Jet physics

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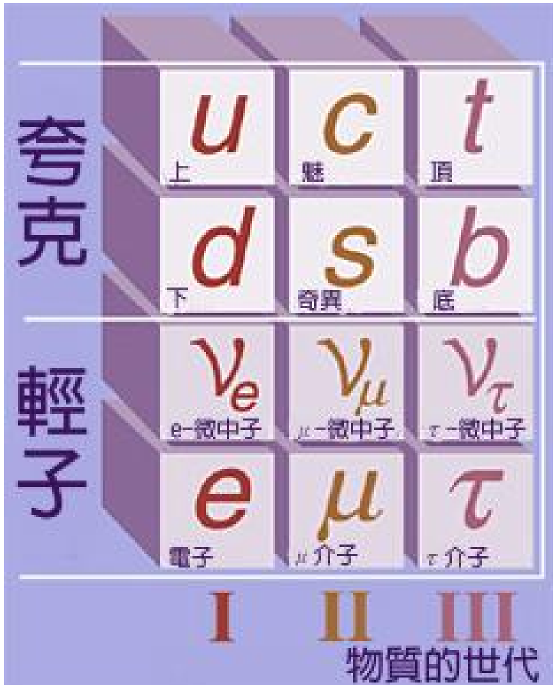
Outlines

- introduction
- Jet in theory
- Jet in experiment
- Jet identification
- On-going projects and summary

Introduction

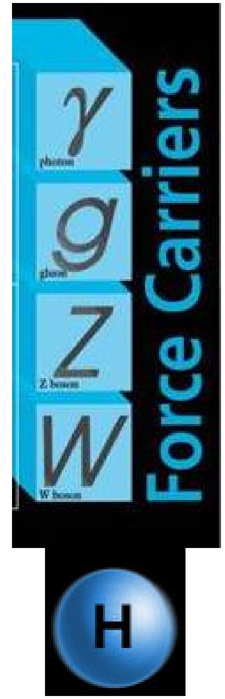
今天我們「已瞭解」的宇宙組成

基本粒子



+反物質

+



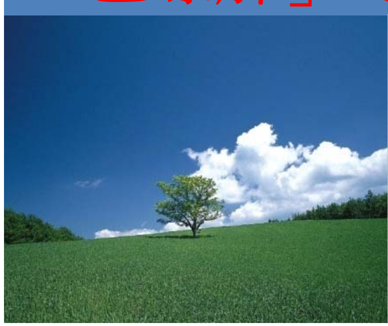
載力者

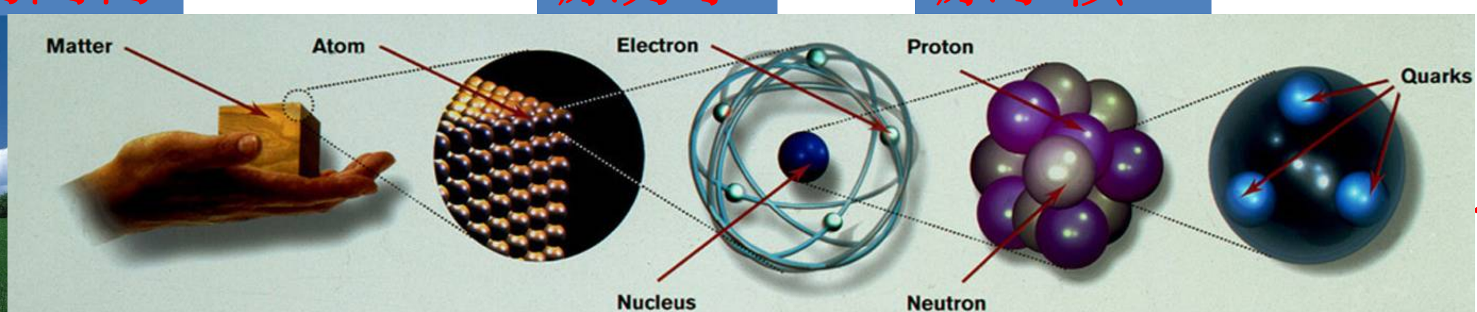
Higgs

電磁力
原分子

強作用力
原子核

「已瞭解」的萬物



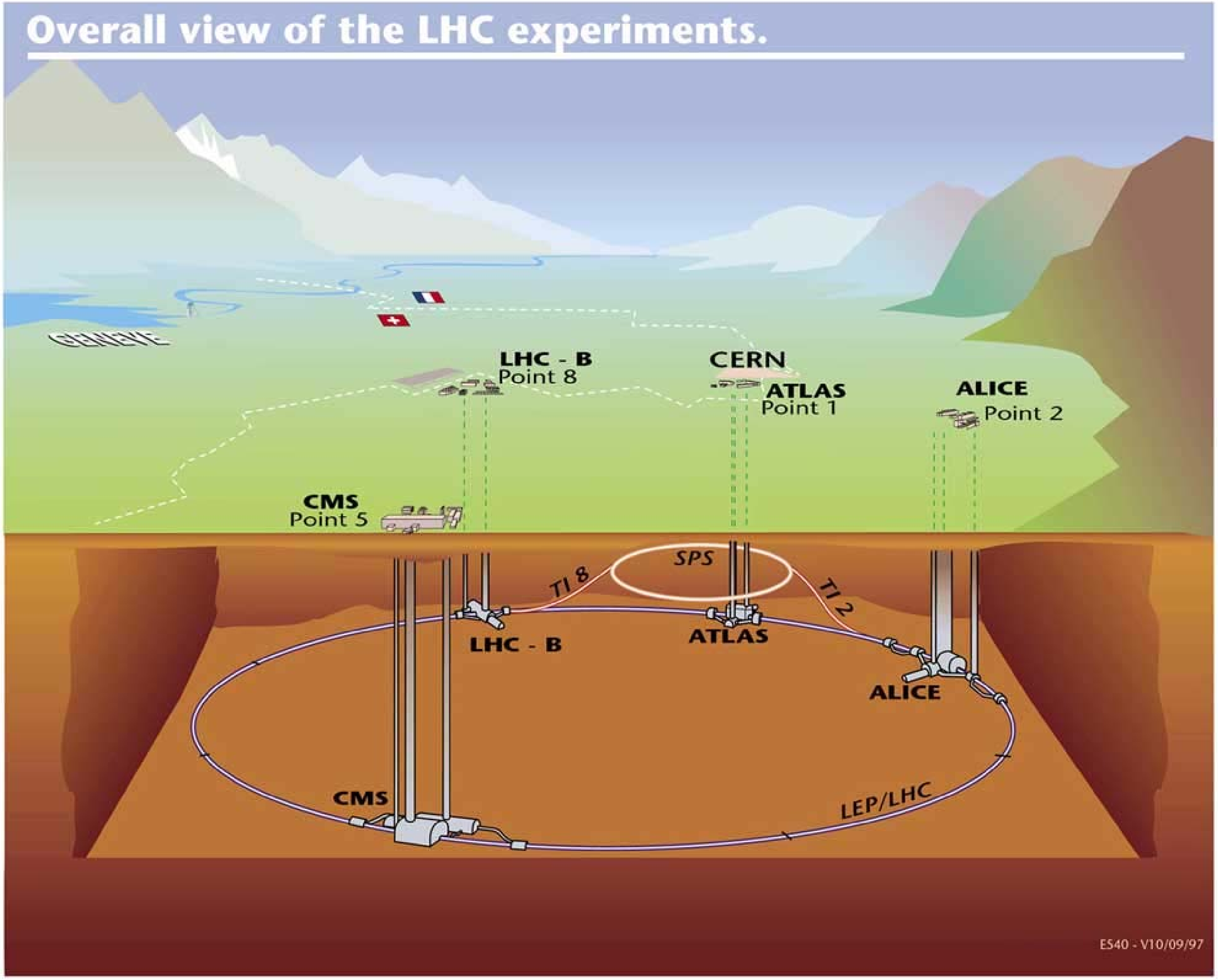


大強子對撞機

- 為了搜尋希格斯粒子(質量起源)
- 為了產生暗物質(宇宙學)
- 為了模擬大爆炸後的瞬間(宇宙起源)
- 為了解決 hierarchy 問題(超對稱…)
- 為了探索新物理(源自現象學動機，標準模型的擴充，如第四代夸克、 Z’介子)
- 來自34個國家的兩千多位科學家通力合作，耗資千億台幣，費時13年，在日內瓦附近的地底下建造了大強子對撞機 (Large Hadron Collider)

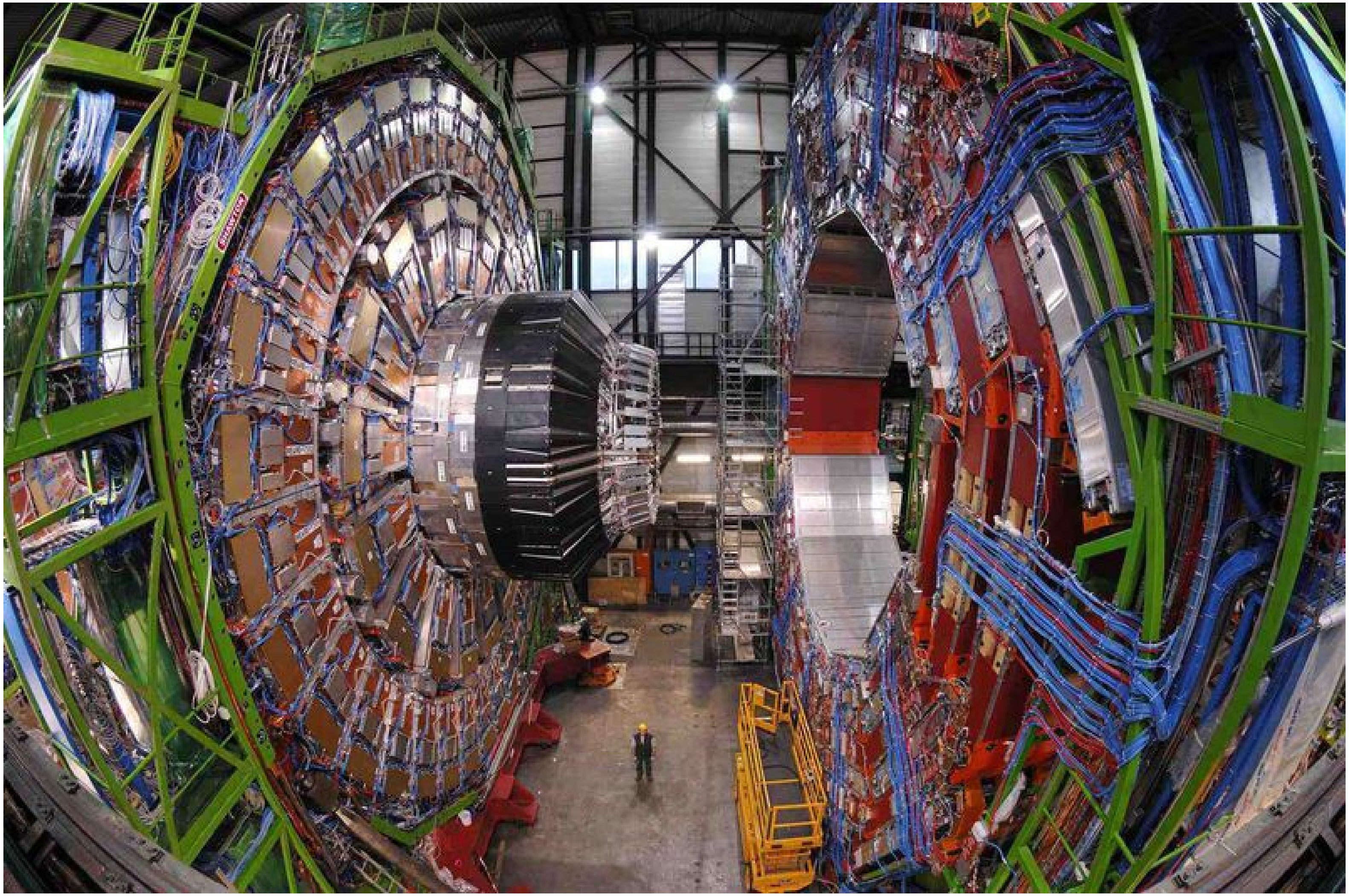
LHC (proton-proton)

4 experiments



Accelerator

ATLAS Detector

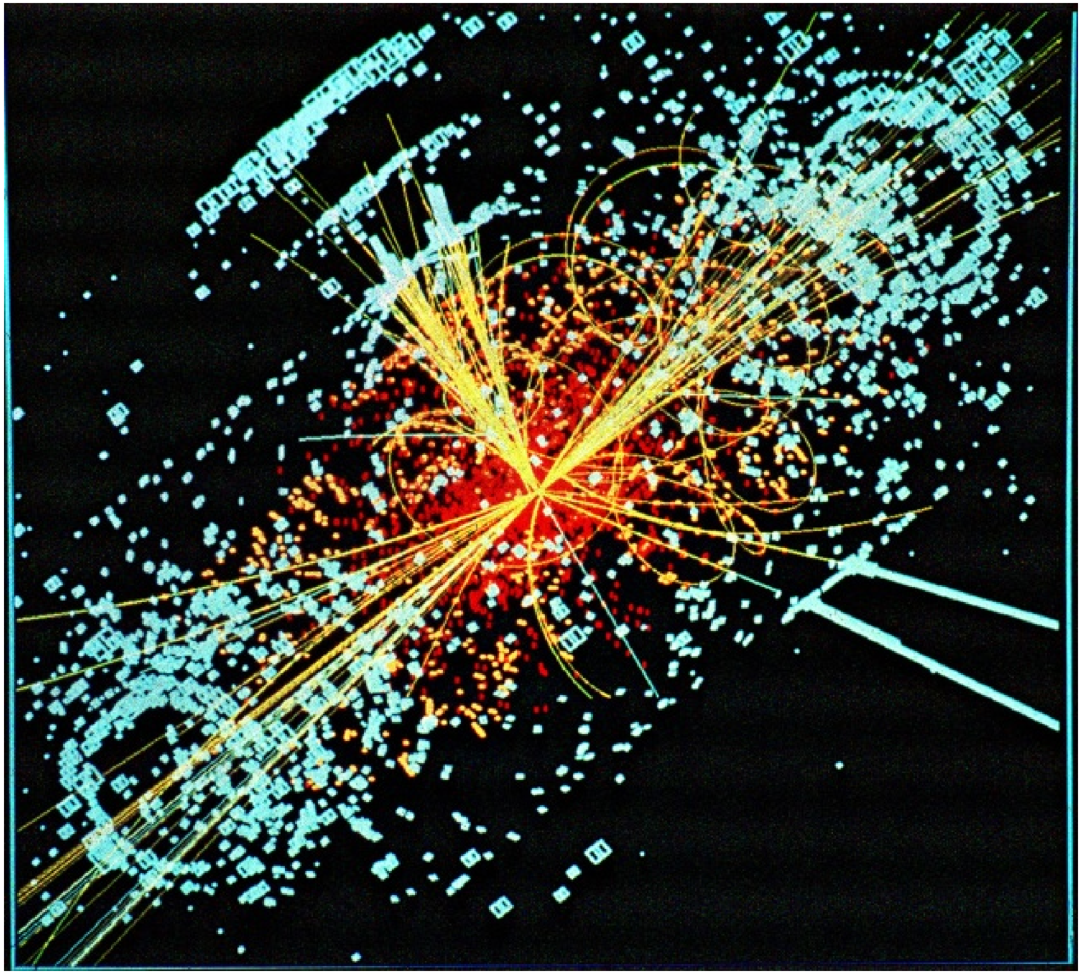


人類工藝的極致

Identification of heavy particles

- Heavy particles decay quickly
- W, Z -> q q’
- H -> b b
- T -> W b -> q q’ b
- Need to differentiate signal p p -> H -> b b from background p p -> q q’
- Especially from thousands of final-state particles

H -> bb event

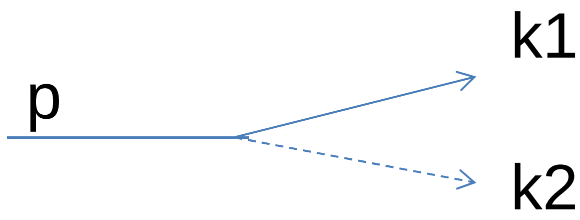


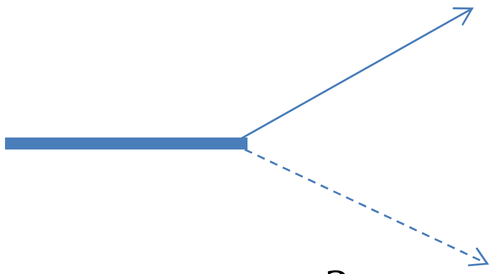
- What can we get from this mess?

Jet in theory

Uncertainty principle

- Radiation from a moving electron, m ~ 0



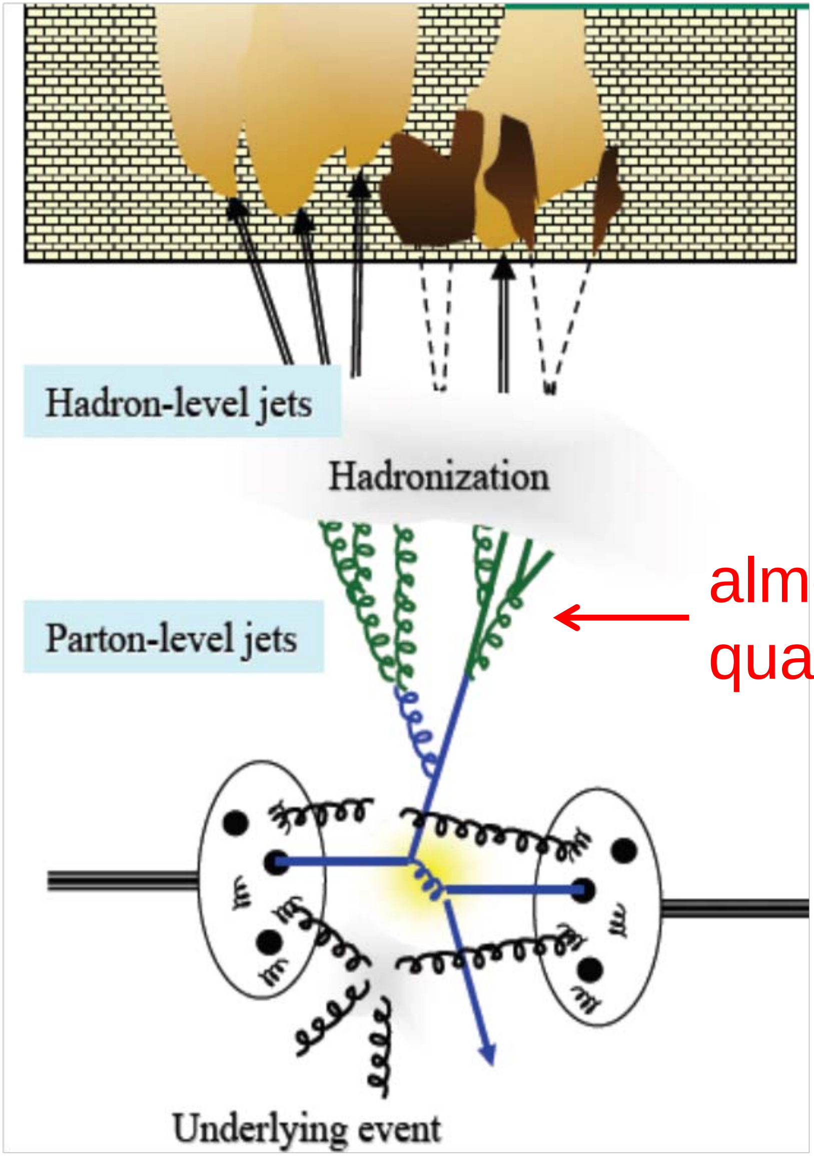


$$(k_1 + k_2)^2 \sim 0 \qquad\qquad (k_1 + k_2)^2 >> 0$$

$$\Delta E \sim 0 \qquad\qquad \Delta E >> 0$$

- Long-lived short-lived
- High probability low probability
- Collinear enhancement -> a jet of particles

Cascades in collider

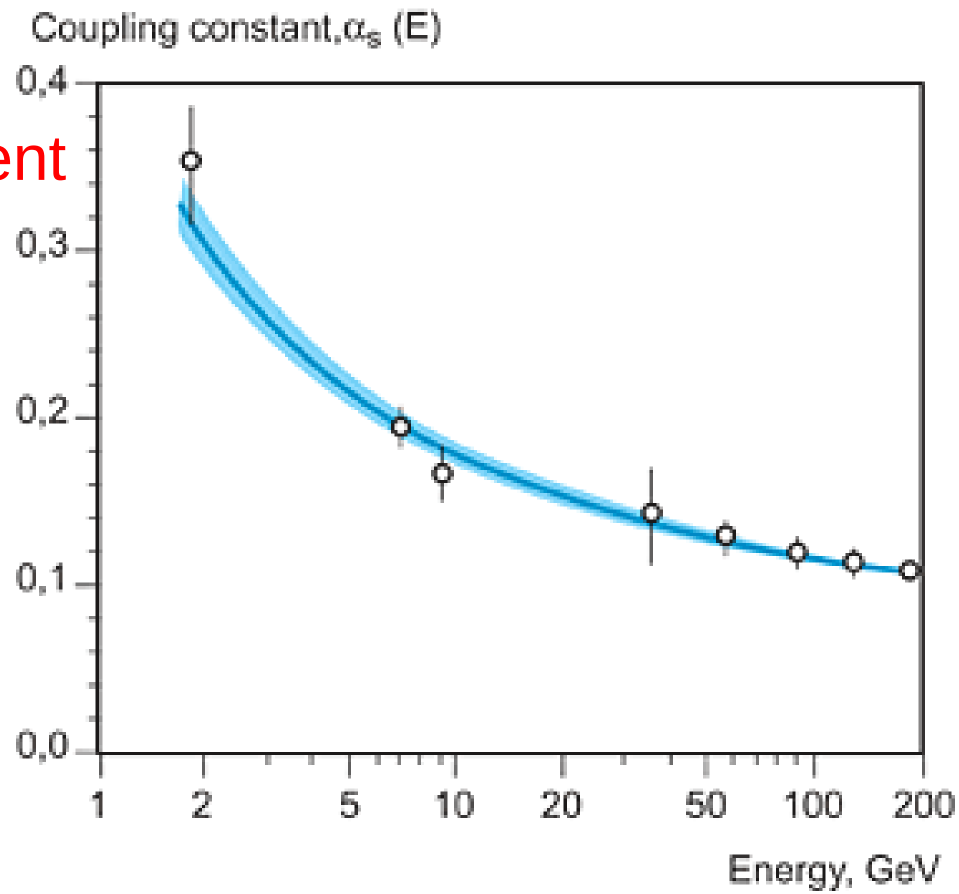


almost parallel
quarks, gluons

Theory for quarks and gluons

- QCD Lagrangian $L = \bar{\psi}(iD^{\mu}\gamma_{\mu} - m)\psi - G^{\mu\nu}G_{\mu\nu}/4$
- Confinement at low energy, hadronic bound states: pion, proton,…
- Manifested by infrared divergences in perturbative calculation of bound-state properties
- Asymptotic freedom at high energy leads to small coupling constant
- Perturbative QCD for high-energy processes

QCD coupling

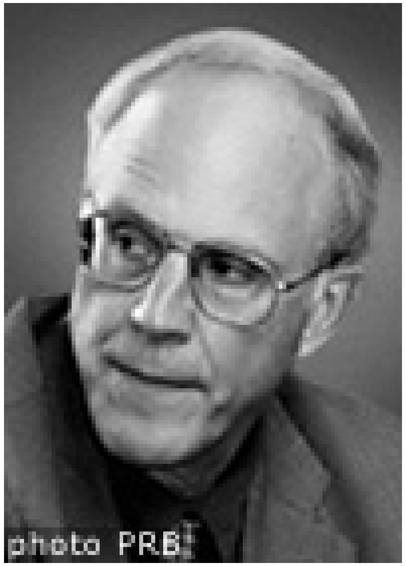


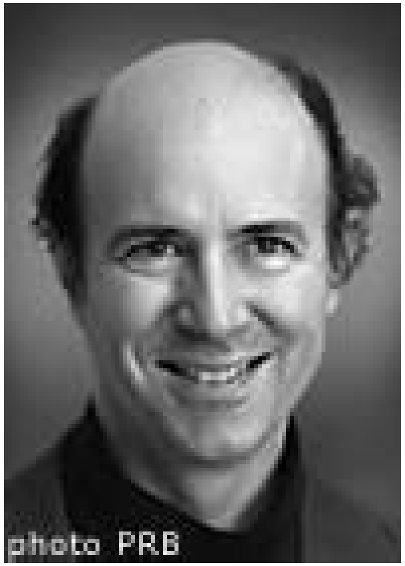
confinement

asymptotic freedom

- QCD coupling decreases with energy scale (opposite to vacuum polarization in QED)

Nobel prize 2004 for asymptotic freedom





David J. Gross
Kavli Institute for Theoretical Physics, University of California, Santa Barbara, USA,
H. David Politzer
California Institute of Technology (Caltech), Pasadena, USA, and
Frank Wilczek
Massachusetts Institute of Technology (MIT), Cambridge, USA

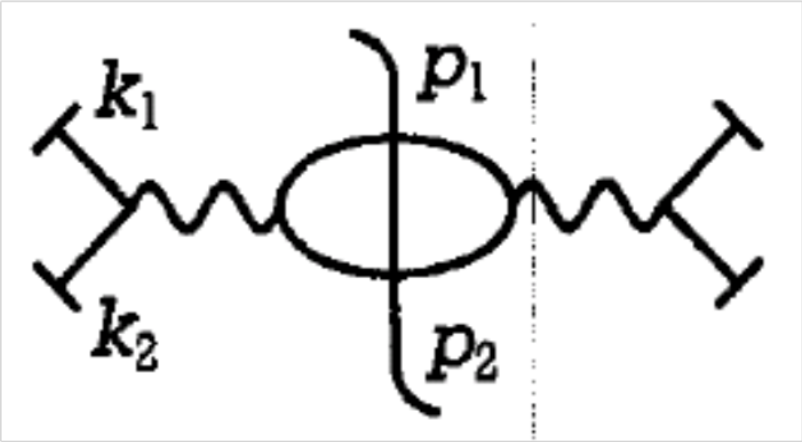
e+e- annihilation

- Start with e+e- annihilation as an example
- Cross section = amplitude X amplitude*
- Born (leading-order) cross section

Feynman diagram
represents
physical process

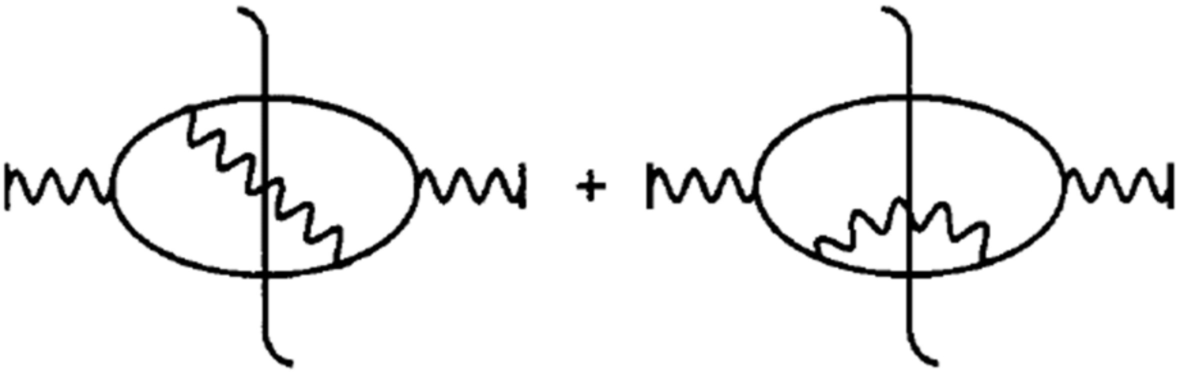
each line and vertex
represents a factor

final-state cut

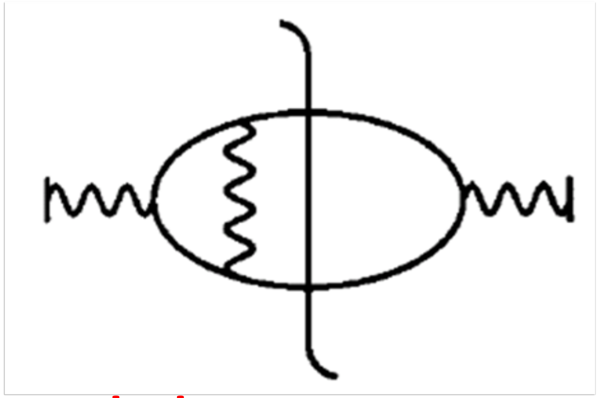


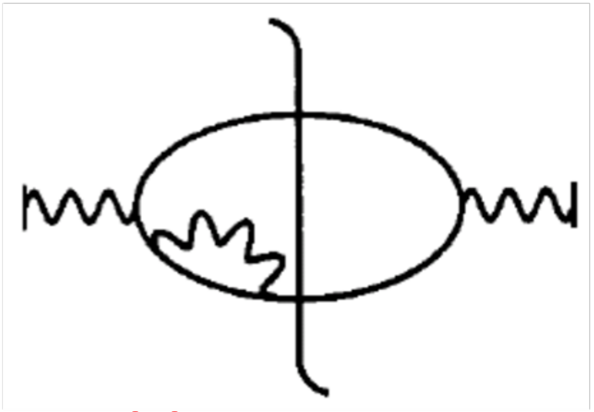
Perturbation---add more lines

- Real corrections



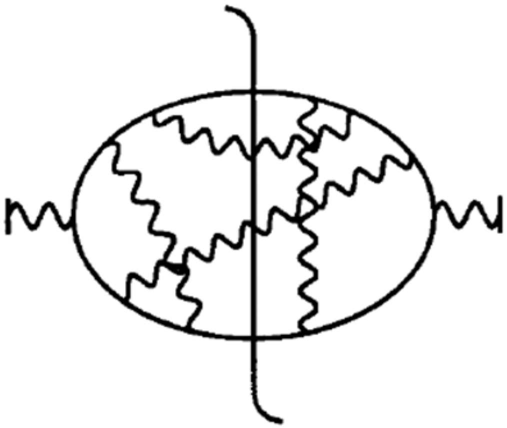
- Virtual corrections

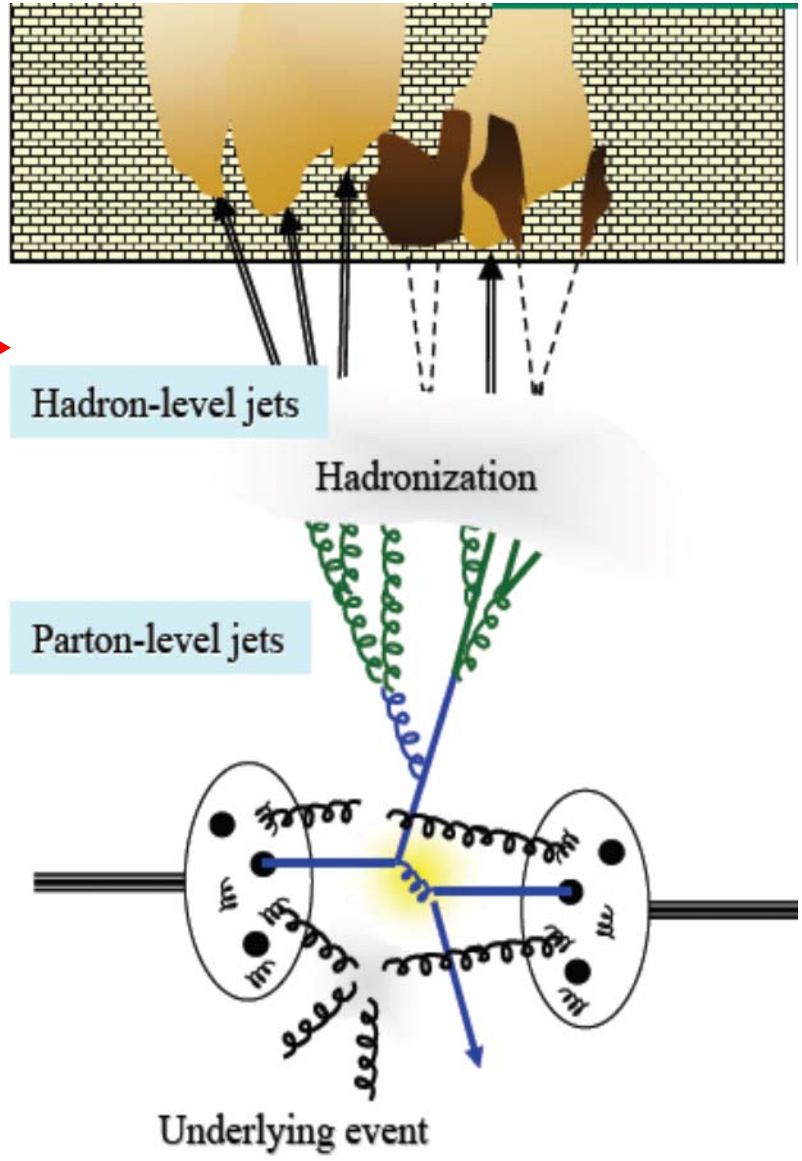




- Infrared divergences cancel between real and virtual diagrams---perturbation at high energy

Quark-hadron duality





a jet of hadrons can be described as a jet of quarks and gluons

Jet phenomenology

VOLUME 39, NUMBER 23 PHYSICAL REVIEW LETTERS 5 DECEMBER 1977

Jets from Quantum Chromodynamics

George Sterman
Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11790

and

Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 26 July 1977)

coinear enhancement

The properties of hadronic jets in e^+e^- annihilation are examined in quantum chromodynamics, without using the assumptions of the parton model. We find that two-jet events dominate the cross section at high energy, and have the experimentally observed angular distribution. Estimates are given for the jet angular radius and its energy dependence. We argue that the detailed results of perturbation theory for production of arbitrary numbers of quarks and gluons can be reinterpreted in quantum chromodynamics as predictions for the production of jets.

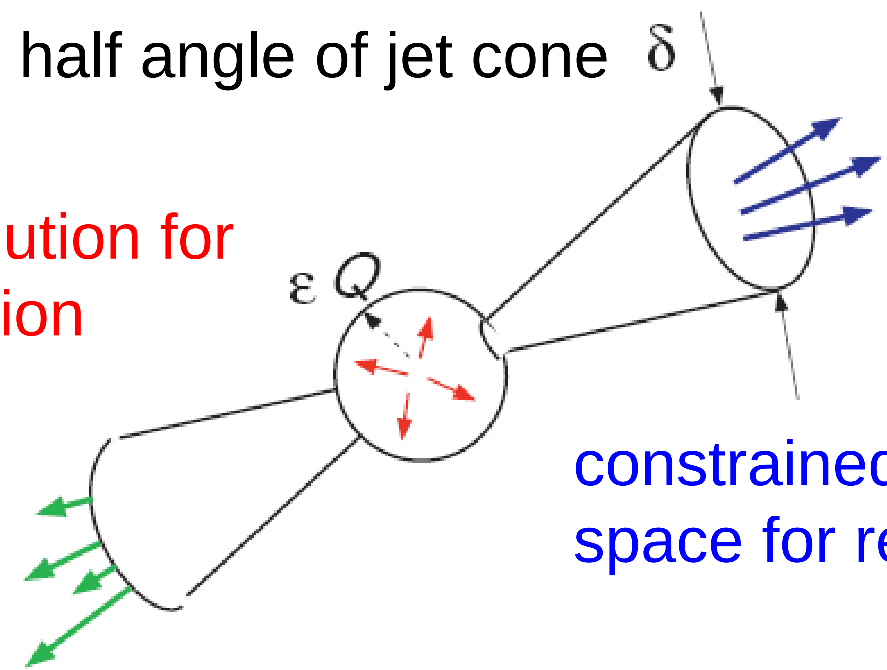
quark-hadron duality (jet physics)

jet substructures

Dijet production

- Dijet production is part of total cross section
- Born cross section is the same as e+e- annihilation

$$\sigma_{2j}{}^{(0)}(Q, \epsilon, \delta) = N\left(\sum_f Q_f{}^2\right)\frac{4\pi\alpha^2}{3Q^2}$$



NLO corrections

- Isotropic soft gluons within energy resolution

$$\left[2\ln^2(2\epsilon E/\mu) - \pi^2/6\right]$$

- Collinear gluons in cone with energy higher than resolution

$$\left[-3\ln(E\delta/\mu) - 2\ln^2 2\epsilon - 4\ln(E\delta/\mu)\ln(2\epsilon) + \tfrac{17}{4} - \pi^2/3\right]$$

- Virtual corrections

$$\left[-2\ln^2(E/\mu) + 3\ln(E/\mu) - \tfrac{7}{4} + \pi^2/6\right]$$

- Total dijet cross section is infrared finite

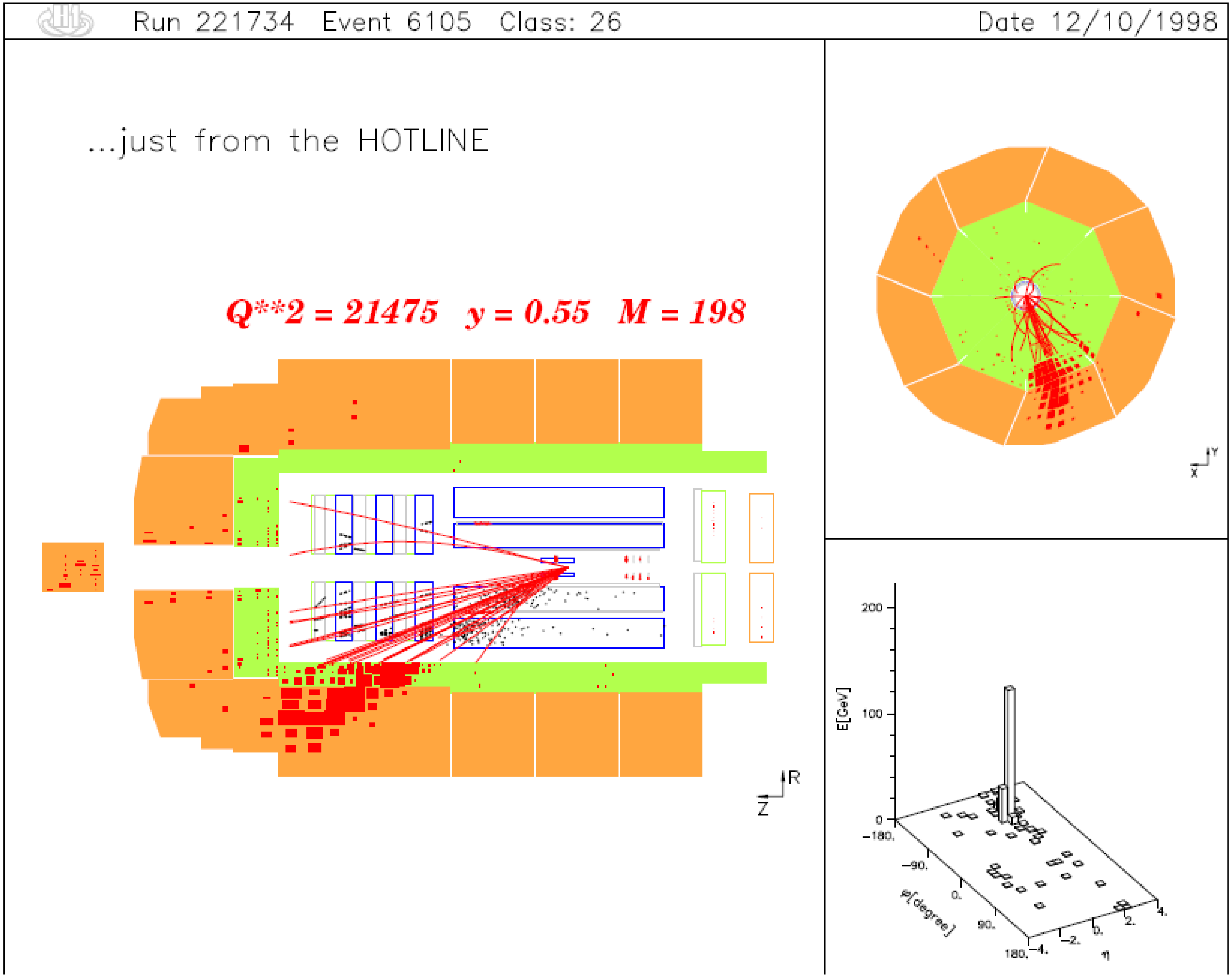
$$\left(3\ln\delta + 4\ln\delta\ln 2\epsilon + \pi^2/3 - \tfrac{5}{2}\right)$$

cone radius dependence

overlap of collinear and soft logs

Jet in experiment

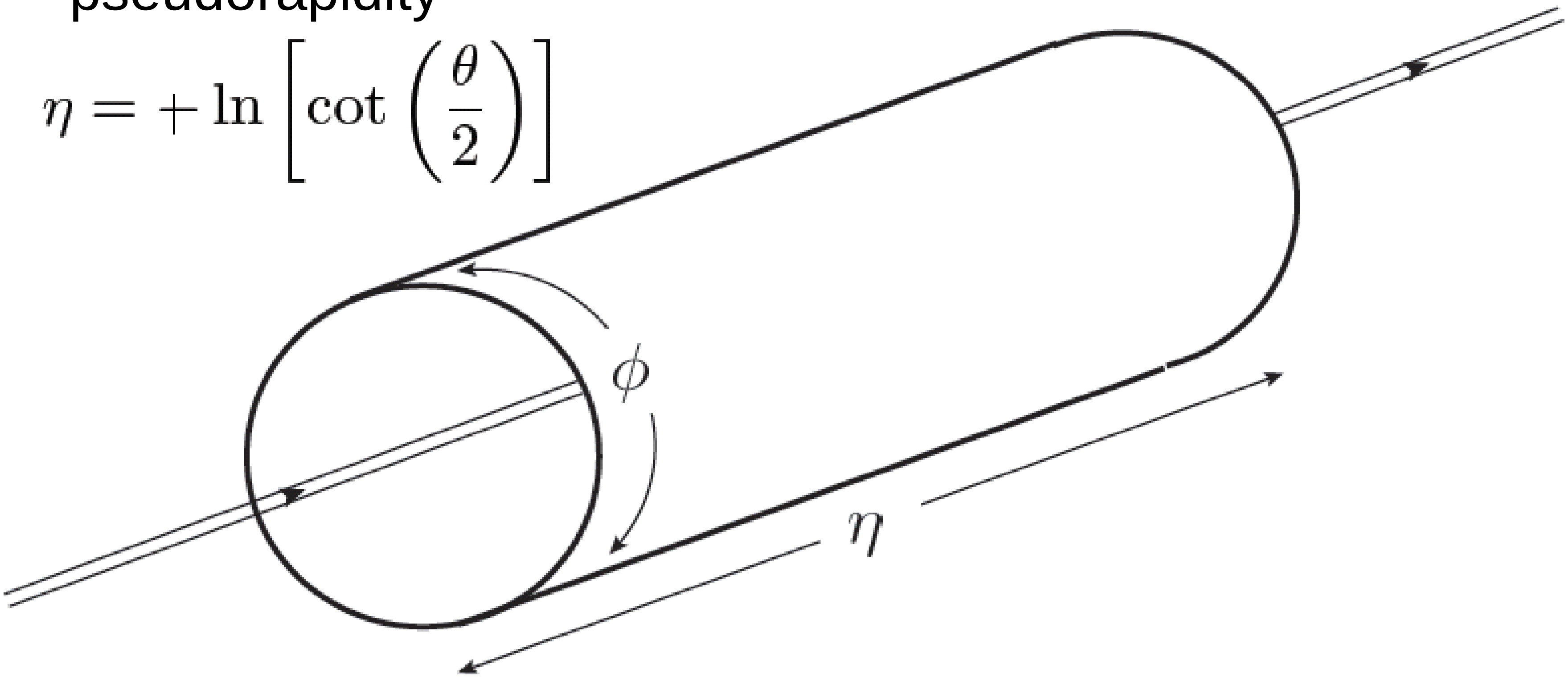
Jet from H1 Collaboration



Coordinates for jets

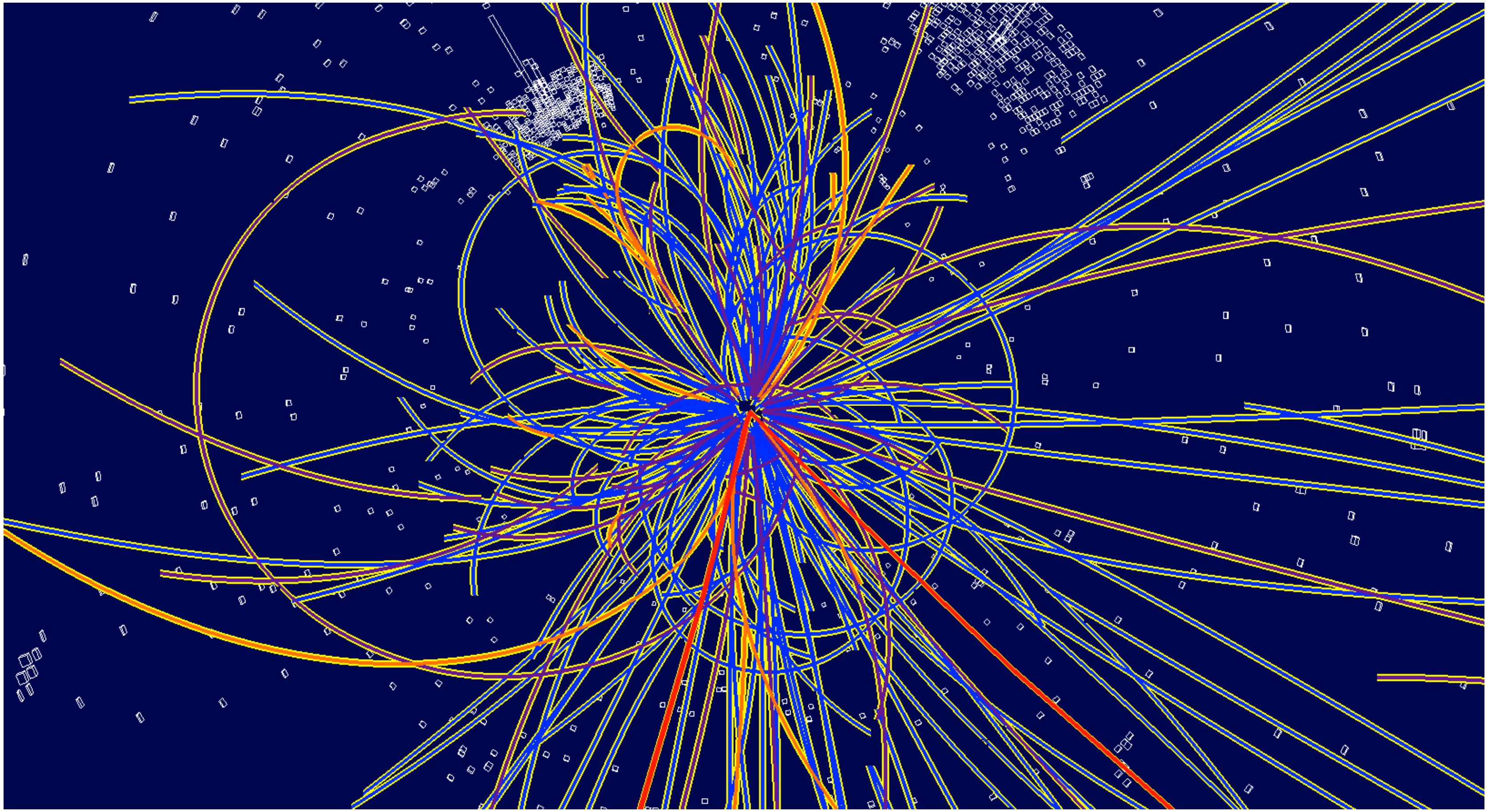
pseudorapidity

$$\eta = +\ln\left[\cot\left(\frac{\theta}{2}\right)\right]$$



$$\theta = 0 \Rightarrow \eta = \infty, \quad \theta = 90^o \Rightarrow \eta = 0, \quad \theta = 180^o \Rightarrow \eta = -\infty$$

Typical event



Jet algorithms

- Comparison of theory with experiment is nontrivial
- Need jet algorithms
- Algorithms should be well-defined so that they map experimental measurements with theoretical calculations as close as possible
- Infrared safety (cancellation of IR divergences) is important guideline, because Sterman-Weinberg jet is infrared finite

Types of algorithms

- Two main classes of jet algorithms
- Cone algorithms: stamp out jets as with a cookie cutter

  Geometrical method
- Sequential algorithms: combine parton four-momenta one by one

  Depend on particle kinematics

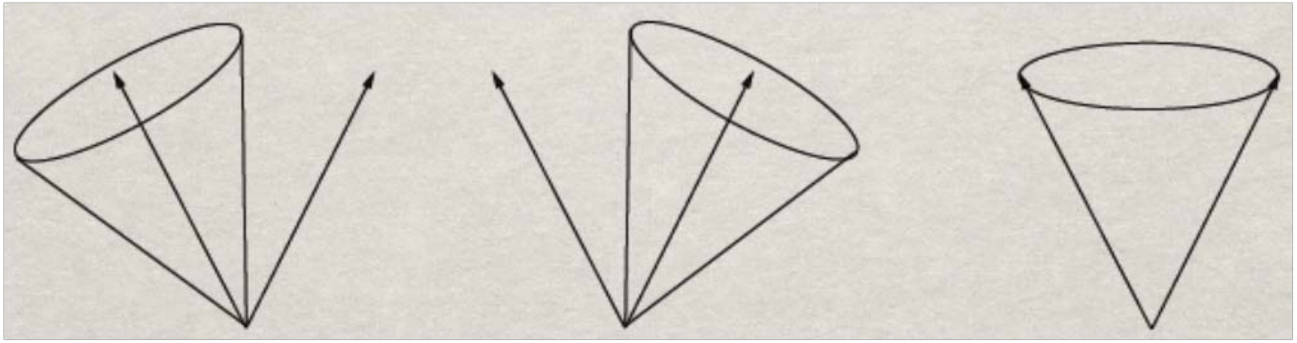
Seeded cone algorithm

- Find stable cones via iterative-cone procedure
- Start from seed particle i and consider set of particles j with separations smaller than jet cone

$$\Delta R_{ij} \equiv (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 < R$$

- If the cone is stable, procedure stops. Otherwise the cone center J is taken as a new seed, and repeat the above procedure
- A stable cone is a set of particles i satisfying

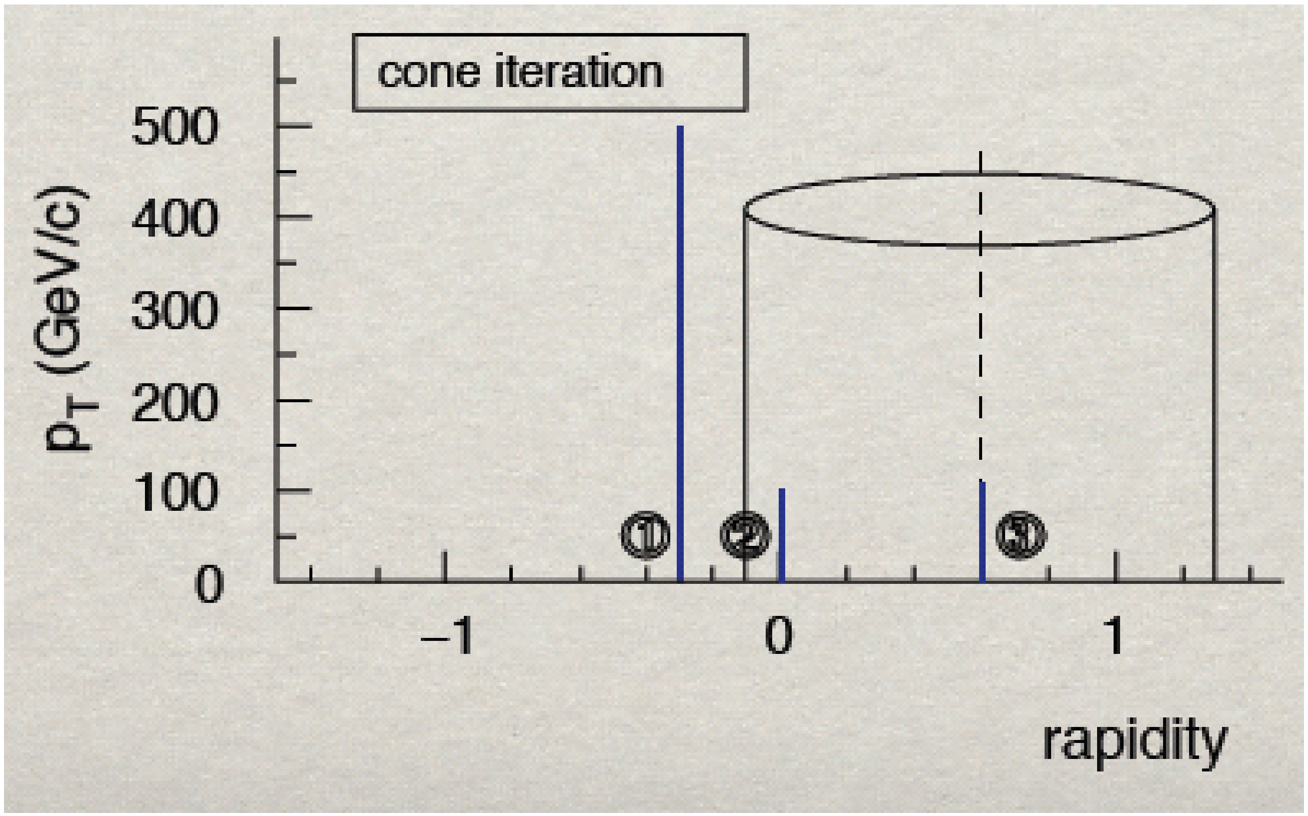
$\Delta R_{iJ} < R$



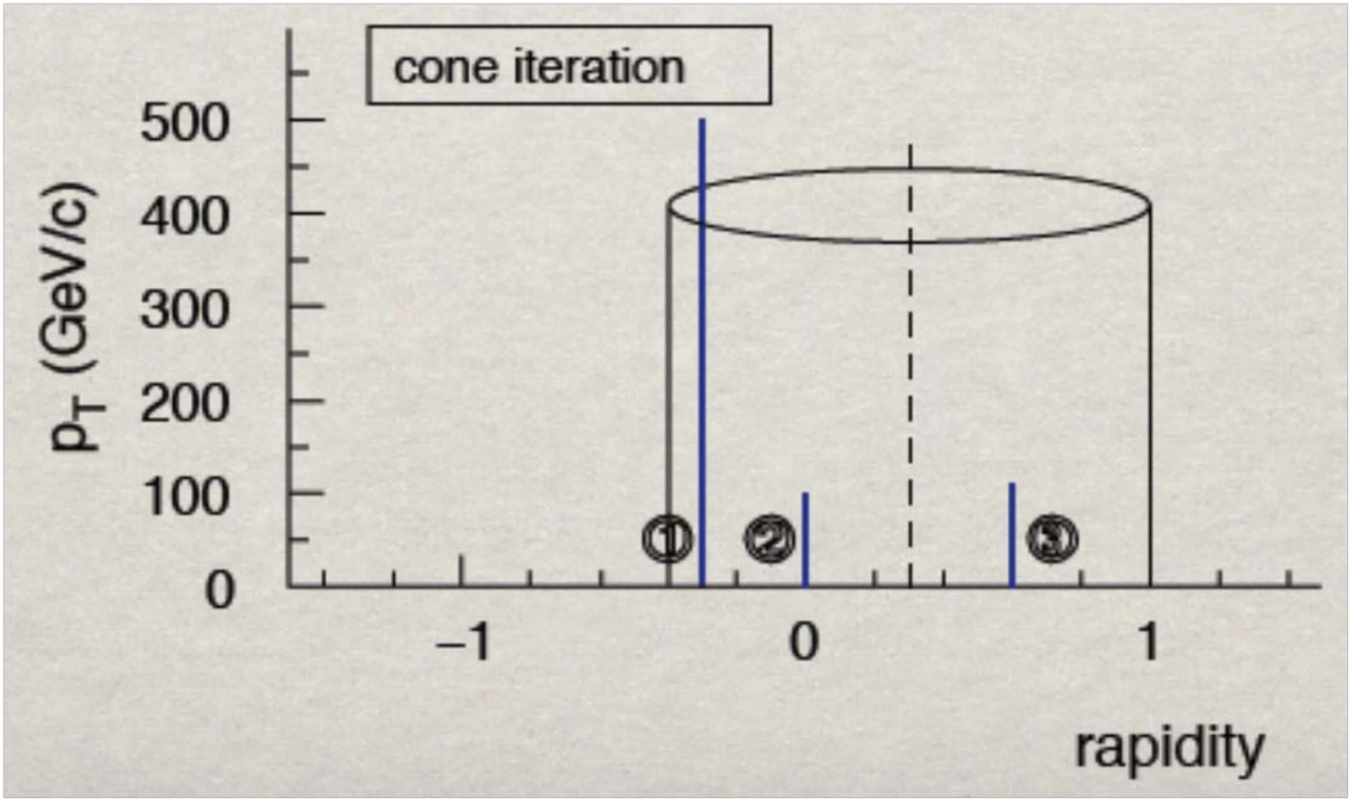
- Examples:

$R < R_{12} < 2R$

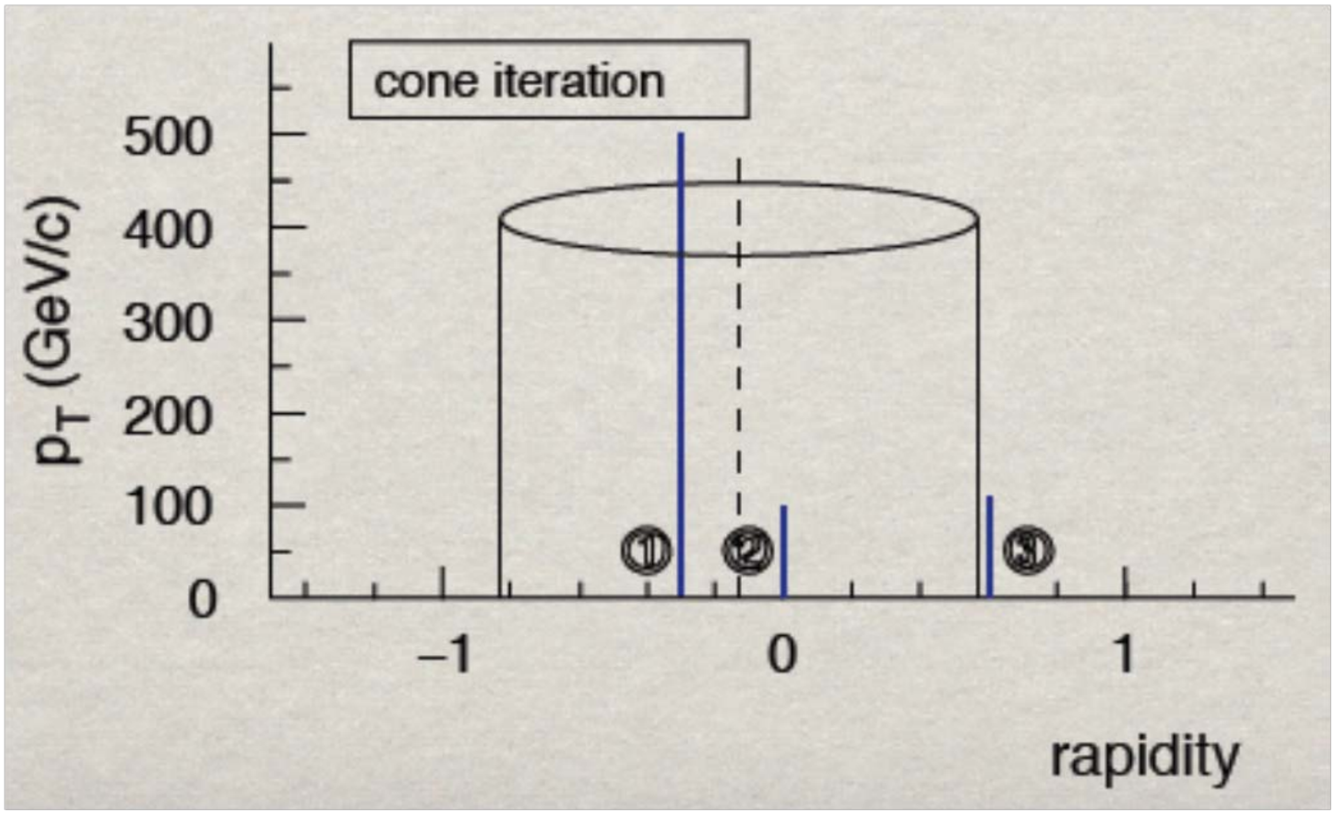
Iterative step 1



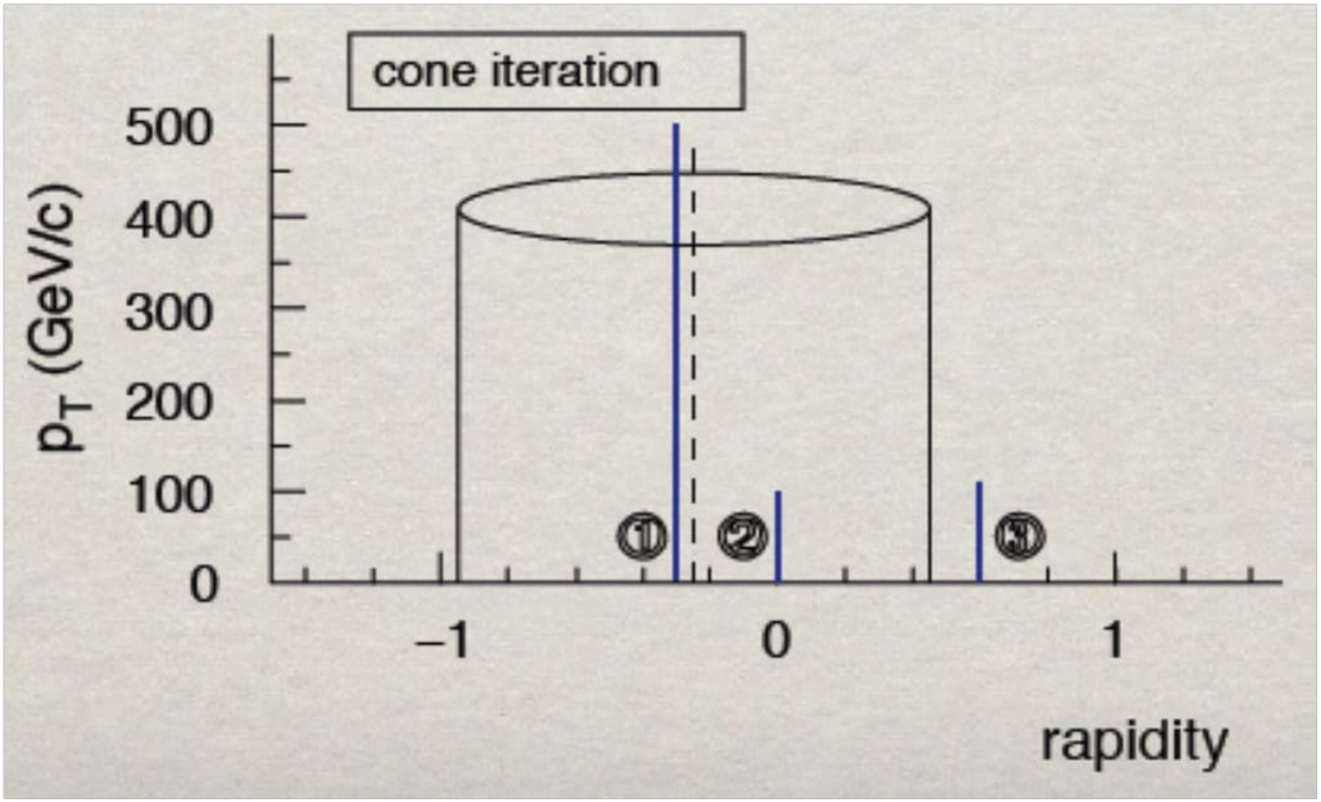
Iterative step 2



Iterative step 3

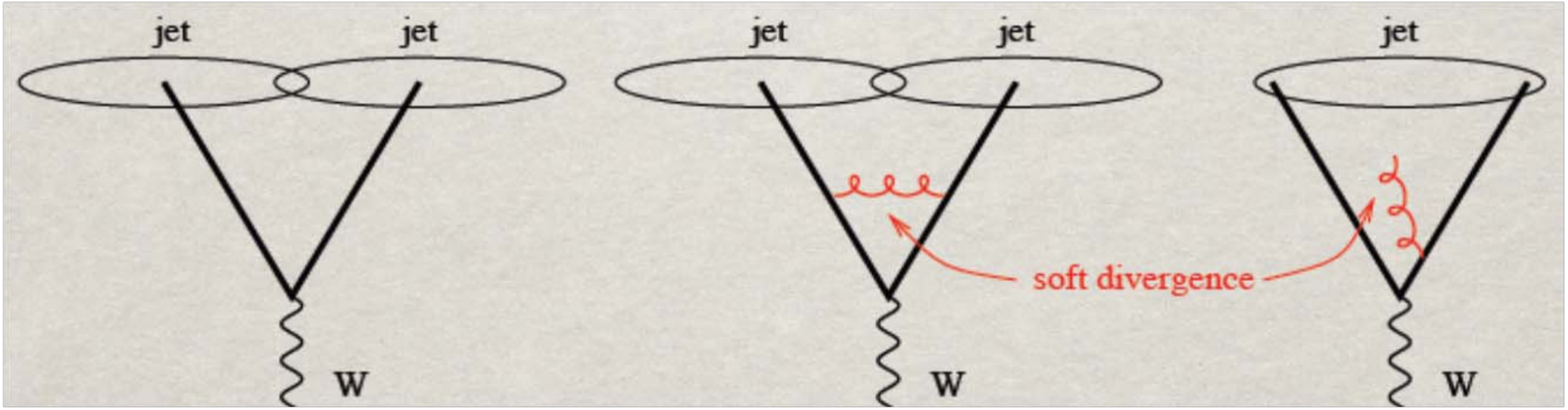


Iterative step 4



Problem of seeded cone

- Geometrical algorithm does not differentiate infrared gluons from ordinary gluons
- Final results (split-merge) depend on soft radiation and collinear splitting



- Virtual (real) soft gluon contributes to two (single) jet cross section, no cancellation

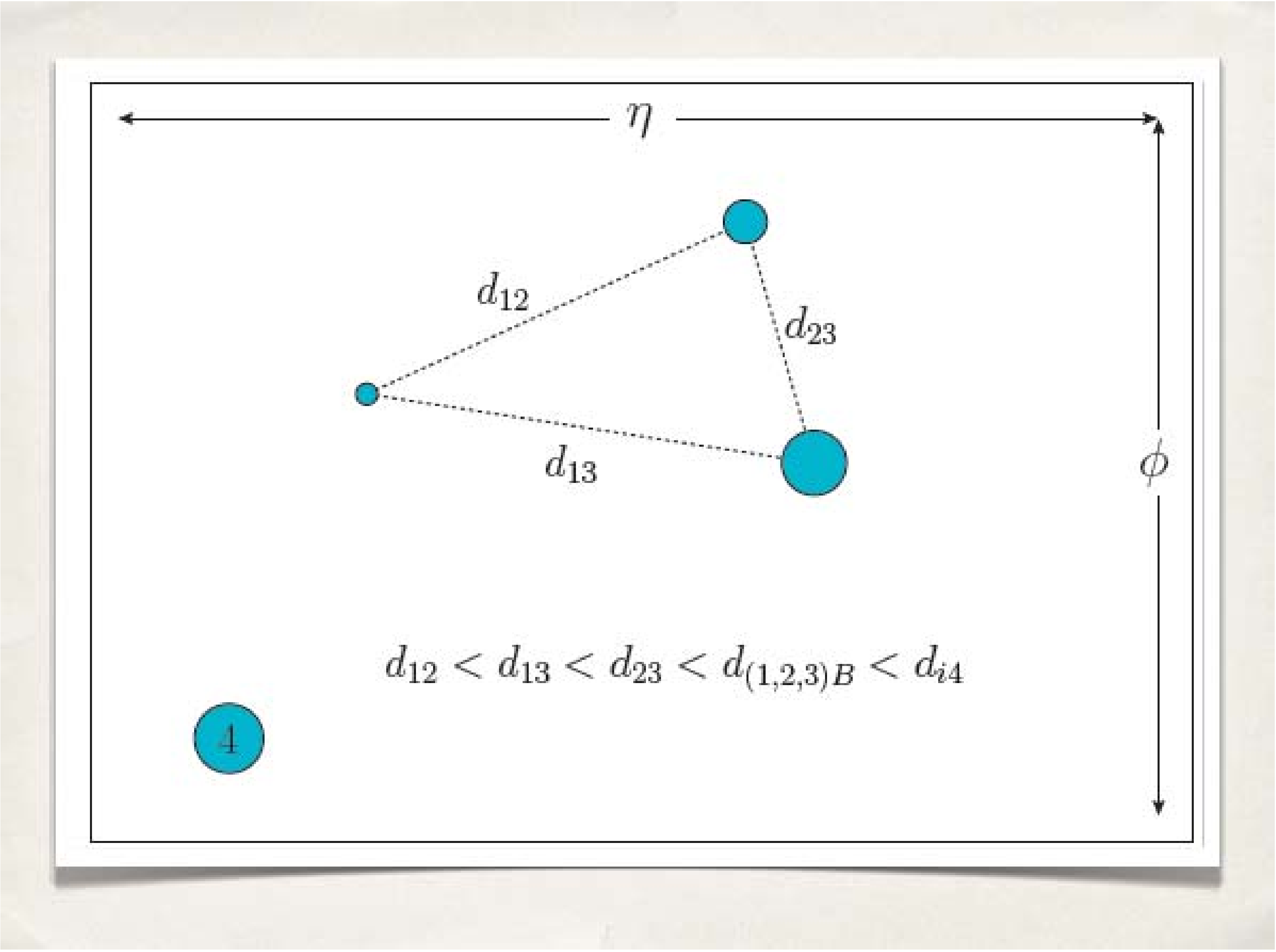
Sequential algorithms

- Take kT algorithm as an example.
- For any pair of particles i and j, find the minimum of

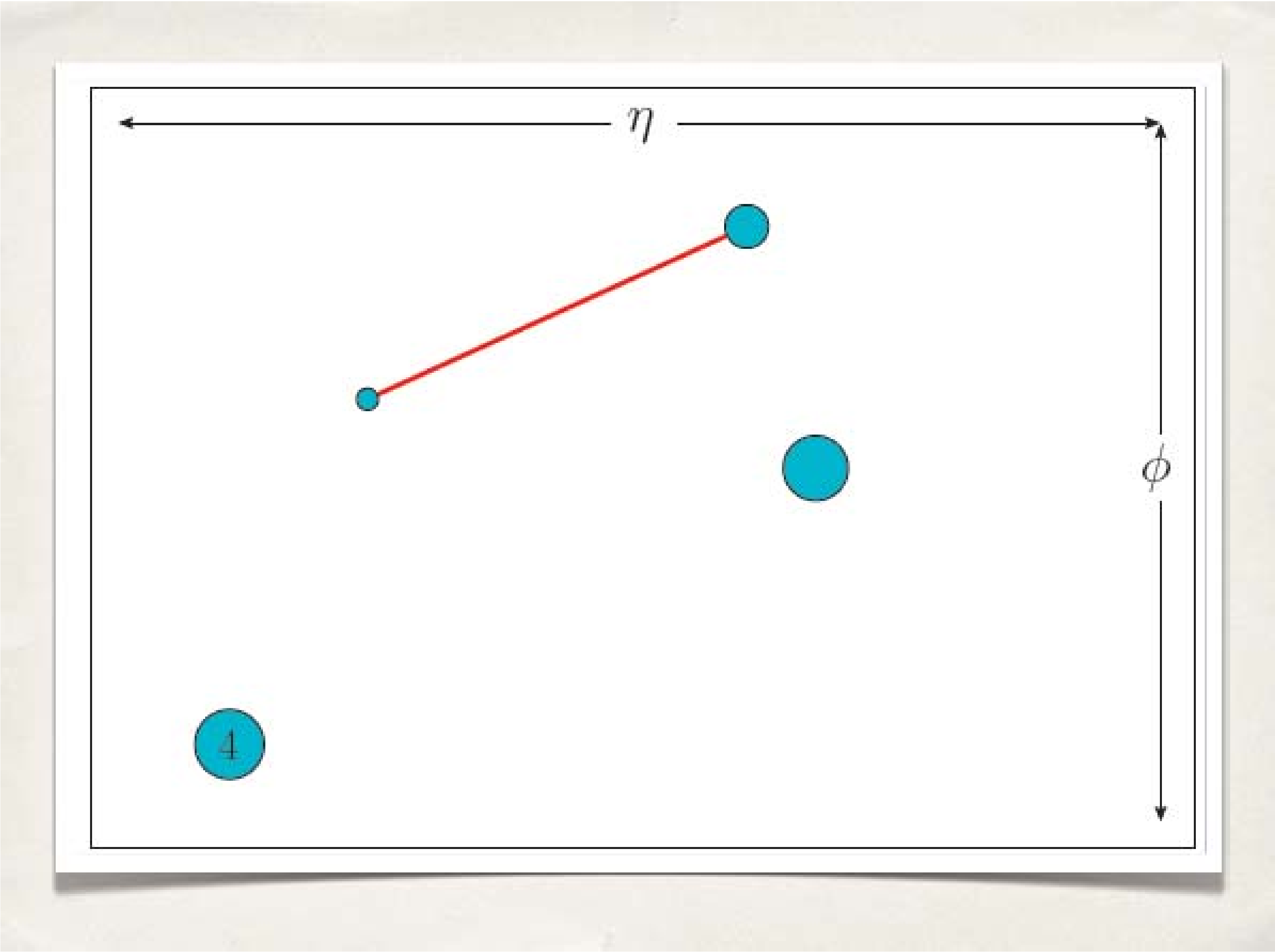
$$d_{ij} = \frac{\min\{k_{ti}^2, k_{tj}^2\}}{R^2} \Delta R_{ij}^2 \simeq k_{t,ij}^2, \quad d_{iB} = k_{ti}^2, \quad d_{jB} = k_{tj}^2$$

- If it is diB or djB, i or j is a jet, removed from the list of particles. Otherwise, i and j merged
- Repeat procedure until no particles are left
- Differentiate infrared and ordinary gluons

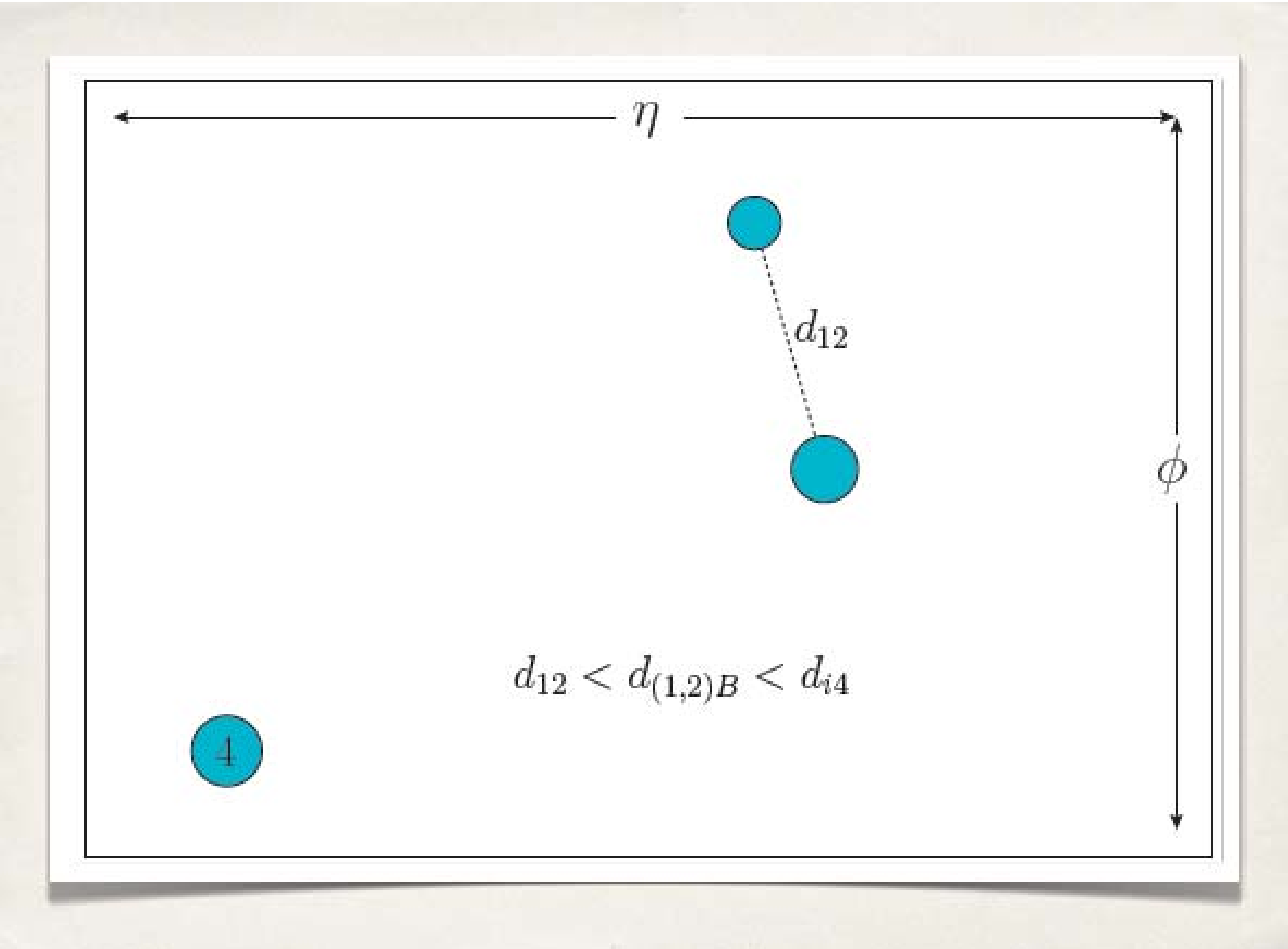
Step 1



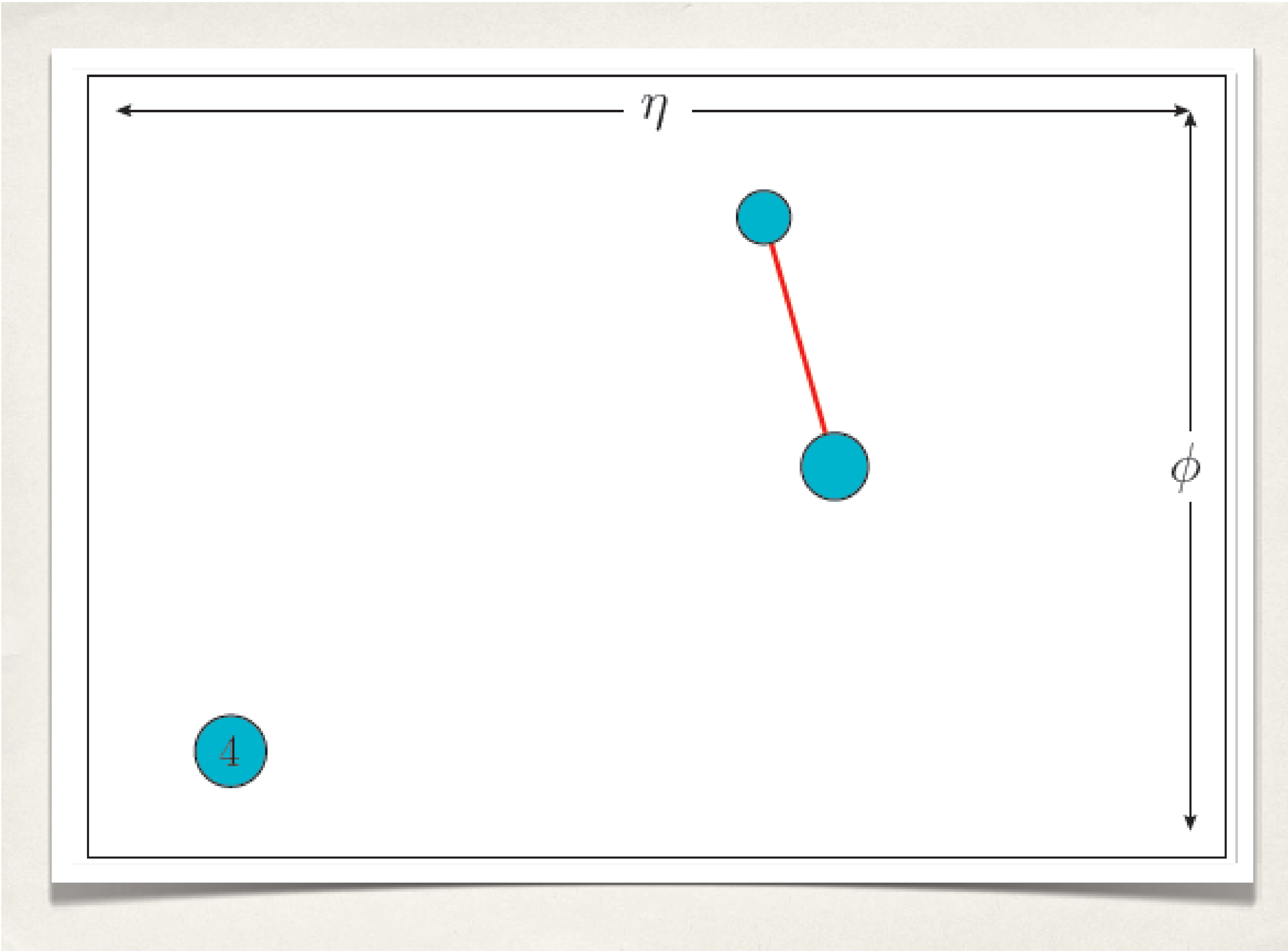
Step 2



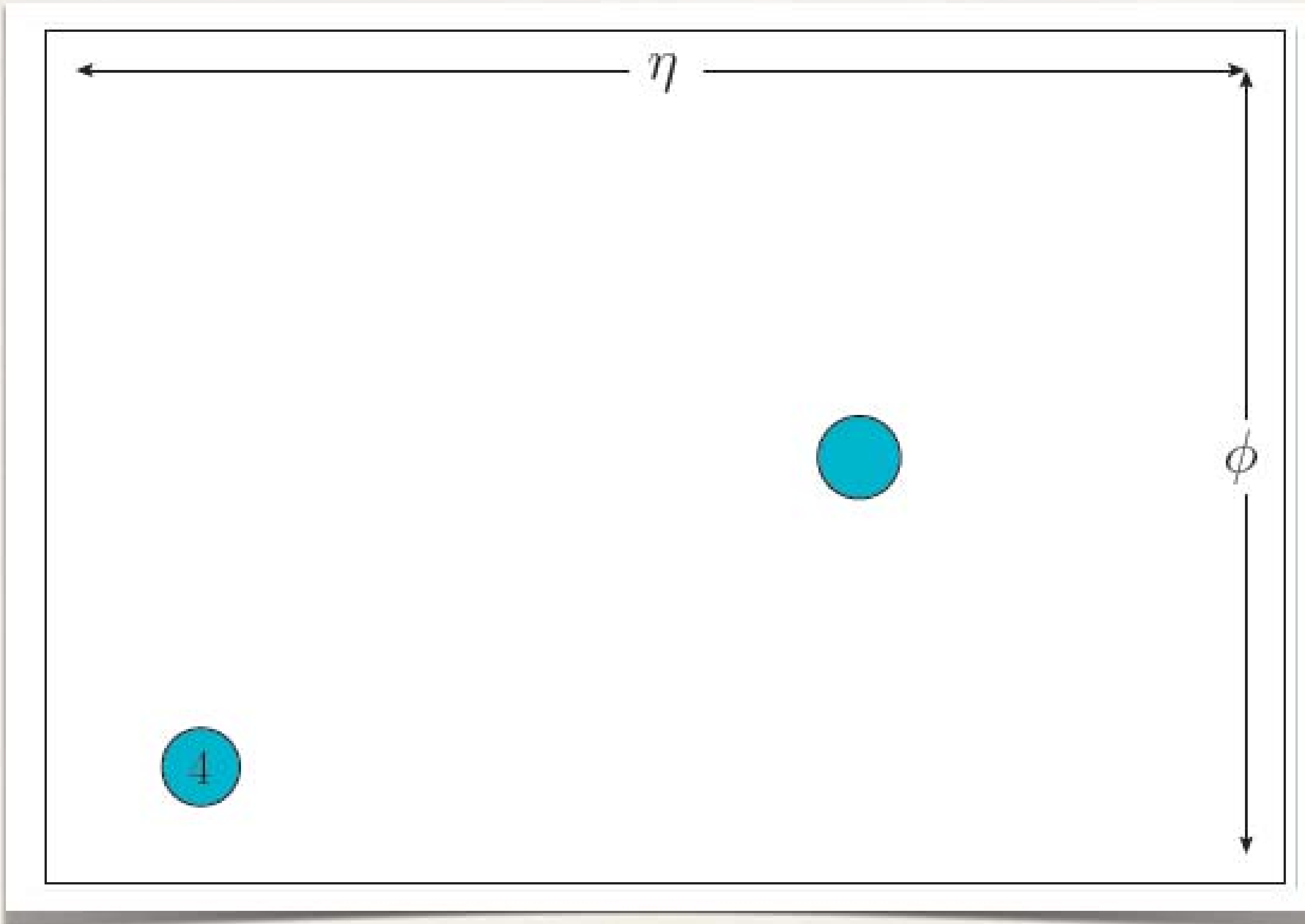
Step 3



Step 4



Step 5



Done!

Recombination Algorithms

- k_T algorithm start with softer particles

$$d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)\left(\frac{\Delta R}{R_0}\right)^2, \; d_{iB} = p_{Ti}^2$$

- C/A algorithm

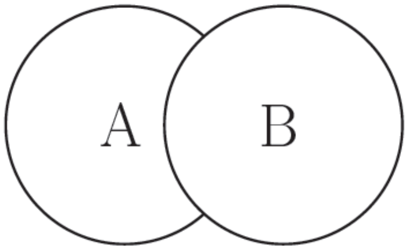
$$d_{ij} = \left(\frac{\Delta R}{R_0}\right)^2, \; d_{iB} = 1$$

- anti-k_T algorithm default for LHC

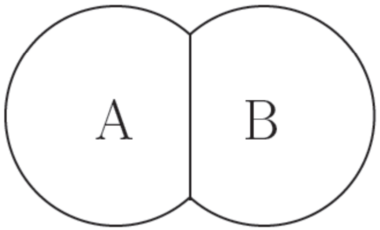
$$d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2})\left(\frac{\Delta R}{R_0}\right)^2, \; d_{iB} = p_{Ti}^{-2}$$

$$(\Delta R)^2 \equiv (\Delta\eta)^2 + (\Delta\phi)^2$$

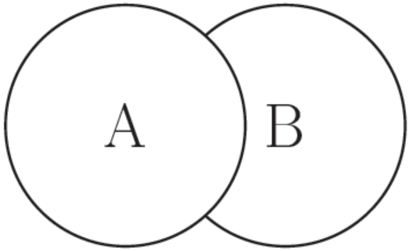
pTA > pTB



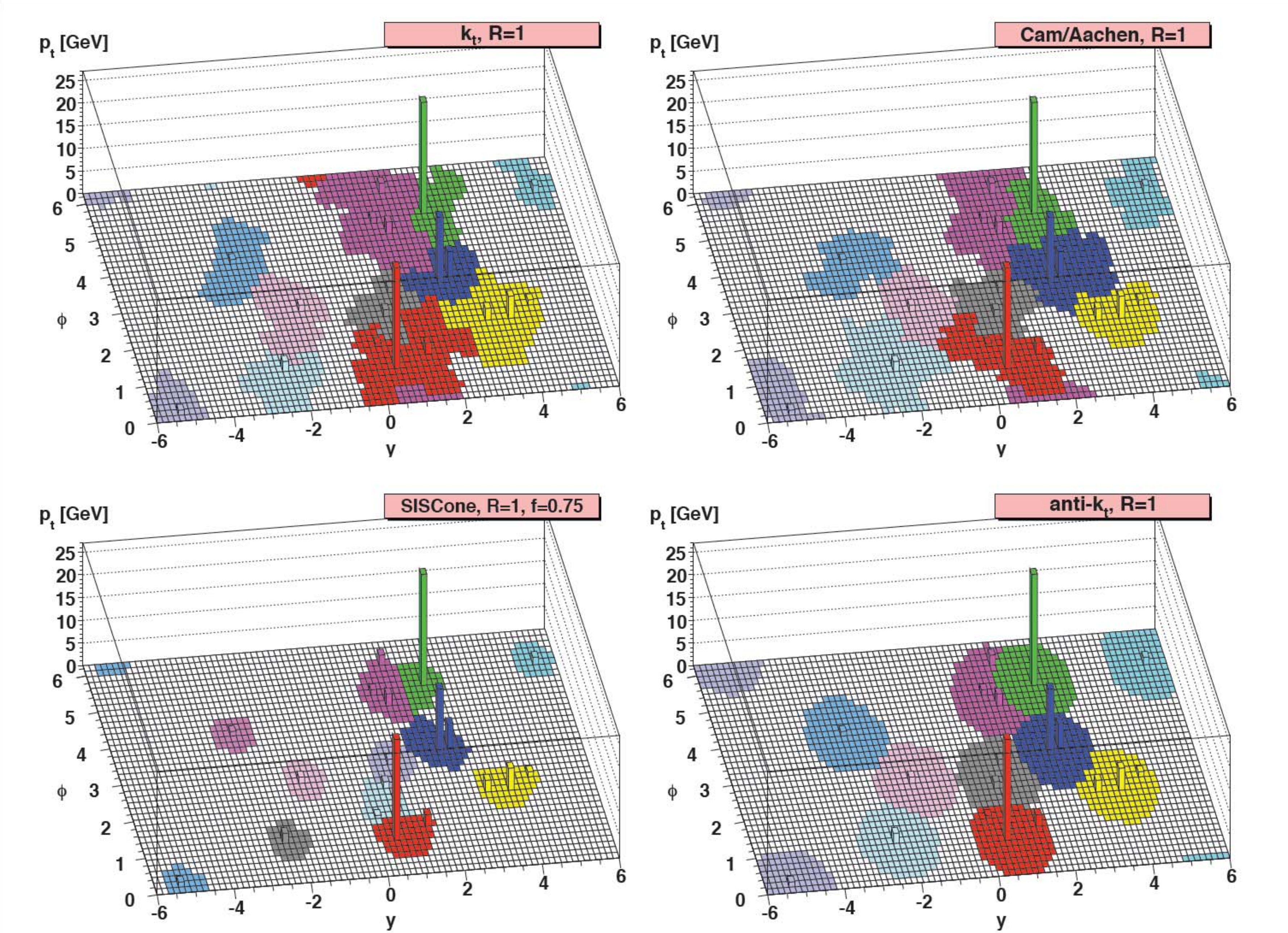
k_T



C/A



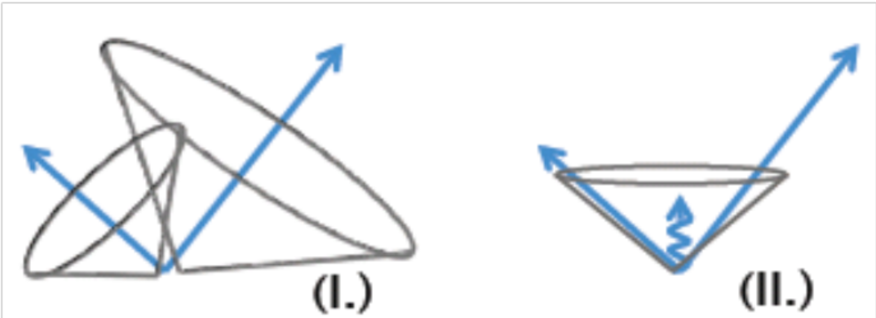
anti$-k_T$



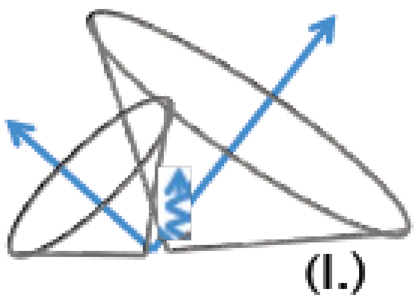
k_t, R=1
Cam/Aachen, R=1
SISCone, R=1, f=0.75
anti-k_t, R=1
p_t [GeV]
ϕ
y

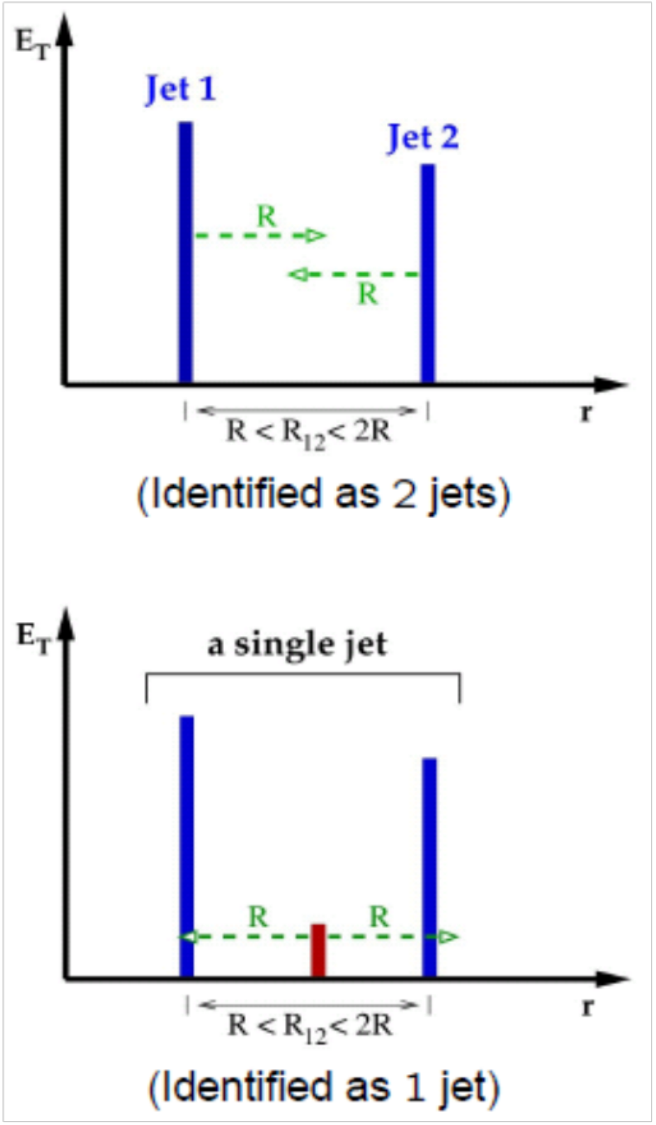
Infrared safety

- In seeded cone algorithm



- In kt algorithm, remain two jets---infrared safety





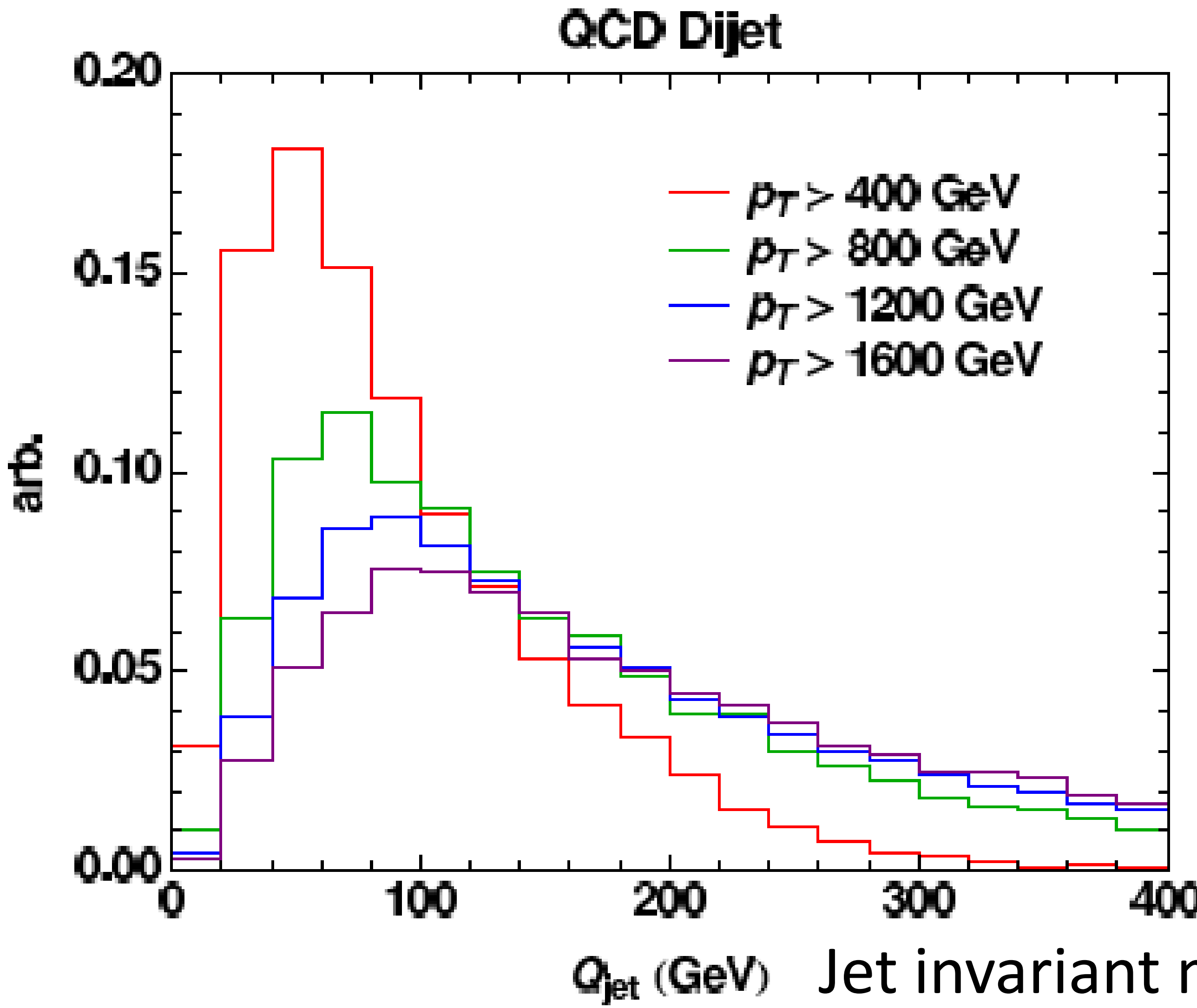
Jet identification

Recent progress

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

Fat QCD jet fakes top jet at high pT

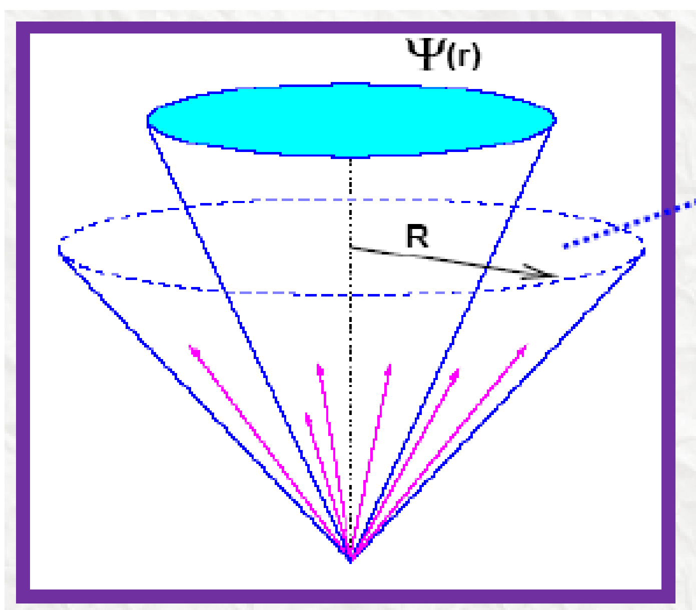


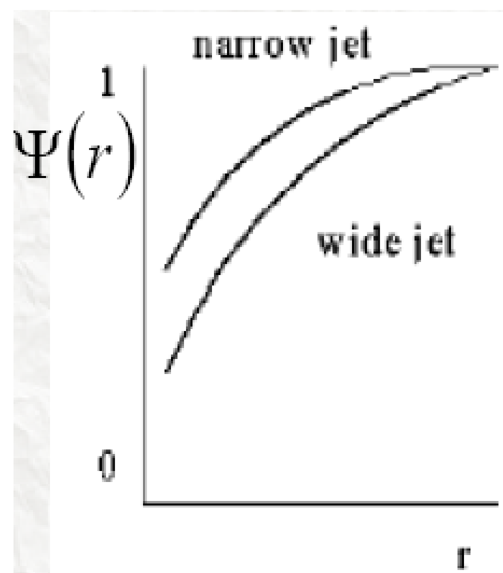
Jet invariant mass

Thaler & Wang
0806.0023
Pythia 8.108

Jet substructure

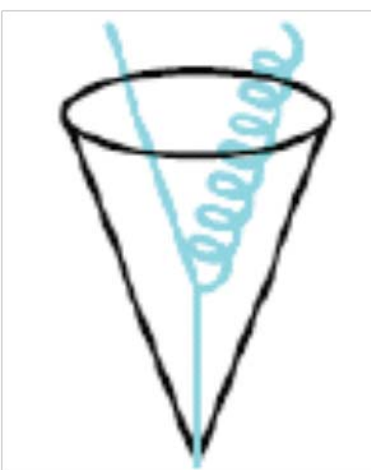
- Make use of jet internal structure in addition to standard event selection criteria
- Energy fraction in cone size of r, $\Psi(r), \Psi(R)=1$
- Quark jet is narrower than gluon jet
- Heavy quark jet energy profile should be different



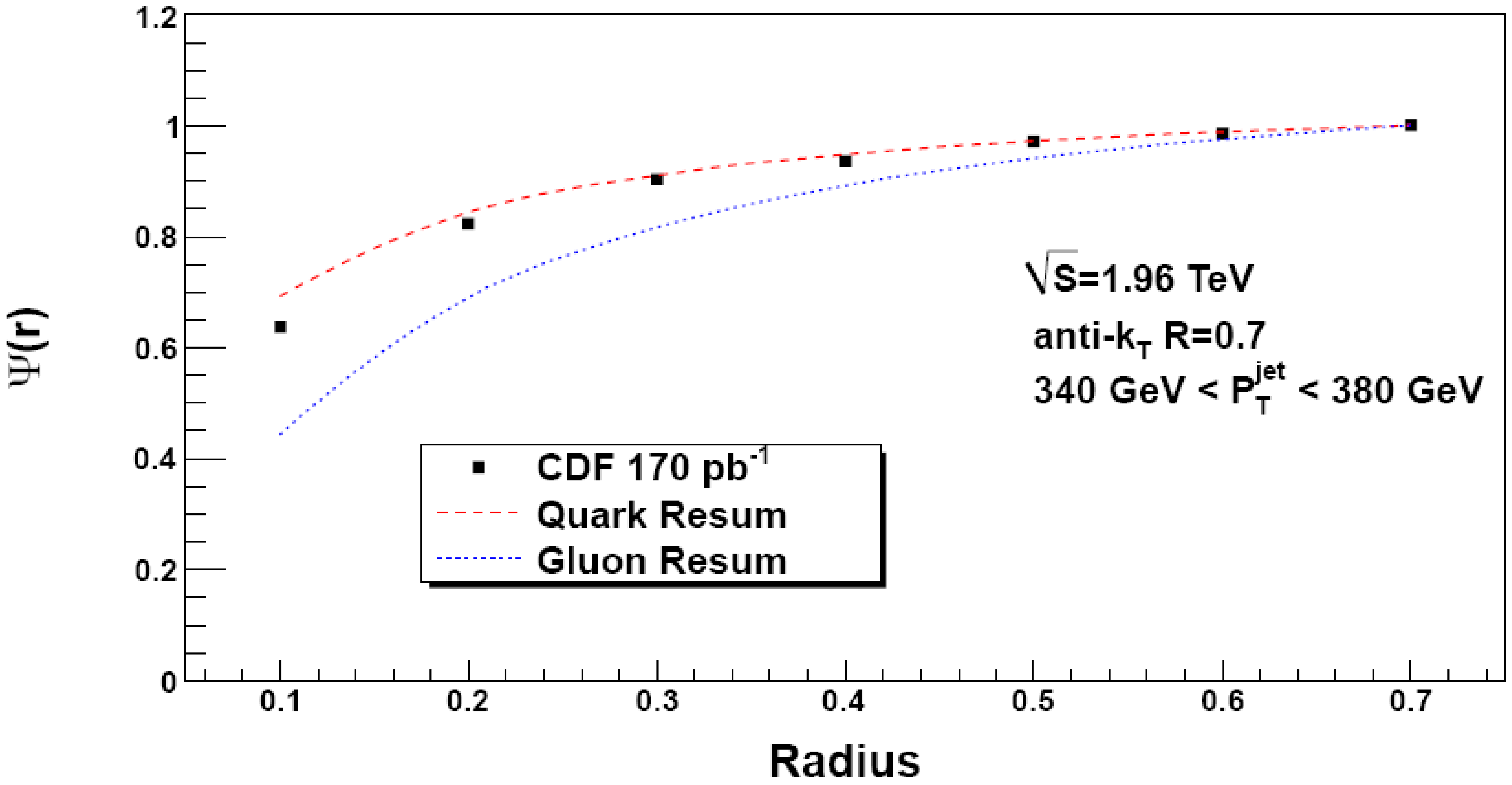


QCD resummation

- All-order summation of collinear and soft gluons
- Dependencies on jet mass, jet energy, jet cone radius can be derived



Quark jet or gluon jet?

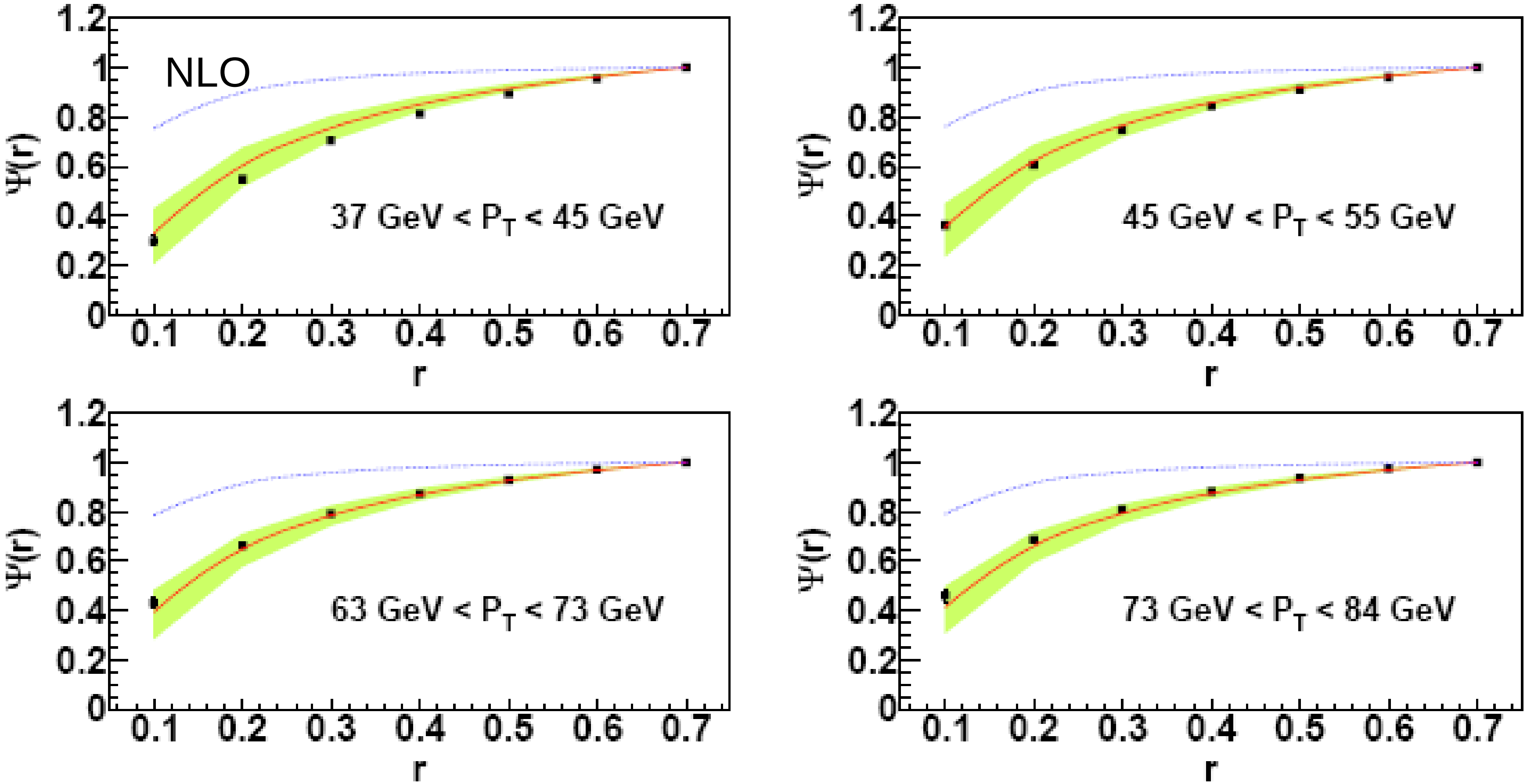


- It is a quark jet!

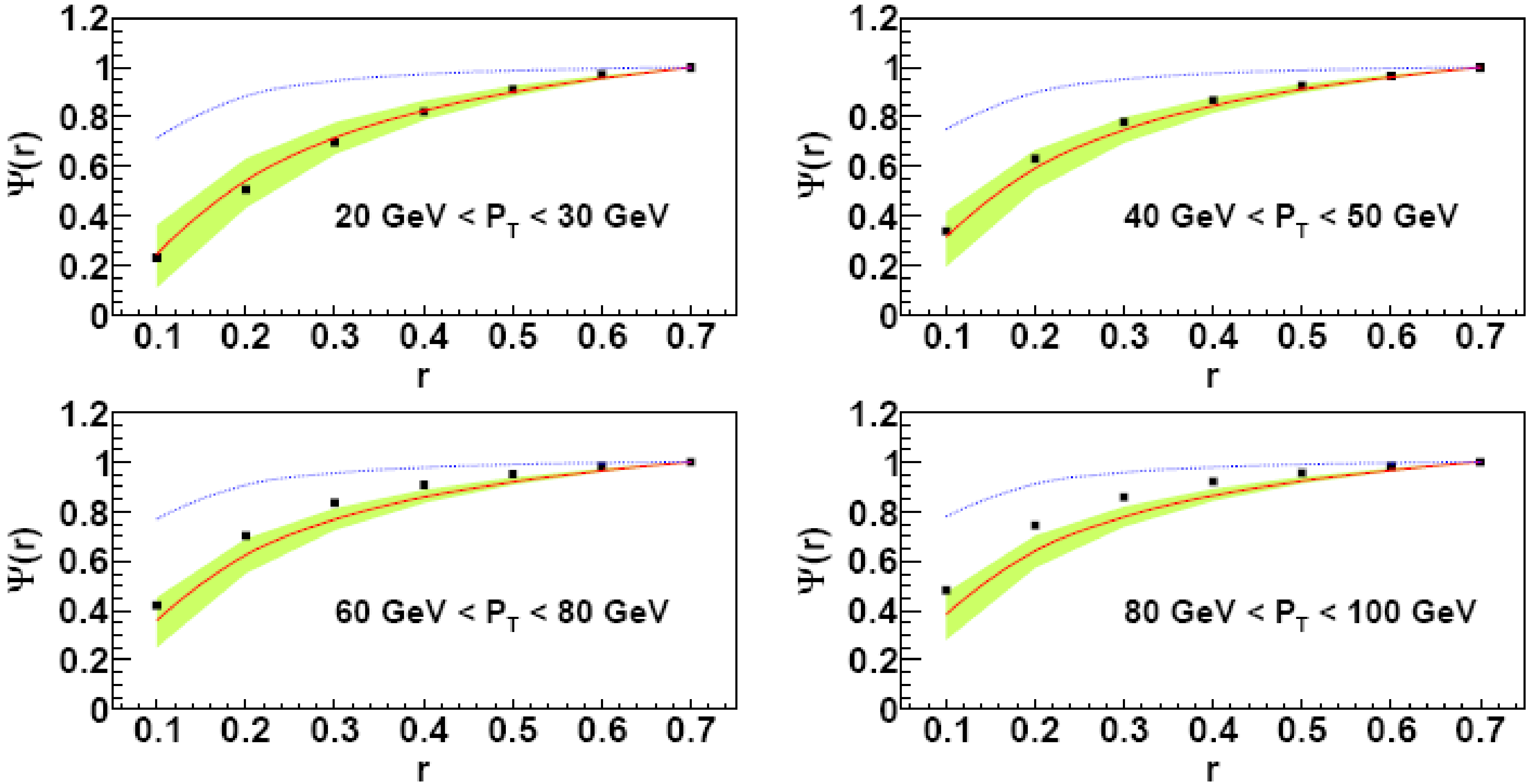
Comparison with CDF data

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

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

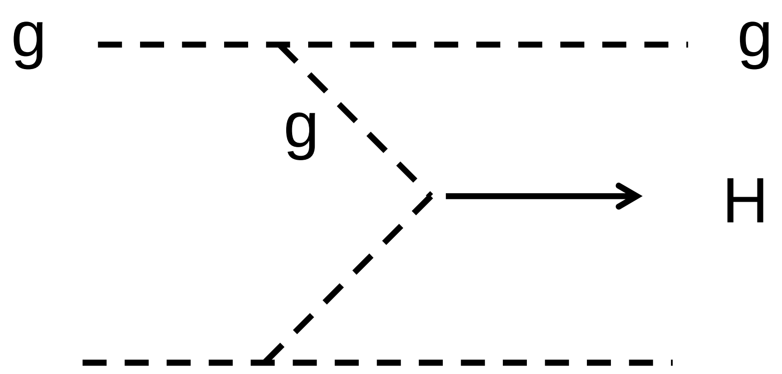


Comparison with CMS data

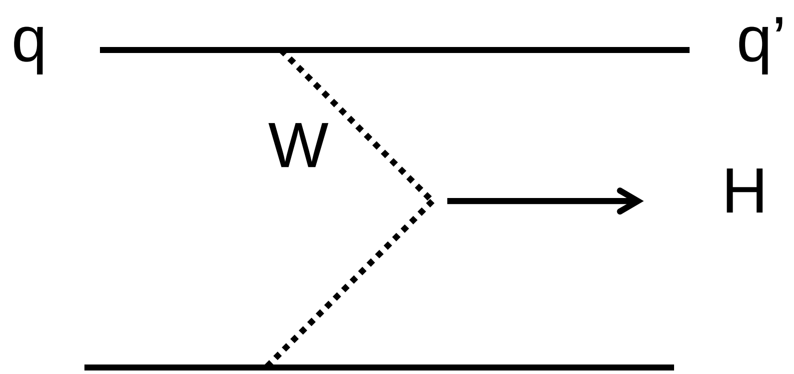


Gluon vs vector-boson fusions

- Higgs can be produced via



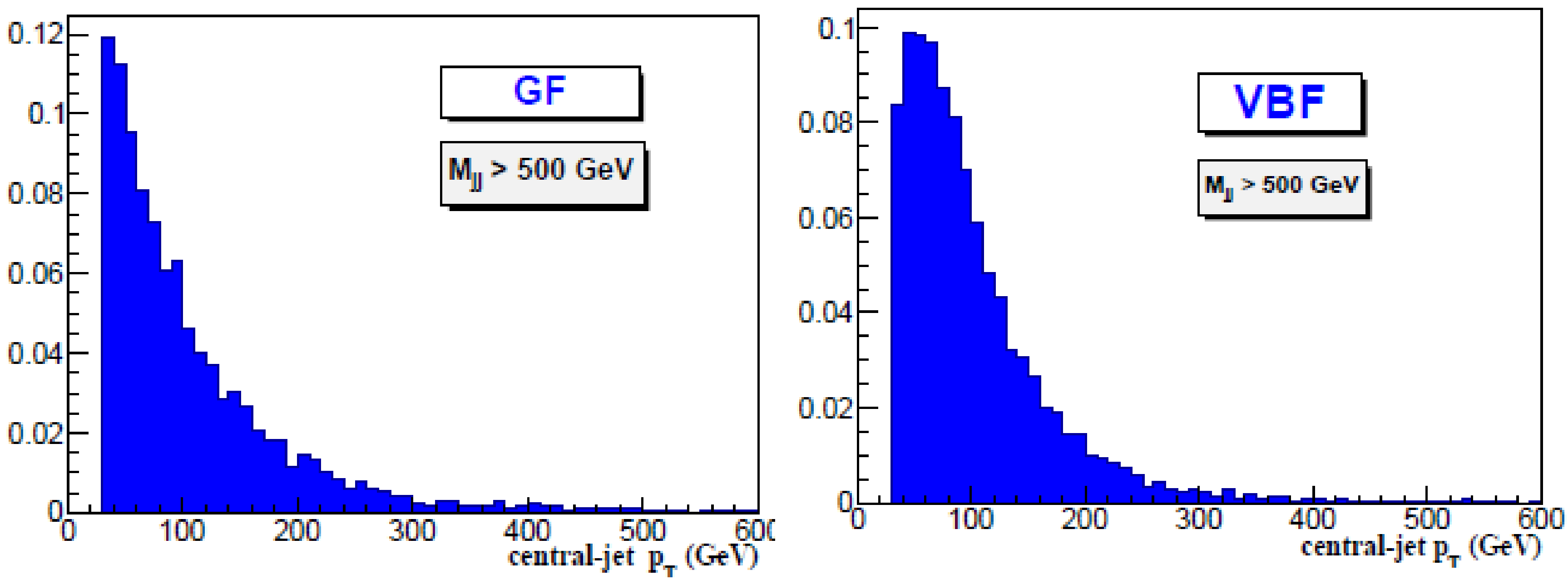
gluon fusion
dominant at LHC
Higgs + 2 gluon jets



vector-boson fusion
important for determinging
Higgs coupling
Higgs + 2 quark jets

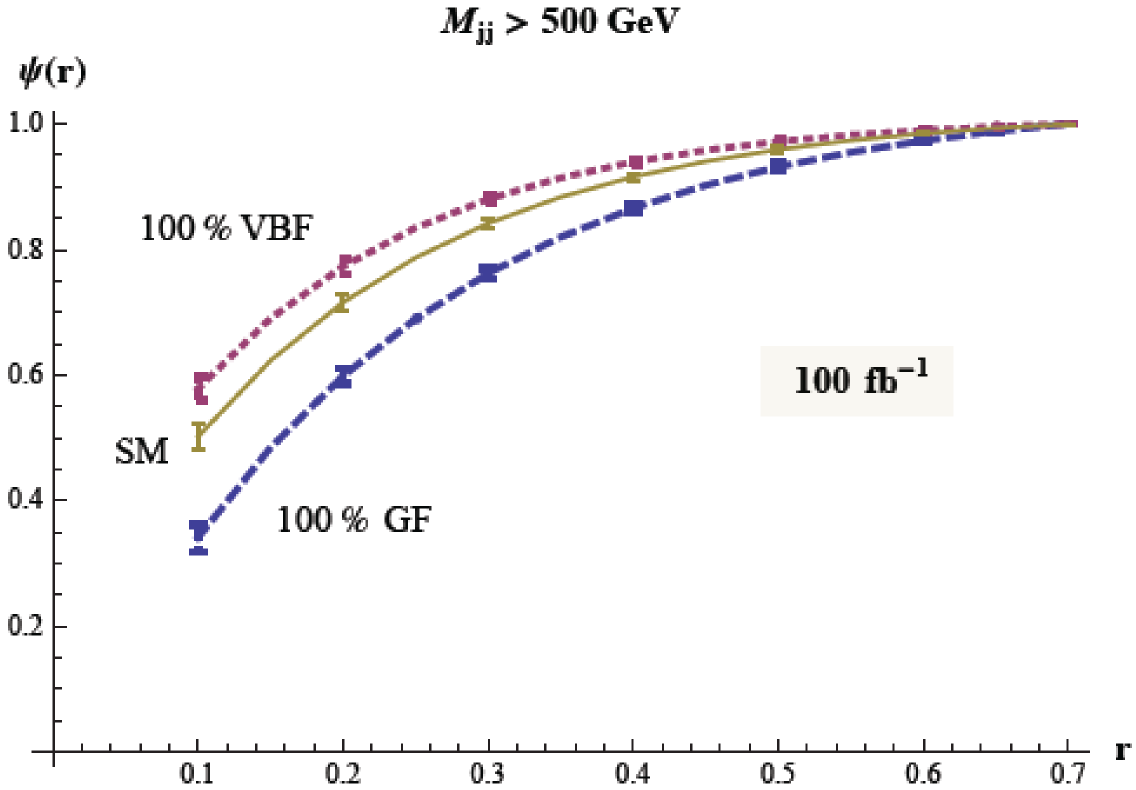
Measuring jet pT distributions

- Difficult to differentiate GF and VBF
- Momentum cut is not efficient



Improvement of VBF identification

- Measuring substructures can differentiate gluon and quark jets, and identify VBF



Rentala et al 2013

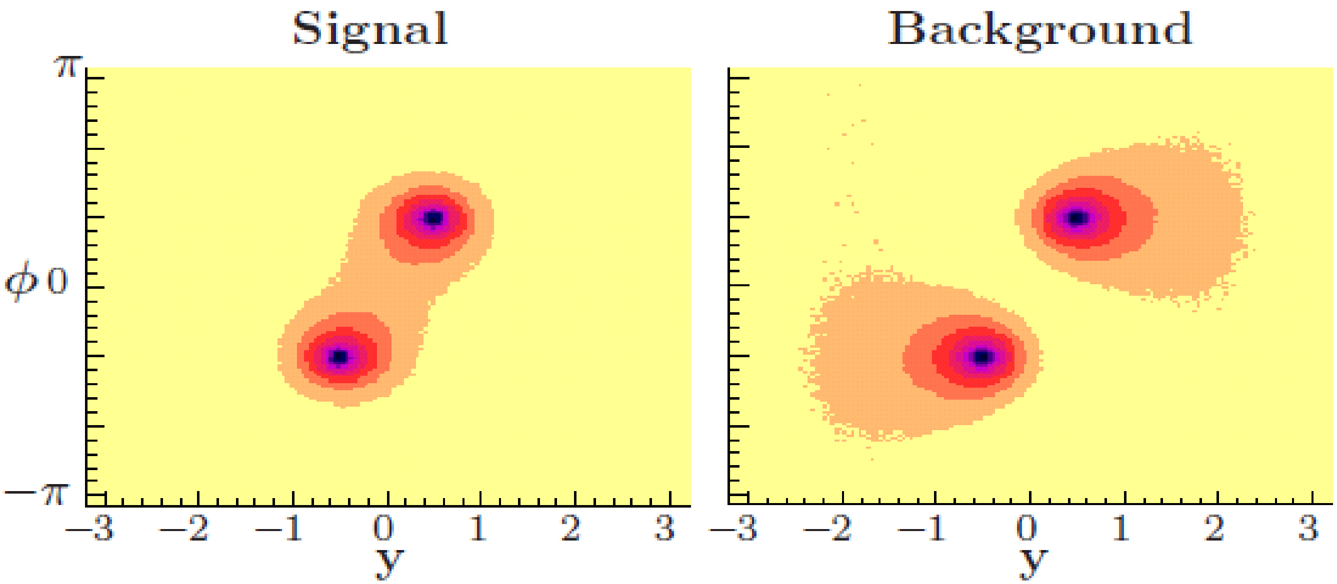
On-going projects and summary

Higgs jet

- One of major Higgs decay modes H -> bb
- Important background g -> bb
- Analyze substructure of
  Higgs jet improves its identification
- For instance, color pull made of soft gluons
- Factorization of heavy-particle jets applies

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



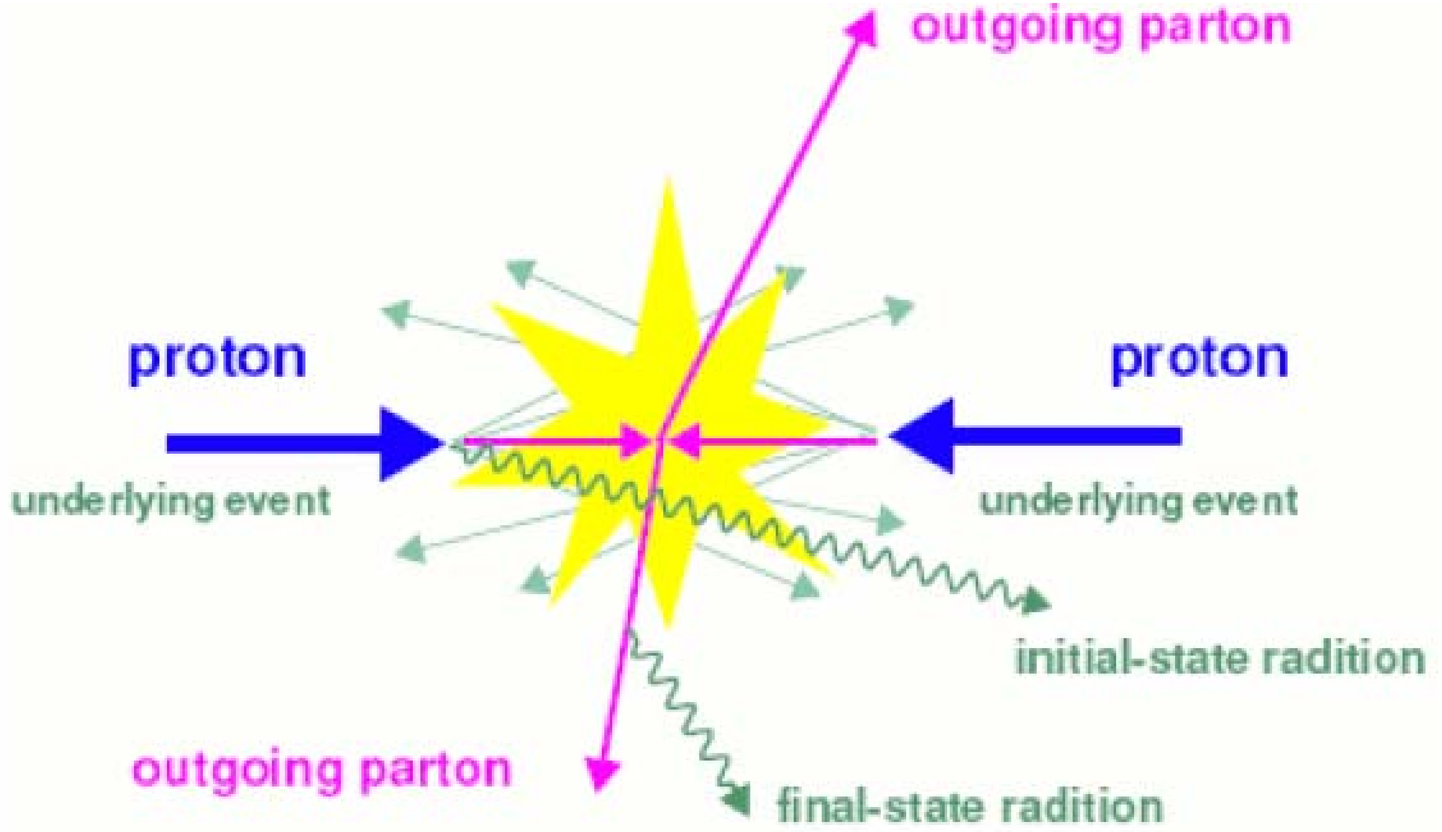
Summary

- Jets abundantly produced in hadron collisions
- Theoretical and experimental studies of jets need to be carefully made for comparison
- Start with Sterman-Weinberg definition, apply factorization and resummation, predict observables consistent with data
- Substructures (energy profile, color pull,…) can be calculated in PQCD and improve jet identification

Back-up slides

Underlying events

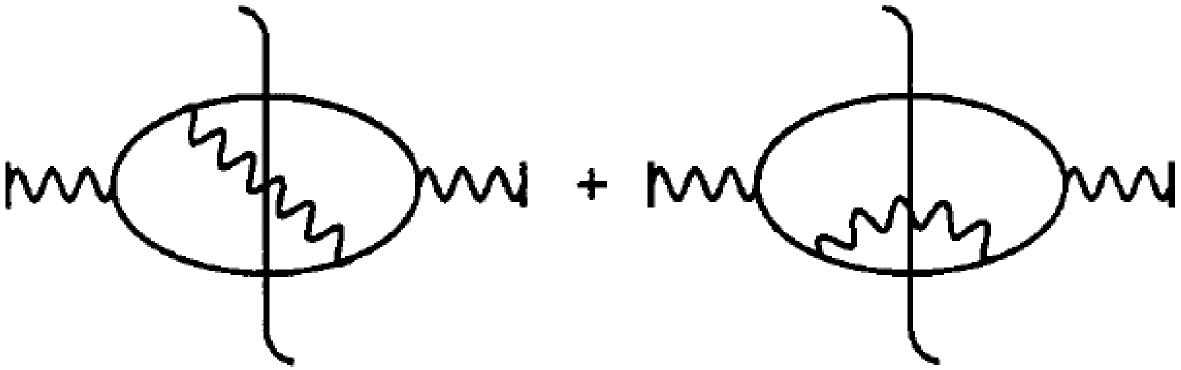
- Everything but hard scattering
- Initial-state radiation, final-state radiation, multi-parton interaction



Real corrections

- Radiative corrections reveal two types of infrared divergences from on-shell gluons
- Collinear divergence: l parallel P1, P2
- Soft divergence: l approaches zero

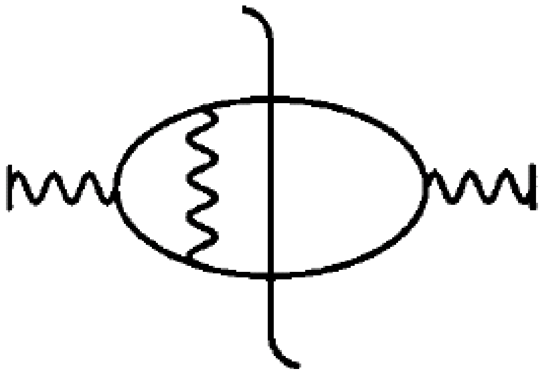
overlap of
collinear and
soft divergences

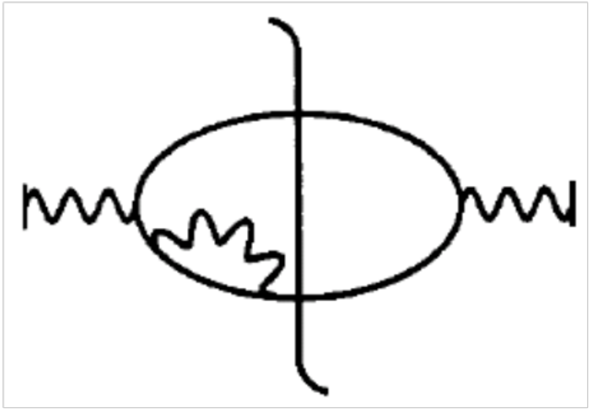


$$2NC_2(\mathrm{F})Q_f^{\,2}(\alpha\alpha_s/\pi)q^2(4\pi\mu^2/q^2)^{2\epsilon}[(1-\epsilon)/\Gamma(2-2\epsilon)]$$
$$\times\,[\epsilon^{-2}+\tfrac{3}{2}\epsilon^{-1}-\tfrac{1}{2}\pi^2+\tfrac{19}{4}+\mathrm{O}(\epsilon)].$$

Virtual corrections

- Double infrared pole also appears in virtual corrections, but with a minus sign





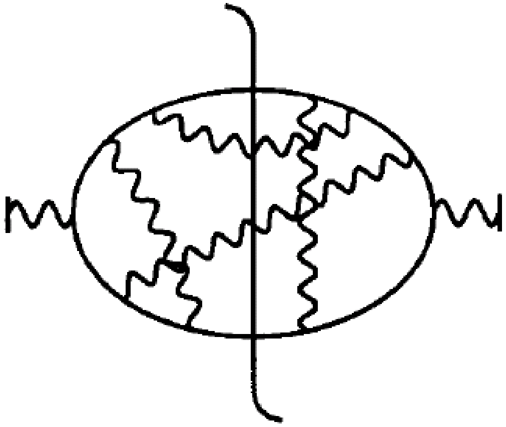
$$-2NC_2(\mathrm{F})Q_f^{\,2}(\alpha\alpha_s/\pi)q^2(4\pi\mu^2/q^2)^{2\epsilon}[(1-\epsilon)/\Gamma(2-2\epsilon)]$$

$$\times\,[\epsilon^{-2}+\tfrac{3}{2}\epsilon^{-1}-\tfrac{1}{2}\pi^2+4+\mathrm{O}(\epsilon)]$$

negative infrared divergence

Infrared safety

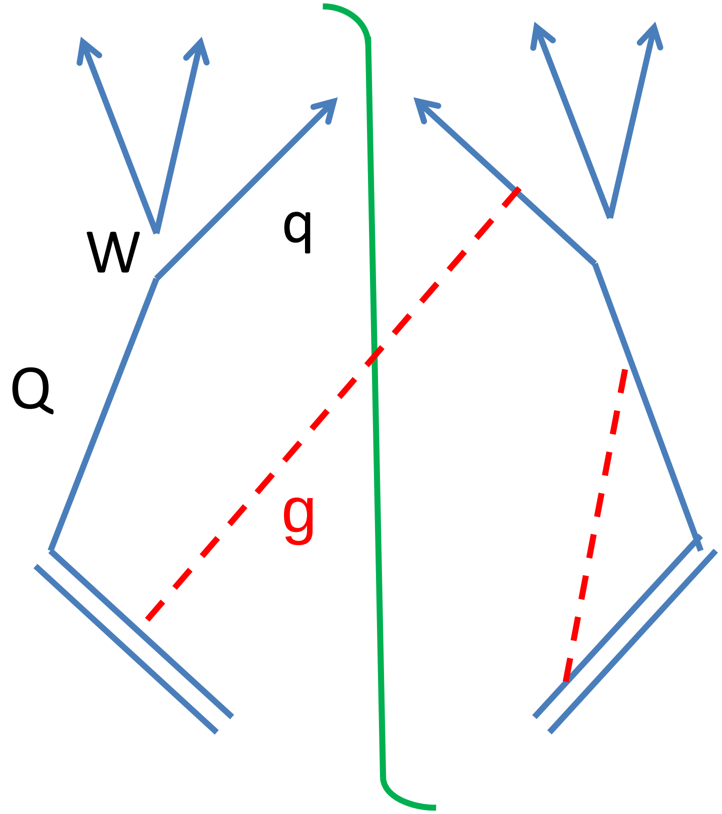
- Infrared divergences cancel between real and virtual corrections
- KLN theorem: cancellation occurs as integrated over all phase space of final states
- Imaginary part of off-shell photon self-energy corrections
- Total cross section e+e- -> X is infrared safe
- Naïve perturbation applies



$$\sigma_{\rm tot}(q^2) = N(4\pi\alpha^2/3q^2)\sum_f Q_f{}^2[1 + (\alpha_s/\pi)\tfrac{3}{4}C_2(\mathrm{F})]$$

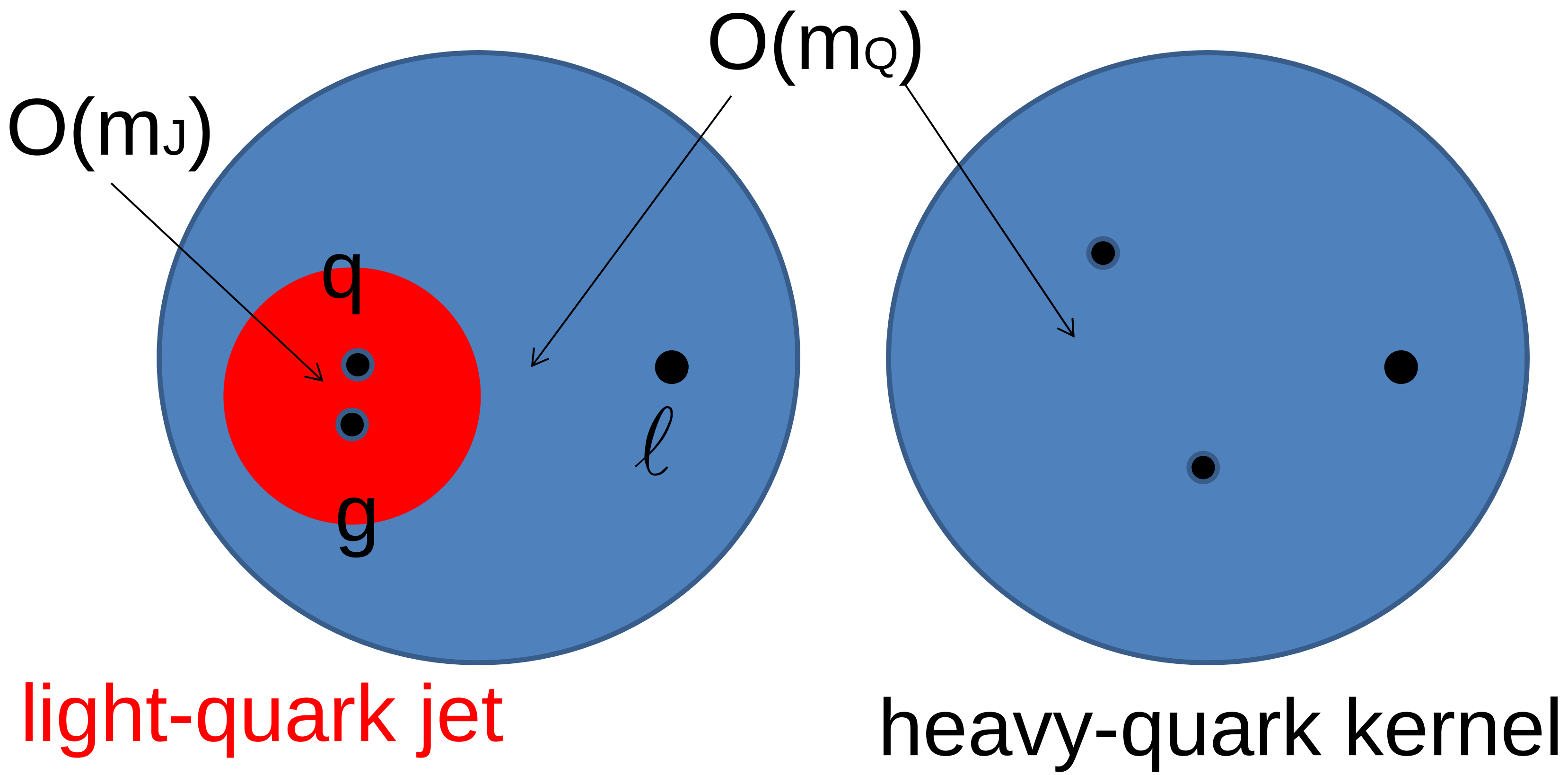
Heavy-quark jet function

- Take semileptonic decay as an example
- Factorize heavy quark-quark jet first at jet energy scale E_Q, which contains weak decay



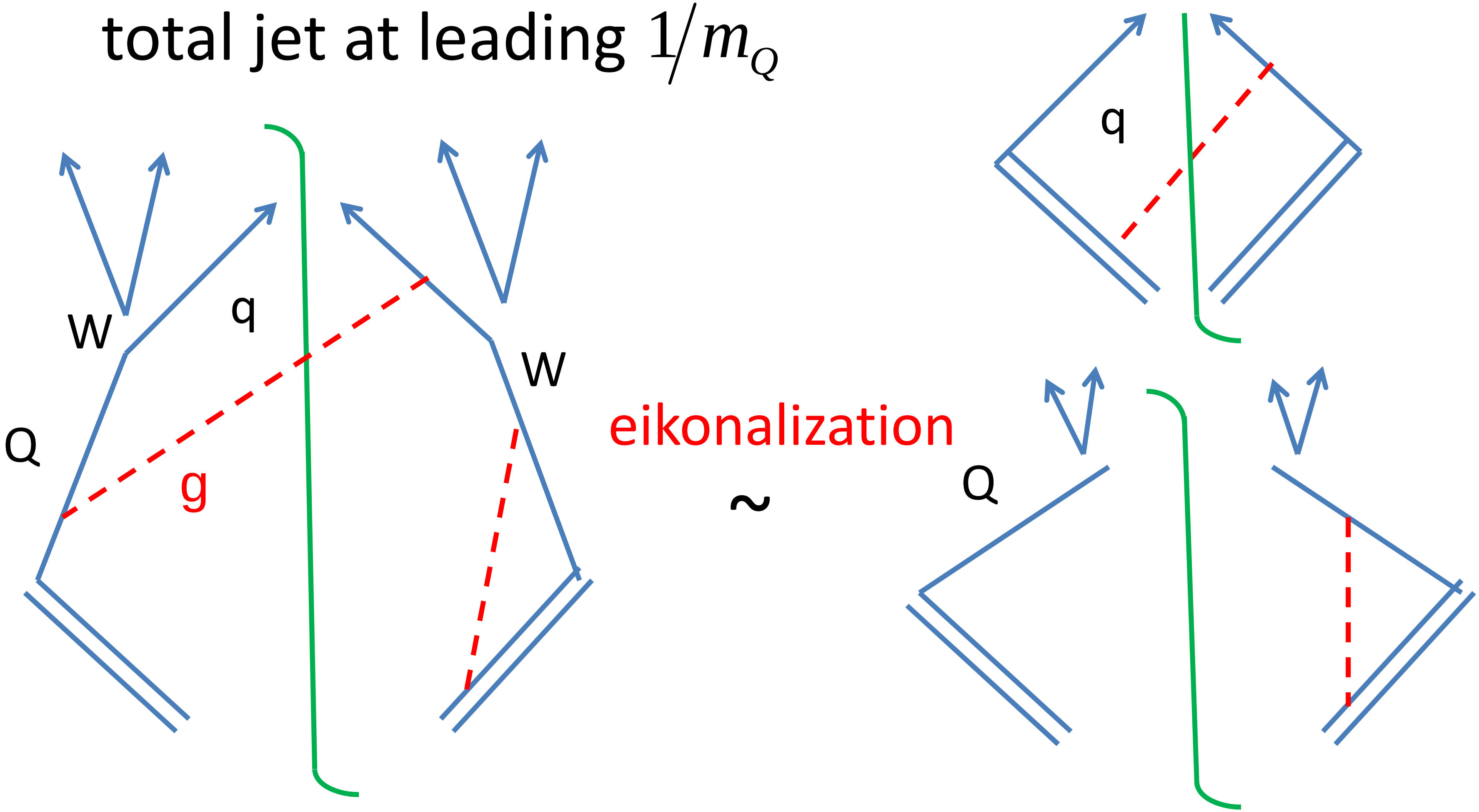
Scale hierarchy $E_Q \gg m_Q \gg m_J$

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



Further factorization

- Then factorize the light-quark jet from the total jet at leading $1/m_Q$



$$J_{Qr}^{(1)} = H_Q^{(0)} \otimes J^{(1)} + H_{Qr}^{(1)} \otimes J^{(0)}$$