Jet substructure

Hsiang-nan Li (李湘楠)
Academia Sinica, Taipei

at CTEQ School, Beijing

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Outlines

- Introduction
- Jet functions
- Resummation
- Energy profiles
- Boosted heavy particles
- Summary

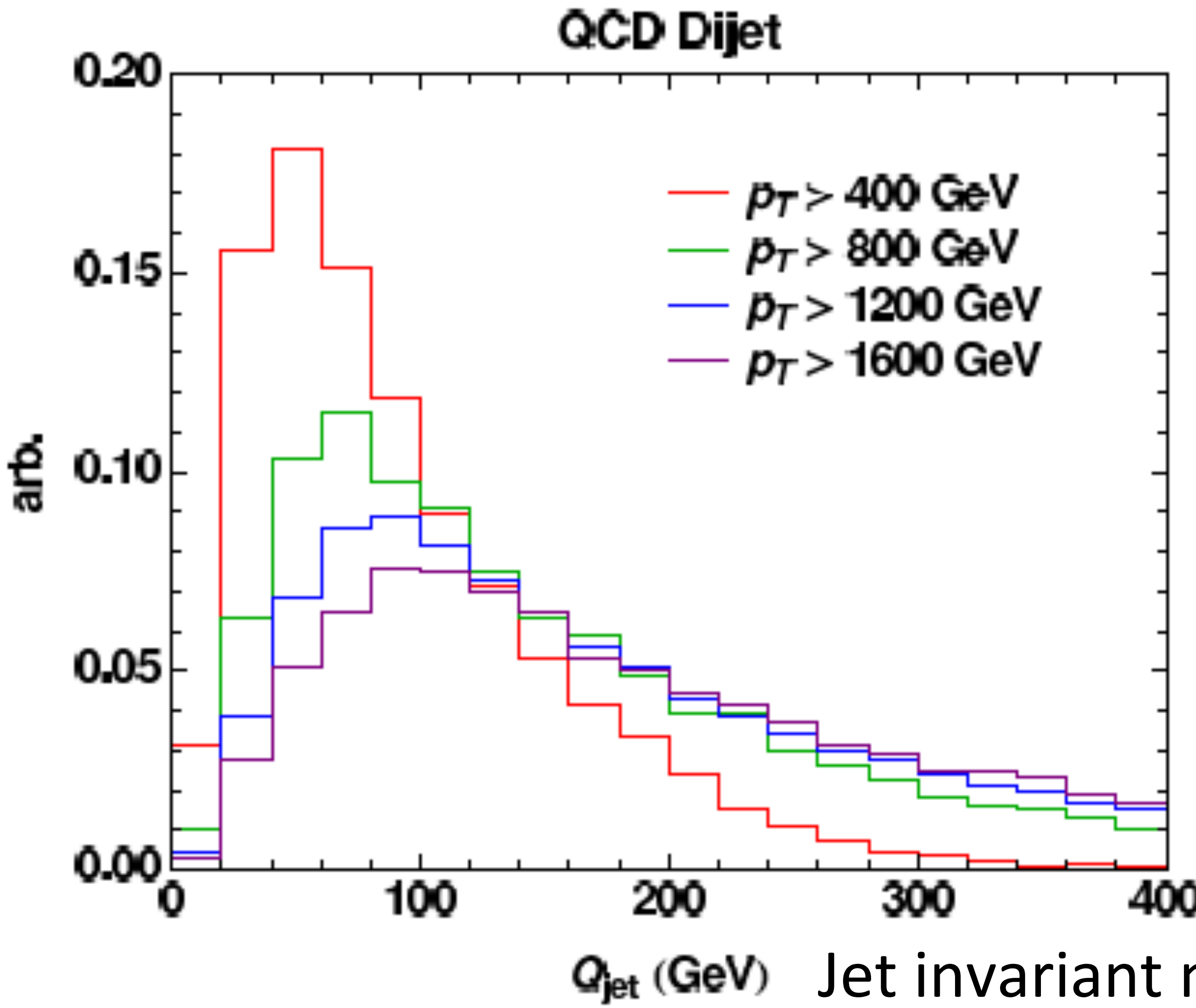
Introduction

Boosted heavy particles

- Large Hadron Collider (LHC) provide a chance to search new physics
- New physics involve heavy particles decaying possibly through cascade to SM light particles
- New particles, if not too heavy, may be produced with sufficient boost -> a single jet
- How to differentiate heavy-particle jets from ordinary QCD jets?
- Similar challenge of identifying energetic top quark at LHC

Zack and Yang's lectures

Fat QCD jet fakes top jet at high pT

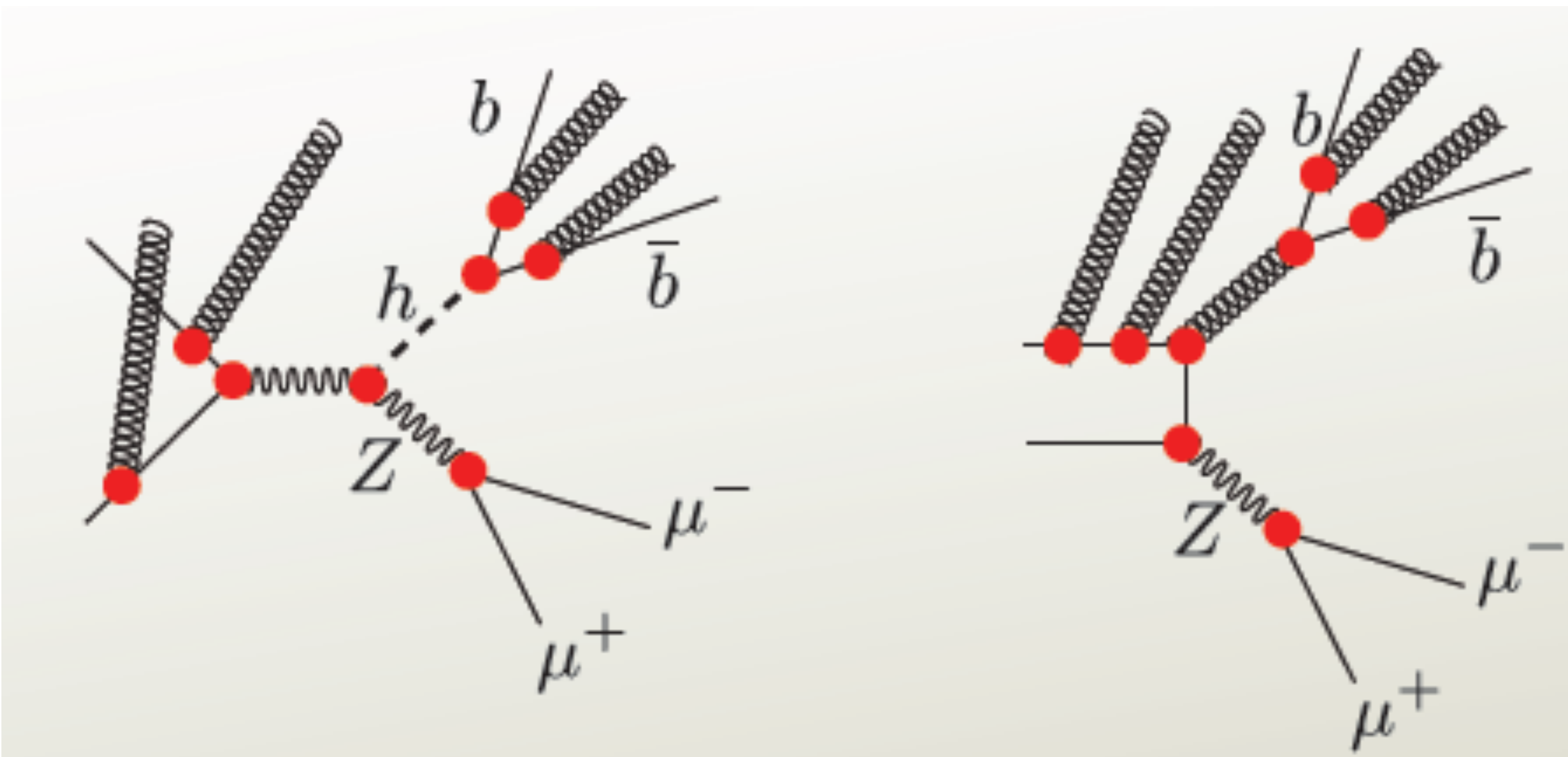


Jet invariant mass

Thaler
& Wang
0806.0023
Pythia 8.108

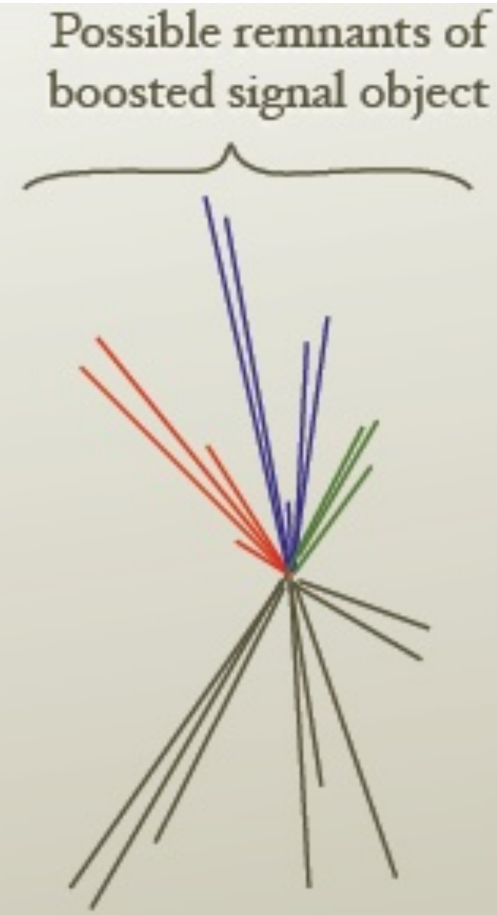
Fat QCD jet fakes Higgs jet too

- Easier to isolate decay products of boosted heavy particles



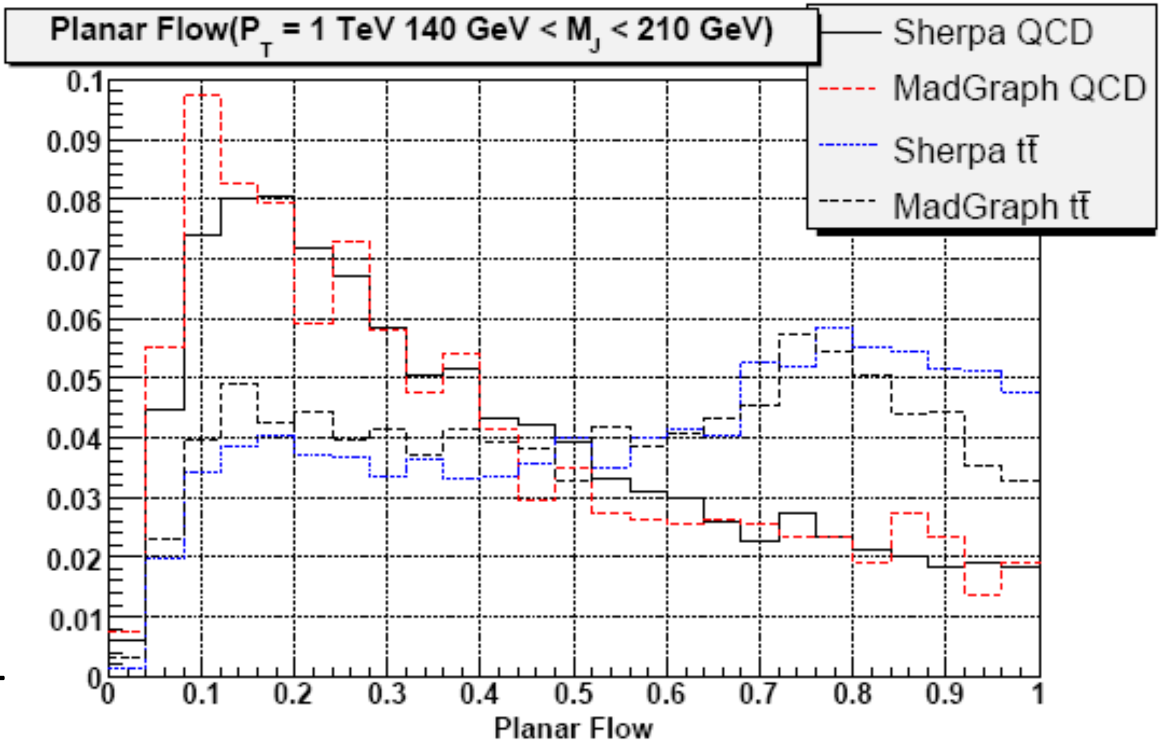
Jet identification

- Both signal and background events have jets.
- There are several techniques for separating signal from background using the structure of the jets.
- This is especially effective for highly boosted heavy objects.



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

Jet substructures are finger
prints of particles
crucial for particle identification

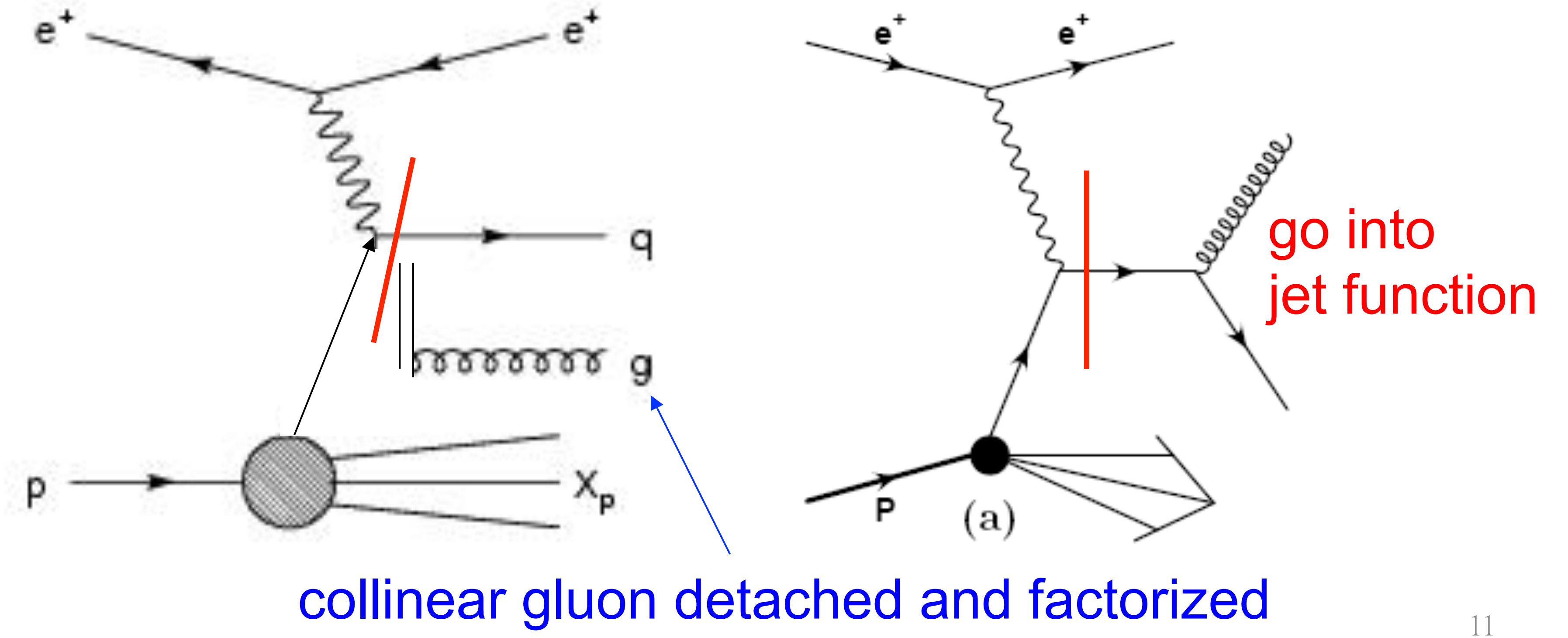
Jet functions

Wilson link

- Feynman rules are derived from Wilson link

$$\Phi_{\xi}^{(f)}(\infty,0;0)=\mathcal{P}\left\{e^{-ig\int_0^{\infty}d\eta\,\xi\cdot A^{(f)}(\eta\,\xi^{\mu})}\right\}$$

- Represented by double lines



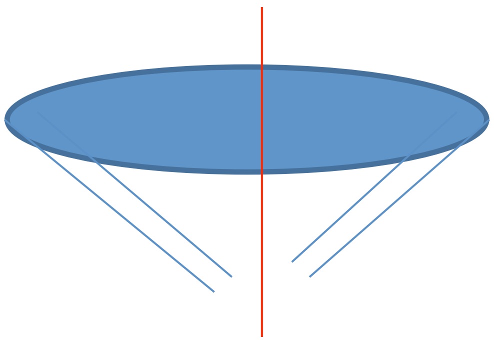
Quark Jet function

- Eikonalization leads to factorization

$$J_i^q(m_J^2, p_{0,J_i}, R) = \frac{(2\pi)^3}{2\sqrt{2}(p_{0,J_i})^2}\frac{\xi_\mu}{N_c}\sum_{N_{J_i}} Tr\left\{\gamma^\mu \langle 0|q(0)\Phi_\xi^{(\bar{q})\dagger}(\infty,0)|N_{J_i}\rangle \right.$$
$$\left. \times \langle N_{J_i}|\Phi_\xi^{(\bar{q})}(\infty,0)\bar{q}(0)|0\rangle \right\} \delta(m_J^2 - \tilde{m}_J^2(N_{J_i}, R))$$
$$\times \delta^{(2)}(\hat{n} - \tilde{n}(N_{J_i}))\delta(p_{0,J_i} - \omega(N_{J_i}))$$

projector

- Define jet axis, jet energy, jet invariant mass
- Wilson links are needed for gauge invariance of nonlocal matrix elements
- LO jet $J_i^{(0)}(m_{J_i}^2, p_{0,J_i}, R) = \delta(m_{J_i}^2)$



Almeida et al. 08

Gluon jet function

- Similar definition for gluon jet function

$$J_i^g(m_J^2, p_{0,J_i}, R) = \frac{(2\pi)^3}{2(p_{0,J_i})^3} \sum_{N_{J_i}} \langle 0|\xi_\sigma F^{\sigma\nu}(0)\Phi_\xi^{(g)\dagger}(0,\infty)|N_{J_i}\rangle$$

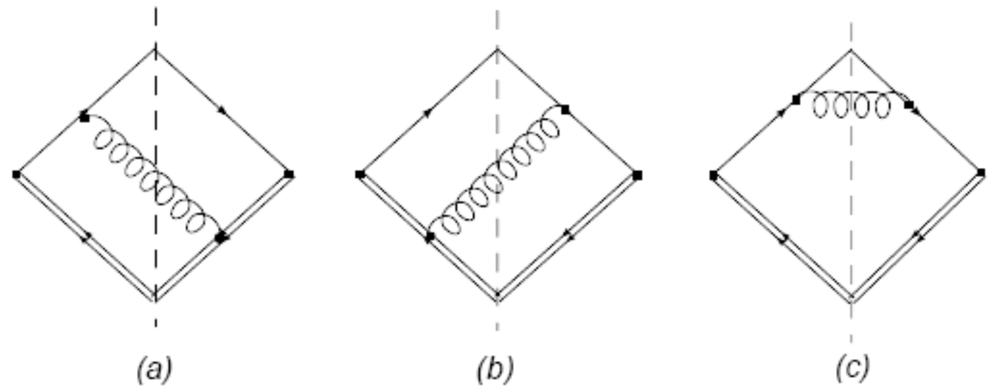
$$\times\langle N_{J_i}|\Phi_\xi^{(g)}(0,\infty)F_\nu^\rho(0)\xi_\rho|0\rangle\delta(m_J^2 - \tilde{m}_J^2(N_{J_i}, R))$$

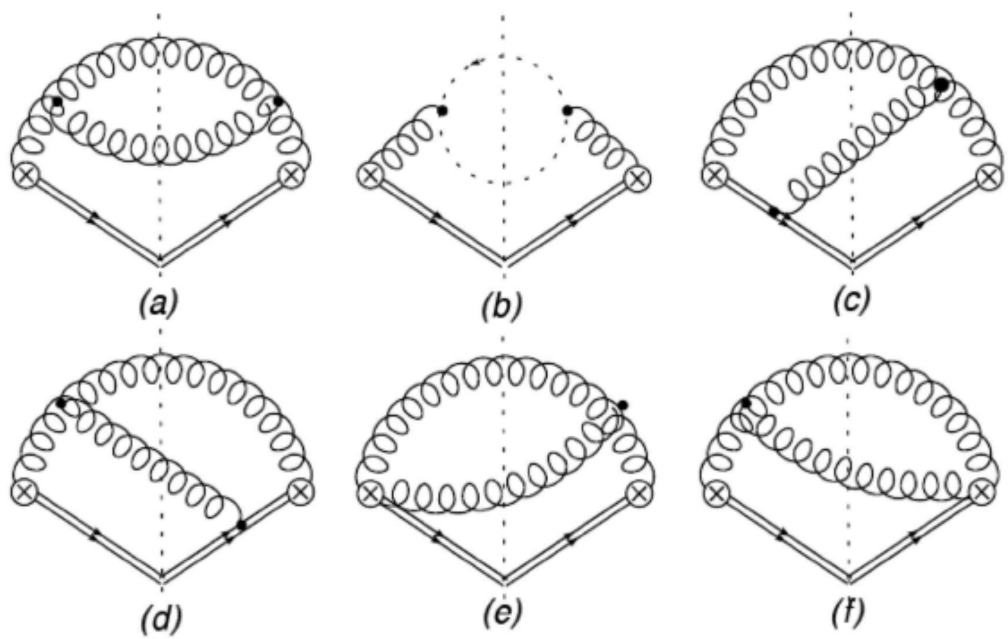
$$\times\delta^{(2)}(\hat{n} - \tilde{n}(N_{J_i}))\delta(p_{0,J_i} - \omega(N_{J_c}))$$

- They are formal definitions. Extraction of physics depends on algorithm

NLO diagrams

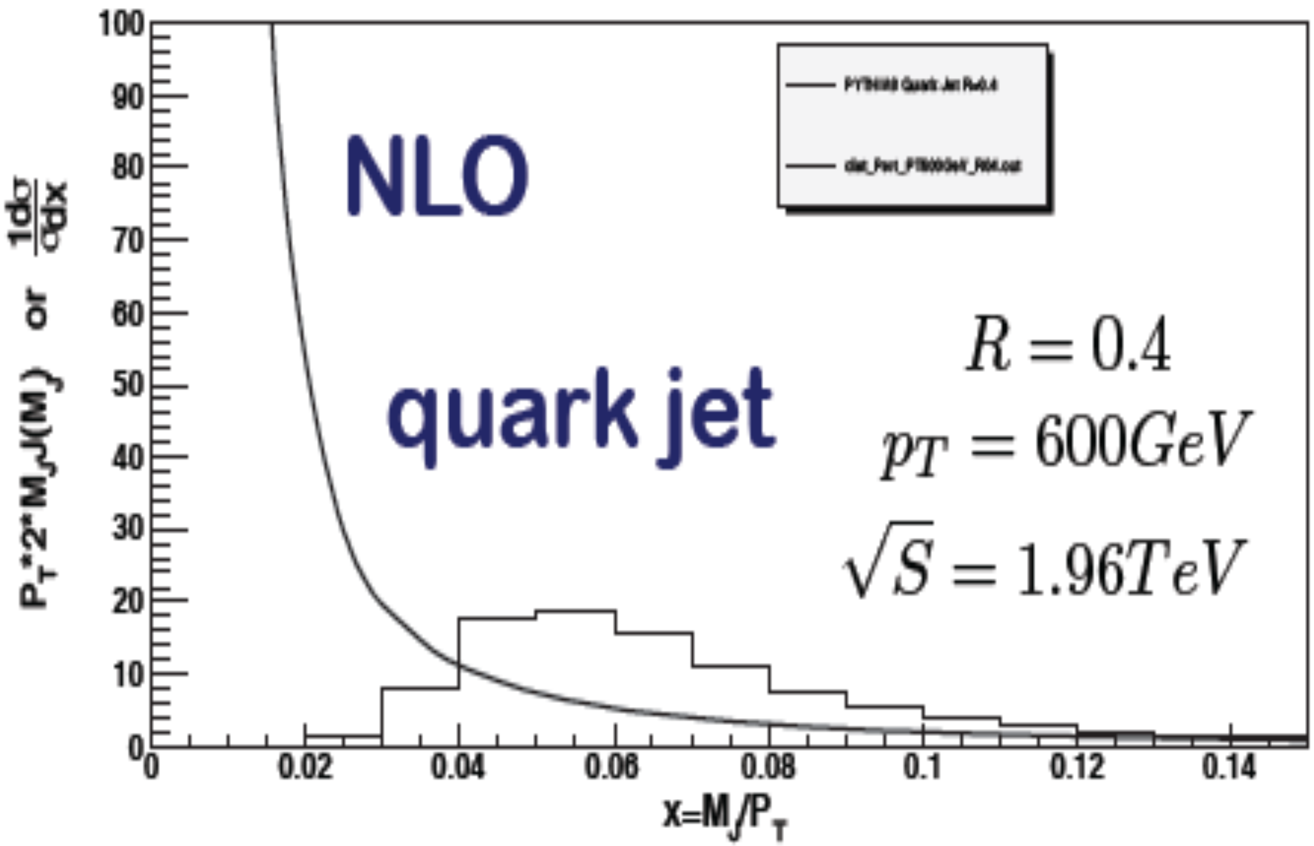
- quark jet
- gluon jet





NLO jet distribution

- Divergence of NLO quark jet distribution at small mJ



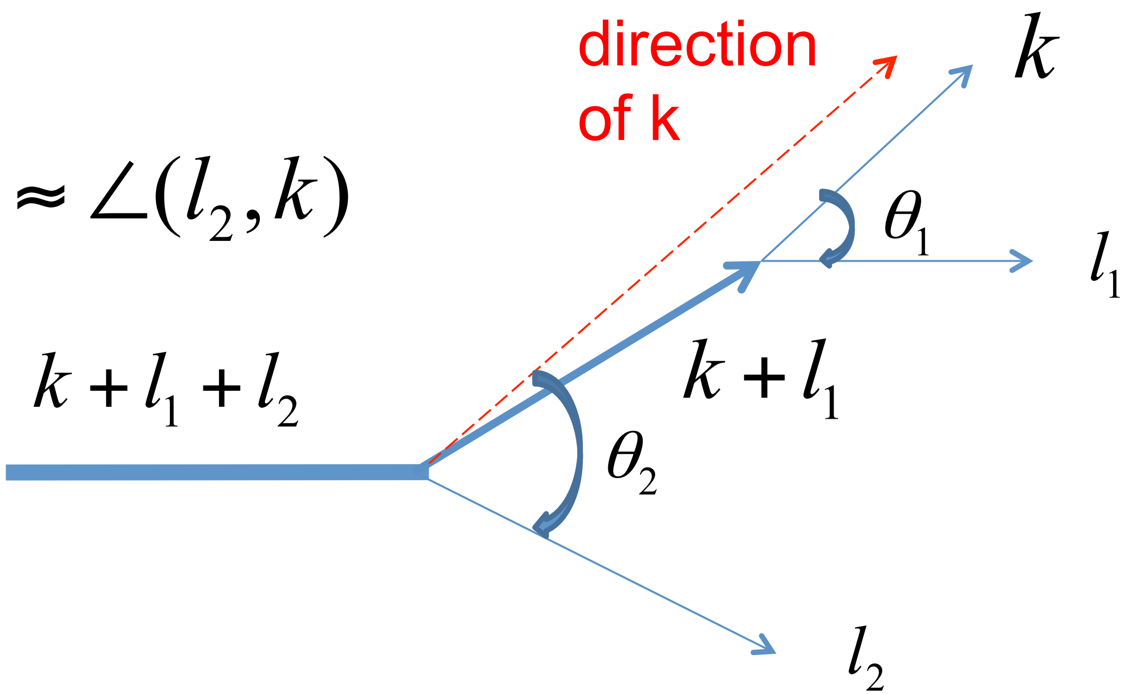
Resummation

Angular ordering

- Dominant radiative contribution comes from angular ordering
- Thickness denotes invariant mass

$$\theta_2 >> \theta_1$$

$$\angle(l_2, k + l_1) \approx \angle(l_2, k)$$



Double logarithm

- Approximate loop integral $k_1 + l_1 \approx \alpha k_1$

$$\int \frac{l_2^0 dl_2^0 d\cos\theta_2}{[(k+l_1)^2 + (k+l_1)\cdot l_2]^2} \approx \int \frac{l_2^0 dl_2^0 d\cos\theta_2}{[\alpha k^0 l_2^0 (1-\cos\theta_2)]^2}$$

$$\propto \int_{m_J}^{P_T} \frac{dl_2^0}{l_2^0} \int_{\beta_J^2} \frac{d\cos\theta_2}{(1-\cos\theta_2)^2}, \quad \beta_J = \sqrt{1 - m_J^2 / P_T^2}$$

jet mass, jet energy

$$\propto \frac{P_T^2}{m_J^2} \ln \frac{P_T^2}{m_J^2} \to \ln^2 N$$

diverge at small mass

$$\int_0^1 dx (1-x)^{N-1},$$

Mellin transformation

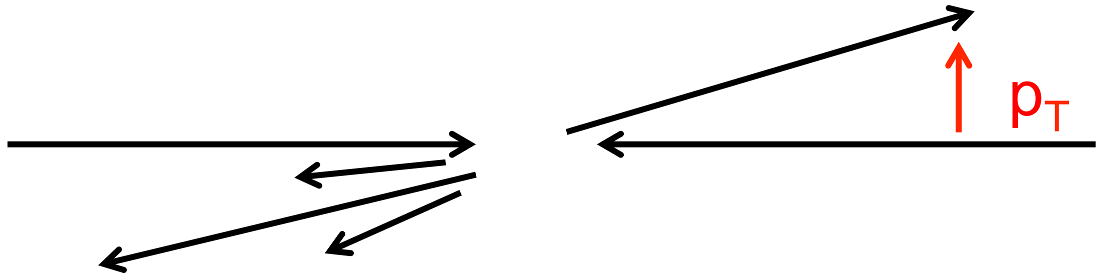
$$x \equiv m_J^2 / (RP_T)^2$$

Energy and angular resolution

- Due to finite energy resolution, soft real gluon with energy lower than m_J is cancelled by soft virtual gluon.
- Lower bound of radiative gluon energy is m_J
- When m_J is not zero, particles in a jet cannot be completely collimated
- Upper bound of radiative gluon angle is related to m_J
- Double log hints resummation

Resummation

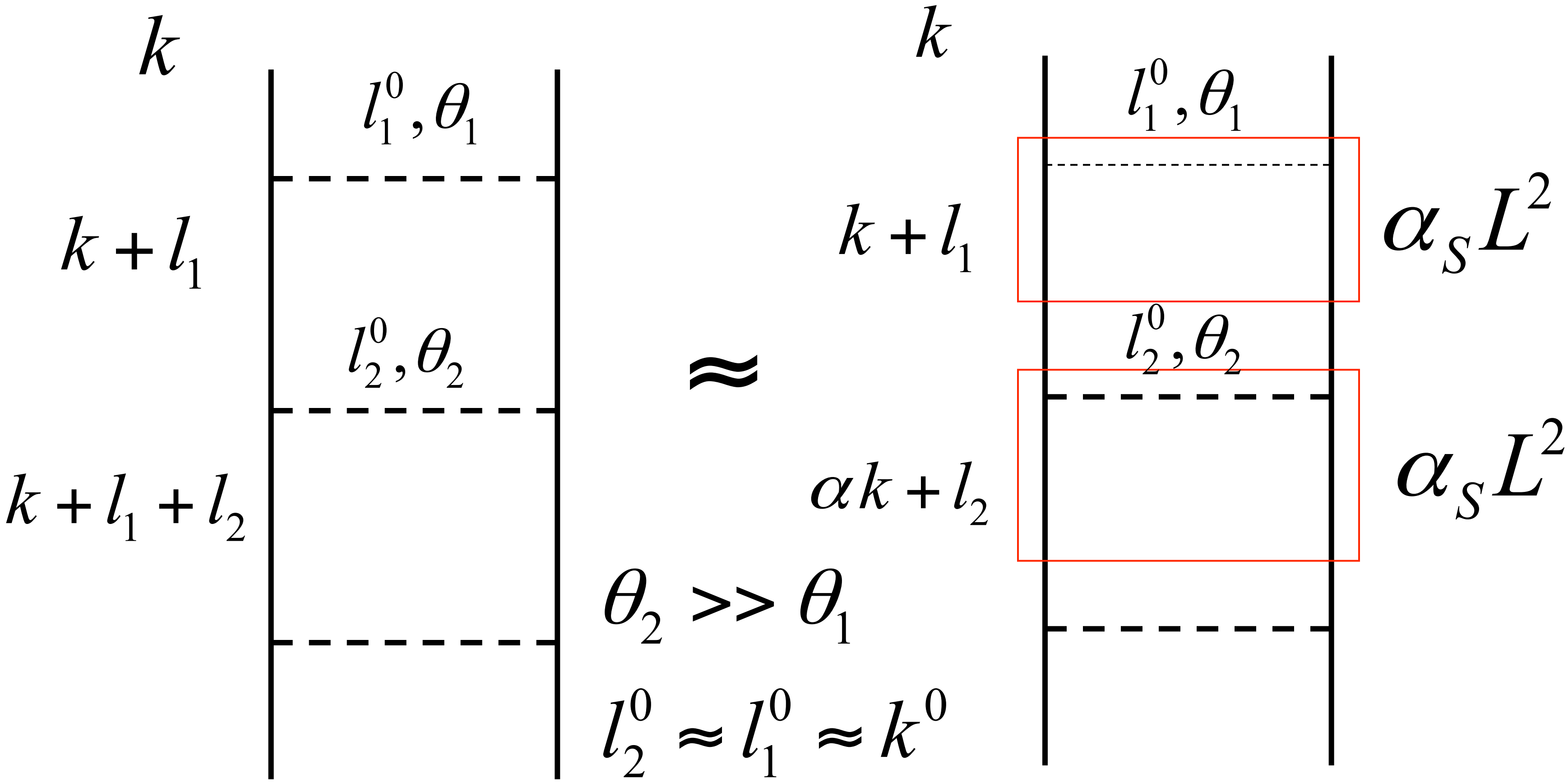
- Recall low pT spectra of direct photon dominated by soft/collinear radiations



- Require kT resummation
- Jet mass arises from soft/collinear radiations
- Can be described by resummation

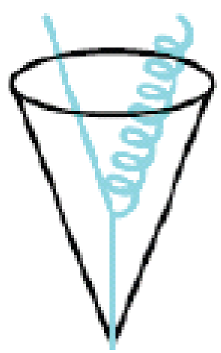
Qiu's lecture

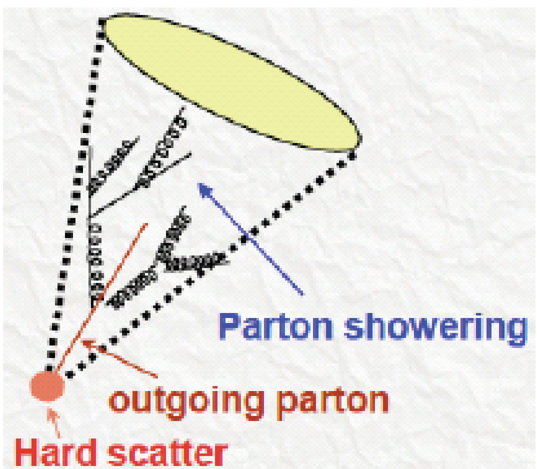
Ladder and exponentiation

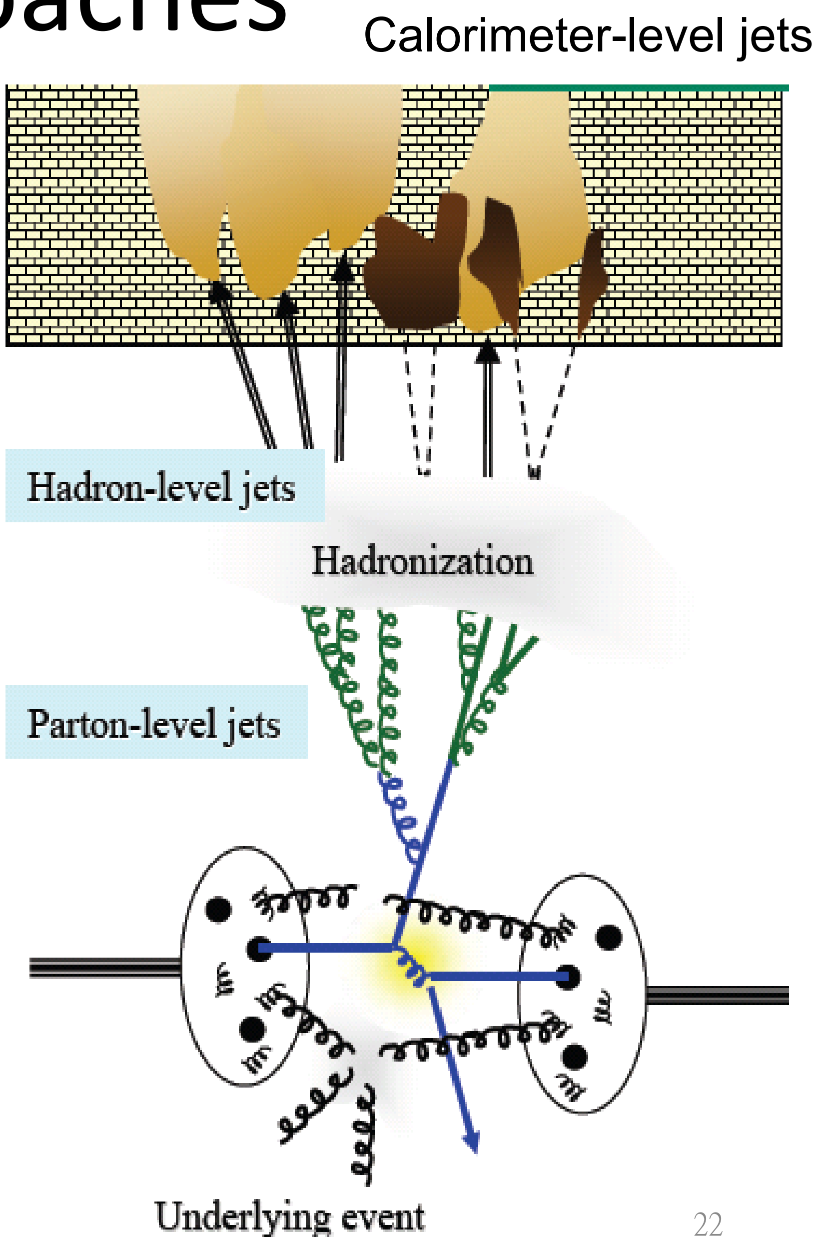


Various approaches

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

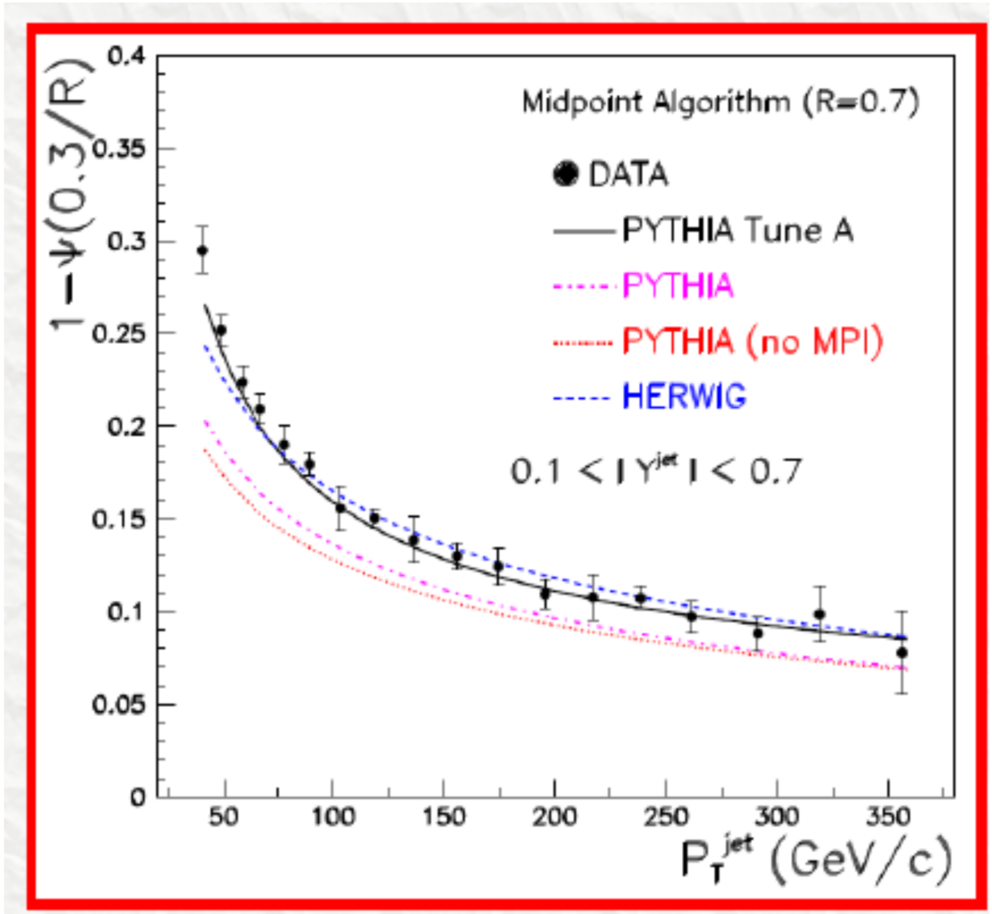






Why resummation?

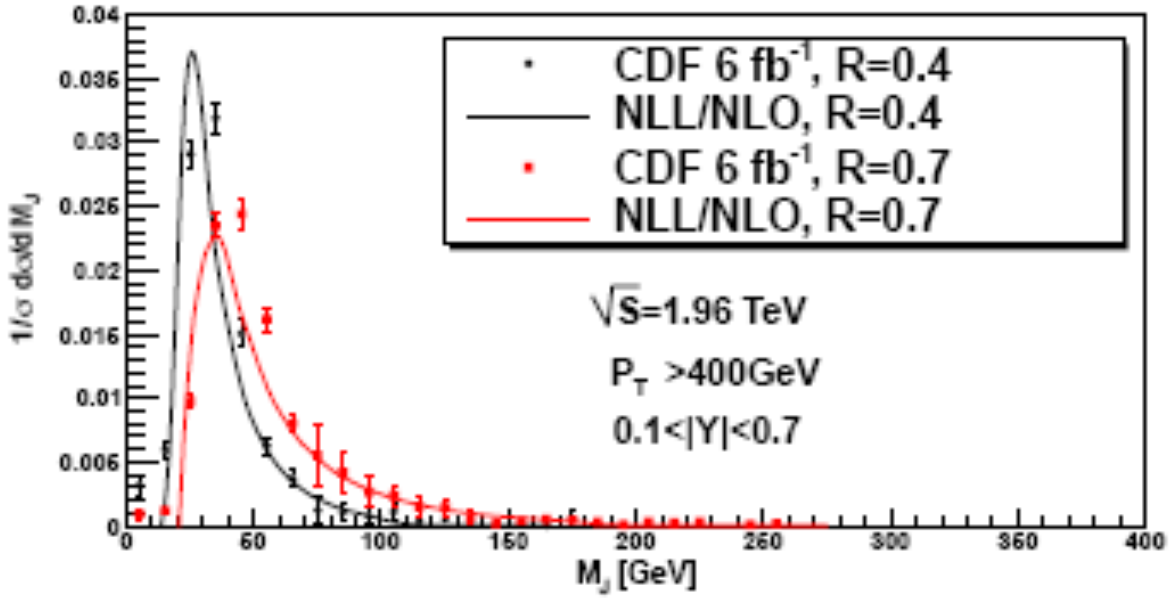
- Monte Carlo may have ambiguities from tuning scales for coupling constant
- NLO is not reliable at small jet mass
- Predictions from QCD resummation are necessary

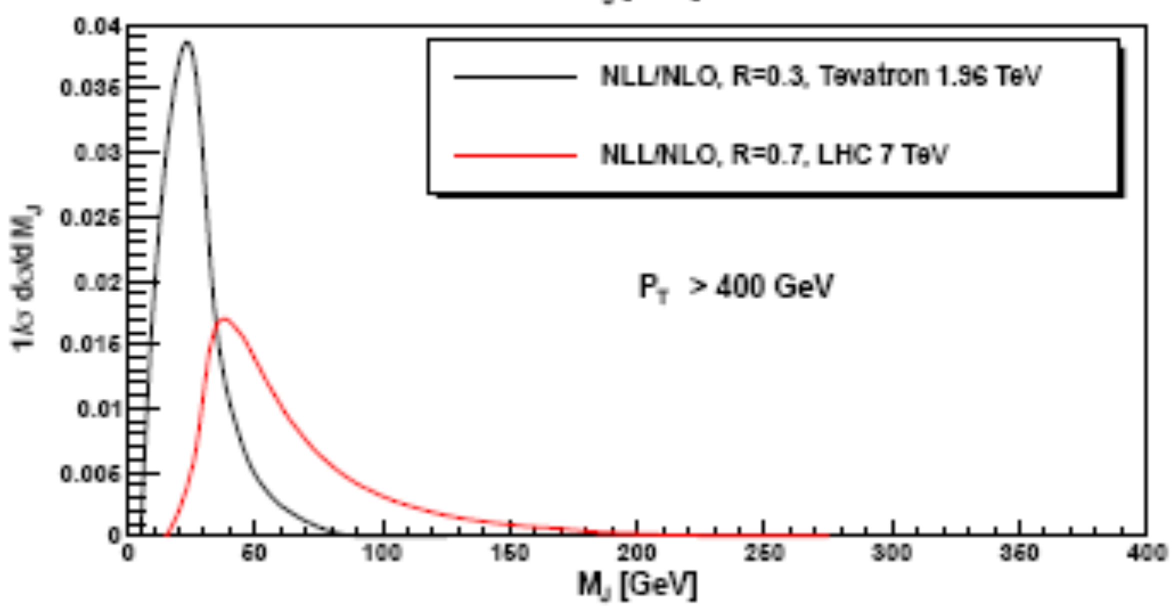


Tevatron data vs MC predictions

N. Varelas 2009

Predictions for jet mass distribution





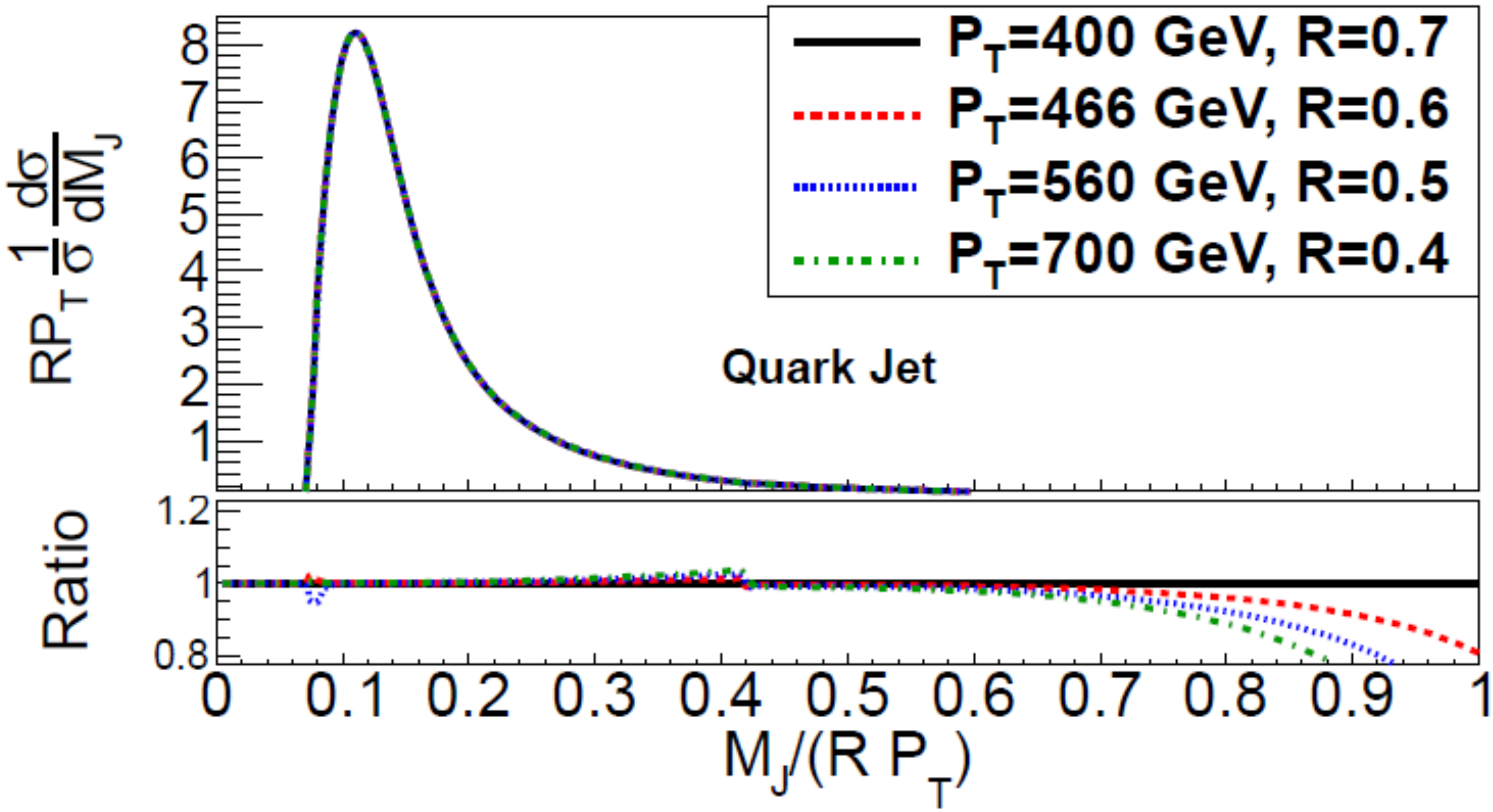
NLL in resummation
NLO in initial condition

CTEQ6L PDFs

Li, Li, Yuan, 2011

Scaling behavior

- Jet mass distribution depends only on the ratio $M_J/(RP_T)$, insensitive to other variables



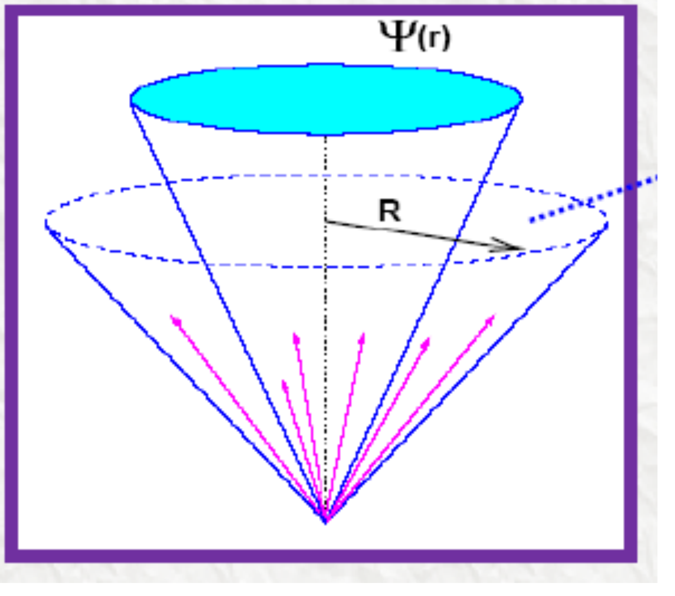
Boost-invariant ratio

- Can either calculate jet property in the rest frame first, and then boost, or can boost first, and then calculate jet property
- These two sequences are equivalent. Their commutability demands that final results for jets depend only on the boost-invariant ratio $M_J/(RP_T)$
- RP_T bears the meaning of the transverse momentum relative to jet axis, and is boost -invariant; jet mass is boost-invariant

Energy profiles

Energy profiles

- If can calculate jet mass in arbitrary jet cone size R, can certainly calculate jet energy in arbitrary jet cone $\Psi(r)$
- It is still attributed to soft/collinear radiations
- Resummation applies



Jet energy functions

- Jet energy function for quark

$$\frac{(2\pi)^3}{2\sqrt{2}(P_J^0)^2 N_c} \sum_{\sigma,\lambda} \int \frac{d^3p}{(2\pi)^3 2p^0} \frac{d^3k}{(2\pi)^3 2k^0} [p^0\Theta(r-\theta_p) + k^0\Theta(r-\theta_k)]$$

$$\times \mathrm{Tr}\left\{ \not{\xi} \langle 0|q(0) W_\xi^{(\bar{q})\dagger}(\infty,0)|p,\sigma;k,\lambda\rangle\langle k,\lambda;p,\sigma|W_\xi^{(\bar{q})}(\infty,0)\bar{q}(0)|0\rangle \right\}$$

$$\times \delta(M_J^2 - (p+k)^2)\delta(\hat{n} - \hat{n}_{\mathbf{p}+\mathbf{k}})\delta(P_J^0 - p^0 - k^0),$$

insert step functions

- Jet energy function for gluon

$$\frac{(2\pi)^3}{2(P_J^0)^3 N_c} \sum_{\sigma,\lambda} \int \frac{d^3p}{(2\pi)^3 2p^0} \frac{d^3k}{(2\pi)^3 2k^0} [p^0\Theta(r-\theta_p) + k^0\Theta(r-\theta_k)]$$

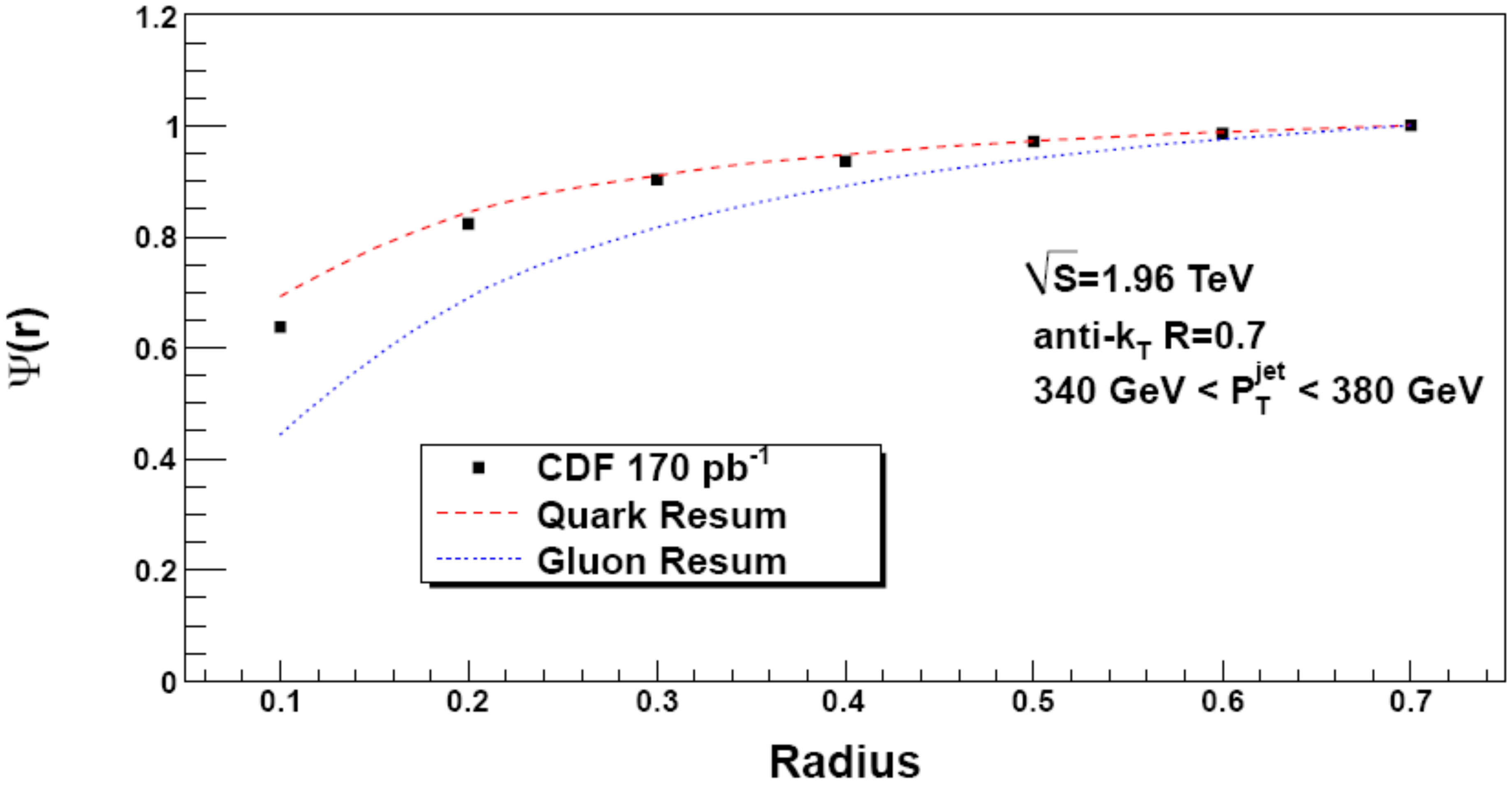
$$\times \langle 0|\xi_\sigma F^{\sigma\nu}(0) W_\xi^{(g)\dagger}(\infty,0)|p,\sigma;k,\lambda\rangle\langle k,\lambda;p,\sigma|W_\xi^{(g)}(\infty,0)F_\nu^{\rho}(0)\xi_\rho|0\rangle$$

$$\times \delta(M_J^2 - (p+k)^2)\delta(\hat{n} - \hat{n}_{\mathbf{p}+\mathbf{k}})\delta(P_J^0 - p^0 - k^0),$$

Resummation

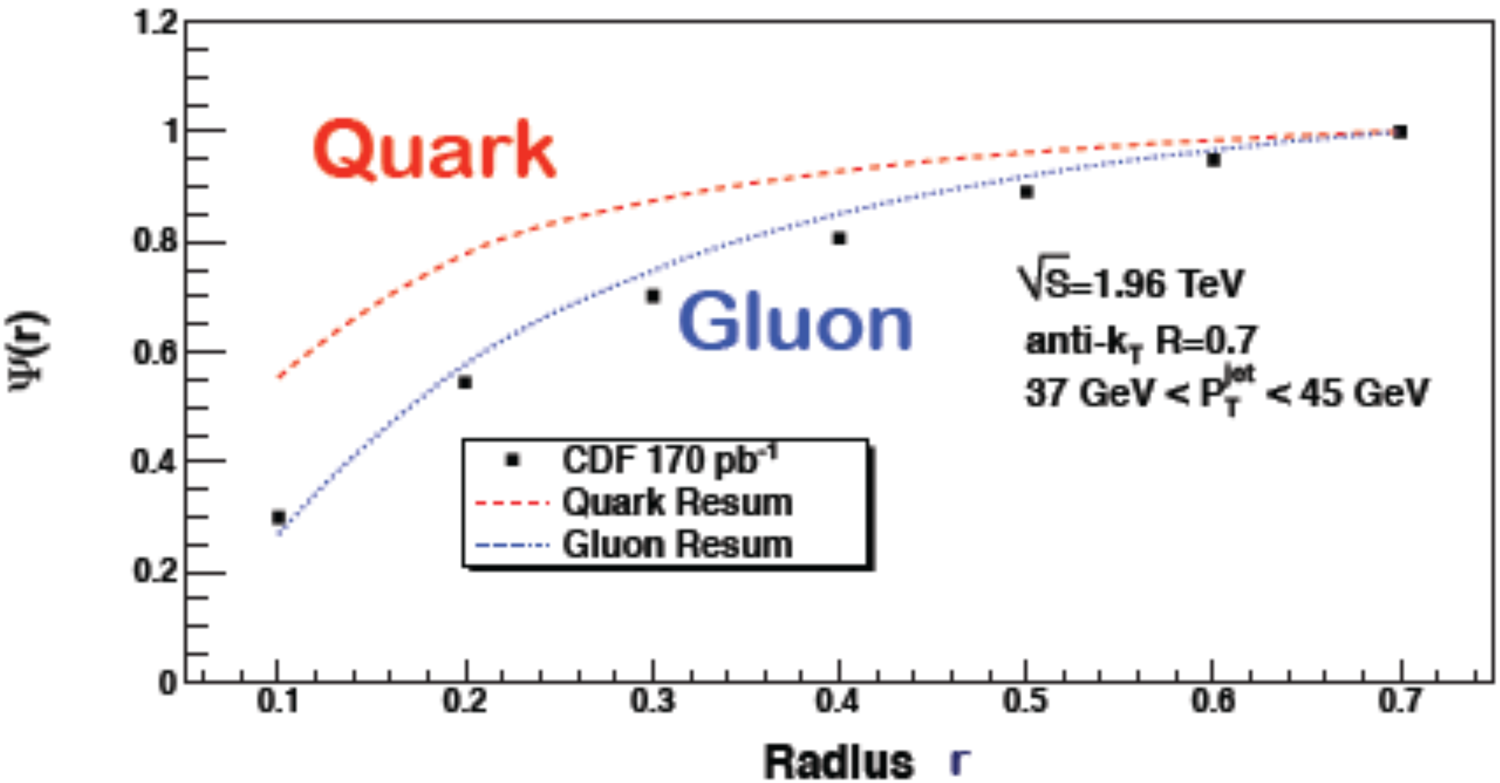
- Have considered N=1 here, corresponding to integration over jet mass (insensitive to nonperturbative physics)
- Boost-invariant ratio becomes rP_T / RP_T
- Double log becomes $\alpha_S \ln^2(r/R)$
- Same argument based on ladder diagrams and exponentiation applies
- Quark jet is narrower than gluon jet

Quark jet or gluon jet?



- It is a quark jet!

Opportunities at LHC

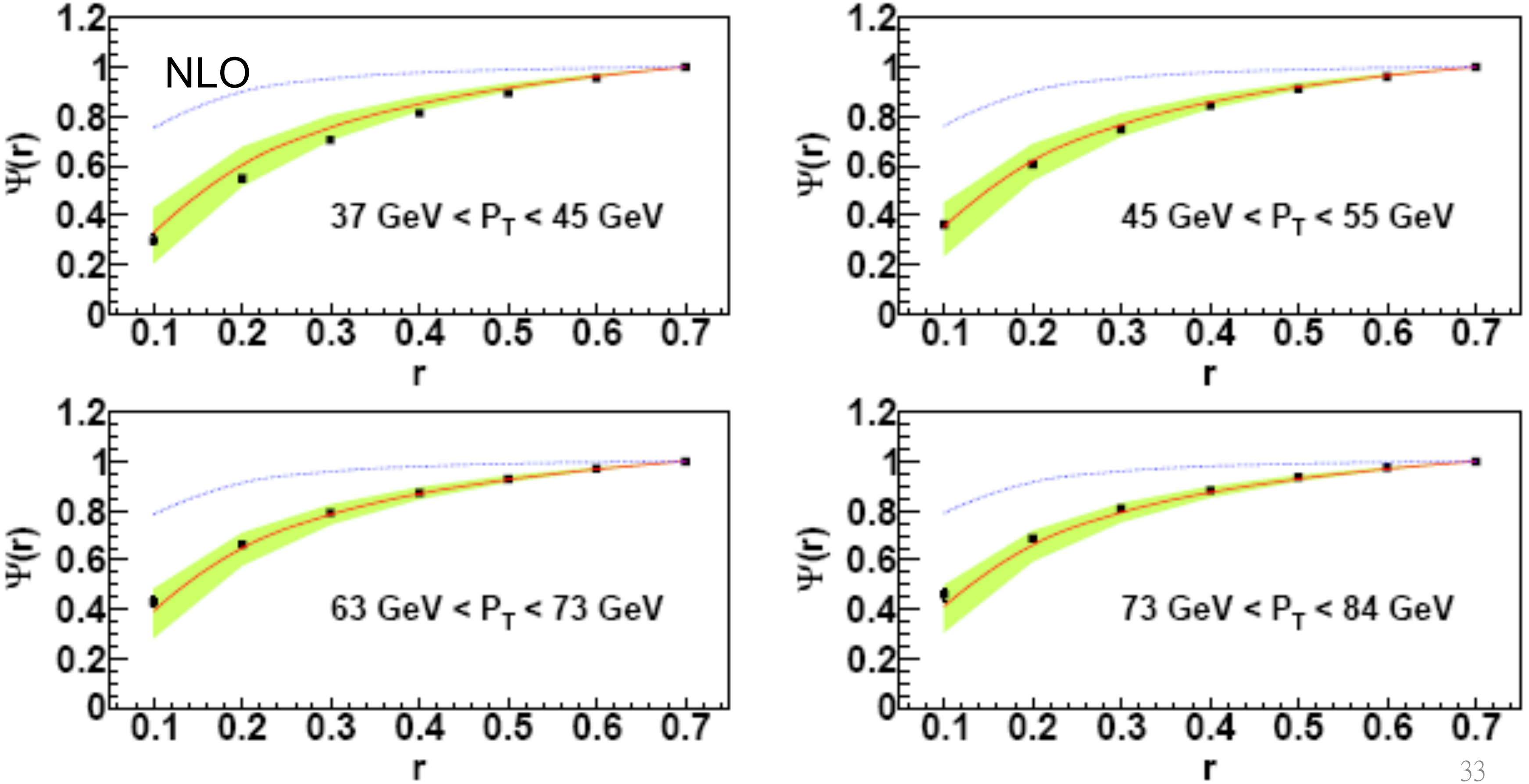


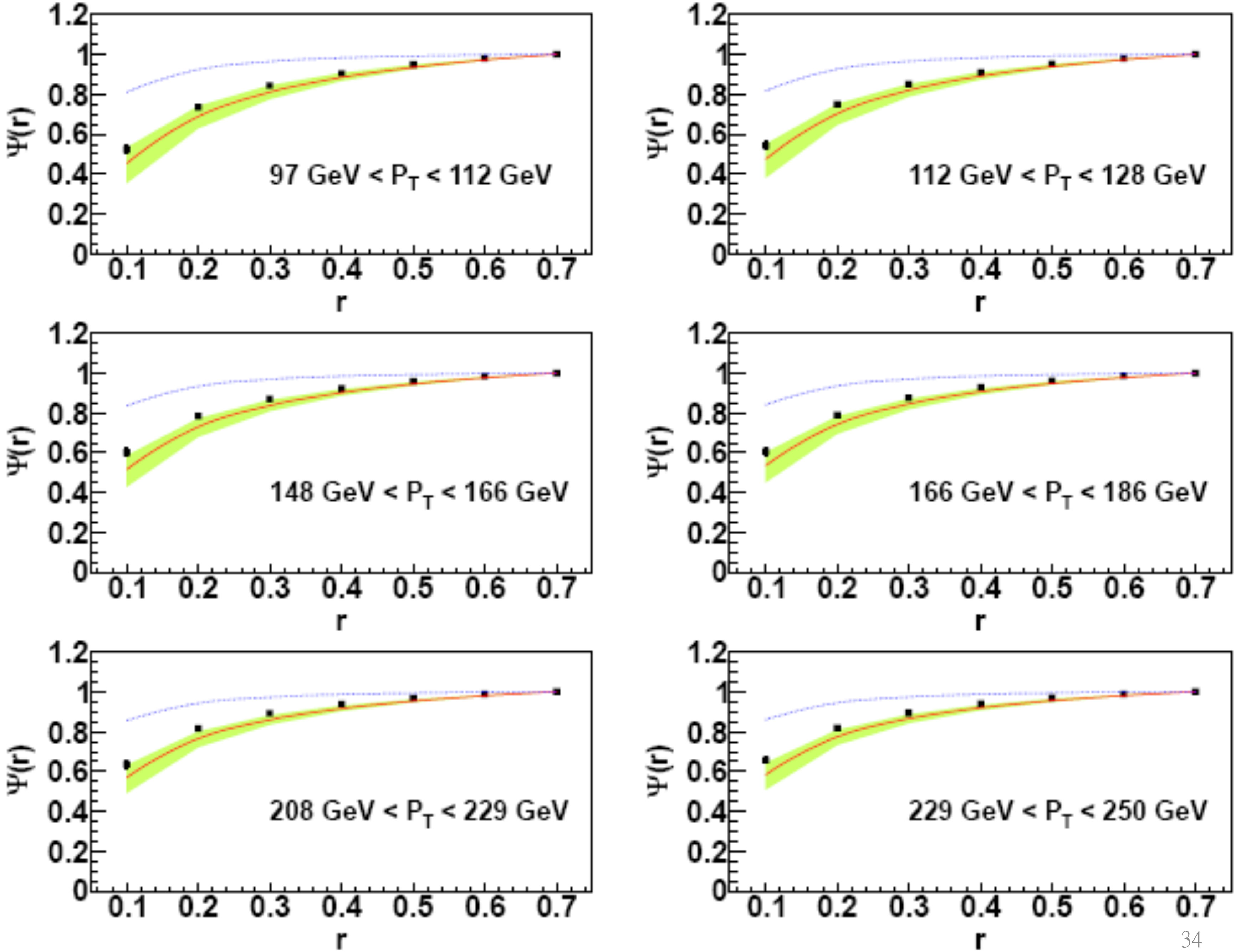
- It is a gluon jet!
- Test new physics models from composition of observed jets

Comparison with CDF data

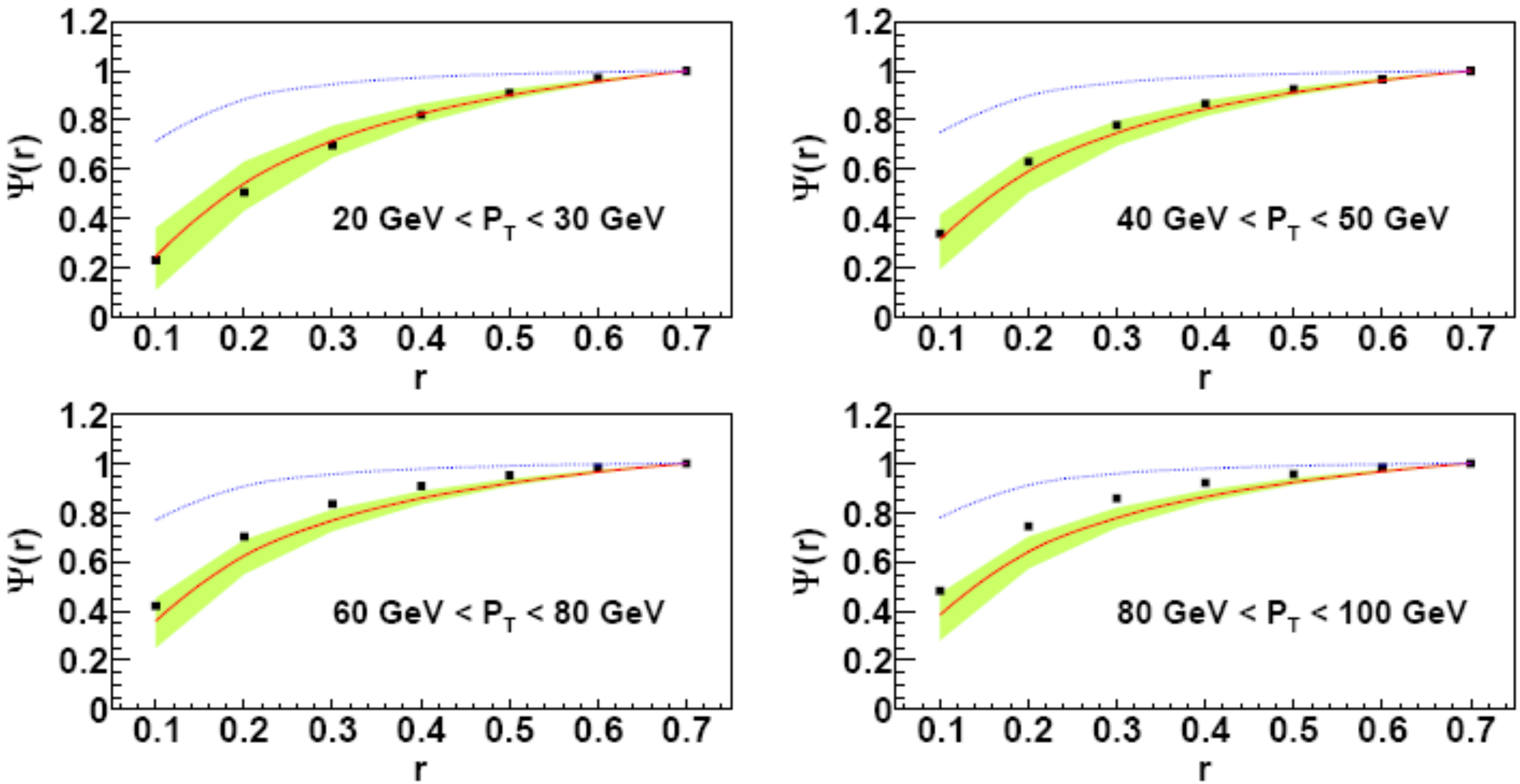
$$\Psi(r) = \frac{1}{N_{jet}} \sum_{jets} \frac{P_T(0,r)}{P_T(0,R)}, \qquad 0 \le r \le R$$

quark, gluon jets, convoluted with LO hard scattering, PDFs




97 GeV < P_T < 112 GeV
112 GeV < P_T < 128 GeV
148 GeV < P_T < 166 GeV
166 GeV < P_T < 186 GeV
208 GeV < P_T < 229 GeV
229 GeV < P_T < 250 GeV
Ψ(r)
r

Compasion with CMS data

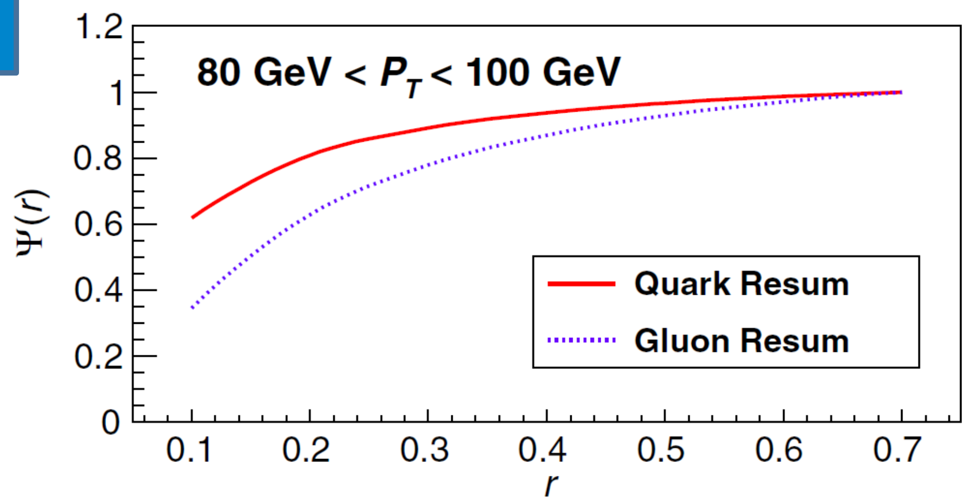


Substructures of QCD jets

Ex1) **Jet energy profile**

H.n.Li, Z.Li, C.P.Yuan, PRD87,074025(2013)

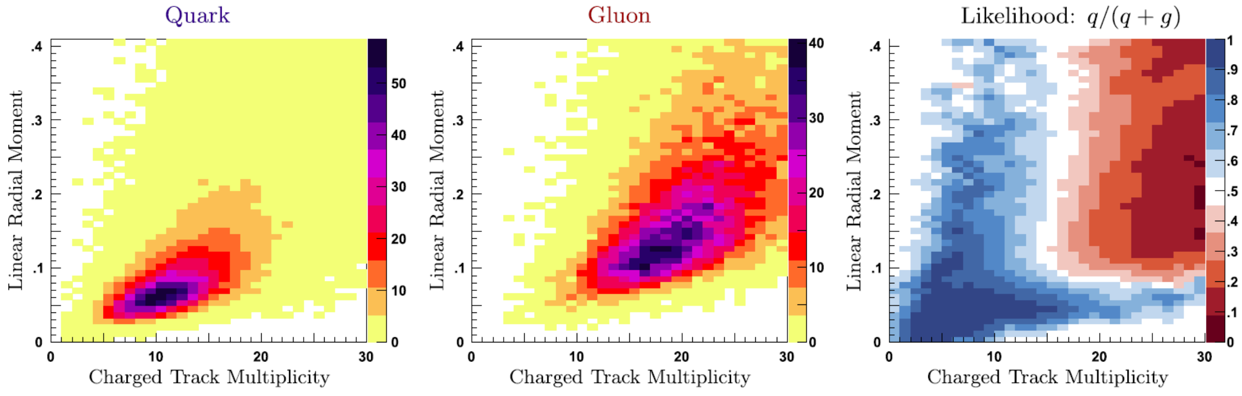
$$\Psi(r) = \frac{1}{N}\sum_J \sum_{i\in J} \frac{p_T(0 < r_i < r)}{p_{T,J}}$$



Ex 2) **Girth**

J.Gallicchio, M.D.Schwartz PRL 107,172001(2011)

$$g_J = \sum_{i\in J} \frac{p_{T,i} r_i}{p_{T,J}}$$



See TASI Lecture, J. Shelton, arXiv:1302.0260 for more detail

Boosted heavy particles

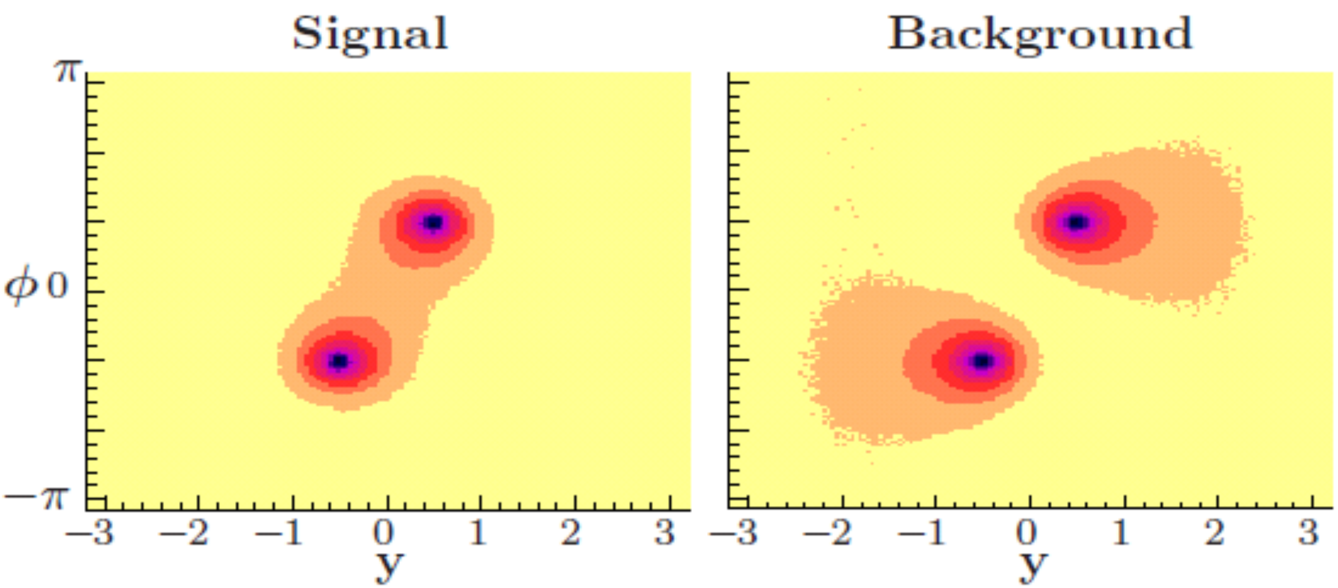
Higgs jet

- One of major Higgs decay modes H -> bb with Higgs mass ~ 125 GeV
- Important background g -> bb
- Analyze substructure of Higgs jet improves its identification
- For instance, color pull made of soft gluons
- This substructure is 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



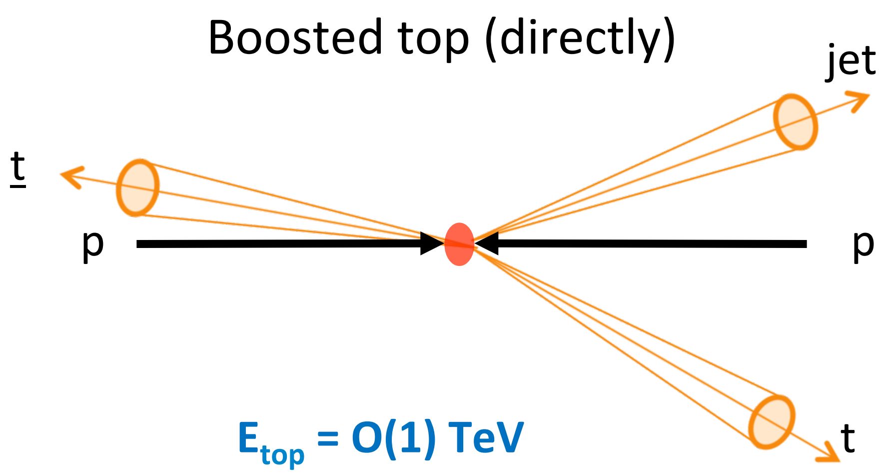
Top jet substructure

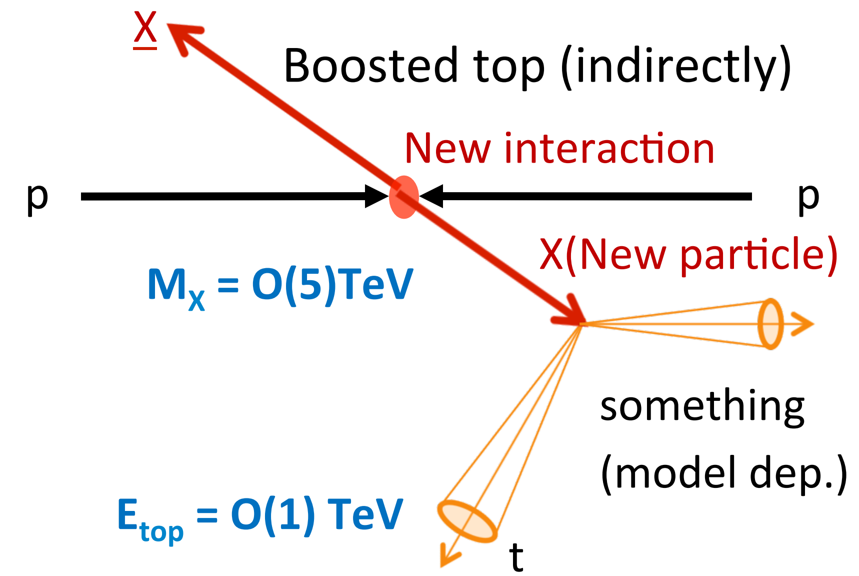
- Top quark properties related to EWSB
- BSM heavy particles decay into boosted tops
- Chirality of BSM physics revealed by helicity of boosted tops
- How to determine helicity of boosted tops?
- Polarization of rest top determined by angular distribution of decay products
- Propose to measure jet substructures---energy profiles depend on helicity
- It is attributed to weak dynamics
- Require no b-tagging, W reconstruction

Review articles: F.-P.Schilling (2012), W.Bernreuther (2008), etc.

Boosted tops

- At LHC(7-14 TeV), even heavy particles (W,Z,h,top...) can be produced with a large velocity = boosted W,Z,h,top...



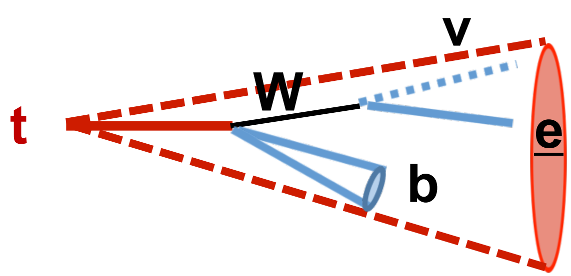


- Boosted top search is important both for SM and BSM

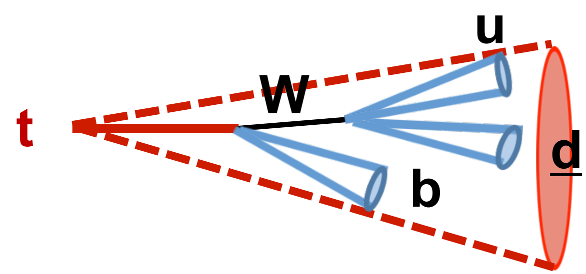
(our results is within SM, but possible to extend it to BSM)

Top jet substructures

- Decay particles from boosted top collimated in a cone.
  Difficult to distinguish them from background QCD jets

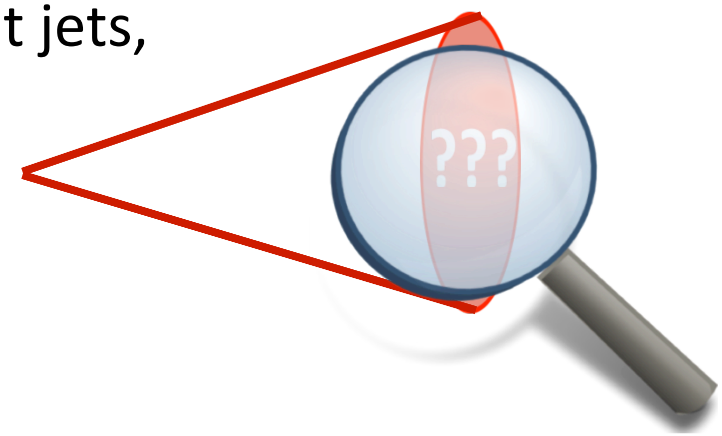


leptonc top (1-jet)



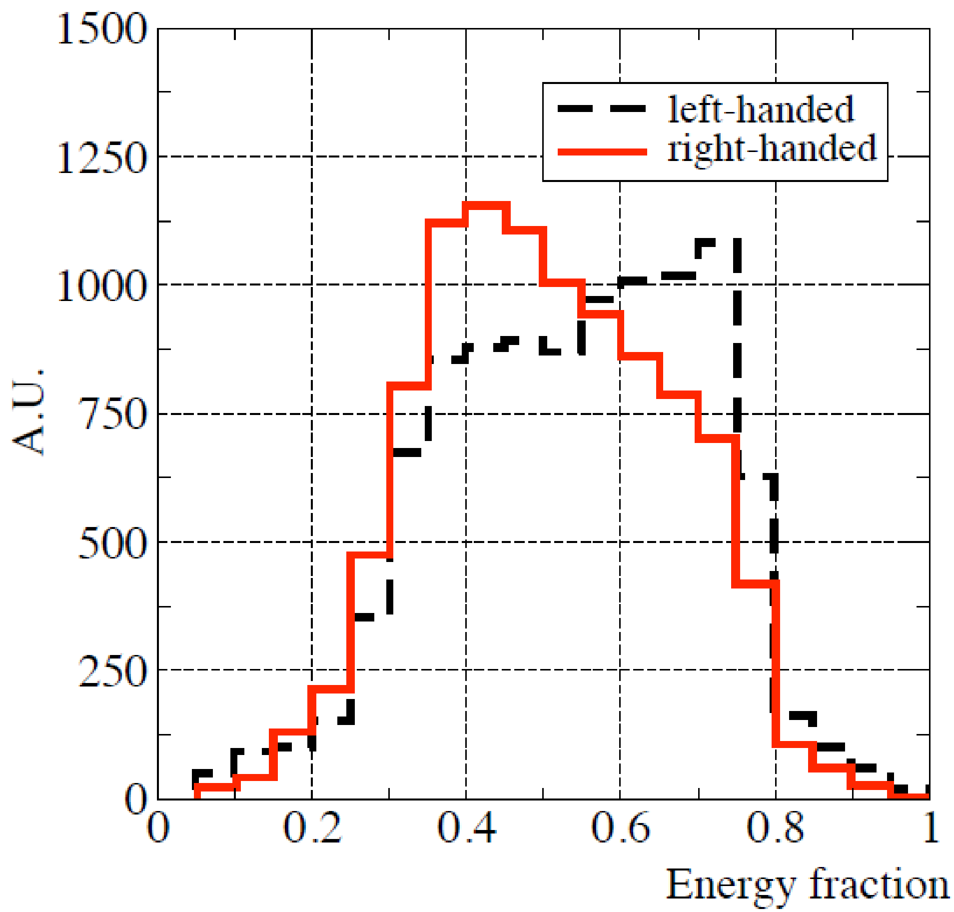
hadronic top (3-jets)
collimated into a single jet !

- We need more information about jets,
  especially inside of jets.



Take a look at detail in the jet
= Study jet substructure !

Energy fractions in L & R tops

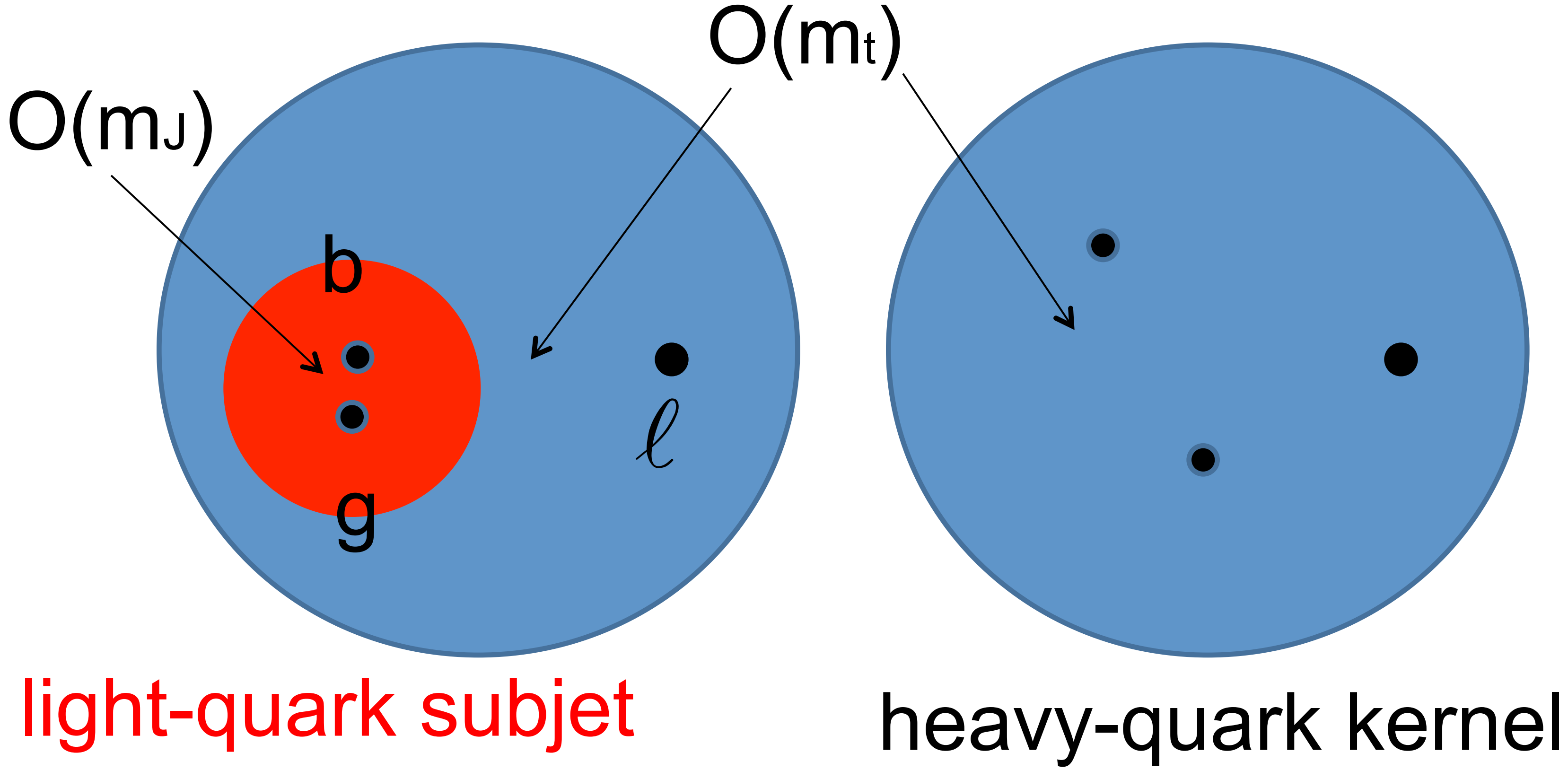


pick up harder subjet
in smallest dij among
three transverse
separation
mainly b subjet in L top
mainly d subjet in R top

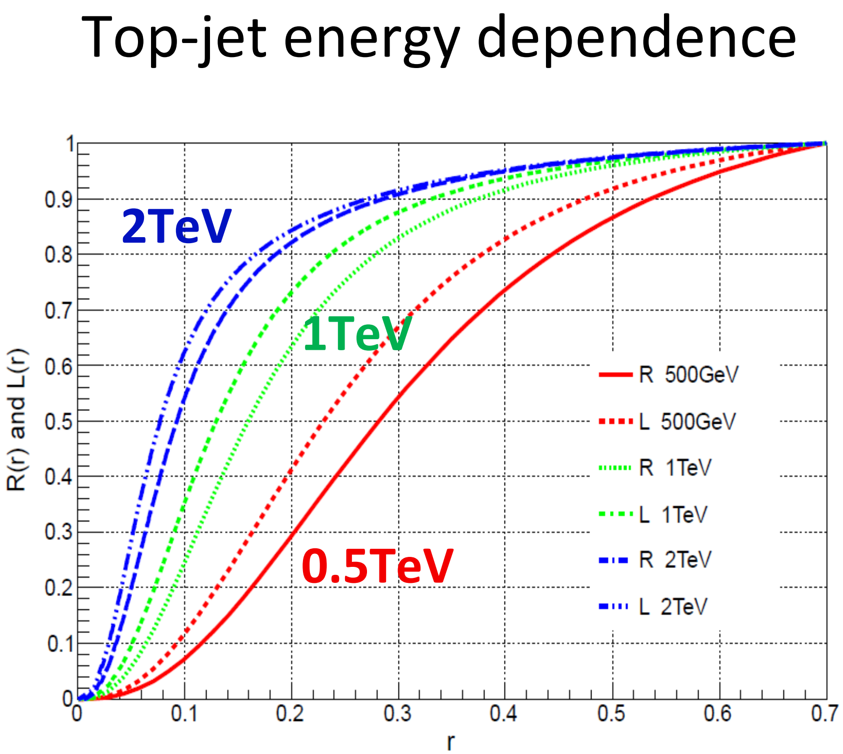
Krohn, Shelton, Wang 2010

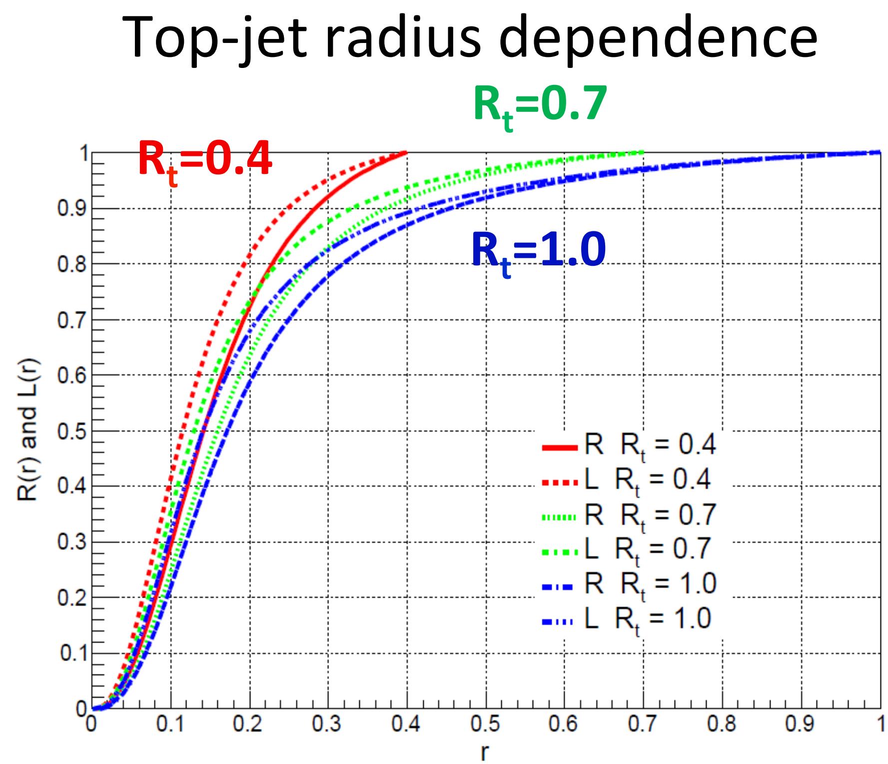
Scale hierarchy $E \gg m_t \gg m_J$

- The two lower scales m_t and m_J characterize different dynamics, which can be factorized



Top-jet energy profile





Left > Right tendency (L is faster than R) again.

|L-R| deference decrease as E_{jt} increase.

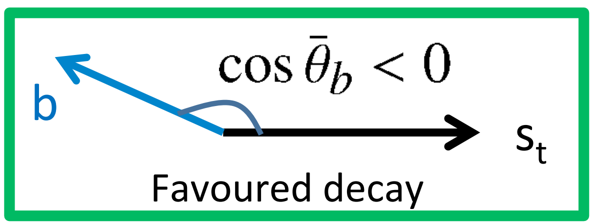
Top-jet radius dependence is not so large.

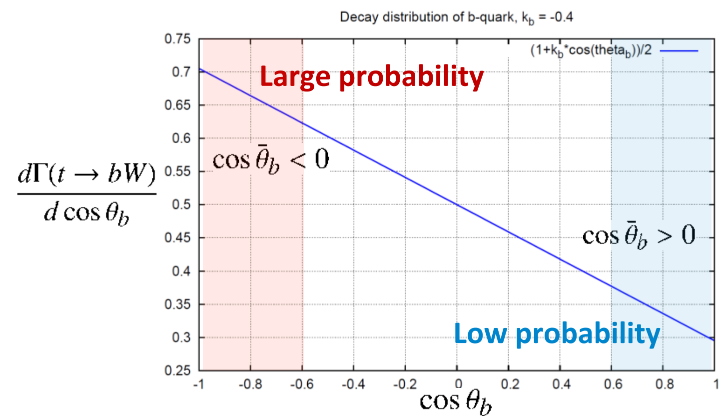
Discussion

- Why **Left(h=-)** is larger than **Right(h=+)** ? → Angular distribution obeys V-A interaction

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_b} = \frac{1}{2}(1 + \kappa_b \cos\theta_b)$$

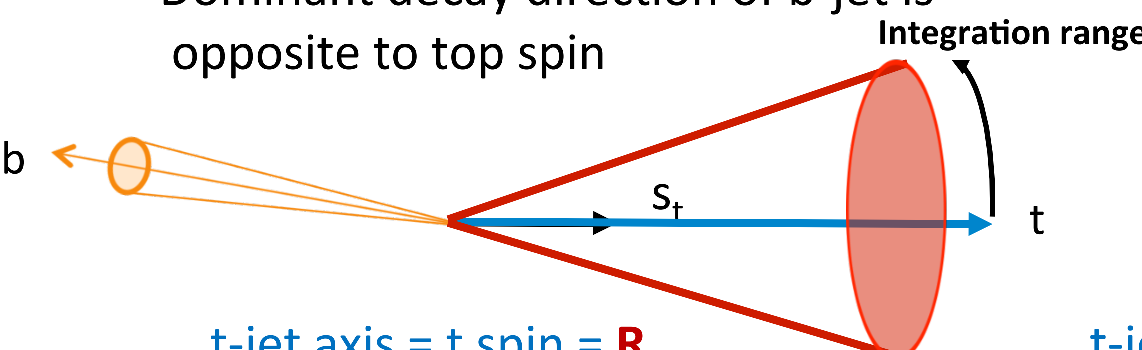
κ_b : b-quark's spin analysing power = **- 0.4**



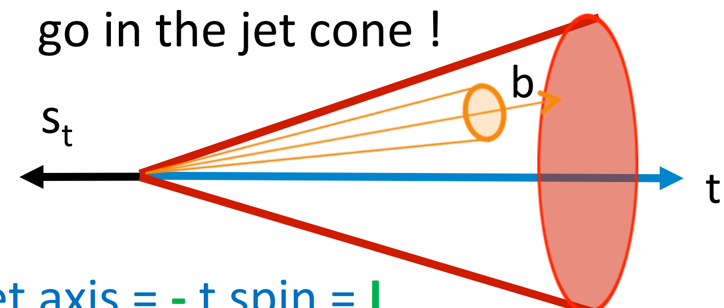


- Dominant decay direction of b-jet is opposite to top spin

L has a larger chance to go in the jet cone !



t-jet axis = t spin = **R**



t-jet axis = - t spin = **L**

Summary

- Jet substructures can be studied in PQCD
- Start with jet definition, apply factorization and resummation, and predict observables consistent with data
- Jet substructures reveal hard dynamics (strong and hard), which helps particle identification
- Jet substructures differentiate helicity (chirality) of tops
- You can find your own jet substructures!