JETS

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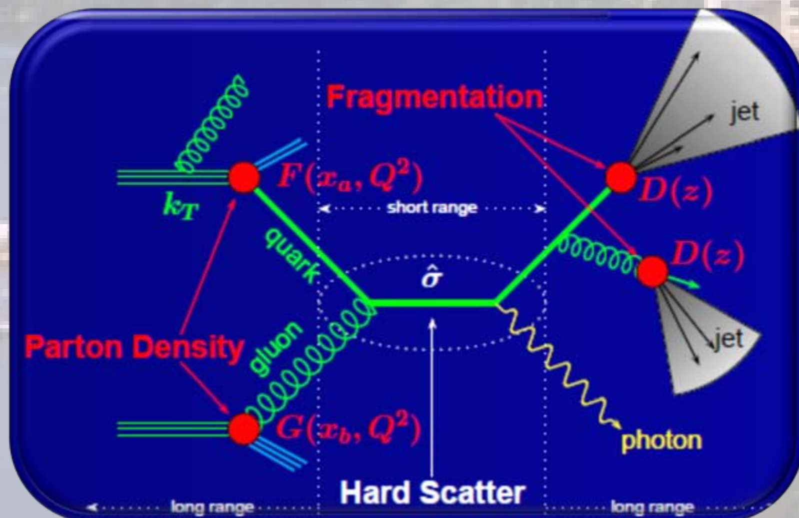


CTEQ Summer School
Madison
June 24 – July 2, 2009

CTEQ

Outline

- Introduction
  - QCD
  - ee, ep, pp Processes – History of Jets
  - What is a Jet?
- Jet Algorithms
- Jet Reconstruction, Calibration, Performance
- Jet Characteristics
  - Jet Energy Profile
  - Quark and Gluon Jets
  - Color Coherence Effects
- Jet Production at Hadron Colliders (Tevatron & LHC)
  - Underlying Event
  - Event Shapes
  - Dijet Azimuthal Decorrelation & Angular Distributions
  - Inclusive Jet Cross Section
  - Dijet Mass
- Summary

QCD in a Nutshell

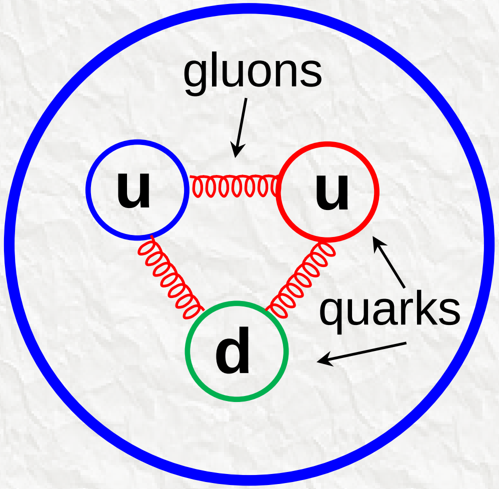
Similar to QED …

- Pointlike fermions 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*

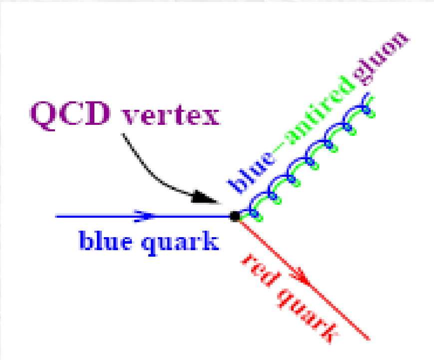
… but different

- Gluons carry two color "charges" and can interact to each other – *very important difference from QED*
  - from Abelian to non-Abelian theory
  - Color charge is conserved in quark-quark-gluon vertex
- At large distances: *parton interactions become large* (confinement)
- At small distances: *parton interactions become small* (asymptotic freedom)

Proton



Partons = quarks & gluons



Coupling constant → a_s (analogous to α in QED)

Free particles (hadrons) are colorless

C T E Q

QCD in a Nutshell

Similar to QED …

- Pointlike fermions called **quarks**
  - Six different "flavors" (u, d, c, s, t, b)
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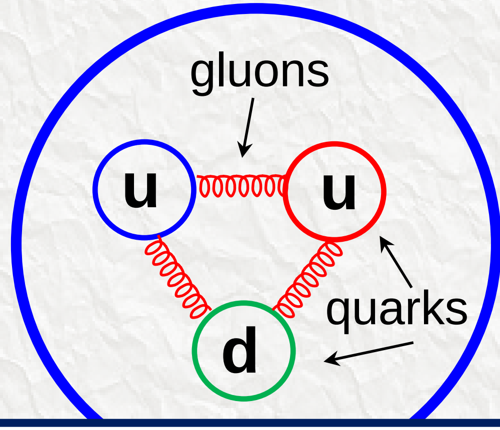
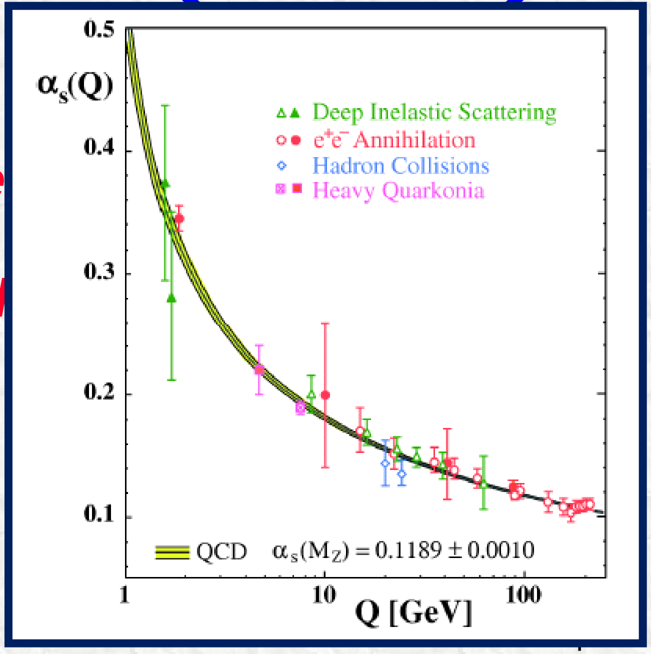
Proton





Historic Prespective

1960

- Introduction of Color and the Quark Model

SLAC

- Experimental evidence of quarks in DIS scattering
  Bjorken scaling

1970
ISR

- Birth of QCD
  Renormalizability, Asymptotic Freedom, Confinement
- Discovery of the c-quark (SLAC, BNL)
- Experimental evidence of jets in e^+e^- annihilations as manifestation of quarks (1975) and gluons (1979)

PETRA

- Discovery of the b-quark (Fermilab)
- Violation of Bjorken scaling, Evolution of Parton Distribution and Parton Fragmentation Functions

1980
Sp$\bar{p}$S

- Computation of higher-order effects in pQCD for many processes
- Discovery of W and Z – Confirmation of Standard Model

Tevatron
LEP
HERA
1990
D0+CDF

- Next to Leading Order pQCD predictions for jet production

1992: 1st CTEQ Summer School ☺

LEP 2

- Discovery of the t-quark (Fermilab)
- Precision EW Data – LEP 2

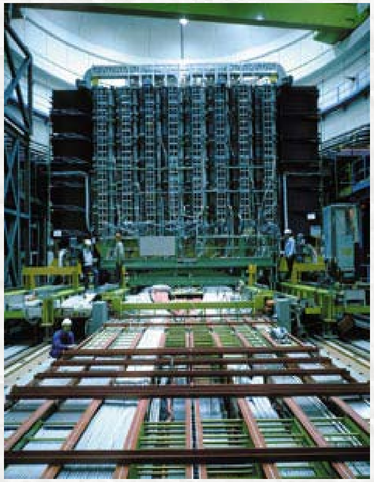
2000

- Tevatron Upgrade, Run IIa
- CTEQ6 PDFs + Errors
- Tevatron Run IIb

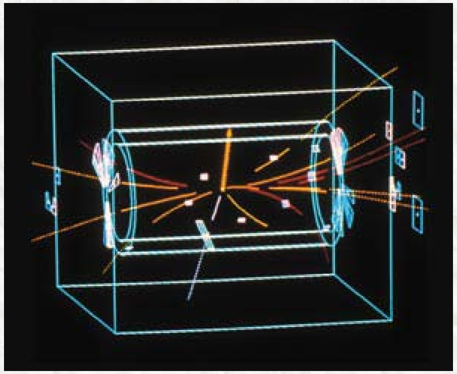
LHC

- LHC Startup

2010



UA1 Detector



First W event

HERA, DESY, Hamburg, Germany
ep collider

PEP-II, SLAC, Palo Alto, USA
e^-e^+ collider

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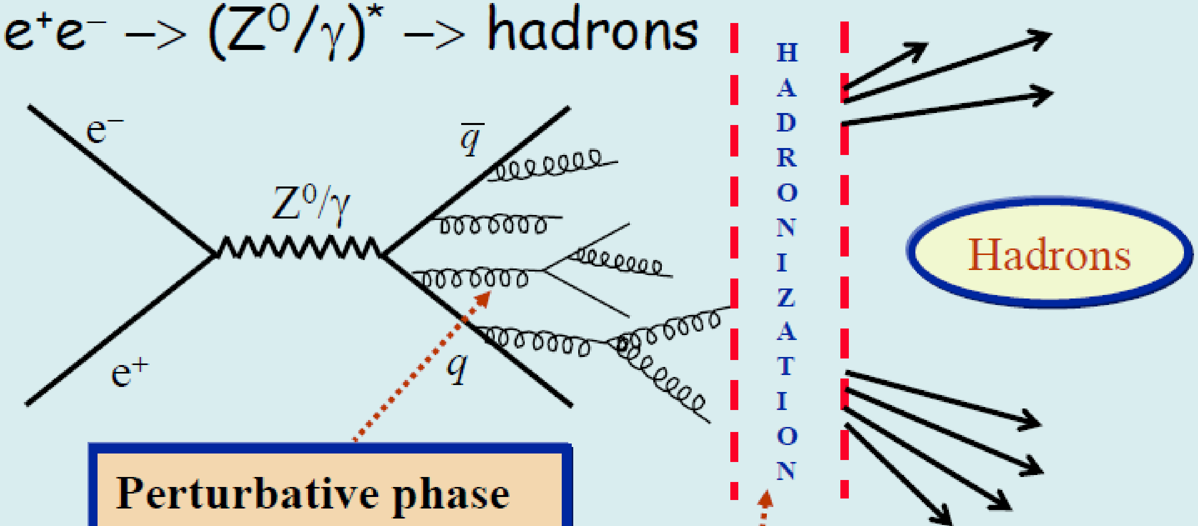
QCD in e^+e^- Annihilations

LEP: $88\ \text{GeV} < E_{cm} < 209\ \text{GeV}$

SLC: $E_{cm} = 91\ \text{GeV}$

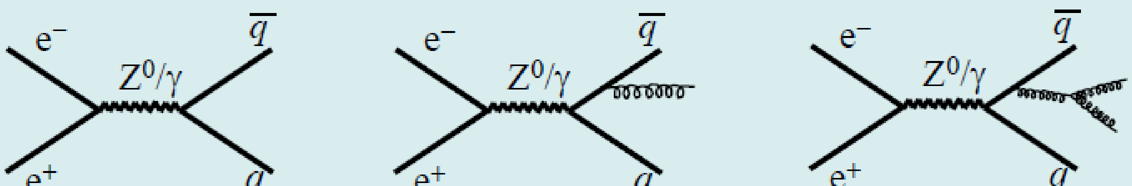
$e^+e^- \to (Z^0/\gamma)^* \to \text{hadrons}$



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

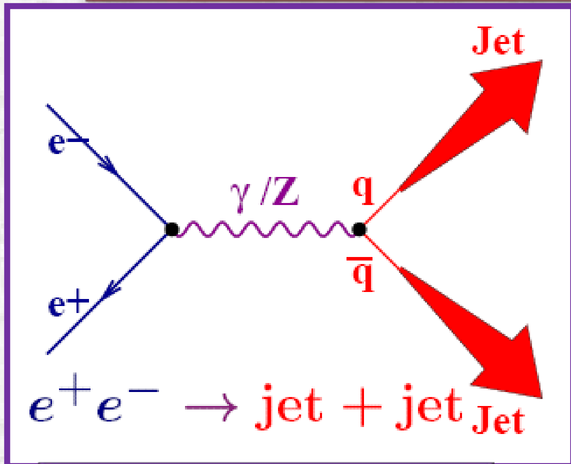
Non-perturbative phase
$\alpha_s \geq 1$ **(Hadron Level)**

Fixed Order QCD

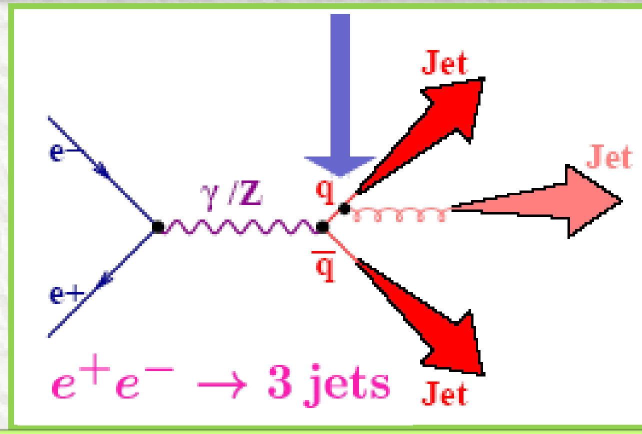


$\mathcal{O}(\alpha_s^0)$ $\mathcal{O}(\alpha_s^1)$ $\mathcal{O}(\alpha_s^2)$

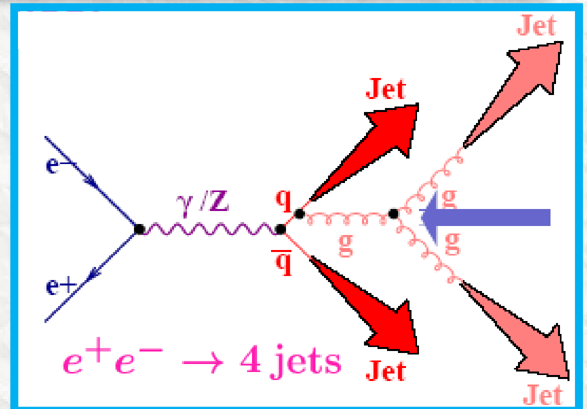
Why do we Study Jets in e^+e^-?



Discover quark jets
Determine quark spin

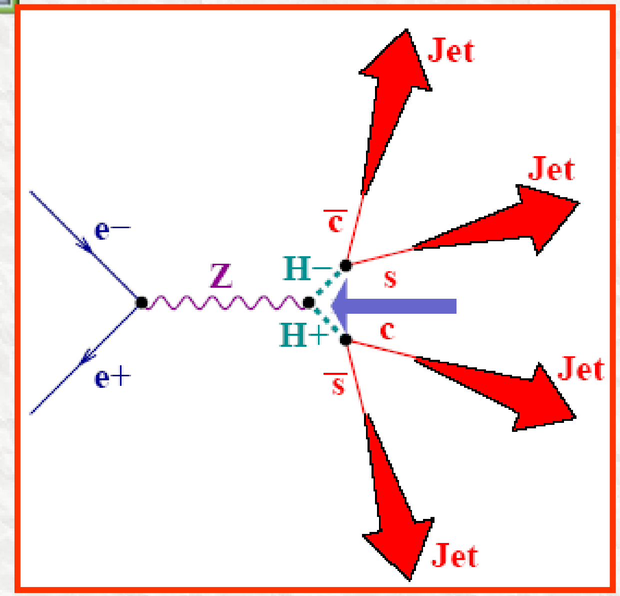


Discover gluon jets, measure α_s
Determine spin of gluon



Establish gluon self-coupling
Non-abelian structure of QCD

- **QCD Studies**
  - Measurements of α_s
  - Fragmentation functions
  - SU(3) gauge structure of OCD
  - Color factors/spin dynamics
  - Quark-gluon jet properties/differences
  - Event shapes
- **Searches for the Higgs**
- **Searches for new physics**



Search for the Higgs

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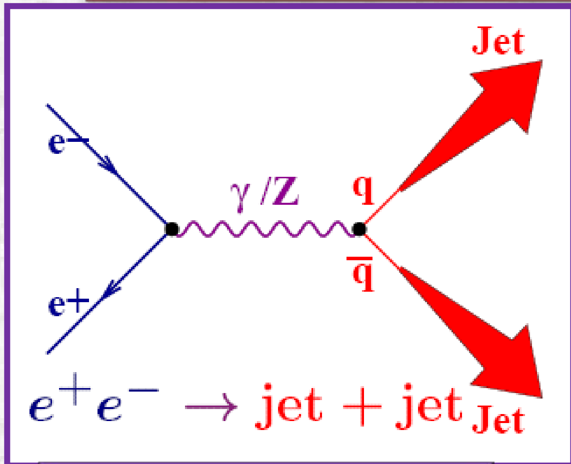
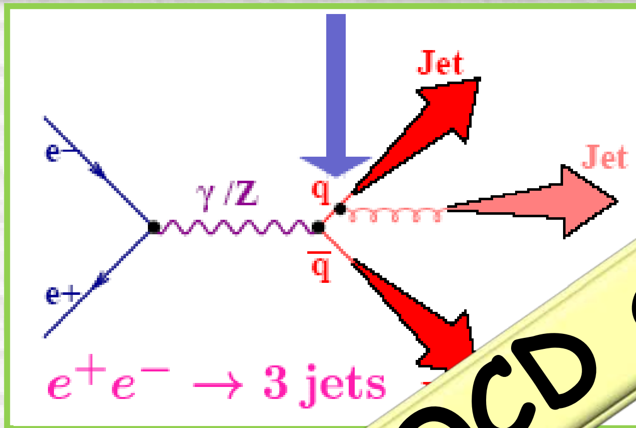
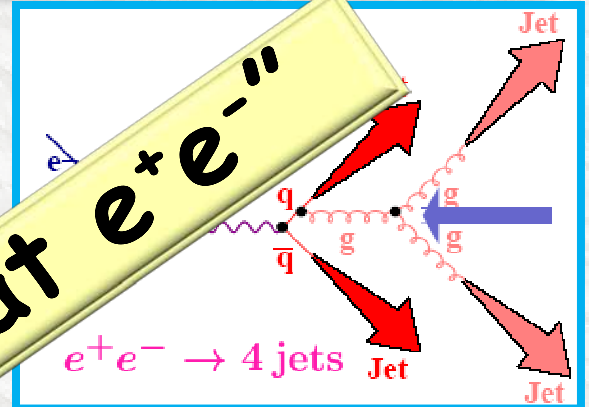
Why do we Study Jets in e^+e^-?



Discover quark jets
Determine quark spin



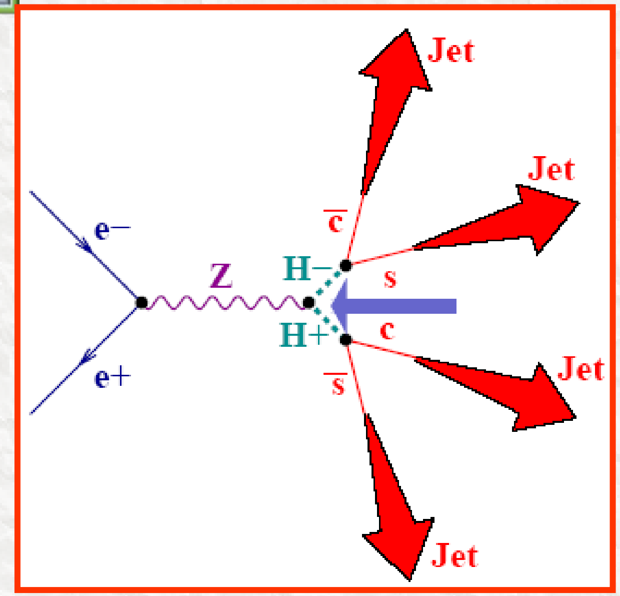
Discover gluon i... ...re α_s
Determi... ...luon



Establish gluon self-coupling
Non-abelian structure of QCD

- QCD Studies
  - Measurements of α...
  - Fragmentation f...
  - SU(3) gauge ... of QCD
  - Color fa... dynamics
  - Quar... ...r properties/differences
  - E... ...es
- S... ...s for the Higgs
- S...ches for new physics

See Gary's talk on "QCD at e^+e^-"



Search for the Higgs

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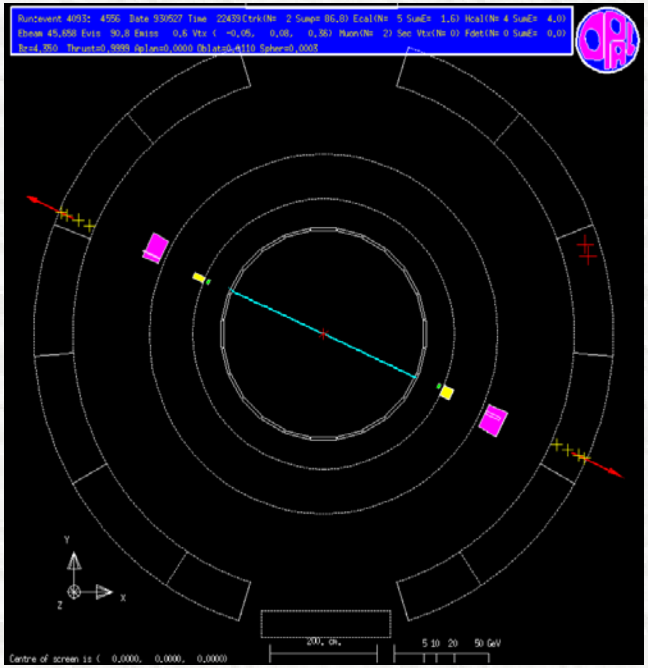
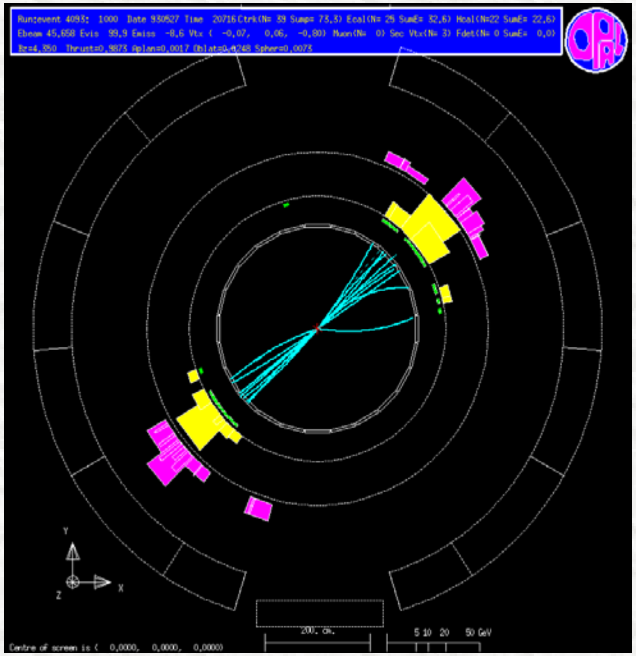
e^+e^- Events are Clean!

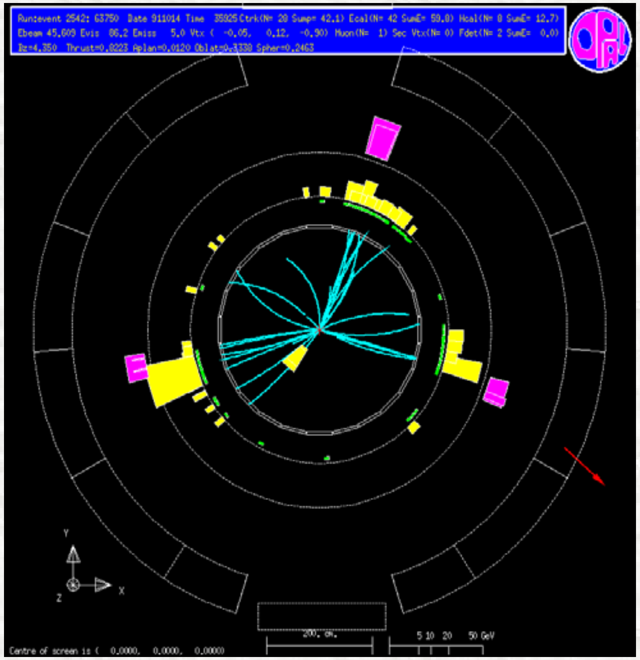
$e^+e^- \to \mu^+\mu^-$



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

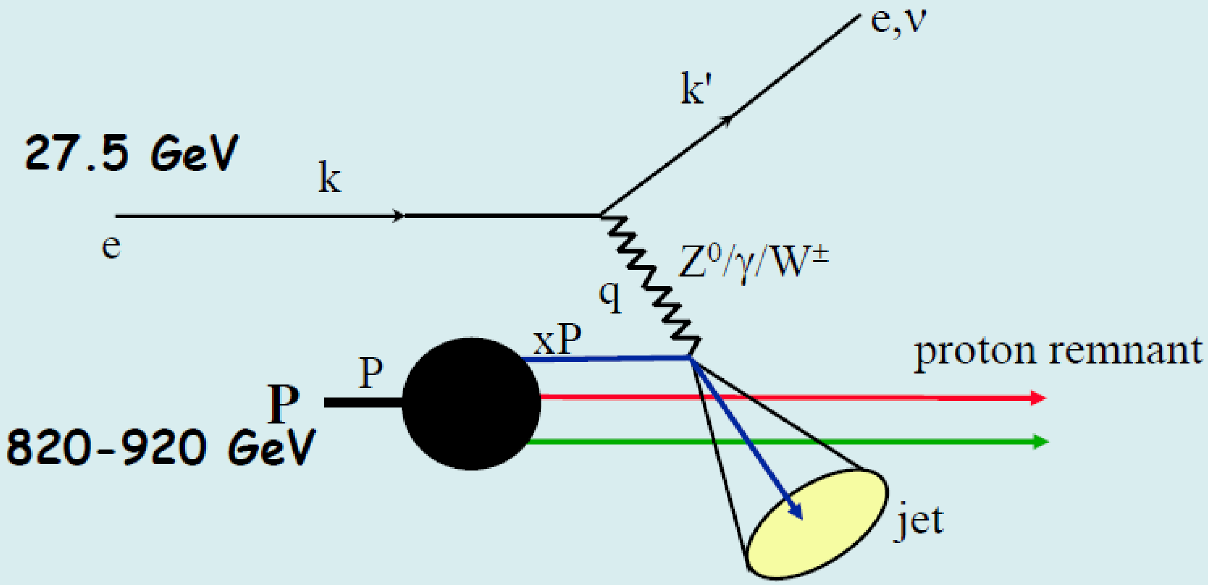


$e^+e^- \to q\bar{q}g$



- ✓ No Initial State Radiation
- ✓ No beam remnants
- ✓ No multiple scatterings
- ✓ Important role in establishing QCD

QCD in ep Interactions



$k = (E, \boldsymbol{k})$ 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

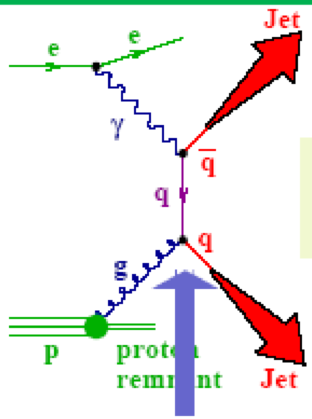
$y = \dfrac{P\cdot q}{P\cdot k} = \dfrac{E-E'}{E}$ fractional energy transfer

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

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

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

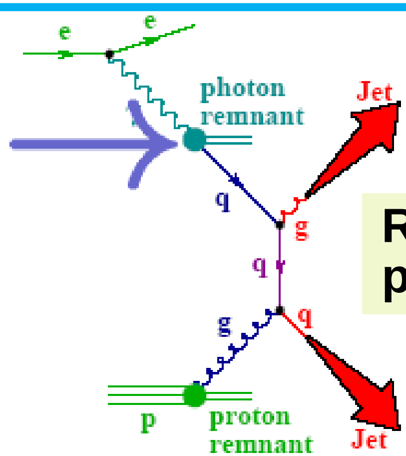
Why do we Study Jets in ep?



Direct photoproduction

→ measurements of α_s

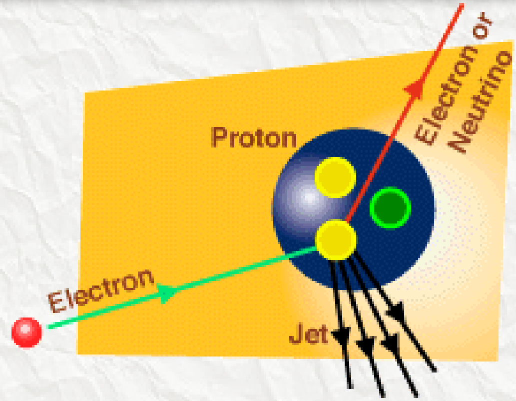
$\gamma p \rightarrow 2 \text{ jets} + X$



Resolved photoproduction

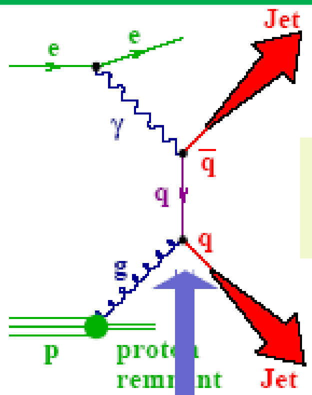
→ tests of photon structure

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



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

Why do we Study Jets in ep?



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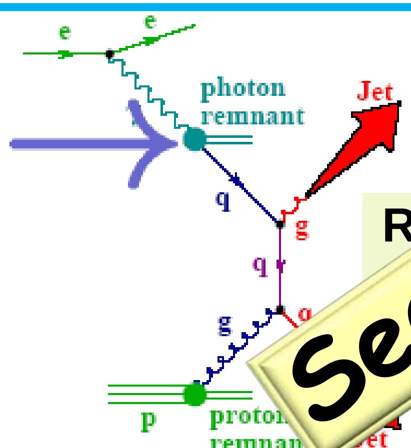

Re
duction

→ tests of photon structure

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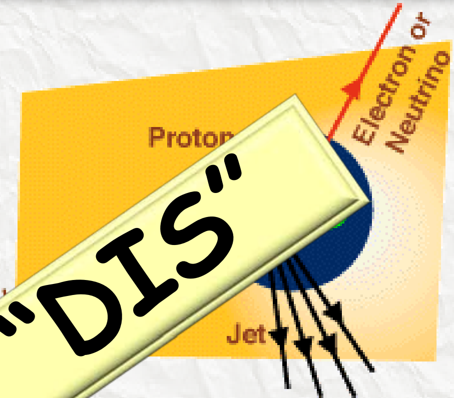

See Magill's talk on "DIS"

- Studies
  - easurements of α_s
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- Searches for new physics

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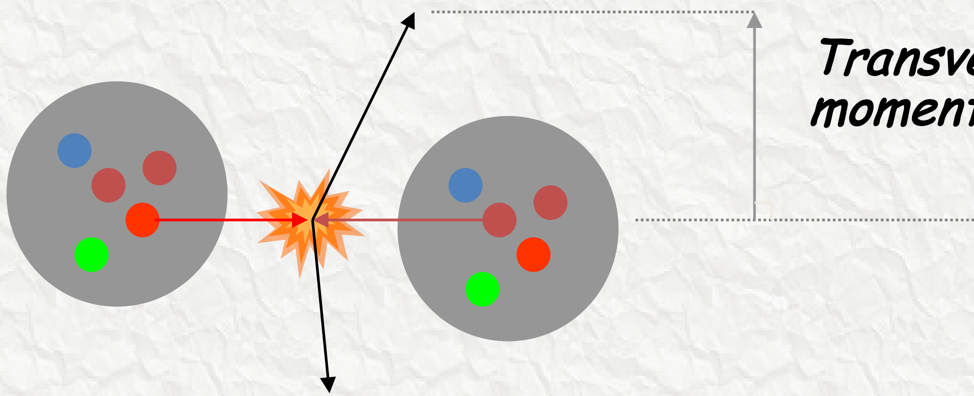
Proton – (Anti)proton Collisions

- **Proton beams can be accelerated to very high energies (good)**
- **But the energy is shared among many constituents – quarks and gluons**
  - **“scan” of wide range of $\hat{s}$ (good and bad)**



Transverse momentum $\equiv p_T$

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

CTEQ

Proton – (Anti)Proton Interactions

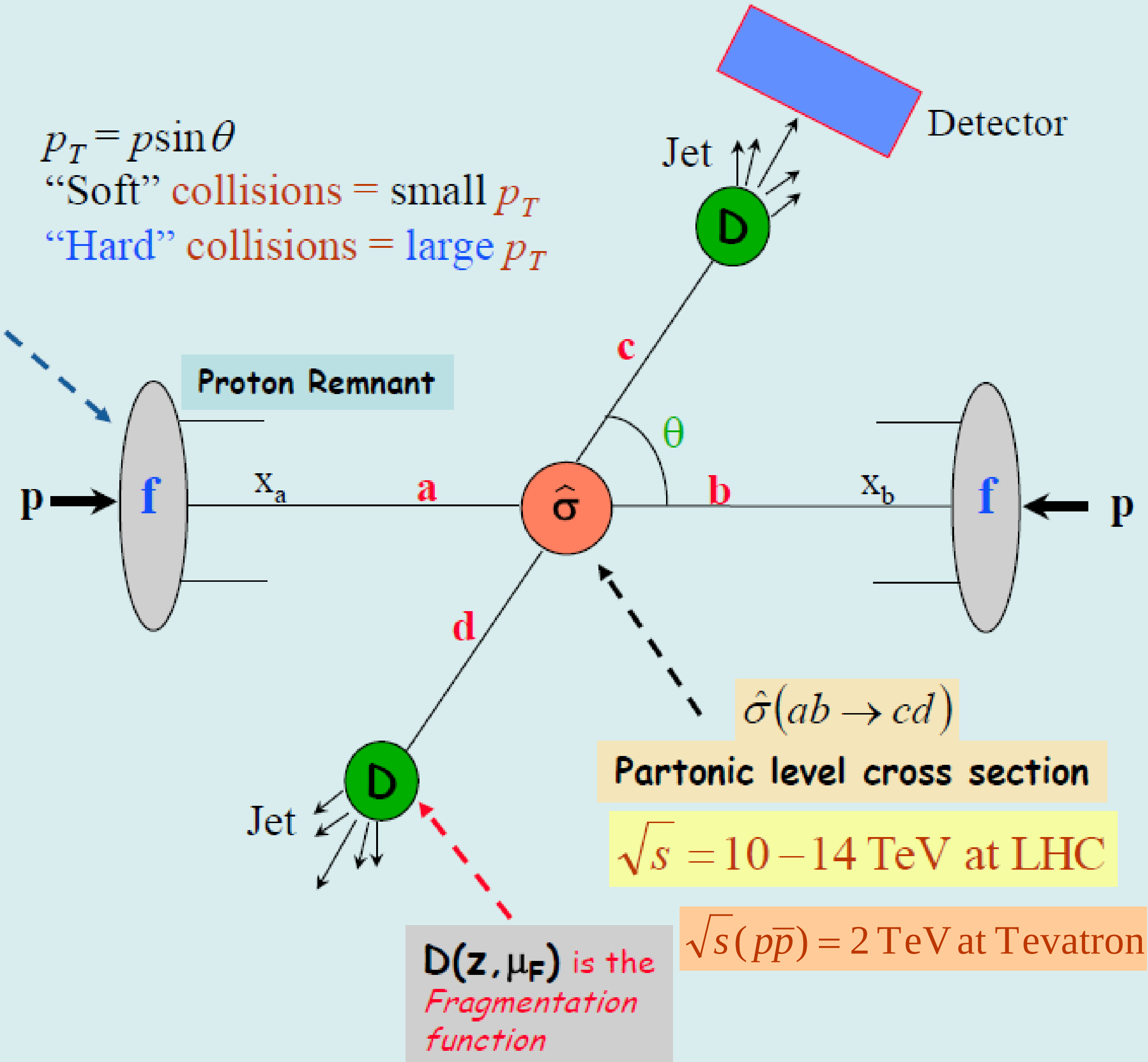
Parton Distribution Functions

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

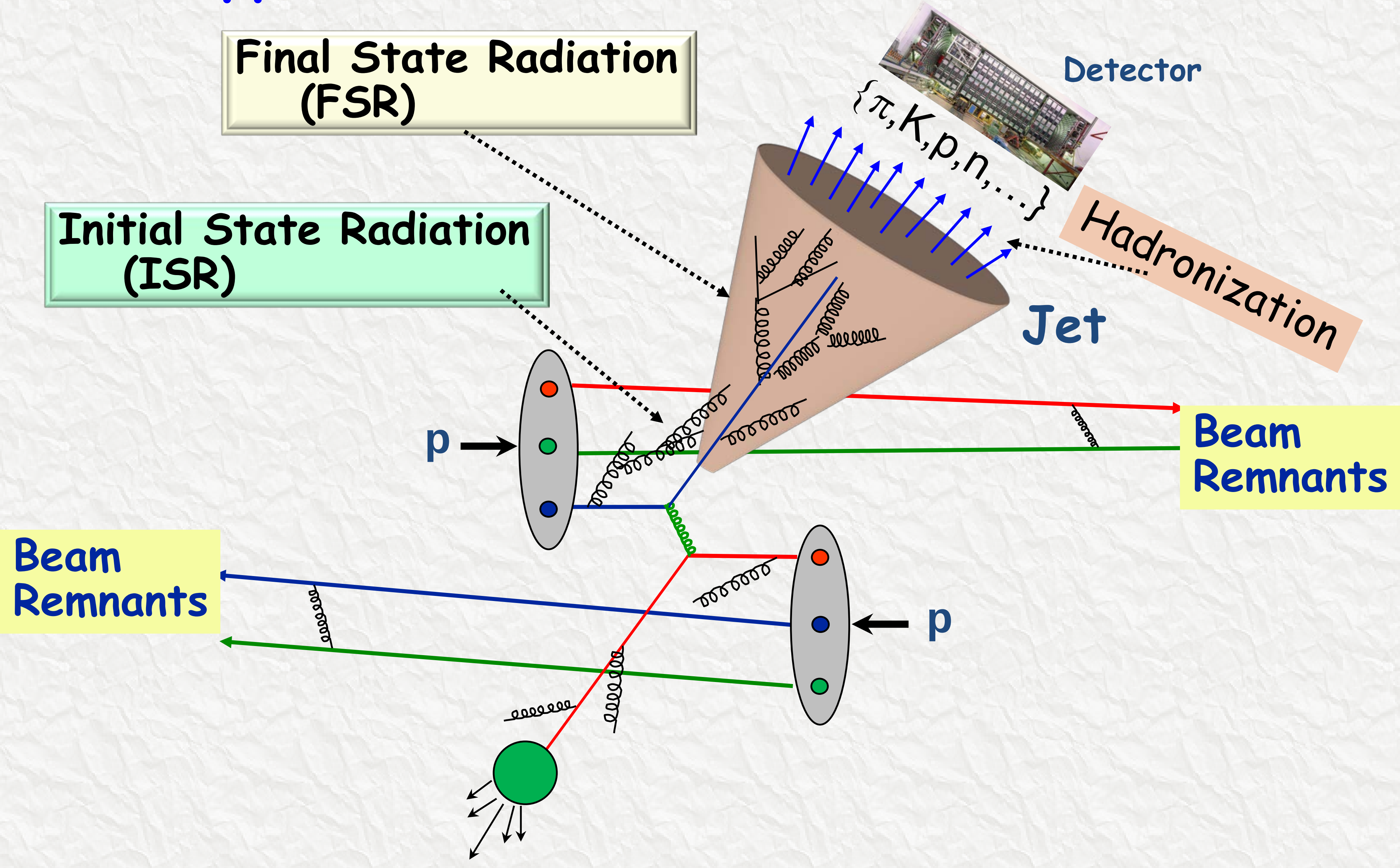
x_a: fraction of hadron's momentum carried by parton **a**

μ_F: related to the "hardness" of the interaction

"Factorization Scale"

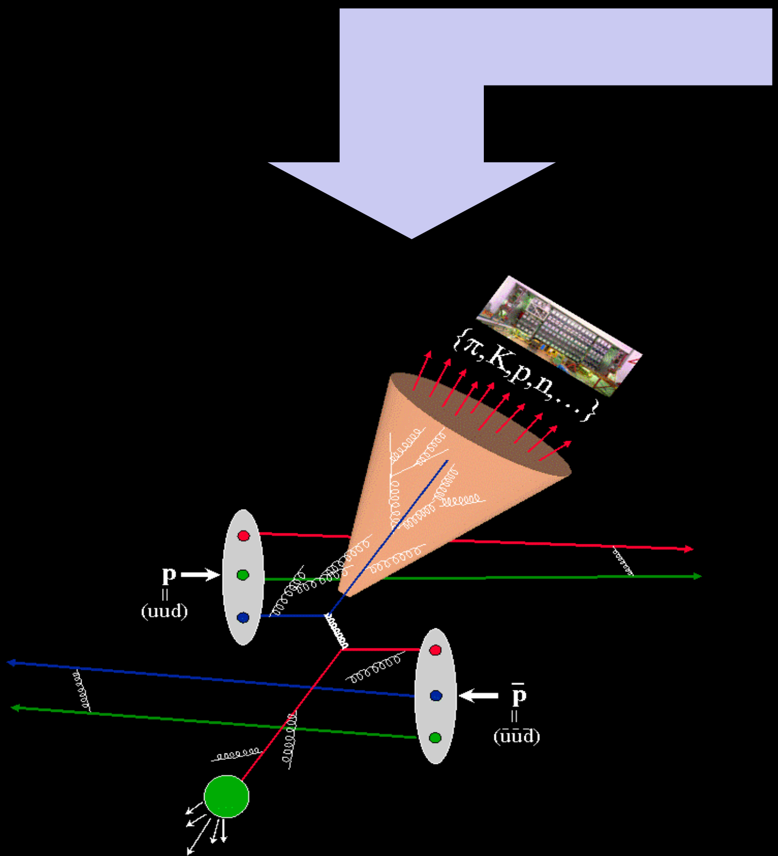


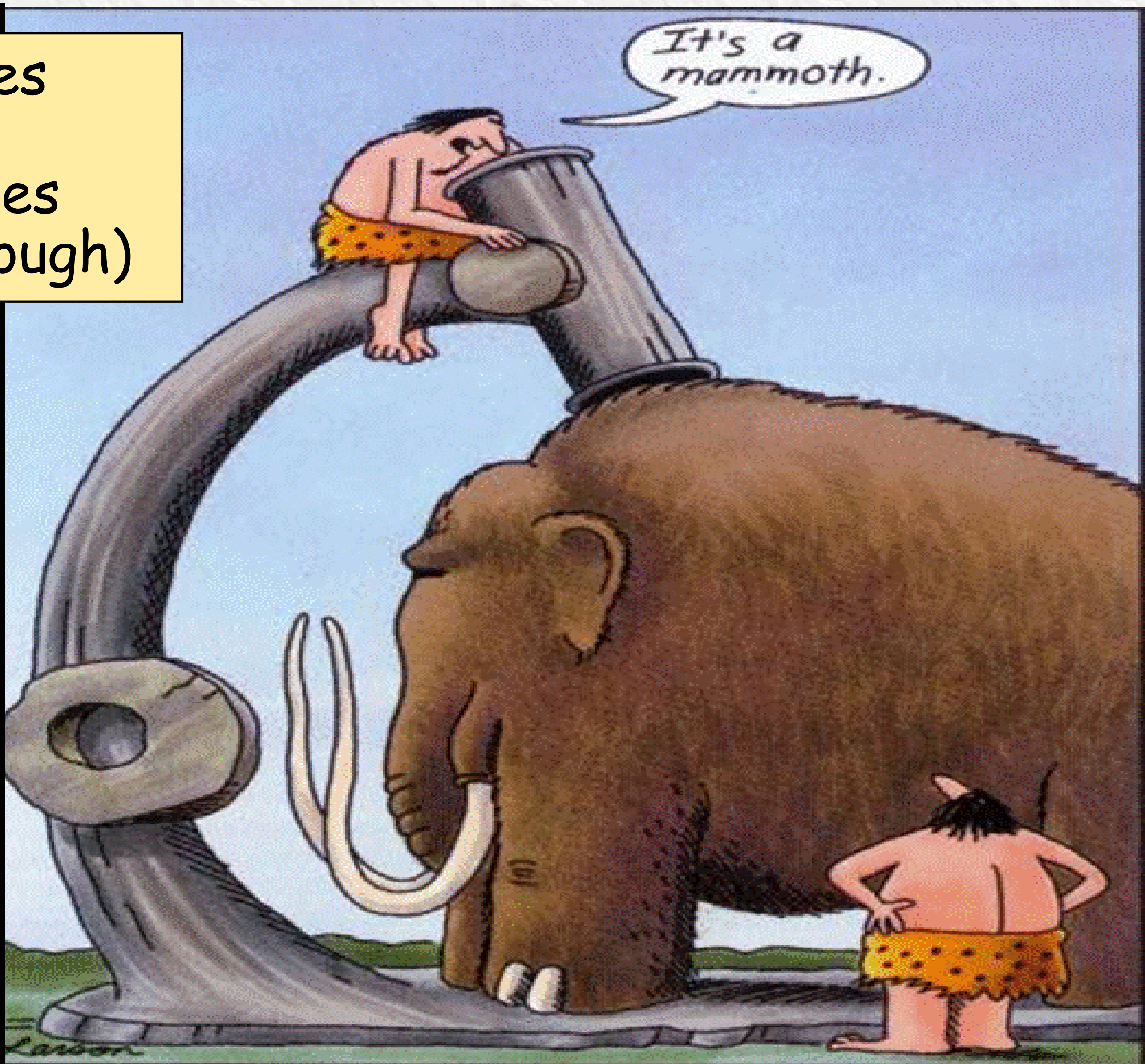
pp Interactions – Creation of Jets



pp Interactions – Creation of Jets

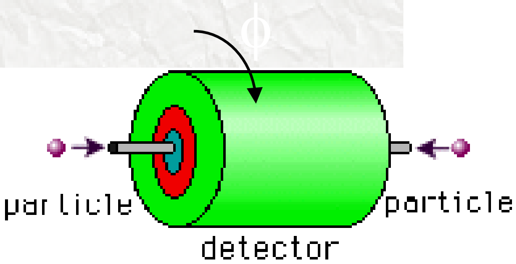
From Early Microscopes
To
Nano-Nano-Microscopes
(a bit more expensive though)

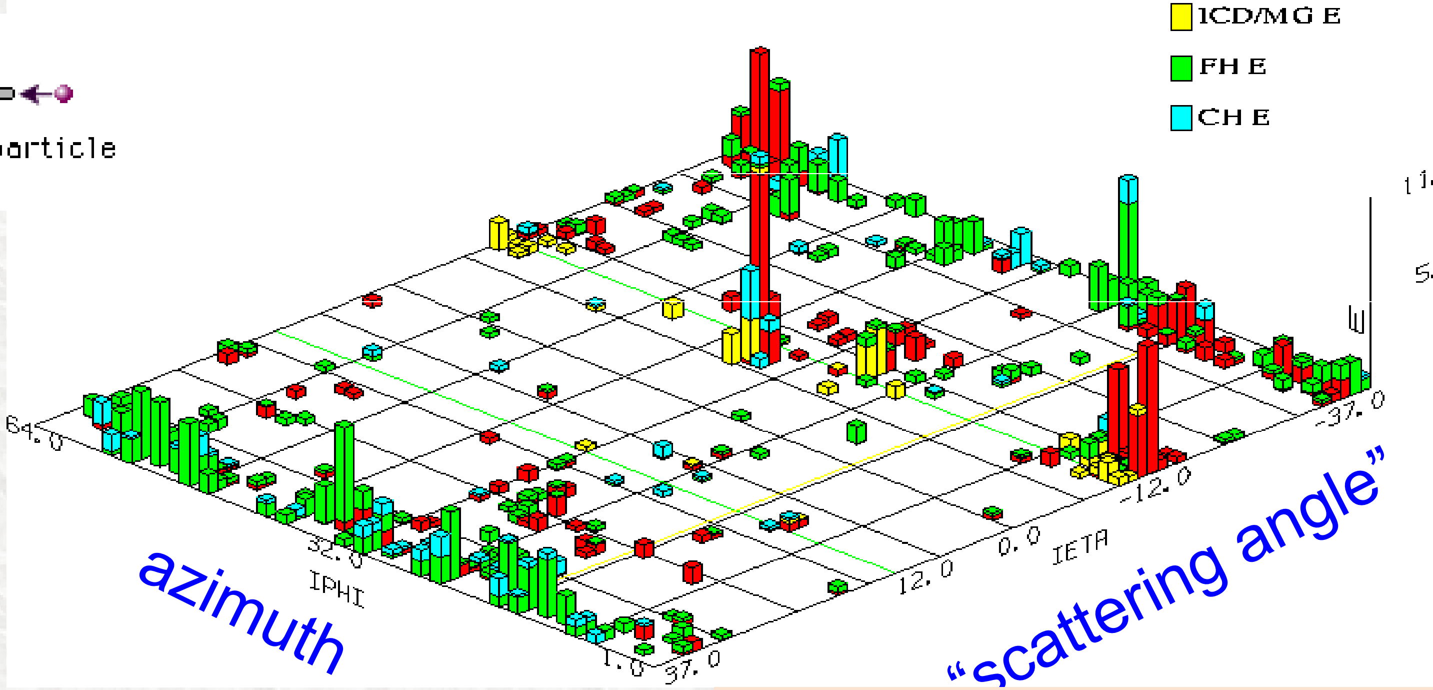


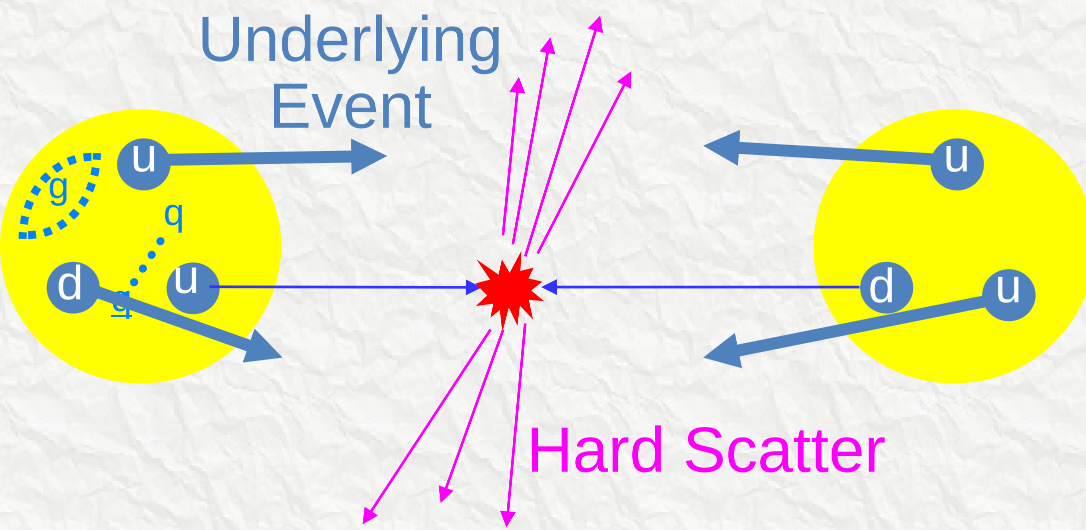


Early microscopes

Hadron Interactions





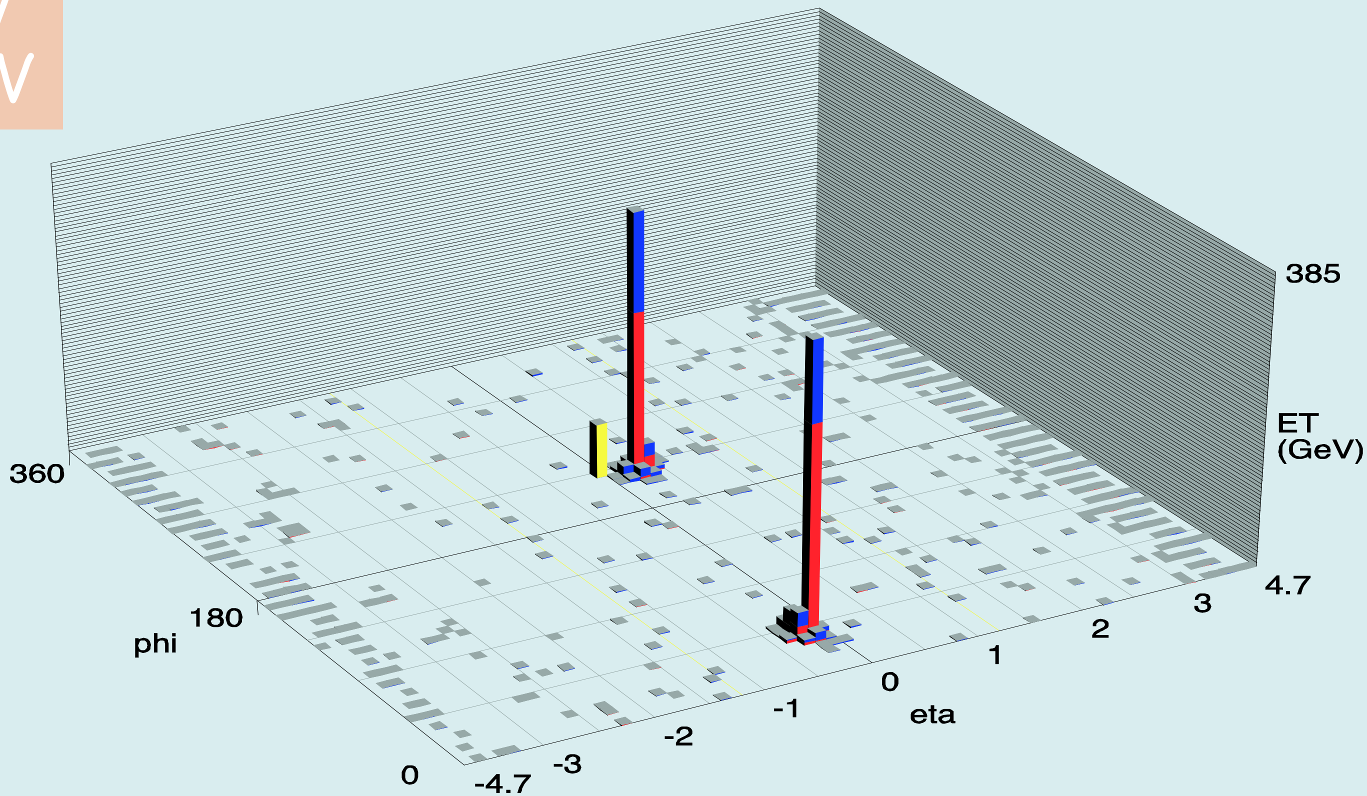


Complications from the e^+e^- due to:

- Parton Distribution Functions (PDFs)
- "Colored" initial <u>**and**</u> final states
- Remnant jets - Underlying event (UE)

DØ Event

E_{T1} ~ 620 GeV
E_{T2} ~ 560 GV
M_{JJ} ~ 1.2 TeV



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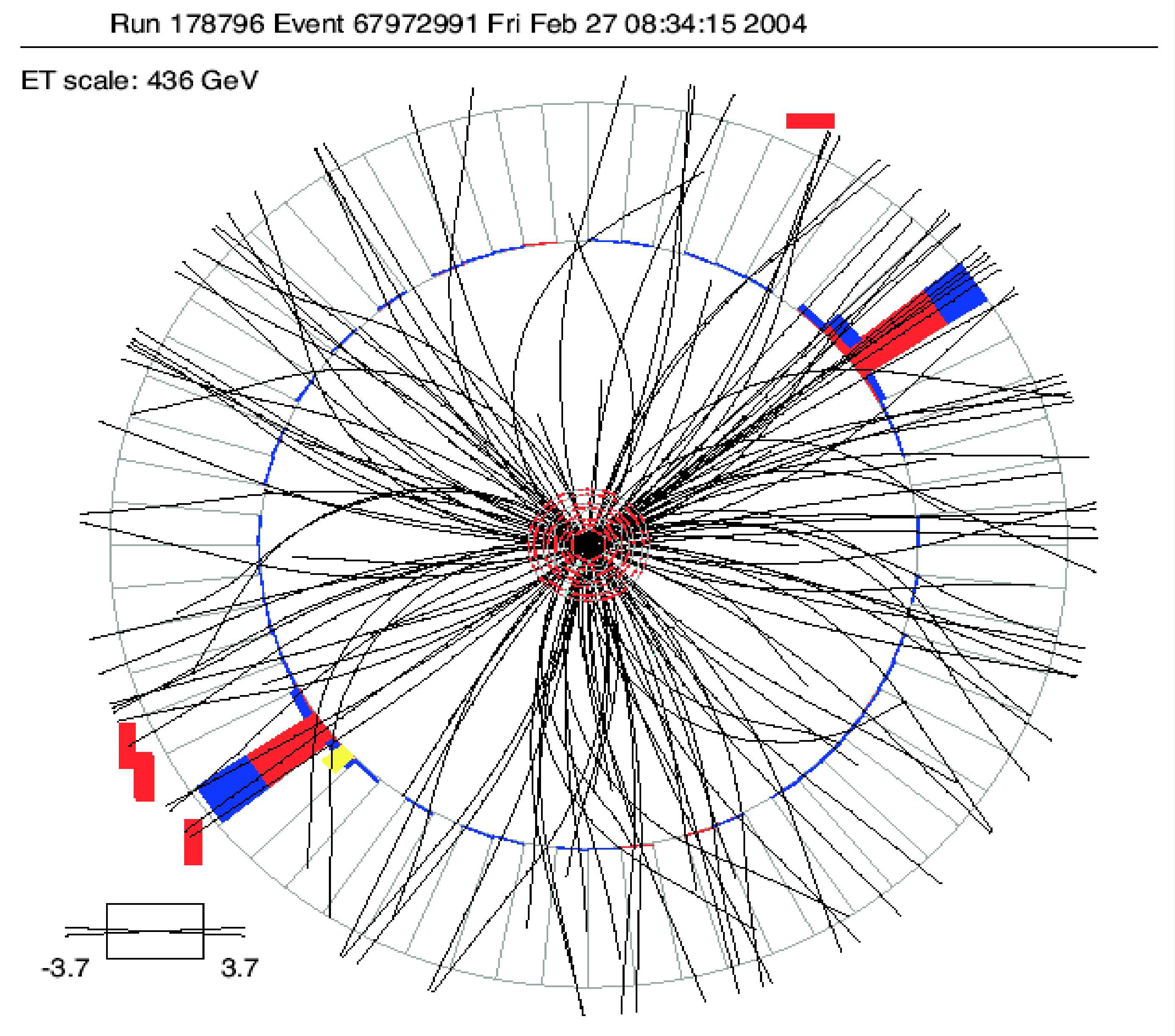
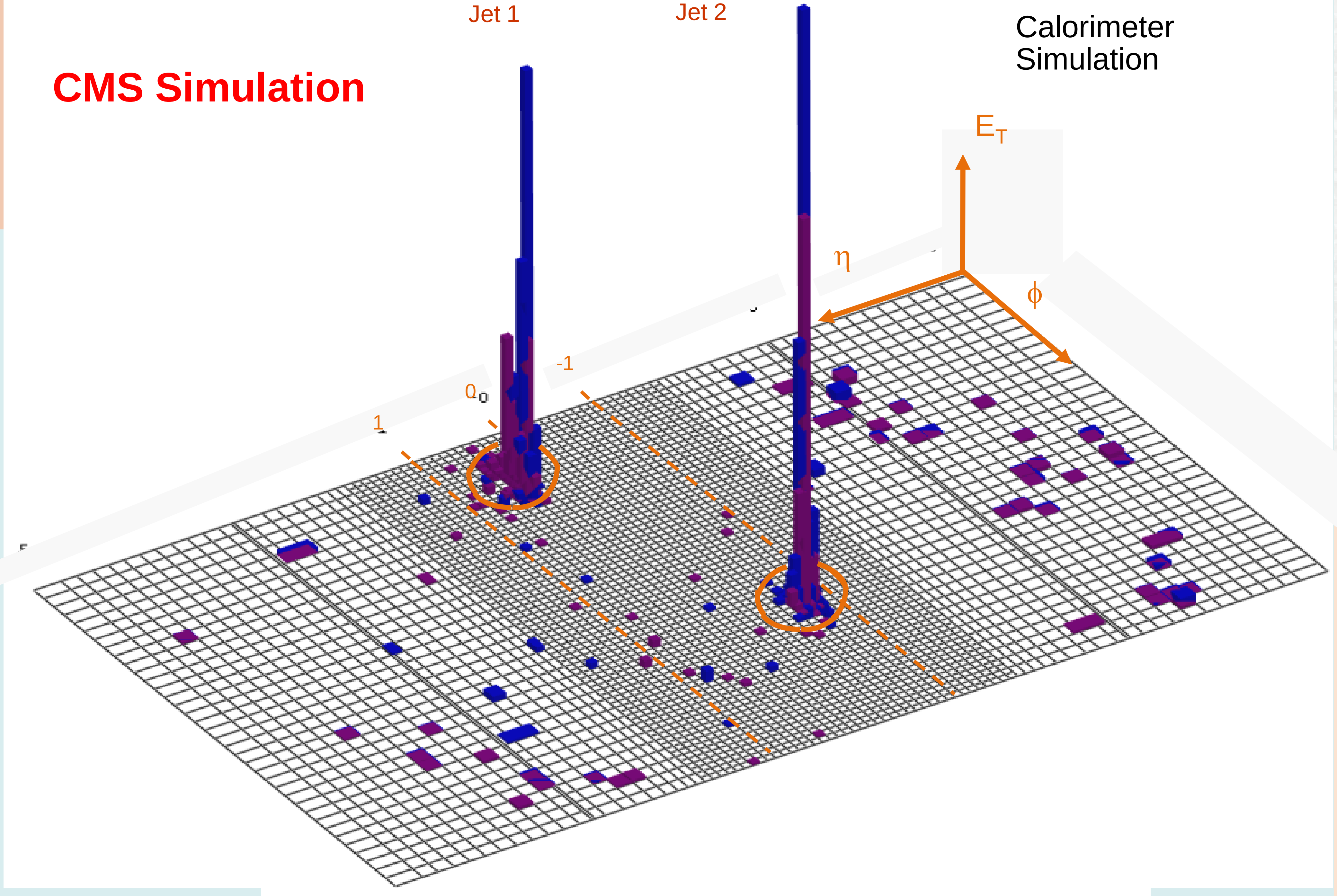
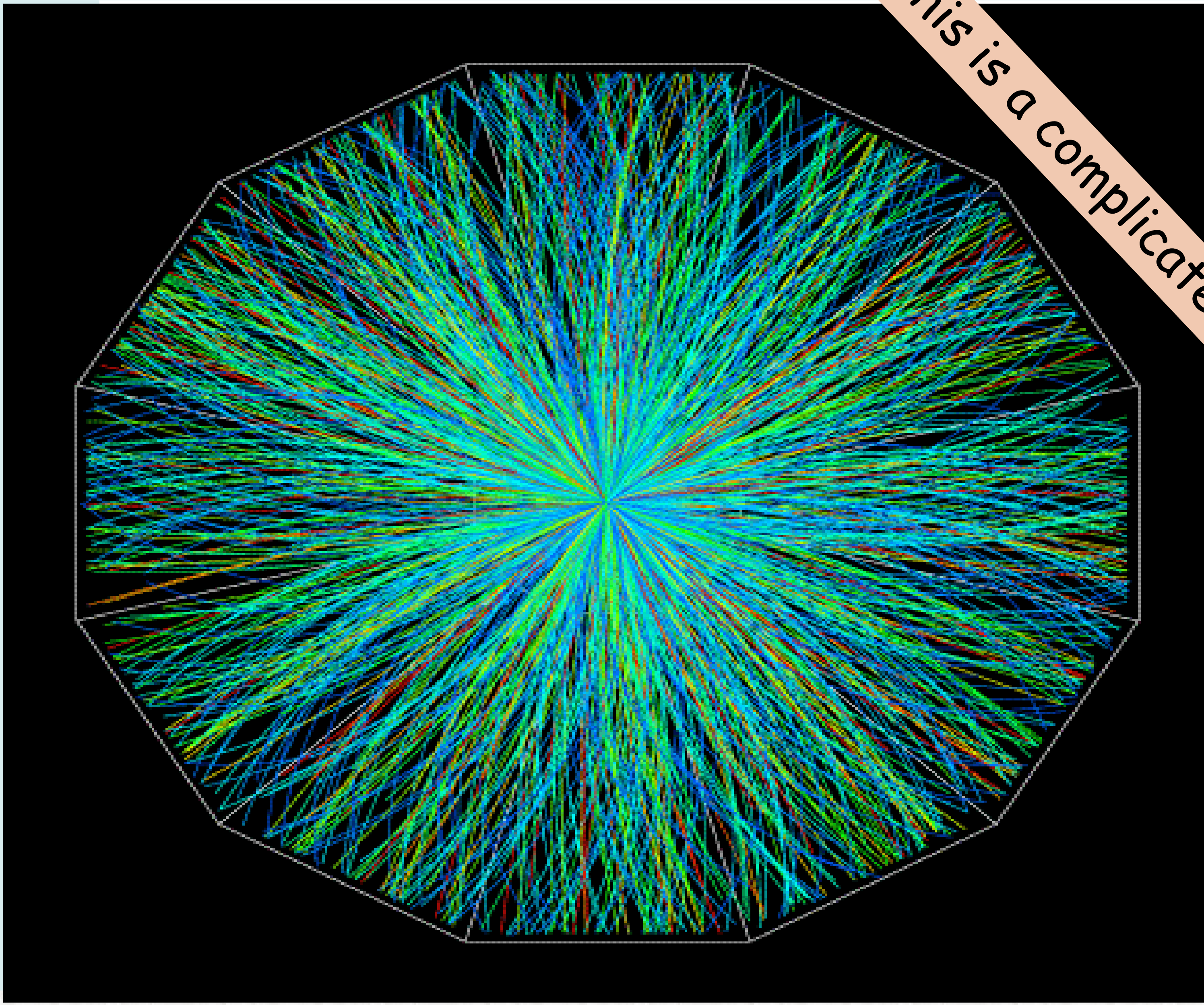



CMS Simulation
Jet 1
Jet 2
Calorimeter
Simulation
E_T
η
ϕ
-1
0
1

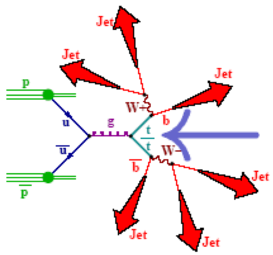
Au+Au collision at RHIC



Now this is a complicated event!

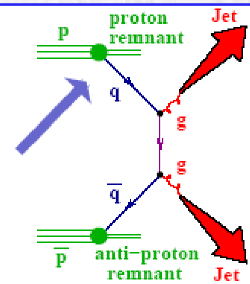
Why do we Study Jets in Hadron Colliders?

Study of heavy particles:



→ measurements of top quark production

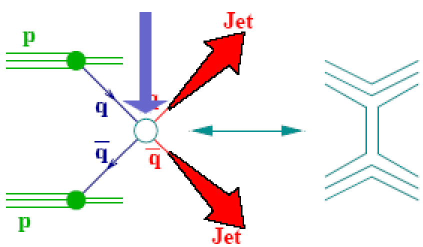
$p\bar{p} \rightarrow 6 \text{ jets} + X$



→ tests of the proton structure function

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

Search for quark substructure:



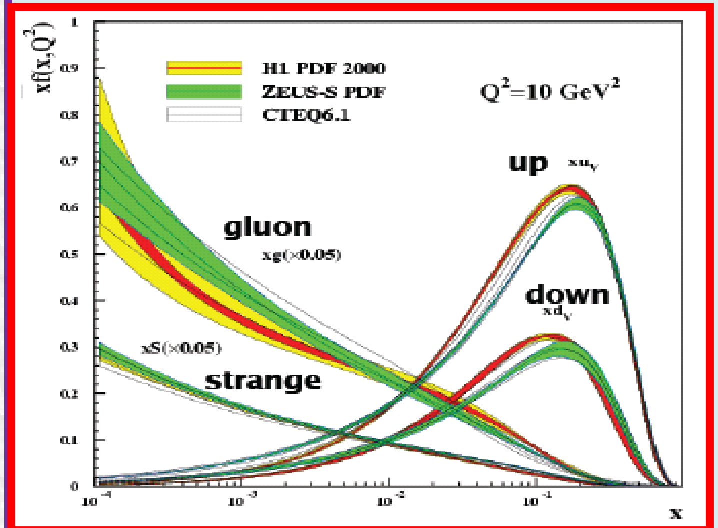
→ search for quark compositeness

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

- QCD Studies
  - Measurements of a_s
  - Fragmentation functions
  - Parton Distribution Functions
  - Color/spin dynamics
  - Quark-gluon jet properties
  - 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
- And much more …

Explanation of the blob's: PDFs

Parton Distribution Functions

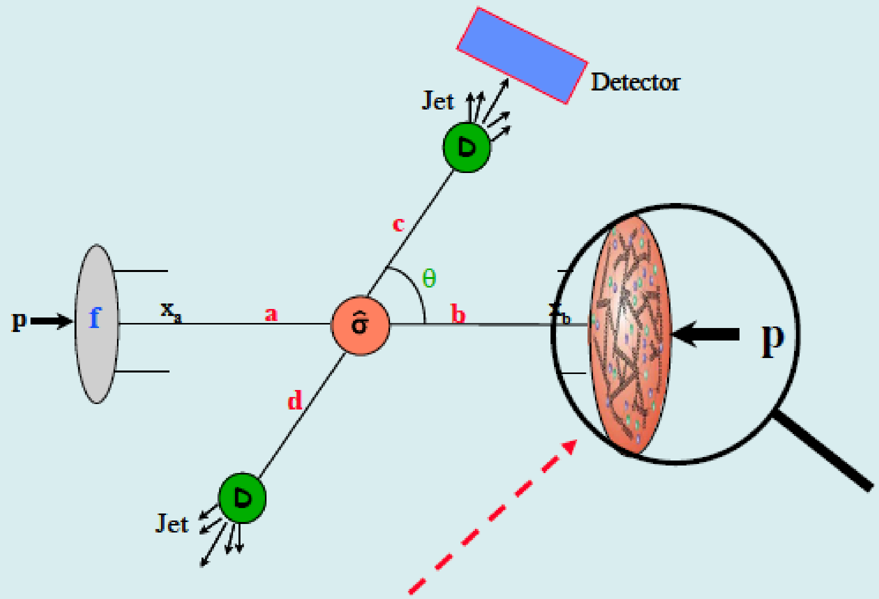


$xf(x,Q_o) = A_o\, x^{A1}\, (1-x)^{A2}\, P(x)$

small x behavior

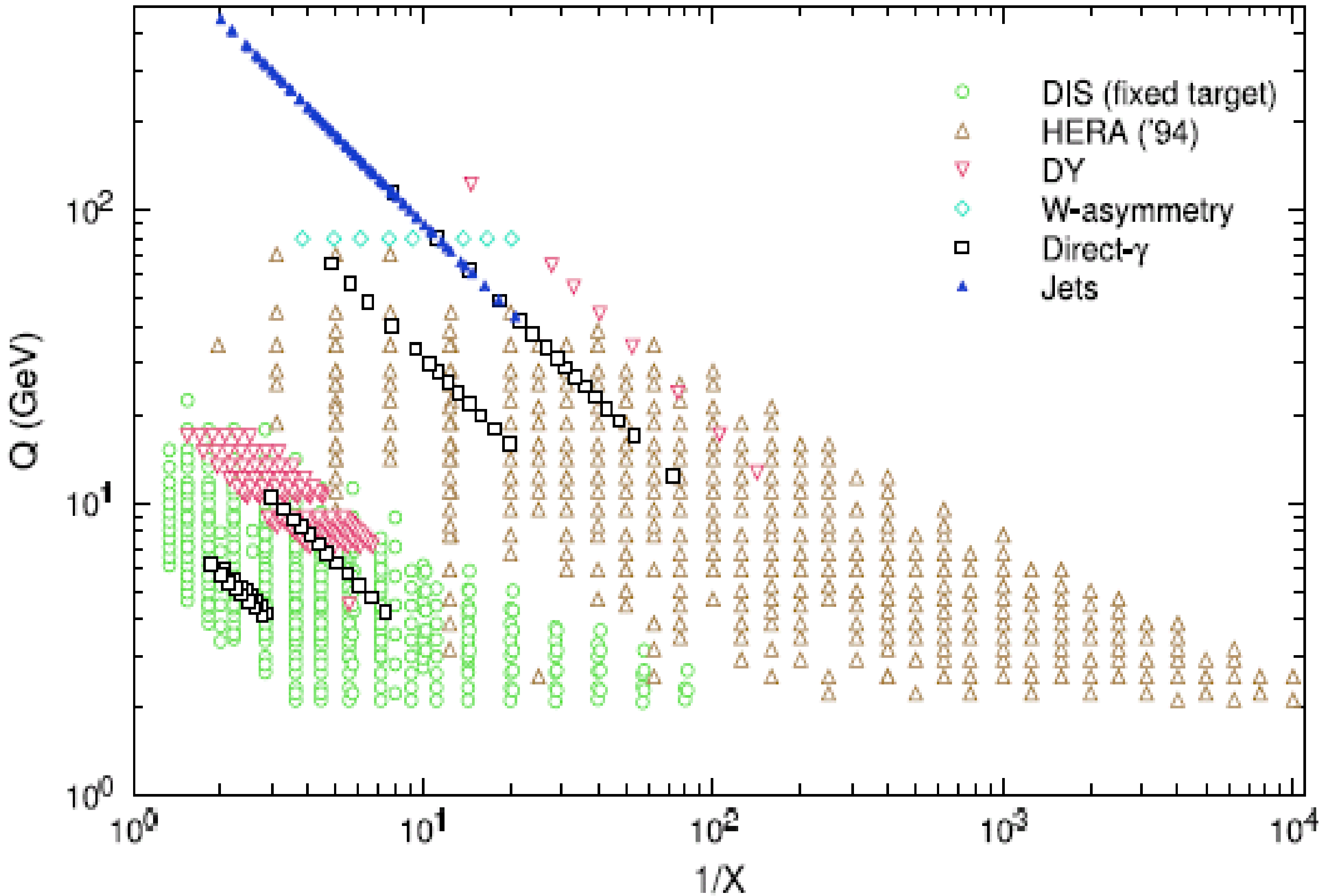
in between

large x behavior



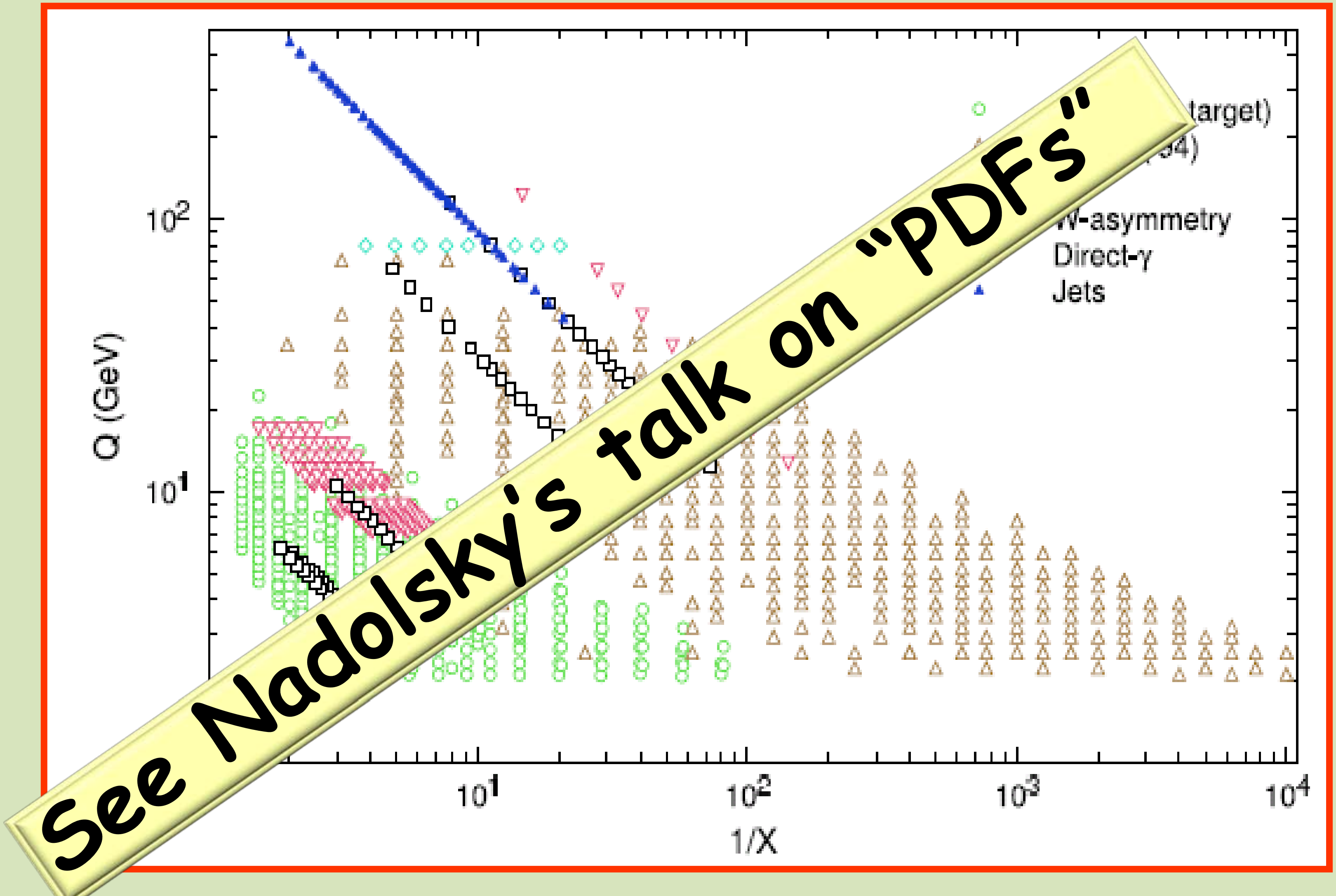
- *Parton Distribution Functions* of the proton are measured at a some "hard scale" and evolved via pertrurbative QCD to the "scale" of the interaction
- PDFs are determined doing Global Fits of data from DIS (Deep Inelastic Scattering), DY (Drell-Yan), Direct Photons, and production of jets (MSTW/CTEQ)

Explanation of the blob's: PDFs



Where the data for extracting PDFs are coming from?

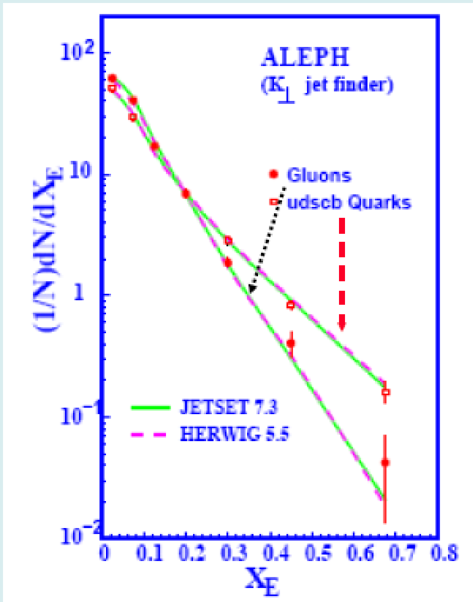
Explanation of the blob's: PDFs

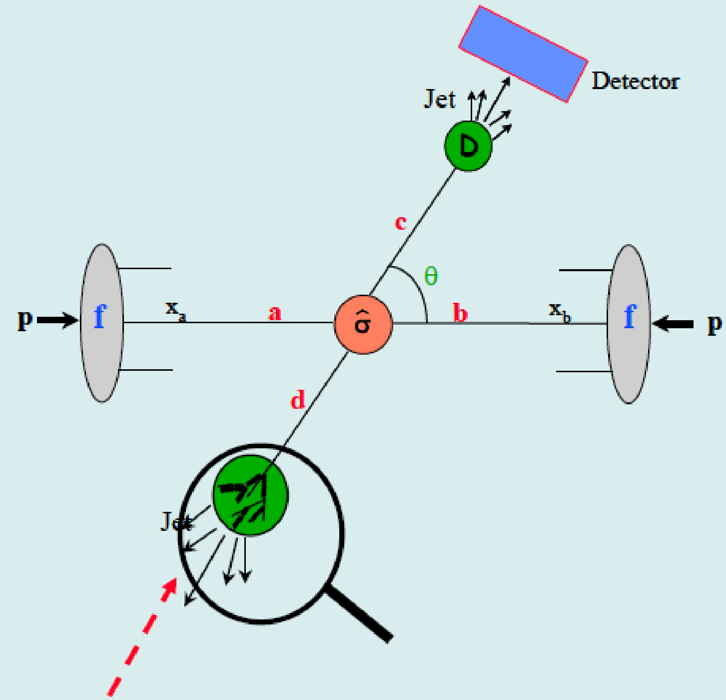


Where the data for extracting PDFs are coming from?

Explanation of the blob's: Fragmentation

Particle Fragmentation Functions





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

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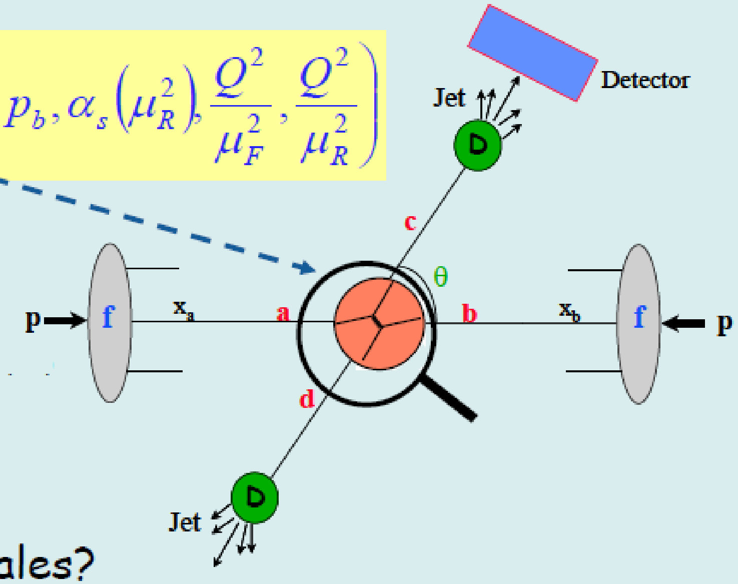
Explanation of the blob's: Hard Scatter

Hard Scattering Cross Section

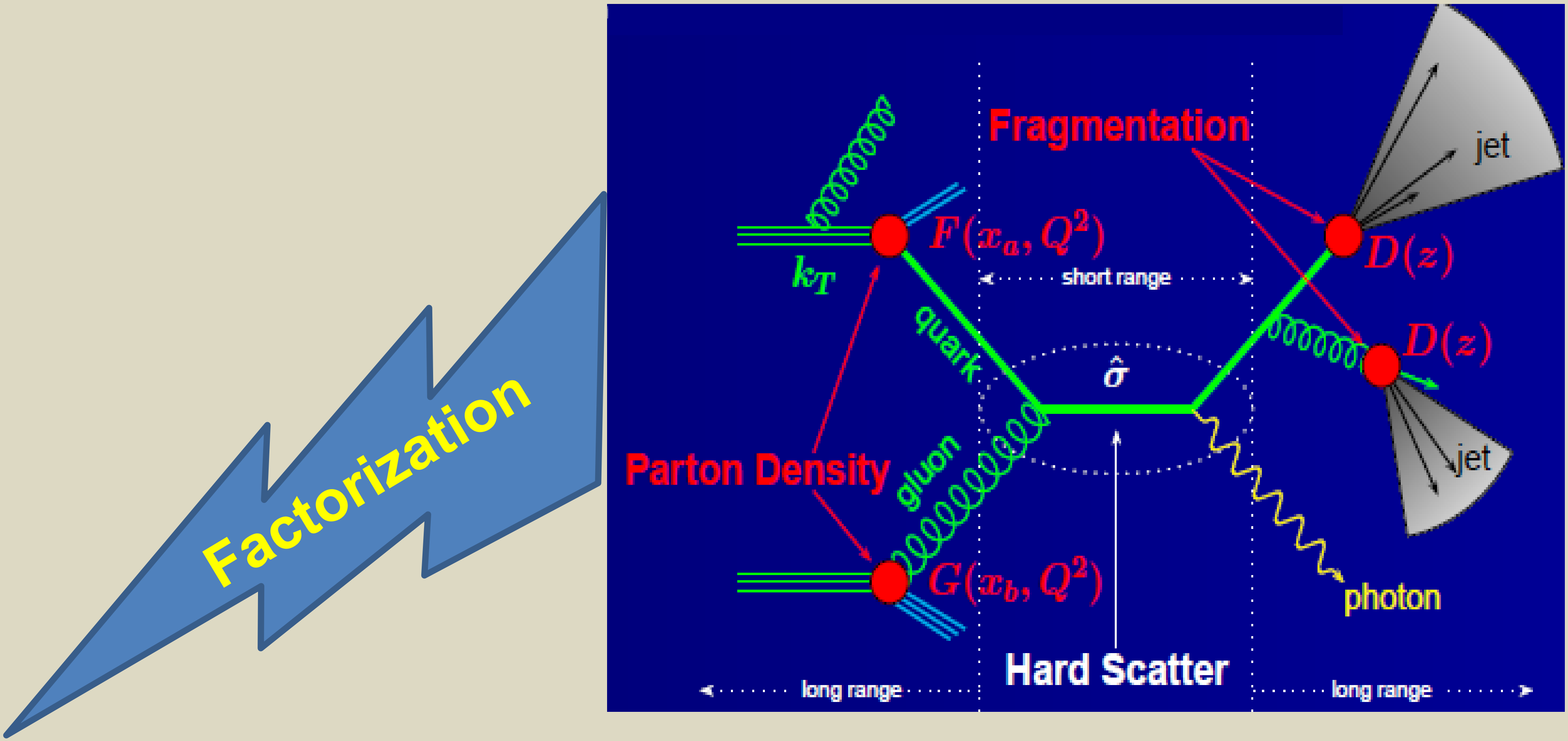
$$\sigma_X = \sum_{i,j} \int_0^1 dx_a dx_b f_i(x_a, \mu_F^2) f_j(x_b, \mu_F^2) \hat{\sigma}_{ij}\left(p_a, p_b, \alpha_s(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2} \right)$$



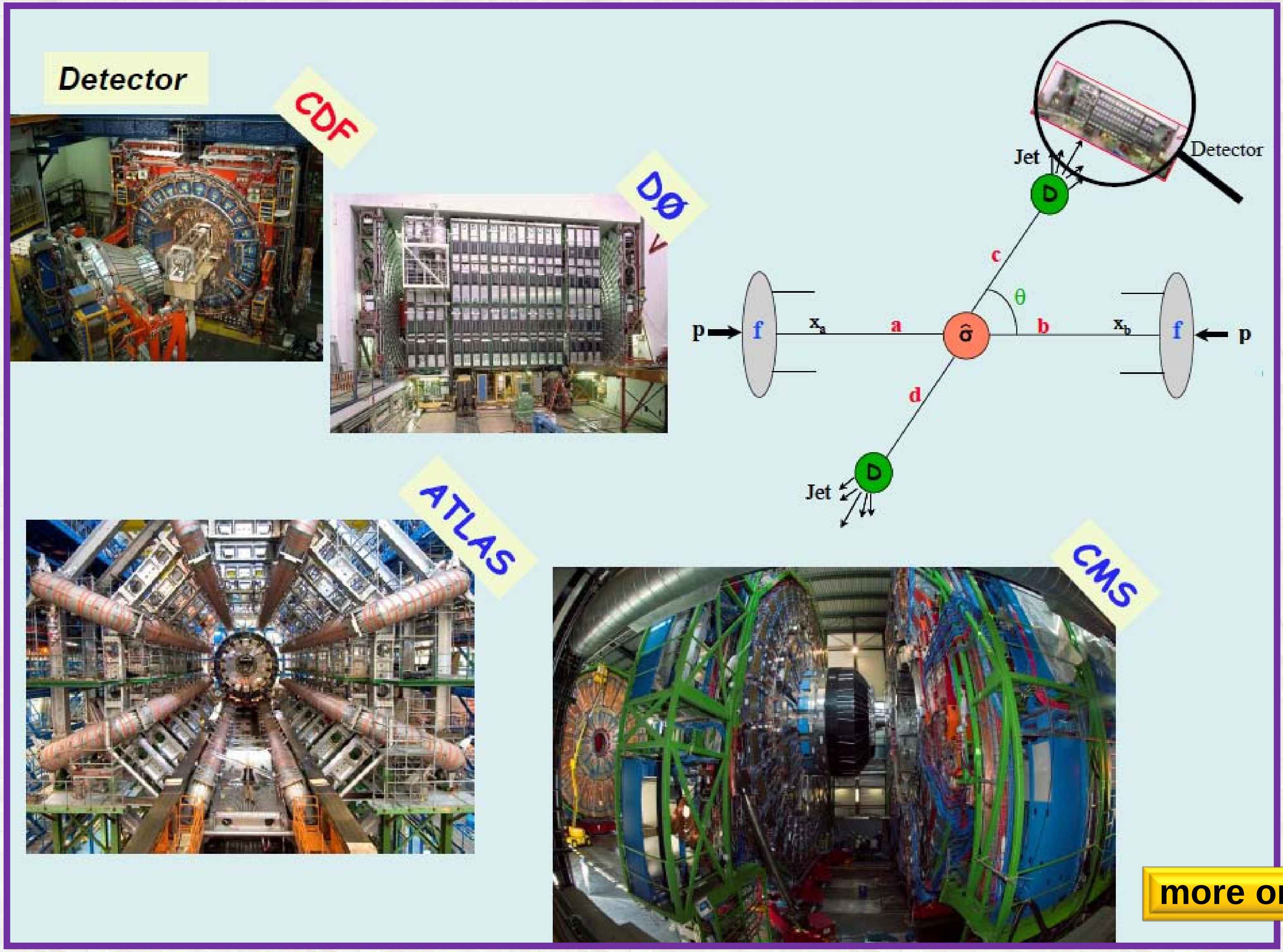
- σ_X = (PDF's for p and p) ⊗ (partonic level cross section)
  - Separate the long-distance pieces (PDF's) from the short-distance cross section → Factorization
- What's the deal with the various scales?
  - μ_F is the factorization scale that enters in the evolution of the PDF's and the Fragmentation 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

CTEQ

Explanation of the blob's: Hard Scatter



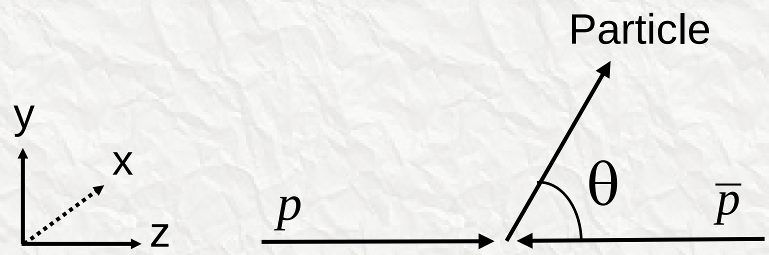
Explanation of the blob's: Detectors



more on that later…

Kinematics in Hadronic Collisions

Rapidity (y) and Pseudo-rapidity (η)



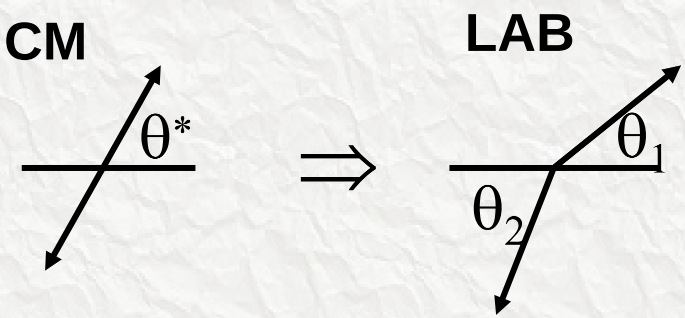
$$y \equiv \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta}$$

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

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



Δη and p_T are invariant under longitudinal boosts

Kinematics in Hadronic Collisions cont'd

Transverse Energy/Momentum

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

$$p_z = E \tanh y$$

$$E = E_T \cosh y$$

$$p_z = E_T \sinh y$$

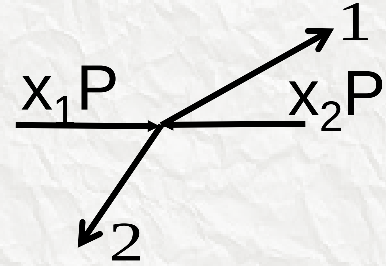
$$p_T \equiv p \sin\theta \xrightarrow[m \to 0]{} E_T$$

Invariant Mass

$$M_{12}^2 \equiv (p_1^{\mu} + p_2^{\mu})(p_{1\mu} + p_{2\mu})$$

$$= m_1^2 + m_2^2 + 2(E_1 E_2 - \boldsymbol{p}_1 \cdot \boldsymbol{p}_2)$$

$$\xrightarrow[m_1, m_2 \to 0]{} 2E_{T1}E_{T2}(\cosh\Delta\eta - \cos\Delta\phi)$$



Partonic Momentum Fractions

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

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

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

$$0 < x_1, x_2 < 1$$

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

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

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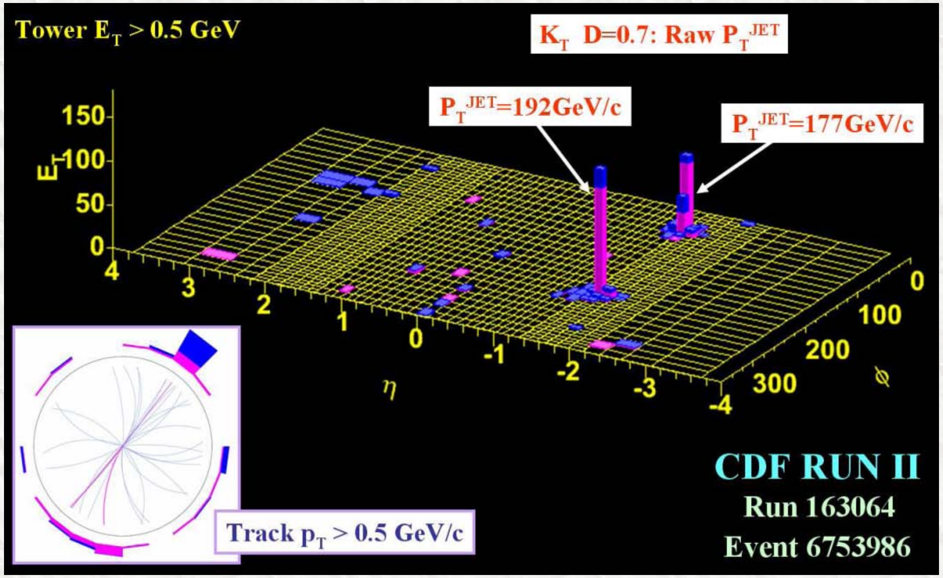
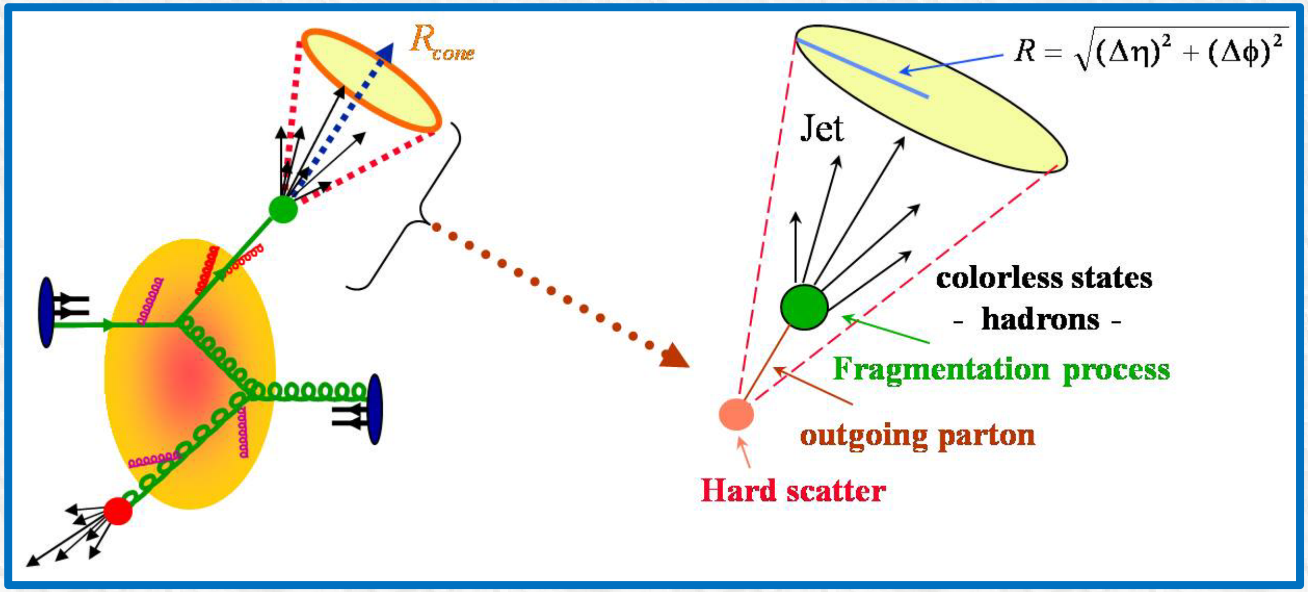
What are Jets?

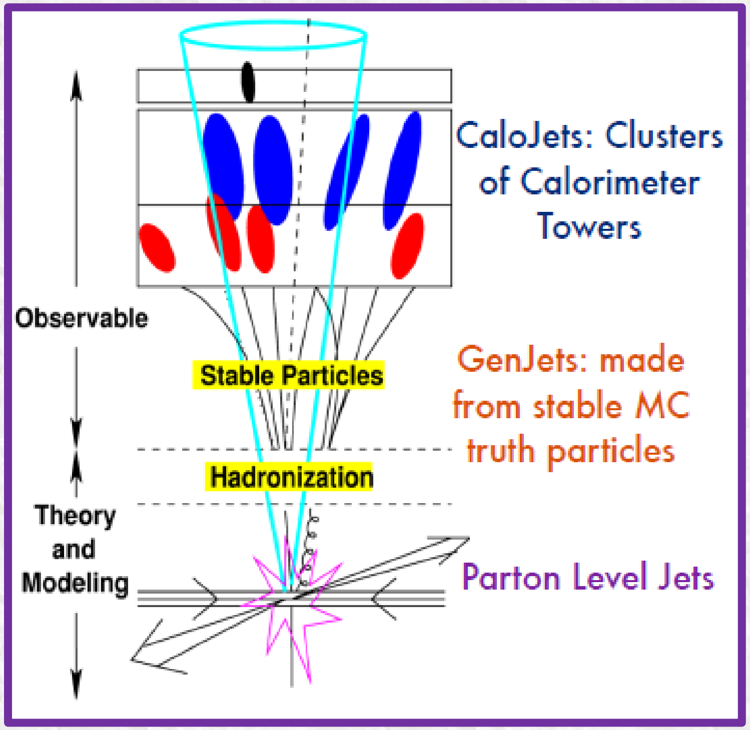
What are Jets?

Whatever objects the jet algorithm finds!



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
- Jets manifest themselves at localized clusters of energy (or particles)
- Jets are the experimental signatures of quarks & gluons

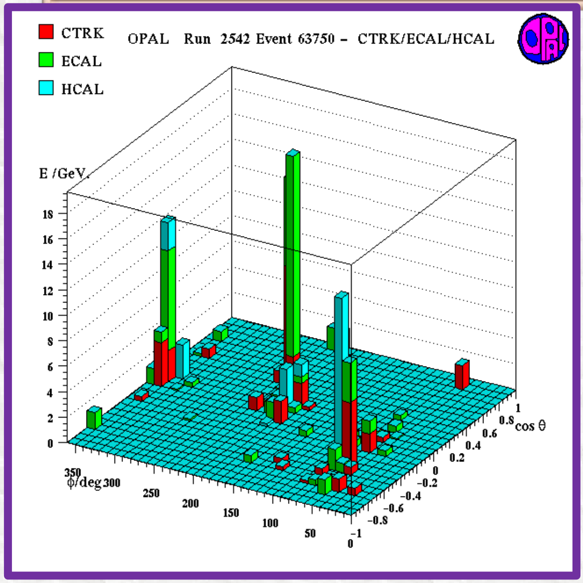
First Evidence for Jets

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

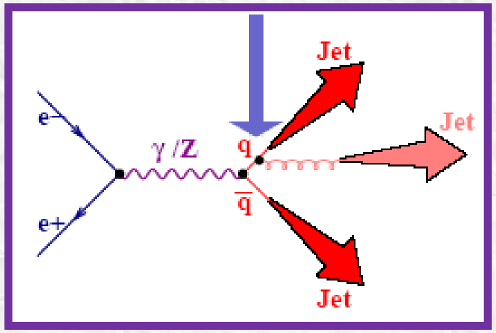
G. Hanson et al. (MARK-I Collab), PRL 35, 1609 (**1975**)

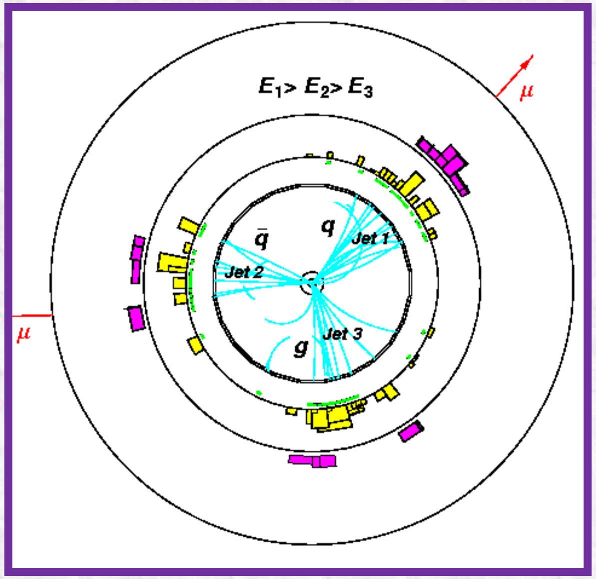
Gluon-initiated jets were discovered in e^+e^- annihilations at DESY-PETRA at E_{cm} > 15 GeV

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)



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





Outline

- Introduction
  - QCD
  - ee, ep, pp Processes – History of Jets
  - What is a Jet?
- **Jet Algorithms**
- Jet Reconstruction, Calibration, Performance
- Jet Characteristics
  - Jet Energy Profile
  - Quark and Gluon Jets
  - Color Coherence Effects
- Jet Production at Hadron Colliders (Tevatron & LHC)
  - Underlying Event
  - Event Shapes
  - Dijet Azimuthal Decorrelation & Angular Distributions
  - Inclusive Jet Cross Section
  - Dijet Mass
- Summary

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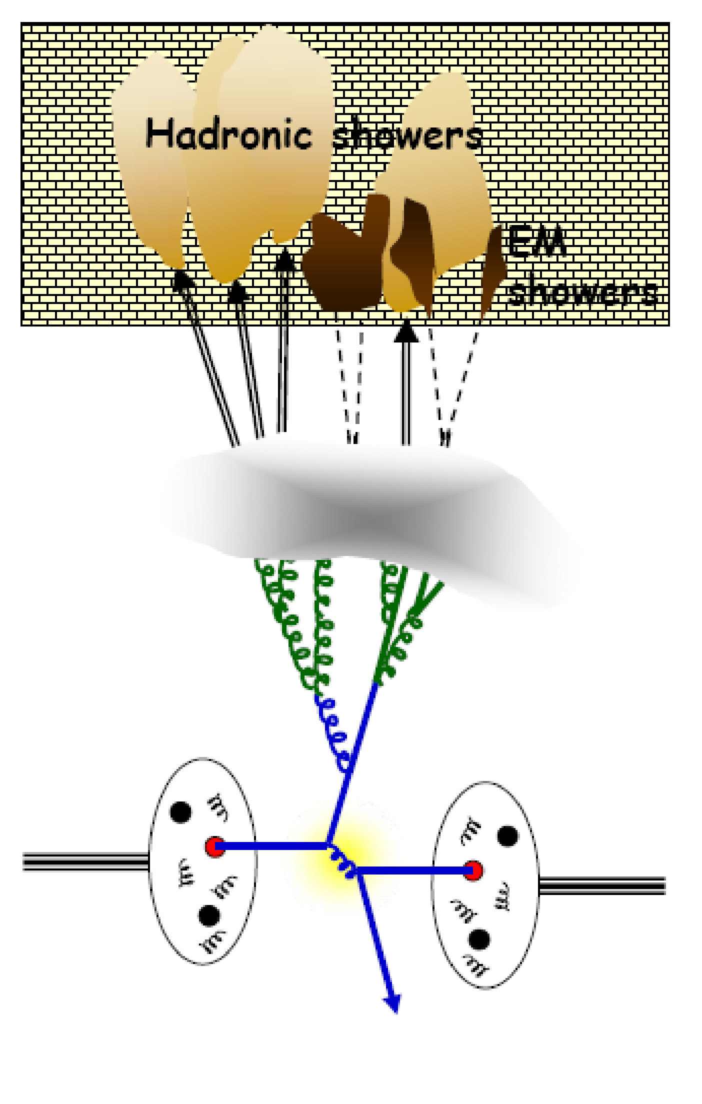
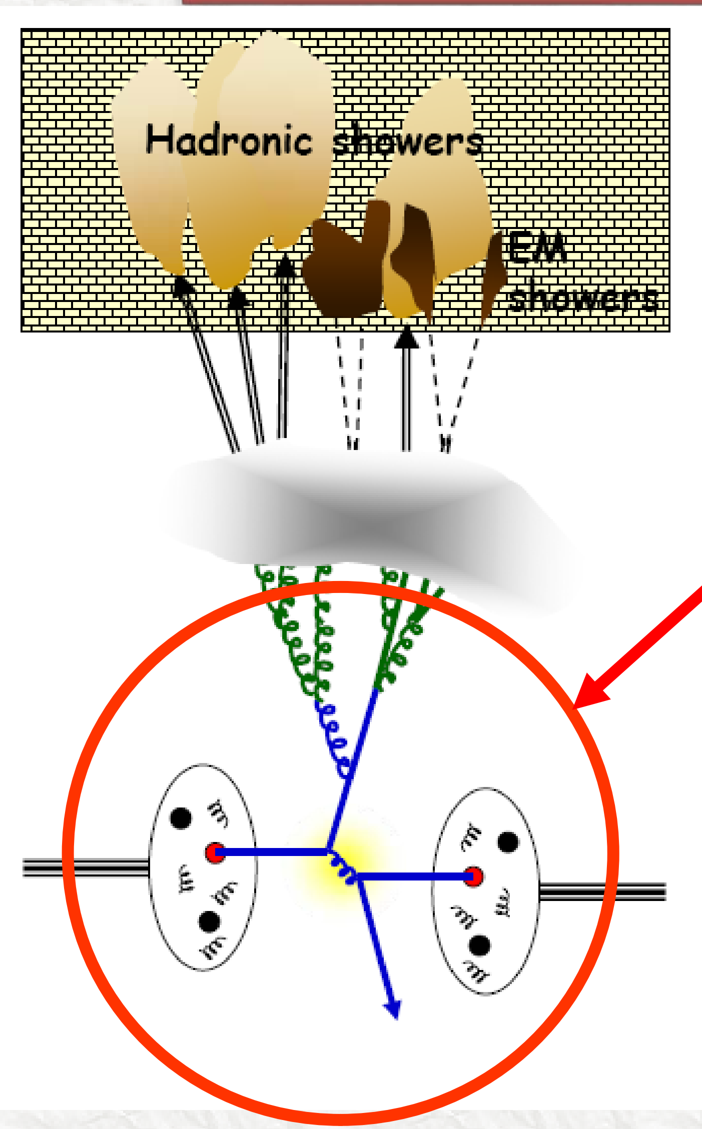
Jet Algorithms



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

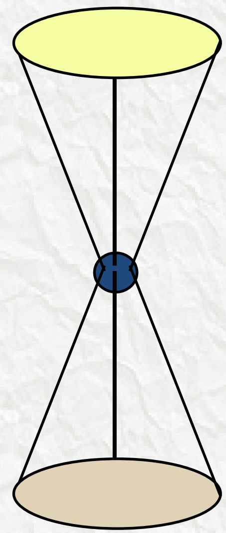
Jet Algorithms



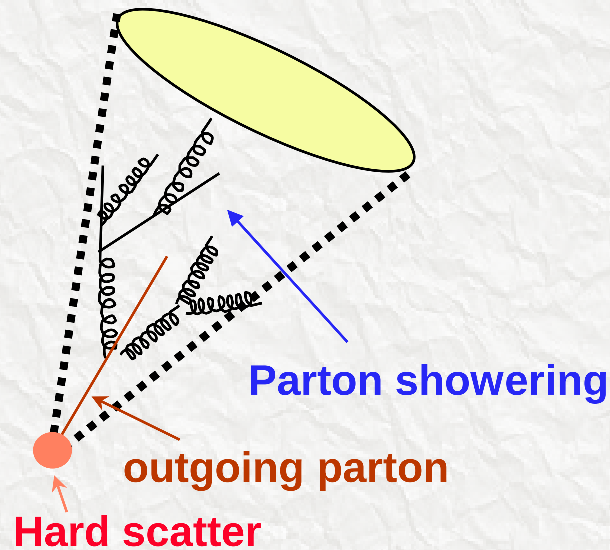
Jets at the "Parton Level" (i.e., before hadronization)

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

2 → 2 process
LO QCD

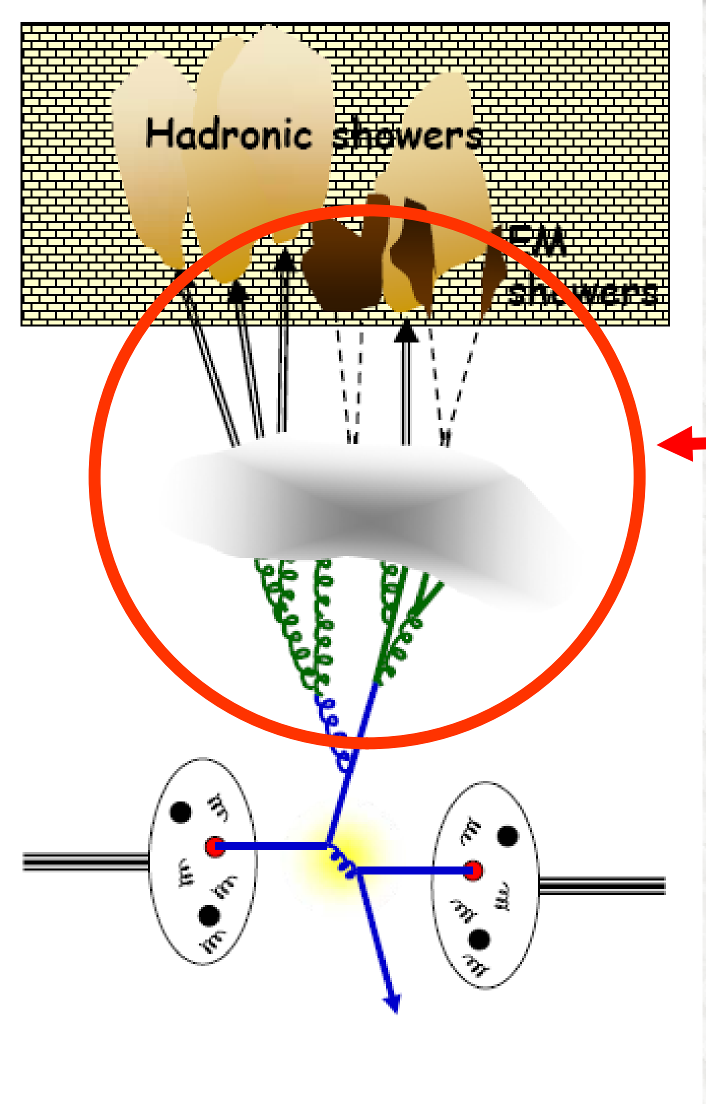


2-jet final state
1 parton/jet

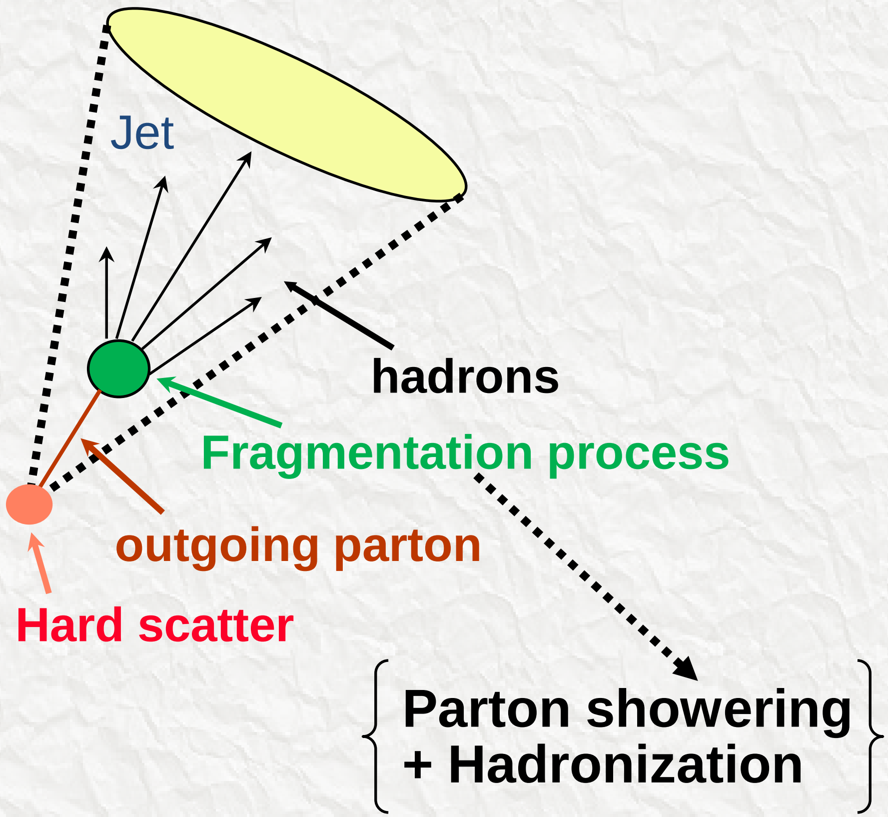


multi-jet final state

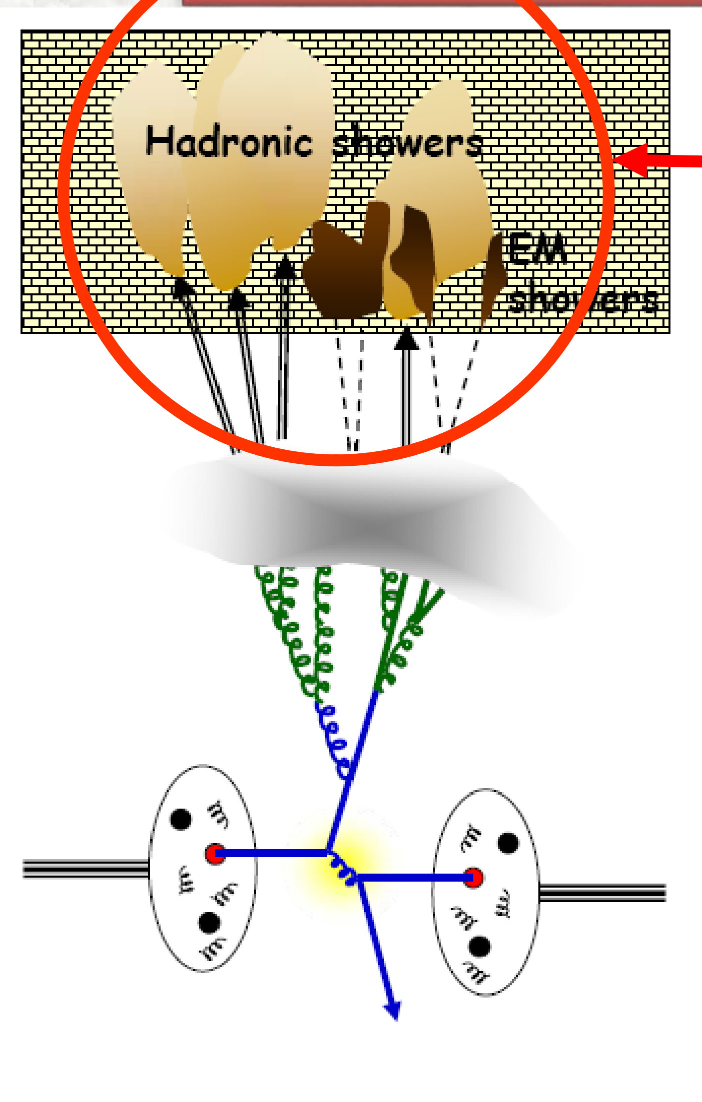
Jet Algorithms

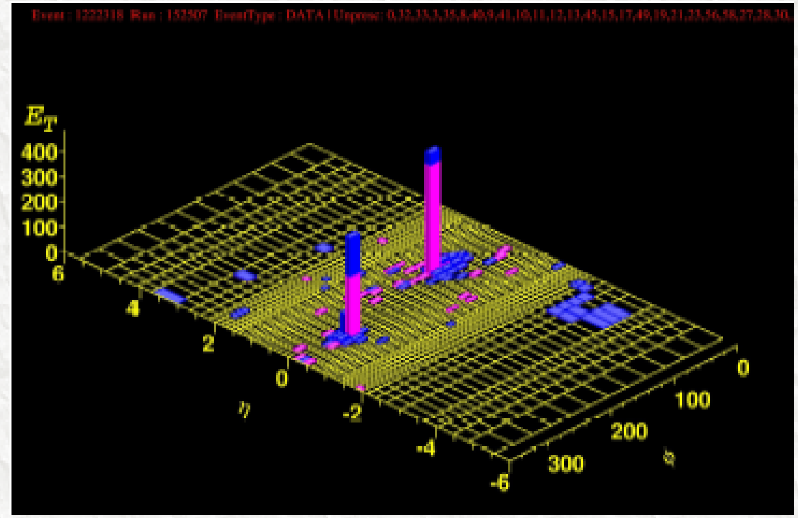


The idea is to come up with a jet algorithms which minimizes the non-perturbative hadronization effects



Jet Algorithms



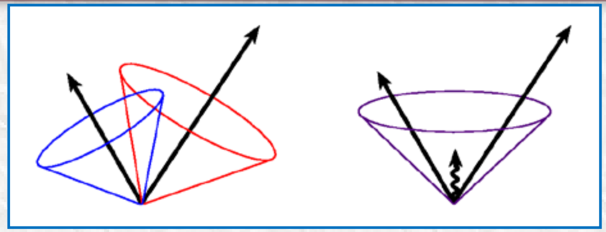


Jets at the "Detector Level":

- ➢ *Calorimeter - clusters of energy "towers"*
- ➢ *Tracking - clusters of tracks*
- ➢ *Combination of detectors*
  - ❖ *Particle Flow*
  - ❖ *Calorimeter + Tracks*

Jet Algorithms – Requirements

- **Theoretical:**
  - Infrared safety
  - Collinear safety



  - Low sensitivity to hadronization
  - Invariance under boosts
  - Same jets at parton/particle/detector levels
- **Experimental:**
  - Detector independence
  - Minimization of resolution effects
  - Stability with Luminosity
  - Computational efficiency
  - Maximal reconstruction efficiency

Tevatron RunII report: hep-ex/0005012
Tev4LHC report: hep-ph/0610012

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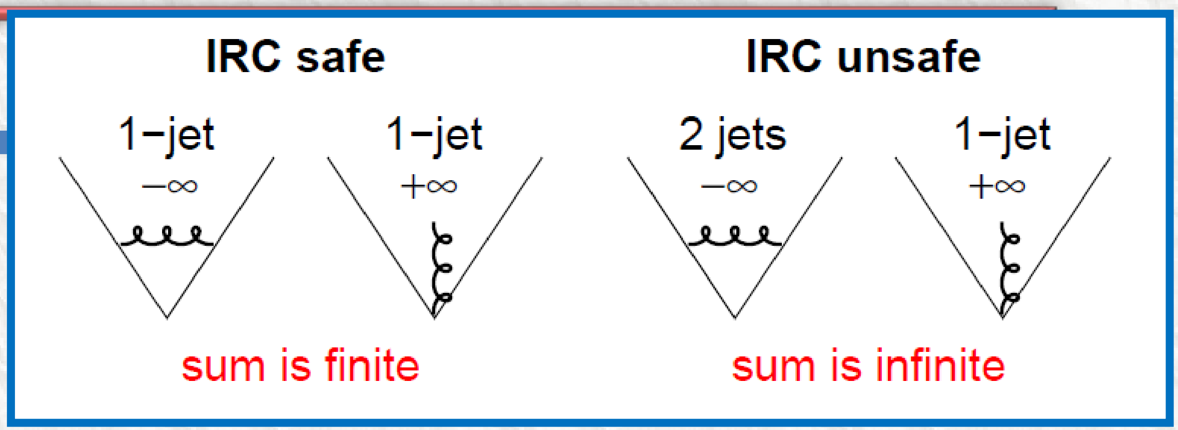

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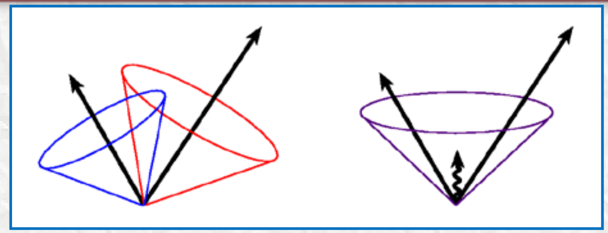
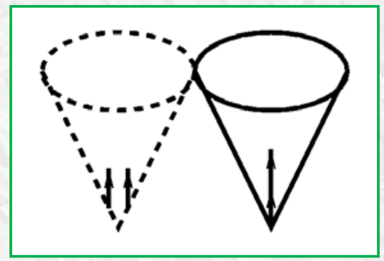
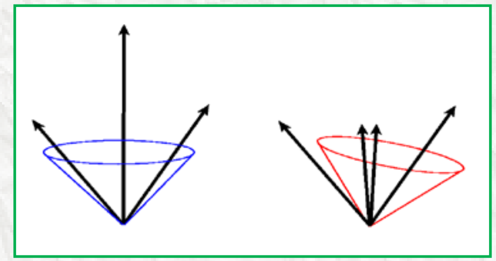


  - Collinear safety





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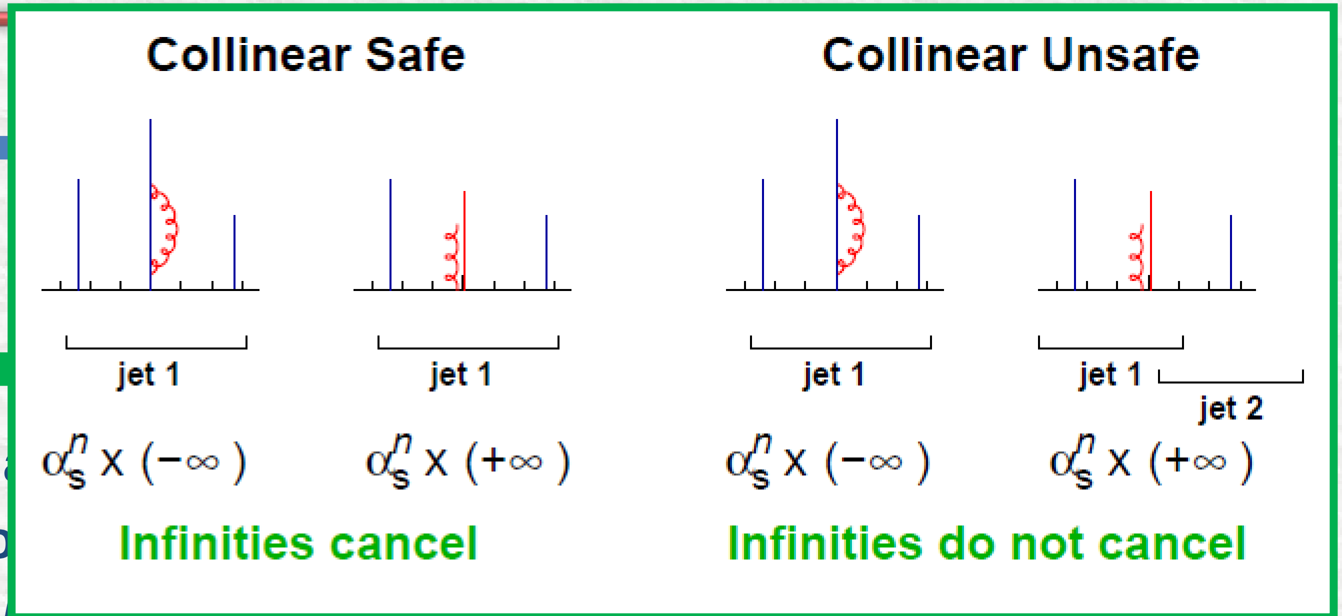

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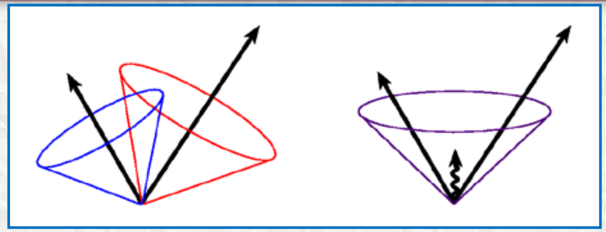

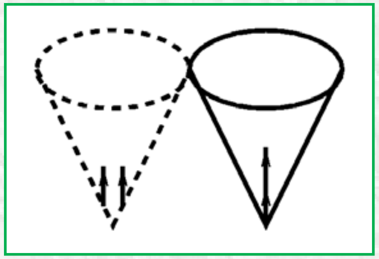

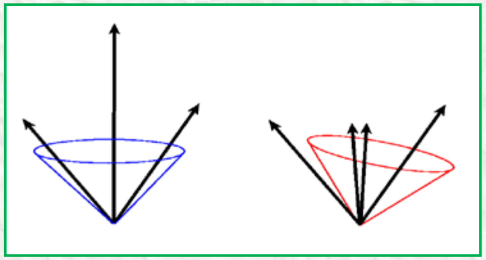

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Jet Algorithms – Types

Types of jet clustering:

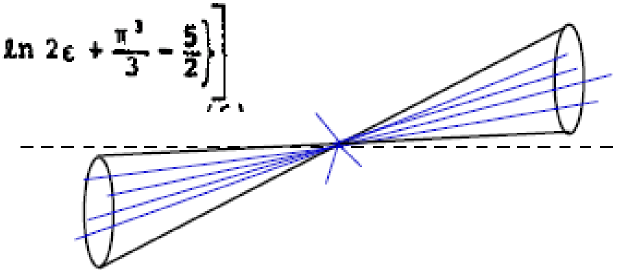
- K_T: cluster objects close in relative p_T
  - Irregular shape, issue for calibration
  - Used extensively at LEP and HERA
- Cone: cluster objects close in angle
  - Simple shape, unless jets overlap
  - Used primarily at hadron colliders

Jet Algorithms – Types

First 'jet algorithm' dates back to Sterman and Weinberg (1977) — the original infrared-safe cross section:

To study jets, we consider the partial cross section $\sigma(E,\theta,\Omega,\varepsilon,\delta)$ for e^+e^- hadron production events, in which all but a fraction $\varepsilon \ll 1$ of the total e^+e^- energy E is emitted within some pair of oppositely directed cones of half-angle $\delta \ll 1$, lying within two fixed cones of solid angle Ω (with $\pi\delta^2 \ll \Omega \ll 1$) at an angle θ to the e^+e^- beam line. We expect this to be measur-

$$\sigma(E,\theta,\Omega,\varepsilon,\delta) = (d\sigma/d\Omega)_0\,\Omega\left[1 - (g_E^2/3\pi^2)\left\{3\ln\delta + 4\ln\delta\,\ln 2\varepsilon + \frac{\pi^2}{3} - \frac{5}{2}\right\}\right]$$



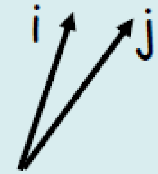
Gavin Salam's lectures
CTEQ 2008

Groundbreaking; good for 2 jets in e^+e^-; but never widely generalised

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

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

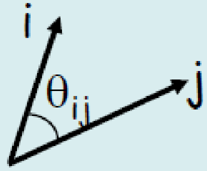
- Iterate until all particle pairs satisfy $y_{ij} > y_{cut}$
- No problems with jet overlap
- Less sensitive to hadronization effects

The JADE Algorithm

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

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

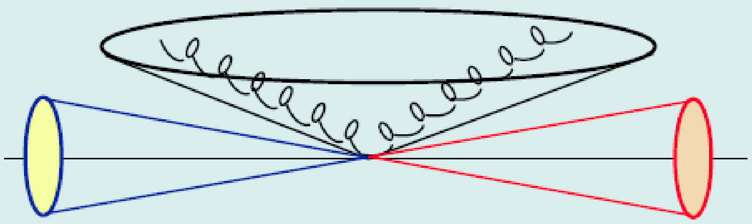
(E_{vis} is the sum of all particle energies)



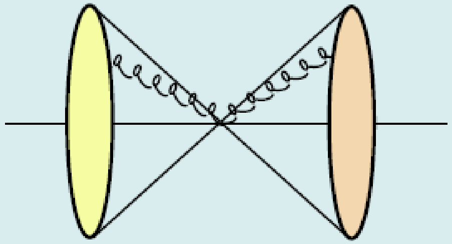
- Recombination: $p_k = p_i + p_j$
- Problems with this algorithm
  - It doesn't allow resummation when y_{cut} is small
  - Tendency to reconstruct "spurious" jets

    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

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The Durham or "k_T" Algorithm

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

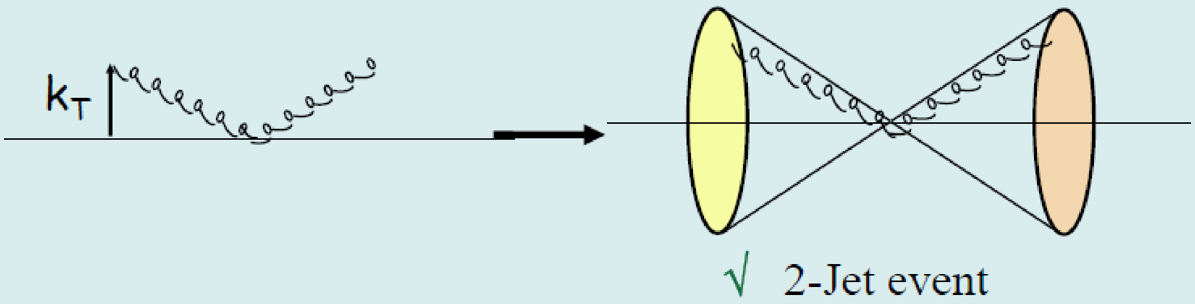
$$\min(y_{ij}) = \frac{M_{ij}^2}{E_{vis}^2} < y_{cut}$$

Most widely-used jet algo in e^+e^-

For small θ_{ij} we get :

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

- 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}



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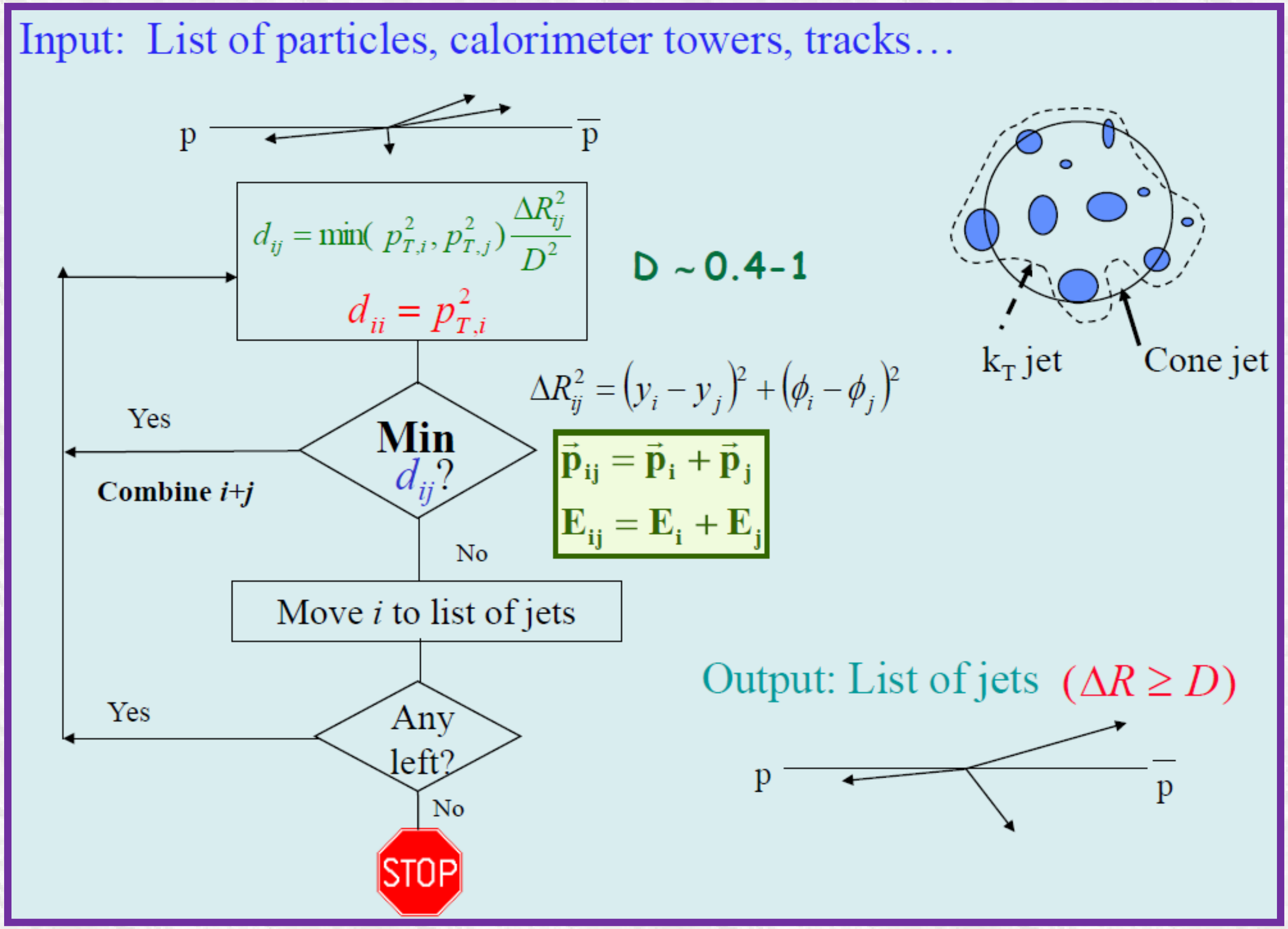
k_T Jet Algorithm: Hadron Colliders

- k_T jets are infrared and collinear safe
- There are no overlapped jets
- Every particle, or detector tower is unambiguously assigned to a single jet
- No biases from seed towers
- k_T jets are sensitive to soft particles and area could depend on pile-up



S.D.Ellis, D.Soper, PRD 48, 3160 (1993)

Developments on "k_T" Algorithms

- Fast kT Algorithm improves speed from $O(N^3)$ to $O(N \ln N)$
  - G.Salam, M.Cacciari, Phys. Lett. B641, 41 (2006)
  - Add ghost particles to determine the area of jets
    - Could be used to subtract pile-up contributions
  - Already adopted as the default k_T algorithm at LHC
- Other recombination algorithms:

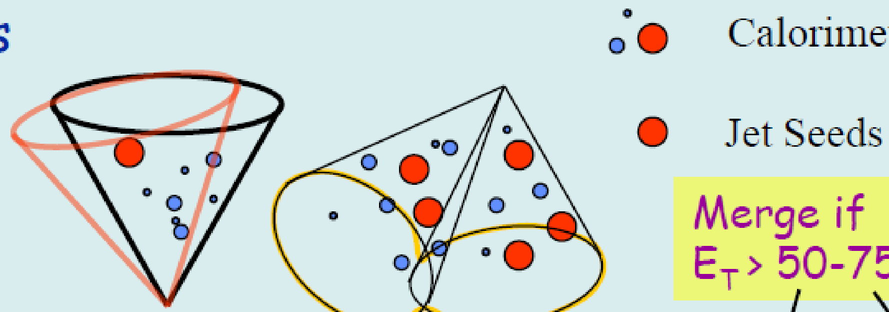
$$d_{ii} = p_{T,i}^{2p} \qquad d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p}) \frac{\Delta R_{ij}^2}{D^2}$$

  - p=1 → regular k_T jet algorithm
  - p=0 → Cambridge/Aachen jet algorithm
    - Dokshitzer, Leder, Moretti, Webber '97 (Cambridge) – Wobisch, Wengler '99 (Aachen)
  - p=-1 → "Anti-k_T" jet algorithm
    - Cacciari, Salam, Soyez '08
    - Soft particles will first cluster with hard particles before among themselves
    - Almost a cone jet near hard partons
      - No merge/split
      - Currently under consideration by CMS (already adopted by ATLAS)

The "Legacy" Cone Jet Algorithm

- A more intuitive representation of a jet that is given by recombination jet finders
- It requires "seeds" with a minimum energy of ~ 1 GeV (to save computing time)
  - Preclusters are formed by combining seed towers with their neighbors within a cone of radius $R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$
  - For each precluster the E_T-weighted centroid is found and a new cone of radius R is drawn around it
  - Iterate until stable solution is found
  - CDF: seeds were not allowed to leave the cone (JetClu algorithm)
- Jet cones may overlap so need to split/merge overlapping jets

Snowmass (1990)



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

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The Midpoint Jet Cone Algorithm

- **Problems with the Legacy (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 (produced massless jets)
- **The Solution: Develop the Midpoint Jet Algorithm**
  - Approximates a seedless algorithm
  - Infrared safe at NLO (inclusive jets)
  - Proper 4-vector kinematics used in all steps –> massive jets
- **Midpoint Algorithm is used at Tevatron Run II (available also at CMS/ATLAS)**

The Midpoint Jet Cone Algorithm

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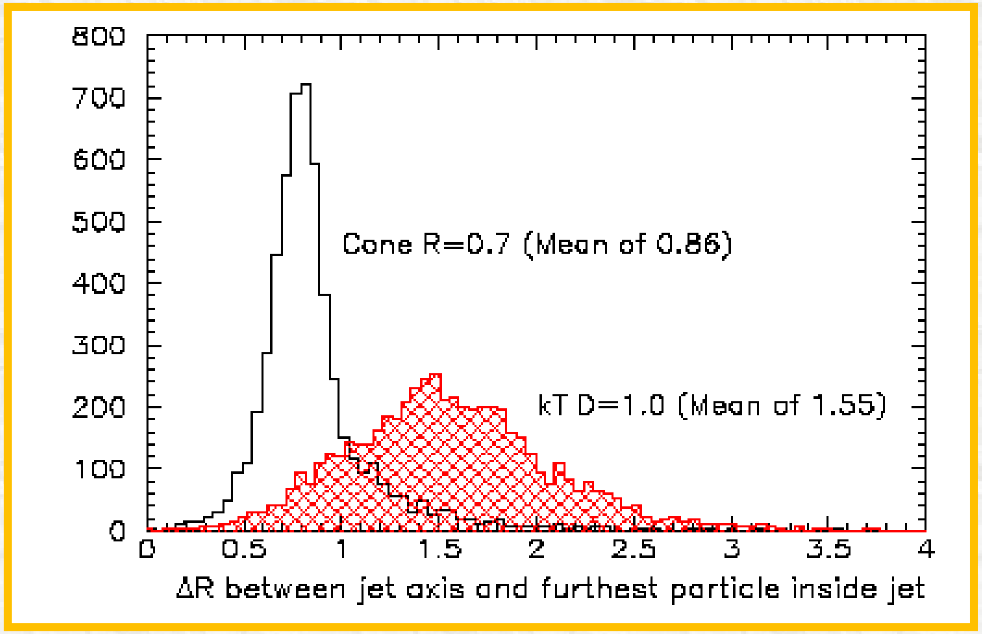
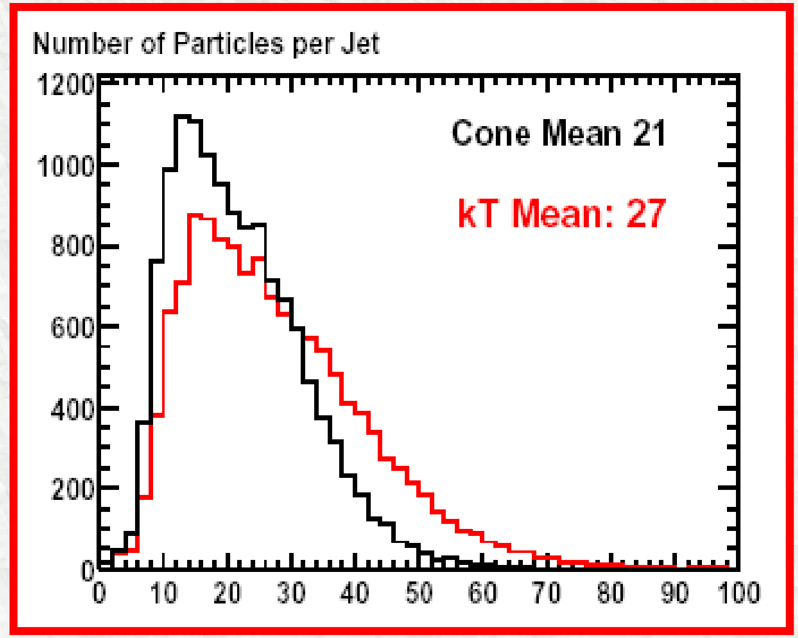
- Proto-jets are formed by combining seed particles with their neighbors within a cone of radius R_{cone} using the E-scheme
  - Particles = calorimeter towers, MC hadrons or partons
- Midpoint seeds are added between proto-jets
  - Only midpoints between proto-jets satisfying the following conditions 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

Cone vs k_T Jets





- k_T jets cluster more particles away from the jet centroid than cone jets
- k_T jets have more particles than cone jets

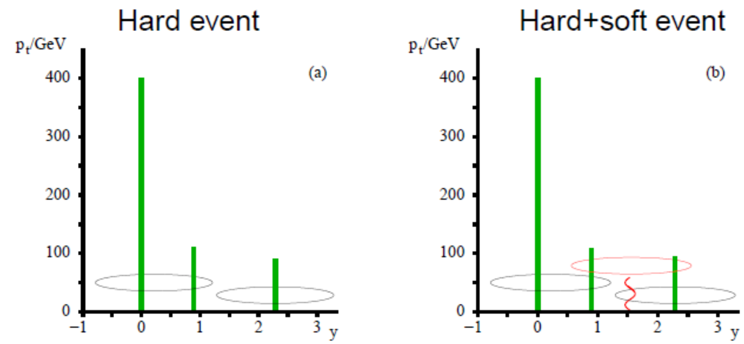
Stability of Midpoint Jets

- Infrared safety on Midpoint jets works well for 2 –> 3 hard-parton final state BUT not for 2 –> 4 when 3 hard partons could cluster to one jet
- p_T threshold on seeds is collinear unsafe
- Seed approach → stable cones missed → infrared unsafety

- **Infrared safety is important for reliable pQCD predictions**
  - cancelation of real & virtual divergences
- **Detector imperfections could have an impact to infrared unsafe jet algorithm**
  - Thresholds, magnetic field effects to soft particles
  - Calorimeter tower segmentation (i.e., two particles hit a single tower, one particle showers to two towers)
  - Spurious seeds (pile-up, noise)

Solution: Seedless Cone Algorithm

Midpoint IR Unsafety



Stable cones:

	Hard event	Hard+soft event
Midpoint:	{1,2} & {3}	{1,2} & {3} & {2,3}
Seedless:	{1,2} & {3} & {2,3}	{1,2} & {3} & {2,3}

Jets: $(f = 0.5)$

	Hard event	Hard+soft event
Midpoint:	{1,2} & {3}	{1,2,3}
Seedless:	{1,2,3}	{1,2,3}

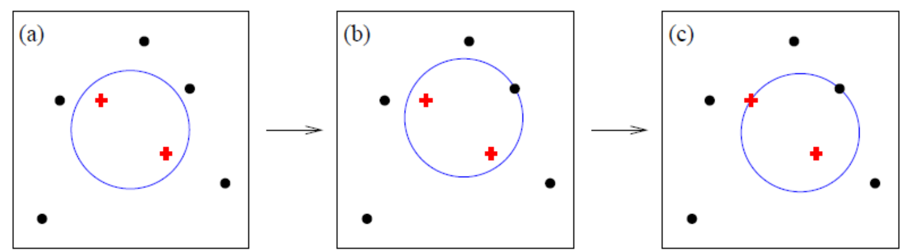
⟶ IR unsafety of the midpoint algorithm

Grégory Soyez   HERA/LHC, Hamburg, Germany, 12-16 March 2007   SISCone – p. 5/15

The Seedless Cone Jet Algorithm

- Seedless: no seeds – all stable cones are considered
- Merge/Split: still applied at the end
- Collinear & Infrared safe: now it is added to the name – Seedless Infrared Safe Cone jet algorithm (SISCone)
  - G.Salam, G.Soyez, arXiv:0704.0292, April 2007
- Simple approach: take all possible sub-sets of N particles in the event and final all stable cones
  - CPU time ~ $O(N2^N)$ – 10^{17} years for N=100 (unrealistic!)
- SISCone approach: use geometry to find all distinct circular enclosures of a set of points (particles)

See Gavin Salam's lectures at CTEQ 2008



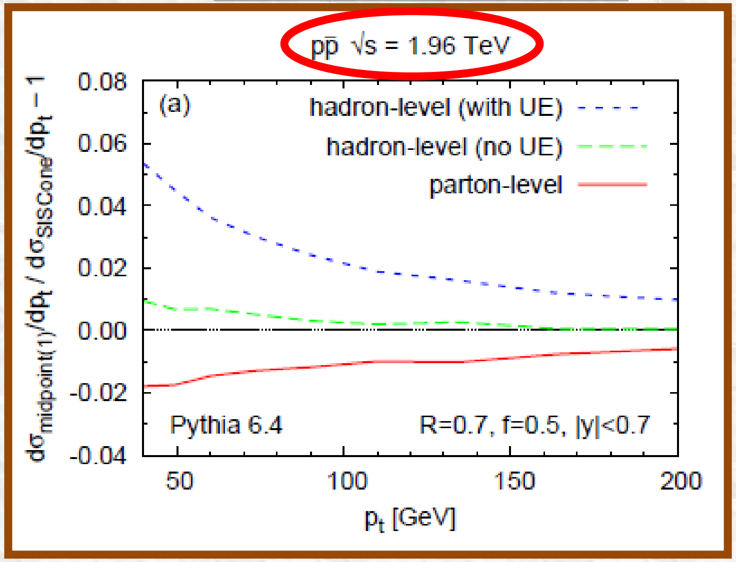
Any enclosure can be moved until a pair of points lies on its edge.

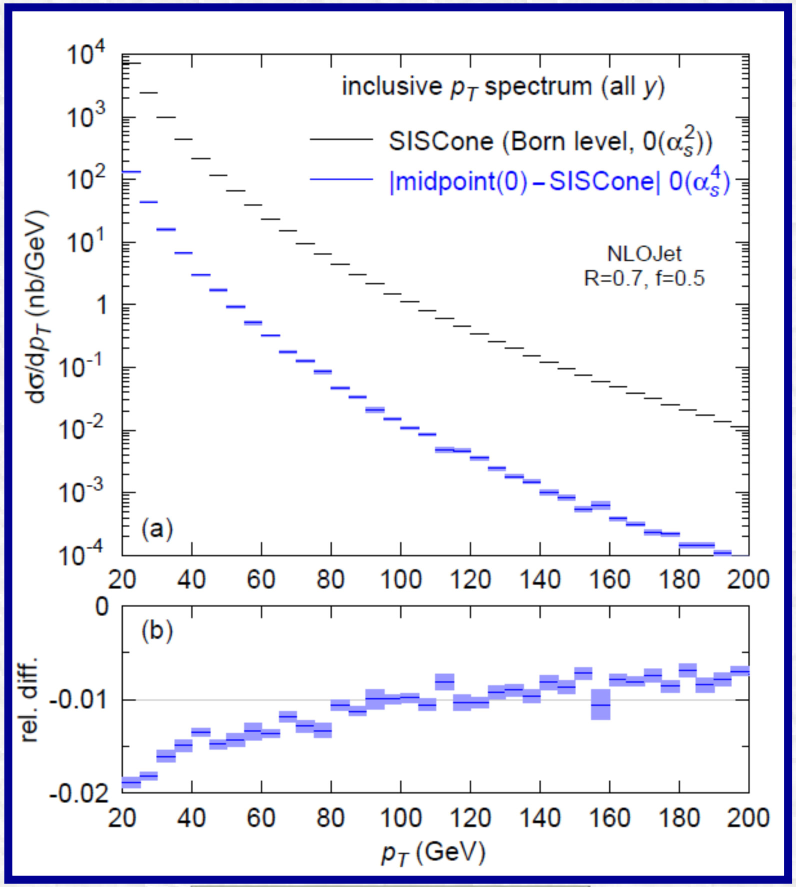
- CPU time ~ $O(N^2 \ln N)$
  - Similar speed with Midpoint with seeds >1 GeV
  - Slower than Fast k_T

Midpoint vs. SISCone

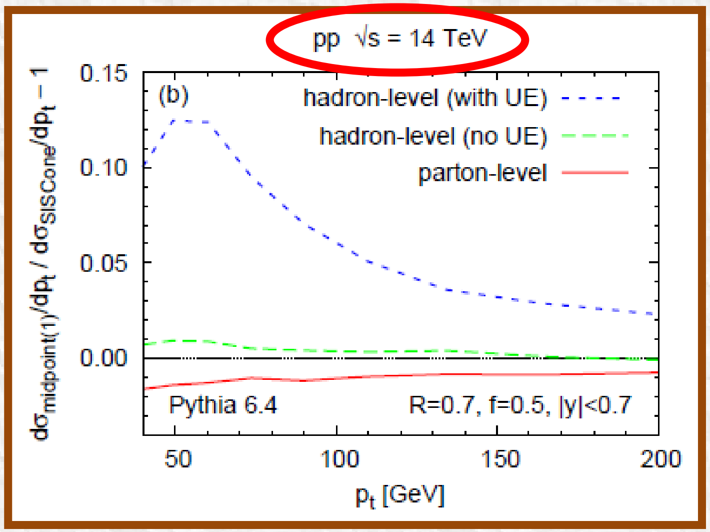
- **Test process 2→4 partons**
- **Midpoint(0 or 1) = seed threshold at 0 or 1 GeV**

Diffs up to 6/%





Diffs up to <15%

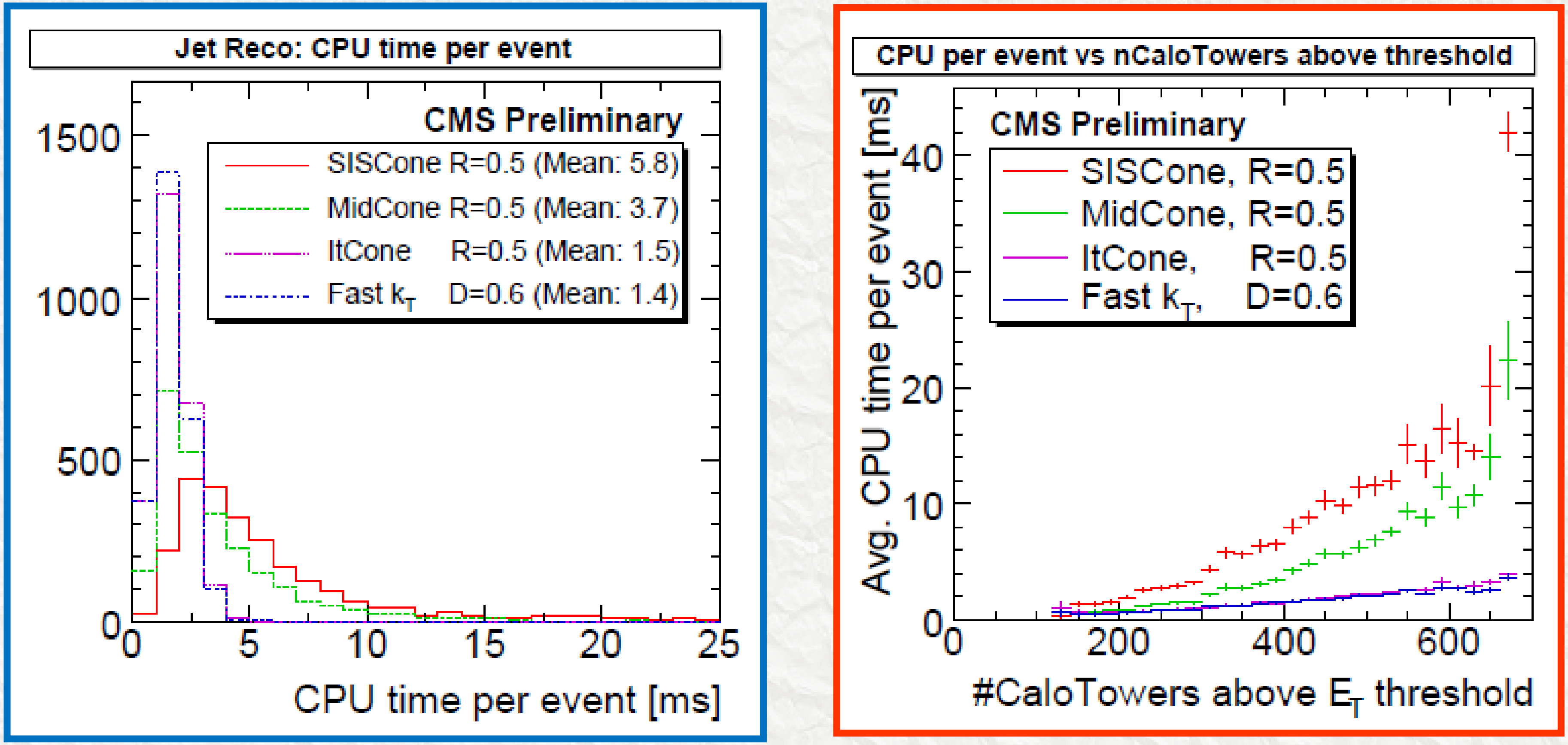


Diffs up to 2%

Algorithm Timing

CMS-JME-07-003

- **SISCone is the slowest algorithm**
- **Fast-kT and Iterative Cone have similar timing performance**
  - **Iterative Cone is used in the CMS High Level Trigger**



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Recap on Jet Algorithms

- There is no such thing as “Best Jet Algorithm”
  - There are several algorithms available and they are not equivalent
  - It is difficult for an experiment to fully support many algorithms

- Be careful about Infrared and Collinear Safety
  - It is easier to think in terms of partons

- The most commonly used (so far) jet clustering algorithms:
  - Iterative Cone (IC) (CMS)
  - JetClu (CDF/ATLAS)
  - SISCone (LHC)
  - Midpoint (Tevatron/LHC)
  - (Fast) k_T (Tevatron/LHC)

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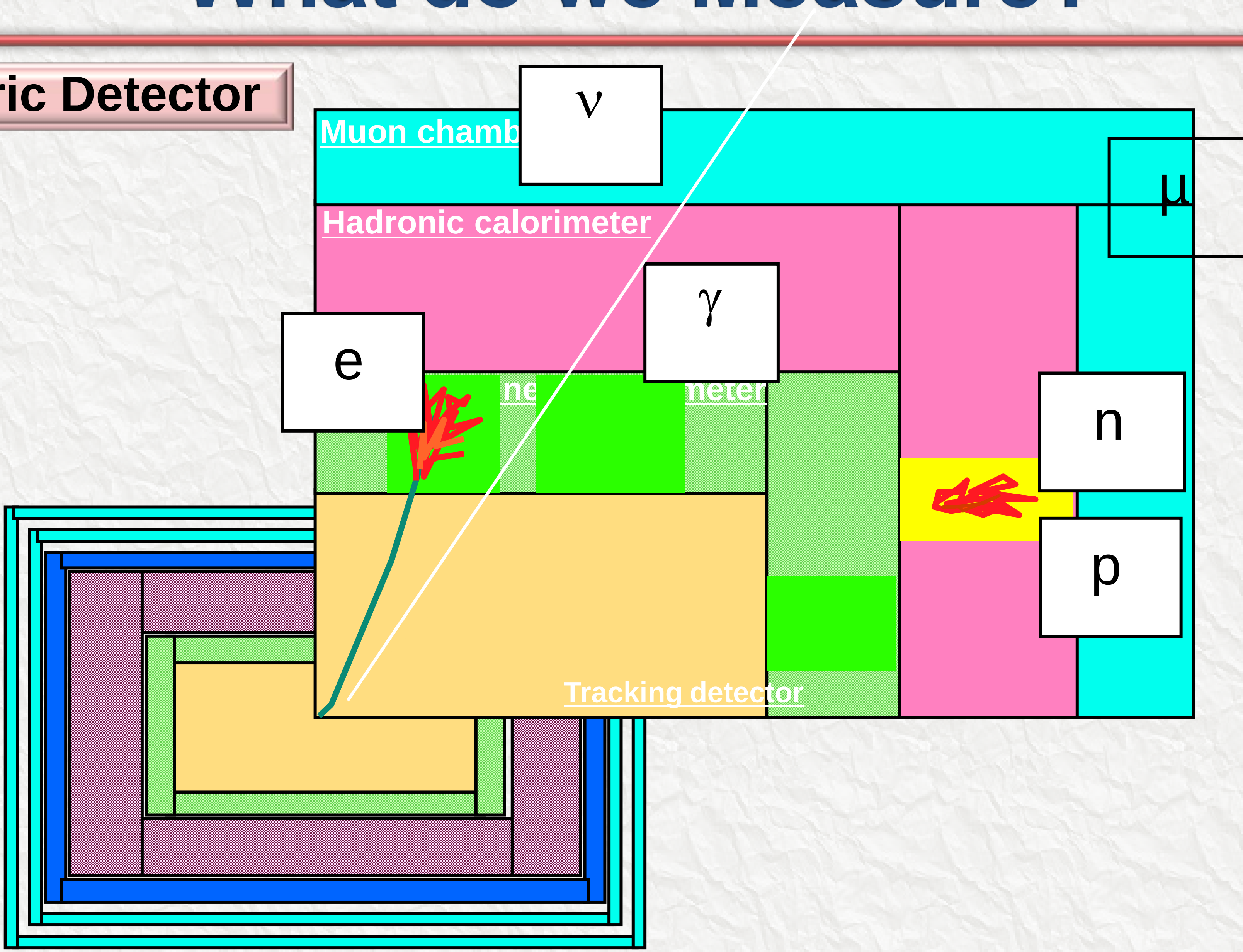
Outline

- Introduction
  - QCD
  - ee, ep, pp Processes – History of Jets
  - What is a Jet?
- Jet Algorithms
- **Jet Reconstruction, Calibration, Performance**
- Jet Characteristics
  - Jet Energy Profile
  - Quark and Gluon Jets
  - Color Coherence Effects
- Jet Production at Hadron Colliders (Tevatron & LHC)
  - Underlying Event
  - Event Shapes
  - Dijet Azimuthal Decorrelation & Angular Distributions
  - Inclusive Jet Cross Section
  - Dijet Mass
- Summary

What do we Measure?

Generic Detector



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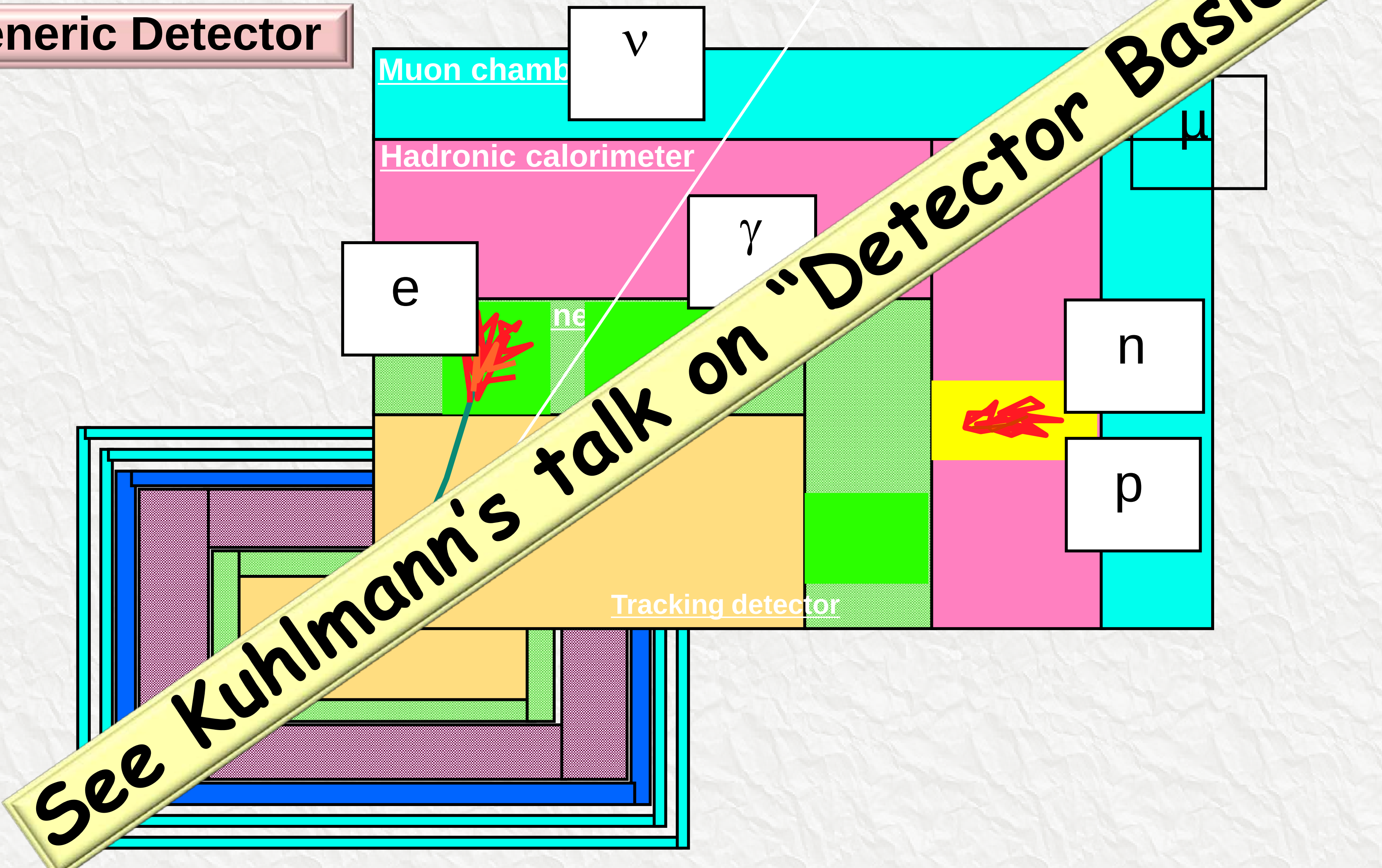
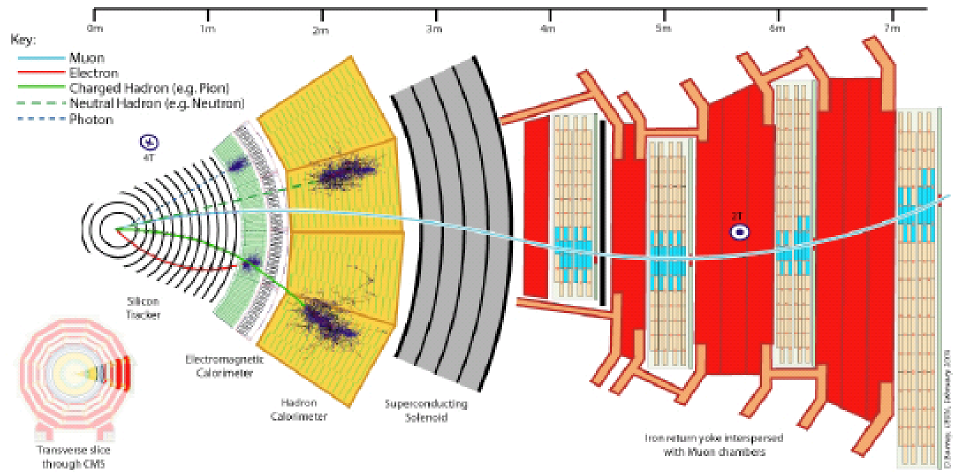
What do we Measure?



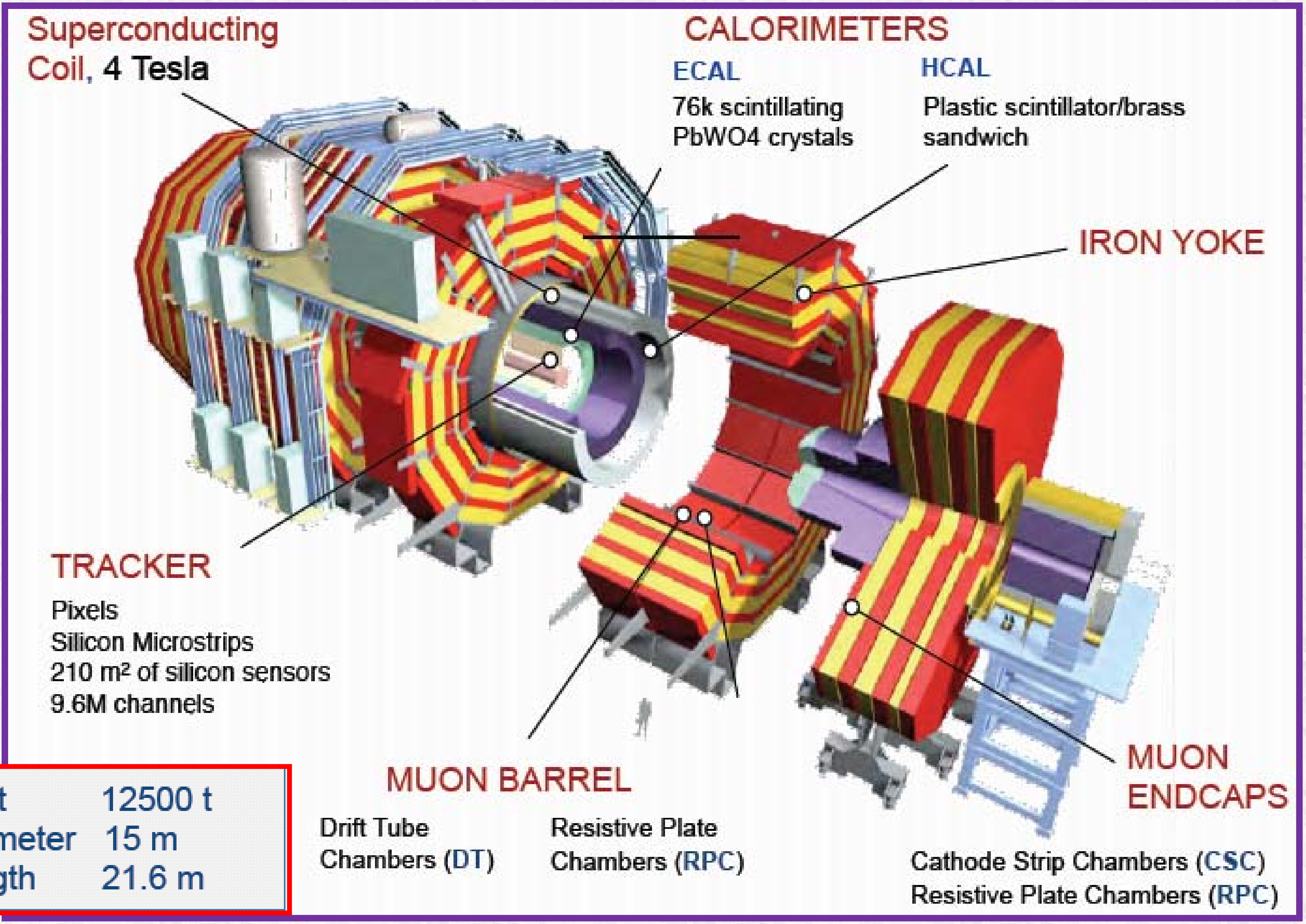
Example: CMS Detector



- Detectors
  - Silicon tracker: pixels and strips ($|\eta| < 2.4$)
  - Electromagnetic ($|\eta| < 3$) and hadronic ($|\eta| < 5$) calorimeters
  - Muon chambers ($|\eta| < 2.4$)
  - Extension with forward detectors (CASTOR $5.3 < |\eta| < 6.6$, ZDC $|\eta| > 8.3$)

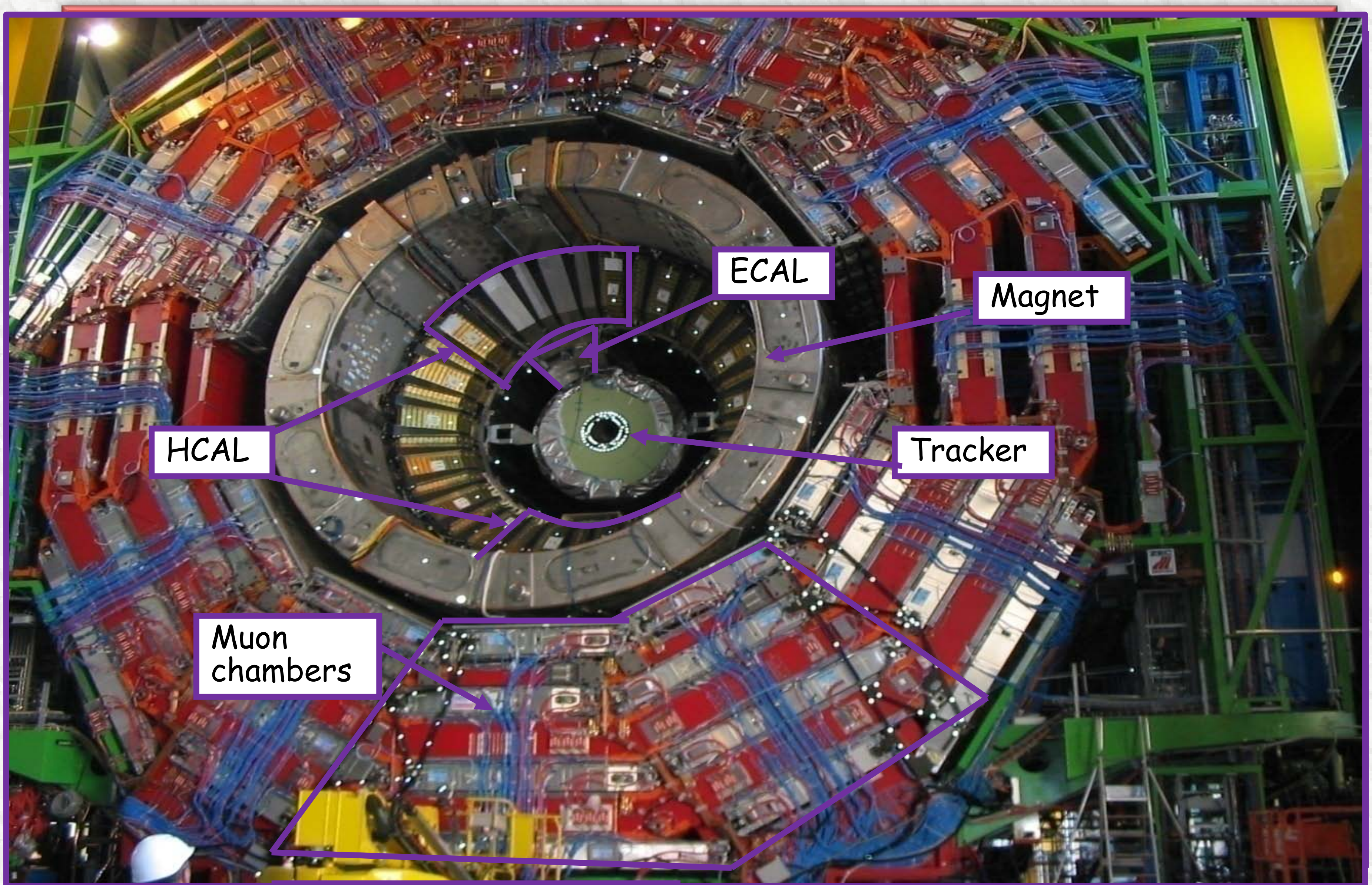
Detector	resolution	coverage
tracker	σ_{pT}/pT = 1-5% pT	$|\eta|<2.4$
ECAL	$\sigma_E/E = 3\%/\sqrt{E} + 0.5\%$	$|\eta|<3$
HCAL	$\sigma_E/E = 100\%/\sqrt{E} + 4\%$	$|\eta|<3$ barrel $|\eta|<5$ forward
Muon	σ_{pT}/pT = 10% pT (1 TeV)	$|\eta|<2.4$

Example: CMS Detector



Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

Example: CMS Detector



Jet Input Flavors

- Calorimeter Jets
  - Clustering of energy depositions
  - EM+HAD towers
- Track Jets
  - Clustering of tracks
  - Sampling only charged particles
- JetPlusTrack
  - Calorimeter jets with energy corrections based on tracks
- Particle Flow (PFlow)
  - Clustering of identified particles

Challenges with Jets

- **Triggering on Jets**
  - reduce rate from ~2-40 10^6 to ~100 Hz (multiple triggering stages)
  - implement fast/crude jet clustering algorithms for low level triggers
- **Selection of a Jet Algorithm**
  - at detector, particle, parton/NLO++ level
- **Jet Reconstruction, Selection, and Trigger Efficiencies**
- **Jet Calibration**
  - corrections back to particle jet (detector response, pile-up,…)
  - parton showering, hadronization, and multiple interaction effects
- **Jet Energy/Position Resolutions**
  - difficulties with low-p_T region and near reconstruction threshold
  - unsmearing of observables
- **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

Jet Energy Calibration

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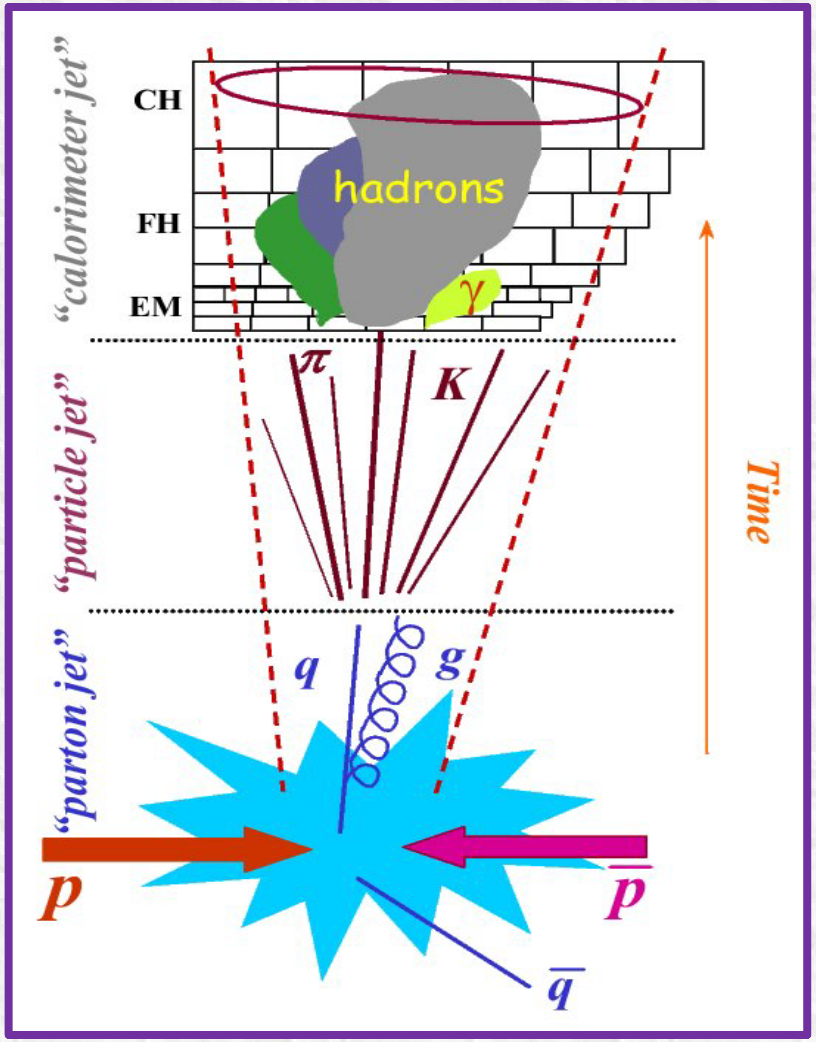
example

Jet Energy Uncertainty ~ 1%

- **Jet energies are calibrated to *particle level***

$$p_T^{part} = \frac{p_T^{calo} - Offset}{R_{response} \times \text{Out\_of\_Cone\_Showering}}$$

  - **Offset: noise, pile-up, multiple $p\bar{p}$ interactions**
  - **$R_{response}$: fraction of particle jet energy deposited in the calorimeter**
    - **measured in situ using p_T balance in γ/Z+jet events**
  - **Out of Cone Showering: account for energy emitted inside (outside) the jet cone but showered outside (inside) the calorimeter jet cone**



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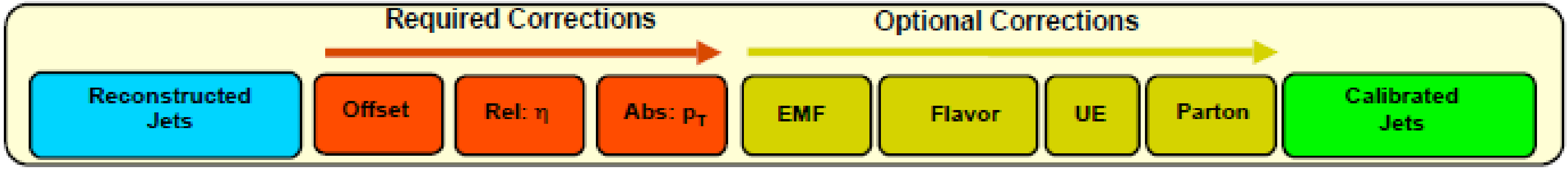
Jet Energy Calibration

example

CMS-JME-07-002

CMS develops a factorized multi-level jet correction



Correct CaloJets to have same pT as GenJet on average

correcctions back to parton level quantities

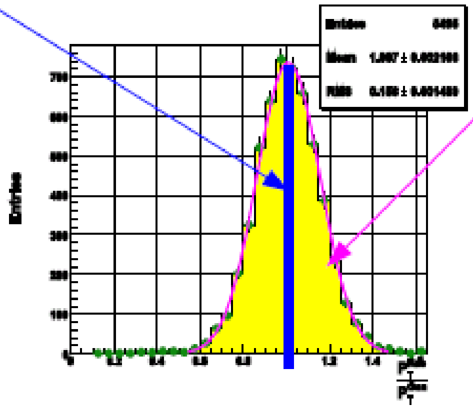
- Offset: correct for Pile Up and electronic noise in the detector (measure in zero-bias data
- Relative(eta): variations in jet response with eta relative to a control region
- Absolute (p_T): correcting the p_T of a measured jet to particle level jet versus jet p_T
- EMF: variations in jet response with electromagnetic energy fraction
- Flavor: variations in jet response to different jet flavor (light quark, c,b, gluon)
- Underlying Event
- Parton: correcting measured jet p_T to the parton level

➠ derive from MC simulation tuned on test-beam data at start-up, data driven when available, on the long term from simulation tuned on collision data

Jet Energy Resolutions

Perfect detector:

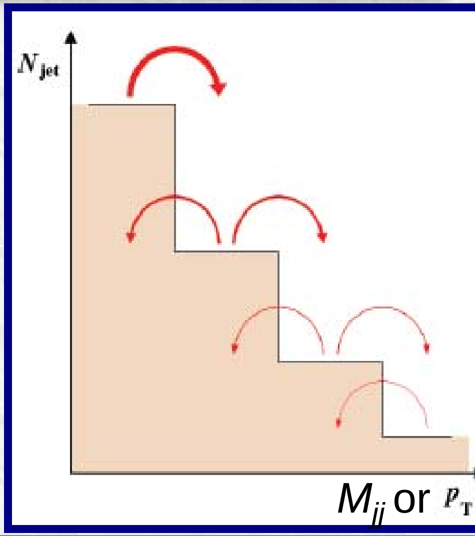
$$x=\frac{p_T^{observed}}{p_T^{particle}}=1$$



Real detector:

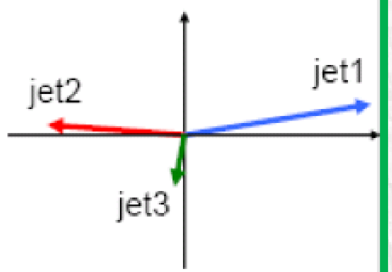
$$f=A\,e^{\frac{-(x-1)^2}{2\sigma^2}}$$

$$Resolution=\sigma(f)$$



- In true dijet events jets should balance exactly in p_T.
  In reality we usually see a small third jet contribution and a non-zero asymmetry in p_T given by:

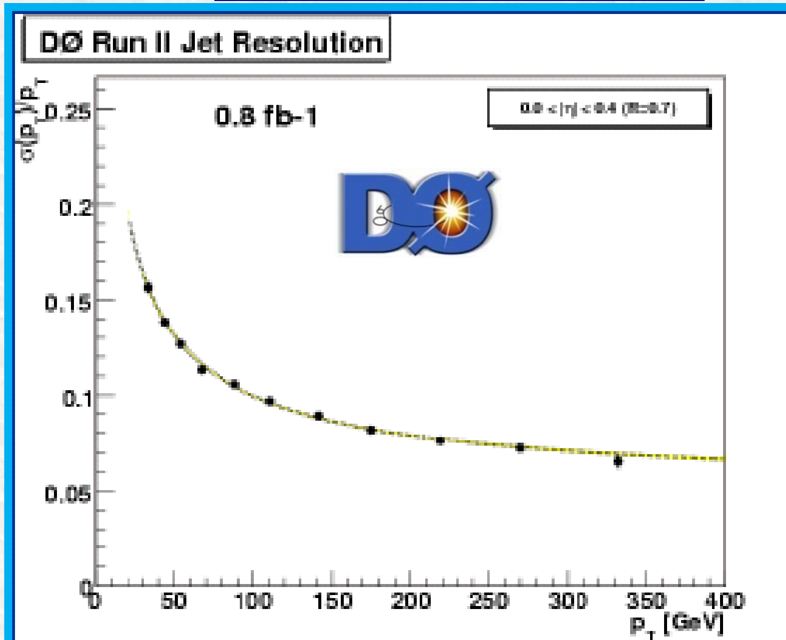
$$A=\frac{(p_T^{jet1}-p_T^{jet2})}{(p_T^{jet1}+p_T^{jet2})}$$



where jet1 and jet2 are the 2 leading jets in the event

- The calorimeter resolution is related to the width of the asymmetry distribution by: $\frac{\sigma(p_T)}{p_T}=\sqrt{2}\,\sigma_A$

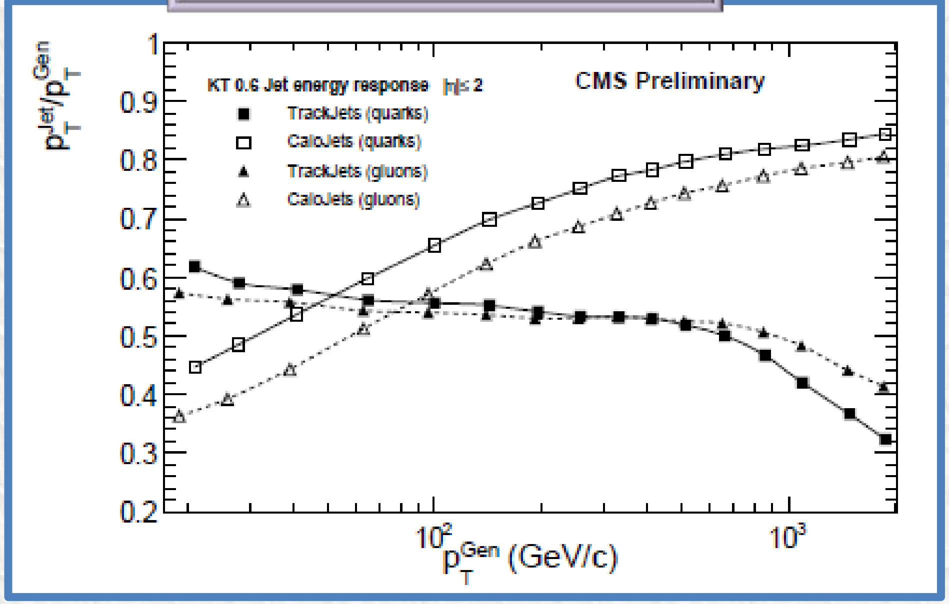
where σ_A is a sigma of the asymmetry distribution



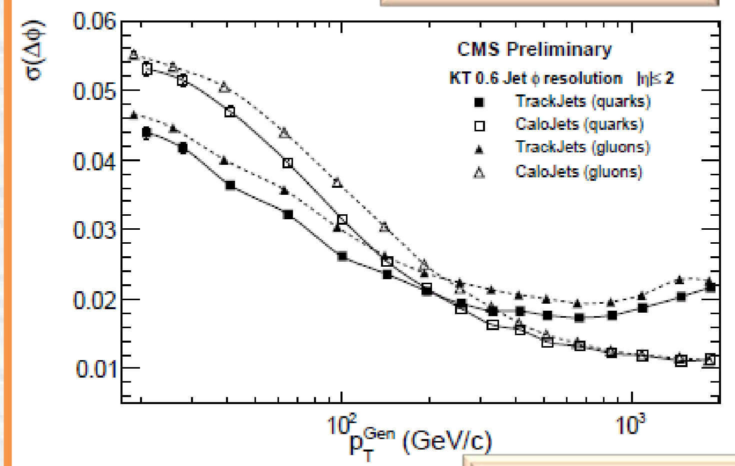
TrackJets

- **Tracking momentum is more accurate than calorimeter measurement for up to several hundreds of GeV**
- **The charged energy fraction in jets is about 60%**
  - **With significant resolutions ~0.3 f_{ch}**
- **Cluster tracks pointing to the vertex**

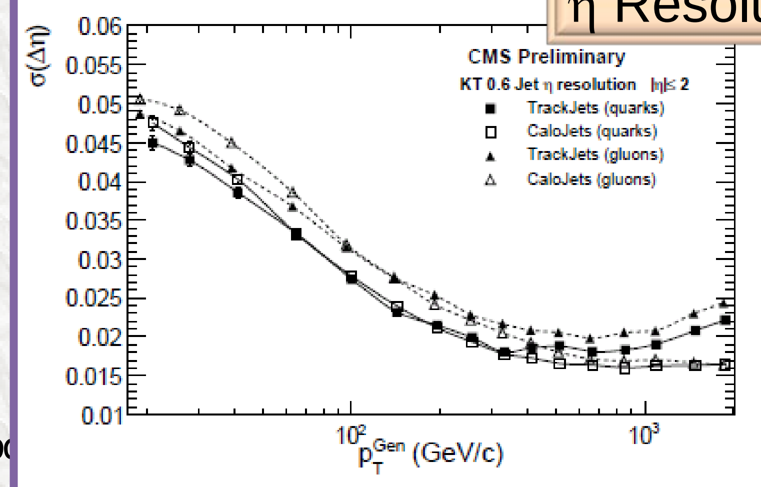
Jet Energy Response



ϕ Resolution

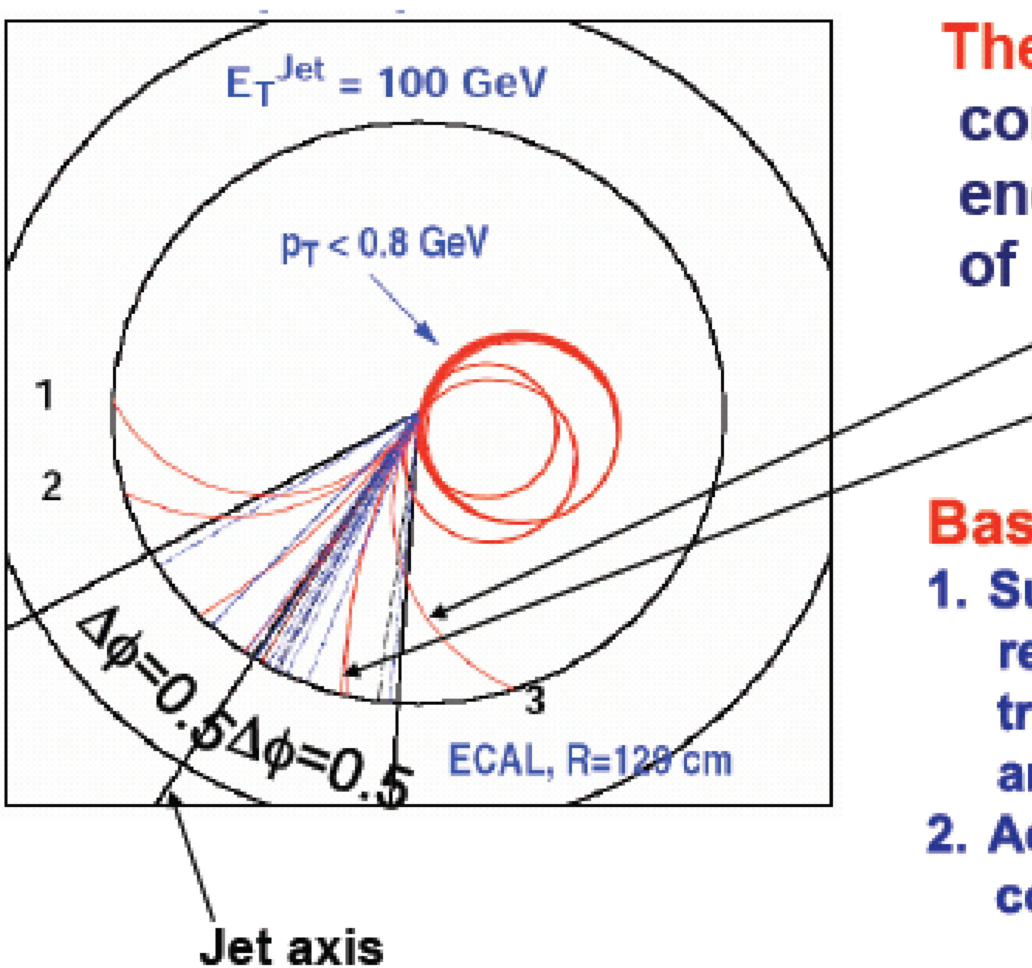


η Resolution



CMS-JME-08-001

JetPlusTrack Algorithm



The goal of algorithm:

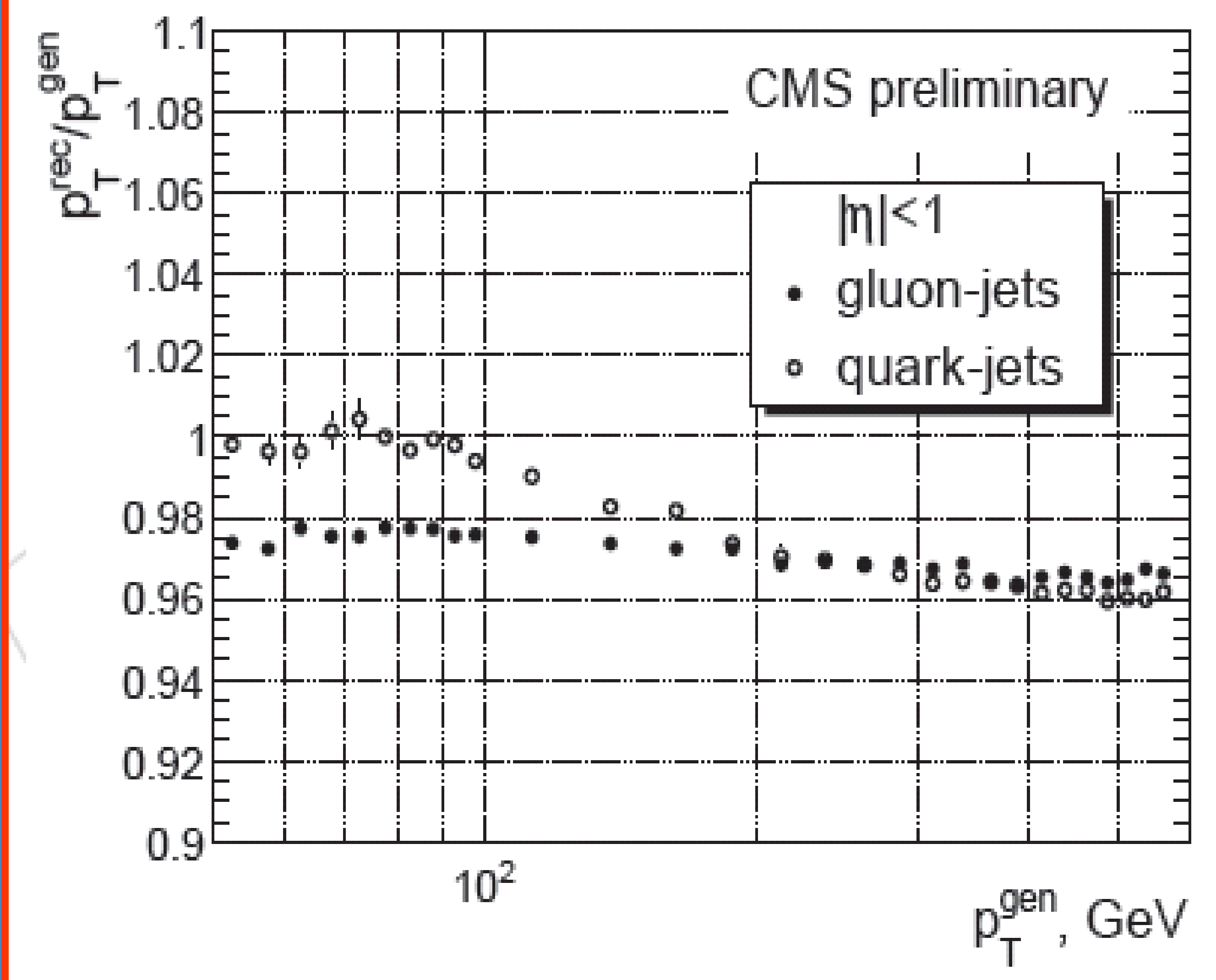
correct calorimeter jet energy to the energy of particles at vertex.

Basic algorithm steps:

1. **Subtract average expected response of "in-calo-cone" tracks from calo jet energy and add track momentum**
2. **Add momentum of "out-of-cone" tracks**

$$E_{JPT} = E_{jet}^{raw\ calo} \times f_{ZSP} + \sum_{in-cone\ trk} (p_{trk} - < E_{trk}^{calo} >) + \sum_{out-of-cone\ trk} p_{trk} + \Delta E_{trk.ineff}$$
$$+ \sum_{muons} (p_{\mu} - 2\,\mathrm{GeV}),$$

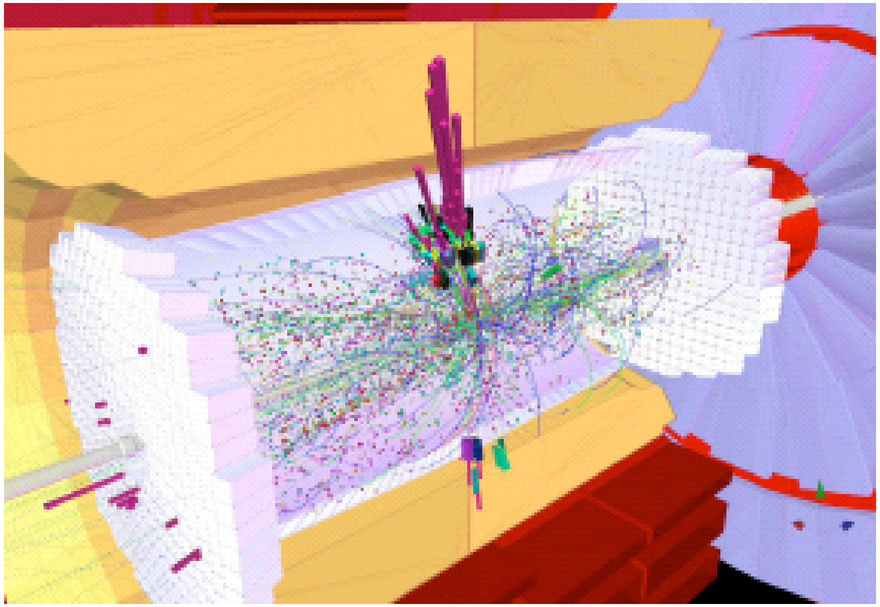
JetPlusTrack Algorithm



Particle Flow Algorithm

CMS-PFT-09-001

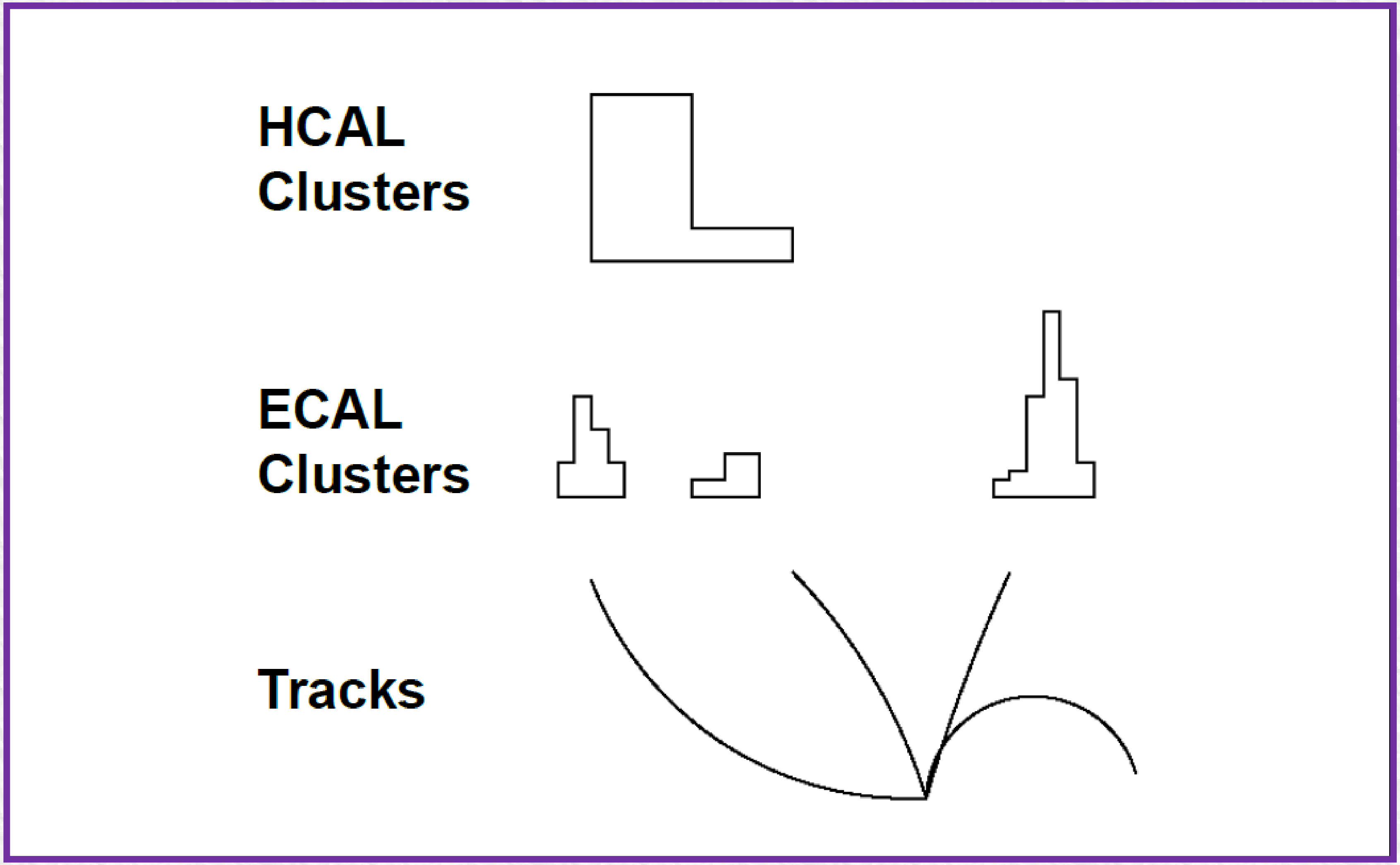
- Reconstruct and identify all particles
  - Charged hadrons
  - Photons
  - Neutral hadrons
  - Electrons (also non isolated)
  - Muons



- Identify and utilize an optimal combination of all (CMS) sub-detector information
- Provide a unique list of particles
  - for a global, coherent, accurate event description

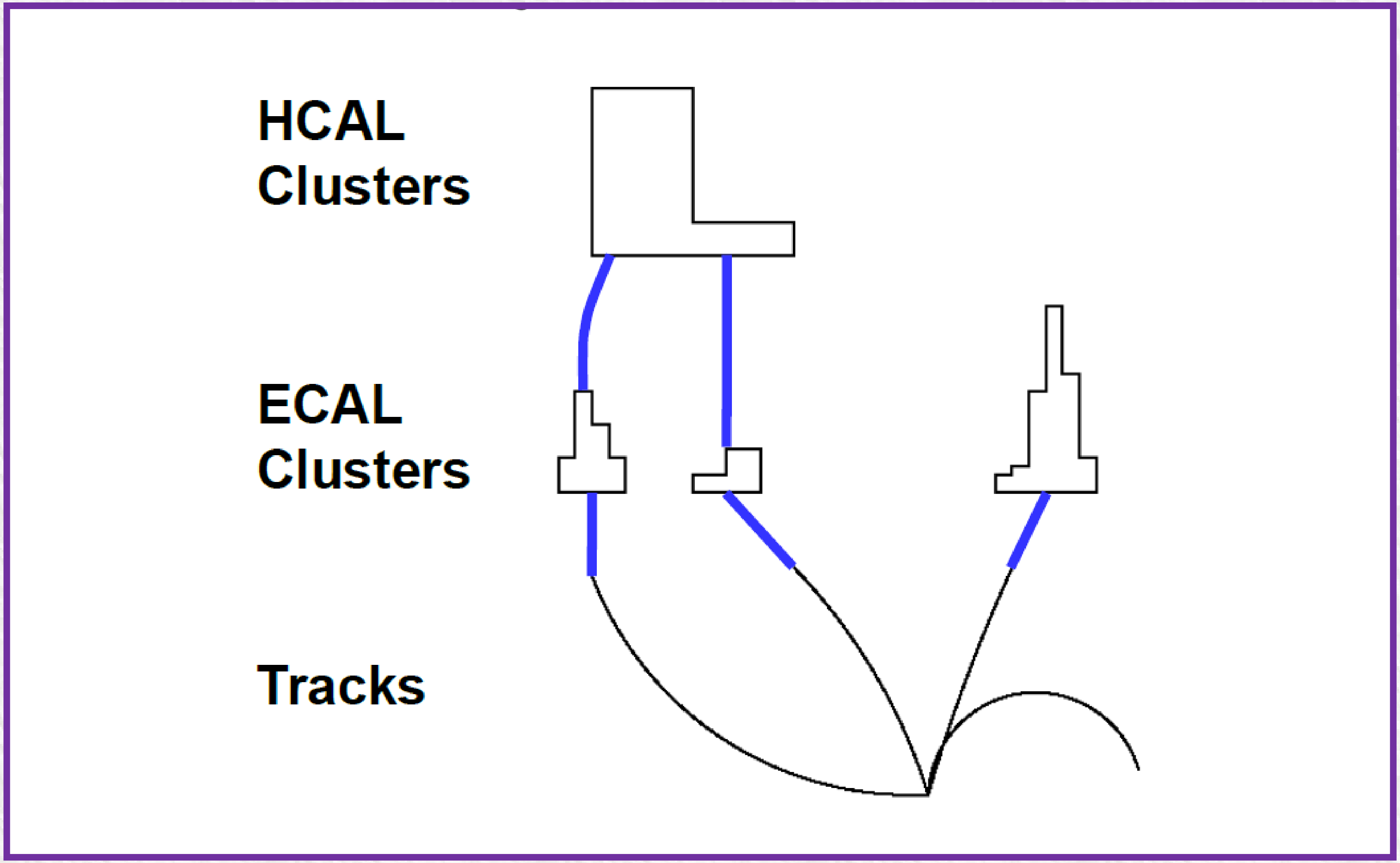
Particle Flow Algorithm

CMS-PFT-09-001



Particle Flow Algorithm

CMS-PFT-09-001



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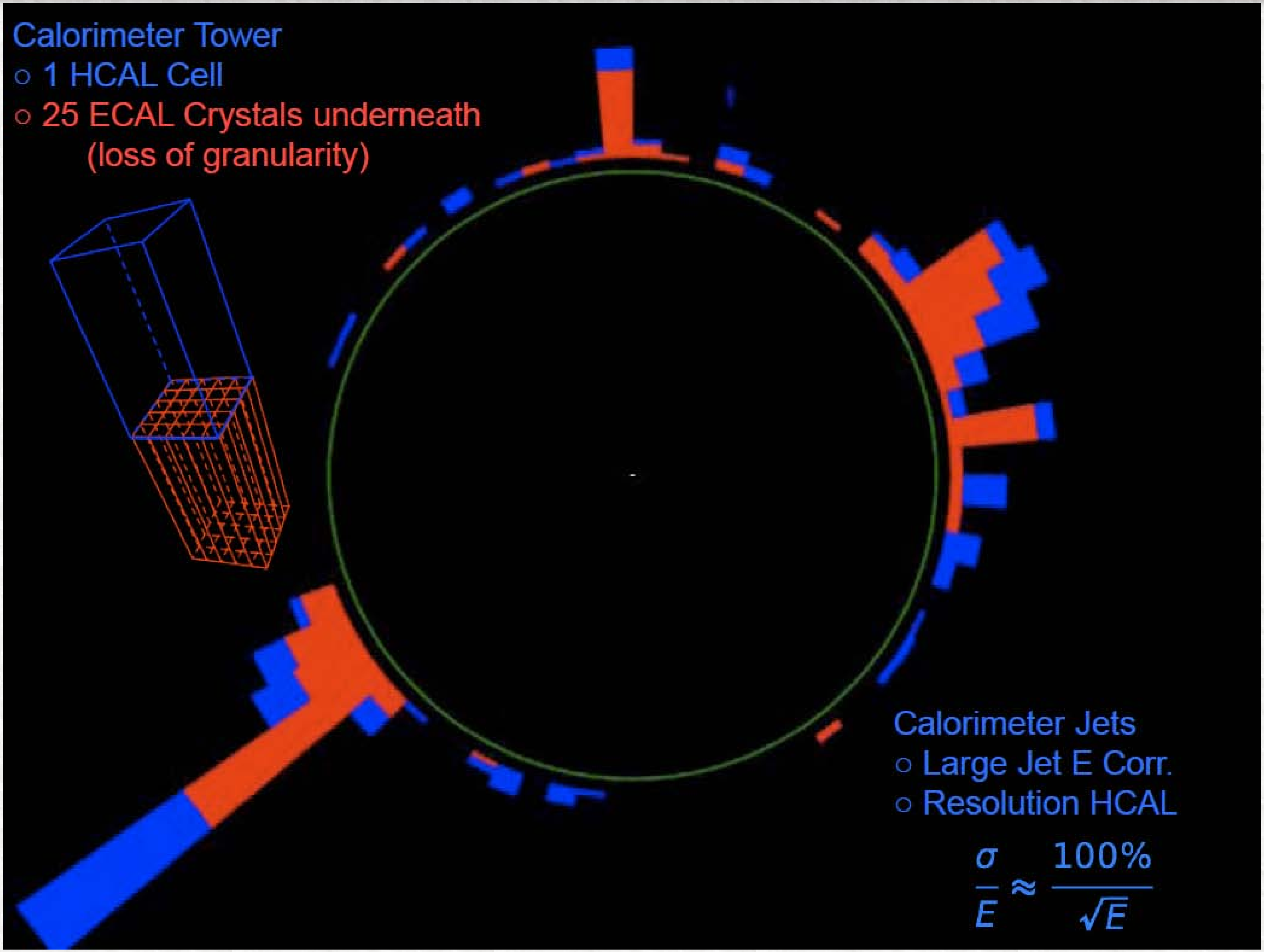

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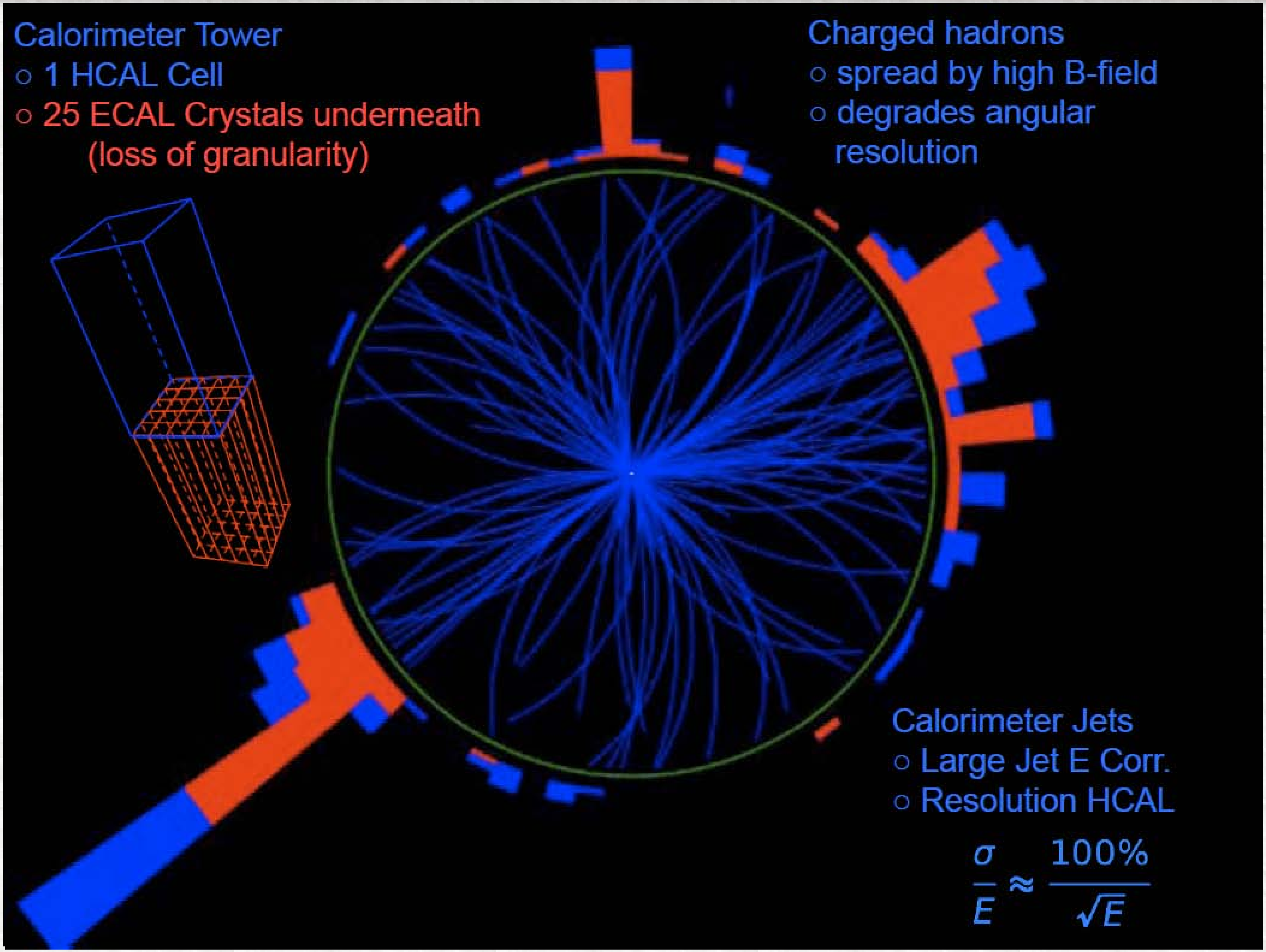
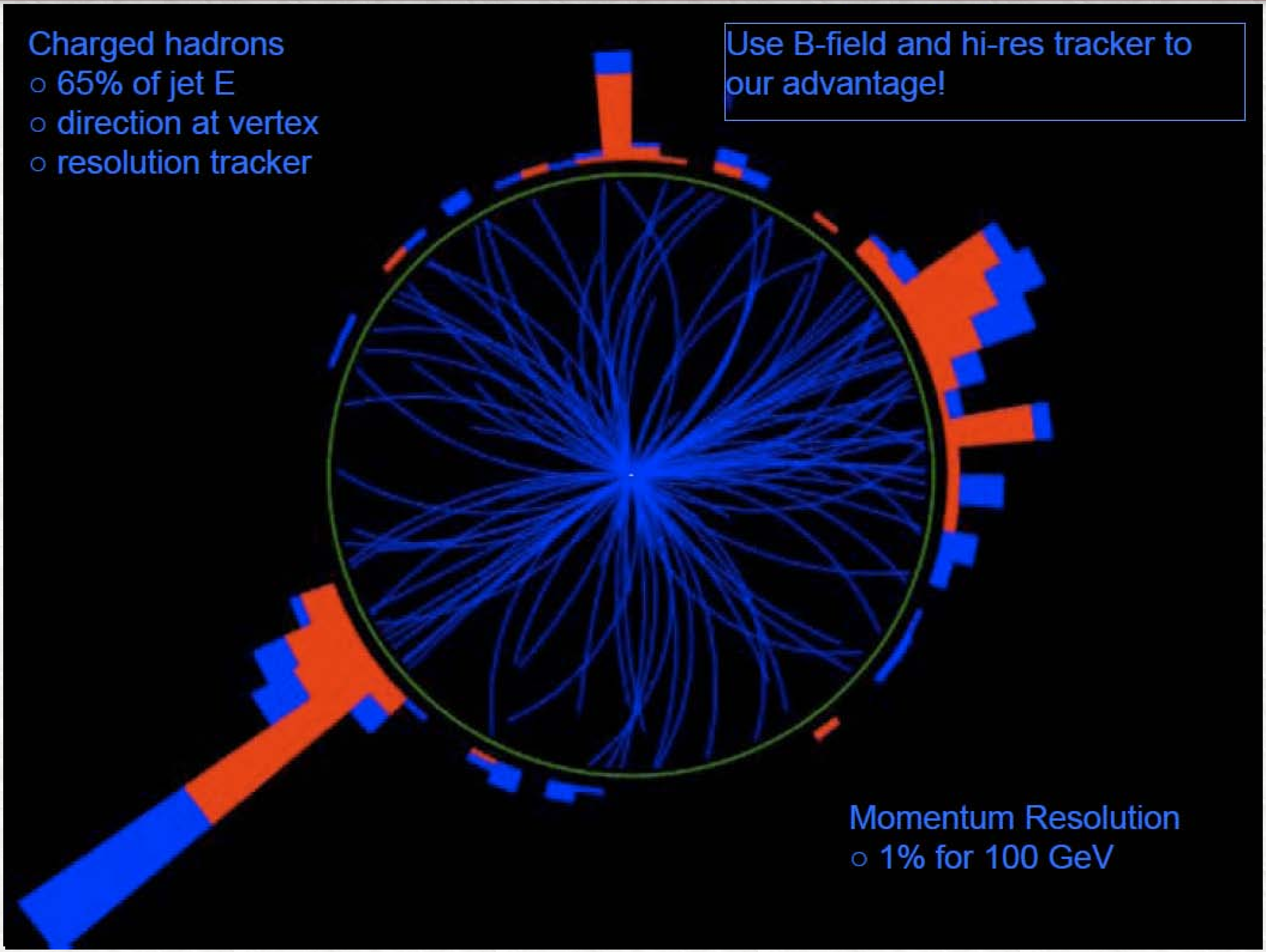
Particle Flow Algorithm



Particle Flow Algorithm



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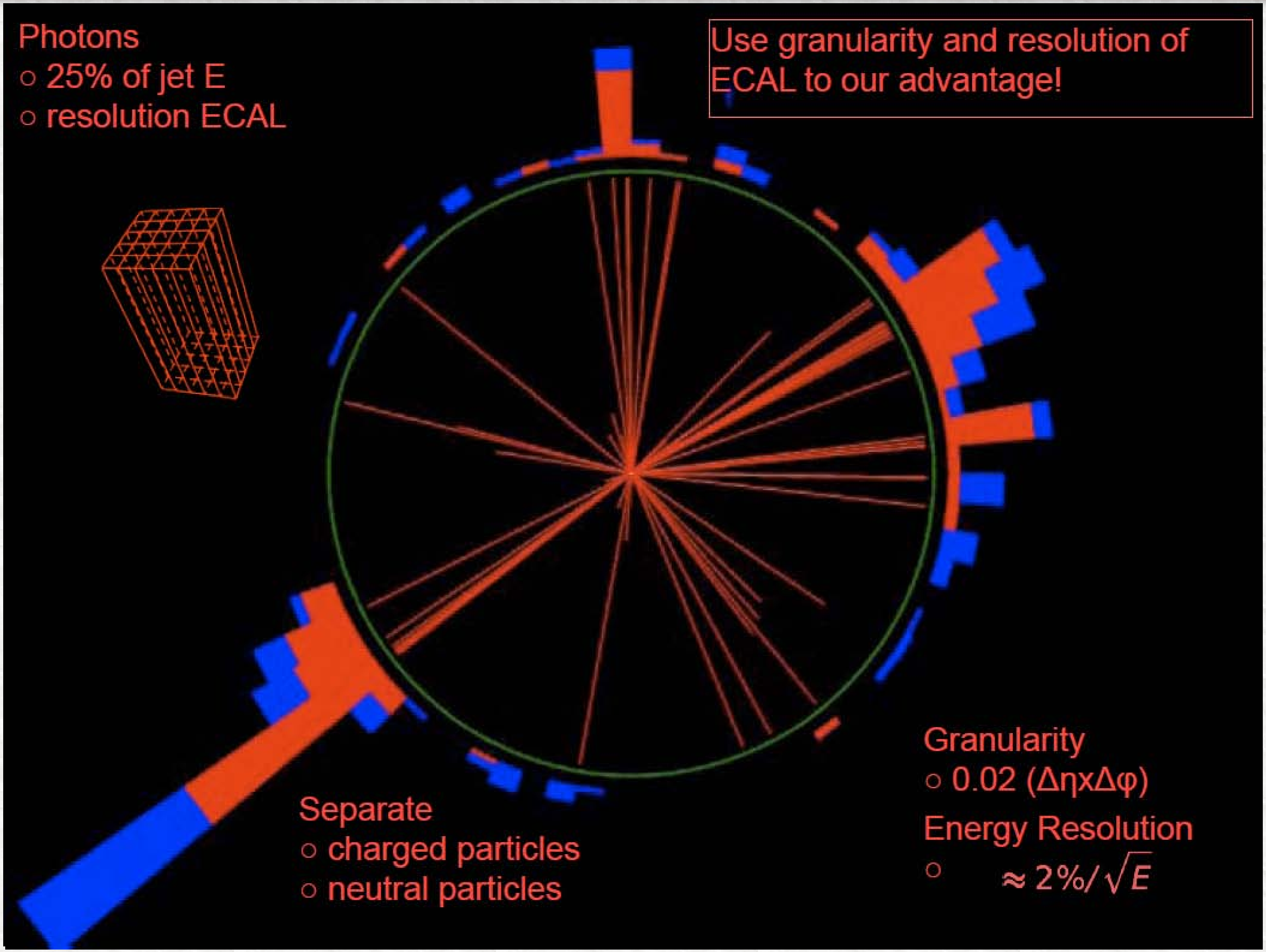
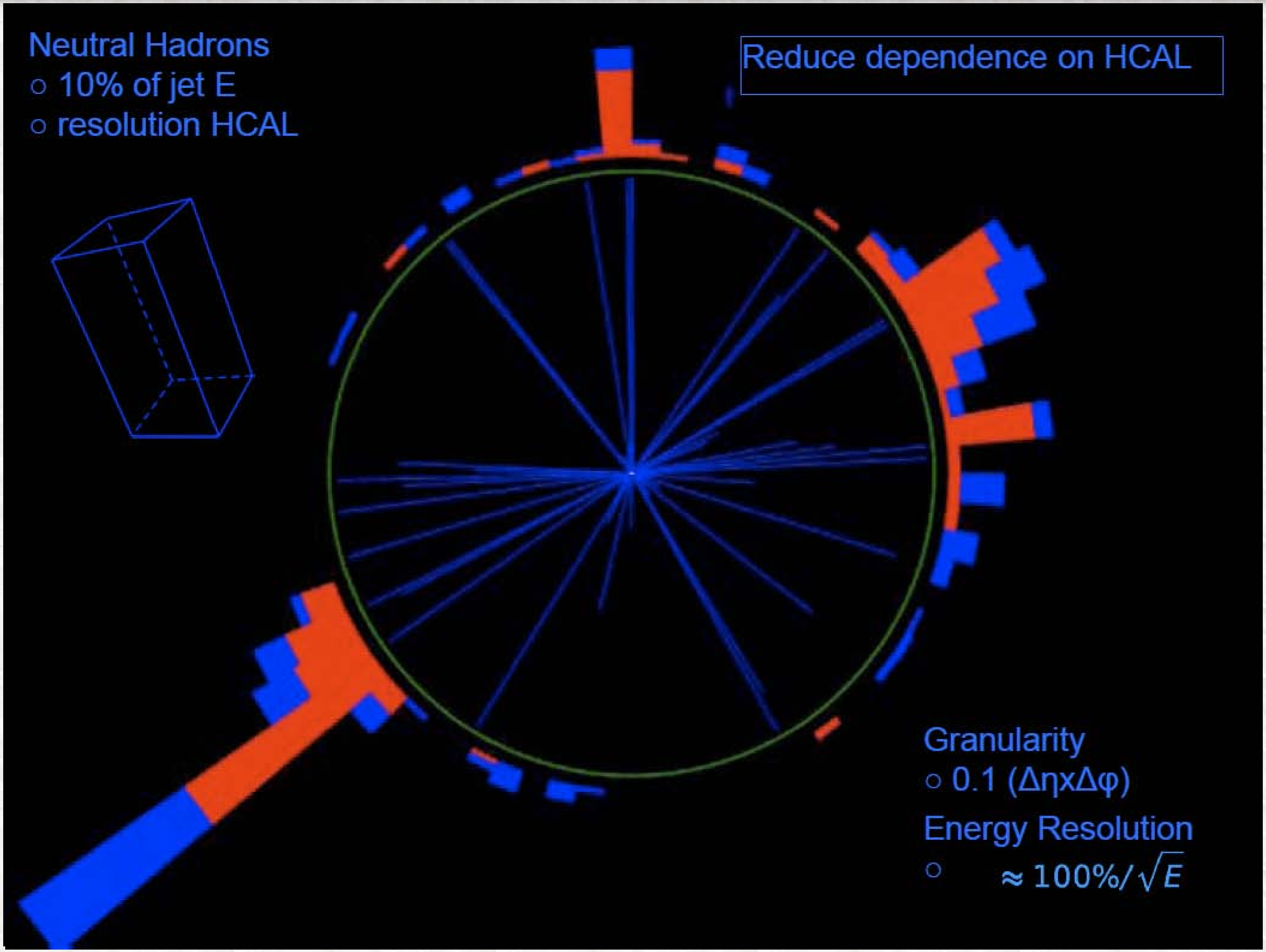
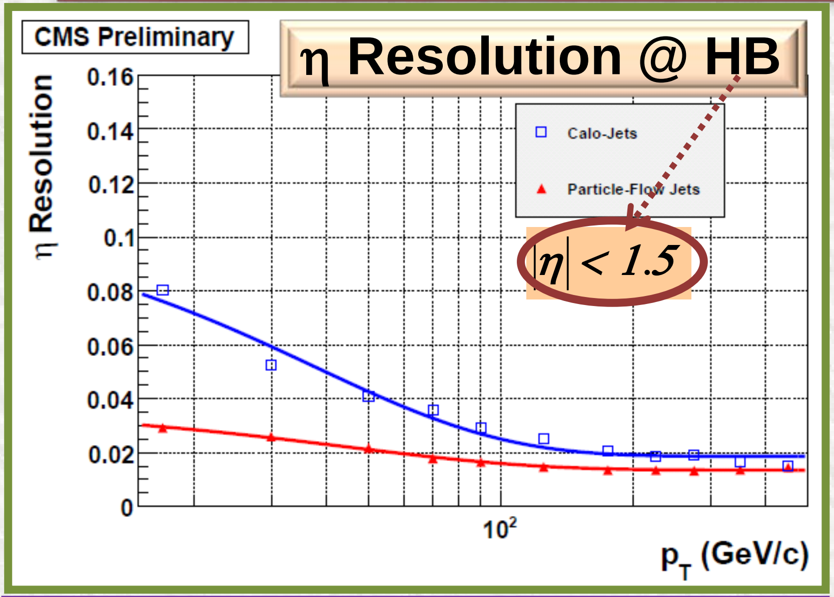
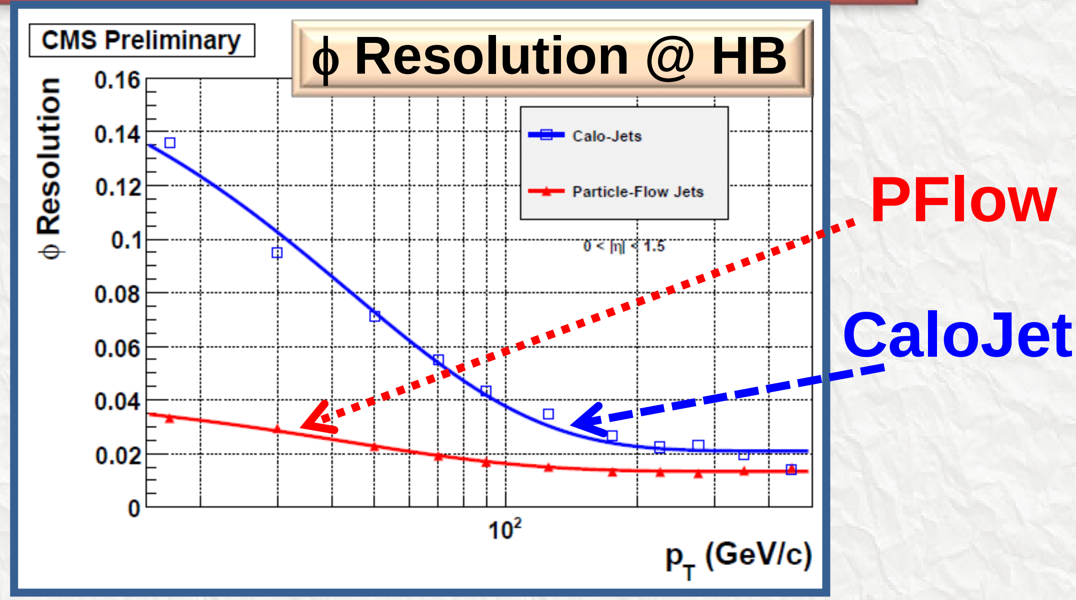


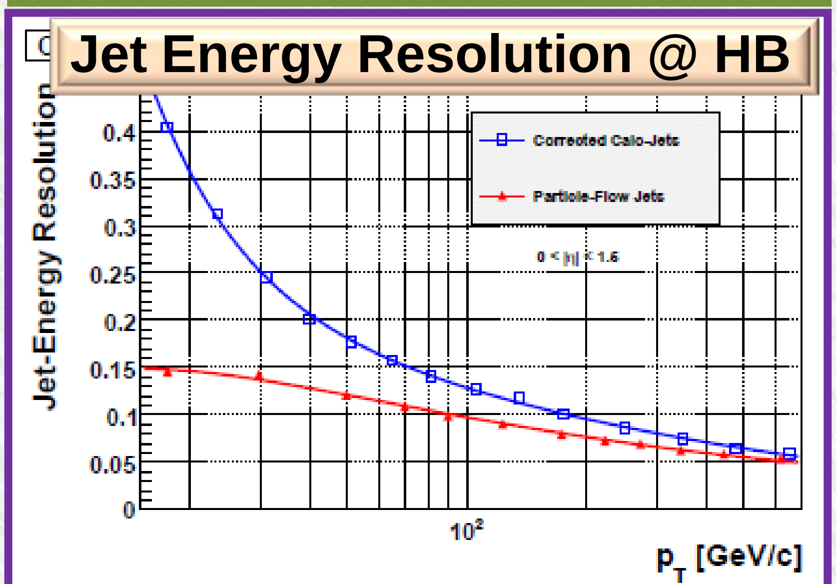
Particle Flow Algorithm

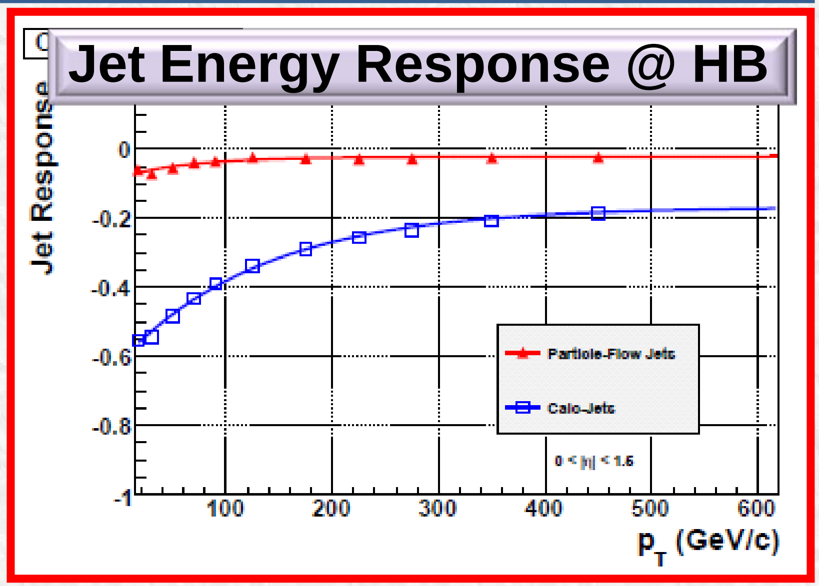


PFlow Algorithm Performance









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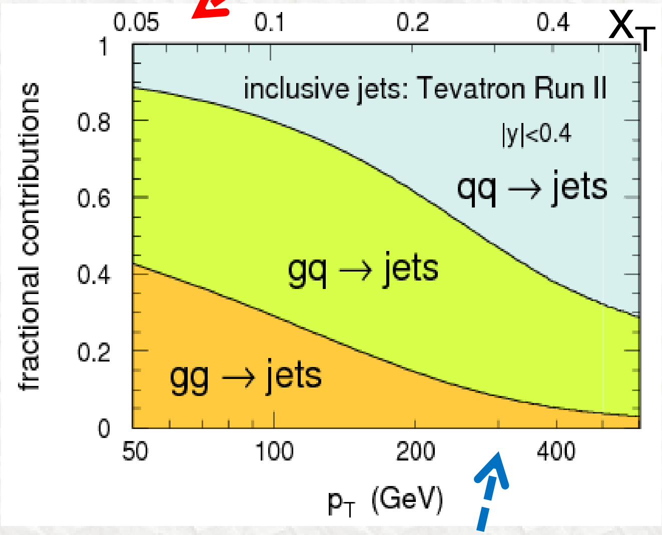
Jet Energy Profile (Jet Shape)

- **Motivation:**
  - Jet shapes probe the transition between a parton produced in the hard process and the observed spray of hadrons
  - Sensitive to the quark/gluon jet mixture
  - Test of parton shower event generators at non-/perturbative levels
  - Useful for jet algorithm development and tuning

- **Challenges**
  - Dependence on parton shower and hadronization models
    - Corrections need to be examined for different tunes/generators
  - Sensitive to particle calibration at low energies
    - MC tuning of calorimeter and tracker is critical
  - Sensitive to detector resolution, noise, pile-up effects
  - Sensitive to initial state radiation effects and the underlying event

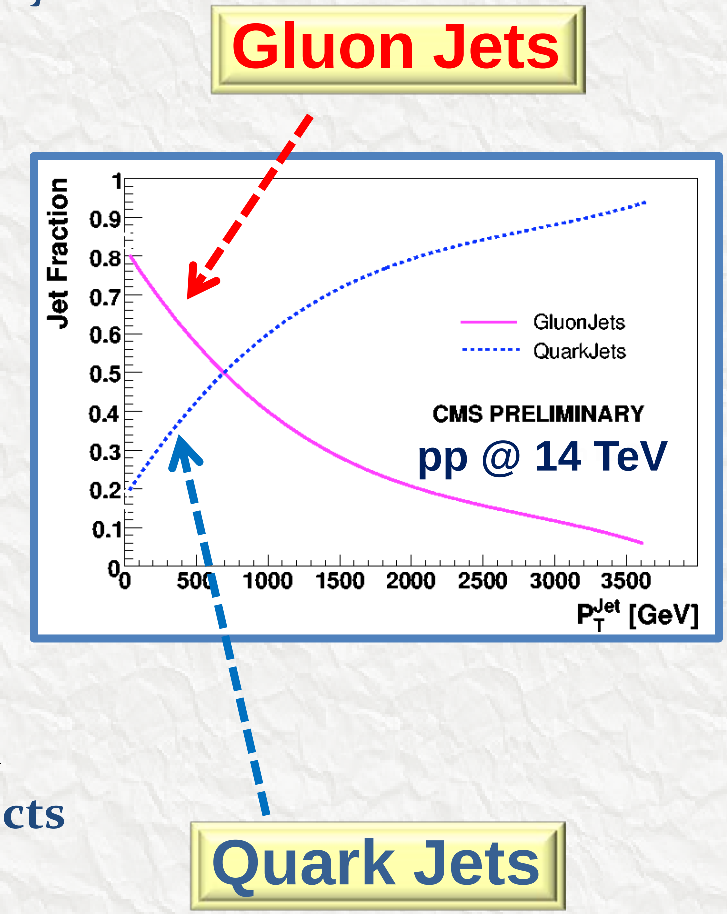
Mostly Gluon Jets



Mostly Quark Jets

Jet Energy Profile (Jet Shape)

- **Motivation:**
  - Jet shapes probe the transition between a parton produced in the hard process and the observed spray of hadrons
  - Sensitive to the quark/gluon jet mixture
  - Test of parton shower event generators at non-/perturbative levels
  - Useful for jet algorithm development and tuning



- **Challenges**
  - Dependence on parton shower and hadronization models
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  - Sensitive to particle calibration at low energies
    - MC tuning of calorimeter and tracker is critical
  - Sensitive to detector resolution, noise, pile-up effects
  - Sensitive to initial state radiation effects and the underlying event

Jet Shapes: Energy Profiles

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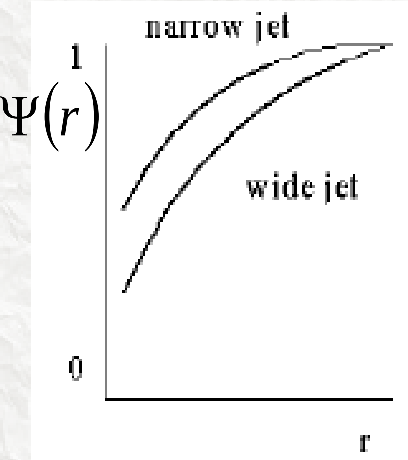
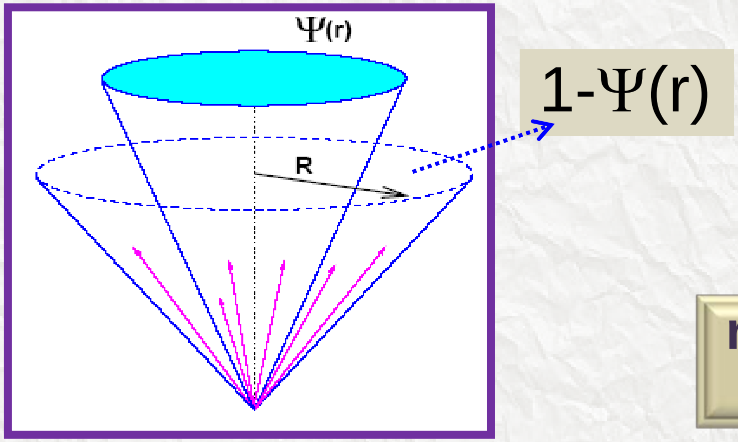
Definition: **Integrated Jet Shape is defined as the average fraction of jet transverse momentum that lies inside a <u>cone</u> of radius r concentric to the jet axis**

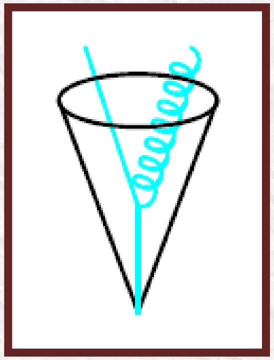
$$\Psi(r) = \frac{1}{N_{jets}} \sum_{jets} \frac{p_T(0,r)}{p_T(0,R)}$$

$$\Psi(R) = 1$$

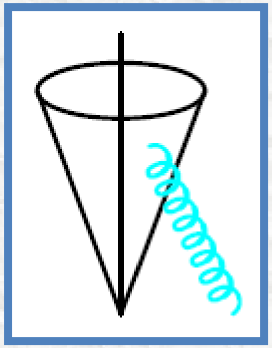
pQCD Contributions







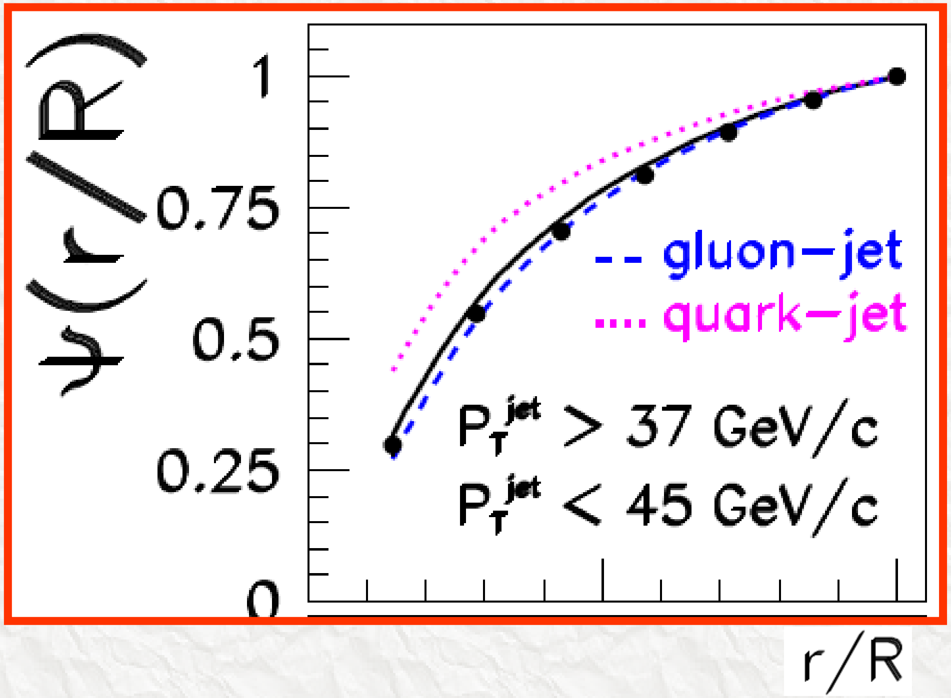
radiation inside the jet

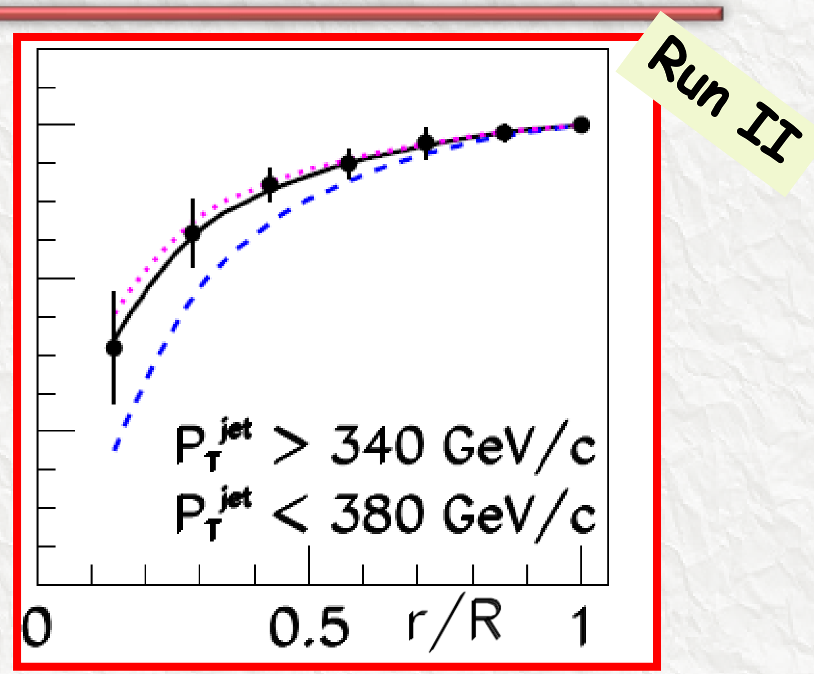


Soft radiation from outside the jet

Quark jets are narrower than gluon jets

Jet Shapes at Tevatron



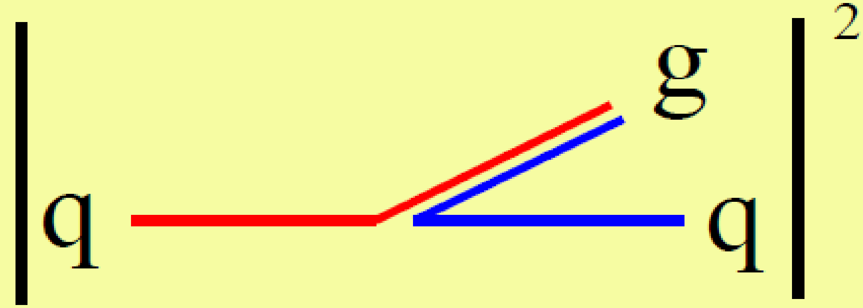


Gluon enriched jets (low-x/low-p_T jets at Tevatron) are "broader" (i.e. less collimated, higher multiplicity of soft energy particles) than Quark-enriched jets (high-x/high-p_T jets)

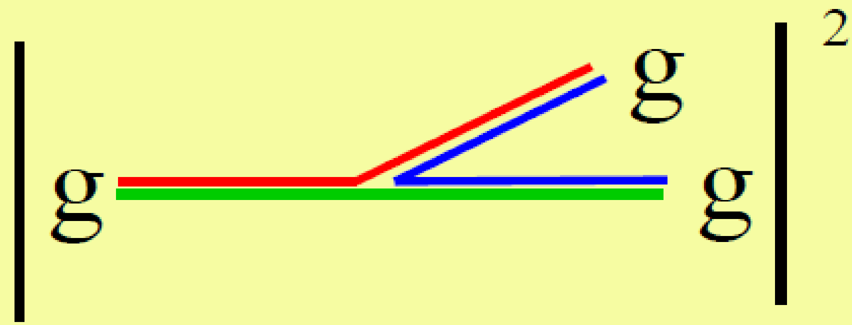
Consistent with results from LEP and HERA

(a Jet is a Jet no matter where you measure it!)

Quark & Gluon jets radiate proportional to their color factor:



$\sim C_F = 4/3$



$\sim C_A = 3$

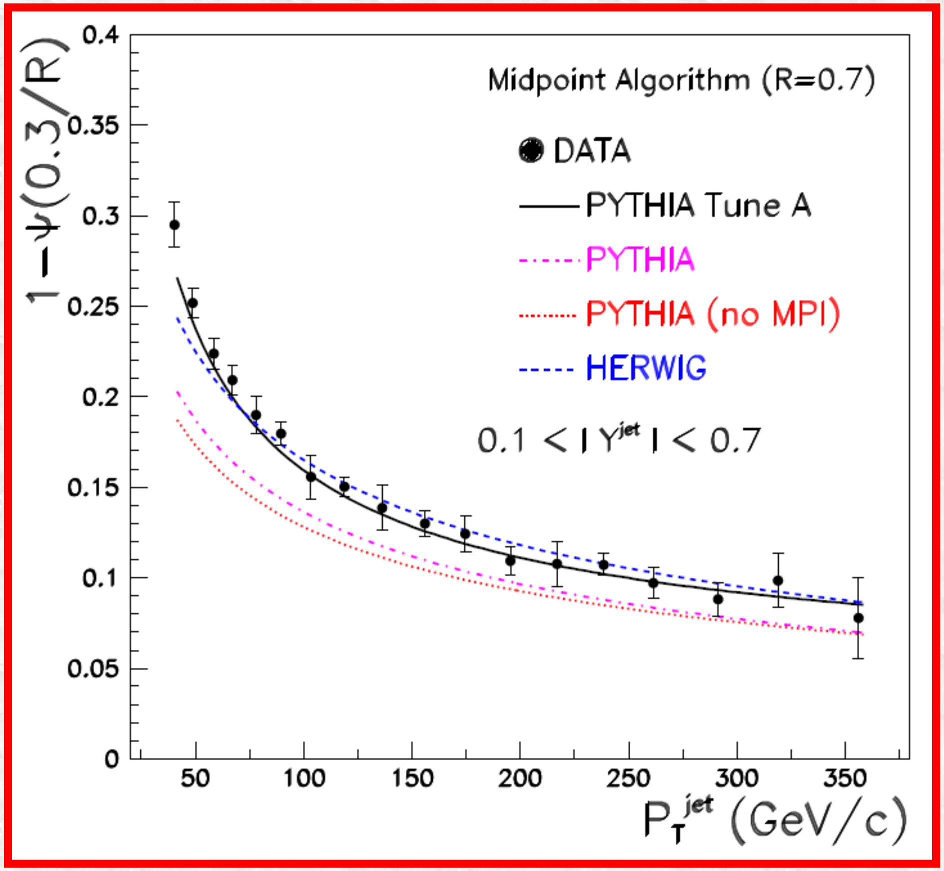
$$r \equiv \frac{< n_g >}{< n_q >} \equiv \frac{< \text{gluon jet multiplicity} >}{< \text{quark jet multiplicity} >}$$

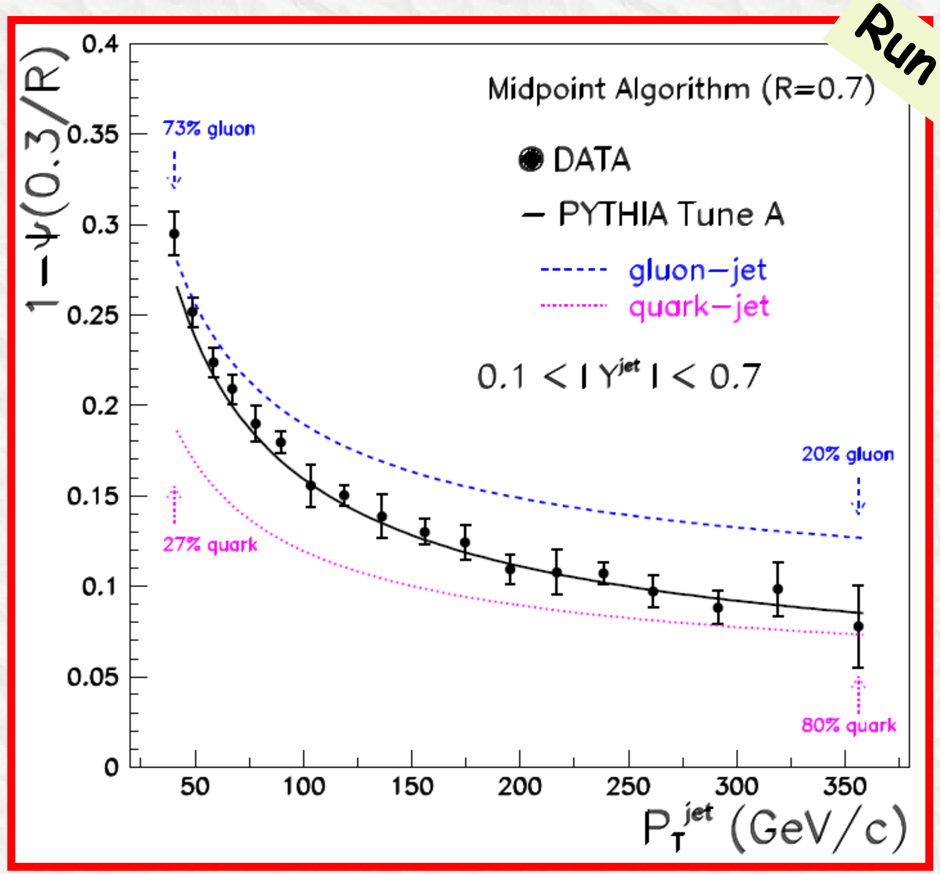
At Leading Order ($E_{jet} \rightarrow \infty$): $r \sim \frac{C_A}{C_F} = \frac{9}{4} = 2.25$

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

Jet Shapes at Tevatron

Run II





Data vs MC Predictions

Gluon → Quark jets

Jet Shapes at LHC

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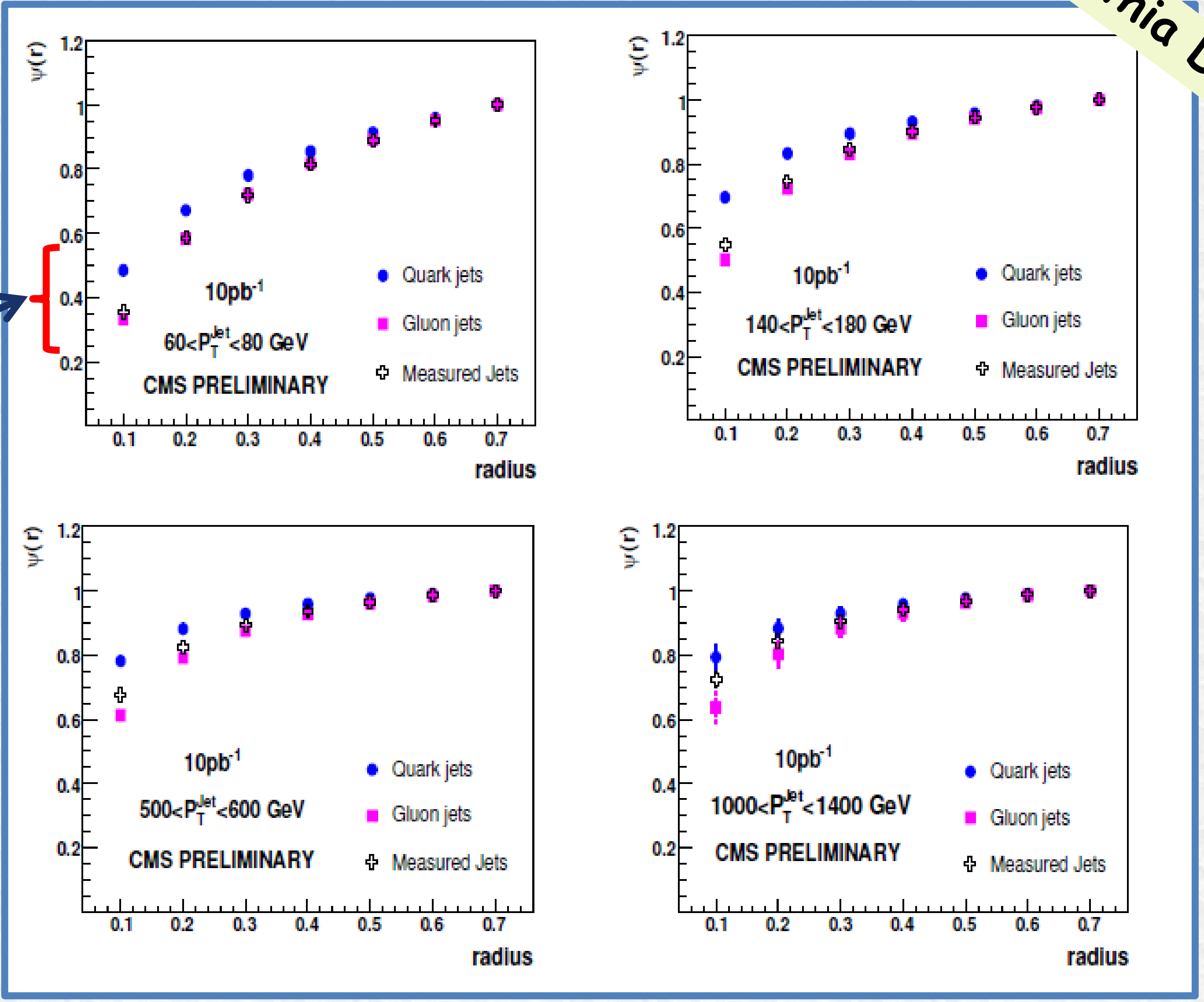
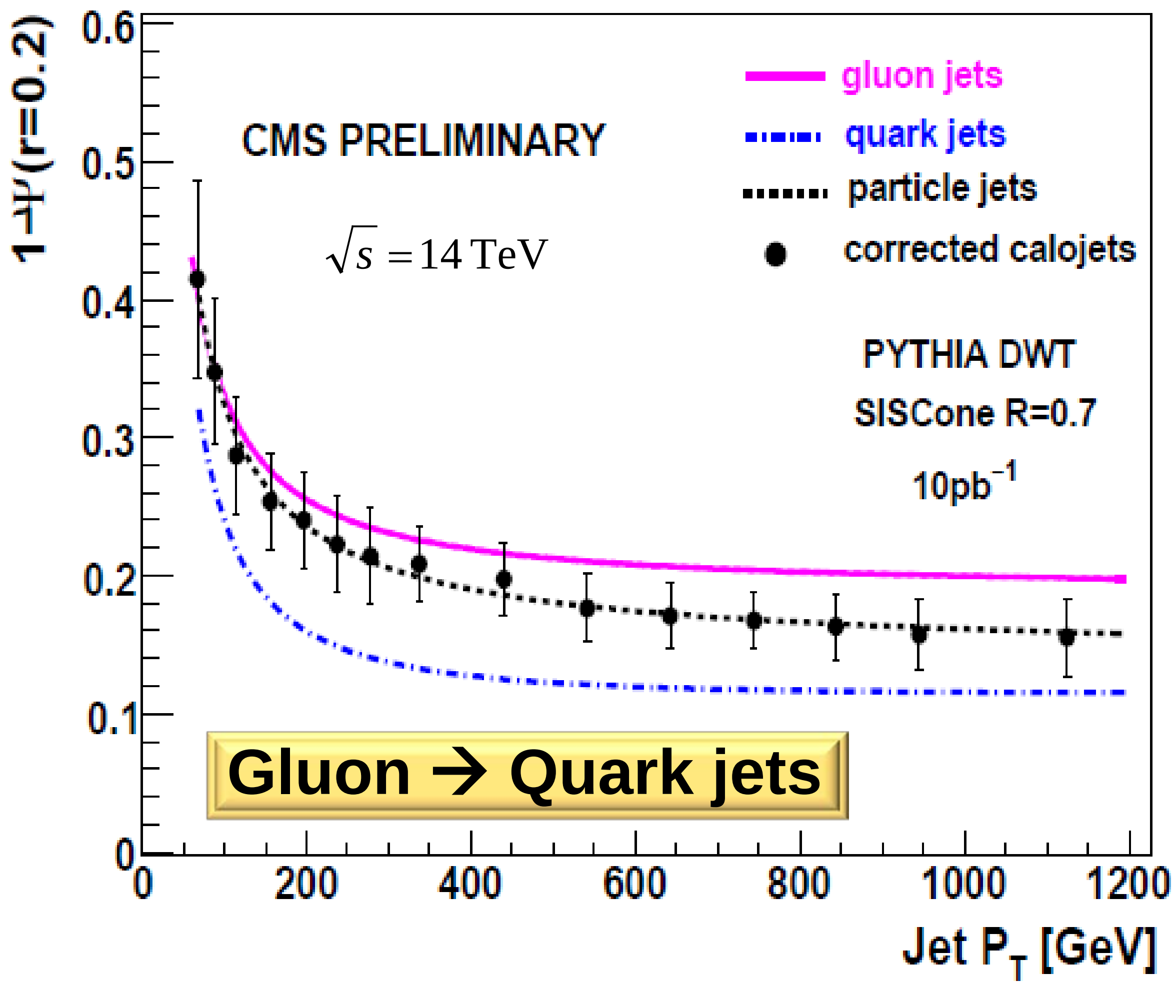
Pythia Data!

Quark jets are narrower than Gluon jets



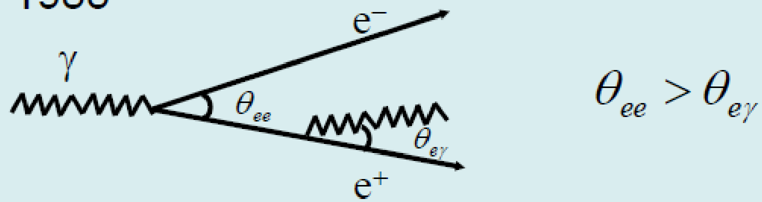
Jet Shapes at LHC: q/g mix

CMS-QCD-08-005

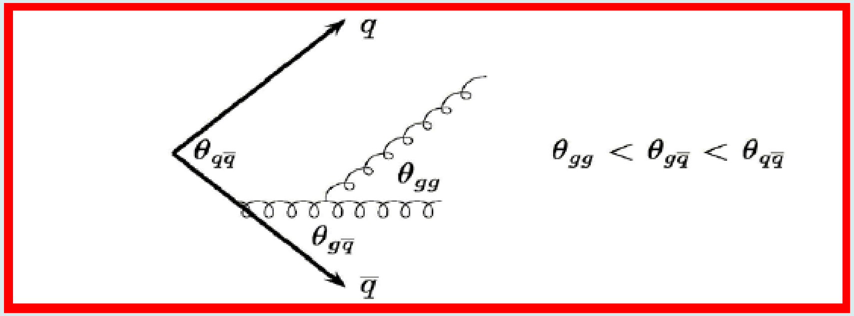


Color Coherence

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



- 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
    - Affects distribution of particles in jets



  - Interjet Coherence
    - String or Drag effect in multijet hadronic events
    - Production of soft particles is affected by the presence of energetic partons from hard interaction

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Shower Development

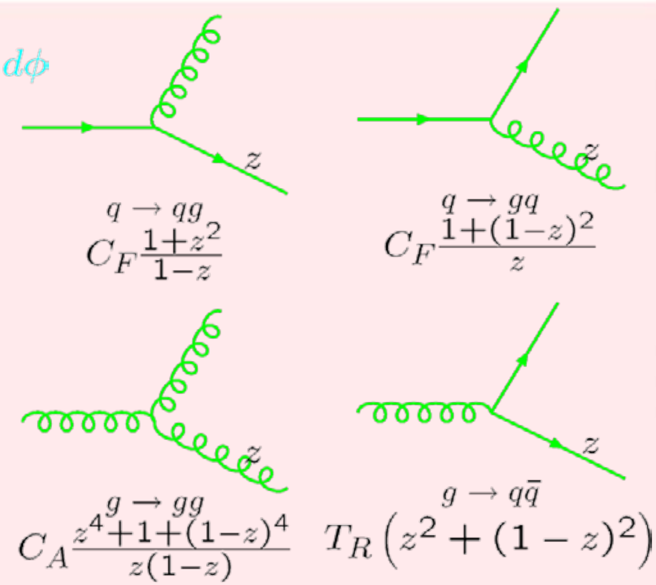
"Traditional Approach"

- ➔ 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



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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

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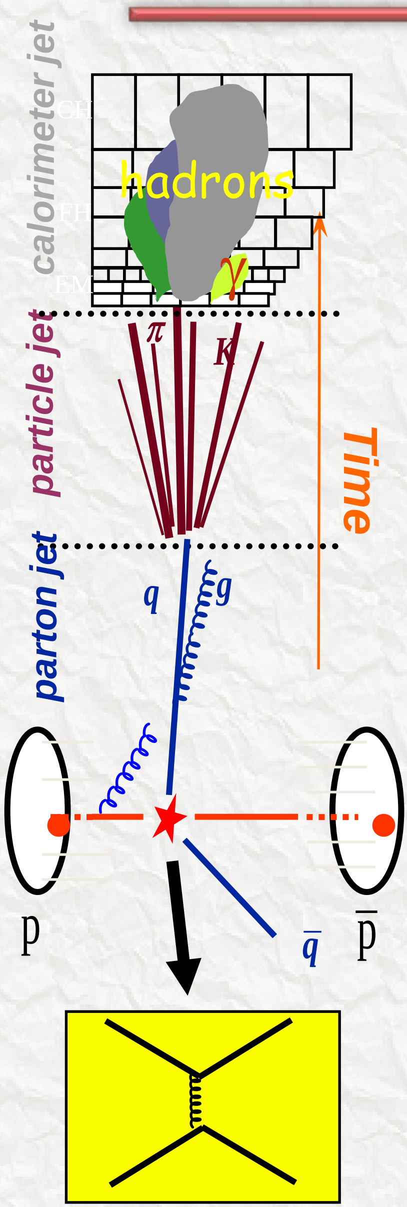
About Event Generators



- Event Generator: a ("C++" or "Fortran") program that tries to simulate Nature!
- Events vary from one to the next (random numbers)
- Goal: reproduce average behavior and fluctuations of data
  - But using many parameters that need to be tuned to data…
- Event Generators typically include:
  - Parton Distribution functions (PDF)
  - Initial state radiation (ISR)
  - Hard interaction
  - Final state radiation (FSR)
  - Color coherence
  - Beam remnants
  - Multiple Parton Interactions (MPI)
  - Hadronization and decays
- Some programs in the market:
  - PYTHIA, HERWIG (+JIMMY), SHERPA, JETSET, LEPTO, ARIADNE, ISAJET, COJETS...
- Some parton-level only:
  - ALPGEN, NLO++, MADGRAPH, VECBOS, NJETS, JETRAD, HERACLES, COMPOS, PAPAGENO, EUROJET...

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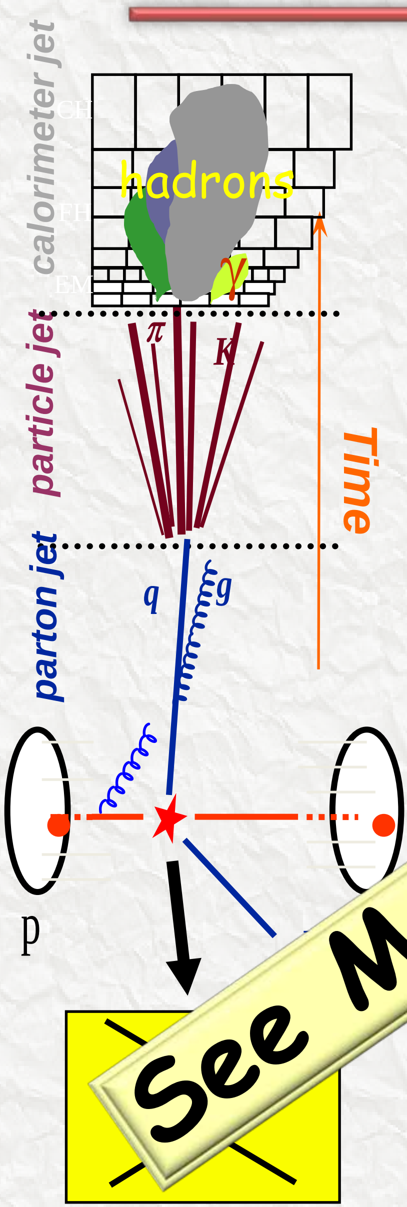
About Event Generators



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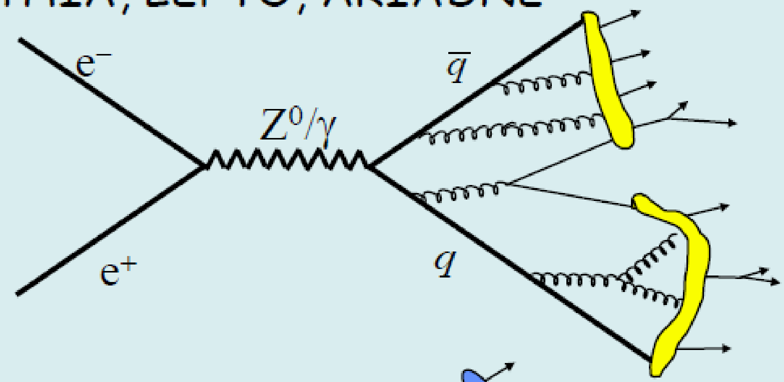
See Mrenna's talk on "Monte Carlo"

Hadronization Models

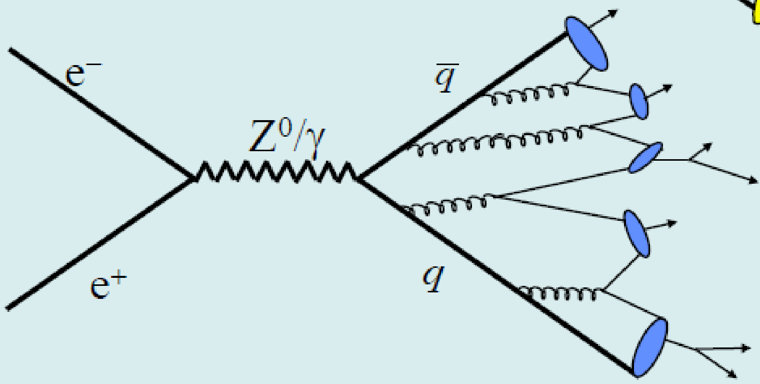
- **Independent fragmentation**
  - it is being used in ISAJET and COJETS
  - simplest scheme - each parton fragments independently following the approach of Field and Feynman
- **String fragmentation**
  - it is being used in JETSET, PYTHIA, LEPTO, ARIADNE

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

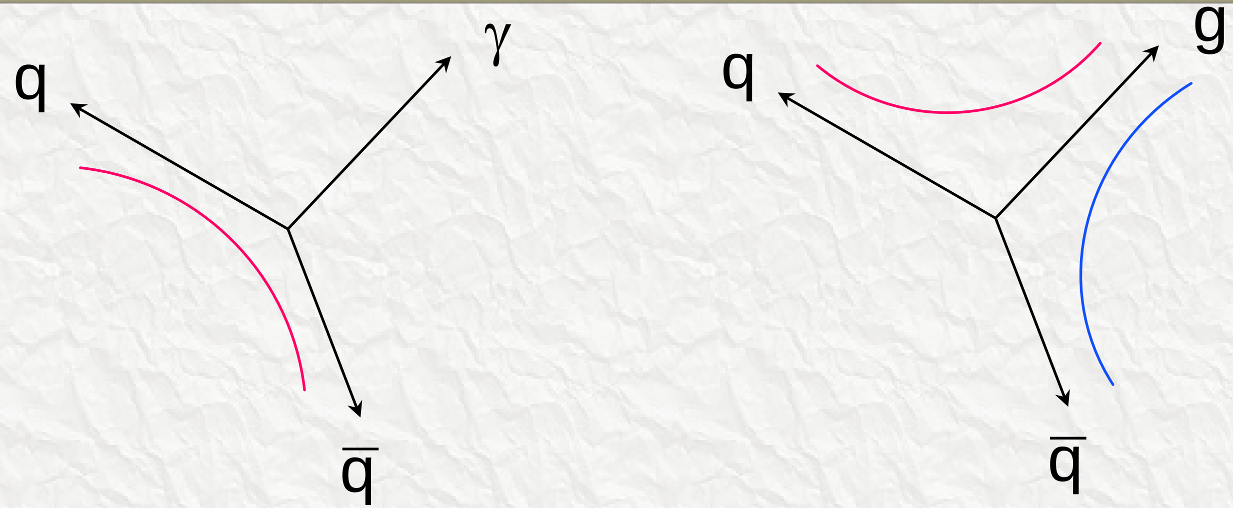
Cluster Fragmentation: Pairs of color connected neighboring partons combine into color singlets.



Color 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)**



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

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

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**

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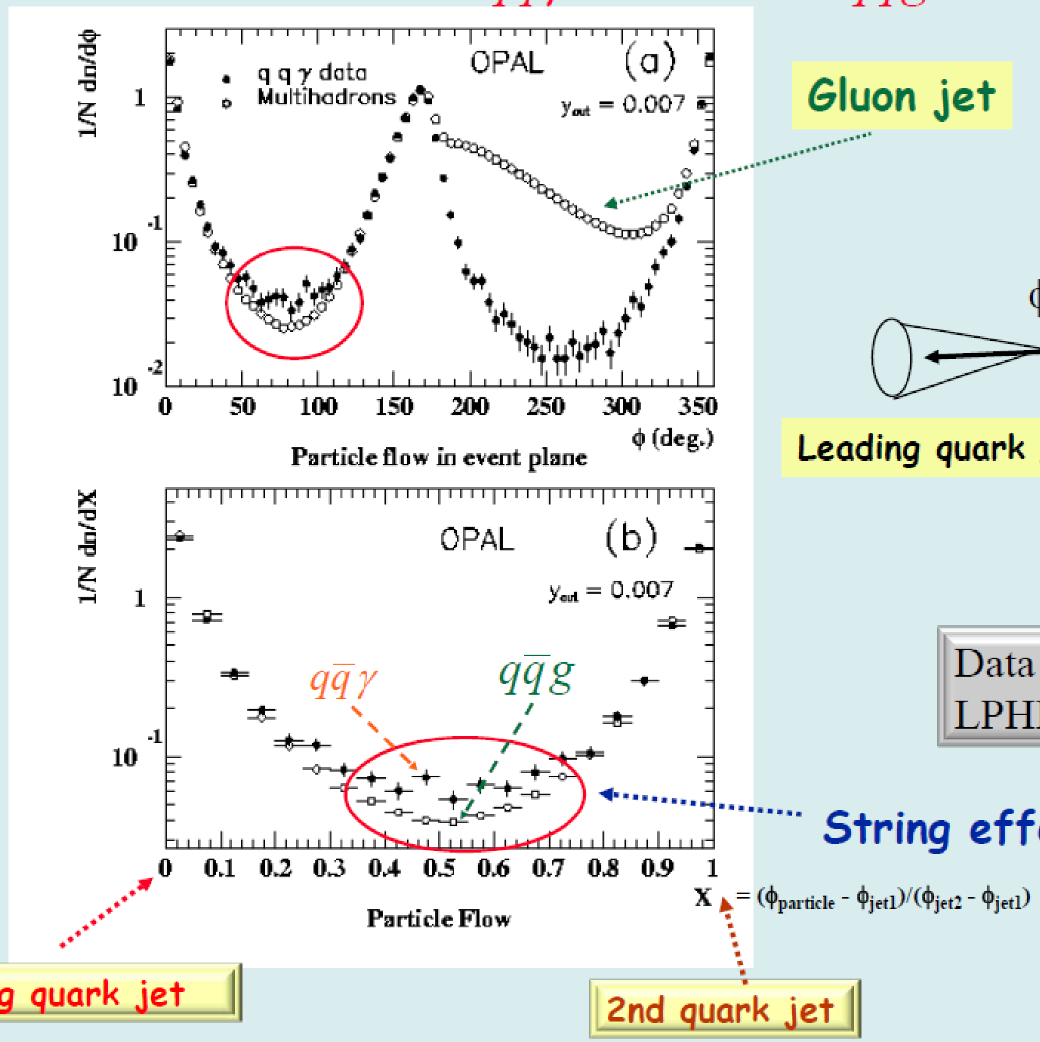
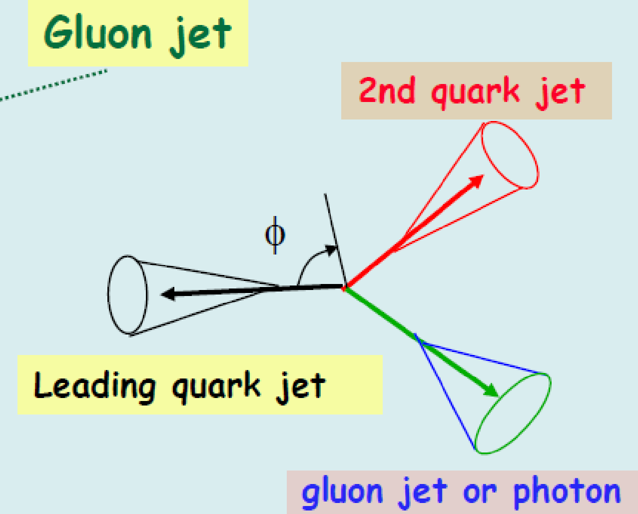
Coherence Results from LEP

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



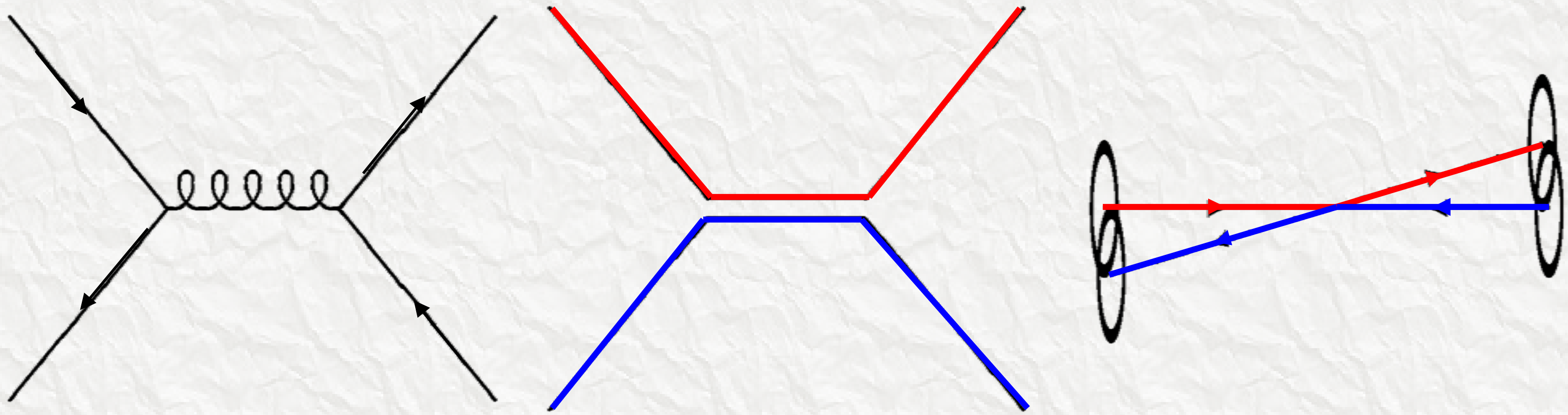


Data agree with analytic LPHD calculations

Coherence Observations

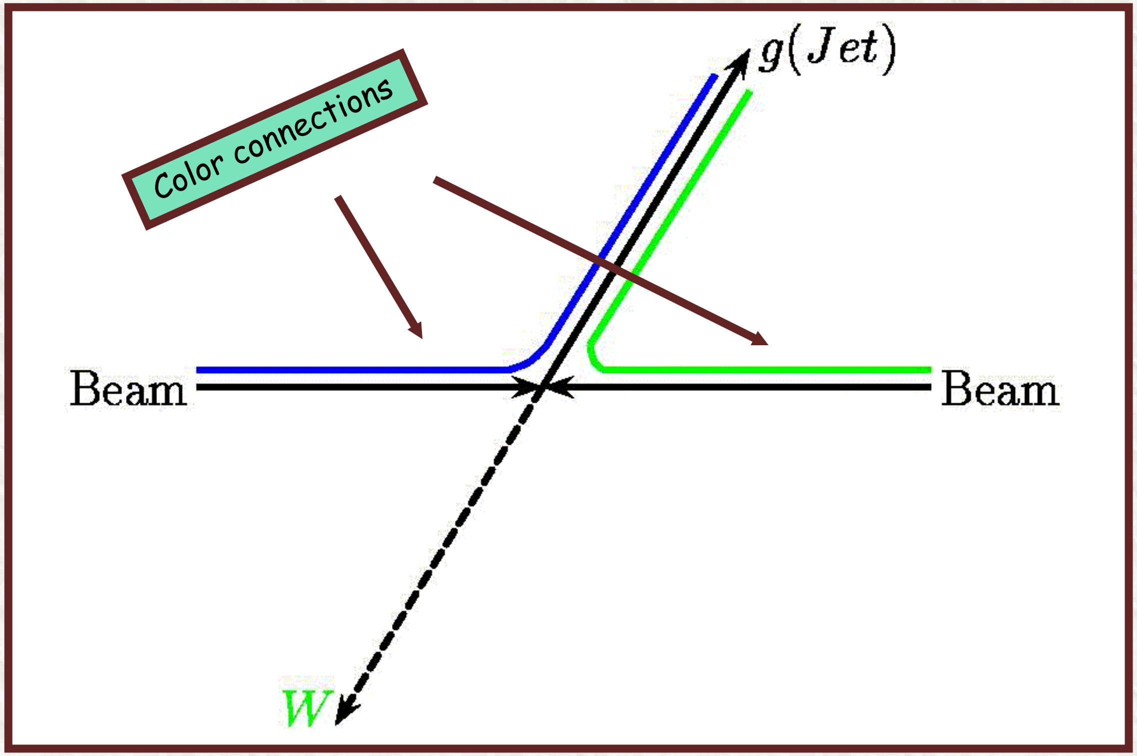
→ $p\bar{p}$ interactions: (observed in 3-jet and W+jet events)

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

Coherence Results from Tevatron

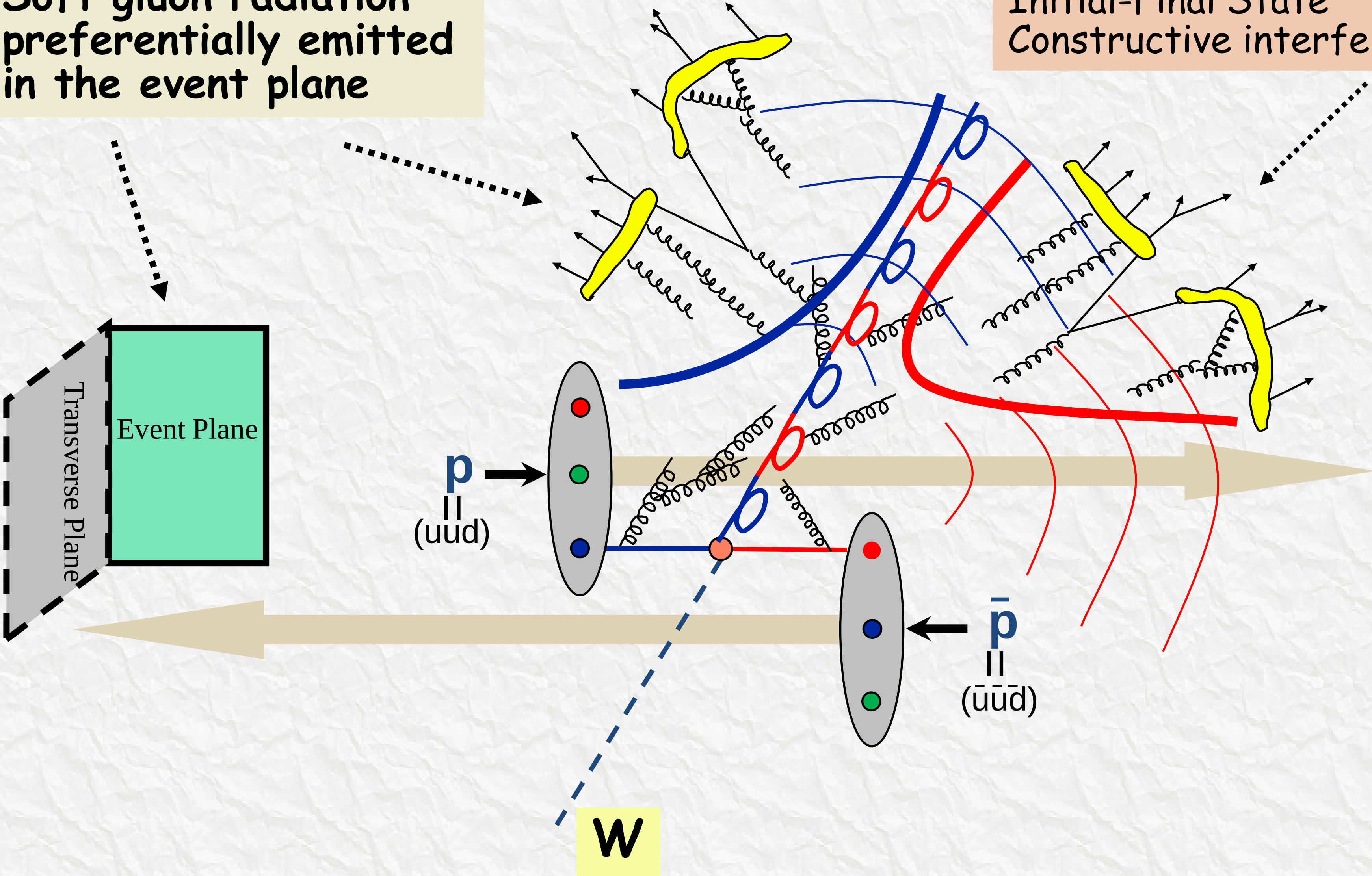


Compare pattern of soft particle flow around jet to that around (colorless) *W*

Coherence Results from Tevatron

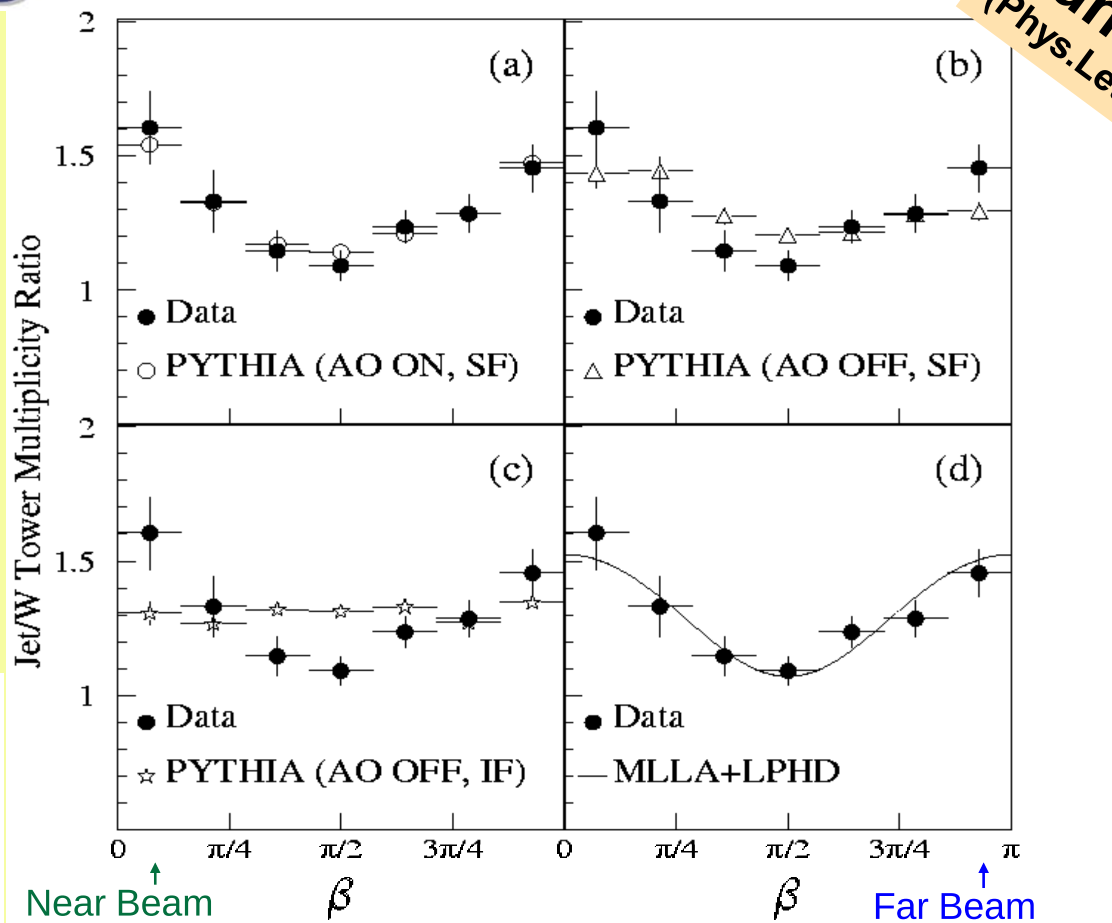
Soft gluon radiation preferentially emitted in the event plane

Initial-Final State Constructive interference

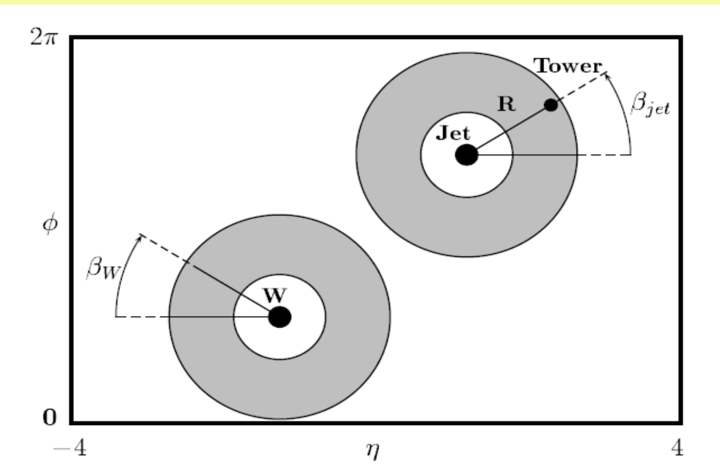


Ratio of particle multiplicity around the Jet to that around the W

- Multiplicity higher around jet than around W
- Multiplicity around jet peaks in event plane
- Observations consistent with coherence models in Pythia (Angular Ordering + String Fragmentation) and in LPHD calculation



Run I data
(Phys.Lett. 1999)



- Count particles (towers) in annulus around W & jet
- W does not contribute to particle production and serves to “normalize” jet data

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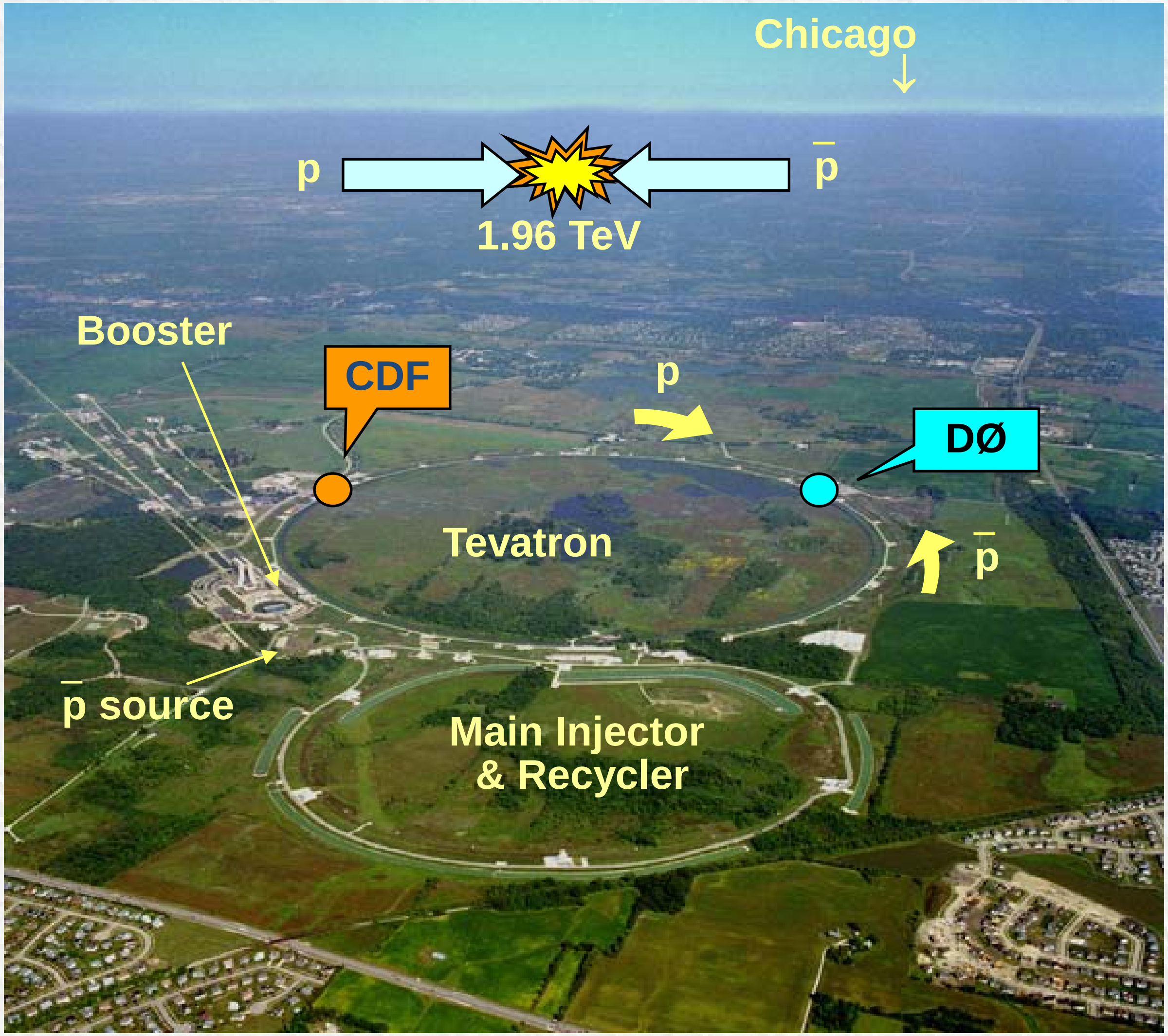
Outline

- Introduction
  - QCD
  - ee, ep, pp Processes – History of Jets
  - What is a Jet?
- Jet Algorithms
- Jet Reconstruction, Calibration, Performance
- Jet Characteristics
  - Jet Energy Profile
  - Quark and Gluon Jets
  - Color Coherence Effects
- **Jet Production at Hadron Colliders (Tevatron & LHC)**
  - **Underlying Event**
  - **Event Shapes**
  - **Dijet Azimuthal Decorrelation & Angular Distributions**
  - **Inclusive Jet Cross Section**
  - **Dijet Mass**
- Summary

Tevatron Complex

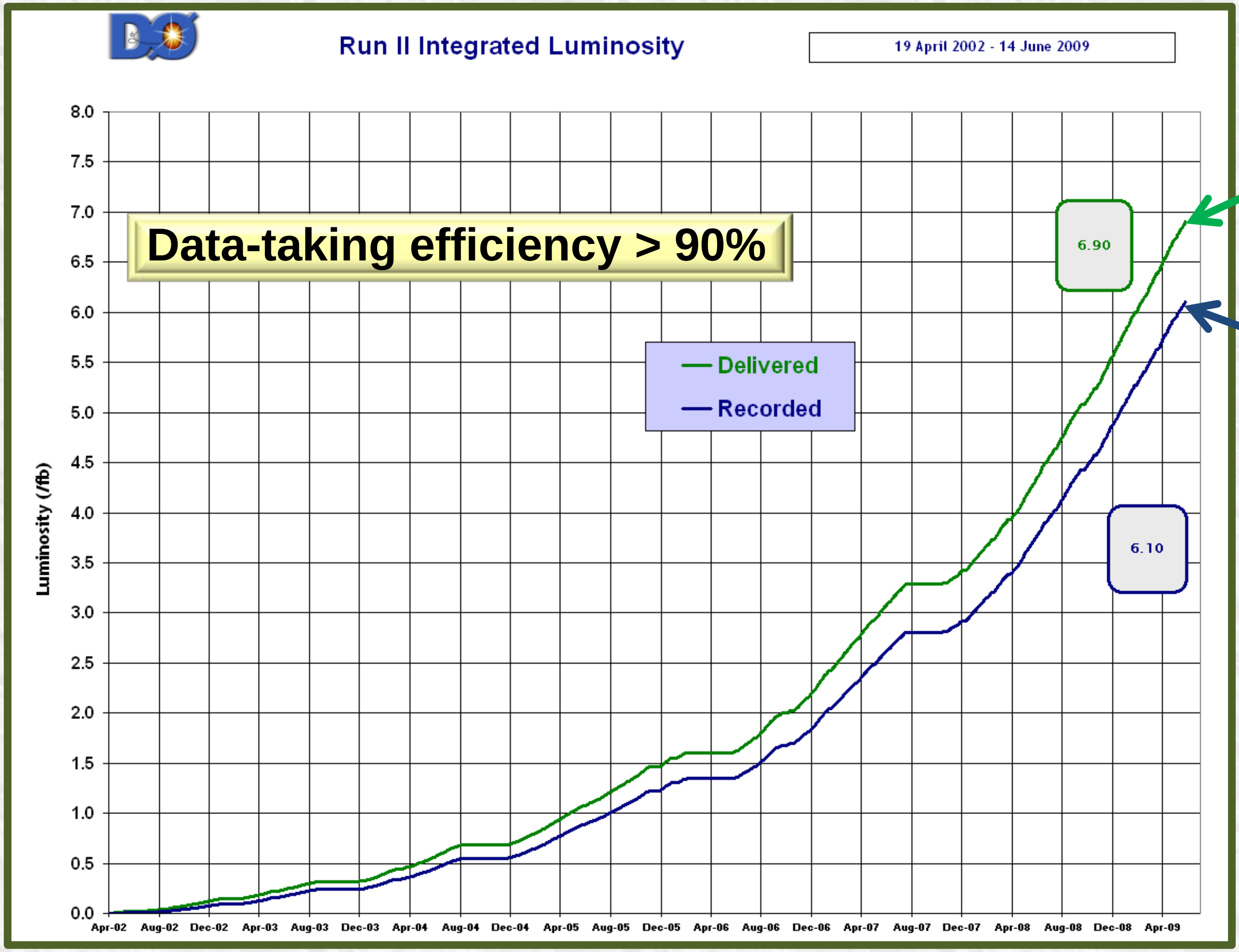


Run I
- 1992-1996
- E_{CM} = 1.8 TeV
- ~ 120 pb^{-1}
- (0.63 TeV ~600 nb^{-1})

Run IIA
- 2002-2005
- E_{CM} = 1.96 TeV
- ~ 1.5 fb^{-1}

Run IIB
- 2006-
- E_{CM} = 1.96 TeV
- ~ 5.5 fb^{-1}

Luminosity



Delivered 6.9 fb^{-1}

Recorded 6.1 fb^{-1}

LHC

The LHC Machine and Experiments

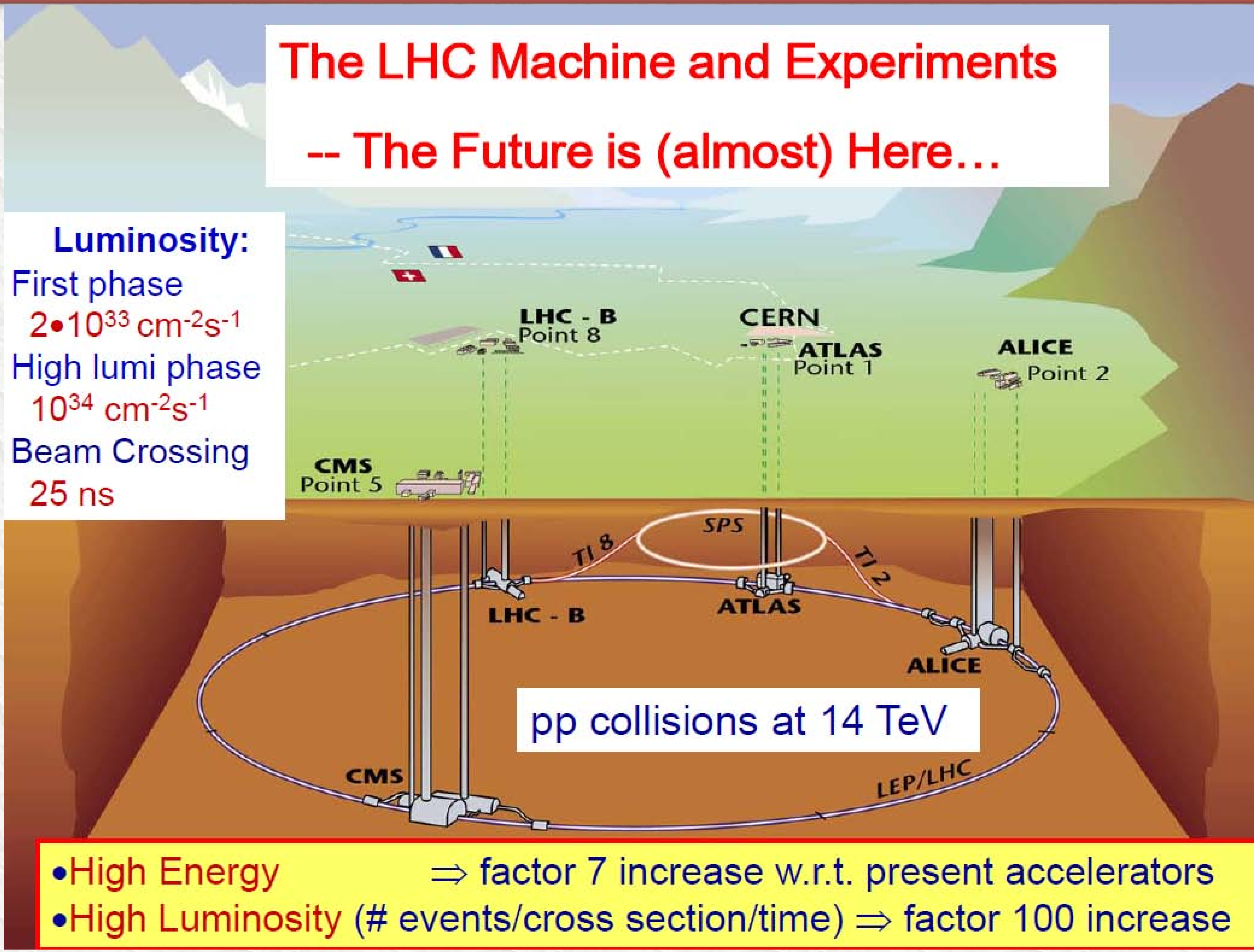
-- The Future is (almost) Here…

Luminosity:

First phase
$2 \bullet 10^{33}\ cm^{-2}s^{-1}$

High lumi phase
$10^{34}\ cm^{-2}s^{-1}$

Beam Crossing
25 ns

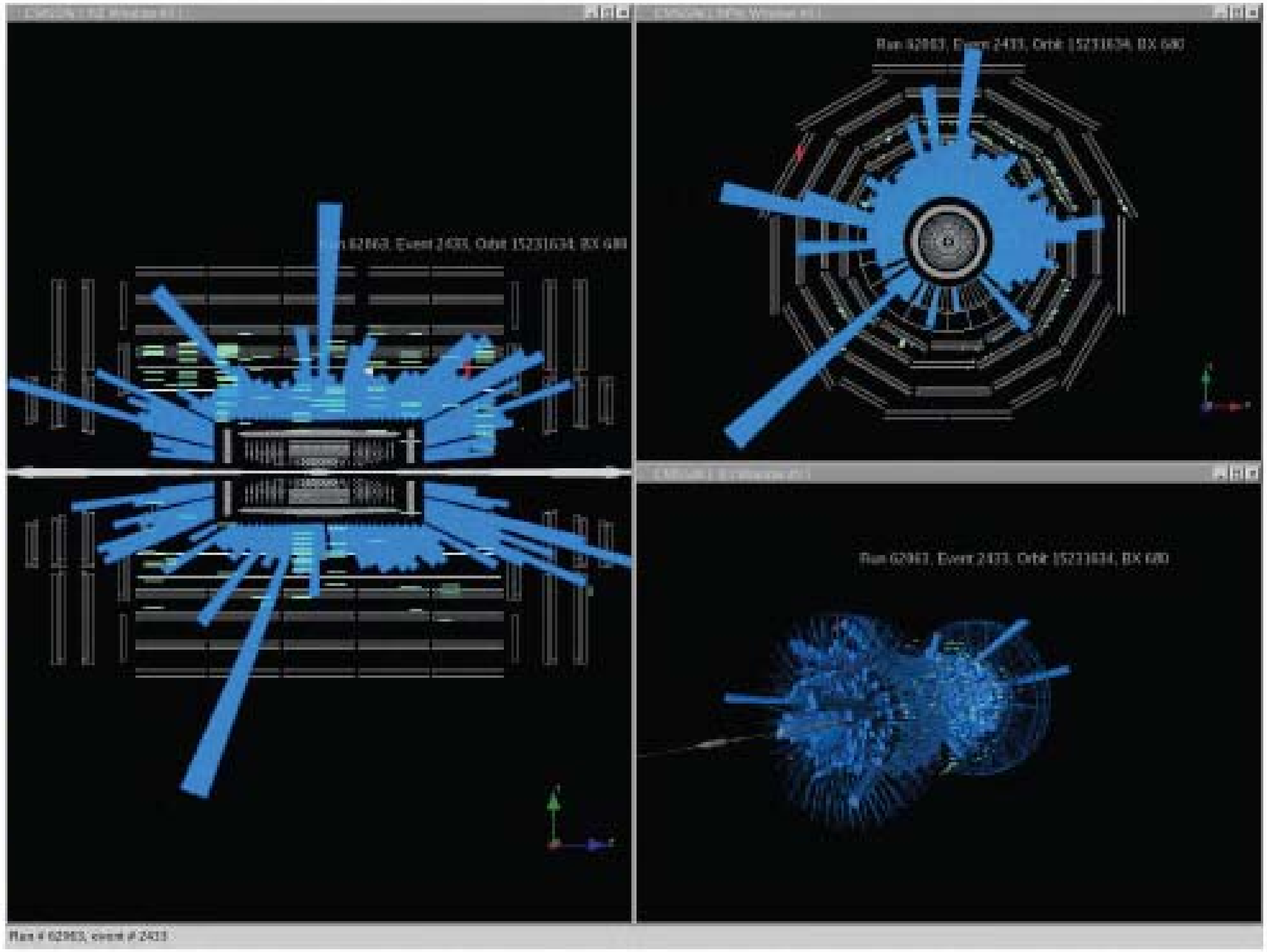


pp collisions at 14 TeV

- High Energy $\Rightarrow$ factor 7 increase w.r.t. present accelerators
- High Luminosity (# events/cross section/time) $\Rightarrow$ factor 100 increase

Sept. 10, 2008: First Protons

At 10:00 CMS saw the beam pass through the experiment for the first time ever, in the clockwise direction. The beam was initially intentionally stopped by blocks around 150 meters before CMS ($2\ 10^9$ protons), producing these images of the debris or "splash" from the particles hitting the blocks.



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Sept. 10, 2008: First Protons

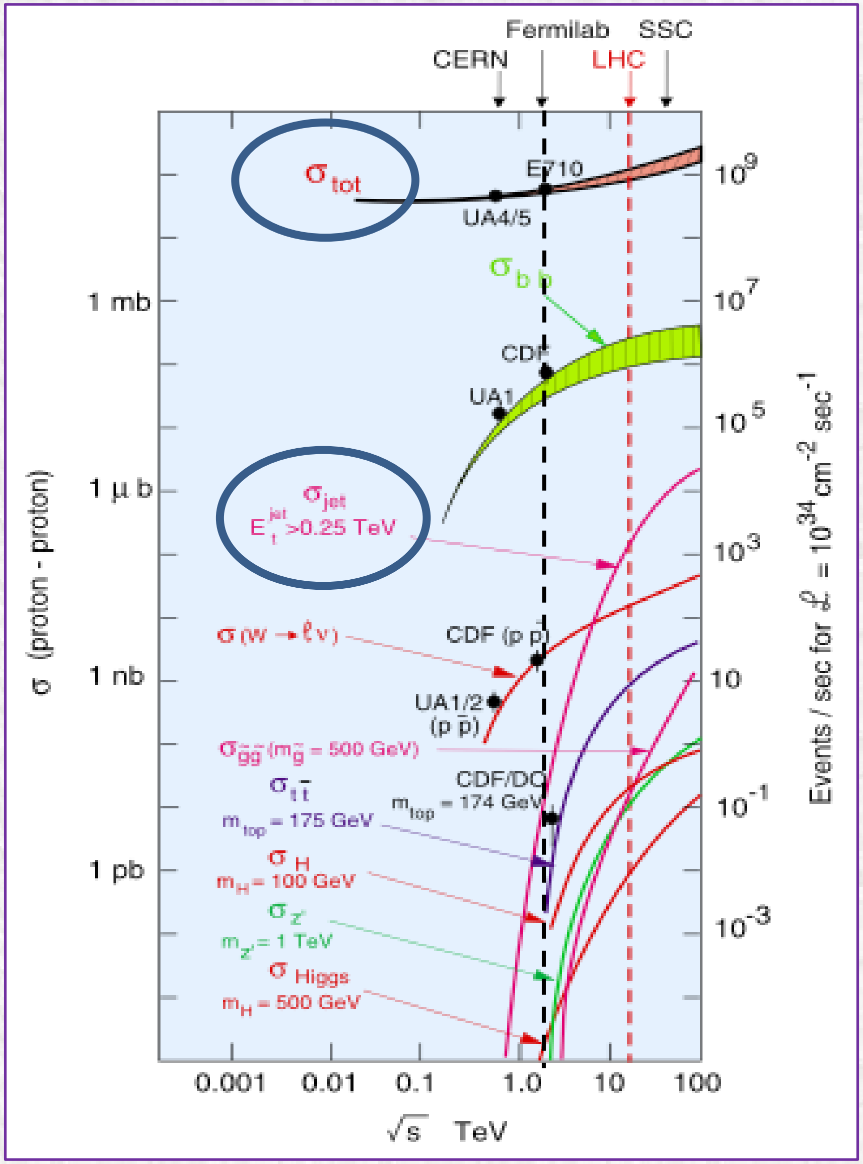
Startup in the Fall'09

Month	Max # of Bunches	Peak Luminosity	Integrated Luminosity
1	Beam Commissioning		
2	43	1.2×10^{30}	100 – 200 nb^{-1}
3	43	3.4×10^{30}	~ 2 pb^{-1}
4	156	2.5×10^{31}	~ 13 pb^{-1}
5	156	4.9×10^{31}	~ 25 pb^{-1}
6	720	4.0×10^{31}	~ 21 pb^{-1}
7	720	1.1×10^{32}	~ 60 pb^{-1}
8	720	1.1×10^{32}	~ 60 pb^{-1}
9	720	1.1×10^{32}	~ 60 pb^{-1}
10	Ions		

Total Luminosity: 200 – 300 pb^{-1}

Physics at LHC

- Total cross section ~ 100-120 mb
- The goal at startup is to *re-discover* the "*bread-and-butter*" physics (i.e., QCD, SM candles)
  - $\sigma_{jet}(p_T>250\text{ GeV})$
    - 100x higher than Tevatron
  - Electroweak
    - 10x higher than Tevatron
  - Top
    - 100x higher than Tevatron
- QCD processes not statistics limited!



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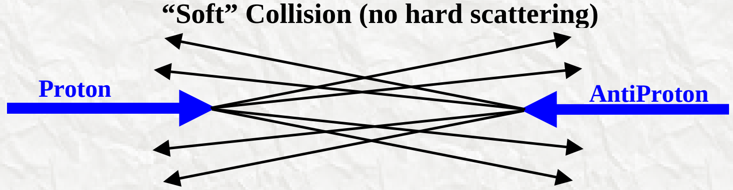
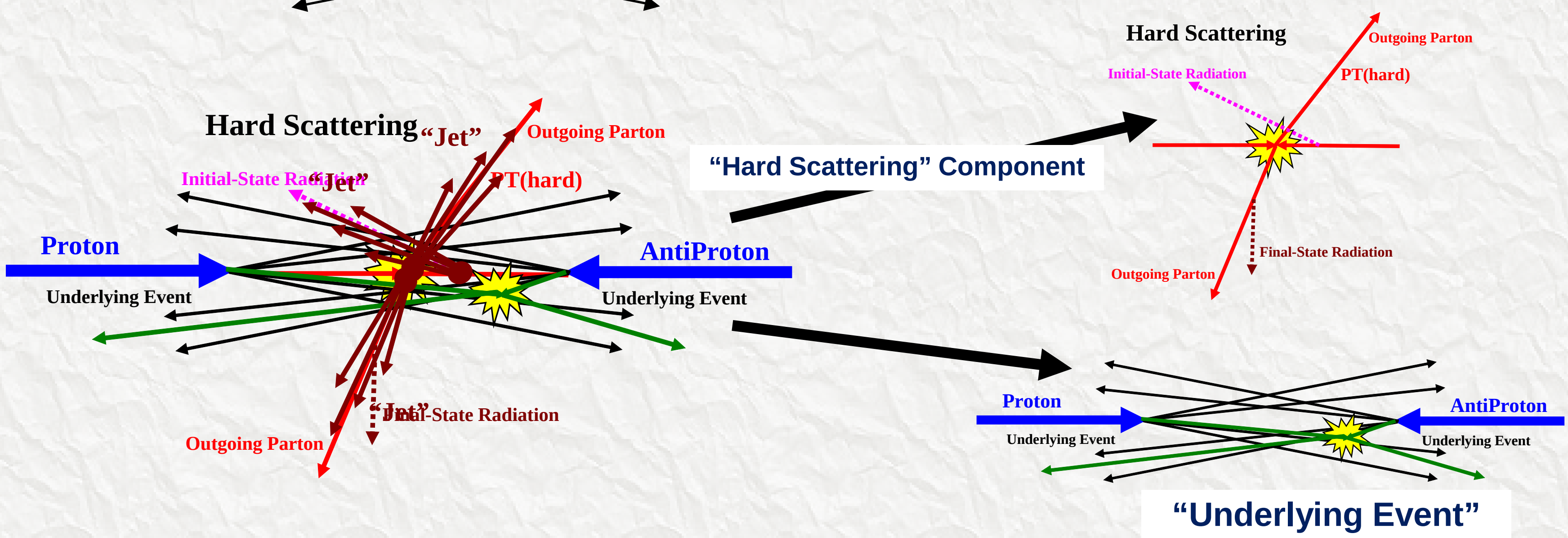
What is Underlying Event?

- The "underlying event" consists of the "beam-beam remnants" and from particles arising from soft or semi-soft multiple parton interactions (MPI)
- Underlying event is <u>not</u> the same as a minimum bias event
- Modeling of UE is important ingredient for jet physics and lepton isolation, energy flow, object tagging, etc

à la R. Field



No hard scattering "Min-Bias" event



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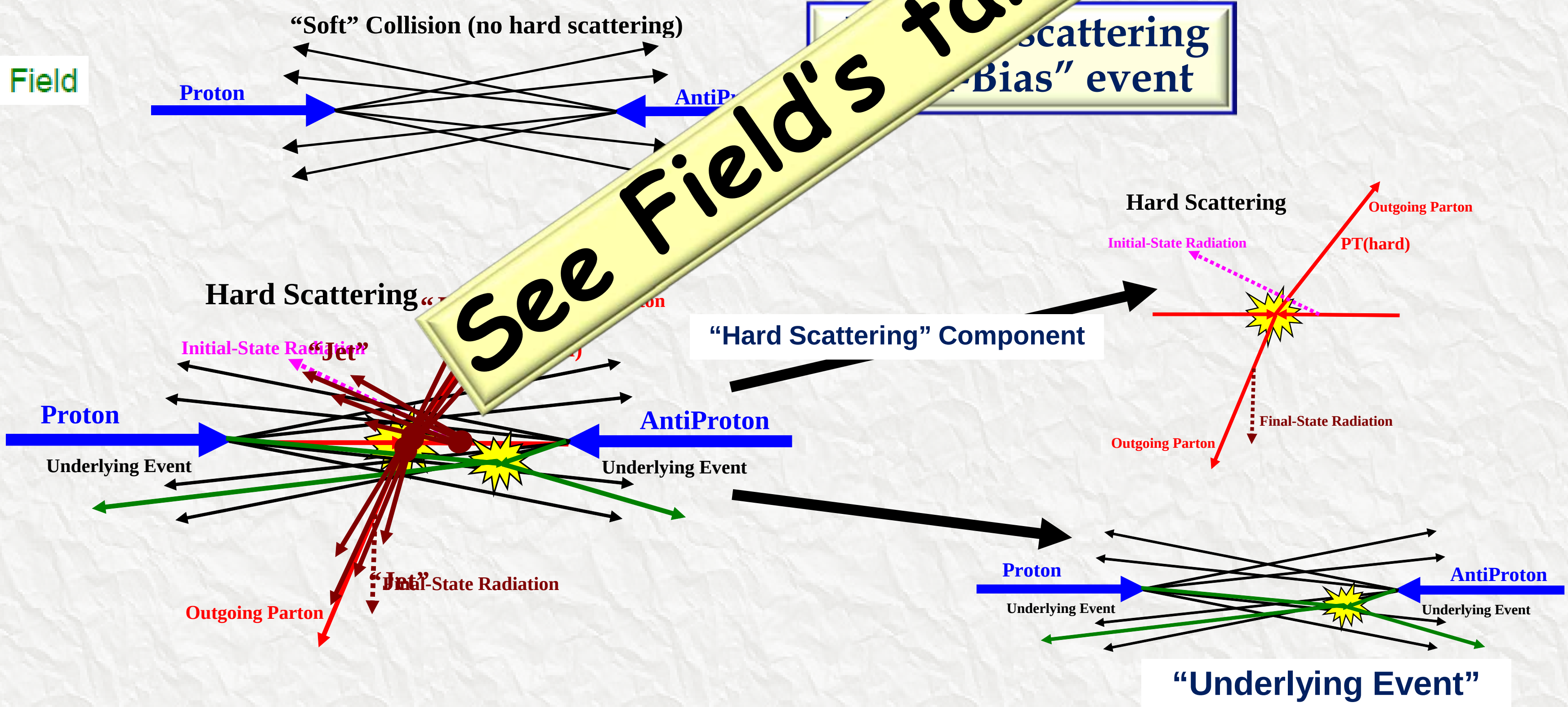
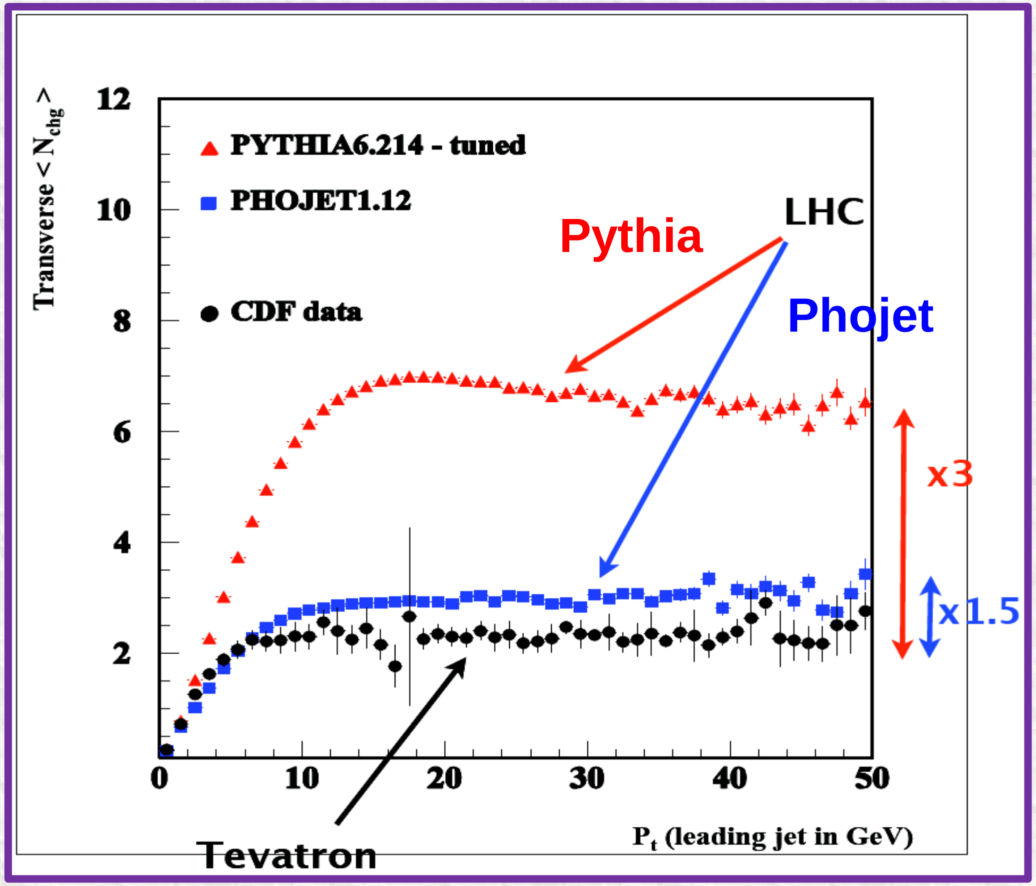


Underlying Event at LHC

- Large model dependence on LHC predictions from Tevatron data

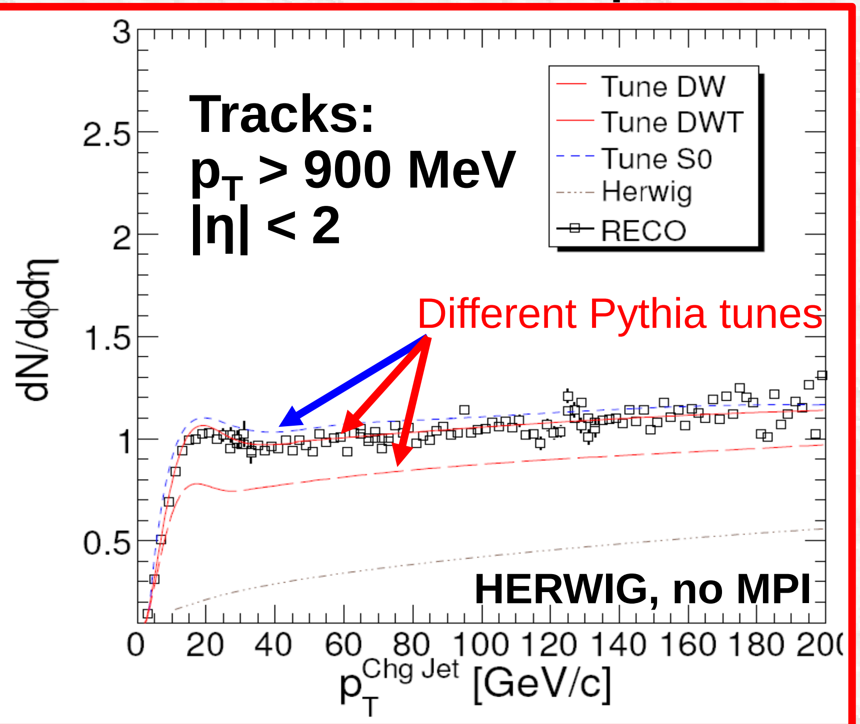


ATLAS

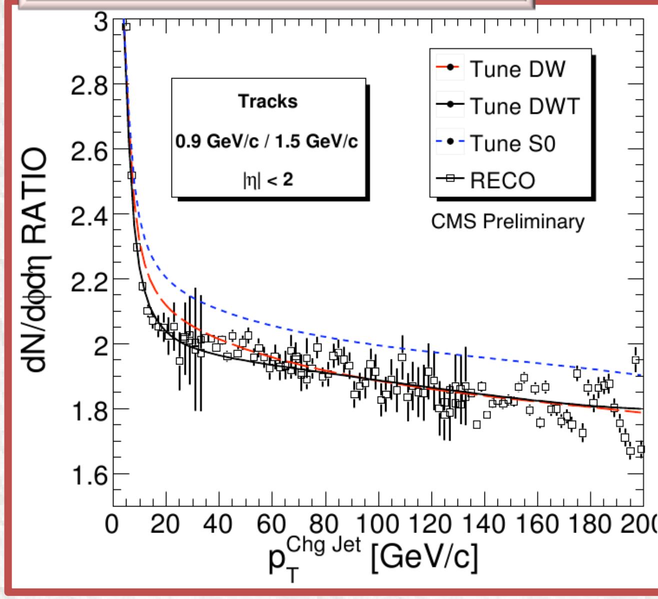
Underlying Event at CMS

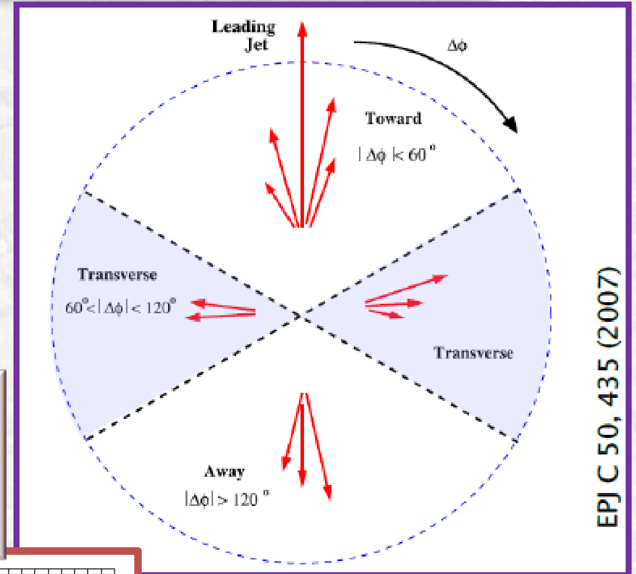
- Study track multiplicity and p_T density in "transverse" jet region
  - CDF approach
  - Use "track jets" identified with ICone algorithm

Statistics as for 100/pb



Decrease systematic effects with ratio: 0.9/1.5





CMS-QCD-07-003

CTEQ

Event Shapes (1)

- **Motivation:**
  - Test pQCD using collinear and infrared safe observables which are sensitive to the topology of the event
  - Can be used to distinguish between different MC models of QCD multi-jet production
  - Could help in searches for new physics signals
  - Normalized event shape distributions are robust against jet energy calibration and resolution effects

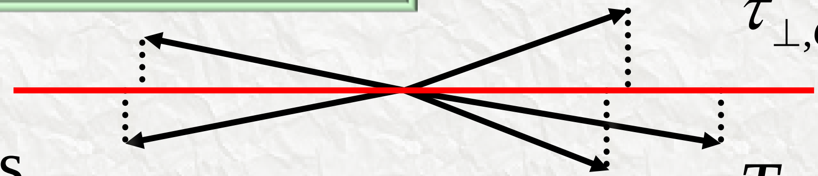
- **Challenges**
  - Corrections to the particle level
    - Jet energy/resolution effects around low p_T-threshold – avoid low values
  - Instrumental backgrounds to multijet events

C T E Q

Event Shapes (2)

Central Transverse Thrust:

CMS-QCD-08-003

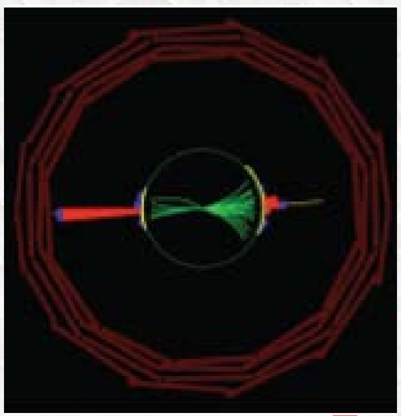


$$\tau_{\perp,C} \equiv 1 - T_{\perp,C}$$

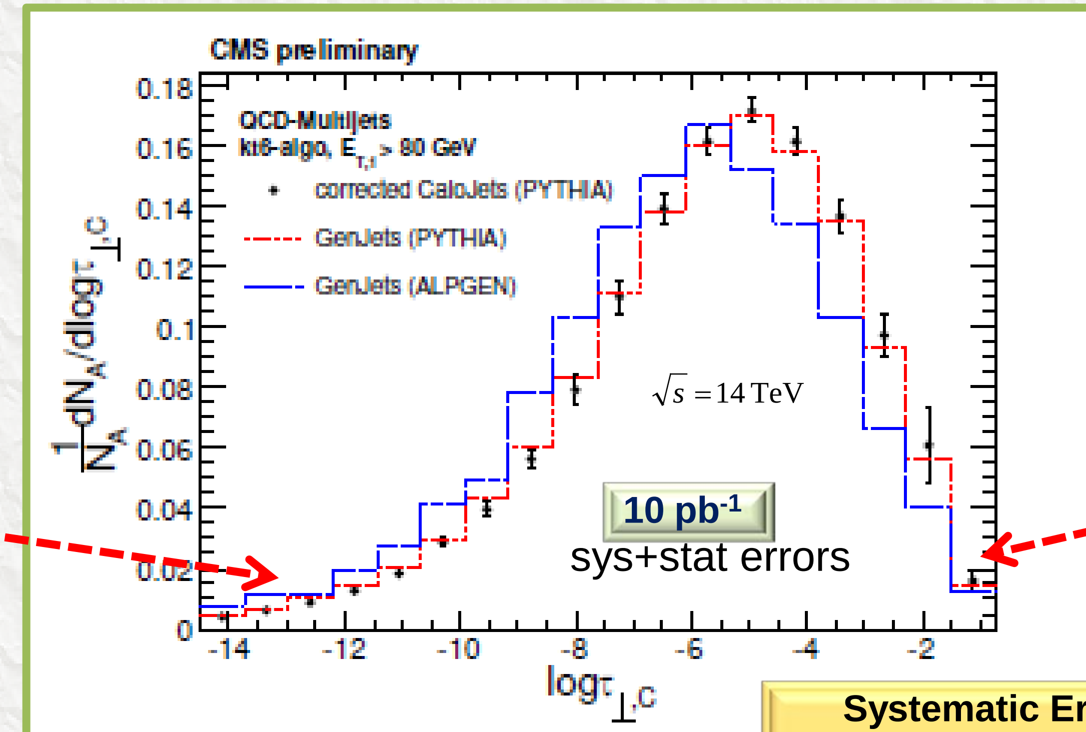
$$T_{\perp,C} \equiv \max_{\vec{\eta}_T} \frac{\sum_i \left| \vec{p}_{\perp,i} \bullet \vec{\eta}_T \right|}{\sum_i p_{\perp,i}}$$

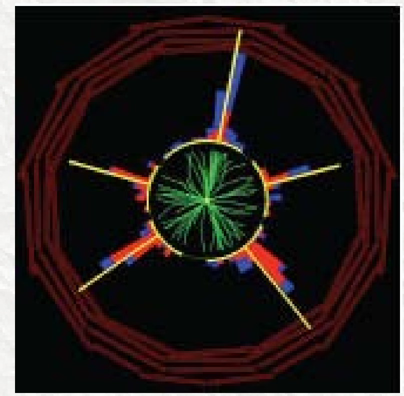
$T_{\perp,C} = 1$ for $2 \to 2$ process

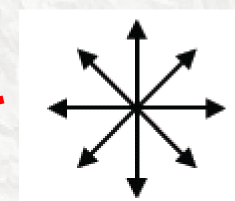
$T_{\perp,C} = 1/2$ for homogeneously distributed event



T = 1





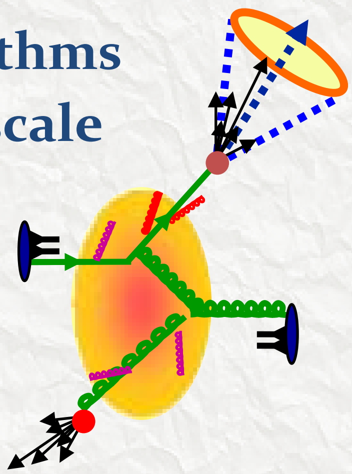


T = 1/2

Systematic Errors from JES and Resolutions ~ 2-10%

High-p_T Jet Production

- **Motivation:**
  - Confront pQCD calculations
  - Input to PDF/α_s determination
  - Sensitivity to new physics (e.g., quark substructure, new particles decaying into jet final states)
  - Understanding of background for other analyses
  - Test LO Matrix-Element + Parton Shower generators
- **Theory challenges**
  - Correct parton-level pQCD predictions to particle level (e.g., hadronizaton, MPI)
  - Understand non-perturbative effects for different jet algorithms
  - Tuning of fragmentation model, understanding of PDF/Q-scale uncertainties
  - Incorporate new physics models



CTEQ

High-p_T Jets Tevatron → LHC

DØ: N_{jets} for 700 pb^{-1} $|y|<0.8$

CMS: N_{jets} / pb^{-1} $|y|<1.3$

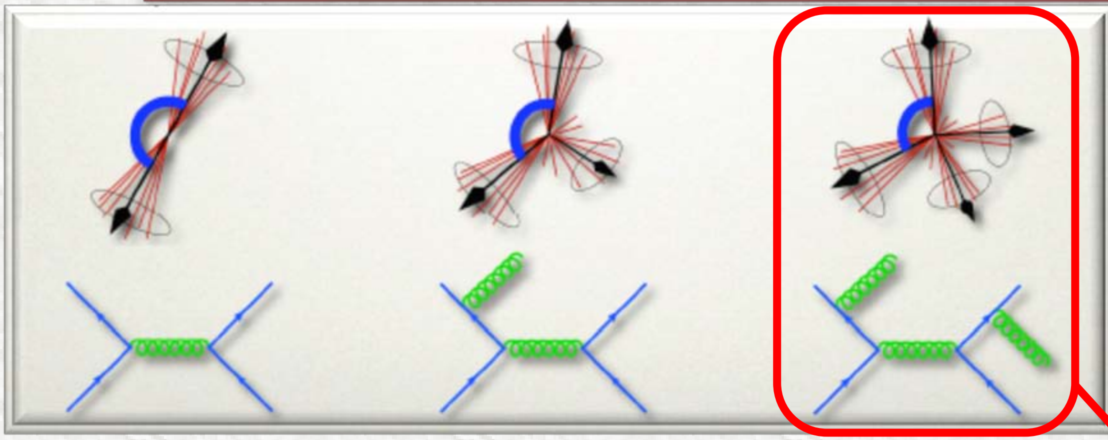
Sqrt(s)	pT>0.5 TeV	pT>1 TeV
2 (DØ)	34 (700 pb^{-1})	-
6	50 / pb^{-1}	0.3 / pb^{-1}
10	320 / pb^{-1}	5 / pb^{-1}
14	860 / pb^{-1}	20 / pb^{-1}

DØ: # evts for M_{jj} >1TeV, 700 pb^{-1}
$|\eta_1|,|\eta_2| < 2.4$

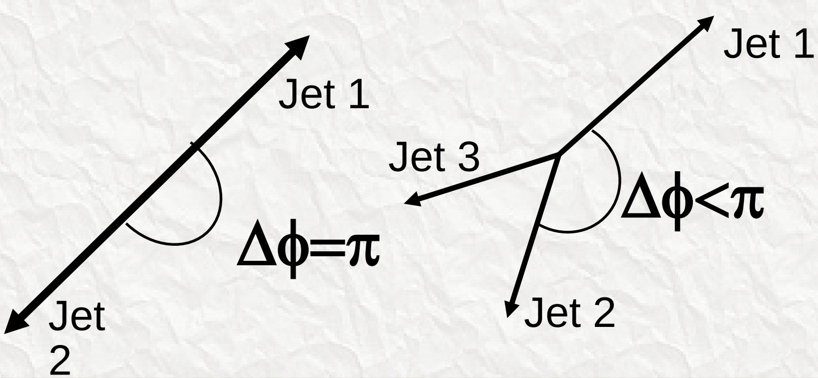
For CMS: # evts/M_{jj}/pb^{-1}
$|\eta_1|,|\eta_2| < 1.3$

Sqrt(s)	M_{jj}>1 TeV	M_{jj} >1.4 TeV	M_{jj} >2 TeV
2 (DØ)	~200 (700 pb^{-1})		
6		8.4 / pb^{-1}	0.6 / pb^{-1}
10		50 / pb^{-1}	7.4 / pb^{-1}
14		140 / pb^{-1}	20 / pb^{-1}

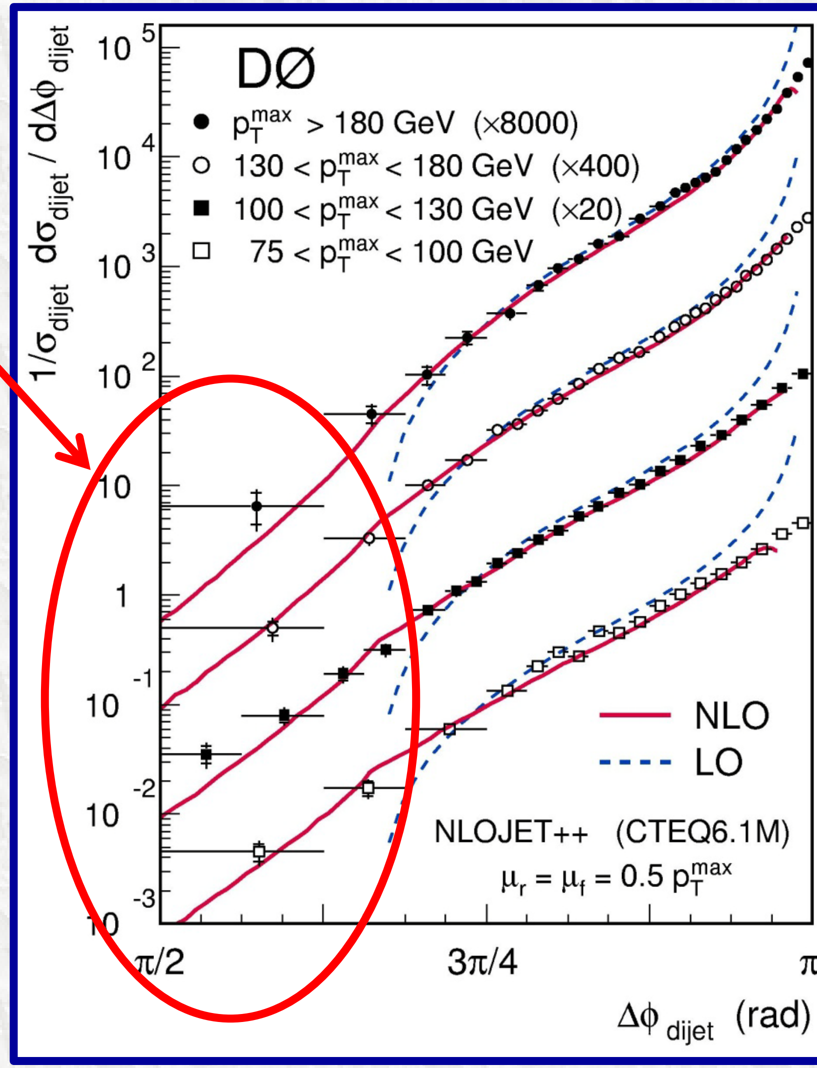
Dijet Azimuthal Decorrelation



2-jet event 3-jet event



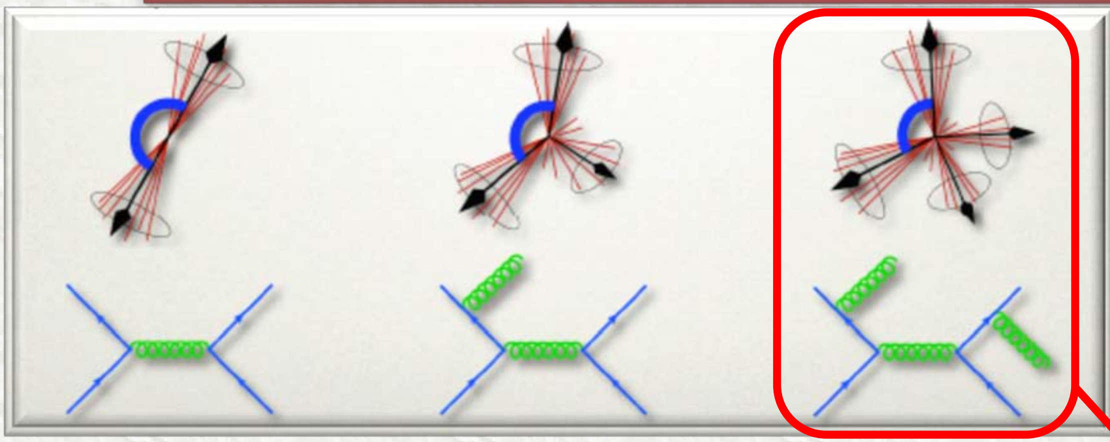
PRL 94, 221801 (2005)



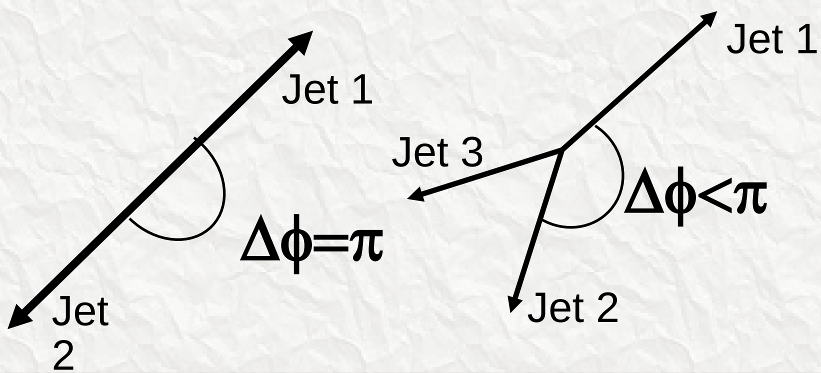
Δφ distribution of leading jets is sensitive to higher order radiation w/o explicitly measuring the radiated jets

Dijet Azimuthal Decorrelation

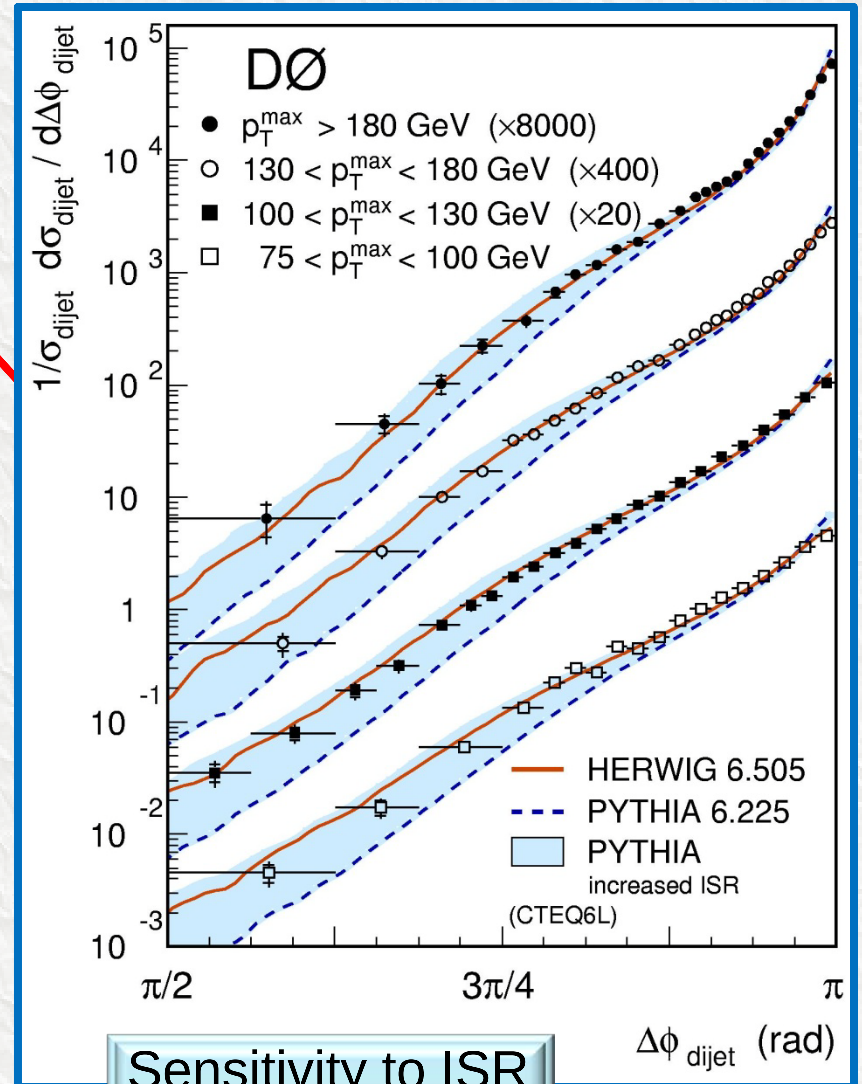
PRL 94, 221801 (2005)



2-jet event 3-jet event



Δφ distribution of leading jets is sensitive to higher order radiation w/o explicitly measuring the radiated jets



Sensitivity to ISR

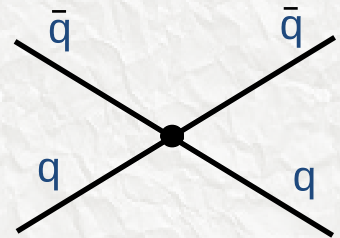
Use high-p_T jets to search for New Physics

C T E Q

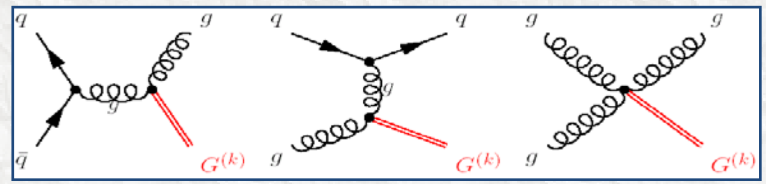
Compositeness and Large Extra Dim.

- **Quark Compositeness:**
  - For $\sqrt{\hat{s}} << \Lambda$ the composite interactions can be represented by contact terms:

$$L_{qq} = \pm \frac{g^2}{2\Lambda^2} \bar{q}_L \gamma^{\mu} q_L \bar{q}_L \gamma_{\mu} q_L$$



    - Eichten, Lane, Peskin, PRL 50, 811 (1983)
    - $\Lambda=\infty$ → point-like quarks
    - Λ=finite → substructure of mass scale Λ



- **Large Extra Dimensions (LED)**
  - In the ADD Model:
    - N.Arkani-Hamed, S.Dimopoulos, G.R.Dvali, PLB 429, 263 (1998), *et al.*
    - 3+n spacelike dimensions
    - n dimensions compactified to a n-torus with radius R
      - R~1 mm for n=2, R~3 nm for n=3, …
    - All SM fields are confined to a 3-dim membrane (*brane)*
    - Only gravity propagates in all dimensions *(bulk)*
  - Mass hierarchy problem is solved
  - The unification scale can be lowered to M_s~TeV

CTEQ

TeV^{-1} Extra Dimensions

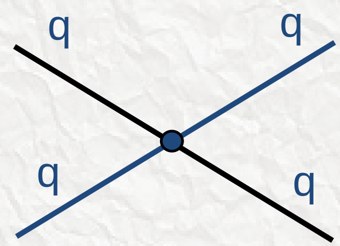
- **In the TeV^{-1} Extra Dimension Model**
  - **K.Dienes, E.Dudas, T.Gherghetta, Nucl. Phys. B 537, 47 (1999)**
  - **A.Pomarol, M.Quirós, PLB 438, 255 (1998)**
  - **I.Antoniadis, K.Benakli, M.Quirós, PLB 460, 176 (1999), *et al.***
- **Matter resides on a *p*-brane (spacelike dim *p*>3):**
- **Fermions are confined to 3-dim world**
- **SM gauge bosons can also propagate in the extra (*p*-3) dimensions**
  - **SM cross sections are modified due to the exchange of virtual Kaluza-Klein excitations ($M_n = \sqrt{M_{SM}^2 + n^2 / R^2}$, *n*=1,2,…) of the SM gauge bosons (e.g., gluons) through the ED**
  - **Compact dimension $R=1/M_C$ (M_C is the compactification scale)**
    - **the 95% CL limit: M_C=6.6 TeV from combined LEP data**

Dijet Angular Distributions

CTEQ

dσ ~ [QCD + Interference + Compositeness]

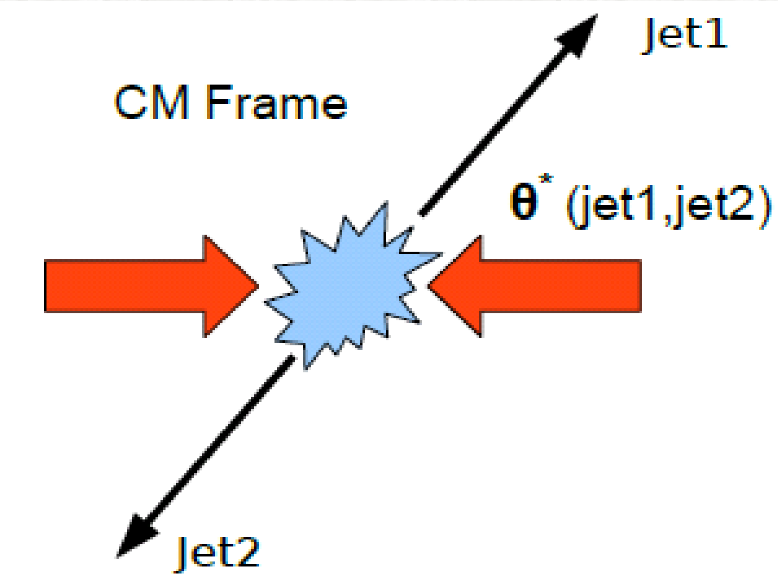
$$\alpha_s^2(\mu^2)\frac{1}{\hat{t}^2} \qquad \alpha_s(\mu^2)\frac{1}{\hat{t}}\cdot\frac{\hat{u}^2}{\Lambda^2} \qquad \left(\frac{\hat{u}}{\Lambda^2}\right)^2$$

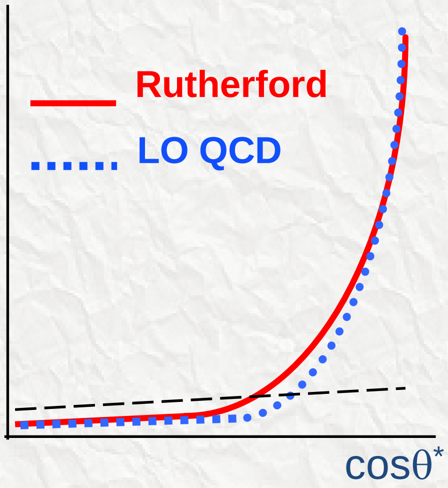


$$\sqrt{\hat{s}} << \Lambda$$

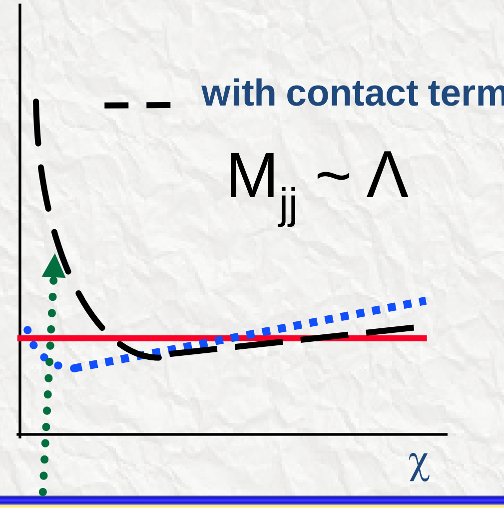
***dσ* ~ 1/(1-cosθ*)² angular distribution**

***dσ* ~ (1+cosθ*)² angular distribution**





$\Longrightarrow$

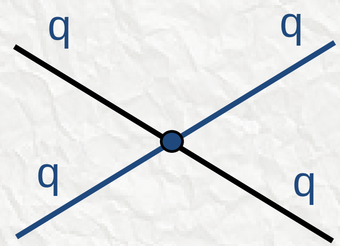


dN/dχ sensitive to contact interactions

Dijet Angular Distributions

$d\sigma \sim$ [QCD + Interference + Compositeness]

$$\alpha_s^2(\mu^2)\frac{1}{\hat{t}^2} \qquad \alpha_s(\mu^2)\frac{1}{\hat{t}}\cdot\frac{\hat{u}^2}{\Lambda^2} \qquad \left(\frac{\hat{u}}{\Lambda^2}\right)^2$$



$$\sqrt{\hat{s}} << \Lambda$$

$d\sigma \sim 1/(1-\cos\theta^*)^2$ angular distribution

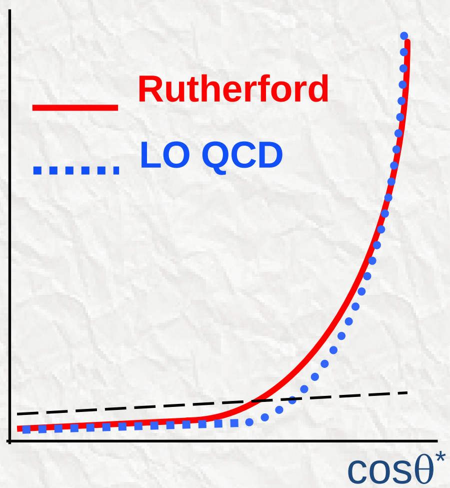
$d\sigma \sim (1+\cos\theta^*)^2$ angular distribution

From $\cos\theta^*$ variable to χ

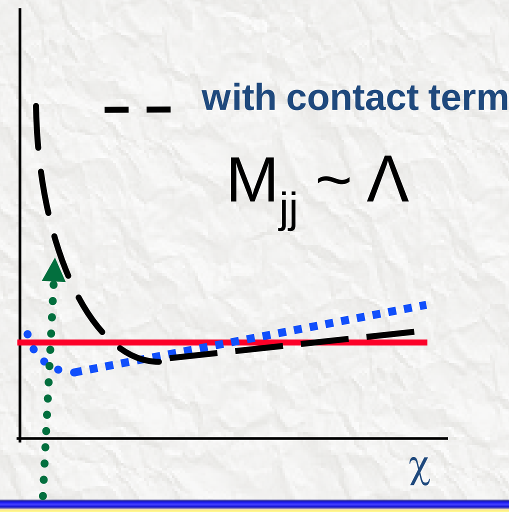
$$\chi = e^{2|y^*|}$$

$$y^* = \frac{1}{2}(y_1 - y_2)$$

$$y_{boost} = \frac{1}{2}(y_1 + y_2)$$



$\Longrightarrow$

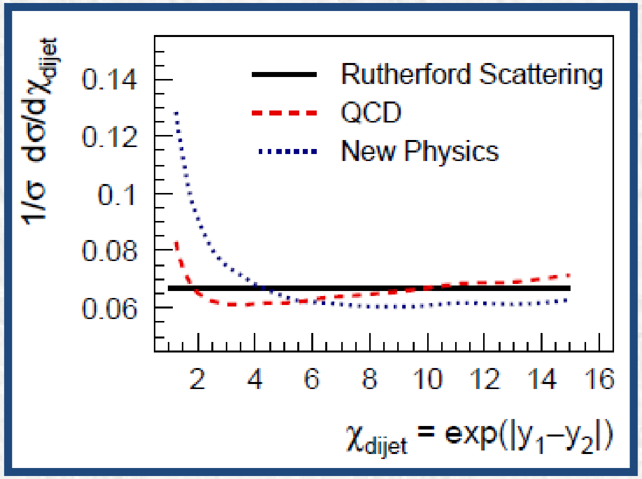


$dN/d\chi$ sensitive to contact interactions

CTEQ

Search for BSM Signatures

- **BSM signatures will populate the low-χ region at high M_{jj}:**
  - **Compositeness (scale Λ)**
  - **ADD Large Extra Dimensions (scale M_s)**
  - **TeV^{-1} Extra Dimensions (scale M_C)**



- **Theory implementation:**
  - **Multiply NLO/LO QCD scale factor to New Physics LO:**

$$\sigma_{NP}^{NLO} = \sigma_{QCD}^{NLO} \cdot \frac{\sigma_{NP}^{LO}}{\sigma_{QCD}^{LO}} = \sigma_{NP}^{LO} \cdot \frac{\sigma_{QCD}^{NLO}}{\sigma_{QCD}^{LO}}$$

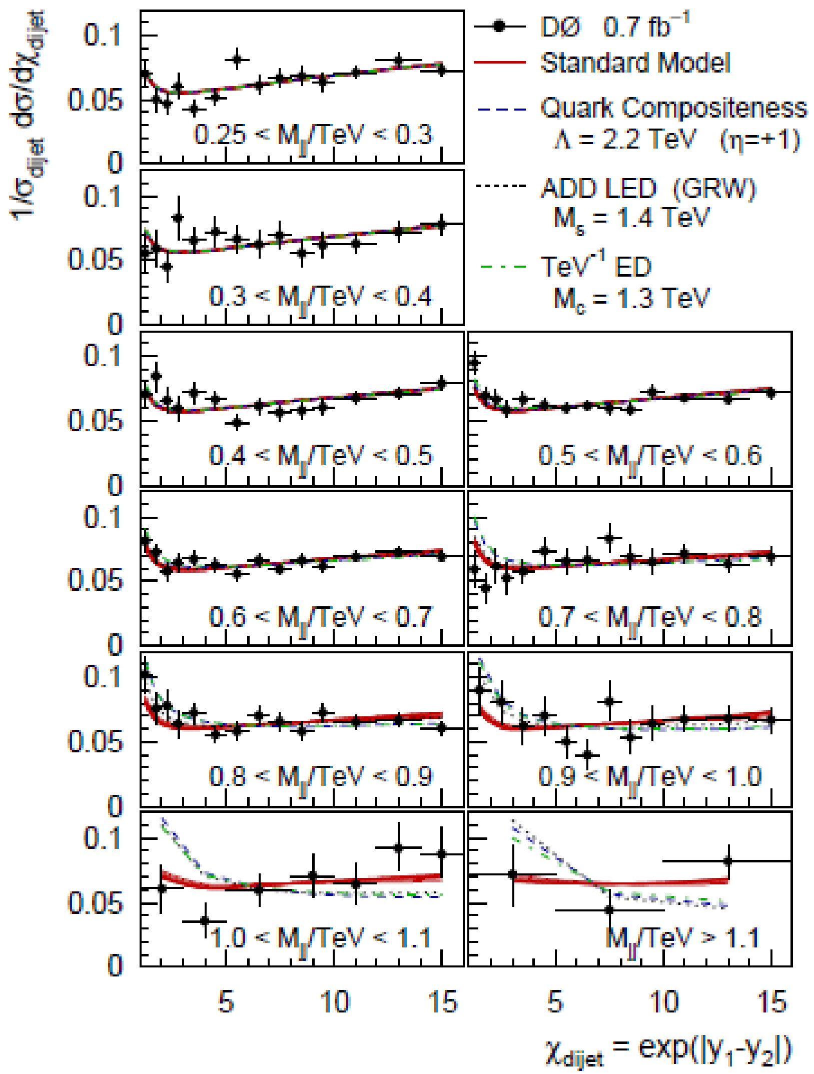
$$\xi = \lambda / \Lambda^2 \text{ (QC)}$$

$$\xi = 1/M_s^4 \text{ (ADD LED)}$$

$$\xi = 1/M_C^2 \text{ (TeV}^{-1}\text{ ED)}$$

$$\sigma_{NP} = ME_{SM} + \xi \cdot ME_{\text{int}} + \xi^2 \cdot ME_{NP}$$

Search for BSM Signatures



Limits

- **Compositeness (Λ): ~2.8 – 3 TeV**
- **ADD LED (GRW, M_s): ~1.6 – 1.7 TeV**
- **TeV^{-1} Extra Dim (M_C): ~1.6 – 1.7 TeV**

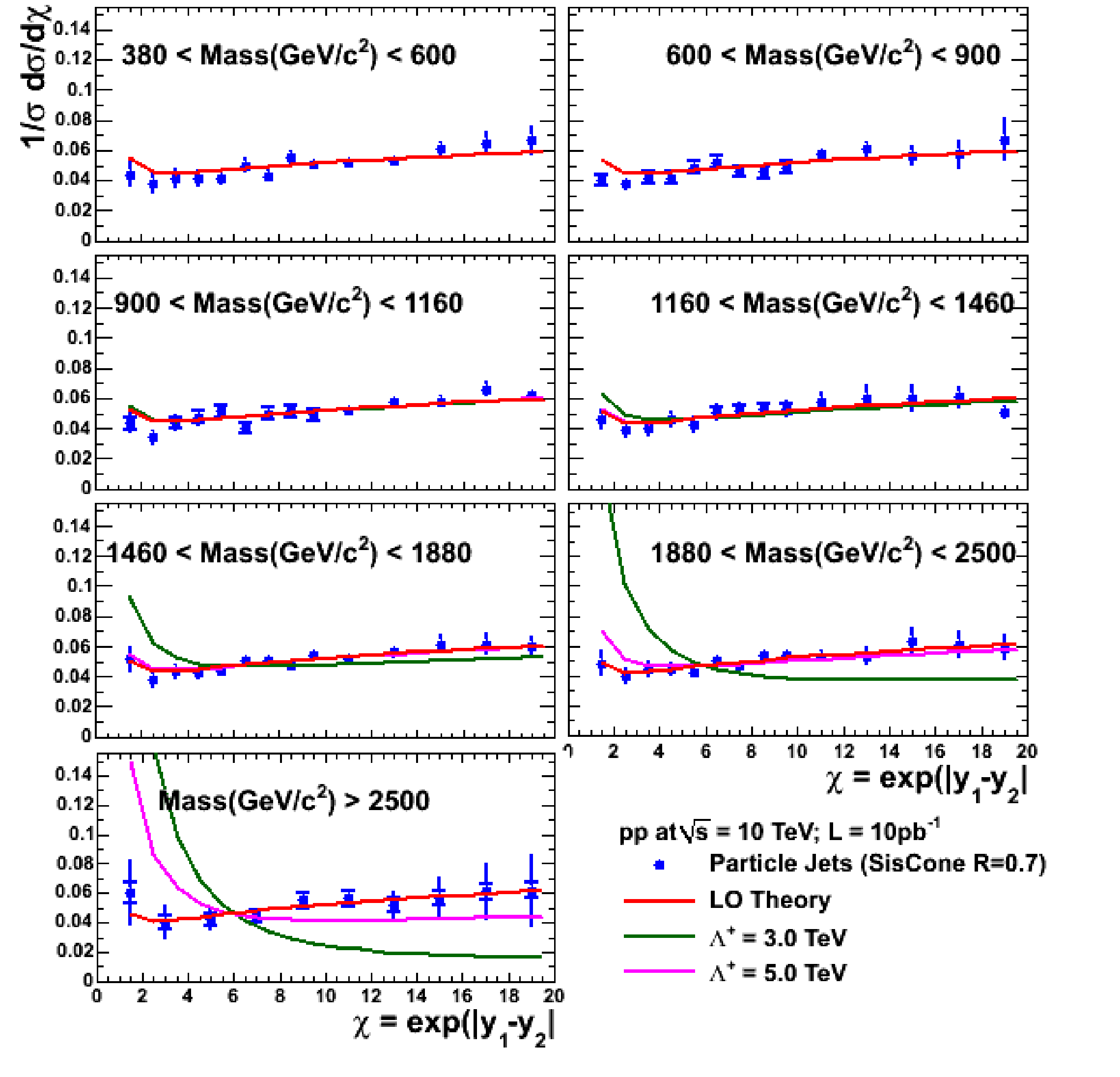
Dijet Angular Distributions @ LHC

Angular distributions are insensitive to PDFs

Reduced sensitivity to detector effects

Particle level information

Errors dominate by JEC



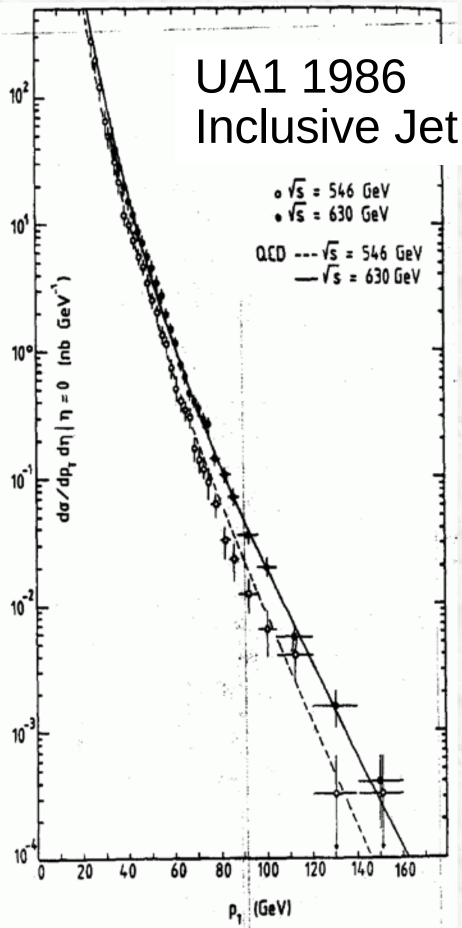
Inclusive Jets – The Old Days

CTEQ

$$\frac{1}{\Delta E_T \Delta\eta}\iint d\eta\, dE_T \frac{d^2\sigma}{dE_T d\eta} \longleftrightarrow \frac{N_{jet}}{\Delta E_T \Delta\eta\, \varepsilon \int L dt} \text{ vs. } E_T$$

ΔE_T	$\rightarrow$	E_T bin size	ε	$\rightarrow$	selection efficiency
$\Delta\eta$	$\rightarrow$	η bin size	L	$\rightarrow$	inst. Luminosity
N_{jet}	$\rightarrow$	# of jets in the bin			

UA1 1986
Inclusive Jet CS



Uncertainties ~ 70% on CS:
±50% accept./jet corr (smearing)
±40% calib ±10% aging ±15% Lum
Λ_C > 400 GeV *"Exp and theo. Uncerts. taken in to account"*

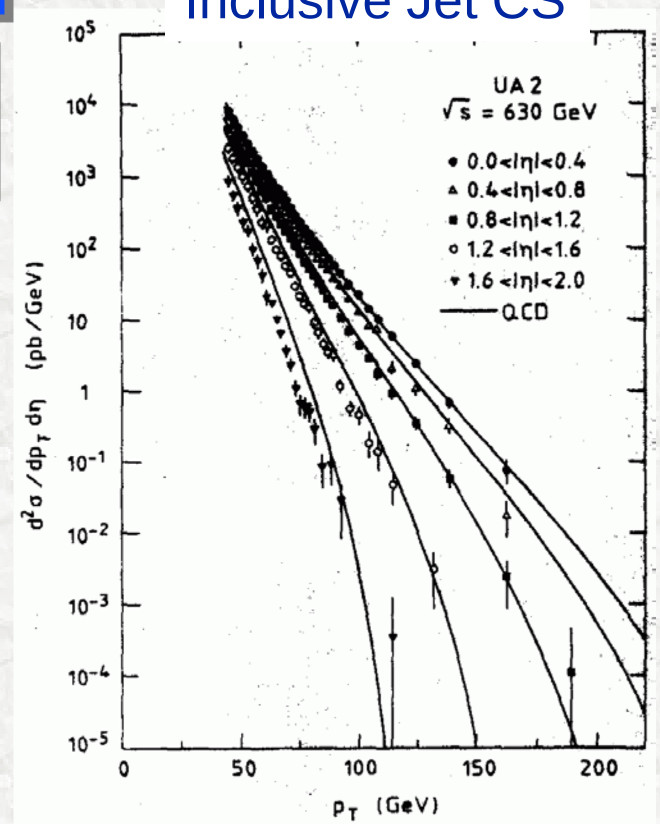
- **√s = 0.5 – 0.6 TeV**
- **Cone jet clustering**
- **P_T range: 20 – 200 GeV**
- **Comparison to LO QCD**
- **Compositeness L_C > 0.8 TeV**

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

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

State of art: 3-jet production @ NLO
(Next-to-Leading Order ~$O(\alpha_s^4)$)

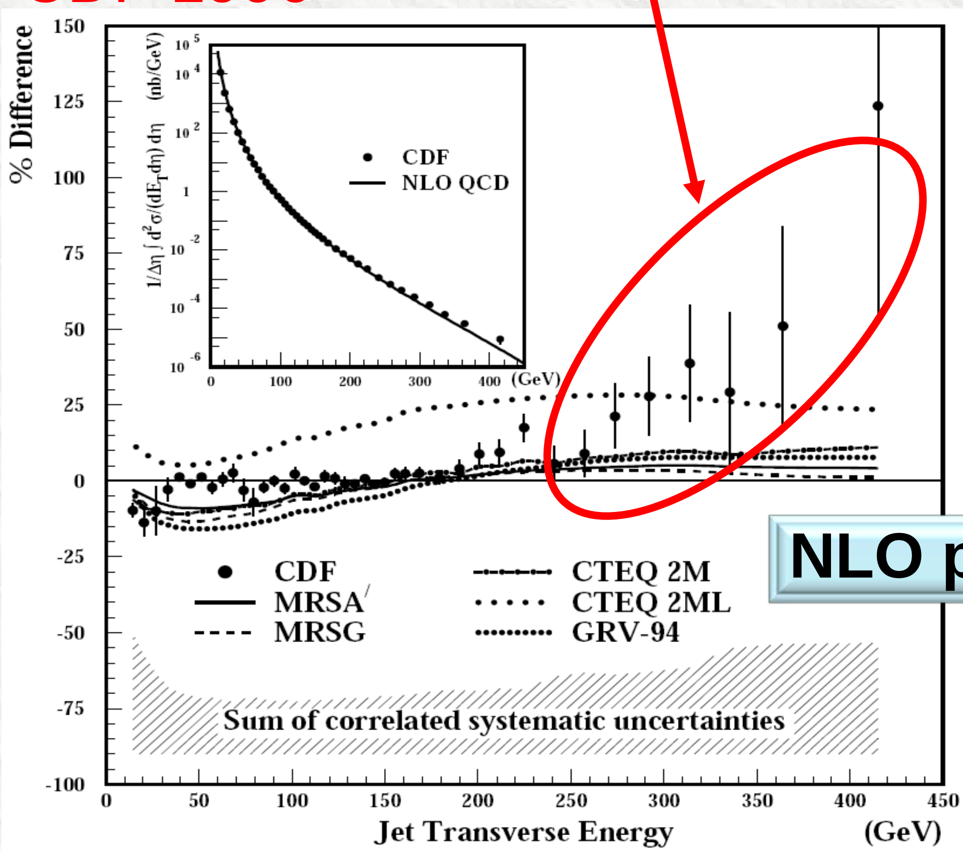
UA2 1991
Inclusive Jet CS

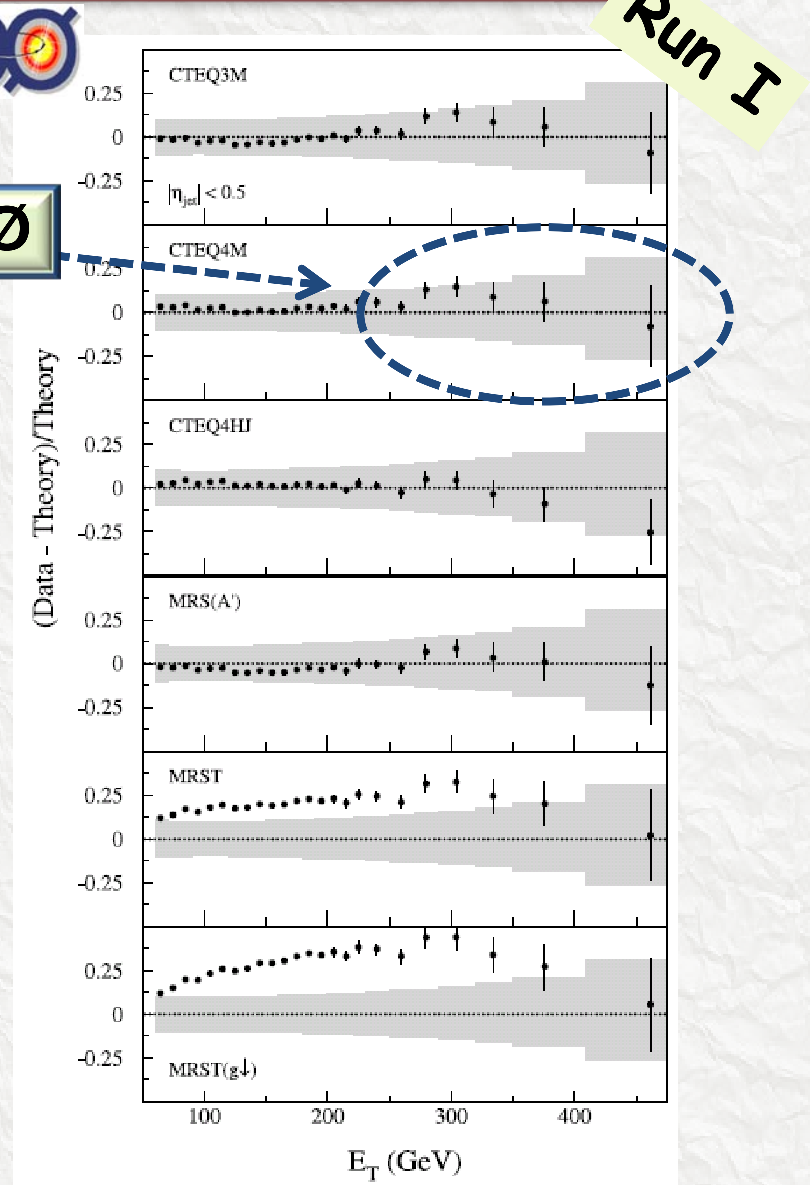


Uncertainties ~ 32% on CS:
±25% model dep. (fragmentation)
±15% jet alg/analysis params
±11% calib ±5% Lum
Λ_C > 825 GeV *"...include sys. effects which could distort the CS shape"*

Inclusive Jets – Ten Years Ago

Excess due to high-x gluon PDFs and theory parameters





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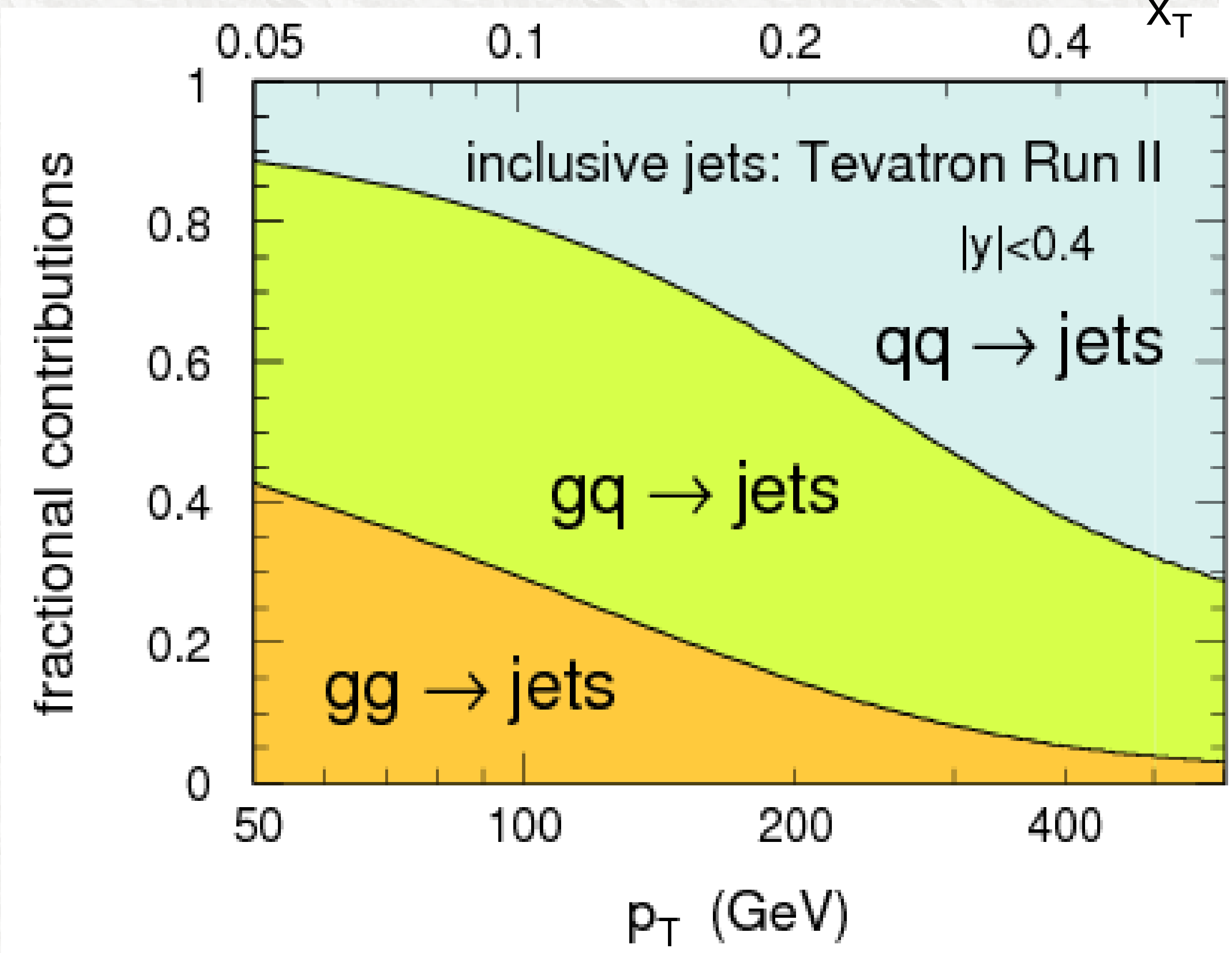
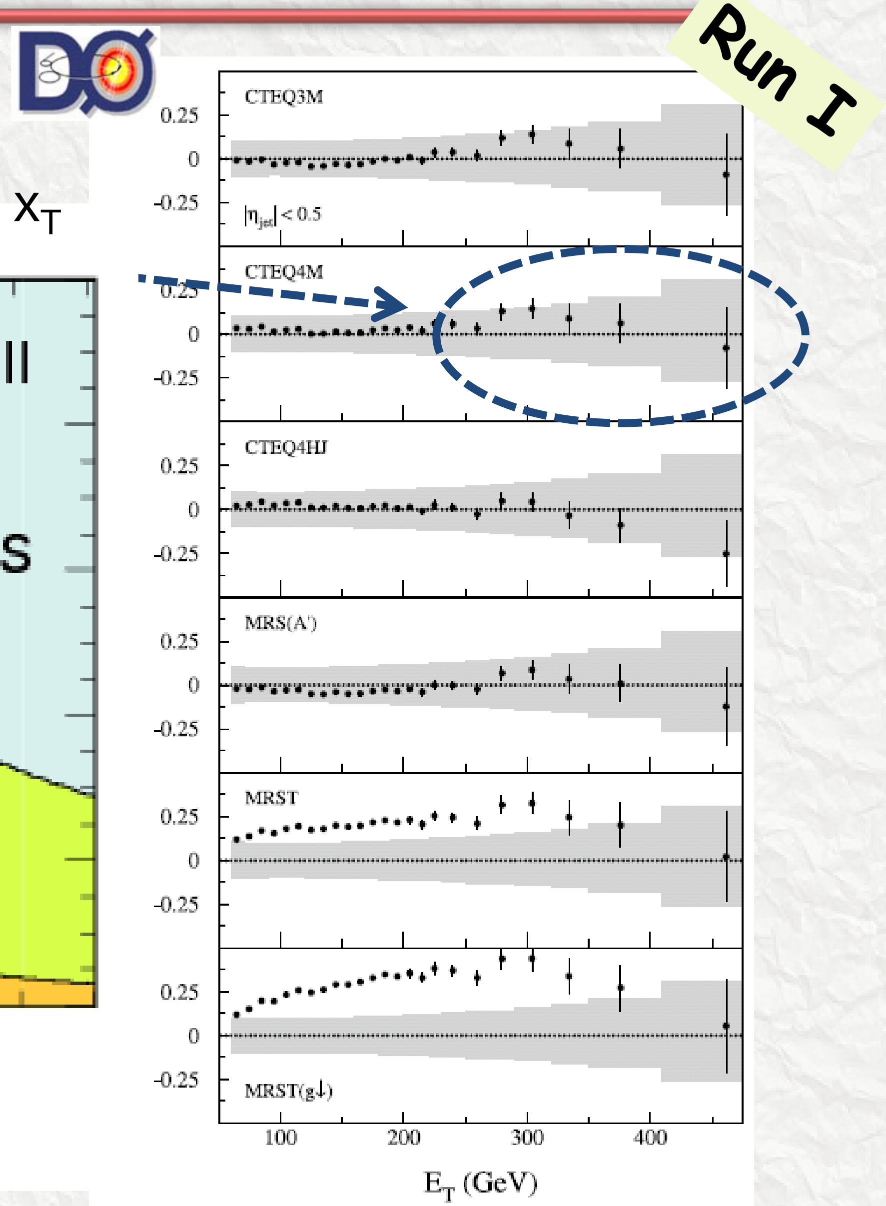
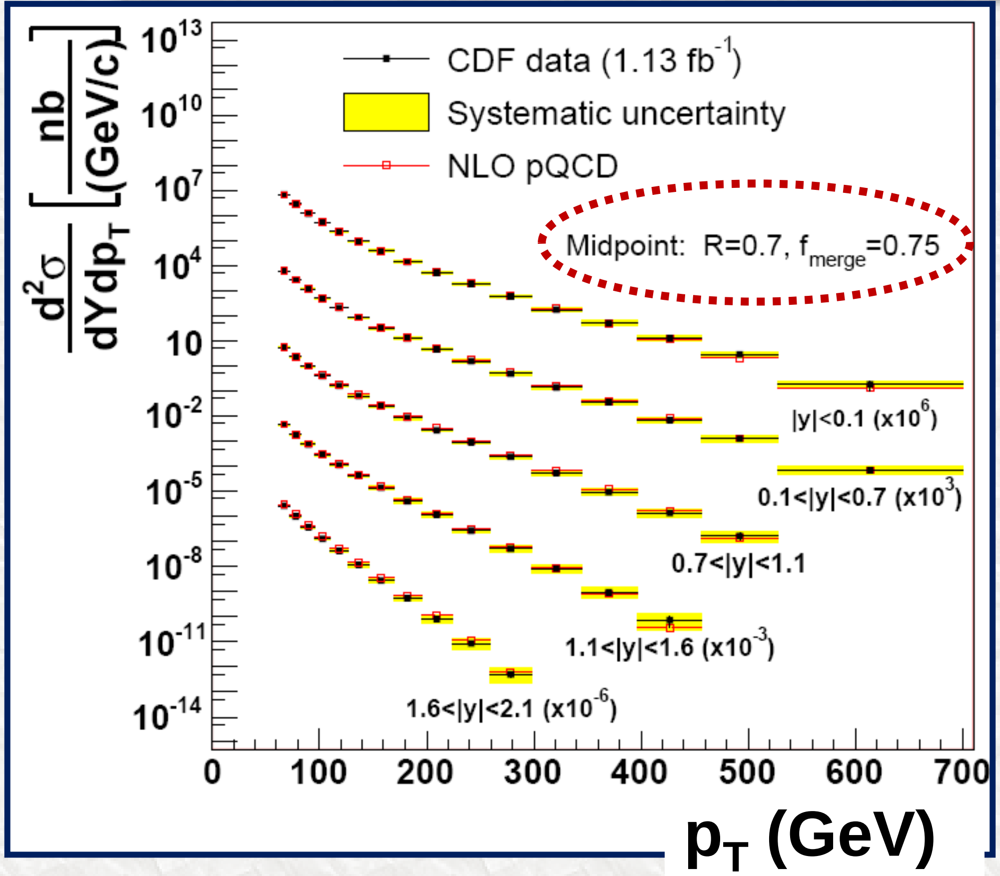
Inclusive Jets – Ten Years Ago

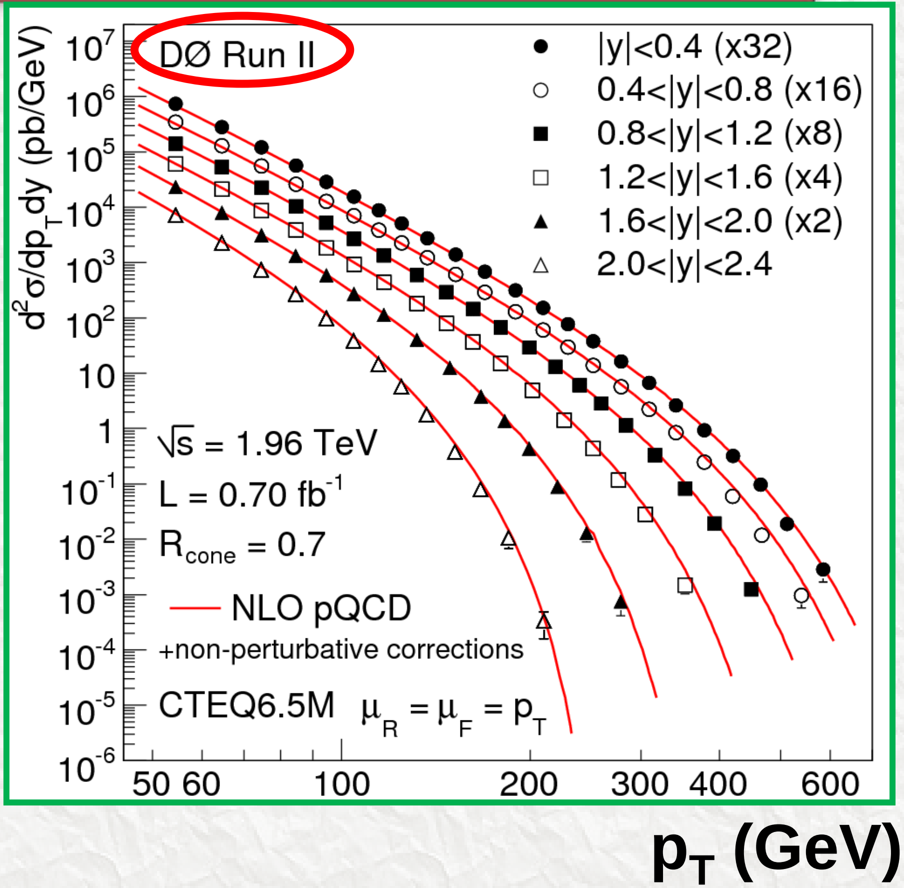
Excess due to high-x gluon PDFs and theory parameters





Inclusive Jets – Now





steeply falling pT spectrum:

1% error in jet energy calibration

→ 5—10% (10—25%)

central (forward) x-section

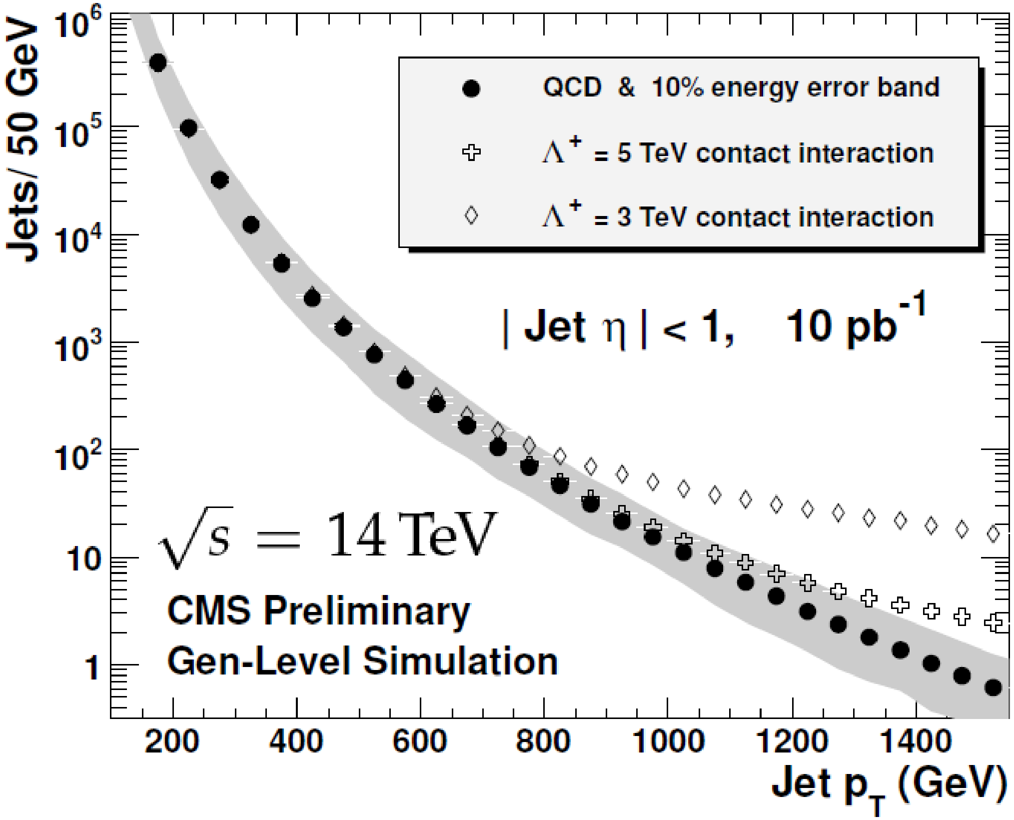
Benefit from:

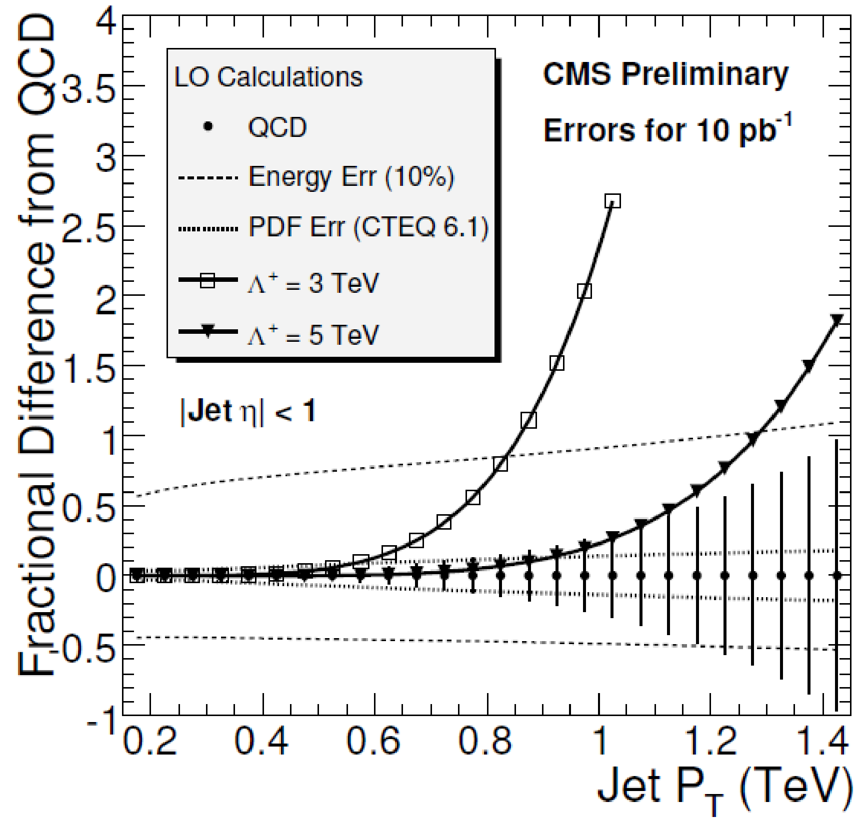
- **high luminosity in Run II**
- **increased Run II cm energy → high pT**

Jet Energy Uncertainty ~ 1%

Inclusive Jet Cross Section at CMS

CMS-SBM-07-001 & hep-ex/0807.4961





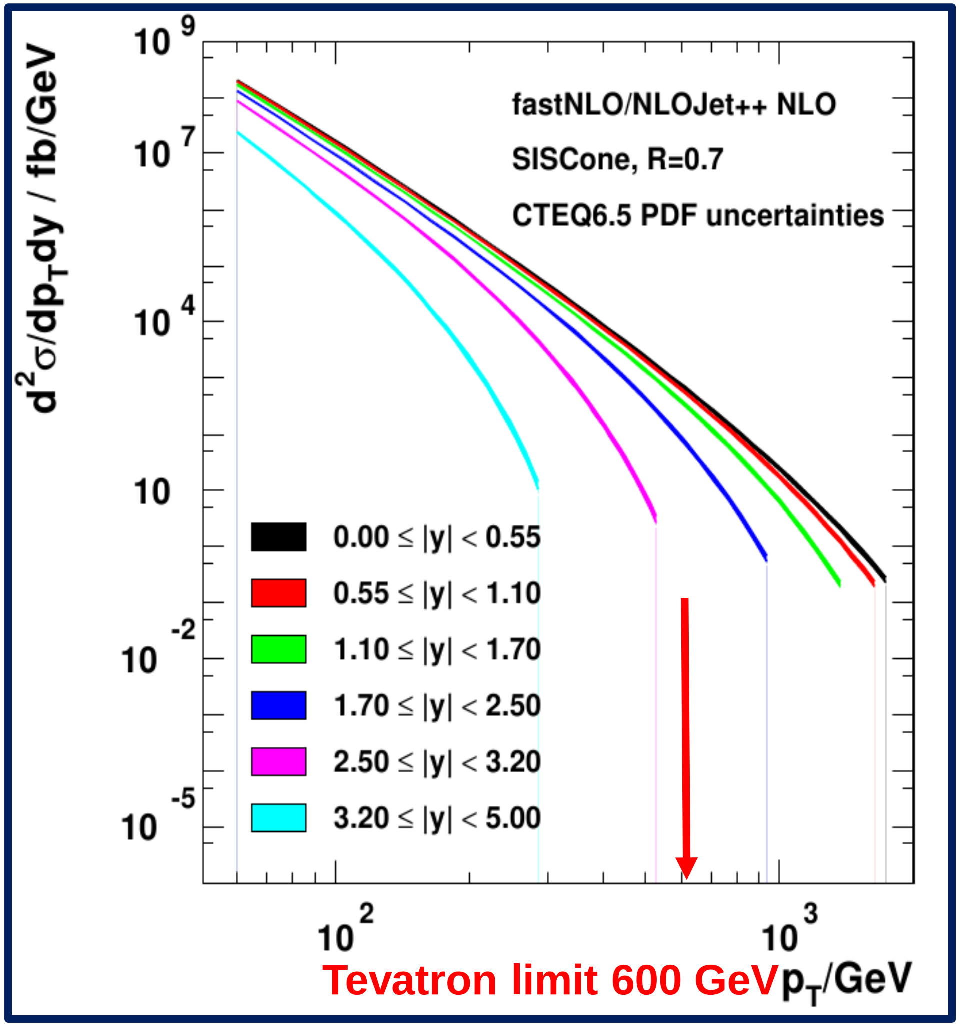
With 10 pb^{-1} at 14 TeV:

Can probe contact interactions beyond the Tevatron reach

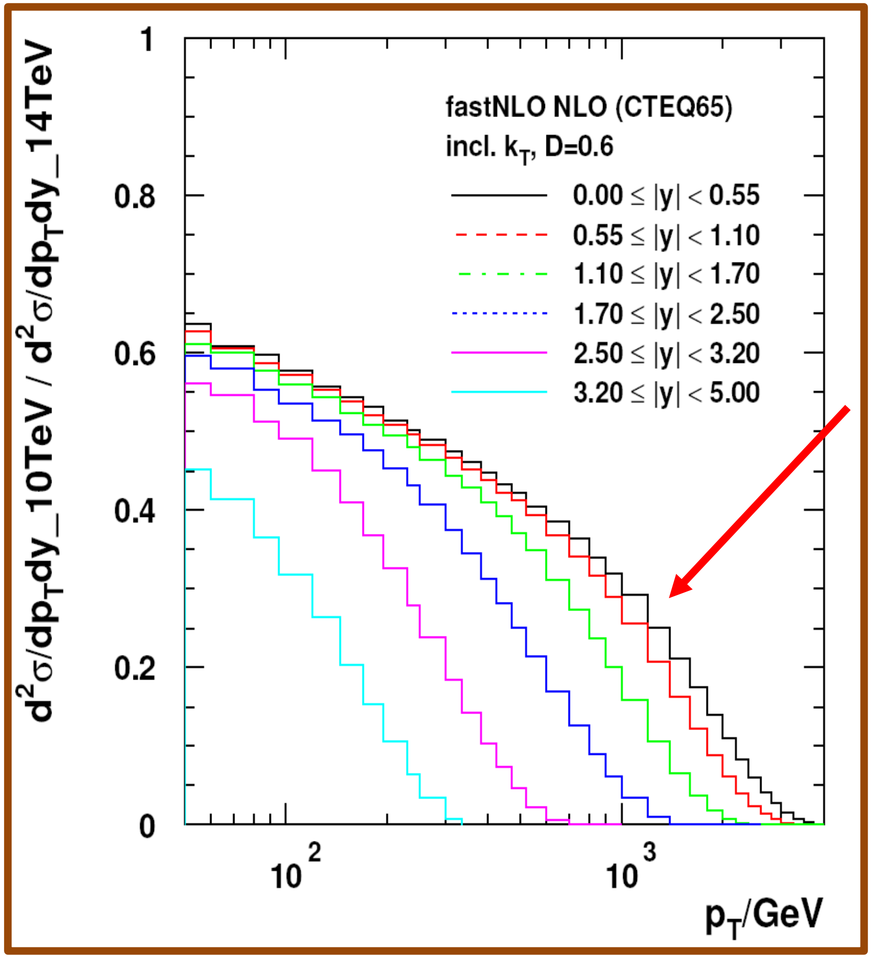
(main uncertainty: JES – assume 10% at startup, asymptotically to 1-2%)

Inclusive Jet Cross Section at CMS

SISCone, R=0.7, 10 TeV



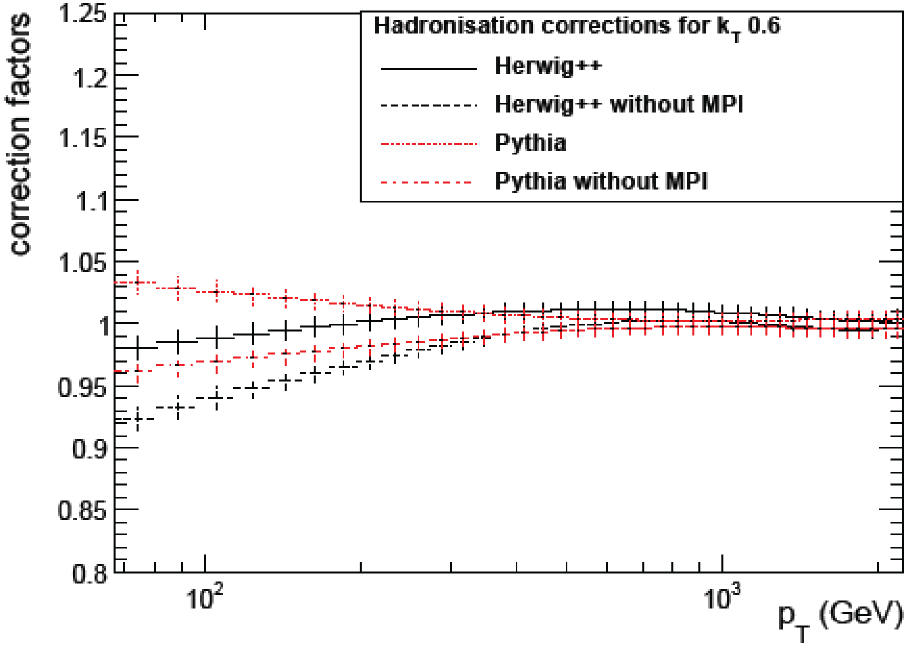
k_T 0.6 10 TeV / 14 TeV



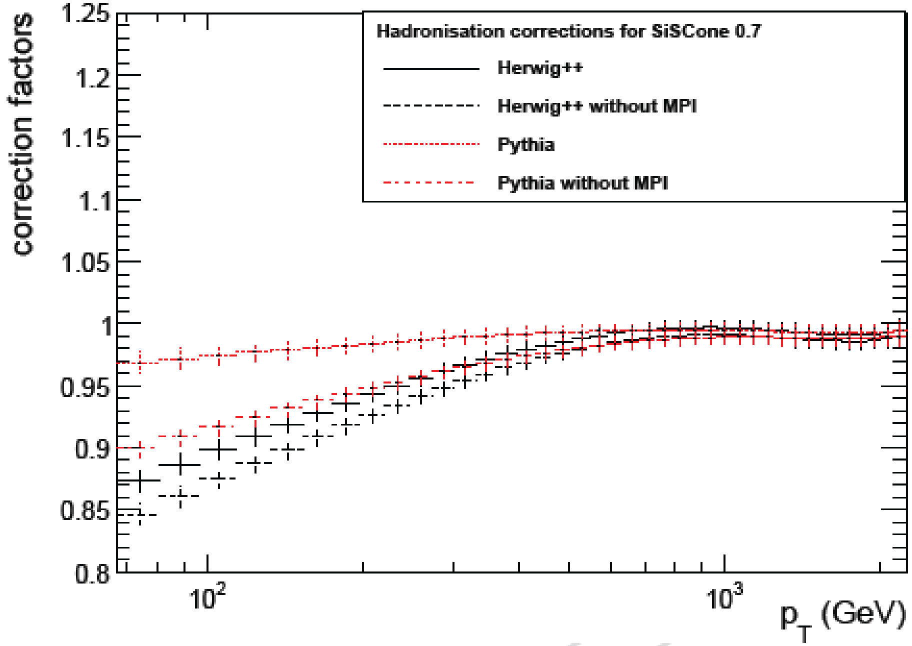
Loss in p_T reach

Inclusive Jet Cross Section at CMS

Jet Algo k_T 0.6 @ 10 TeV



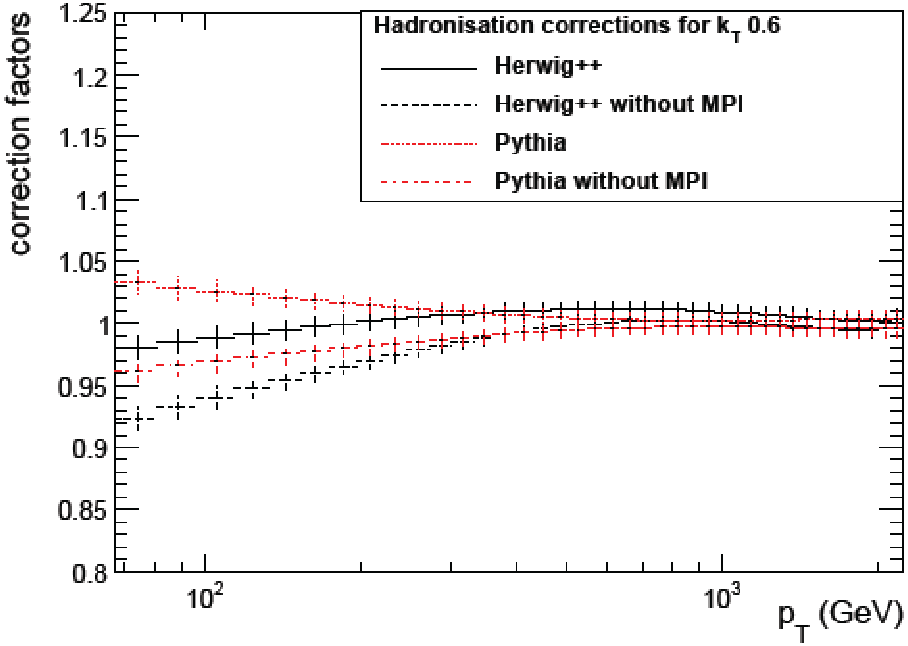
Jet Algo SISCone, R=0.7 @ 10 TeV



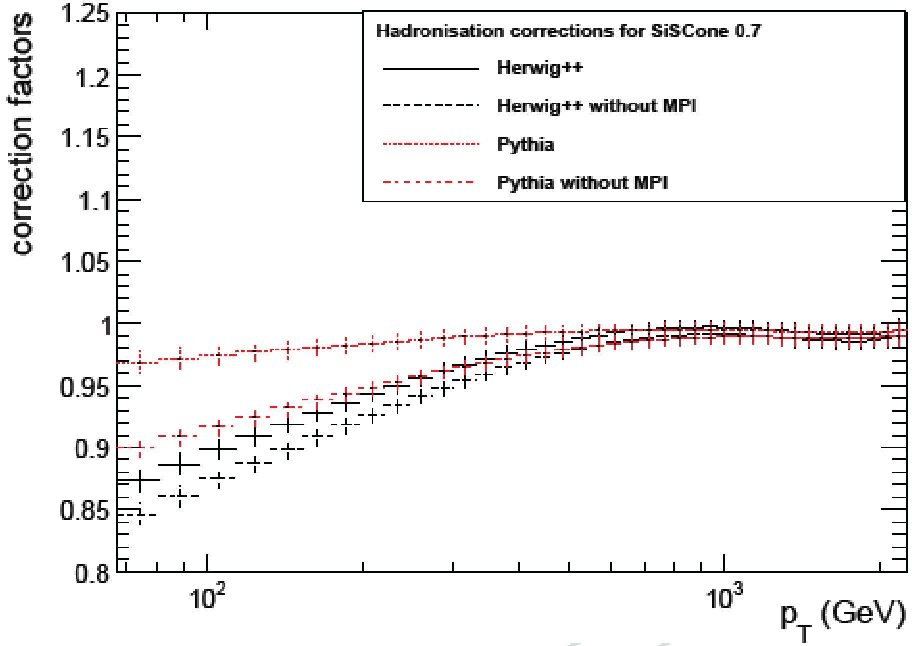
Hadronization Corrections for inclusive jet cross section

Inclusive Jet Cross Section at CMS

Jet Algo k_T 0.6 @ 10 TeV



Jet Algo SISCone, R=0.7 @ 10 TeV

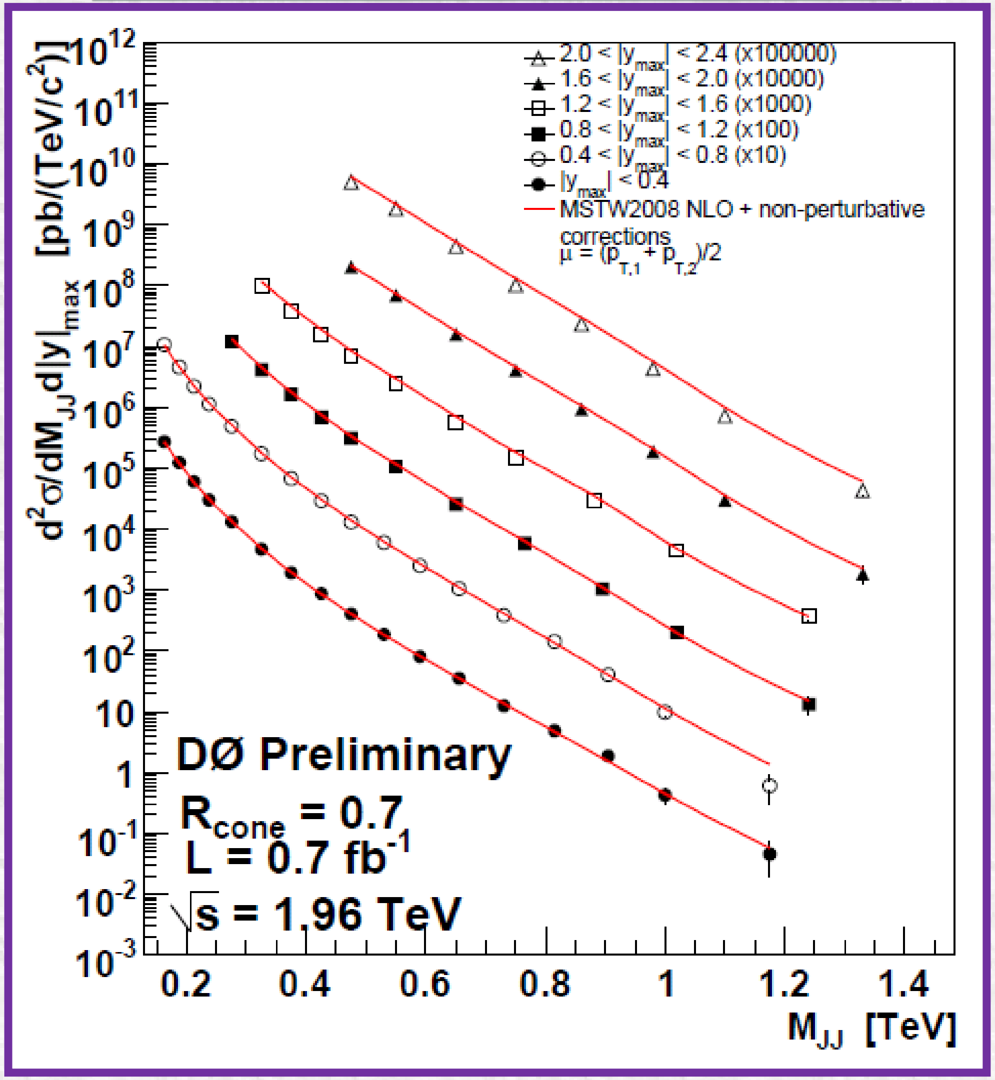


Hadronization Corrections for inclusive jet cross section

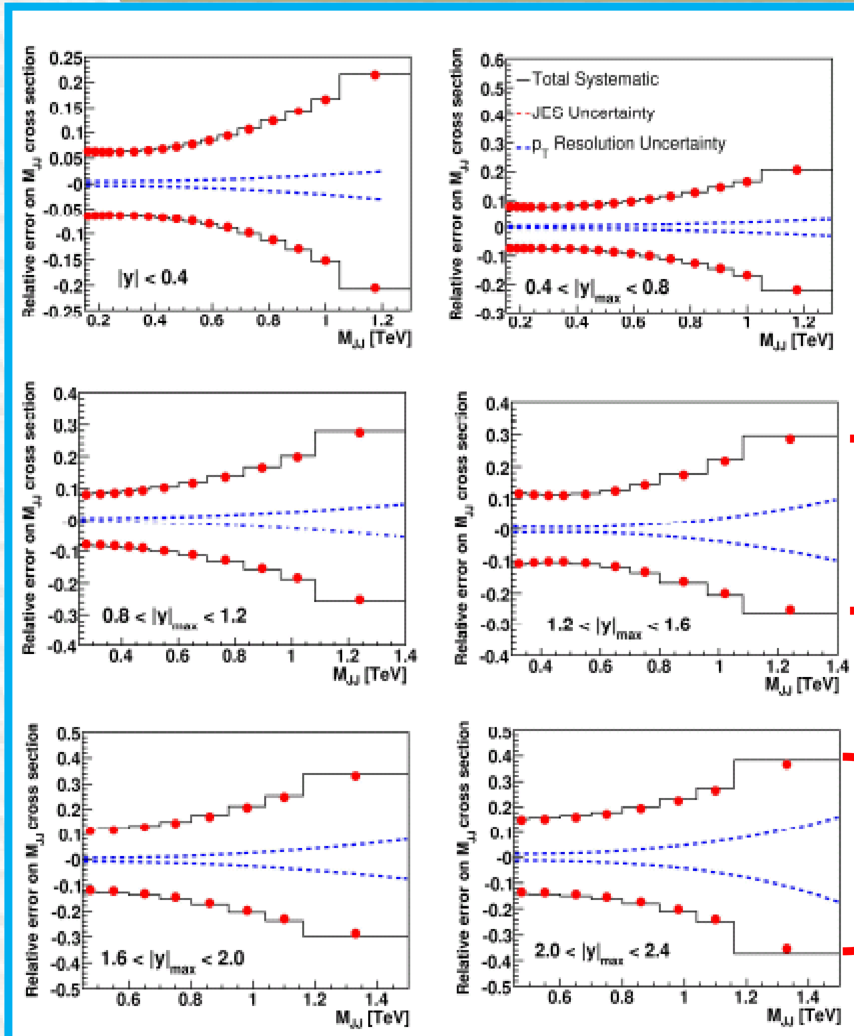
CTEQ

Dijet Mass Cross Sections

Unfolded Cross Sections



Systematic Uncertainties
(dominated by Jet Energy Scale)



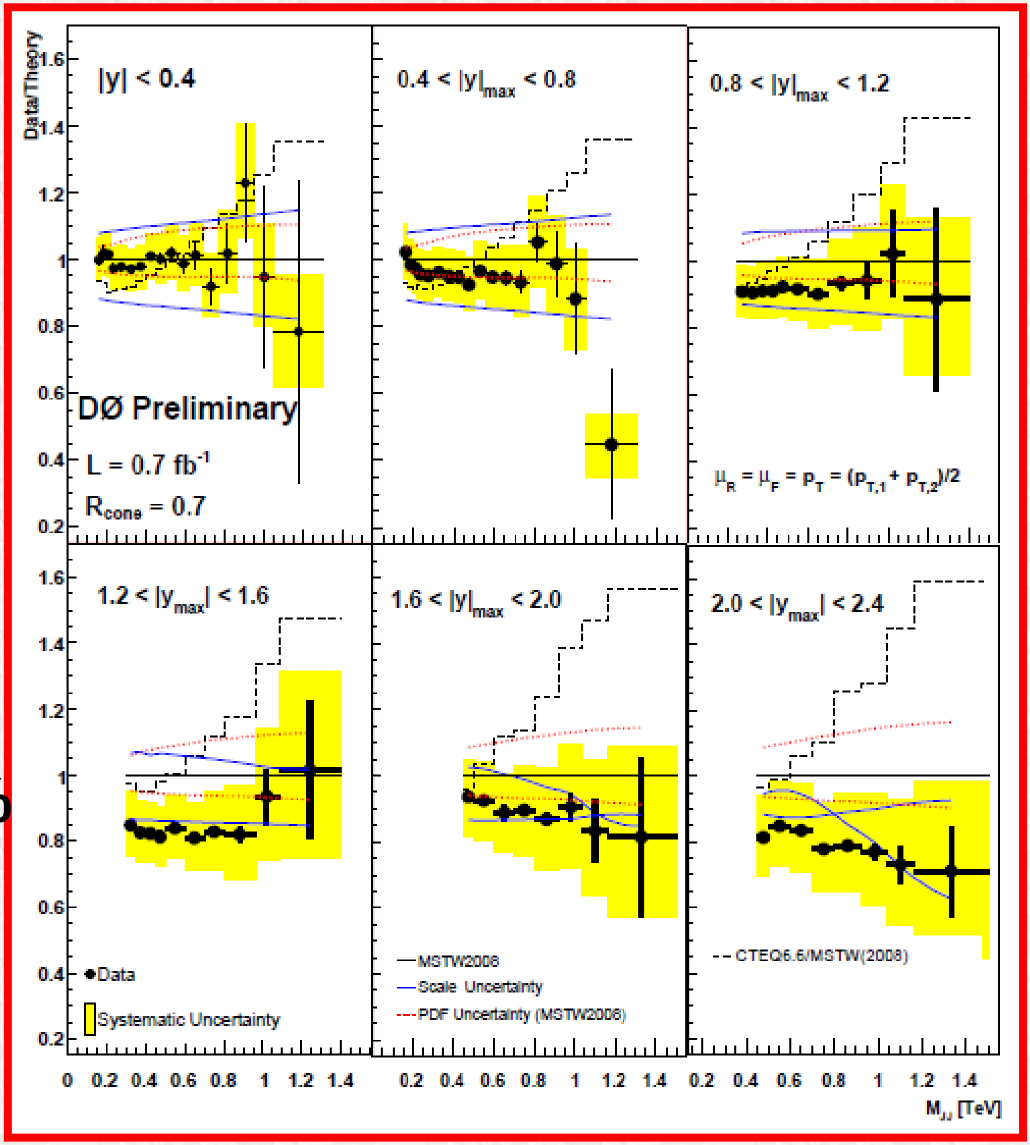
± 20%

± 30%

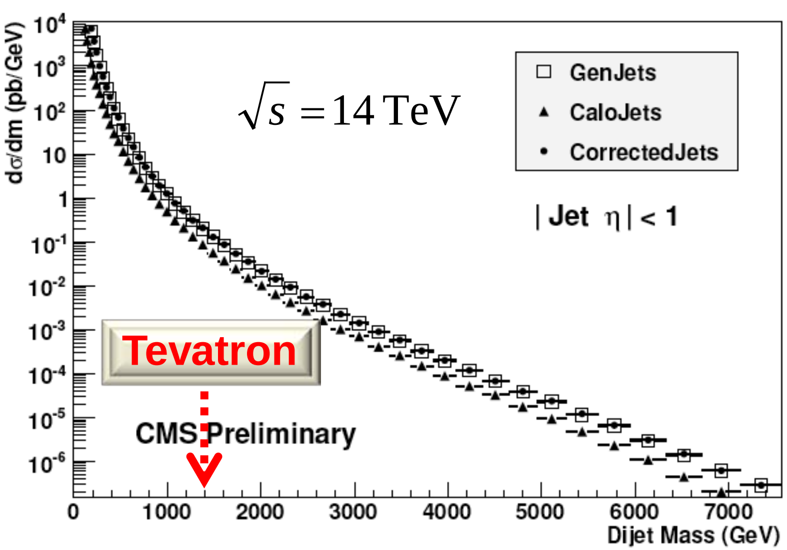
± 40%

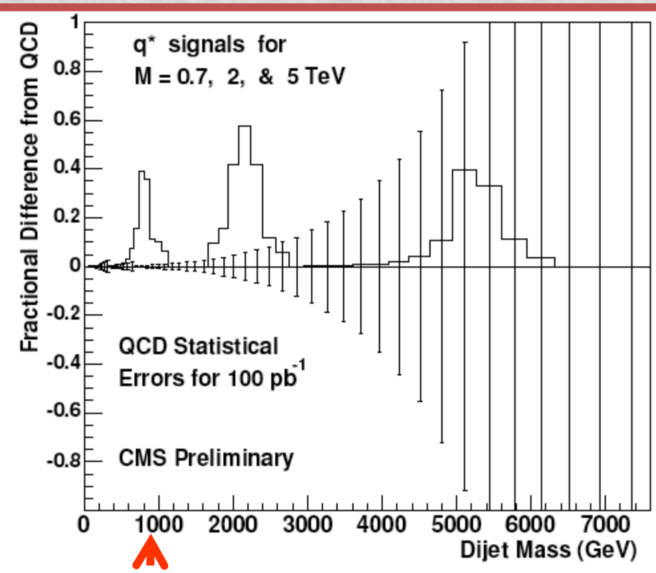
Dijet Mass: Data vs. Theory

- **Theory**
  - **NLO pQCD (NLOJET++)**
  - $\mu_R = \mu_F = \langle p_T \rangle = (p_{T1}+p_{T2})/2$
  - **PDF: MSTW2008**
  - **Hadronization+Underlying Event corrections applied to the theory (5-20%)**
- **Theory uncertainties**
  - **PDFs: (MSTW2008) 5-15%**
  - **Scale ($\langle p_T \rangle/2$–$2\langle p_T \rangle$): 10-15%**
- **Luminosity: ± 6%**
- **Good agreement with theory**

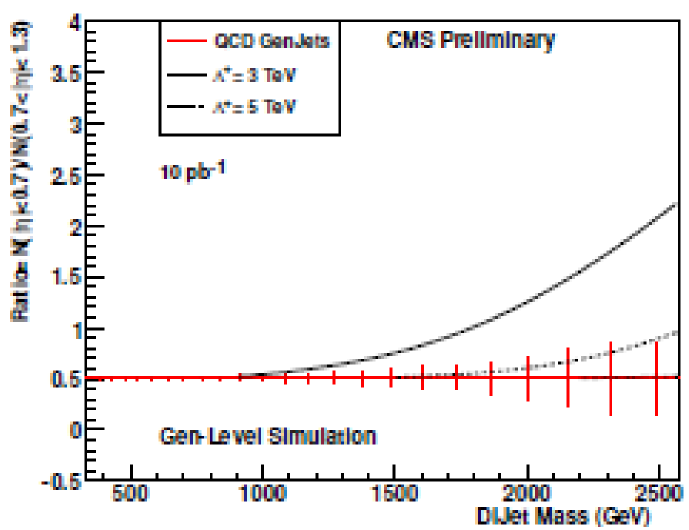


Dijet Mass Cross Section & Ratio at CMS





Tevatron Limit



With 10 pb^{-1} @ 14 TeV (~30 pb^{-1} @ 10 TeV): Can probe contact interactions up to 5 TeV

CTEQ

Summary

- Since their first observation 35 years ago, jets have provided the means to study the Standard Model and explore possibilities beyond
- Jet algorithms have matured – latest algorithms need to be validated with data @ LHC
- Jet results at the Tevatron have reached high precision
- LHC will start producing collisions this year!
- Rich QCD program at startup and beyond
- New physics might be around the corner !