FISICA ADRONICA AL TEVATRON (..e in generale ad una macchina adronica)

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Lezione 1:

- Il Tevatron
- Highlights del programma di fisica
- Problematiche QCD - PDF
- Fisica dei Jet

Tevatron

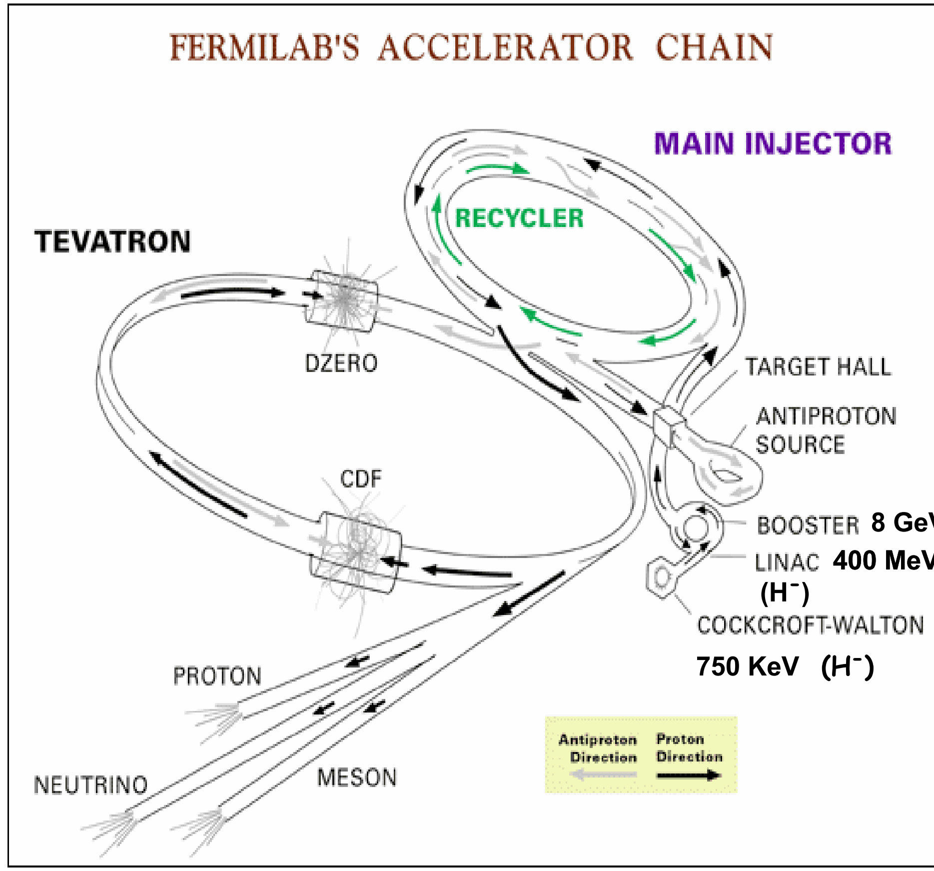
- proton-antiproton collisions

  $\sqrt{s} = 1.96$ TeV (Run I $\rightarrow$ 1.8 TeV)

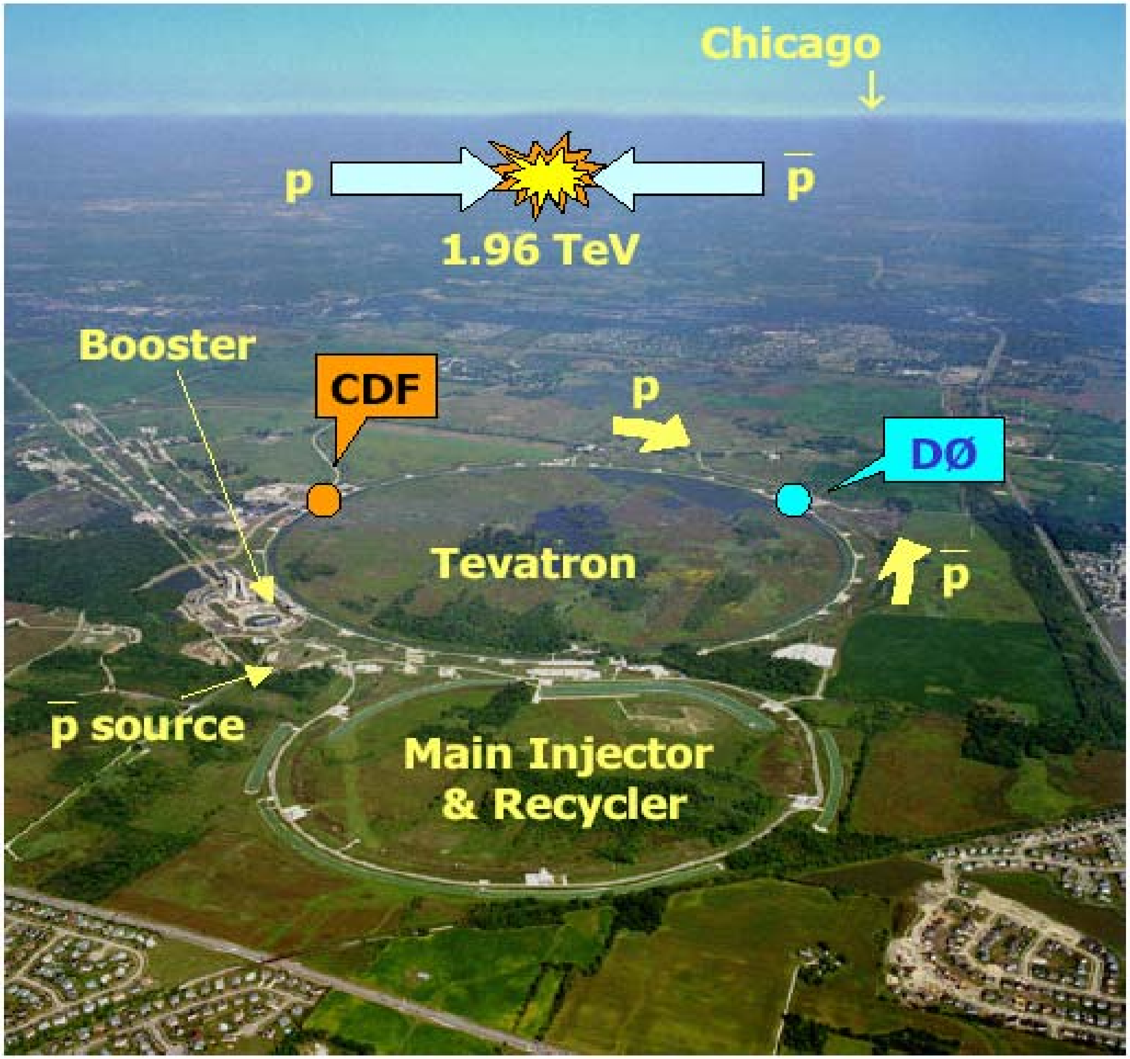
  ~6.3 Km circumference
  Superconducting magnets – since 1983
  36 bunches (396 ns crossing time)

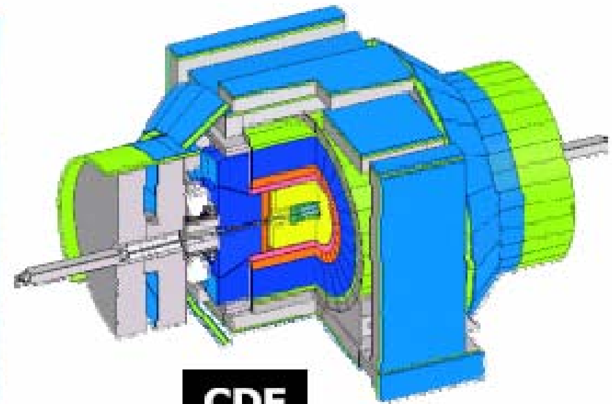
- Main injector (new in Run II – 2001)
  (150 GeV proton storage ring)

- antiproton recycler (still commissioning)
  - Electron cooling
  - 40% increase in Luminosity

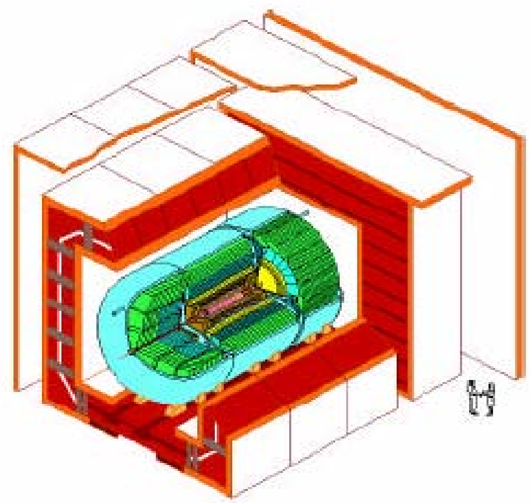


Acceleratore





CDF



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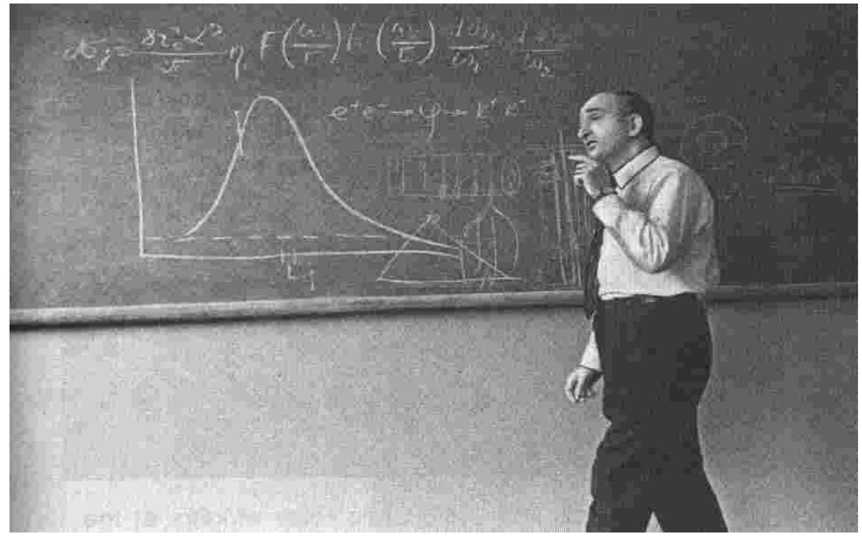
The Recycler & e-cooling

- The Recycler is a fixed-energy storage ring placed in the Main Injector tunnel. The purpose of the Recycler is to further increase the luminosity of the Tevatron Collider over the luminosity goals of the Main Injector by itself.
- The Recycler is just a ring of steel cases holding bricks of permanent magnets (*magnetized strontium ferrite: the same material used in refrigerator magnets*).
- The Recycler will function as a post-Accumulator ring. As the stack size in the Accumulator ring increases, there comes a point when the stacking rate starts to decrease. By emptying the contents of the Accumulator into the Recycler periodically, the Accumulator is always operating in its optimum antiproton intensity regime.
- In the Recycler antiprotons will be cooled both by stochastic and e-cooling.
- Originally the Recycler was supposed to act as a receptacle for antiprotons left over at the end of Tevatron stores (origin of his name)→I believe this feature has been dropped from the project

Electron cooling

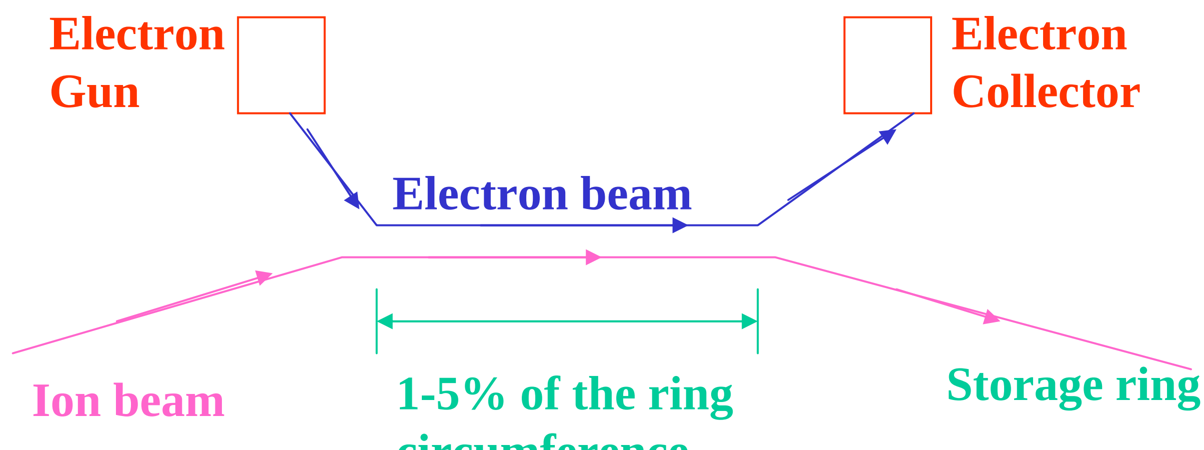
- Was invented by G.I. Budker (INP, Novosibirsk) as a way to increase luminosity of p-p and p-pbar colliders.
- First mentioned at Symp. Intern. sur les anneaux de collisions á electrons et positrons, Saclay, 1966: “Status report of works on storage rings at Novosibirsk”



How does electron cooling work?

The velocity of the electrons is made equal to the average velocity of the ions.

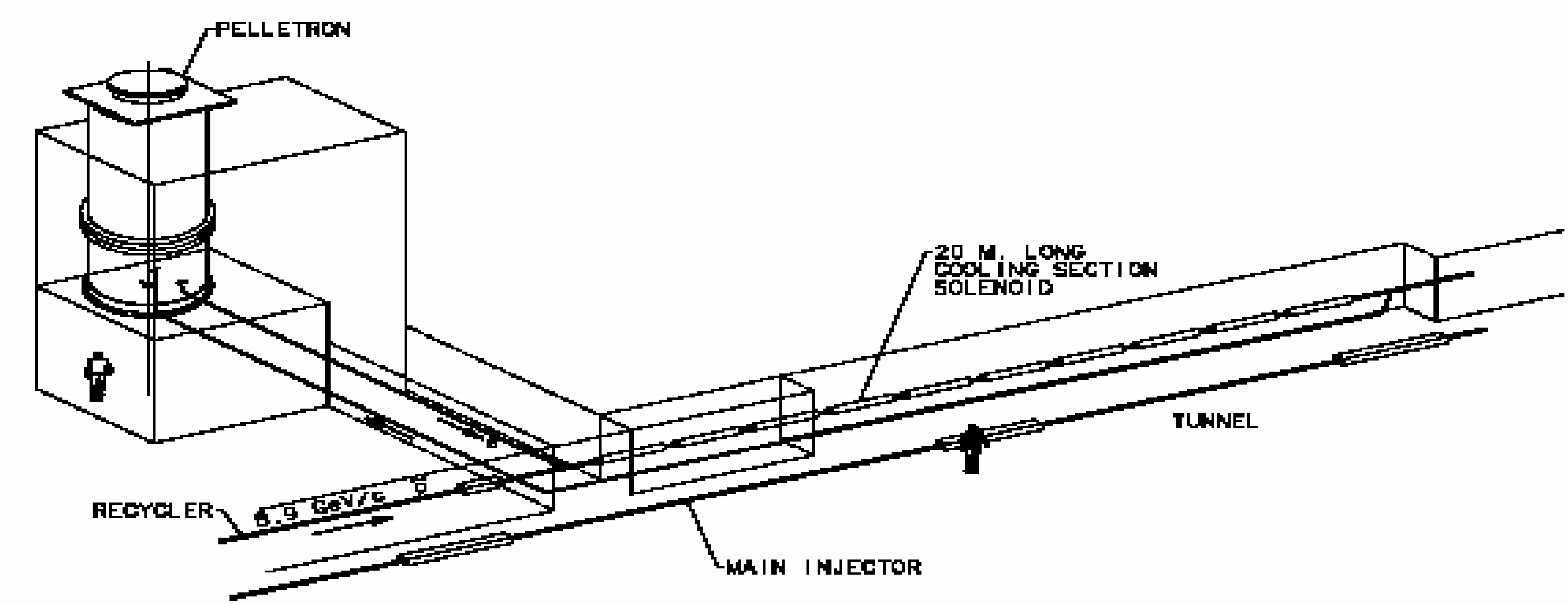
The ions undergo Coulomb scattering in the electron “gas” and lose energy, which is transferred from the ions to the co-streaming electrons until some thermal equilibrium is attained.



e-cooling

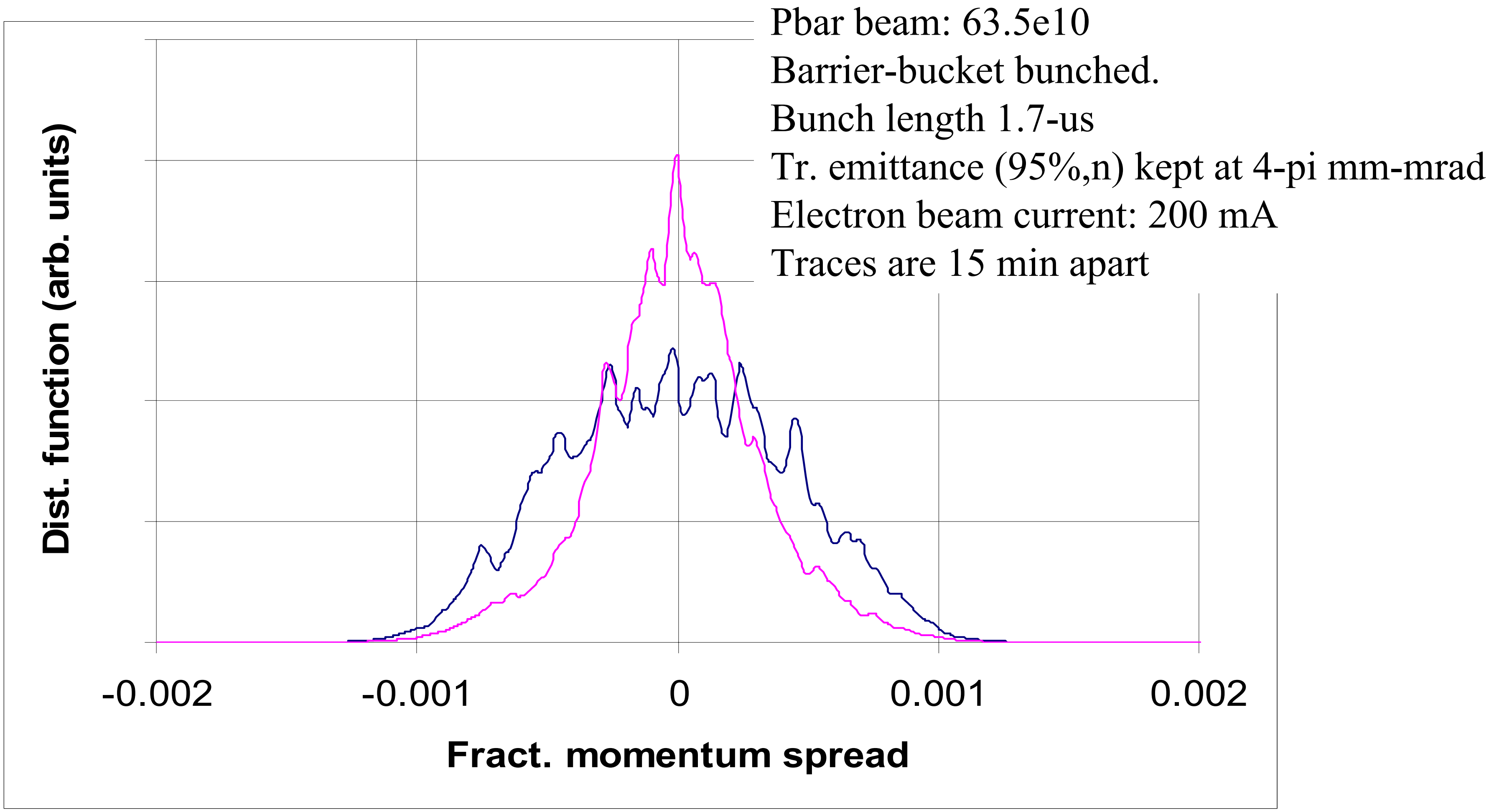
Never implemented at high energy! <u>**R&D project**</u> at Fermilab in the last years: **result and success** was far from obvious!!

<u>Schematic Layout of the Fermilab Electron Cooling:</u>



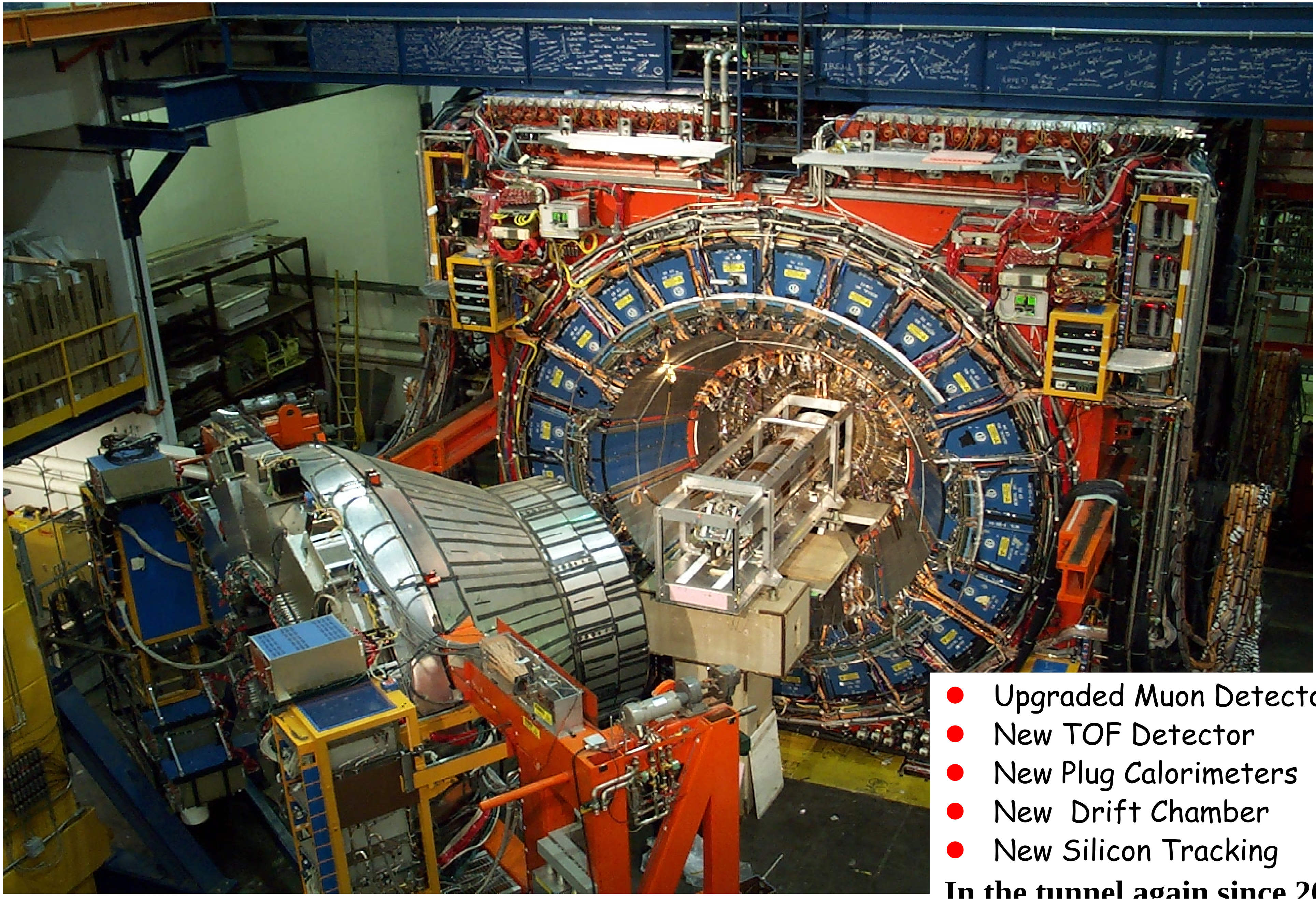
It should significantly increase the number of antiprotons stored in the Recycler and improve the antiproton production rate in the Accumulator

First e-cooling demonstration – 07/15/05



Since August e-cooling is routinely working in the Recycler

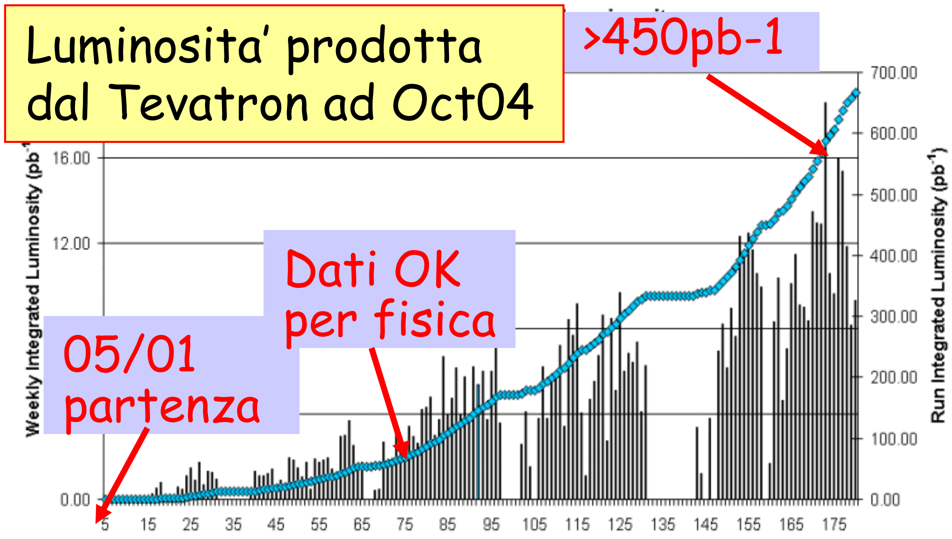
CDF Detector

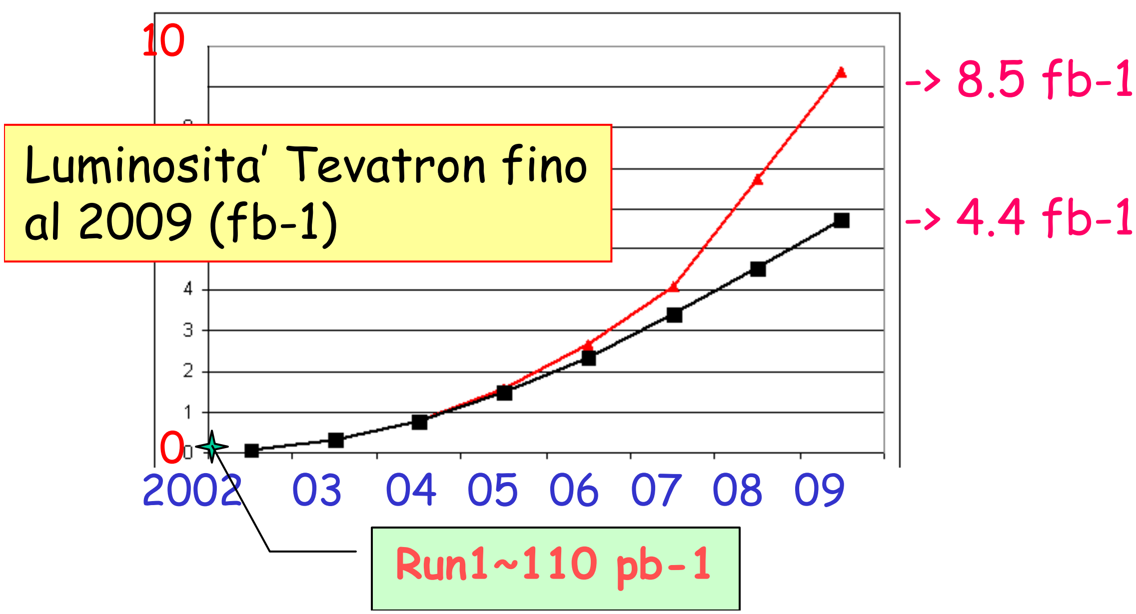


- Upgraded Muon Detectors
- New TOF Detector
- New Plug Calorimeters
- New Drift Chamber
- New Silicon Tracking

In the tunnel again since 2001

IL RUN 2 DI CDF





- Run1: 1.8Tev ~110 pb-1
  max L~ 2×10^{31} cm^{-2} s^{-1}
- Run2: 1.96Tev (+30% top !)
  goal L~ 2-4 $\times 10^{32}$ cm^{-2} s^{-1}
  oggi L~ 1.8×10^{32} cm^{-2} s^{-1}
  - Miglior SVX, calor., muon, + SVT
- Run2 fino a quando parte LHC

Il programma di Fisica

- Misure di precisione: test dello SM
  - Fisica EW con W/Z e dibosons (e.g. δM_W ~30Mev)
  - Studio delle proprieta' del top (e.g. δM_{top} ~2-3GeV, sezione d'urto ~8%)
  - Vincoli a SM Higgs da massa top e massa W
  - Struttura dei quark (QCD jet)
- Ricerca diretta di SM Higgs
- Ricerca di nuova fisica
- Fisica del beauty e charm
  - Produzione, Vite Medie, Asimmetrie di CP, Bs Mixing, D^0 mixing, Decadimenti Rari (B,D)

Run II Physics Program

15 fb^{-1}

- 5σ Higgs signal @ m_H = 115 GeV
- 3σ Higgs signal @ m_H = 115-135, 150-175 GeV
- Reach ultimate precision for top, W, B physics

10 fb^{-1}

- 3σ Higgs signal @ m_H = 115-125, 155-170 GeV
- Exclude Higgs over whole range of 115-180 GeV
- Possible discovery of supersymmetry in a larger fraction of parameter space

5 fb^{-1}

- 3σ Higgs signal @ m_H = 115 GeV
- Exclude SM Higgs 115-130, 155-170 GeV
- Exclude much of SUSY Higgs parameter space
- Possible discovery of supersymmetry in a significant fraction of minimal SUSY parameter space (the source of cosmic dark matter?)

2 fb^{-1}

- Measure top mass ± 3 GeV and W mass ± 25 MeV
- Directly exclude m_H = 115 GeV
- Significant SUSY and SUSY Higgs searches
- Probe extra dimensions at the 2 TeV (10^{-19} m) scale
- B physics: constrain the CKM matrix

300 pb^{-1}

- Improved top mass measurement
- High p_T jets constrain proton structure
- Start to explore B_s mixing and B physics
- SUSY Higgs search @ large tan β
- Searches beyond Run I sensitivity

Scattering at Hadron Colliders

Scattering processes at high energy hadron colliders can be classified as either **HARD** or **SOFT**

Quantum Chromodynamics (QCD) is the underlying theory for **all** such processes, but the approach (and the level of understanding) is very different for the two cases

For **HARD** processes, e.g. W or high-E_T jet production, the rates and event properties can be predicted with some precision using perturbation theory

↓

Calculate, Predict & Test

For **SOFT** processes, e.g. the total cross section or diffractive processes, the rates and properties are dominated by non-perturbative QCD effects

Note: in these lectures, I'll concentrate mainly on the HARD processes
But soft physics effects will surround us...

Timeline

← Introduction of Color and the Quark Model (Bjorken and Feymann)

SLAC

← Experimental evidence of quarks in DIS scattering, Bjorken scaling

1970

ISR

← Birth of QCD: Renormalizability('t Hooft and Veltmann), Asymptotic Freedom(Gross,Wilczek,Politzer), Confinement

← Discovery of the charm quark (SLAC, BNL)

← Observation of jets in e^+e^- as manifestation of quarks (SLAC,1975) and gluons (DESY,1979)

PETRA

← Discovery of the bottom quark (FNAL)

← Violation of Bjorken scaling, Evolution of Parton Distribution and Fragmentation Functions

1980

$Sp\bar{p}S$

← QCD calculations start to become available for many processes

← Discovery of W and Z (CERN)

LEP
HERA

1990

← Next to Leading Order predictions for jet production

Tevatron Run I

← Discovery of the top quark (FNAL)

2000

← Next to Next to Leading Order predictions for jet production

Tevatron Run II

QCD Lagrangian

- QCD is a gauge theory describing fermions (quarks) which carry charge (color) and interact through the exchange of vector bosons (gluons)

- The statement that QCD is a gauge theory based on the group SU(3) with colour triplet quark matter fields fixes the QCD lagrangian density to be

$$\mathcal{L} = -\frac{1}{4}\sum_{A=1}^{8} F^{A\mu\nu}F^{A}_{\mu\nu} + \sum_{j=1}^{n_f} \bar{q}_j(i\not{D} - m_j)q_j$$

Here: q_j are the quark fields (of n_f different flavours) with mass mj

$\not{D} = D_\mu \gamma^\mu$, $\gamma\mu$ are the Dirac matrices

$D\mu$ is the covariant derivative:

$$D_\mu = \partial_\mu - ie_s \mathrm{g}_\mu$$

$\mathrm{g}_\mu = \sum_A t^A g^A_\mu$ where $g^A{}_\mu$, $A = 1, 8$, are the gluon fields

In QCD:

$$F^A_{\mu\nu} = \partial_\mu g^A_\nu - \partial_\nu g^A_\mu - e_s C_{ABC} g^B_\mu g^C_\nu$$

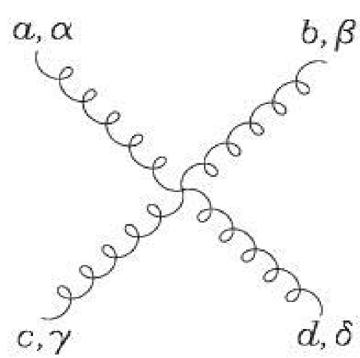
- In QCD the gluons are coloured hence self-coupled:
  - in QCD $F^A_{\mu\nu}$ is quadratic in the gauge field

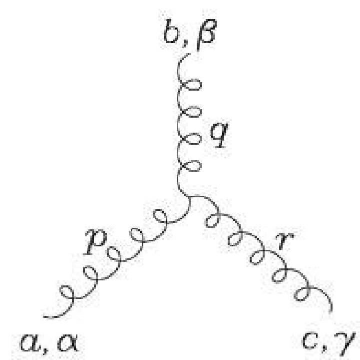
In QED:

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

- In QED the photon is coupled to all electrically charged particles but itself is neutral:
  - This is reflected in the fact that in QED $F_{\mu\nu}$ is linear in the gauge field

- Physical vertices in QCD include g-q-qbar vertex, analogous to the QED photon-fermion-antifermion coupling
  - But there are also the 3-gluon and 4-gluon vertices

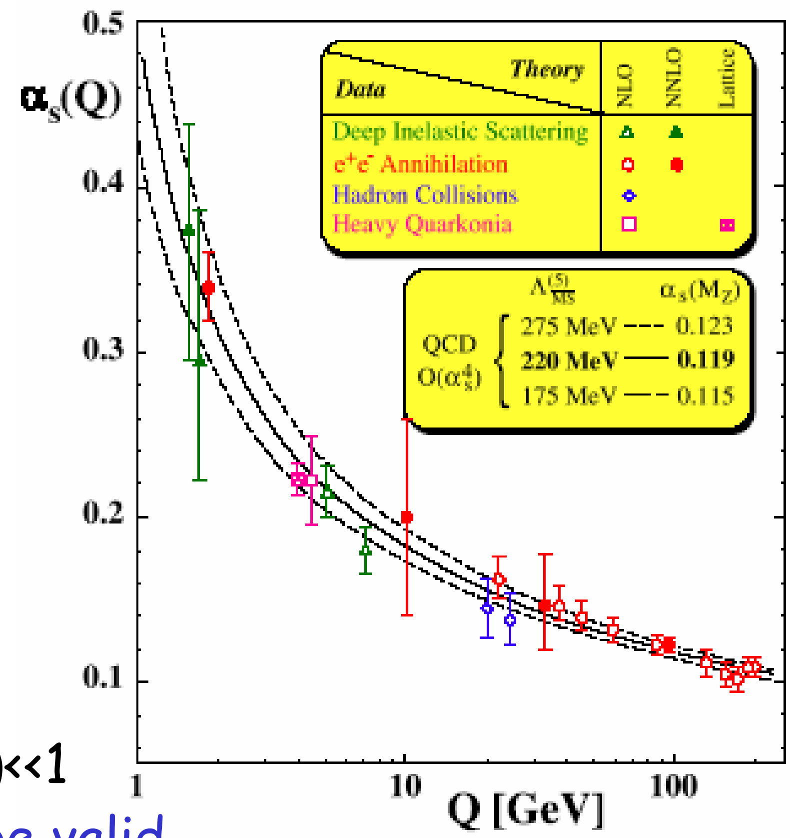




QCD - α_s

- Interesting features:
  - gluons are themselves colored
  - interactions are strong
  - coupling constant runs rapidly
    - ☞ becomes weak at q=momentum transfers above a few GeV

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



- ☞ The existence of a regime in which $\alpha_s(q^2) \ll 1$
  - ➔ here QCD perturbation theory should be valid

  asymptotic freedom

  at very short distances quarks behave almost as free particles within hadrons

- ☞ At large distances α_s grows → related to confinement

QCD at Hadron Colliders

- In hadronic collisions, all phenomena are QCD-related
- Both beam and target have a non-trivial partonic structure: dynamics is more complex than i.e. e+e-
- Collider physics historically was and is "primarily" discovery physics: knowledge of QCD is essential both for the estimate of the expected signals, and for the evaluation of the backgrounds

QCD is:

- an essential and established part of the toolkit for discovering physics beyond the standard model, e.g. at Tevatron and LHC
- a gauge field theory with a very rich structure, much of which is not yet fully understood in a quantitative way

Yesterday:

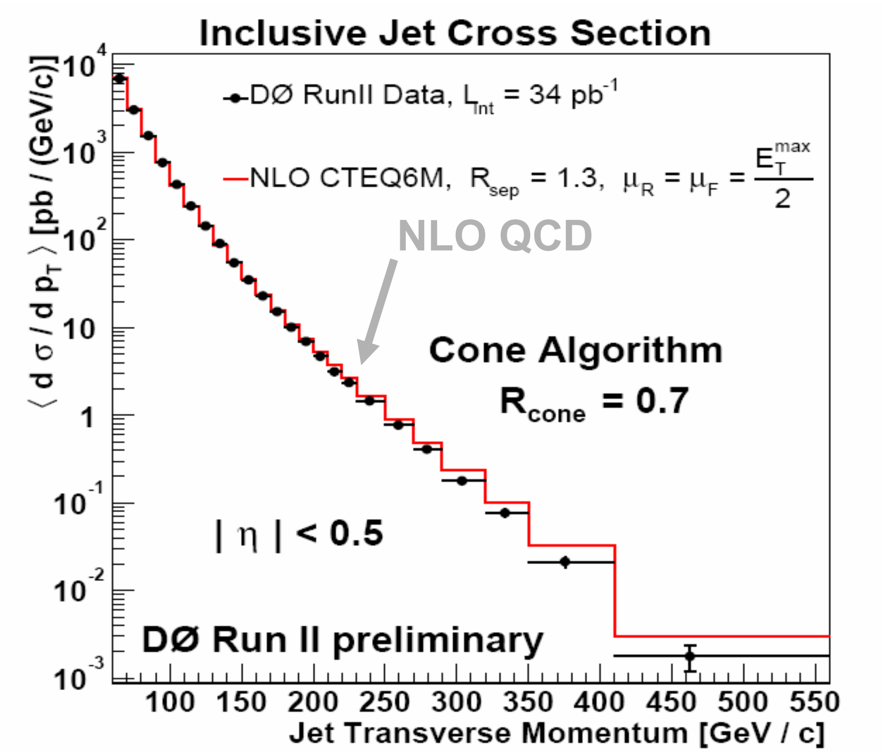
- precision physics: measurements of the W mass and of the properties of b-hadrons etc…but *NOT QCD*

Today:

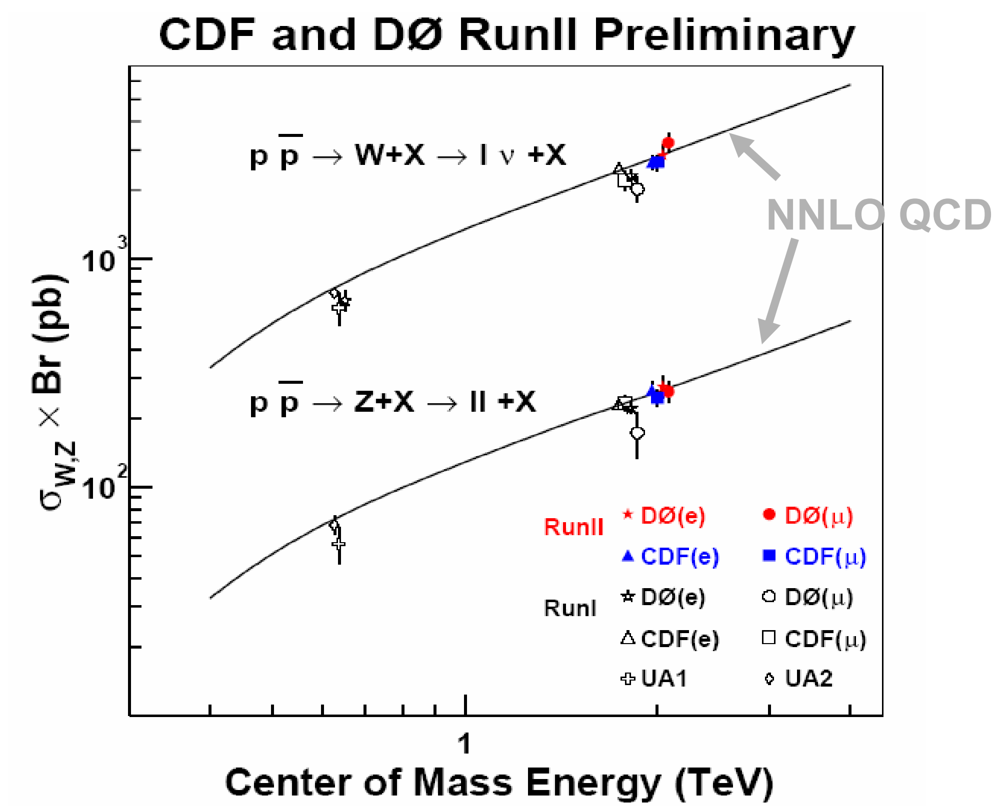
- for 'hard' processes (i.e. suitably inclusive, with at least one large momentum transfer scale), QCD is a *precision tool* – calculations and phenomenology aiming at the per-cent level

examples of 'precision' phenomenology

jet production



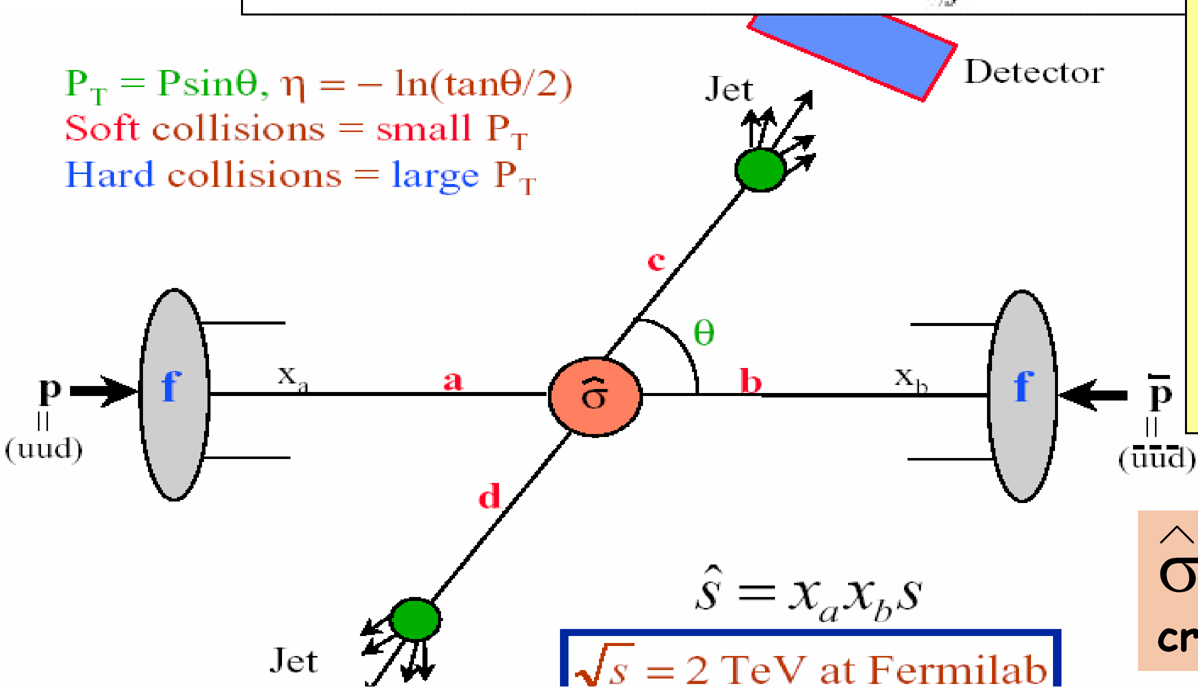
W, Z production



Theoretical predictions at Hadron Colliders

- The key ingredients for the calculation of production rates and distributions in hadronic collisions are:
  - the matrix elements for the hard, partonic process (e.g., gg →gg; gg→ b b; q q' → W)
  - the hadronic parton densities.
- Then the production rate for a given final state H is given by a factorization formula:

$$d\sigma(p\bar{p} \to H + X) = \int dx_1\, dx_2 \sum_{i,j} f_i(x_1, Q)\, f_j(x_2.Q)\, d\hat{\sigma}(ij \to H)$$



fi=$f_{a/A}(x_a, \mu_F)$:Parton Momentum Distributions (PDF) – probability to find parton of type a in hadron A with momentum fraction x_a

μ_F: "factorization scale" of interation->usually is 4 momentum transfer

$\hat{\sigma}$: partonic level cross section

At Hadron Colliders

The QCD **factorization theorem** for hard-scattering (short-distance) inclusive processes

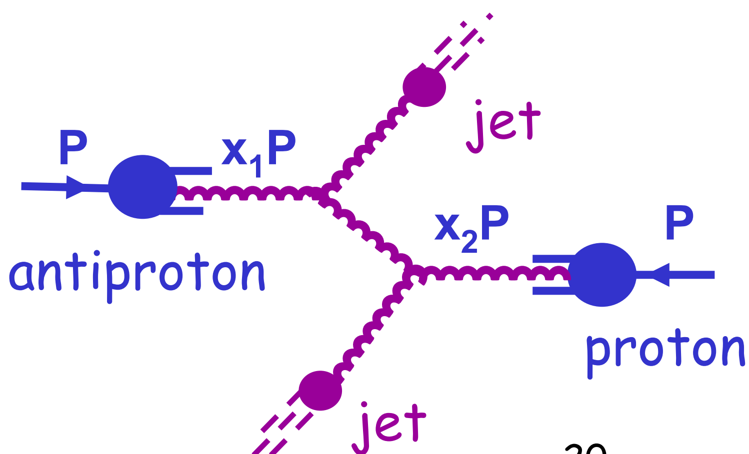
$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2)\, f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab\to X}\left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)$$

where X=W, Z, H, high-E_T jets, SUSY sparticles, black hole, …, and Q is the 'hard scale' (e.g. = M_X), usually $\mu_F = \mu_R = Q$, and $\hat{\sigma}$ is known …

- to some fixed order in pQCD, e.g.

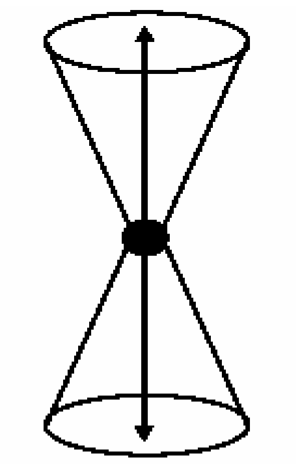
$$\hat{\sigma} = A\alpha_S^2 + B\alpha_s^3$$

- or in some leading logarithm approximation (LL, NLL, …) to all orders via resummation



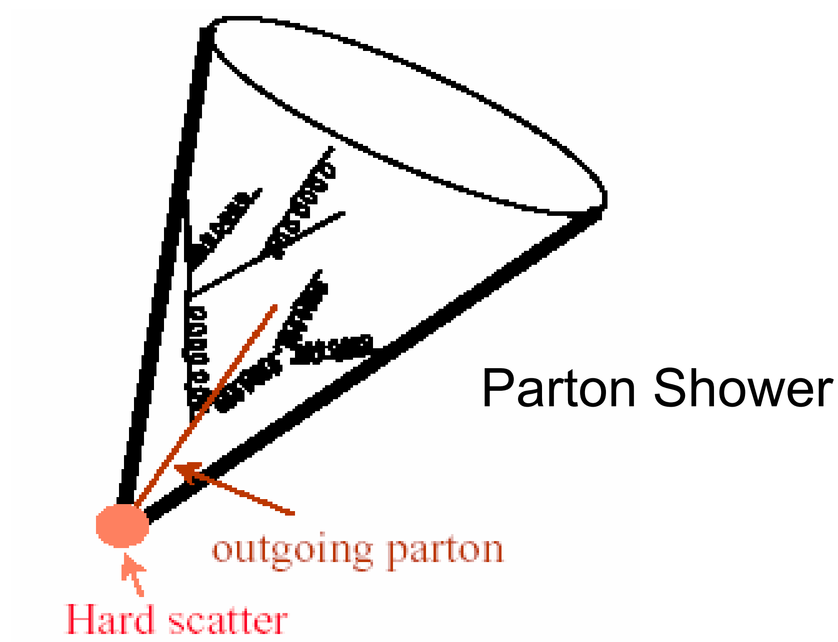
From Partons to Jets

Leading Order Theory
Uses 2→2 matrix elements



Only two jets in final state
Only one parton/jet

Leading Log Approximation (LLA): sum leading contributions to all orders (from ~collinear radiation of quarks and gluons around original parton)



Digression on the scales μ_F and μ_R

- μ_F and μ_R are artifacts of working at fixed order in perturbation theory.
  - The predictions should not depend on the choice of scales (Data doesn't!)
- The renormalization scale μ_R shows up in the strong coupling constant because it is introduced when the bare fields are redefined in terms of the physical fields
- The factorization scale μ_F is introduced when absorbing the divergence from collinear radiation into the PDFs
- Can choose any value for μ_F and μ_R
  - Typical choice $\mu_F = \mu_R \sim E_T/2$ of the jets
  - Usually study predictions with range $\mu = E_T/4$ to $2E_T$
- Dependence of predictions on scale
  - indicates potential size of higher order contributions
  - should get smaller as higher order terms are included

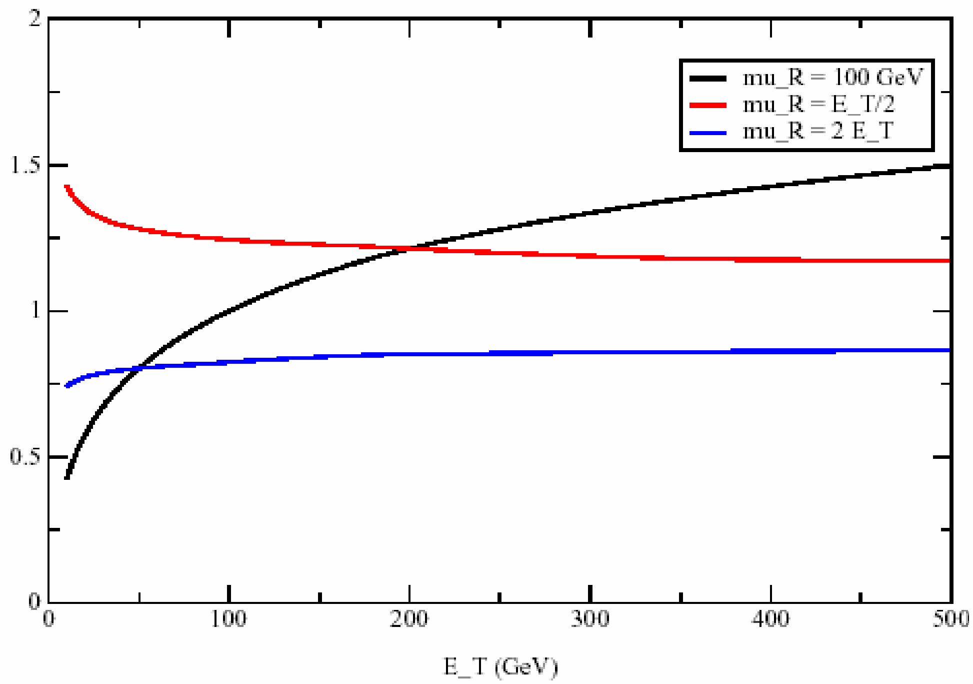
Digression on the scales μ_F and μ_R cont.

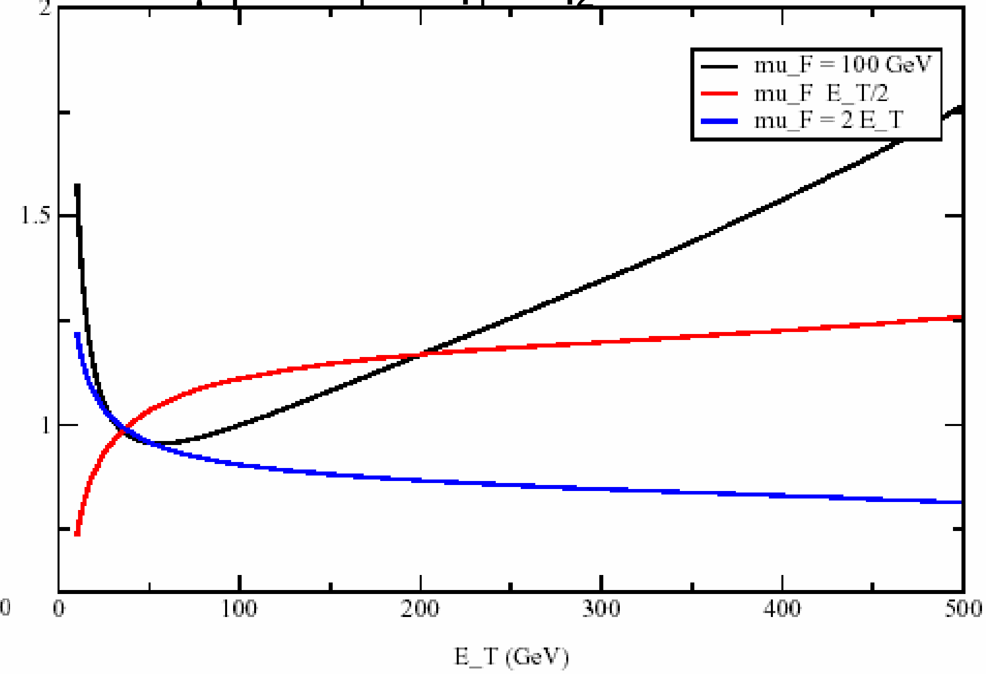
α_s^2 for different μ_R
compared to $\mu_R = E_T$

$$x_1 f_i(x_1, \mu_F)\ x_2 f_j(x_2, \mu_F)$$

for different μ_F compared
to $\mu_F = E_T$ at $\eta_1 = \eta_2 = 0$

Ratio





Dependence of LO on choice of scales flat at ~ 10% level for $\mu = E_T/2$
but normalization uncertain at ~±50% level

pdfs from global fits

Formalism
NLO DGLAP
MSbar factorisation
Q_0^2
functional form @ Q_0^2
etc.

Data
DIS (SLAC, BCDMS, NMC, E665, CCFR, H1, ZEUS, …)
Drell-Yan (E605, E772, E866, …)
High E_T jets (CDF, D0)
W rapidity asymmetry (CDF)
νN dimuon (CCFR, NuTeV)
etc.

→

$f_i(x,Q^2) \pm \delta f_i(x,Q^2)$

$\alpha_S(M_Z)$

Who?
Alekhin, CTEQ, MRST, GKK, Botje, H1, ZEUS, GRV, BFP, …

↓

http://durpdg.dur.ac.uk/hepdata/pdf.html typical data ingredients of a global pdf fit

H1, ZEUS $F_2^{e^+p}(x,Q^2)$, $F_2^{e^-p}(x,Q^2)$

BCDMS $F_2^{\mu p}(x,Q^2), F_2^{\mu d}(x,Q^2)$

NMC $F_2^{\mu p}(x,Q^2), F_2^{\mu d}(x,Q^2), (F_2^{\mu n}(x,Q^2)/F_2^{\mu p}(x,Q^2))$

SLAC $F_2^{\mu p}(x,Q^2), F_2^{\mu d}(x,Q^2)$

E665 $F_2^{\mu p}(x,Q^2), F_2^{\mu d}(x,Q^2)$

CCFR $F_2^{\nu(\bar{\nu})p}(x,Q^2), F_3^{\nu(\bar{\nu})p}(x,Q^2)$

$\rightarrow q,\ \bar{q}$ at all x and g at medium, small x

H1, ZEUS $F_{2,c}^{e^+p}(x,Q^2) \rightarrow c$

E605, E772, E866 Drell-Yan $pN \rightarrow \mu\bar{\mu} + X \rightarrow \bar{q}\ (g)$

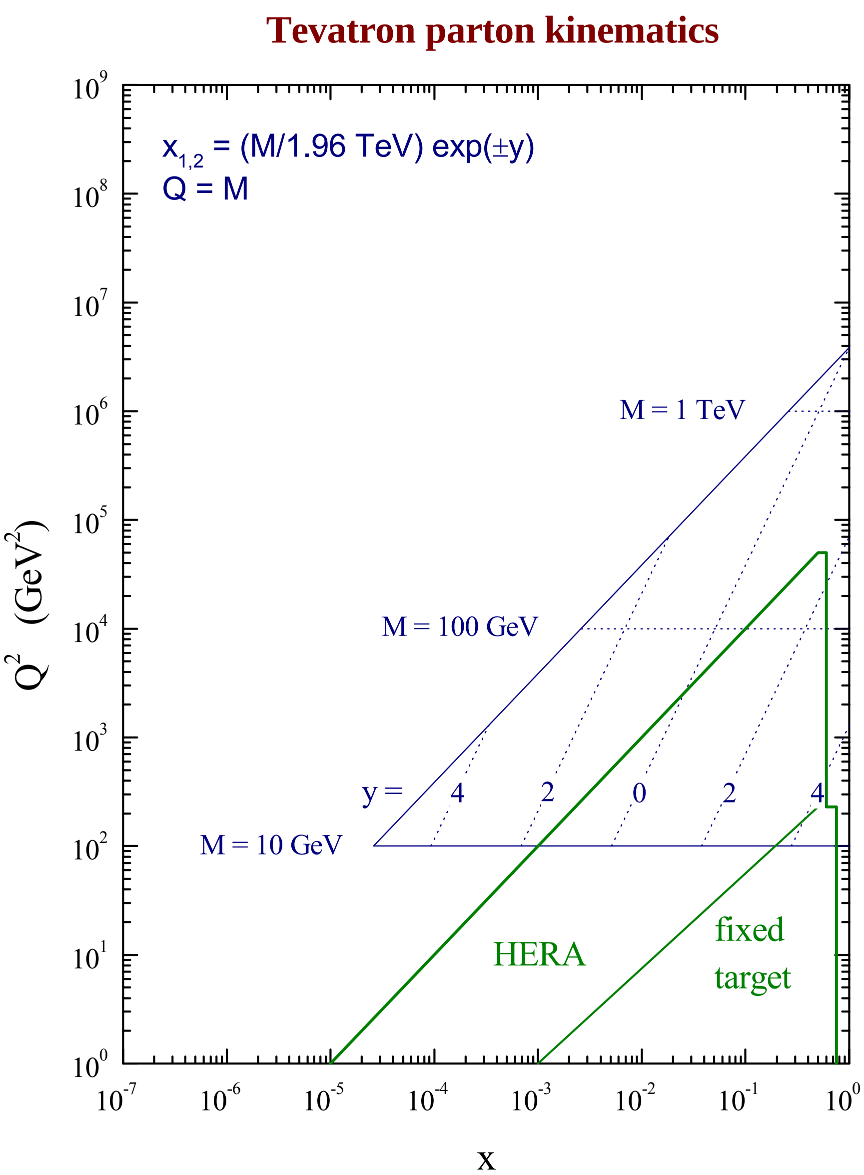
E866 Drell-Yan p,n asymmetry $\rightarrow \bar{u}, \bar{d}$

CDF W rapidity asymmetry $\rightarrow u/d$ ratio at high x

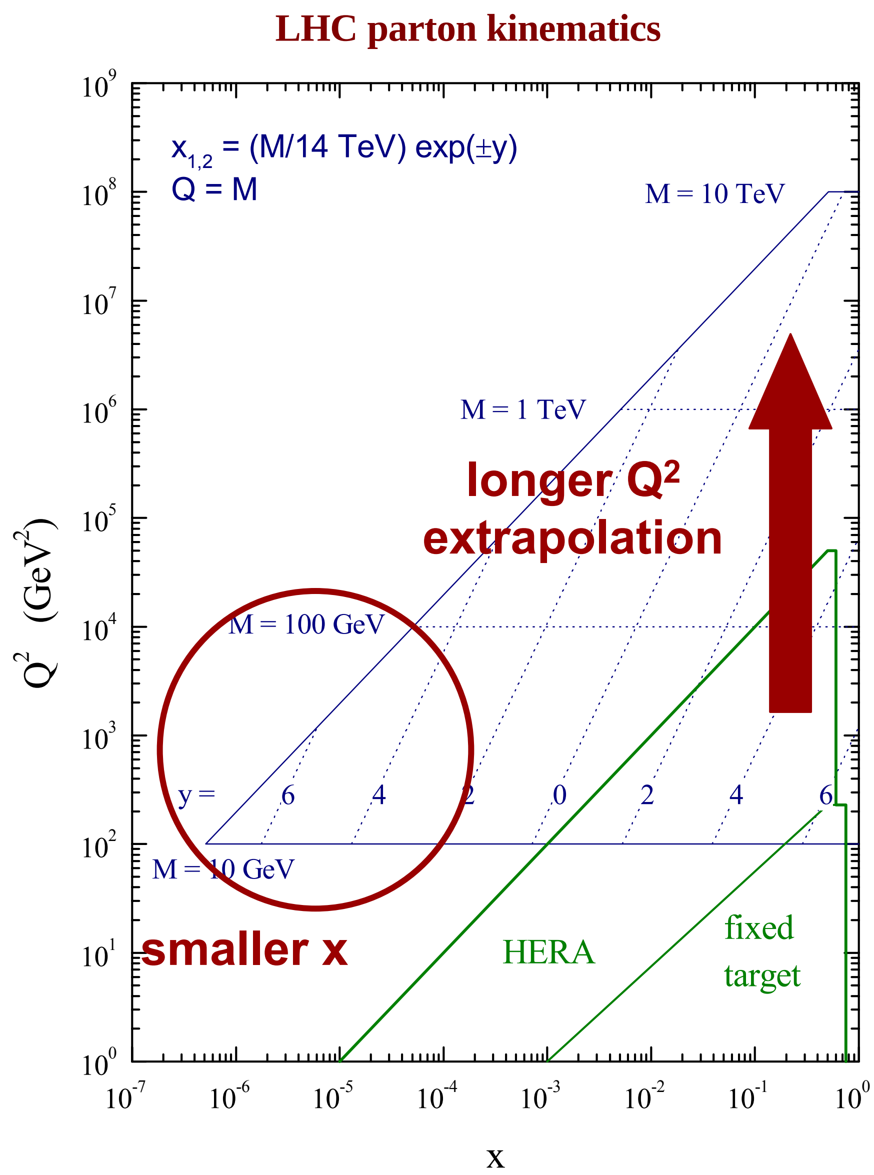
CDF, D0 Inclusive jet data $\rightarrow g$ at high x

CCFR, NuTeV Dimuon data constrains strange sea $s,\ \bar{s}$

Note: nowadays, no prompt photon data included in fits



Tevatron parton kinematics
$x_{1,2}$ = (M/1.96 TeV) exp(±y)
Q = M
M = 1 TeV
M = 100 GeV
M = 10 GeV
y = 4 2 0 2 4
HERA
fixed target
Q^2 (GeV^2)
x



LHC parton kinematics
$x_{1,2}$ = (M/14 TeV) exp(±y)
Q = M
M = 10 TeV
M = 1 TeV
longer Q²
extrapolation
M = 100 GeV
y = 6 4 2 0 2 4 6
M = 10 GeV
smaller x
HERA
fixed target
Q^2 (GeV^2)
x

why do 'best fit' pdfs and errors differ?

- different data sets in fit
  - different subselection of data
  - different treatment of exp. sys. errors
- different choice of
  - tolerance to define $\pm \delta f_i$ (CTEQ: $\Delta\chi^2=100$, Alekhin: $\Delta\chi^2=1$)
  - factorisation/renormalisation scheme/scale
  - Q_0^2
  - parametric form $Ax^a(1-x)^b[..]$ etc
  - α_S
  - treatment of heavy flavours
  - theoretical assumptions about $x\rightarrow 0,1$ behaviour
  - theoretical assumptions about sea flavour symmetry
  - evolution and cross section codes (removable differences!)

pdfs at LHC

- high precision (SM and BSM) cross section predictions require precision pdfs: $\delta\sigma_{th} = \delta\sigma_{pdf} + \ldots$
- 'standard candle' processes (e.g. σ_Z) to
  - check formalism
  - measure machine luminosity?
- learning more about pdfs from LHC measurements (e.g. high-E_T jets $\rightarrow$ gluon.)

σ: status of pQCD calculations

fixed order: $d\sigma = A\, \alpha_S^N\, [\, 1 + C_1\, \alpha_S + C_2\, \alpha_S^2 + \ldots\,]$

thus LO, NLO, NNLO, etc, or resummed to all orders using a leading log approximation, e.g.

current frontier

$$d\sigma = A\, \alpha_S^N\, [\, 1 + (c_{11}\, L + c_{10}\,)\, \alpha_S + (c_{22}\, L^2 + c_{21}\, L + c_{20}\,)\, \alpha_S^2 + \ldots\,]$$

where $L = \log(M/q_T), \log(1/x), \log(1-T), \ldots \gg 1$ thus LL, NLL, NNLL, etc.

LO

- automated codes for arbitrary matrix element generation
- jet = parton, but 'easy' to interface to hadronisation MCs
- large scale dependence $\alpha_S(\mu)^N$ therefore not good for precision analyses

NLO

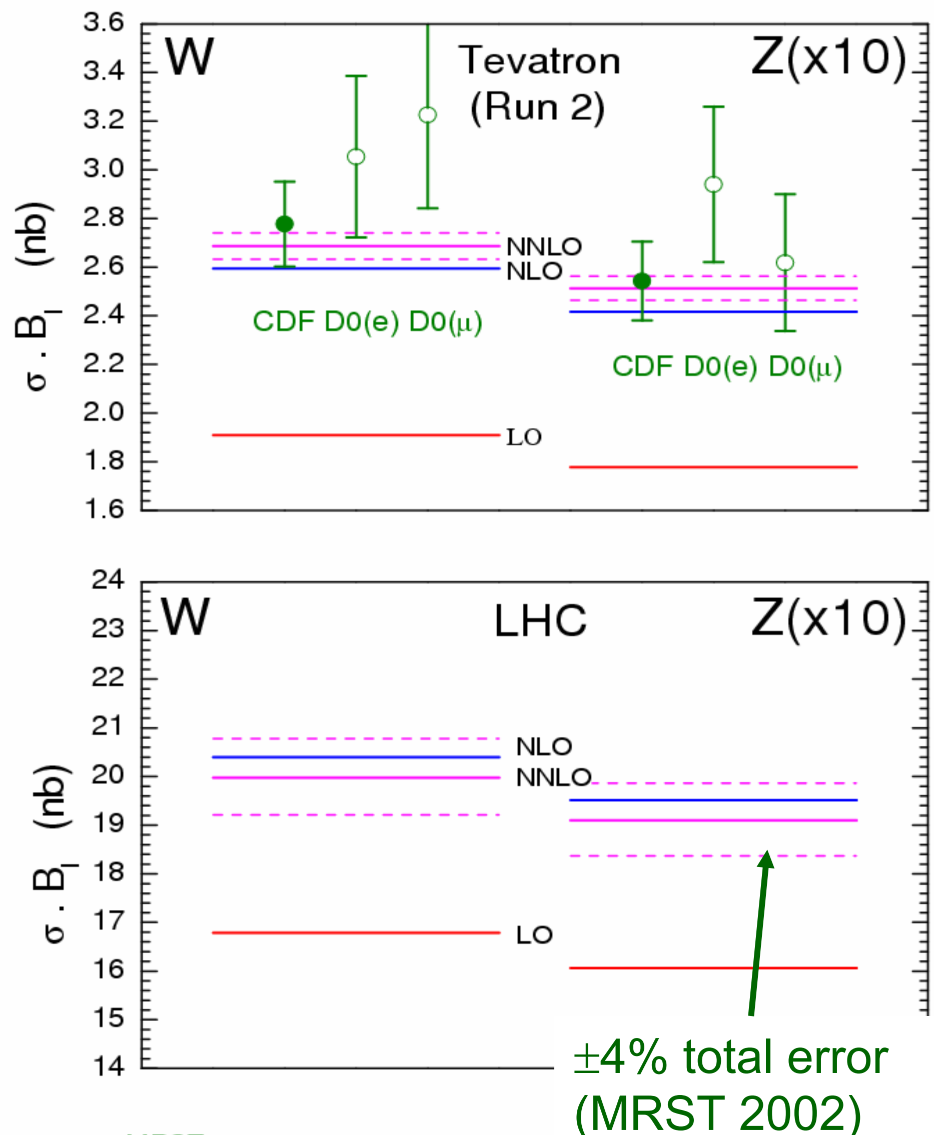
- now known for 'most' processes of interest
- reduced scale dependence
- jet structure begins to emerge
- no automation yet, but many ideas
- now can interface with PS

NNLO phenomenology already under way…

σ(W) and σ(Z) : precision predictions and measurements at the Tevatron and LHC

- the pQCD series appears to be under control

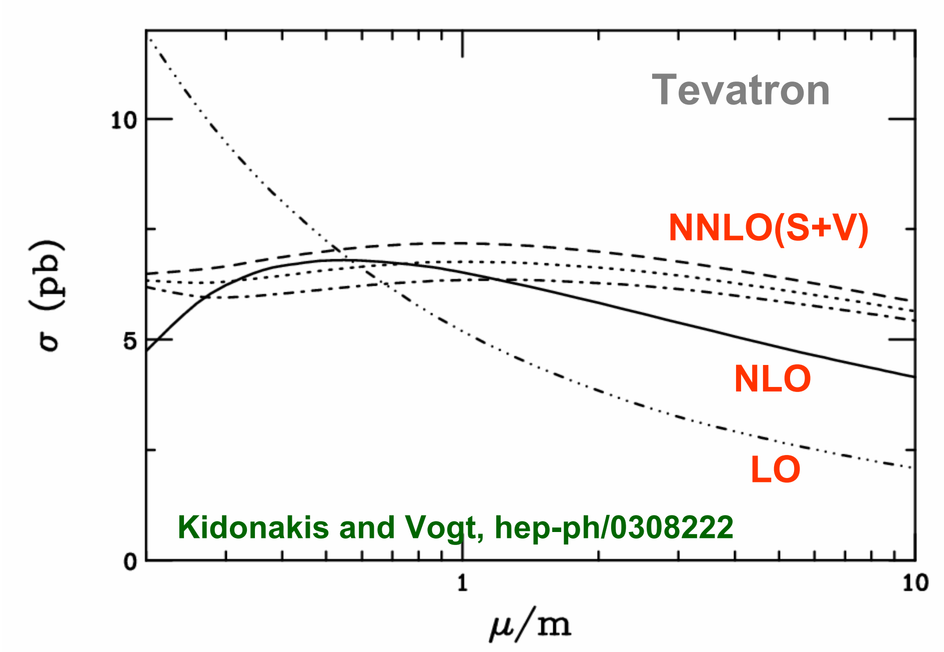
- with sufficient theoretical precision, these ‘standard candle’ processes could be used to measure the ***machine luminosity***

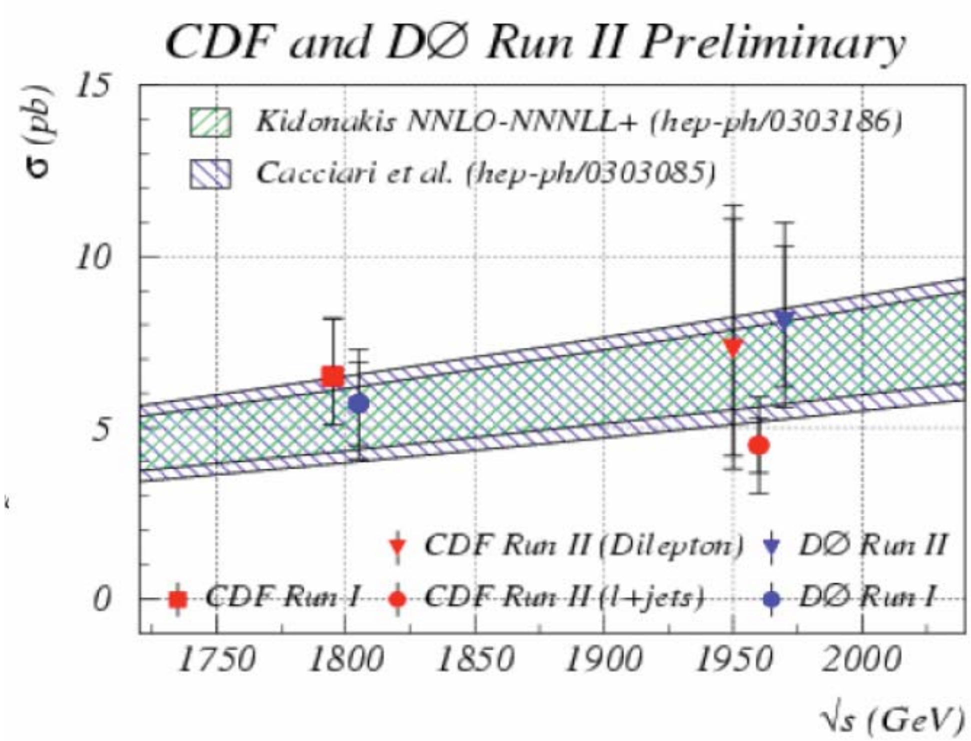


partons: MRST2002
NNLO evolution: Moch, Vermaseren, Vogt
NNLO W,Z corrections: van Neerven et al. with Harlander, Kilgore corrections

Top quark production

awaits full NNLO pQCD calculation; NNLO & N^{n}LL approximations exist (Cacciari et al, Kidonakis et al), probably OK for Tevatron at ~ ±10% level (> $\delta\sigma_{pdf}$)

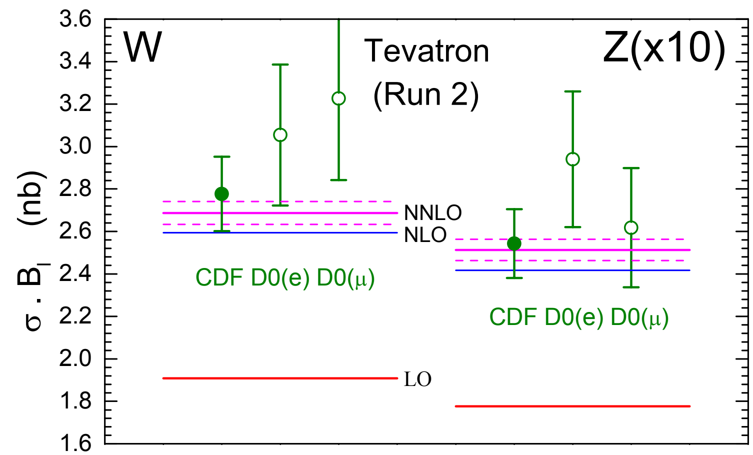




… but such approximations work less well at LHC energies

What limits the precision of the predictions?

- the order of the perturbative expansion
- the uncertainty in the input parton distribution functions

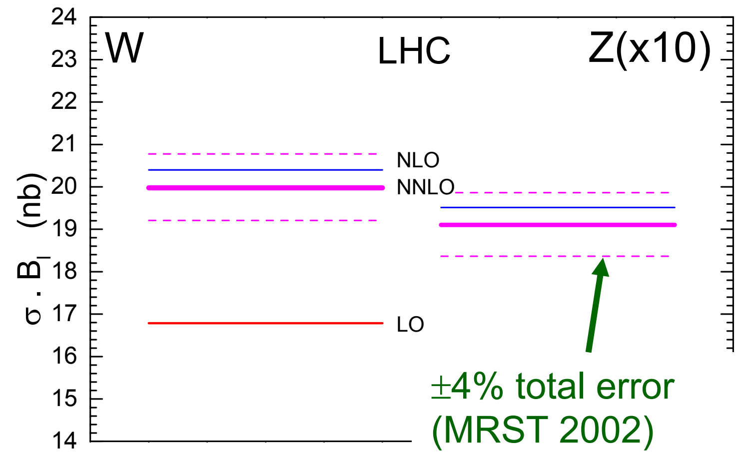


- **Example**: σ(Z) @ LHC

$\delta\sigma_{pdf} \approx \pm 3\%, \quad \delta\sigma_{pt} \approx \pm 2\%$

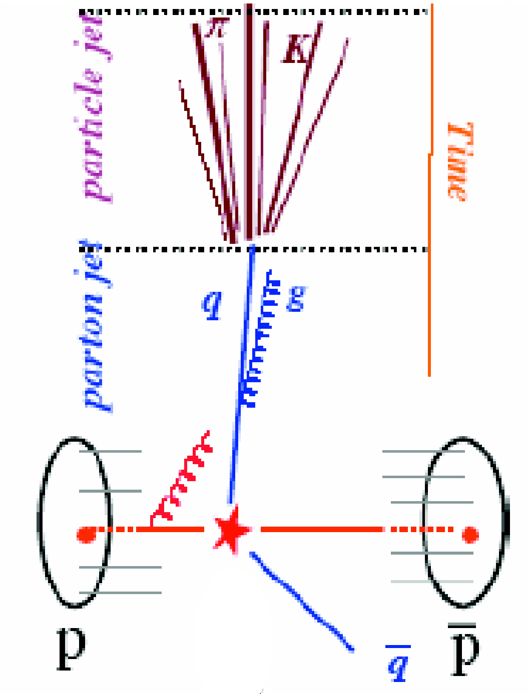
$\rightarrow \delta\sigma_{theory} \approx \pm 4\%$

but situation changes for different processes



partons: MRST2002
NNLO evolution: van Neerven, Vogt approximation to Vermaseren et al. moments
NNLO W,Z corrections: van Neerven et al. with Harlander, Kilgore corrections

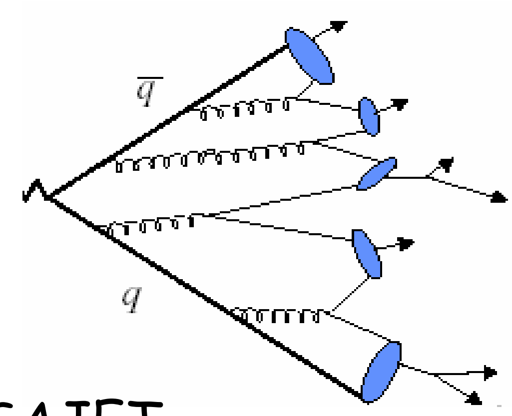
Event Generators: PS MonteCarlos



- Monte Carlo programs such as HERWIG, ISAJET, and PYTHIA are used to reproduce all aspects of the events
  - In the past: based only on LO matrix elements + Leading Log Approximation.
  - Include the effects of Initial and Final State radiation
  - Different parton shower models are used by the different programs
    - primary goal is to generate the shower of partons near the scattered parton direction.
  - also includes some wide angle radiation which could produce additional jets.
- Hadronization model to covert *colored partons* to *colorless hadrons*
- Parton shower and hadronization parameters can be (are) adjusted to give good agreement with data.
- Underlying event
  - assumed to be similar to Minimum Bias events in number of particles produced and their P_T spectrum
  - empirical and parameters can be tuned to give agreement with the data
- Output of these programs is a *list of particles* (mostly hadrons) which can be fed into a detector simulation

Fragmentation models

- String Fragmentation: Used in PYTHIA and others
  - separate partons are connected by color strings with uniform energy/unit length



- Cluster Fragmentation: Used by HERWIG and others
  - Pairs of neighboring partons are combined into color singlets.
- Independent Fragmentation (Feynman-Field): Used in ISAJET and others ***OLD***
  - each parton fragments independently
    - scattered partons shower independently
    - resulting partons are converted into hadrons independently
    - can trace every particle back to original scattered parton
    - can tune every aspect to give agreement with data

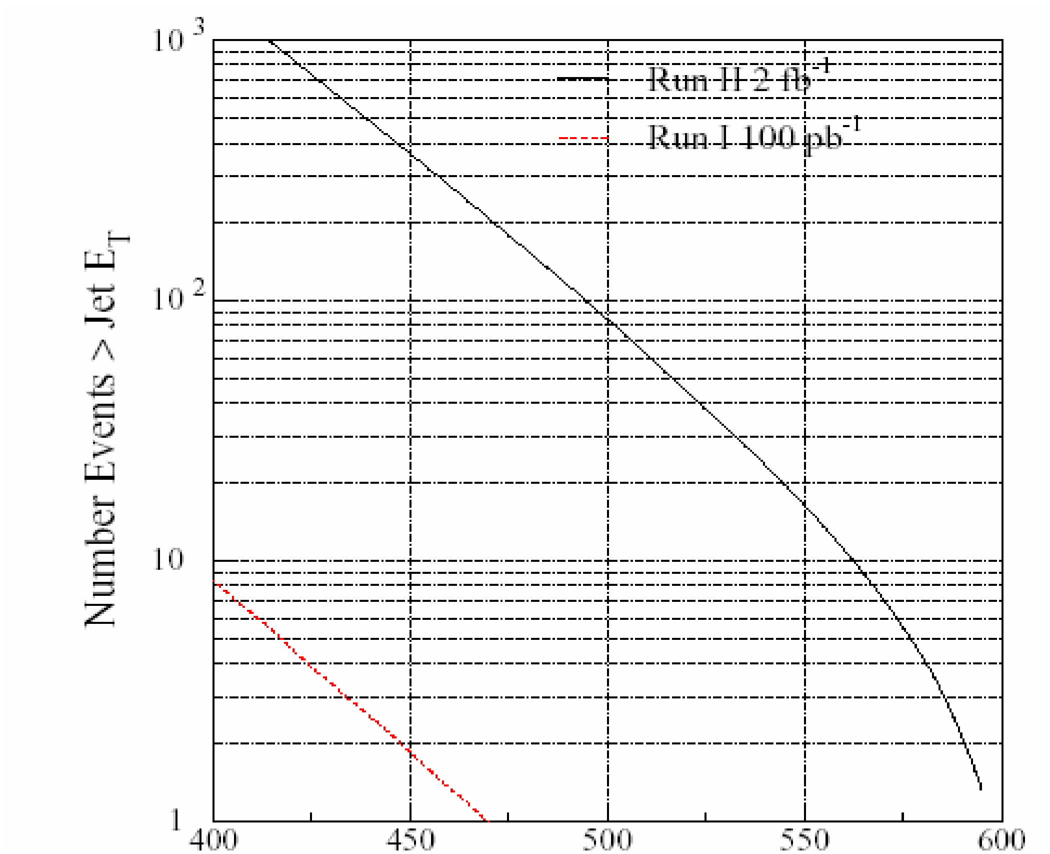
New: MC @ NLO!!

- MC @ NLO *combines* the best features of parton shower Monte Carlos and NLO calculations
- The hard cross section is calculated to NLO and then passed on to Herwig for additional gluon radiation and hadronization
- Inclusive jet production was supposed to be included in 2005…(I did not check it)

…and now some Jet Physics

- Jet production is the hard process with the largest rate in hadronic collisions.
- For example, the cross section for producing at the Tevatron (sqrt(S) = 1.8 TeV) jets of transverse energy $Ejet_T$<=50 GeV is of the order of a μb. This means 50 events/sec al Tevatron in run I.
- The data collected at the Tevatron so far extend all the way up to the E_T values of the order of 550 GeV. These events are generated by collisions among partons which carry over 50% of the available p p energy, and allow to probe the shortest distances ever reached.

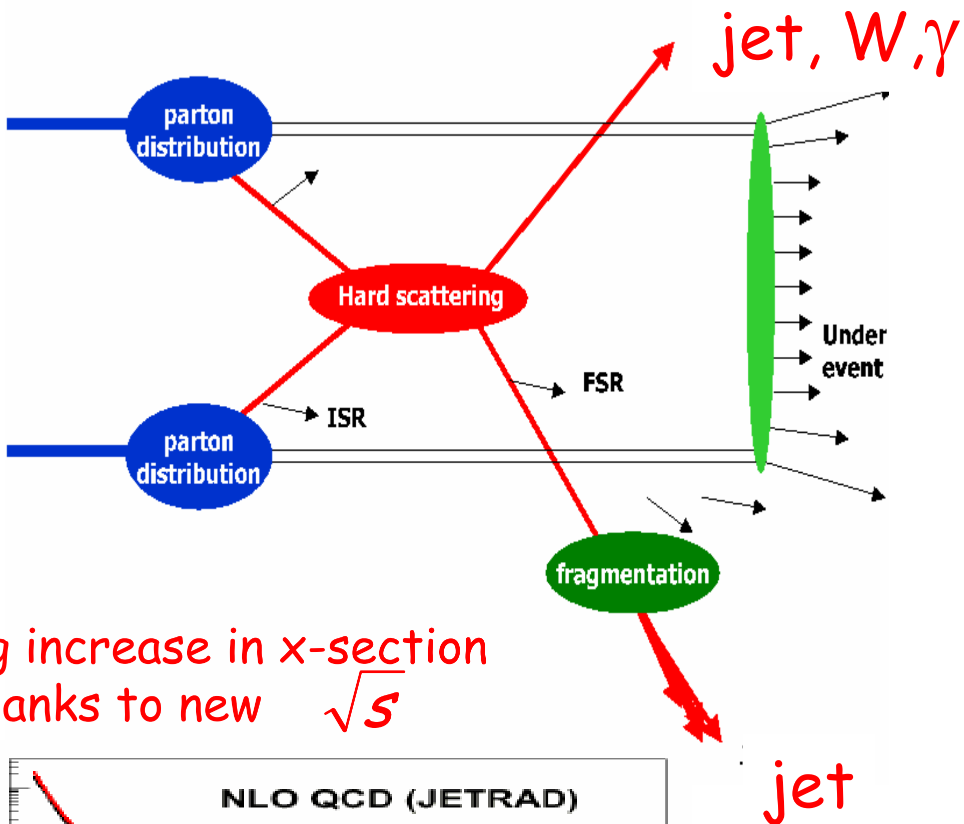
QCD in Run II



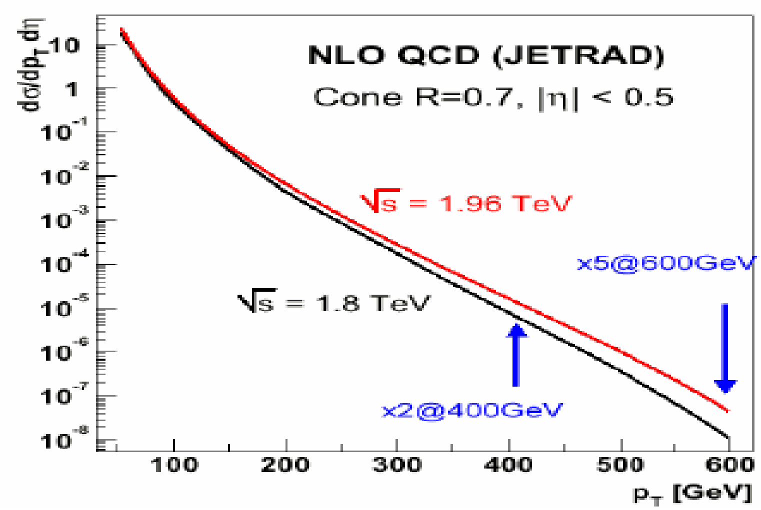
Jet E_T

- Run I
  - ~20 events with E_T> 400 GeV
- Run II
  - ~1K events E_T> 400 GeV
  - ~100 Events E_T> 490 GeV
- Great reach in high x and Q^2
- search for new physics
- test QCD predictions in new regions

Jet Physics at 2 TeV



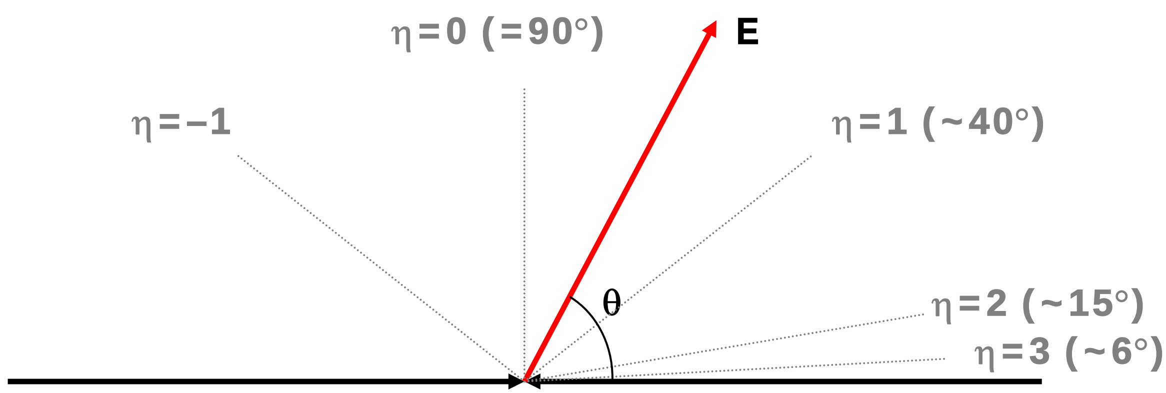
**Big increase in x-section thanks to new $\sqrt{s}$



- Jet Cross Sections
  - Jet Algorithms
  - Data vs NLO pQCD
  - etc
- Underlying Event
- Dijet $\Delta\phi$ correlations
- Jet Shapes
- Boson +jet production
- B-jet production

Hadron Collider variables

- The incoming parton momenta x_1 and x_2 are unknown, and usually the beam particle remnants escape down the beam pipe
  - *longitudinal motion of the centre of mass cannot be reconstructed*

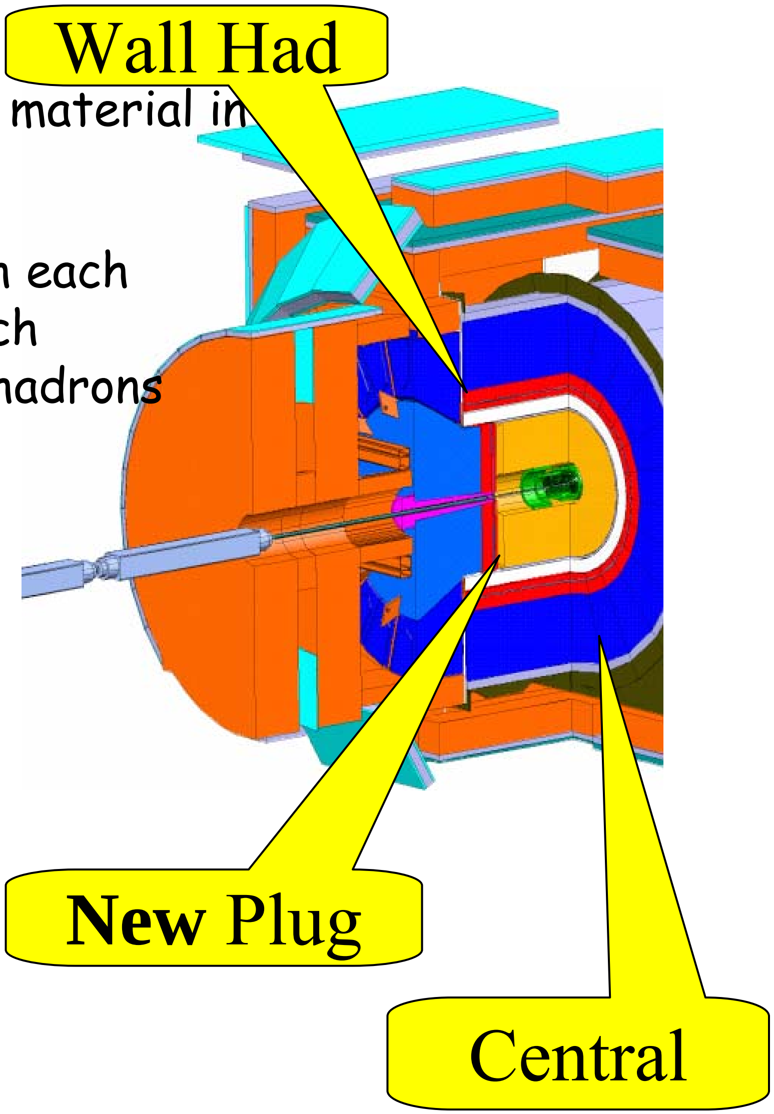


- Focus on transverse variables
  - Transverse Energy $E_T = E \sin\theta$ (= p_T if mass = 0)

- and longitudinally boost-invariant quantities
  - Pseudorapidity $\eta = -\log(\tan\theta/2)$ (= rapidity y if mass = 0)

CDF calorimeter

- Central and Wall($|\eta|<1.2$):
  - Scintillating tile with lead (iron) as absorber material in EM (HAD) section
  - Coarse granularity:
    - Φ: 24 towers cover 15 degrees in azimuth each
    - η: 10 towers cover 0.1 unit in rapidity each
  - Non-compensating➔ non-linear response to hadrons
  - Rather thin: 4 interaction lengths
  - Resolutions:
    - EM energies: $\sigma/E=13.5\% / \sqrt{E}$
    - HAD energies: $\sigma/E=80\% / \sqrt{E}$
- New Plug ($1.2<|\eta|<3.6$):
  - Similar technology to central
  - Differences
    - 48 towers in azimuth
    - EM energies: $\sigma/E=16\ \% / \sqrt{E}$
    - HAD energies: $\sigma/E=80\ \% / \sqrt{E}$
    - More linear response
    - Thicker: 7 interaction lengths



Run I -> Cone algorithm

1. Seeds with E_T > 1 GeV

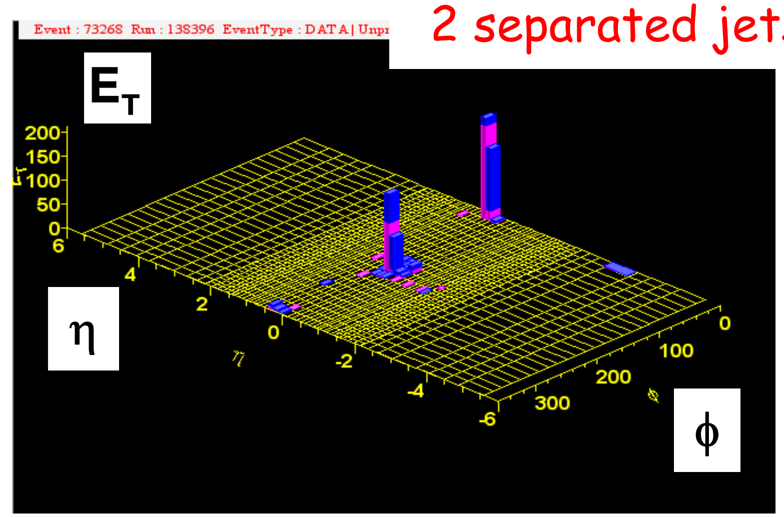
2. Draw a cone around each seed and reconstruct the "proto-jet"

$$E_T^{jet} = \sum_k E_T^k ,$$

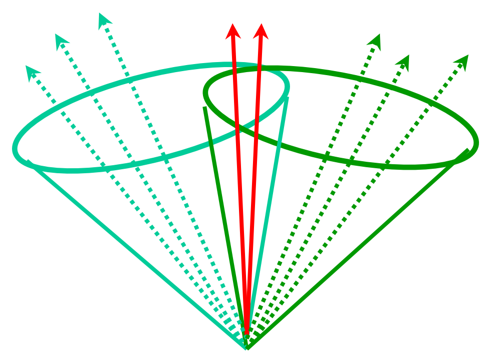
$$\eta^{jet} = \frac{\sum_k E_T^k \cdot \eta_k}{E_T^{jet}}, \quad \phi^{jet} = \frac{\sum_k E_T^k \cdot \phi_k}{E_T^{jet}}$$

3. Draw new cones around "proto-jets" and iterate until stability is achieved

4. Look for possible overlaps



2 separated jets



merged if common E_T is more than 75 % of smallest jet

pQCD NLO has to emulate experimental procedure -> arbitrary parameter in calculation

Jet Corrections

1. Calibrate EM and HAD calorimeters in situ
2. Reconstruct jets (JetClu cone algorithm):P_T^{raw}
3. Correct jets in plug calorimeter w.r.t. central "relative corrections": f_{rel}
   - use di-jet data (versus η)
4. Correct for Multiple pp Interactions : UEM
5. Correct measured jets back to particle level jets: tune MC simulation: f_{abs}
   - Response of calorimeter to single particles
   - Fragmentation: Pt spectra in data
6. Correct for Underlying Event: UE
7. Correct particle jet back to parton: OC

$$P_T(\Delta R) = (P_T^{raw}(\Delta R) \times f_{rel} - UEM(\Delta R)) \times f_{abs}(\Delta R) - UE(\Delta R) + OC(\Delta R)$$

Systematic error associated with each step

Detector to Particle Level

- Do not use data since no high statistics calibration processes at high Et>100 GeV
- Extracted from MC

MC needs to:

1. Simulate accurately the response of detector to single particles (pions, protons, neutrons, etc.):
   CALORIMETER SIMULATION
2. Describe particle spectra and densities at all jet Et:
   FRAGMENTATION
   - Measure fragmentation and single particle response in data and tune MC to describe it
   - Use MC to determine correction function to go from observed to "true"/most likely Et:

$$E^{true}=f\ (\ E^{obs},\ \eta,\ \text{conesize})$$

Absolute Correction from MC

- Wanted:
  - Most likely true Et value for given measured Et value

- BUT cannot be obtained universally for all analyses since it depends on Et spectrum:
  - E.g. most likely value in falling spectrum dominated by smearing from lower Et bins
  - Different for flat Et spectrum (e.g. top or new resonance)

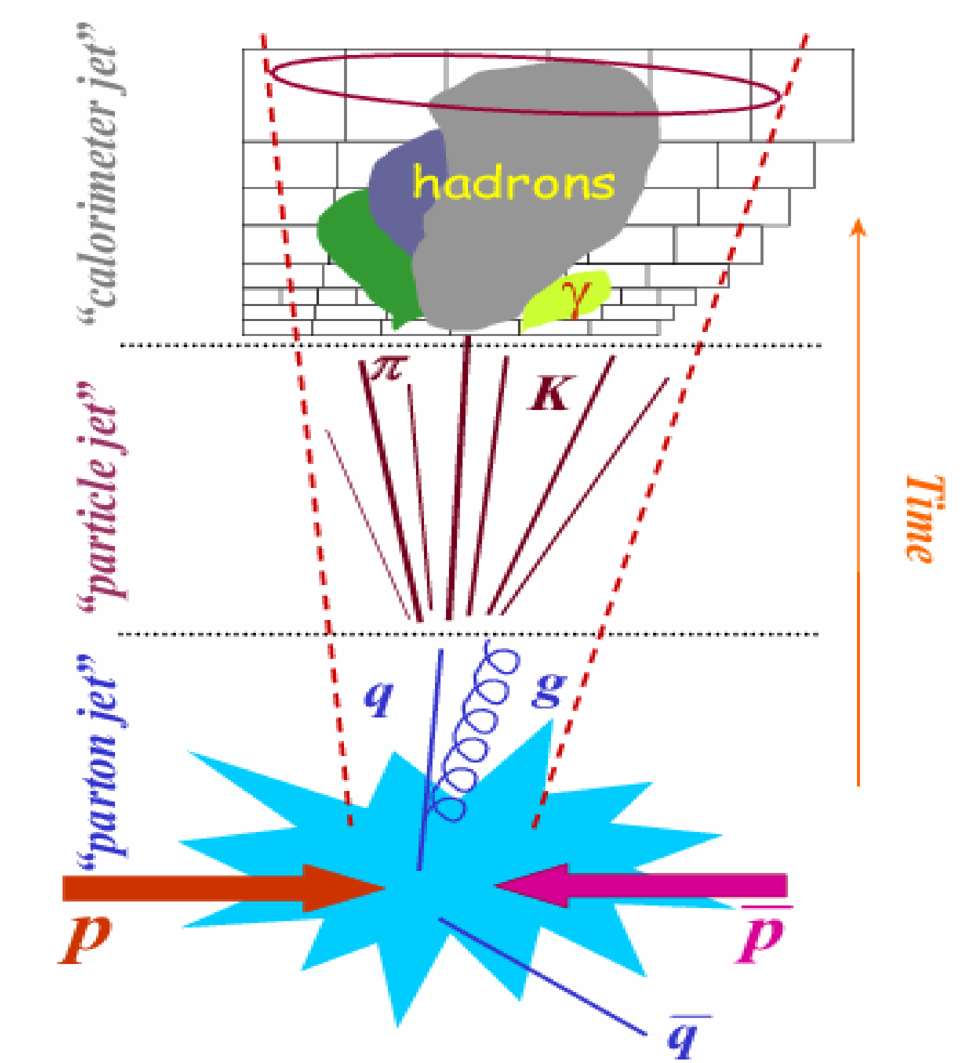
- CDF:
  - Provide standard "generic" jet corrections using flat Pt spectrum
  - Individual analyses determine their "specific" residual corrections themselves from their MC

Summary Jet Calibrations

- Calibration signals:
  - MIP peak, E/p, Z→ ee and Min Bias for calorimeter calibration
  - Di-jet balancing for relative response in cracks and in plug calorimeter
  - Isolated tracks for understanding calorimeter response to π, p, K (fragmentation needs to be modeled)
- Independent channels used for cross checks/systematic error:
  - γ-Jet and Z-jet balancing
  - Z→ bb peak and W→jj peak in tt events

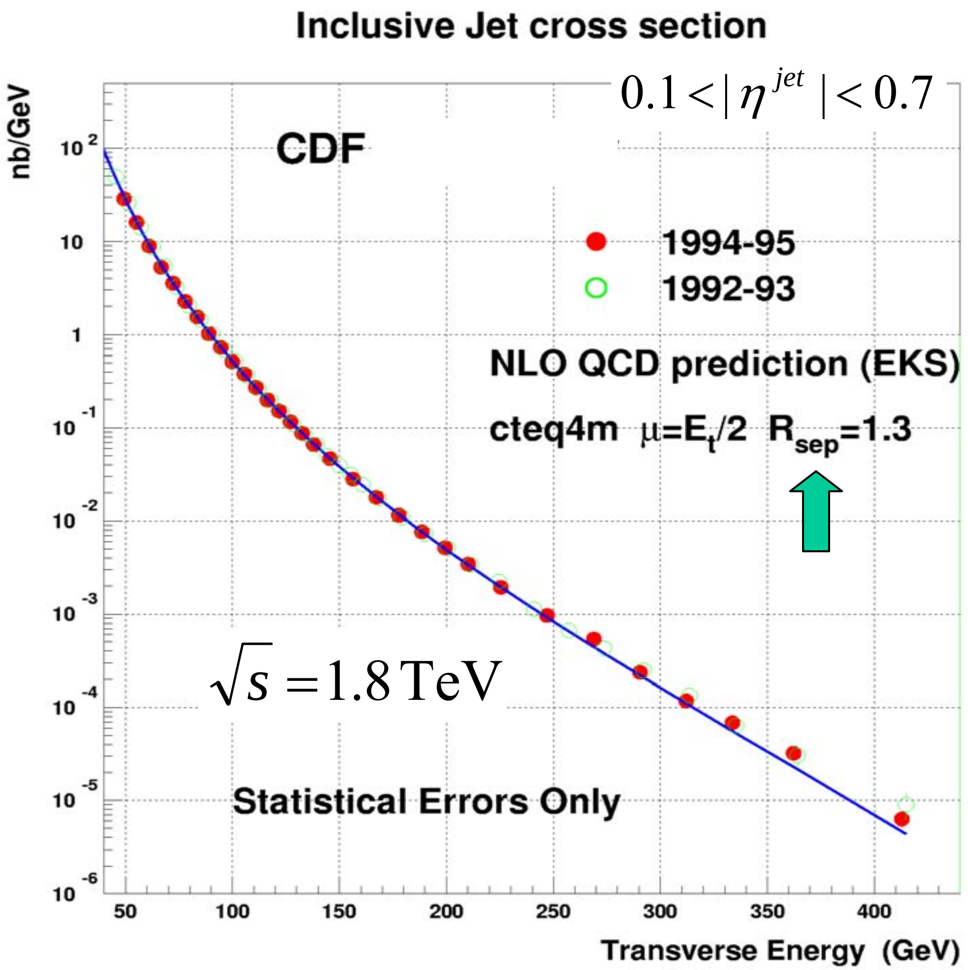
Excellent simulation required, particularly for high Et jets where no physics channels available for calibration

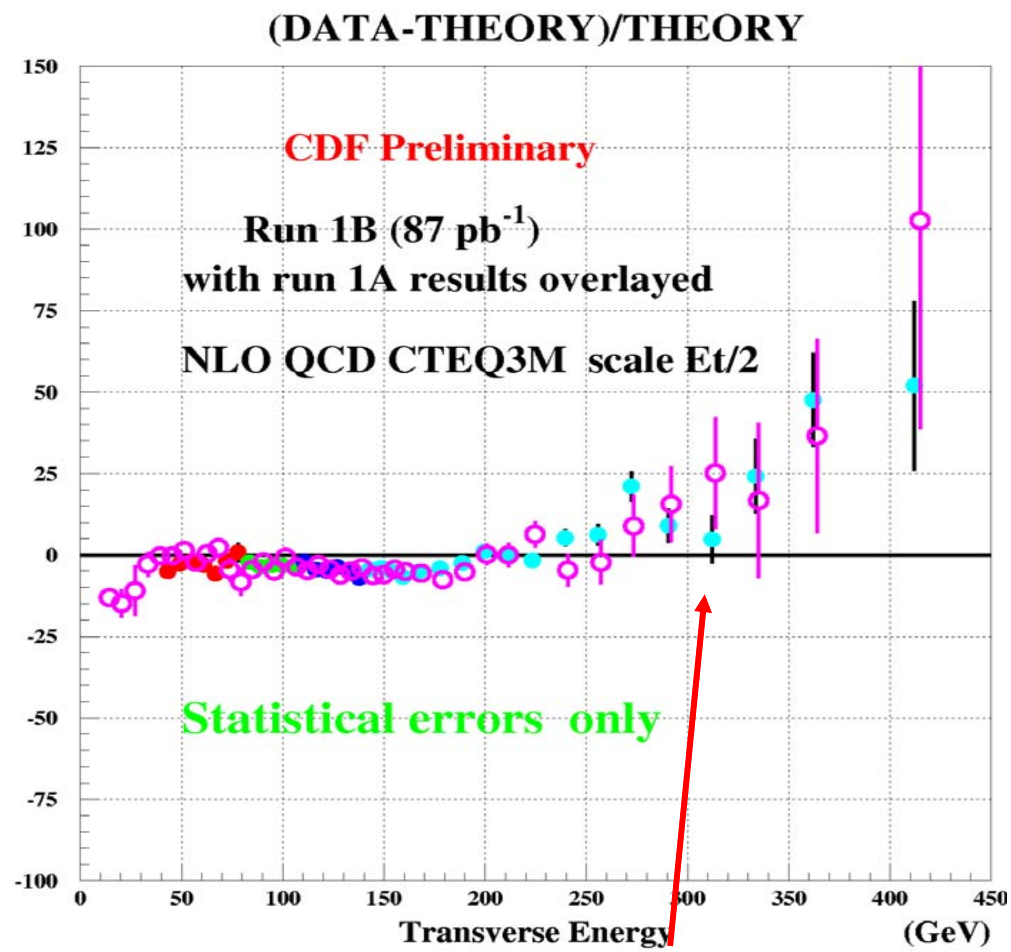
Jet algorithms & physics



- Final state partons are revealed through collimated flows of hadrons called jets
- Measurements are performed at hadron level & theory is parton level (hadron → parton transition will depend on parton shower modeling)
- Precise jet search algorithms necessary to compare with theory and to define hard physics
- Natural choice is to use a cone-based algorithm in $\eta-\phi$ space (invariant under longitudinal boost)

Run I Results





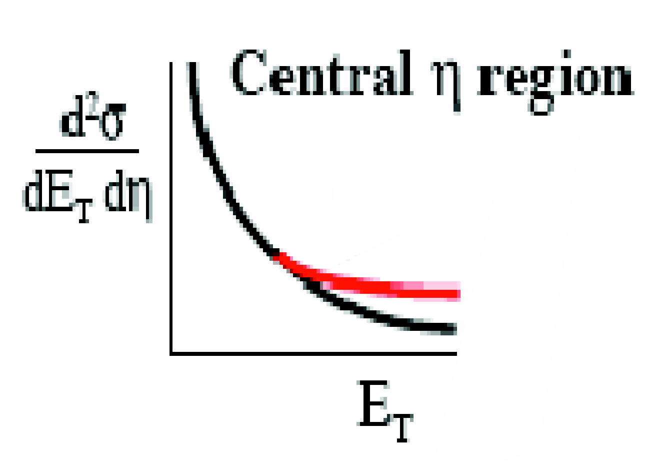
Run I data compared to pQCD NLO

Observed deviation in tail ....
was this a sign of new physics ?

Compositness

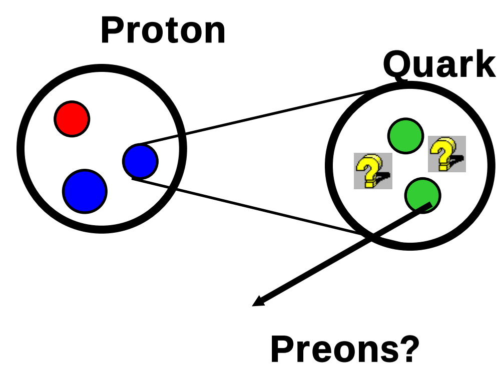
- Jet production at the Tevatron currently probes the most "violent" collisions currently achievable
  - smallest distance scales (10^{-17} cm)
  - some of greatest sensitivity to new physics->quark compositenes
- New version of Rutherford scattering
  - production of jets at high pT indicates that there must be point-like constituents within proton, i.e. quarks
  - If we observe a deviation from the expected jet cross sections at the highest jet pT's (smallest distance scales), this may also be an indication of something inside the quarks
- Energia jet ~500 GeV - Probes proton structure to smallest distance scales

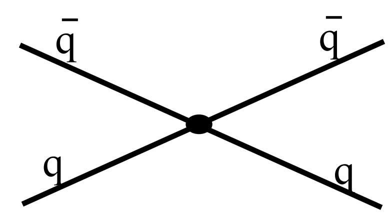
$$\lambda = hc/Mc^2$$
$$= 197 MeVfm/500\ GeV$$
$$= 4x10^{-17} cm$$



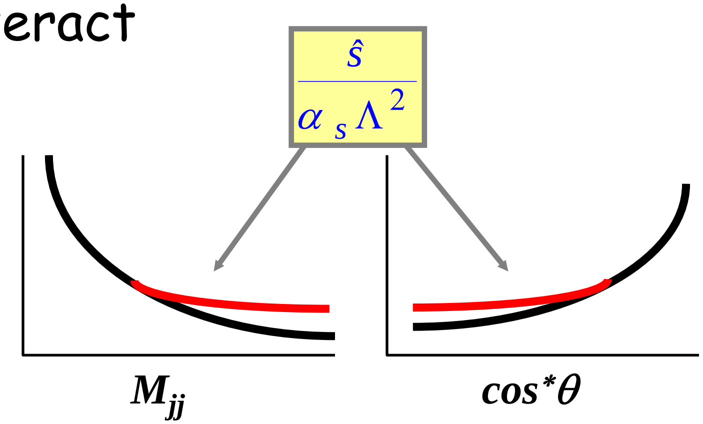
Using jets as a probe of quark structure

- If quarks contain smaller constituents
  - constituent interactions have a scale Λ
  - at momentum transfers << Λ, quarks appear pointlike and QCD is valid
  - as we approach scale Λ, interactions can be approximated by a four-fermion contact term:
  - at and above Λ, constituents interact directly



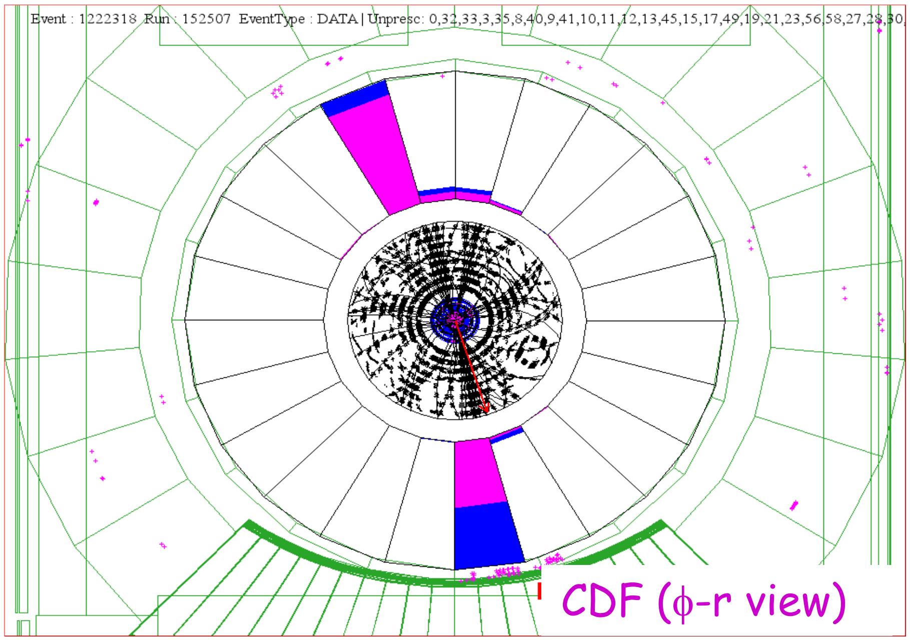


σ ~ [QCD + Interference
+ Compositeness]



Modifies dijet mass and centre of mass scattering angle distribution

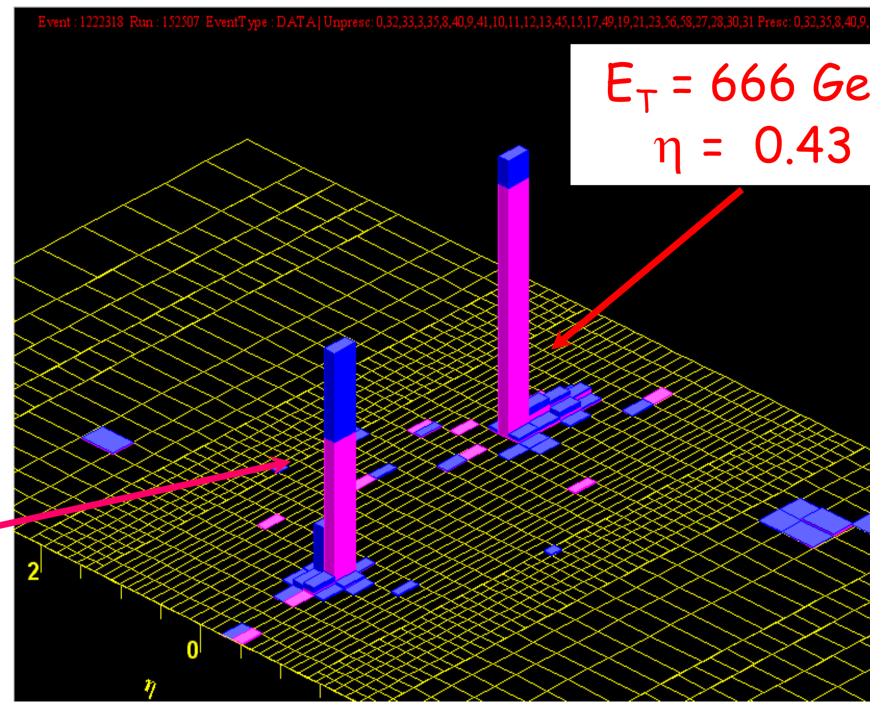
One of the Highest Mass Dijet Event



Dijet Mass = 1364 GeV

(probing distance ~10^{-19} m)

E_T = 666 GeV
η = 0.43



E_T = 633 GeV
η = -0.19