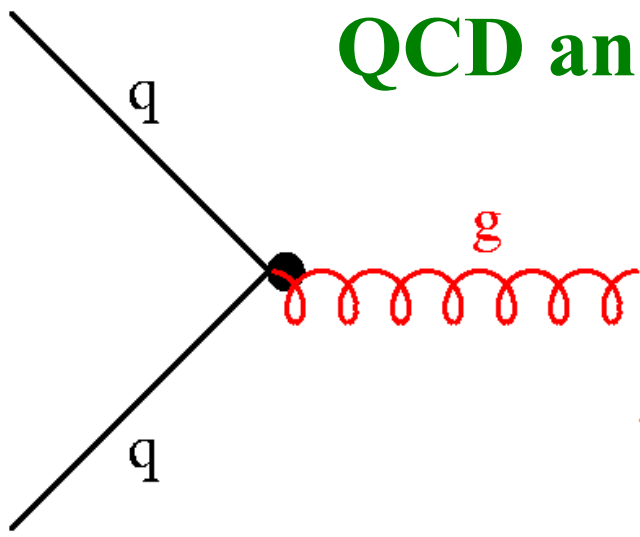
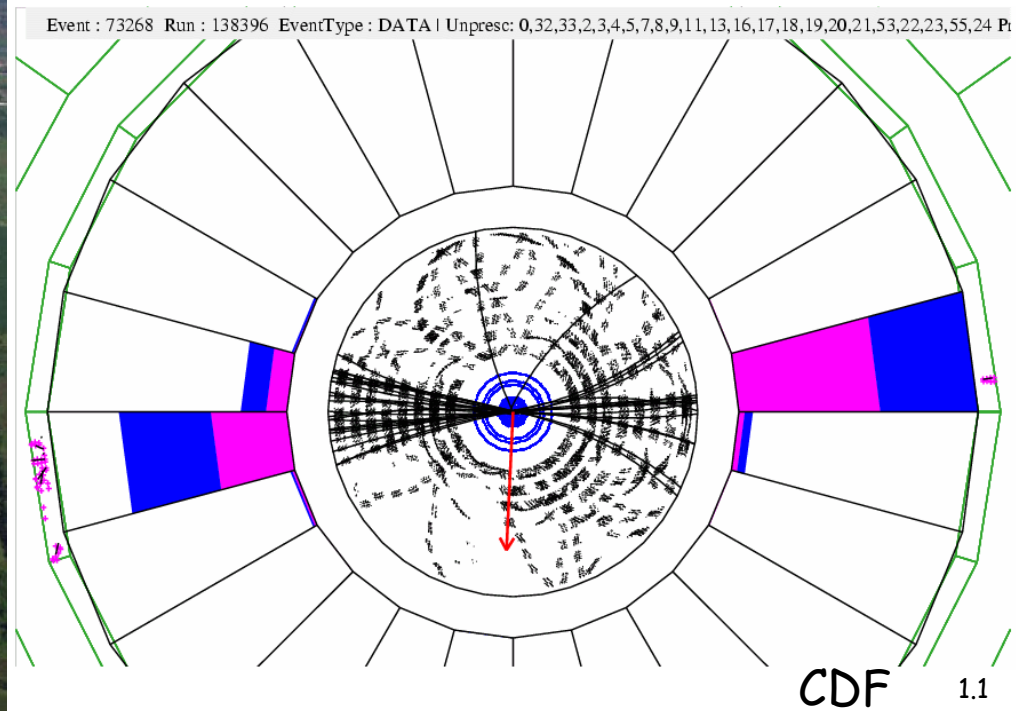
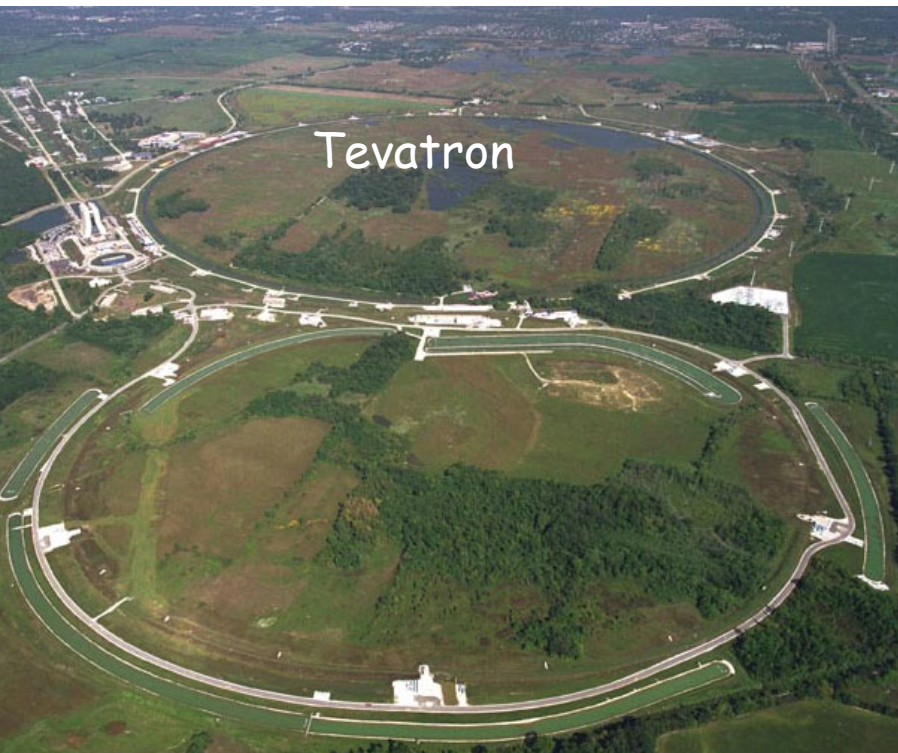
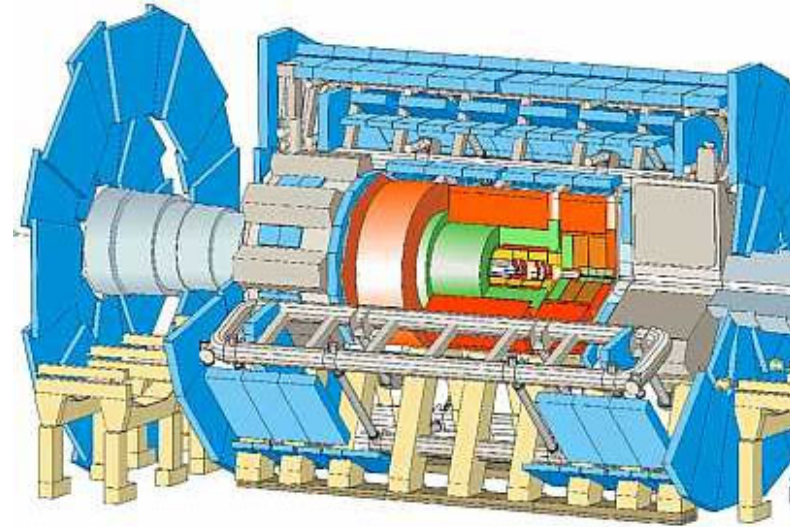


QCD and Hadron Colliders



Thomas Hebbeker
RWTH Aachen
Dortmund, Oct. 2005

ATLAS



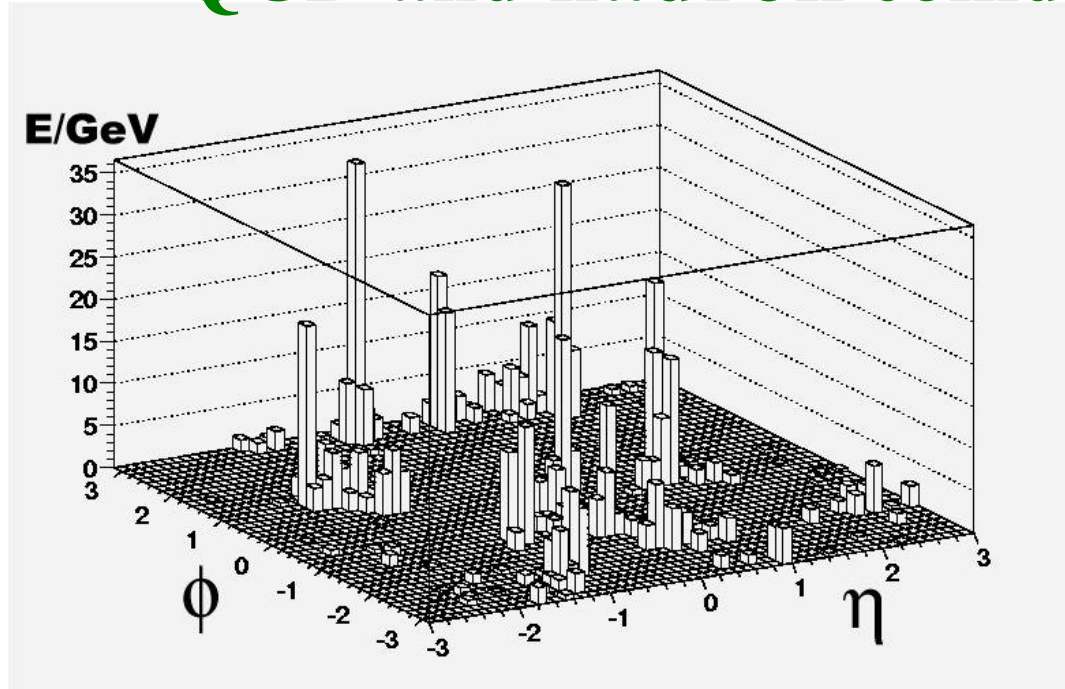
QCD and hadron colliders ???

QCD precision tests ?

well...

huge background !

yes !



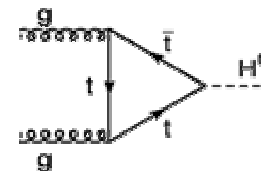
Q
C
D

• test QCD



S
M
&
N
P

- QCD = background
- prod. /dec. of SM/new particles
- corr. to elw. processes



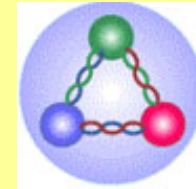
... $t \rightarrow bW$

$gg \rightarrow H$

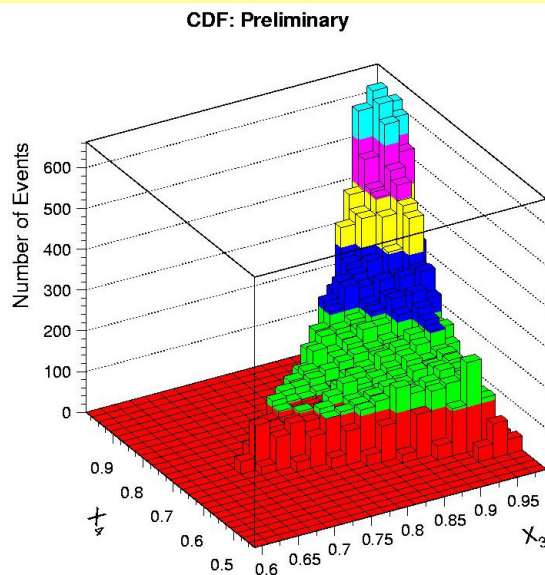
$q\bar{q} \rightarrow W g$

1) Introduction

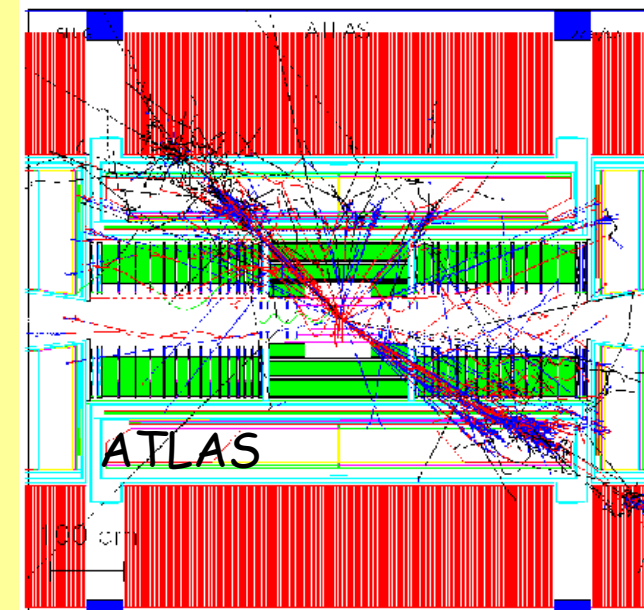
- **QCD** theory tests
- **Hadron** (anti) protons
- **Colliders** kinematics background jets ...



2) Tevatron $p + \bar{p}$ 2 TeV



3) LHC $p + p$ 14 TeV



t

QCD = SU(3) gauge theory

$$\mathcal{L} = \underbrace{\bar{q} [i \gamma^\mu \partial_\mu - m] q}_{\text{free quarks}} + \underbrace{i g_s \bar{q} q g}_{\text{quark-gluon-int.}} - \underbrace{\frac{1}{4} F F}_{\text{gluons}}$$

spin $\frac{1}{2}$ quarks

coupling constant (only free parameter)

spin 1 gluons

QCD = SU(3) [nonabelian] gauge theory

$$\mathcal{L} = \underbrace{\bar{q}_\alpha^{a,j}}_{\text{spin } \frac{1}{2} \text{ quarks}} \left[i \gamma_{\alpha\beta}^\mu (\delta_{ab} \partial_\mu + i \underbrace{g_s}_{\text{SU(3)}} t_{ab}^r \underbrace{g_\mu^r}_{\text{spin 1 gluons}}) - m_j \delta_{ab} \delta_{\alpha\beta} \right] \underbrace{q_\beta^{b,j}}_{\text{spin } \frac{1}{2} \text{ quarks}} - \frac{1}{4} F_{\mu\nu}^r F^{r,\mu\nu}$$

$\alpha, \beta, \dots =$	$1, 2, 3, 4$	Dirac index	
$\mu, \nu, \dots =$	$1, 2, 3, 4$	space time index	
$a, b, \dots =$	$1, \dots, N_C = 3$	quark color index	} SU(3)
$r, s, \dots =$	$1, \dots, N_C^2 - 1 = 8$	gluon color index	
$j, k, \dots =$	$1, \dots, N_F$	$\stackrel{= N_A}{\text{flavor index}}$	

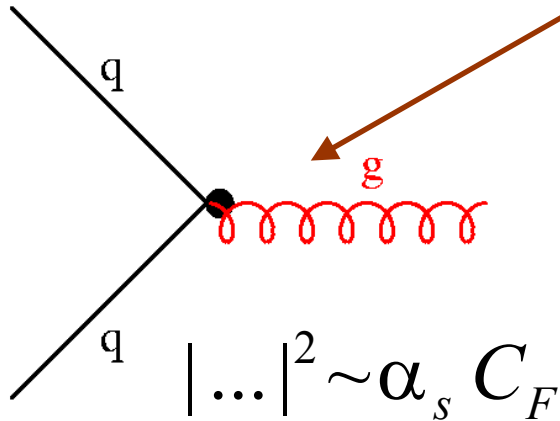
$$\alpha_s = \frac{g_s^2}{4\pi}$$

coupling constant (only free parameter)

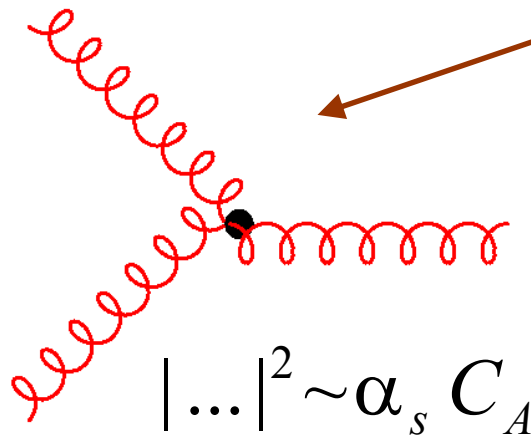
$$F_{\mu\nu}^r = \partial_\mu \underbrace{g_\nu^r}_{\text{spin 1 gluons}} - \partial_\nu \underbrace{g_\mu^r}_{\text{spin 1 gluons}} - \underbrace{g_s}_{\text{SU(3)}} f^{rst} \underbrace{g_\mu^s}_{\text{spin 1 gluons}} \underbrace{g_\nu^t}_{\text{spin 1 gluons}}$$

QCD – basic Feynman diagrams

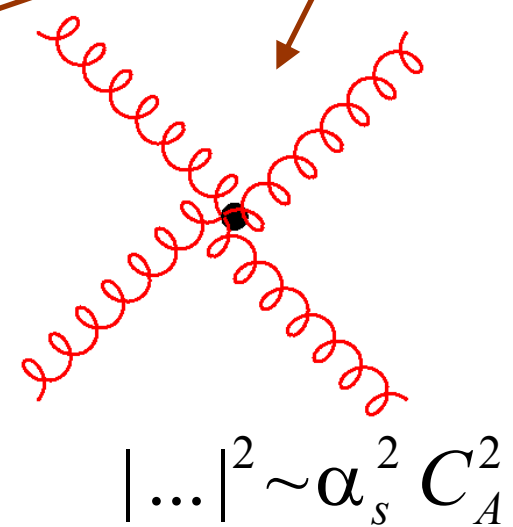
$$\mathcal{L} = \underbrace{\bar{q}_\alpha^{a,j} \left[i \gamma_{\alpha\beta}^\mu (\delta_{ab} \partial_\mu + i g_s t_{ab}^r g_\mu^r) - m_j \delta_{ab} \delta_{\alpha\beta} \right] q_\beta^{b,j}}_{\text{quark kinetic and mass terms}} - \underbrace{\frac{1}{4} F_{\mu\nu}^r F^{r,\mu\nu}}_{\text{gluon kinetic term}}$$



$$|\dots|^2 \sim \alpha_s C_F$$



$$|\dots|^2 \sim \alpha_s C_A$$

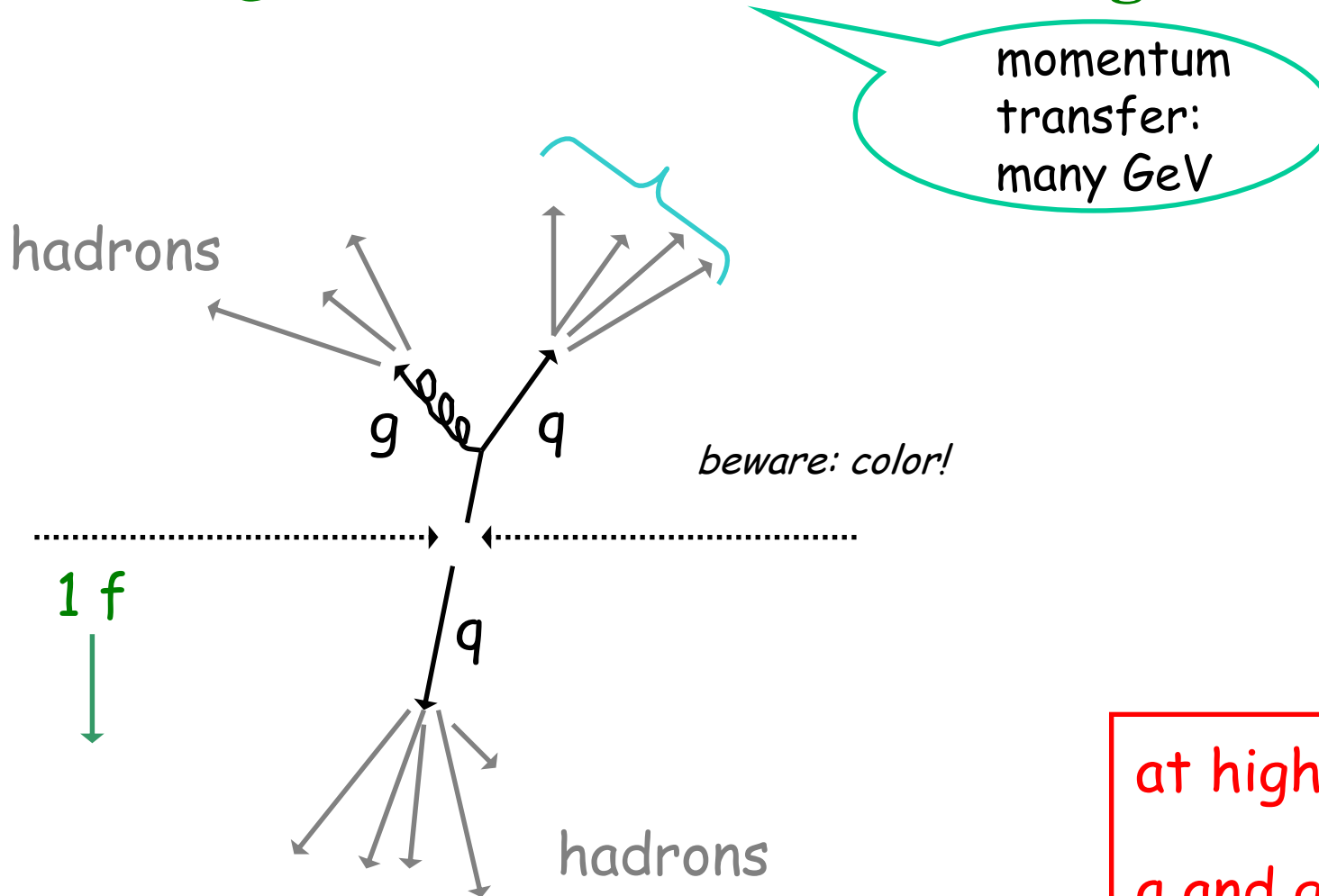


$$|\dots|^2 \sim \alpha_s^2 C_A^2$$

$$C_A = N_C = 3 \quad C_F = \frac{1}{2} \cdot \frac{N_A}{N_C} = \frac{4}{3}$$

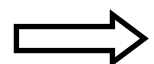
$$F_{\mu\nu}^r = \partial_\mu g_\nu^r - \partial_\nu g_\mu^r - g_s f^{rst} g_\mu^s g_\nu^t$$

QCD tests in hard scattering ?



at high energies:
 q and g = **jet**

Hadronization: non-perturbative



need models!

Pythia Herwig ...

(include parton showers)

QCD tests ?



- quark spin ? [1/2]
- gluon spin ? [1]
- quark colors ? [3]

**n
o
n
a
b
e
l
i
a
n**

- gluon colors ? [8]
- triple gluon vertex ?
- four gluon vertex ?
- universality of α_s ?

qqg ggg gggg ?

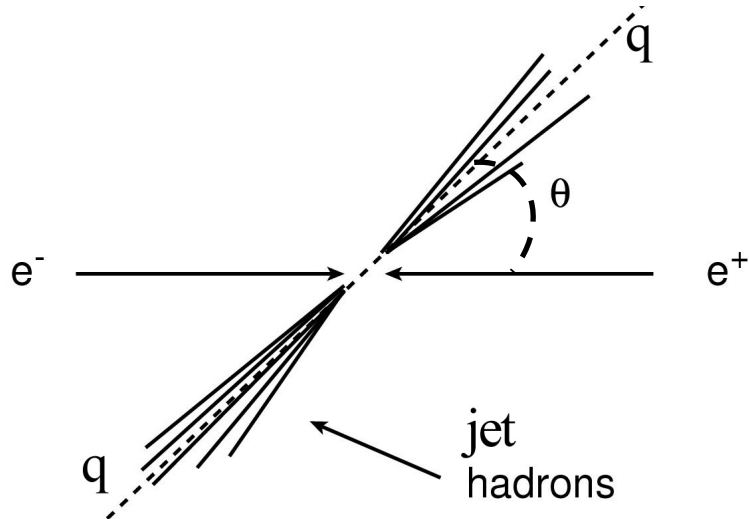
flavor independence ?

- running of α_s ?



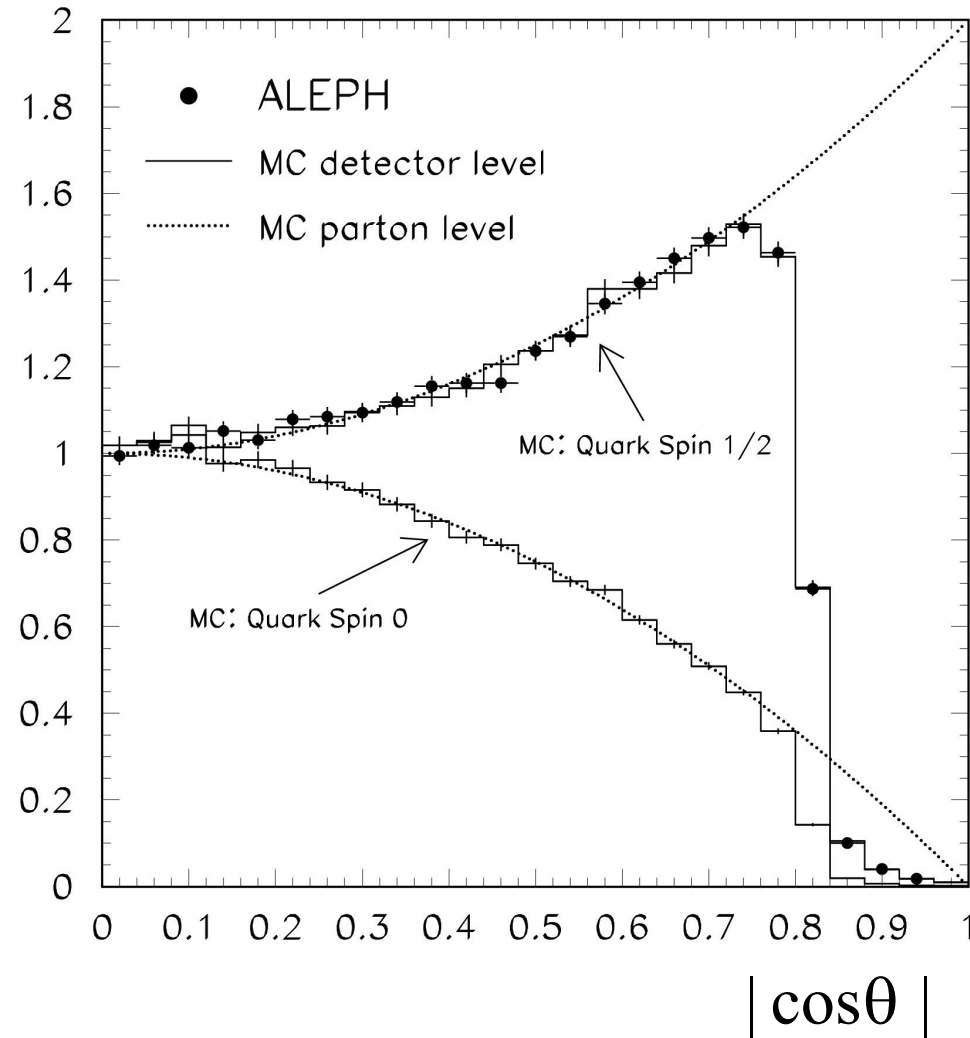
Test: Quark spin ?

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



$$\frac{d\sigma}{d\cos\theta} \sim \begin{cases} 1 + \cos^2\theta & 1/2 \\ 1 - \cos^2\theta & 0 \end{cases}$$

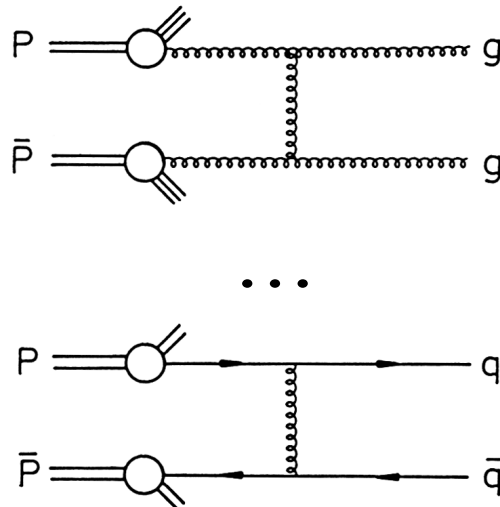
$$\sim d\sigma / d|\cos\theta|$$



quark spin = 1/2

Test: Gluon spin ?

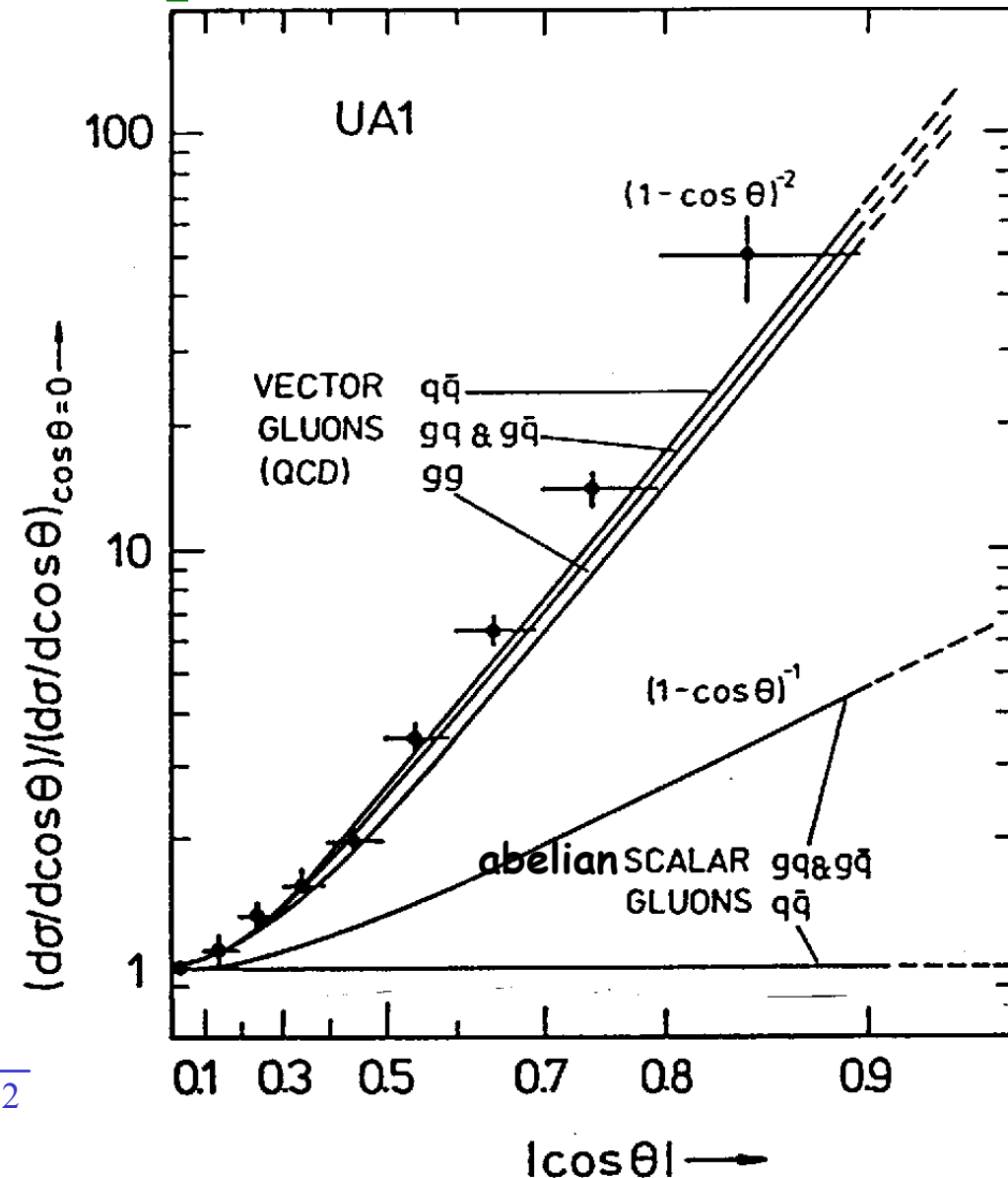
$p \bar{p} \rightarrow jet \ jet$



Spin-1 gluon:
Rutherford formula:

$$\frac{d\sigma}{d\cos\theta} \sim \frac{1}{\sin^4\theta/2} \sim \frac{1}{(1-\cos\theta)^2}$$

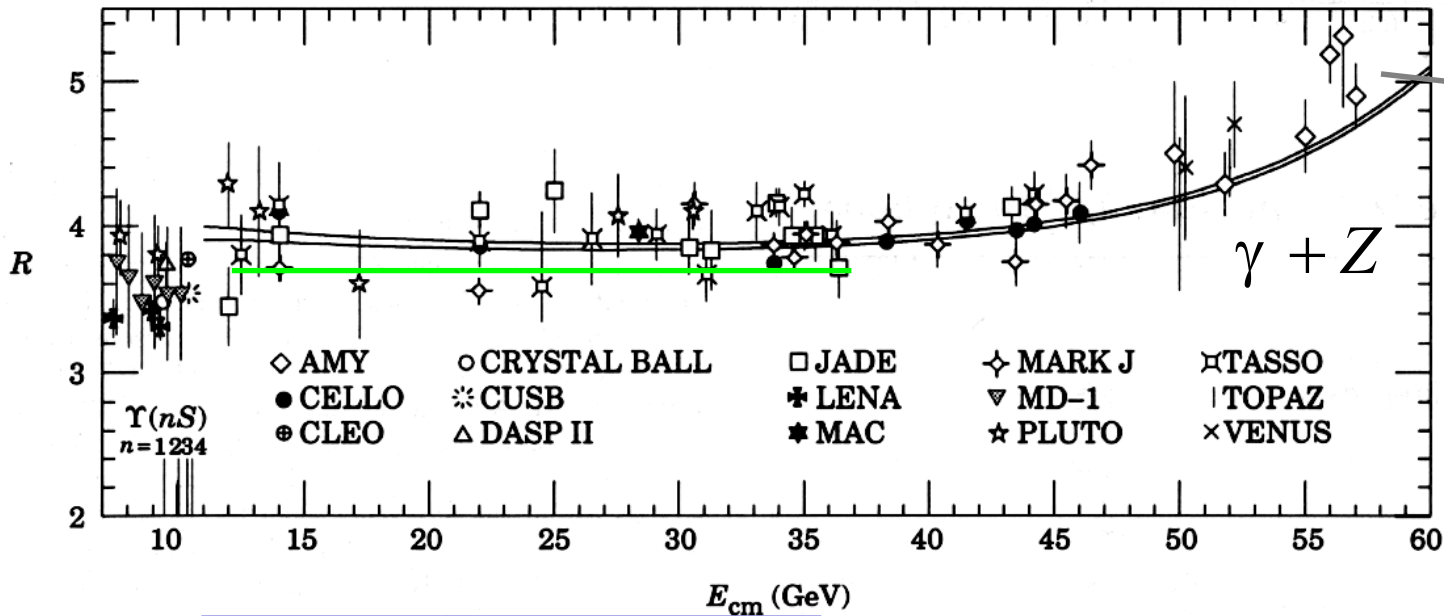
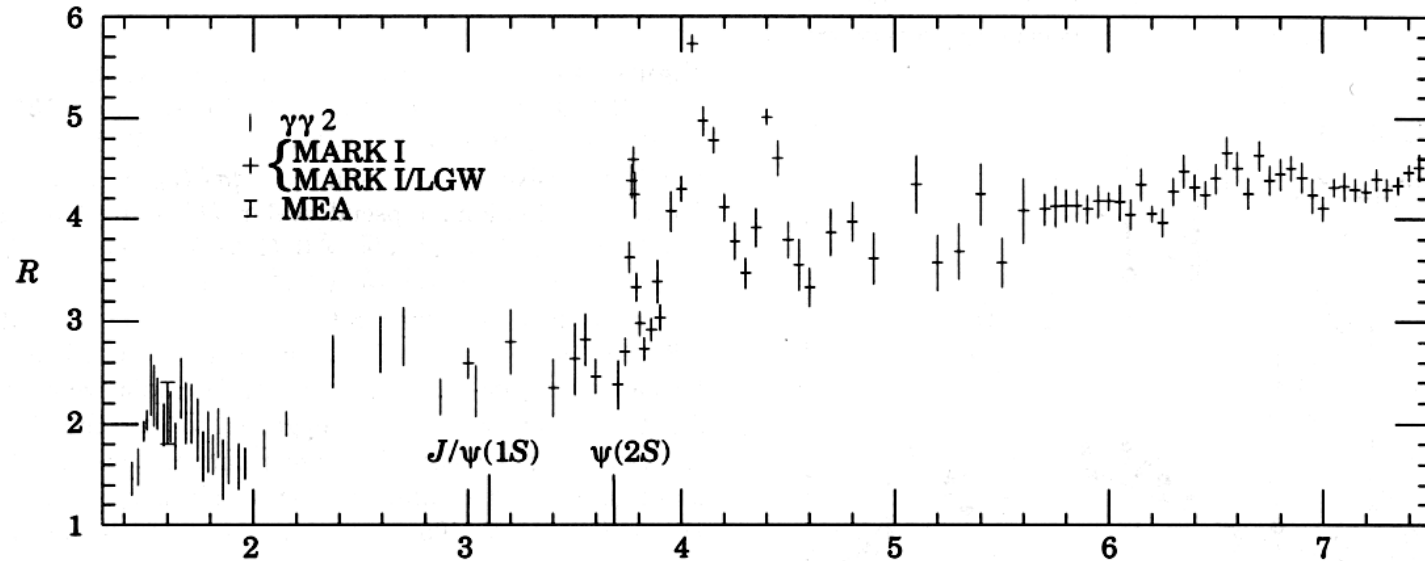
in c.m.s.



gluon spin = 1

Test: # quark color degrees of freedom

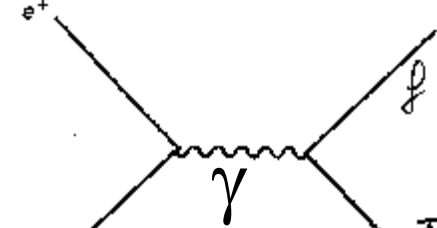
R in e^+e^- Collisions



$$R =$$

$$\frac{\sigma(ee \rightarrow \text{hadrons})}{\sigma(ee \rightarrow \mu\mu)}$$

$$= N_C \cdot \sum Q_q^2$$



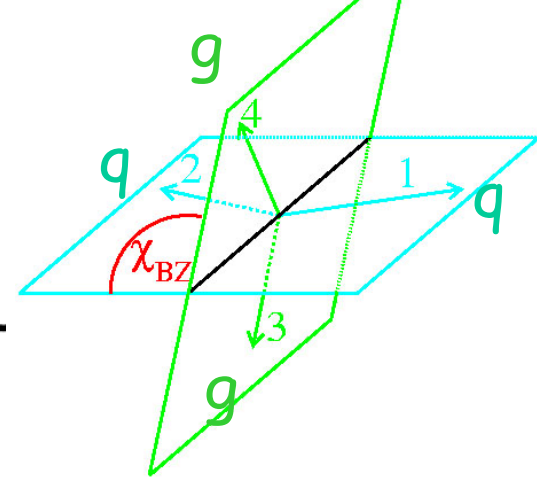
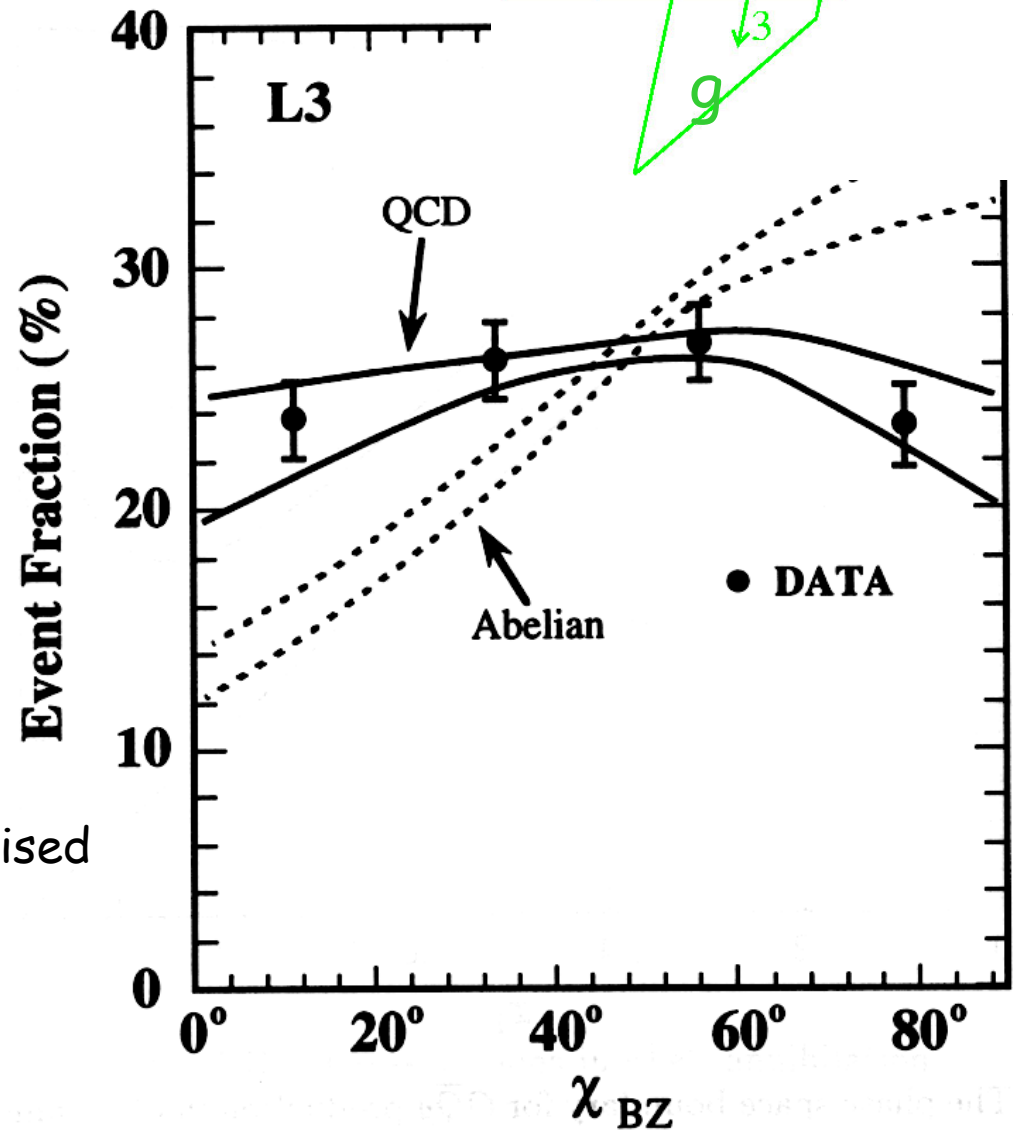
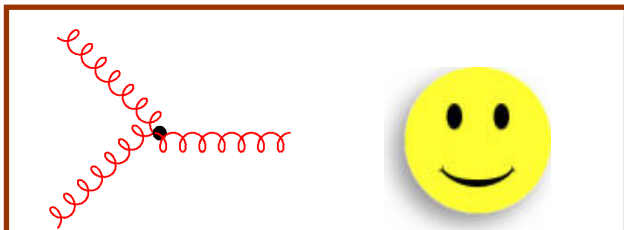
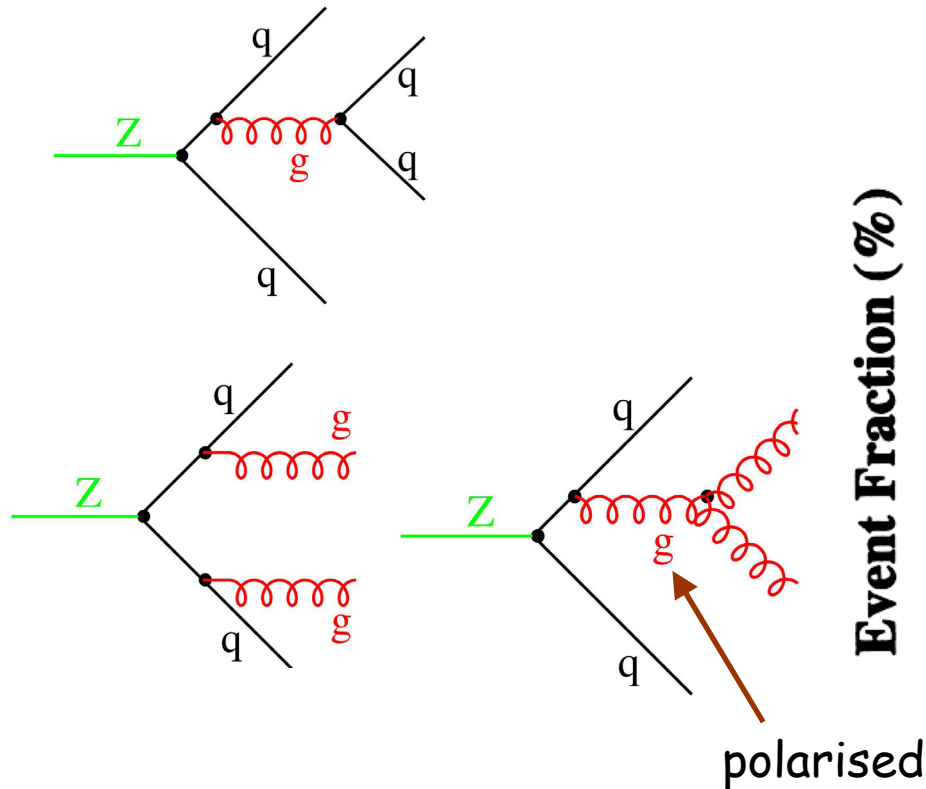
LEP,
Z-Resonanz:

$$N_C = 3.00 \pm 0.01$$

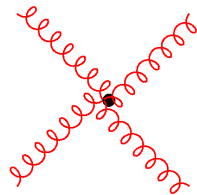
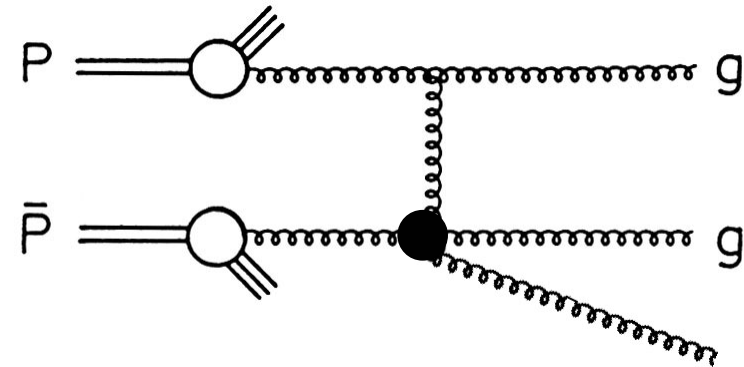
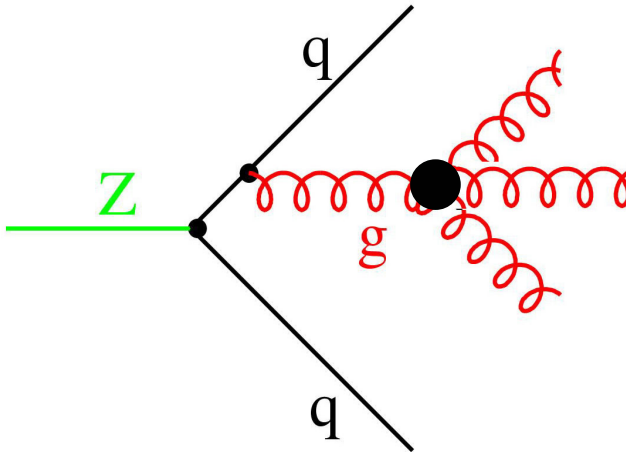
$$N_C = 3$$

Test: Triple gluon vertex ?

$$e^+e^- \rightarrow 4 \text{ jets}$$



Test: Four gluon vertex ?

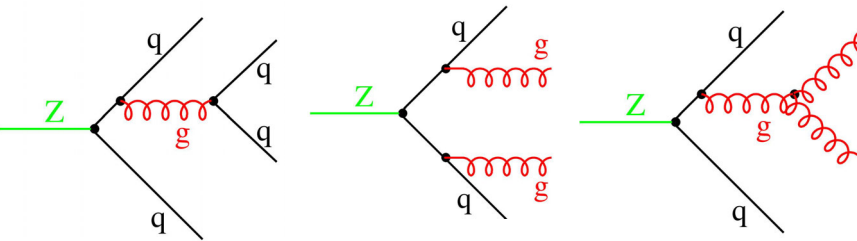


?

NO quantitative test yet !

Test: # gluon color degrees of freedom

$$e^+e^- \rightarrow 4 \text{ jets}$$

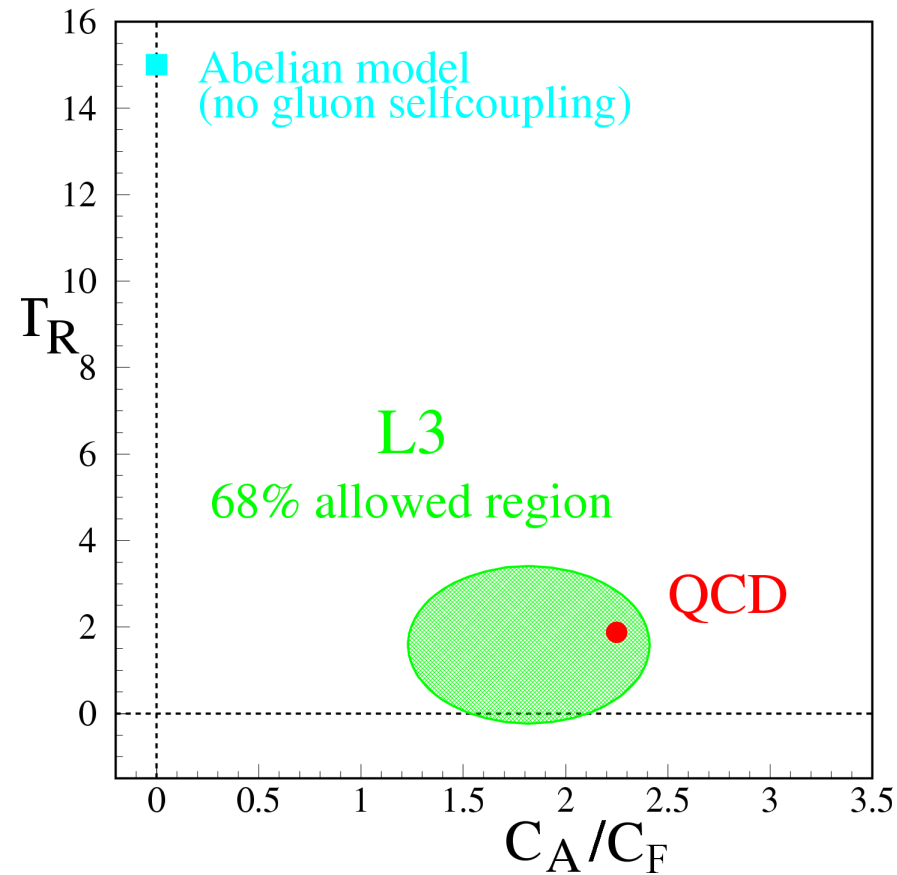


quantitative analysis (LEP+SPS):

$$\begin{aligned} C_A / C_F &= 2N_C^2 / N_A \\ &= 2.21 \pm 0.19 \end{aligned}$$

Schmelling 1994

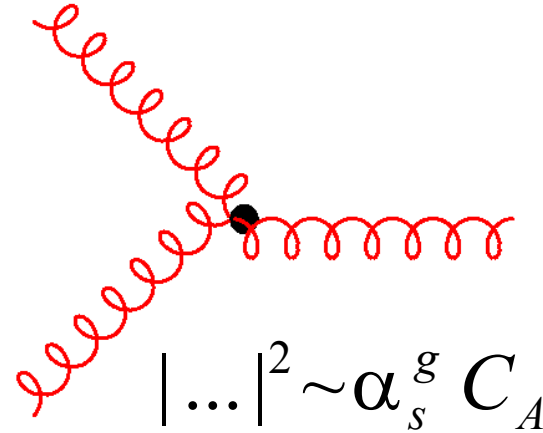
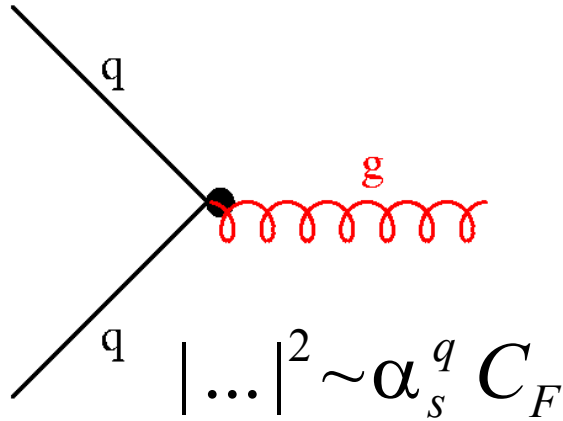
$$N_A = 8.1 \pm 0.7 \rightarrow 8$$



here: assume $q\bar{q}g$ and ggg couplings equal !

Test: Universality of strong coupling constant ?

a) quark-quark-gluon versus gluon-gluon-gluon



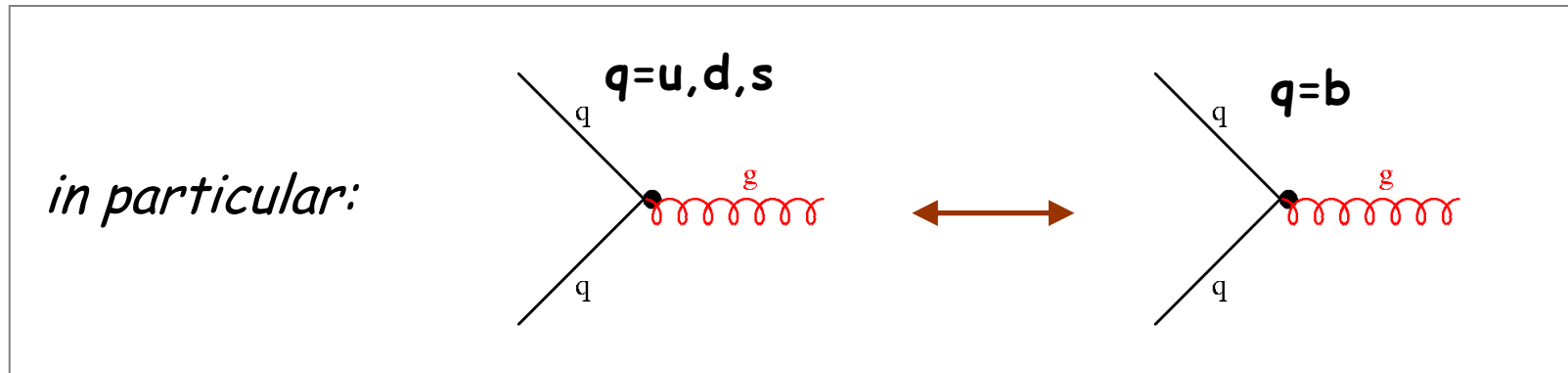
quantitative analysis of $e^+e^- \rightarrow 4 \text{ jets}$ (see above):

$$\alpha_s^q / \alpha_s^g = 1.02 \pm 0.09$$

here: assume C_F and C_A !

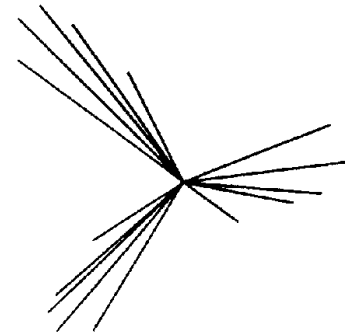
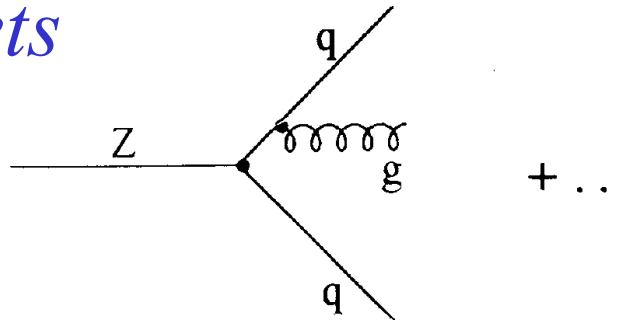
Test: Universality of strong coupling constant ? T. Hebbeker

b) quark-quark-gluon quark flavor dependence ?



$$e^+e^- \rightarrow Z \rightarrow 3 \text{ jets}$$

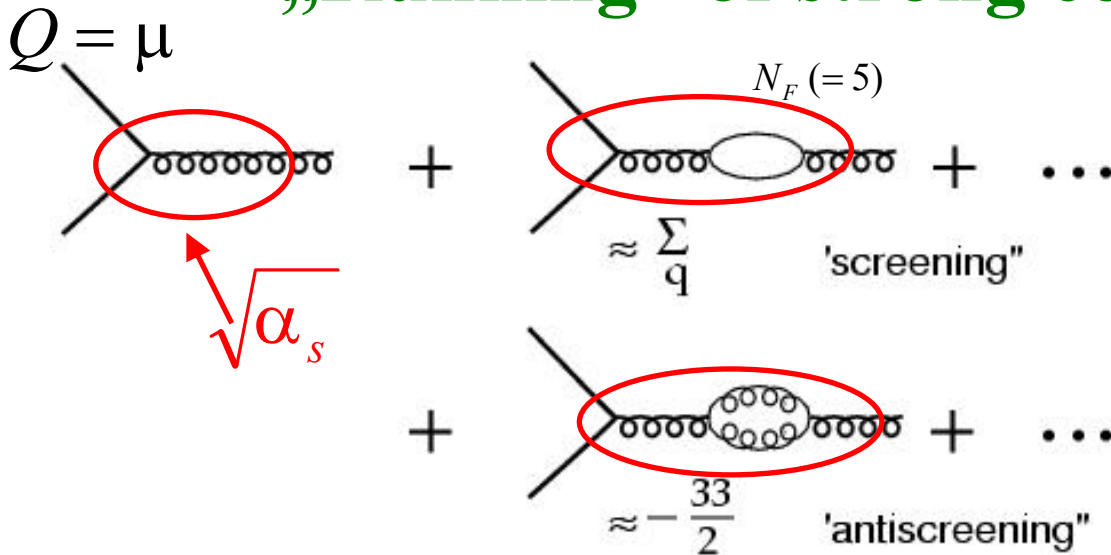
$$\sigma \sim \alpha_s$$



b-tag:
semileptonic decay,
lifetime

$$\alpha_s^b / \alpha_s^{uds} = 1.004 \pm 0.013$$

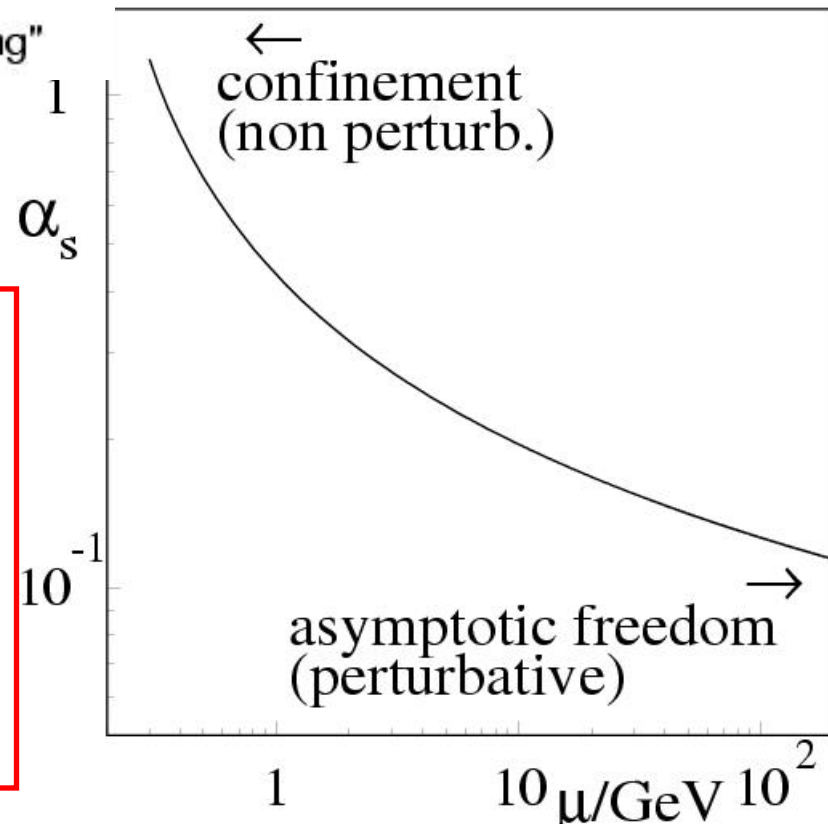
„Running“ of strong coupling constant



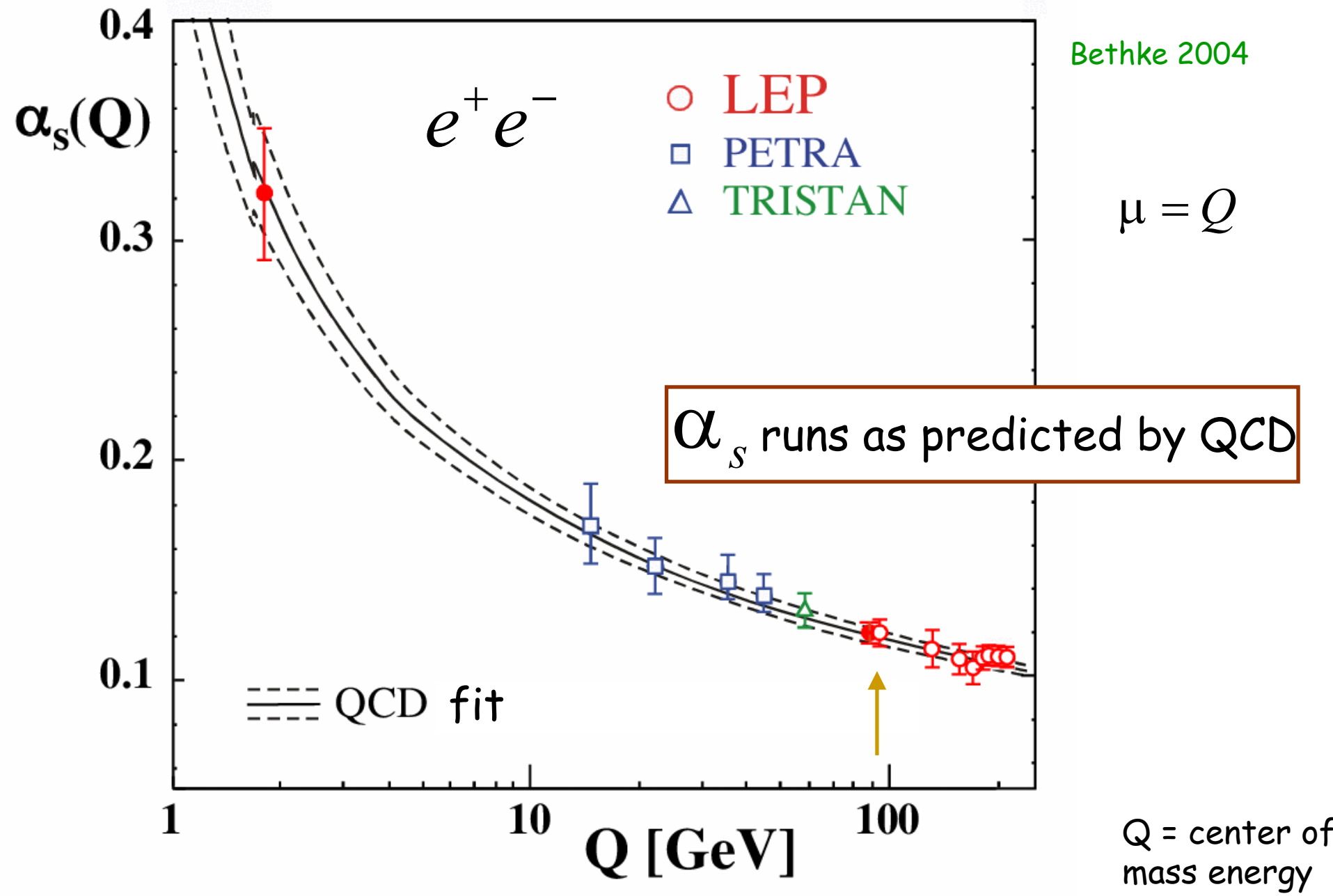
lowest order:

$$\alpha_s(\mu) = \frac{\alpha_s(\mu_0)}{1 - \beta_0 \alpha_s(\mu_0) \ln(\mu^2 / \mu_0^2)}$$

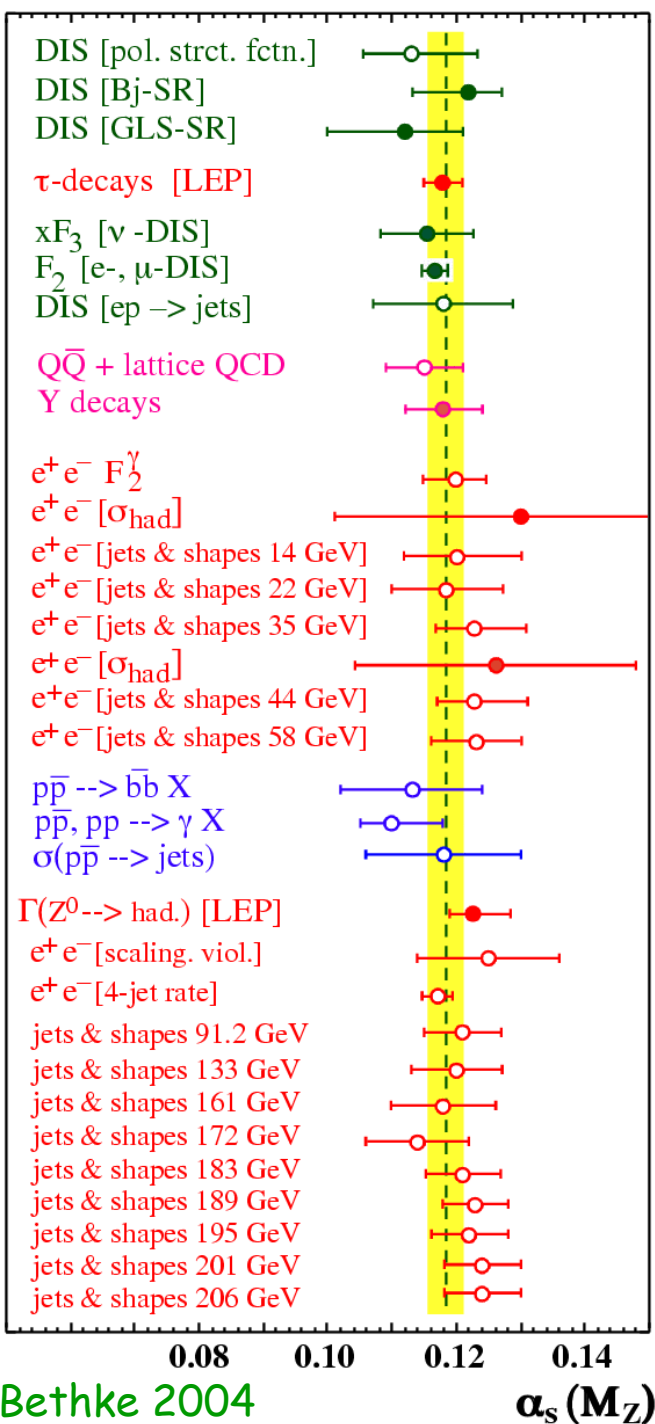
$$\beta_0 = \frac{2N_F - 33}{12\pi} = -0.610$$



Test: „Running“ strong coupling constant ?



strong coupling constant α_s



$$\alpha_s(m_Z) = 0.1182 \pm 0.0027$$

note: $g_s(m_Z) \approx 1.2$

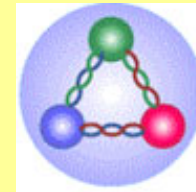
1) Introduction

- QCD theory tests



hadron machines: work less on fundamental tests, rather focus on „**can we understand the data** (*structure functions, higher orders*)?“

- **Hadron** (anti) protons
- **Colliders** kinematics background jets ...



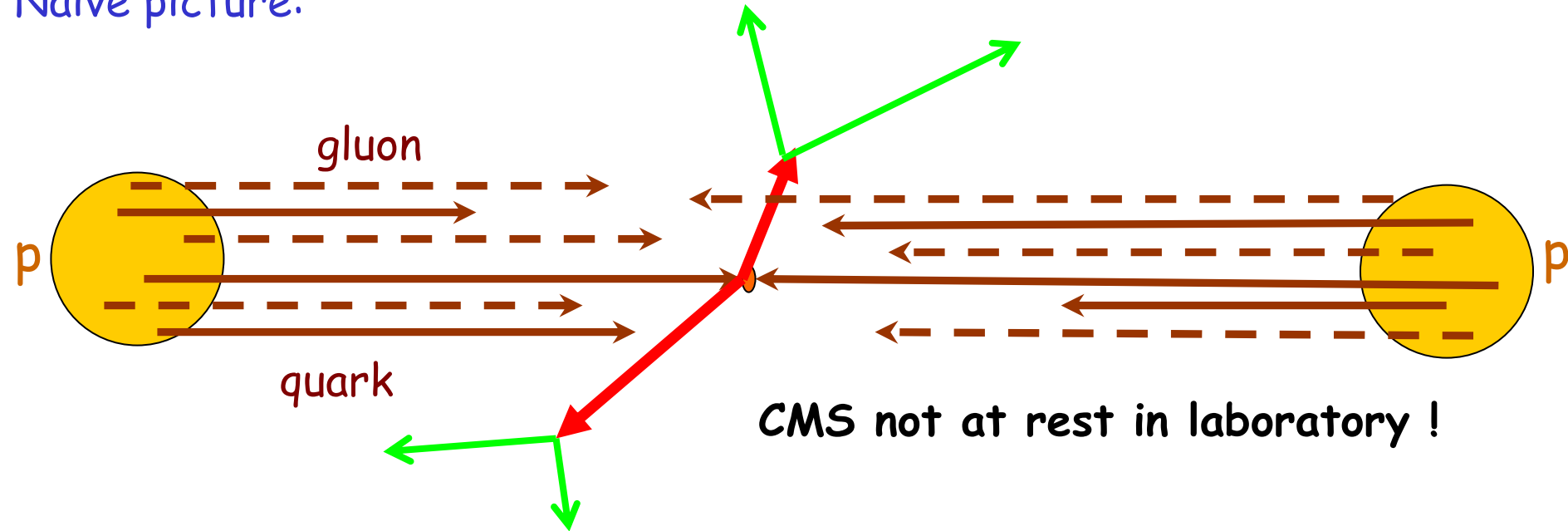
2) Tevatron

3) LHC

t

(hard) hadron collisions

Naive picture:



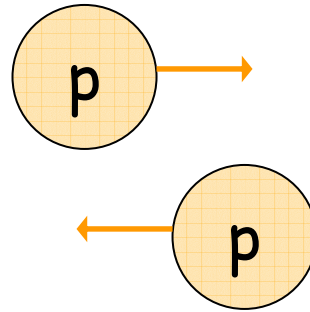
center of mass energy $\sqrt{s'}$ of colliding partons (q, g):

Rough estimate: $\sqrt{s'} \approx \frac{1}{6} \bullet \sqrt{s}$ Calculation: structure functions!

Examples: $q\bar{q} \rightarrow W$ $gg \rightarrow h$ $qg \rightarrow qg$

Cross Section (LHC)

Elastic cross section

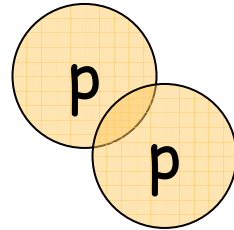


strong,
electromagnetic

scattering angle tiny

BACKGROUN
"minimum bias"

Total inelastic cross section

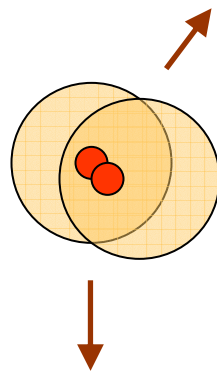


strong

$$\sigma \approx 10 \text{ fm}^2 \approx 10^{-25} \text{ cm}^2$$

forward scattering

Pointlike cross section
SIGNAL



electroweak

$$\sigma \approx \frac{\alpha^2}{s'} \approx 10^{-32} \text{ cm}^2$$

high p_T

strong

$$\sigma \approx \frac{\alpha_s^2}{s'} \approx 10^{-30} \text{ cm}^2$$

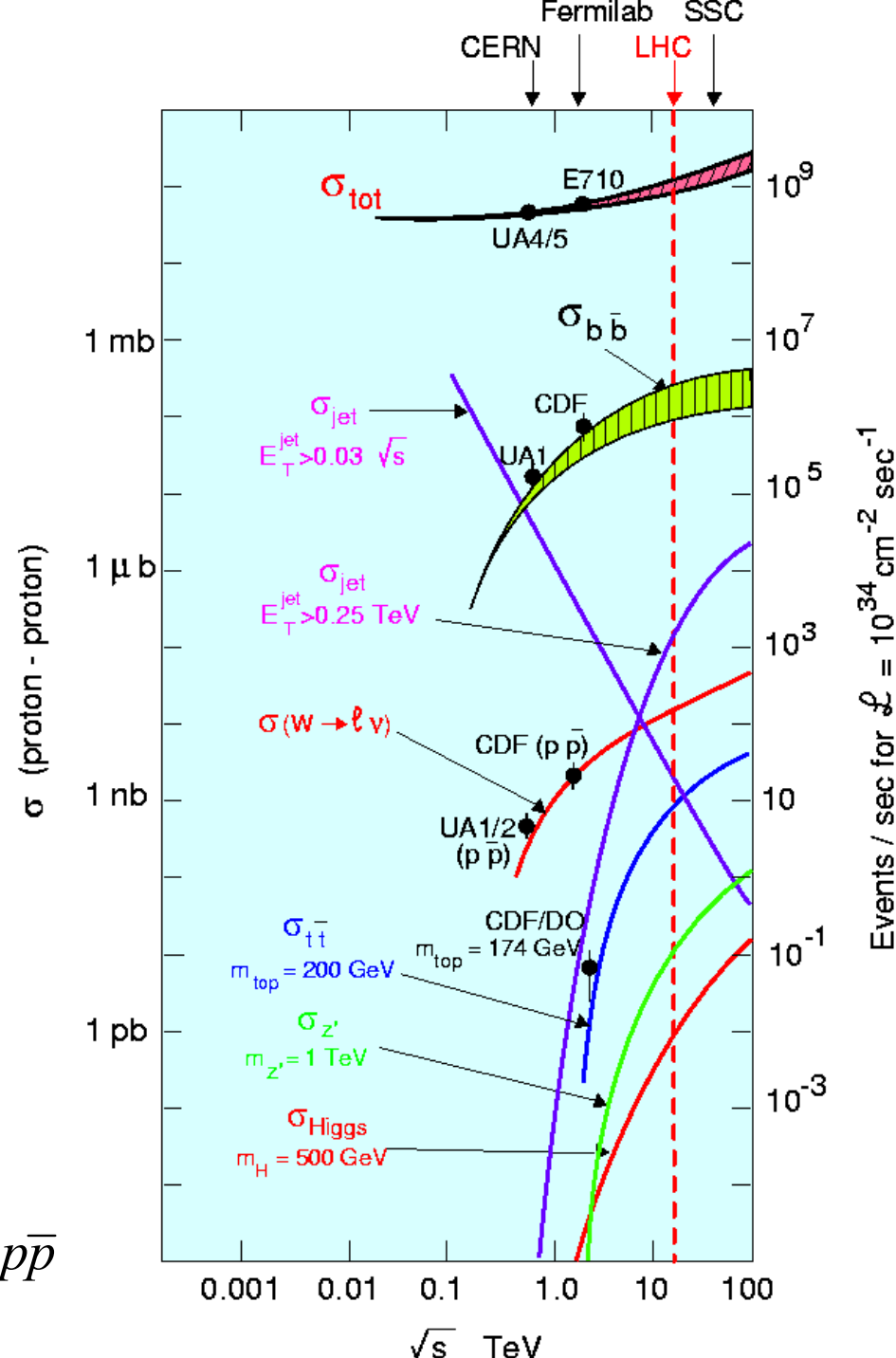
Cross Sections at Hadron Colliders

jet production
(LHC, full luminosity):

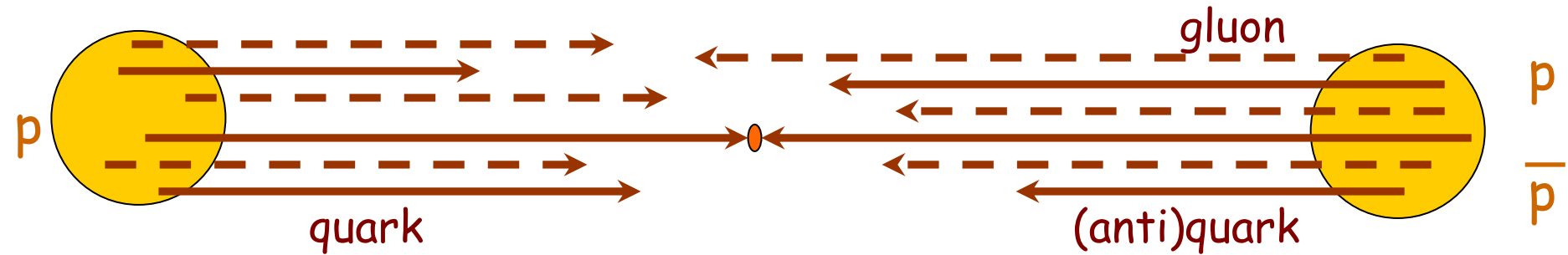
1000 events/s

$p_T > 250 \text{ GeV}$

watch out: $pp \neq p\bar{p}$



Proton or Antiproton ? Physics:

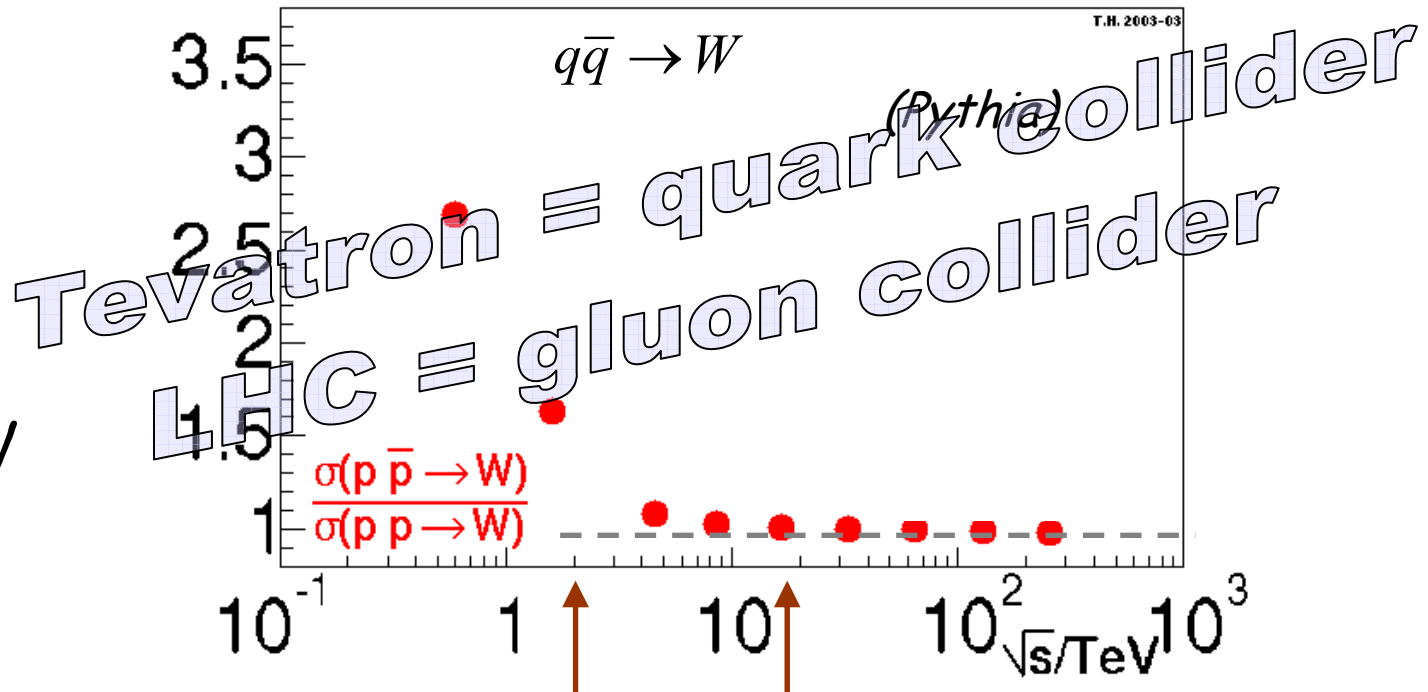


At low energy: valence quarks dominate hard scattering: $p p \neq p \bar{p}$

At high energy: sea quarks and gluons dominate hard scattering: $p p \approx p \bar{p}$

Example:

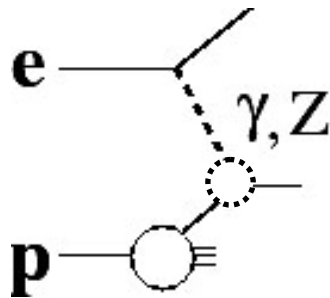
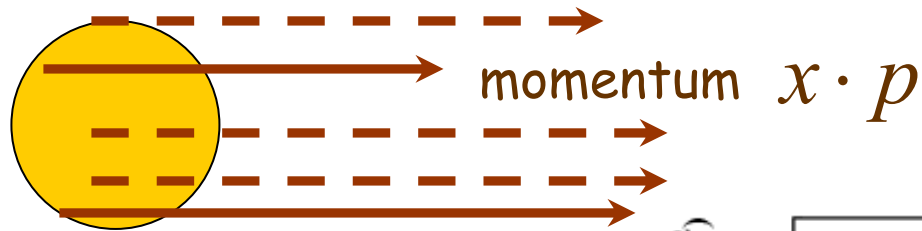
inclusive W
production



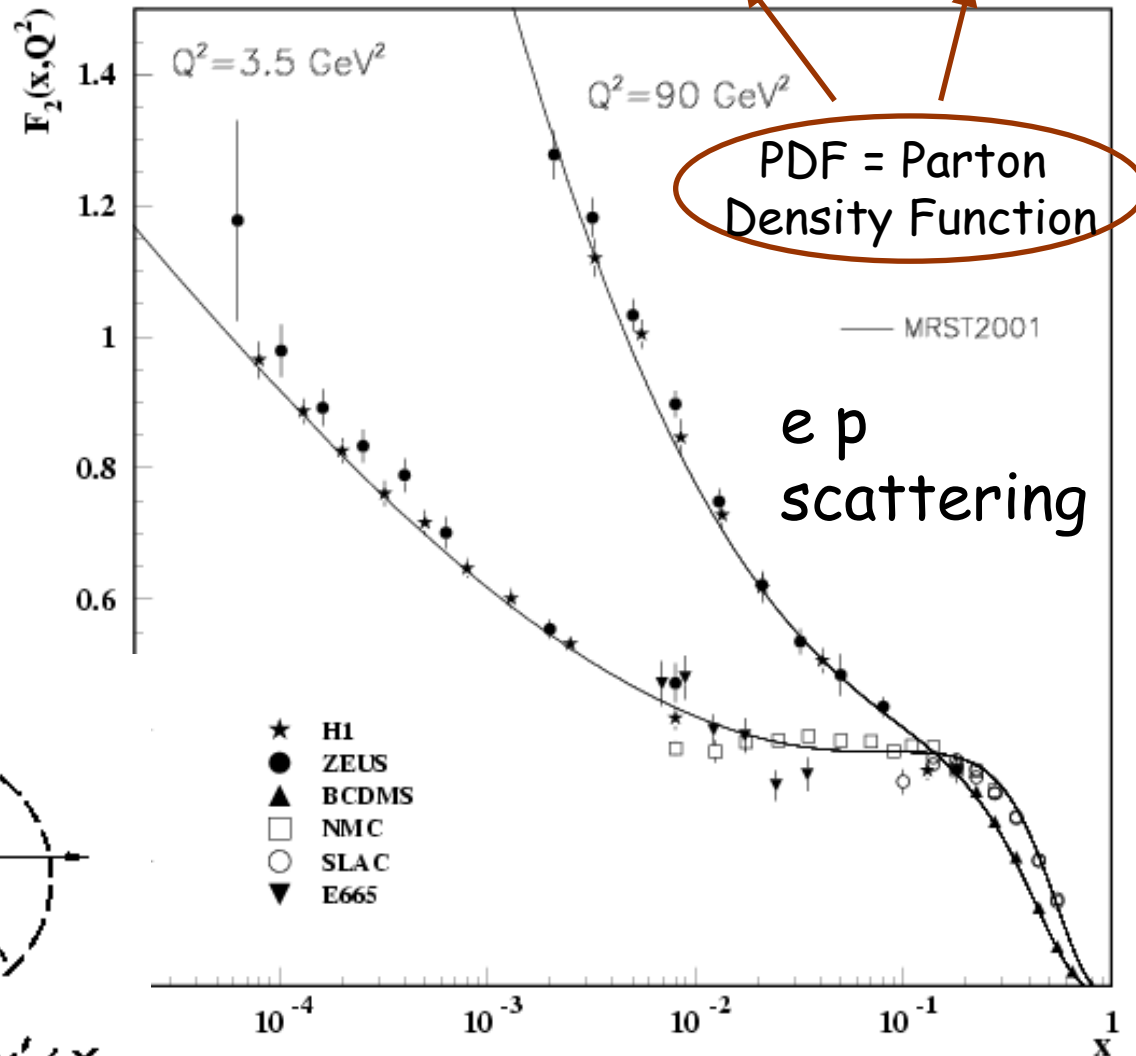
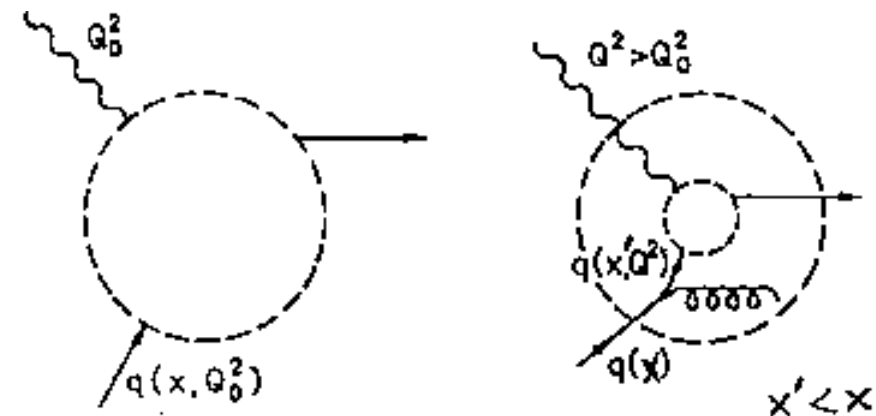
Parton density functions $f(x, Q^2)$

QCD $x: ?$
 $Q^2: \text{yes}$

$$F_2(x) = x \left[\frac{4}{9} u(x) + \frac{1}{9} d(x) + \dots \right]$$



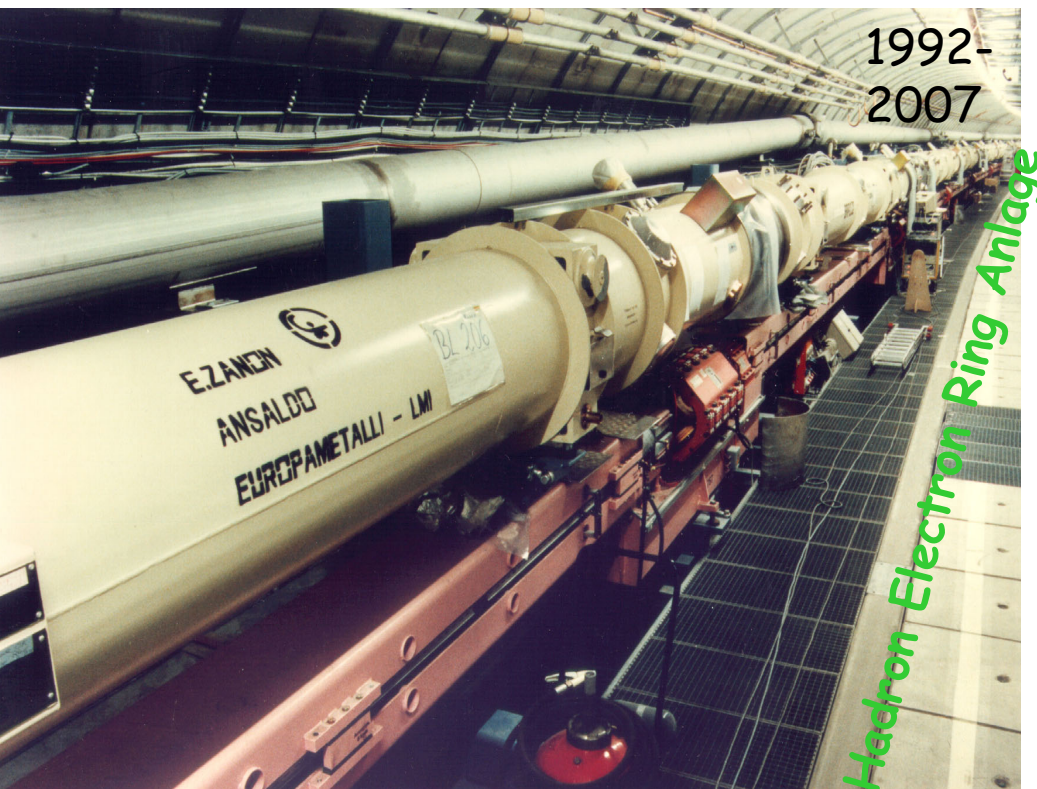
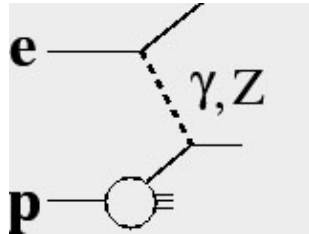
depends on
 resolution,
 given by Q^2 :



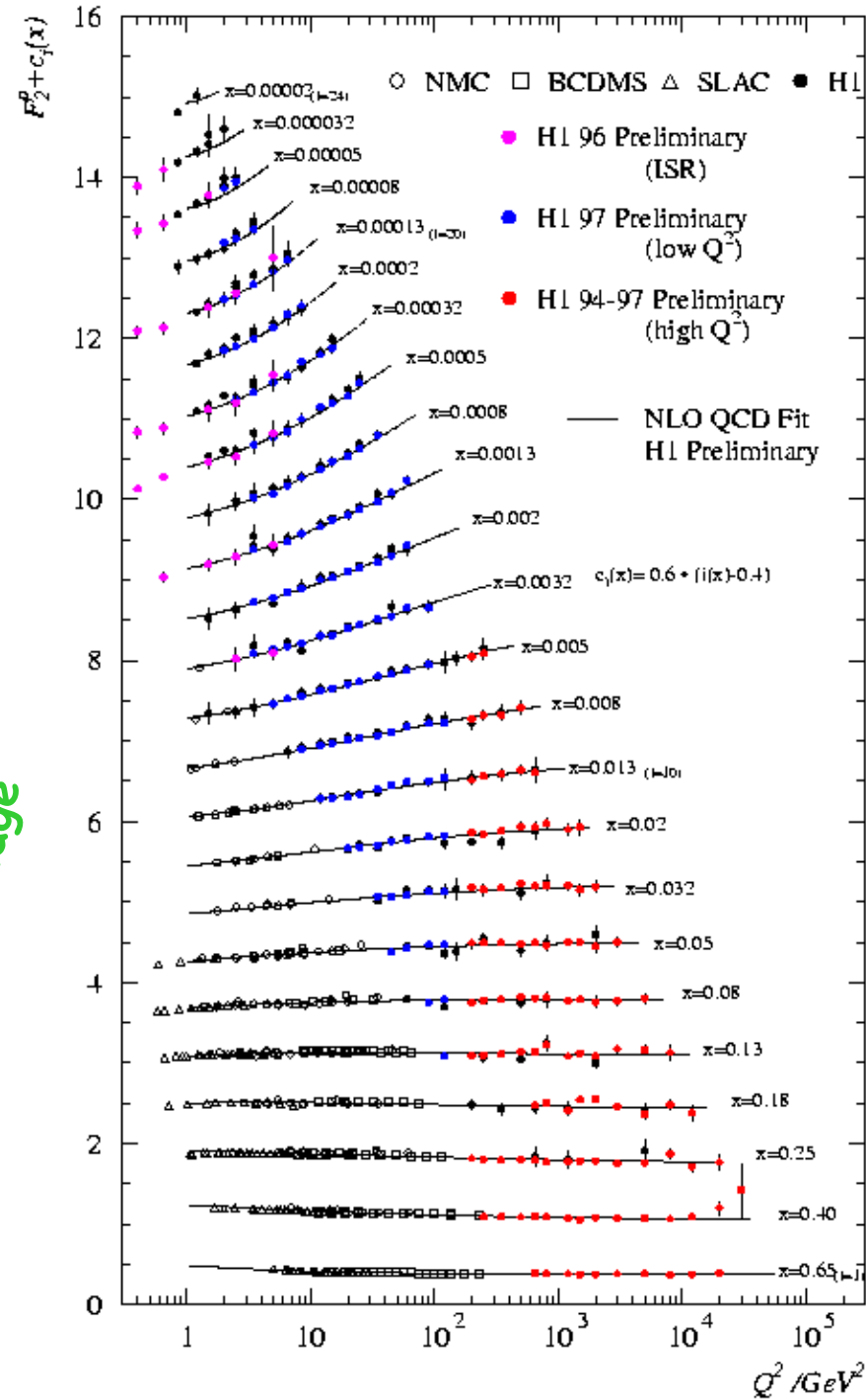
HERA electron microscope

e (30 GeV) + p (900 GeV)

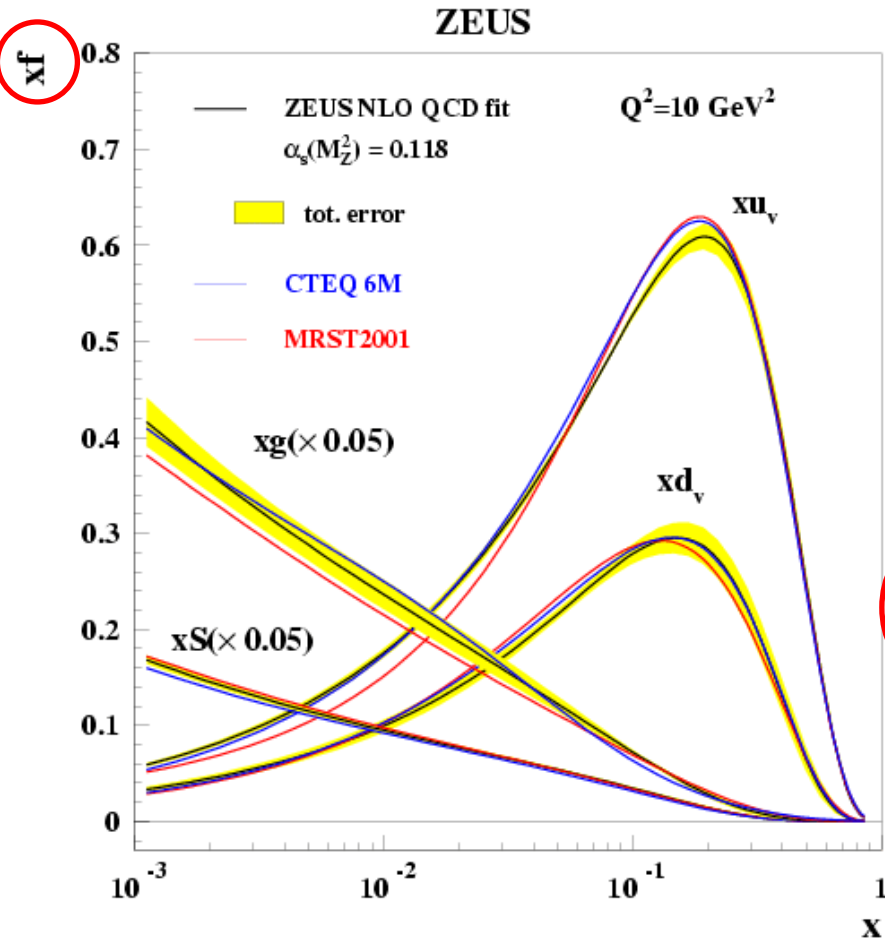
Deep Inelastic Scattering



1992-
2007

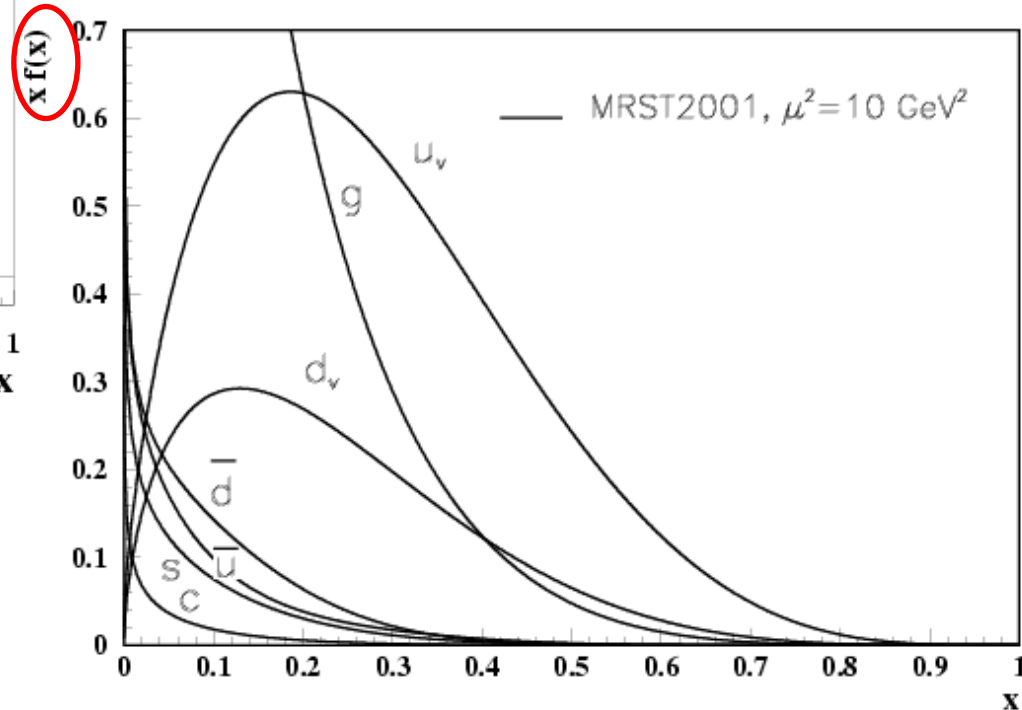


Parton density functions $f(x, Q^2)$



there are
uncertainties!

in particular at
large x



Fits/parametrisations:

- CTEQ
- MRST

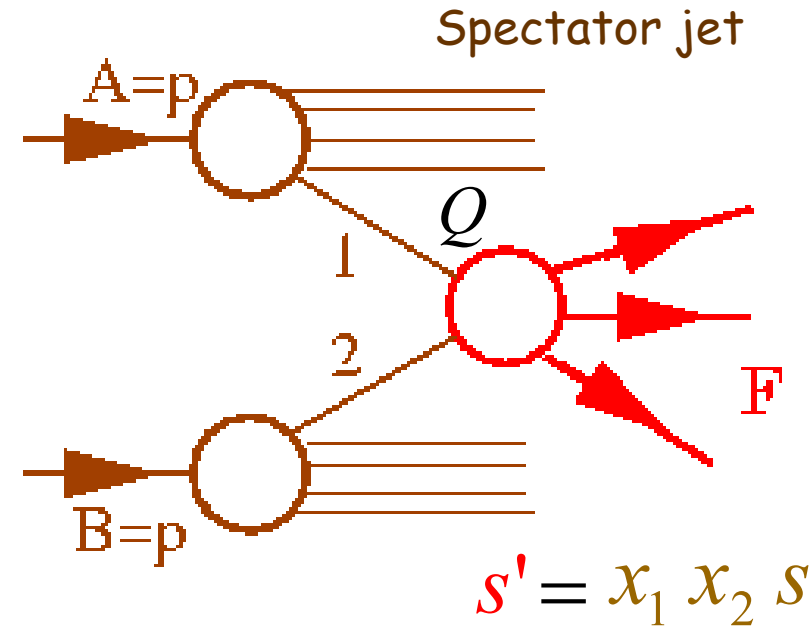
Cross section calculation in pp

Wanted: $\frac{d\sigma_F(\sqrt{s}, Q^2)}{dV}$

final state $\rightarrow$ dV $\leftarrow$ kinematical variable

Calculable: $\frac{d\sigma_F^{ij}(x_i, x_j, Q^2)}{dV}$

Known: $f_i(x_i, Q^2)$ $\leftarrow$ $Q^2 = (\text{„momentum transfer“})^2$
depends on final state



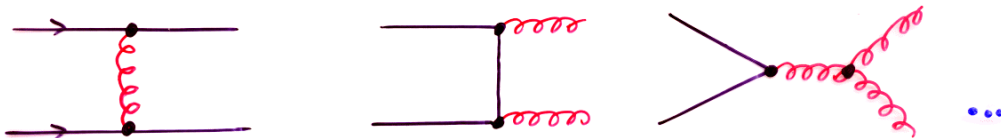
$$\frac{d\sigma_F(\sqrt{s}, Q^2)}{dV} = \sum_{i,j} \int dx_i dx_j f_i(x_i, Q^2) f_j(x_j, Q^2) \bullet \frac{d\sigma_F^{ij}(x_i, x_j, Q^2)}{dV}$$

factorization

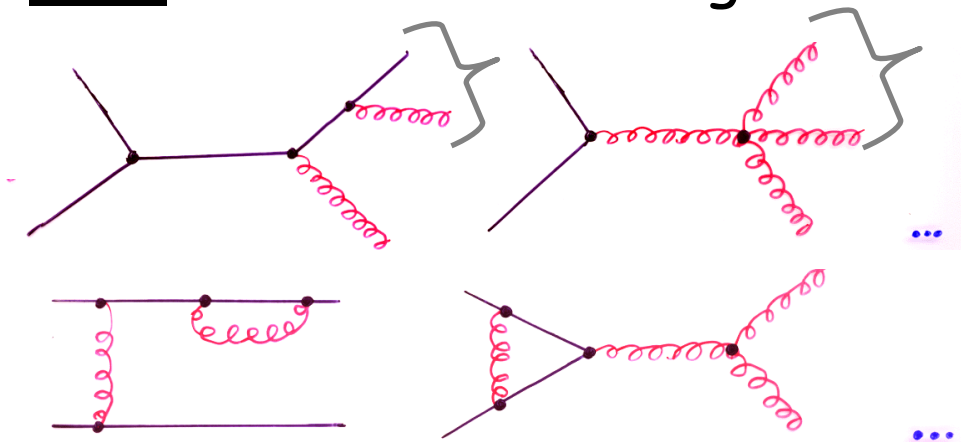
2 jets

Higher orders - K factors

LO = Leading Order in α_s



NLO = Next-to-Leading Order:



NNLO = Next-to-Next-to-Leading ...

...

calculated (<2005):

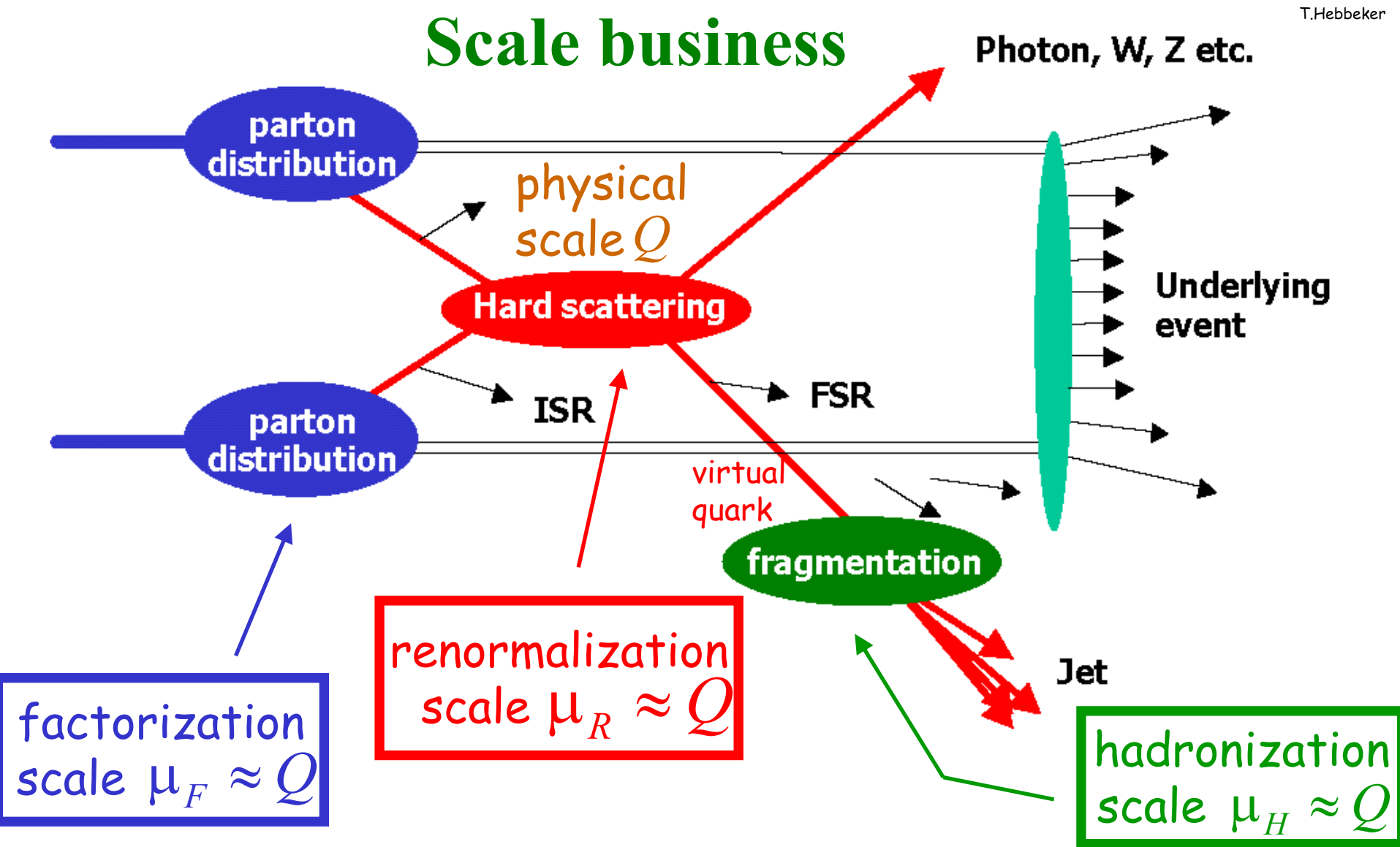
5 jets: LO

W+jets: NNLO

$$K = \frac{\sigma(N^x LO)}{\sigma(LO)}$$

typical: $K \sim 1.3$

(often
event topolgy
~ unchanged)



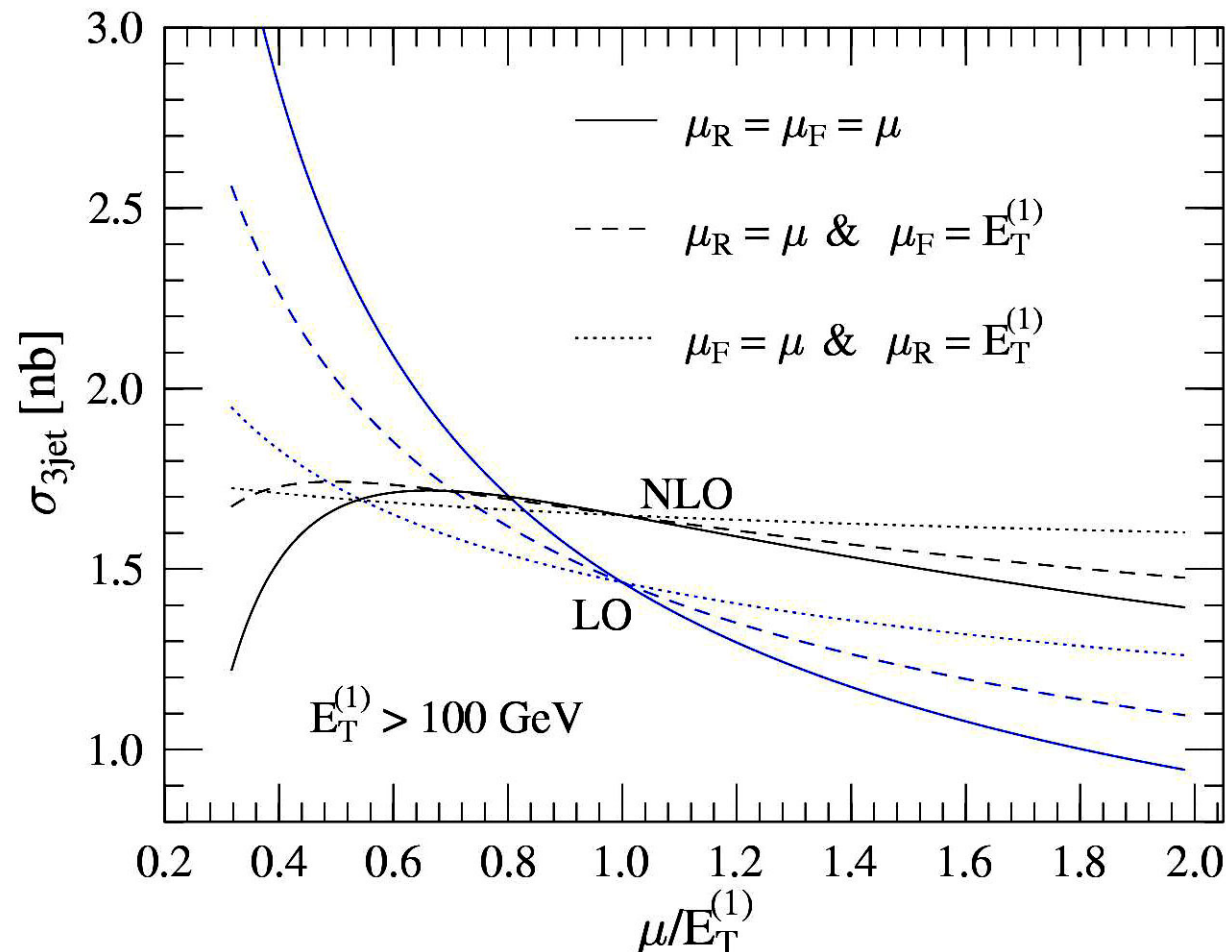
$$\frac{d\sigma_F(\sqrt{s})}{dV} = \sum_{i,j} \int dx_i dx_j f_i(x_i, \mu_F^2) f_j(x_j, \mu_F^2) \frac{d\sigma_F^{ij}(x_i, x_j, \mu_R^2)}{dV}$$

Renormalization Scale

$$\sigma = \underbrace{A \cdot \alpha_s(\mu_R) + B(\mu_R) \cdot \alpha_s^2(\mu_R) + \dots}_{\text{indep. of } \mu_R \text{ (all orders)}}$$

$k_\perp$ algorithm

indep. of μ_R (all orders)



missing higher
orders

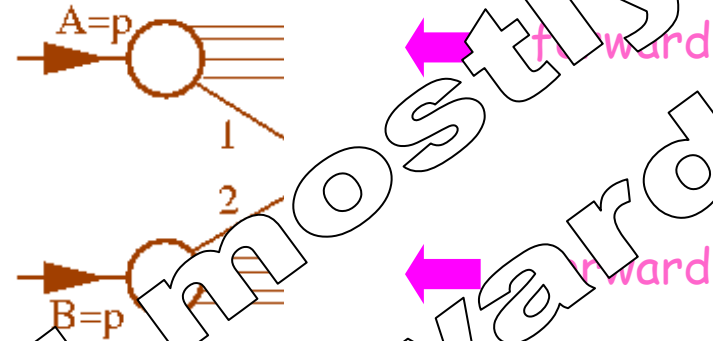


scale dependence

„Dirty“ environment

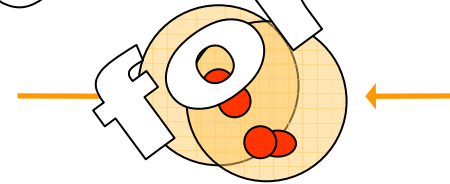
- beam remnants

underlying event



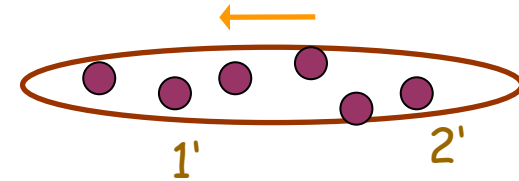
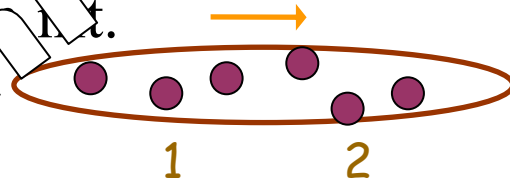
- double parton interactions

some percent



- „pile up“ = multiple proton-p.p. int.

minimum bias event



2 (Tevatron) / 3 (LHC) / crossing

40 ns

25 ns

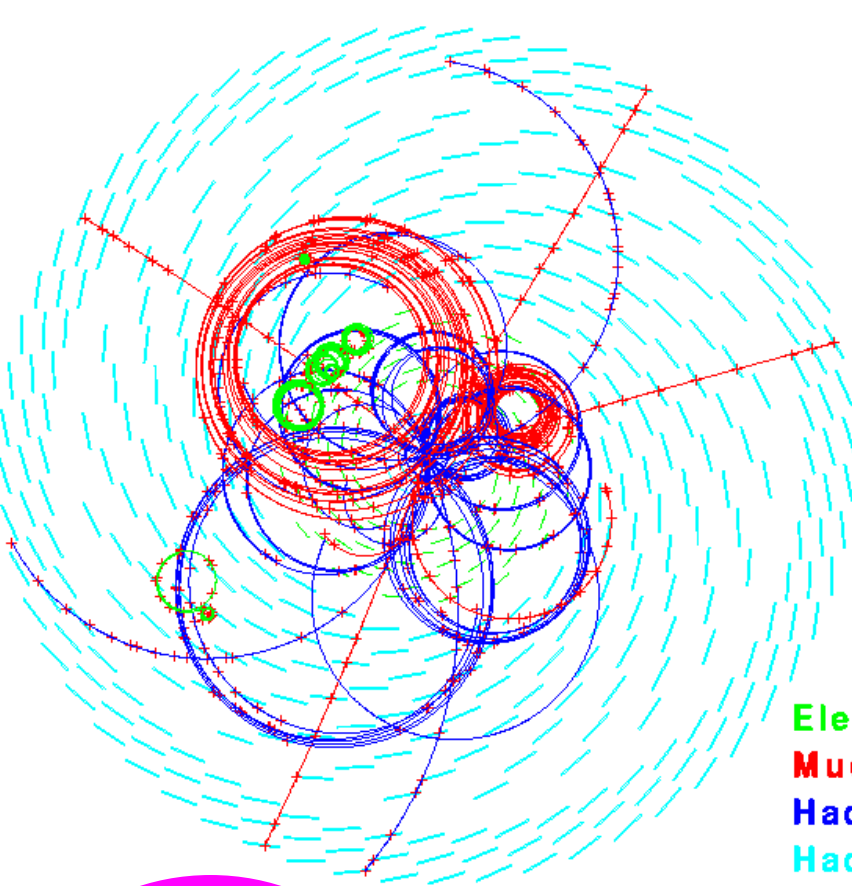
- „detector pile up“

- drift time $\gg$ bunch distance
- thermalized neutrons

CMS

„Pile-Up“

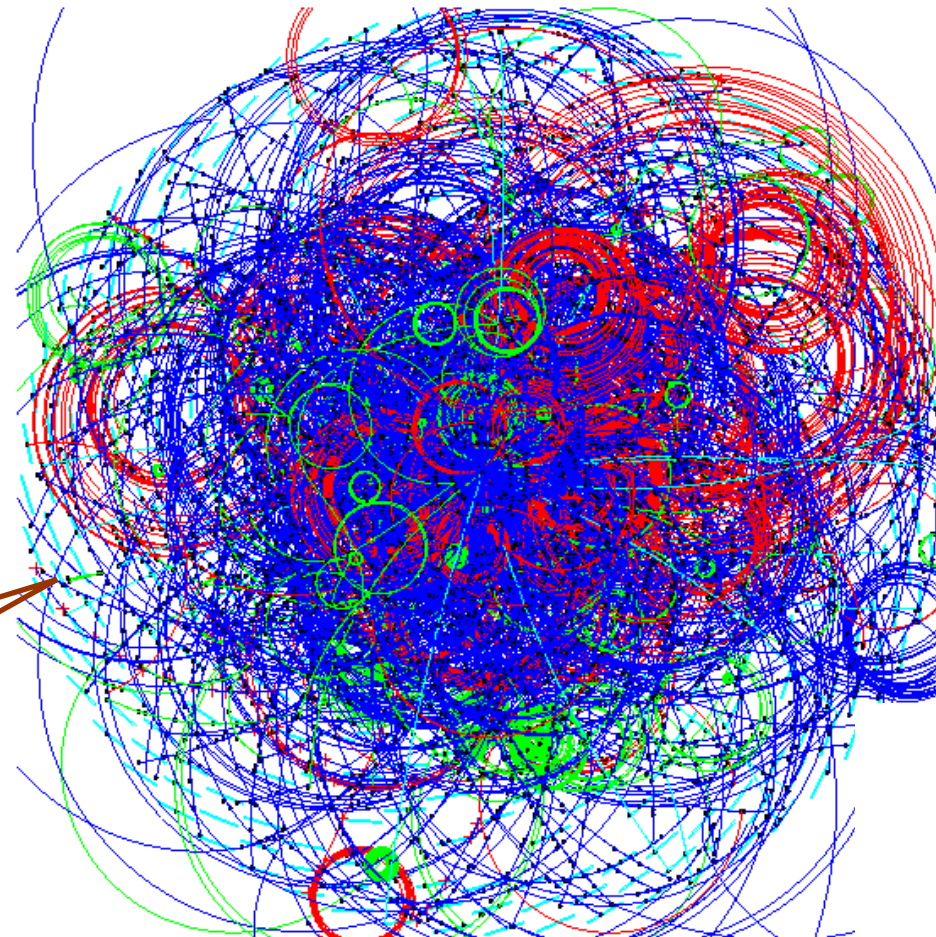
$H \rightarrow \mu\mu\mu\mu$
 $m(H) = 150 \text{ GeV}$



Electrons
Muons
Hadrons
Hadrons

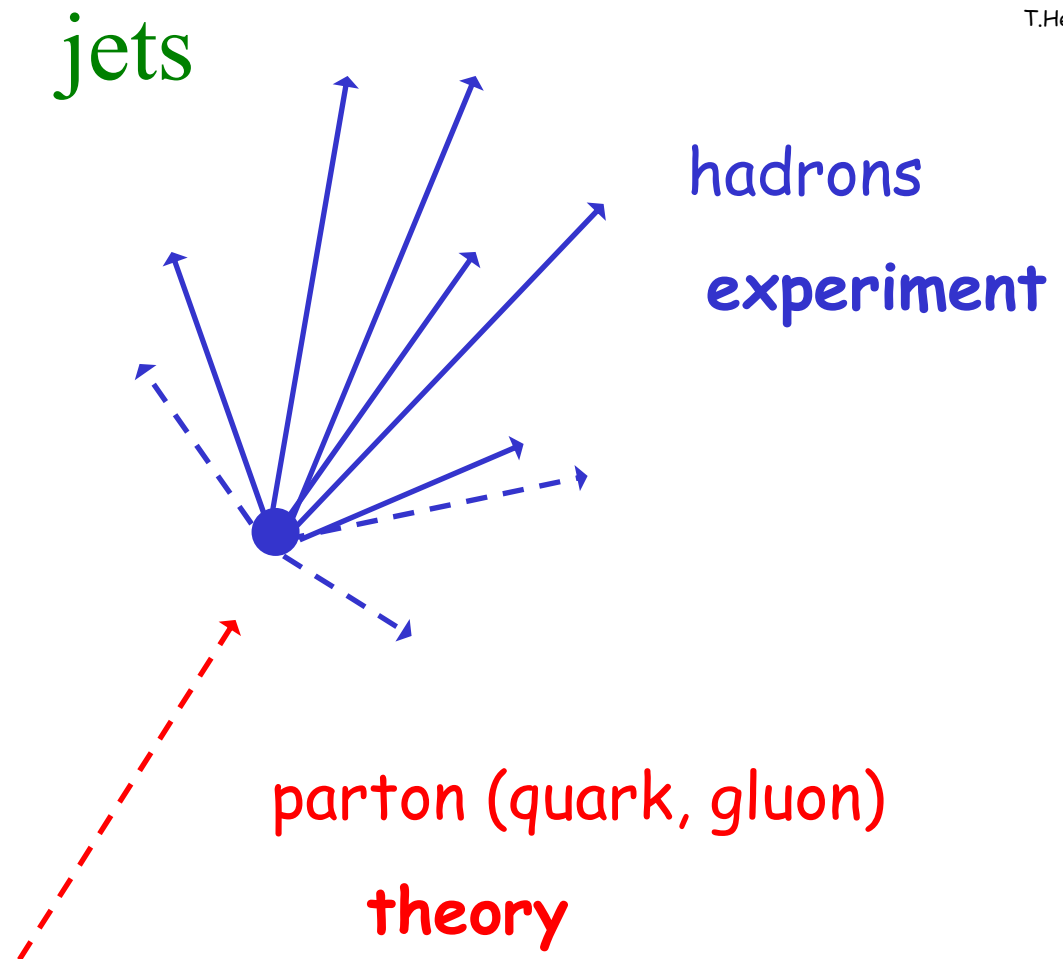
~100 tracks
per crossing

+ 20
minimum-bias
events



Typical: 100
particles total
(LHC)

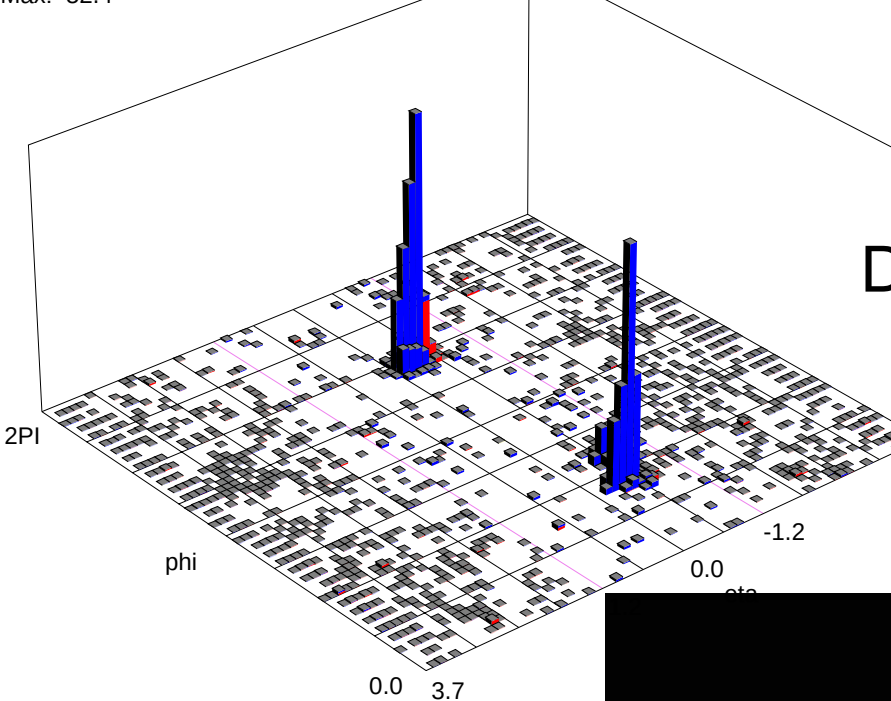
2-5 jets per event



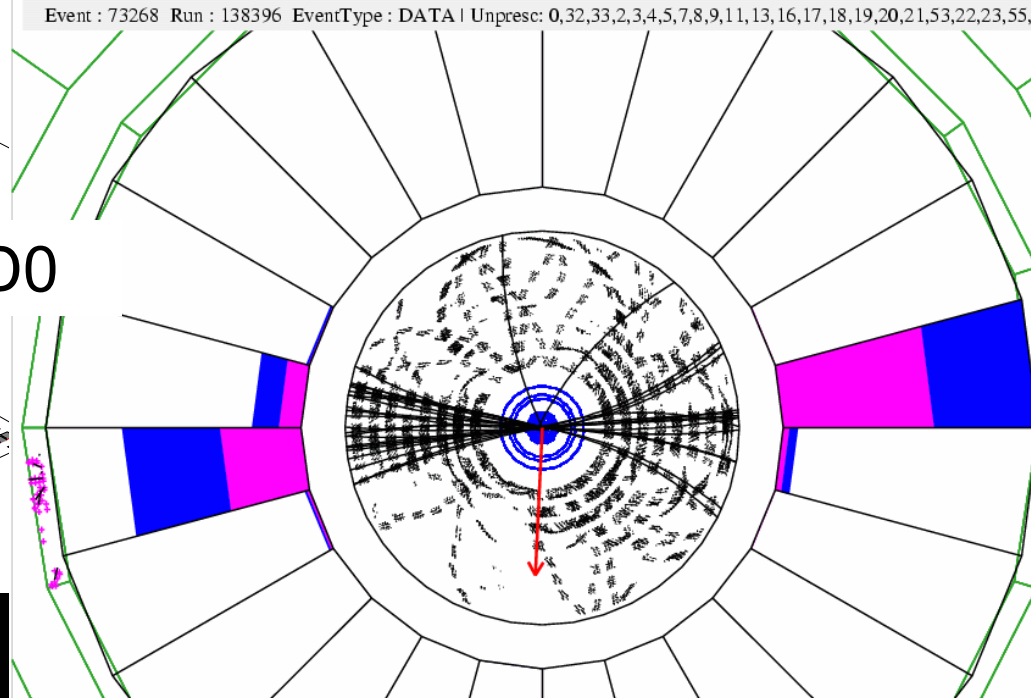
jets reveal hard process (direction, energy of partons)

experiment and theory must use the same language:

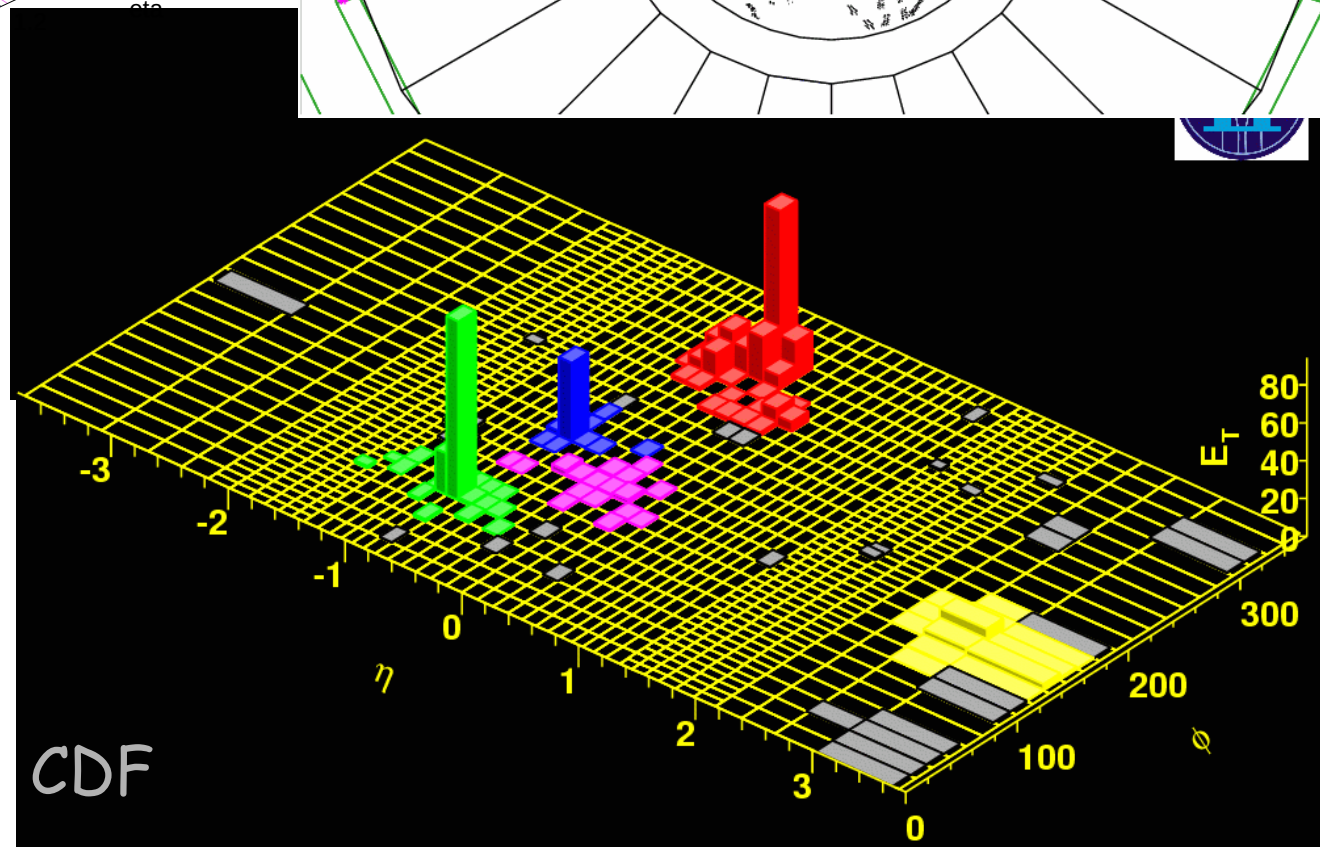
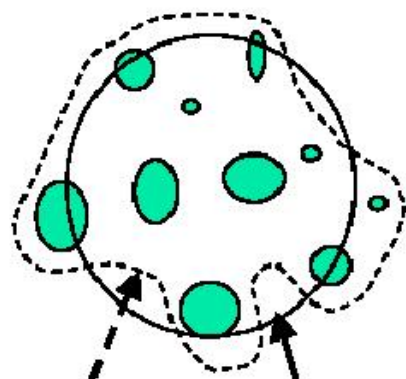
jets need to be defined: „jet algorithm“



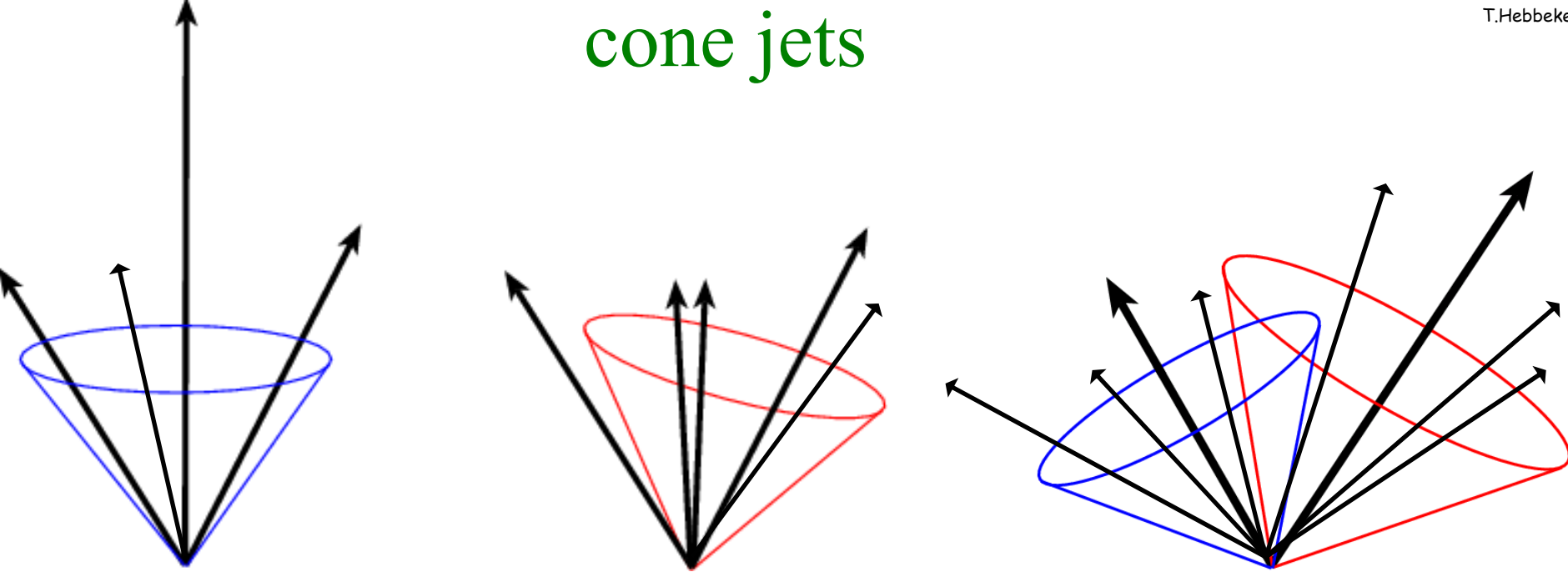
D0



Jet events



cone jets



Cone defined in η, ϕ projection, radius = $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ (typ = 0.7)

Isolated low energy particles are ignored

Sum of 4-momenta of objects inside cone = jet 4-momentum

potential problems: seed dependence, infrared sensitivity ...

several variations exist

kT jets

a) list of hadrons = clusters

b) each cluster:

$$d_i = p_{T,i}^2$$

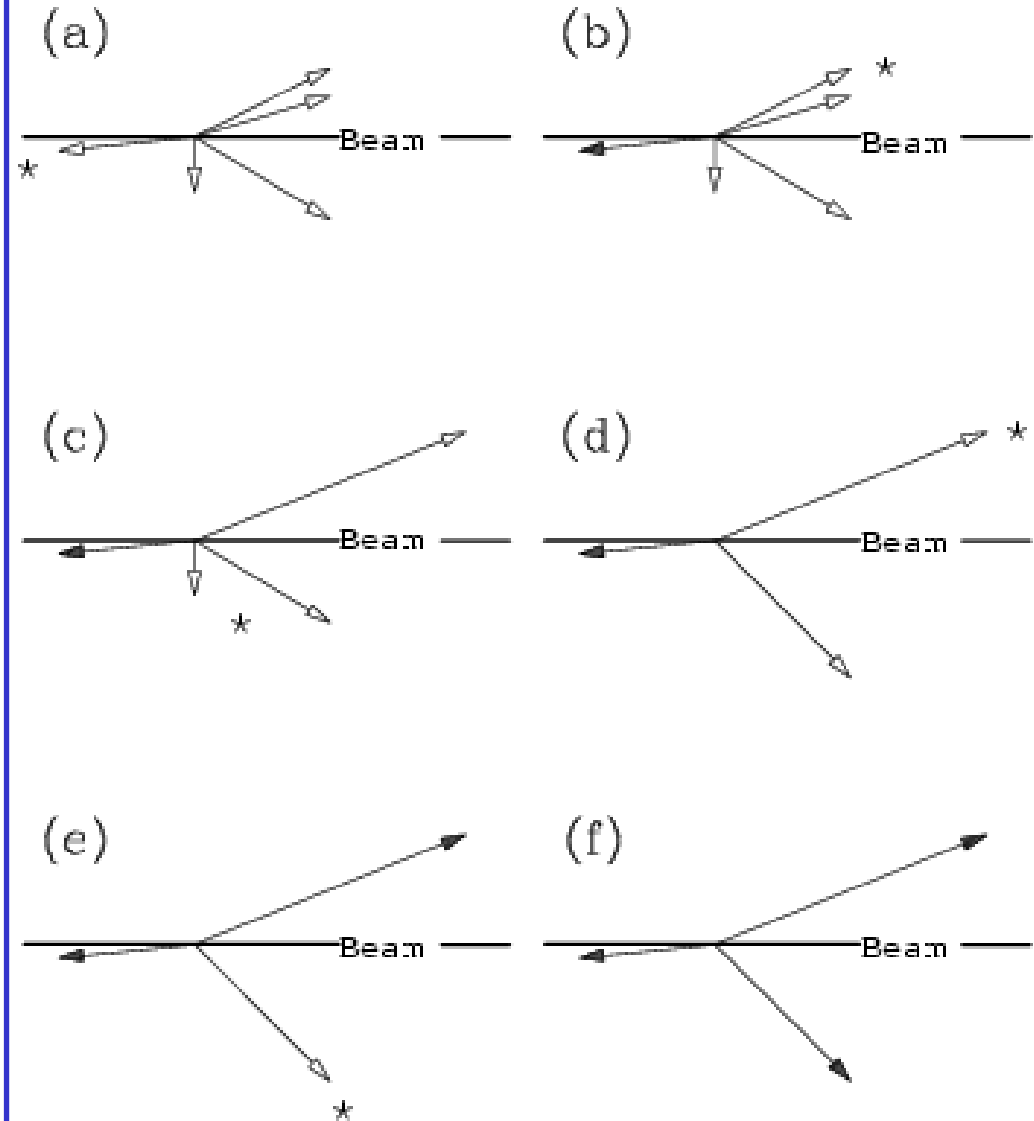
each pair of clusters:

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

c) minimum of d_{ij}, d_i
 → combine or remove from list)

d) iterate: goto b)
 till list empty

Example:

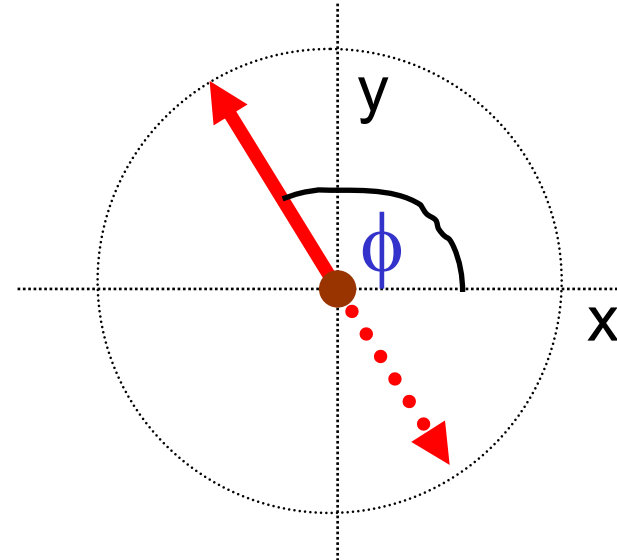
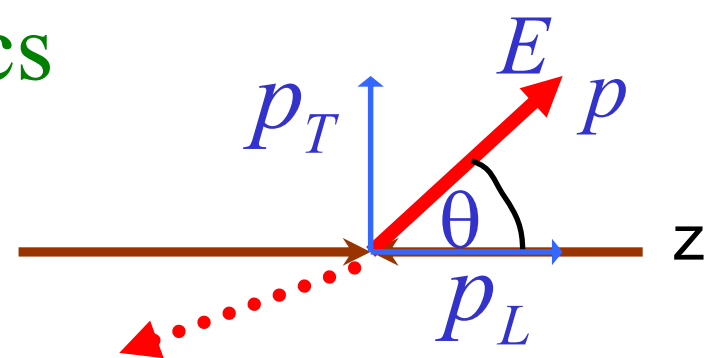


... several variations exist

Kinematics

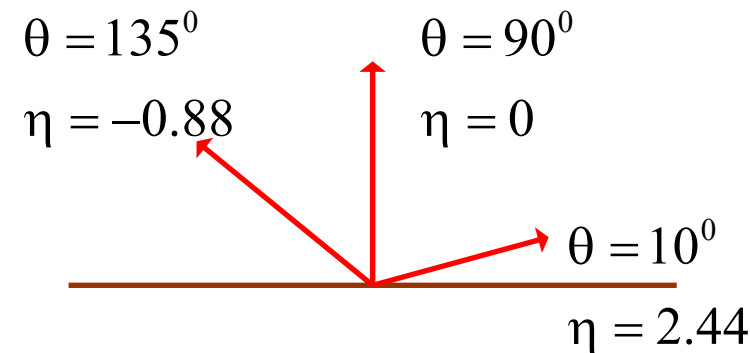
Kinematical variables:

- azimuthal angle ϕ
- polar angle θ
- energy E
- momentum p
- transverse momentum p_T
- longitudinal momentum p_L

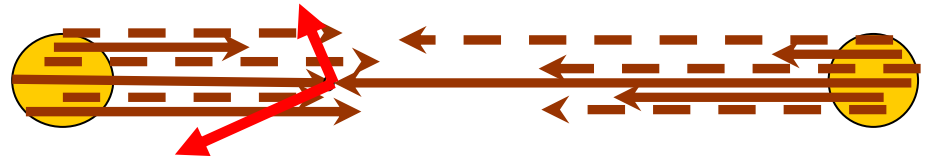


- rapidity $y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$

- pseudorapidity $\eta = -\ln \tan \frac{\theta}{2}$

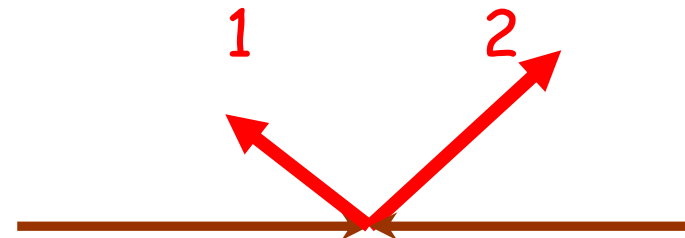


„boost“ of c.m.s. along
beam axis = a priori unknown !



- azimuthal angle ϕ 
- polar angle θ
- energy E
- momentum p
- transverse momentum p_T 
- longitudinal momentum p_L

boost
invariance ?

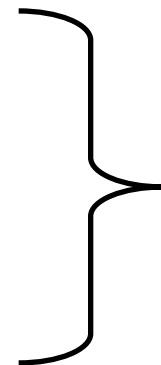


- rapidity $y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$

$$y_1 - y_2$$

- pseudorapidity $\eta = -\ln \tan \frac{\theta}{2}$

$$\eta_1 - \eta_2$$



(Pseudo-)Rapidity

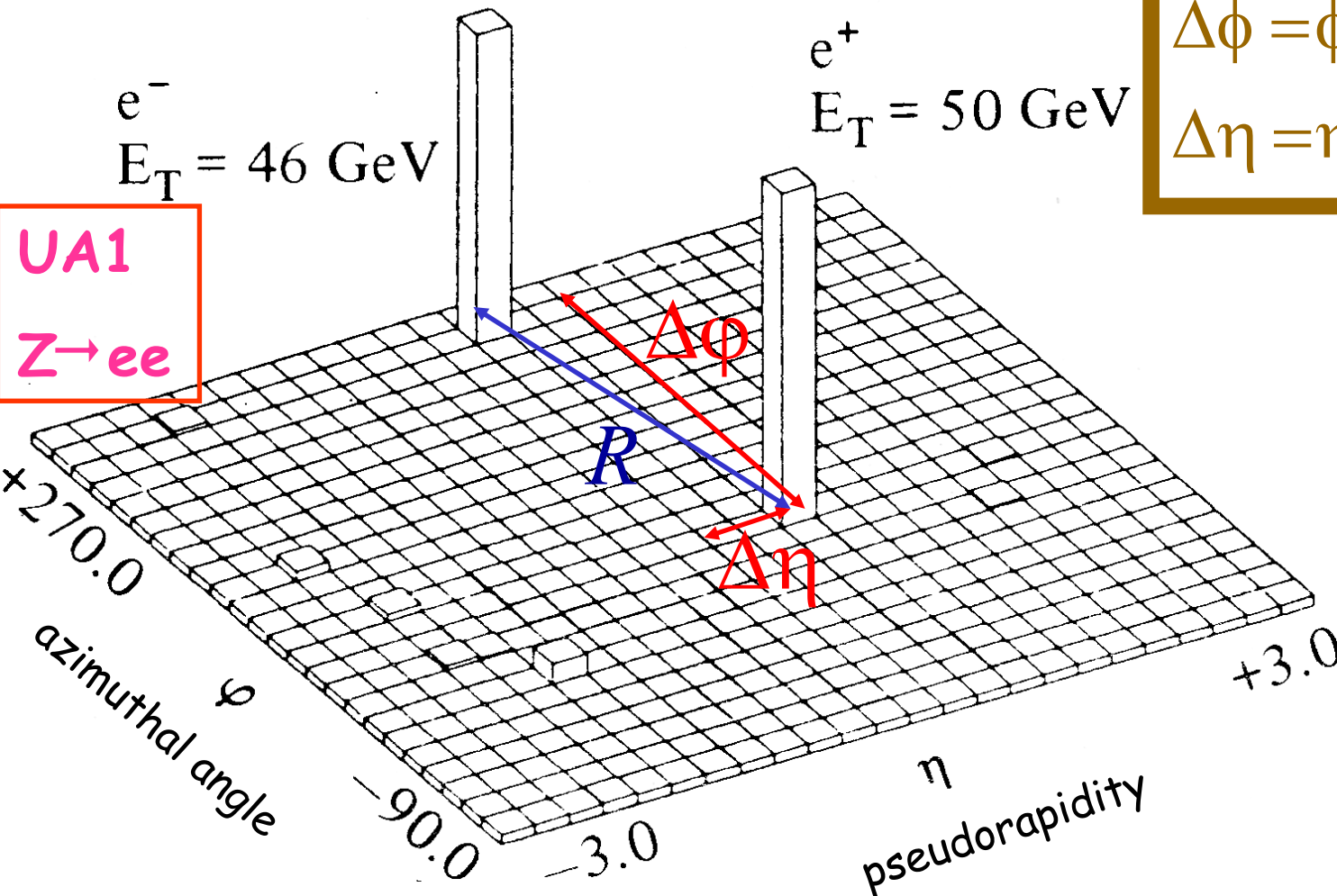
Particle directions $\longleftrightarrow \phi, \eta$

distance measure:

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

$$\Delta\phi = \phi_1 - \phi_2$$

$$\Delta\eta = \eta_1 - \eta_2$$



Note:

- rotation:

$$\Delta\phi = \text{const}$$

- boost:

$$\Delta\eta = \text{const}$$

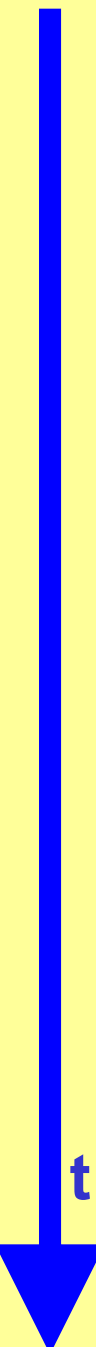
1) Introduction

2) Tevatron

$$p + \bar{p}$$
$$2 \text{ TeV} \quad (1.8 \text{ TeV})$$

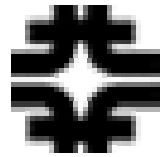
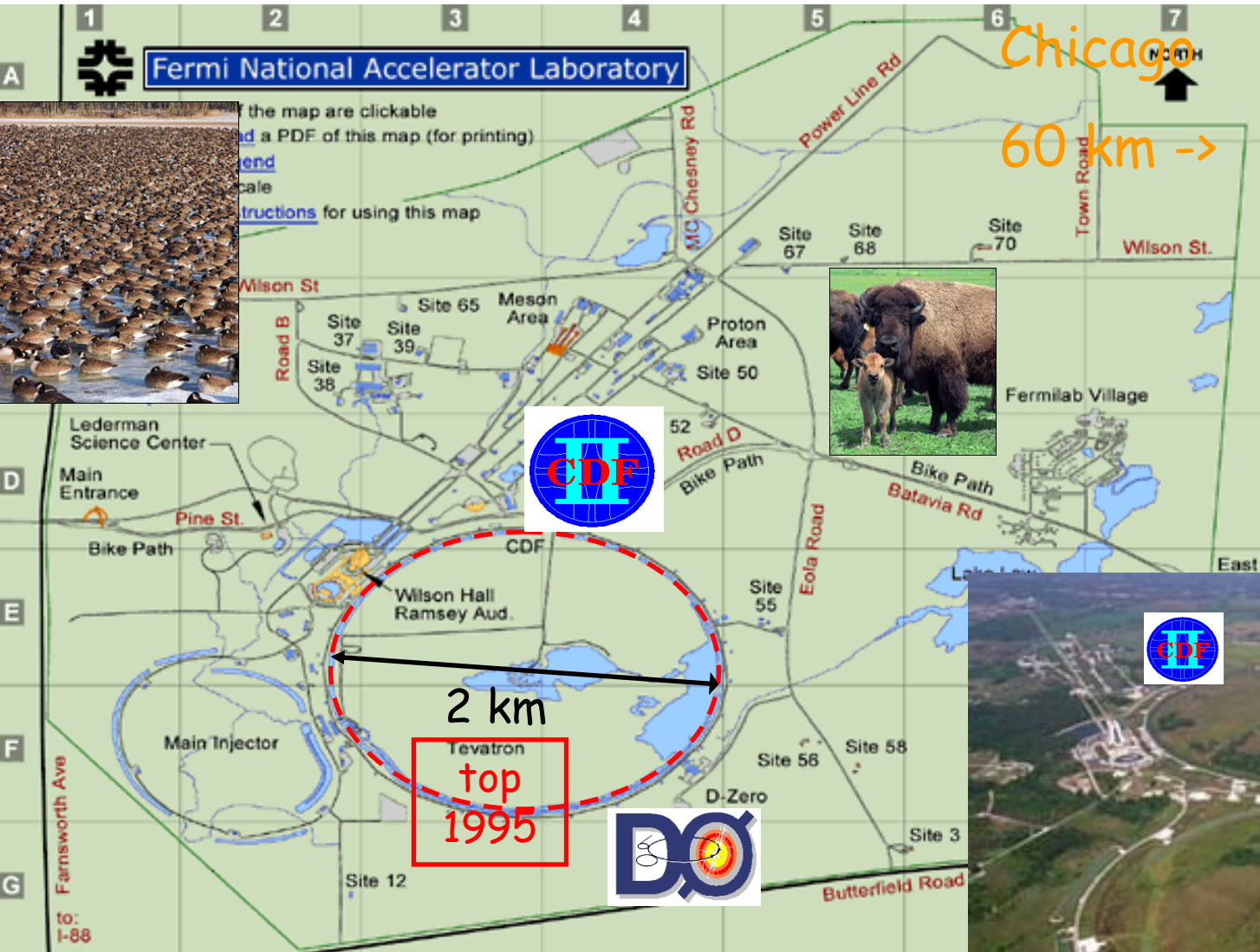
- experimental aspects
- jet production
- electroweak processes

3) LHC

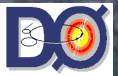


t

Fermilab/Tevatron

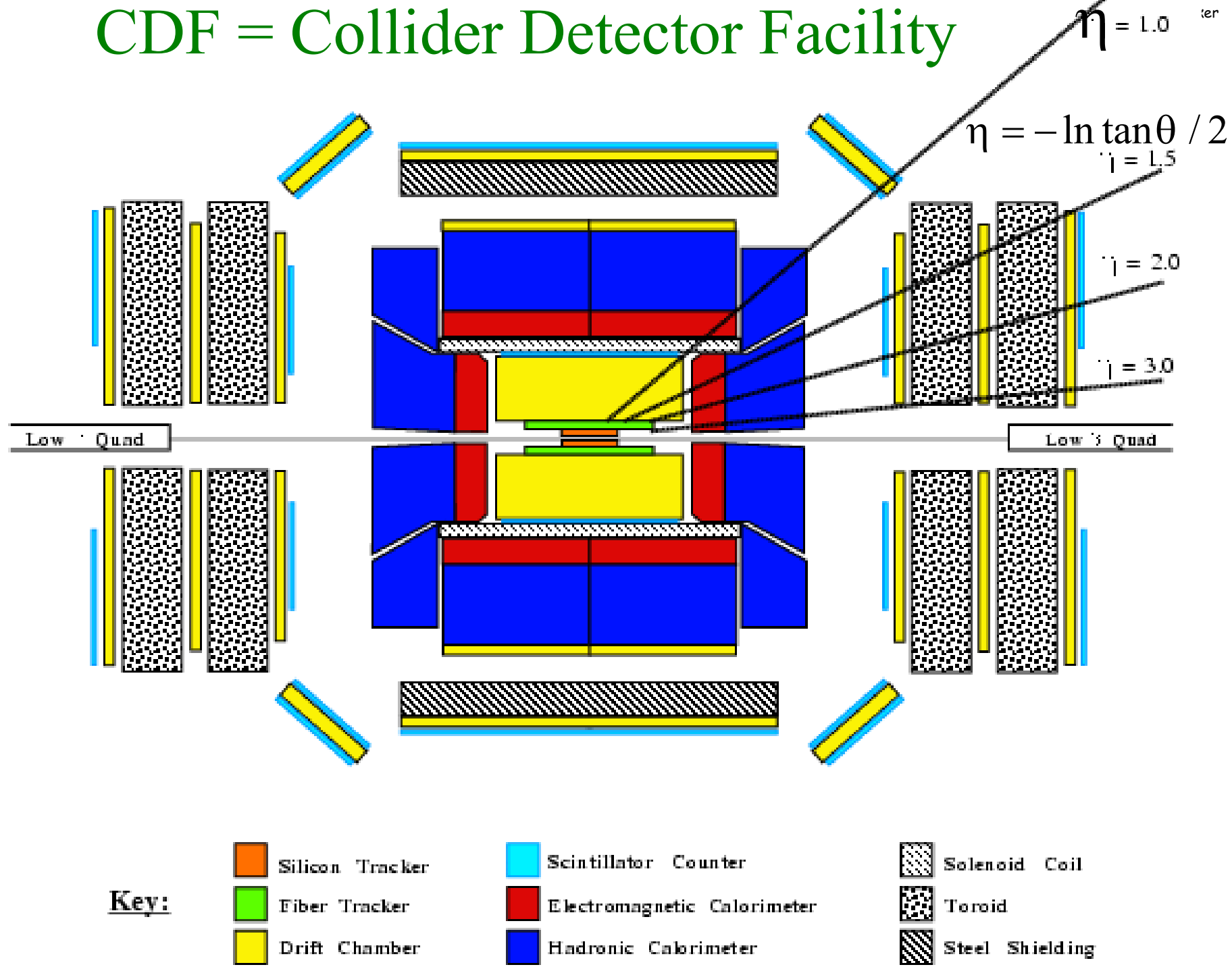


FNAL =
Fermilab
(Enrico Fermi)
1967



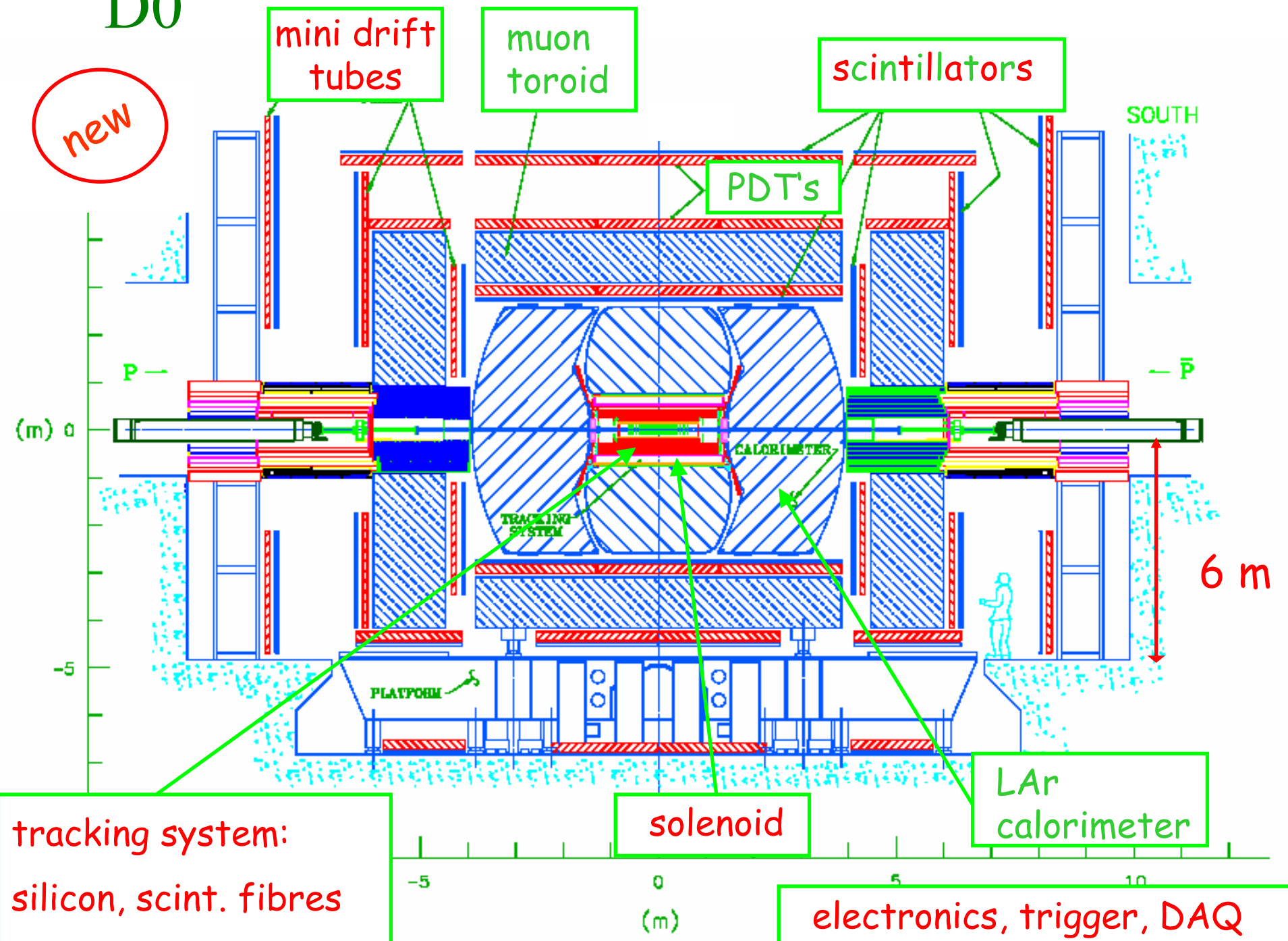
Tevatron = TEV machine

CDF = Collider Detector Facility

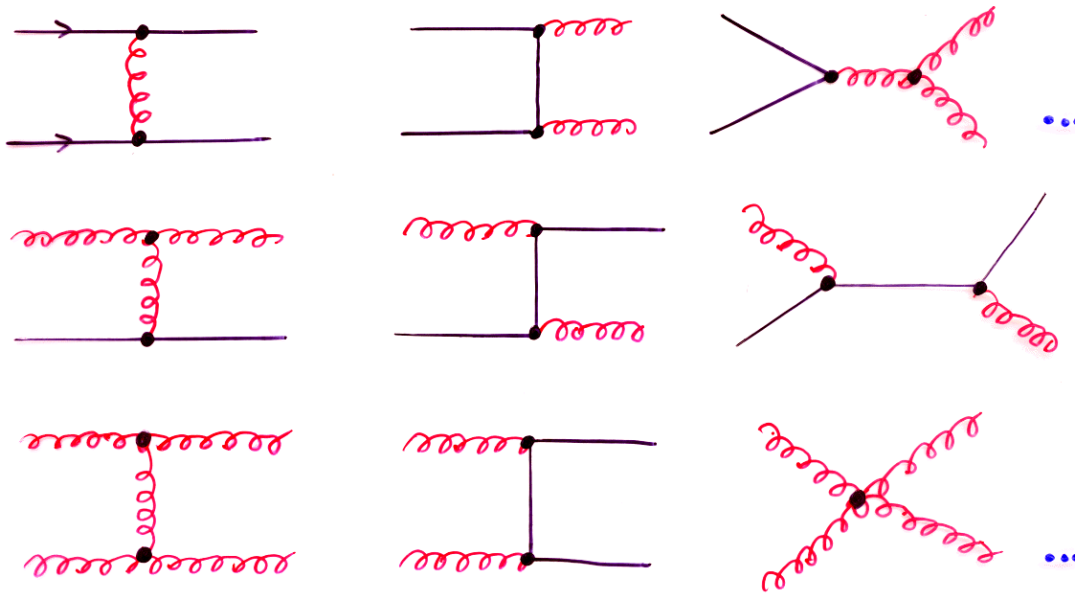


D0

new



Jet production (theory)



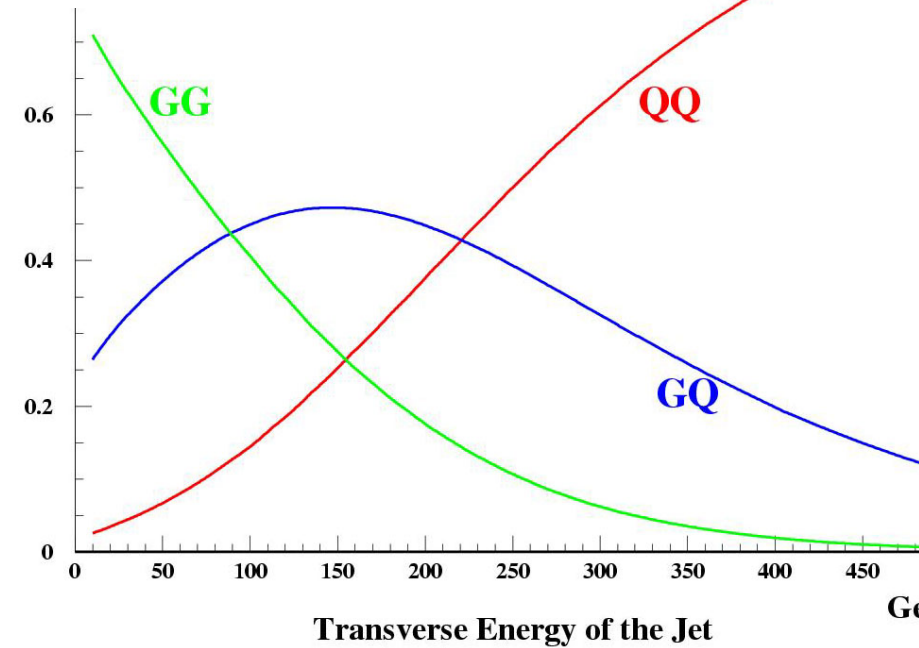
Tevatron

Leading Order QCD (MRS0')

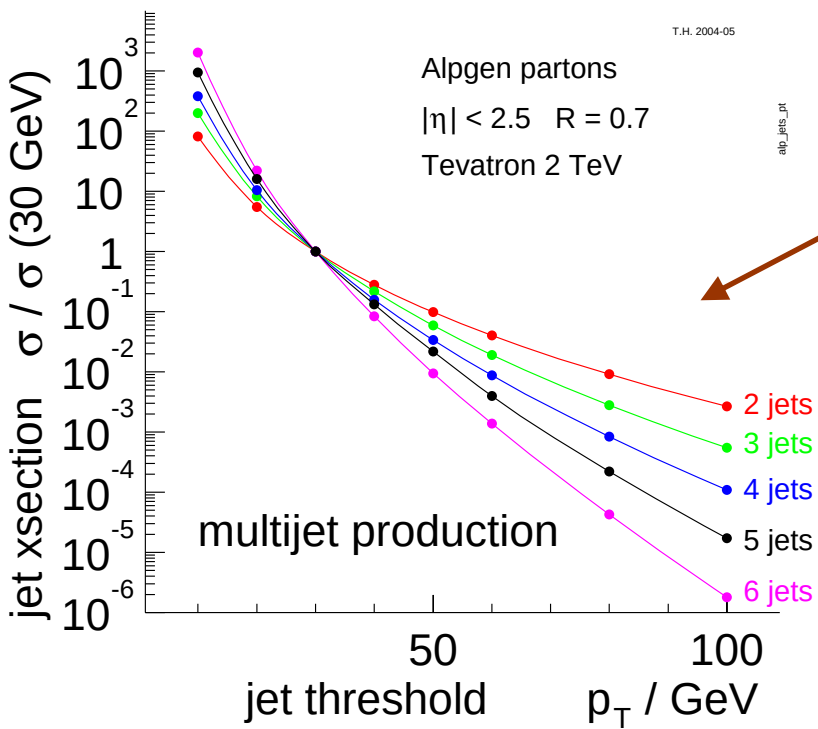
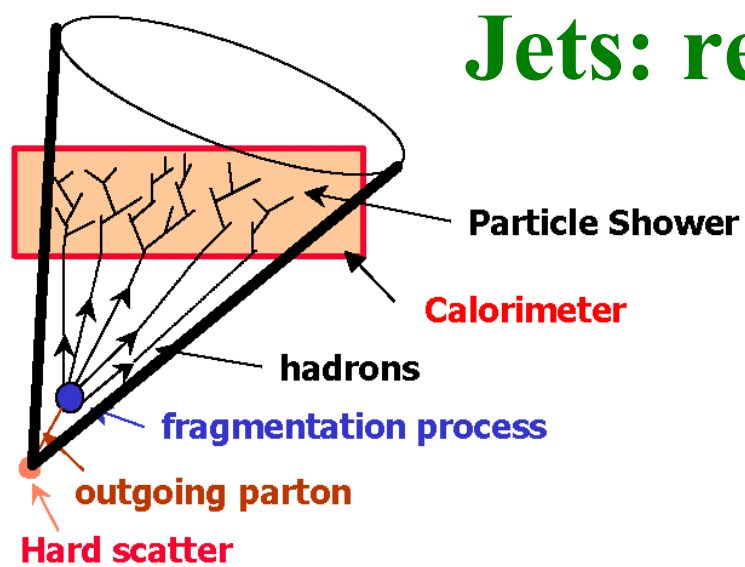
$$\eta_1 = \eta_2 = 0$$

GG Gluon-Gluon Scattering
 QQ Quark-Quark scattering
 QG Quark-Gluon scattering

+ higher orders
 + electroweak diagrams



Jets: resolution and precision

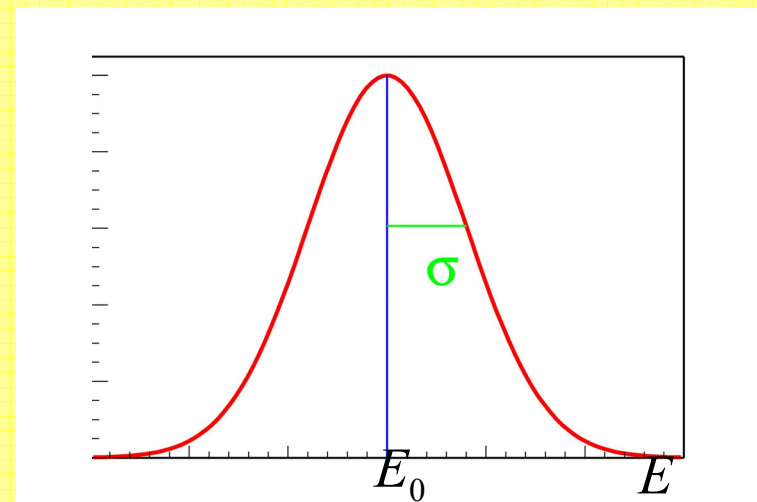


angle: $\sigma = \frac{10^\circ}{\sqrt{E / \text{GeV}}} \text{ uncritical}$

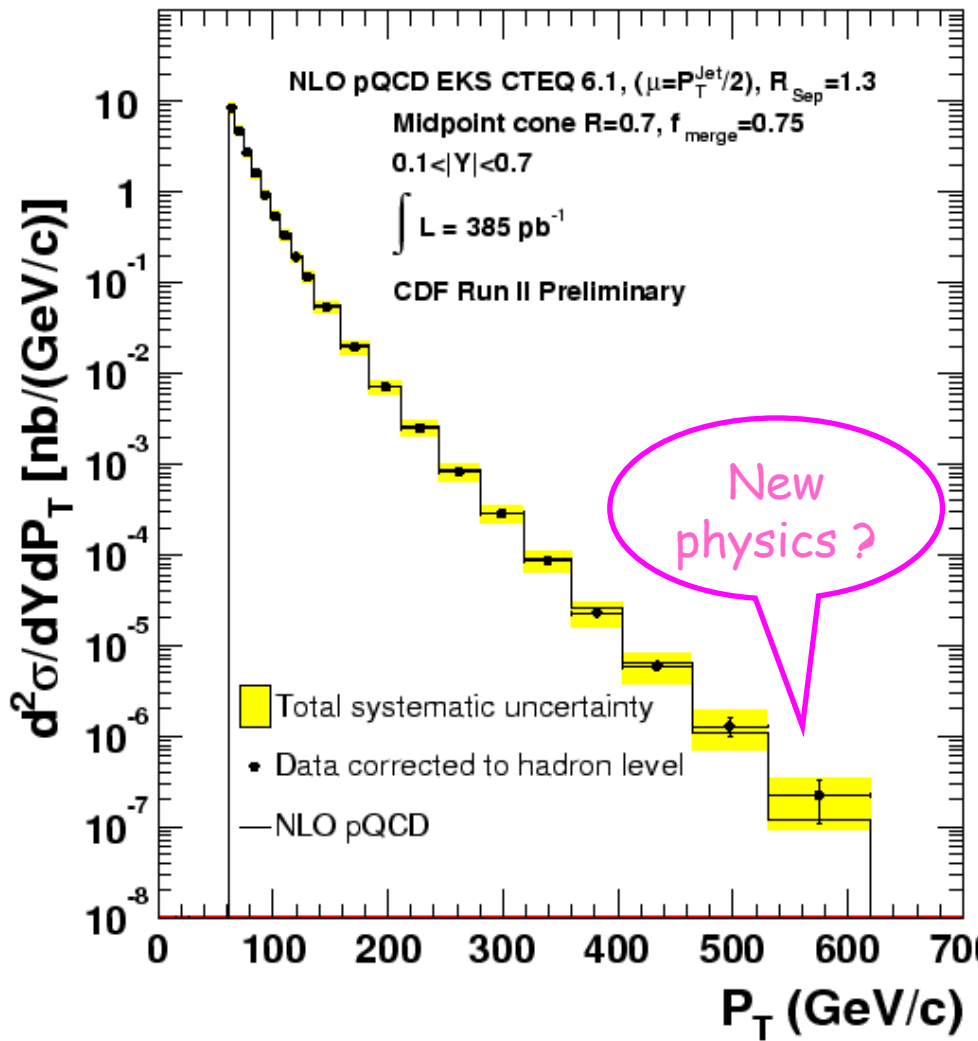
energy:

resolution: $\frac{\sigma}{E} = \frac{80\%}{\sqrt{E / \text{GeV}}} \oplus 4\%$

scale: $\frac{\delta E}{E_0} = 5\%$



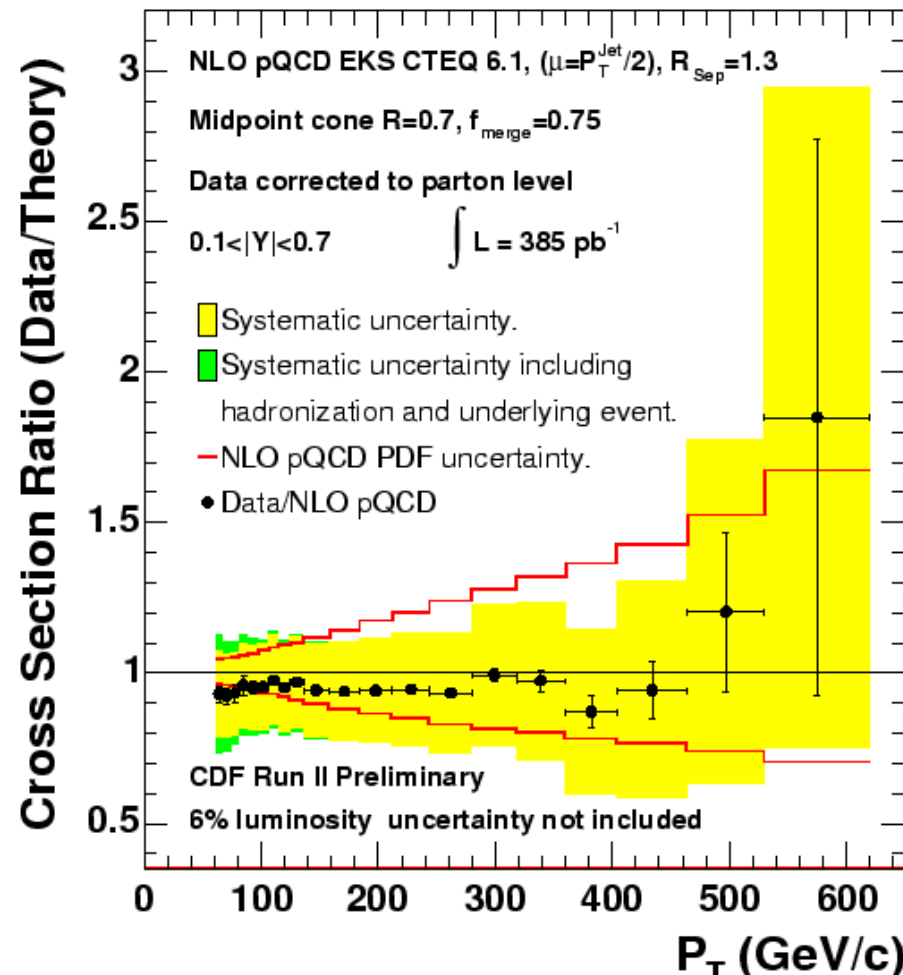
DO



ok !

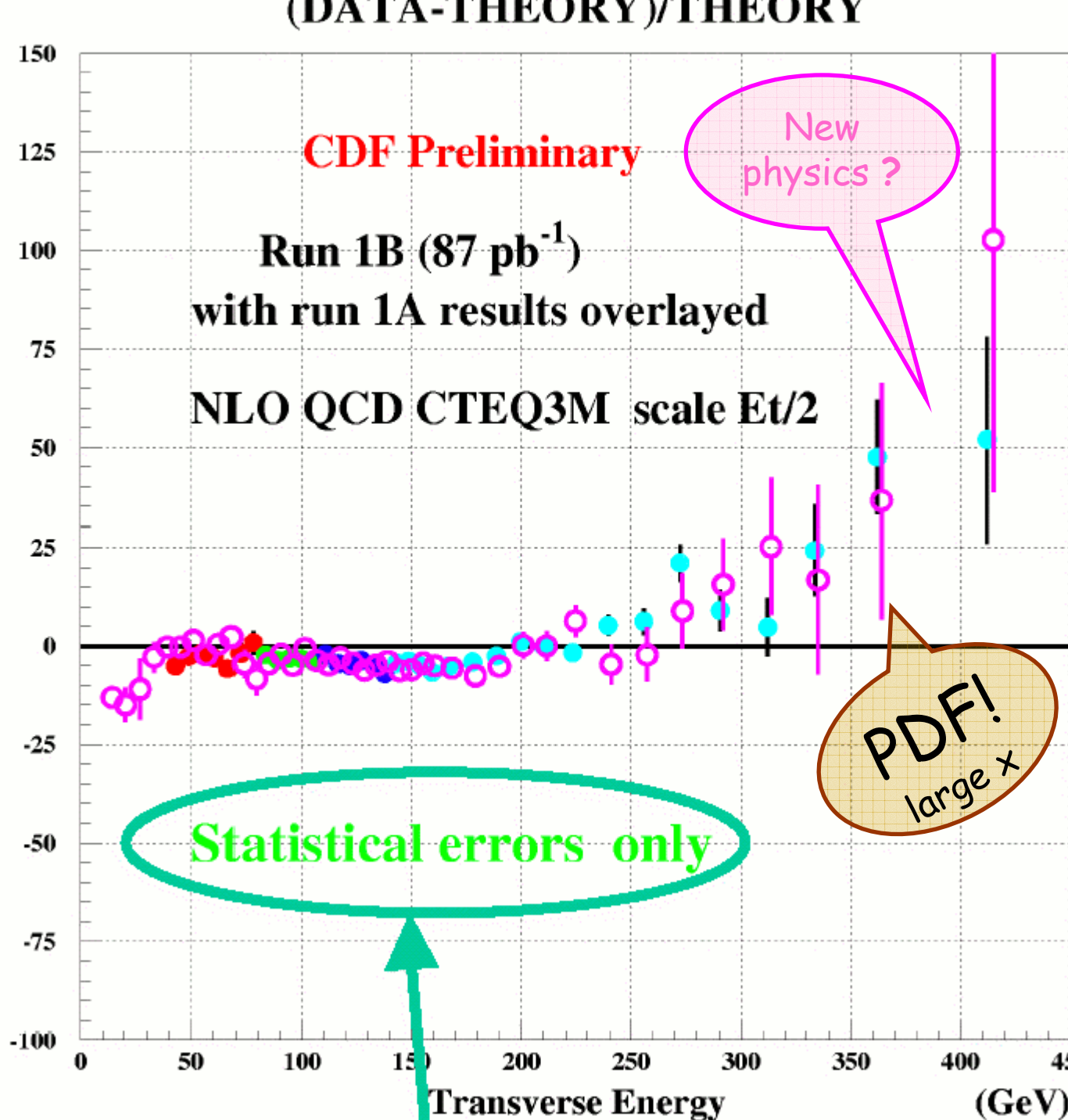
absolute normalization
(luminosity, jet scale) : $\pm 15\%$

Inclusive jet production



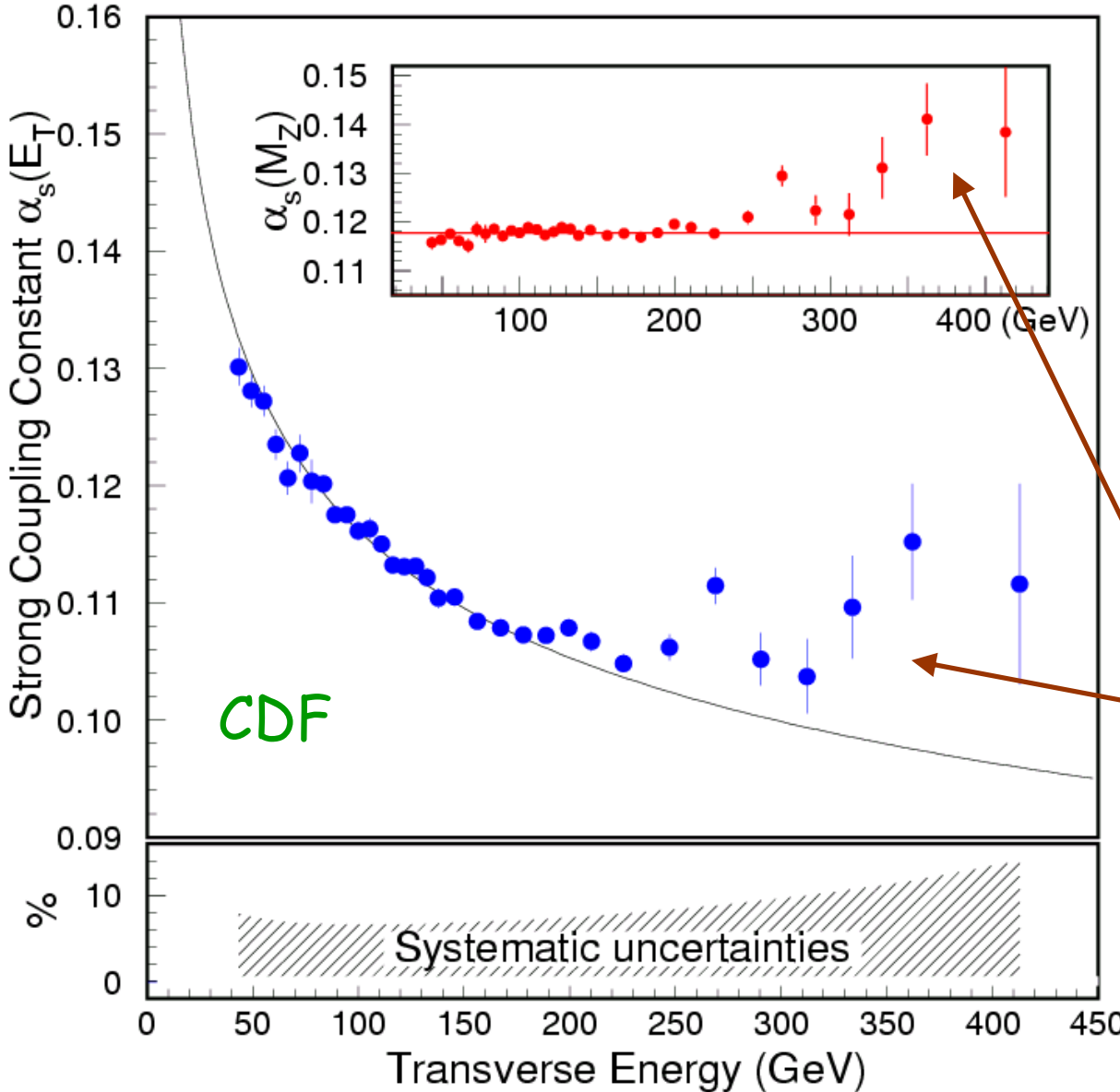
Inclusive jet production (old analyses)

Newer PDF
give
agreement
within total
uncertainties



Determination of α_s

from inclusive
jet production



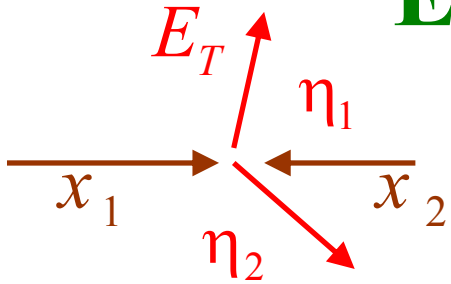
„old“ pdf
problem

ok !

$$\alpha_s(M_Z) = 0.1178 \pm 0.0120$$

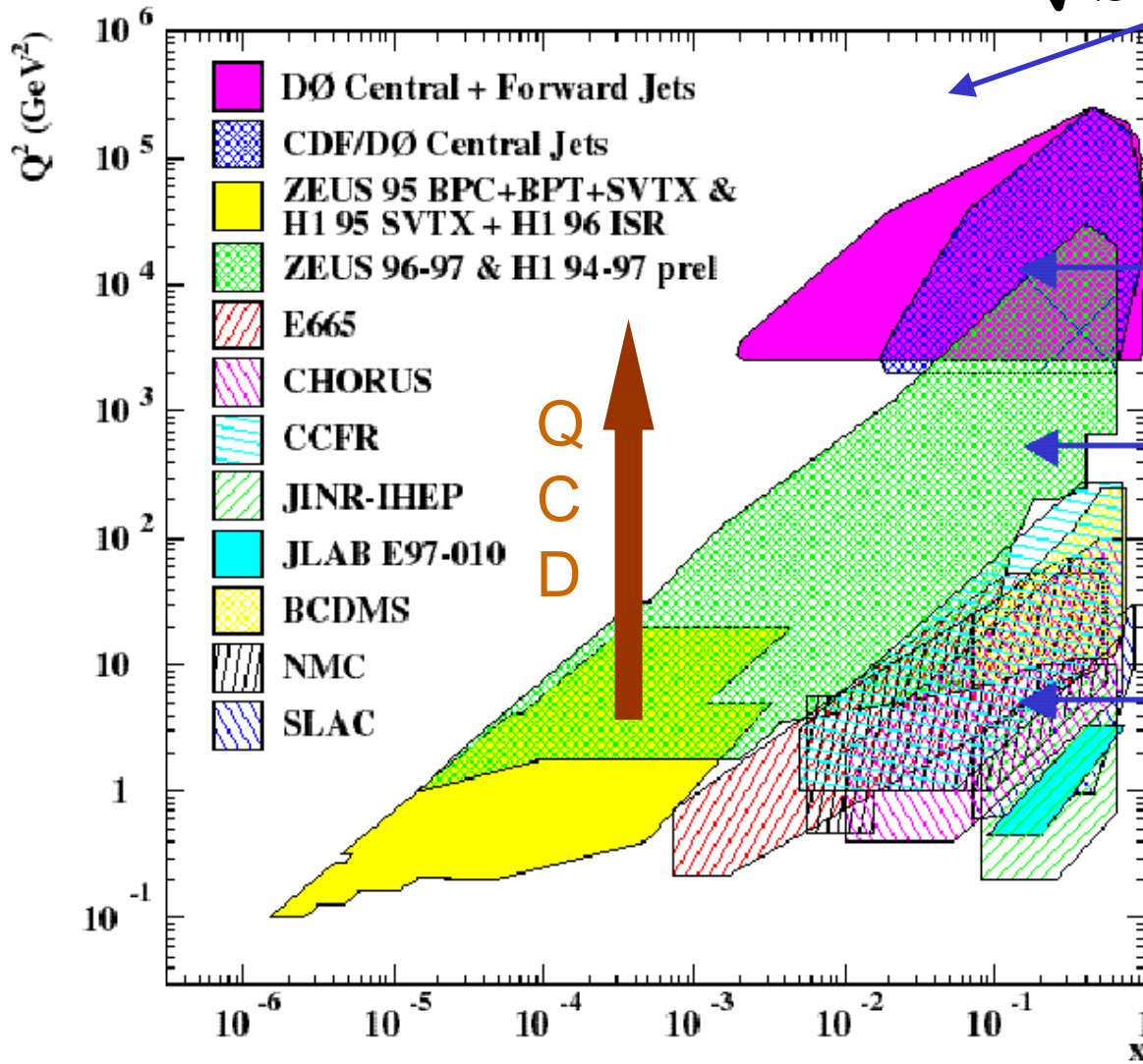
(dominated by exp. systematics,
ren. scale uncertainty and pdf)

Exclusive Dijet production



$$x_{1,2} = (e^{\pm\eta_1} + e^{\pm\eta_2}) \cdot \frac{E_T}{\sqrt{s}}$$

LHC



Tevatron

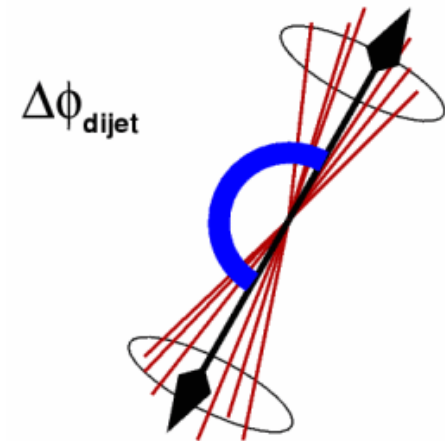
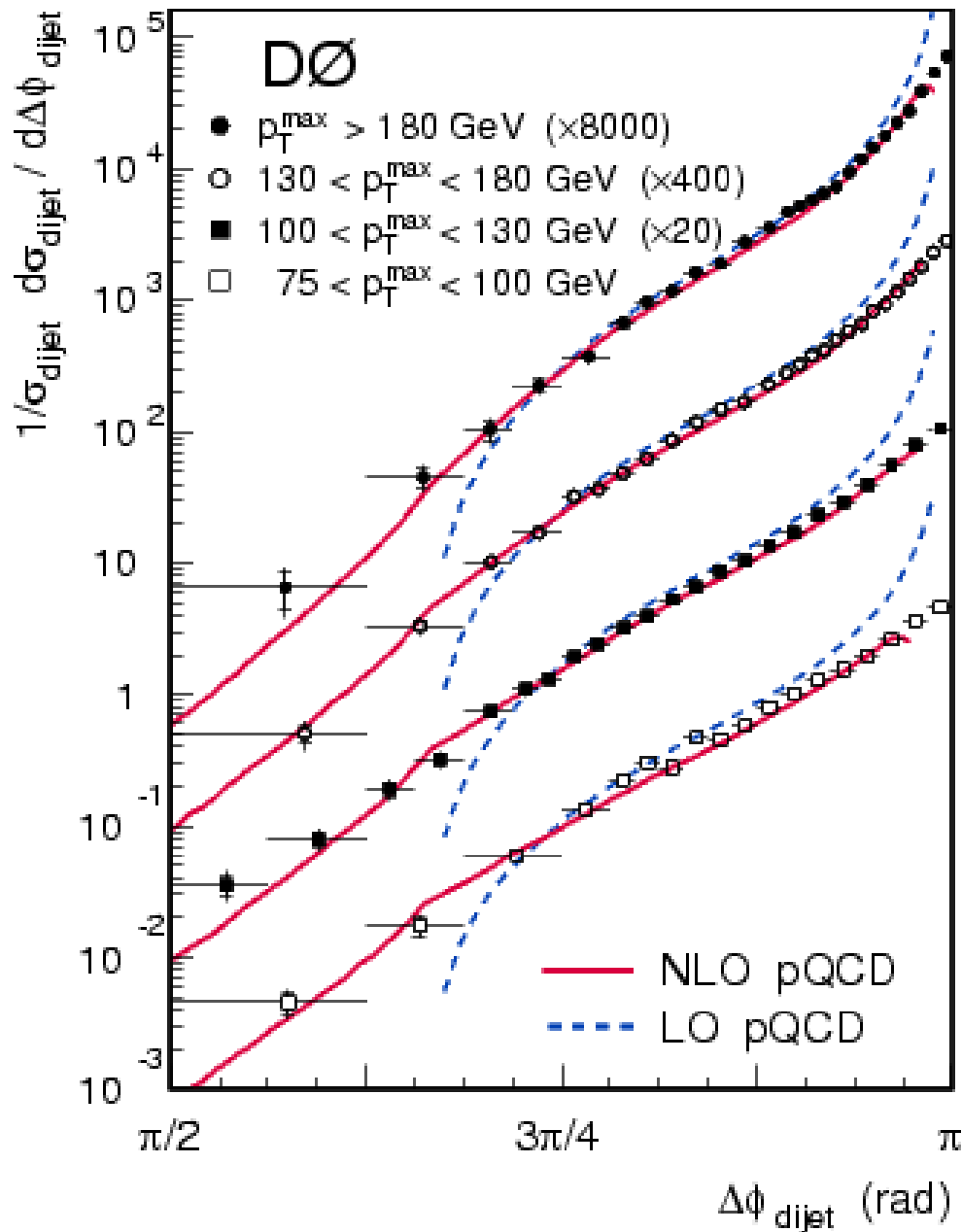
HERA

Fixed Target

Can
measure
parton
momenta

constrain
structure
functions!

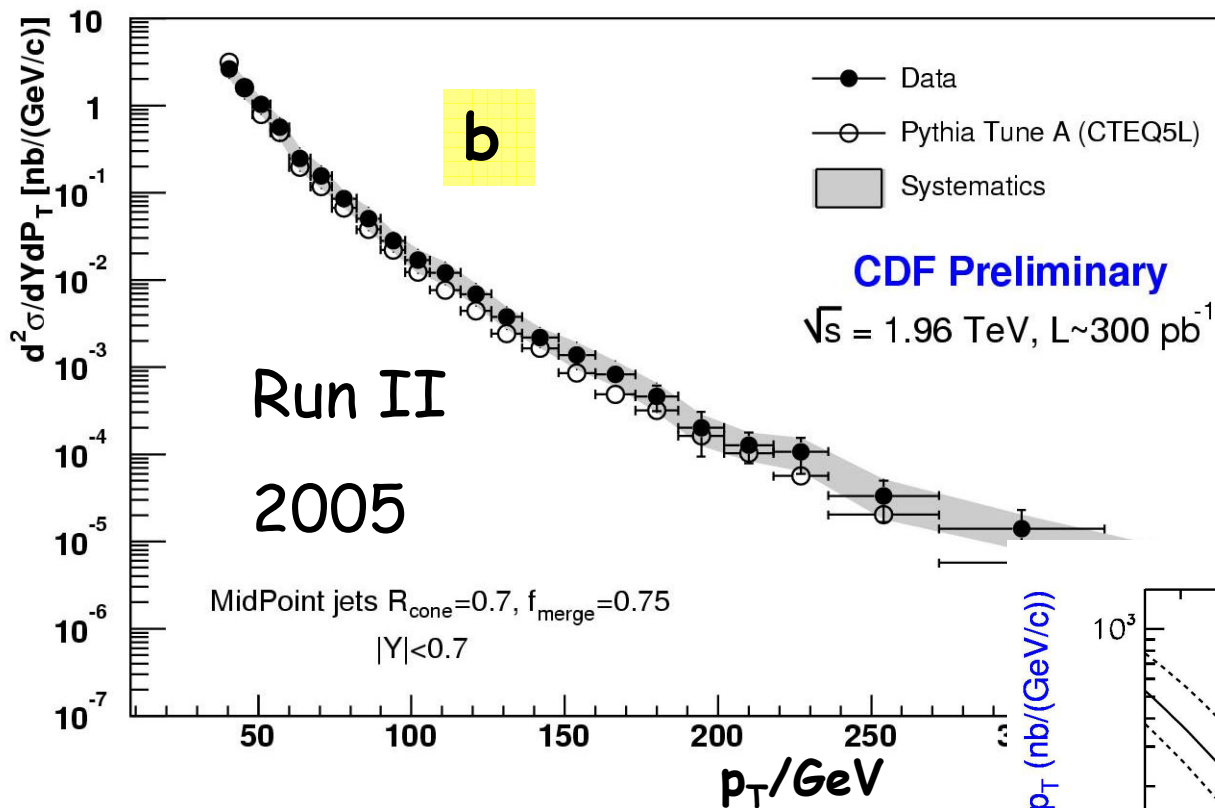
Inclusive dijet production



contributions at
angles $< \pi$ from multi
parton final states

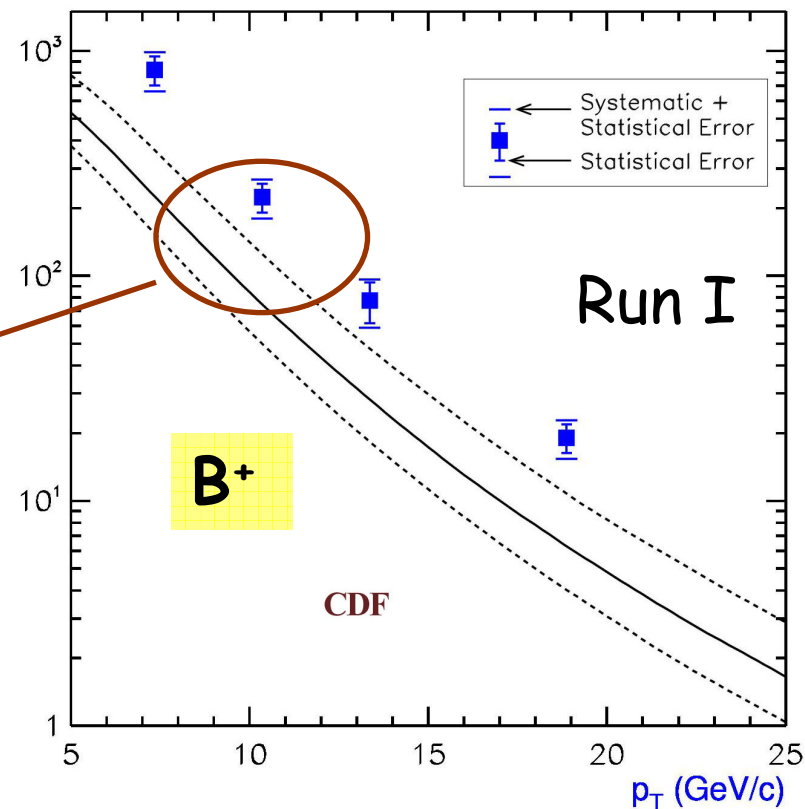
ok !

Bottom quark production



$\frac{d\sigma}{dp_T} (\text{nb}/(\text{GeV}/c))$

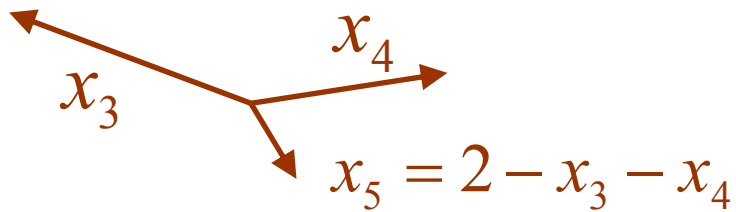
B^+ Meson Differential Cross Section



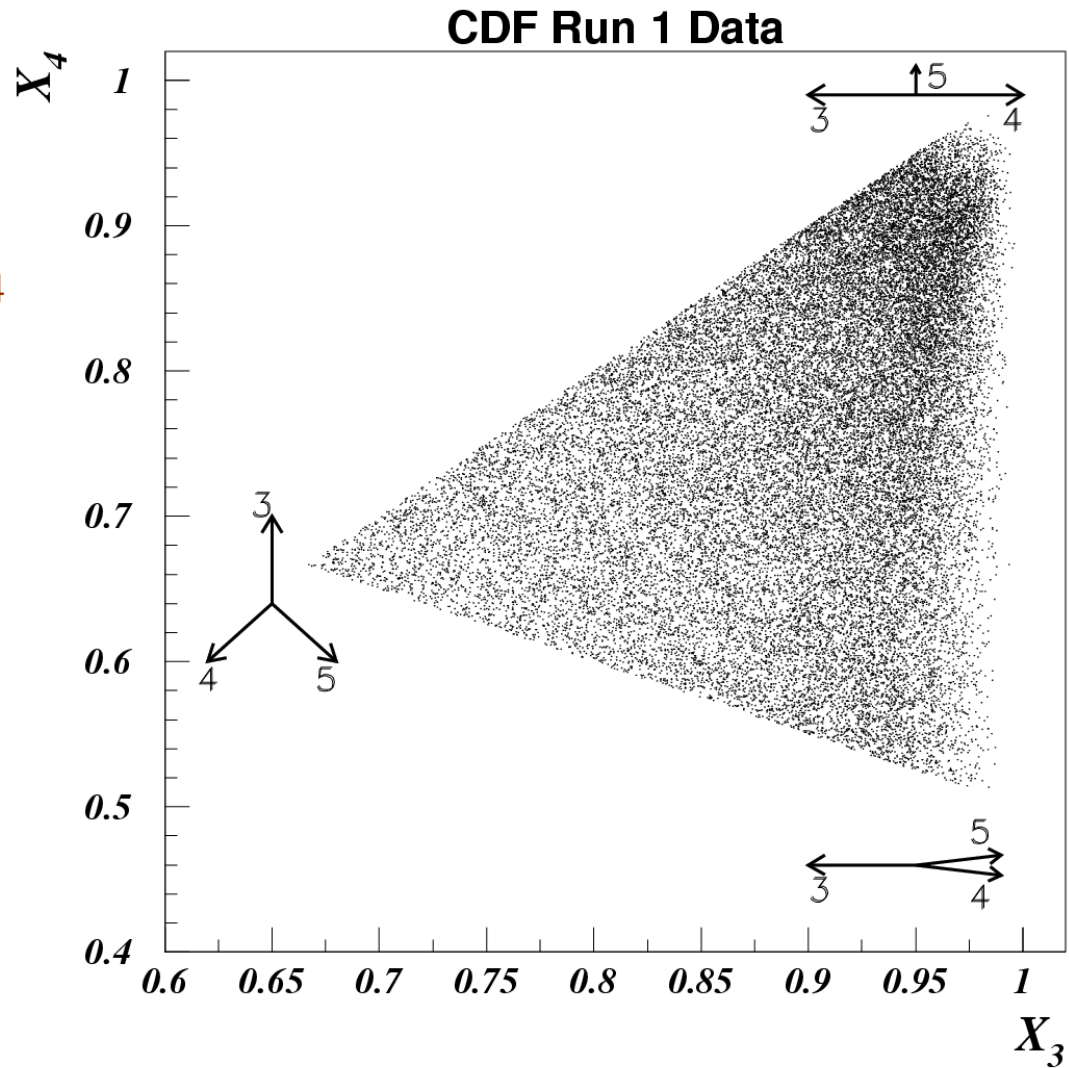
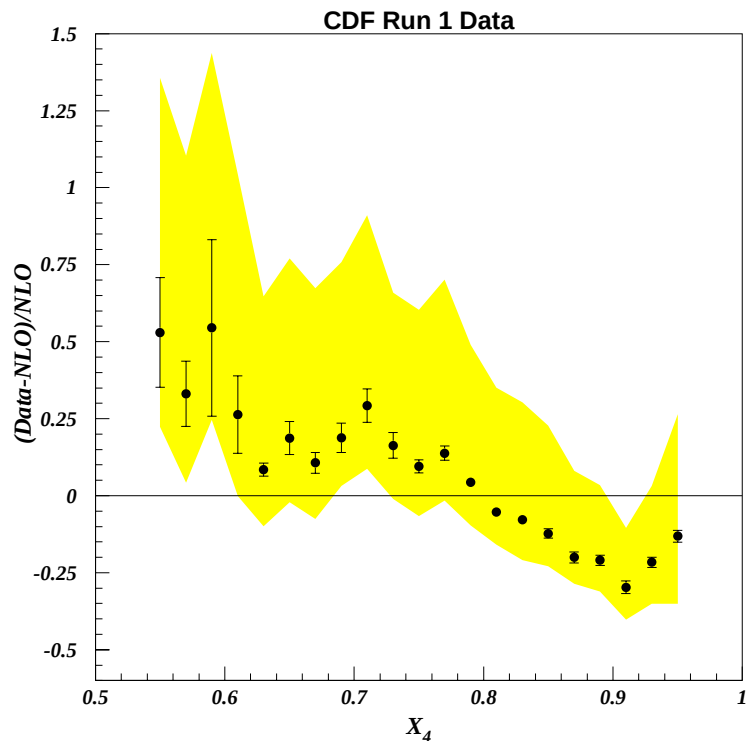
(old) discrepancy due to improper use of fragmentation model [tuned at LEP]

Three jet distributions

c.m.s ($\sqrt{s'}$):

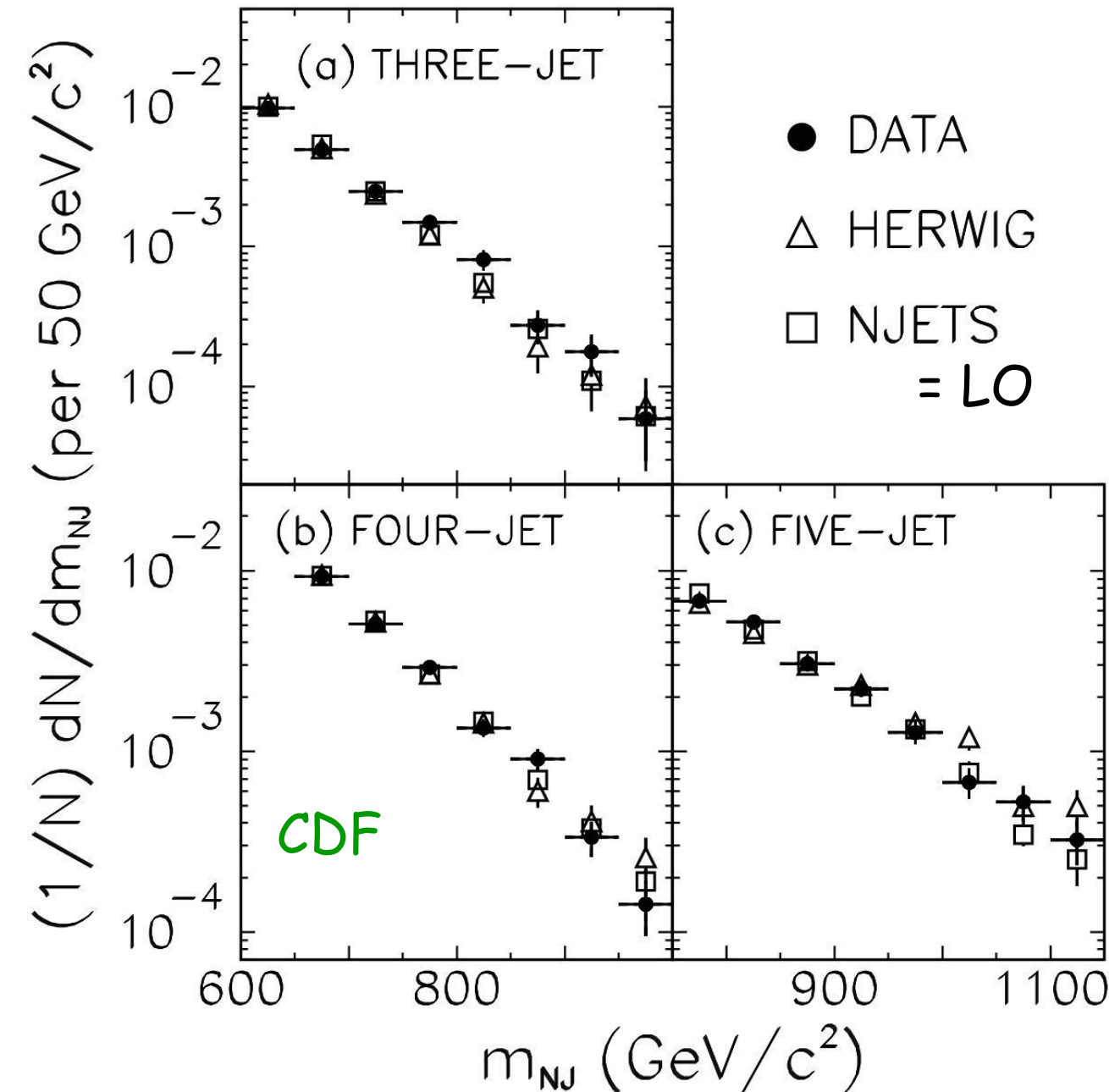


$$x_i = 2 E_i / \sqrt{s'}$$



ok !

Multi jet distributions



$$|\eta| < 4.2$$

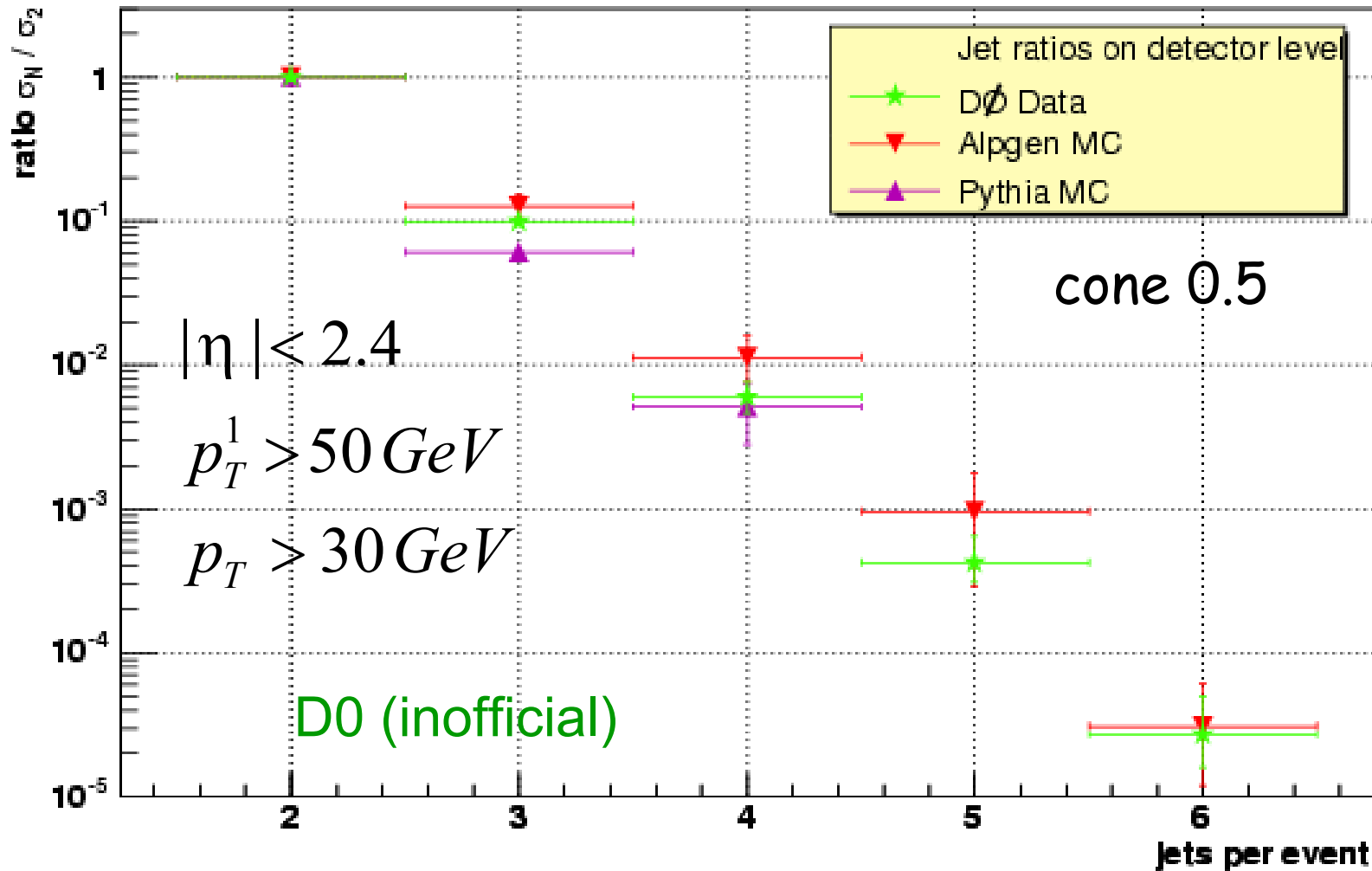
$$E_T > 20 \text{ GeV}$$

$$\Sigma E_T > 420 \text{ GeV}$$

$$\text{cone } 0.7$$

ok!

Multi jet xsection

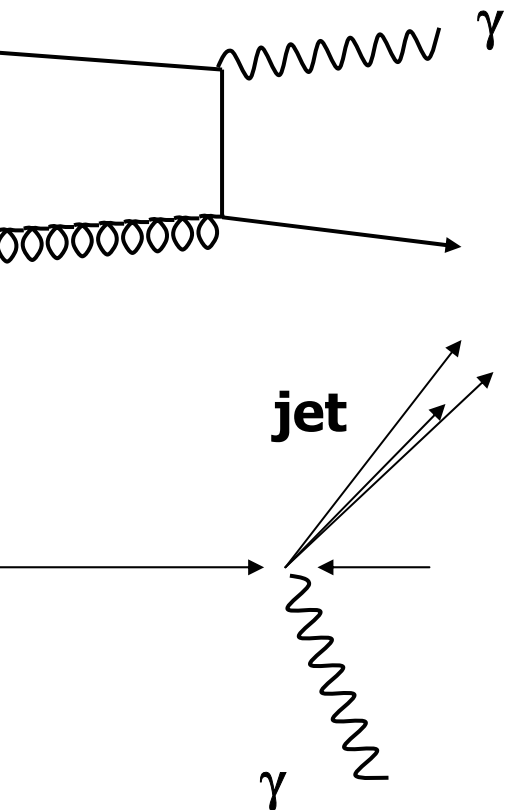


Wilke

4 and more jets calculated
only to leading order

„missing“:
 α_s from 3/2 jets

Jet + Photon

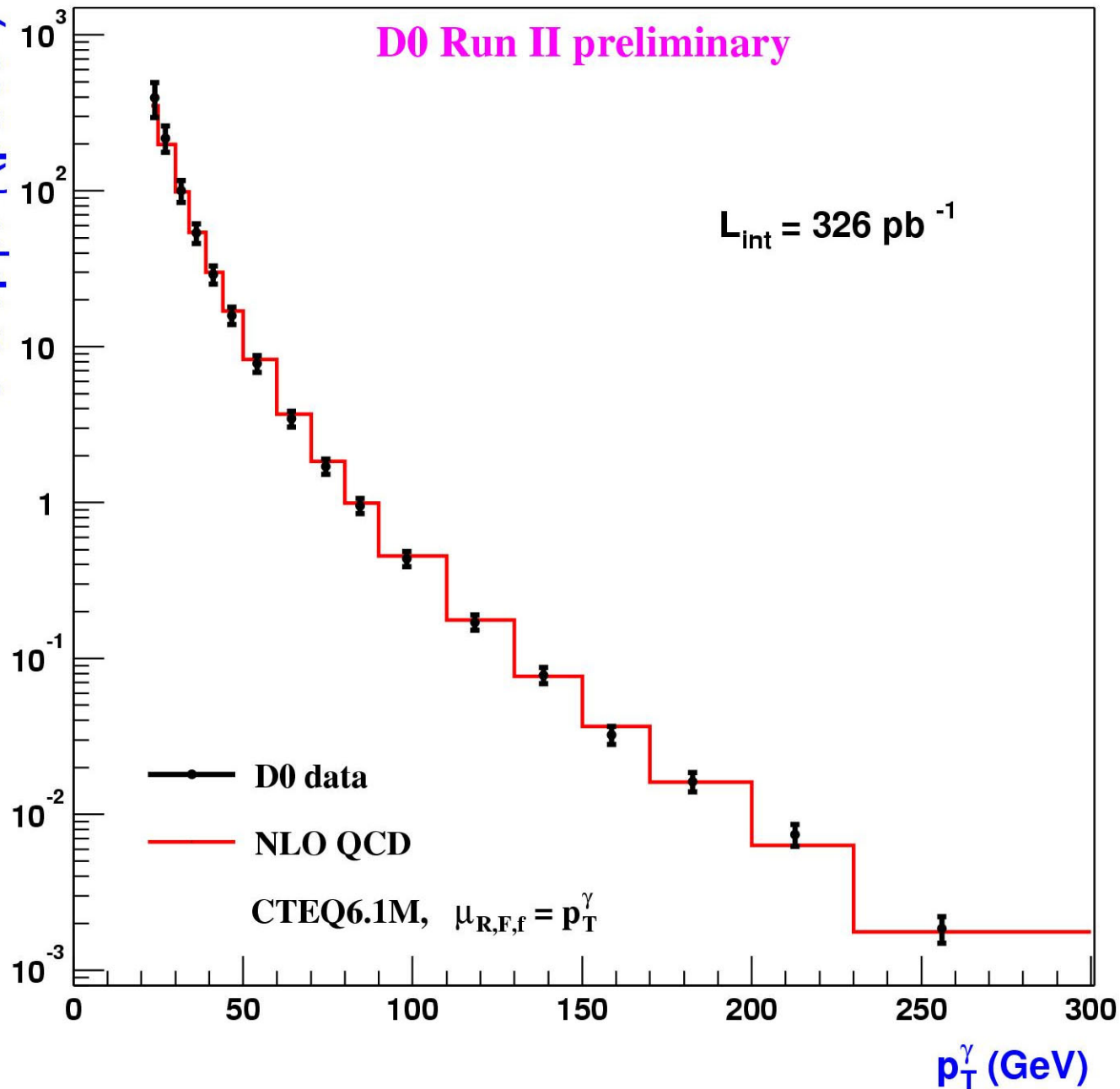


sensitive
to
pdf's

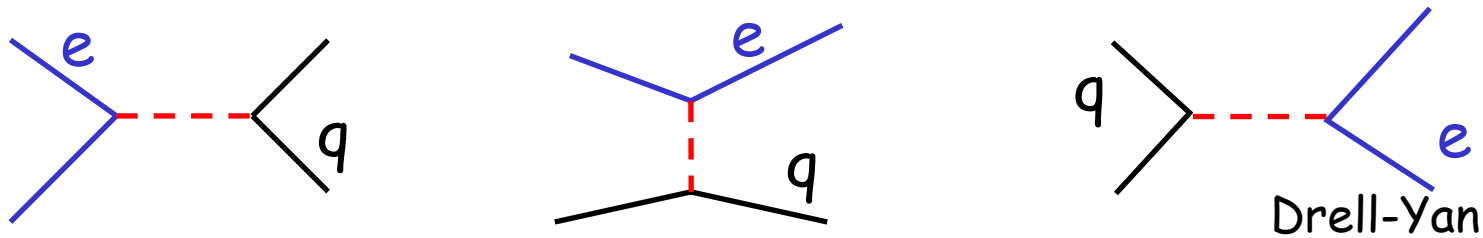
$d^2\sigma/dp_T/d\eta$ (pb/GeV)

D0 Run II preliminary

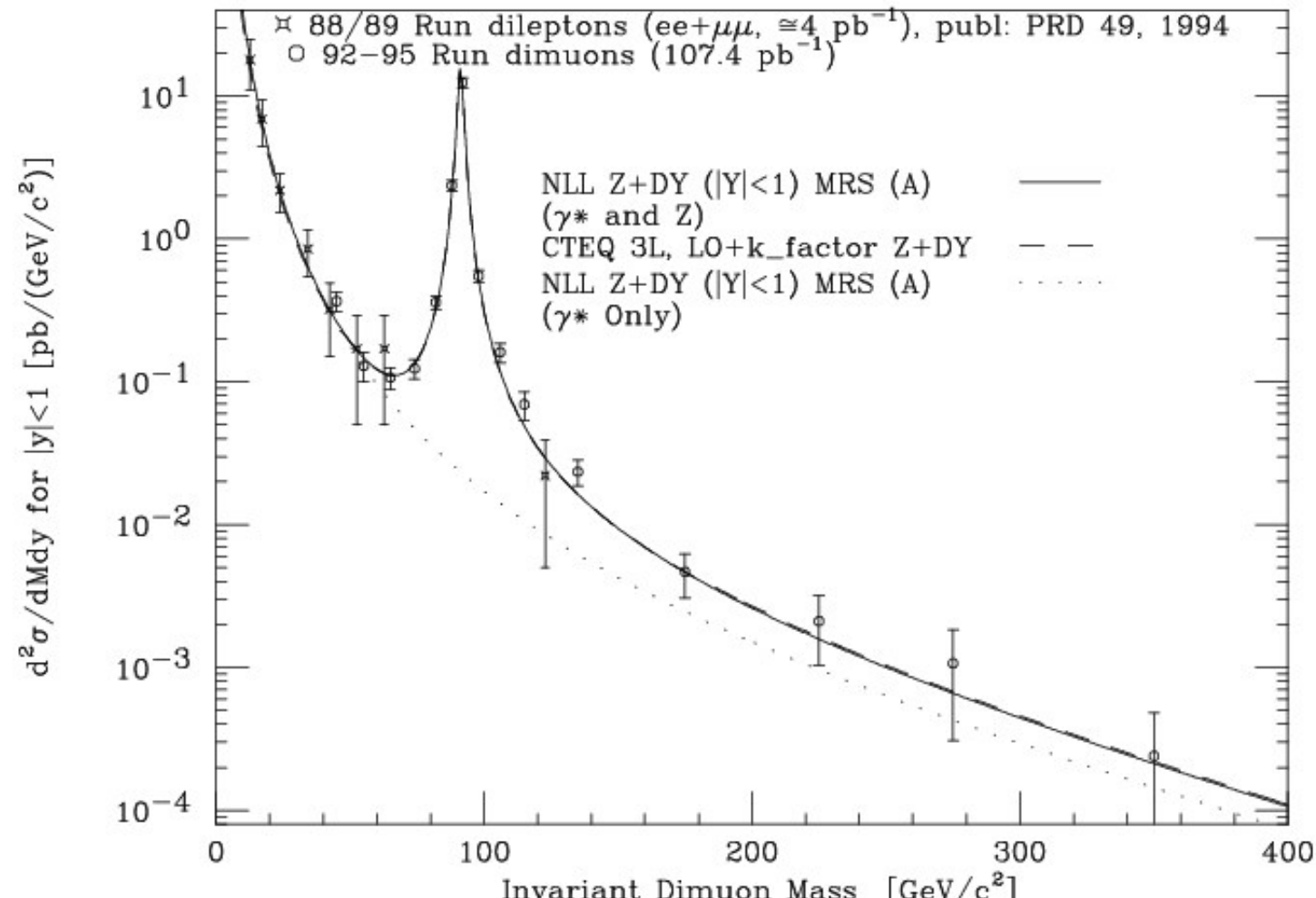
$L_{\text{int}} = 326 \text{ pb}^{-1}$



Drell-Yan (γ, Z) inclusive

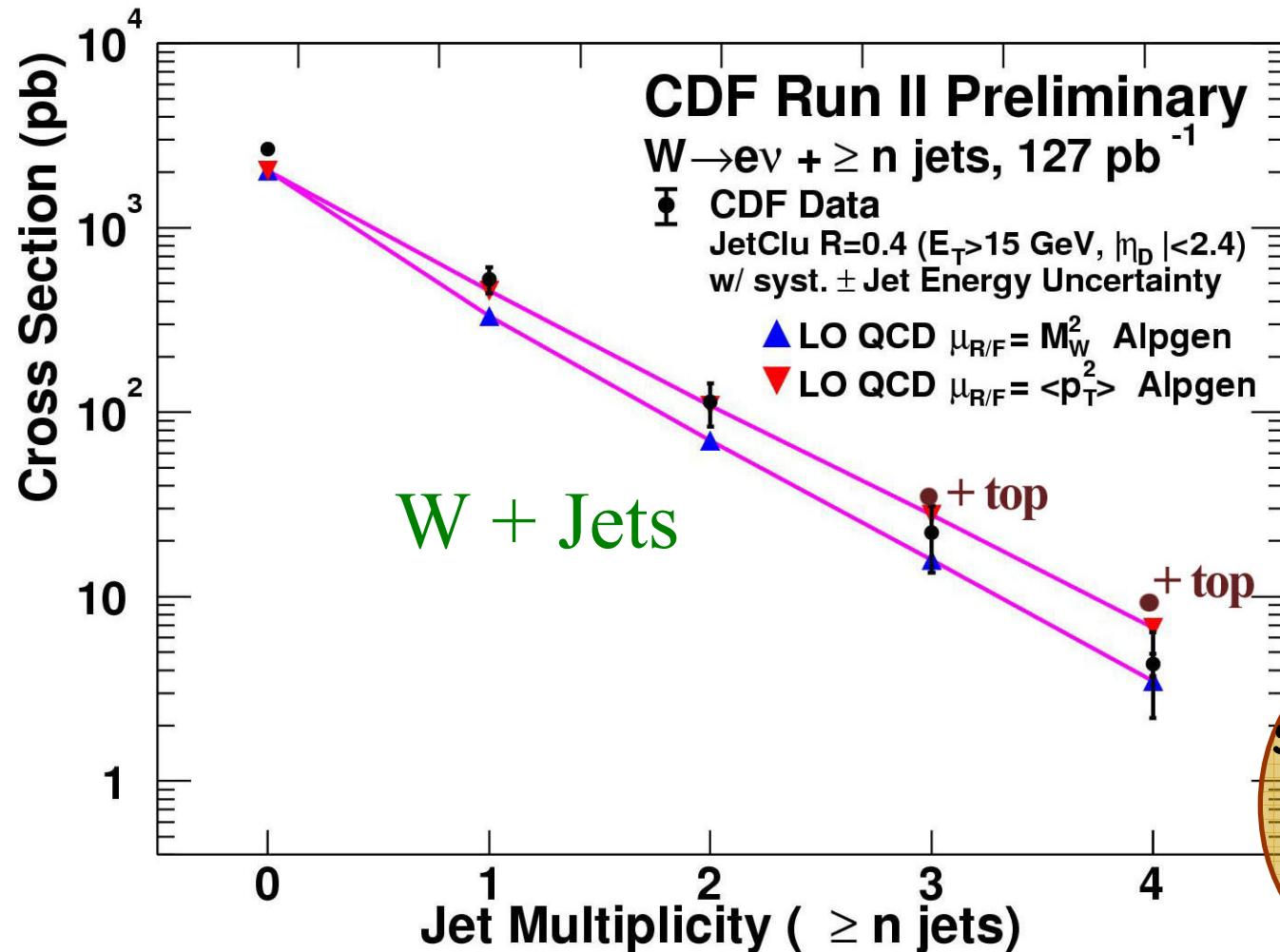
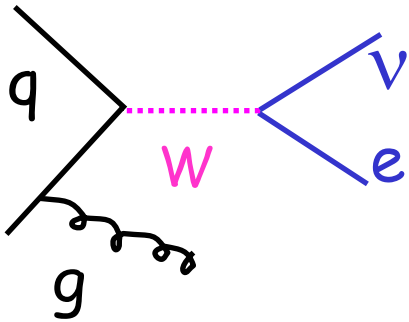


Drell-Yan differential cross-section



sensitive
to
pdf's

Drell-Yan: $W + \text{jets}$



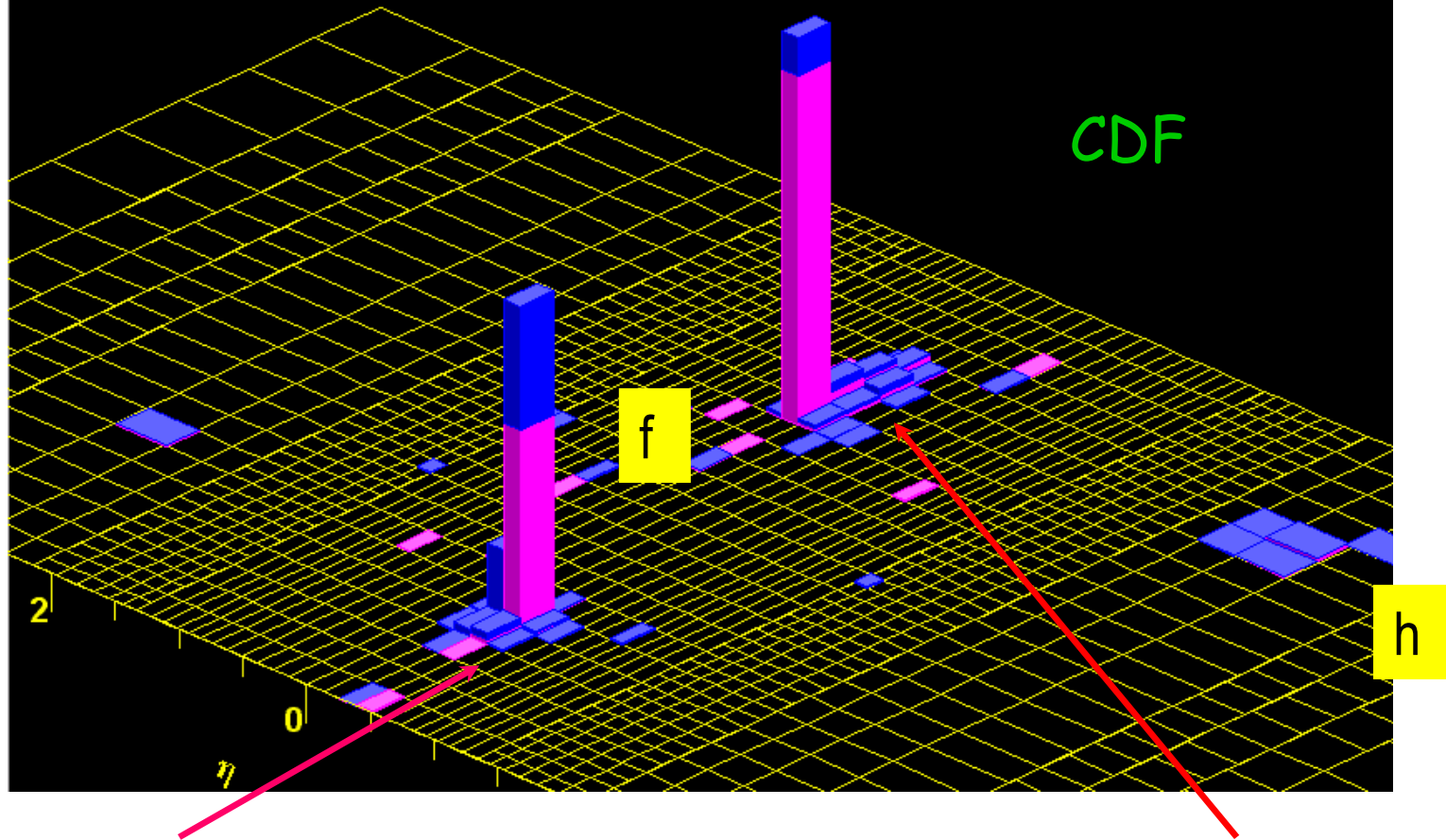
sensitive
to
pdf's

High energy dijet event

Event : 1222318 Run : 152507 EventType : DATA | Unpresc: 0,32,33,3,35,8,40,9,41,10,11,12,13,45,15,17,49,19,21,23,56,58,27,28,30,31 Presc: 0,32,35,8,40,9,10

dijet mass = 1364 GeV

CDF



$E_T = 633 \text{ GeV}$
 $h = -0.19$

$E_T = 666 \text{ GeV}$
 $h = 0.43$

1) Introduction

2) Tevatron

3) LHC

$p + p$
14 TeV

- detectors
- Tevatron → LHC
- examples

t

LHC / CERN

European Laboratory
for Particle Physics

LHC = Large Hadron Collider



p
p

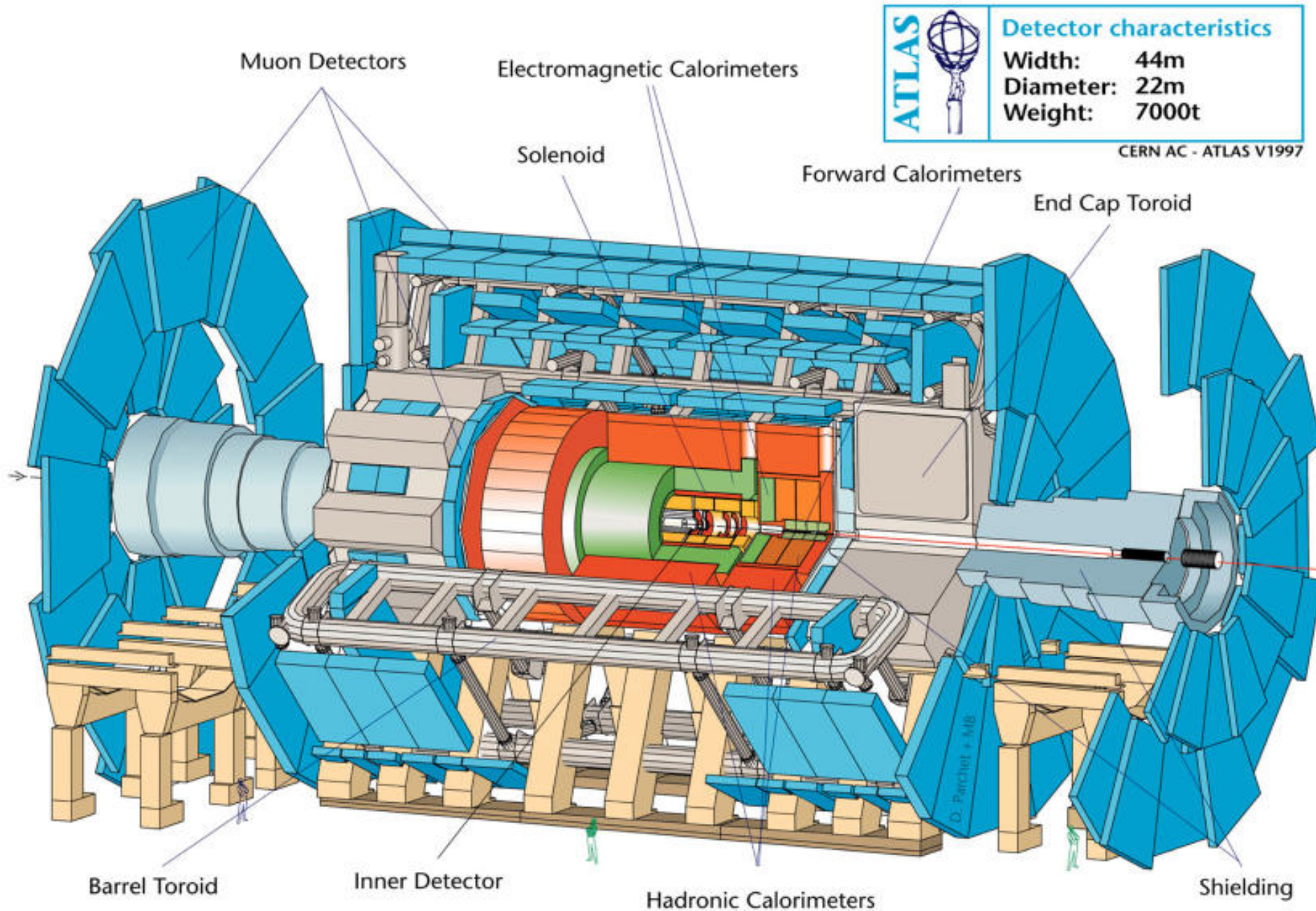
UA2

UA1

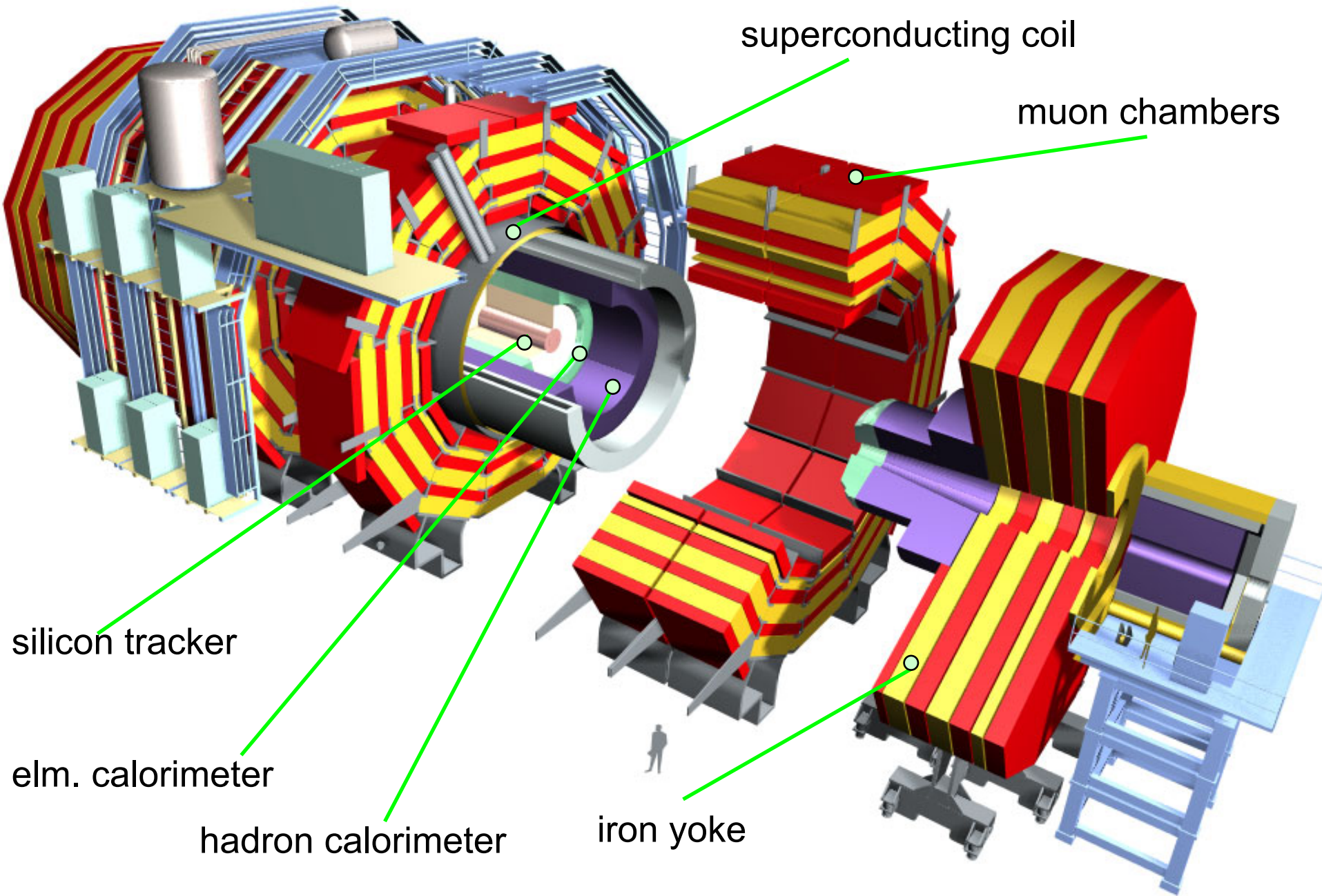
SPS = Super Proton Synchrotron



ATLAS = A Toroidal LHC ApparatuS



CMS = Compact Muon Solenoid



LHC machine/detector performance (jets)

Tevatron

LHC

2TeV

$10^{32} / \text{cm}^2 / \text{s}$

$$\frac{\sigma}{E} = \frac{80\%}{\sqrt{E / \text{GeV}}} \oplus 4\%$$

$$\frac{\delta E}{E_0} = 6\%$$

DO

14TeV

$10^{34} / \text{cm}^2 / \text{s}$

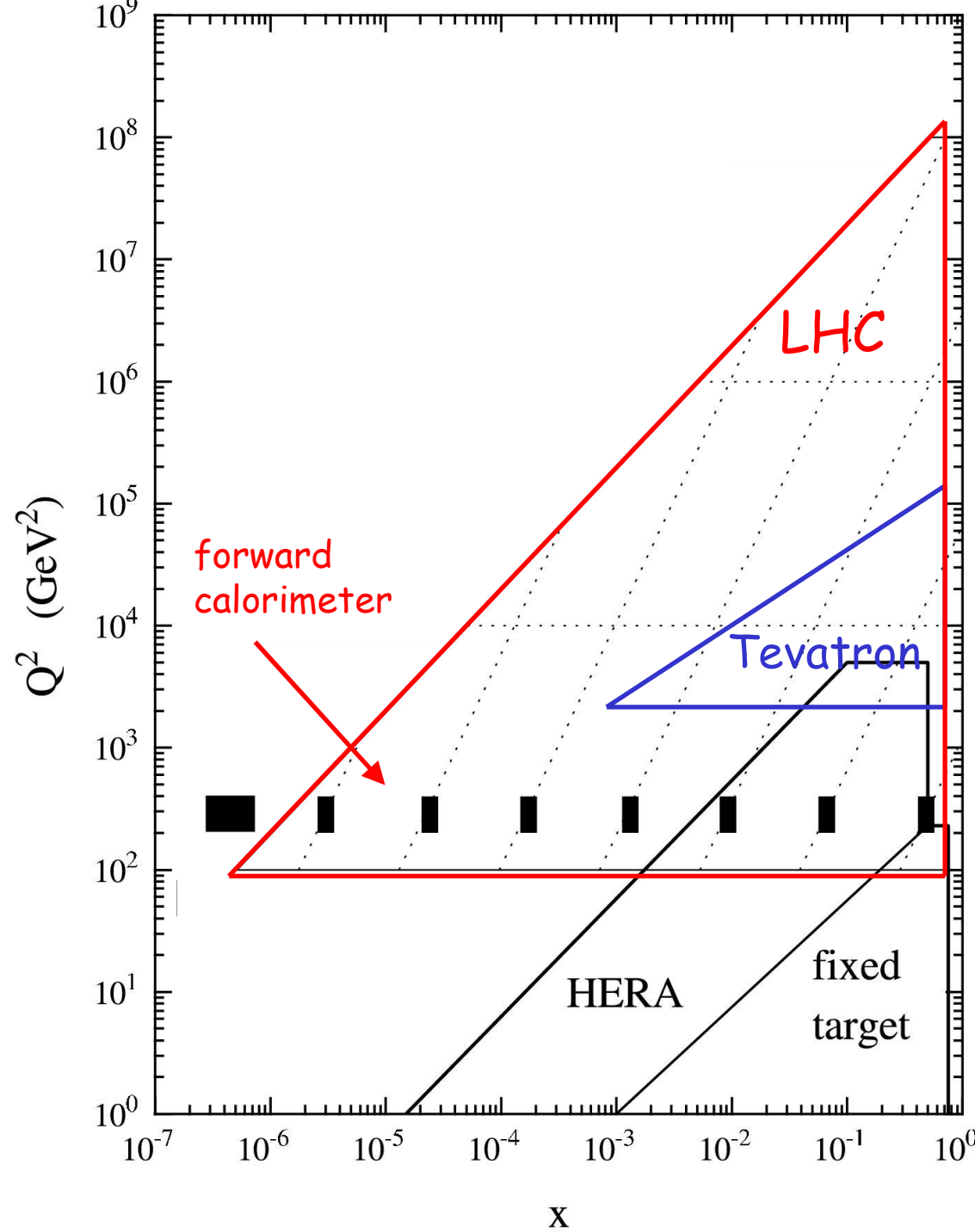
$$\frac{\sigma}{E} = \frac{50\%}{\sqrt{E / \text{GeV}}} \oplus 3\%$$

$$\frac{\delta E}{E_0} = 1\%$$

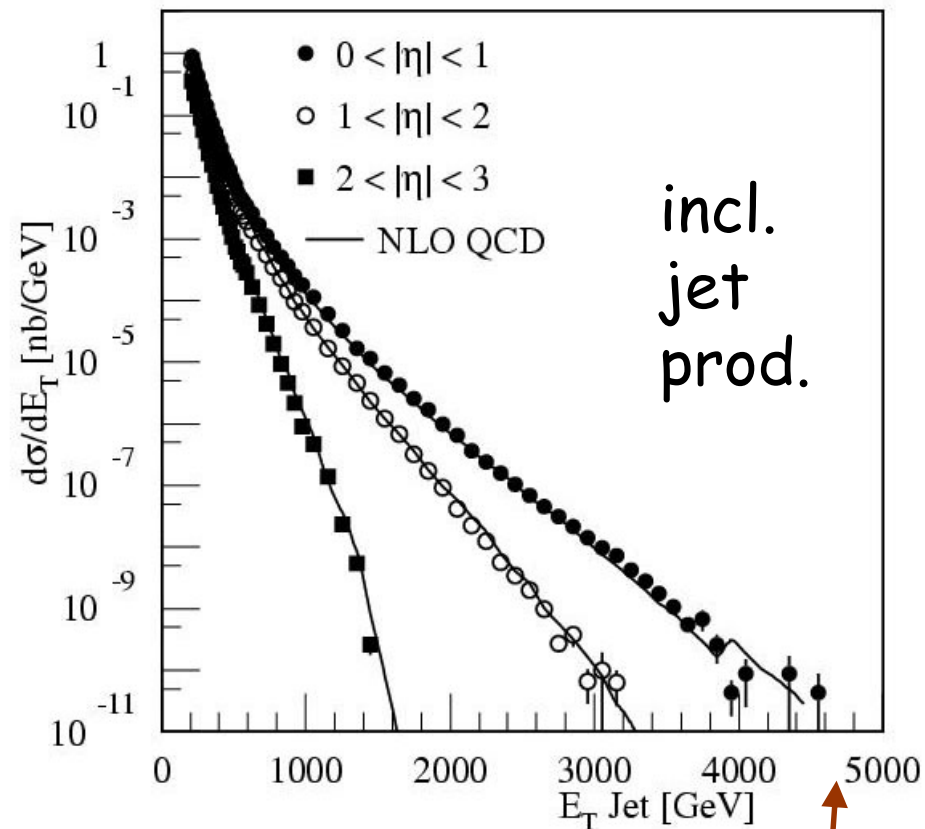
ATLAS

Kinematic Range

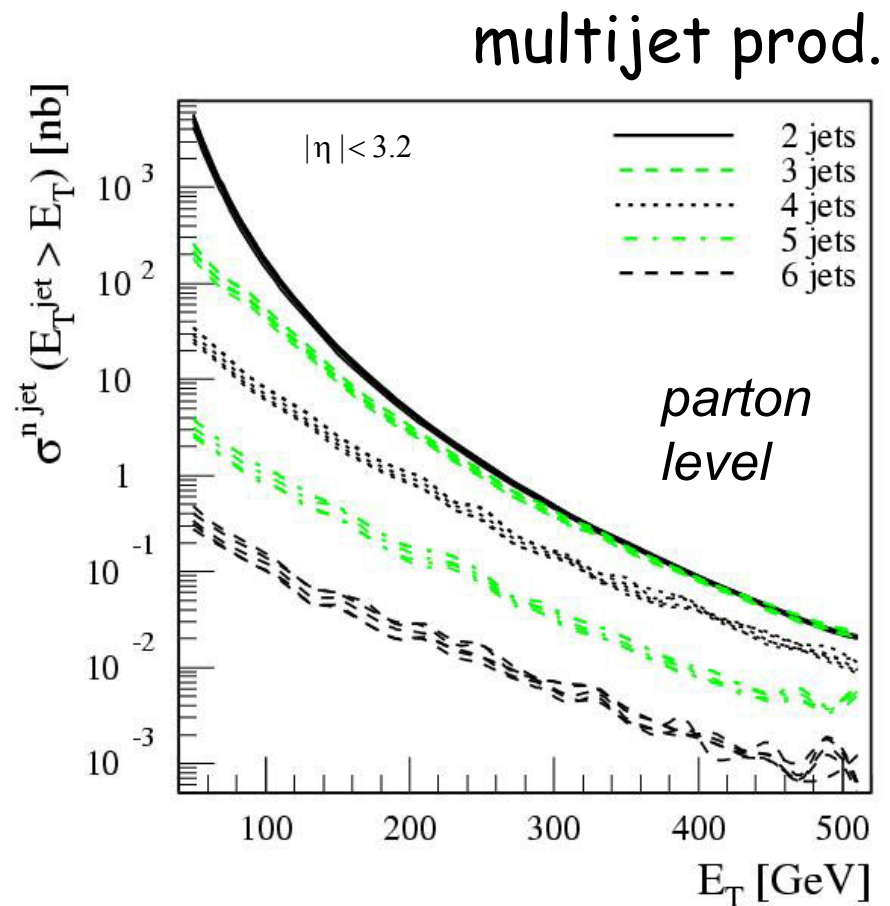
LHC will
improve
knowledge
of gluon pdf
at low x



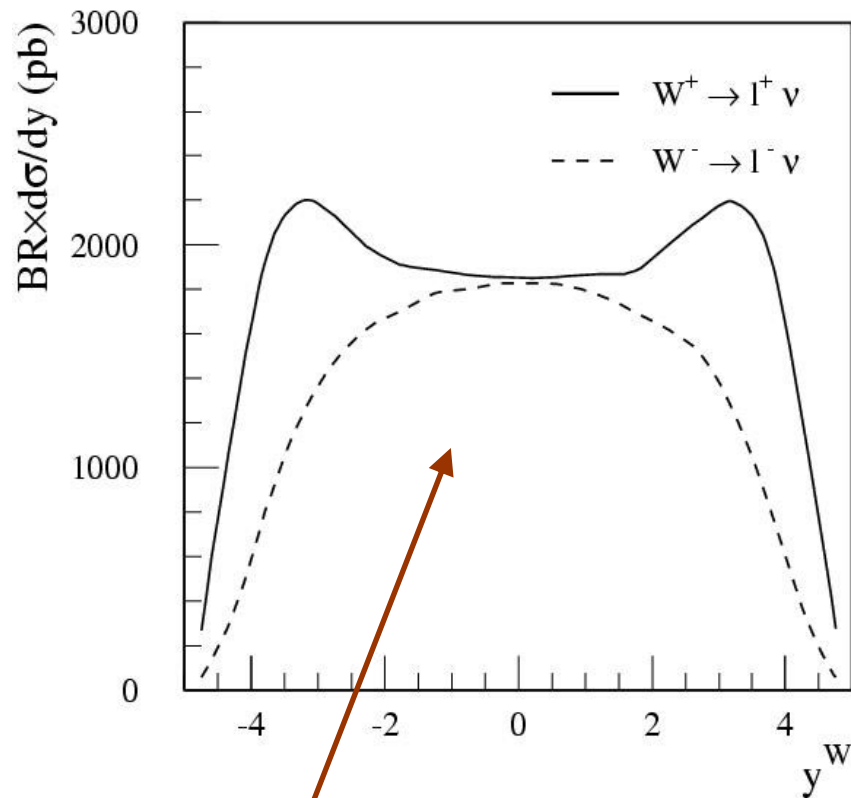
Tevatron - LHC: Similarities



$\sim 5 \text{ TeV}!$



Tevatron - LHC: Differences



pp , (not $p\bar{p}$)

$$u\bar{d} \rightarrow W^+$$

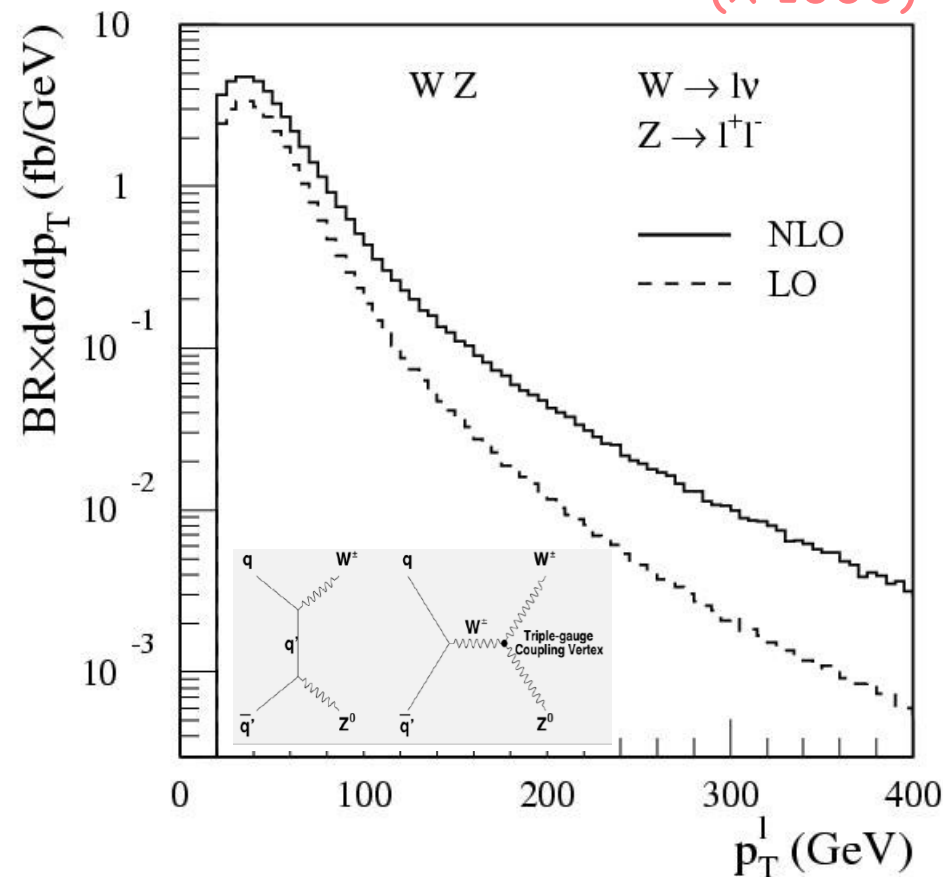
$$\bar{u}d \rightarrow W^-$$

$$\sigma(WZ, 2TeV) = 2.5 pb$$

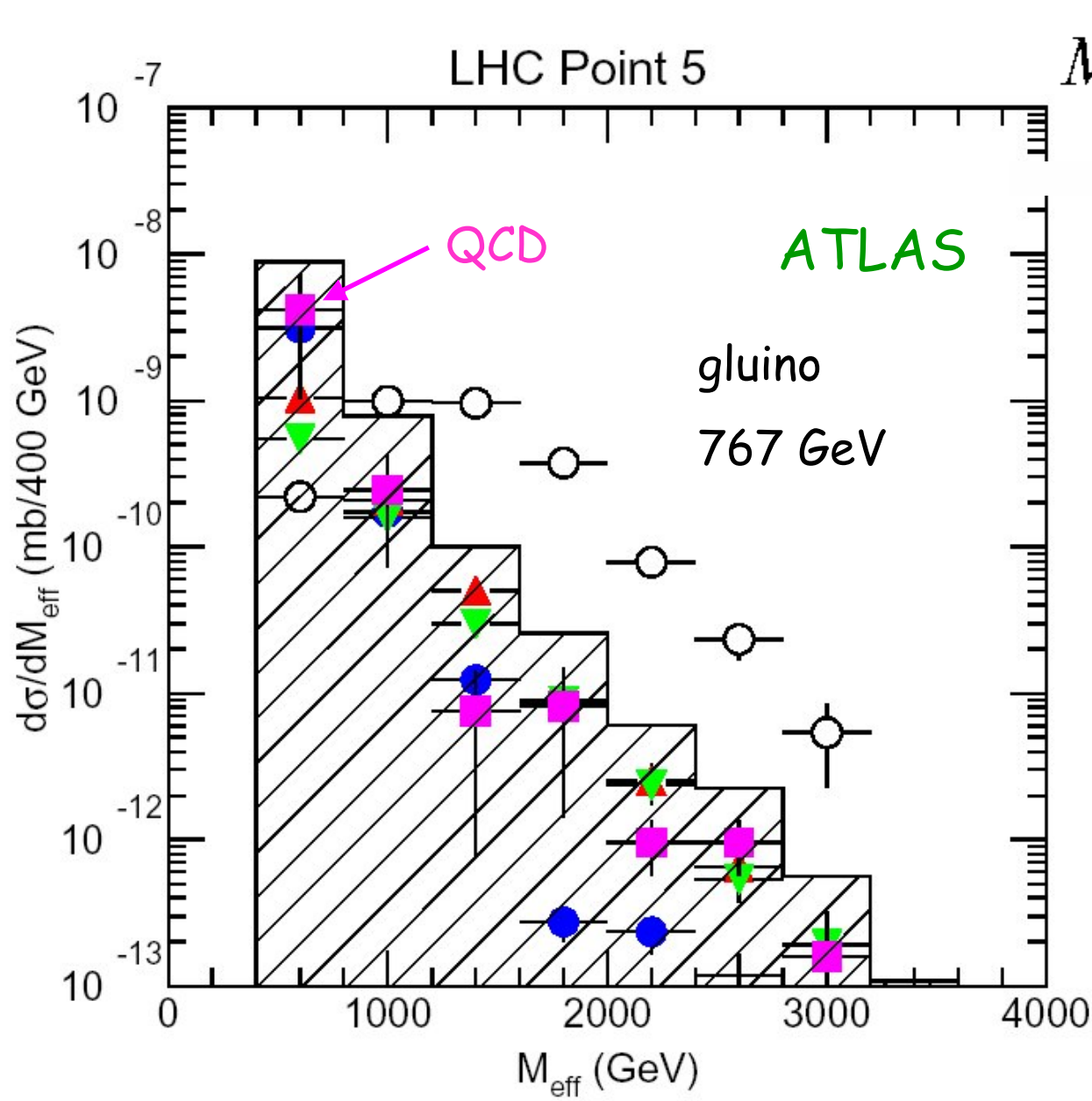
$$\sigma(WZ, 14TeV) = 27 pb$$

statistics!

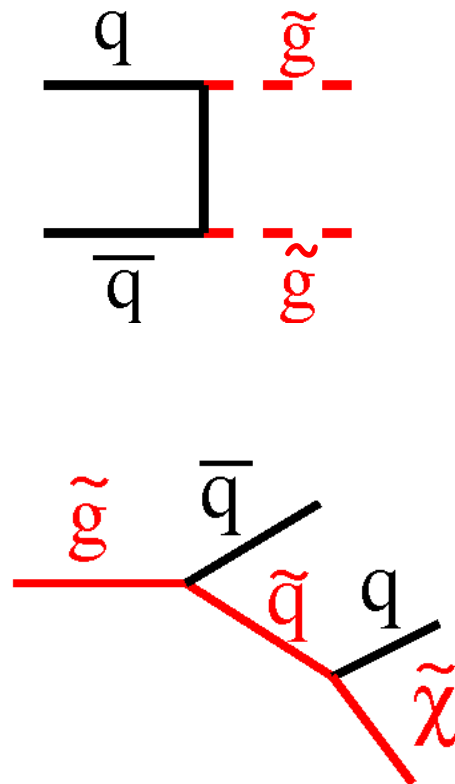
($\times 1000$)



SUSY searches with jet events



$$M_{\text{eff}} = \sum_{j=1} p_{T,j} + E_T^{\text{miss}}$$

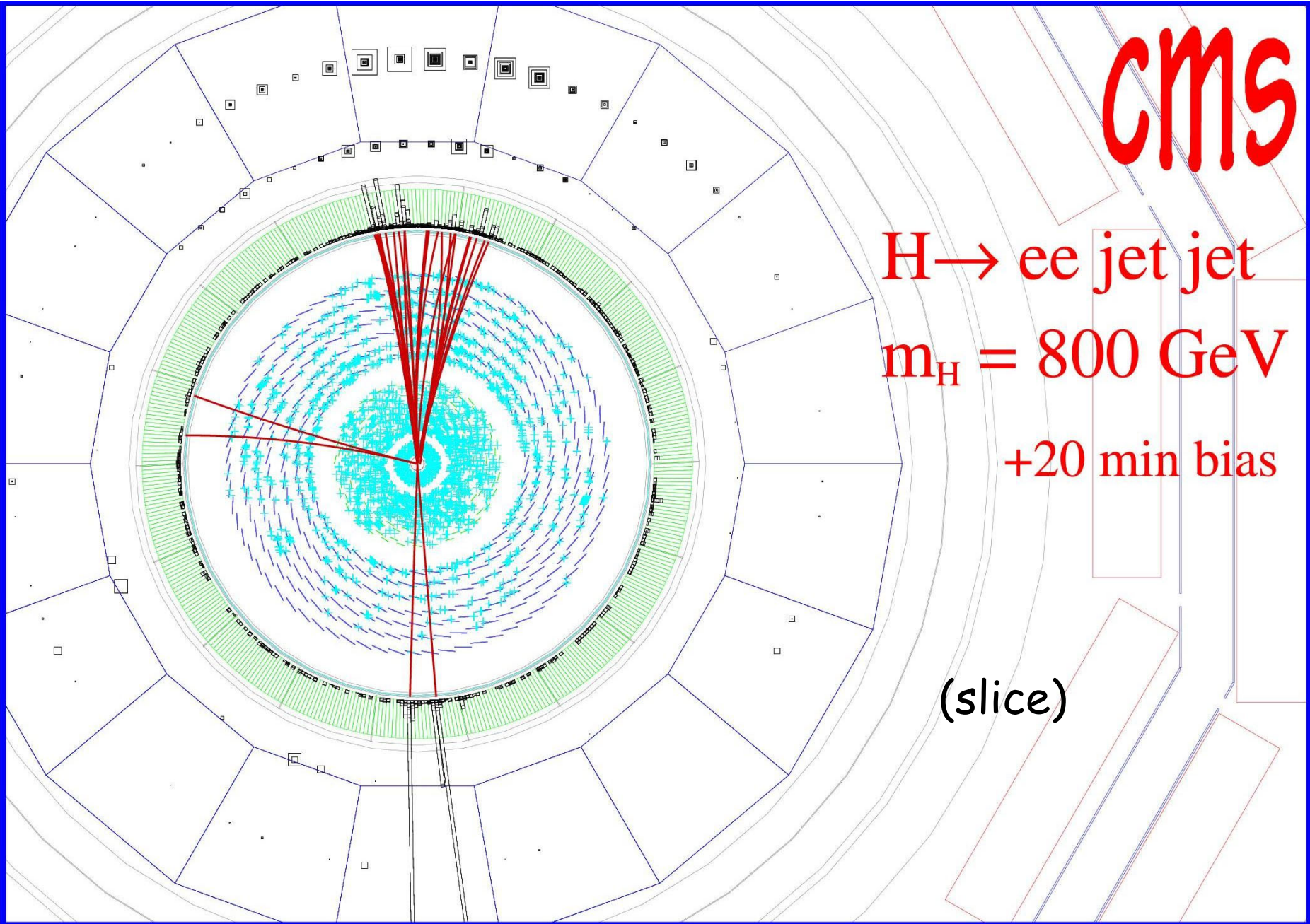


2007 ?

CMS

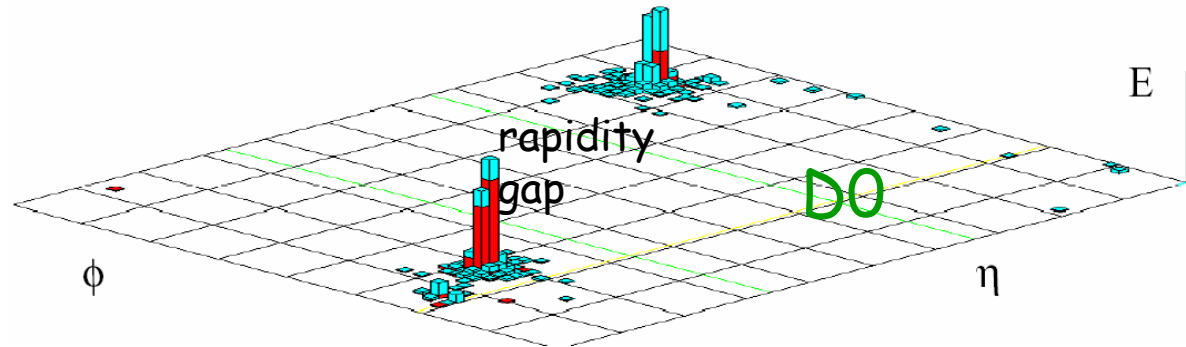
$H \rightarrow ee \text{ jet jet}$
 $m_H = 800 \text{ GeV}$
+20 min bias

(slice)

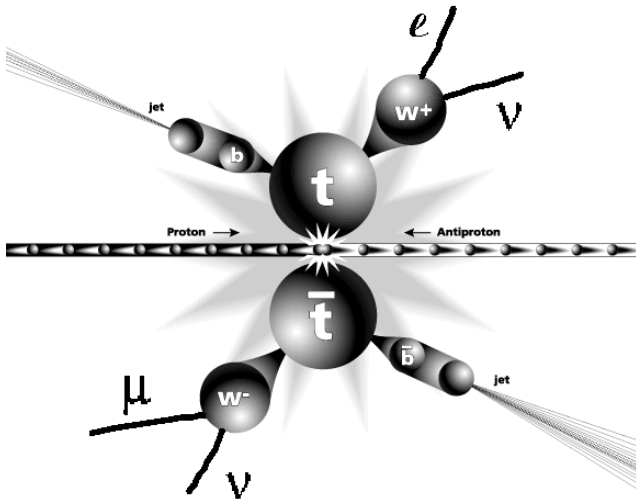


Not covered ...

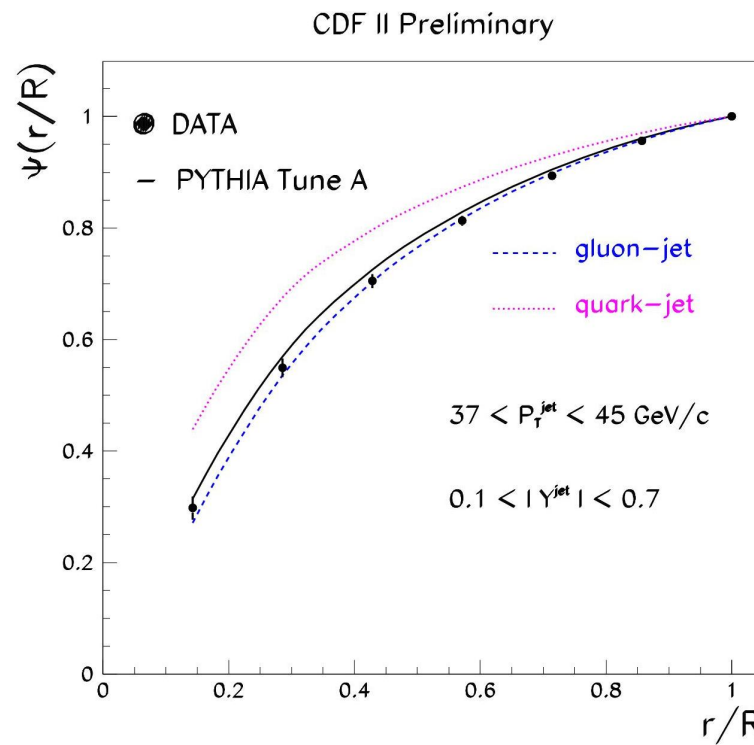
- diffractive processes



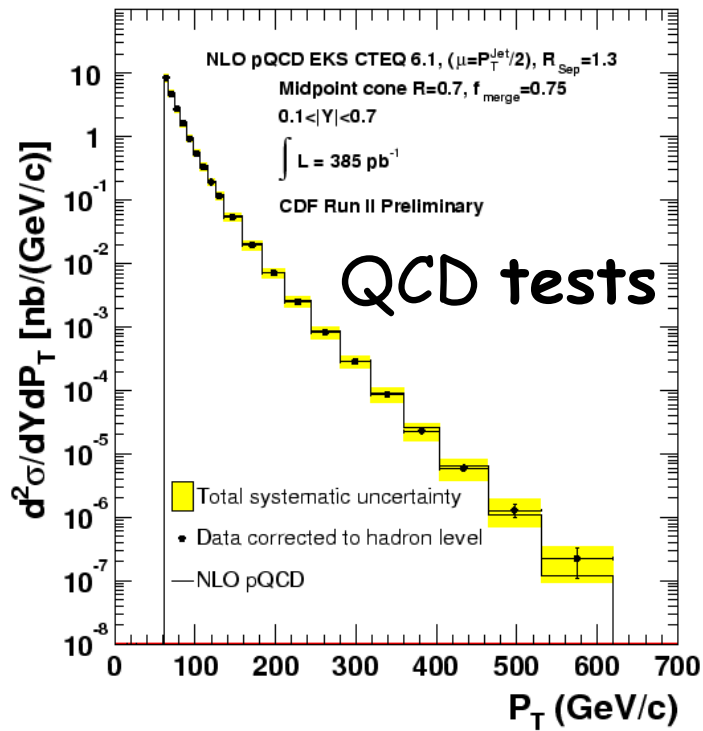
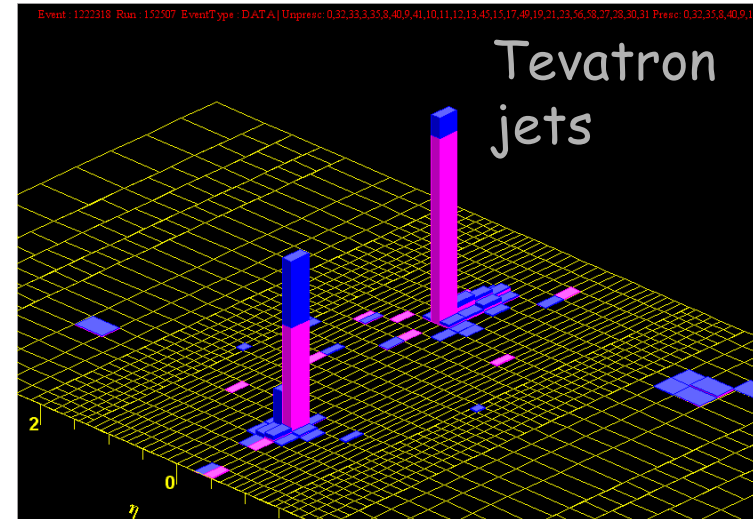
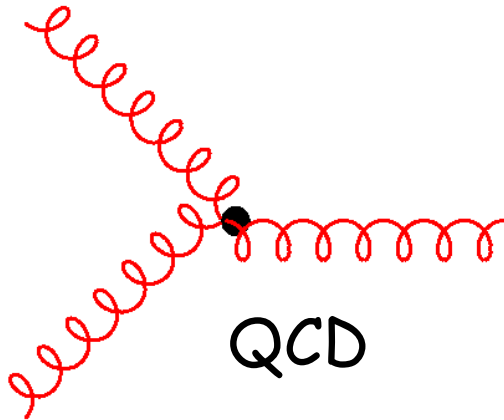
top physics



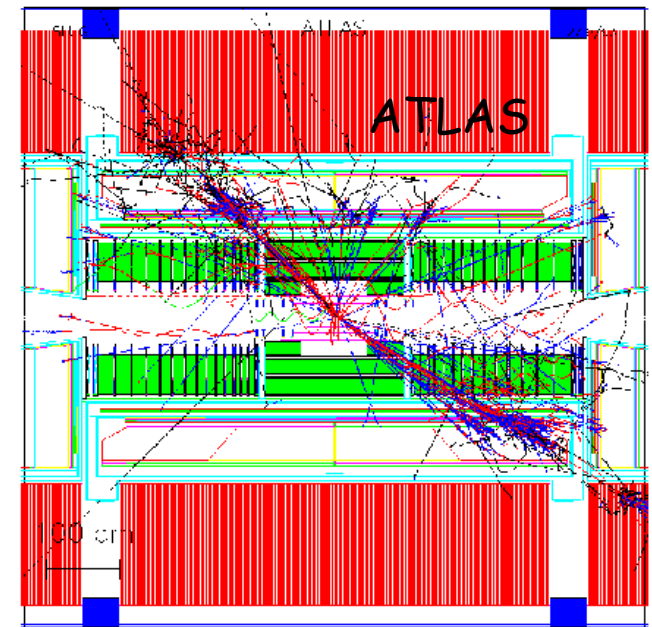
- jet shape and structure



Summary



outlook: LHC



References

- QCD review by I. Hinchcliffe, Review Particle Prop. 2004
- CERN Academic Training, Altarelli, Collider Physics, 1986
- CERN Academic Training, Stirling, QCD, 1992
- ATLAS Physics TDR, Vol II, 1999
- Thomas Gehrmann, talk on precision QCD at colliders, 2003
- CDF and D0 web pages

Appendices

QCD = SU(3) gauge theory

$$\mathcal{L} = \bar{q}_\alpha^{a,j} \left[i \gamma_{\alpha\beta}^\mu (\delta_{ab} \partial_\mu + i g_s t_{ab}^r g_\mu^r) - m_j \delta_{ab} \delta_{\alpha\beta} \right] q_\beta^{b,j} - \frac{1}{4} F_{\mu\nu}^r F^{r,\mu\nu}$$

$\alpha, \beta, \dots =$	$1, 2, 3, 4$	Dirac index
$\mu, \nu, \dots =$	$1, 2, 3, 4$	space time index
$a, b, \dots =$	$1, \dots, N_C = 3$	quark color index
$r, s, \dots =$	$1, \dots, N_C^2 - 1 = 8$	gluon color index
$j, k, \dots =$	$1, \dots, N_F$	flavor index .

$$F_{\mu\nu}^r = \partial_\mu g_\nu^r - \partial_\nu g_\mu^r - g_s f^{rst} g_\mu^s g_\nu^t .$$

Missing transverse energy/momentum

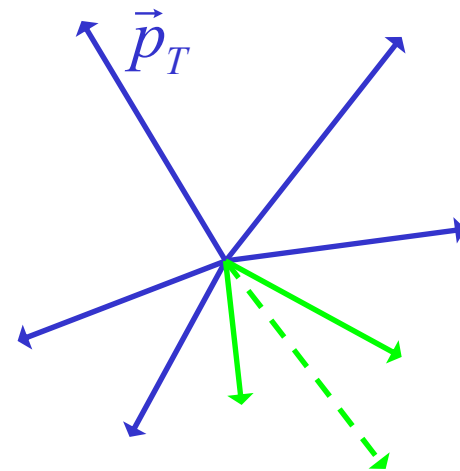
- a) energy = momentum (masses small)
- b) $\vec{p}_T$ can be measured for all „visible“ particles:
 - i) small angle to beam pipe: escapes but $\vec{p}_T$ small
 - ii) large angle: seen in detector
- c) „invisible particles“ (neutrinos, gravitons, ...):

$$\sum_{invis} \vec{p}_T = - \sum_{vis} \vec{p}_T$$

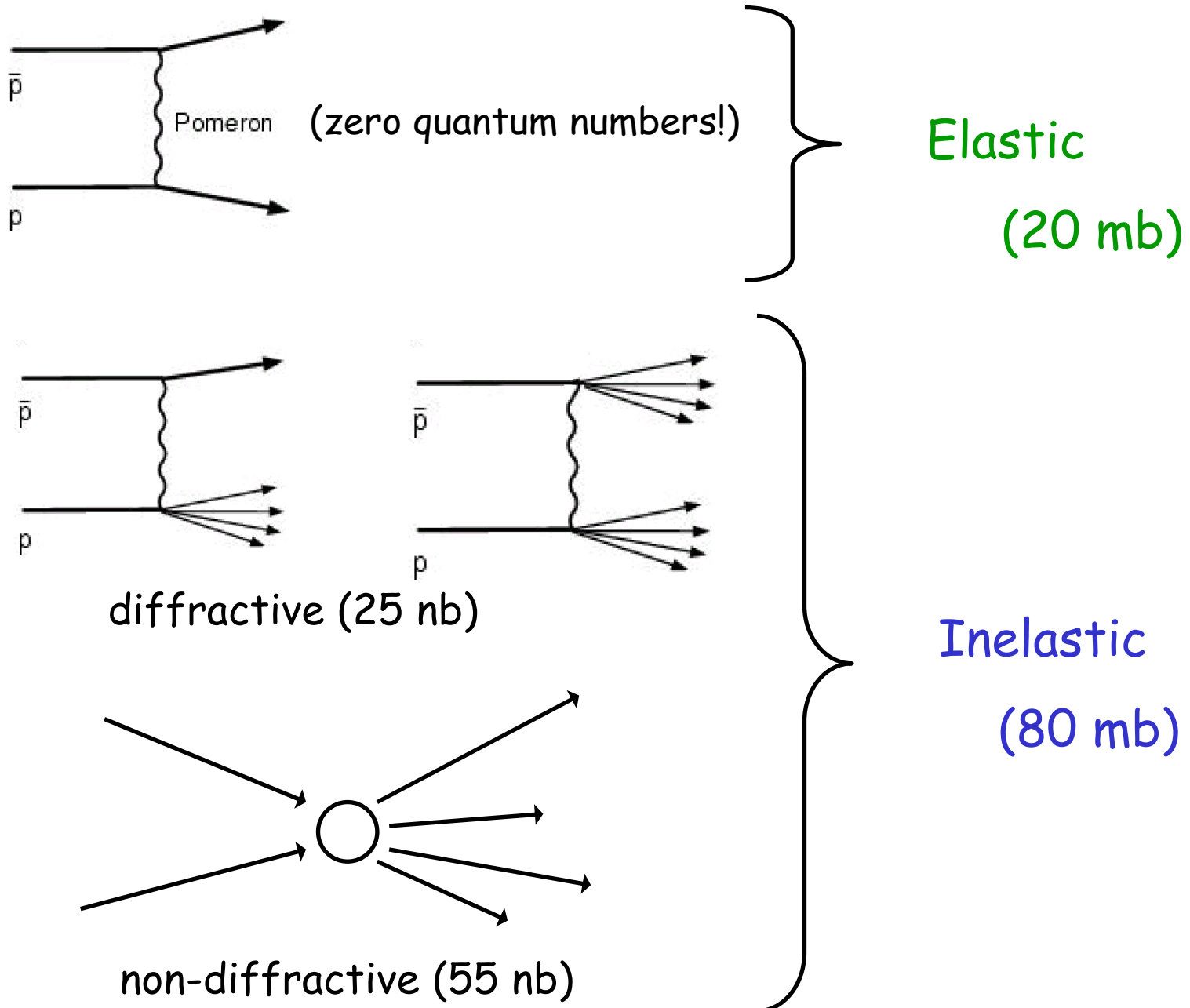
$$MET = \left| \sum_{invis} \vec{p}_T \right|$$

(Example: $W \rightarrow \mu \nu$)

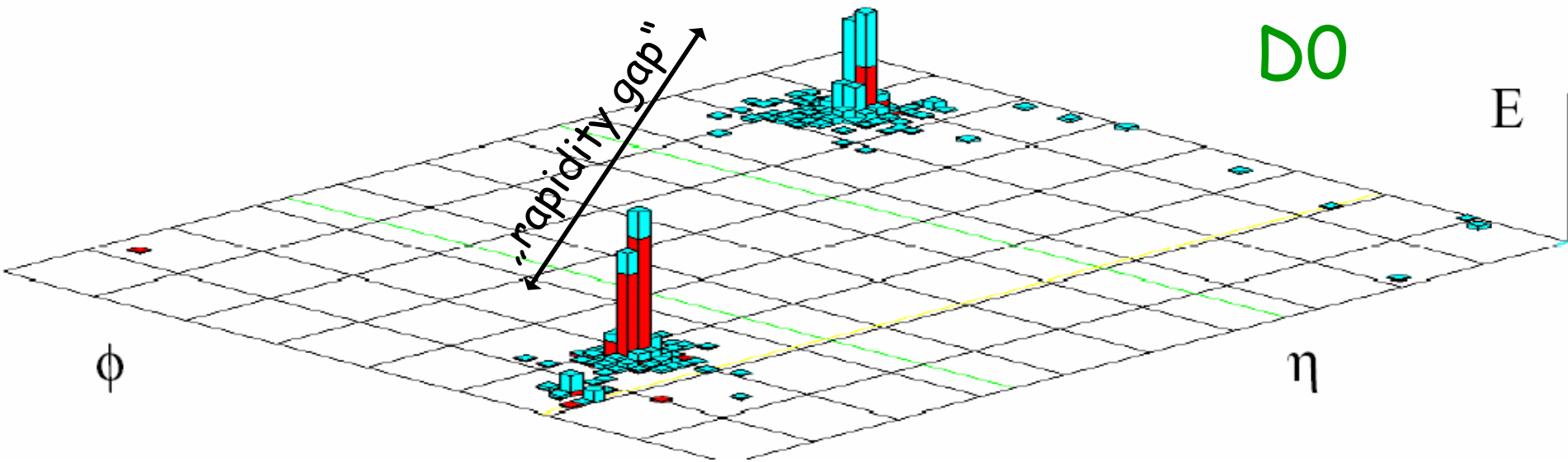
plane perpendicular to beam:



Soft hadronic processes (LHC)



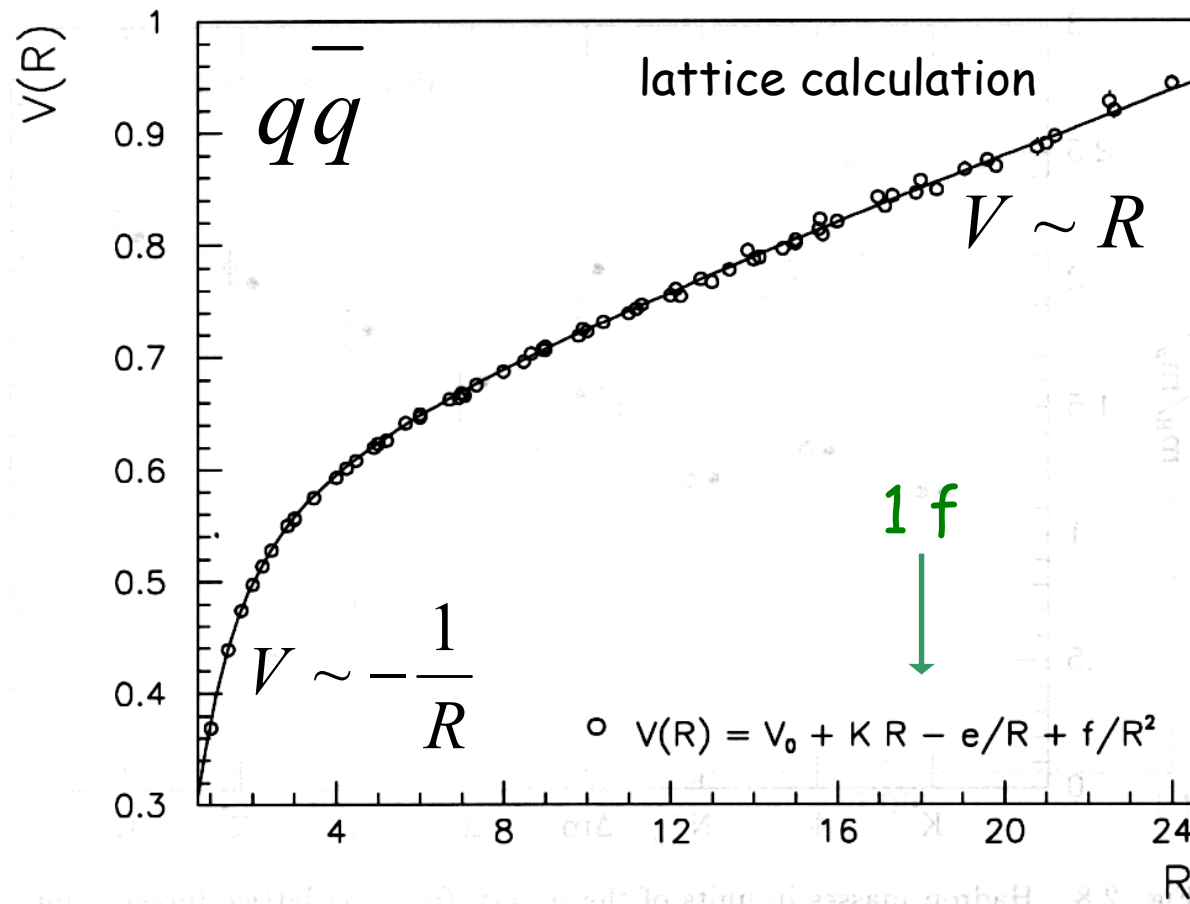
Double-Diffractive Event



explanation: exchange of a color neutral object,
for example made up of 2 gluons („pomeron“)

QCD at large distances

quarks and gluons confined:

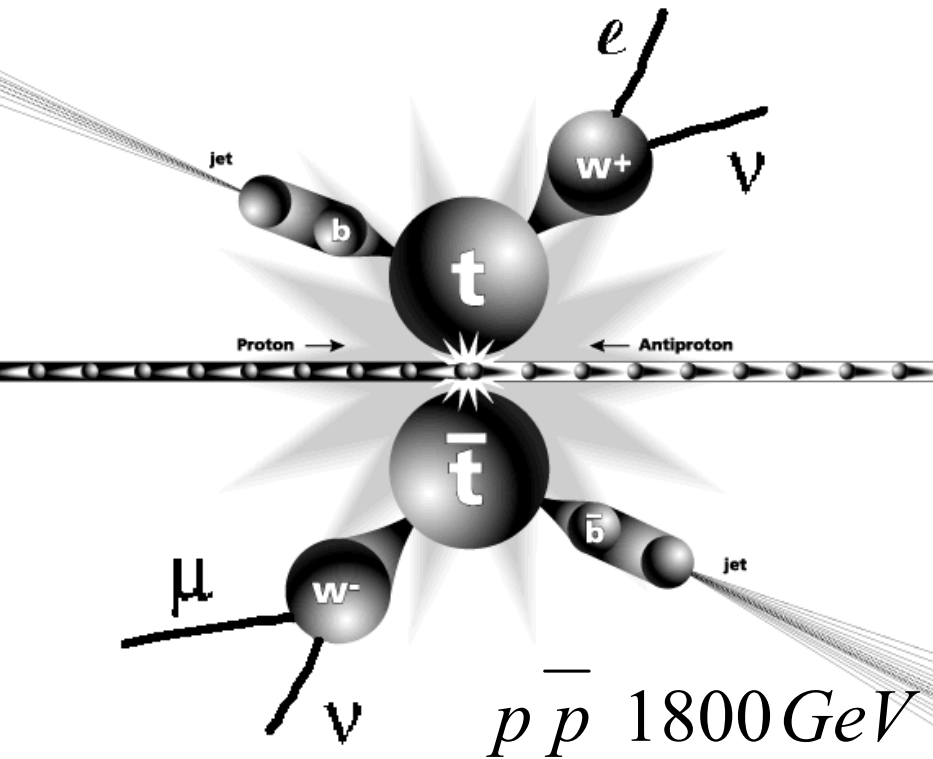


bound states

$q\bar{q}$ qqq $qqqqqqq$...

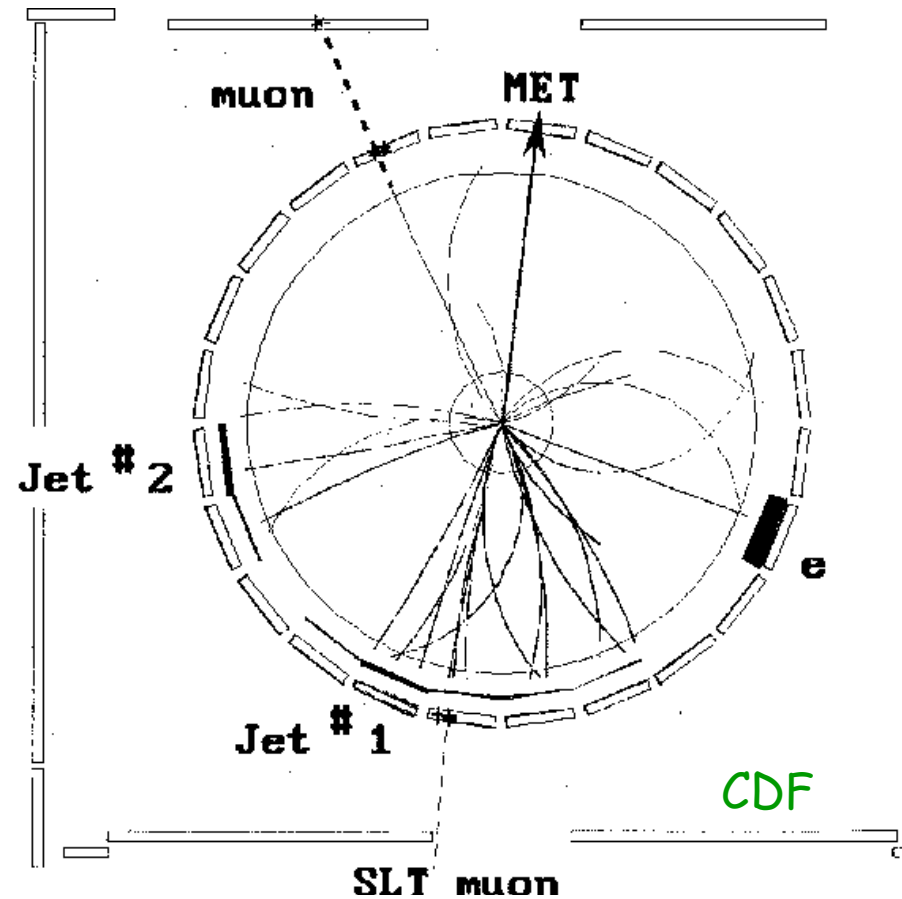
Top Discovery

Fermilab, 1995



$m \sim 175\text{ GeV}$

CDF, D0

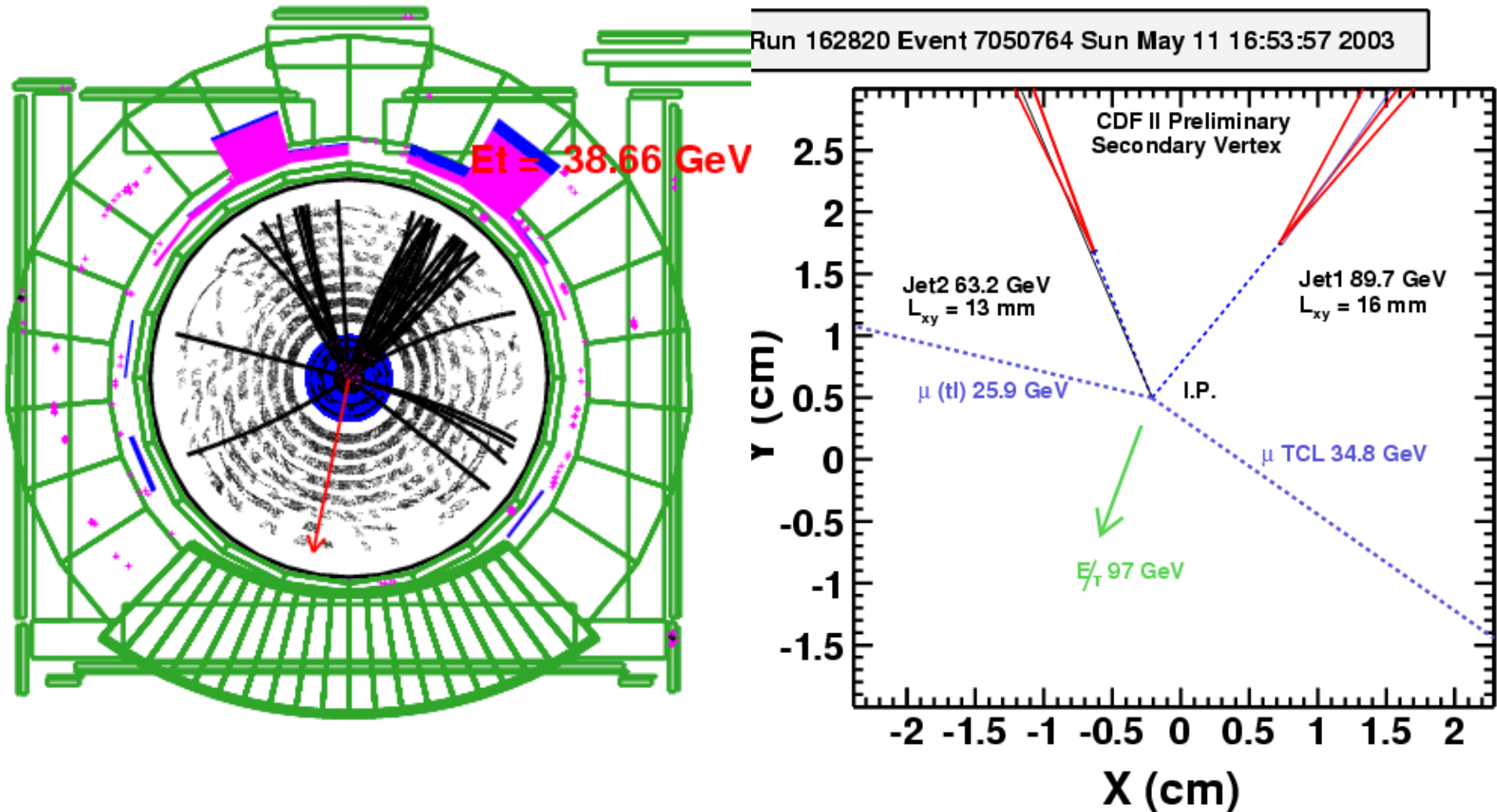


CDF

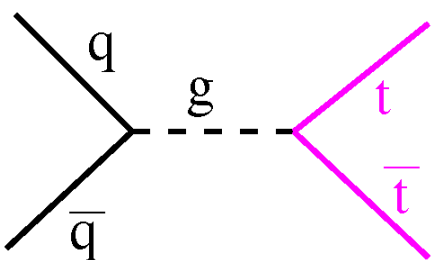
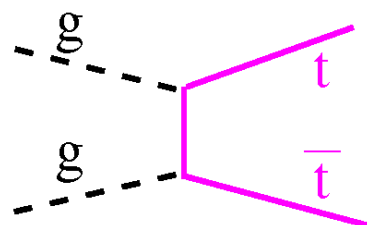
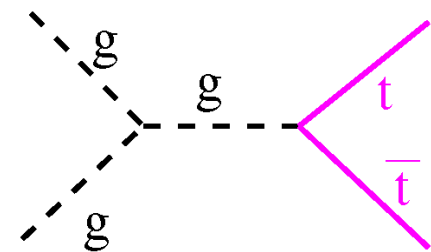
Top event in CDF

Run II

(~ 100 events)



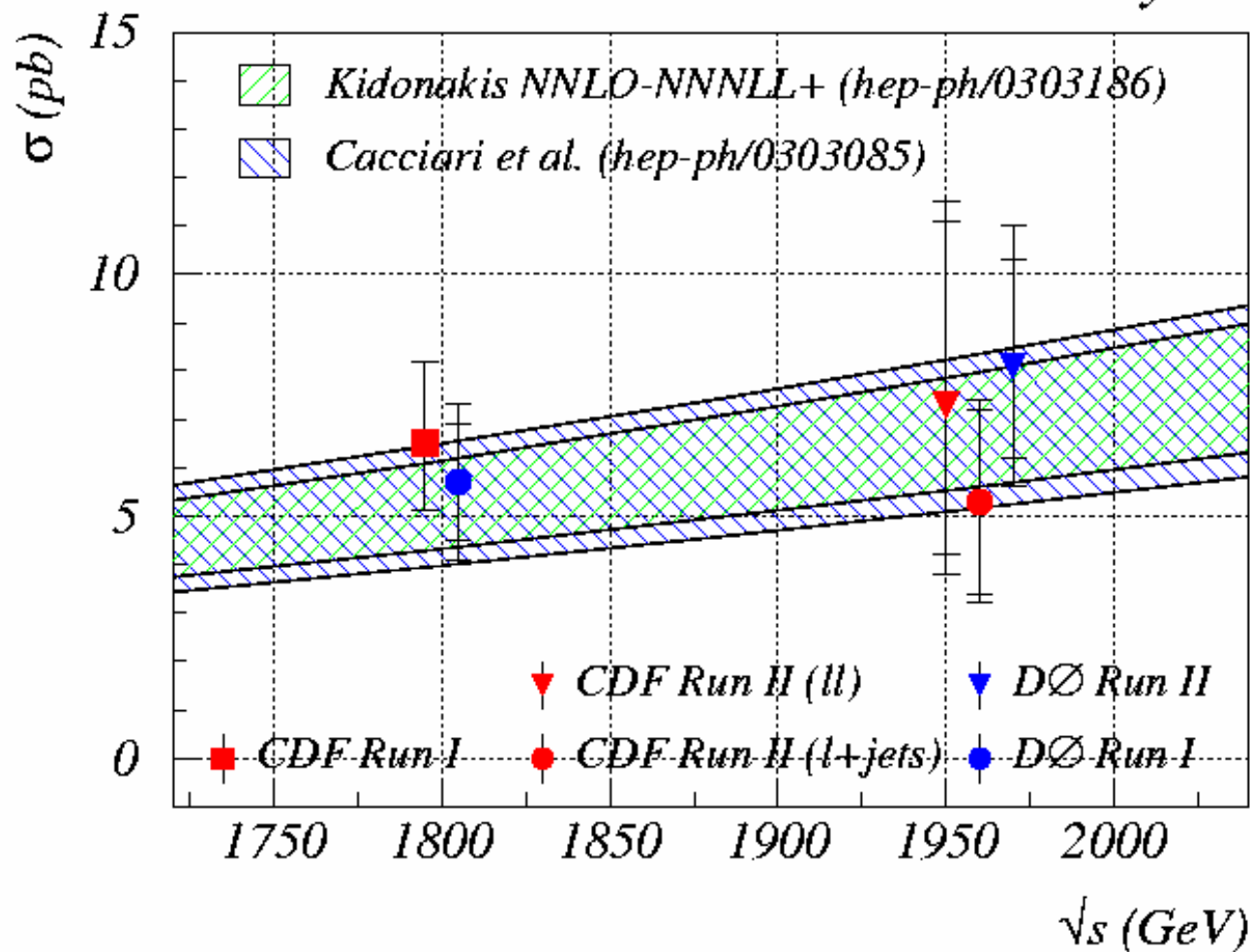
Top Pair Production



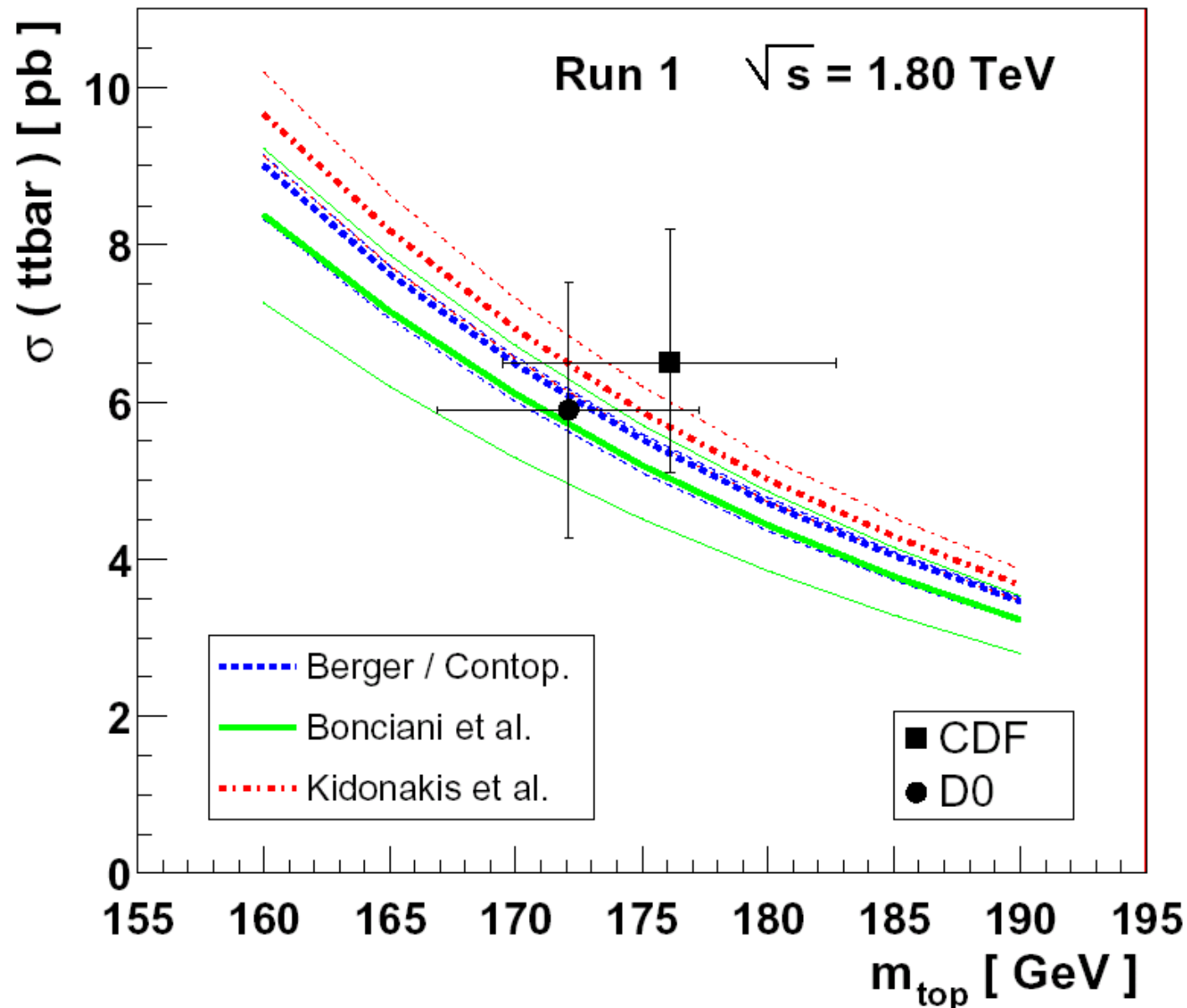
gg contributes

- 15% at 2 TeV
- 95% at 14 TeV

CDF and DØ Run II Preliminary



Top Cross Section and Top Mass



cross section measurement = indirect mass determination!

Rapidity distribution

Distribution of hadrons dN / dy (form invariant!) in (soft) p p collisions ?

In center of mass system of hard collision ($2 \rightarrow 2$):

$$y = \ln \frac{E + p_L}{\sqrt{p_T^2 + m^2}} \leq \ln \frac{2E}{m} = \ln \frac{\sqrt{s'}}{m}$$

m = particle mass

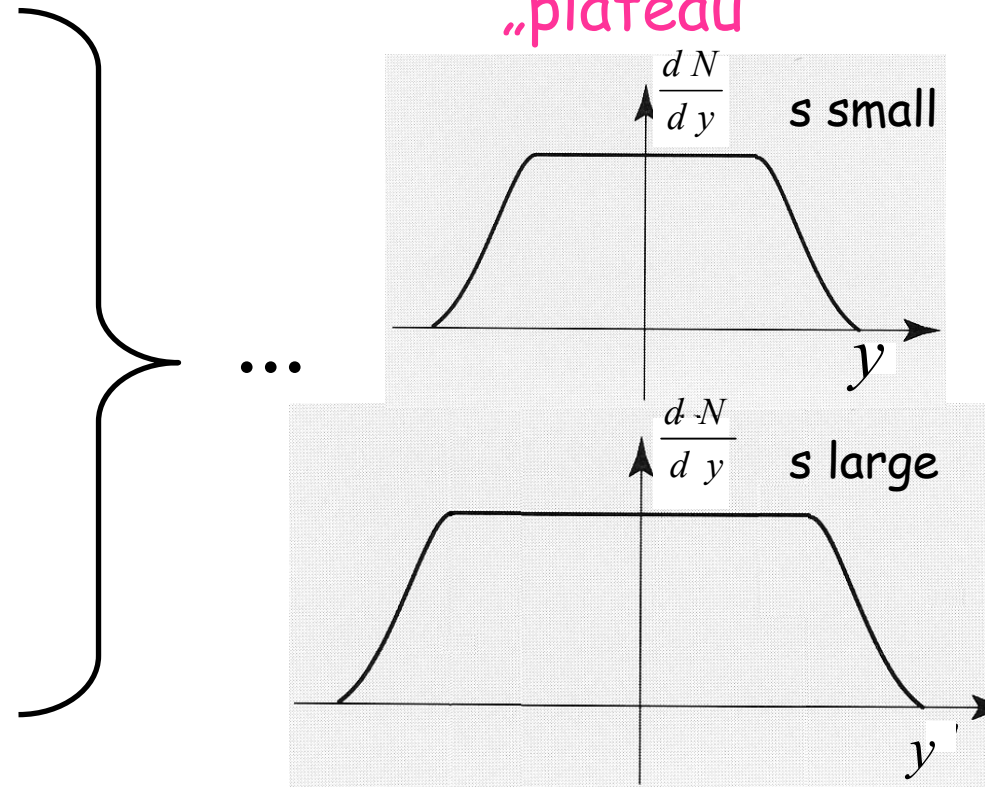
Rapidity range:

$$-\ln \frac{\sqrt{s'}}{m} \leq y \leq \ln \frac{\sqrt{s'}}{m}$$

Empirical in pp collisions:

$$N_{tot} \sim \ln \sqrt{s}$$

$$\frac{dN}{dy} \sim \text{const}$$



QCD and hadron colliders ???

From spaan@physik.uni-dortmund.de **Mon Jul 25 15:23:00 2005**
Date: Fri, 08 Jul 2005 15:57:56 +0200
From: Bernhard Spaan <spaan@physik.uni-dortmund.de>
To: Thomas Hebbeker <hebbeker@physik.rwth-aachen.de>
Subject: Graduiertenkolleg in Dortmund -Tagung im Oktober

Lieber Thomas,

im Oktober (11.-13.) 2005 findet unsere jährliche GK-Tagung hier in Dortmund statt. Thema der Tagung ist "harte Prozesse". Dabei sollte auch die QCD am Tevatron und der Ausblick auf LHC nicht fehlen. Wir planen auf eine 90-minütige lecture. ...

Beste Grüße

Bernhard