Introduction to High-Energy Jets

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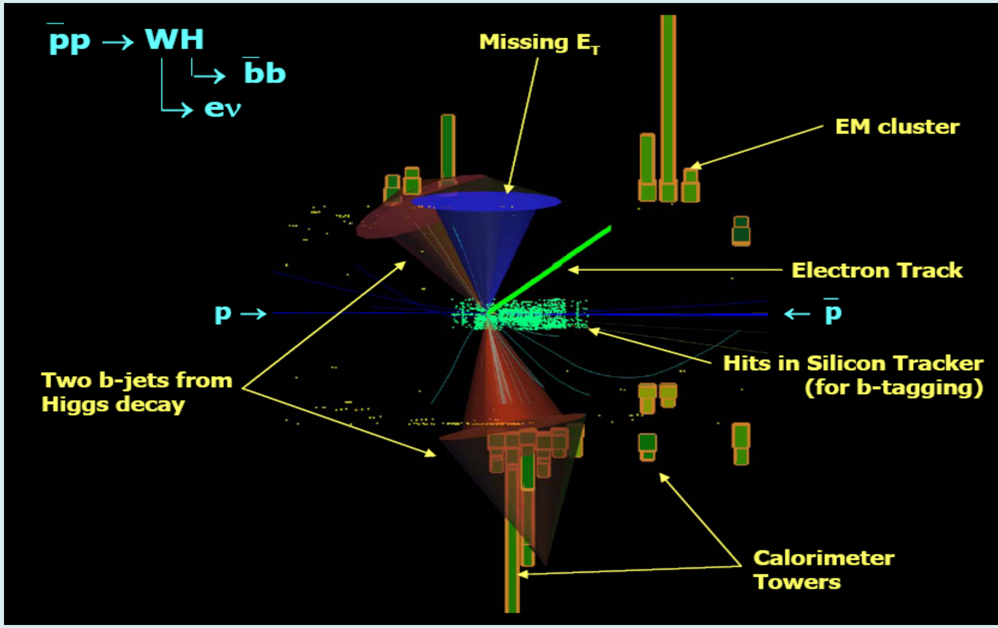
Outline



- Introduction
  - ee, ep, $p\bar{p}$ processes
  - What is a jet
  - Jet algorithms
- Jet Characteristics
  - Jet energy profile
  - Differences between Quark and Gluon jets
  - Color coherence effects
- Jet Production at Tevatron
  - Challenges with jets
  - Inclusive jet cross sections
- Outlook

QCD in a Nutshell

QCD : Theory of Strong Interactions

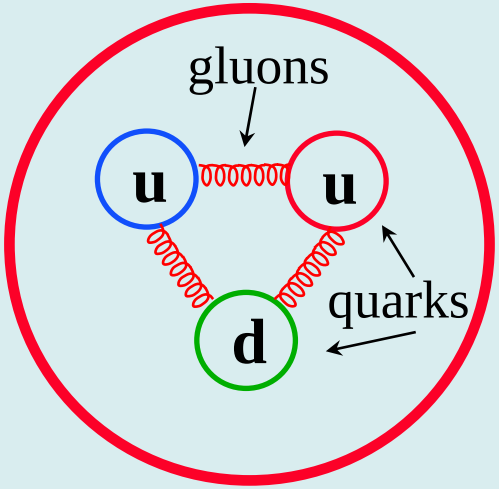
Similar to QED BUT Different

- Pointlike particles called quarks
- Six different "flavors" (u, d, c, s, t, b)
- Quarks carry "color" - analogous to electric charge
- There are three types of color (red, blue, green)
- Mediating boson is called gluon - analogous to photon
- Color charge is conserved in quark-quark-gluon vertex
- Gluons carry two color "charges" and can interact to each other – very important difference from QED - from Abelian to non-Abelian theory
- At large distances: parton interactions become large **(confinement)**
- At small distances: parton interactions become small **(asymptotic freedom)**

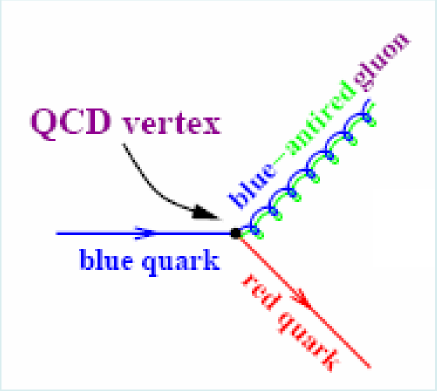
Coupling constant → α_s (analogous to α in QED)

Free particles (hadrons) are colorless

Proton

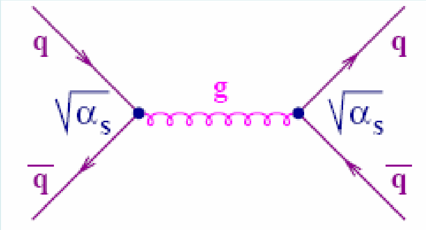


Partons = quarks & gluons



The "Running" α_s

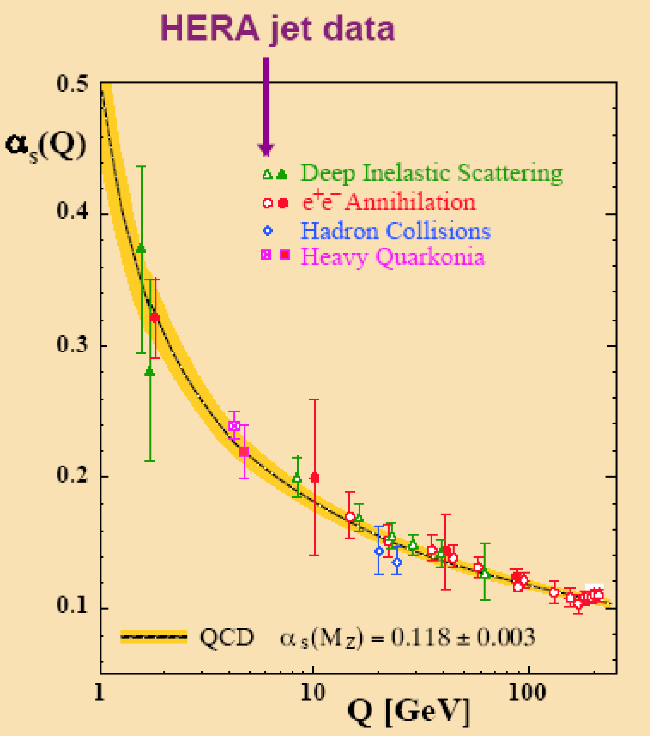
SU(3) gauge coupling constant (α_s) varies with Q^2, decreasing as Q^2 increases:



$$\alpha_s(Q^2) = \frac{12\pi}{(33-2n_f)\ln Q^2/\Lambda^2}$$

Leading-Log Approximation

Compilation of many experiments



Measurements of the strong coupling are made in many processes at different Q^2, clearly establishing the running of α_s.

Increase of α_s as $Q^2 \to 0$ means that color force becomes extremely strong when a quark or gluon tries to separate from the region of interaction (large distance ~ small Q^2).

A quark cannot emerge freely, but is "clothed" with color-compensating quark-antiquark pairs.

Asymptotic freedom ($\alpha_s \to 0$ as $Q^2 \to \infty$)
Infrared slavery ($\alpha_s \to \infty$ as $Q^2 \to 0$)

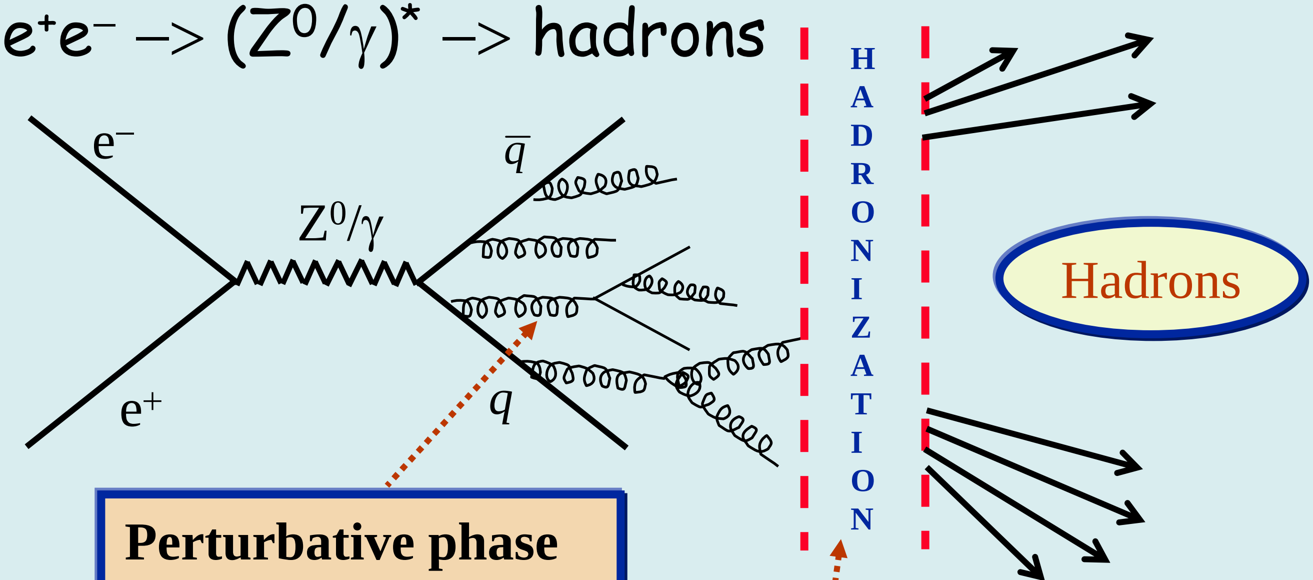
No free quarks or gluons ➔ only **jets**

QCD in e^+e^- Annihilations

LEP: 88 GeV < E_{cm} < 209 GeV

SLC: E_{cm} = 91 GeV

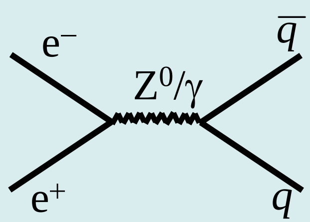
$e^+e^- \to (Z^0/\gamma)^* \to$ hadrons



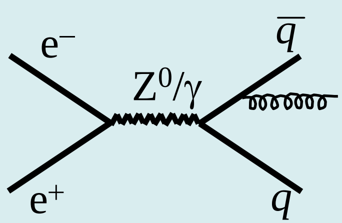
Perturbative phase
$\alpha_s<1$ **(Parton Level)**

Non-perturbative phase
$\alpha_s\geq1$ **(Hadron Level)**

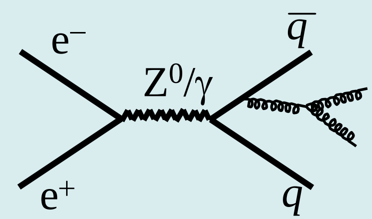
Fixed Order QCD



$\mathcal{O}(\alpha_s^0)$

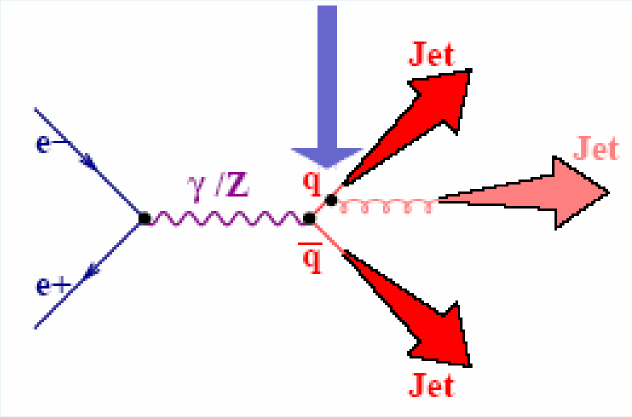


$\mathcal{O}(\alpha_s^1)$

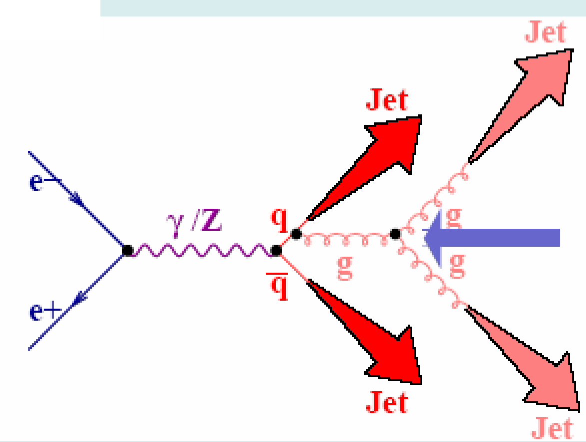


$\mathcal{O}(\alpha_s^2)$

Why do we Study Jets in e^+e^- ?

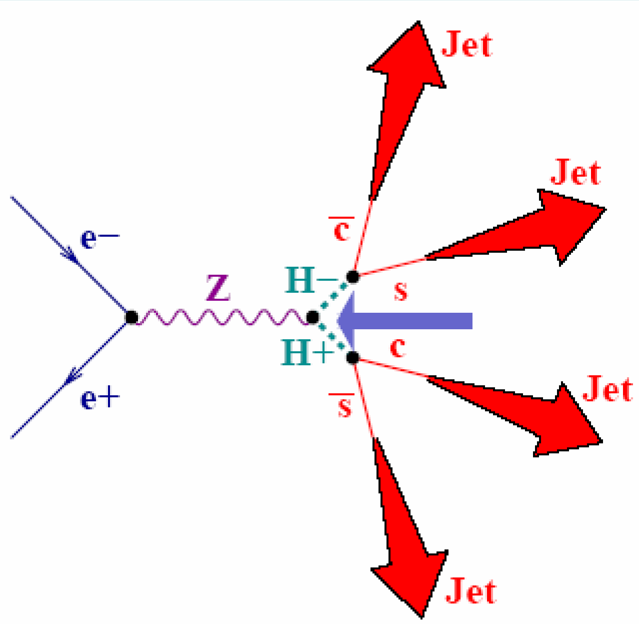


$e^+e^- \to 3$ jets



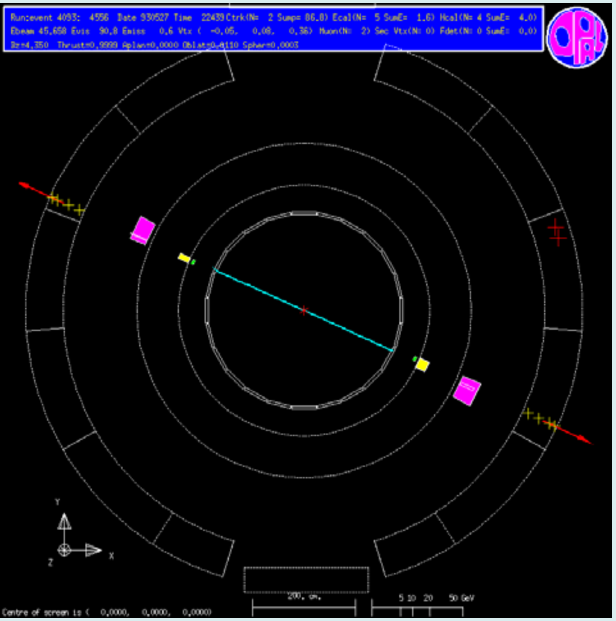
$e^+e^- \to 4$ jets

- QCD Studies
  - Measurements of α_s
  - Fragmentation functions
  - Color/spin dynamics
  - Quark-gluon jet properties
  - Event shape variables (sphericity, thrust, …)
- Searches for the Higgs
- Searches for new physics

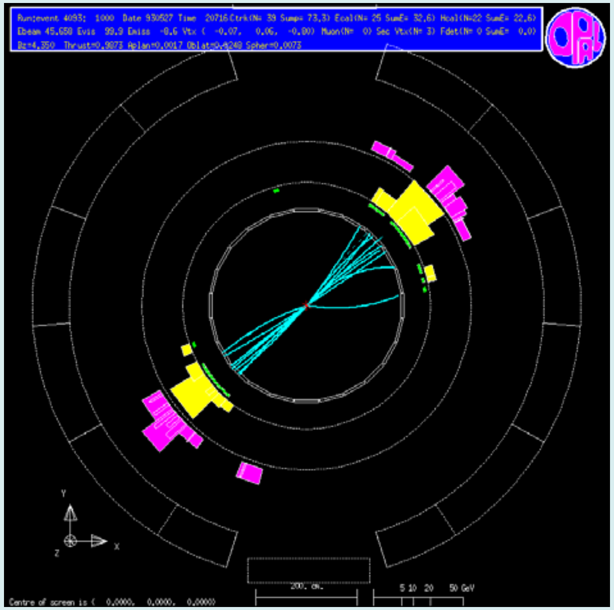


e^+e^- Event Displays

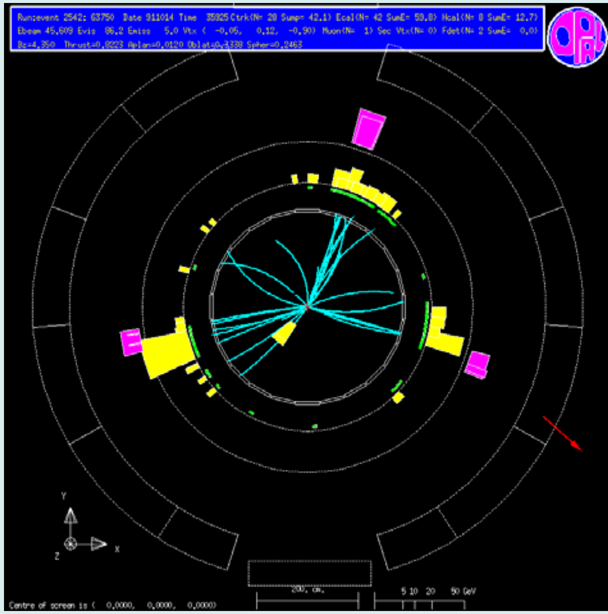
$e^+e^- \to \mu^+\mu^-$



$e^+e^- \to q\bar{q}$

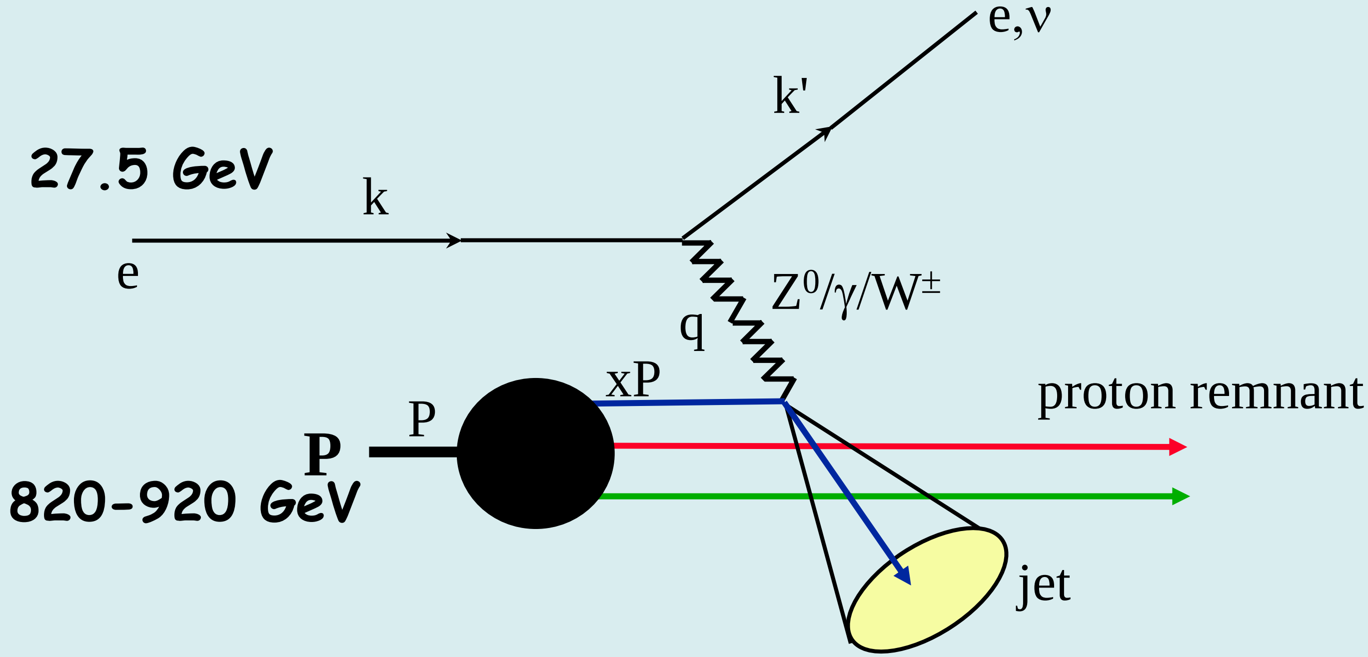


$e^+e^- \to q\bar{q}g$



Much cleaner events than hadron-hadron collisions

QCD in ep Interactions



$\sqrt{s} \approx 300 - 320\,\text{GeV at HERA}$

$k = (E, \boldsymbol{k})$ 4-momentum for incoming e⁻

$k' = (E', \boldsymbol{k}')$ 4-momentum for outgoing e⁻

$Q^2 = -q^2 = -(k - k')^2$ 4-momentum transfer

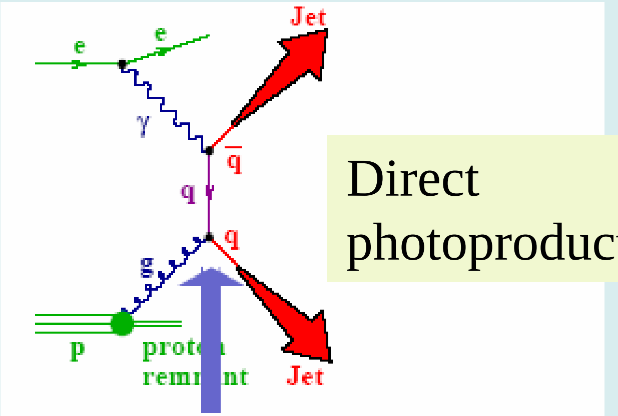
$x = \dfrac{Q^2}{2P \cdot q}$ parton momentum fraction

$y = \dfrac{P \cdot q}{P \cdot k} = \dfrac{E - E'}{E}$ fractional energy transfer

$s = (P + k)^2 \approx 2P \cdot k = \dfrac{Q^2}{xy}$ electron-proton mass squared

$\hat{s} = (xP + k)^2 \approx sx$ electron-parton mass squared

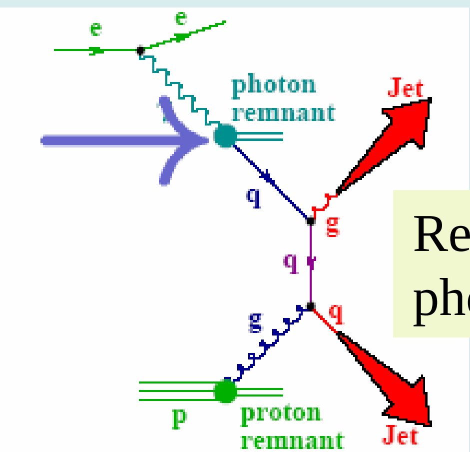
Why do we Study Jets in ep ?



Direct photoproduction

→ measurements of α_s

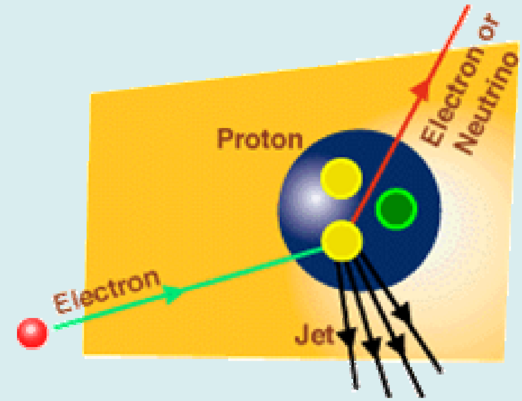
$\gamma p \rightarrow 2 \text{ jets} + X$



Resolved photoproduction

→ tests of photon structure

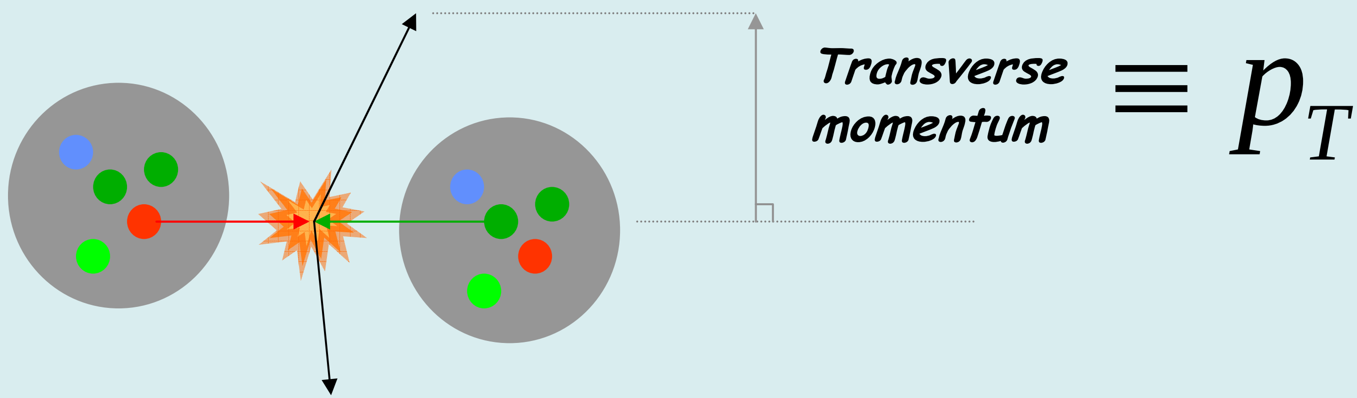
$\gamma p \rightarrow 2 \text{ jets} + X$



- QCD Studies
  - Measurements of α_s
  - Fragmentation functions
  - Parton Distribution Functions
  - Color/spin dynamics
  - Quark-gluon jet properties
  - Event shapes
  - Inclusive- and Multi-jet production
  - Rapidity Gaps/Diffraction
- Searches for new physics

Proton-(Anti)proton Collisions

- **Proton beams can be accelerated to very high energies (good)**
- **But the energy is shared among many constituents – quarks and gluons (bad)**



- **To select the interesting collisions: look for outgoing particles produced with high momentum perpendicular to the beamline ("transverse momentum") → *hard collisions***
  - *Hard collisions* take place at small impact parameter and are more accurately collisions between partons inside the two protons
  - Analog of Rutherford's experiment
  - Forms the basis of the on-line event selection ("triggering")

$p\bar{p}$ Interactions

Parton Distribution Functions

$f_{a/A}(x_a,\mu_F)$: Probability function to find a parton of type **a** inside hadron **A** with momentum fraction x_a

x_a: fraction of hadron's momentum carried by parton **a**

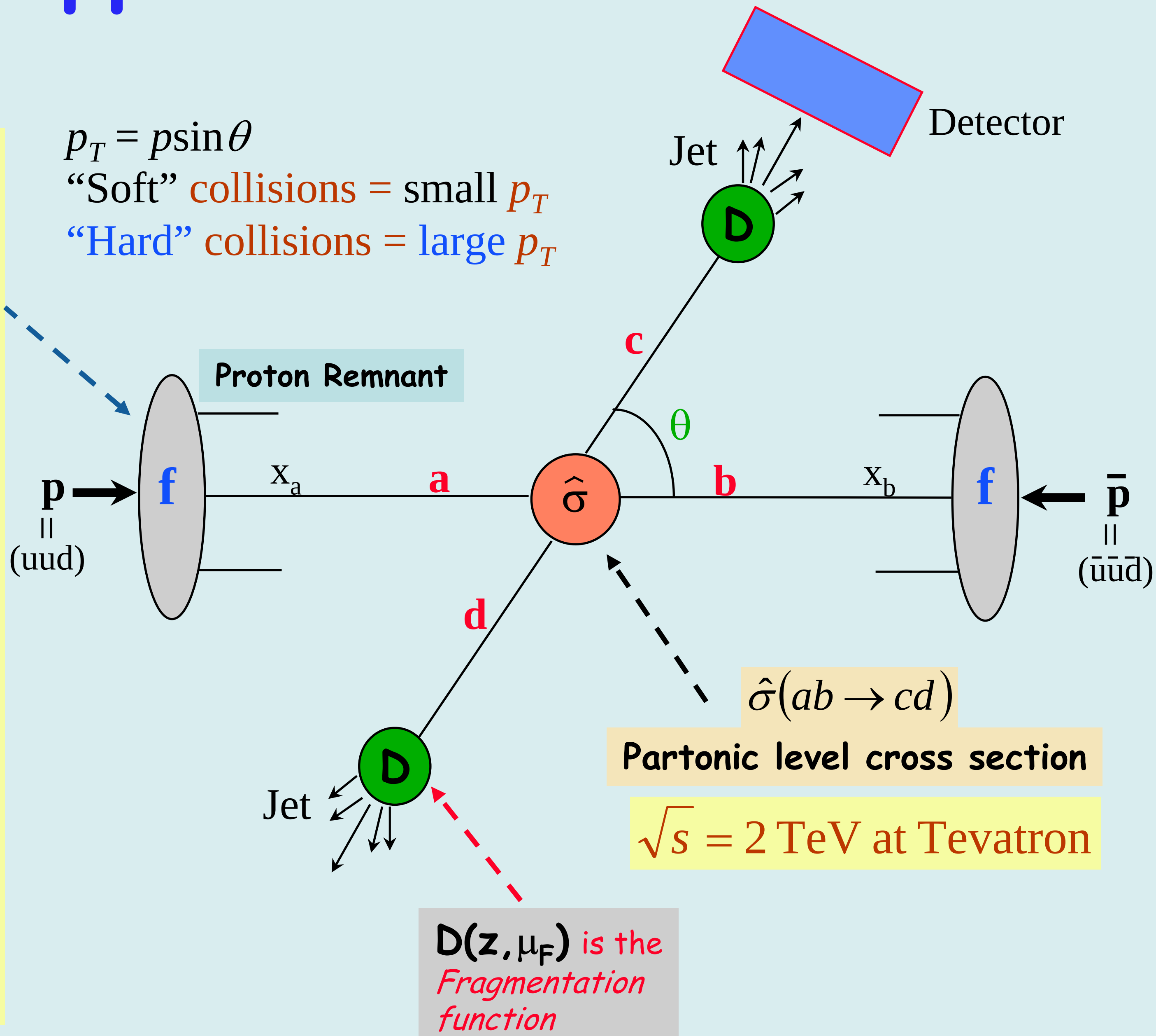
μ_F: related to the "hardness" of the interaction

"Factorization Scale"

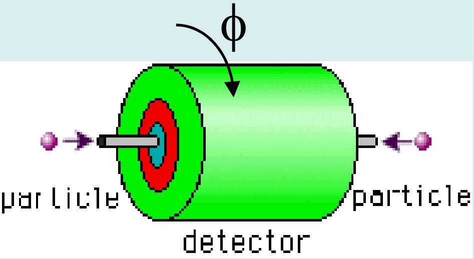
$p_T = p\sin\theta$

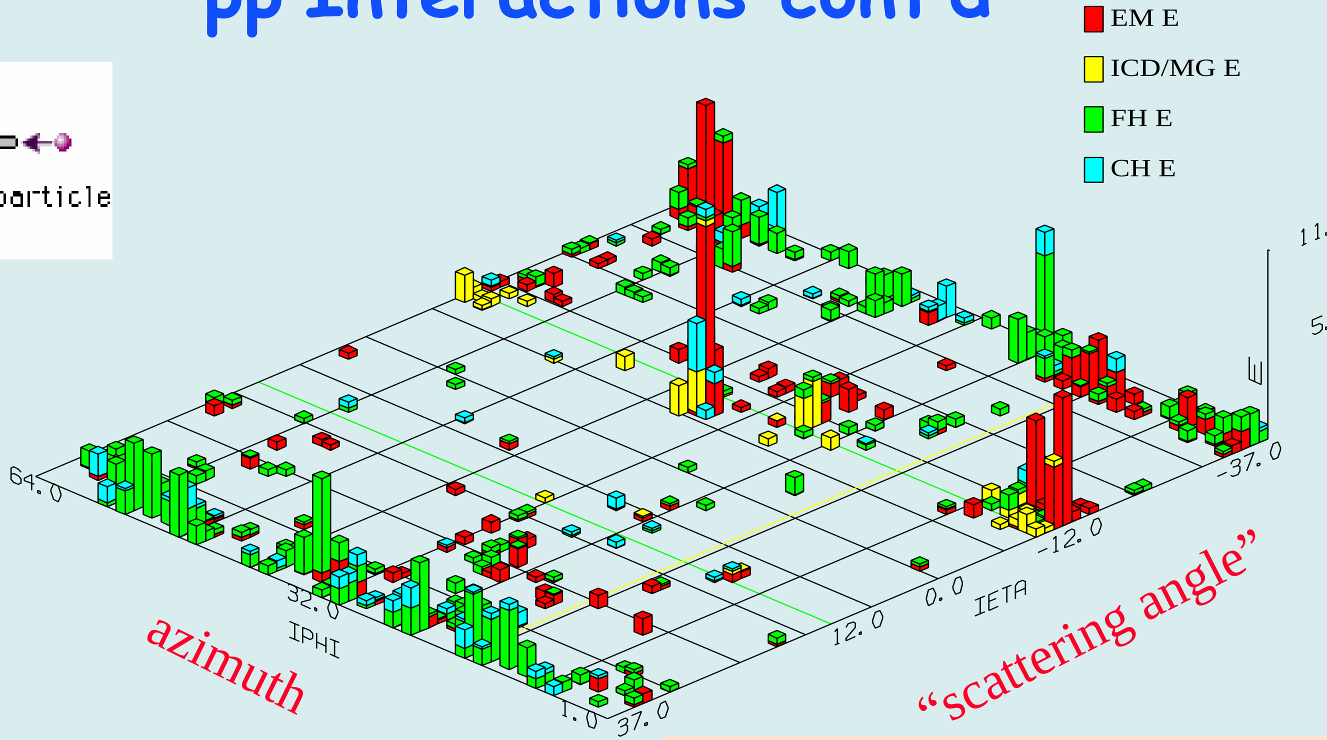
"Soft" collisions = small p_T

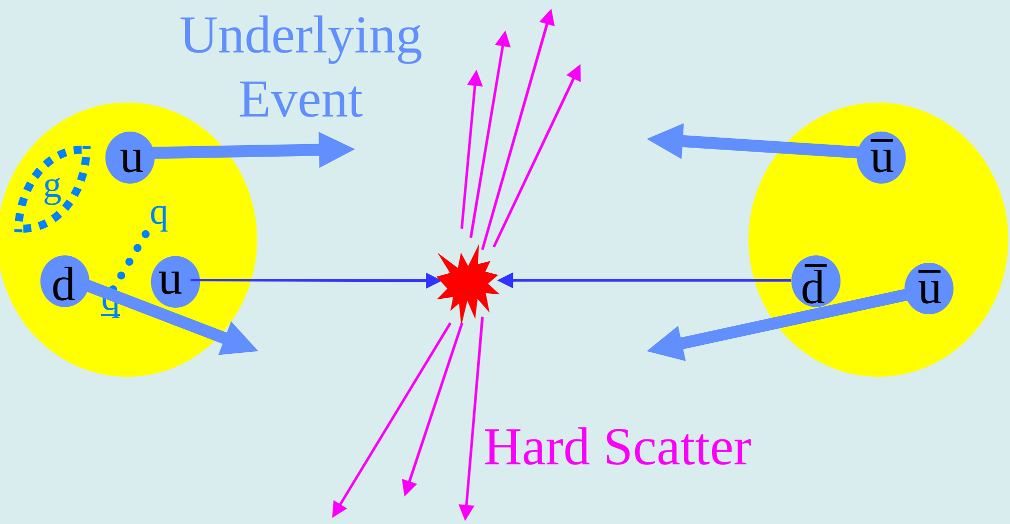
"Hard" collisions = large p_T



$p\bar{p}$ Interactions cont'd





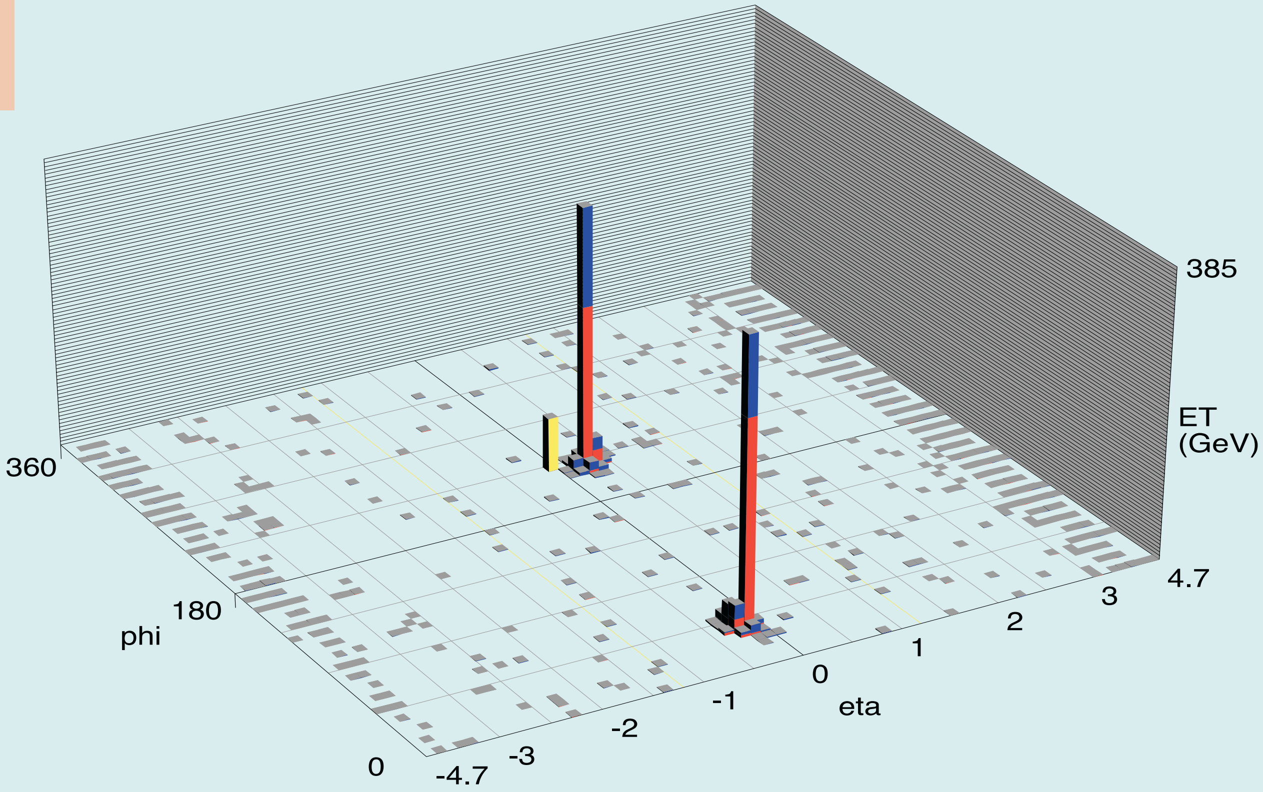


Complications from the e^+e^- due to:

- Parton Distribution Functions (PDFs)
- "Colored" initial and final states
- Remnant jets - Underlying event (UE)

DØ Event

$E_{T1} \sim 620$ GeV
$E_{T2} \sim 560$ GV
$M_{JJ} \sim 1.2$ TeV



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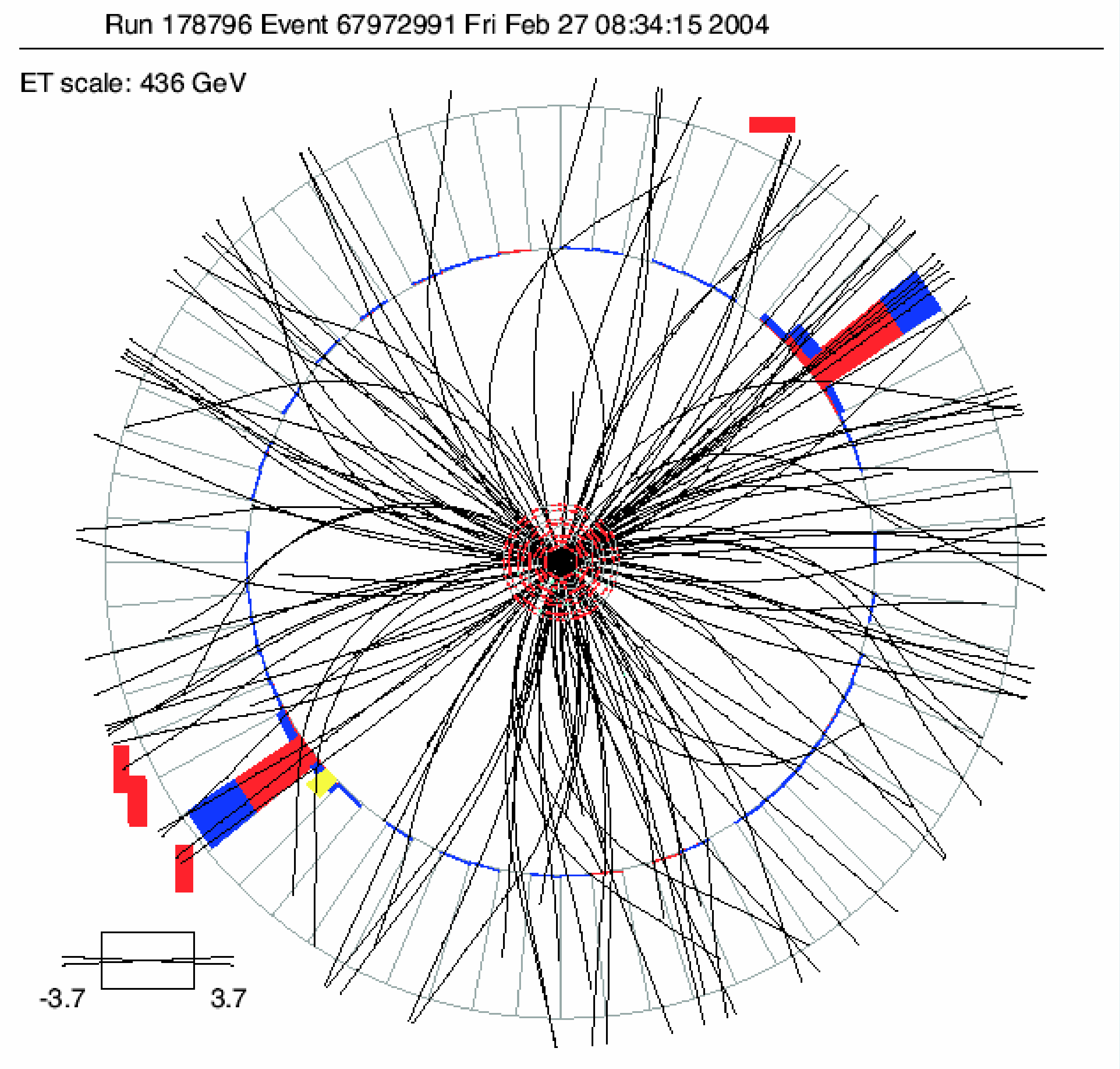
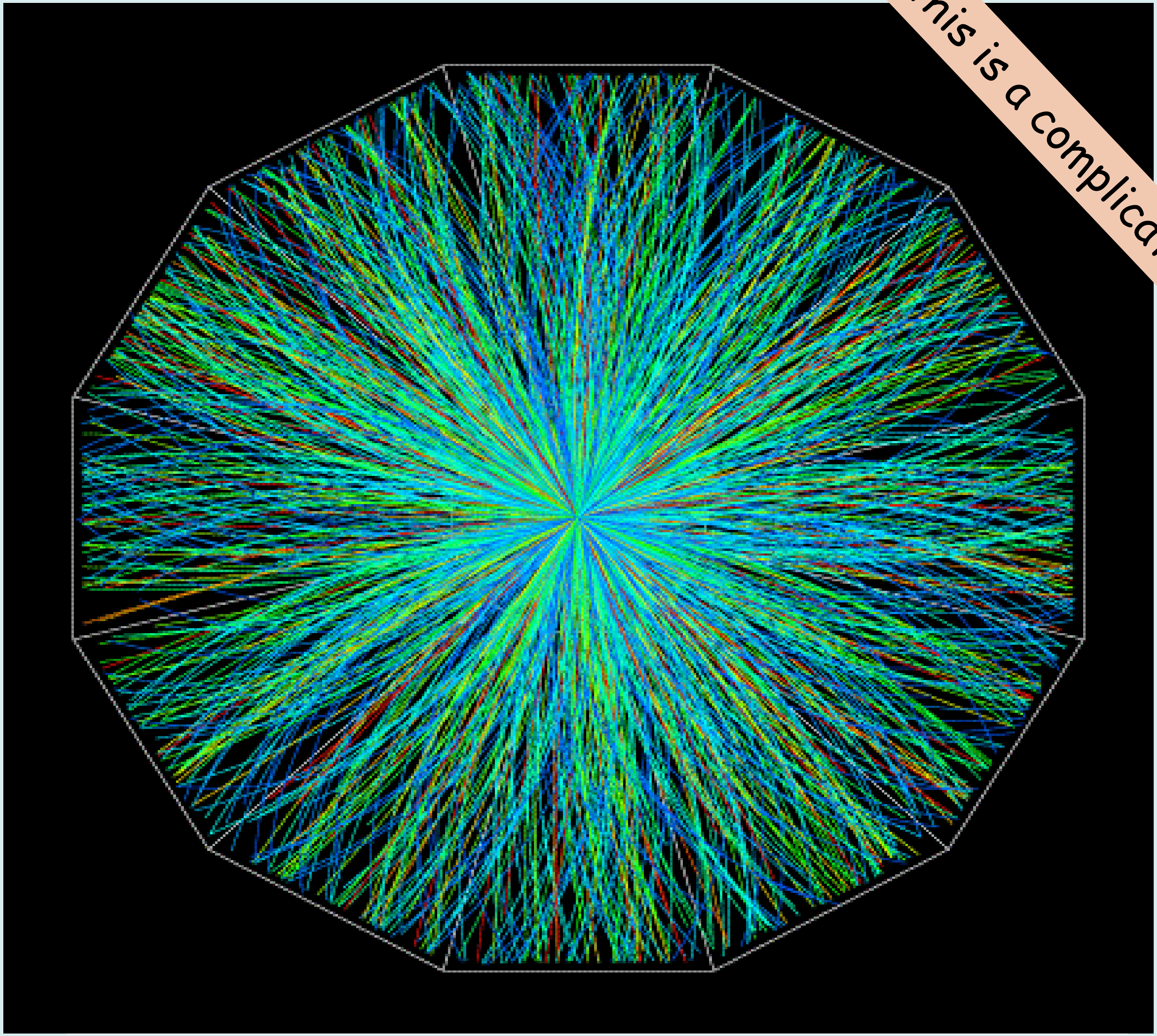
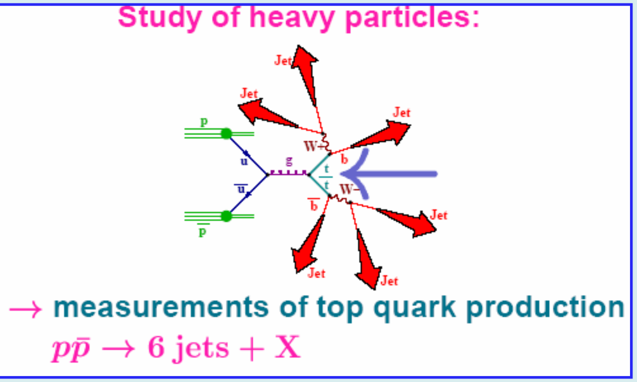


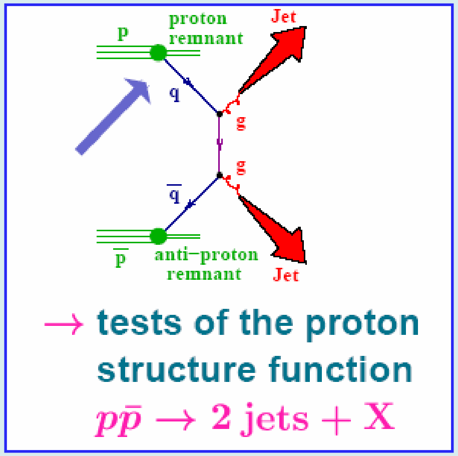
Au+Au collision at RHIC

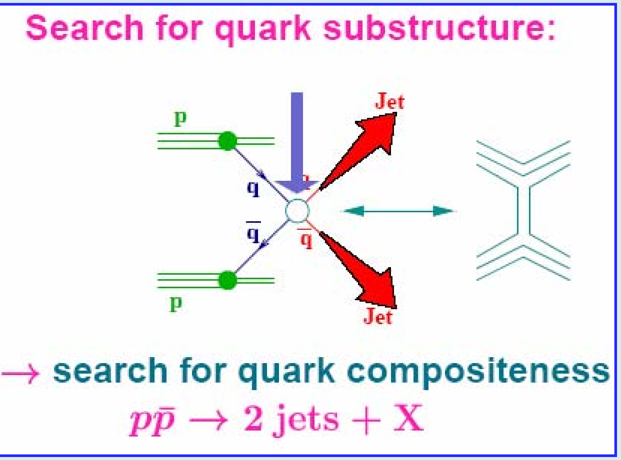
Now this is a complicated event!



Why do we Study Jets in Hadron Colliders?







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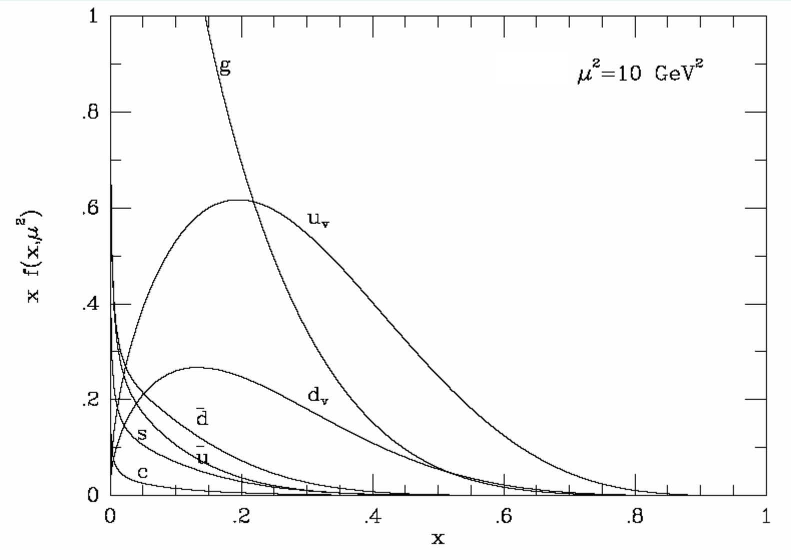
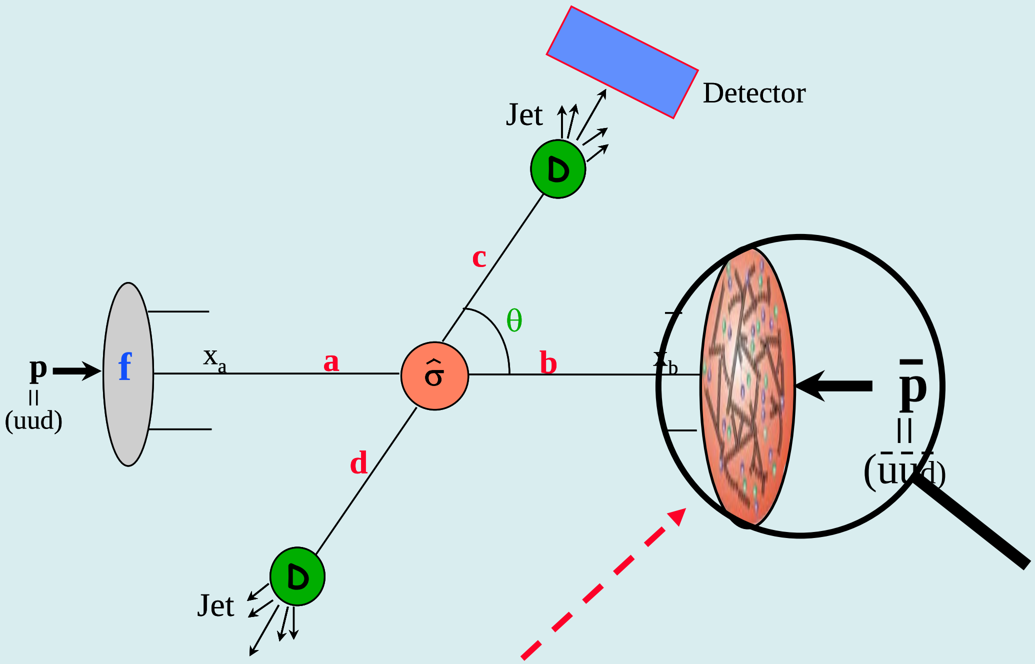
  - Event shapes
  - Inclusive- and Multi-jet production
  - Rapidity Gaps/Diffraction
  - Production of Vector Bosons + jets
- Study of heavy particles (e.g. top production)
- Searches for Higgs
- Searches for new physics
  - Quark sub-structure + …
- And much more …

Explanation of the blob's

Parton Distribution Functions





$xf(x,Q_o) = A_o\, x^{A1}\, (1-x)^{A2}\, P(x)$

small x behavior

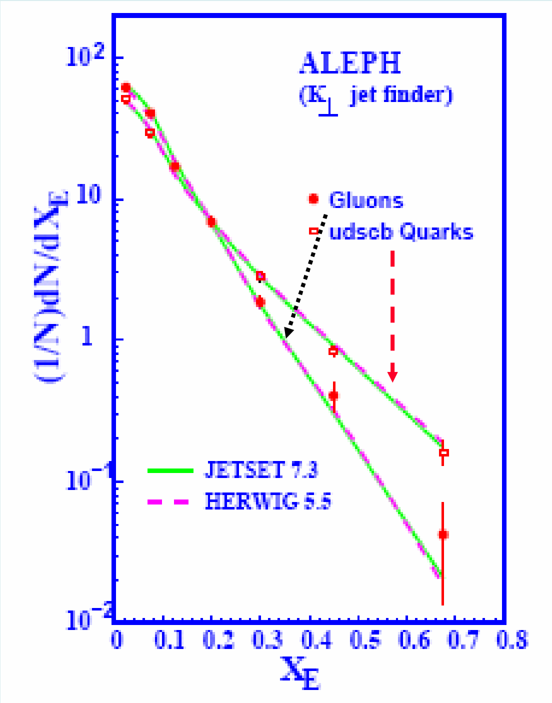
large x behavior

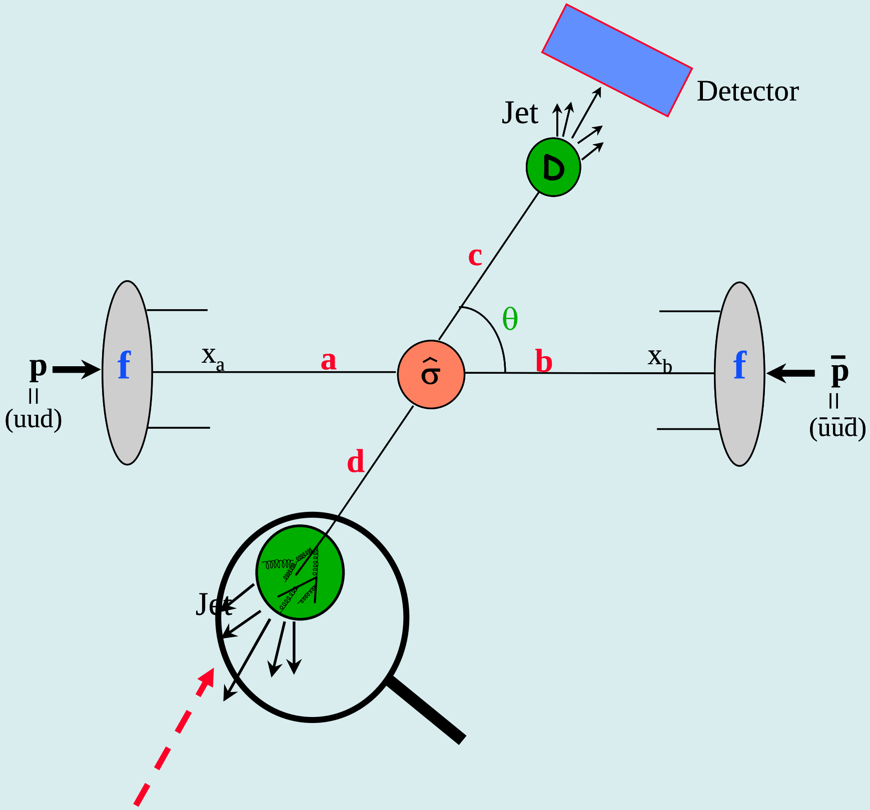
in between

- *Parton Distribution Functions* of the proton are measured at a some "hard scale" and evolved via pertrurbative QCD to the "scale" of the interaction
- PDFs are determined doing Global Fits of data from DIS (Deep Inelastic Scattering), DY (Drell-Yan), Direct Photons, and production of jets

Explanation of the blob's cont'd

Particle Fragmentation Functions



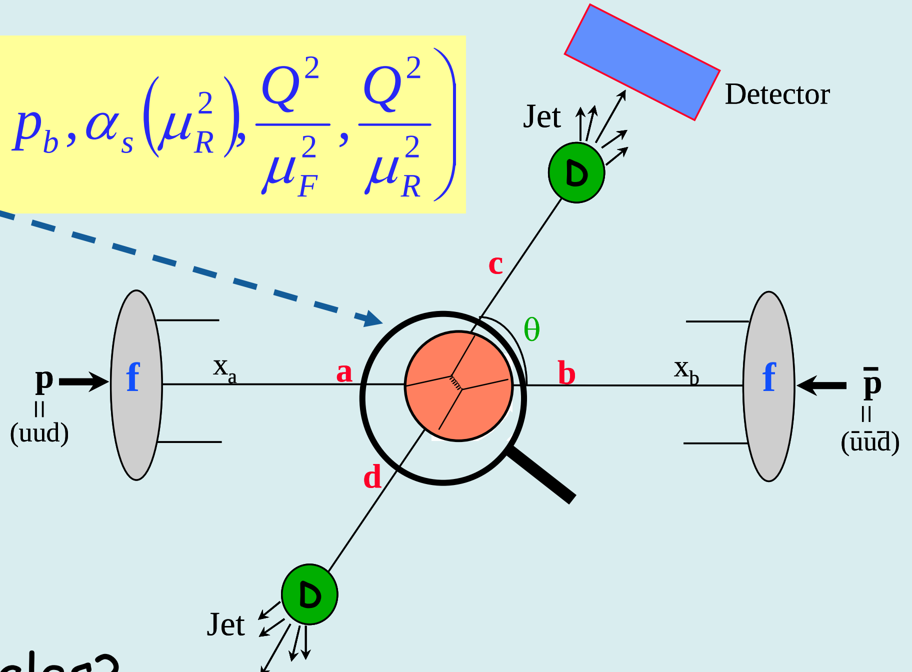


- Particle Fragmentation Functions $D_{A/a}(z_A, \mu_F)$ measure the probability of finding a particle of type A with momentum fraction z_A of parent parton a
- Fragmentation functions are determined doing Global Fits of data from DIS and e^+e^-
- The "evolution" of the Fragmentation functions can be calculated by pQCD

Explanation of the blob's cont'd

Hard Scattering Cross Section

$$\sigma_X = \sum_{i,j} \int_0^1 dx_a dx_b\, f_i\left(x_a, \mu_F^2\right) f_j\left(x_b, \mu_F^2\right) \hat{\sigma}_{ij}\left(p_a, p_b, \alpha_s\left(\mu_R^2\right), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

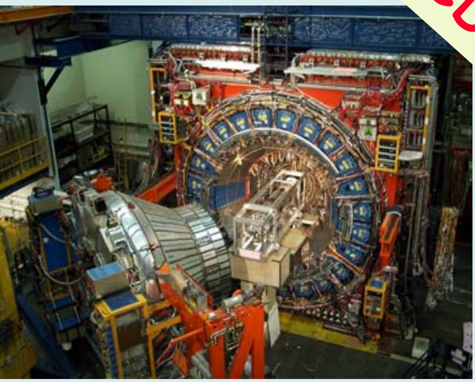


- σ_X = (PDF's for p and $\bar{p}$) ⊗ (partonic level cross section)
  - Separate the long-distance pieces (PDF's) from the short-distance cross section → **Factorization**
- What's the deal with the various scales?
  - μ_F is the factorization scale that enters in the evolution of the PDF's and the Fragmentation functions (could be two different scales). It is an arbitrary parameter that can be thought as the scale which separates the long- and short-distance physics
  - μ_R is the renormalization scale that shows up in the strong coupling constant
  - Q is the hard scale which characterizes the parton-parton interaction
  - Typical choice: $\mu_F = \mu_R = Q \sim p_T/4 - 2p_T$ of the jets

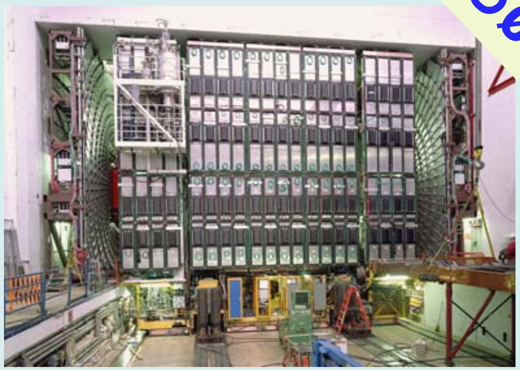
Explanation of the blob's cont'd

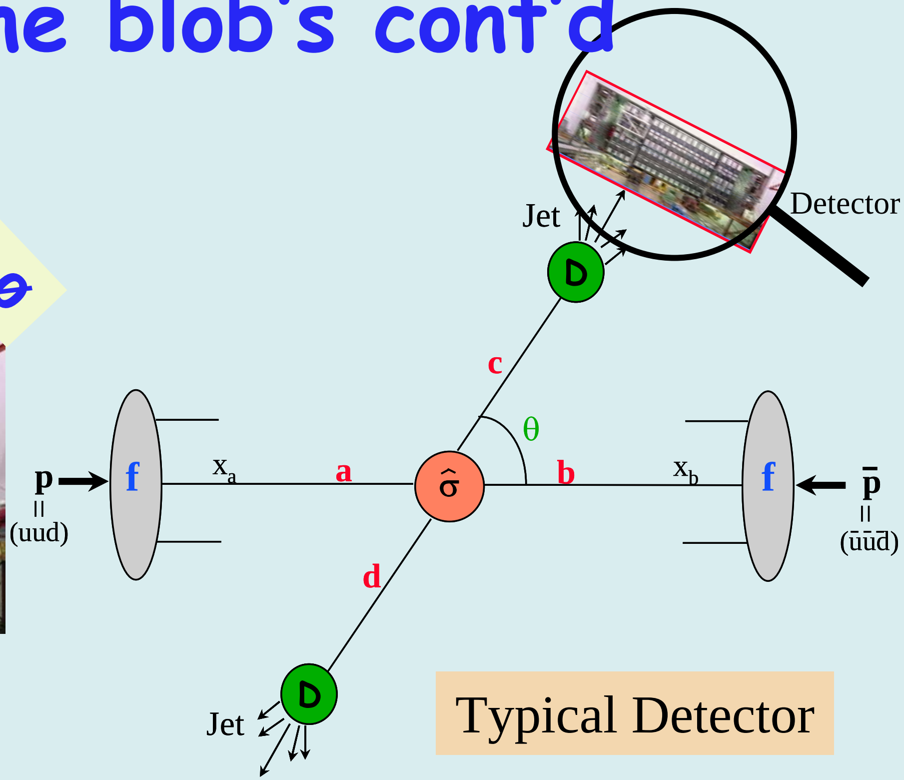
Detector

CDF

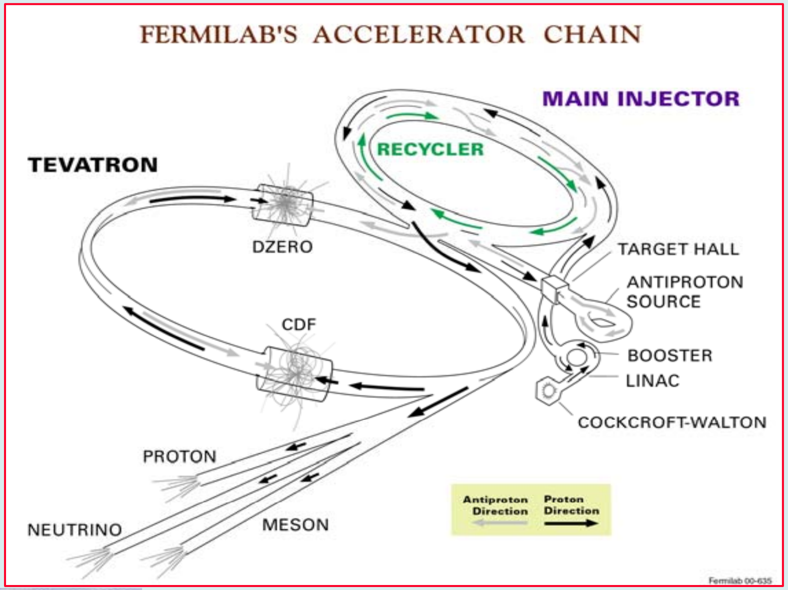


DØ

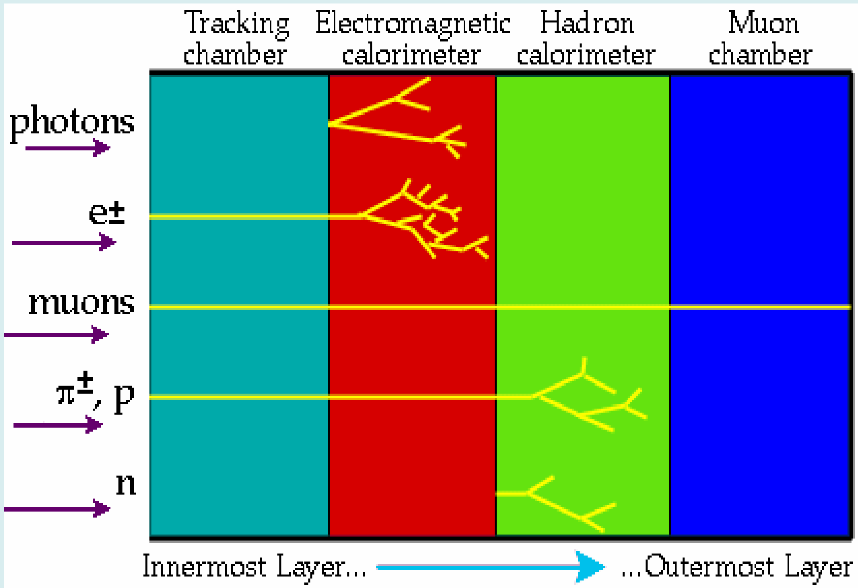




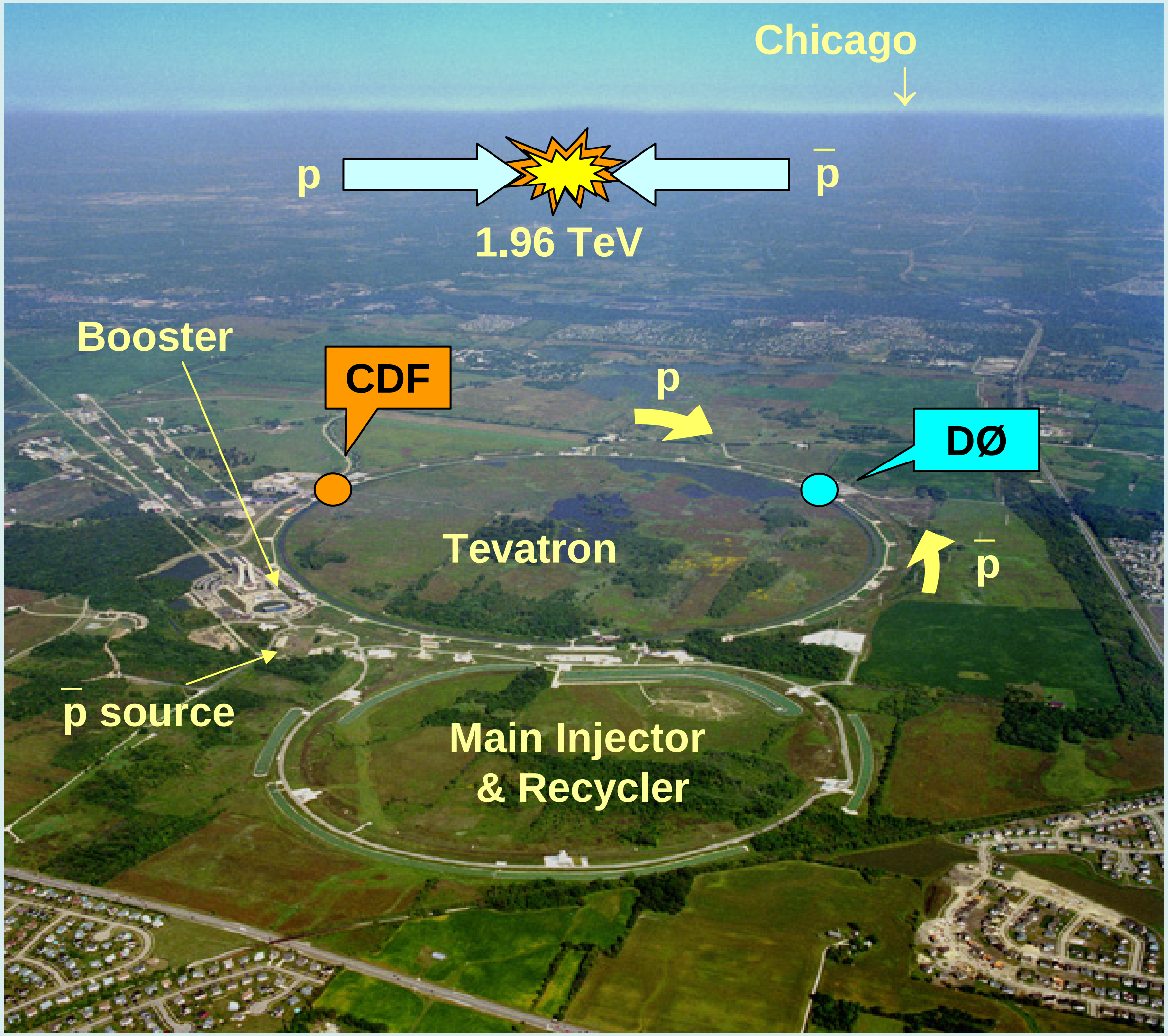
Fermilab Accelerators



Typical Detector



Tevatron Runs



Run I

1992-1996

E_{CM} = 1.8 TeV

~120 pb^{-1}

(0.63 TeV ~600 nb^{-1})

Run IIa

2002-2005

E_{CM} = 1.96 TeV

~ 1.5 fb^{-1}

Run IIb

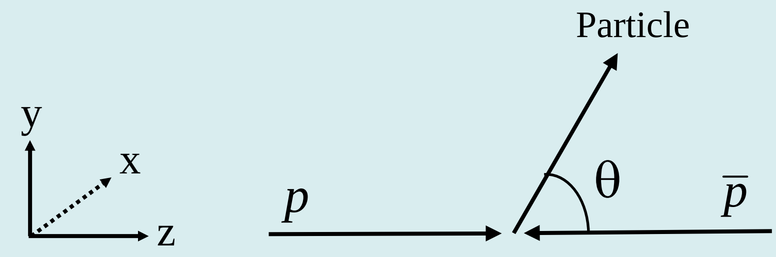
2006-2009

E_{CM} = 1.96 TeV

~4-8 fb^{-1}

Kinematics in Hadronic Collisions

Rapidity (y) and Pseudo-rapidity (η)



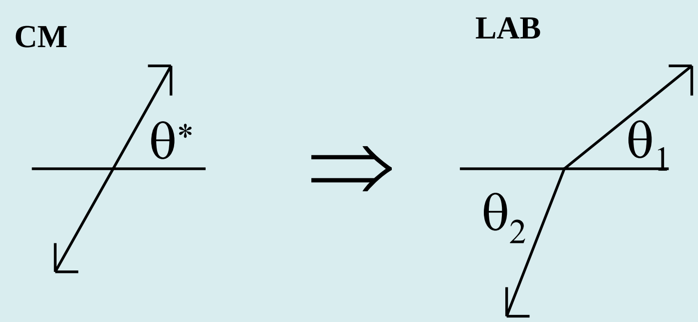
$$y \equiv \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta}$$

$$\beta\cos\theta = \tanh y \quad \text{where} \quad \beta = p/E$$

In the limit $\beta \to 1$ (or $m \ll p_T$) then

$$\eta \equiv y\big|_{m=0} = \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta} = -\ln\tan\frac{\theta}{2}$$

LAB System ≠ parton-parton CM system



Kinematics in Hadronic Collisions cont'd

Transverse Energy/Momentum

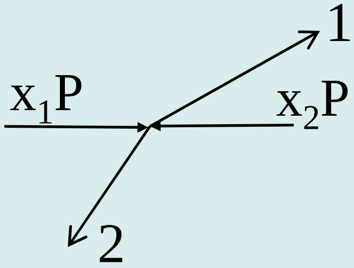
$$E_T^2 \equiv p_x^2 + p_y^2 + m^2 = p_T^2 + m^2 = E^2 - p_z^2$$

$$p_z = E \tanh y$$
$$E = E_T \cosh y$$
$$p_z = E_T \sinh y$$

$$p_T \equiv p \sin\theta$$

Invariant Mass

$$\begin{aligned} M_{12}^2 &\equiv (p_1^\mu + p_2^\mu)(p_{1\mu} + p_{2\mu}) \\ &= m_1^2 + m_2^2 + 2(E_1 E_2 - \boldsymbol{p}_1 \cdot \boldsymbol{p}_2) \\ &\xrightarrow[m_1, m_2 \to 0]{} 2 E_{T1} E_{T2} (\cosh \Delta\eta - \cos\Delta\phi) \end{aligned}$$



Partonic Momentum Fractions

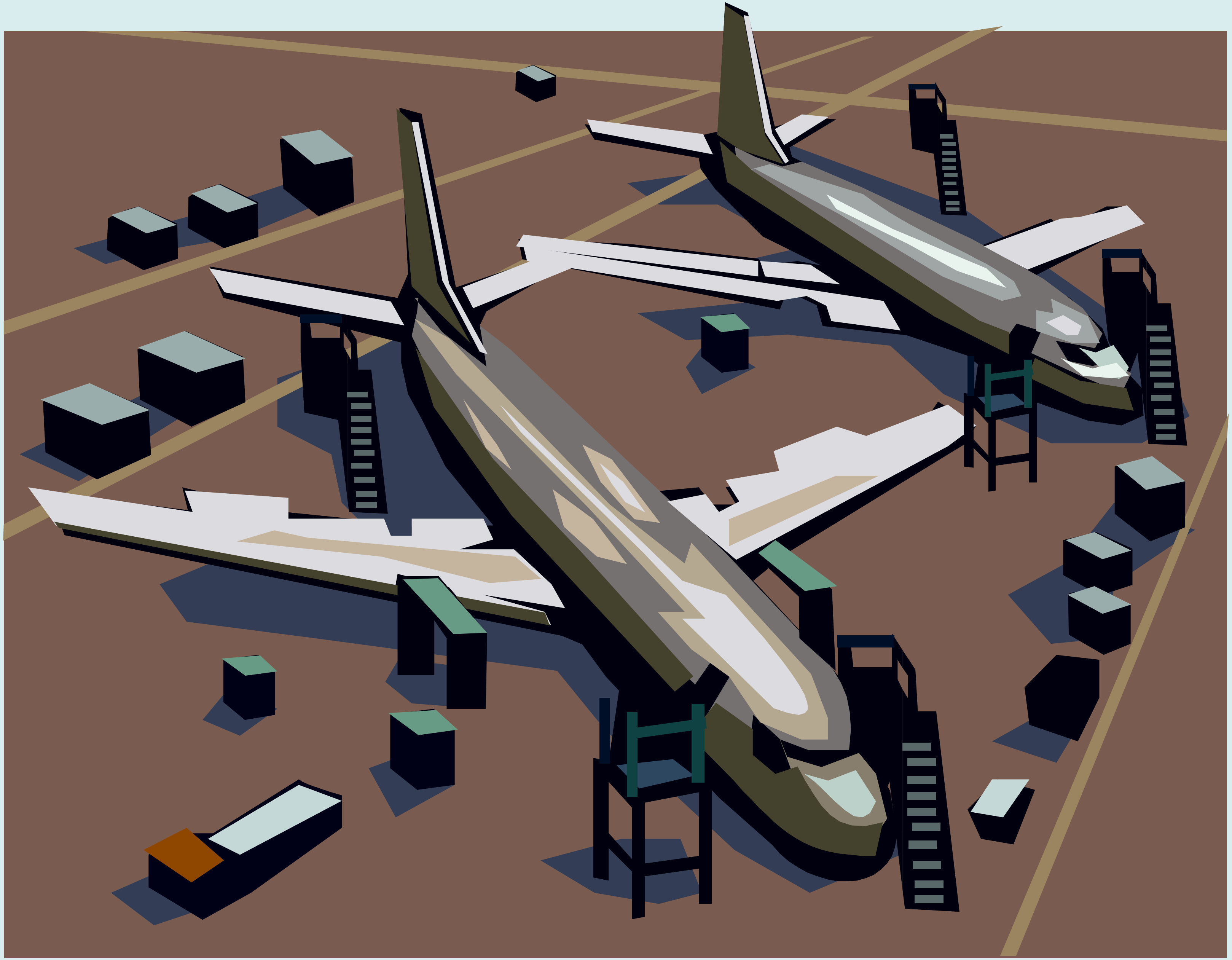
$$x_1 = \left(e^{\eta_1} + e^{\eta_2}\right) E_T / \sqrt{s}$$
$$x_2 = \left(e^{-\eta_1} + e^{-\eta_2}\right) E_T / \sqrt{s}$$

$$x_T \equiv 2E_T / \sqrt{s} = x_{1,2}(\eta_{1,2} = 0)$$

$$0 < x_1, x_2 < 1$$
$$x_T^2 < x_1 x_2 < 1$$

Parton CM (energy)^2 $\rightarrow \hat{s} = x_a x_b s$

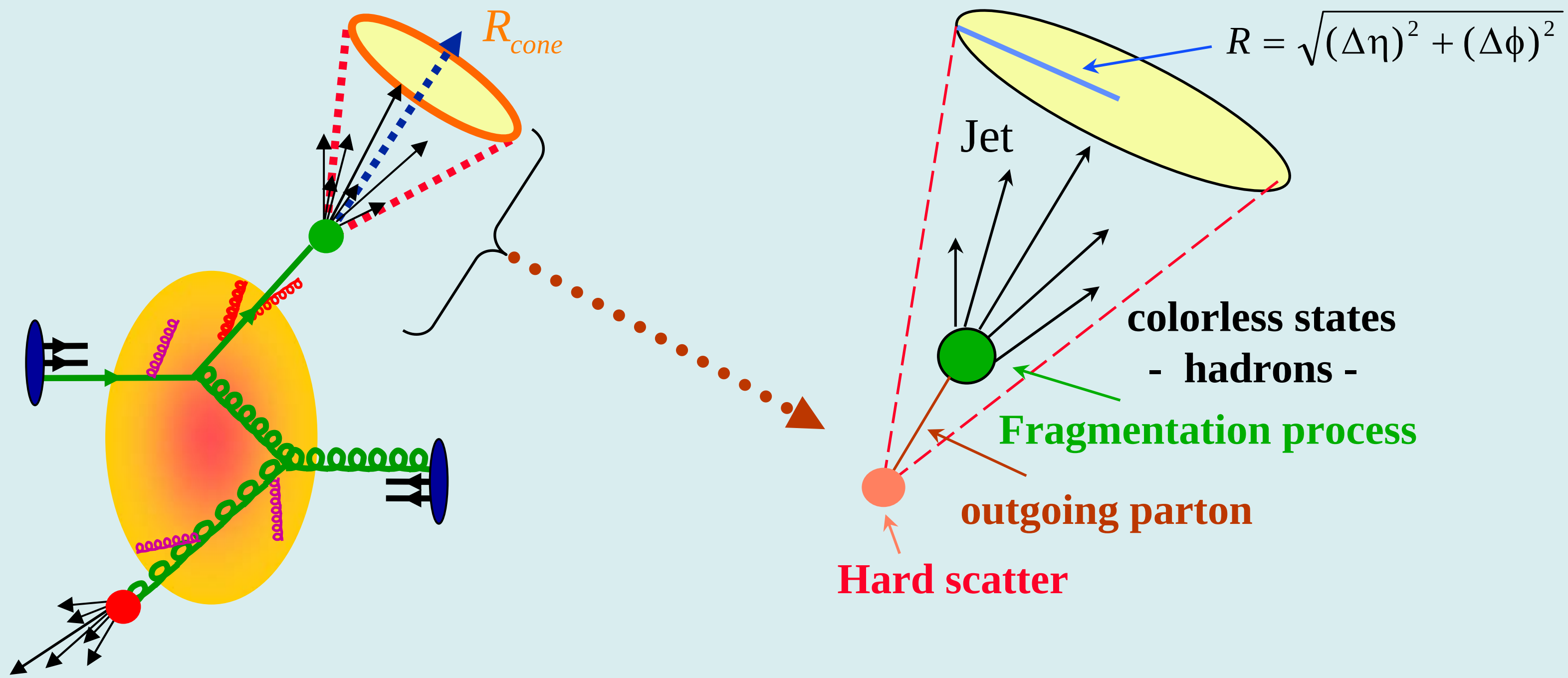
What are Jets ?



What are Jets ?

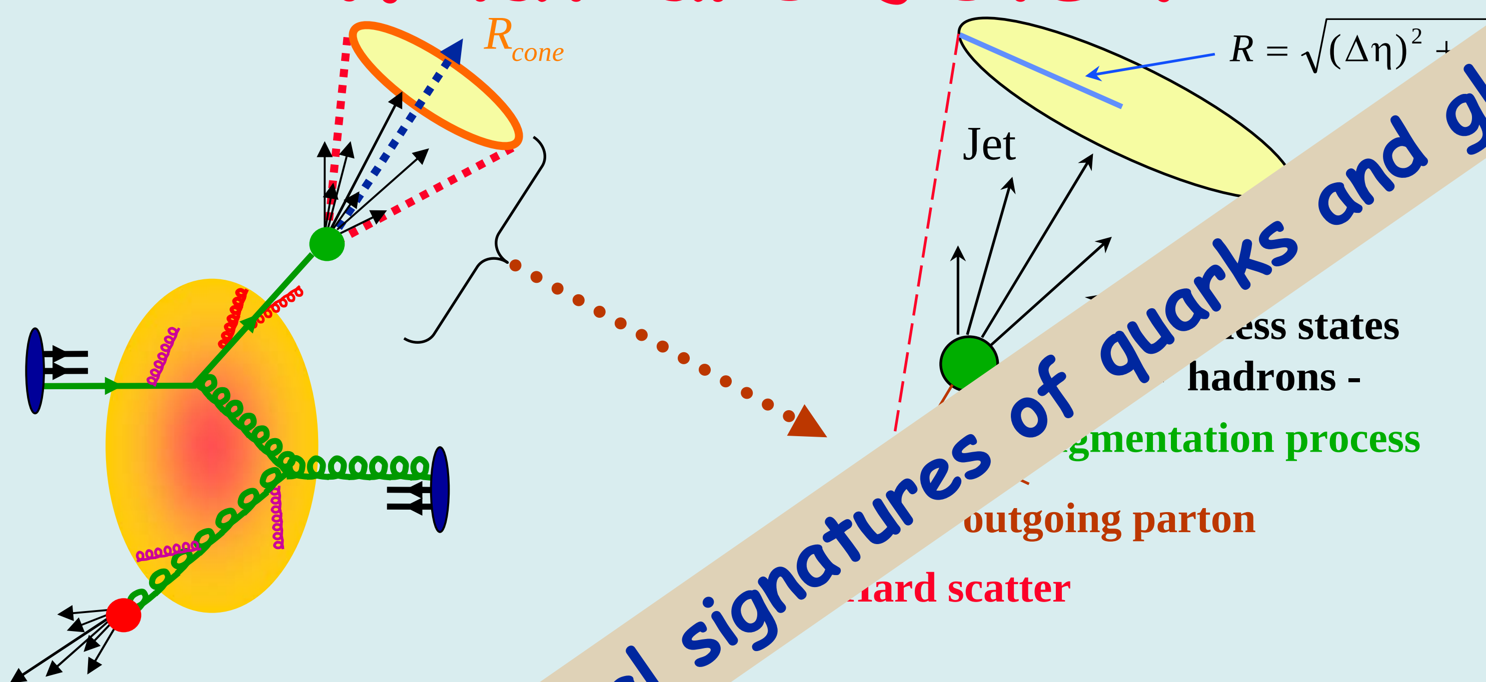
Whatever objects my jet algorithm finds!

What are Jets ?



- Colored partons from the hard scatter evolve via soft quark and gluon radiation and hadronization process to form a "spray" of roughly collinear colorless hadrons –> JETS
- The hadrons in a jet have small transverse momenta relative to their parent parton's direction and the sum of their longitudinal momenta roughly gives the parent parton momentum
  - Keep in mind that there are particles in a jet originating from other partons in the event
- Jets manifest themselves as localized clusters of energy

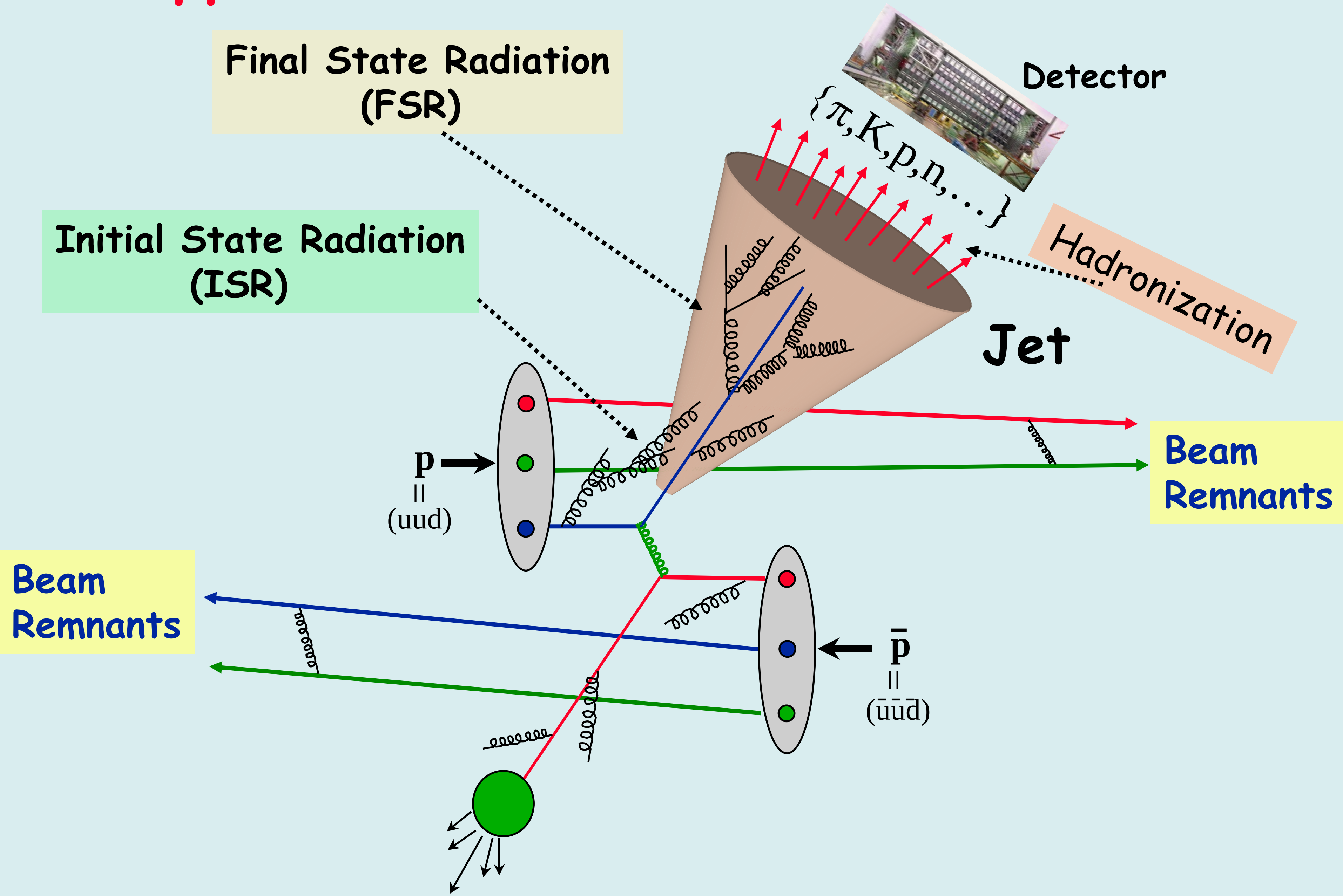
What are Jets ?



Jets are the experimental signatures of quarks and gluons

- Colored partons from th[illegible] d scatter evolve via soft quark and gluon radiation and hadro[illegible] n process to form a "spray" of roughly collinear colorle[illegible] ons –> JETS
- The hadron[illegible] jet have small transverse momenta relative to their parent [illegible] s direction and the sum of their longitudinal momenta rou[illegible] es the parent parton momentum
- [illegible] p in mind that there are particles in a jet originating from other partons in the event
- Jets manifest themselves as localized clusters of energy

$p\bar{p}$ Interactions – Creation of Jets



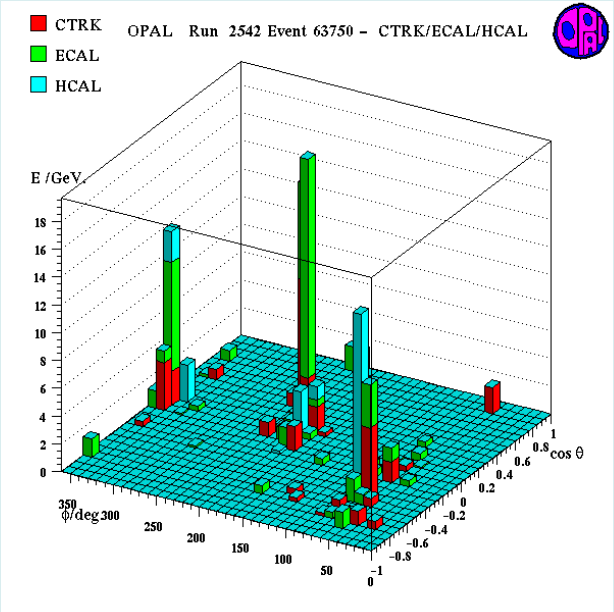
First Evidence for Jets

First experimental evidence of **quark**-initiated jets in e^+e^- annihilations, SLAC-SPEAR at $E_{cm} \sim 7$ GeV

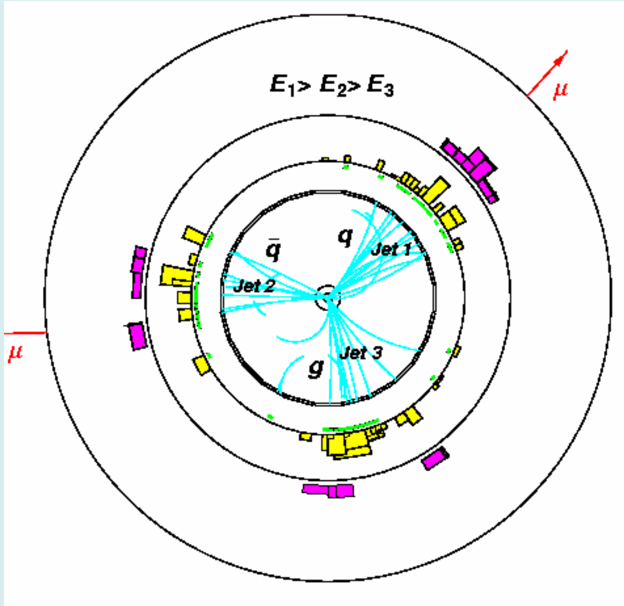
G. Hanson et al. (MARK-I Collab), PRL **35**, 1609 (1975)

Gluon-initiated jets were discovered in e+e- annihilations DESY-PETRA at $E_{cm} > 15$ GeV

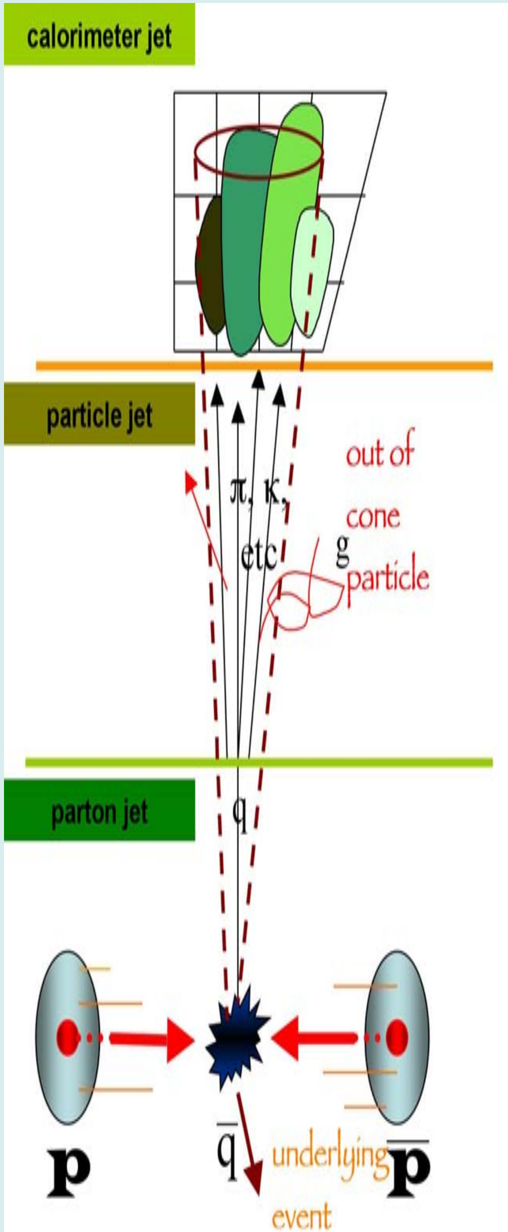
MARK-J Collab., PRL **43**, 830 (1979); TASSO Collab., Phys. Lett. **B86**, 243 (1979); PLUTO Collab., Phys. Lett. **B86**, 418 (1979); JADE Collab., Phys. Lett. **B91**, 142 (1980)



$$e^+e^- \to q\,\bar{q}\,g$$

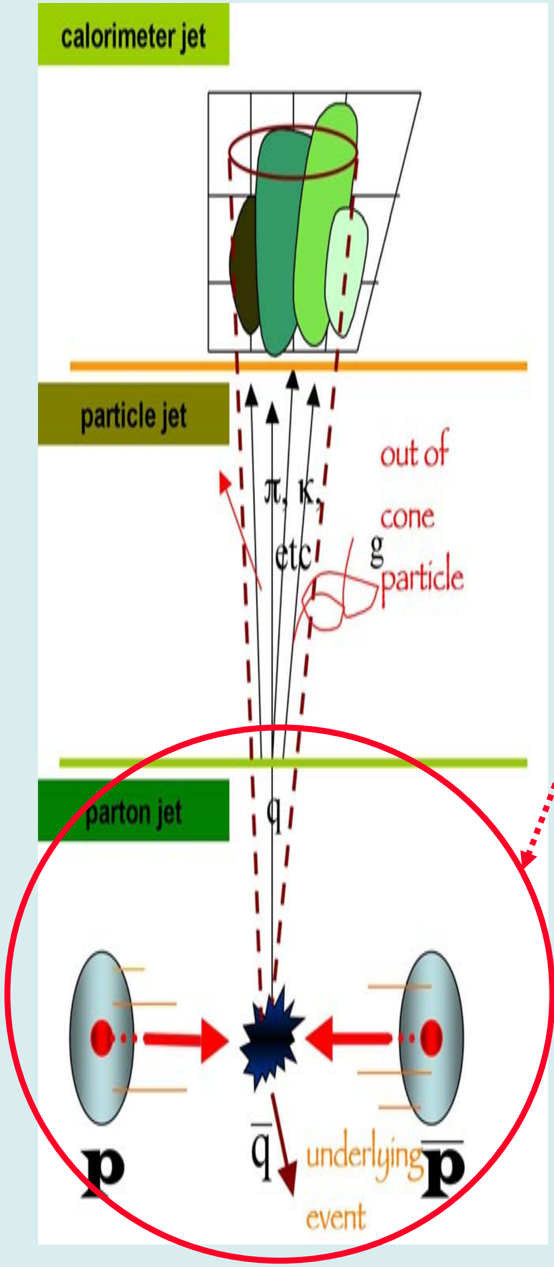


Jet Algorithms



The goal is to apply the "same" jet clustering algorithm to data and theoretical calculations without ambiguities

Jet Algorithms

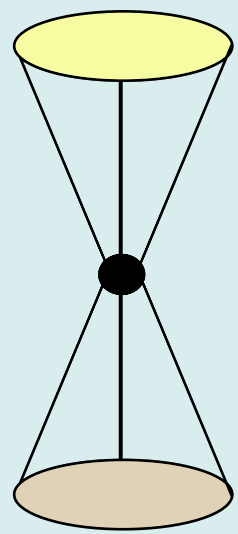


Th… g
alg… s
wi…

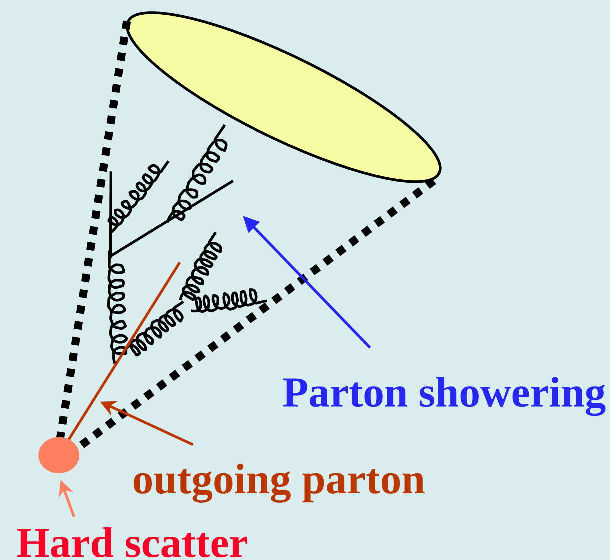
Jets at the "Parton Level" (i.e., before hadronization)

- Fixed order QCD or (Next-to-) leading logarithmic summations to all orders

2 → 2 process
Leading Order QCD

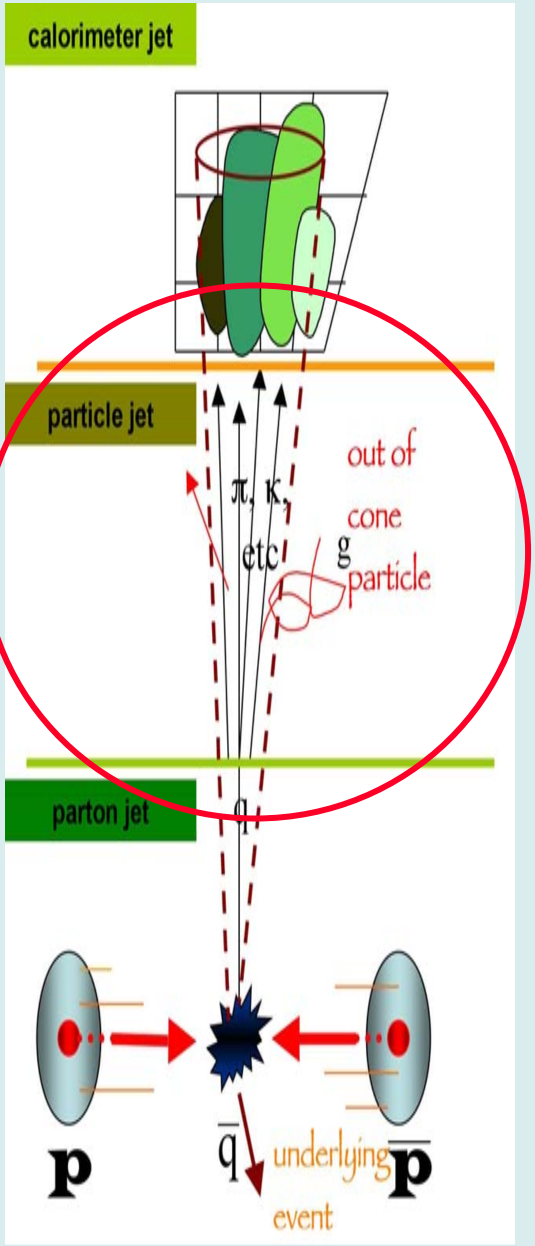


2-jet final state
1 parton/jet

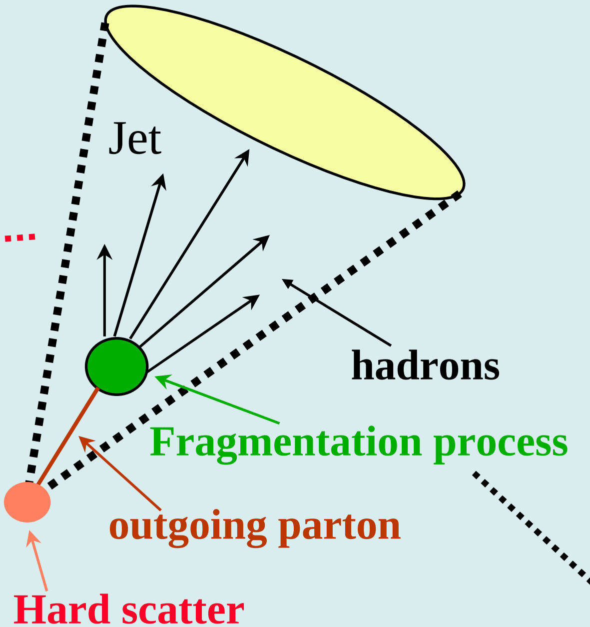


multi-jet final state

Jet Algorithms

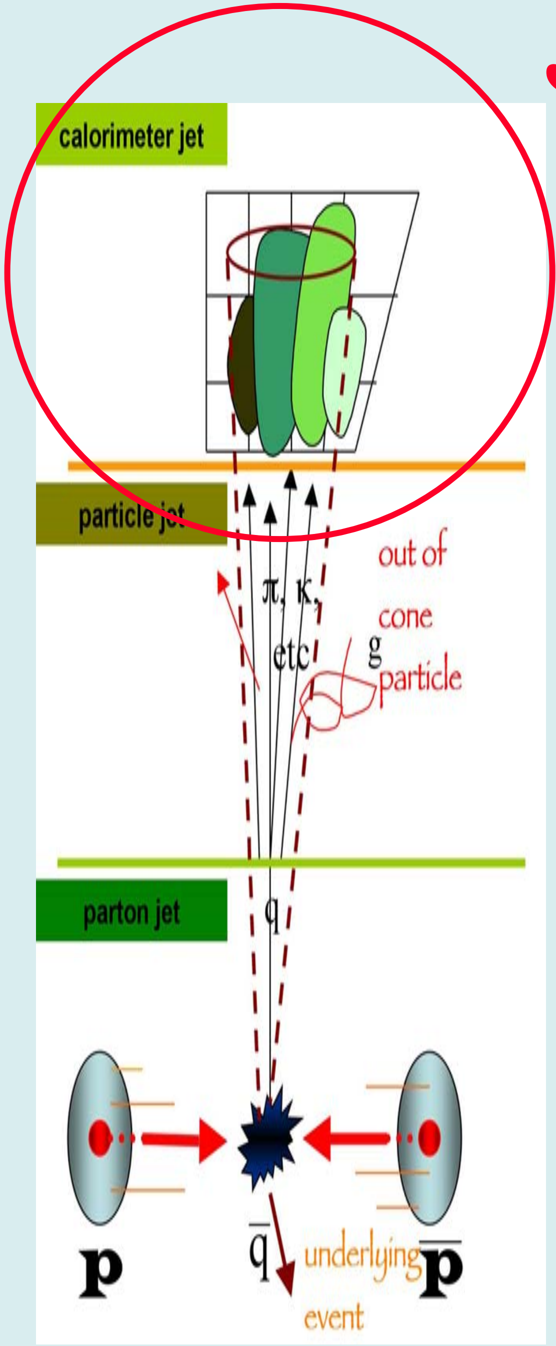


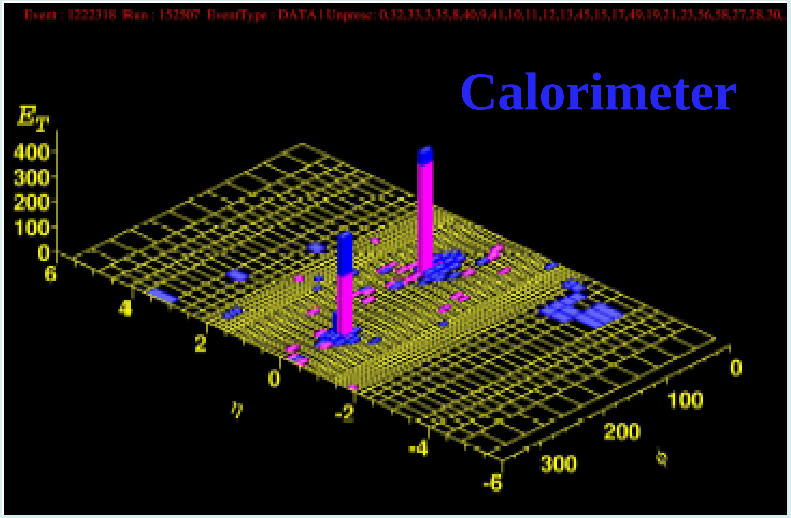
The idea is to come up with a jet algorithm which minimizes the non-perturbative hadronization effects



$\left\{ \begin{array}{l} \text{Parton showering} \\ \text{+ Hadronization} \end{array} \right\}$

Jet Algorithms





Jets at the "Detector Level"

Calorimeter - clusters of energy "towers"

Tracking - clusters of tracks

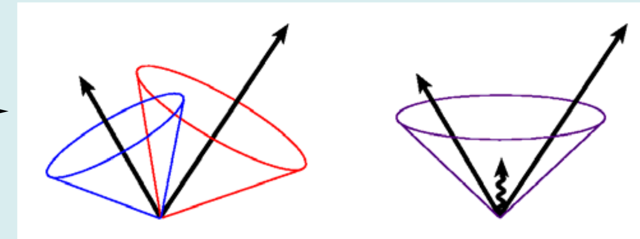
Combination of detectors

Calorimeter jet energy resolution:

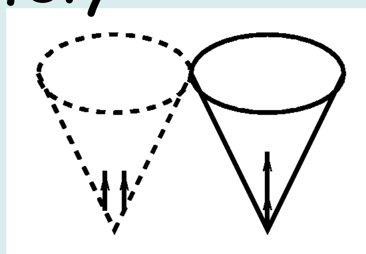
$$\frac{\sigma}{E_T} \approx \frac{80\%}{\sqrt{E_T}} \oplus 5\%$$

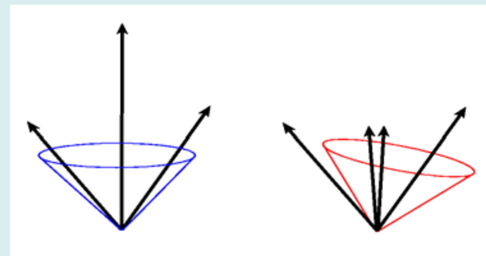
Jet Algorithms - Requirements

- **Theoretical:**
  - Infrared safety
    - insensitive to "soft" radiation



  - Collinear safety





  - Low sensitivity to hadronization
  - Invariance under boosts
  - Same jets at parton/particle/detector levels
  - Straight forward implementation
- **Experimental:**
  - Detector independence - Can everybody implement this?
  - Minimization of resolution smearing/angle bias
  - Stability with Luminosity
  - Computational efficiency
  - Maximal reconstruction efficiency

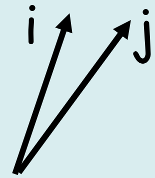
The full report of the Run II Jet algorithm specification is available at hep-ex/0005012

Jet Finders

(Generic Recombination)

- Define a resolution parameter y_{cut}
- For every pair of particles (i,j) compute the "separation" y_{ij} as defined for the algorithm

$$y_{ij} = \frac{M_{ij}^2}{E_{vis}^2}$$



- If $\min(y_{ij}) < y_{cut}$ then combine the particles (i,j) into k
  - E scheme: $p_k = p_i + p_j$ → massive jets
  - E_0 scheme: $E_k = E_i + E_j$ → massless jets

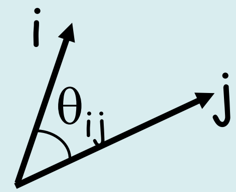
$$\boldsymbol{p}_k = E_k \frac{\boldsymbol{p}_i + \boldsymbol{p}_j}{\left|\boldsymbol{p}_i + \boldsymbol{p}_j\right|}$$

- Iterate until all particle pairs satisfy $y_{ij} > y_{cut}$
- No problems with jet overlap
- Less sensitive to hadronization effects

The JADE Algorithm

$$M_{ij}^{2} = 2E_i E_j (1 - \cos\theta_{ij})$$

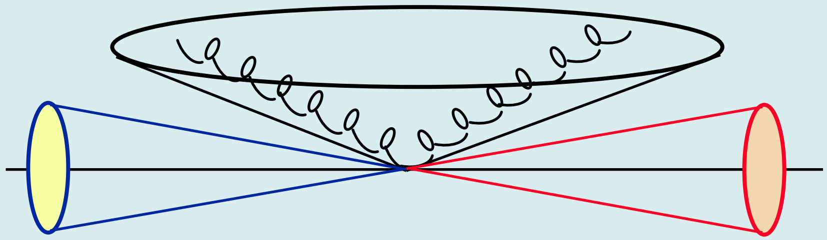
$$\min(y_{ij}) = \min(\frac{M_{ij}^{2}}{E_{vis}^{2}}) < y_{cut}$$ (E_{vis} is the sum of all particle energies)



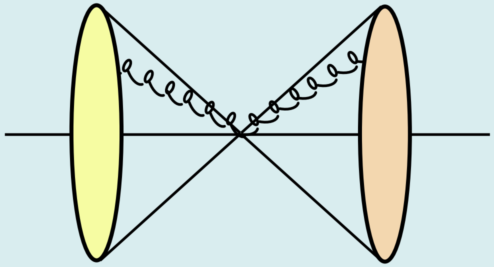
- Recombination: $p_k = p_i + p_j$
- Problems with this algorithm
  - It doesn't allow resummation when y_{cut} is small
  - Tendency to reconstruct "spurious" jets

i.e. consider the following configuration where two soft gluons are emitted close to the quark and antiquark

The gluon-gluon invariant mass can be smaller than that of any gluon-quark and therefore the event will be characterized as a 3-jet one instead of a 2-jet event



✗ 3-Jet event



√ 2-Jet event

The Durham or "k_T" Algorithm

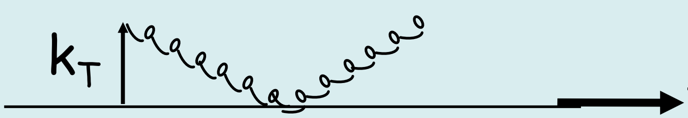
$$M_{ij}^2 = 2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})$$

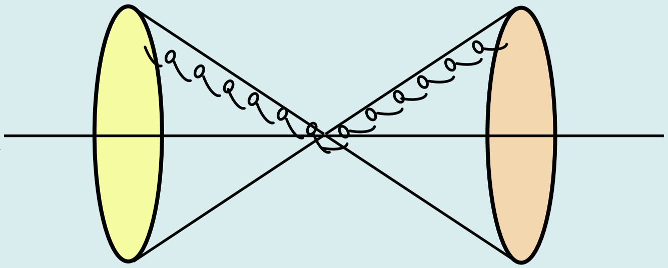
$$\min(y_{ij}) = \frac{M_{ij}^2}{E_{vis}^2} < y_{cut}$$

For small θ_{ij} we get :

$$M_{ij}^2 \approx 2\min(E_i^2, E_j^2)\left(1-(1-\frac{\theta_{ij}^2}{2}+\cdots)\right) \approx 2\min(E_i^2, E_j^2)\left(\frac{\theta_{ij}^2}{2}\right) \approx \min(k_{Ti}^2, k_{Tj}^2)$$

- Recombination: $p_k = p_i + p_j$
- It allows the resummation of leading and next-to-leading logarithmic terms to all orders for the regions of low y_{cut}





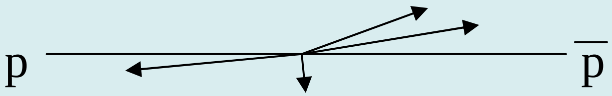
√ 2-Jet event

The "k_T" Jet Algorithm for Hadron Colliders

- The k_T jet algorithm successively merges pairs of partons, particles, calorimeter towers, or tracks in order of increasing relative transverse momentum (k_T)
- It contains a parameter D (~0.5-1) that controls the termination of the merging and characterizes the approximate size of the resulting jets
- k_T jets are infrared and collinear safe
- There are no overlapped jets
- Every parton, particle, or detector tower is unambiguously assigned to a single jet
- No biases from seed towers
- Less sensitive to hadronization effects

The "k_T" Algorithm cont'd

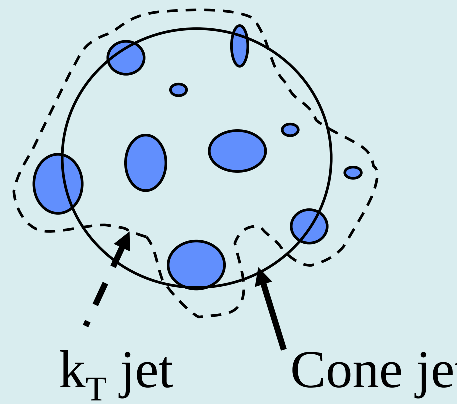
Input: List of Energy preclusters $(\Delta R_{precluster} \approx 0.2)$



$$d_{ij} = \min(p_{T,i}^2, p_{T,j}^2)\frac{\Delta R_{ij}^2}{D^2}$$

$$d_{ii} = p_{T,i}^2$$

D ~ 0.5-1



$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

Min d_{ij}?

Yes

Combine *i+j*

$$\mathbf{\vec{p}_{ij}} = \mathbf{\vec{p}_i} + \mathbf{\vec{p}_j}$$

$$\mathbf{E_{ij}} = \mathbf{E_i} + \mathbf{E_j}$$

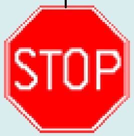
No

Move *i* to list of jets

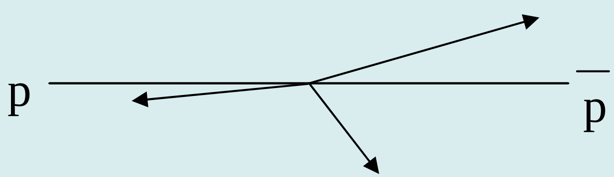
Any left?

Yes

No

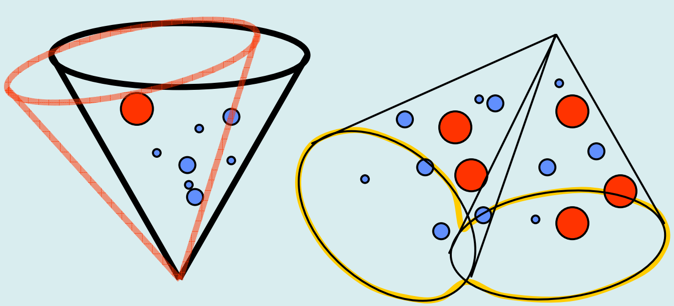


Output: List of jets $(\Delta R \geq D)$



The Cone Jet Algorithm for Hadron Colliders

- A more intuitive representation of a jet that is given by recombination jet finders
- It requires "seeds" with a minimum energy of $\leq$ 1 GeV (to save computing time)
  - Preclusters are formed by combining seed towers with their neighbors within a cone of radius R is $\eta-\phi$ space
  - For each precluster the ET-weighted centroid is found and a new cone of radius R is drawn around it
  - Iterate until stable solution is found
- Jet cones may overlap so need to split/merge overlapping jets

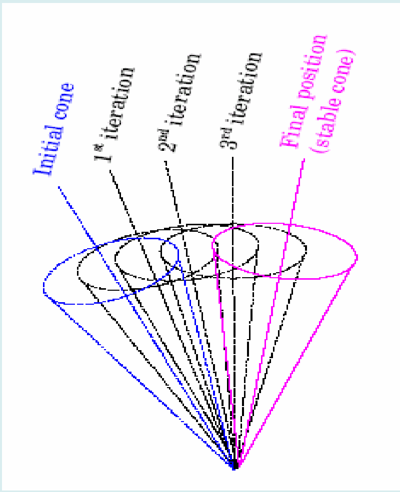


Calorimeter E_T

Jet Seeds

Merge if shared
E_T > 50-75% of min(E_{T1},E_{T2})

DØ - CDF



The DØ/CDF Jet Cone Algorithm for Run I

In Run I: DØ and CDF used Snowmass (1990) clustering and defined angles via momentum vectors

$$
\begin{aligned}
E^i_x &= E^i_T \cdot \cos(\phi^i)\ , \\
E^i_y &= E^i_T \cdot \sin(\phi^i)\ , \\
E^i_z &= E^i \cdot \cos(\theta^i)\ , \\
E^J_{x,y,z} &= \sum_{i \subset J=C} E^i_{x,y,z}\ , \\
\theta^J &= \tan^{-1}\left(\frac{\sqrt{(E^J_x)^2 + (E^J_y)^2}}{E^J_z}\right).
\end{aligned}
$$

$$i \subset C \quad : \quad \sqrt{(\eta^i - \eta^C)^2 + (\phi^i - \phi^C)^2} \leq R. \qquad (1)$$

In the Snowmass algorithm a "stable" cone (and potential jet) satisfies the constraints

$$\eta^C = \frac{\sum_{i \subset C} E^i_T \eta^i}{E^C_T}, \quad \phi^C = \frac{\sum_{i \subset C} E^i_T \phi^i}{E^C_T} \qquad (2)$$

(*i.e.*, the geometric center of the previous equation is identical to the E_T-weighted centroid) with

$$E^C_T = \sum_{i \subset C} E^i_T\ . \qquad (3)$$

DØ and CDF's Angles:

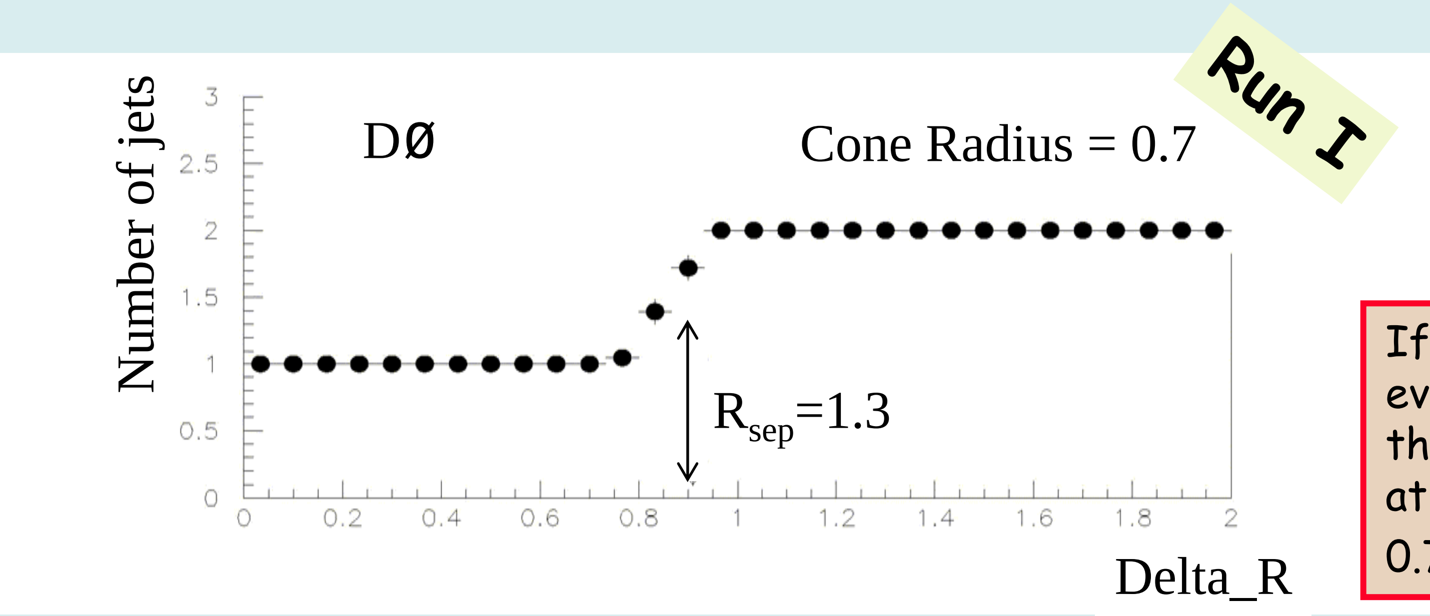
$$
\begin{aligned}
\eta^J &= -\ln\left(\tan\left(\frac{\theta^J}{2}\right)\right)\ , \\
\phi^J &= \tan^{-1}\left(\frac{E^J_y}{E^J_x}\right).
\end{aligned}
$$

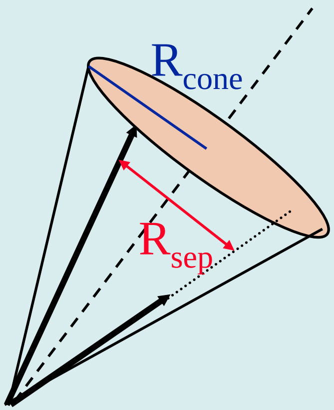
CDF's E_T: $$E^J_T = E^J \cdot \sin(\theta^J), \quad E^J = \sum_{i \subset J} E^i\ .$$

DØ's E_T: $$\boxed{E^J_T = \sum_{i \subset J} E^i_T}$$

The Cone Algorithm at 3-Parton Final States

- Apply Snowmass jet algorithm
  - Each parton must be within R_{cone} of centroid
- The two partons must be within $R_{sep} \times R_{cone}$ of one another, where R_{sep} varies from 1 - 2 (R_{sep}=1.3 for DØ/CDF)
  - introduce *ad-hoc* parameter R_{sep} to control parton recombination in the theoretical jet algorithm and simulate the role of seeds and merging in the experimental algorithm
  - it <u>doesn't</u> generalize to higher orders





If jets from separate events are overlaid then they can be distinguished at $1.3 \times R_{cone}$=0.9 for 0.7 cone jets:

The Next Generation of Cone Algorithm

- Issues with the Snowmass Cone Algorithm
  - Sensitivity to infrared and collinear radiation
  - Not proper 4-vector kinematics used in particle clustering and in calculating the final jet parameters

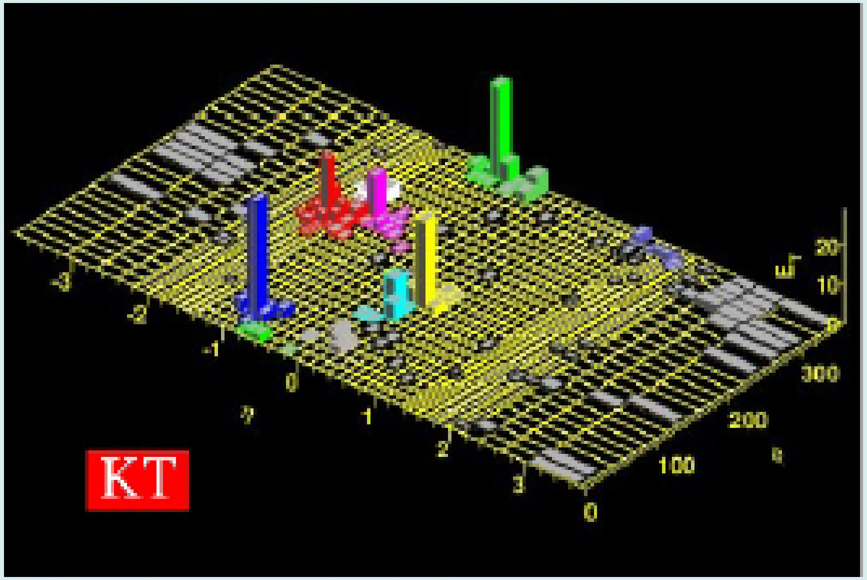
- The Solution: Develop a "seedless" jet algorithm with proper kinematics
  - Infrared and Collinear safe
  - Very computationally intensive

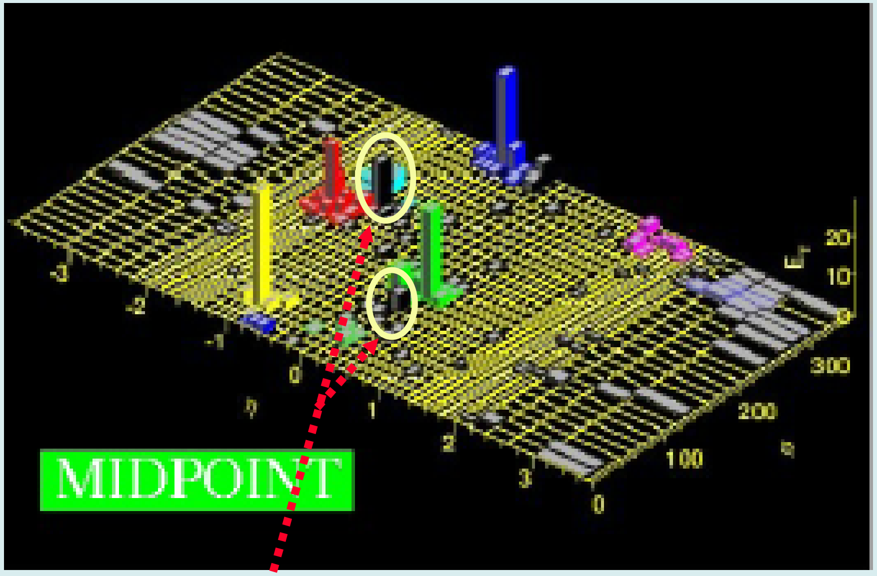
- What was done: Develop the Midpoint jet algorithm
  - Approximates the seedless algorithm
  - Infrared safe
  - Proper 4-vector kinematics used in all steps → massive jets

The Midpoint Jet Cone Algorithm for Run II

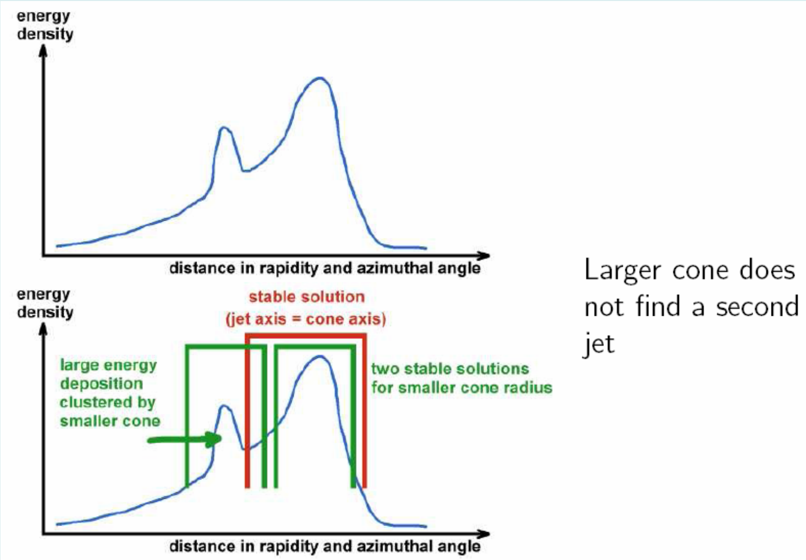
- Proto-jets are formed by combining seed particles with their neighbors within a cone of radius R_{cone} using the E-scheme
  - Particles = calorimeter towers, MC hadrons or partons
- Midpoint seeds are added between proto-jets
  - Only midpoints between proto-jets satisfying the following conditions are considered: $\Delta R > R_{cone}$ and $\Delta R < 2 \times R_{cone}$
- Proto-jets found around seeds and midpoints can share particles
  - Merging/splitting procedure has to be applied
  - Merge jets, if more than a fraction f (50% for DØ, 75% for CDF) of $\min(p_{T1}, p_{T2})$ of overlapping jets is contained in the overlap region
  - Otherwise split jets; assign the particles in the overlap region to the nearest jet
- Keep only final jets with $p_T >$ threshold

Not a Perfect World After All!





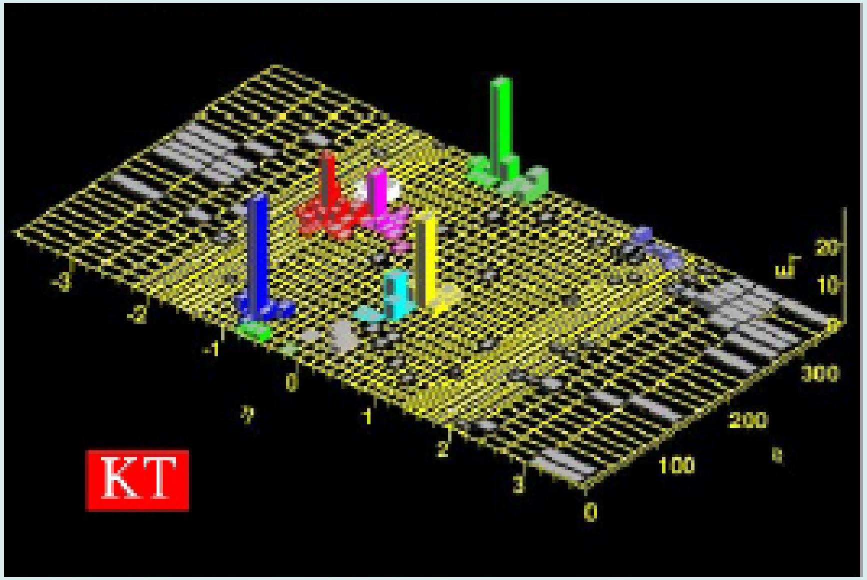
Significant amounts of energy is not clustered in Midpoint algorithm

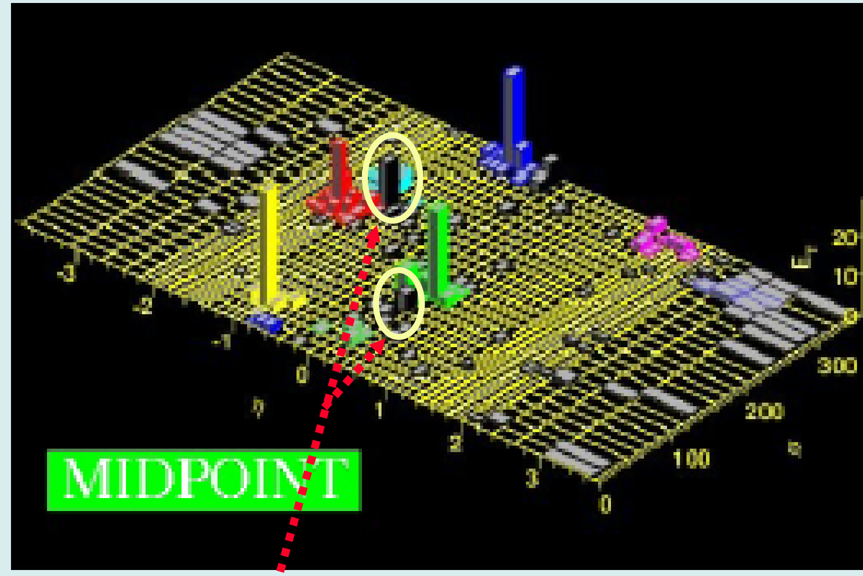


Overall this effect is <u>quite</u> small

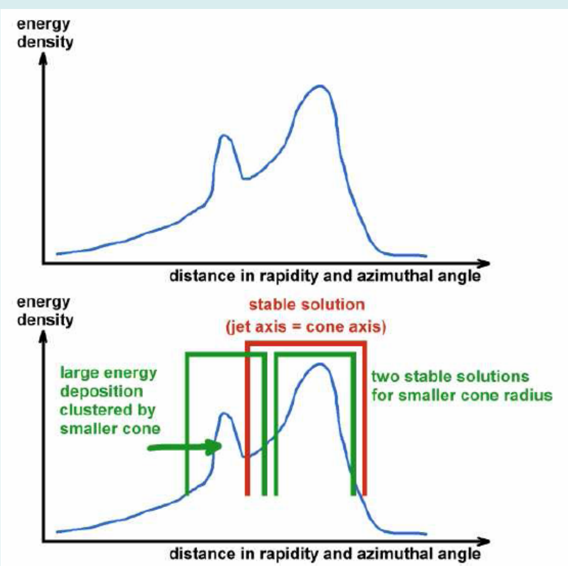
To reduce this effect CDF is using two values for the cone radius: one during search for stable cones ($R_{cone}/2$) and the second (R_{cone}) during the calculation of the final jet properties → Search Cone Algorithm… *this leads to other "features"*

Not a Perfect World After All!





Significant amounts of energy is not clustered in Midpoint algorithm



Larger cone does not find a second jet

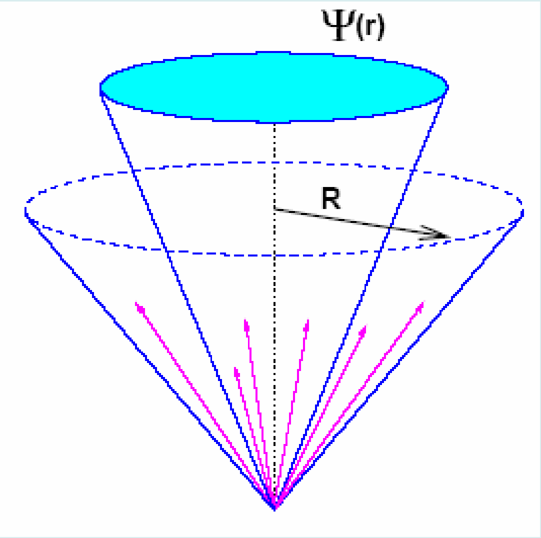
Overall this effect is quite small

To reduce this effect CDF i... two values for the cone r... ...ing search for stab... ...one/2) and the secon... ...g the calculation of t... ...operties → Search Co... ...thm... *this leads to other "features"*

This effect is currently under study between the two experiments

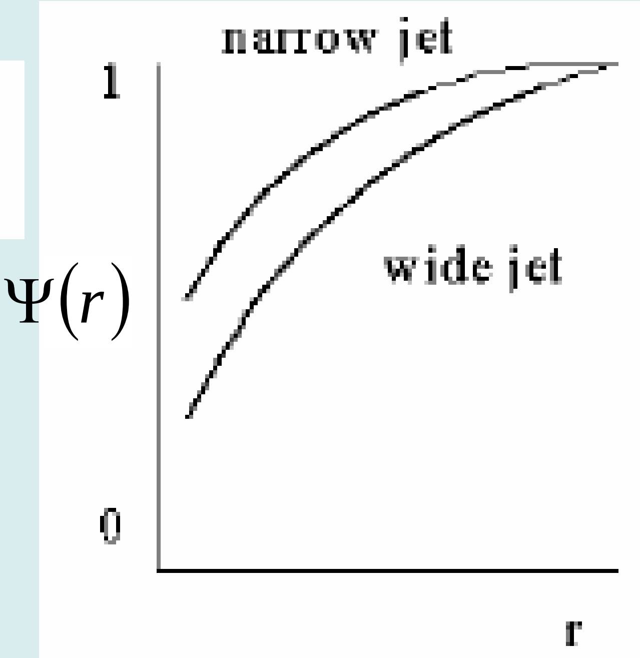
Looking Inside the Jets

- The investigation of jet profiles gives insights into the transition between the parton produced in the hard process and the observed spray of hadrons
- Jet profiles are sensitive to the quark/gluon jet mixture
  - Could separate quark and gluon jets in a statistical way
- **Energy Flow (Jet Shape):**
  - Measure the average transverse energy flow in sub-cones as a function of radial distance from the jet axis
  - Use calorimeter towers or charged tracks



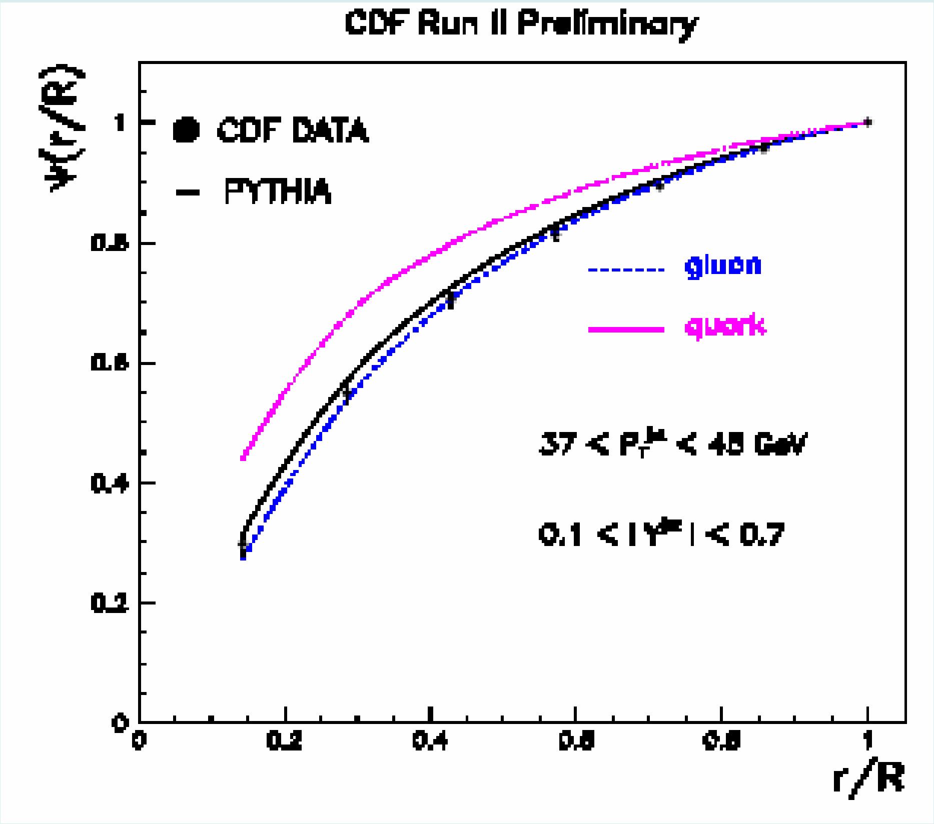
$$\Psi(r) = \frac{1}{N_{jets}} \Sigma_{jets} \frac{P_T(0,r)}{P_T(0,R)}$$

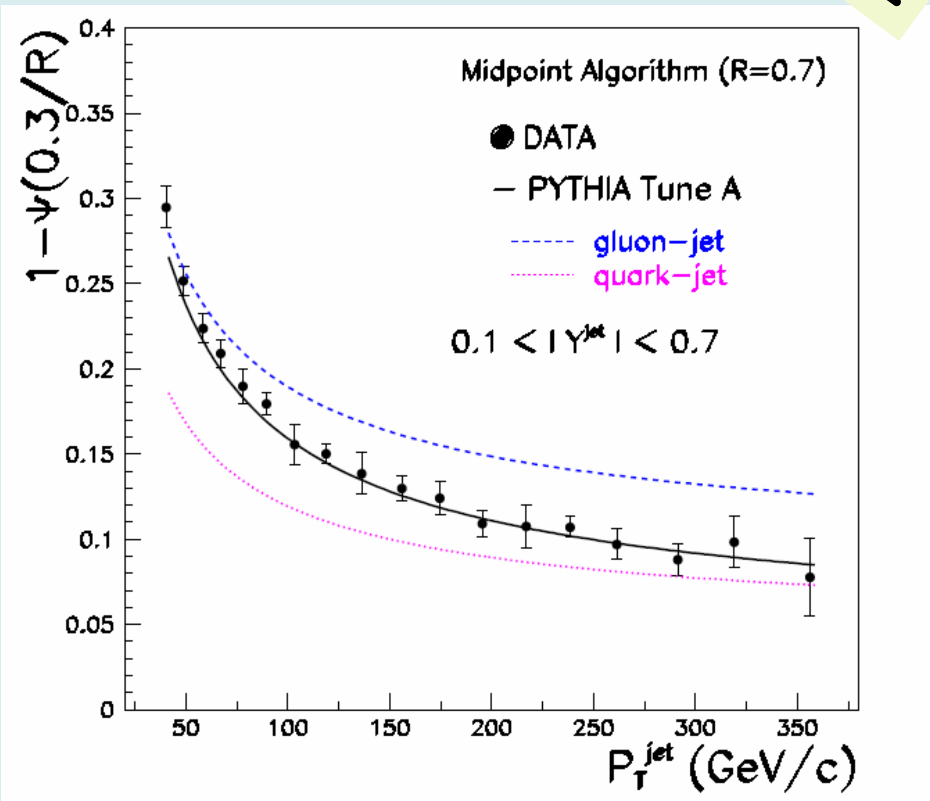
$$r = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$



Jet energy profiles at Tevatron

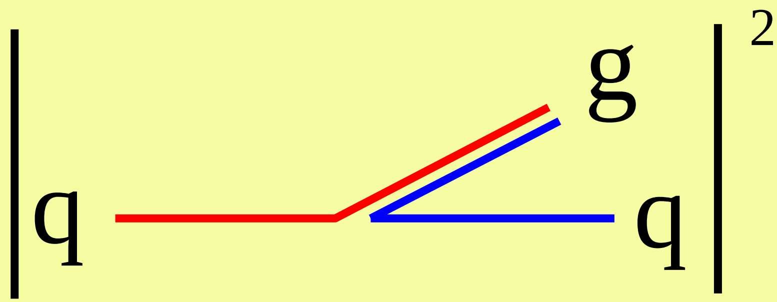
Run II



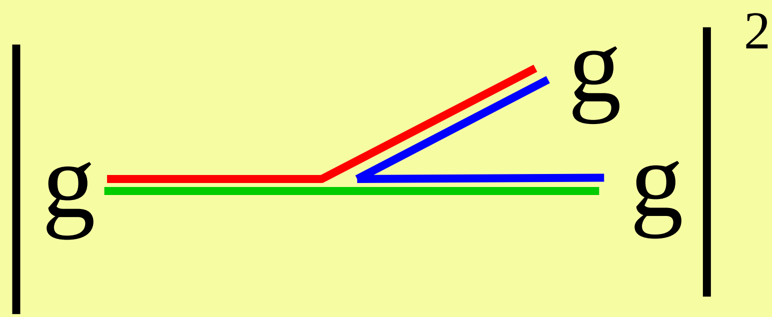


Gluon enriched jets (low-x/low-p_T jets at Tevatron) are "broader" (i.e. less collimated, higher multiplicity of soft energy particles) than Quark-enriched jets (high-x/high-p_T jets)

Quark & Gluon jets radiate proportional to their color factor:



$\sim C_F = 4/3$



$\sim C_A = 3$

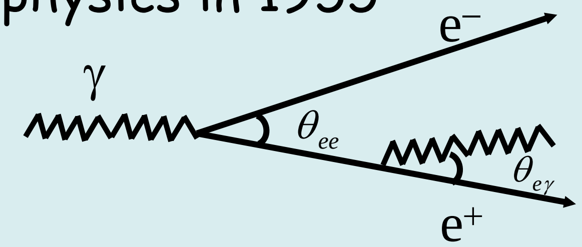
$$r \equiv \frac{< n_g >}{< n_q >} \equiv \frac{< \text{gluon jet multiplicity} >}{< \text{quark jet multiplicity} >}$$

At Leading Order ($E_{jet} \to \infty$): $r \sim \dfrac{C_A}{C_F} = \dfrac{9}{4} = 2.25$

With higher order corrections at E_{jet} (LEP) ~ 40 GeV: $r \sim 1.5$

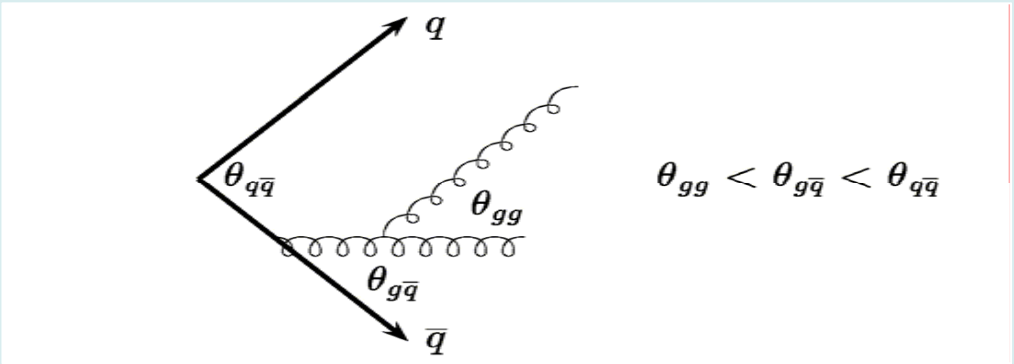
Coherence

- **Property of gauge theories.** Similar effect in QED, the "Chudakov effect" observed in cosmic ray physics in 1955



$$\theta_{ee} > \theta_{e\gamma}$$

- In QCD color coherence effects are due to the interference of soft gluon radiation emitted along color connected partons
- **Two types of Coherence:**
  - Intrajet Coherence
    - *Angular Ordering of the sequential parton branches in a partonic cascade*



  - Interjet Coherence
    - String or Drag effect in multijet hadronic events

Shower Development

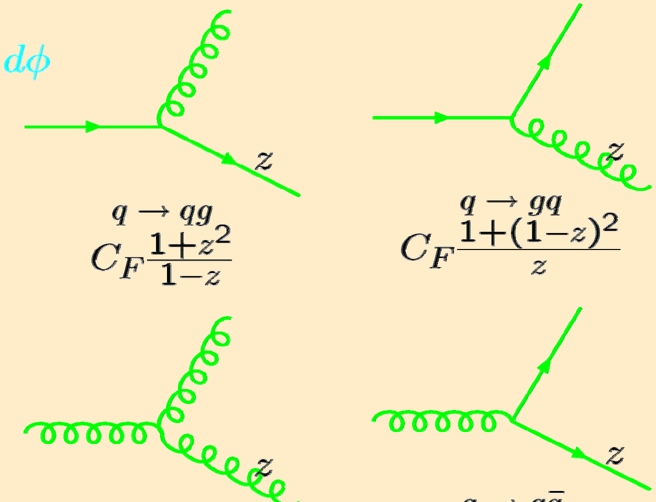
"Traditional Approach"

- Shower develops according to pQCD into spray of partons until a scale of $Q_0 \sim 1$ GeV.
- Thereafter, non-perturbative processes take over and produce the final state hadrons
- Coherence effects are included probabilistically (e.g., Angular Ordering, color dipole) and in the hadronization model

$$d\sigma = \sigma_0 \frac{\alpha_s}{2\pi} \frac{d\theta^2}{\theta^2} dz \, P(z, \phi) d\phi$$

$$P(z, \phi) =$$

DGLAP Splitting Kernel



$q \to qg$: $C_F \frac{1+z^2}{1-z}$

$q \to gq$: $C_F \frac{1+(1-z)^2}{z}$

$g \to gg$: $C_A \frac{z^4+1+(1-z)^4}{z(1-z)}$

$g \to q\bar{q}$: $T_R \left(z^2 + (1-z)^2\right)$

Shower Development

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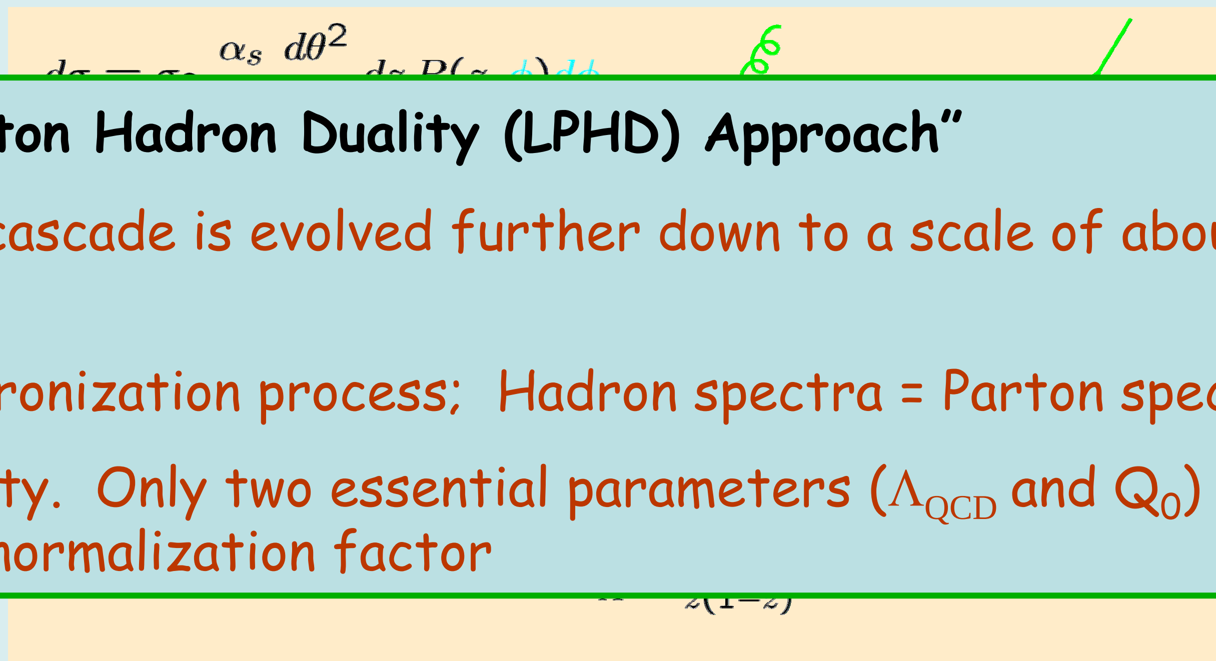
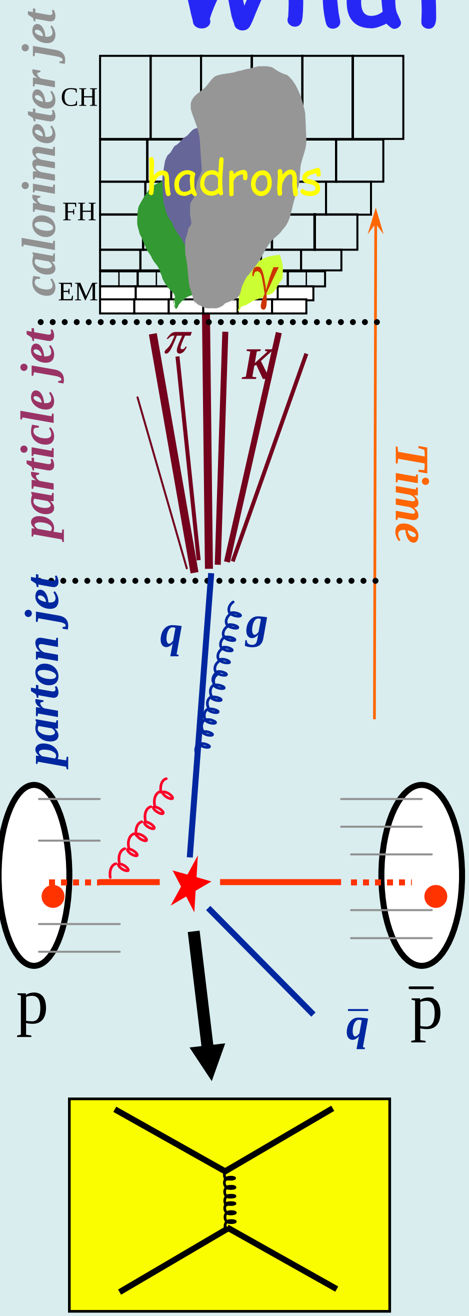


"Local Parton Hadron Duality (LPHD) Approach"

- Parton cascade is evolved further down to a scale of about $Q_0 \sim 250$ MeV.
- No hadronization process; Hadron spectra = Parton spectra
- Simplicity. Only two essential parameters (Λ_{QCD} and Q_0) and an overall normalization factor

What is an Event Generator ?

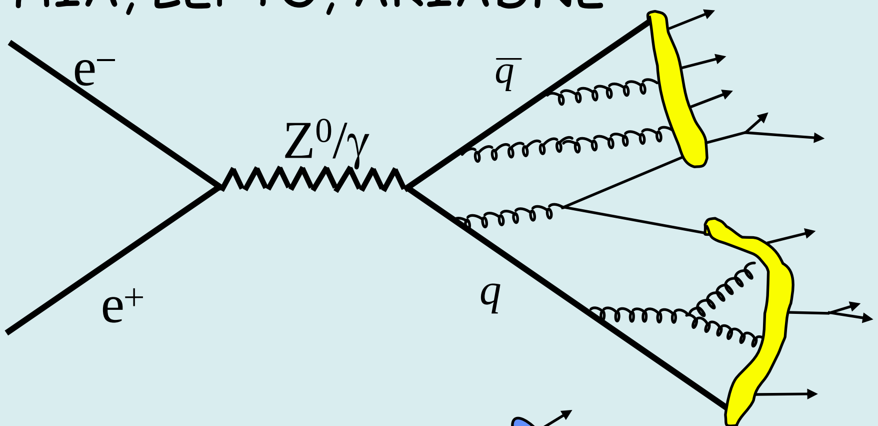


- A "C" (of "Fortran") program that generates events, trying to simulate Nature!
- Events vary from one to the next (random numbers)
- Expect to reproduce average behavior and fluctuations of real data
- Event Generators include:
  - Parton Distribution functions
  - Initial state radiation
  - Hard interaction
  - Final state radiation
  - Beam jet structure
  - Multiple Parton Interactions
  - Hadronization and decays
- Some programs in the market:
  - JETSET, PYTHIA, LEPTO, ARIADNE, HERWIG, COJETS...
- Some parton-level only:
  - VECBOS, NJETS, JETRAD, HERACLES, COMPOS, ALPGEN, PAPAGENO, MADGRAPH, EUROJET...

Hadronization Models

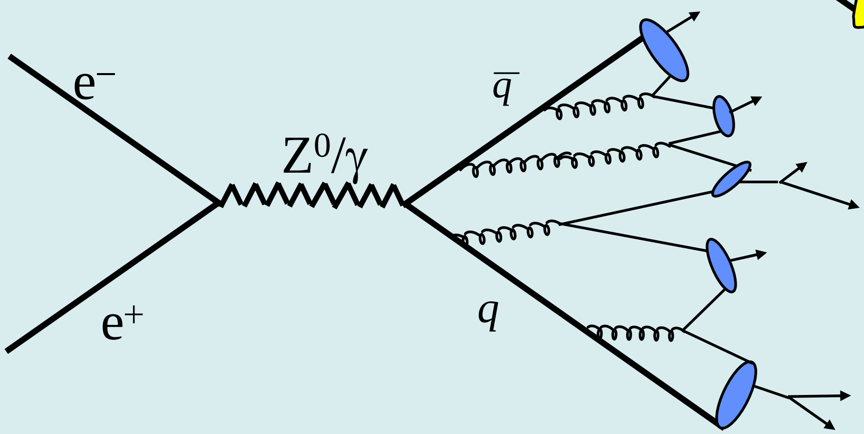
- **Independent fragmentation**
  - it is being used in ISAJET and COJETS
  - simplest scheme - each parton fragments independently following the approach of Field and Feynman
- **String fragmentation**
  - it is being used in JETSET, PYTHIA, LEPTO, ARIADNE

***String Fragmentation*: Separating partons connected by color string which has uniform energy per unit length, corresponding to a linear quark confining potential**



- **Cluster fragmentation**
  - it is being used in HERWIG

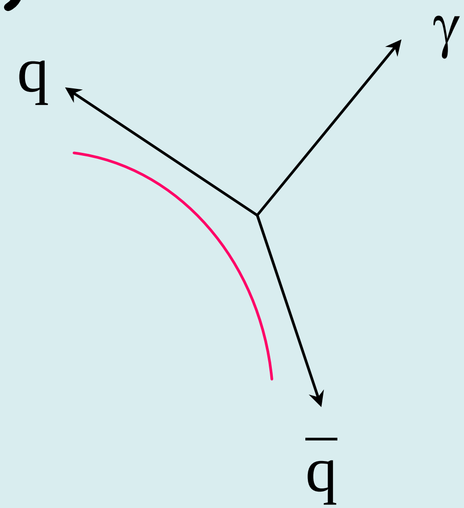
***Cluster Fragmentation*: Pairs of color connected <u>neighboring</u> partons combine into color singlets.**

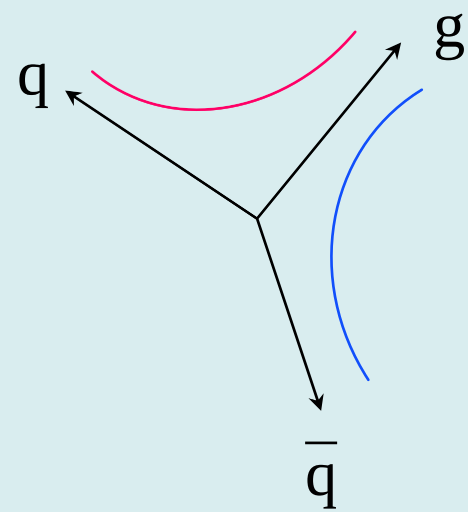


Coherence Observations

e^+e^- **interactions:**

First observations of final state color coherence effects in the early '80's (JADE, TPC/2g, TASSO, MARK II Collaborations) **("string" or "drag" effect)**

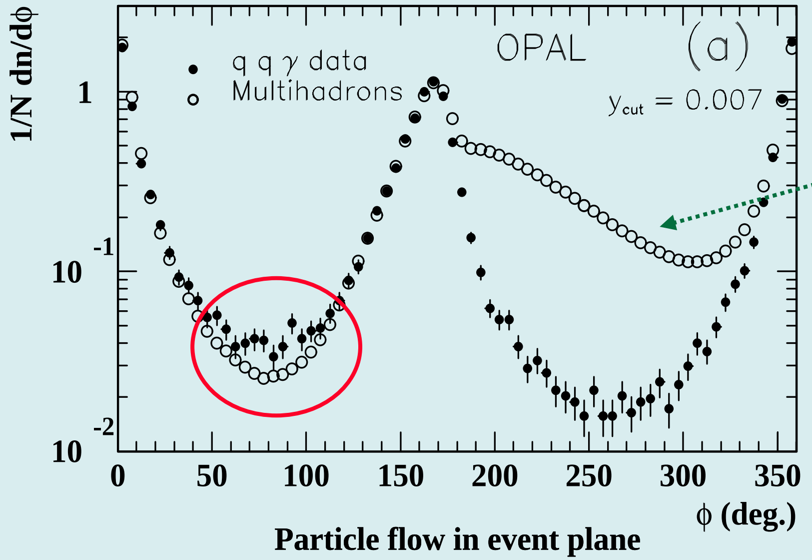




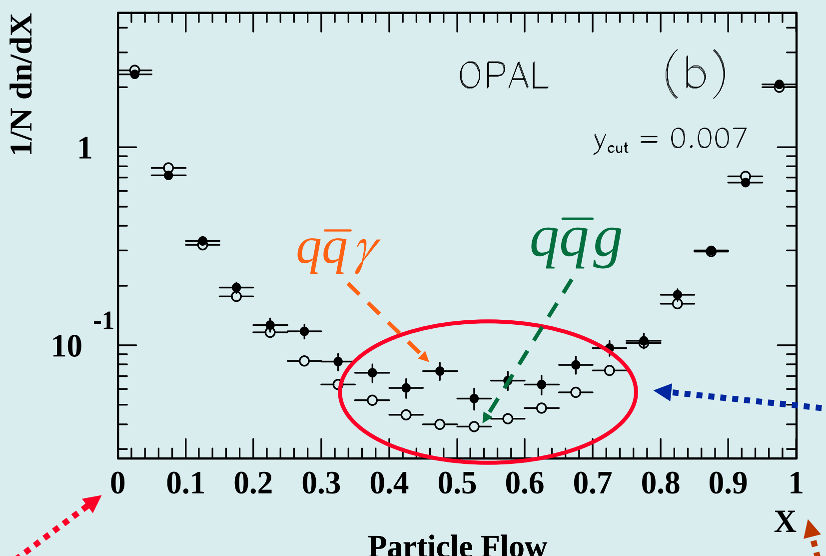
$$e^+e^- \rightarrow q\,\bar{q}\,\gamma \qquad\qquad e^+e^- \rightarrow q\,\bar{q}\,g$$

Depletion of particle flow in region between q and $\bar{q}$ jets for $q\bar{q}g$ events relative to that of $q\bar{q}\gamma$ jets.

$e^+e^- \to q\bar{q}\gamma$ vs $e^+e^- \to q\bar{q}g$



Gluon jet

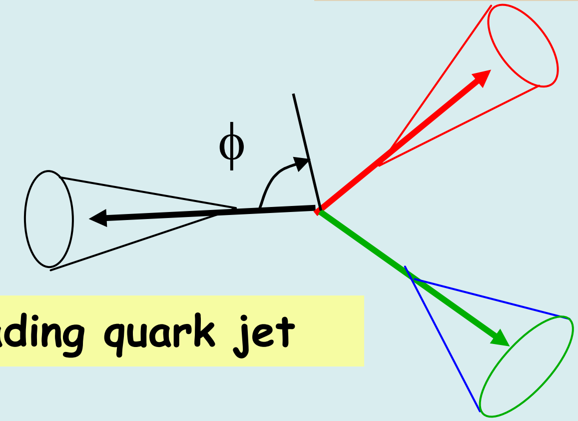


$q\bar{q}\gamma$ $q\bar{q}g$

String effect

Leading quark jet

2nd quark jet



2nd quark jet

Leading quark jet

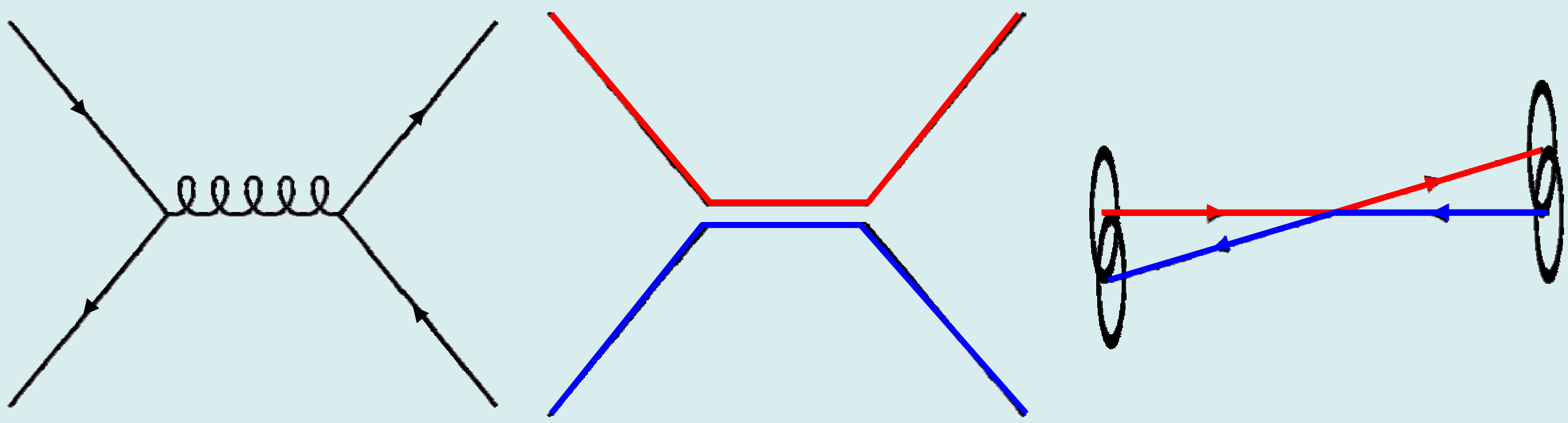
gluon jet or photon

Data agree with analytic LPHD calculations

Coherence Observations cont'd

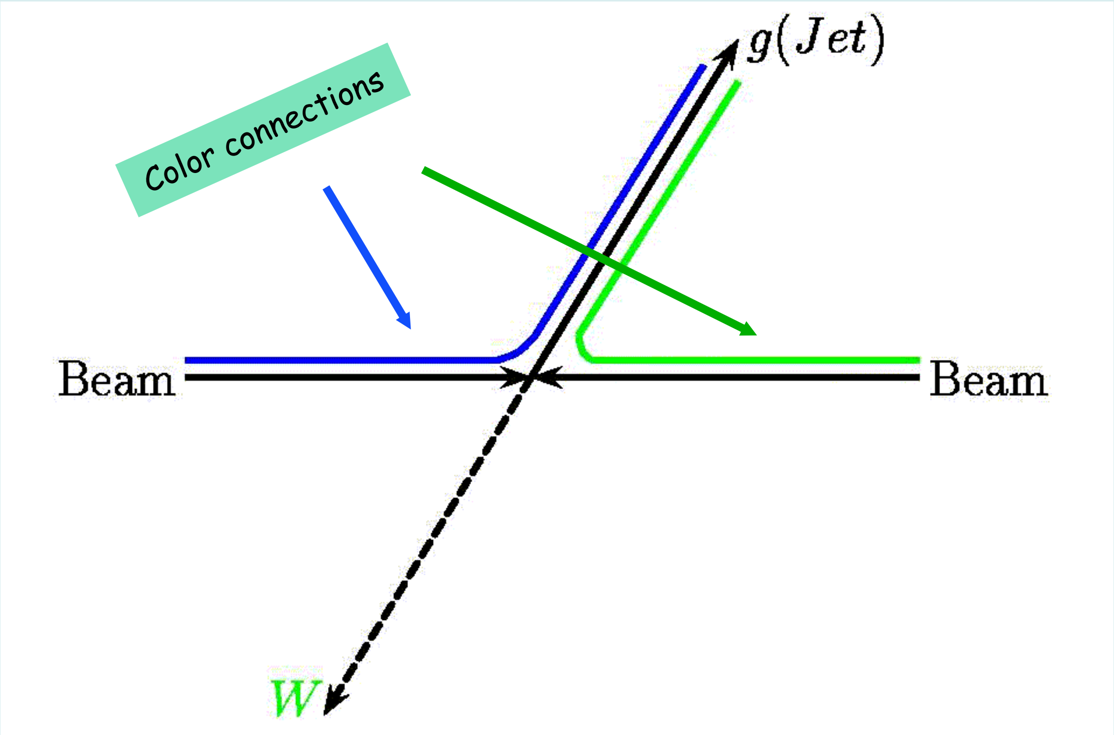
$p\bar{p}$ interactions:

Colored constituents in initial *and* final state (more complicated that e^+e^-)



Emission from each parton is confined to a cone stretching to its color partner

Color Coherence - $q\bar{q} \rightarrow Wg$

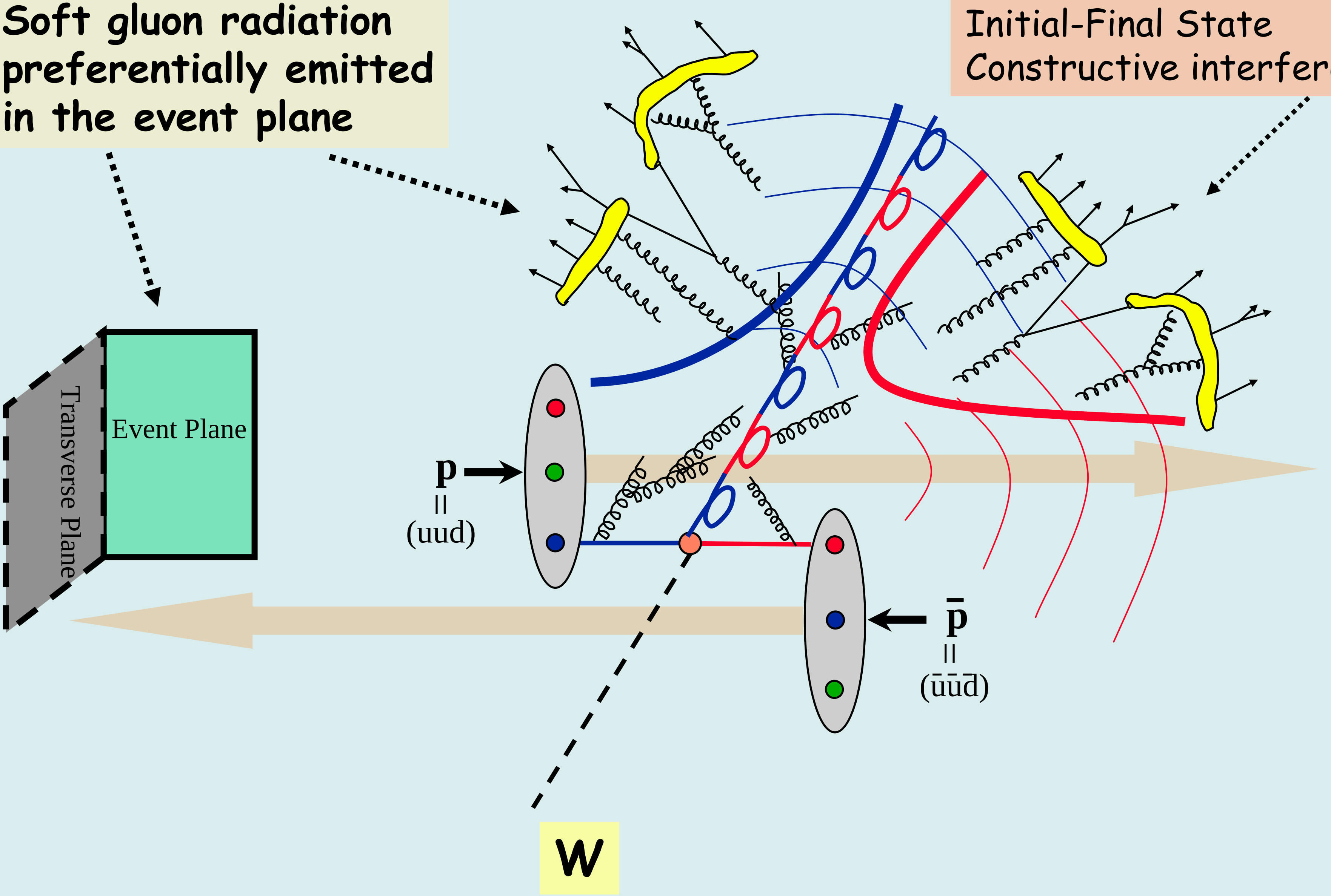


Compare pattern of soft particle flow around jet to that around (colorless) *W*

Color Coherence - $q\bar{q} \rightarrow Wg$

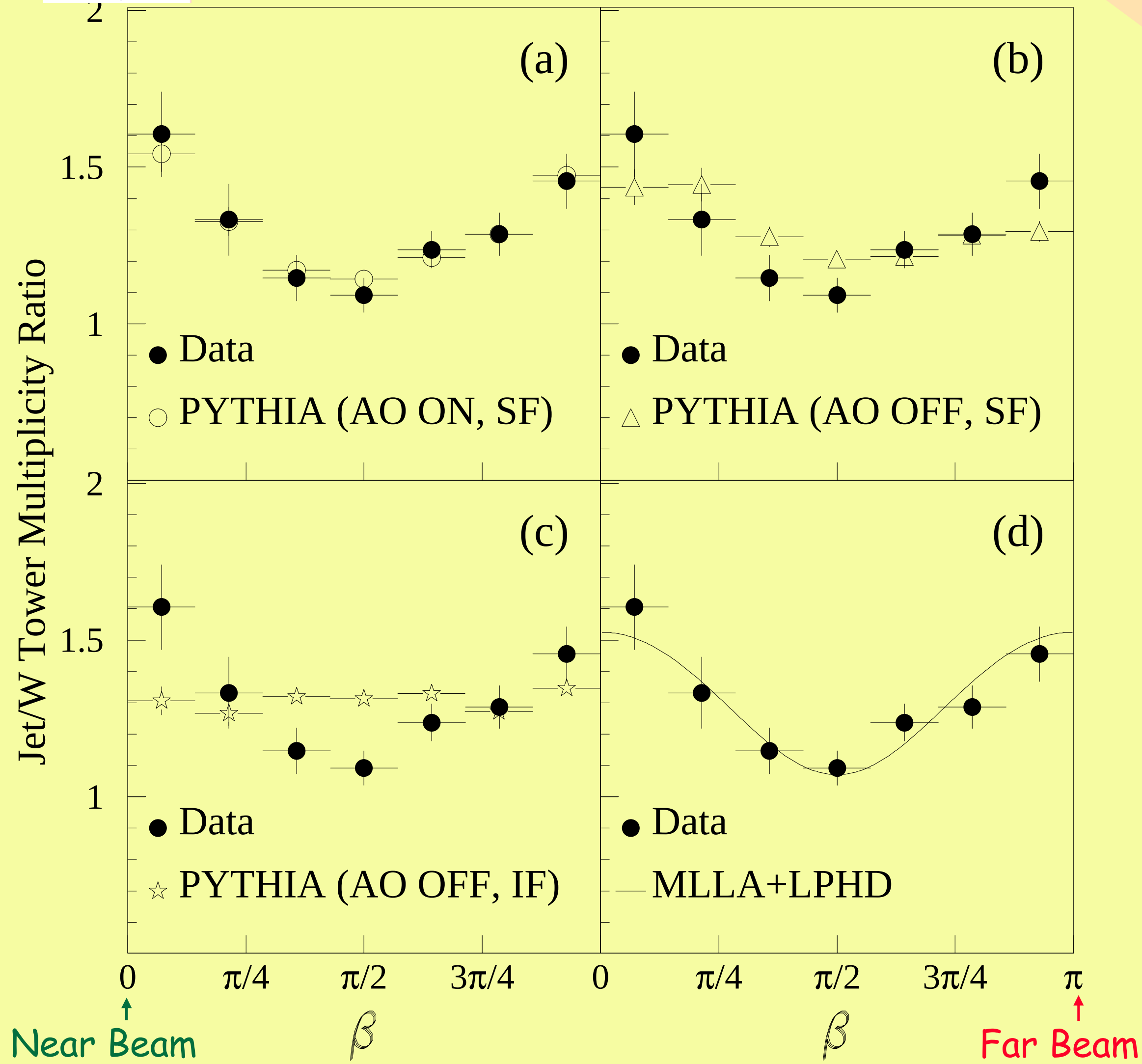
Soft gluon radiation preferentially emitted in the event plane

Initial-Final State Constructive interference



Ratio of partile multipliity around the Jet to that around the W

Run I



Jet Production @ Tevatron

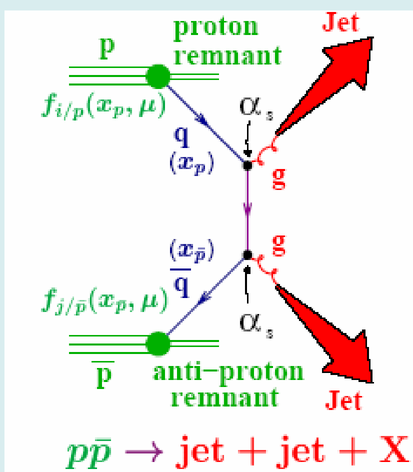
Motivation:

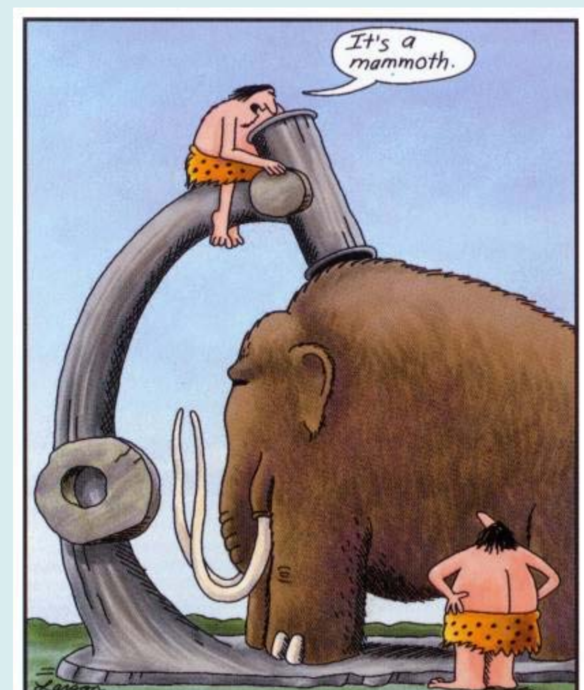
- Search for breakdown of the Standard Model at shortest distances
  - At Tevatron energies:

$$
\begin{aligned}
&p_T \sim 500\,GeV \\
&\Rightarrow \text{distance} \sim \frac{\hbar c}{p_T} \sim \frac{200\ \text{MeV}\cdot\text{fm}}{500\ \text{GeV}} \sim 4\times 10^{-19}\,m
\end{aligned}
$$

World's best microscope !

- Search for new particles decaying into jet final states
- Search for quarks substructure
- Constrain gluon density at high x
- Precision studies of QCD



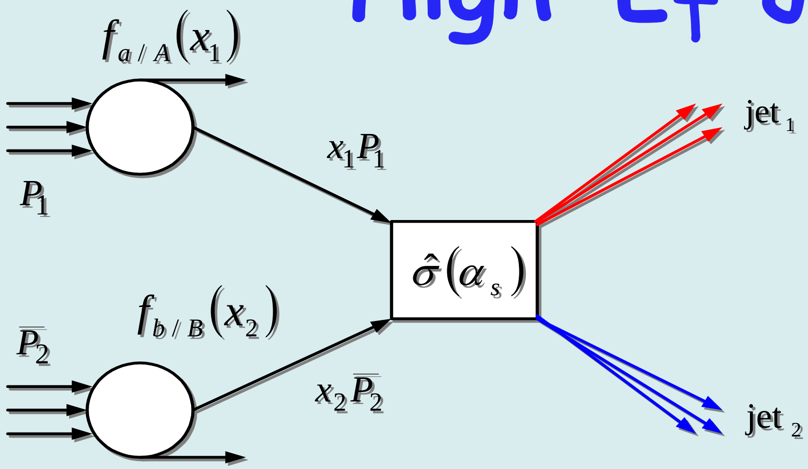


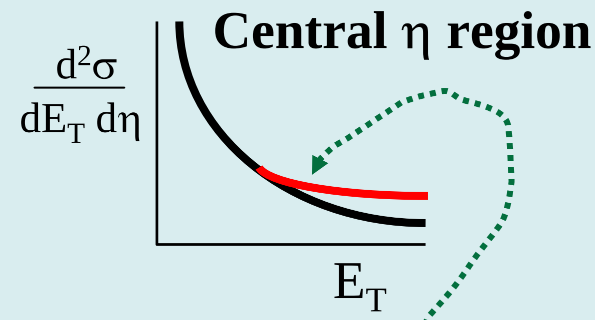
Early microscopes

Challenges with Jets

- Triggering on Jets
  - reduce rate from ~10^6 to ~ tens of Hz
    - multiple triggering stages; Level-1,2,3
  - implement fast/crude jet clustering algorithms for L1/2
- Selection of a Jet Algorithm
  - at detector, particle, parton/NLO++ level
- Jet Reconstruction, Selection, and Trigger Efficiencies
- Jet Calibration
  - underlying event definition (subtract or not?)
  - out-of-cone showering effects
  - correction back to particle jet or original parton?
- Jet Resolution
  - difficulties with low-E_T region and near reconstruction threshold
- Simulation of Jet/Event/Detector Characteristics
  - precision of detector modeling vs CPU time
  - ability to overlay zero/minimum-bias events from data
  - tuning of fragmentation model, selection of PDF, hard scale parameter Q, …
  - Interface a ME event generator with a parton-shower simulation

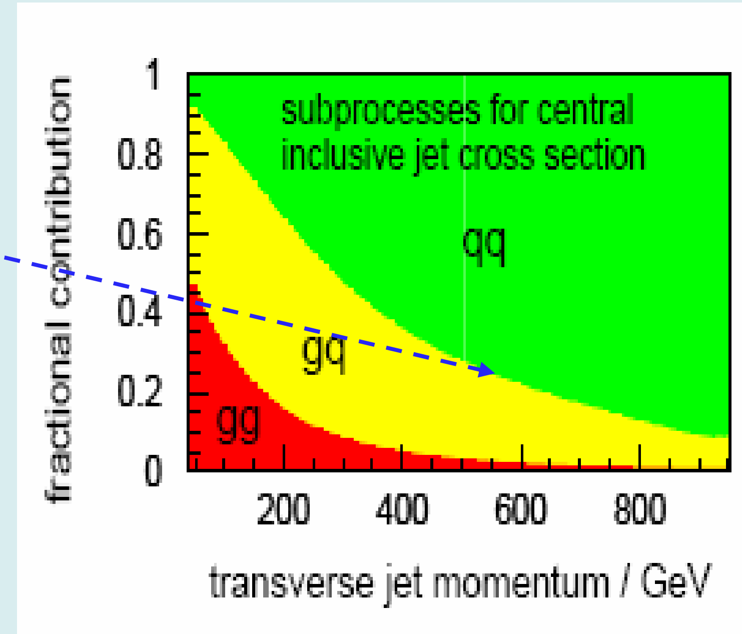
High-E_T Jet Production





Quark substructure ?
PDFs ?

Significant gluon contribution at high p_T



$$\frac{d\sigma}{dP_T} \approx \sum_{a,b} \int dx_a\, f_{a/A}(x_a,\mu) \int dx_b\, f_{b/B}(x_b,\mu)\, \frac{d\hat{\sigma}}{dP_T}$$

$$\frac{d\hat{\sigma}}{dP_T}(ab \to cd) \approx \sum_N \left(\frac{\alpha_s(\mu^2)}{\pi} \right)^N M_N$$

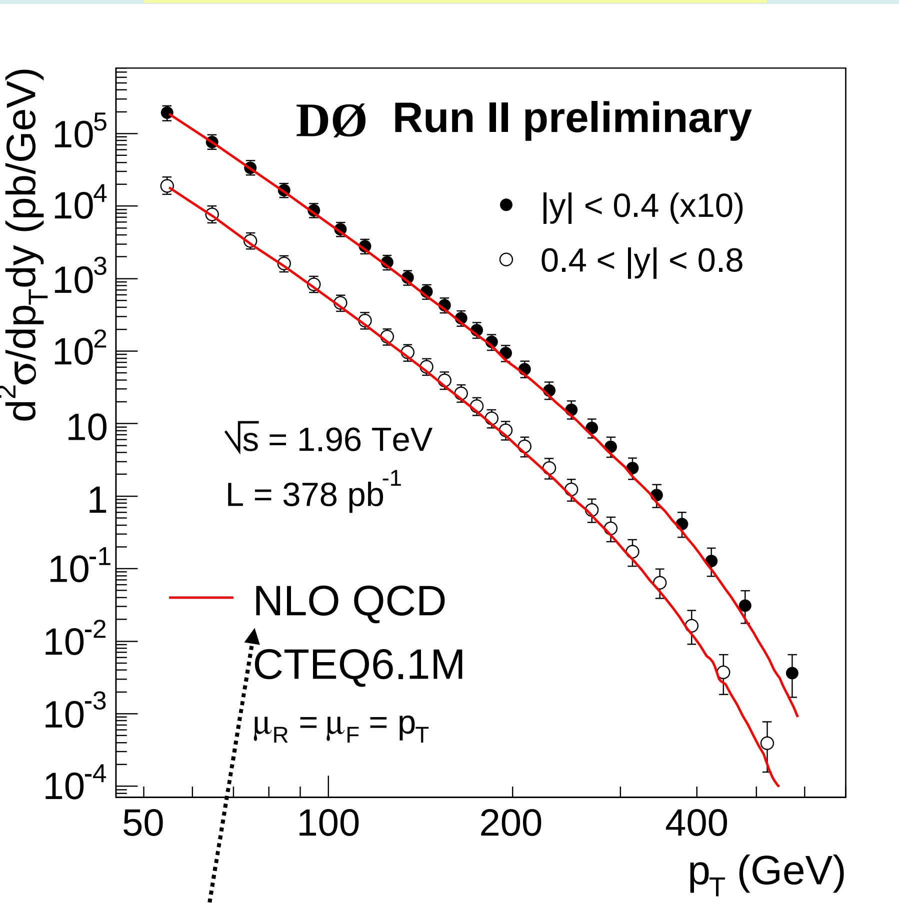
Currently 3-jet production @ NLO

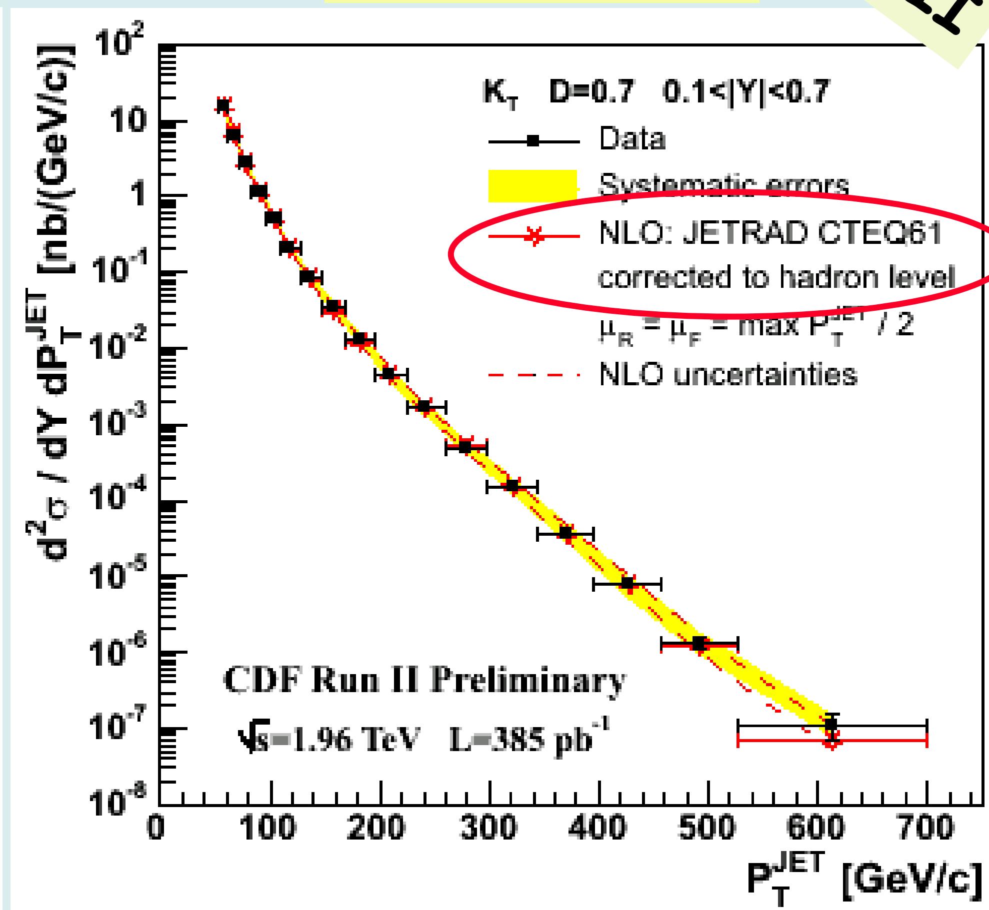
Resent results from Tevatron

Mid-point jet algorithm

k_T jet algorithm

Run II





NLOJET++

Resent results from Tevatron cont'd

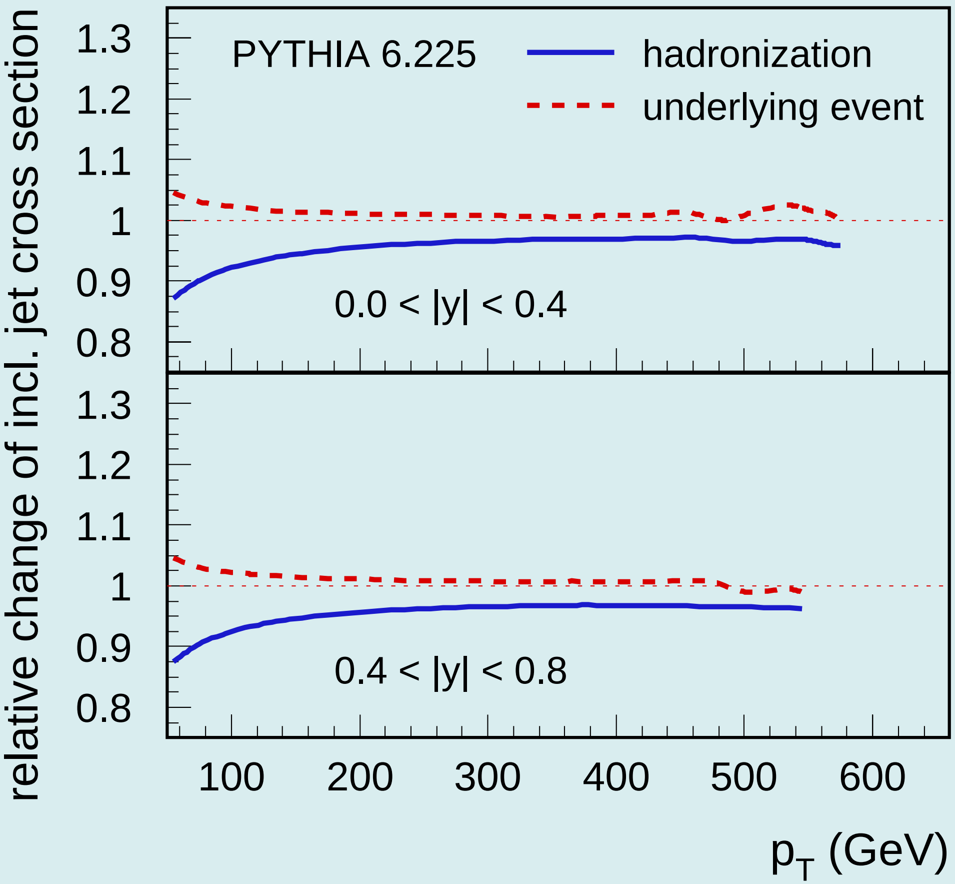
Run II

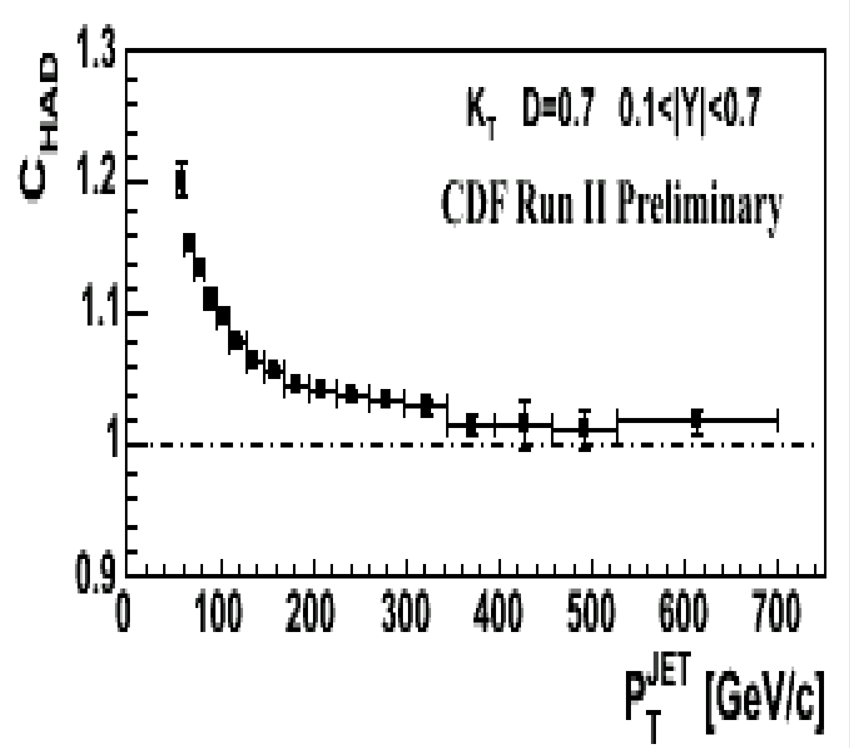
Mid-point jet algorithm

k_T jet algorithm

Hadronization + Underlying event/multiple-parton scattering corrections using Pythia applied to NLO QCD

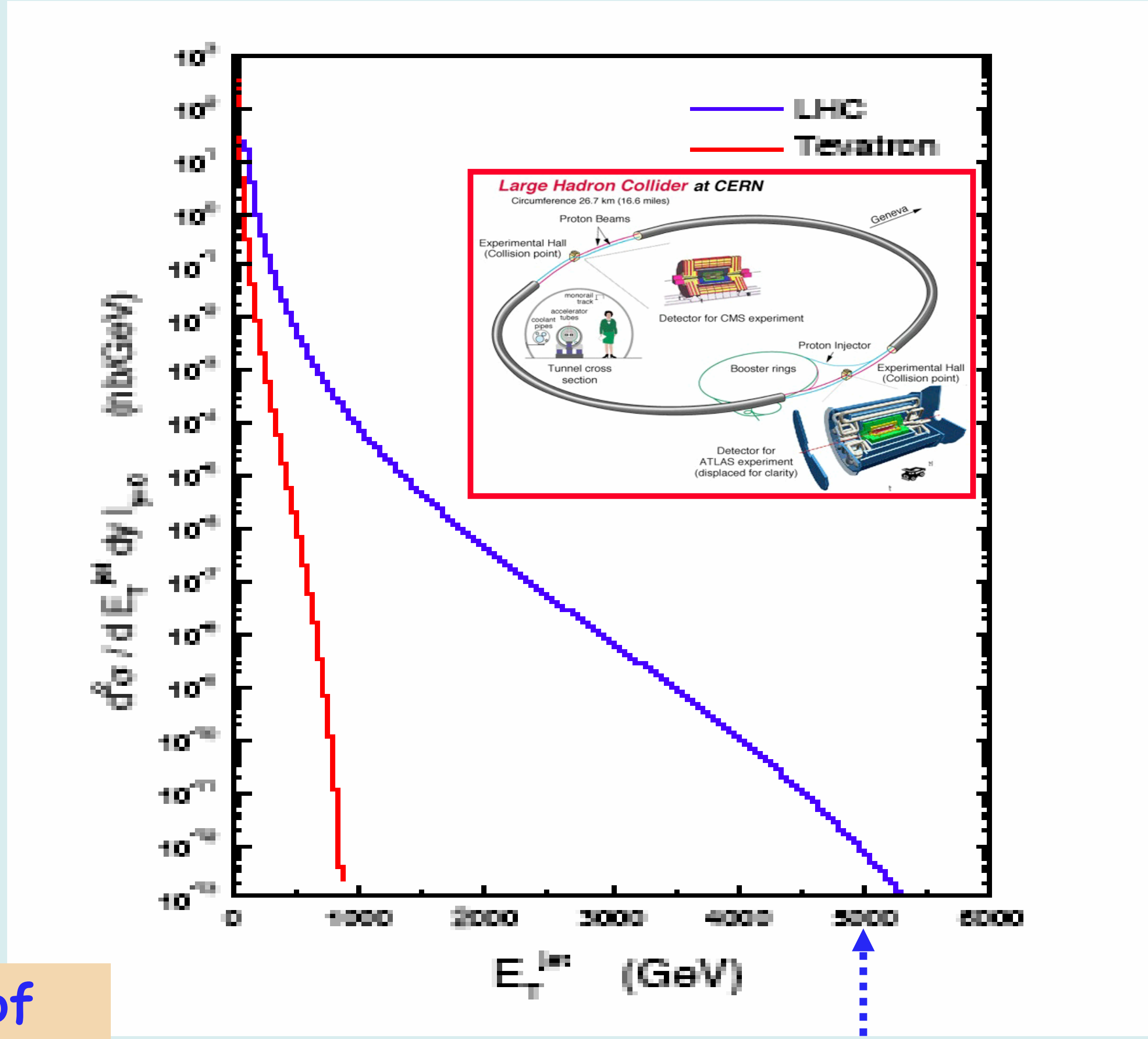
non-perturbative corrections





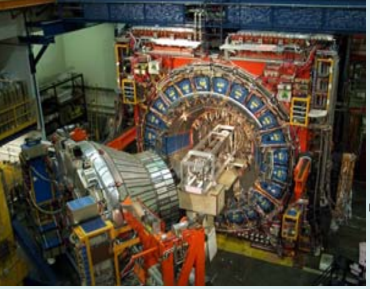
The far future...

$$\begin{pmatrix} p \rightarrow\leftarrow p \\ \sqrt{s} = 14\,\text{TeV} \end{pmatrix}$$



16 orders of magnitude drop

distance resolution ~10^{-20} m



Outlook

http://conferences.fnal.gov/tev4lhc/

- Jets celebrate their 30th year since first observed in e^+e^-
- Jets have provided the means to study the SM and explore possibilities beyond
- There are still issues to be resolved with the jet algorithms
    - See the current effort in the TeV4LHC Workshop
    - More sophisticated jet algorithms are under development
- Tevatron Run II is setting the stage for jet physics at LHC