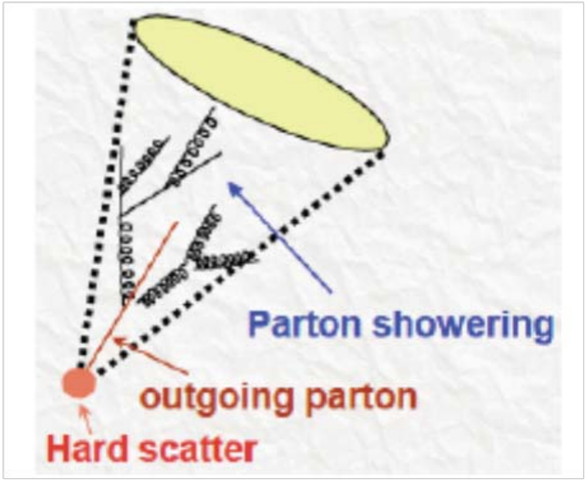
- Everything but hard scattering
- Initial-state radiation, final-state radiation, multi-parton interaction all contribute to jets

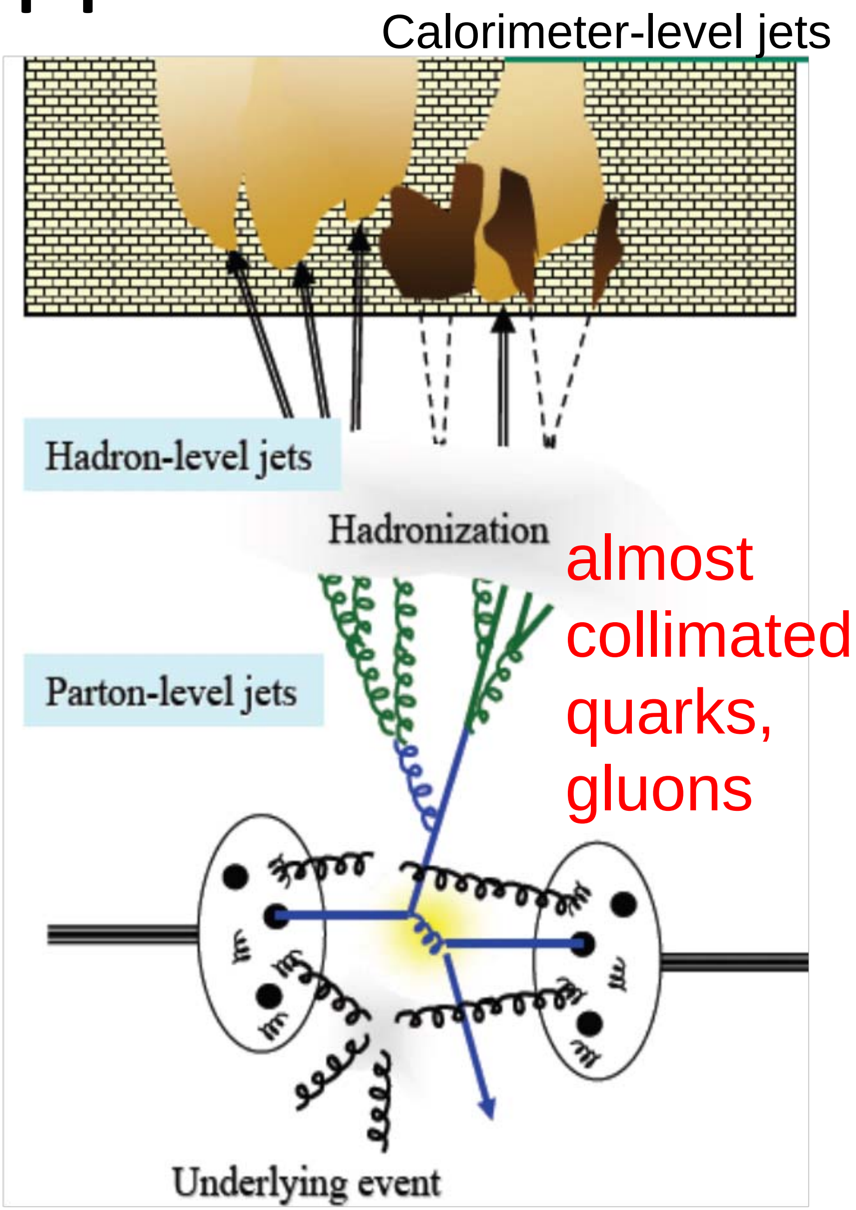


Resummation approach

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

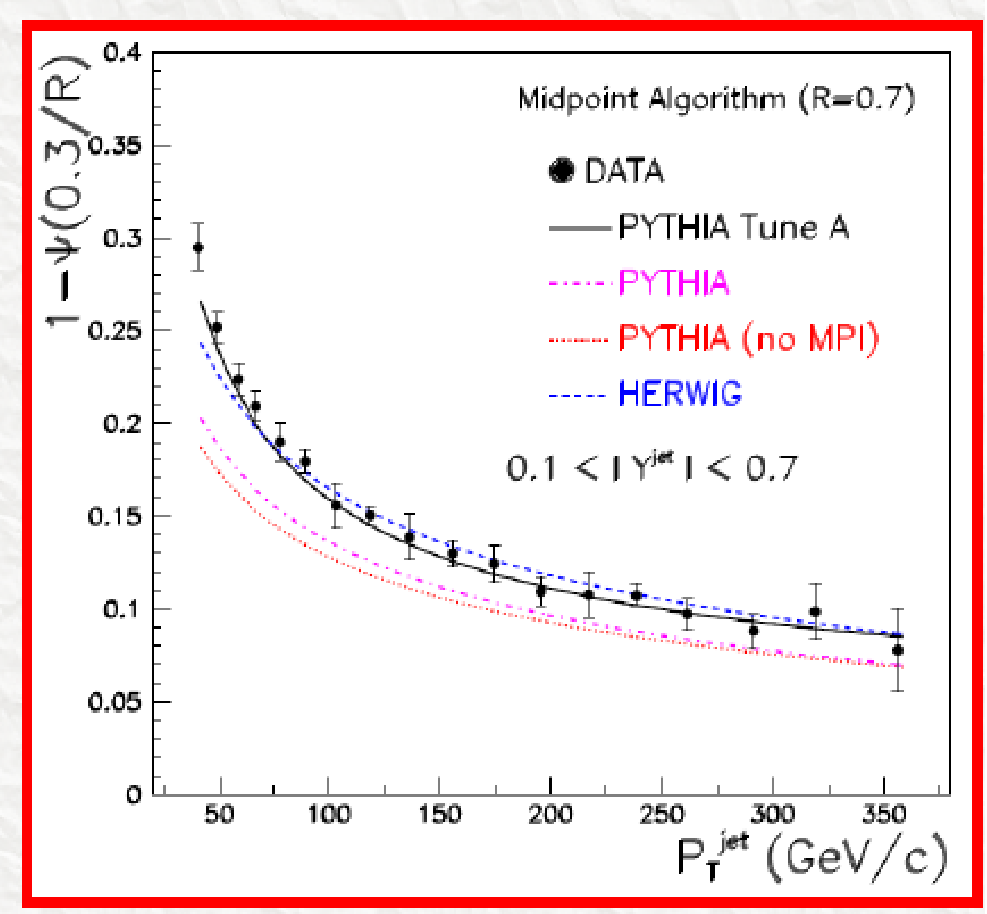






Why resummation?

- Monte Carlo may have ambiguities from tuning scales for coupling constant
- NLO is not reliable at small jet mass
- Predictions from QCD resummation are necessary



Tevatron data vs MC predictions

N. Varelas 2009