Jet Physics

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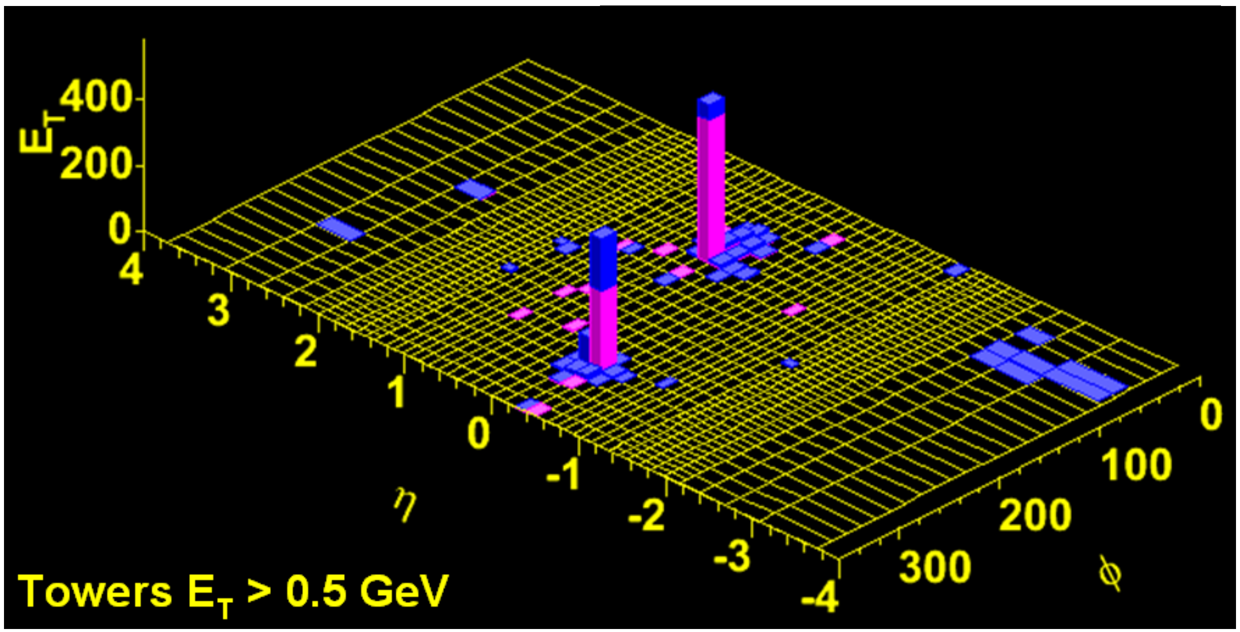
Disclaimers

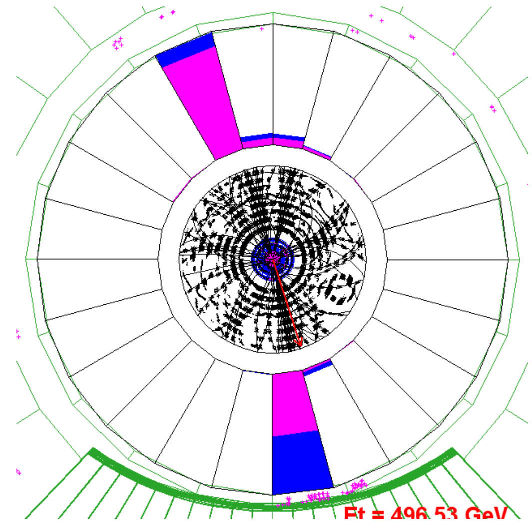
- I am an experimentalist, so I have a little more emphasis on experimental aspects and findings

- A lot of new "results" were released from LHC experiments at ICHEP 2010 in Paris about one week ago; however, since there are separate talks on early LHC results next week by Klaus Rabbertz and Jan Fiete Grosse-Oetringhaus, I will not talk about them extensively

- Although very interesting, I will not discuss jet physics in heavy ion collisions due to time constraints

What Are Jets?





$$p\bar{p} \rightarrow jet + jet + anything$$

A collimated spray of particles originating from hard scattered partons

QCD

See lecture by Dr. Olness

- The non-abelian SU(3) gauge theory of the strong interaction
- Similar to QED, but there are important differences.
  - QED Lagrangian

$$L_{QED} = \bar{q}(i\gamma^{\mu}\partial_{\mu} - m)q + e\bar{q}\gamma^{\mu}A_{\mu}q - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \qquad F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$$

$(A_{\mu}$: *photon field*)

  - QCD Lagrangian

$$L_{QCD} = \bar{q}_a(i\gamma^{\mu}\partial_{\mu} - m)q_b - g(\bar{q}_a\gamma^{\mu}T_A q_b)G_{\mu}^{A} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu},$$

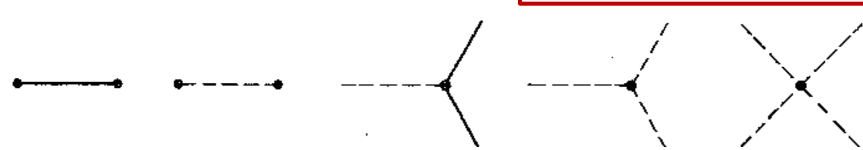
$$G_{\mu\nu}{}^{A} = \partial_{\mu}G_{\nu}{}^{A} - \partial_{\nu}G_{\mu}{}^{A} \boxed{+ g f_{ABC}G_{\mu}{}^{B}G_{\nu}{}^{C}} \quad (G_{\mu}{}^{A} : \textit{gluon field})$$

$[a, b = 1,2,3$ (*quark color charges*), $\quad A, B, C = 1,\ldots,8$ (*gluon color charges*)$]$

This non-abelian term distinguishes QCD from QED
(introduces triplet and quartic gluon self-interactions)

$$(L_{QCD} = "\bar{q}q" + "G^2" + g"\bar{q}qG" + \boxed{g"G^3" + g^2"G^4"})$$

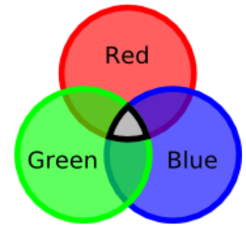
Gluon self interactions



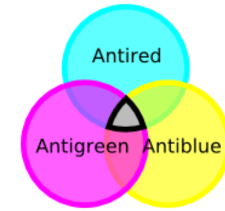
QCD

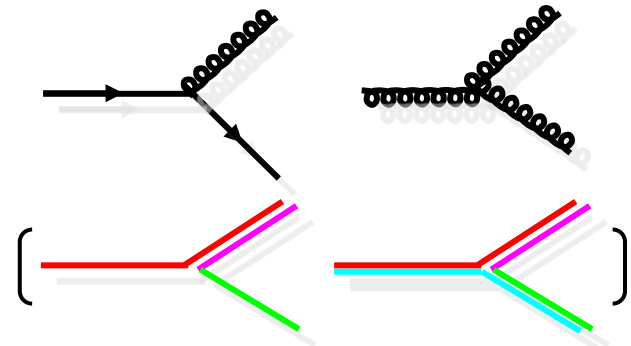
- There are three color charges (c.f. one electric charge in QED)
  - Quarks carry one color charge
  - Gluons carry one color charge and one anti-color charge (c.f. photons do not carry electric charge)
    - Gluons have self-interactions (c.f. photons do not)
    - Color charge is conserved at all vertices
  - Gluon self-interaction leads to "anti-screening" of color charge (c.f. electric charge screening)
    - A quark can emit gluons, and gluons can make a quark loop or gluon loop
    - Spread out original quark color (color cloud) $\rightarrow$ confinement and asymptotic freedom
    - **Both features important to describe jets**

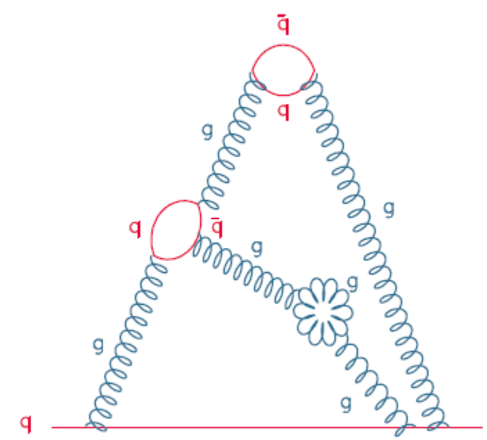
quark colors



quark anticolors

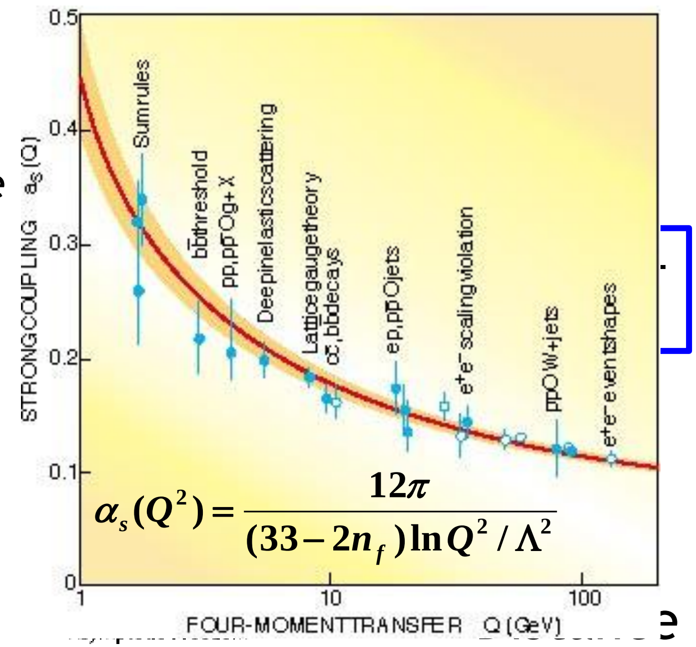






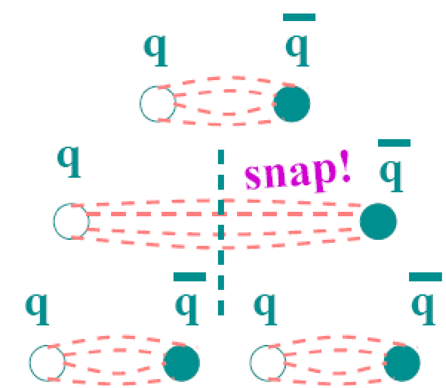
Basic Aspects of QCD

- **Asymptotic freedom**
  - A test charge inside the color "cloud" will experience smaller force than at large distance
  - At small distances, quarks can interact through color fields of reduced strength and asymptotically behaves as free particles
    - The coupling constant α_s decreases at small distances
    - Applicability of perturbation theory



- **Confinement**
  - The energy injected into a hadron does not separate the quarks but goes into creating qqbar pairs, and hence hadrons

    $\rightarrow$ answer the non-observation of free quarks
  - Origin of jets: partons from hard scatter evolve via radiation and hadronization processes to form a "spray" of collinear hadrons (limited k_T relative to "jet" axis)

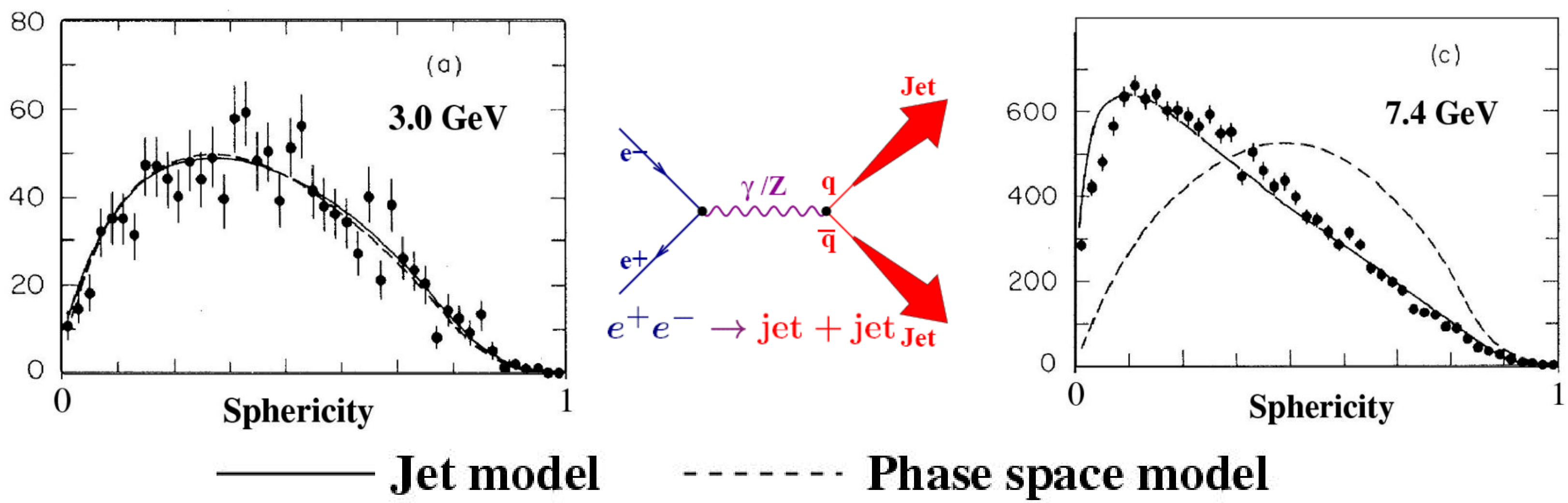


Observation of Quark Jets

- First evidence of jets arising from quarks in e+e- $\rightarrow$ qq events was obtained at the SPEAR e^+e^- collider in 1975.
- Use "sphericity": $S = 3(\sum_i p_{\perp,i}^2)_{\min} / (2\sum_i p_i^2)$

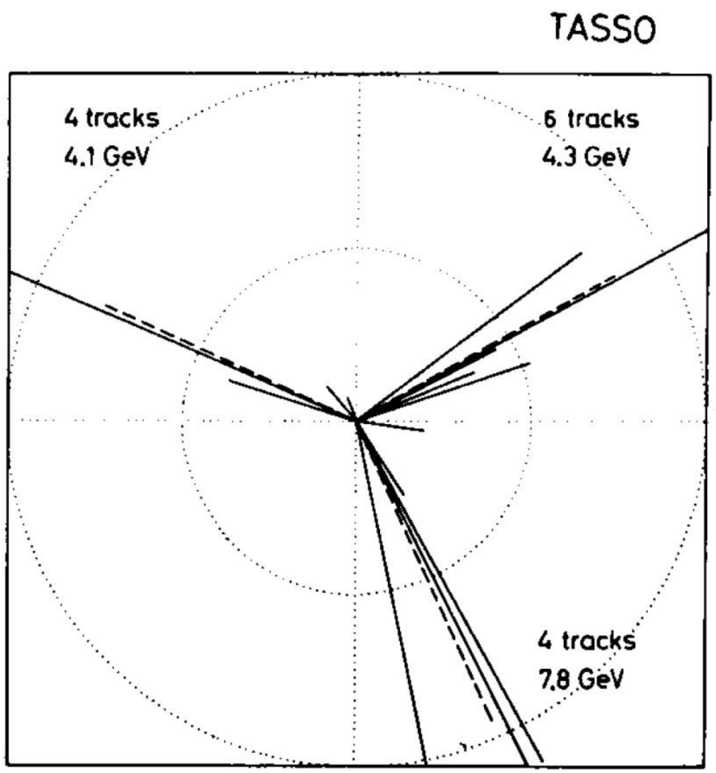
  Jet like: S=0
  Isotropic: S~1
- QCD predicts that, as the cms energy increases, events should become more jet-like; sphelicity should peak toward lower S values

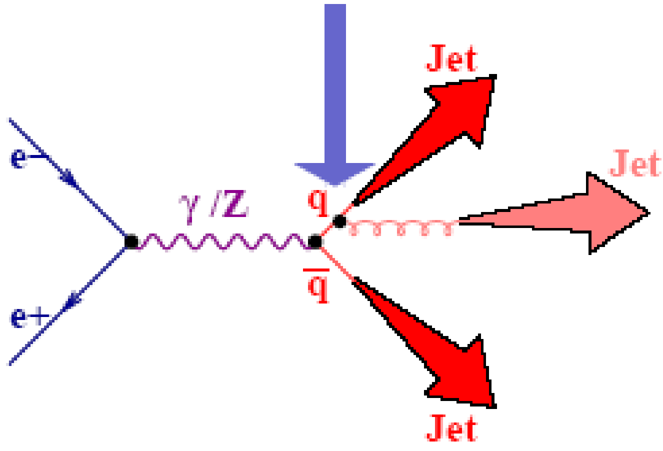
G. Hanson et al. (MARK-I Collaboration), PRL 35 (1975) 1609



Observation of Gluon Jets

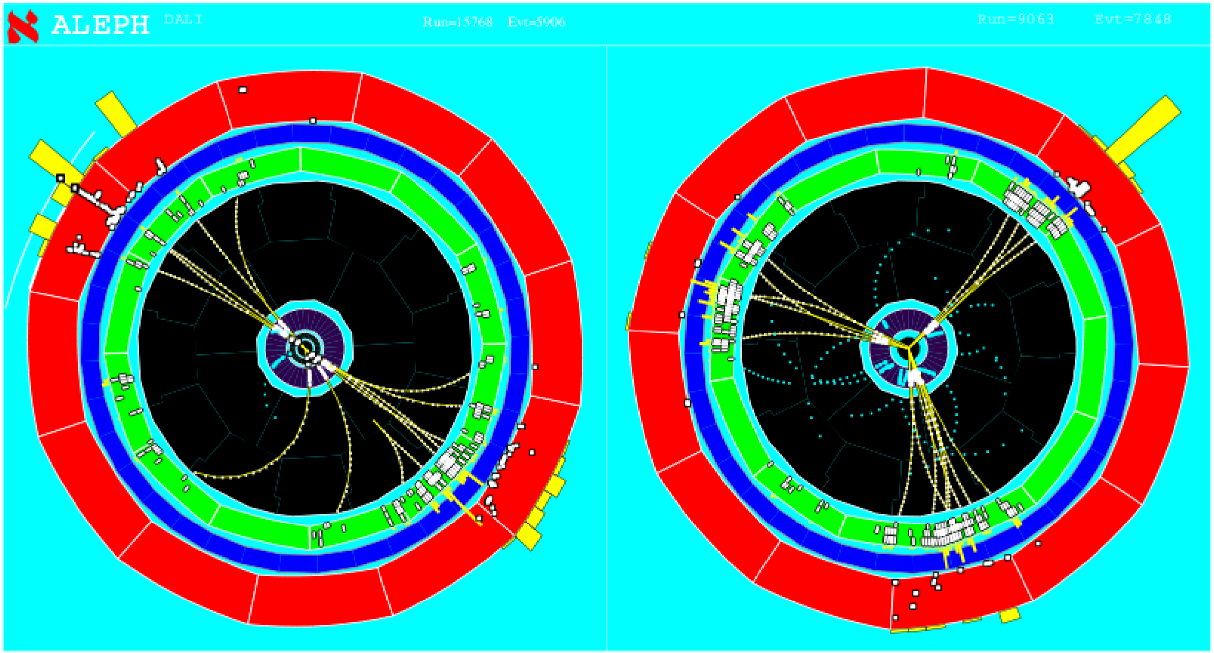
TASSO [PETRA] PLB(1979)243; MARK-J [PEP] PRL43(1979)830;
PLUTO [PETRA] PLB86(1979)418; JADE [PETRA] PLB91(1980)142
e^+e^- at E_{cm} = 13 – 32 GeV





1st three-jet event from TASSO

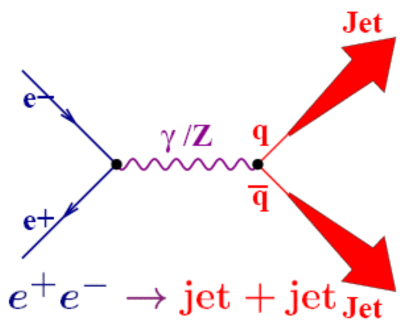
Jets in e^+e^- Annihilations



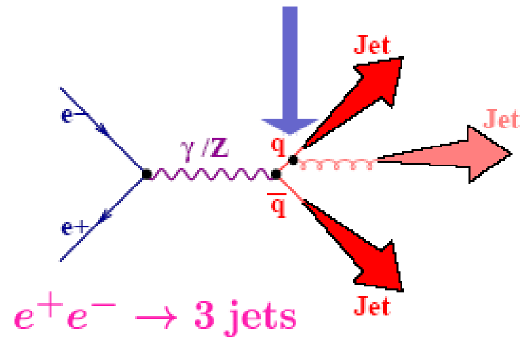
$e^+e^- \to jet + jet$ $e^+e^- \to jet + jet + jet$

- e^+e^- events are clean
  - No initial state QCD radiation
  - No beam remnant
  - No multiple interaction
- Played a critical role in establishing QCD

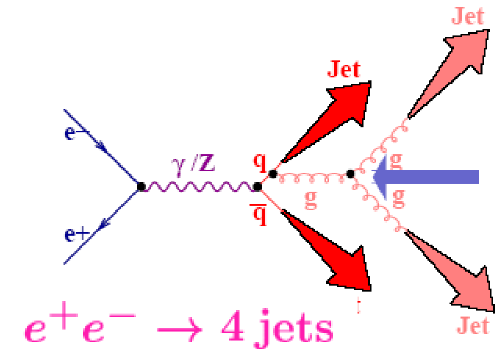
Why Study Jets in e^+e^-?



Determine quark spin

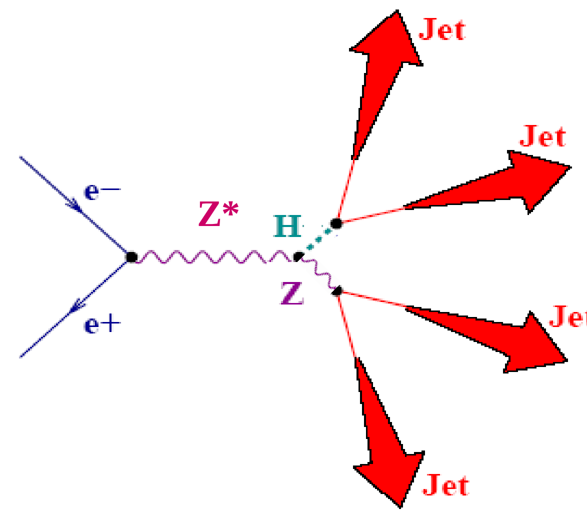


Measure a_s,
Determine spin of gluon



Study non-abelian
structure of QCD

- QCD Studies
  - Spin of quarks and gluons
  - SU(3) gauge structure of QCD, color factors, triple-gluon vertex
  - Measurements of a_s
  - Quark & gluon jet properties/differences
  - Fragmentation functions
- Search for the Higgs and new physics



Search for Higgs

Jets in e⁺e⁻: Spin of the Quark

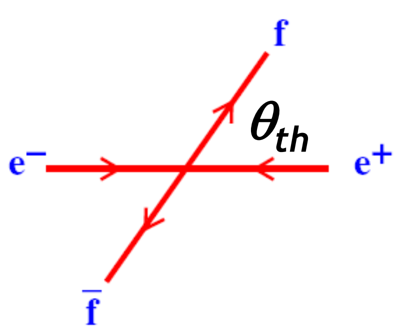
- The quark spin can be inferred from the angular distributions of the "thrust axis" (~direction of jets)
  - Thrust is another event shape variable used in e^+e^- analyses
  - Thrust axis: maximize $\Sigma|p_{i,\,\text{parallel}}|$

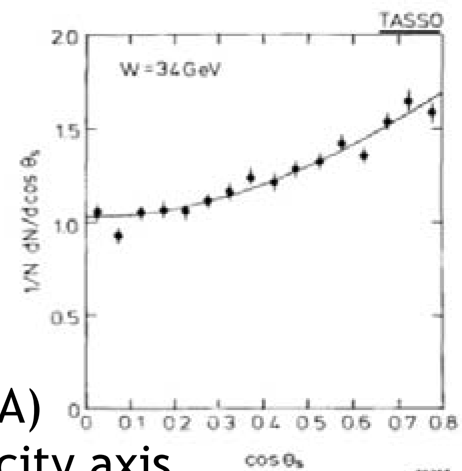
$$T = \max\left(\frac{\Sigma \vec{p}_i \cdot \vec{n}_T}{|\Sigma \vec{p}_i|}\right)$$

$$\frac{d\sigma}{d\cos\theta_{th}} \propto 1 + \alpha\cos^2\theta_{th}$$

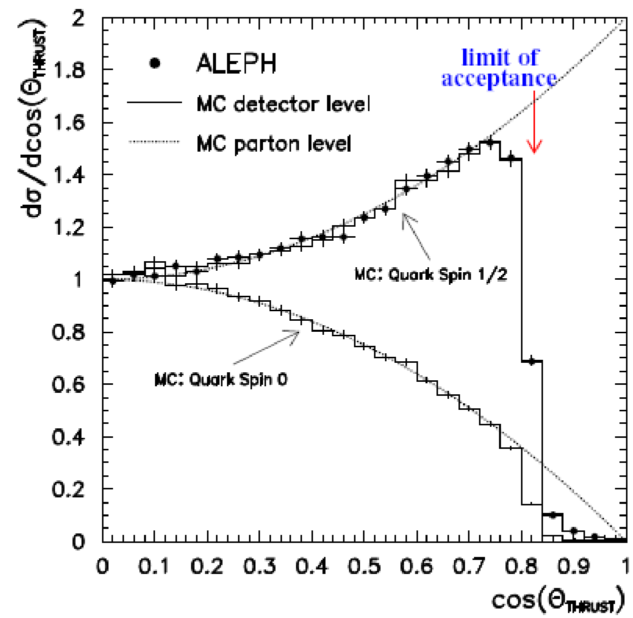
$\rightarrow$ spin-1/2 quarks: $\alpha = +1$

$\rightarrow$ spin-0 quarks: $\alpha = -1$



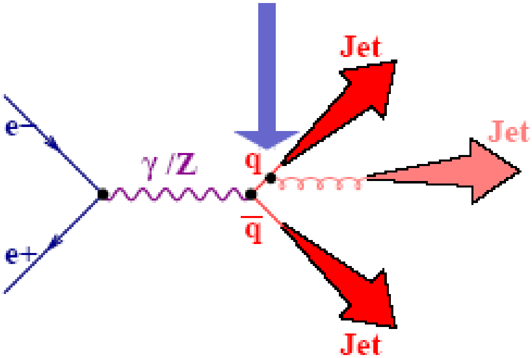


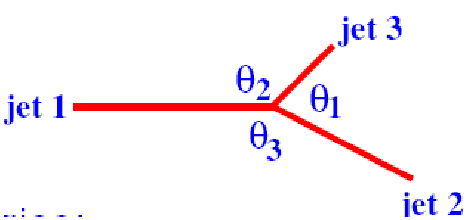
TASSO (PETRA)
1984: Sphericity axis

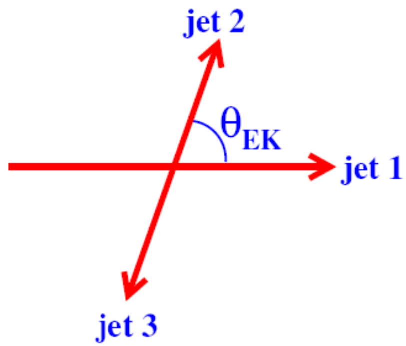


Jets in e^+e^-: Spin of the Gluon

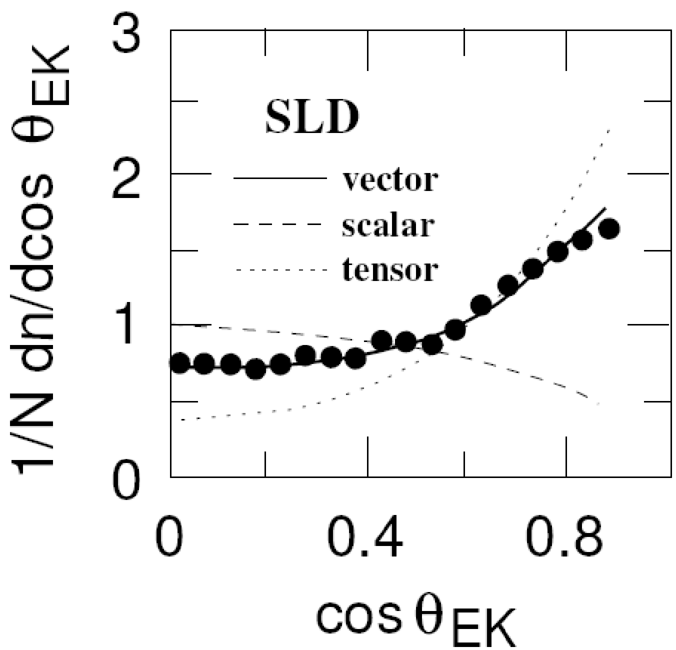
- Study 3-jet events:
  - Order jets in decreasing E_i
    - Third jet more likely to be the radiated gluon
  - Angle θ_{EK} between axis of (2,3) relative to 1 in the frame where 2 & 3 are back-to-back (Ellis-Karliner angle) sensitive to gluon spin



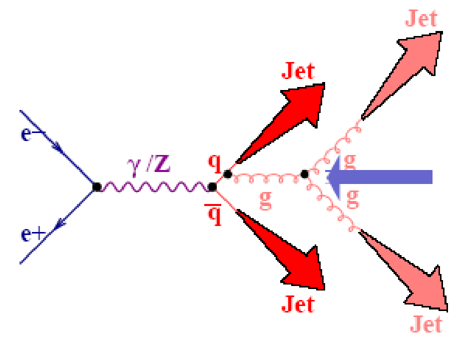




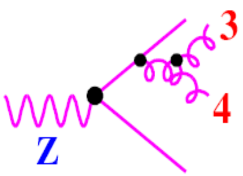
Boost along jet 1 to the frame where jets 2 & 3 are back–to–back



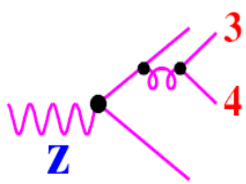
Jets in e$^+$e$^-$: Three Gluon Vertex

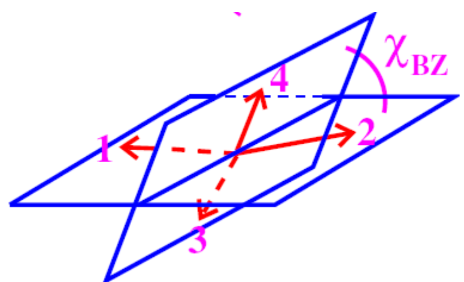


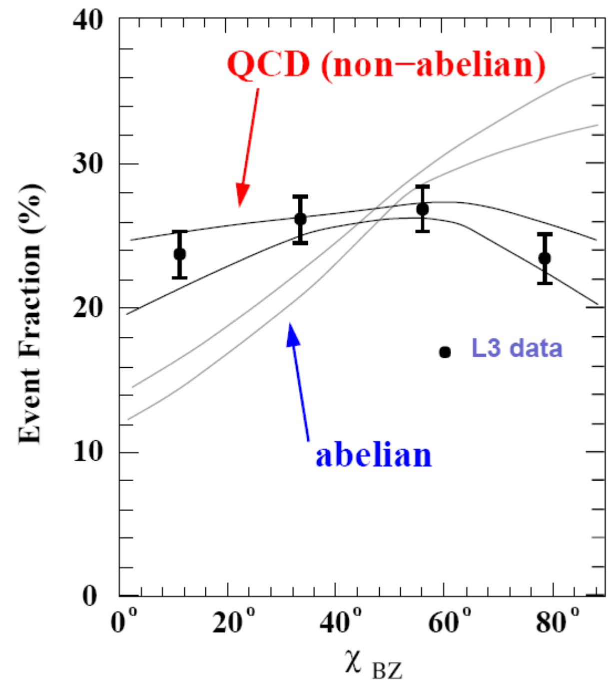
- Study 4-jet events:
  - Order jets in decreasing E_i
    - Jets 3 & 4 more likely to be "radiated" jets
    - Angle χ_{BZ} between planes spanned by (1,2) & (3,4) (Bengtsson-Zerwas angle) sensitive to the three-gluon vertex



VERSUS



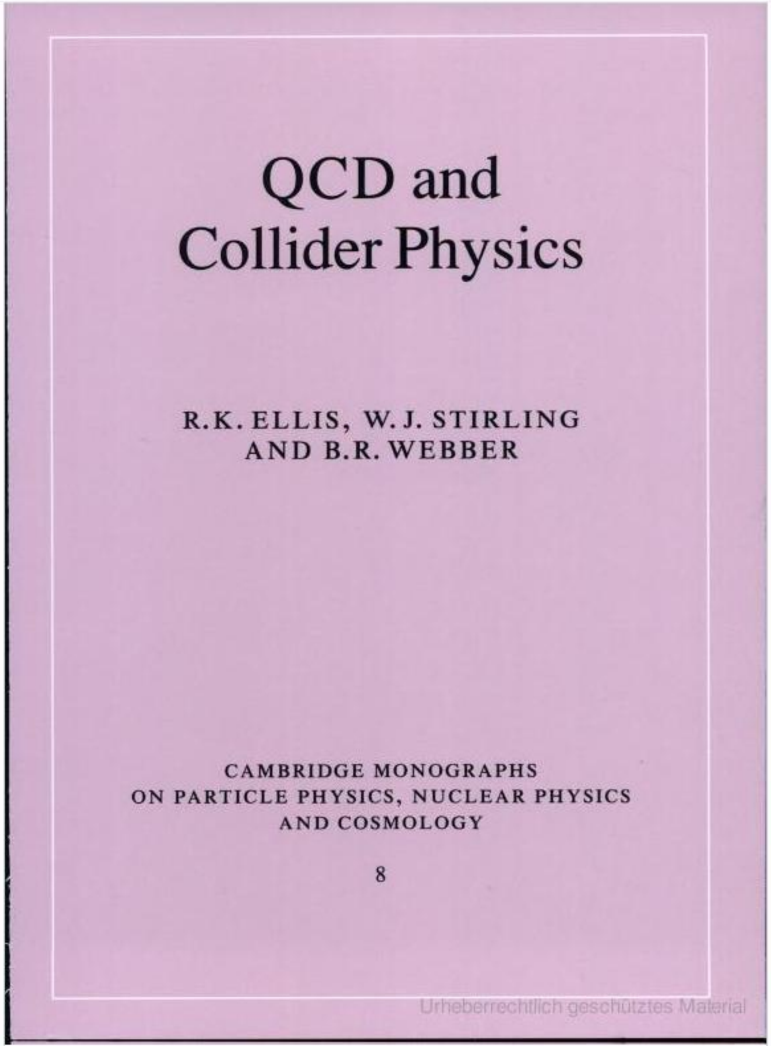




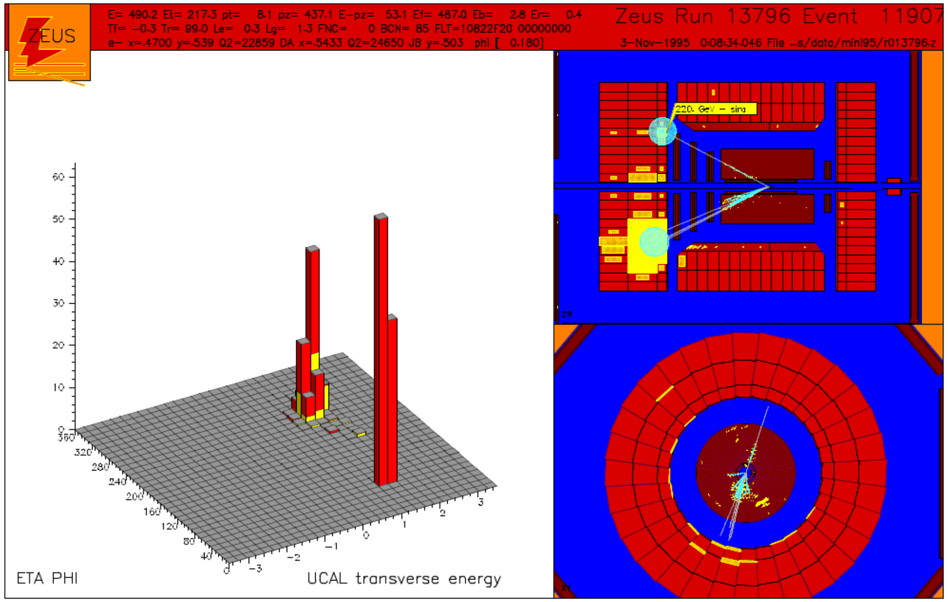
- Full analysis of angular distributions allows determination of contributions from different diagrams
  - Confirm SU(3) gauge group structure of QCD

References

- You can find a lot more interesting jet physics studies from e^+e^- in:

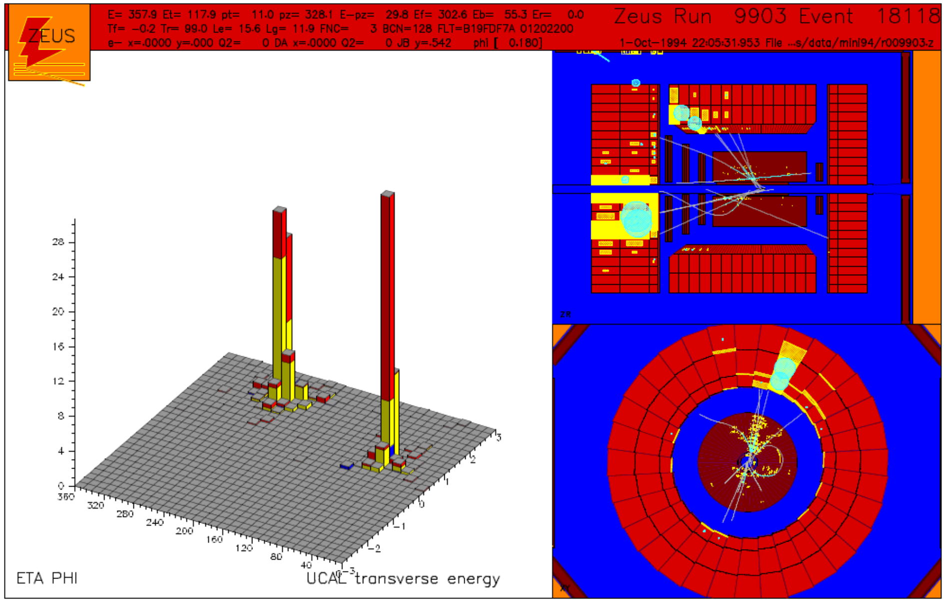


Jet Production in ep Collisions



$$ep \rightarrow e + jet + anything$$

(NC DIS)

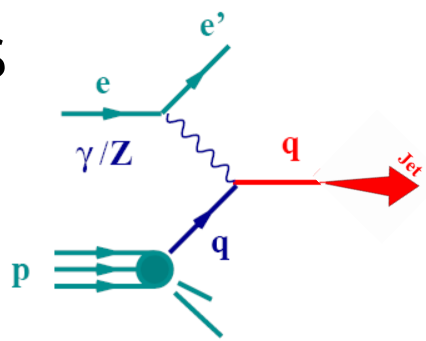


$$\gamma\, p \rightarrow jet + jet + anything$$

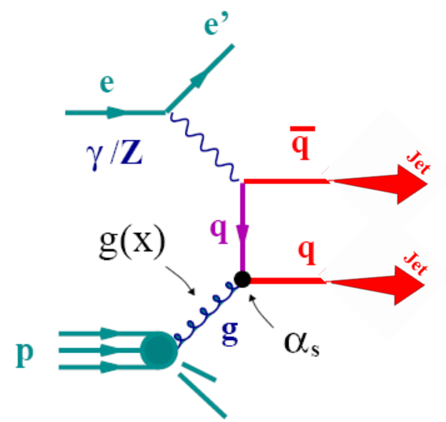
(Photoproduction)

Why Study Jets in ep Collisions?

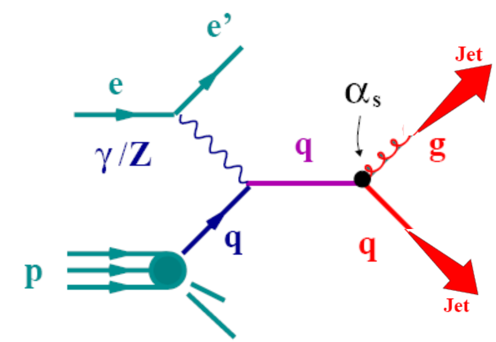
NC DIS



Born Process

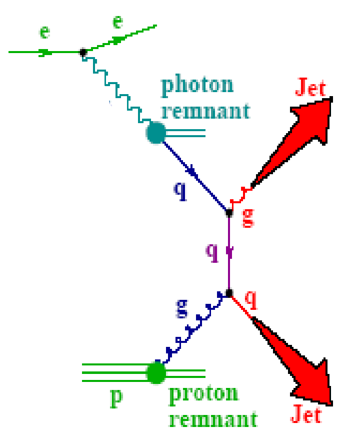


Boson-Gluon Fusion



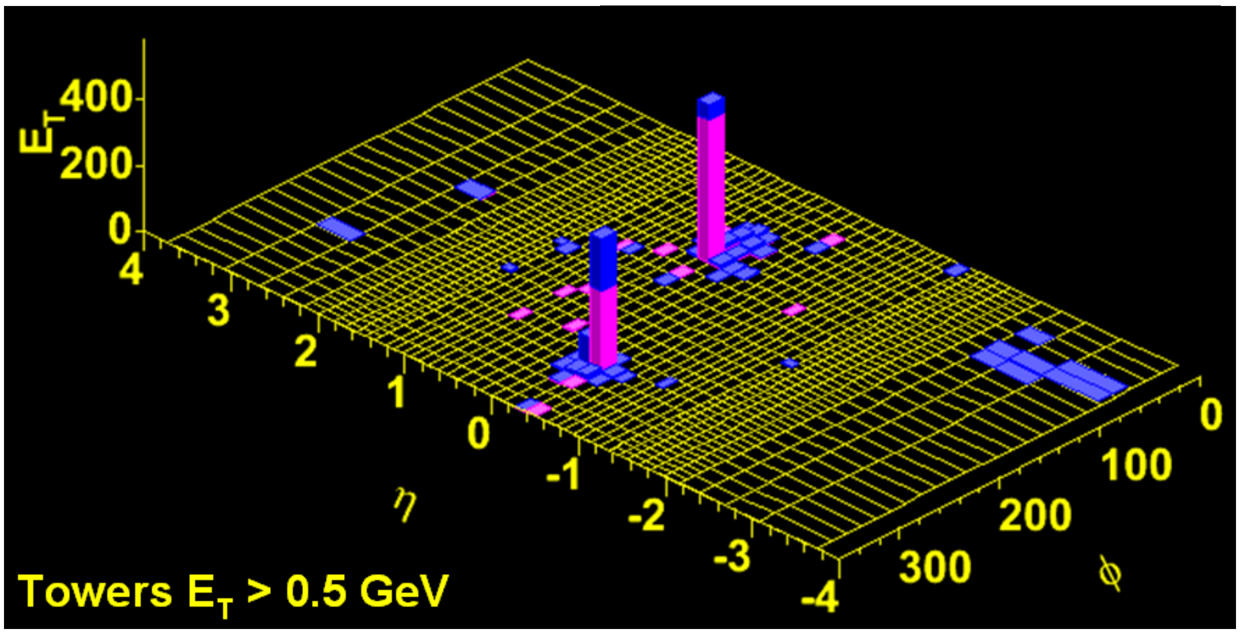
QCD Compton

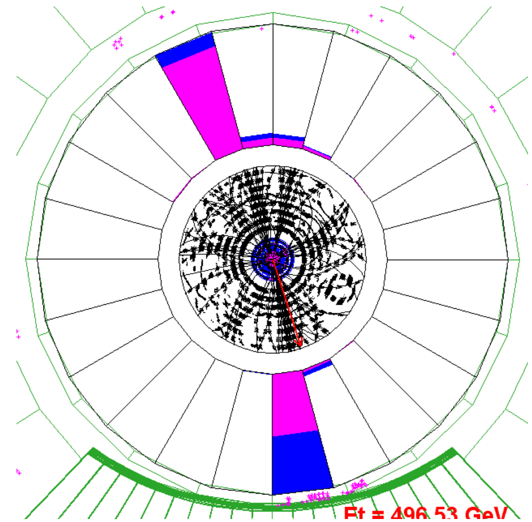
Photoproduction



- QCD Studies
  - Proton and photon PDFs
  - Measurements of α_s
  - Fragmentation functions
  - Quark-gluon jet properties
  - Inclusive- and multi-jet production
  - Rapidity Gaps/Diffraction
- Search for new physics

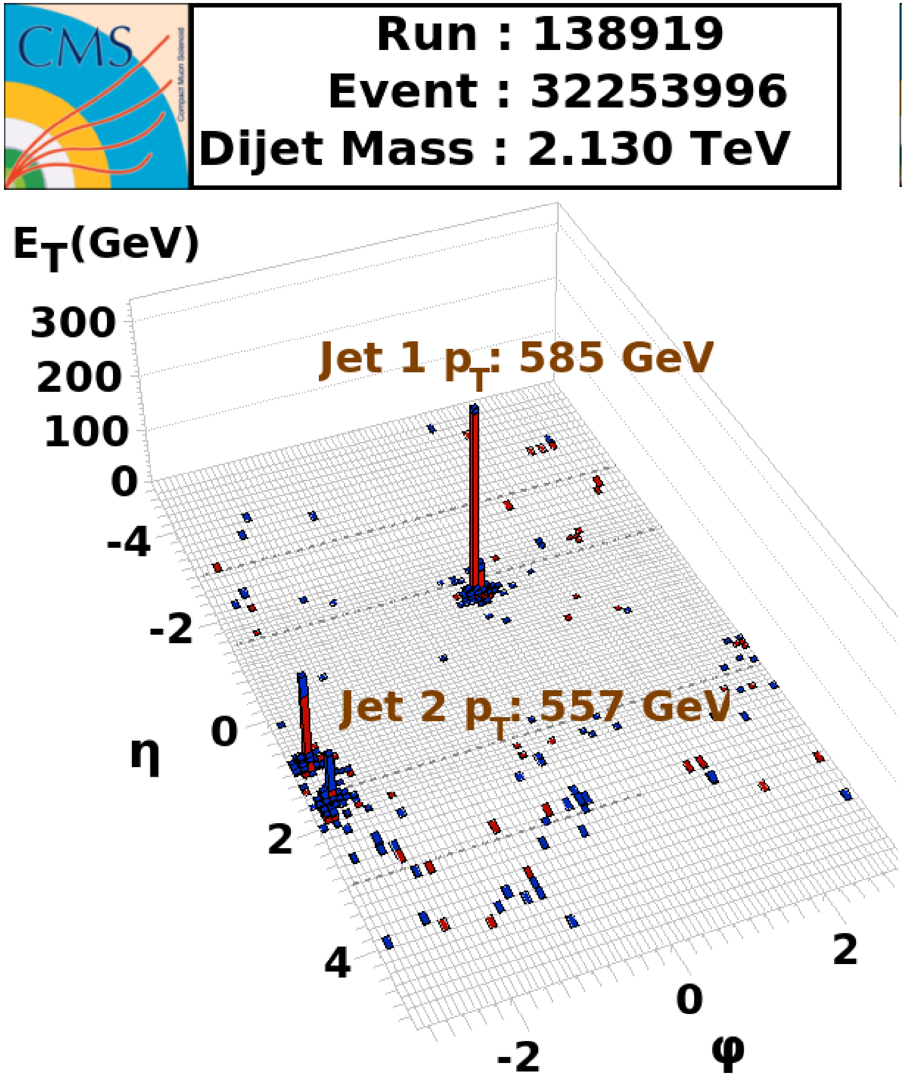
Jets at Hadron Colliders

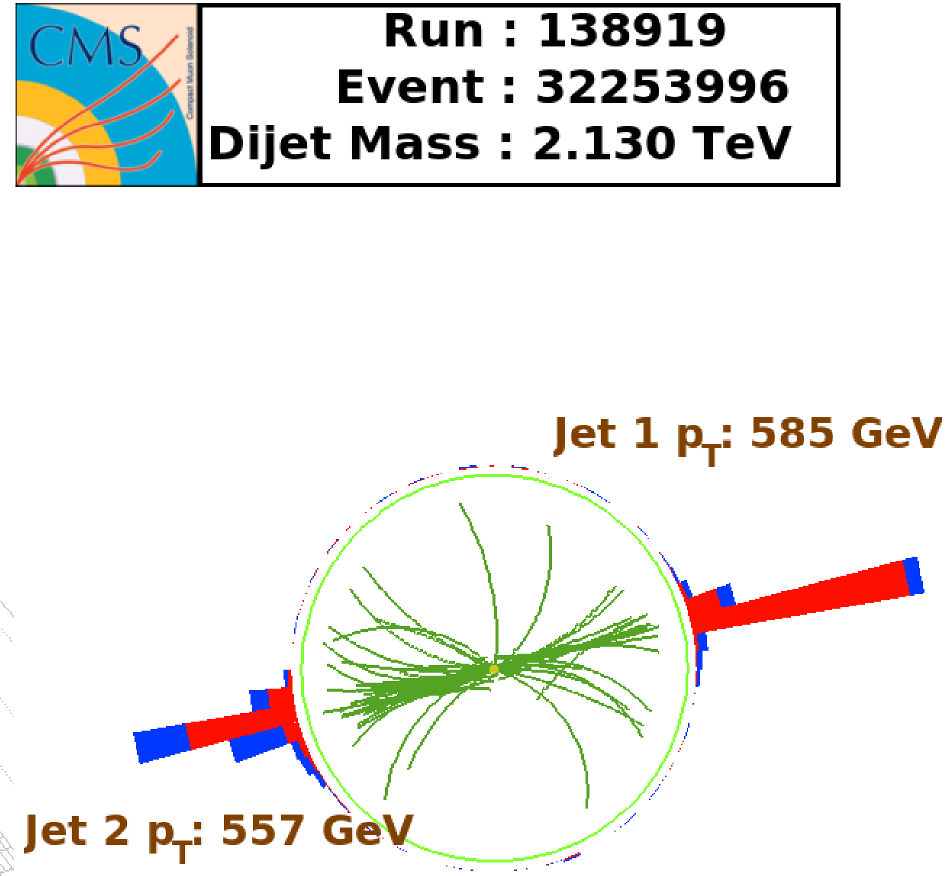




$$p\bar{p} \rightarrow jet + jet + anything$$

Jets at Hadron Colliders





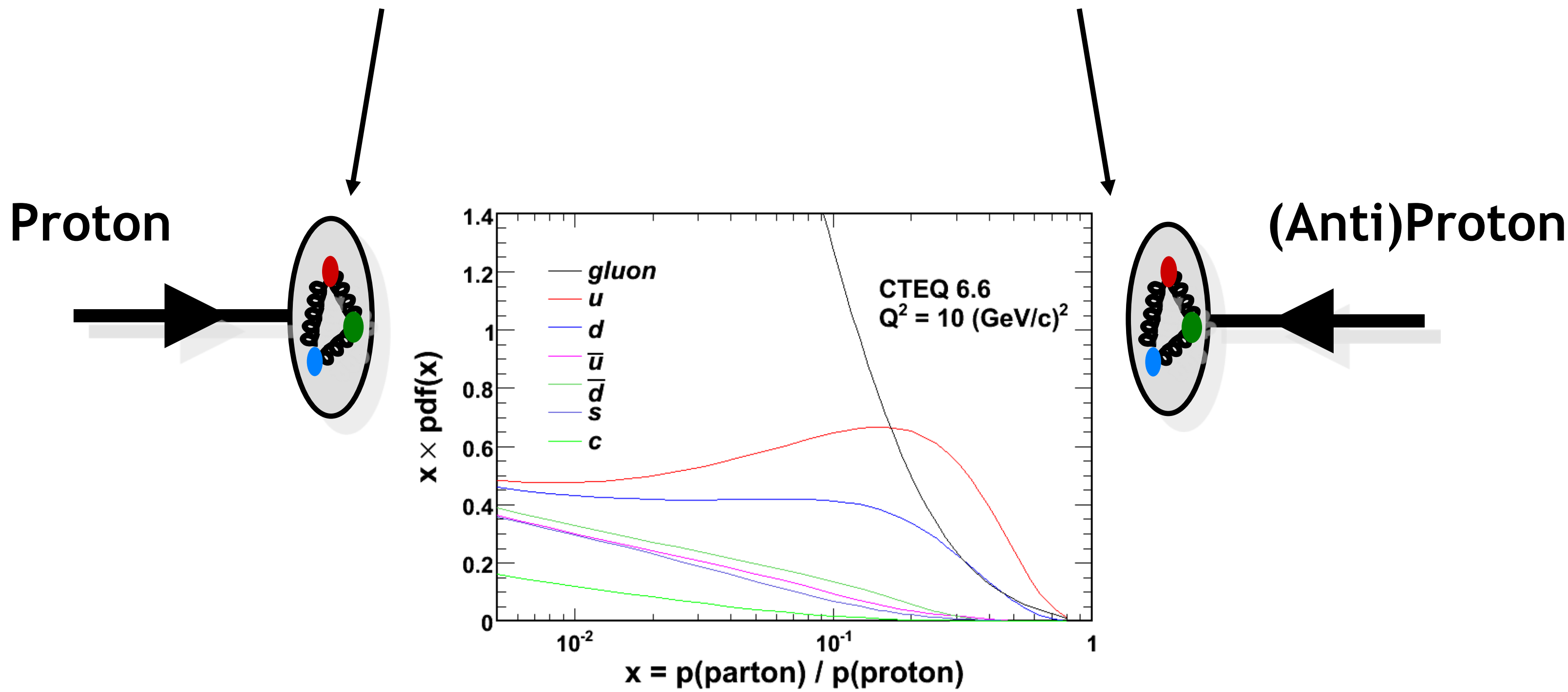
$$pp \to jet + jet + anything$$

Jets at Hadron Colliders

Jets at Hadron Colliders

See lecture by S. Forte

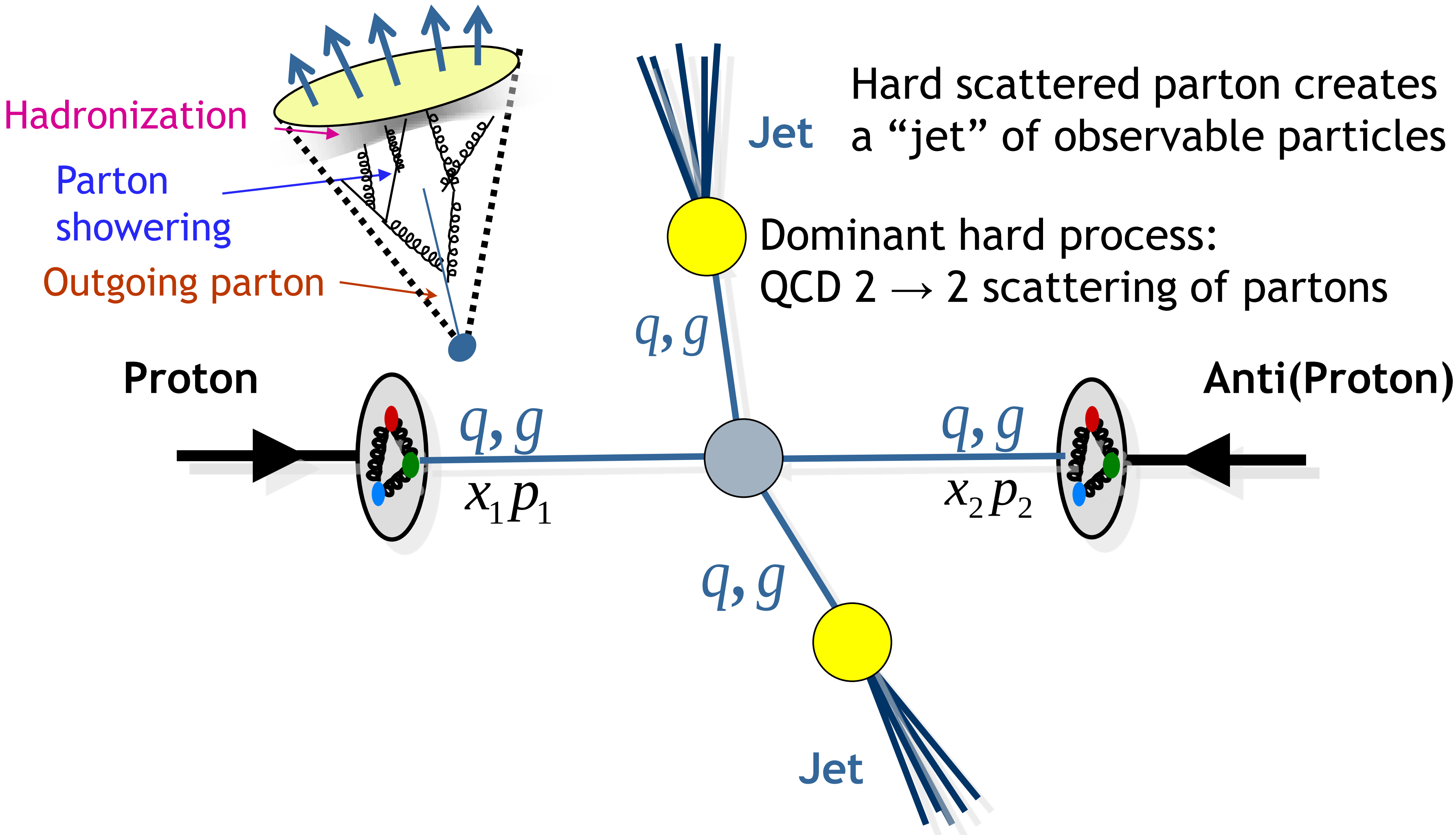
Partons inside proton:
Parton Distribution Functions (PDF's)



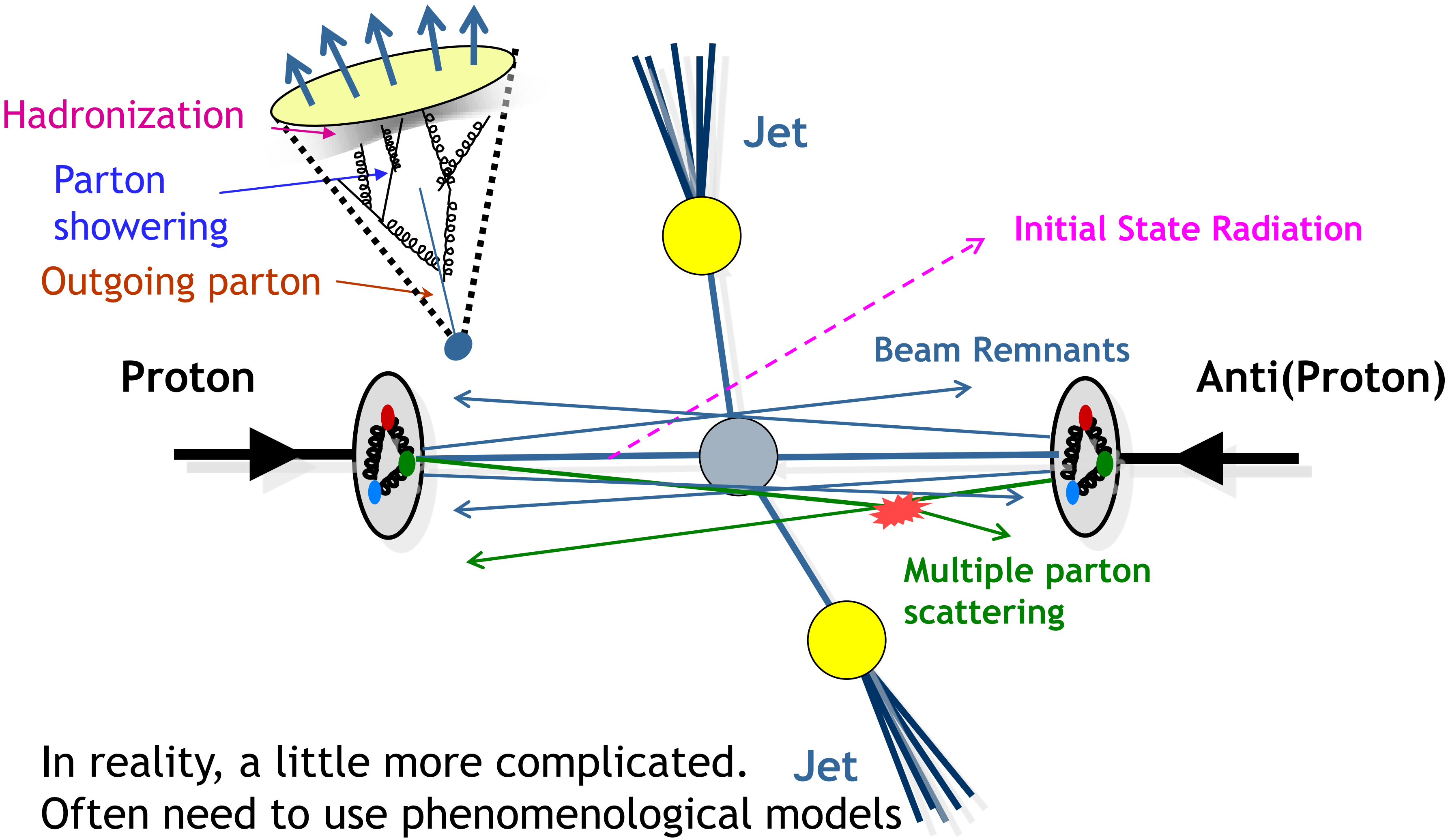
Jets at Hadron Colliders

Hard scattered parton creates a “jet” of observable particles

Dominant hard process:
QCD 2 → 2 scattering of partons



Jets at Hadron Colliders

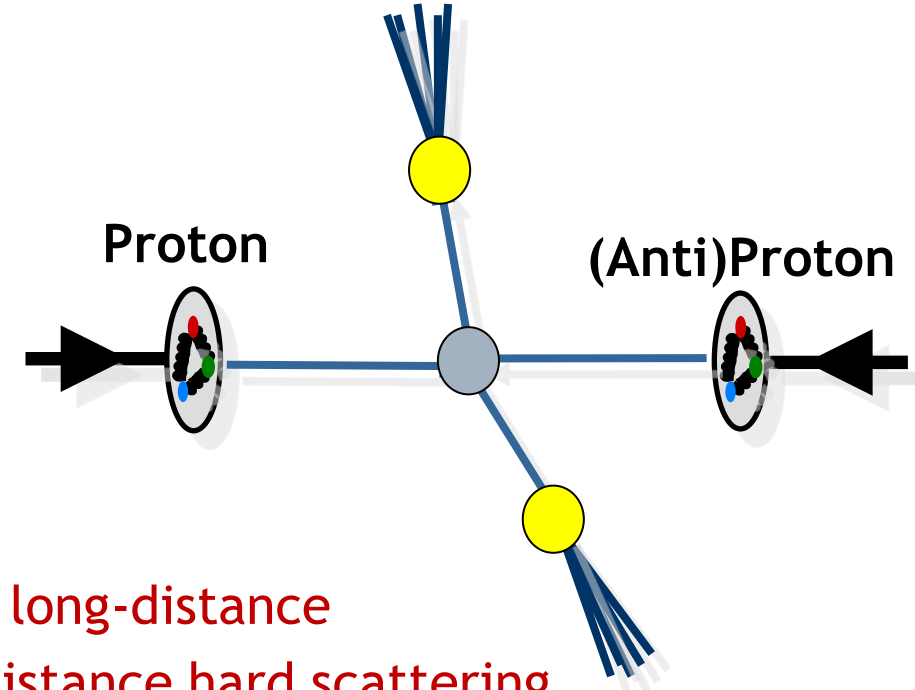


In reality, a little more complicated.
Often need to use phenomenological models to account for non-perturbative effects

Jets at Hadron Colliders

$$\sigma_{jet} = \sum_a \sum_b \overbrace{f_{a/p}(x_p, \mu_F^2)\, f_{b/\bar{p}}(x_{\bar{p}}, \mu_F^2)}^{\text{PDFs}}$$

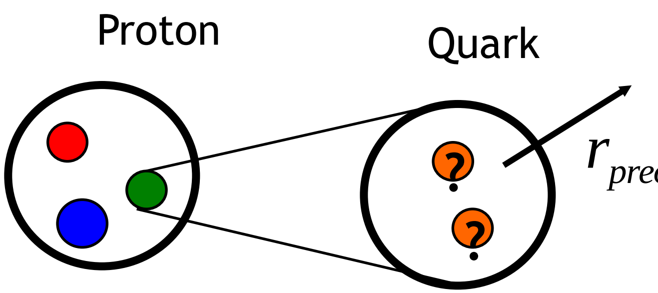
$$\underbrace{\hat{\sigma}_{a,b}\left(p_p, p_{\bar{p}}, \alpha_s(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)}_{\text{Hard Scatter}}$$



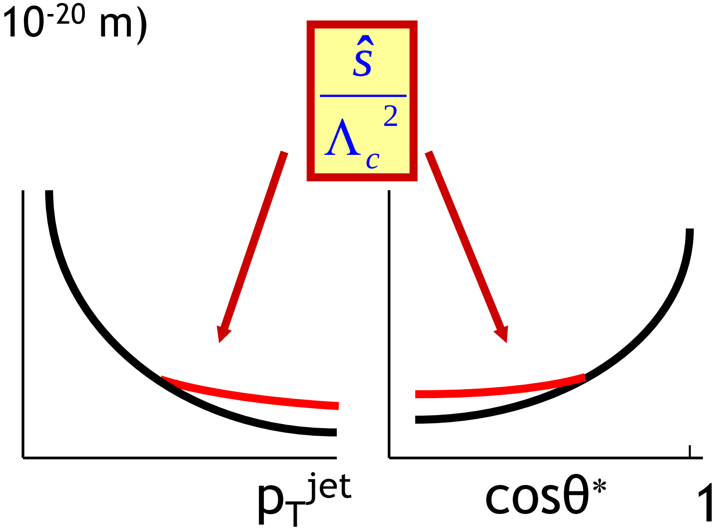
- QCD factorization separates the long-distance components (PDFs) from short-distance hard scattering
  - μ_F: factorization scale that enters into the evolution of the PDF's and the fragmentation functions. May be considered as a scale that separates long- and short- distance physics
  - μ_R: renormalization scale that shows up in strong coupling constant
  - Q^2 : hard scale that characterizes the parton-parton interaction
  - Typically $\mu_F = \mu_R$ = (0.5 -2) of jet Pt

BSM Production of Jets in pp($p\bar{p}$)

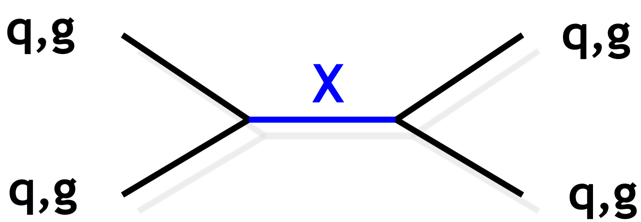
- Many beyond the Standard Model (BSM) scenarios predict final states including high momentum jets
- Quark compositeness (If Λ_c=4 TeV, r ~ 5 $\cdot 10^{-20}$ m)



$$r_{preon} \sim \hbar c / \Lambda_c$$

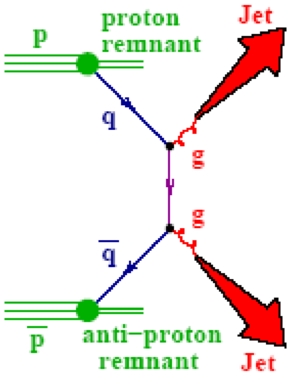


- New massive particles decaying into dijets

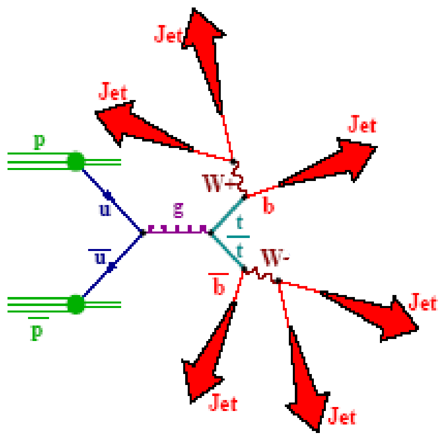


X: excited quark, heavy gluon, W’, Z’, diquark, Randall-Sundrum graviton

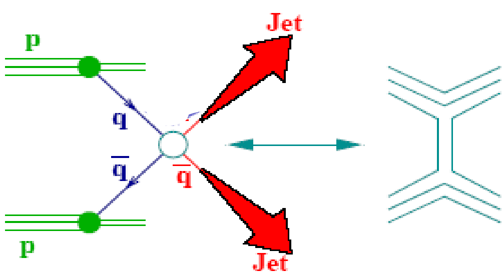
Why Study Jets at Hadron Colliders?



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



Top quark studies



Quark compositeness search

- QCD Studies
  - Proton PDF
  - Measurement of α_s
  - Test of QCD calculations & Monte Carlo models
  - Inclusive and dijet production
  - Jet fragmentation
  - Vector bosons + jets
  - Rapidity Gaps/Diffraction

See lecture by J. Owens

- Top quark properties measurements

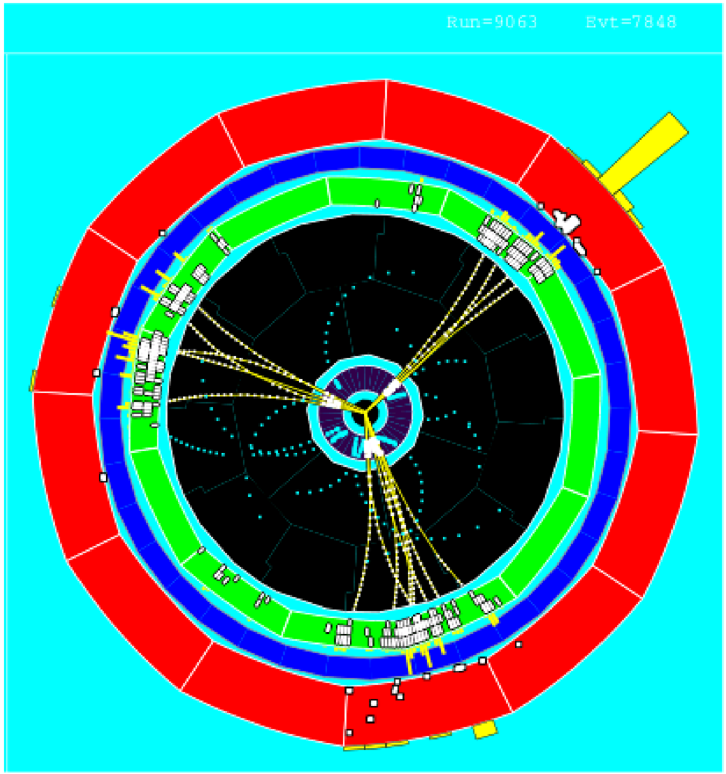
See lecture by W. Wagner

- Search for Higgs boson
- Searches for new physics
- …

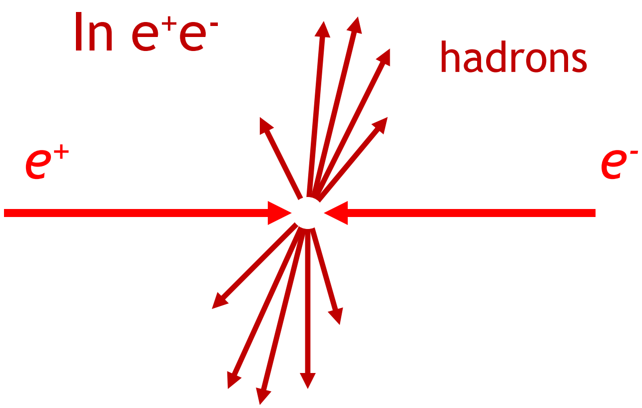
Jet Algorithms

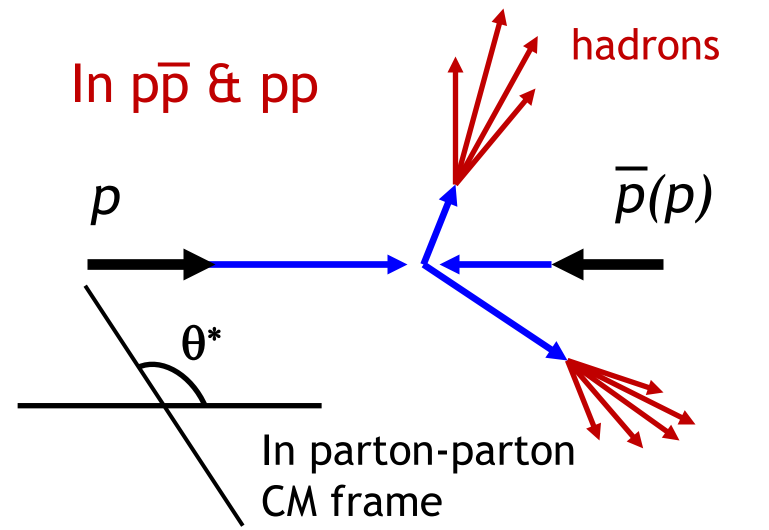
Finding / Defining Jets

- To first order, it's simple
  - Find a stream of particles coming from the interaction point
- To be precise, need a "well-defined" jet algorithm
  - Should serve for both experimentalists and theorists
- Jet algorithms
  - Start with choosing the appropriate reference frame and particle/object variables
  - Scheme/algorithm to combining particles/objects



Particle Variables & Distance





- The e^+e^- center-of-mass (CM) frame is the same as the lab frame (except for B factories)
- Invariant under angular rotations
- Distance between i,j: their angular separation $\theta_{i,j}$ and $\varphi_{i,j}$
- Use the absolute energy for jet "hardness"

- The hadron-hadron CM frame ≠ parton-parton CM frame
- Energy and angular separations are not invariant under boosts
  - Particles appear more collimated /dispersed depending on the boost (next page)
  - Use the transverse momentum Pt instead of energy for jet "hardness"

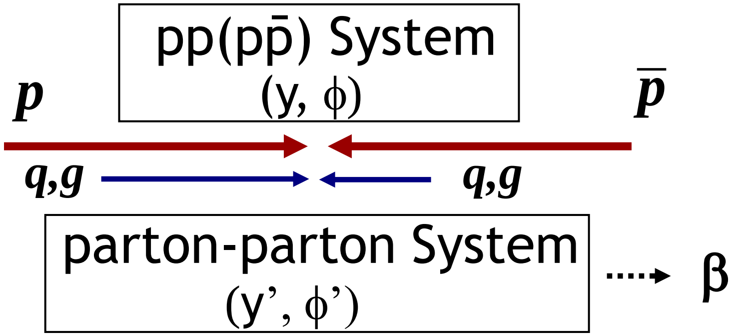
Hadron Collider Variables

- Rapidity (y) or Pseudorapidity (η) for polar angle :

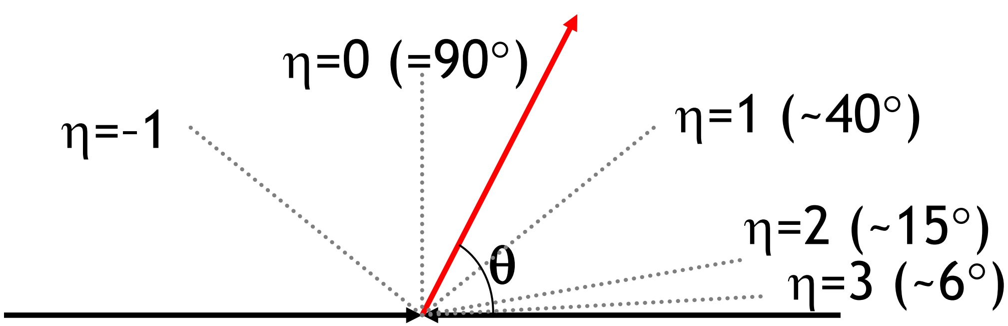
$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

$$\eta = \frac{1}{2}\ln\frac{p+p_z}{p-p_z} = -\log(\tan(\theta/2))$$

($\eta = y$ when a particle is massless)



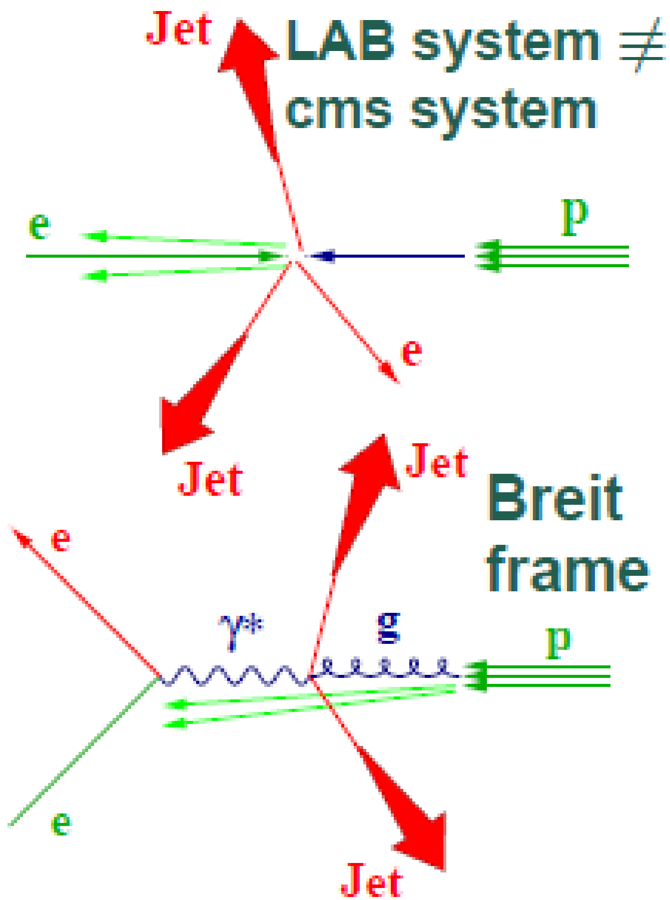
$$y' = y + \frac{1}{2}\ln\frac{(1-\beta)}{(1+\beta)}$$



Therefore, the rapidity interval is boost-invariant, $\Delta y' = \Delta y$.

For polar-angle separation, use $y_{i,j}$.

Reference Frame in High Q^2 DIS



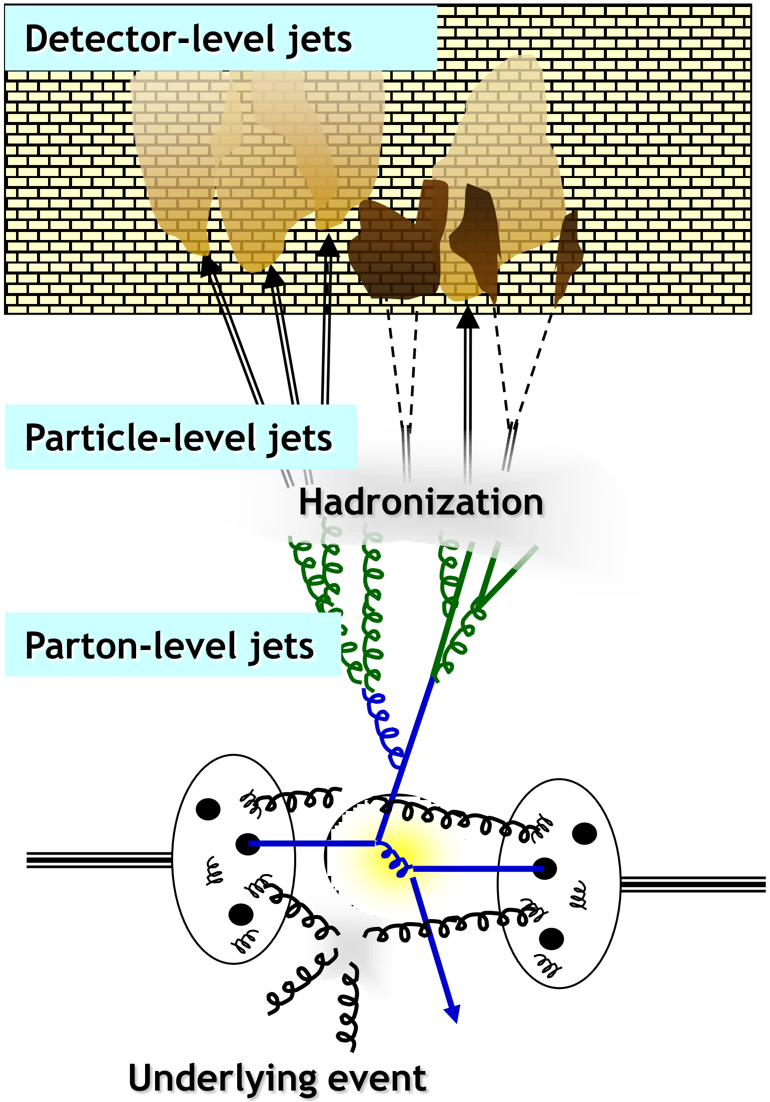
- We use the lab frame for other processes, but for high Q^2 DIS, use the "Breit frame"

$$2x\vec{P}+\vec{q}=0$$

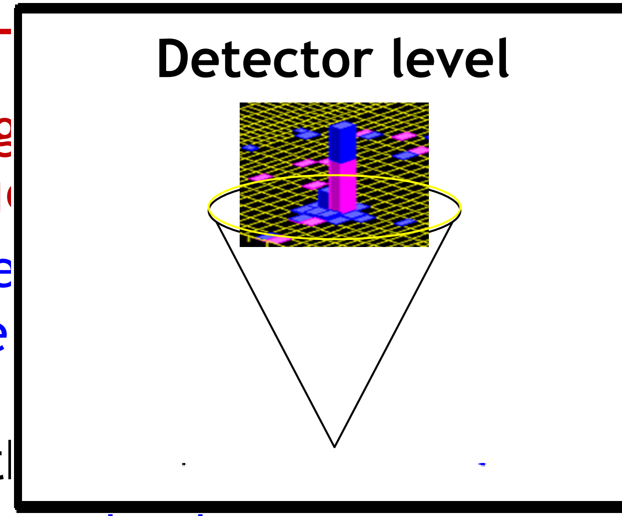
- Initial-state γ^*-parton system boosted and rotated (γ^* carries Pt)
- Breit frame, in which γ^* collides head-on with proton, removes this effect

- Use the same variables as in hadron-hadron collisions
  - Pt, $y_{i,j}$, $\varphi_{l,j}$

Jet Algorithm



- Jet alg … and form j…
- Our de… "same… at all levels … data-t…



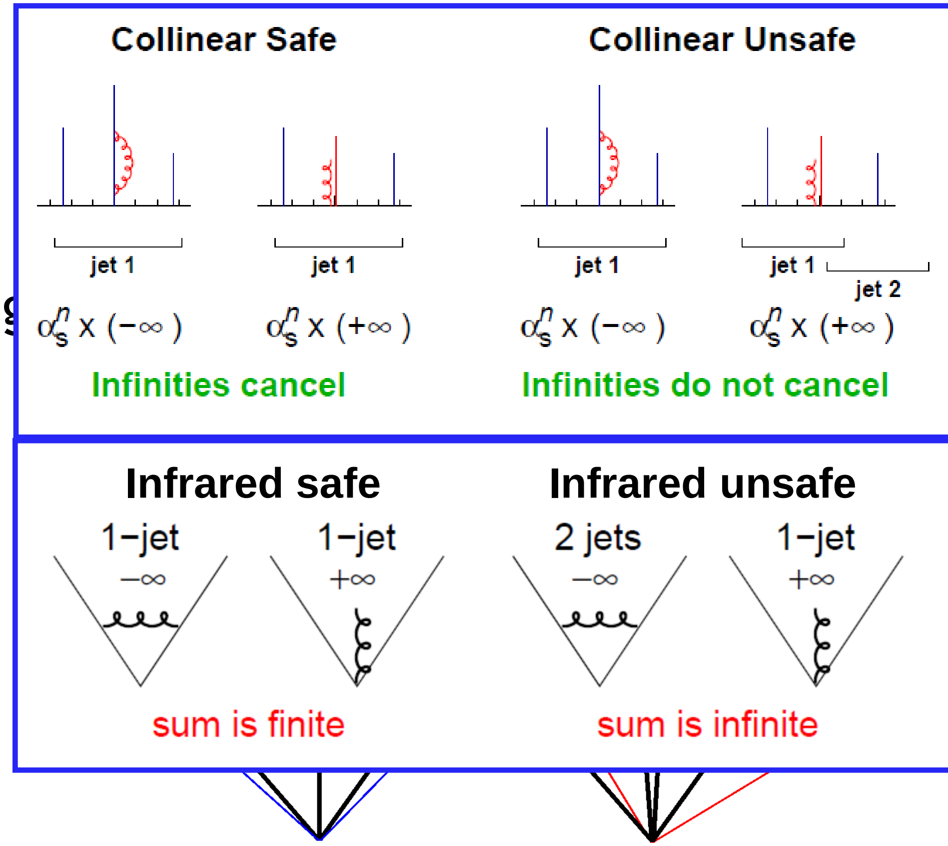
  - Parton level
    - E.g. fixed order pQCD calculation or partons after parton showering
  - Particle level
    - E.g. Monte Carlo event generator
  - Detector level
    - E.g. Calorimeter towers
    - Combinations of many detectors
      - Reconstructed (e.g. particle flow) objects
      - Calorimeter towers + tracks

Jet Algorithm Requirements

- Theoretically well-behaved
  - Infrared safety

    adding a soft parton should not change the jet clustering results
  - Collinear safety

    replacing a parton by a collinear pair of partons should not change the jet clustering results



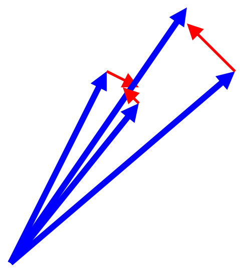
- Order ~independence: work well at parton, particle, detector-levels
- Minimize hadronization effects
- Detector ~independence

More details in:
hep-ex/0005012
hep-ph/0610012,
Prog.Part.Nucl.Phys.60, 484,2008.

Jet Algorithms

- Recombination algorithms

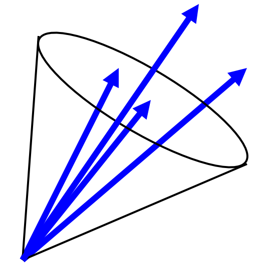
  Basic Idea: Successively find the "closest" pair of particles & combine them



  - Used extensively in ee / ep
  - Theoretically well-behaved ☺
    - Infrared & collinear safe
  - Irregular shape (except Anti-Kt) is a challenge for experimentalists (underlying event and pileup corrections)

- Cone algorithms

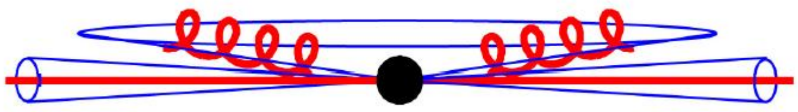
  Basic Idea: Search for the "stable" cone, in which the vector sum of particles insize a cone points toward the cone centroid



  - Primarily used in pp (ppbar)
  - Regular cone shape ☺ (unless cones overlap)
  - Often infrared & collinear unsafe (except SISCone) ☹
  - Stable cones overlapping is tricky ☹

JADE & Kt Algorithms for e^+e^-

- **JADE:** Original recombination algorithm (Z. Phys. C33 (1986) 23)
  - Metric: $M_{ij} \approx 2E_iE_j(1-\cos\theta_{ij})$ ~ (invariant mass)^2
  - Can lead to "junk jets"



A two-jet with soft, collinear radiation can be classified, unnaturally, as a three-jet event

Inhibits NLLA-resummation techniques (what is 2-jets @ one order becomes >2 jets at higher order)

- **Kt (Durham):** S. Catani et al., Phys. Lett. B269 (1991) 432
  - Metric: $M_{ij}^2 = 2\min(E_i^{\,2}, E_j^{\,2})(1-\cos\theta_{ij})$
  - For small emission angles θ_{ij},

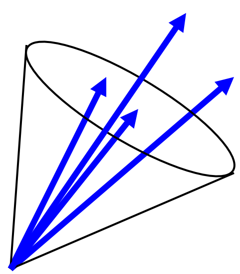
$$\boxed{M_{ij} \approx 2\min(E_i^{\,2}, E_j^{\,2})[1-(1-\theta_{ij}^{\,2}/2+\cdots)] \approx \min(E_i^{\,2}, E_j^{\,2})\theta_{ij}^{\,2} \approx k_T^{\,2}}$$

  - Smaller of the transverse momentum of i wrt j or j wrt i
  - Soft collinear radiation is attached to the correct jet (solve "junk jet" problem)

Extensively used in ee / ep

Cone Algorithms for Hadron Colliders

- "Has been" a primary choice for hadron colliders
- Basic idea: Cluster objects based on their proximity in y-ϕ space and find stable cones (kinematic centroid = geometric center).



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

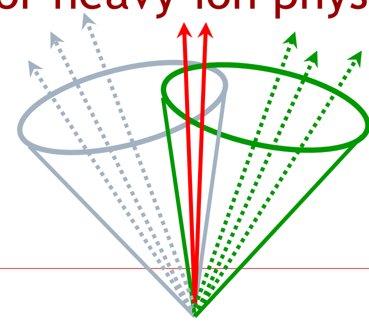
$$p^C = (E^C, \mathbf{p}^C) = \sum_{i \subset C} (E^i, p_x^i, p_y^i, p_z^i) ,$$

$$\bar{y}^C = \frac{1}{2} \ln \frac{E^C + p_z^C}{E^C - p_z^C} , \quad \bar{\phi}^C = \tan^{-1} \frac{p_y^C}{p_x^C} .$$

Stable cone when

$$y^C = \bar{y}^C , \varphi^C = \bar{\varphi}^C$$

- Intuitive, but a few undesired aspects…
- Often infrared unsafe
  - Solved by the seedless SISCone algorithm (arXiv:0704.0292) (but speed is somewhat issue. Not usable for heavy ion physics)
- Still stable cones sometime overlap
  → Need a procedure to merge/split:
  merge cones when p_T overlap > 75%



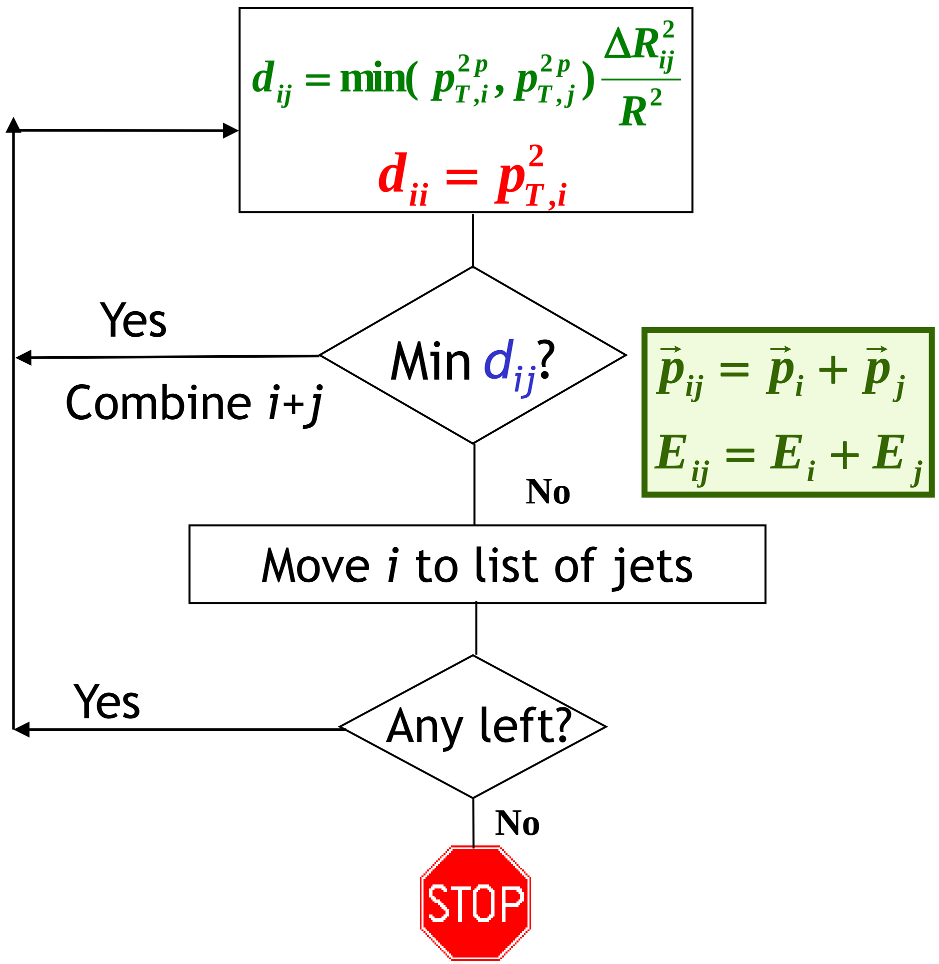
Recombination Algorithms for Hadron Collider

- Metric:

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

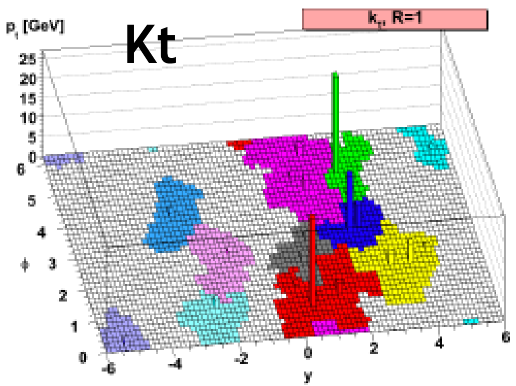
$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

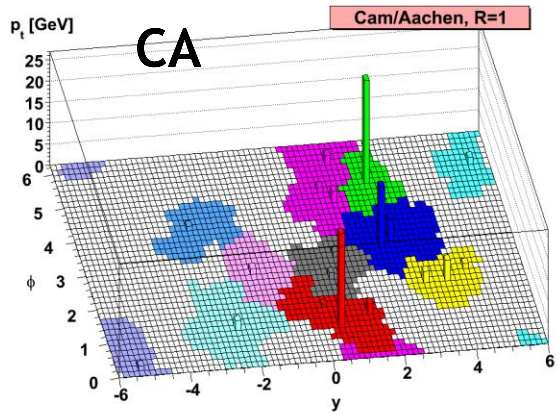
- p=1: Kt algorithm
  p=0: Cambridge/Aachen algorithm
  p=-1: Anti-Kt algorithm
- R parameter (typically 0.5-1.0) characterizes jet size
- These algorithms are infrared and collinear safe!
- Speed used to be an issue, but solved by Fastjet by Salam et al (hep-ph/0512210)

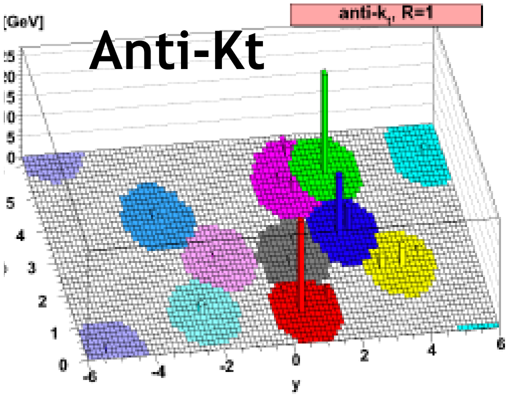


Recombination algorithms for Hadron Collider

Characteristics of each algorithm – look at "jet area"







M. Cacciari, G. Salam, G. Soyez 0802.1188

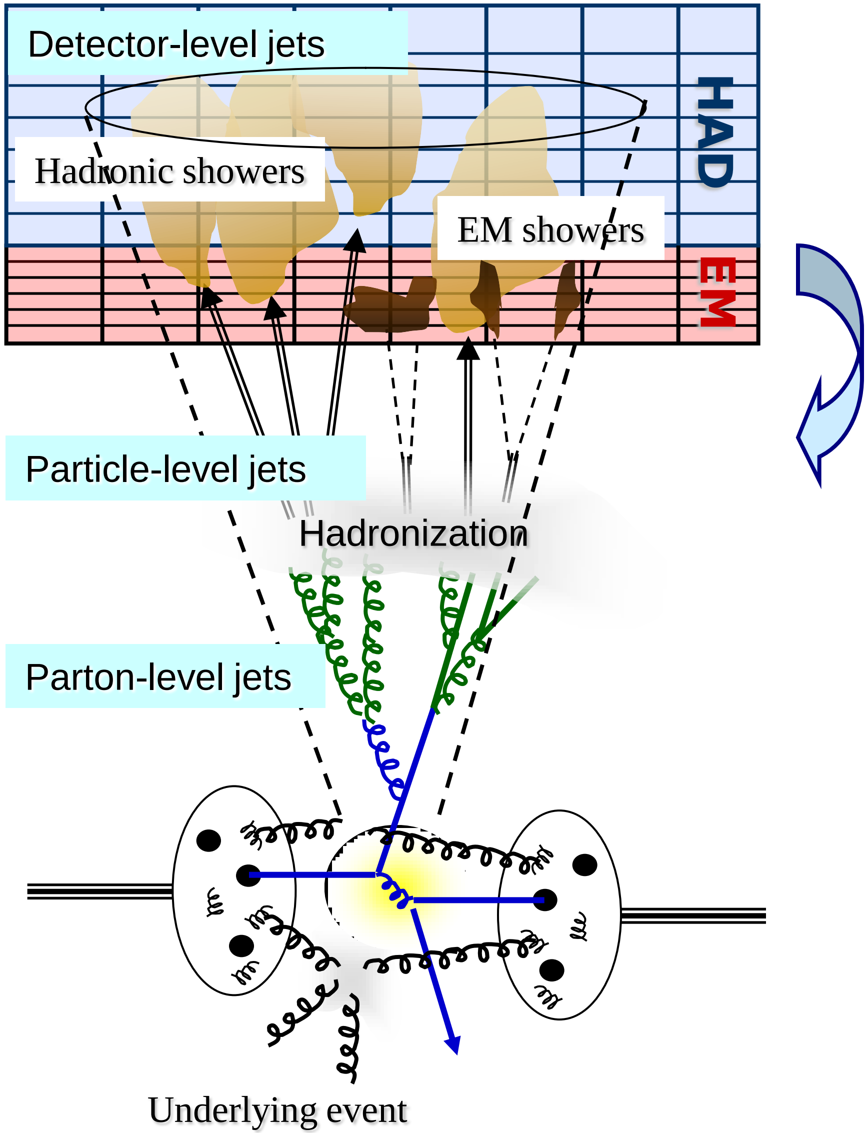
- **Kt:** Cluster from pairs of low-Pt particles
  - Proactively include QCD radiation
  - Irregular shape : complication for UE & pileup subtraction, but the area calculation offers a solution
- **Anti-Kt**: Cluster from pairs of high-Pt particles
  - Circular shape, radius ~R resolution parameter
  - Easy for experimental calibration
- **Cambridge/Aachen (CA)**: Relies only on distance weighting
  - Works well for subjet studies (more later, or see e.g. PRL 101, 142001)

Jet Algorithm: Remarks

- After two decades of development, **jet clustering has quite matured**, and we appear to be **ready for LHC jet physics from the jet clustering point of view**
- Critical to have infrared and collinear safe algorithms
  - Available algorithms are e.g. Kt, Cambridge/Aachen, Anti-Kt, SISCone
  - May facilitate the development of higher order pQCD calculation: Higher order pQCD calculation does not benefit much if jet algorithms are infrared and collinear unsafe
- Same algorithm (Anti-Kt algorithm) is used as the “default” algorithm in various experiments (e.g. CMS and ATLAS)
  - Results will be more transparent to outside world and between experiments (although still jet size parameter R still differ between experiments so far)

Jet Measurement and Jet Energy Correction

Jet Measurement

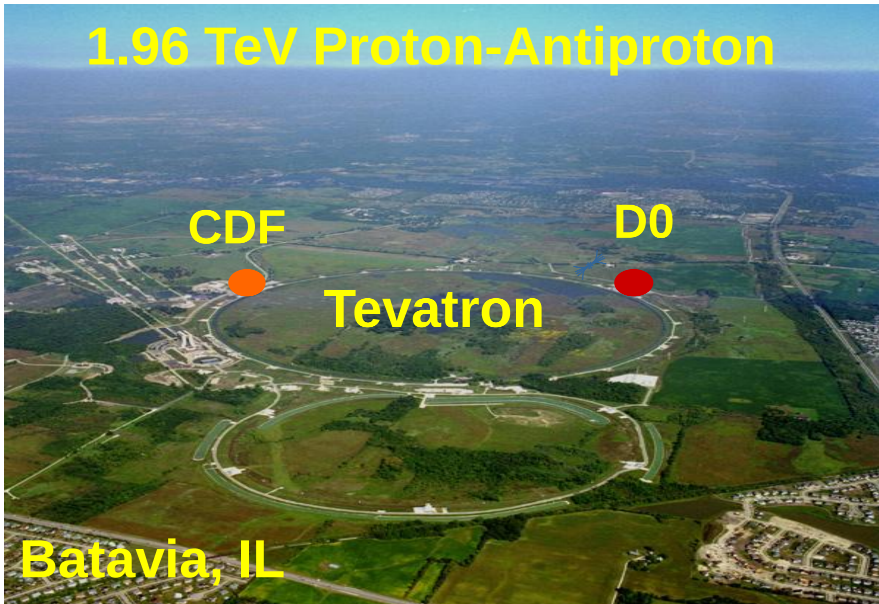


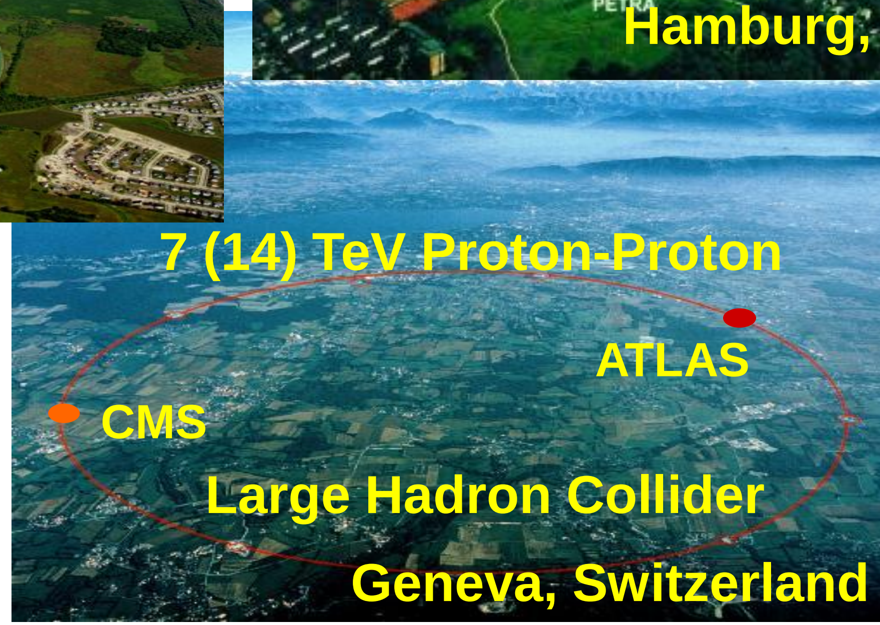
Experimentally, jets are measured in the detectors.

Need to “unfold” the measured jets to the “true” particle level for comparisons with theoretical predictions

Big experimental challenge!

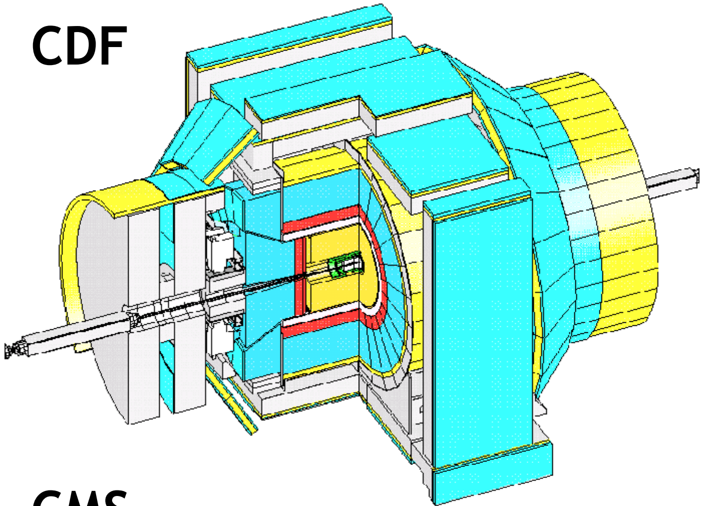
Jets Production at HERA, Tevatron, and LHC



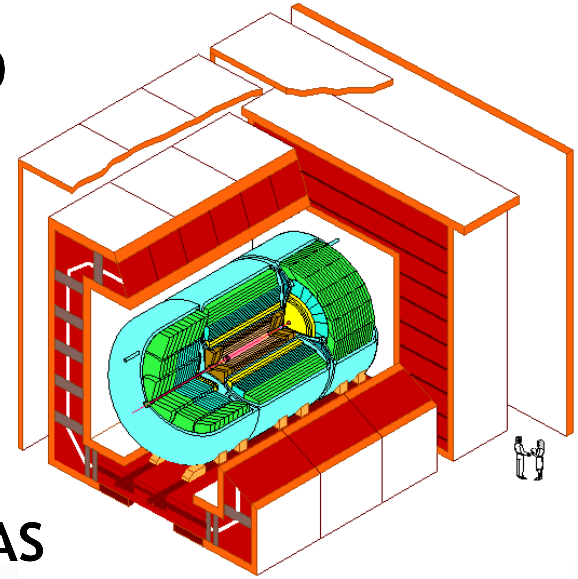


Typical Detectors

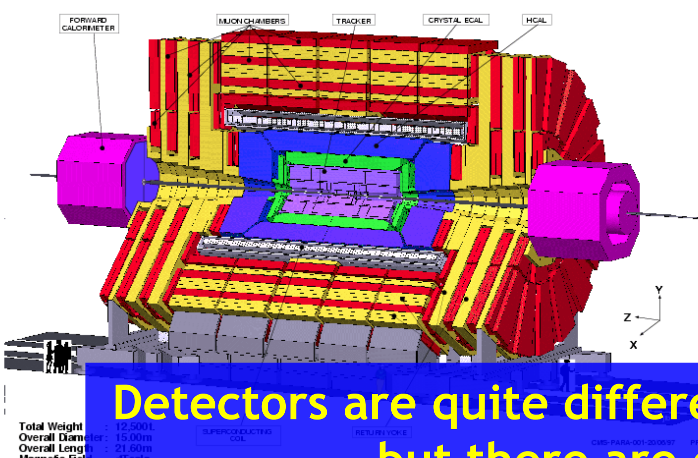
CDF



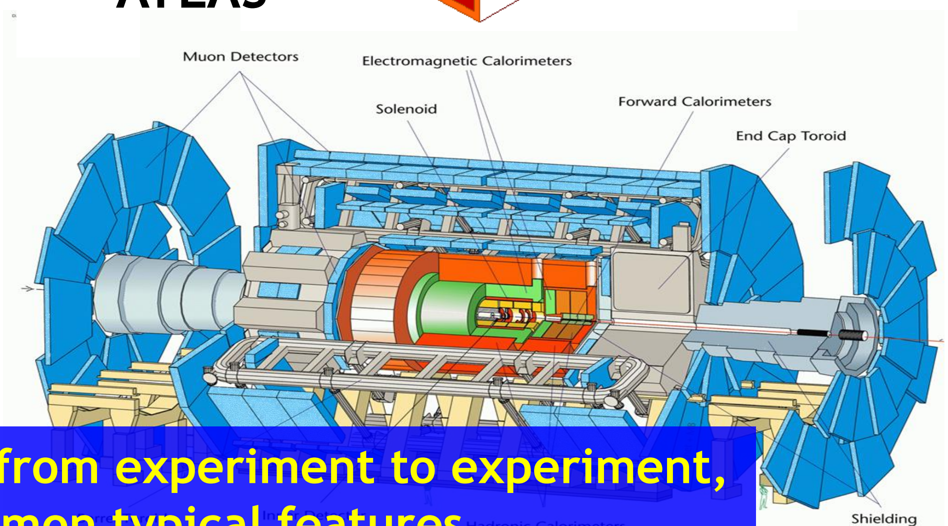
D0



CMS



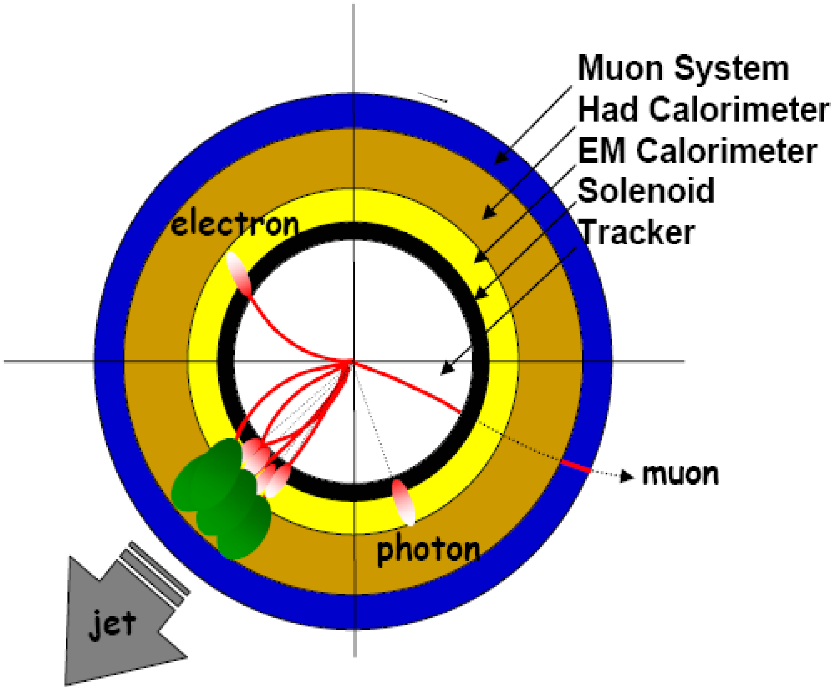
ATLAS



Detectors are quite different from experiment to experiment, but there are common typical features

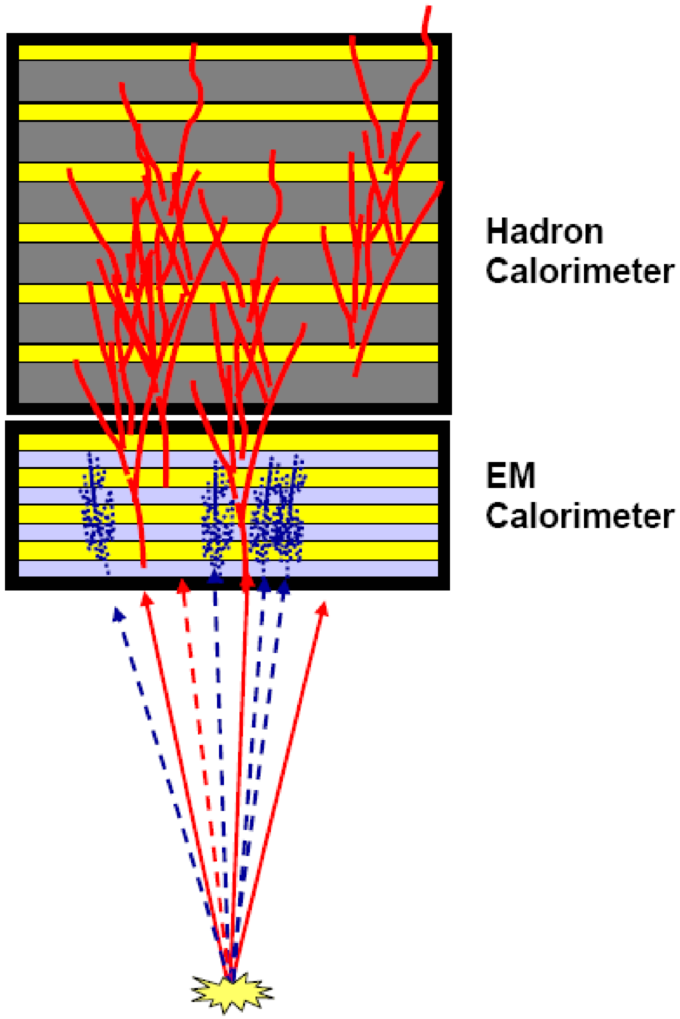
Typical Detectors

- Main detector components
  - Solenoid
    - Bend charged particles
  - Tracker
    - Charged particles (charged hadrons, leptons)
  - EM calorimeter
    - Primarily for photons and electrons
  - Hadron calorimeter
    - Charged & neutral hadrons
  - Muon system
    - Muons



- Jets typically consist of ~65% charged hadrons, ~25% of $\pi^0 \to \gamma\gamma$, ~10% of neutral hadrons
  - Calorimeters are most critical for jets

Calorimeter Response for Jets



- *Calorimeters "destroy"* (i.e. stop) particles to measure their energy by making them "shower"
- EM showers (from photons, electrons) are dense & short, with intrinsic fluctuations
- Had showers (from hadrons) are broad & long, with large intrinsic fluctuations
- Typical calorimeters use sampling technology (passive/active media) which adds fluctuations
  - Measure only a fraction of ionization
- EM cal response on hadrons is larger than the Had cal (different sampling density): different starting points of had shower give large fluctuations and non-linearity in the response

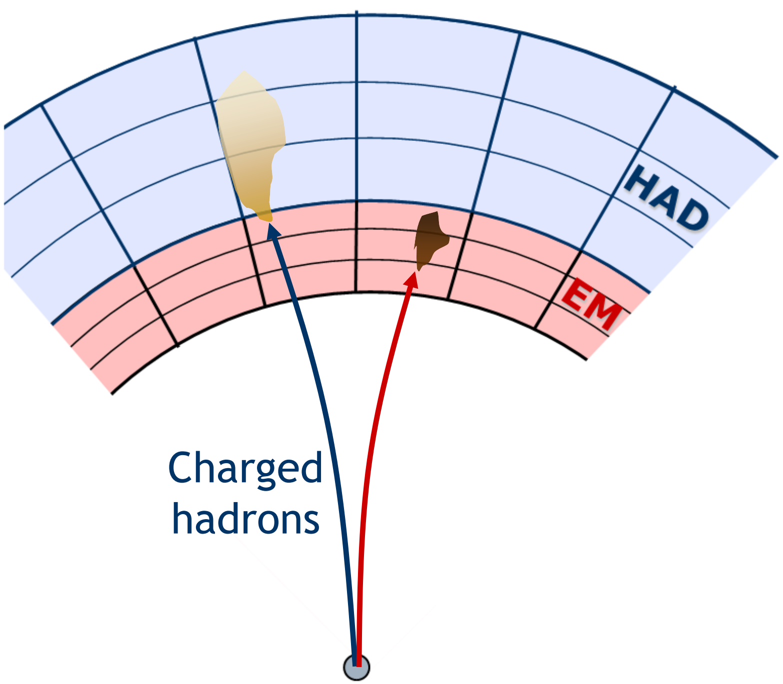
Calorimeter Calibration & Jet Energy Correction

- Establish calorimeter stability, uniformity, absolute scale in data
  - Pulsers, radio active source, and light source
  - Azimuthal symmetry of energy flow in collisions for uniformity
  - Muon minimum ionizing particle signal for stability
  - Set E/p = 1 for isolated tracks (charged hadrons and electrons)
    - Use momentum from central tracker as a reference
  - EM resonances ($\pi^0 \rightarrow \gamma\gamma$, J/ψ, Υ & $Z \rightarrow e^+e^-$)
    - Adjust calibration to obtain the known mass

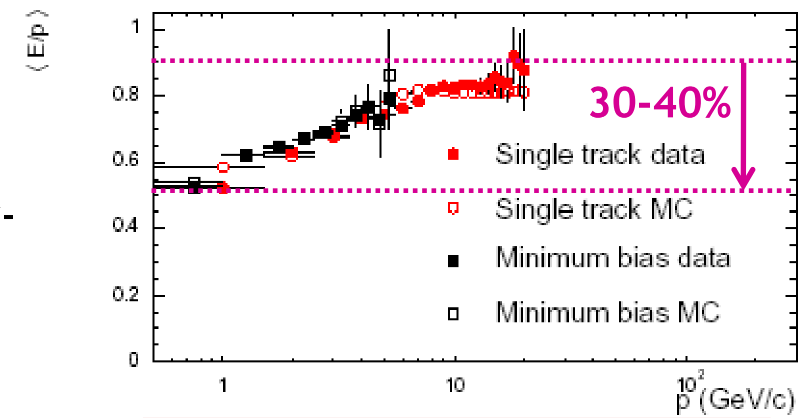
- Obtained the jet energy correction
  - Tune single particle response in detector simulation, use MC modeling of jet fragmentation: use the calo-jet vs particle-jet correlation
  - Pt balance in photon(Z)+jet: correct jet Pt to calibrated photon scale
  - Hybrid of the above two options
  - Hadronic resonances ($W/Z \rightarrow jj$)

Calorimeter Response Tuning

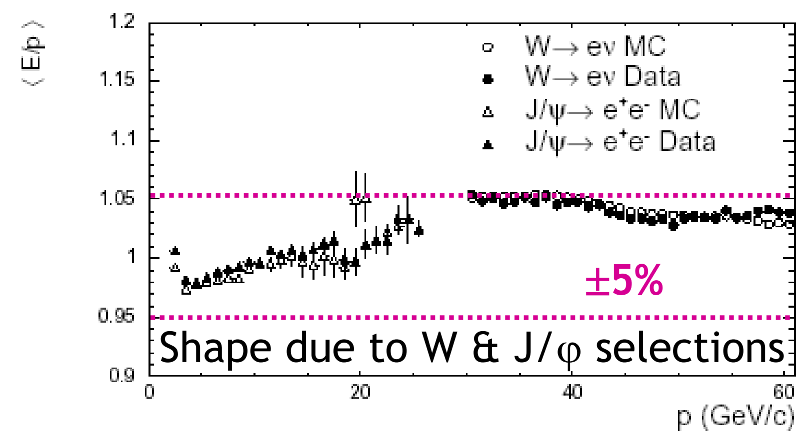
- Tune individual particle response (E/p)
  - EM shower particles
  - Had shower particles
- Use jet fragmentation model
  - Correlate particle-level and detector-level jets



Charged hadrons ($\pi^{\pm}$, $K^{\pm}$, p, ...)

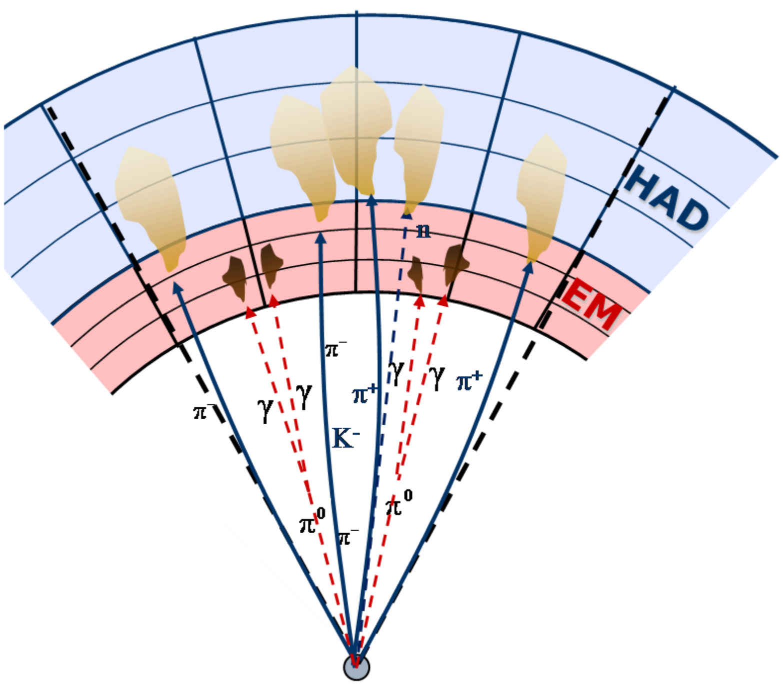


Electromagnetic particles (electrons, photons, π^0, ...)

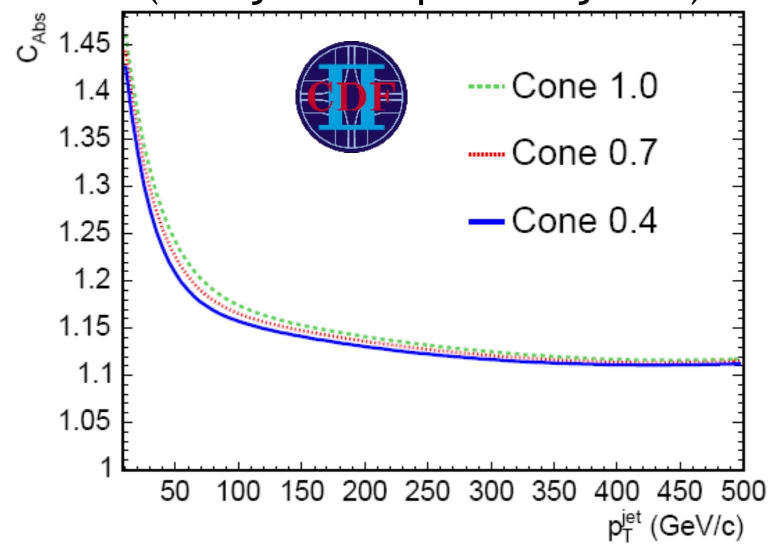


Jet Energy Scale Correction

- Tune individual particle response (E/p)
  - EM shower particles
  - Had shower particles
- Use jet fragmentation model
  - Correlate particle-level and detector-level jets



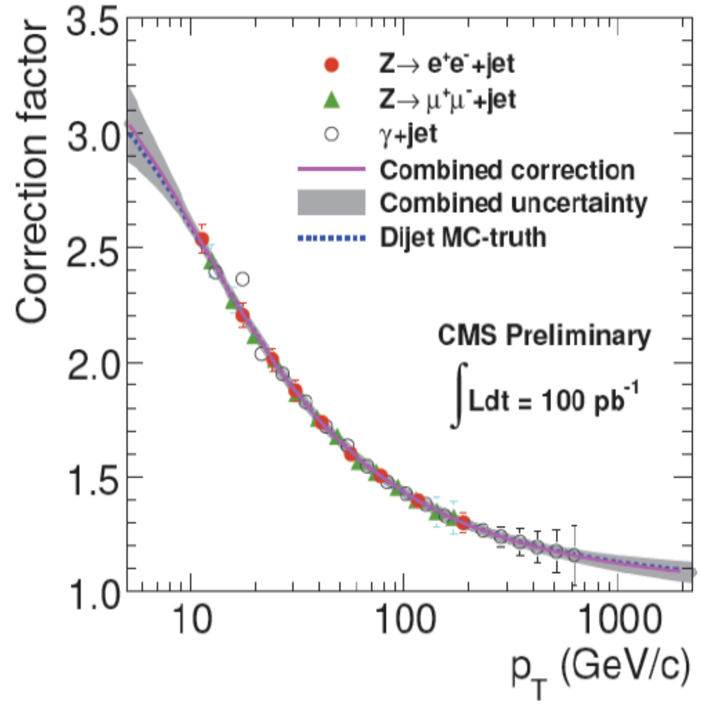
C(calo jet Pt →particle jet Pt)

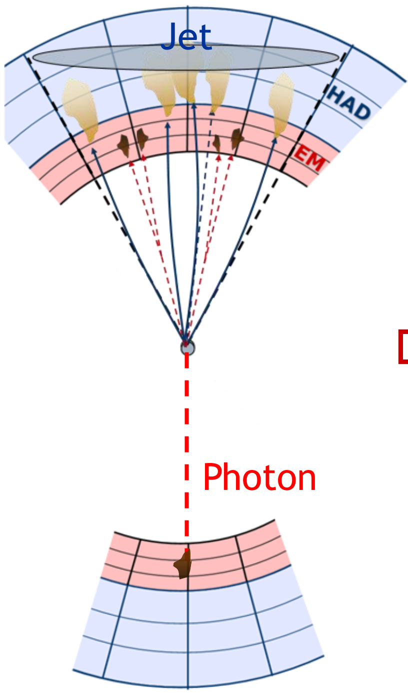


NIM A566, 375 (2006)

Jet Energy Correction

- Utilize Pt balance in γ(Z)+jet events
  - In leading-order QCD, photon/Z and jet are balanced
- Photon & Z($\rightarrow$ee & $\mu\mu$) Pt's well measured by ECAL or tracker
  - Use their Pt as a reference

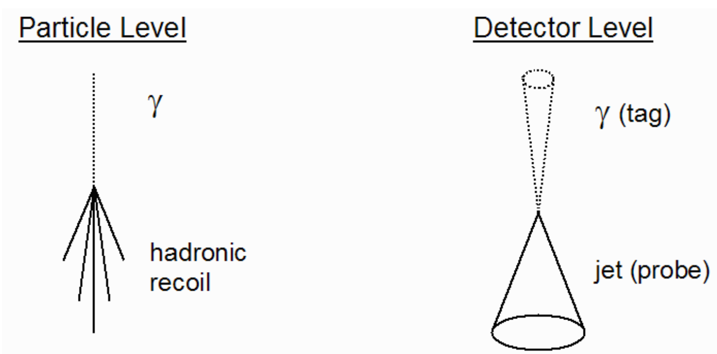


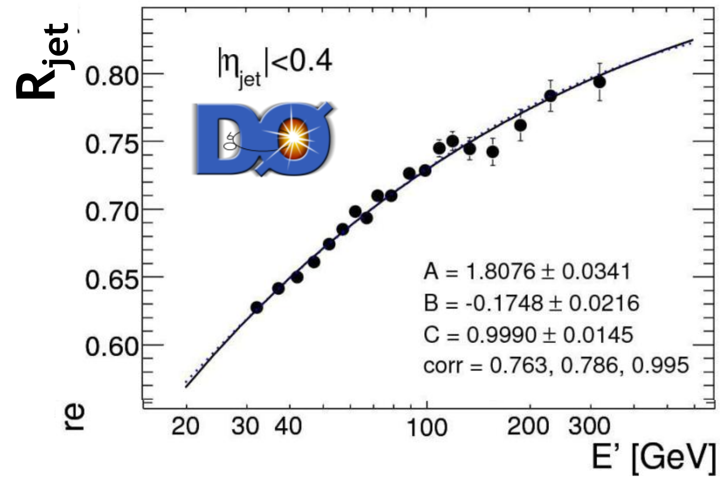


- Need do account for:
  - QCD radiation which spoils the Pt balance
    - Tight cut on additional jets, extrapolate 3rd jet Pt $\rightarrow$ 0, missing Et projection fraction method
  - Statistics will run out at high Pt. Need extrapolation to high Pt (hybrid with a MC-based method)

Missing Et Projection Fraction

- Using missing Et projection fraction makes the method insensitive to the jet cone and showering
  - Small showering correction applied later





$$\boxed{\vec{p}_T^{\,\gamma} + \vec{p}_T^{\,recoil} = 0}$$

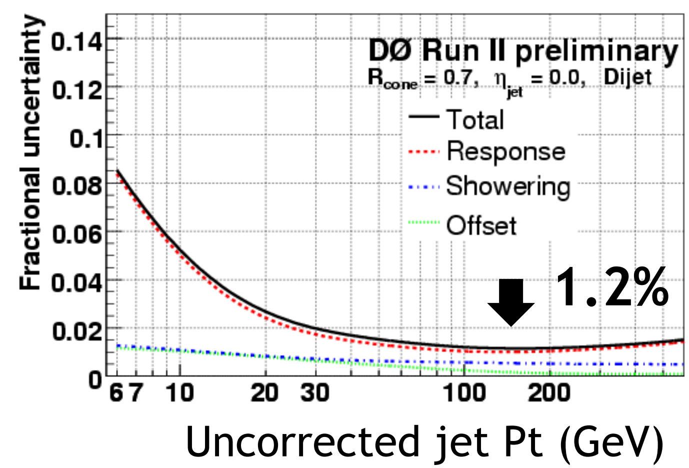
$$\boxed{R_\gamma \vec{p}_T^{\,\gamma} + R_{recoil}\,\vec{p}_T^{\,recoil} = -\vec{\cancel{E}}_T}$$

- After EM energy calibration, R_γ=1.

$$\boxed{R_{recoil} = 1 + \frac{\vec{\cancel{E}}_T \cdot \vec{n}_T^{\,\gamma}}{p_T^\gamma} \Rightarrow R_{jet}\left(= \frac{1}{Corr}\right)}$$

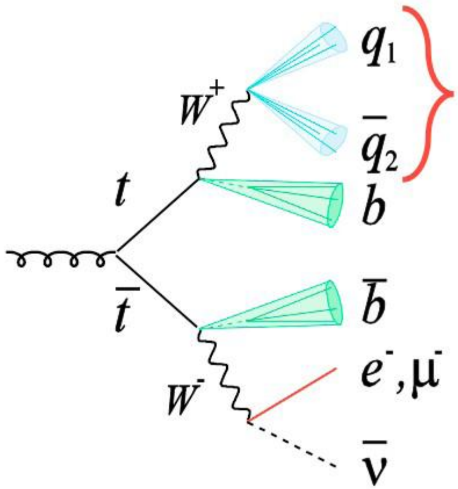
- Perform the study vs $E' = E_T^\gamma \cosh(\eta_{jet})$

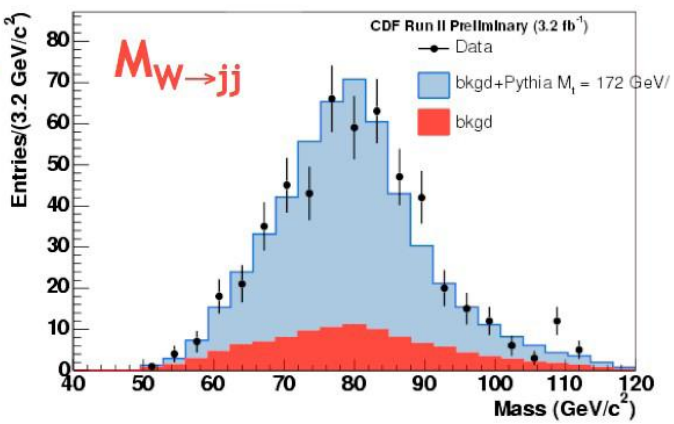
E_T^γ, η_{jet} better measured than E_{jet}

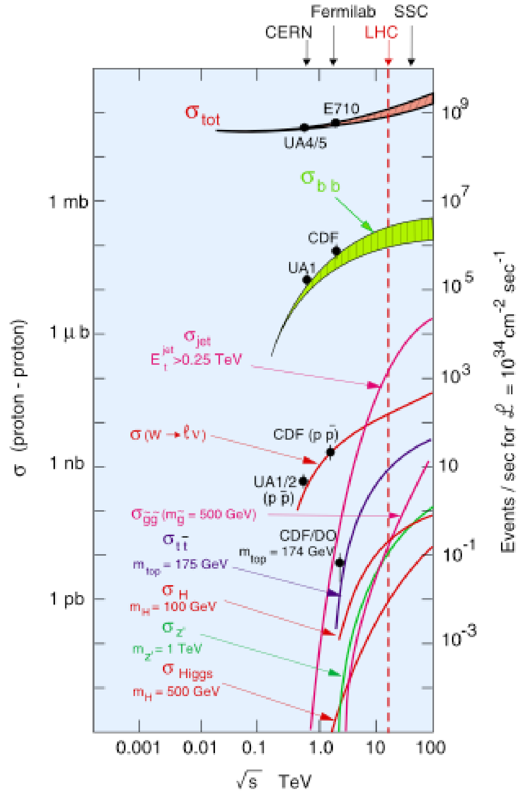


Jet Energy Calibration with W/Z→jj

- Very difficult to see incl. W/Z decays into jets at hadron colliders
- Possibilities are:
  - W from top decays - powerful technique at the Tevatron
    - More so at the LHC! (Now, only handful of ttbar events, but eventually 40K per month)
  - $Z \rightarrow$ bb jets
    - Achieved at the Tevatron. Will be hard at the LHC (more QCD BG)
  - $WW/WZ/ZZ \rightarrow (ll/l\nu/\nu\nu)+(jj)$



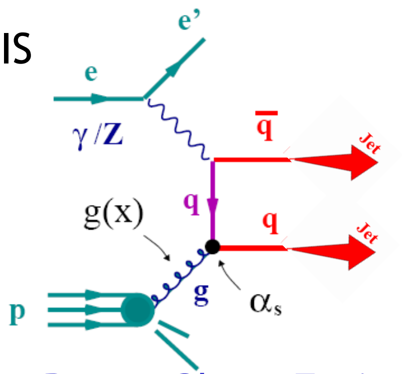




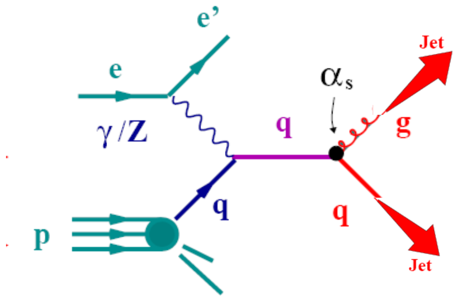
Inclusive Jet & Multijet Production

Jet Cross Section In ep Collisions

NC DIS



Boson-Gluon Fusion



QCD Compton

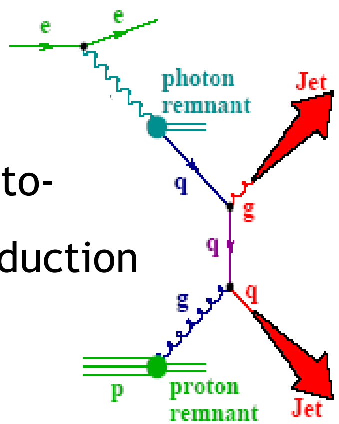
Measurements of these jet cross sections allow:

- Constrain proton (and photon) PDF
- Measurement of α_s
- Search for new physics
- …

$$d\sigma = \sum_{i=q,\bar{q},g}\int dx \boxed{f_i(x,\mu_F)}\, d\hat{\sigma}(x,\boxed{\alpha_s(\mu_R)},\frac{Q^2}{\mu_F^2},\frac{Q^2}{\mu_R^2},s)$$

Proton PDF Strong coupling constant

Photo-production



Photon flux in e Photon PDF

$$d\sigma = \sum_{i,j}\int dy \boxed{f_{\gamma/e}(y)}\int dx_p \int dx_\gamma \boxed{f_{j/\gamma}(x_\gamma,\mu_{F\gamma})}$$

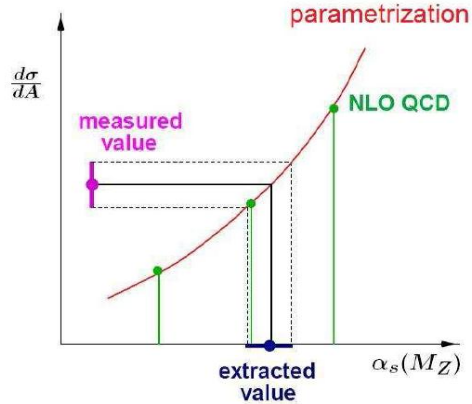
$$\boxed{f_{i/p}(x_p,\mu_{Fp})}\, d\hat{\sigma}(x_{\gamma,p},\boxed{\alpha_s(\mu_R)},\frac{Q^2}{\mu_{F_{\gamma,p}}^2},\frac{Q^2}{\mu_R^2},W)$$

Inclusive Jets in Photoproduction

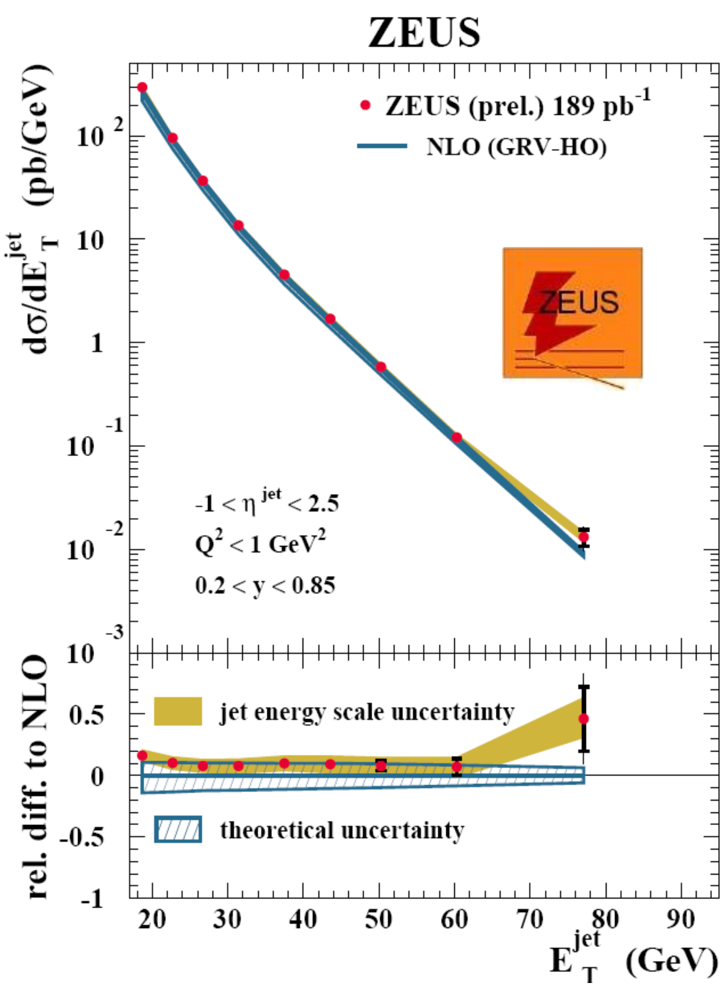
- Measured $d\sigma/dE_T$ in good agreement with NLO pQCD calculations
- α_s determination:
  - Parameterize $\alpha_s(M_Z)$ dependence of observable $d\sigma/dE_T$ in bin i by

$$\frac{d\sigma_i}{dE_T} = C_1^{\,i} \cdot \alpha_s(M_Z) + C_2^{\,i} \cdot \alpha_s^2(M_Z)$$

Treat correctly the correlation between $\alpha_s(M_Z)$ and the PDFs in the NLO calculations:



ZEUS-prel-10-003



$$\alpha_s(M_Z) = 0.1208^{+0.0030}_{-0.0018}(\text{exp.})^{+0.0044}_{-0.0033}(th.)$$

Total +2.2-1.2% uncertainty

Inclusive Jets in High-Q^2 DIS

ZEUS-prel-10-002

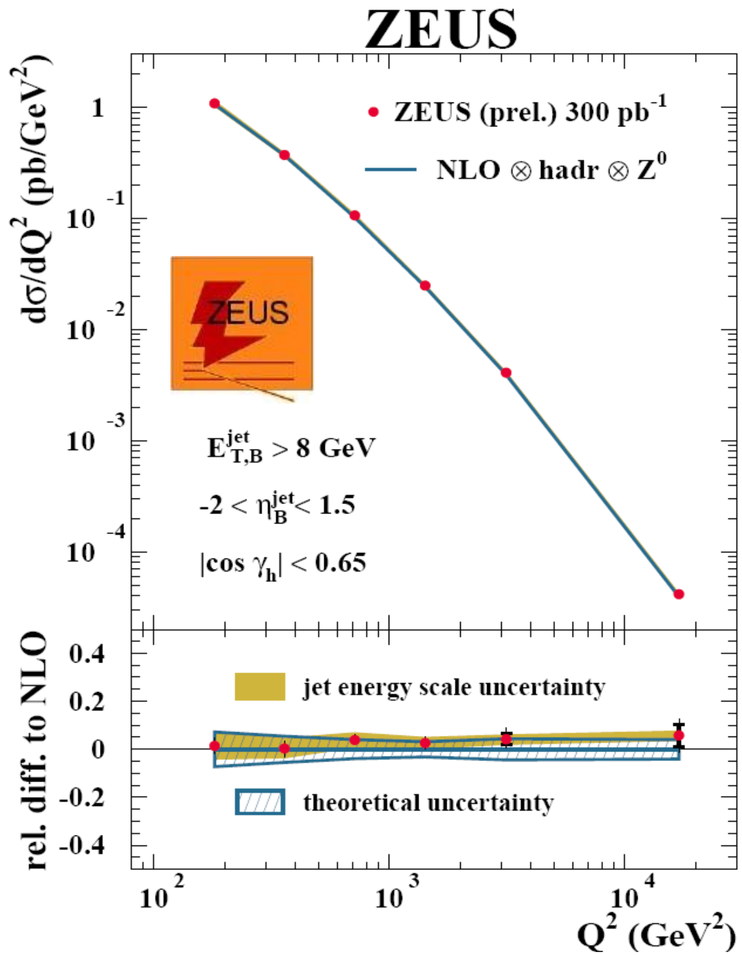
- Good description of data by NLO pQCD over many orders of magnitude in Q^2

- α_s from $d\sigma/dQ^2$ at Q^2>500 GeV^2

$$\alpha_s(M_Z) = 0.1208^{+0.0037}_{-0.0032}(\mathrm{exp.})^{+0.0022}_{-0.0022}(th.)$$

total +3.5-3.2% uncertainty
(theory uncertainty ~1.9%)

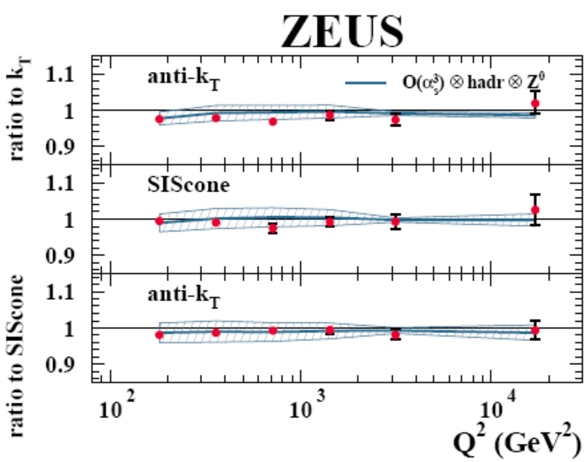
- Scale uncertainty still sizable. NNLO calculation has been waited for many years…

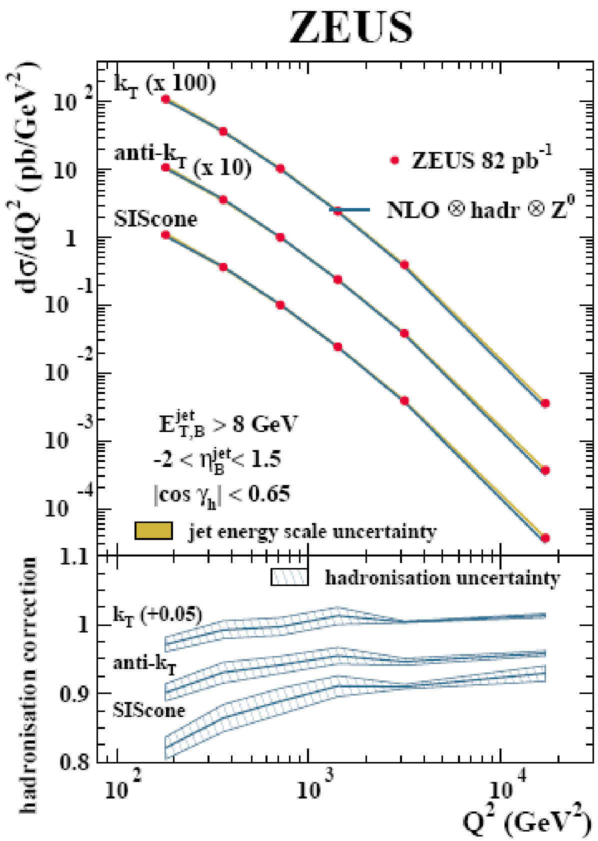


Inclusive Jets in High-Q^2 DIS

- Measurement made with Kt, Anti-Kt, and SISCone algorithms

The ratio of different algorithm results can be calculated up to NNLO (Note: cross section is calculable now up to NLO)





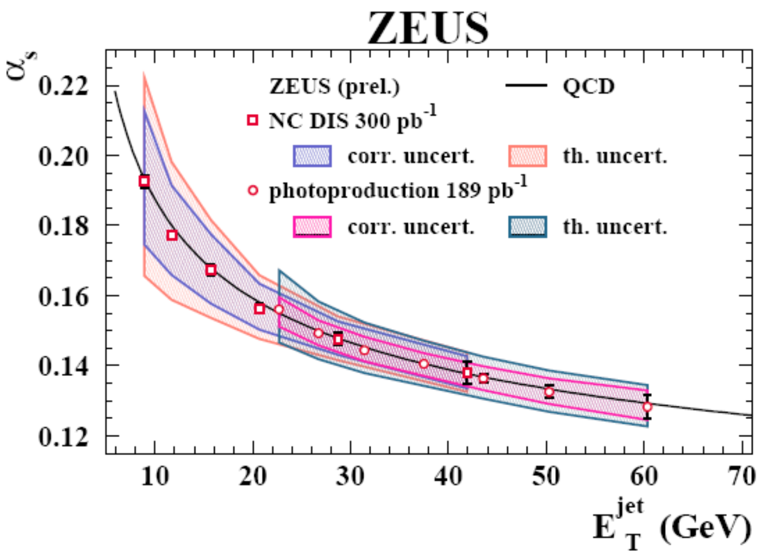
PLB 691 (2010) 127.

- Consistent results with different algorithms
- Good demonstration that the well-defined algorithms provide consistent results

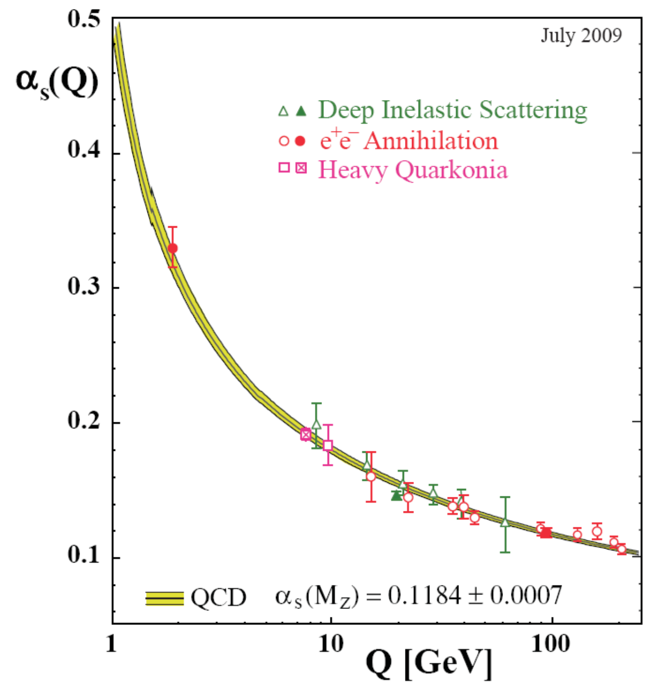
See lecture by Dr. Reisert

Strong Coupling Constant

- The HERA jet measurements can show a "running" of α_s in a single measurement

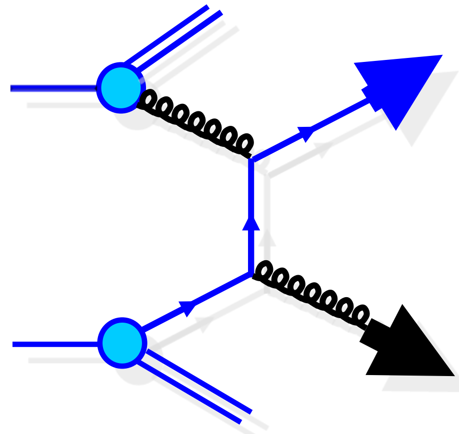


- α_s also from e^+e^- annihilation
  - Event shape – thrust distribution
  - Jet broadening
  - …



Consistent between different processes. Success of QCD!

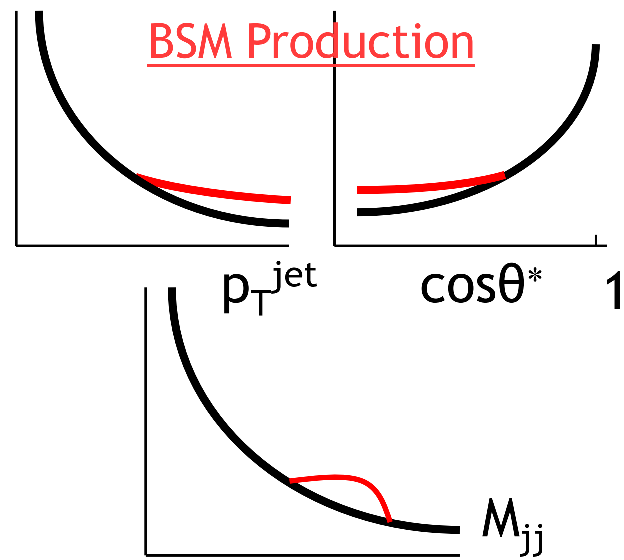
Inclusive Jet & Dijet Production in pp($\bar{p}$p)



QCD Production

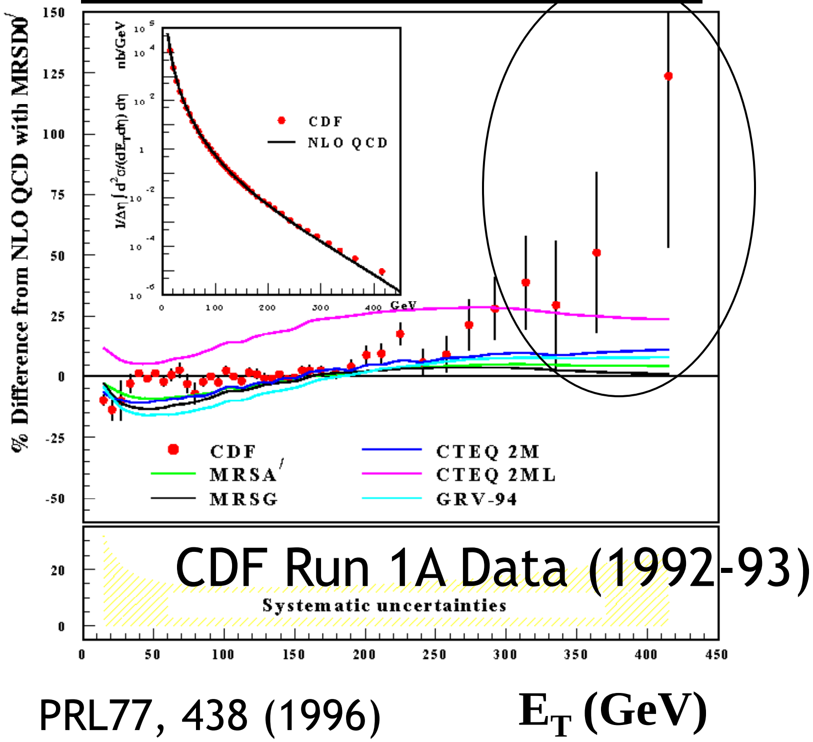
$$\sigma_{jet} = \sum_a \sum_b f_{a/p}(x_p, \mu_F^2)\, f_{b/\bar{p}}(x_{\bar{p}}, \mu_F^2)\, \hat{\sigma}_{a,b}\left(p_p, p_{\bar{p}}, \alpha_s(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

- Test pQCD at highest Q^2.
- Unique sensitivity to new physics
  - Compositeness, new massive particles, extra dimensions, …
- Constrain PDFs (especially high-gluons)
- Measure α_s

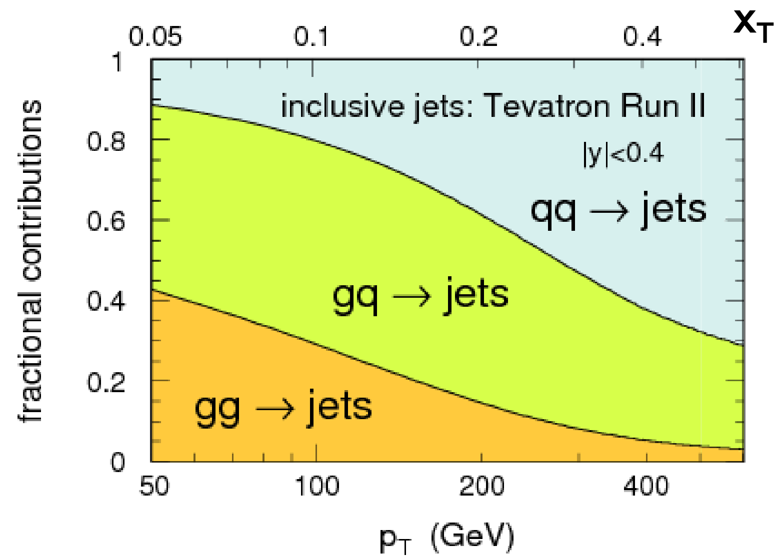


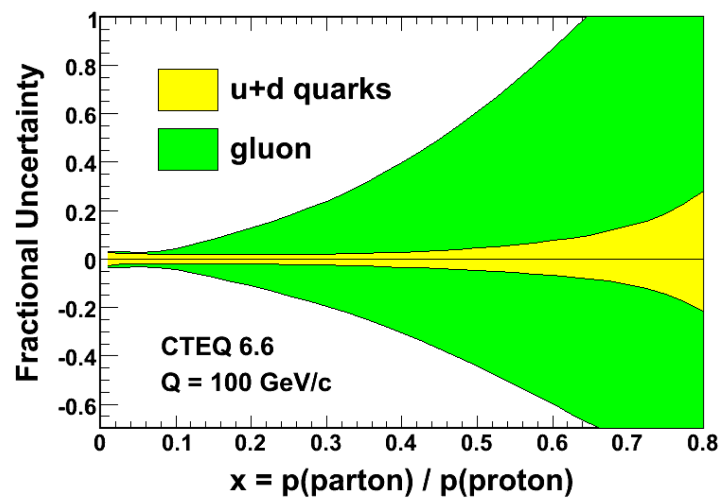
A Little History

Excitement(?) 15 years ago



PRL77, 438 (1996)



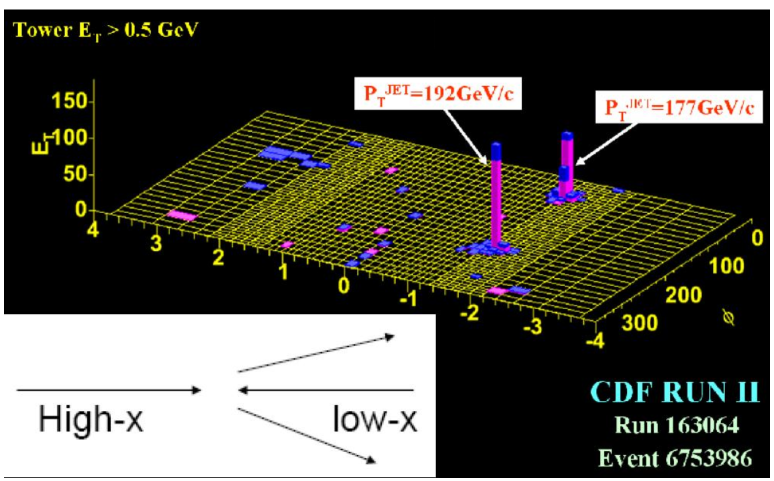


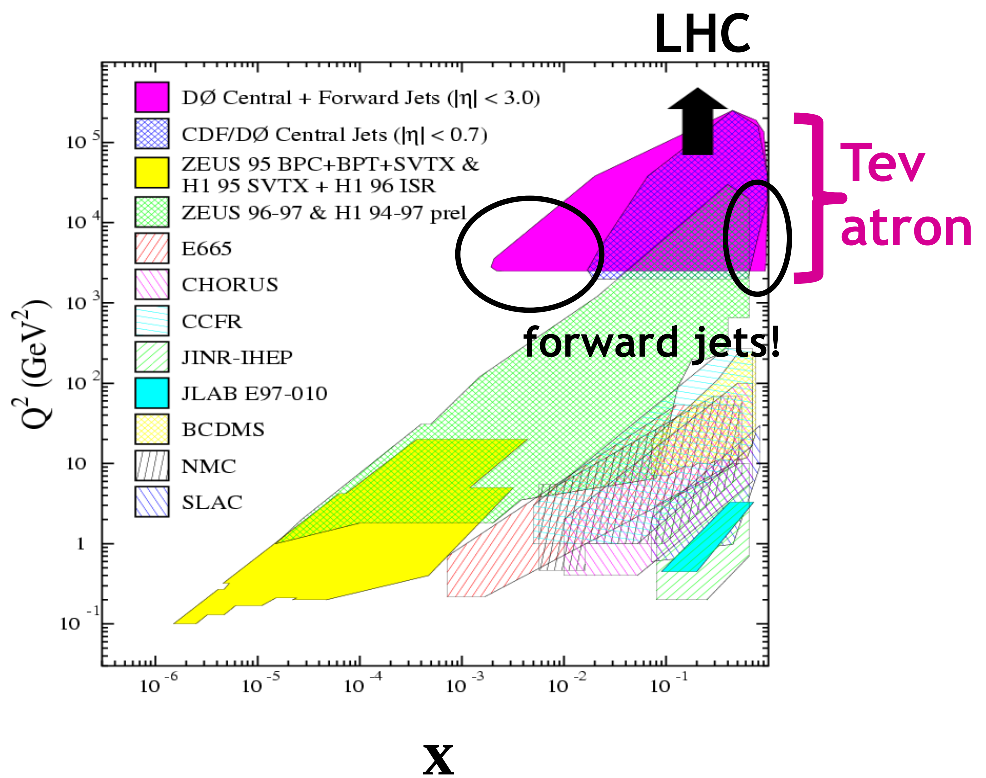
High-x gluon not well known

...can be accommodated
in the Standard Model

Forward (High |y|) Jets

- Forward jets probe high-x at lower Q^2 (= $-q^2$) than central jets
  - Q^2 evolution given by DGLAP
  - Essential to distinguish PDF and possible new physics at higher Q^2
- Also, extend the sensitivity to lower x





Inclusive Jet Cross Section Measurement

- How do we measure?

$$\frac{d^2\sigma}{dp_T\,dy} \leftrightarrow \frac{\boxed{N_{jet}}}{\boxed{\Delta p_T \cdot \Delta y}\cdot\boxed{\varepsilon}\cdot\boxed{\int L dt}}\cdot\boxed{C_{unfolding}} \quad vs. \; \boxed{jet\ p_T}$$

\# of jets in each (Pt, y) bin

Jet energy calibration

Pt and y bin width

Event/jet selection efficiency

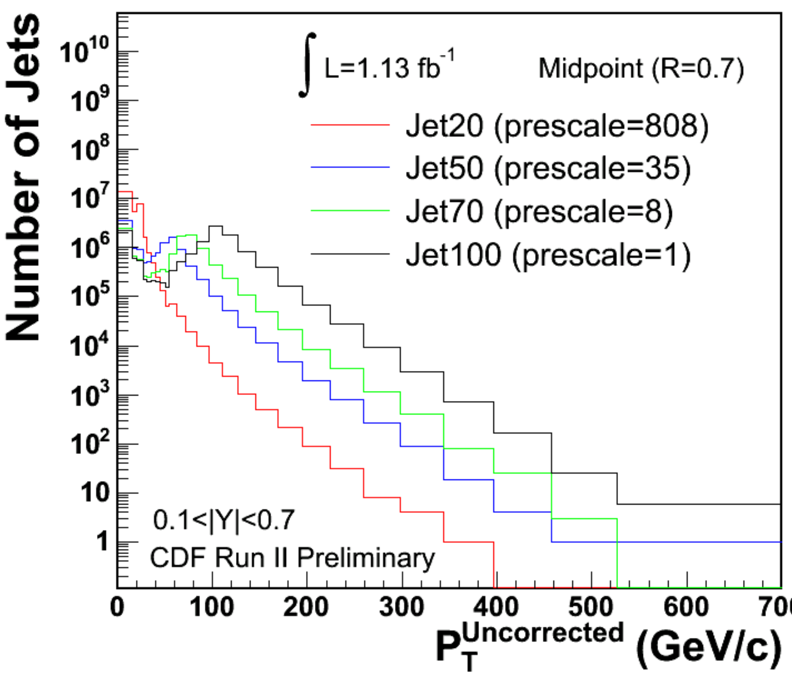
Integrated luminosity

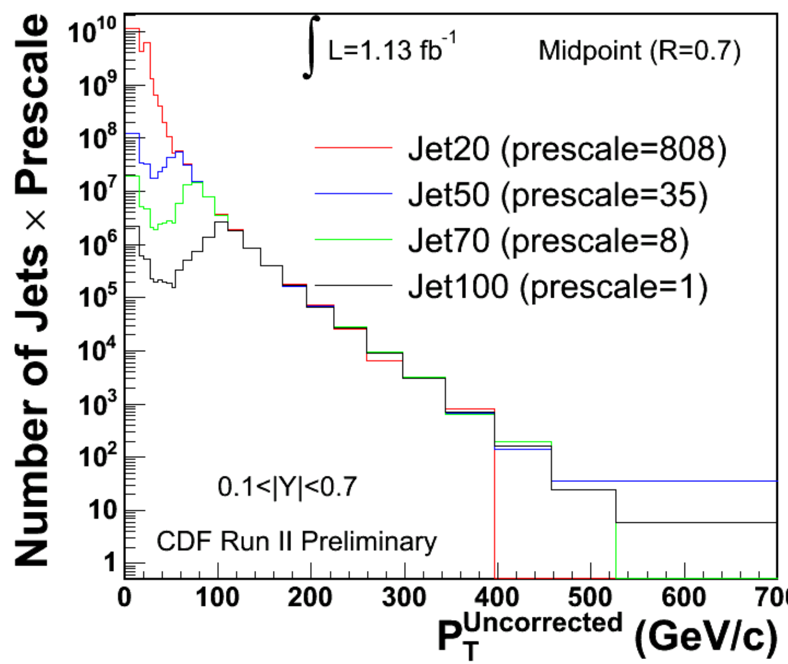
Jet energy resolution: jets move in or out from a bin

- Challenges:
  - Triggering
  - Jet energy scale
  - Unfolding
  - Corrections for non-perturbative effects
  - …

Inclusive Jets @ CDF

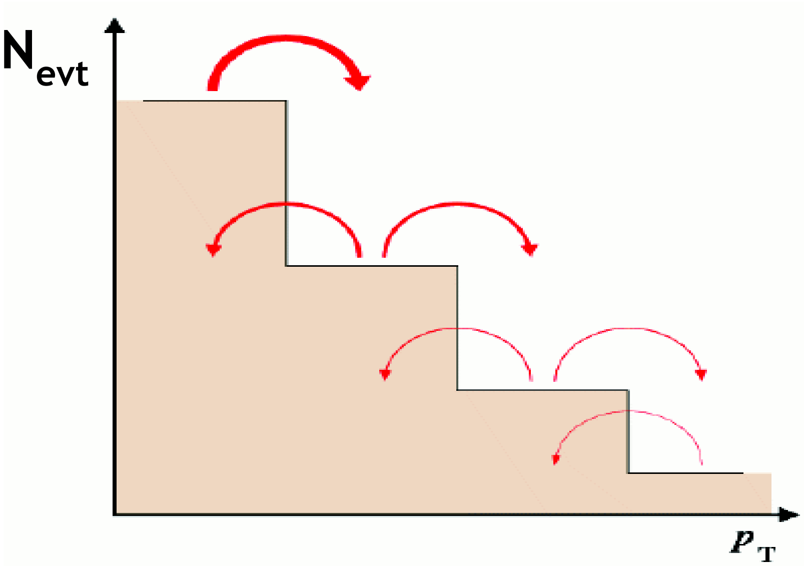
- The measurement spans over 8 orders of magnitude in cross section
- A single trigger (online event selection) system cannot cover all
- Use different trigger samples
  - Trigger on single jets with different Pt thresholds and prescales
- Full pT spectrum combined from seven different triggers

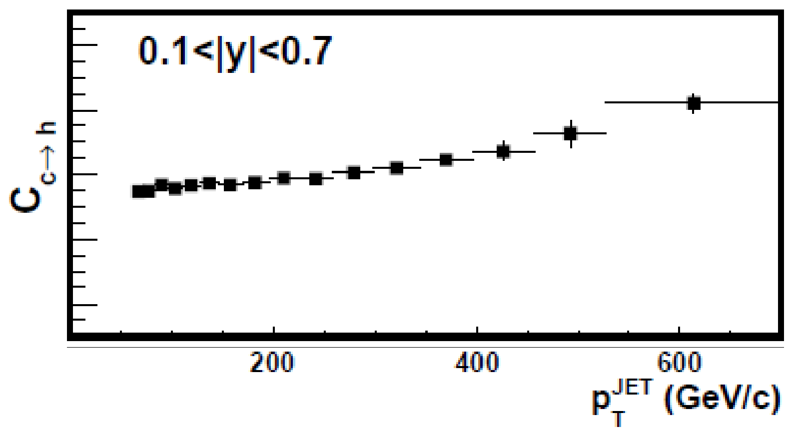




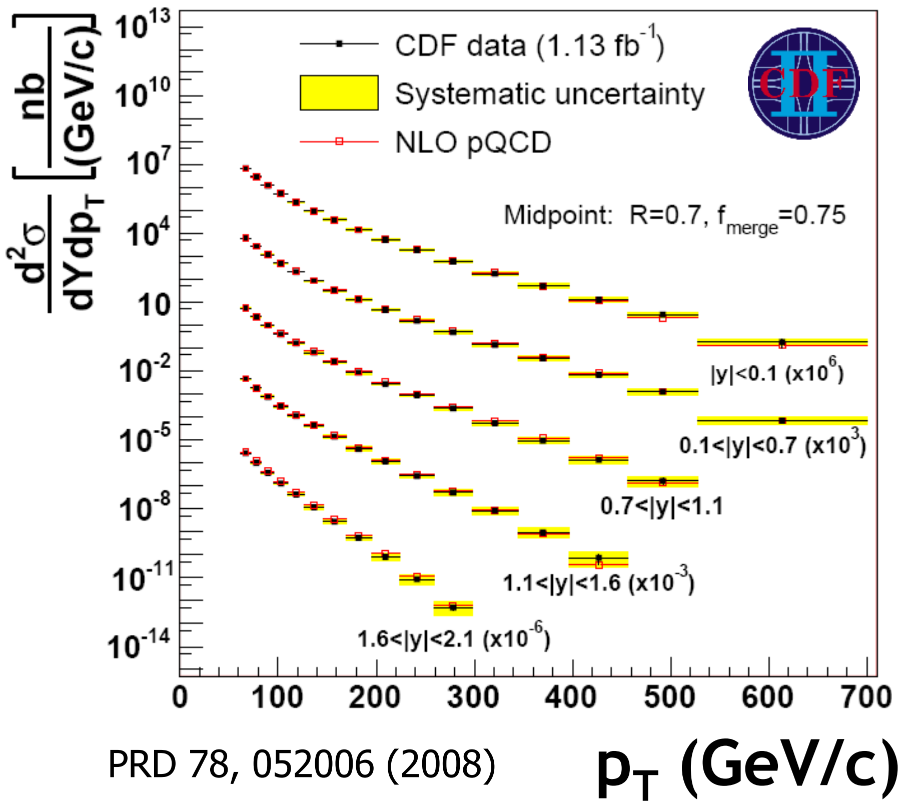
Inclusive Jets @ CDF: Unfolding

- Unfolding correction accounts for finite jet energy resolution
  - Jets move in and outside a pt and y bin due to a finite resolution
  - A steeply falling spectrum gets gets affected
- There are several unfolding techniques:
  - Bin corrections
  - Regularized matrix inversion
  - Bayesian unfolding
- Used the bin correction method
  - taTe a "true distribution" from MC
  - Smear it with full detector simulation
  - Reweight MC
  - Take the ratio of true / smeared in each bin – apply to data

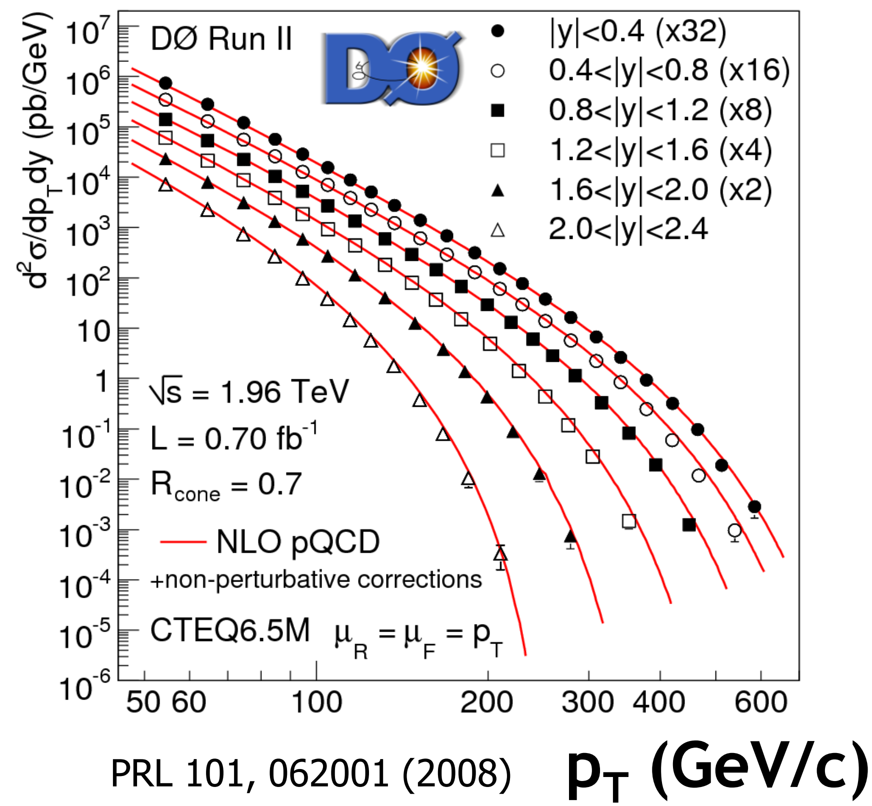




Inclusive Jet Cross Section



PRD 78, 052006 (2008)

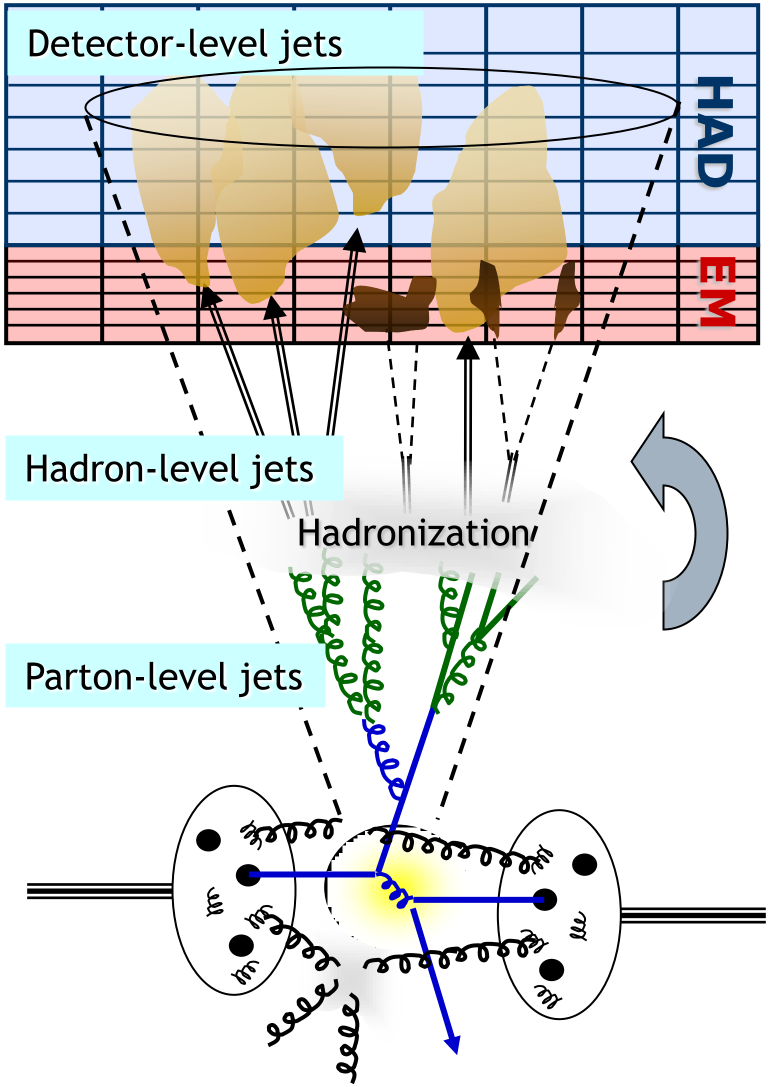


PRL 101, 062001 (2008)

Results with Kt alorithm PRD 75, 092006 (2007)

- Test pQCD over 8 order of magnitude in $d\sigma^2/dp_T dy$
- Highest p_T^{jet} > 600 GeV/c: shortest distance scale – soon to be surpassed…

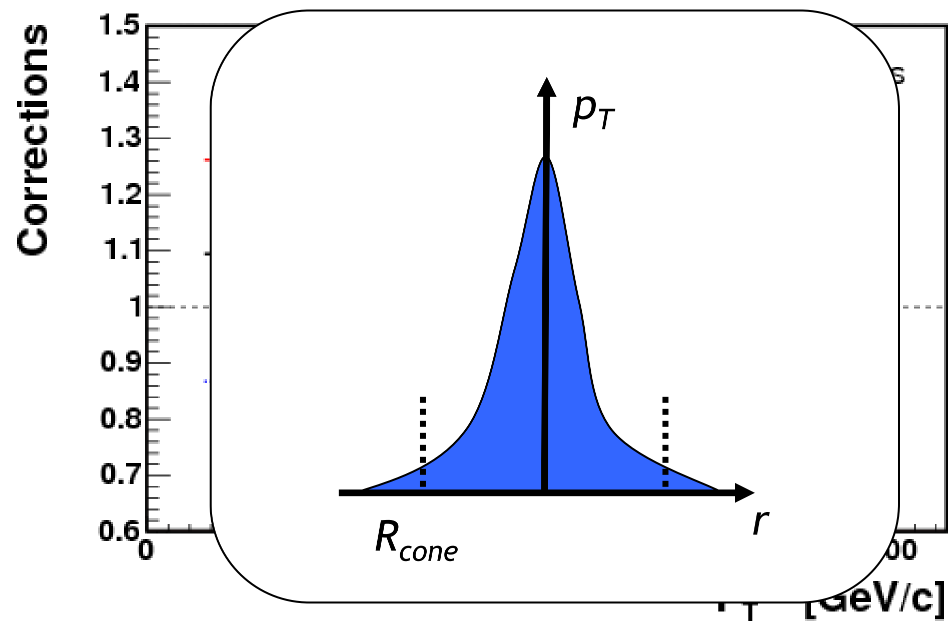
UE & Hadronization Correction



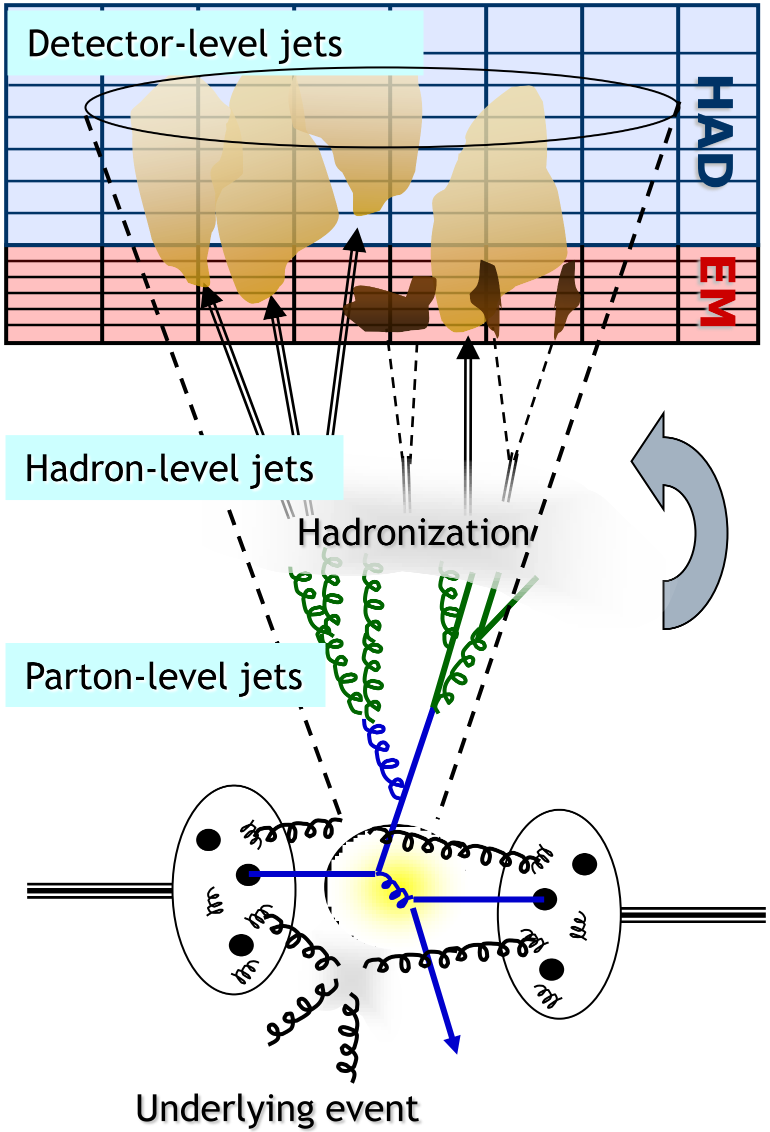
Currently-available state-of-the-art next-to-leading-order QCD predictions do not take into account:

- Underlying event (UE)
- Hadronization

These effects are estimated using Monte Carlo event generator (Pythia) tuned to data.



UE & Hadronization Correction



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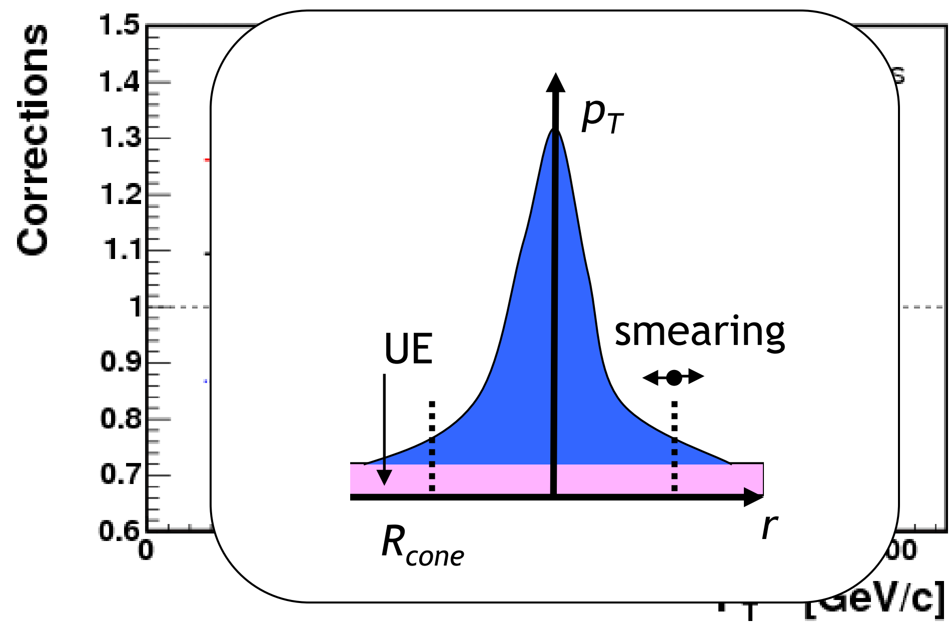
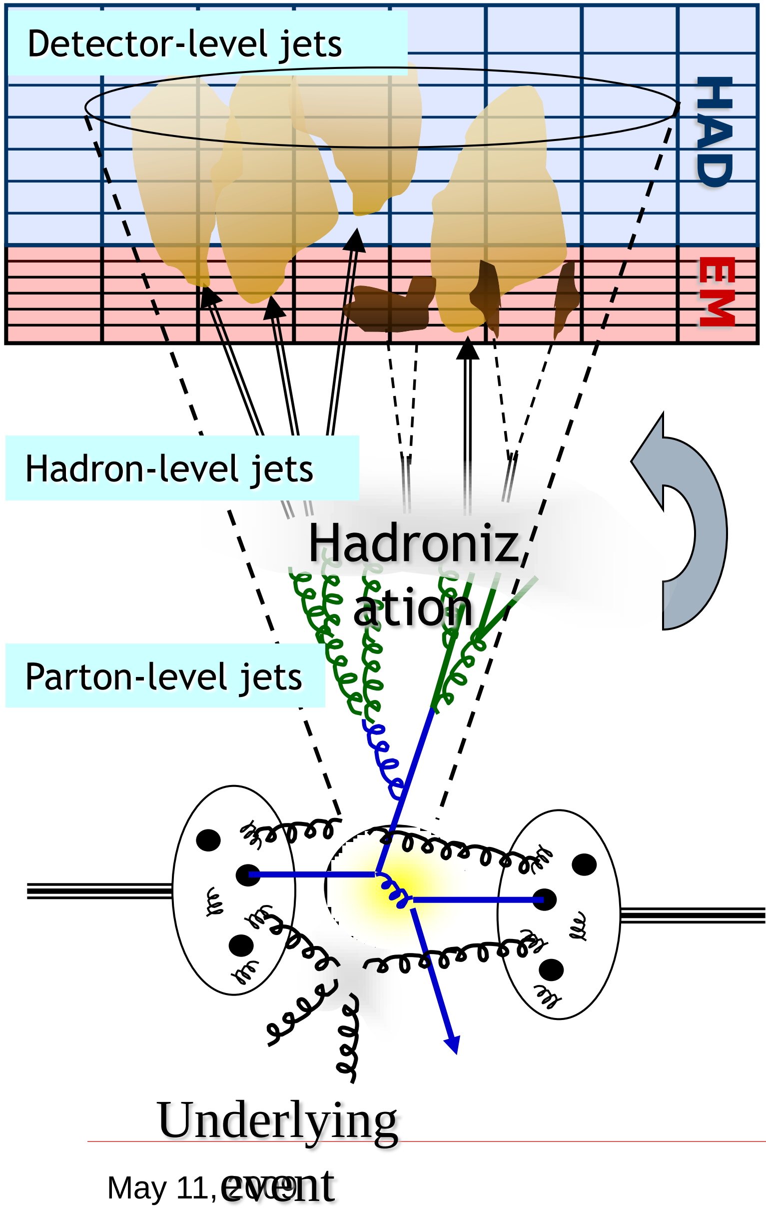


UE & Hadronization Correction



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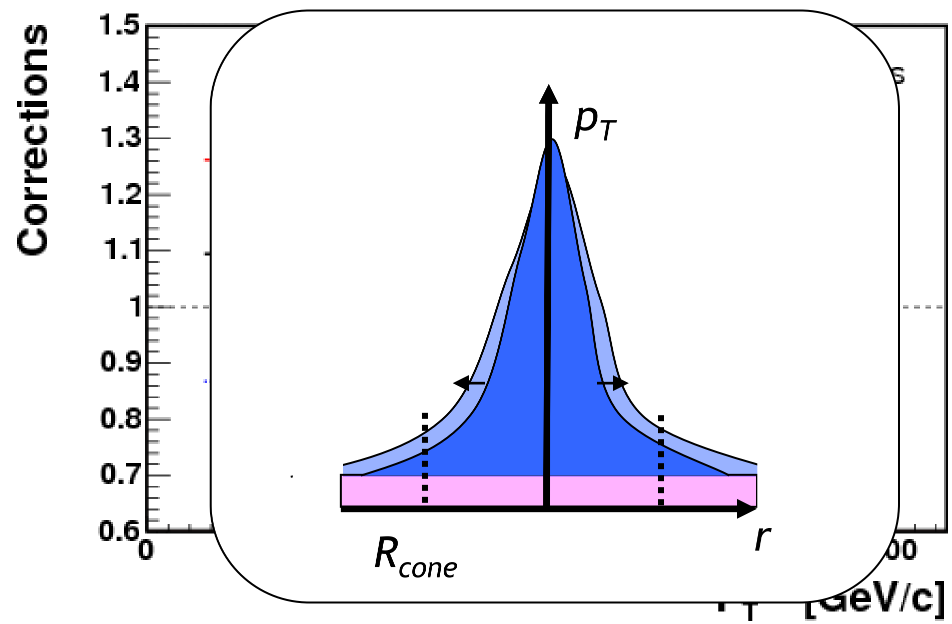
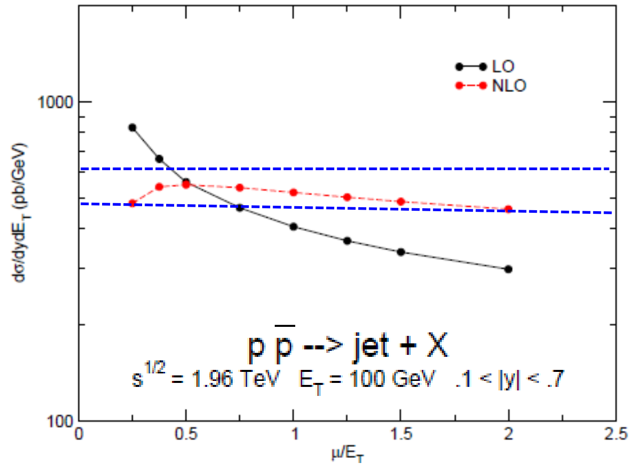


Theoretical Predictions

- The best available theoretical predictions for inclusive jet cross sections at $p\overset{(-)}{p}$ & ep are from next-to-leading order (NLO) pQCD
  - S. Ellis, Z. Kunszt, and D. Soper, PRL 64, 2121 (1990).
  - W. Giele, E. Glover, and D. Kosower, NPB 403, 633 (1993).
  - Z. Nagy, PRD 68, 094002 (2003).

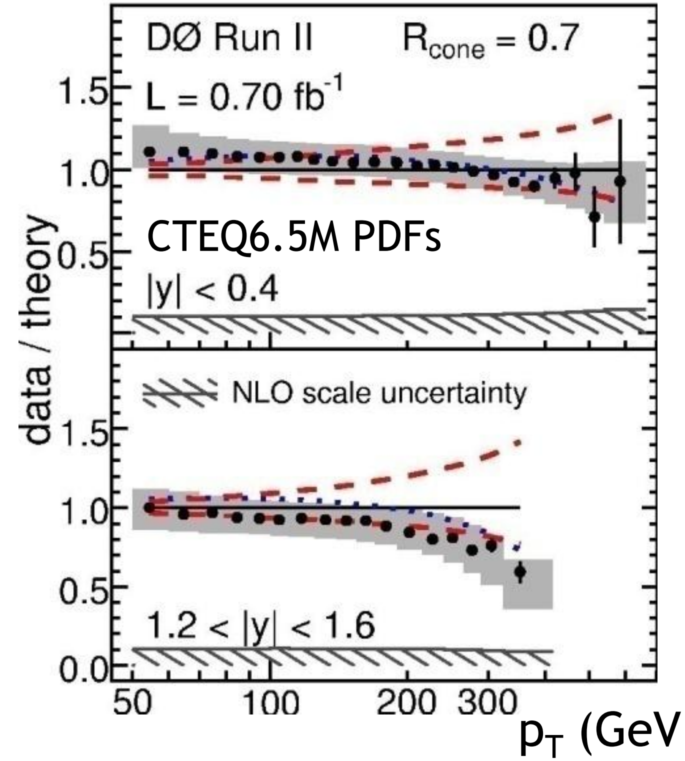


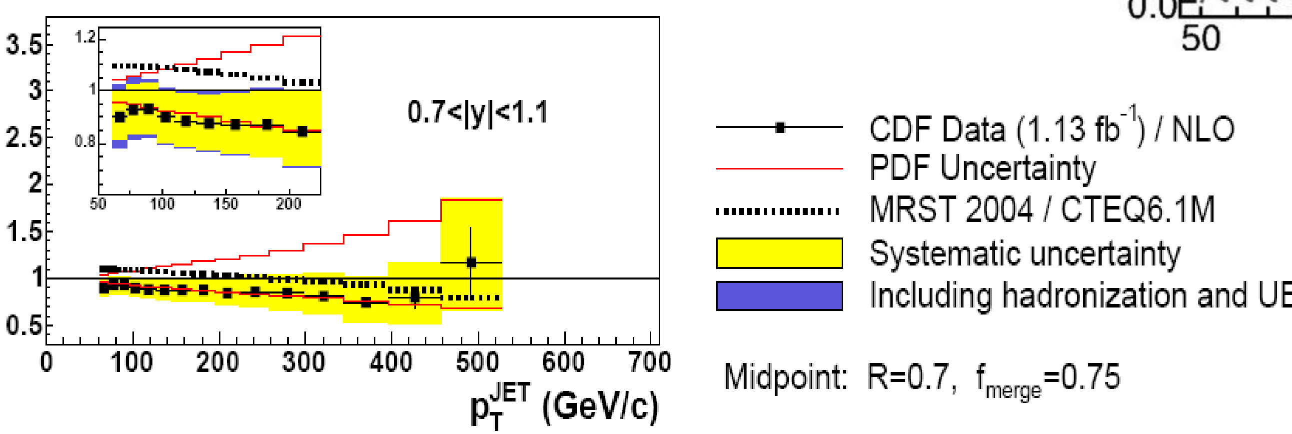
~±10%

- Next-to-next leading order pQCD predictions have been in “will come soon” for quite some years…
  - 2-loop ($O(\alpha_s^4)$) term from threshold corrections (N. Kidonakis, J. F. Owens, PRD 63, 054019) is available and used in some analysis

Inclusive Jet Cross Section

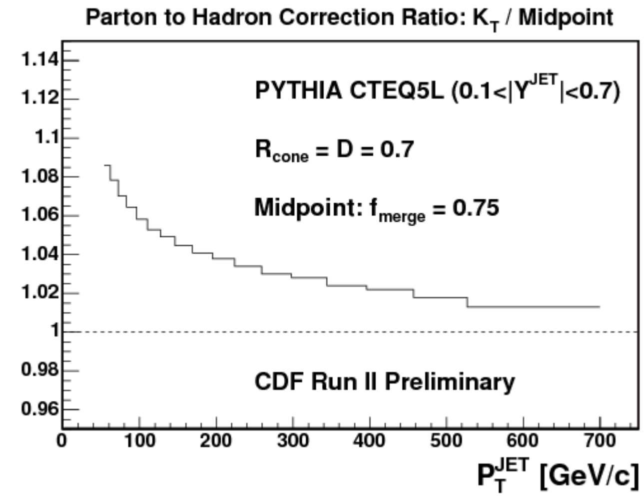
- Run II Tevatron measurements are in agreement with NLO predictions
  - Both in favor of somewhat softer gluons at high-x
- Experimental uncertainties: smaller than PDF uncertainties
- Used in recent global QCD fits

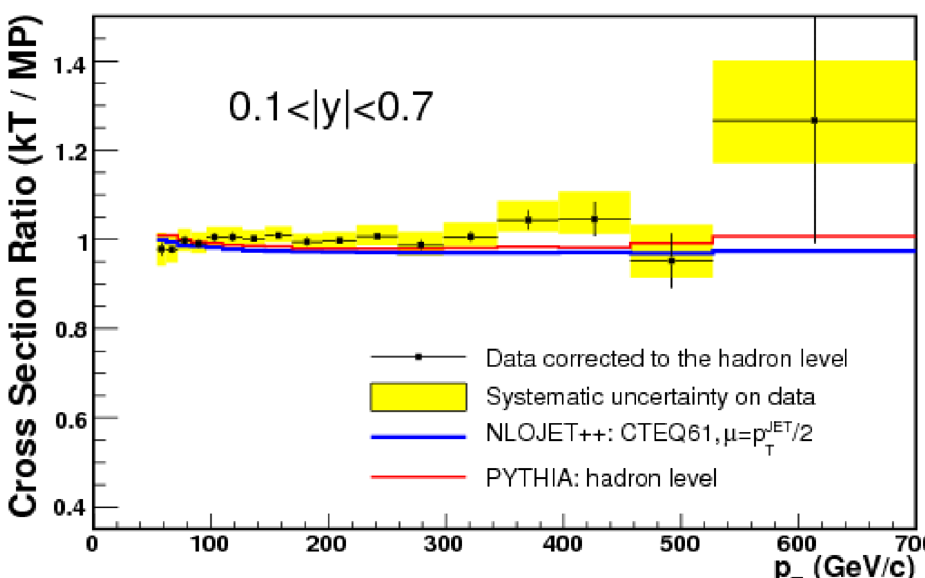




Cone versus Kt Algorithm Results

- At the parton level, $\sigma(k_T)<\sigma(\text{cone})$ with $R_{cone}=D$.
  - Cone algorithm tend to merge two energetic clusters with large separation (>R_{cone}=D) more than the k_T algorithm.
- Non-pertubative (UE+hadronization) effects larger for the k_T algorithm
  - $\sigma(k_T)$ ~ $\sigma(\text{cone})$ at the hadron level.

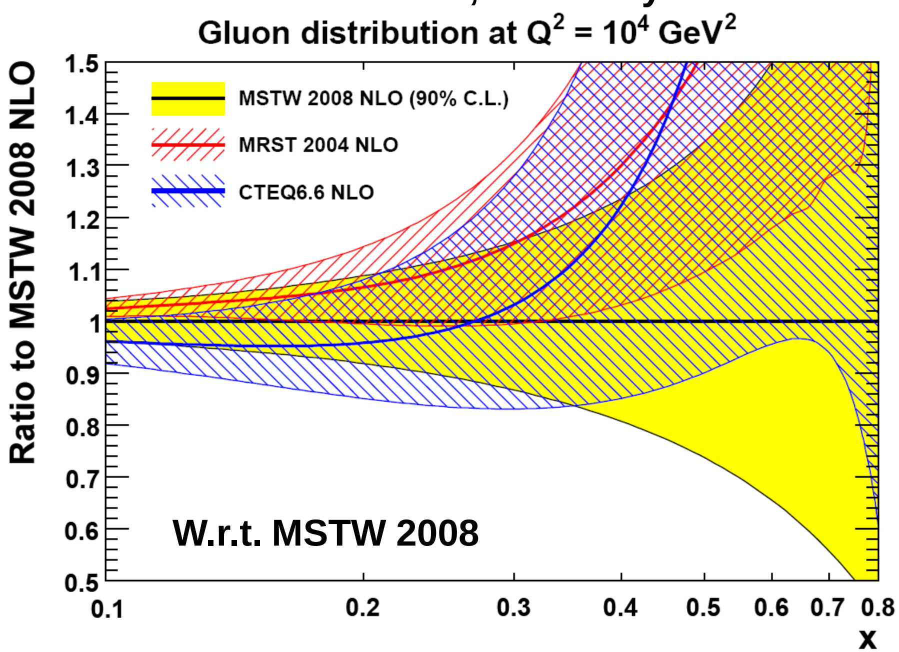




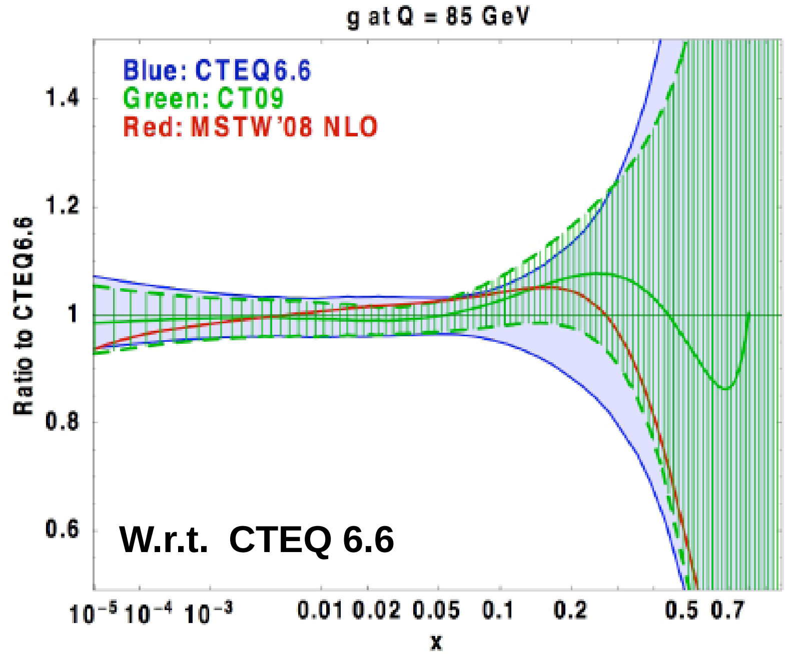
Measured $\sigma(k_T)$ / $\sigma(\text{cone})$ in general agreement with the expecation.
Robust data-theory comparisons

PDF with Recent Tevatron Jet Data

MSTW08: 0901.0002, Euro. Phys. J. C



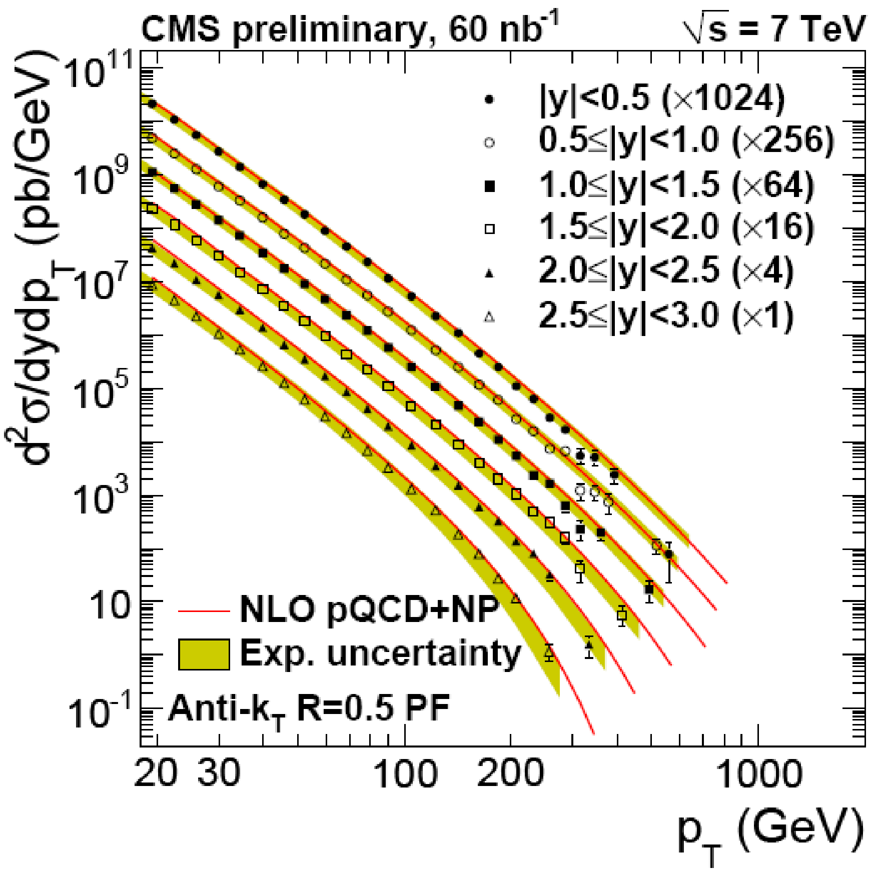
CT09: PRD80:014019, 2009.

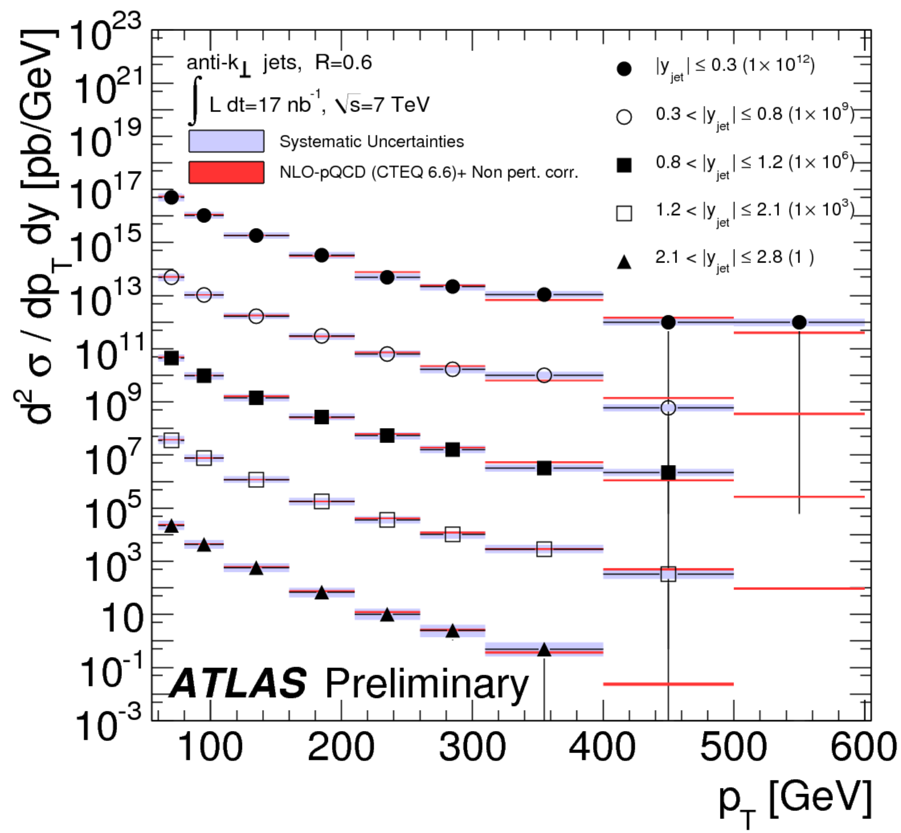


- Tevatron Run II data lead to softer high-x gluons (more consistent with DIS data)

Inclusive Jets at the LHC

ATLAS-CONF-2010-050





- LHC preliminary results are already becoming available
- Jet energy scale uncertainty 5-10% range (c.f. 1-3% at the Tevatron)

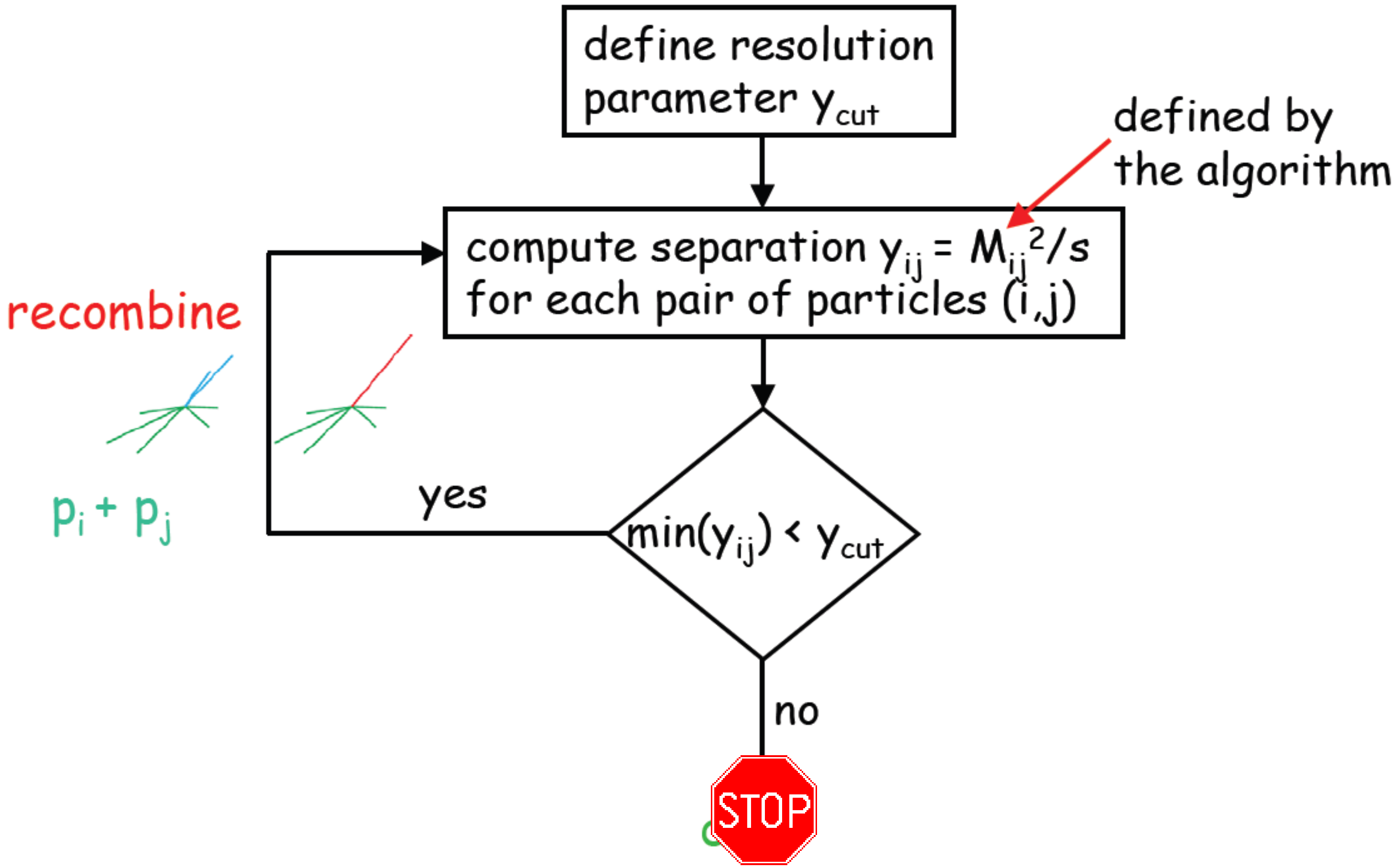
Today's Summary

- Jets play important roles in various aspects of particle physics
  - QCD studies: quark/gluon properties, QCD SU(3) structure, α_s, PDF, etc
  - And searches for Higgs and physics beyond the Standard Model
- After many years of work, jet algorithms are quite established now
  - Infrared and collinear safe algorithms are available that work well for both experimentalists and theorists
  - Features of each algorithm is now well understood
- Jet energy calibration takes a lot of effort
  - The experience from the Tevatron greatly benefits LHC experiments
- Inclusive jet production at HERA and Tevatron
  - Provide important information for α_s and PDF

Backup

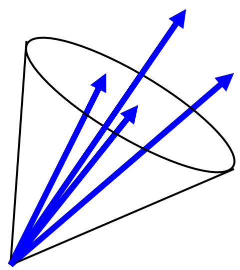
Jet Algorithms: Recombination

Basic Idea: Successively find the "closest" pair of particles & combine them



Cone Algorithms for Hadron Colliders

- “Has been” a primary choice for hadron colliders
- Basic idea: Cluster objects based on their proximity in y-ϕ space and find stable cones (kinematic centroid = geometric center).



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

$$p^C \quad = \quad (E^C, \mathbf{p}^C) = \sum_{i \subset C} (E^i, p_x^i, p_y^i, p_z^i) \,,$$

$$\bar{y}^C \quad = \quad \frac{1}{2} \ln \frac{E^C + p_z^C}{E^C - p_z^C} \,, \quad \bar{\phi}^C = \tan^{-1} \frac{p_y^C}{p_x^C} \,.$$

Stable cone when

$$y^C = \bar{y}^C, \varphi^C = \bar{\varphi}^C$$

- Intuitive, but a few undesired aspects…
- Often infrared unsafe
  - For CPU reason, search for stable cones starting from “seeds” (particles above some Pt threshold) → source of infrared unsafety.
  - Addressed by Midpoint algorithm and seedless SISCone algorithms
  - SISCone is somewhat slow. Not usable for heavy ion physics.
- Still stable cones sometime overlap → Need somewhat adhoc procedure to merge/split: merge cones when p_T overlap > 75%

Jet Algorithms for Hadron Colliders

- Recombination-type

  Basic Idea: Successively find the "closest" pair of particles & combine them

  - Examples: JADE, Kt, Cambridge/Aachen, Anti-Kt
  - Used extensively in ee and ep collider
  - Theoretically well-behaved ☺
    - Infrared and collinear safe
  - Irregular shape (except Anti-Kt?) is a challenge for experimentalists (underlying event and pileup corrections)

- Cone-type

  Basic Idea: Search for the cone, in which the vector sum of particles points toward the cone centroid (stable cones)

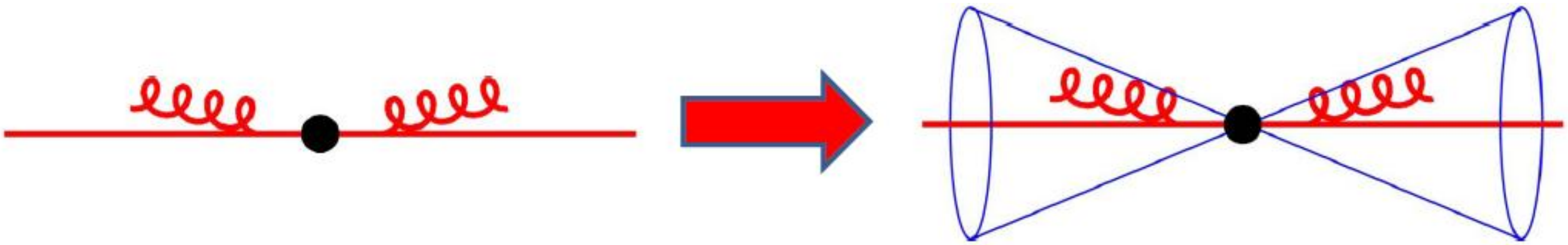
  - Examples: JetClu, MidPoint, SISCone
  - Primarily used in pp (pp) colliders
  - Regular cone shape ☺ (unless cones do not overlap)
  - Infrared and collinear unsafety ☹
  - Stable cones sometimes overlaps ☹

Kt ("Durham") Algorithm

- S. Catani et al., Phys. Lett. B269 (1991) 432
- Metric: $M_{ij}^2 = 2\min(E_i^{\,2}, E_j^{\,2})(1-\cos\theta_{ij})$ ~ (invariant mass)^2
- For small emission angles θ_{ij},

$$M_{ij} \approx 2\min(E_i^{\,2}, E_j^{\,2})[1-(1-\theta_{ij}^{\,2}/2+\cdots)] \approx \min(E_i^{\,2}, E_j^{\,2})\theta_{ij}^{\,2} \approx k_T^{\,2}$$

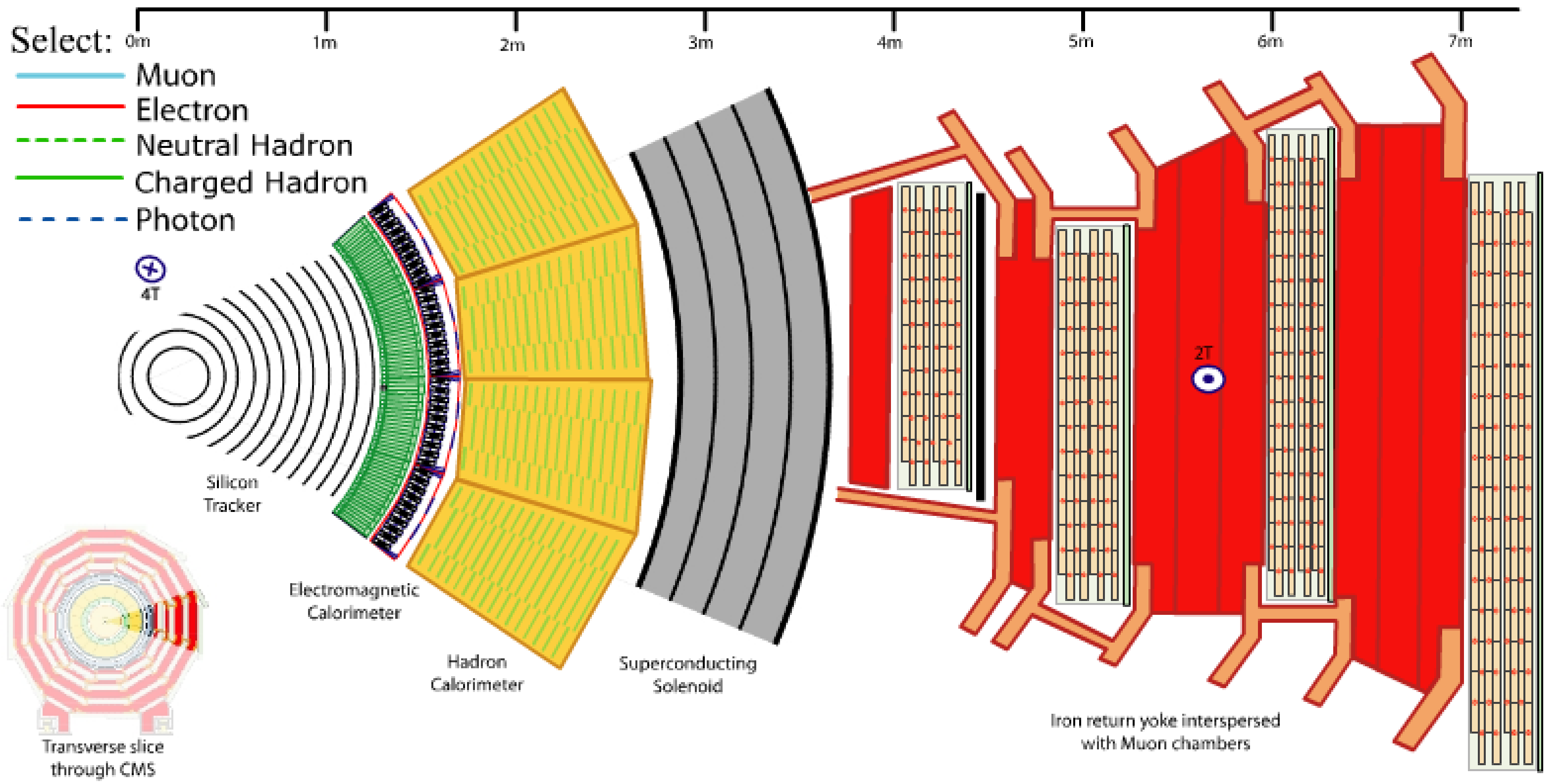
  - Smaller of the transverse momentum of I wrt j or j wrt I
  - Soft colinear radiation is attached to the correct jet



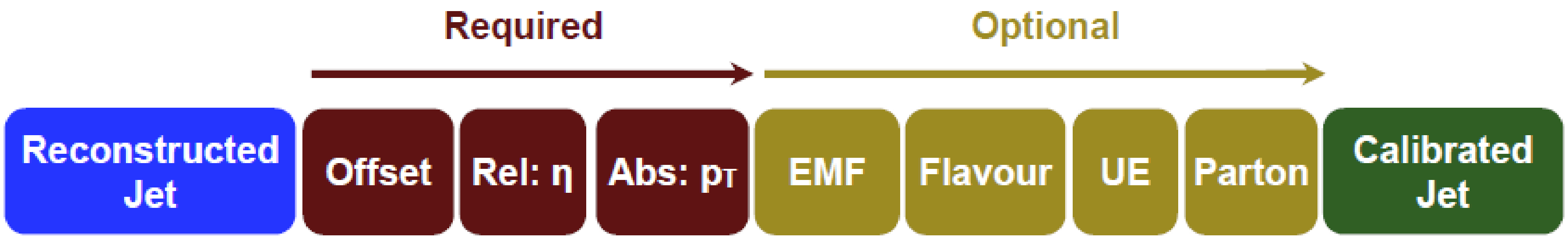
- Largely inhibits junk jets, allows resummation

Measurements in Detectors

Jets typically consist of ~65% charged hadrons, ~25% of $\pi^0 \to \gamma\gamma$, ~10% of neutral hadrons.



Jet Energy Correction

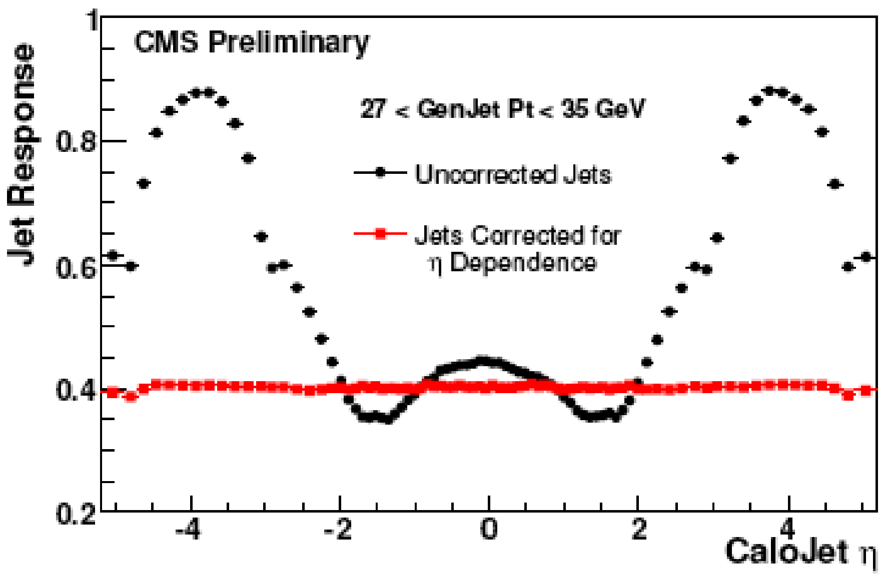


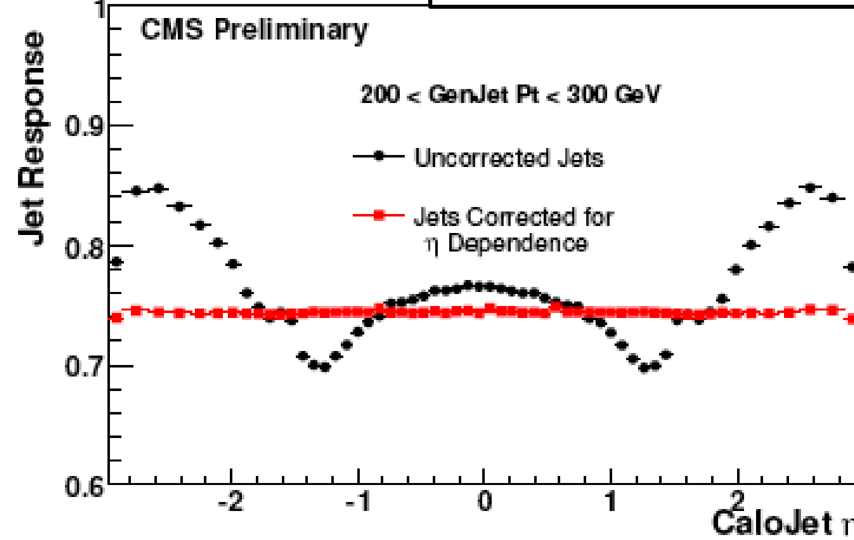
- Energies measured by the calorimeters need to be corrected for the calorimeter non-linearity and non-uniformity
- Multi-step approach a la Tevatron experiments

  (correct for different effects step-by-step)
  - Offset: correct for noise and pileup
  - Relative (η): Equalize jet response to the control region (barrel)
    - Use dijet p_T balance
  - Absolute (p_T): Correct measured p_T to particle level p_T
    - Use photon+jet and Z+jet p_T balance
  - And optional analysis dependent corrections

Relative Jet Energy Correction

CMS PAS JME-07-002
CMS PAS JME-08-003





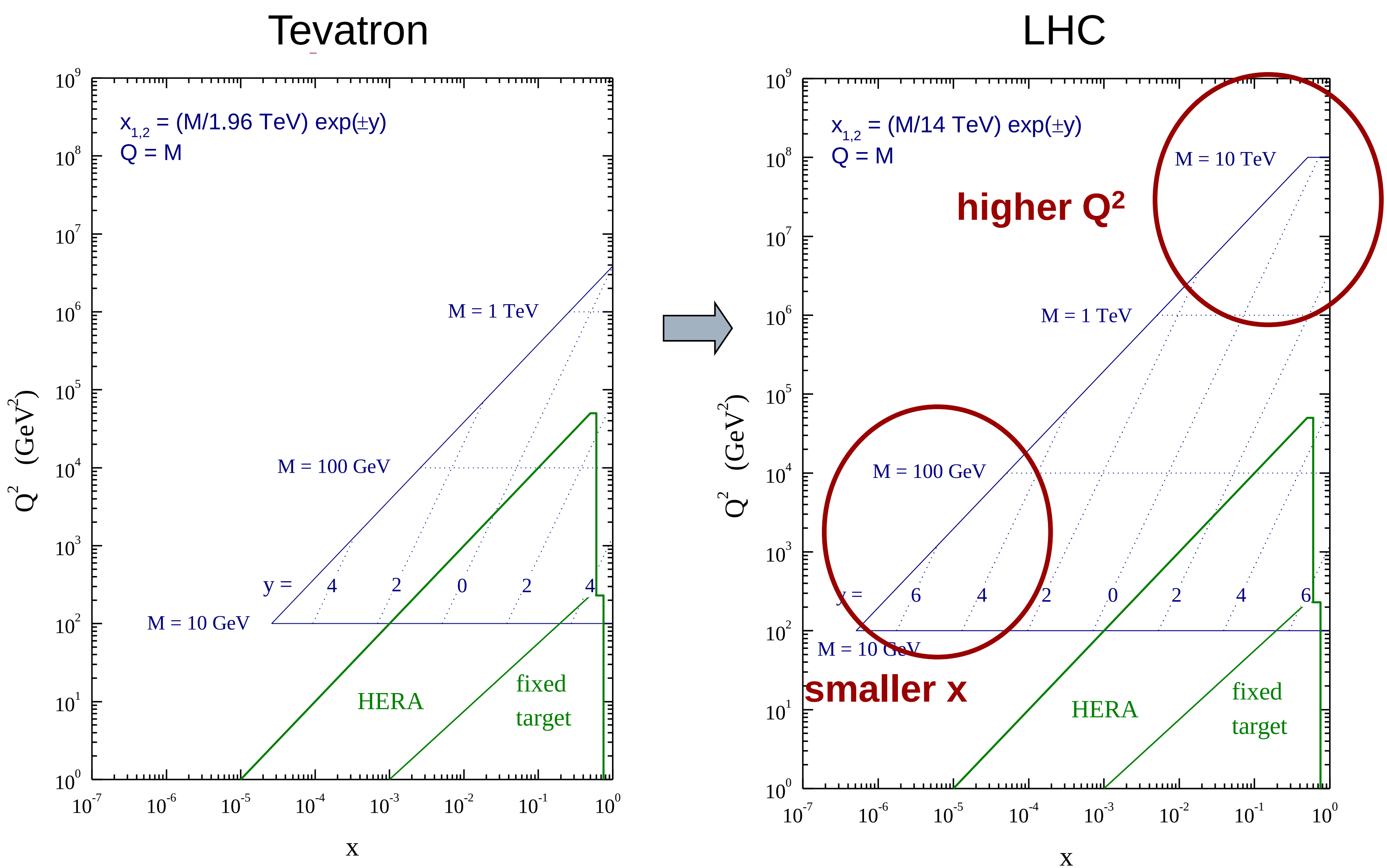
- The relative correction equalize jets outside the "barrel" region to jets in the barrel, where the absolute scale will be determined
- It will be measured from data with the dijet balance method.
- 1 pb^{-1} of data should be enough to derive this correction

Trigger jet: barrel region
Probe jet: anywhere

$$\Delta p_T f \equiv \frac{\Delta p_T}{p_T^{ave}} = \frac{p_T^{probe} - p_T^{trigger}}{(p_T^{probe} + p_T^{trigger})/2}$$

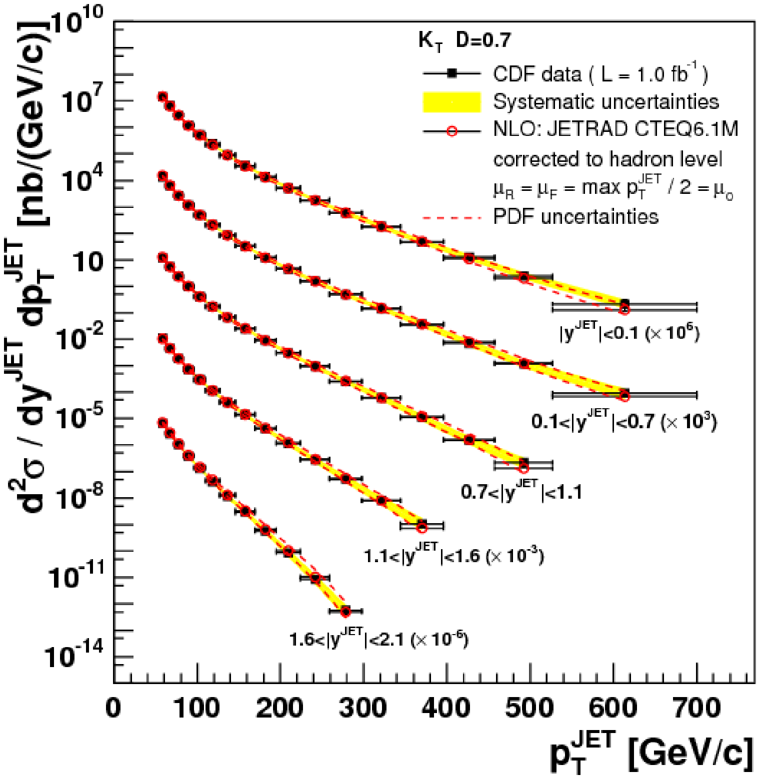
$$\beta \equiv \frac{p_T^{probe}}{p_T^{trigger}} = \frac{2 + \langle \Delta p_T f \rangle}{2 - \langle \Delta p_T f \rangle}$$

Tevatron → LHC Parton Kinematics

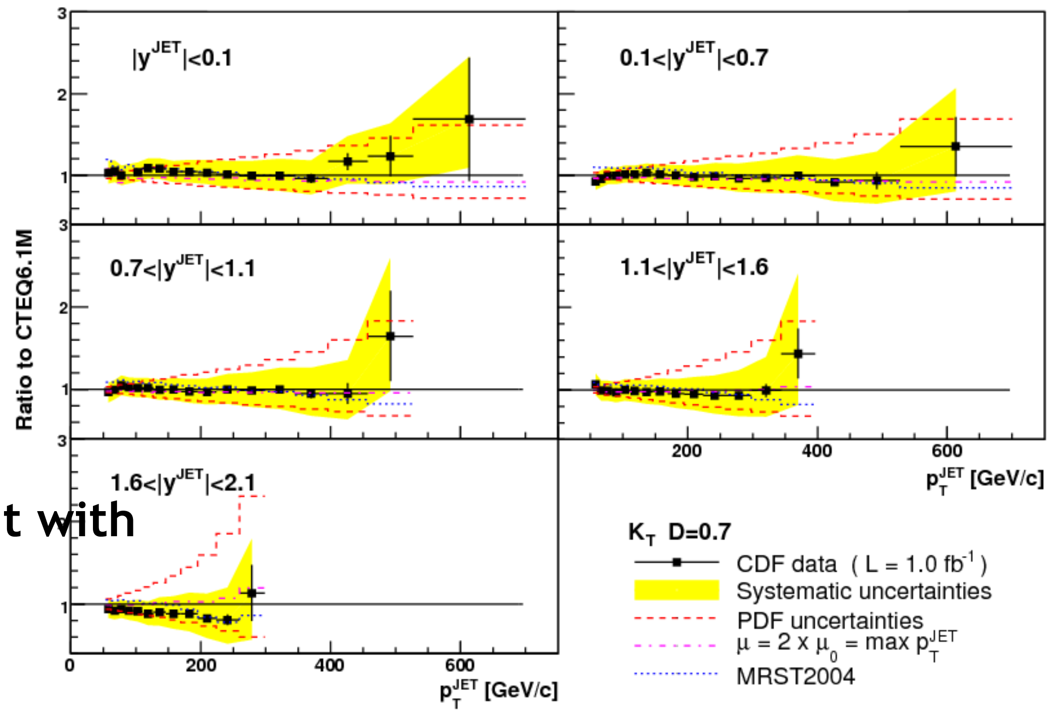


From J. Stirling (U. Durham)

Inclusive Jets with k_T Algorithm



- L = 1.0 fb^{-1}
- Jets reconstructed with the k_T algorithm, *D*= 0.7.



Again, data in good agreement with NLO pQCD predictions

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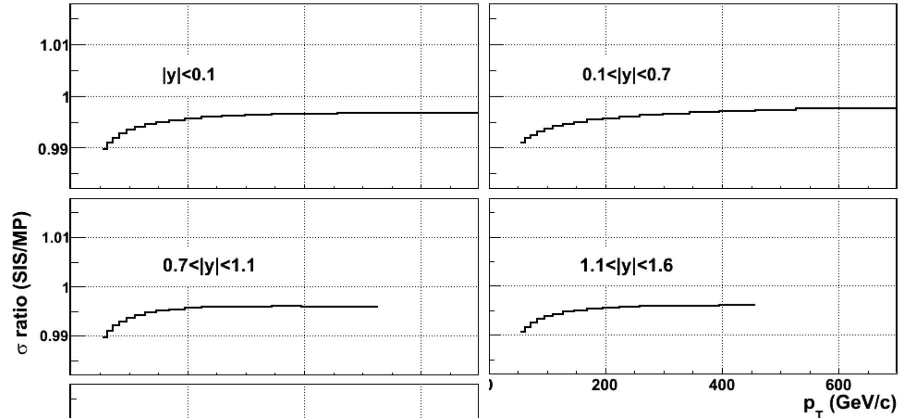
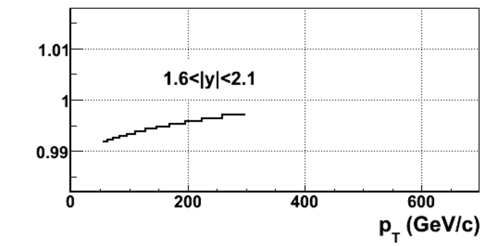
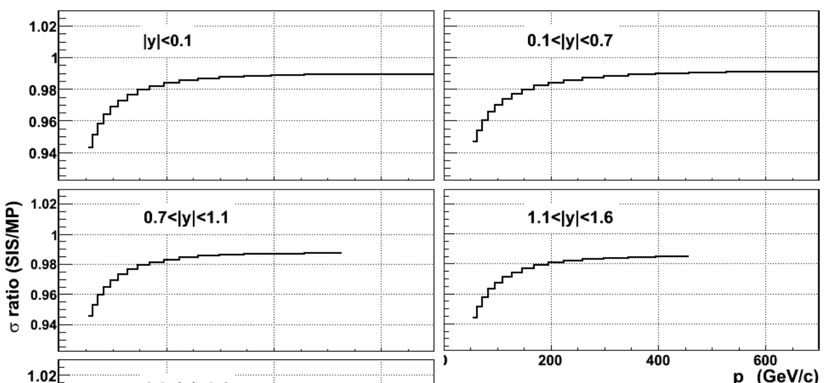
SISCone Vs Midpoint

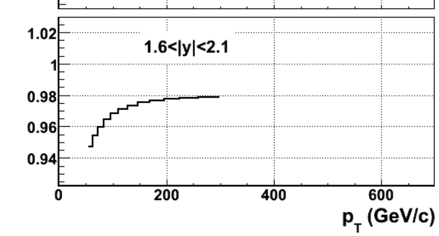
- SISCone is preferred theoretically due to infrared and collinear safety at all orders of pQCD (Midpoint only up to NNLO)





Parton level:
Both corrections are similar





Particle level:
less contribution from UE for SISCone

- No explicit jet cross section measurement with SISCone at the Tevatron, but a MC study was performed
- Differences of a few percent at the particle level reduces to ~1% at the parton level
- Negligible effect

End