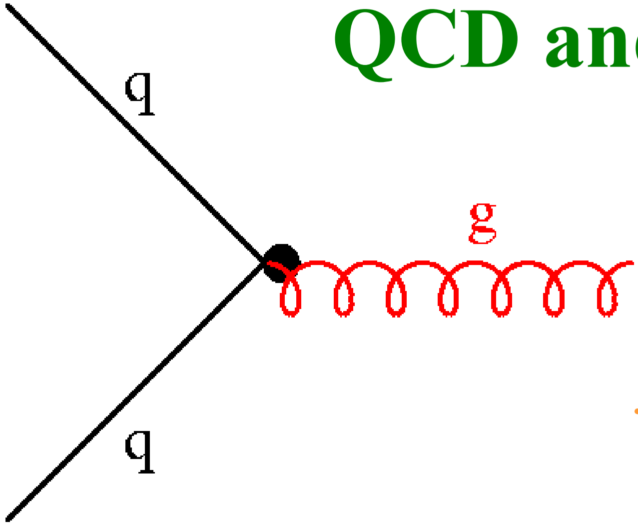
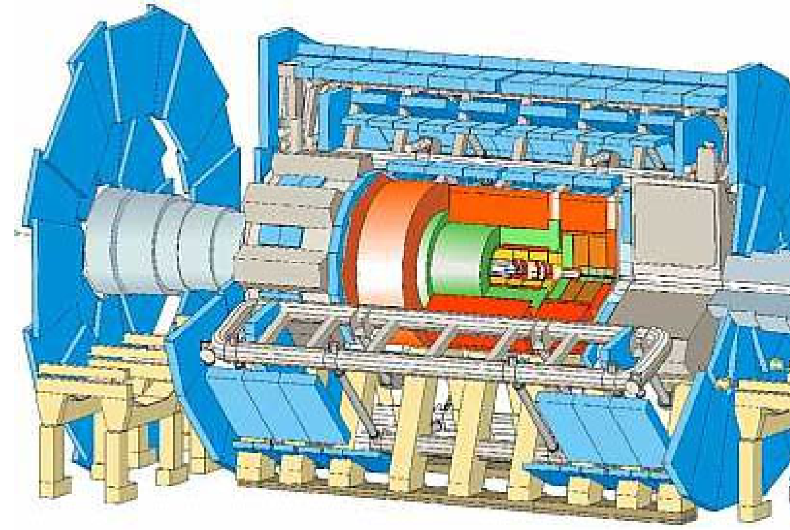
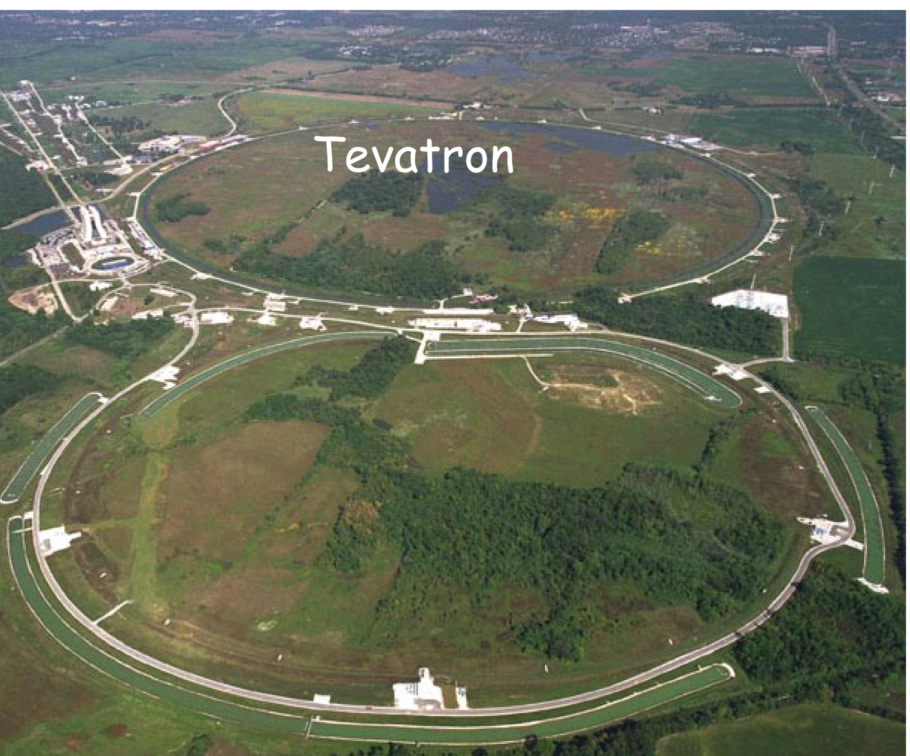
QCD and Hadron Colliders

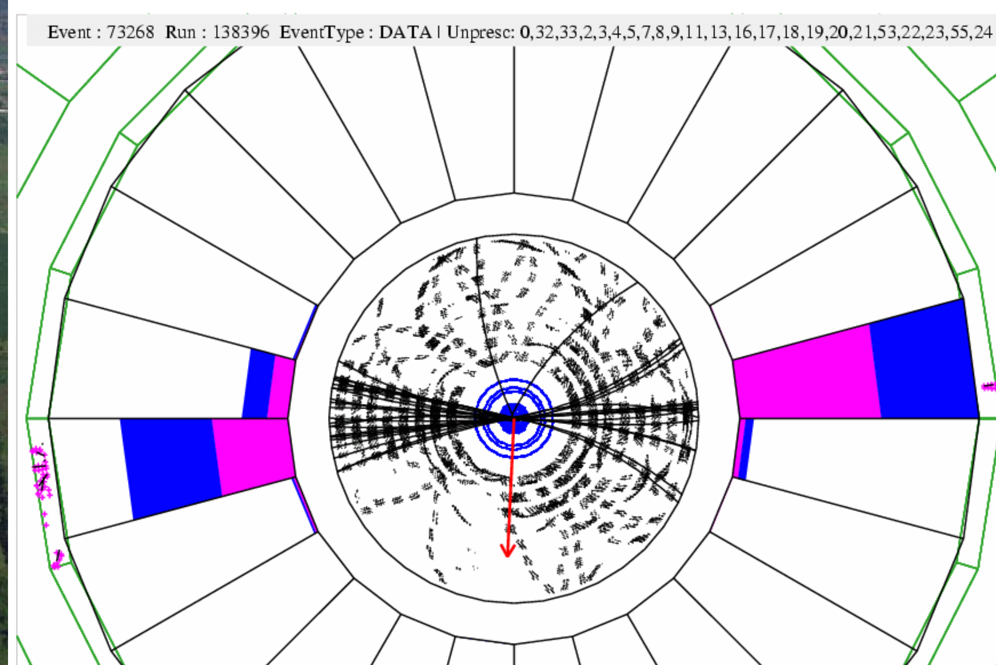


Thomas Hebbeker
RWTH Aachen
Dortmund, Oct. 2005

ATLAS







CDF

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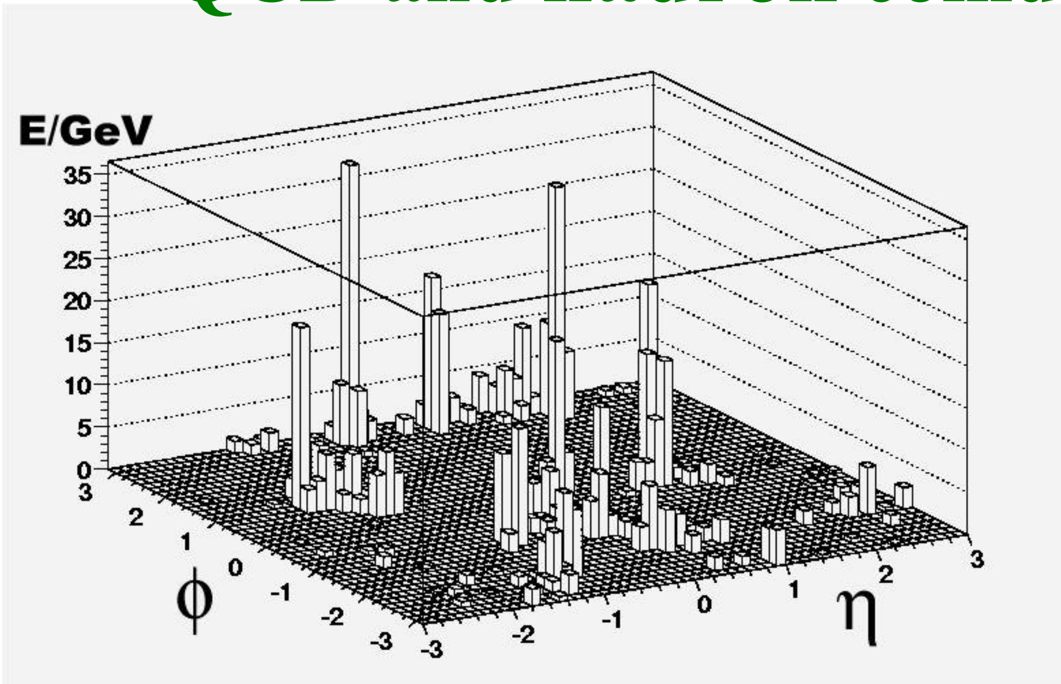
QCD and hadron colliders ???



QCD precision tests ?

well...

huge background !

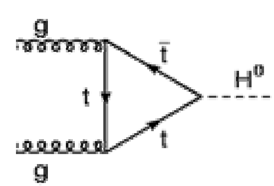
yes !

QCD

- test QCD

SM & NP

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

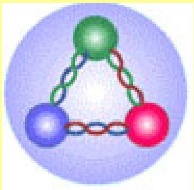


$$\ldots\, t \rightarrow b\, W$$

$$g g \rightarrow H$$

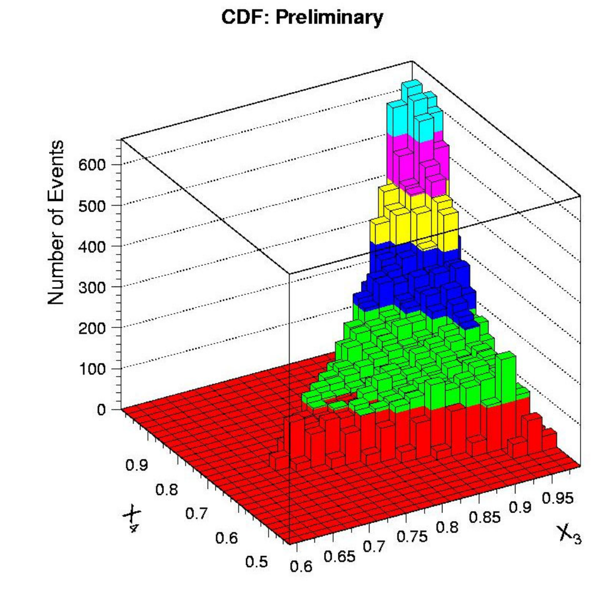
$$q\, \bar{q} \rightarrow W\, g$$

1) Introduction

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

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

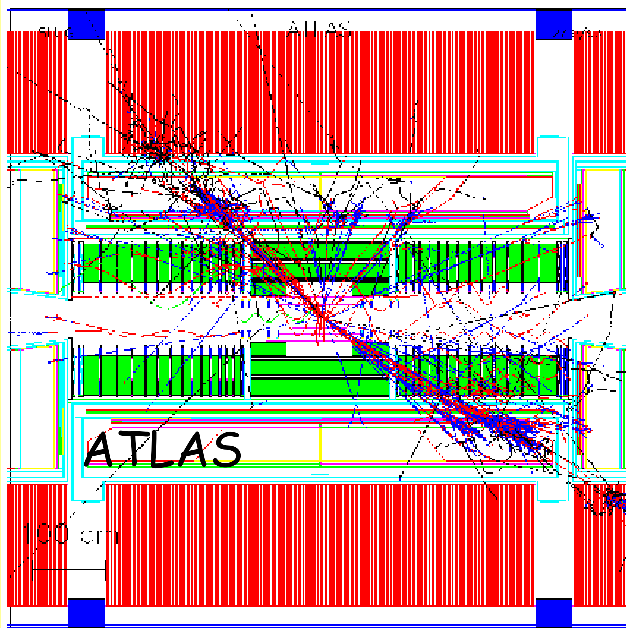
2 TeV



3) LHC

$p+p$

14 TeV



t

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QCD = SU(3) gauge theory

coupling constant (only free parameter)

spin ½ quarks

spin 1 gluons

$$\mathcal{L} = \bar{q}\,[i\,\gamma^{\mu}\,\partial_{\mu} - m\,]\,q \;+\; i\,g_s\,\bar{q}\,q\,g \;-\; \frac{1}{4}F\,F$$

free quarks — quark-gluon-int. — gluons

QCD = SU(3) [nonabelian] gauge theory

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SU(3)

$$\mathcal{L} = \bar{q}_{\alpha}^{a,j} [i\,\gamma^{\mu}_{\alpha\beta} (\delta_{ab}\,\partial_{\mu} + i\,g_{s}\,t^{r}_{ab}\,g^{r}_{\mu}) - m_j\,\delta_{ab}\,\delta_{\alpha\beta}]\, q_{\beta}^{b,j} - \frac{1}{4} F^{r}_{\mu\nu}\,F^{r,\mu\nu}$$

spin ½ quarks

spin 1 gluons

$$\begin{array}{llll} \alpha, \beta, \ldots = & 1,2,3,4 & \text{Dirac index} \\ \mu, \nu, \ldots = & 1,2,3,4 & \text{space time index} \\ a, b, \ldots = & 1, \ldots, N_{\mathrm{C}} = 3 & \text{quark color index} \\ r, s, \ldots = & 1, \ldots, N_{\mathrm{C}}^2 - 1 = 8 = N_A & \text{gluon color index} \\ j, k, \ldots = & 1, \ldots, N_{\mathrm{F}} & \text{flavor index .} \end{array}$$

SU(3) (quark and gluon color index)

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

coupling constant (only free parameter)

$$F^{r}_{\mu\nu} = \partial_{\mu} g^{r}_{\nu} - \partial_{\nu} g^{r}_{\mu} - g_{s}\, f^{rst}\, g^{s}_{\mu}\, g^{t}_{\nu} .$$

SU(3)

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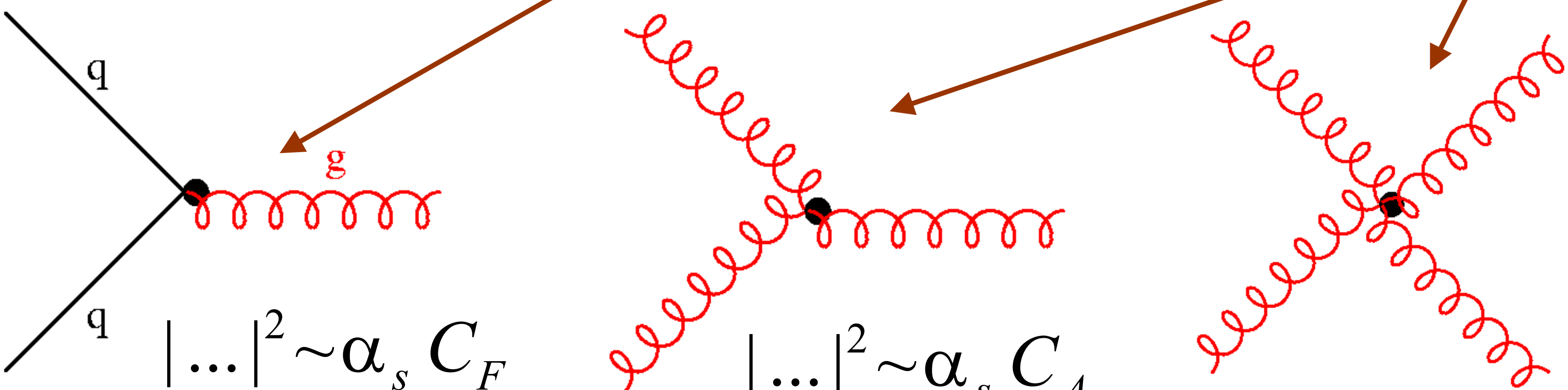
QCD – basic Feynman diagrams

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



$|\ldots|^2 \sim \alpha_s\, C_F$

$|\ldots|^2 \sim \alpha_s\, C_A$

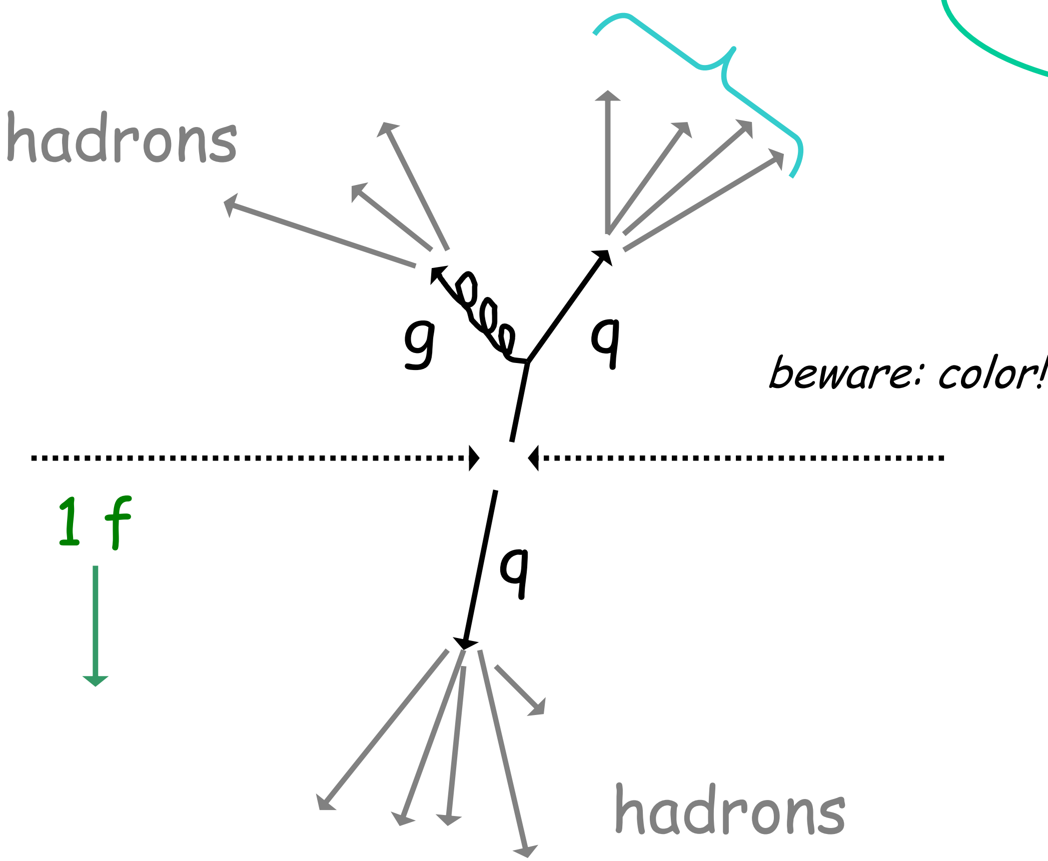
$|\ldots|^2 \sim \alpha_s^2\, C_A^2$

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

$$F^{r}_{\mu\nu} = \partial_{\mu} g^{r}_{\nu} - \partial_{\nu} g^{r}_{\mu} - g_s\, f^{rst}\, g^{s}_{\mu}\, g^{t}_{\nu}.$$

QCD tests in hard scattering ?

momentum
transfer:
many GeV



at high energies:

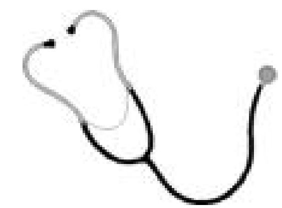
q and g = **jet**

Hadronization: non-perturbative

⇨ need models! Pythia Herwig ...

(include parton showers)

QCD tests ?



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

nonabelian

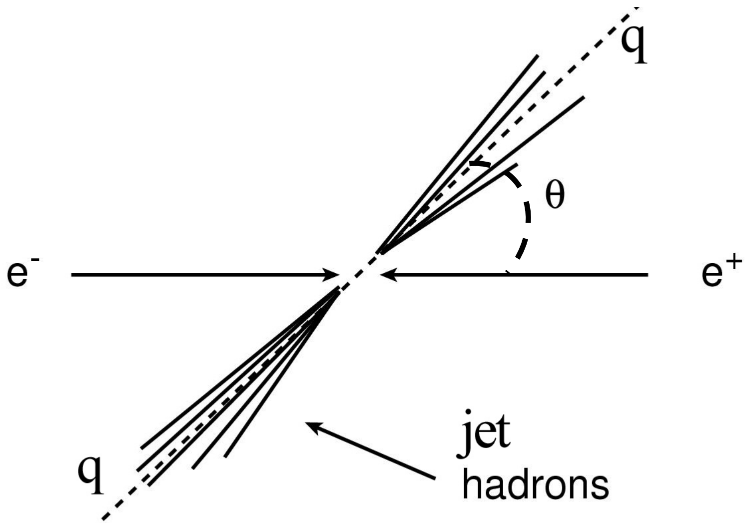
- gluon colors ? [8]
- triple gluon vertex ?
- four gluon vertex ?
- universality of α_s ?

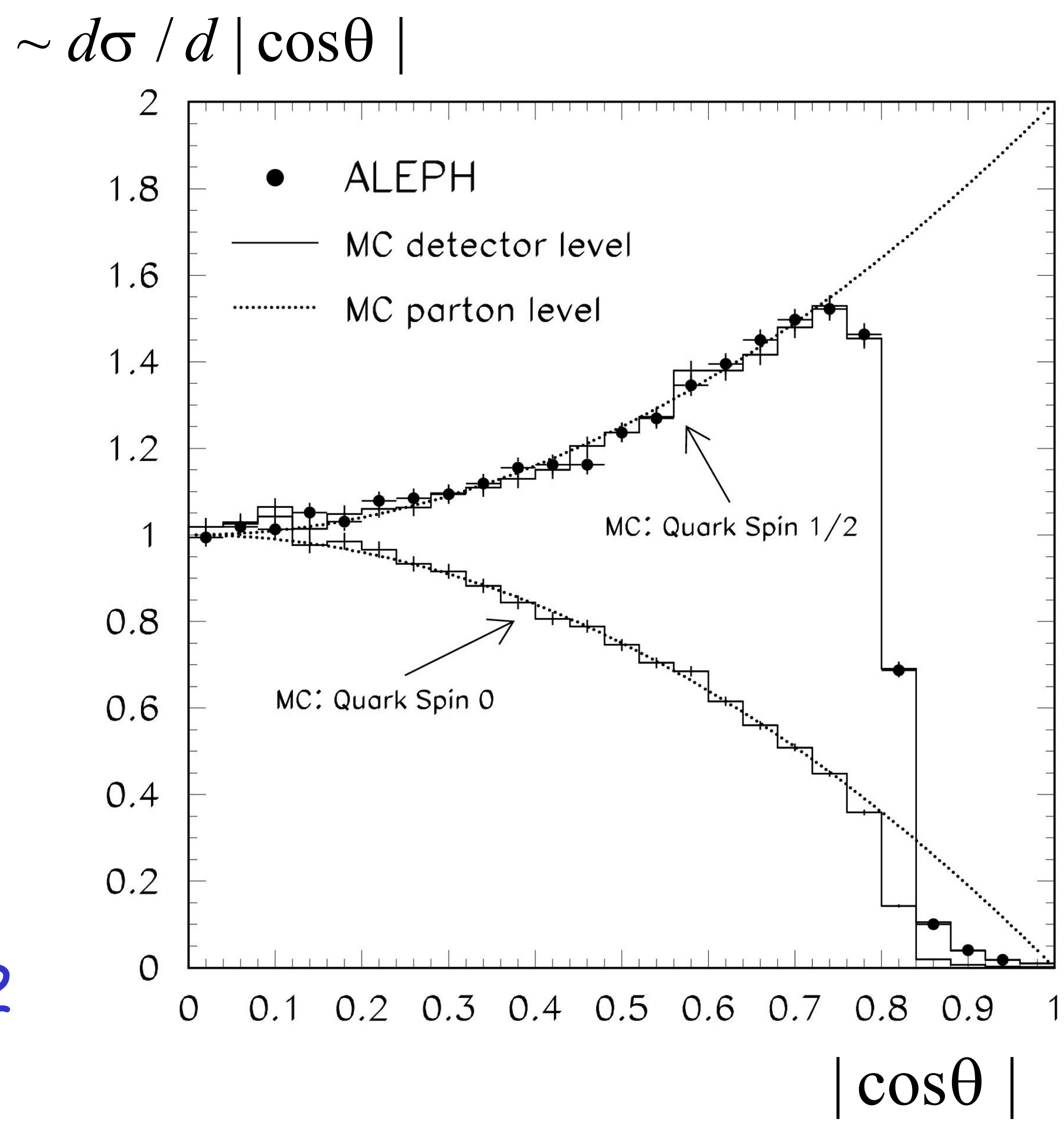
  qqg   ggg   gggg   ?

  flavor independence ?
- running of α_s ?

Test: Quark spin ?

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



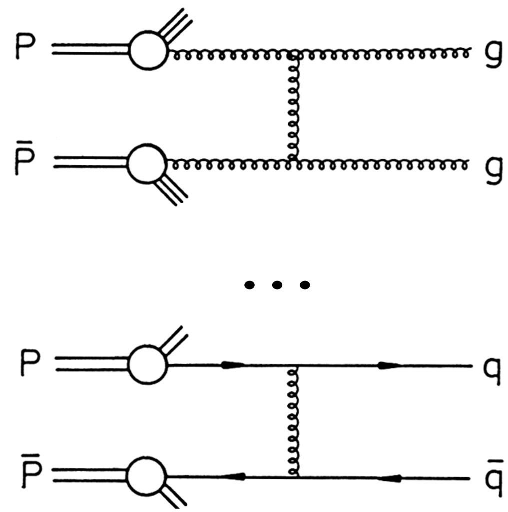


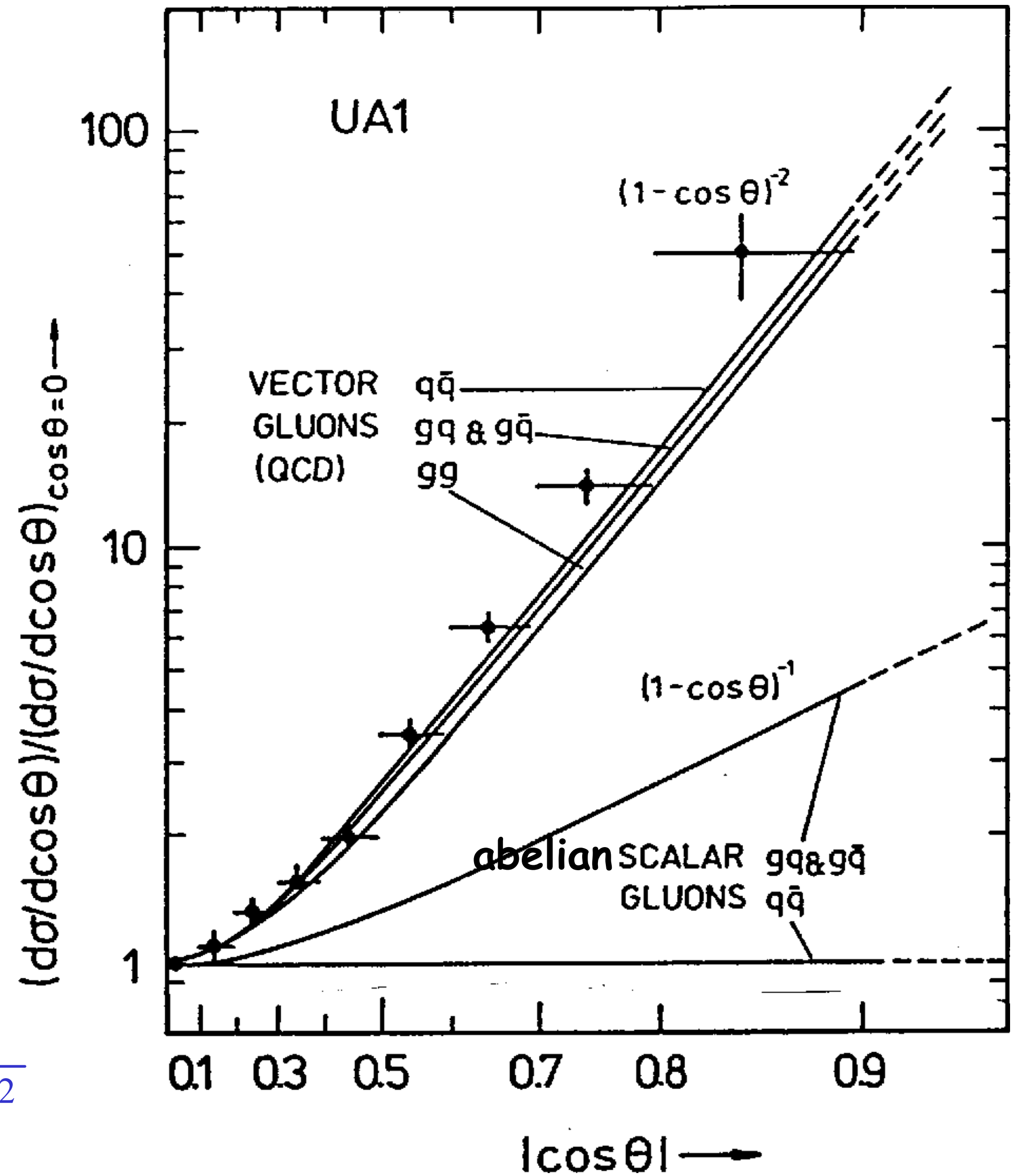
$$\frac{d\sigma}{d\cos\theta} \sim \begin{cases} 1+\cos^2\theta & 1/2 \\ 1-\cos^2\theta & 0 \end{cases}$$

quark spin = 1/2

Test: Gluon spin ?

$p\,\bar{p} \to jet\ jet$





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

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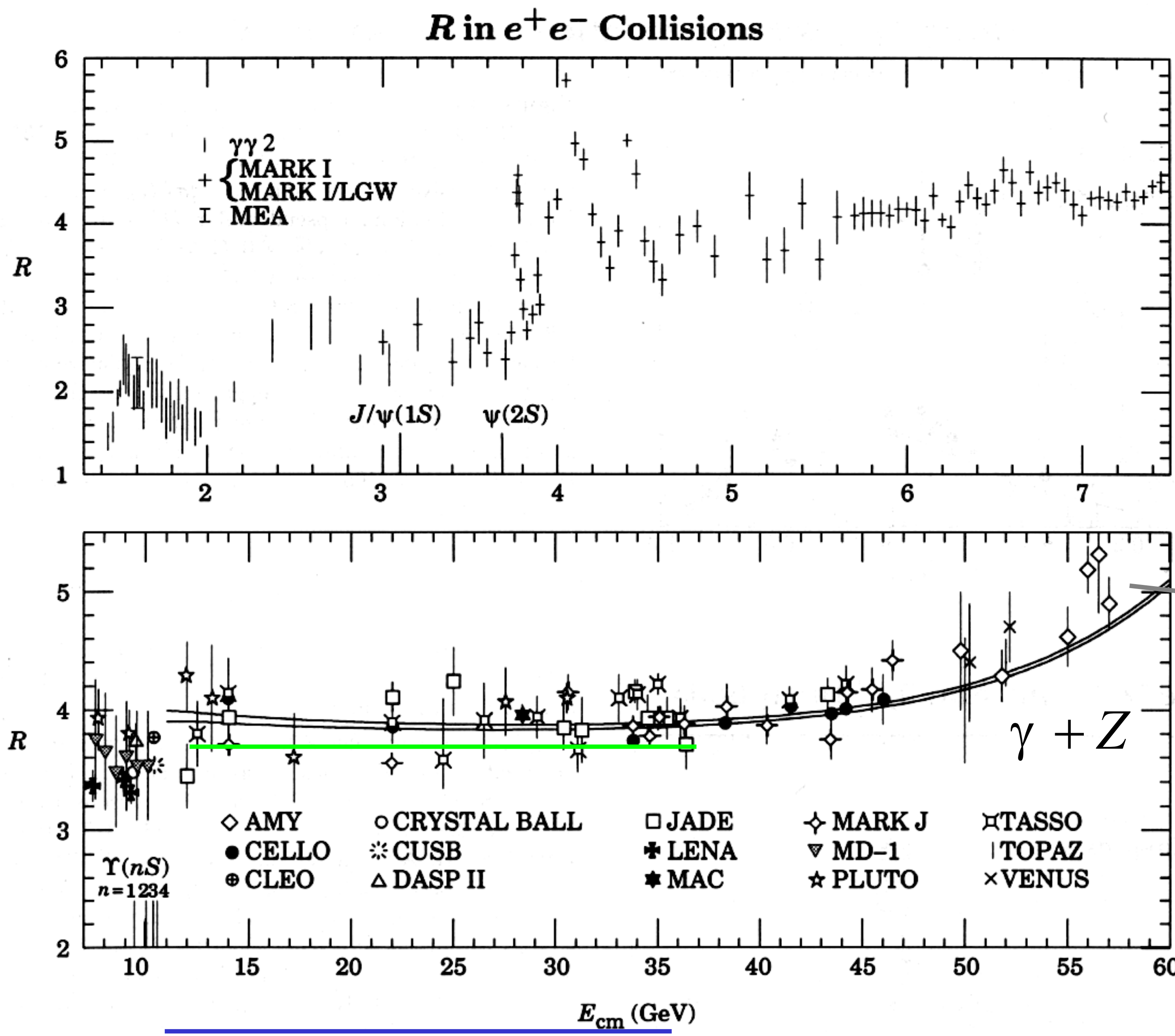
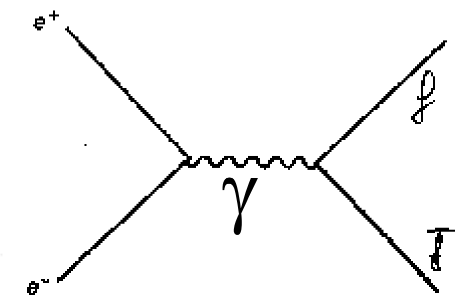
Test: # quark color degrees of freedom



$$R = \frac{\sigma(ee \to hadrons)}{\sigma(ee \to \mu\mu)} = N_C \cdot \sum Q_q^2$$



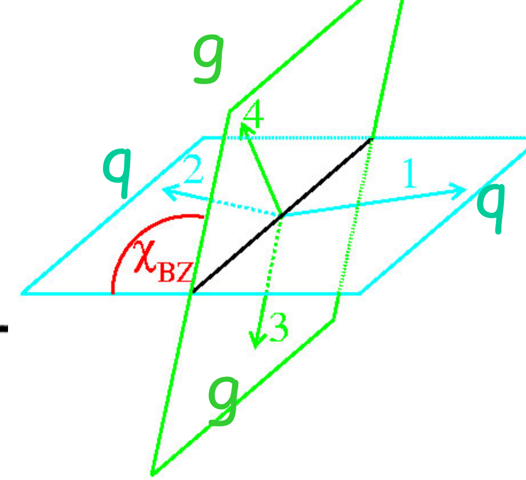
LEP, Z-Resonanz:

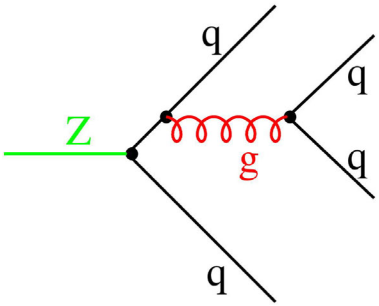
$$N_C = 3.00 \pm 0.01$$

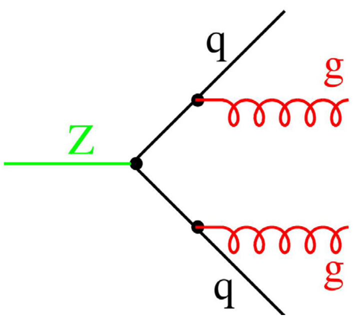
$$N_C = 3$$

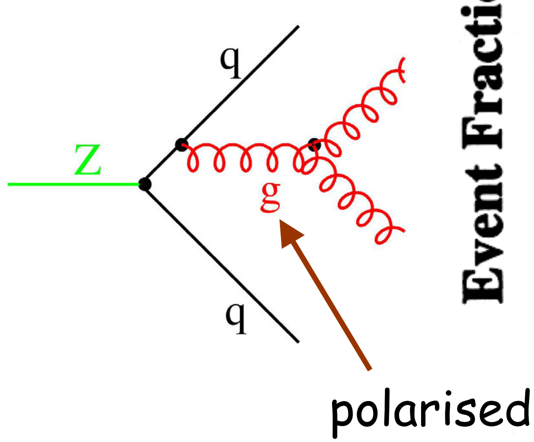
Test: Triple gluon vertex ?

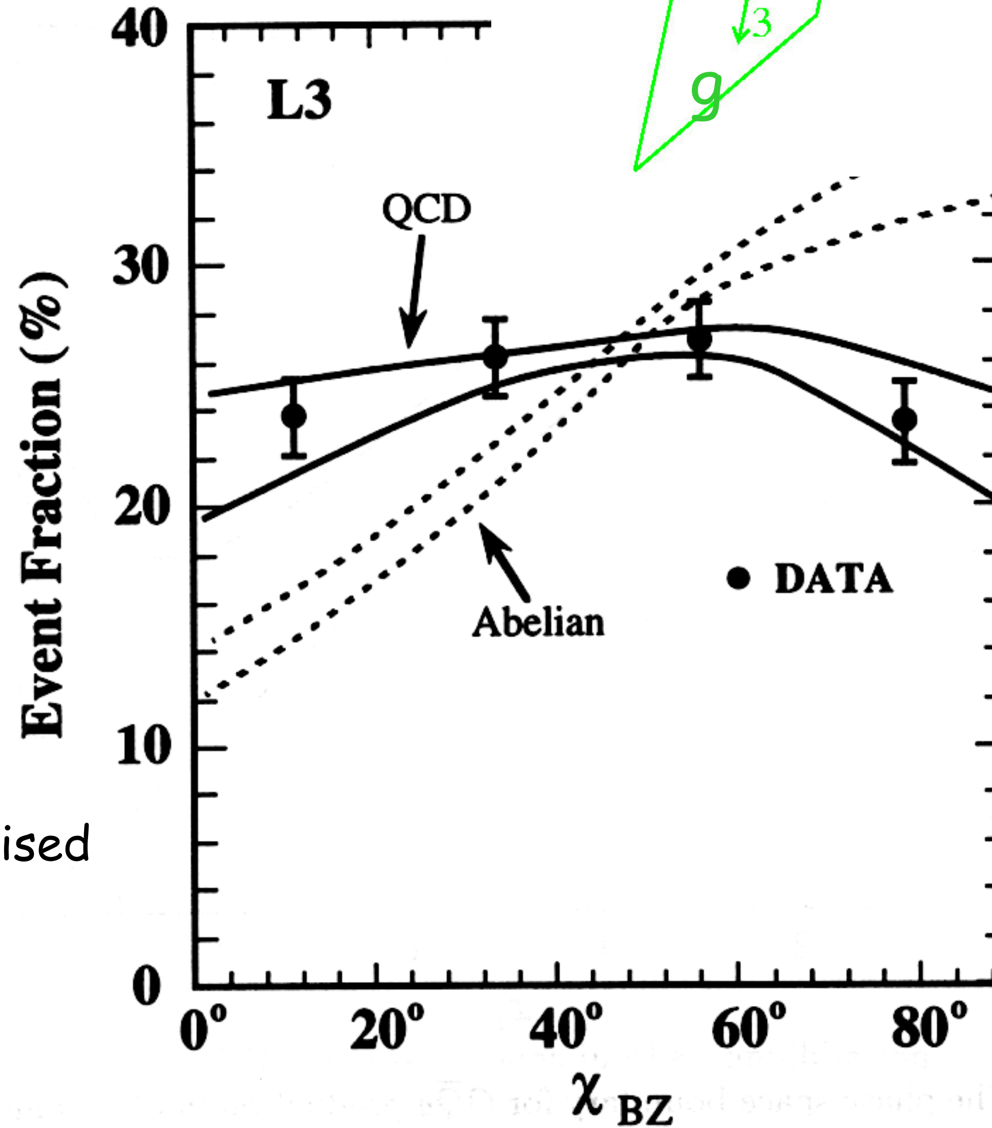
$$e^+e^- \rightarrow 4\,jets$$

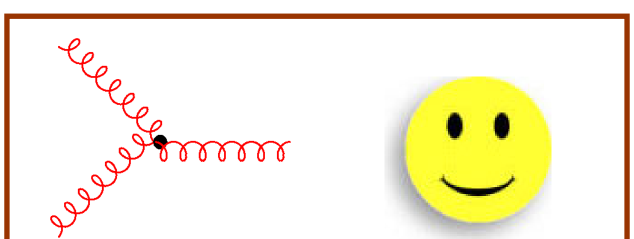












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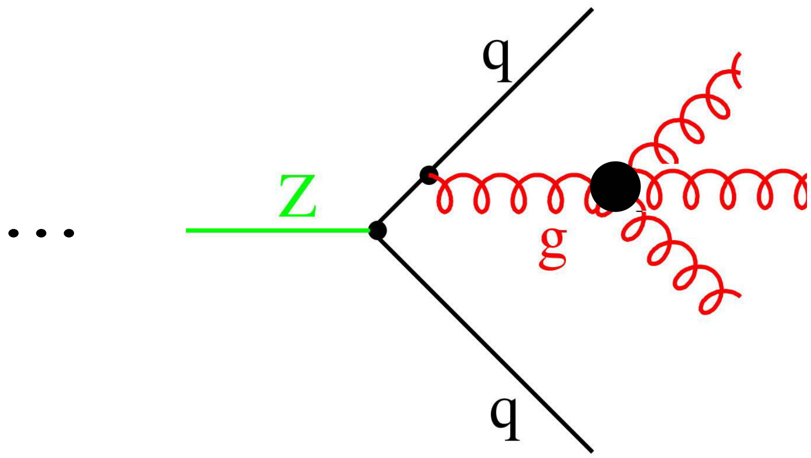
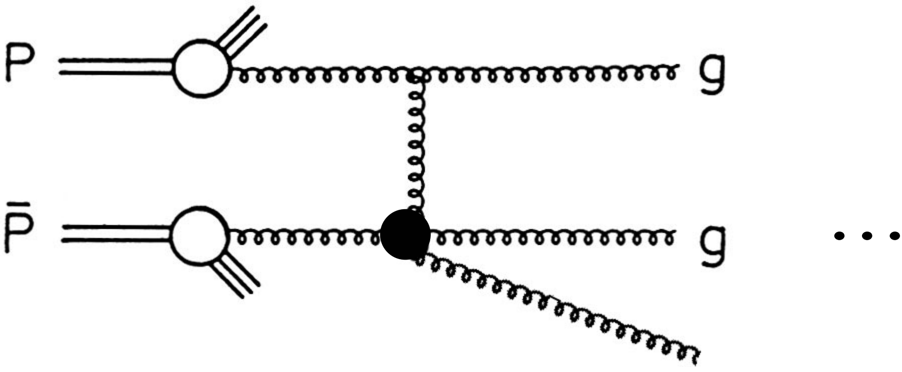
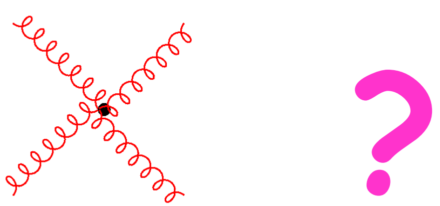
Test: Four gluon vertex ?







NO quantitative test yet !

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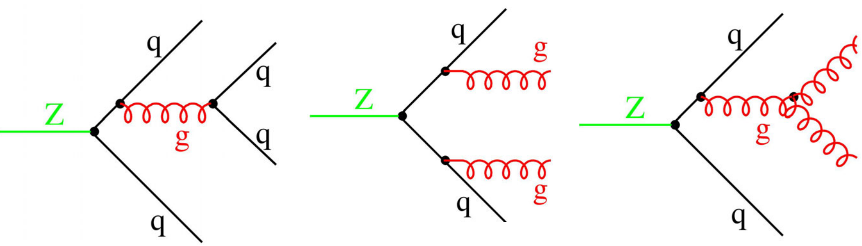
Test: # gluon color degrees of freedom

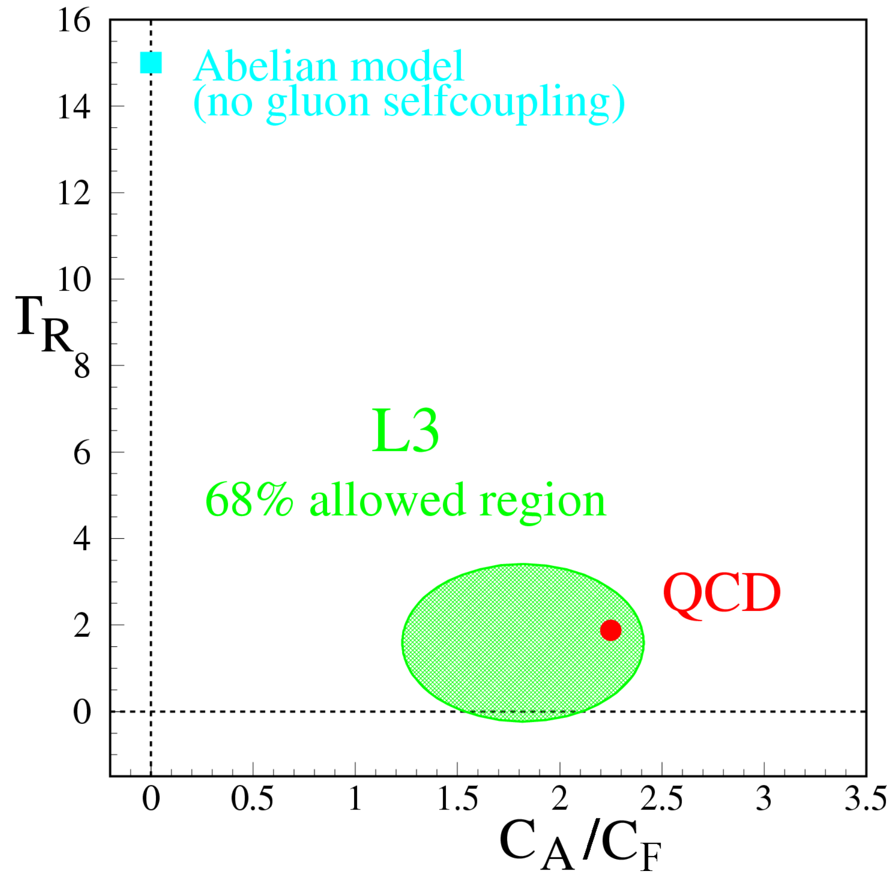
$e^+e^- \rightarrow 4\, jets$



quantitative analysis (LEP+SPS):

$$C_A / C_F = 2N_C^2 / N_A$$
$$= 2.21 \pm 0.19$$

Schmelling 1994



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

here: assume qqg and ggg couplings equal !

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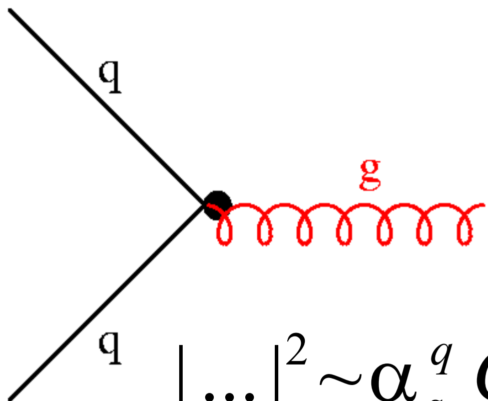
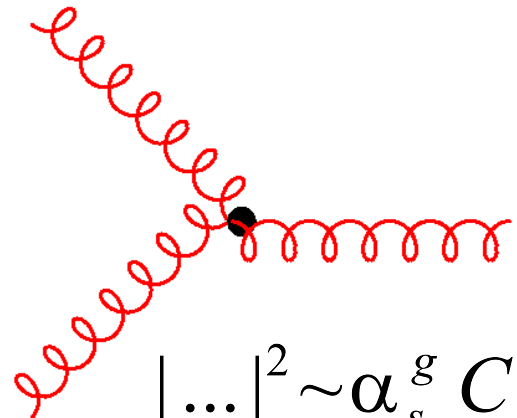
Test: Universality of strong coupling constant ?

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



$|\ldots|^2 \sim \alpha_s^q \, C_F$



$|\ldots|^2 \sim \alpha_s^g \, C_A$

quantitative analysis of $e^+e^- \to 4\,jets$ (see above):

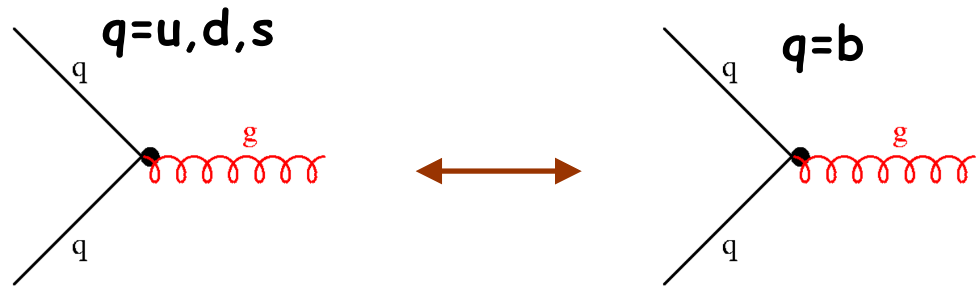
$$\alpha_s^q / \alpha_s^g = 1.02 \pm 0.09$$

here: assume C_F and C_A !

Test: Universality of strong coupling constant ?

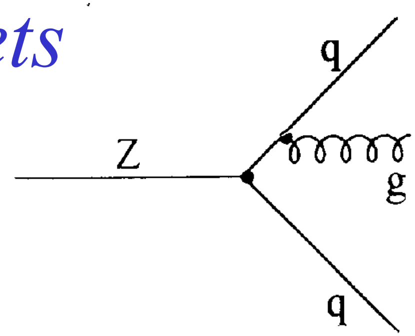
b) quark-quark-gluon quark flavor dependence ?

in particular:

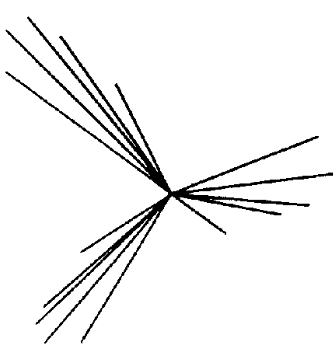


$e^+e^- \to Z \to 3\,jets$

$\sigma \sim \alpha_s$



+ . . .



b-tag:
semileptonic decay,
lifetime

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

Biebel 2001

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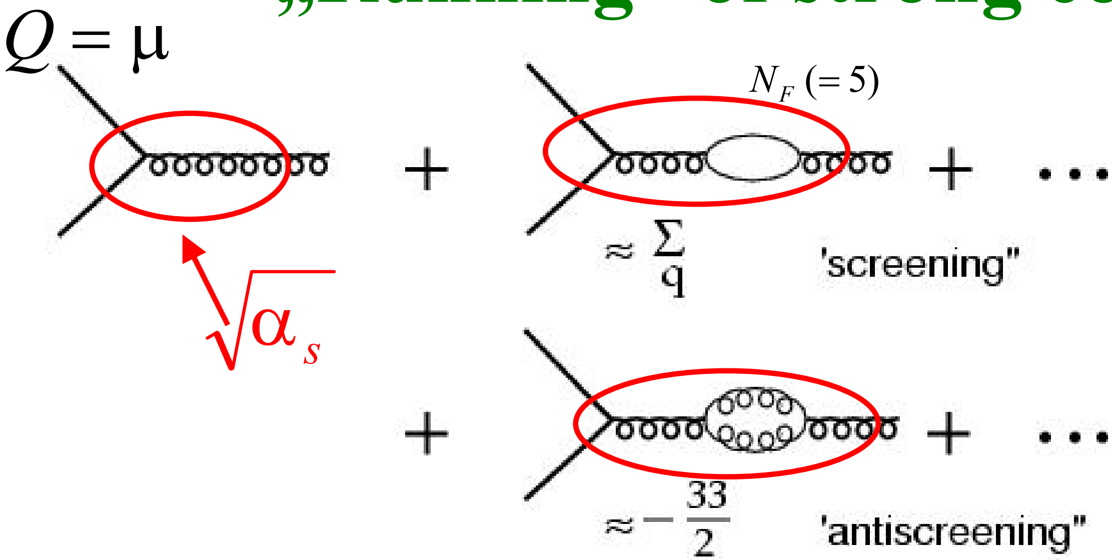
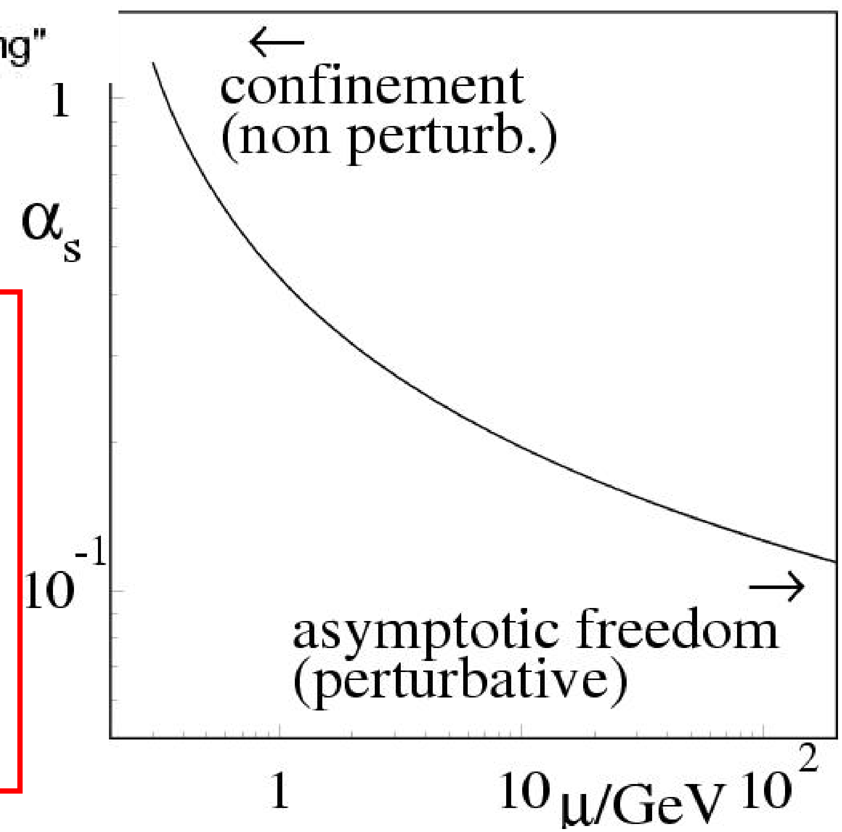
„Running“ of strong coupling constant



<u>lowest order:</u>

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

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



Test: „Running“ strong coupling constant ?

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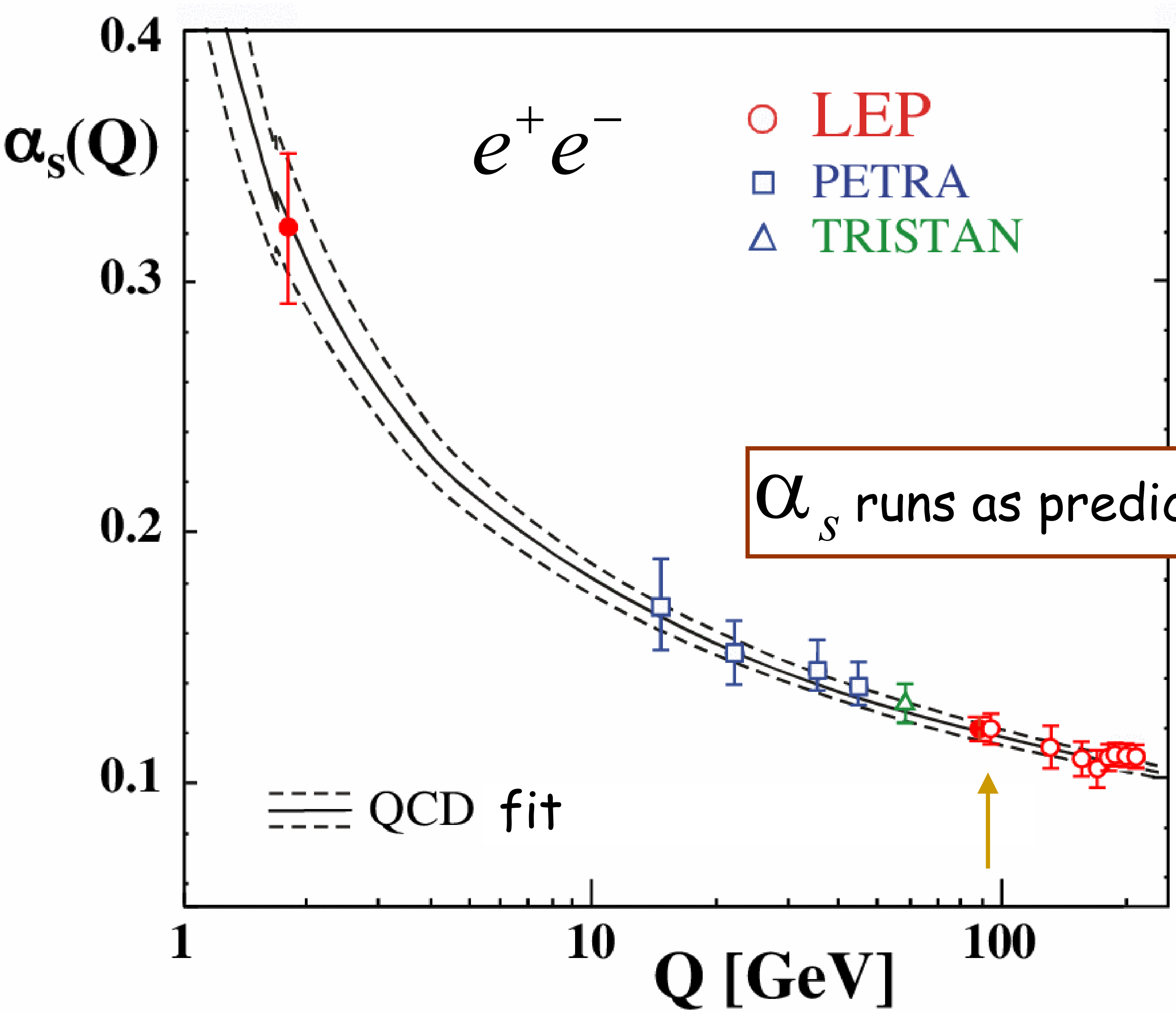

Bethke 2004

$\mu = Q$

α_s runs as predicted by QCD

Q = center of mass energy

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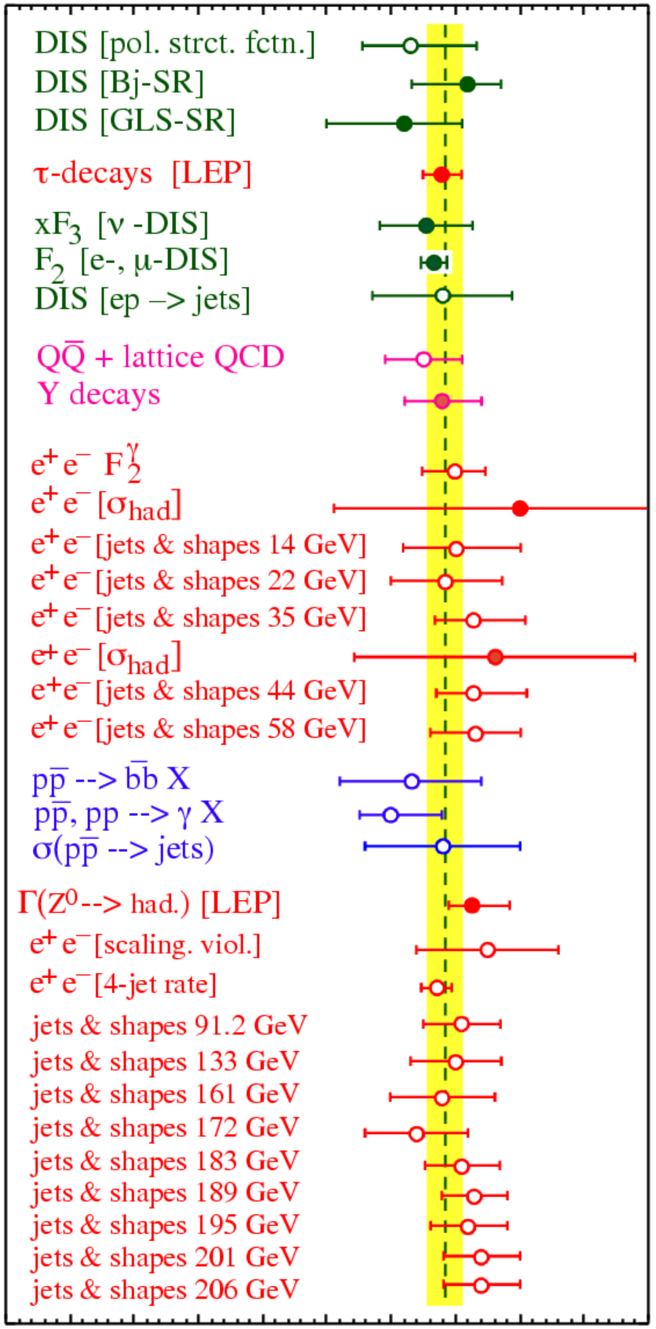
strong coupling constant α_s



Bethke 2004

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

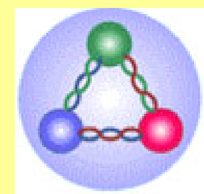
note: $g_s(m_Z) \approx 1.2$

1) Introduction

- QCD   theory   tests

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

- **Hadron**   (anti) protons



- **Colliders**   kinematics   background   jets   ...

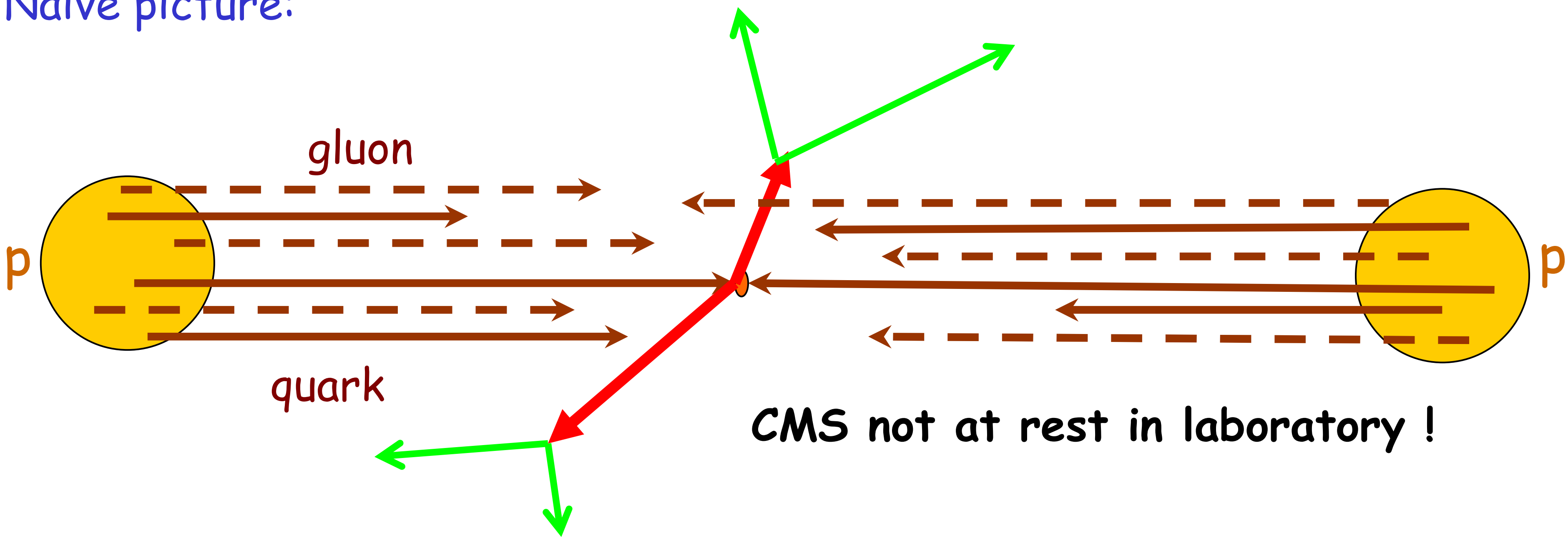
2) Tevatron

t

3) LHC

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

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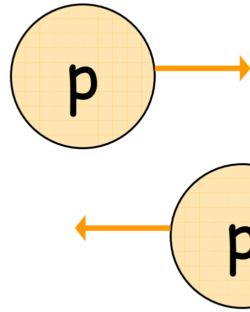
Cross Section (LHC)

Elastic cross section



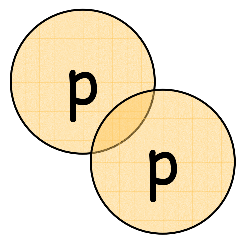
strong, electromagnetic

scattering angle tiny

Total inelastic cross section

BACKGROUND

„minimum bias"



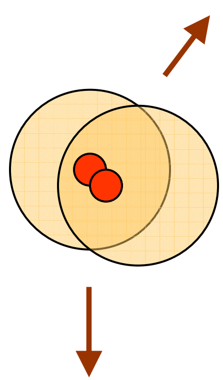
strong

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

forward scattering

Pointlike cross section

SIGNAL



high p_T

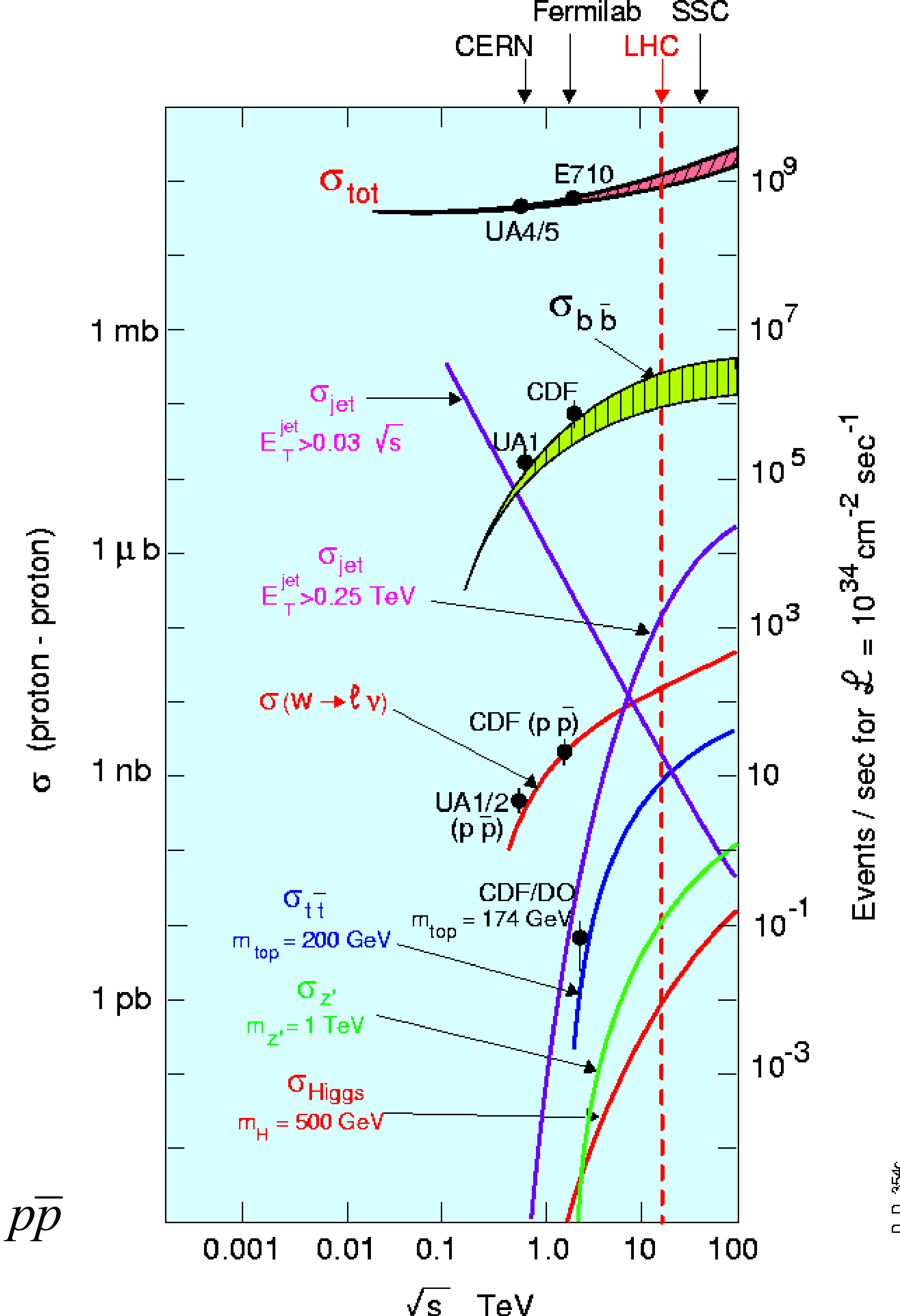
electroweak

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

strong

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

Cross Sections at Hadron Colliders



jet production

(LHC, full luminosity):

1000 events/s

p_T > 250 GeV

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

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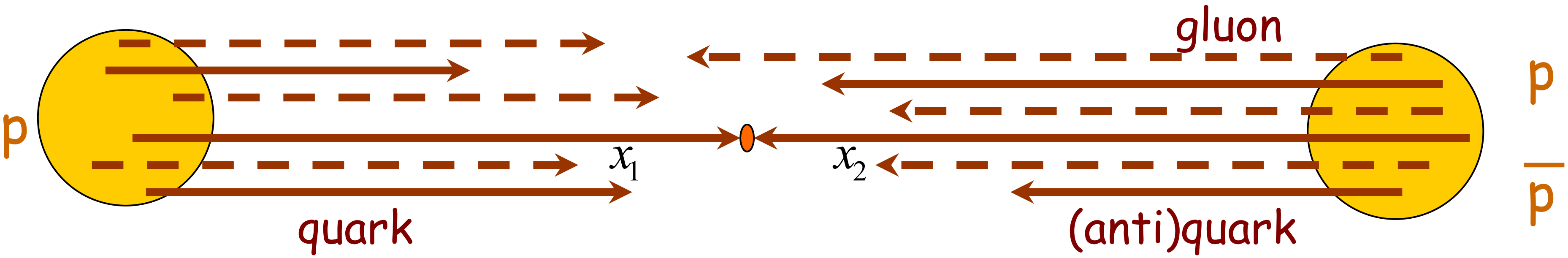
Proton or Antiproton ? Physics:

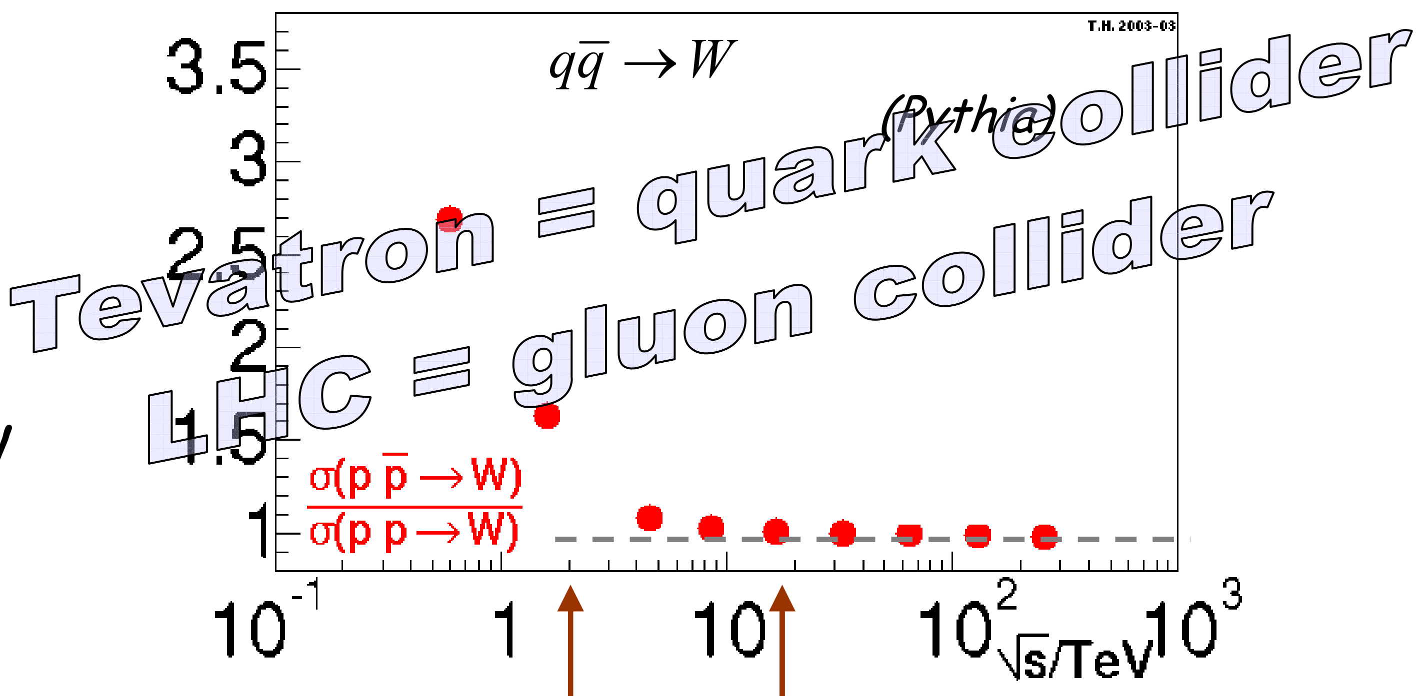


At low energy: valence quarks dominate hard scattering: $p\,p \neq p\,\bar{p}$

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

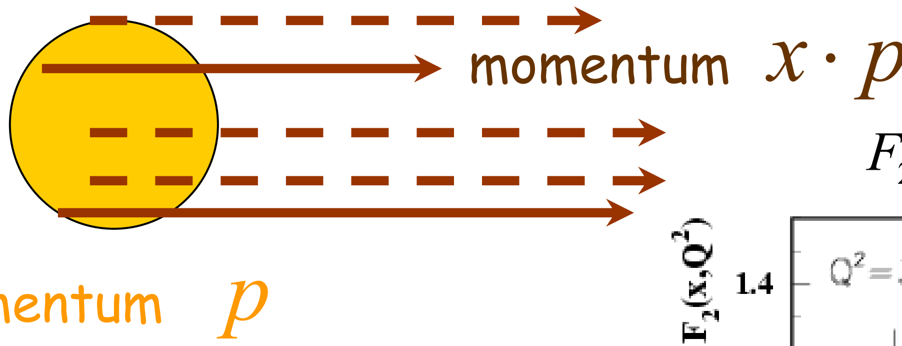
Example:

inclusive W production

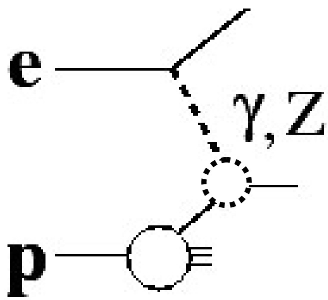


Parton density functions $f(x,Q^2)$

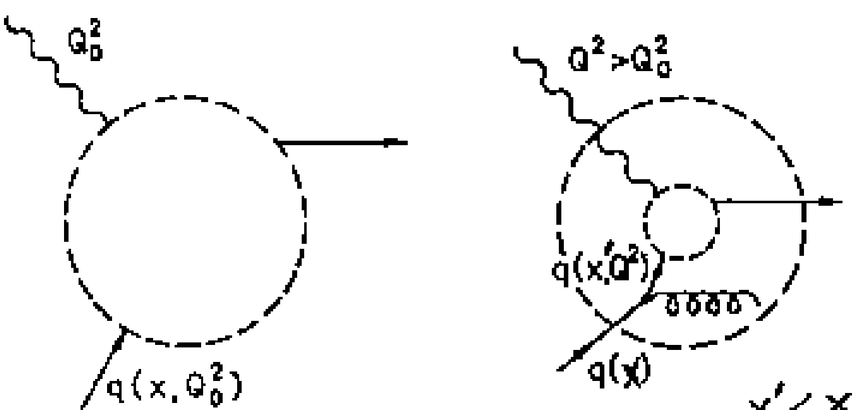
QCD x: ?
Q^2: yes

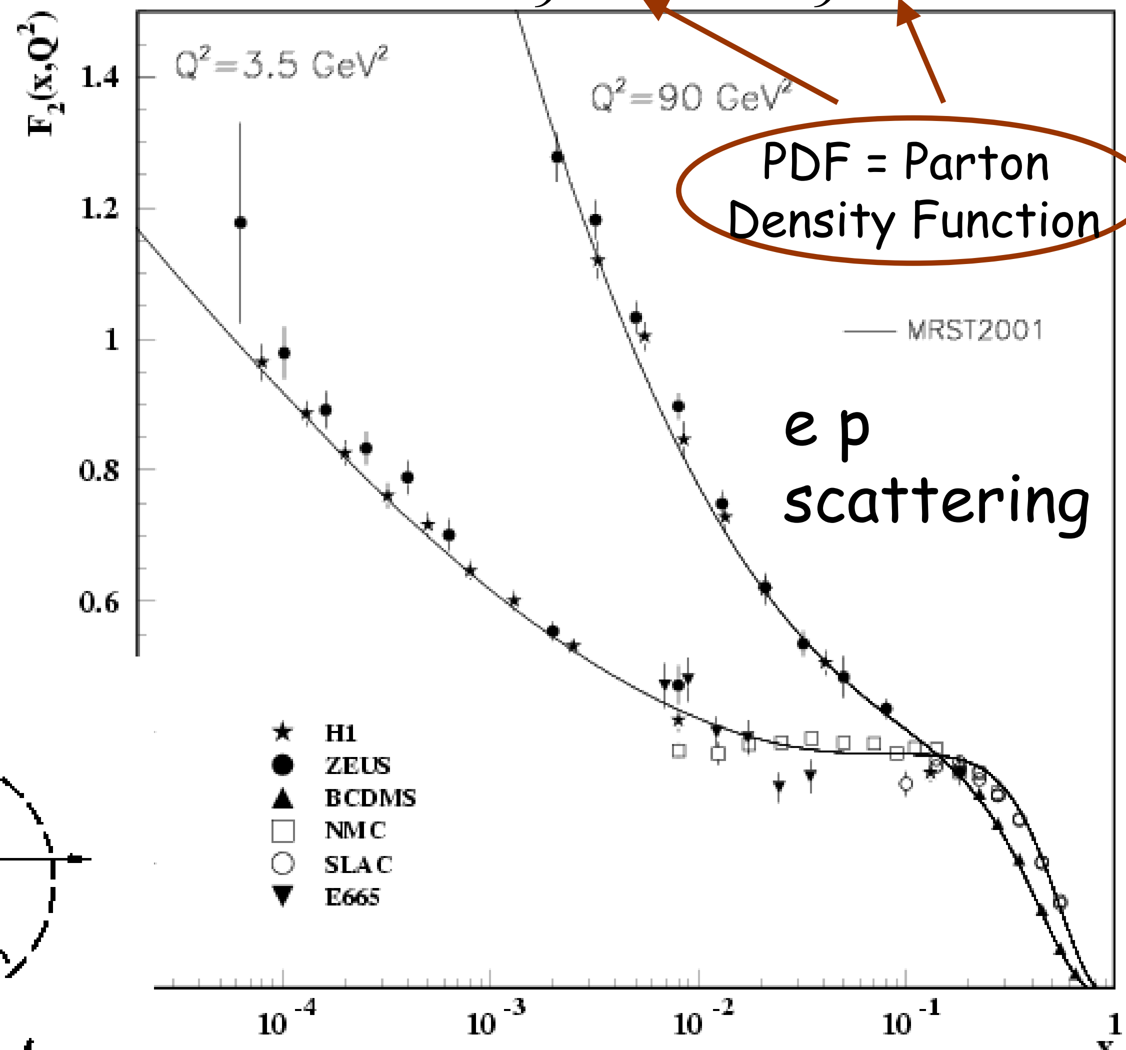


$$F_2(x,Q^2) = x\,[\frac{4}{9}u(x,Q^2) + \frac{1}{9}d(x,Q^2) + \ldots]$$



depends on resolution, given by Q^2:

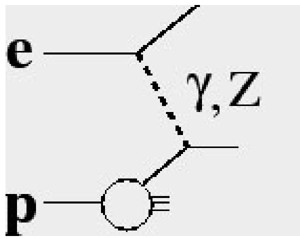


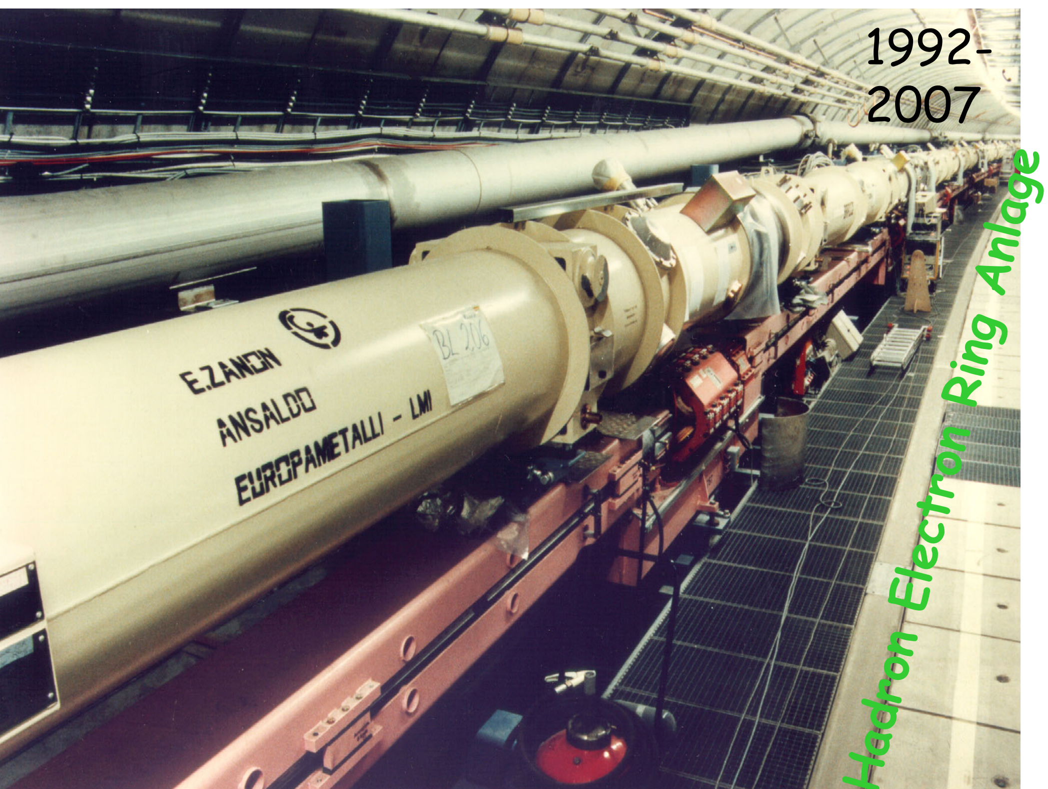


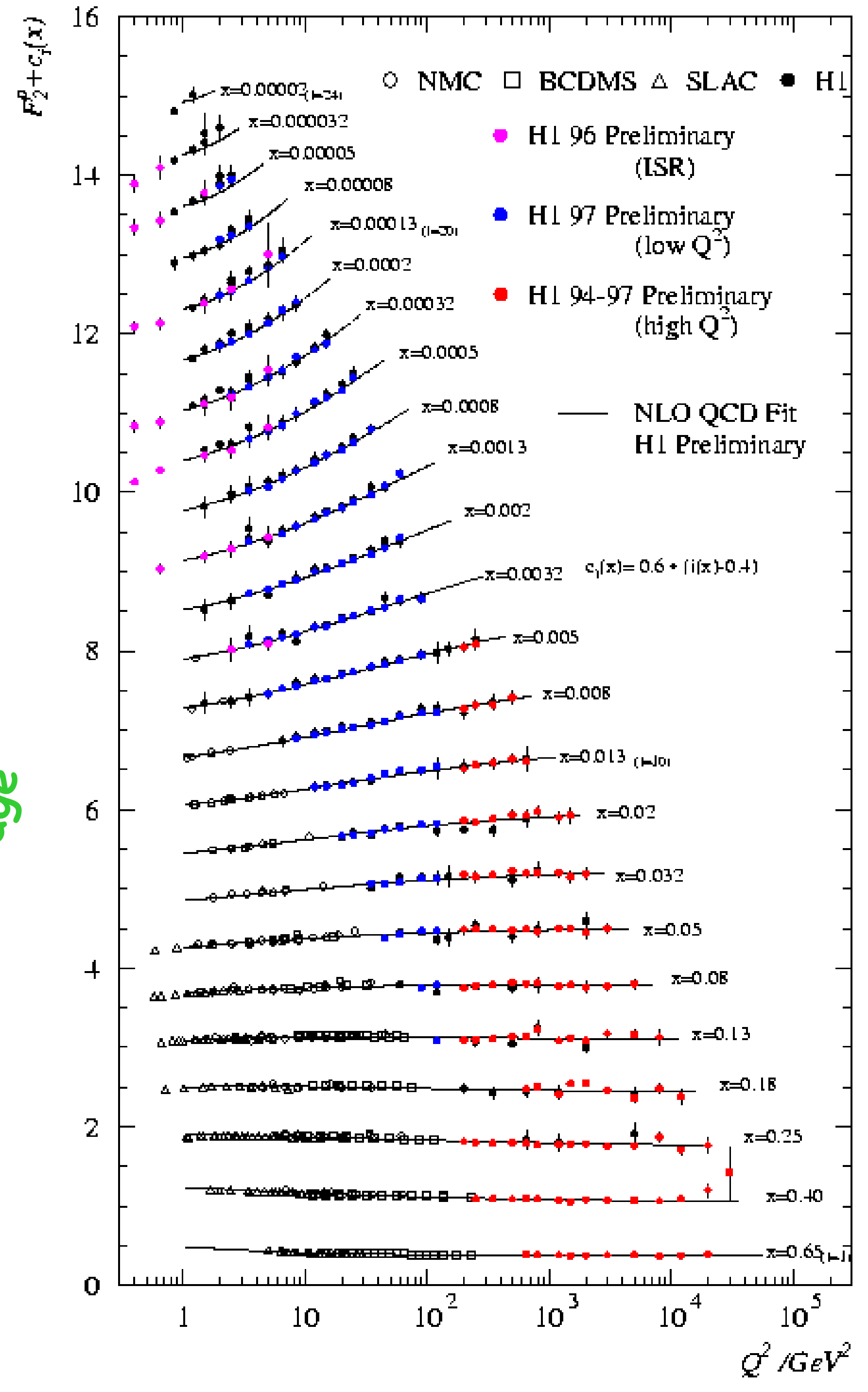
HERA electron microscope

e (30 GeV) + p (900 GeV)

Deep Inelastic Scattering







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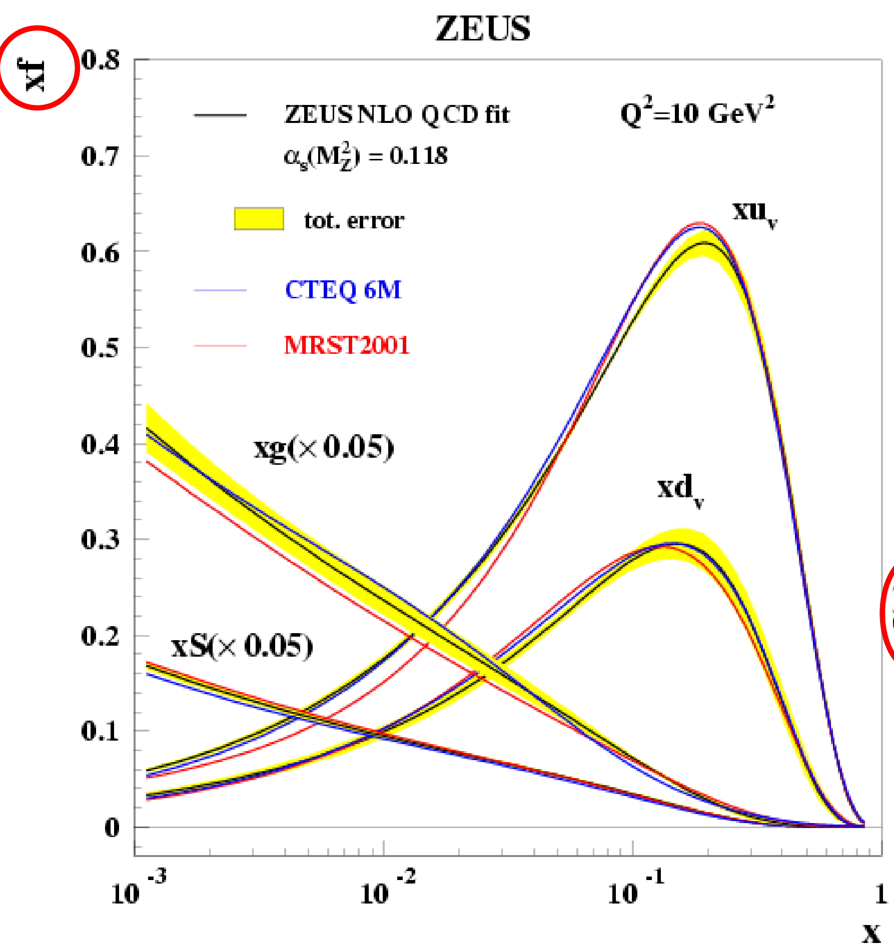
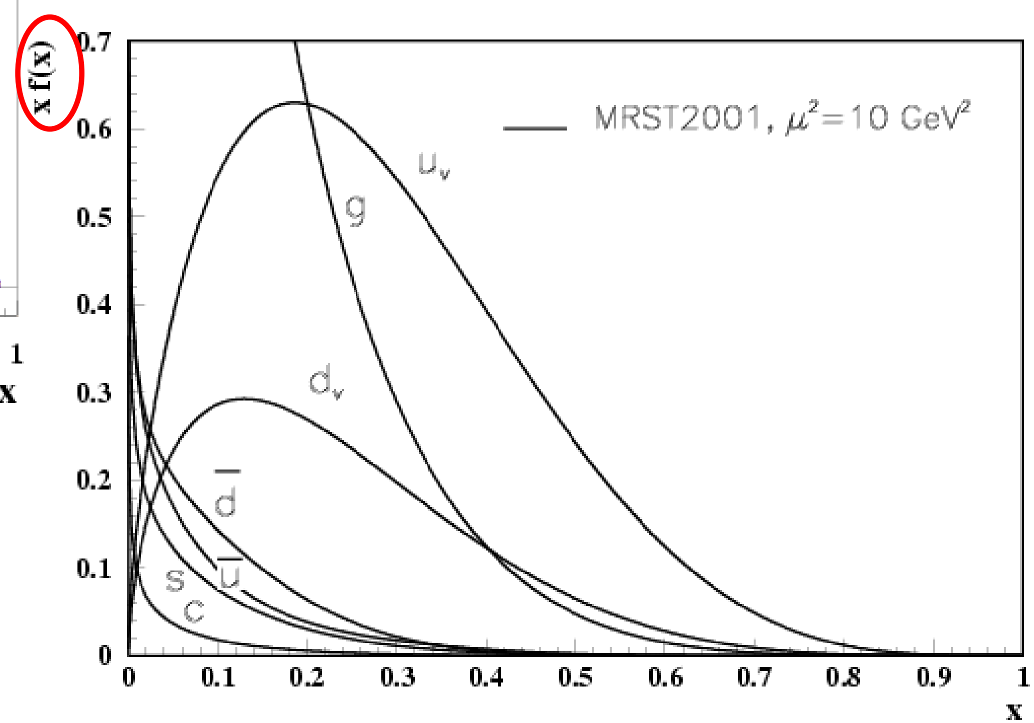
Parton density functions $f(x,Q^2)$



there are uncertainties!

in particular at large x



Fits/parametrisations:

- CTEQ
- MRST

Cross section calculation in pp

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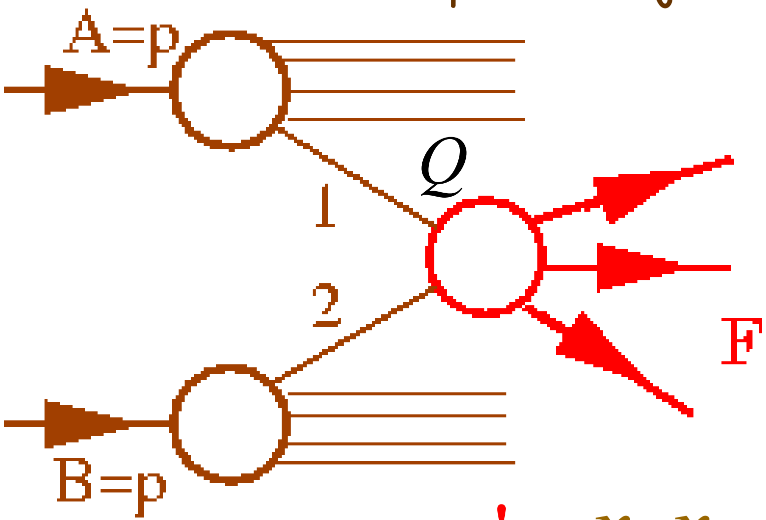
final state

Wanted: $\dfrac{d\sigma_F(\sqrt{s},Q^2)}{dV}$ ← kinematical variable

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



$s' = x_1\, x_2\, s$

Known: $f_i(x_i,Q^2)$

Q^2 = („momentum transfer")^2

depends on final state

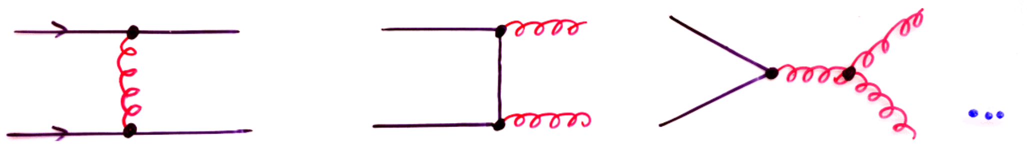
$$\frac{d\sigma_F(\sqrt{s},Q^2)}{dV} = \sum_{i,j}\int dx_i\, dx_j\, f_i(x_i,Q^2)\, f_j(x_j,Q^2) \bullet \frac{d\sigma_F^{ij}(x_i,x_j,Q^2)}{dV}$$

factorization

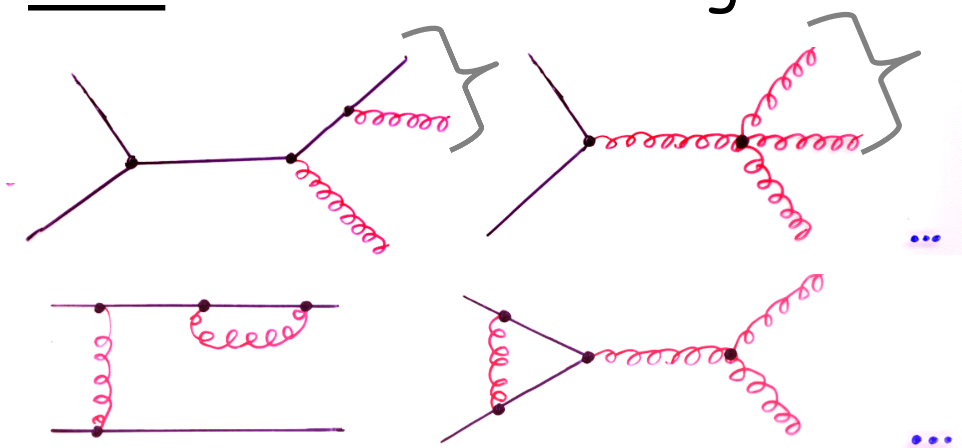
Higher orders - K factors

2 jets

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 ~ 1.3

(often
event topolgy
~ unchanged)

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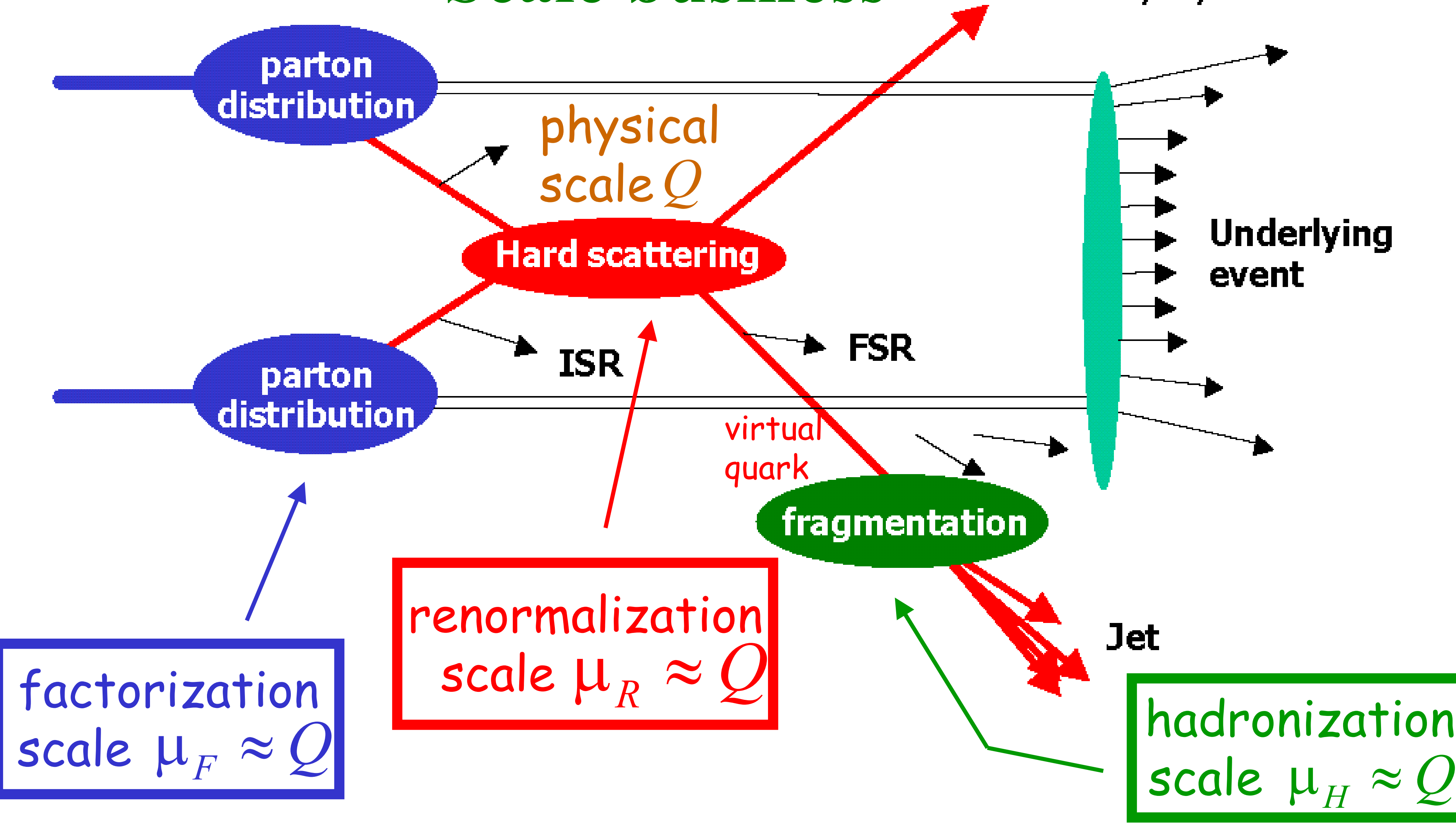
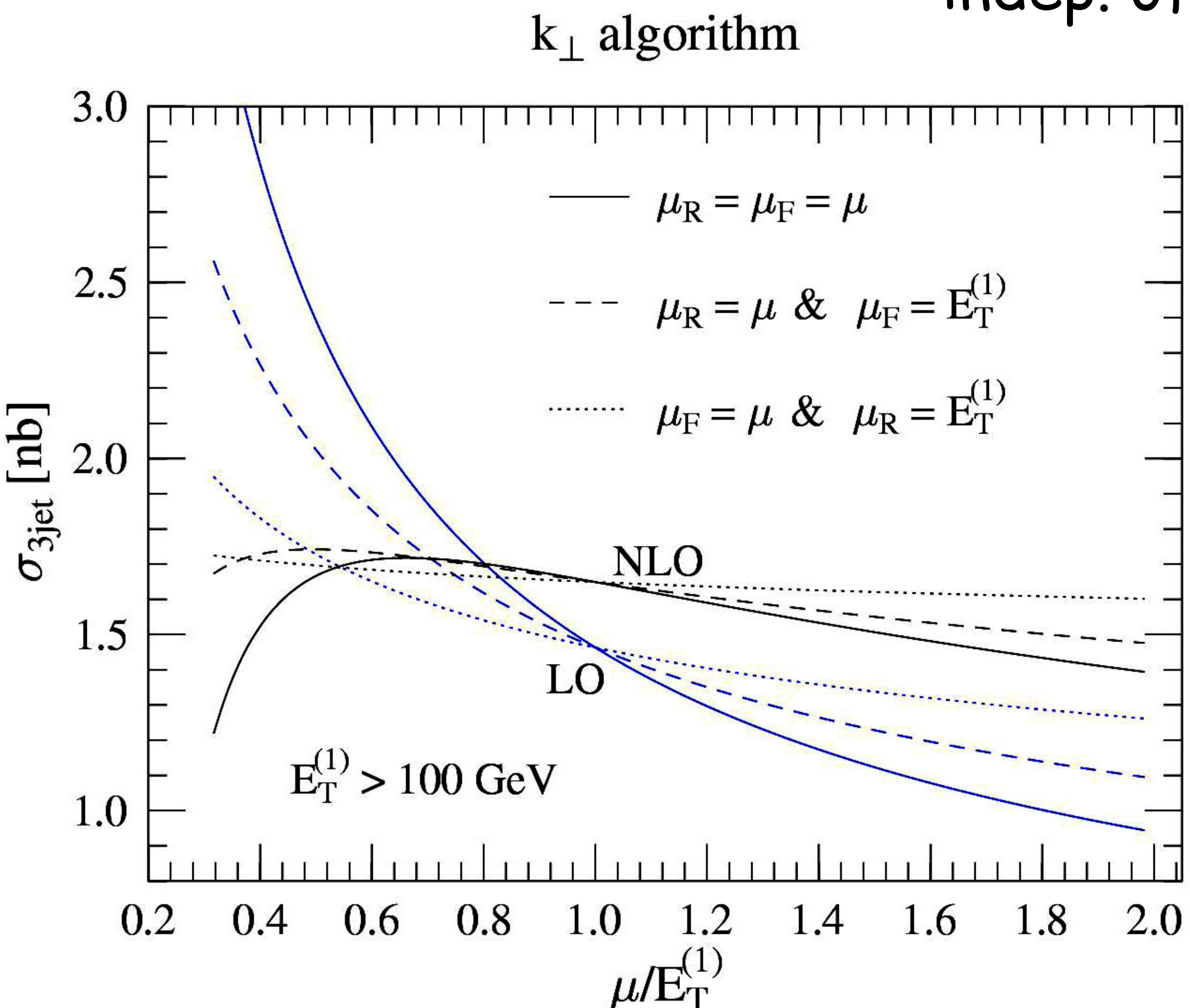
Scale business



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

Renormalization Scale

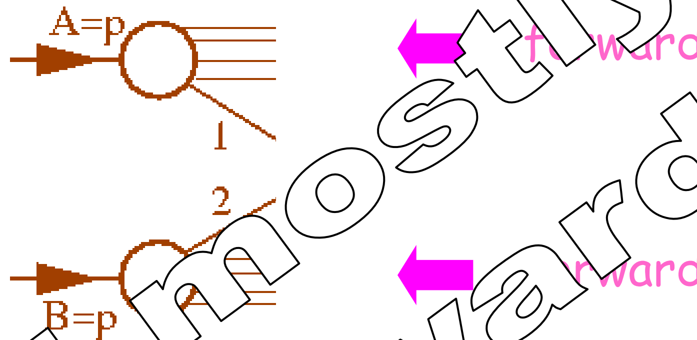
$$\sigma = \underbrace{A \cdot \alpha_s(\mu_R) + B(\mu_R) \cdot \alpha_s^2(\mu_R) + \ldots}_{\text{indep. of } \mu_R \text{ (all orders)}}$$



missing higher orders ↔ scale dependence

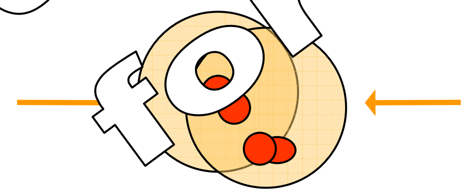
„Dirty“ environment

- beam remnants



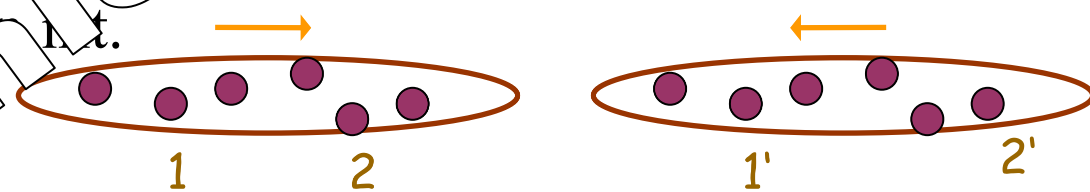
underlying event

- double parton interactions



some percent

- „pile up“ = multiple proton int.



minimum bias events

2 (Tevatron) – 20 (LHC) / crossing

400 ns 25 ns

- „detector pile up“
  - drift time >> bunch distance
  - thermalized neutrons

background mostly hadronic, forward

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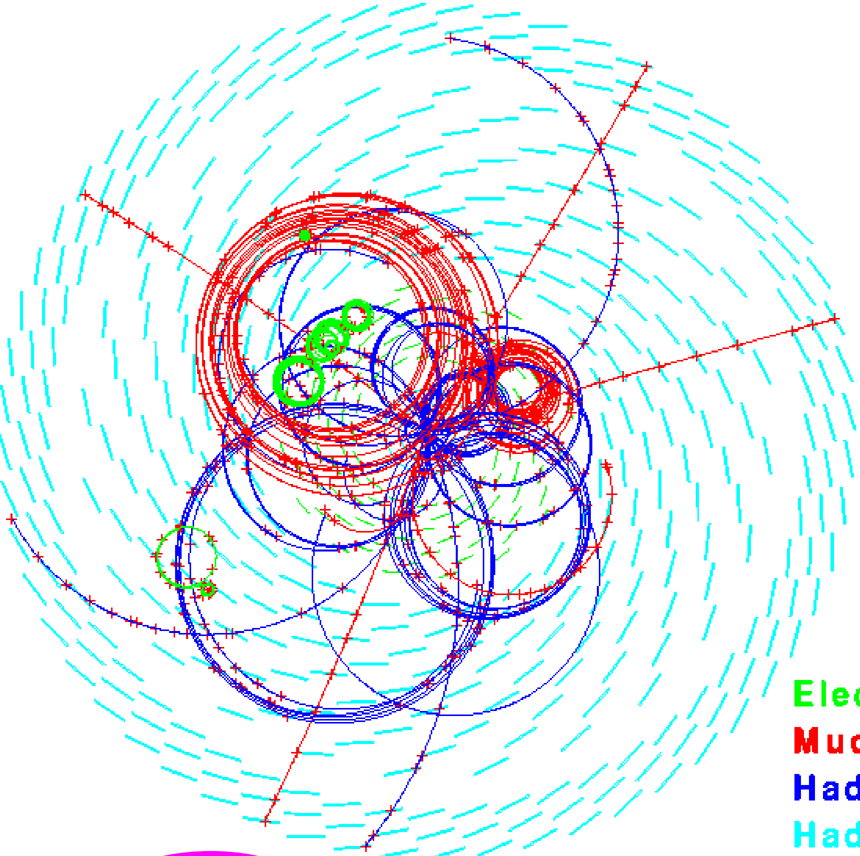
CMS

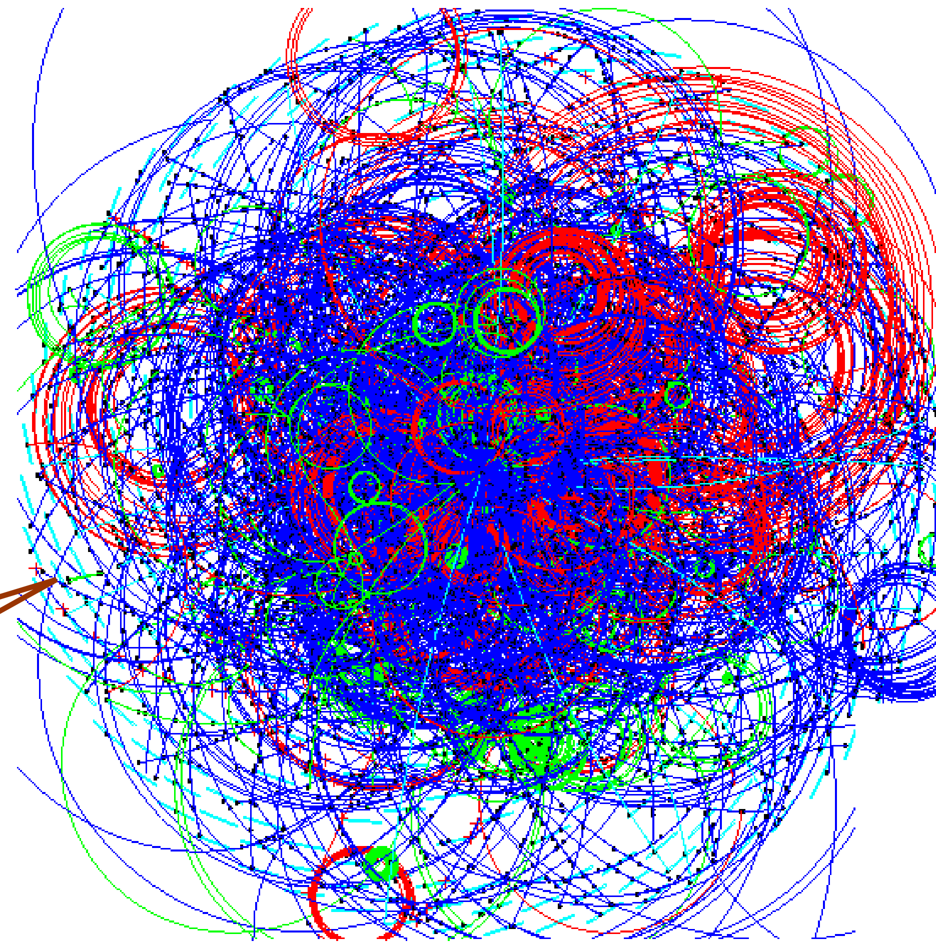
„Pile-Up“

H -> μμμμ
m(H)=150GeV



Electrons
Muons
Hadrons
Hadrons

~100 tracks per crossing



+ 20 minimum-bias events

Kinematics

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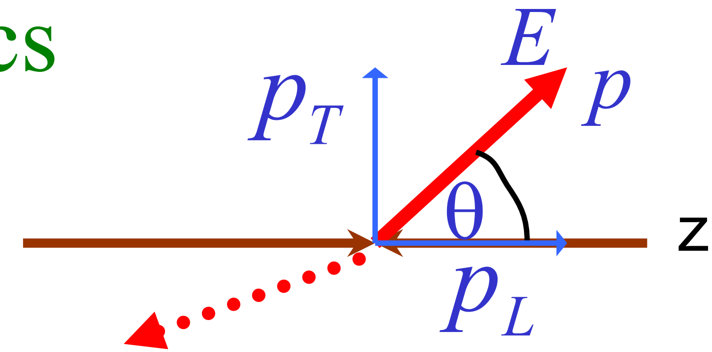
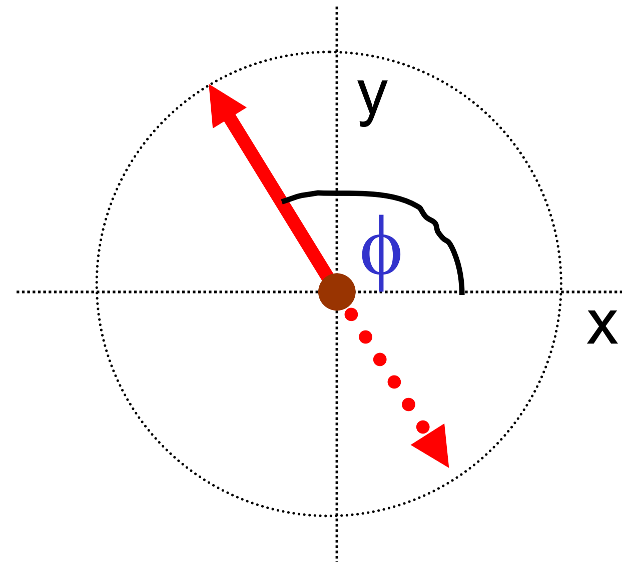


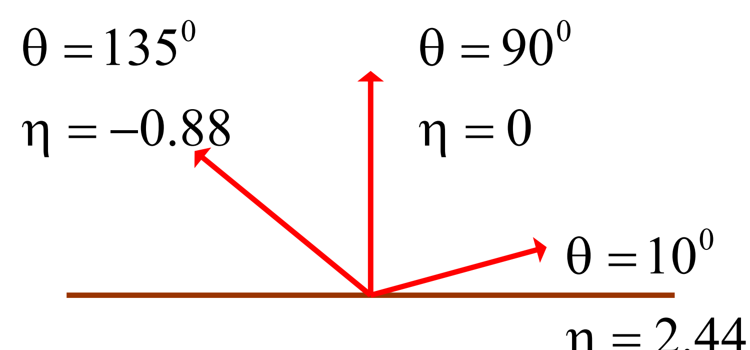


Kinematical variables:

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



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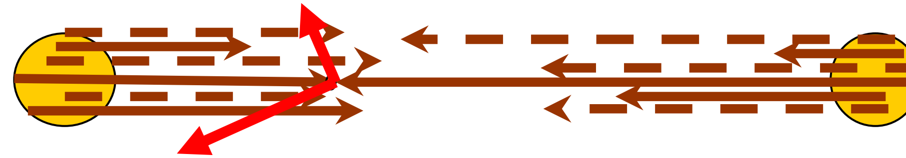
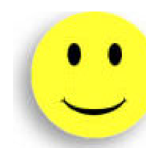
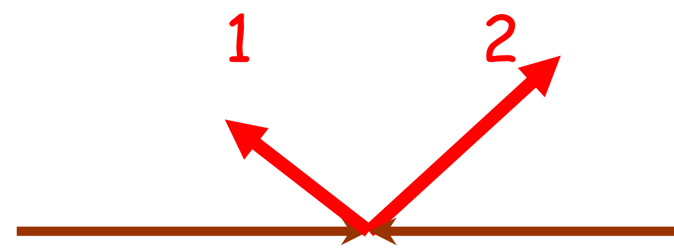
„boost" of c.m.s. along

beam axis = a priori unknown !

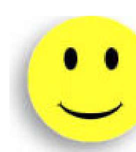


- azimuthal angle ϕ 
- polar angle θ
- energy E
- momentum p
- transverse momentum p_T 
- longitudinal momentum p_L

boost invariance ?

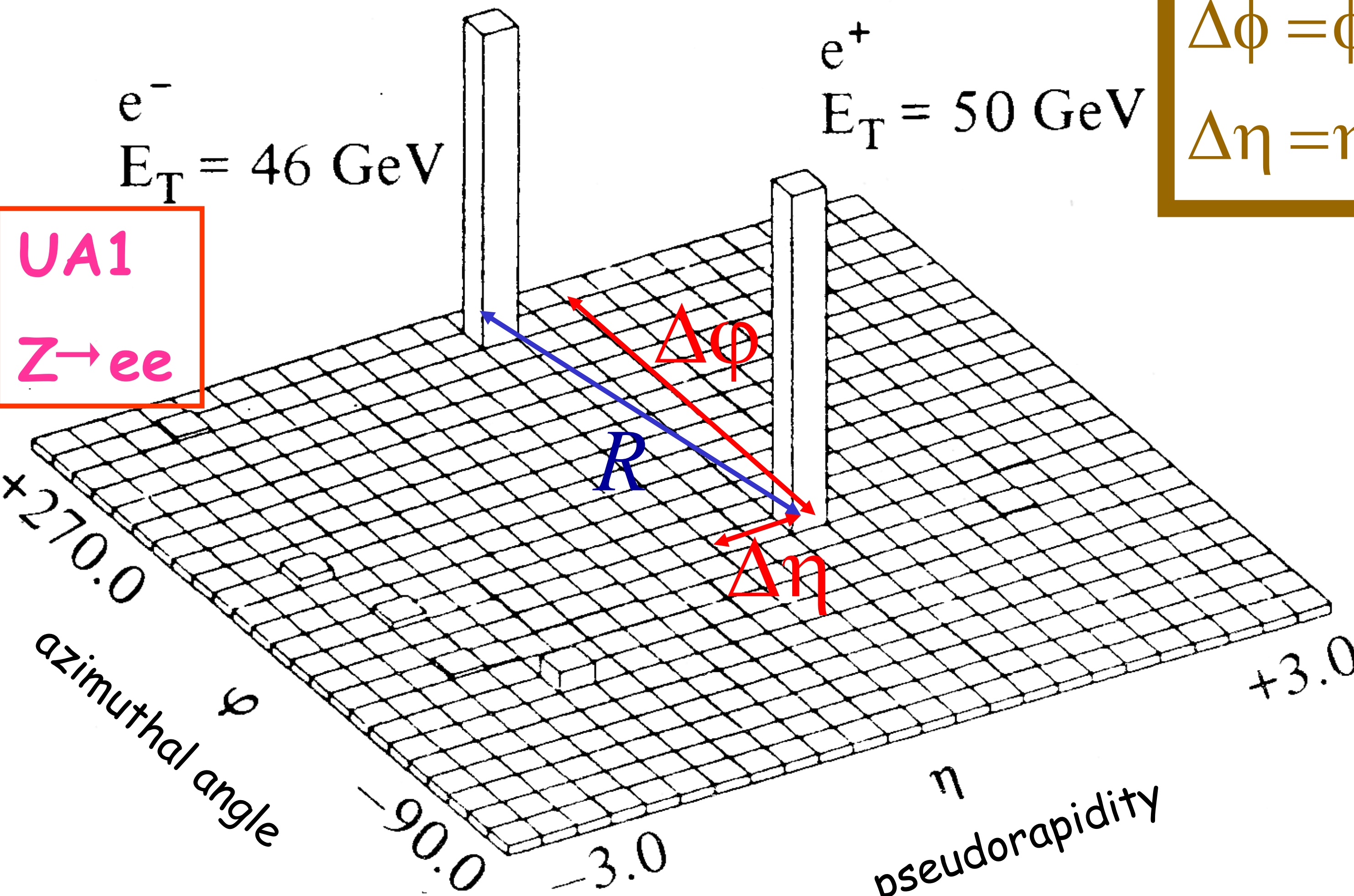


- rapidity $$y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$$ $$y_1 - y_2$$
- pseudorapidity $$\eta = -\ln \tan \frac{\theta}{2}$$ $$\eta_1 - \eta_2$$



(Pseudo-)Rapidity

Particle directions $\longleftrightarrow$ ϕ, η



UA1

Z→ee

distance measure:

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

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

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

Note:

- rotation:

  $\Delta\phi = const$

- boost:

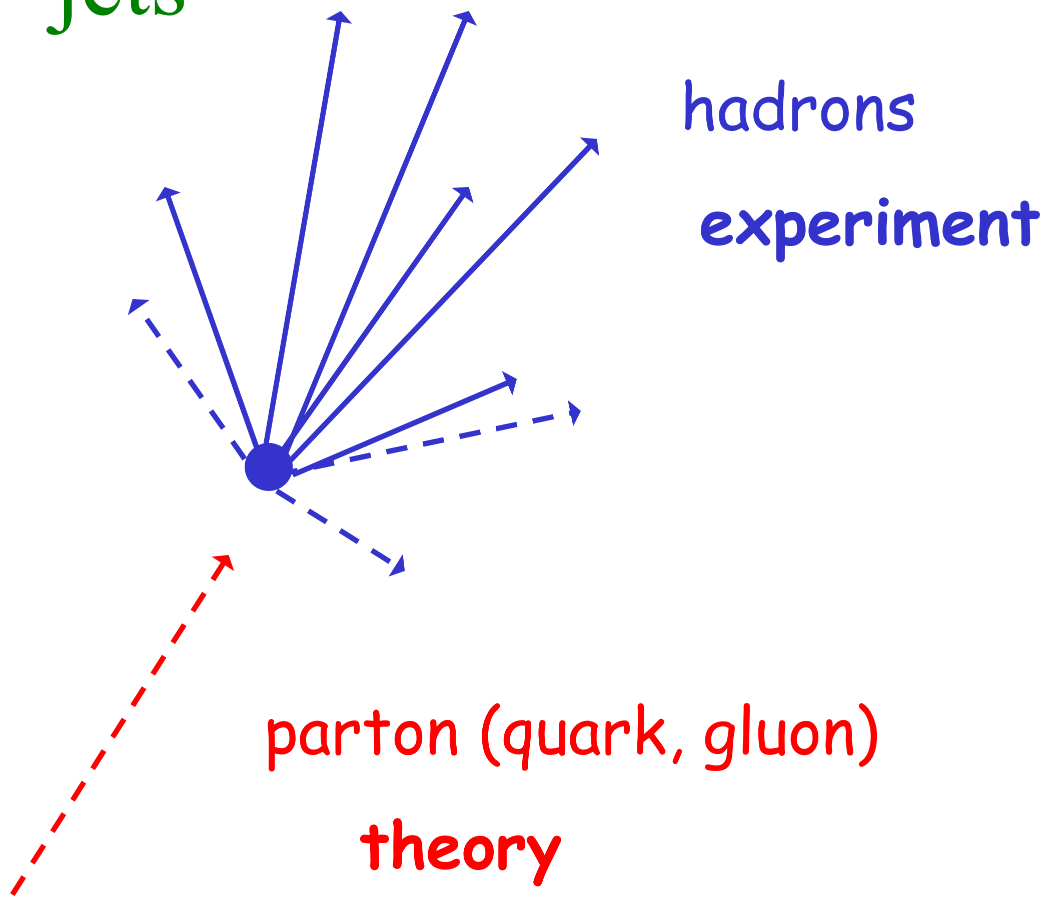
  $\Delta\eta = const$

jets

Typical: 100
particles total

(LHC)

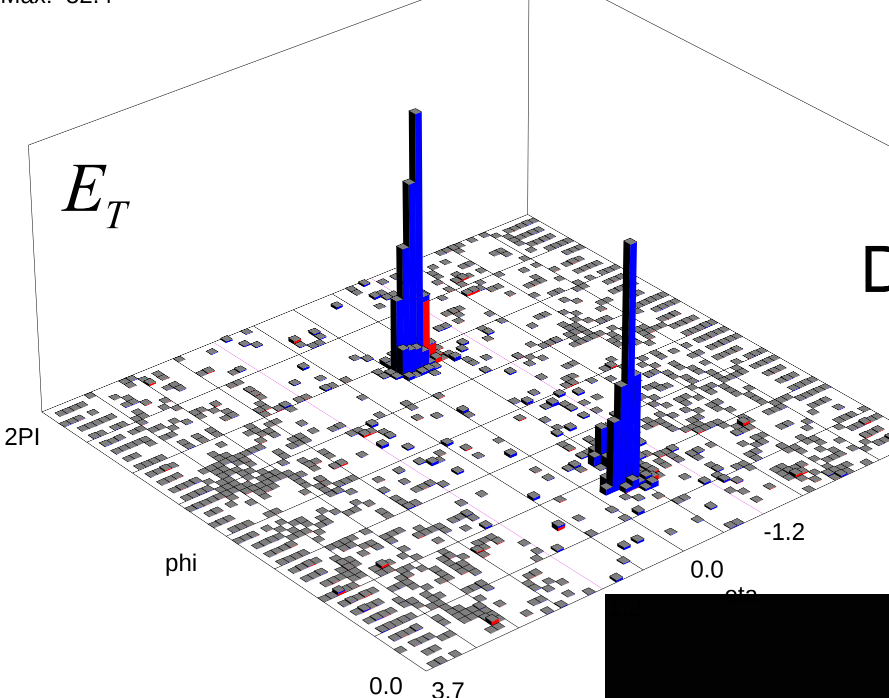
2-5 jets per event

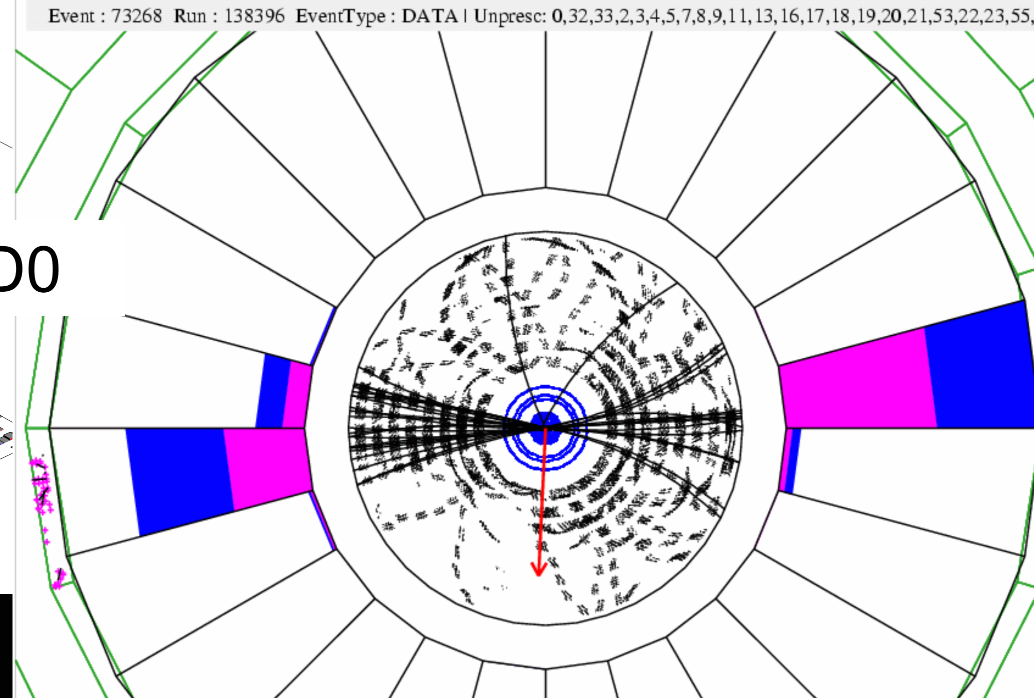


jets reveal hard process (direction, energy of partons)

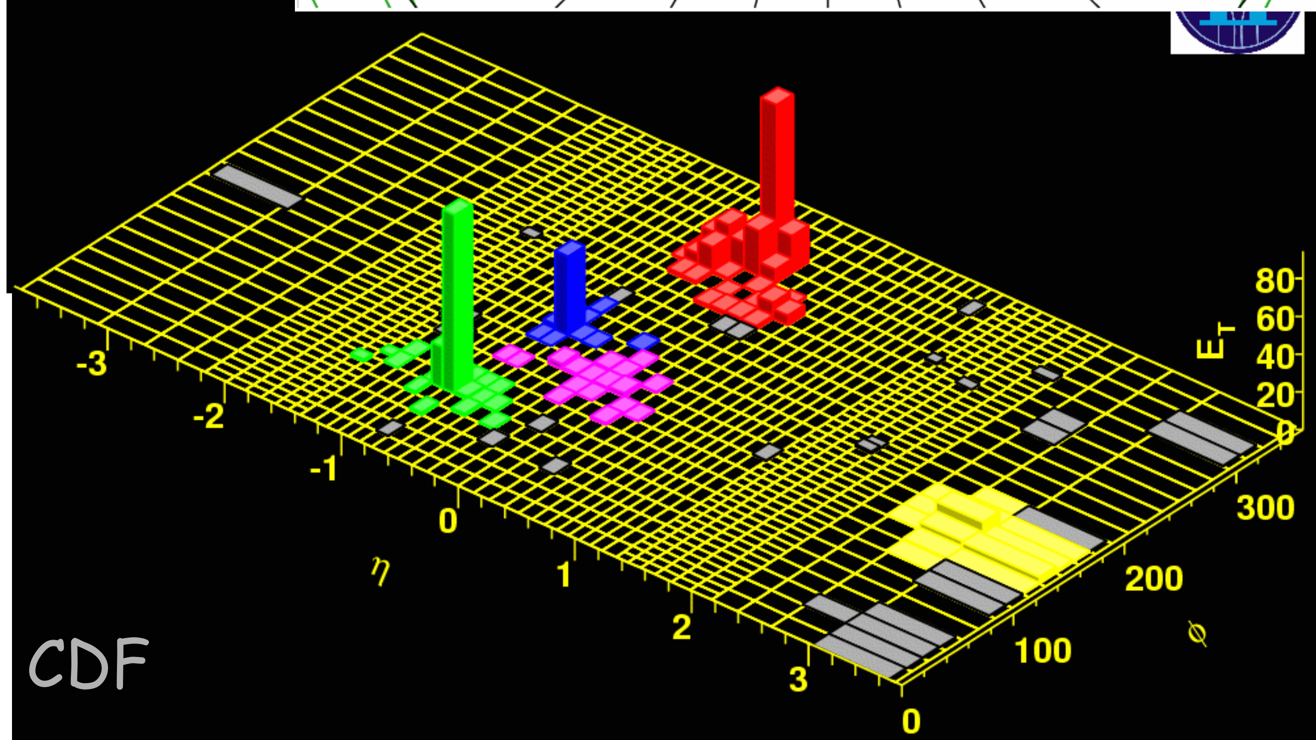
experiment and theory must use the same language:

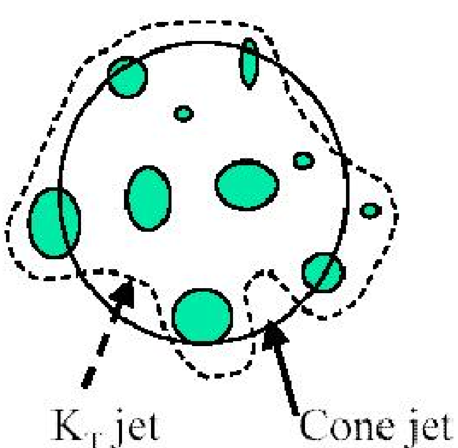
jets need to be defined: „jet algorithm“


E_T
2PI
phi
-1.2
0.0
0.0
3.7

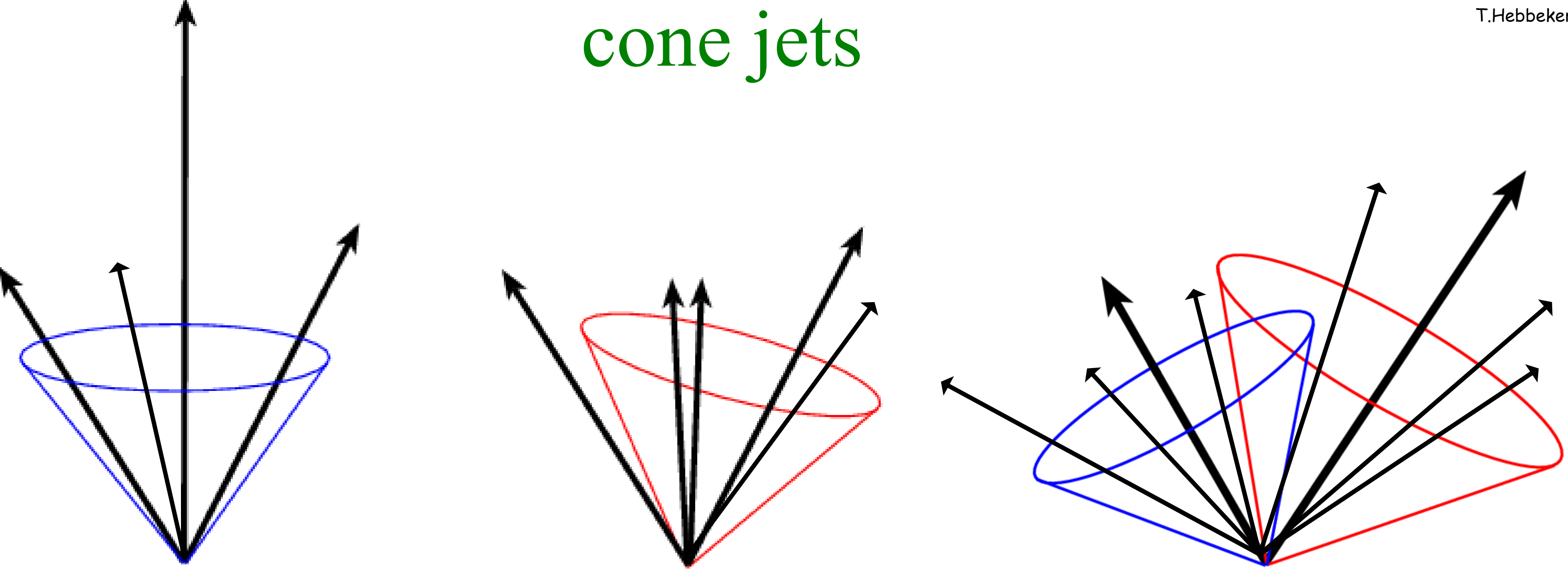

Event : 73268 Run : 138396 EventType : DATA | Unpresc: 0,32,33,2,3,4,5,7,8,9,11,13,16,17,18,19,20,21,53,22,23,55,
D0

Jet events


E_T
80
60
40
20
0
-3
-2
-1
0
1
2
3
η
0
100
200
300
ϕ
CDF


K_T jet
Cone jet

cone jets



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

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

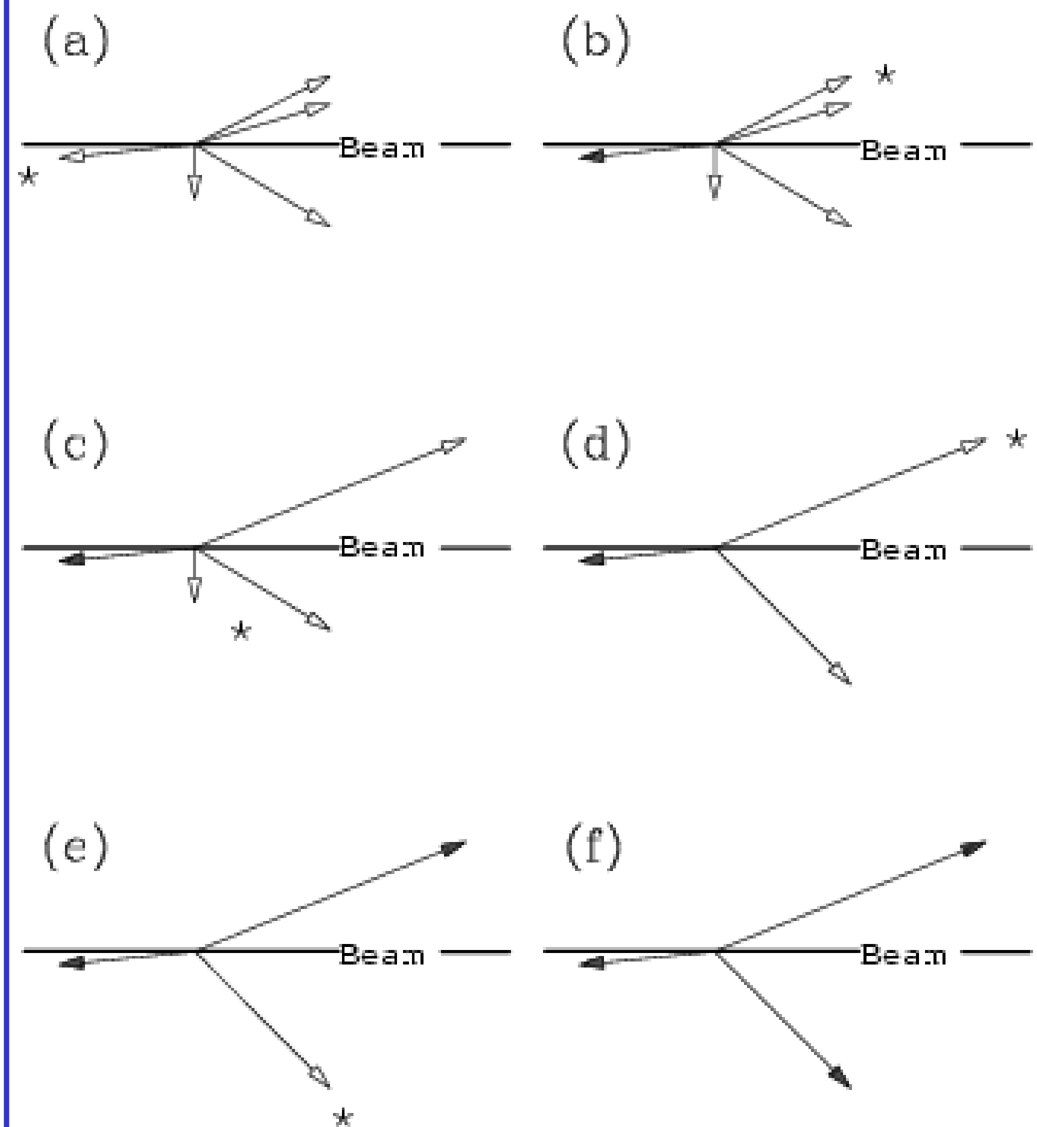
c) minimum of d_{ij}, d_i

→combine or remove from list)

d) iterate: goto b)

till list empty

Example:



... several variations exist

1) Introduction

2) Tevatron

$p + \overline{p}$

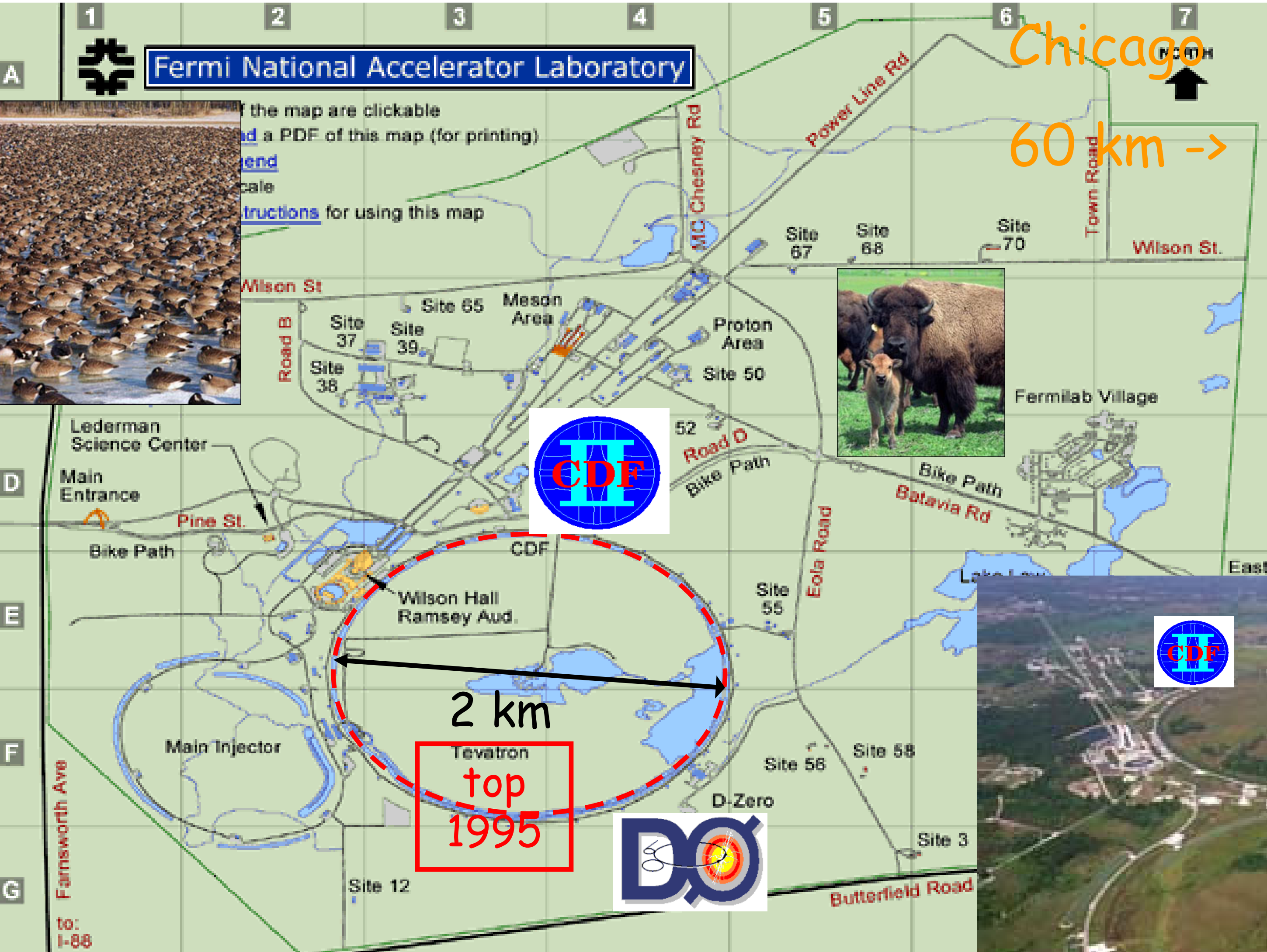
2 TeV (1.8 TeV)

- experimental aspects
- jet production
- electroweak processes

t

3) LHC

Fermilab/Tevatron



FNAL =

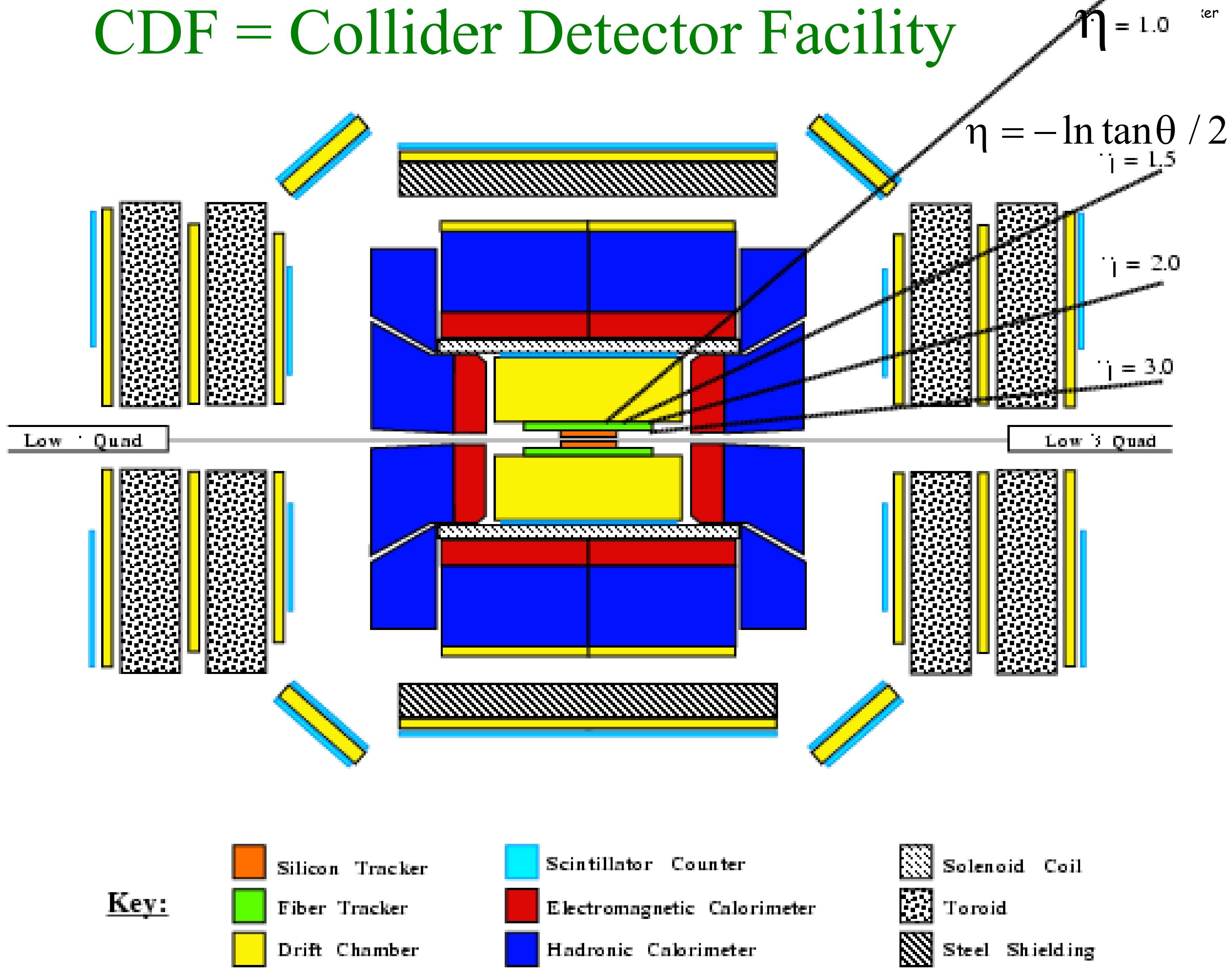
Fermilab

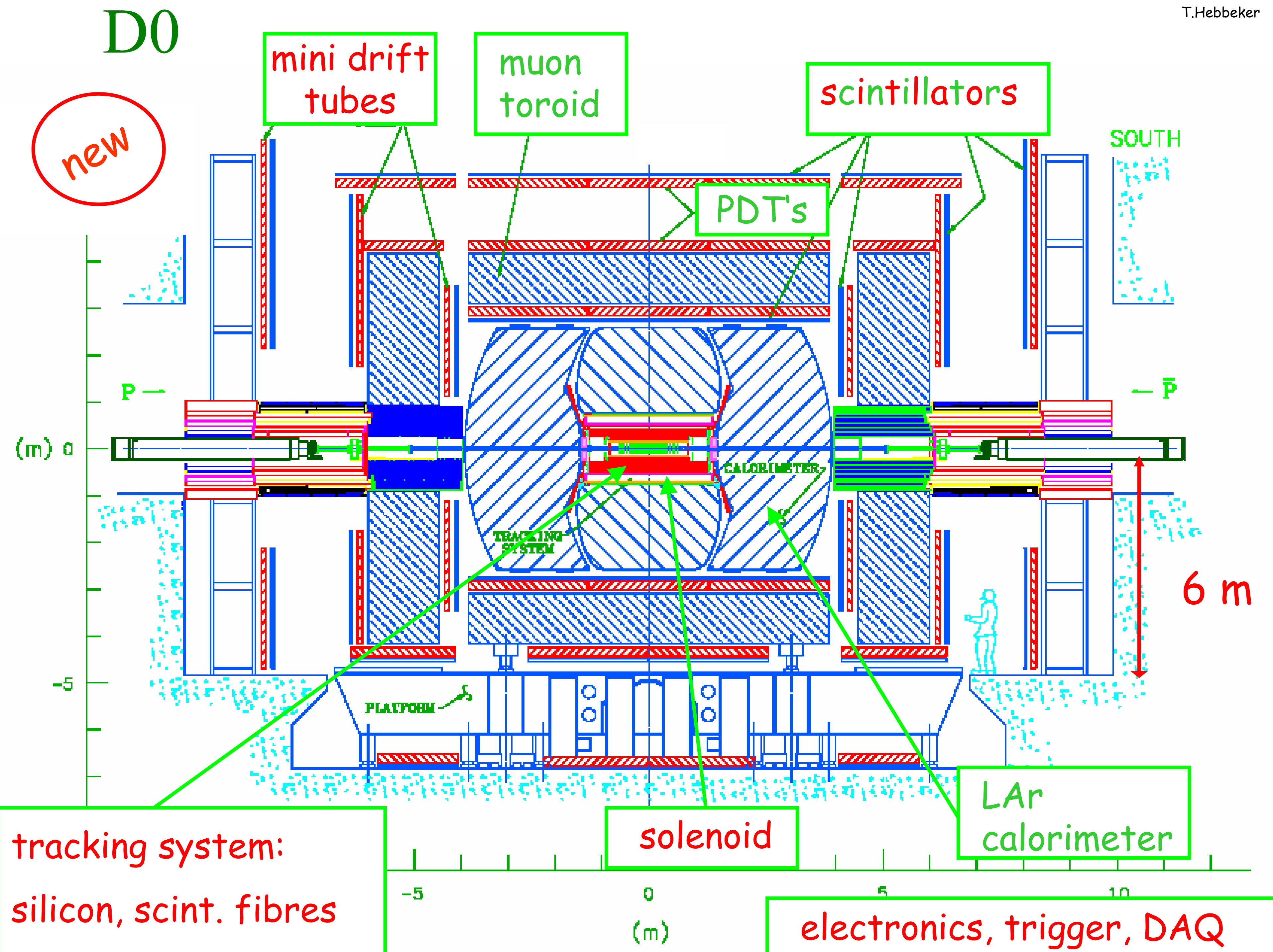
(Enrico Fermi)

1967

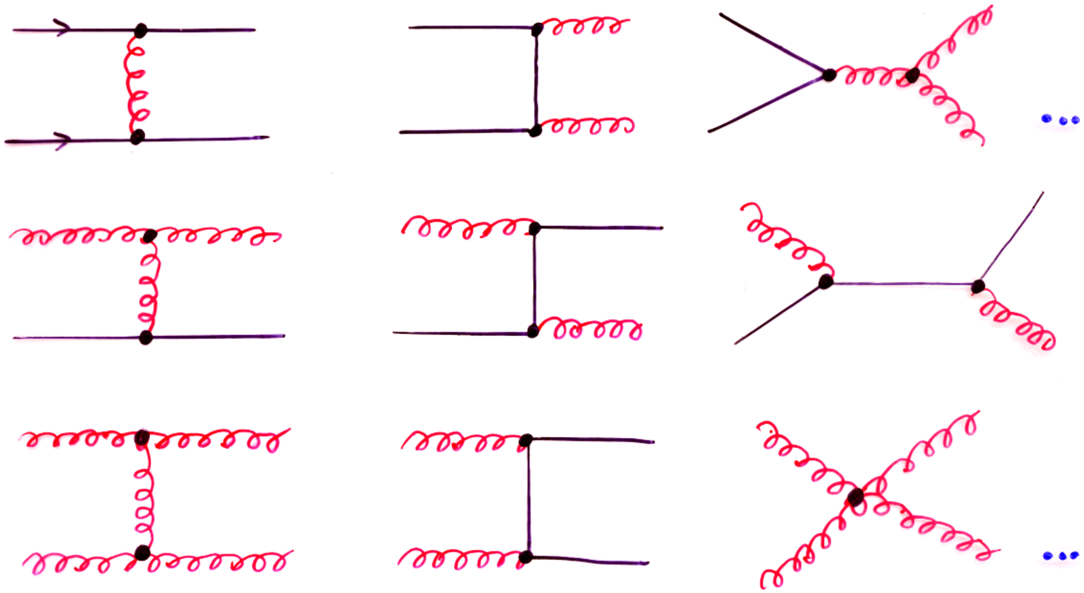
Tevatron = TEV machine

CDF = Collider Detector Facility



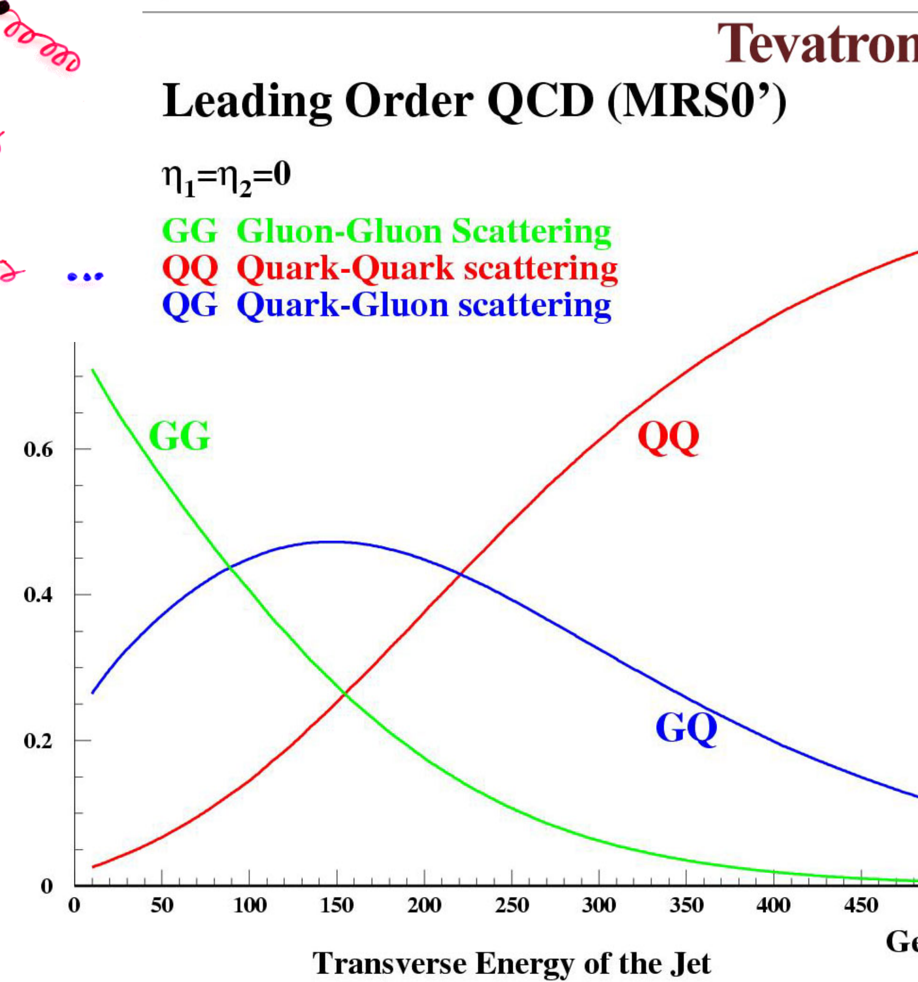

D0
T.Hebbeker
new
mini drift tubes
muon toroid
scintillators
SOUTH
PDT's
P
P̄
(m) 0
-5
CALORIMETER
TRACKING SYSTEM
PLATFORM
6 m
LAr calorimeter
solenoid
tracking system:
silicon, scint. fibres
-5
0
5
10
(m)
electronics, trigger, DAQ

Jet production (theory)

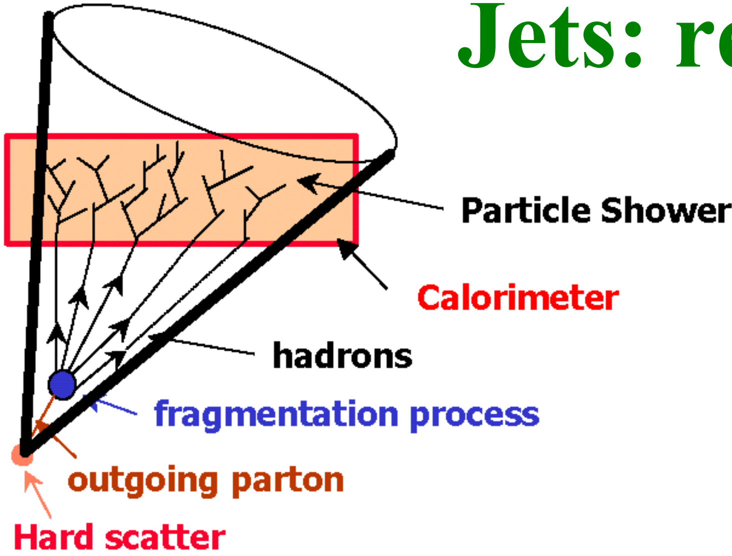


+ higher orders

+ electroweak diagrams



Jets: resolution and precision



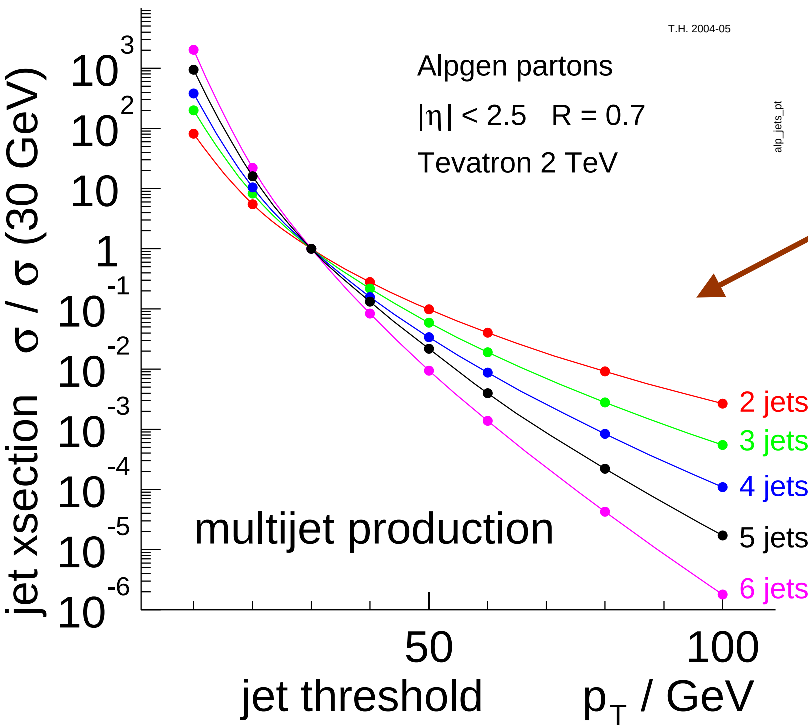
angle: $\sigma = \dfrac{10^o}{\sqrt{E/GeV}}$ *uncritical*

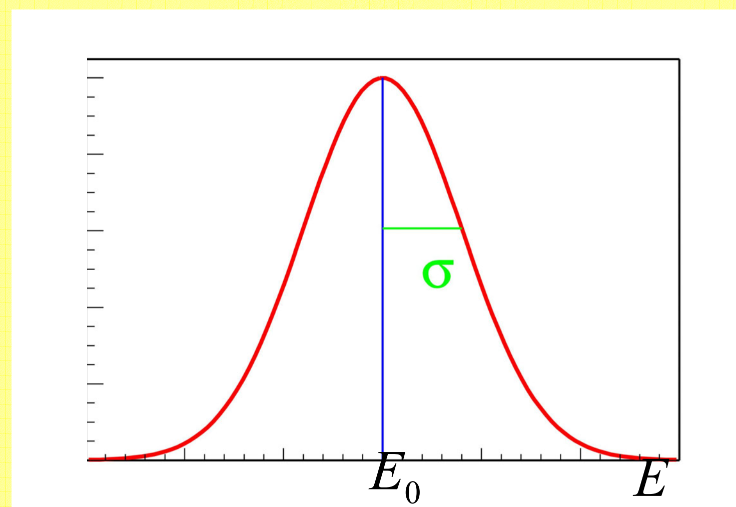
D0

energy:

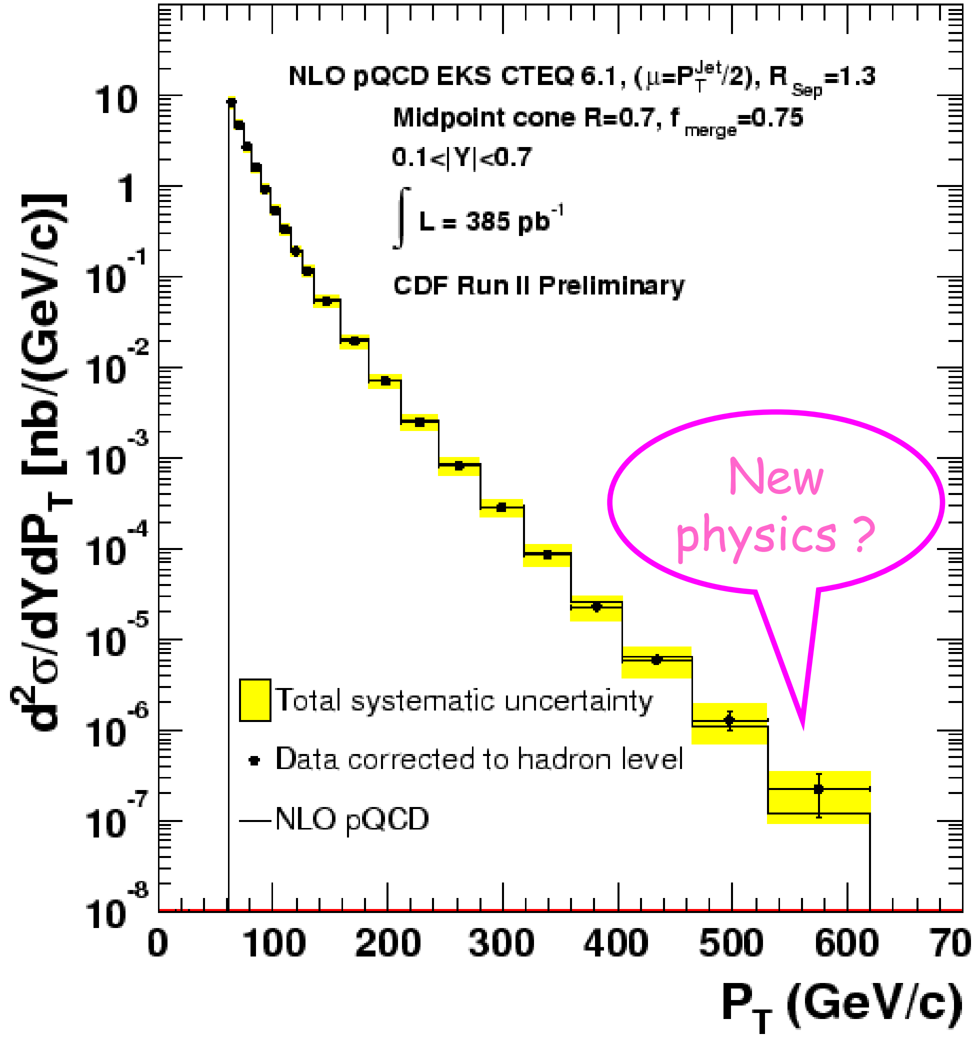
resolution: $\dfrac{\sigma}{E} = \dfrac{80\%}{\sqrt{E/GeV}} \oplus 4\%$

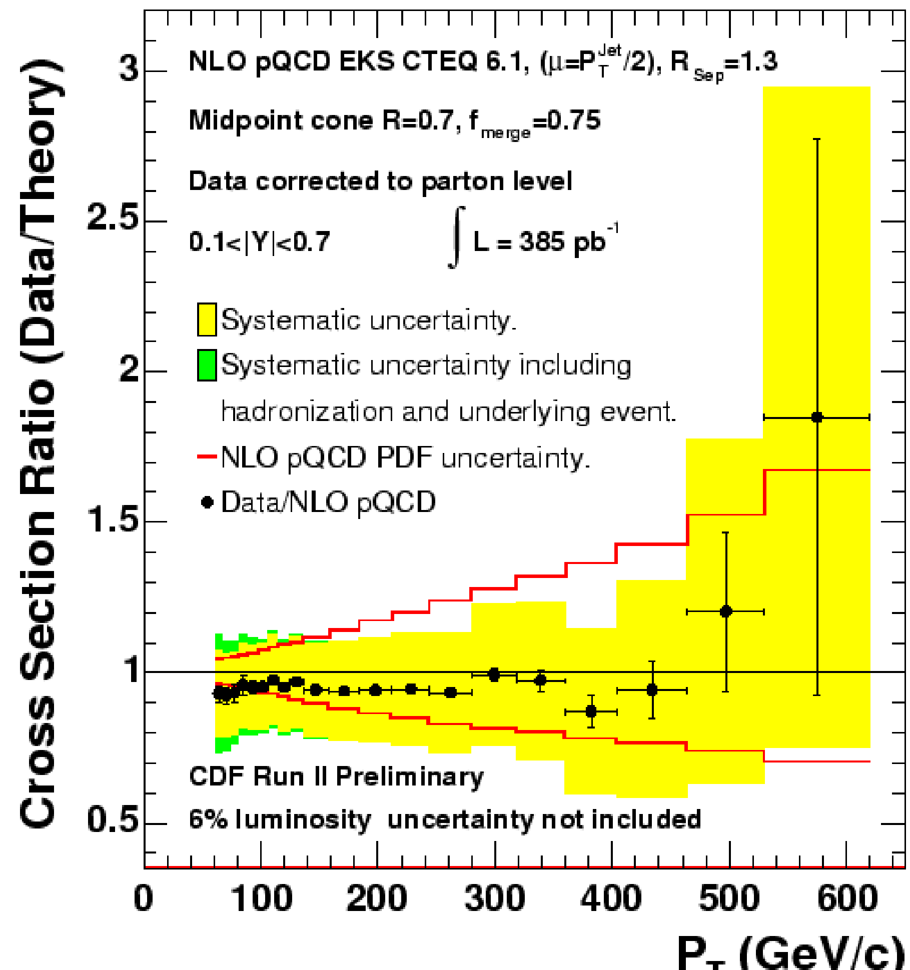
scale: $\dfrac{\delta E}{E_0} = 5\%$





Inclusive jet production

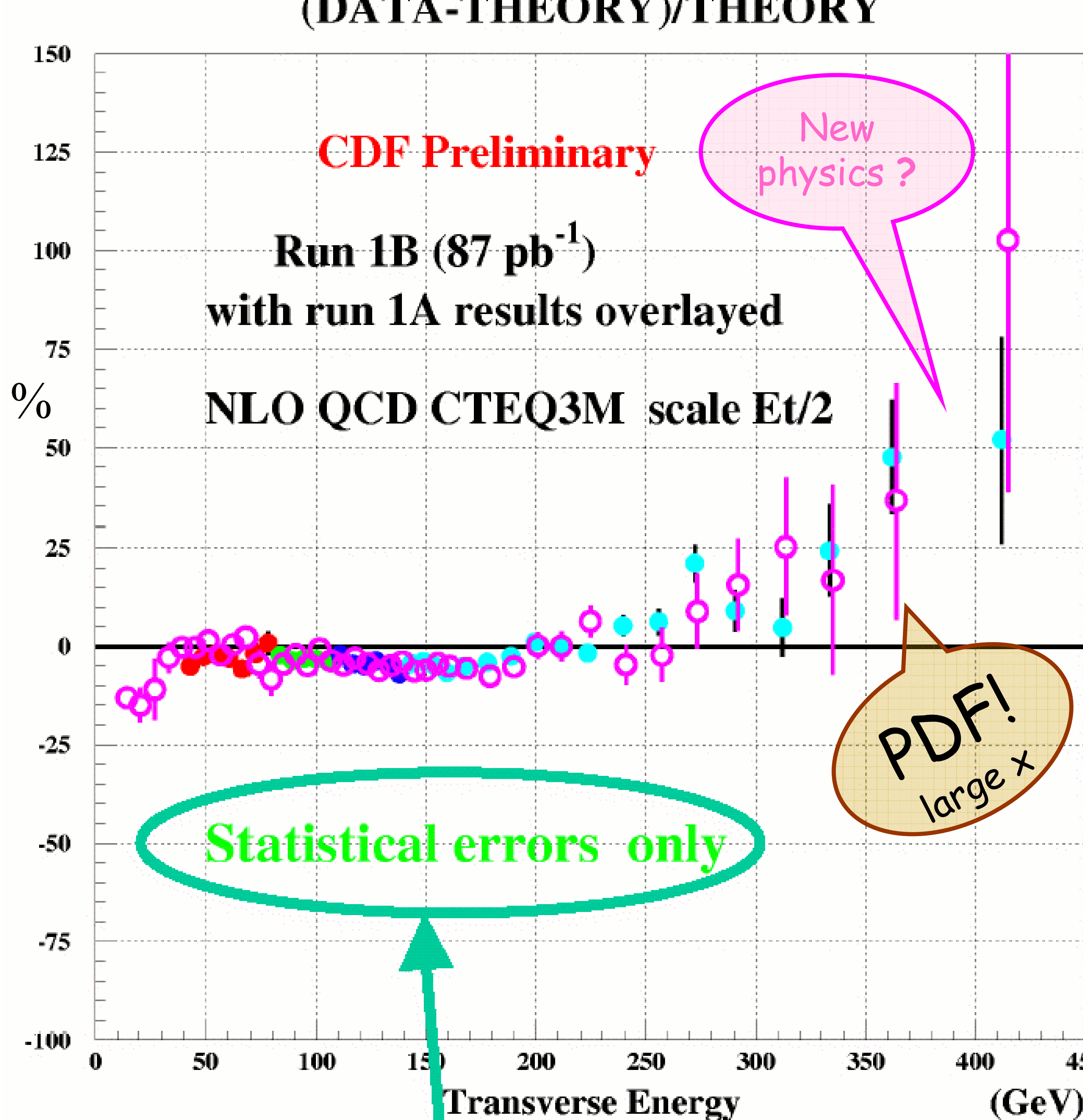




ok !

absolute normalization
(luminosity, jet scale) : ±15%

Inclusive jet production (old analyses)



Newer PDF give agreement within total uncertainties

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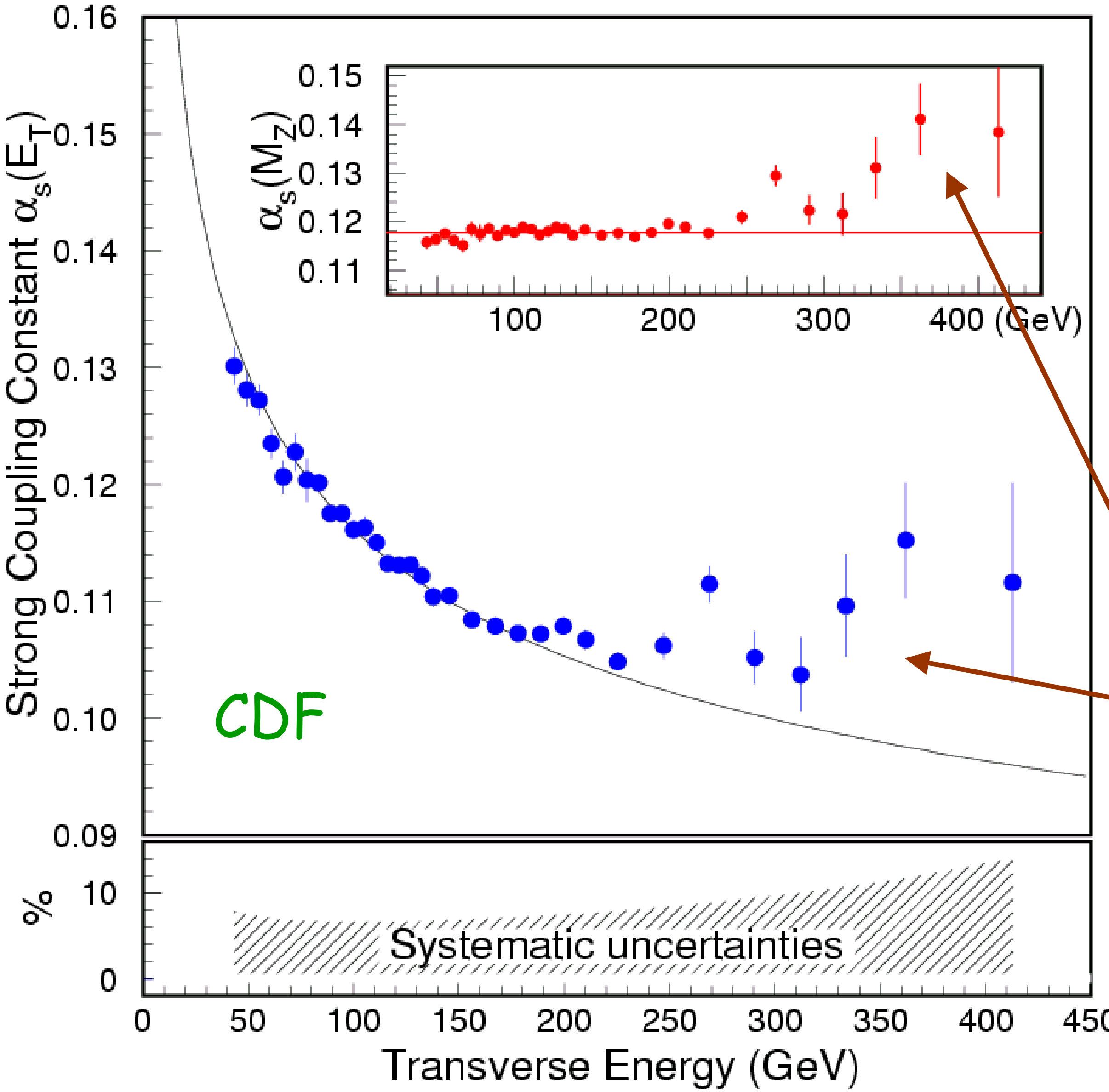
Determination of α_s

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

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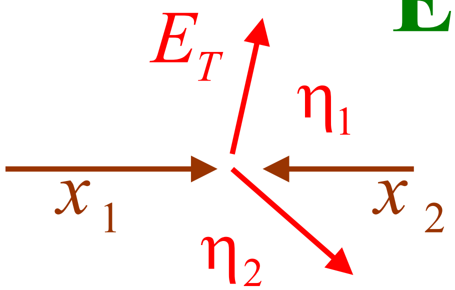
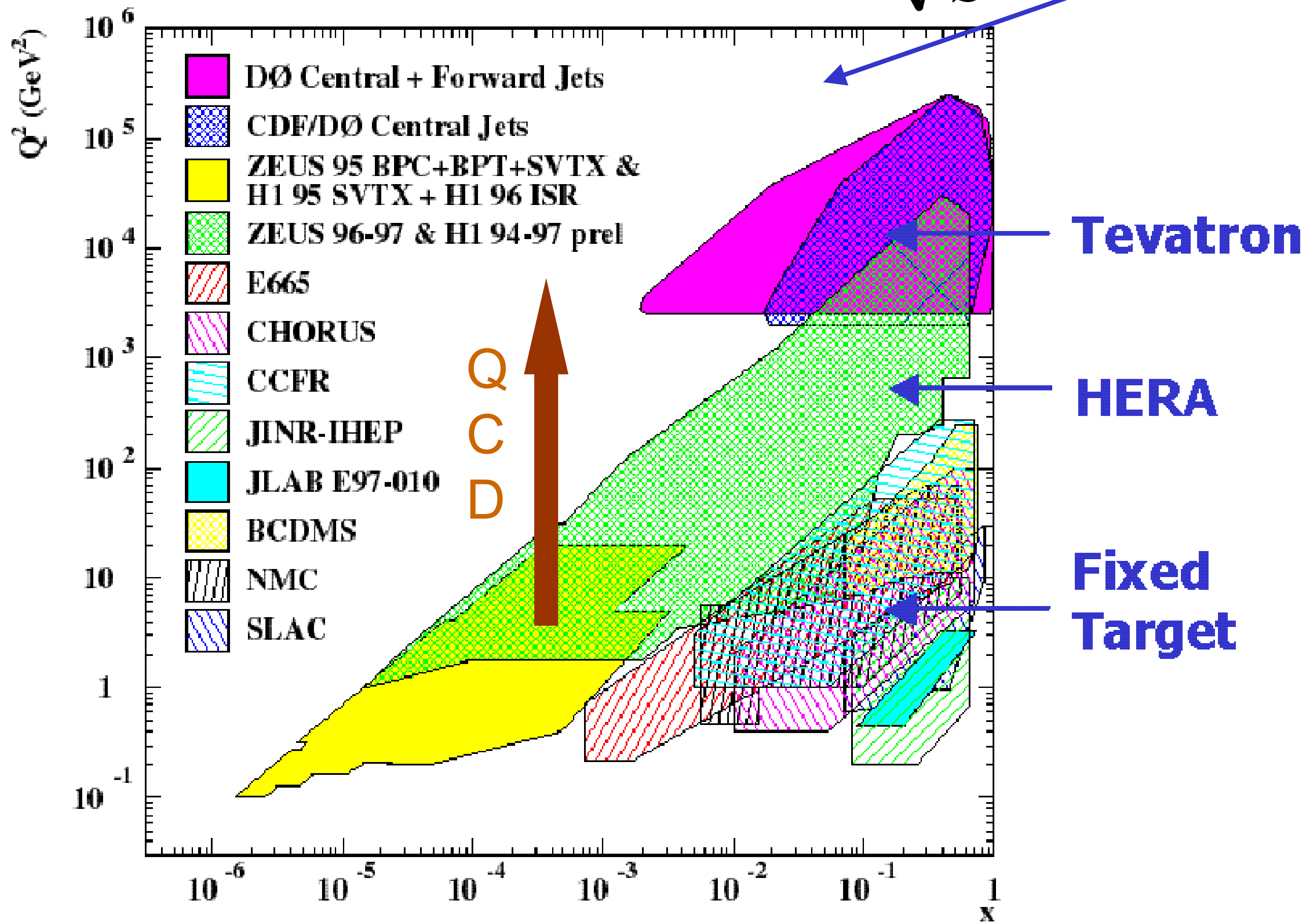


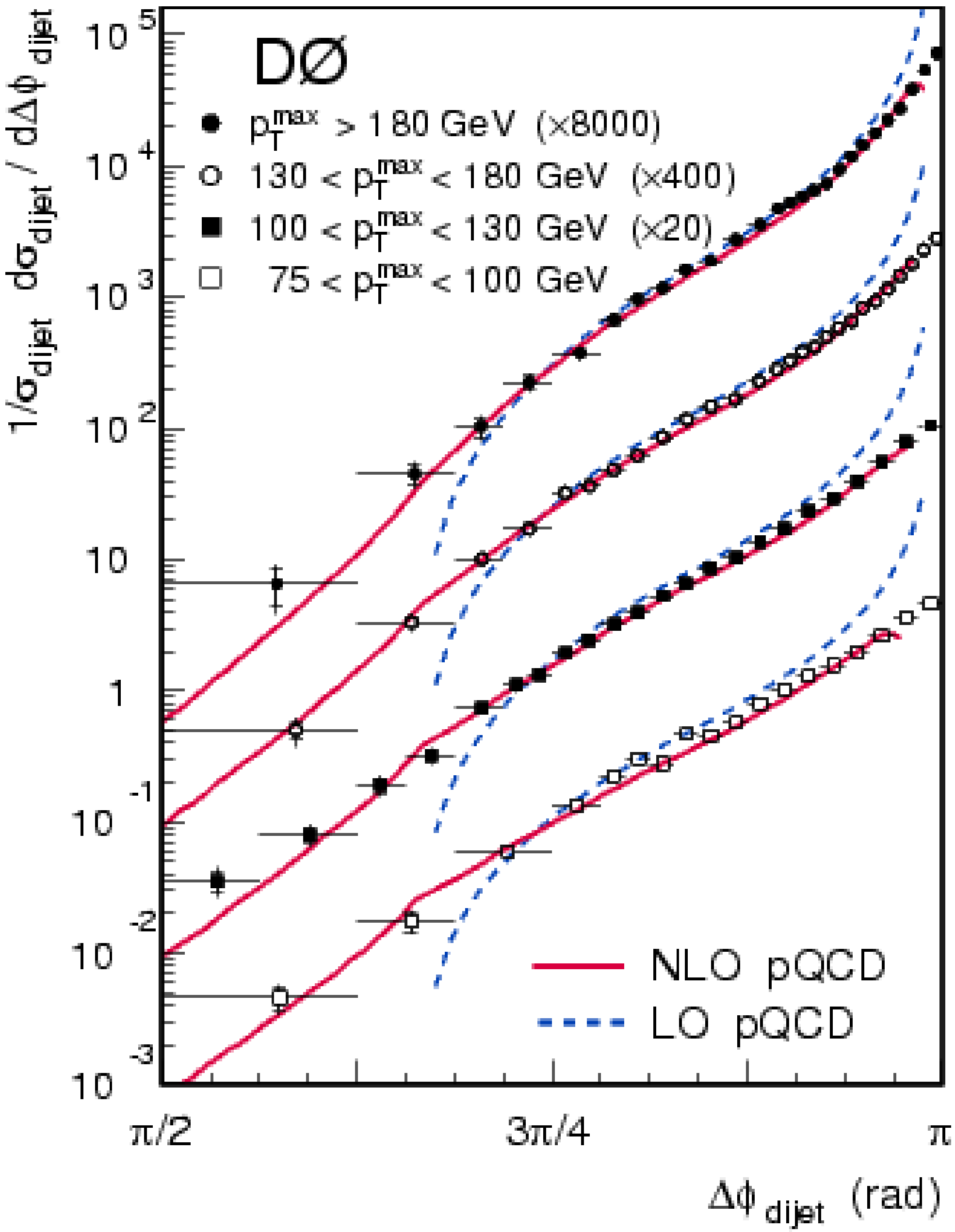
$$x_{1,2} = (e^{\pm\eta_1} + e^{\pm\eta_2}) \cdot \frac{E_T}{\sqrt{s}}$$

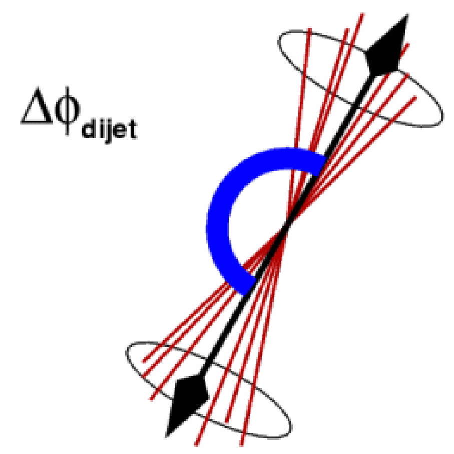


Can measure parton momenta

constrain structure functions!

Inclusive dijet production

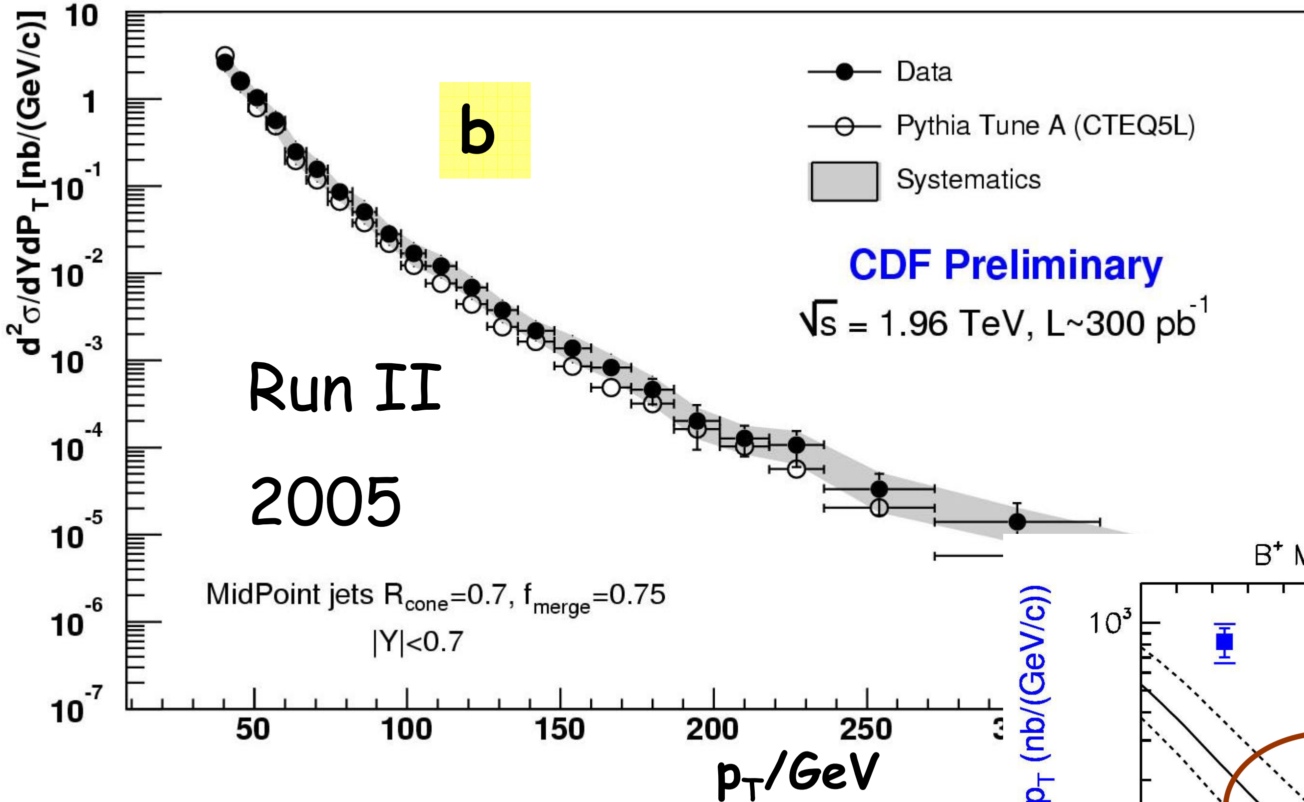


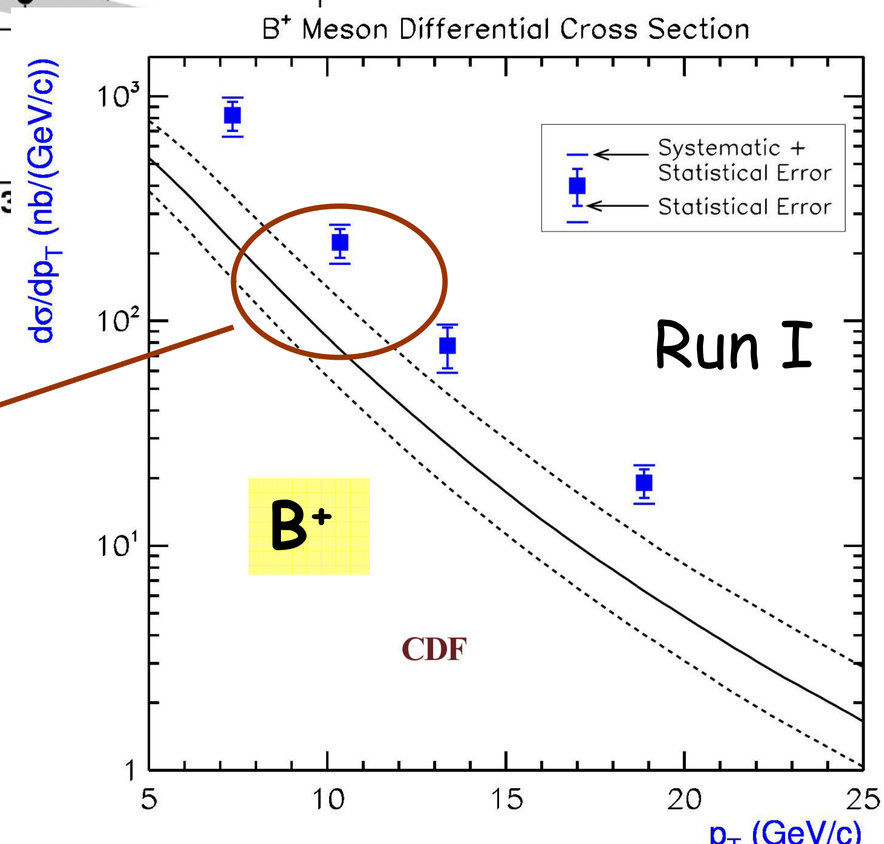


contributions at angles < π from multi parton final states

ok !

Bottom quark production

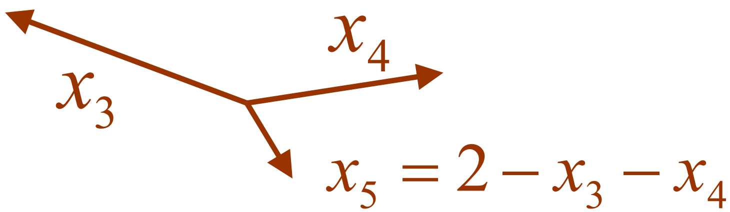




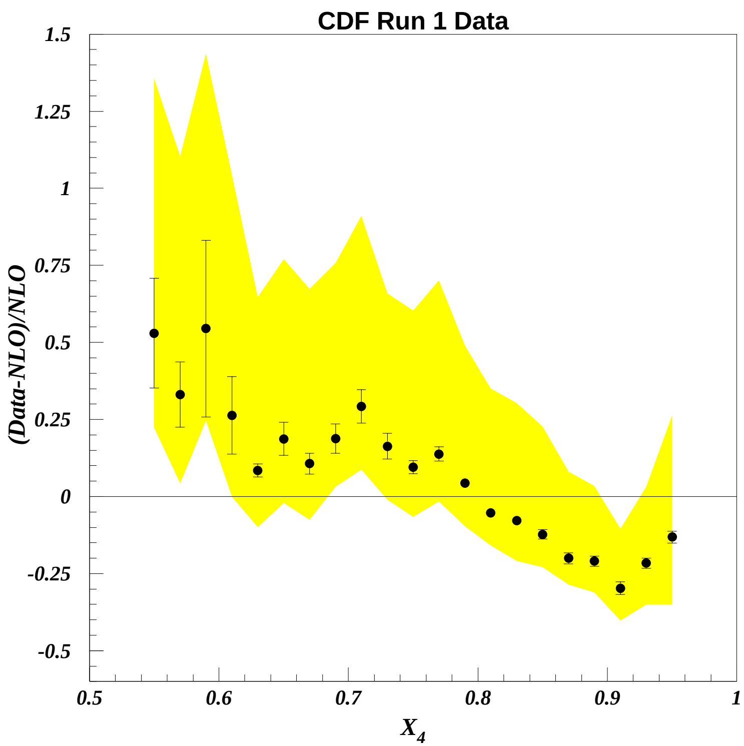
(old) discrepancy due to improper use of fragmentation model [tuned at LEP]

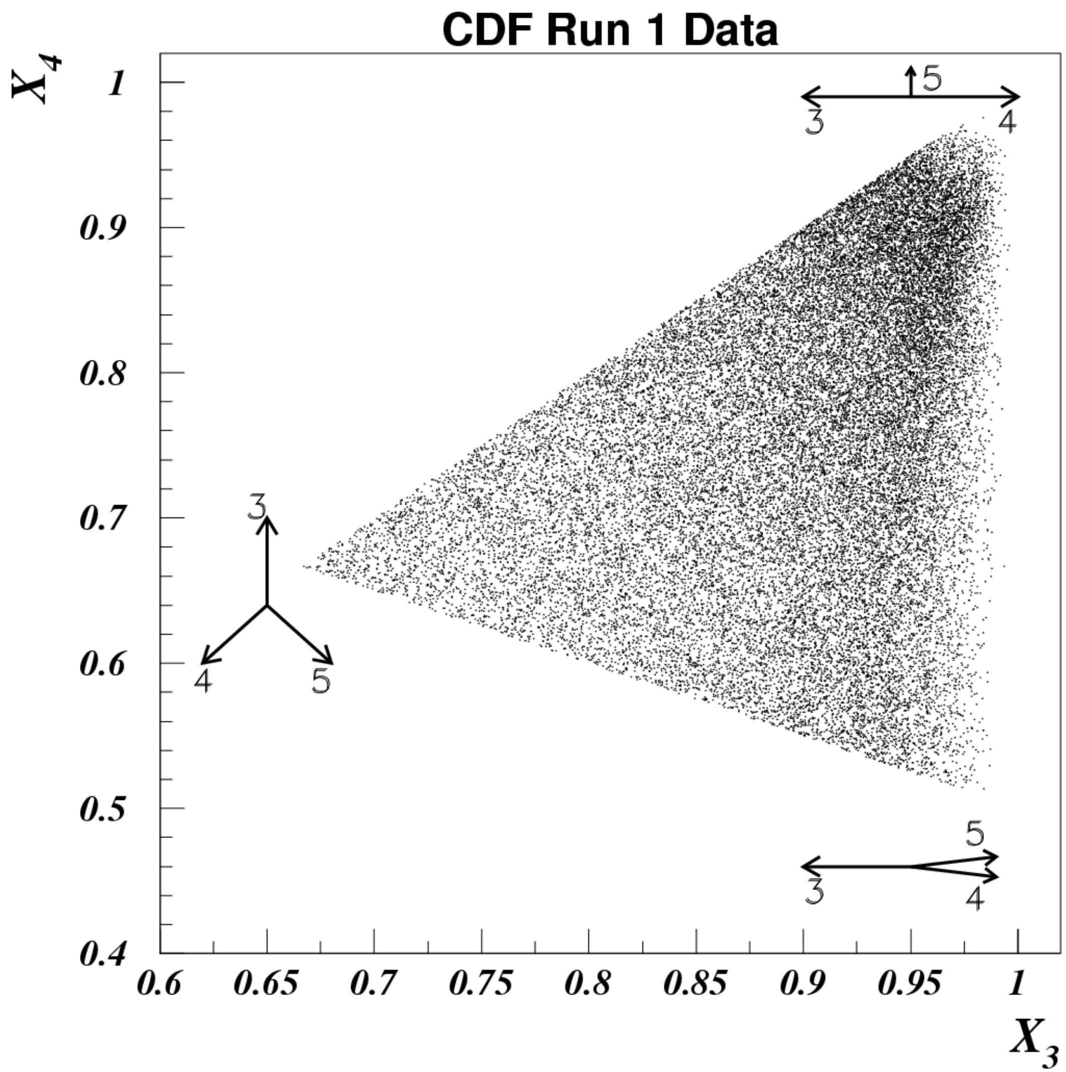
Three jet distributions

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



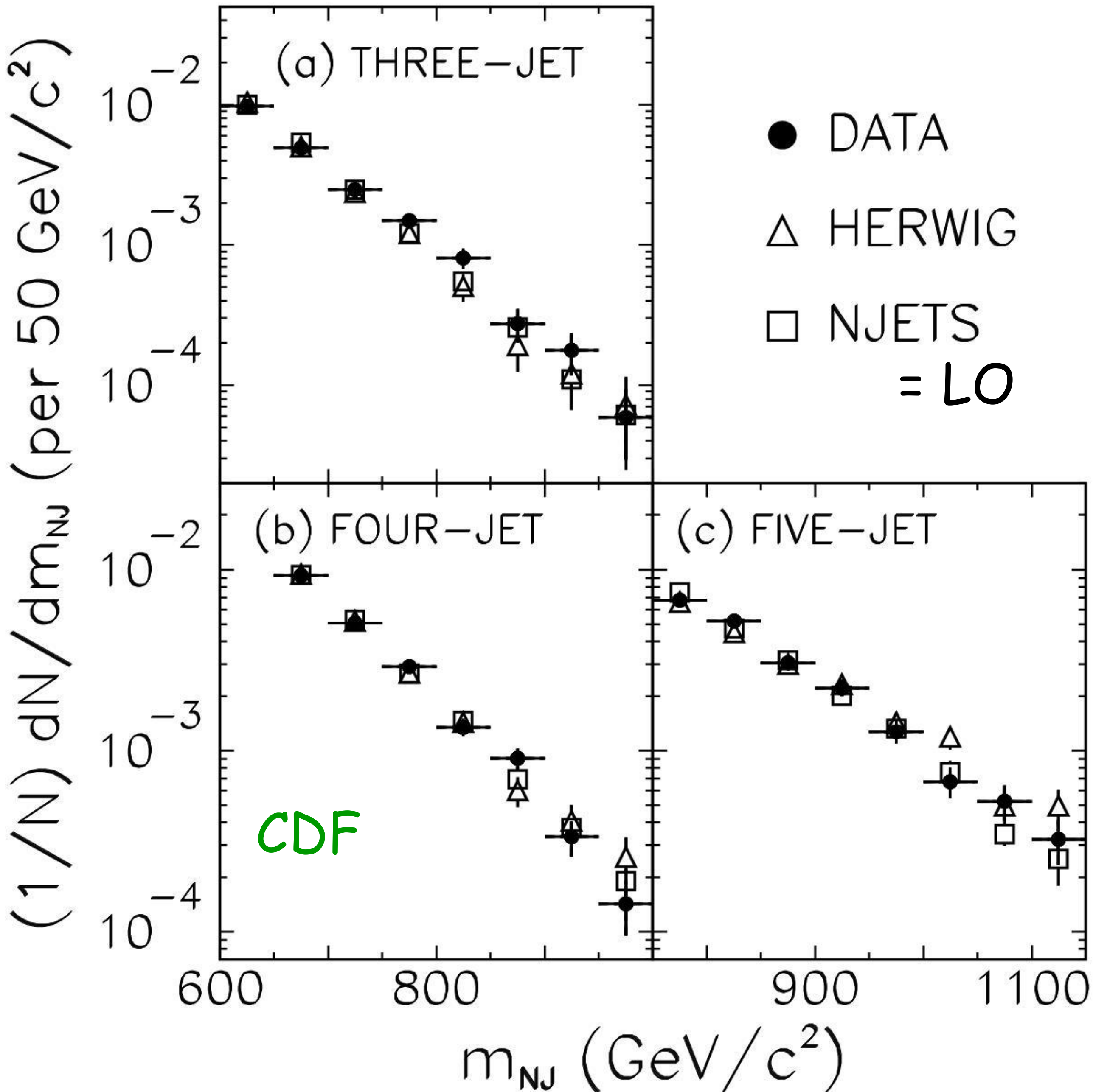
$$x_i = 2E_i / \sqrt{s'}$$





ok !

Multi jet distributions



$|\eta| < 4.2$

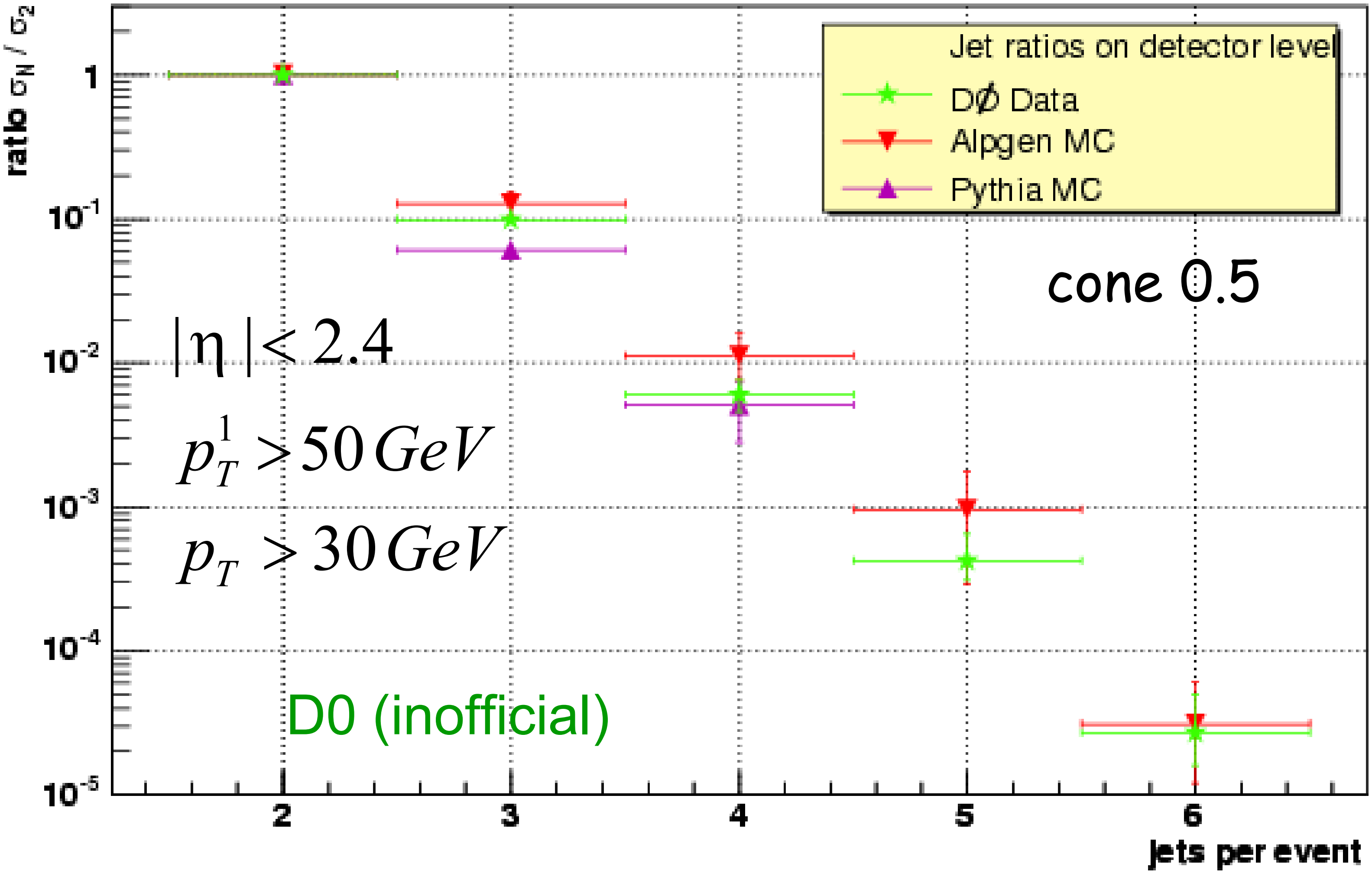
$E_T > 20\, GeV$

$\Sigma E_T > 420\, GeV$

$cone\ 0.7$

ok !

Multi jet xsection



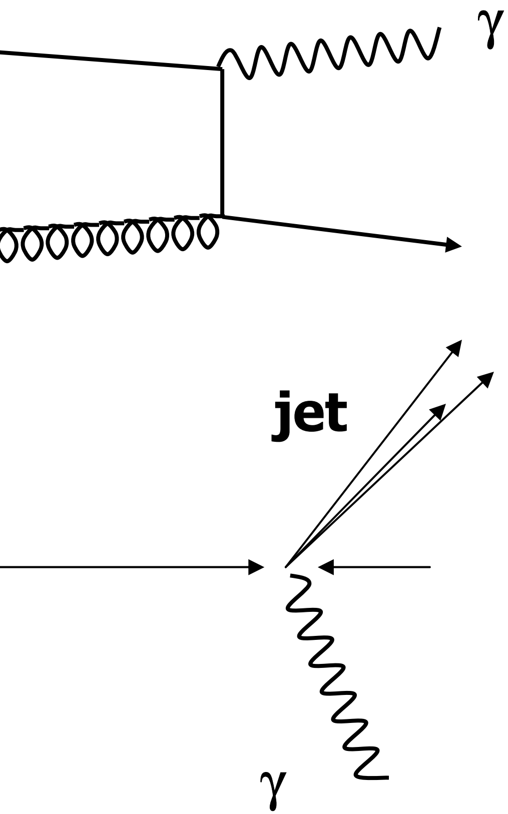
Wilke

4 and more jets calculated

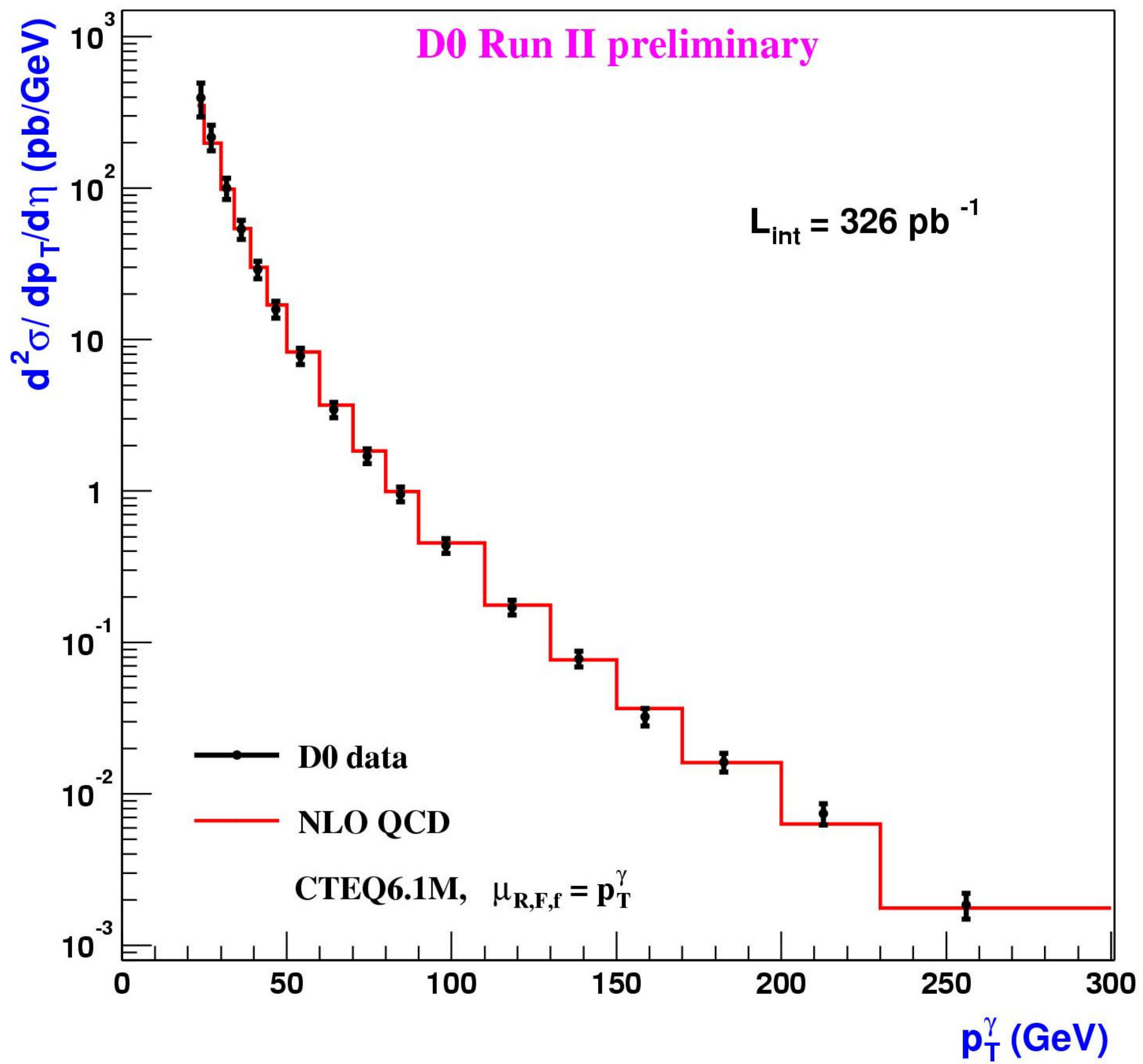
only to leading order

„missing":
α_s from 3/2 jets

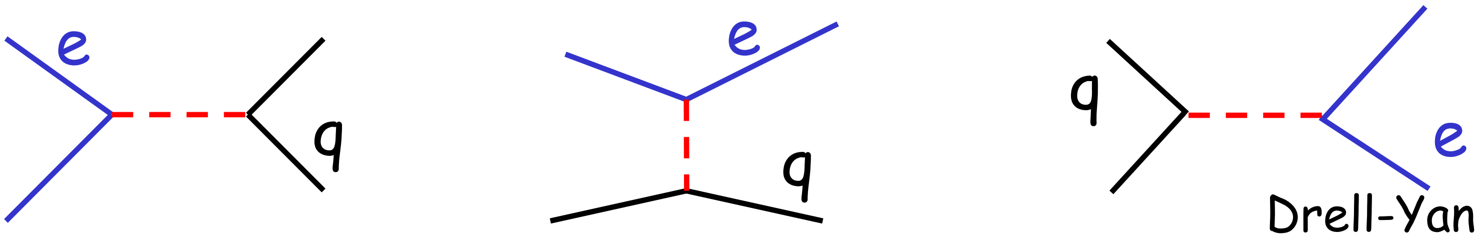
Jet + Photon

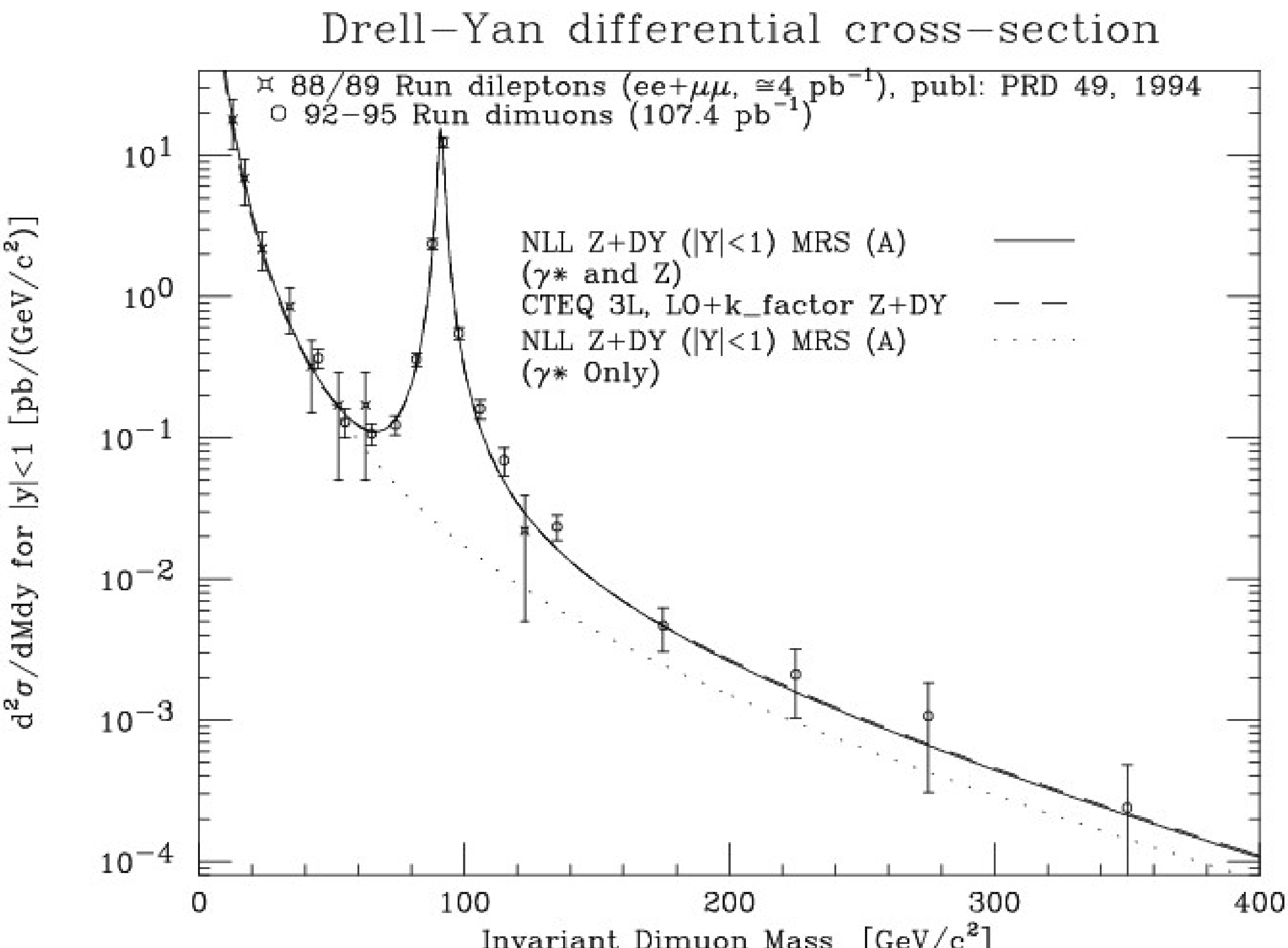


sensitive to pdf's



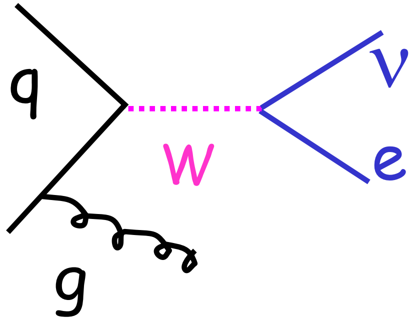
Drell-Yan (γ , Z) inclusive

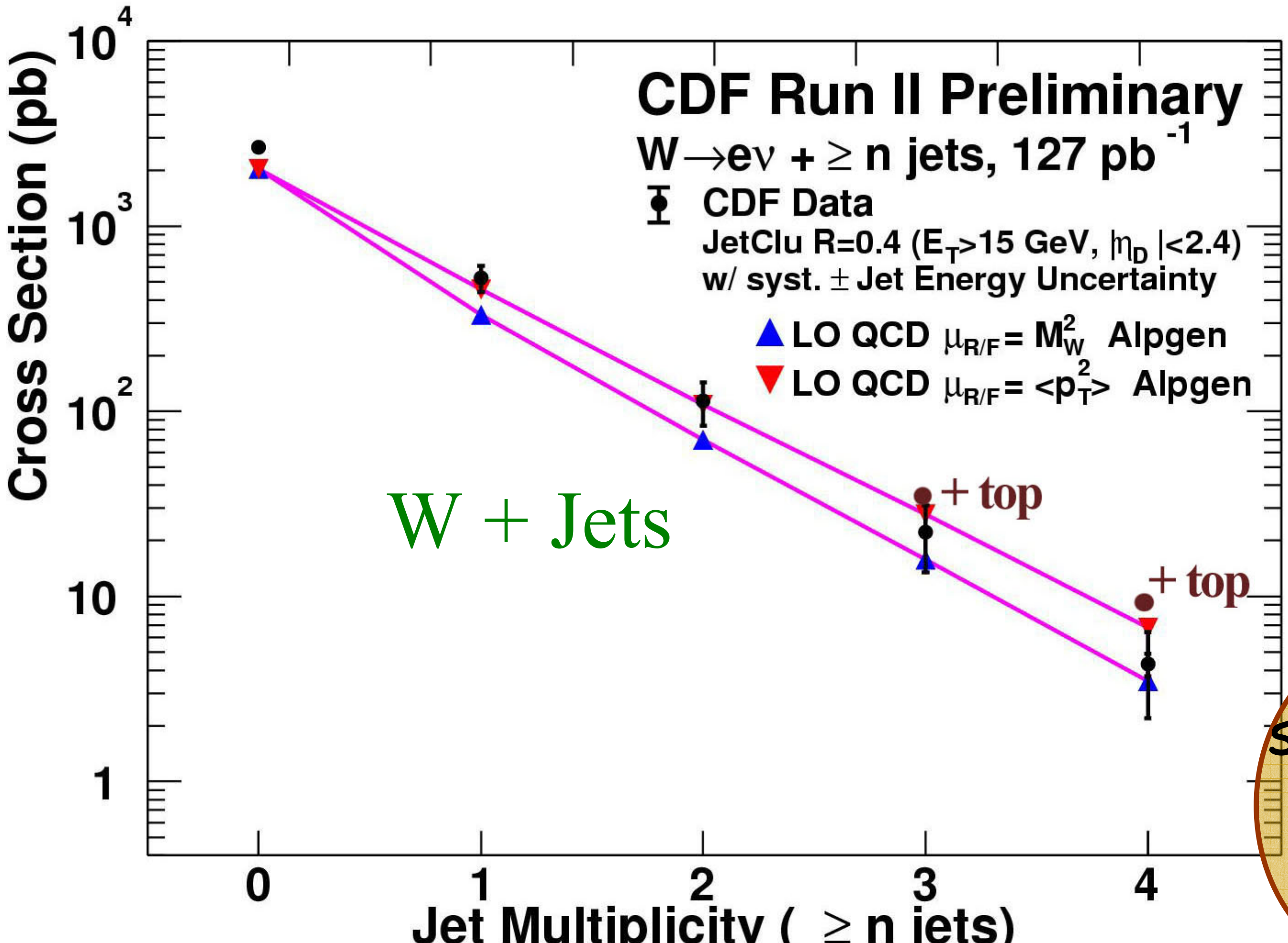




sensitive to pdf's

Drell-Yan: W + jets





sensitive to pdf's

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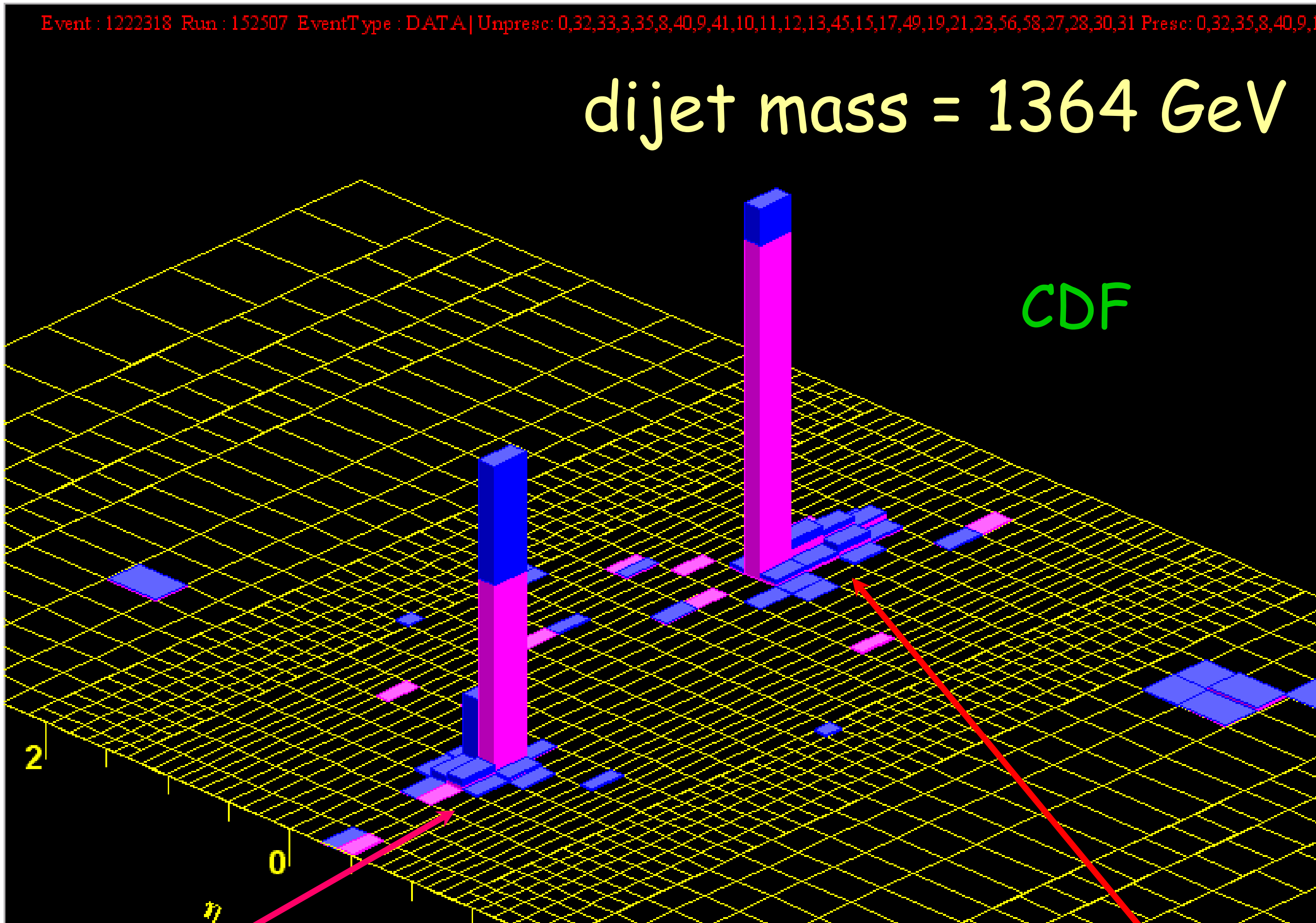
High energy dijet event



E_T = 633 GeV
η = -0.19

E_T = 666 GeV
η = 0.43

1) Introduction

2) Tevatron

3) LHC

$p+p$

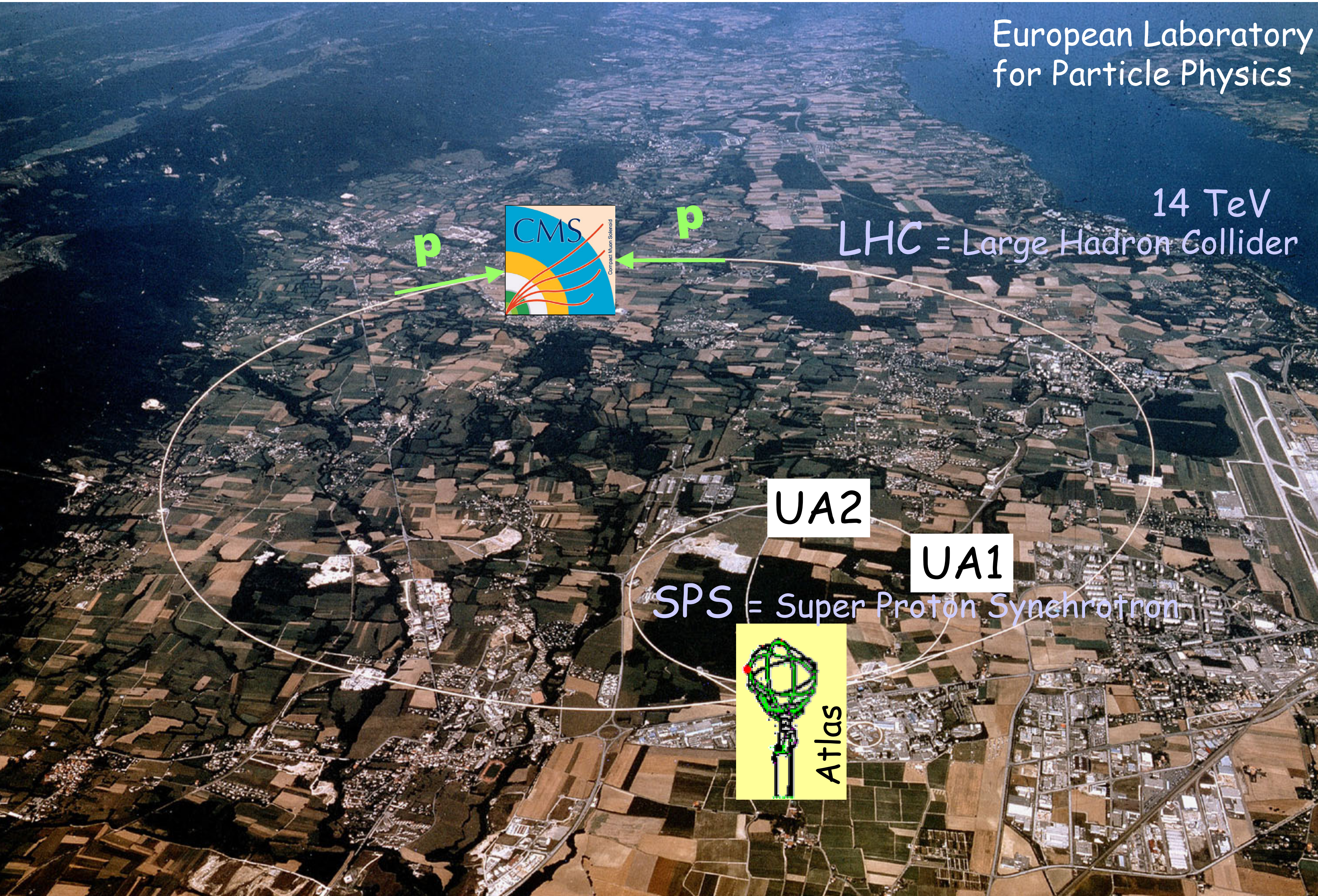
14 TeV

- detectors
- Tevatron ➡ LHC
- examples

t

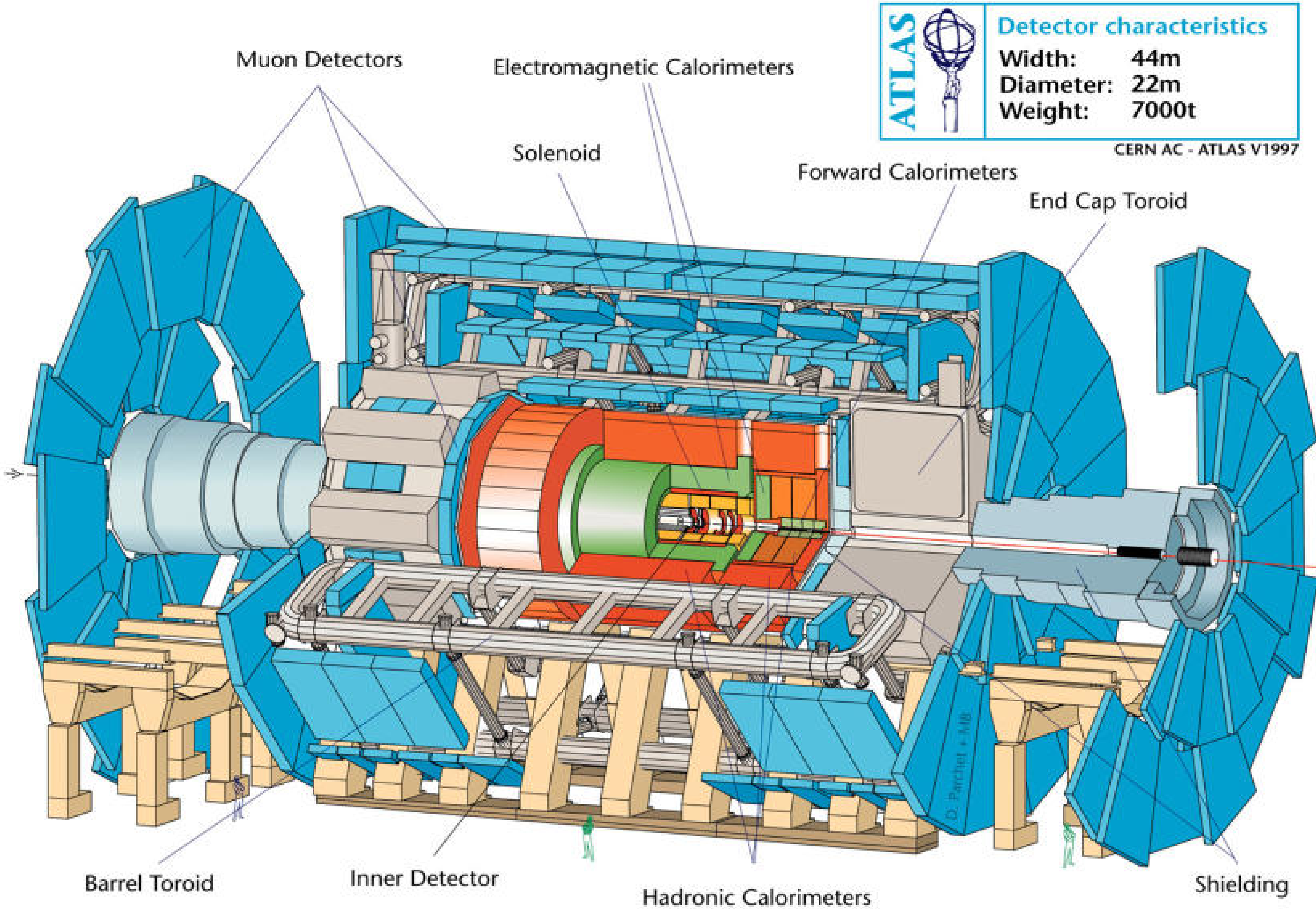
LHC / CERN

T.Hebbeker



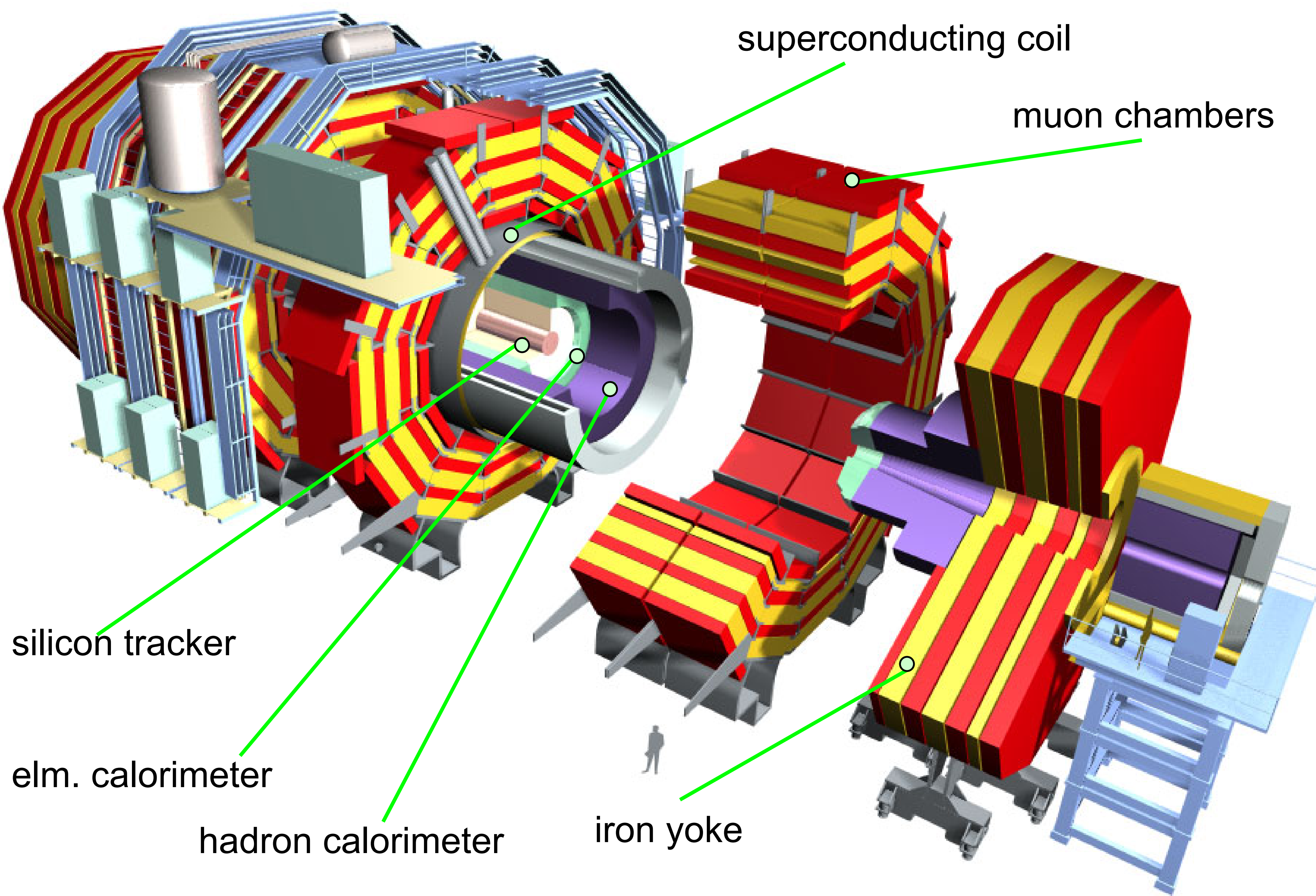
ATLAS = A Toroidal LHC ApparatuS

T.Hebbeker



CMS = Compact Muon Solenoid

T.Hebbeker



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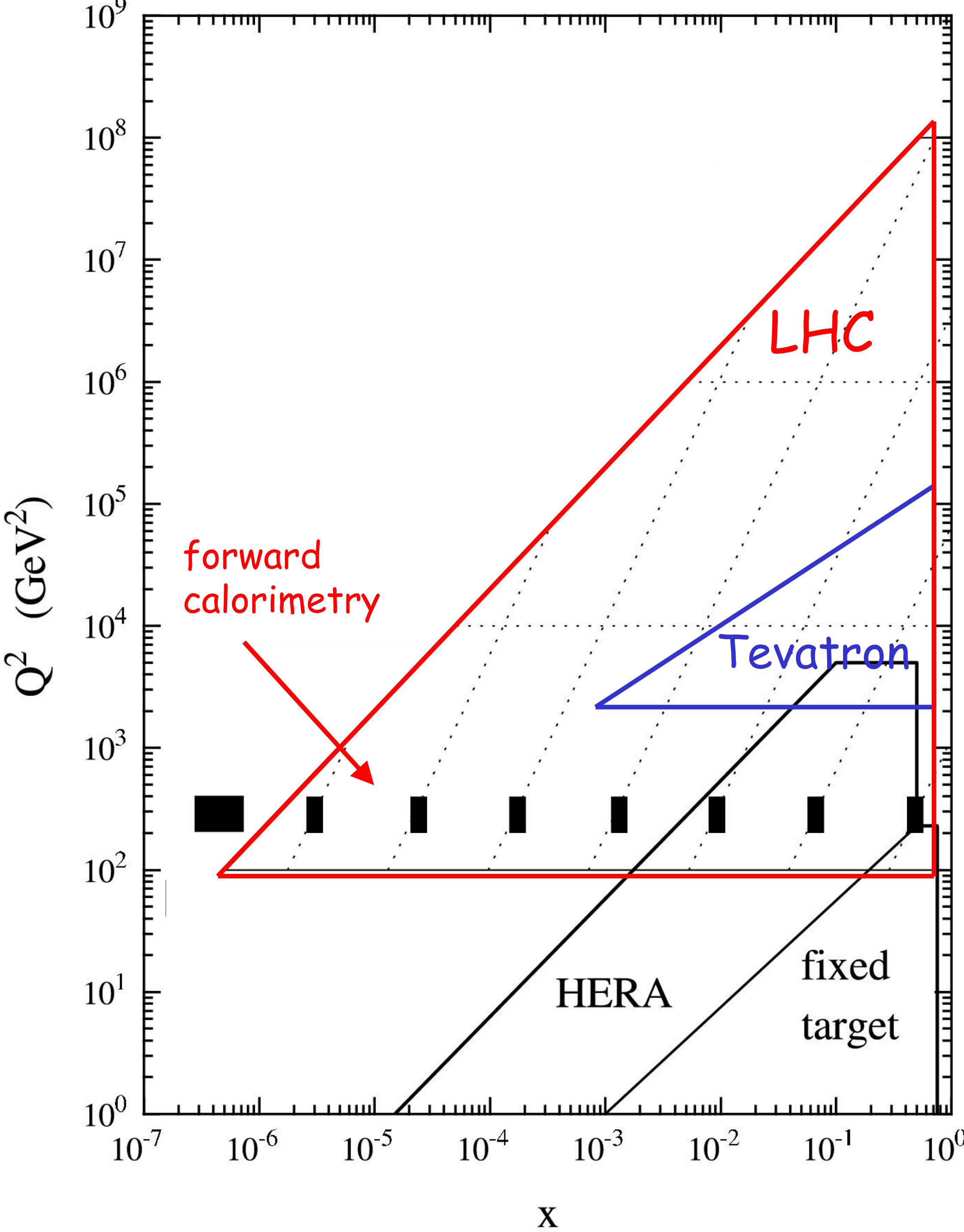
LHC machine/detector perfomance (jets)

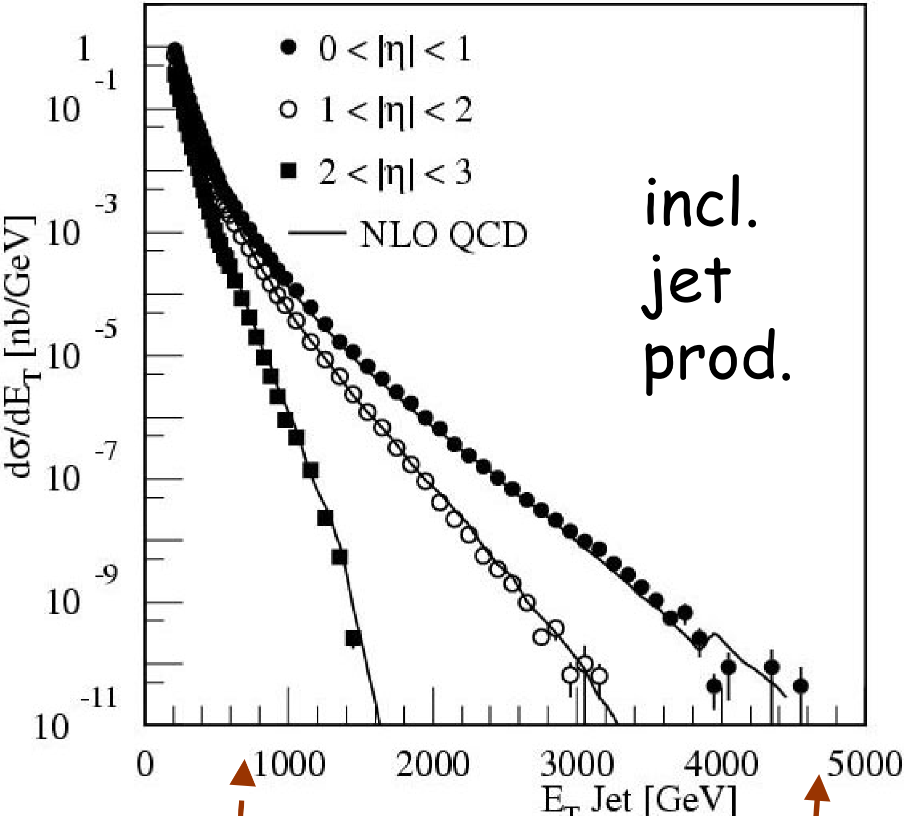
Tevatron	LHC
$2\ TeV$	$14\ TeV$
$10^{32}\ /\ cm^2\ /\ s$	$10^{34}\ /\ cm^2\ /\ s$
$\frac{\sigma}{E} = \frac{80\%}{\sqrt{E\ /\ GeV}} \oplus 4\%$	$\frac{\sigma}{E} = \frac{50\%}{\sqrt{E\ /\ GeV}} \oplus 3\%$
$\frac{\delta\ E}{E_0} = 5\%$	$\frac{\delta\ E}{E_0} = 1\%$
D0	ATLAS

Kinematic Range

LHC will improve knowledge of gluon pdf at low x



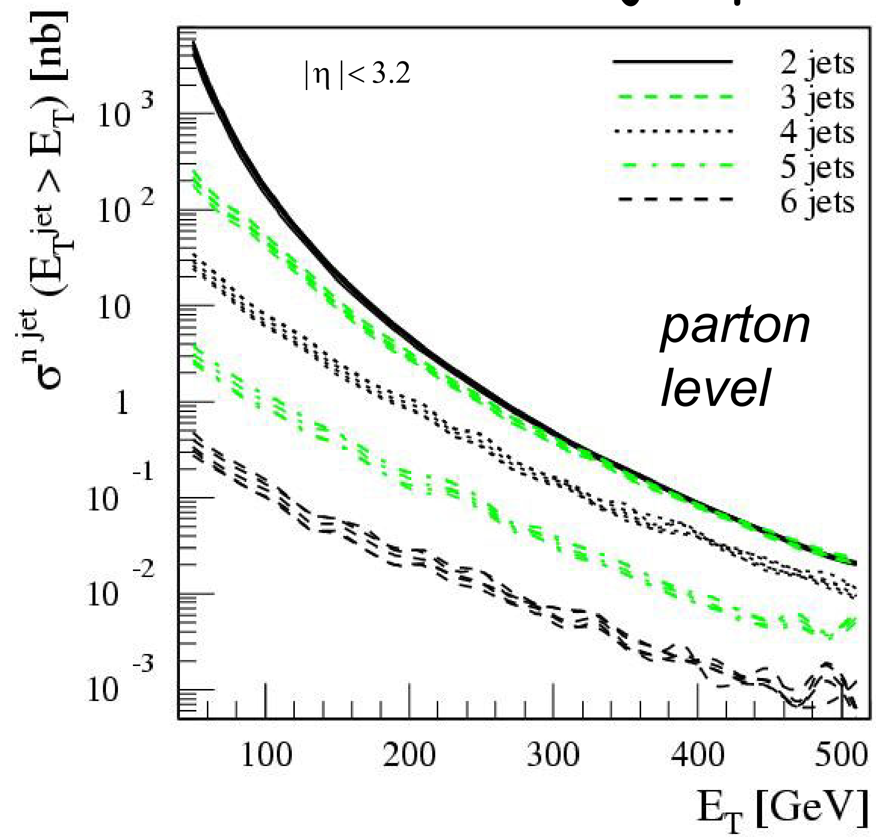
Tevatron - LHC: Similarities



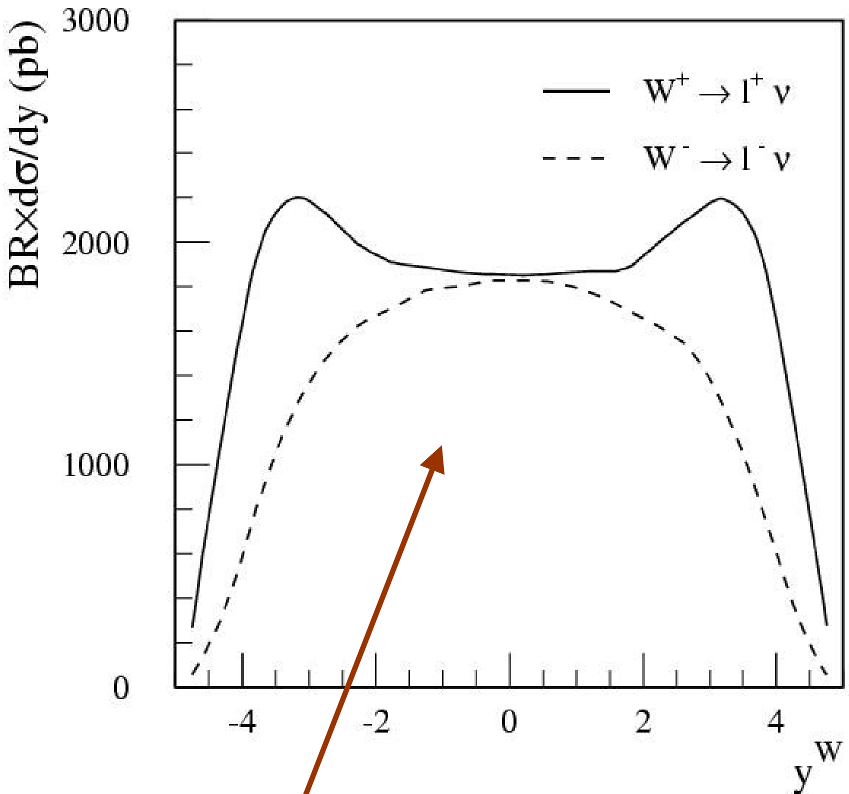
(Tevatron)

~ 5 TeV !

multijet prod.



Tevatron - LHC: Differences



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

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

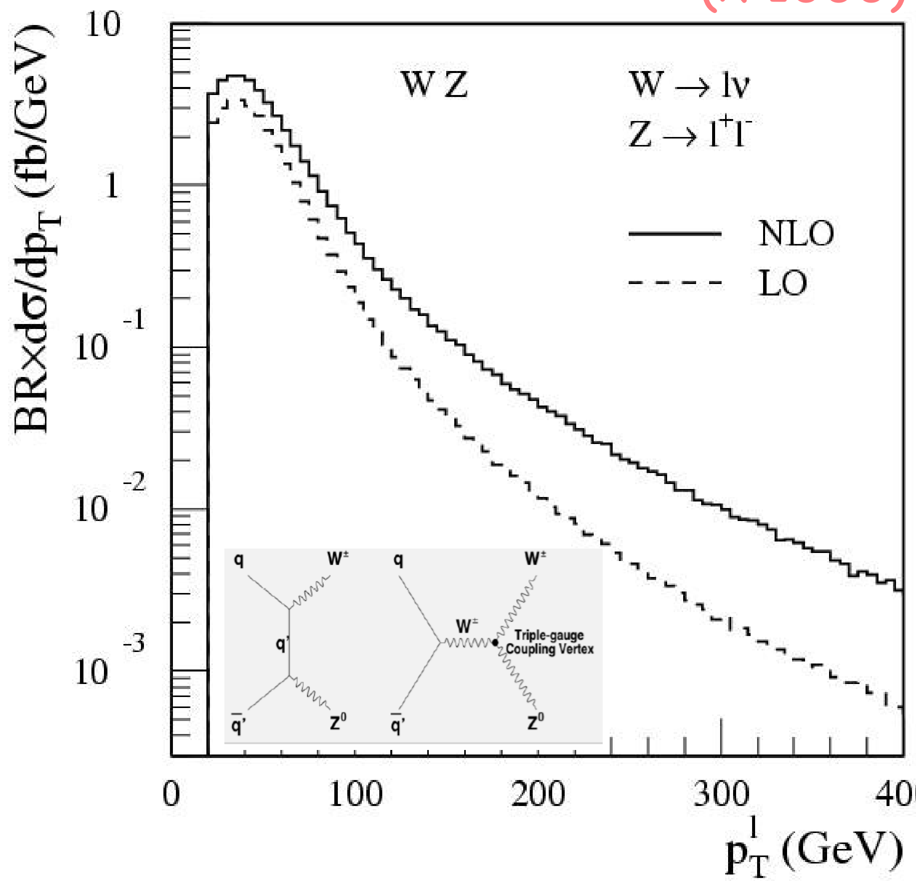
$\bar{u}d \rightarrow W^-$

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

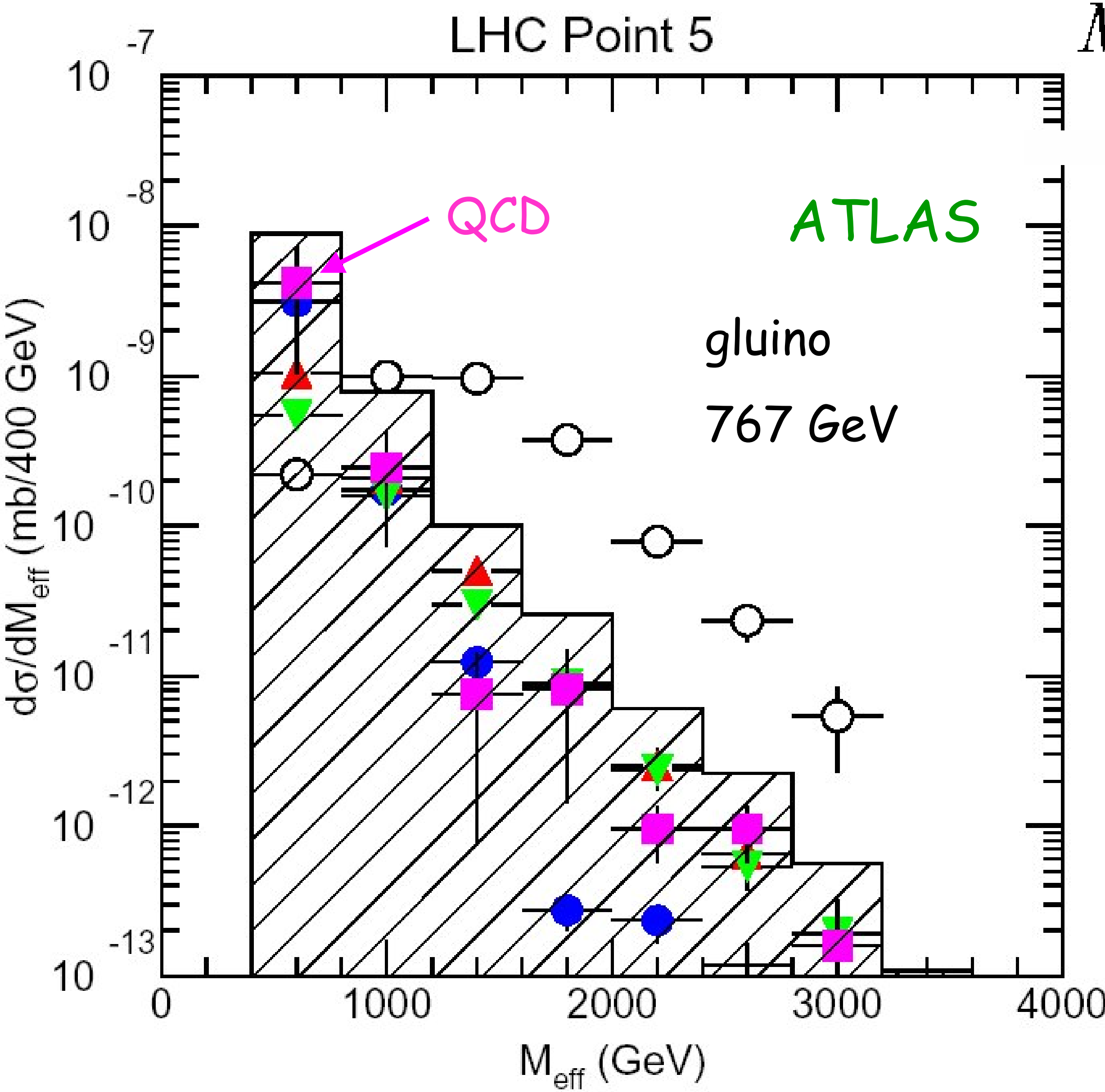
$$\sigma(WZ, 14TeV) = 27\,pb$$

statistics!

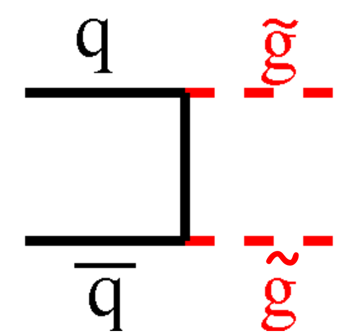
(x 1000)

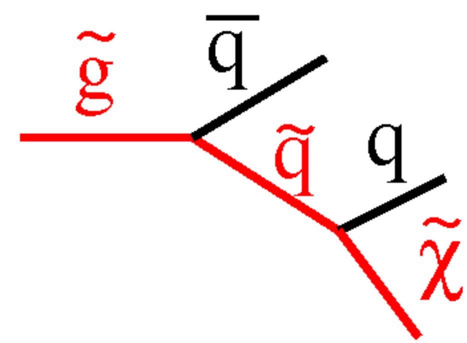


SUSY searches with jet events

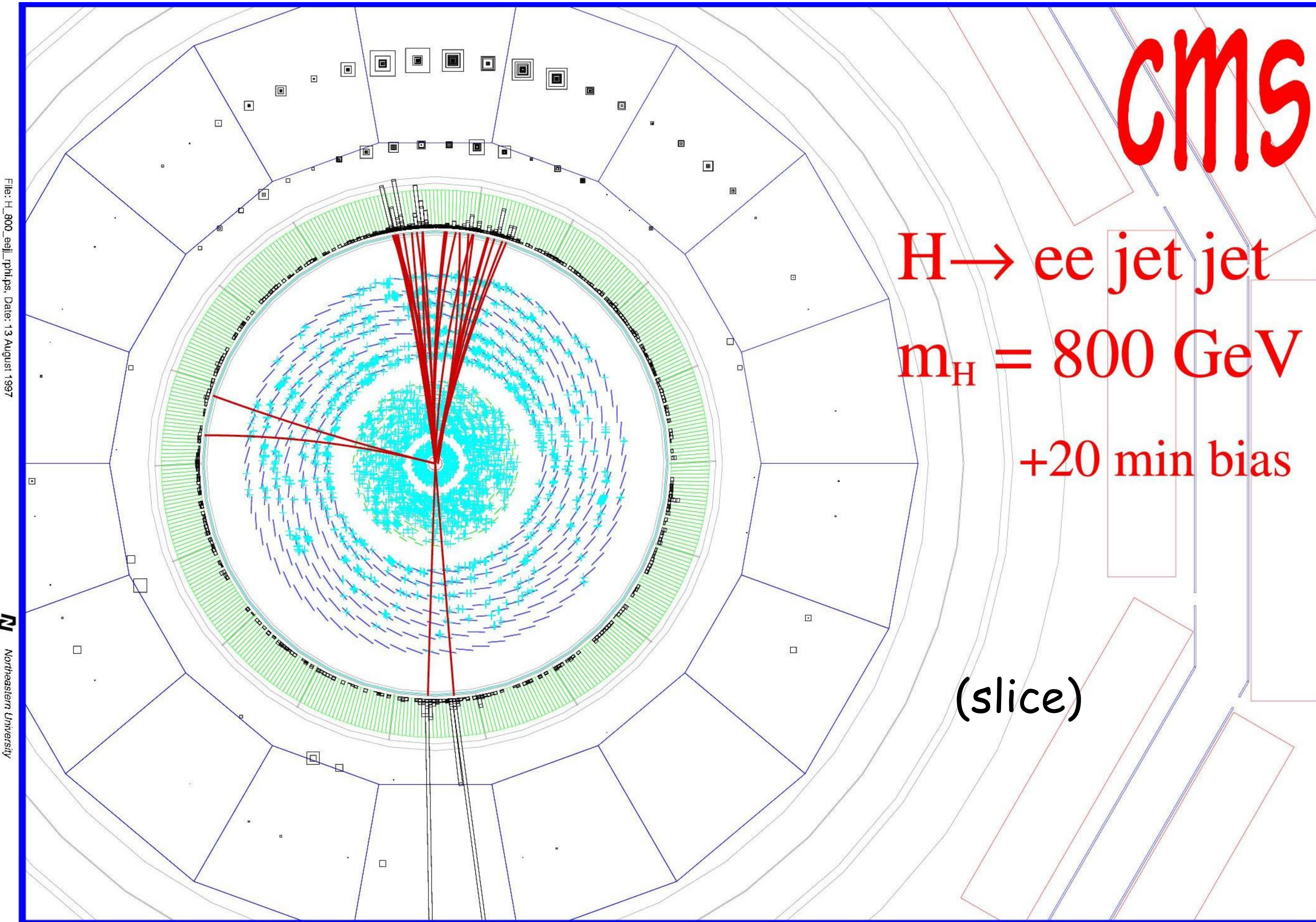


$$M_{eff} = \sum_{j=1} p_{T,j} + E_T^{miss}$$



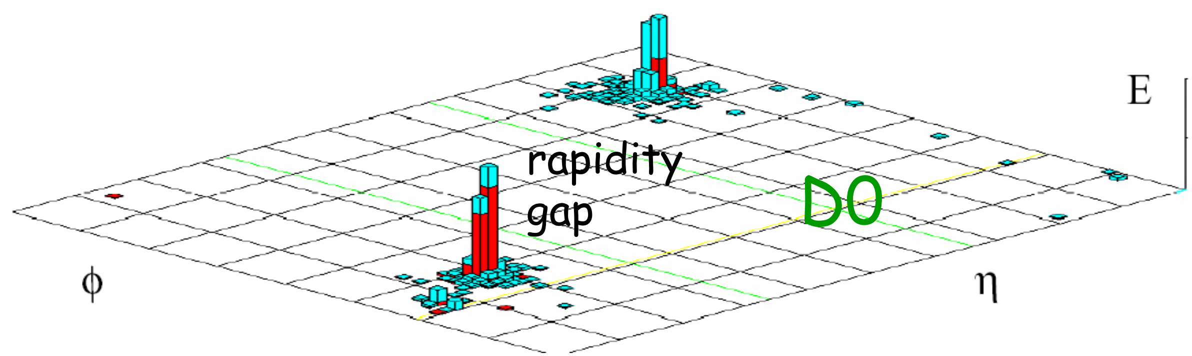


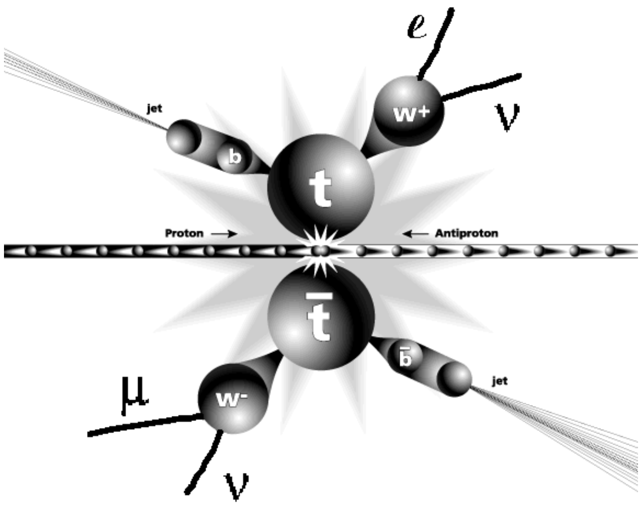
2008 ?


CMS
H→ ee jet jet
m_H = 800 GeV
+20 min bias
(slice)
File: H_800_eejj_rphi.ps, Date: 13 August 1997
Northeastern University

Not covered ...

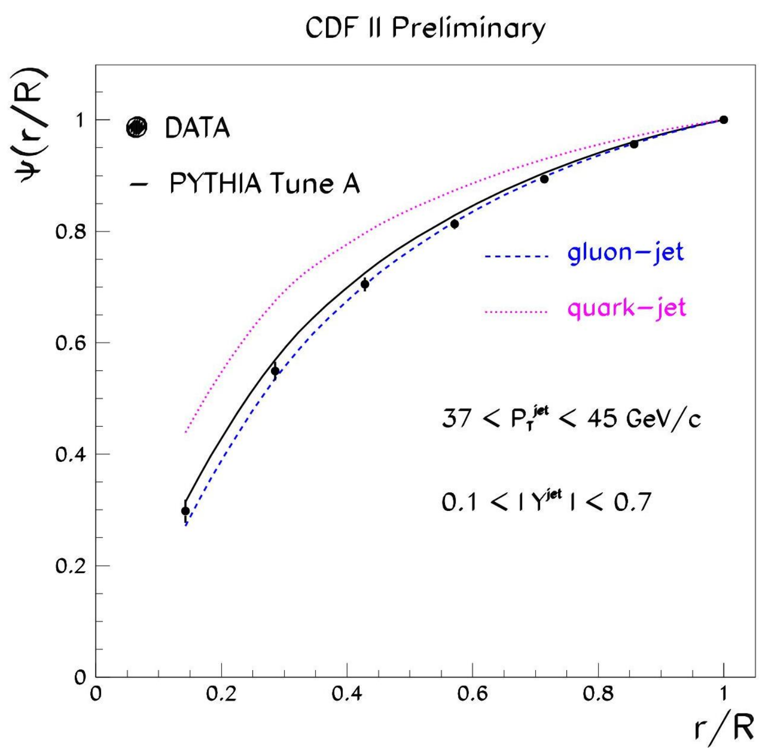
- diffractive processes





- top physics

- jet shape and structure



...

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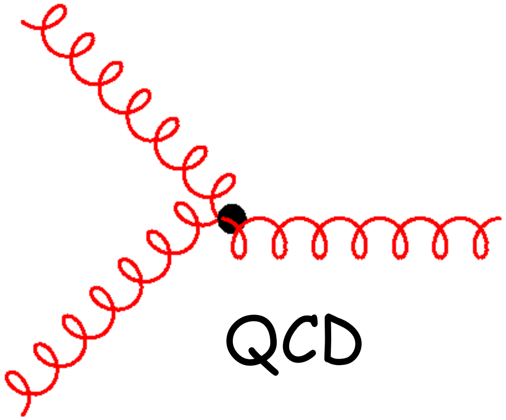
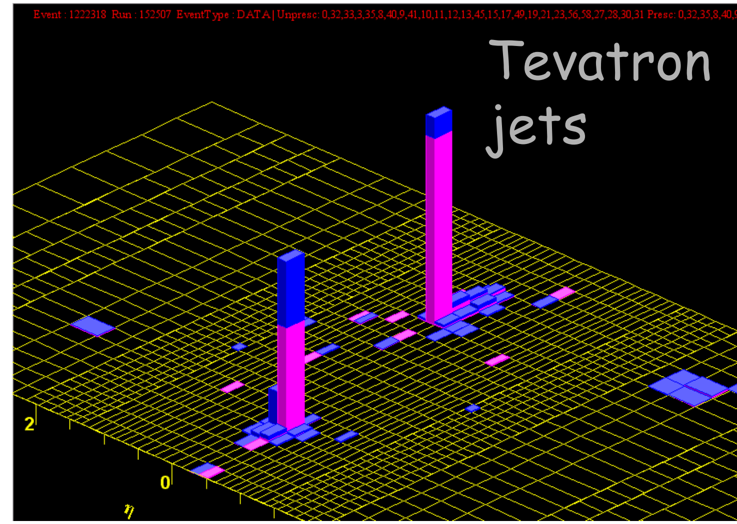
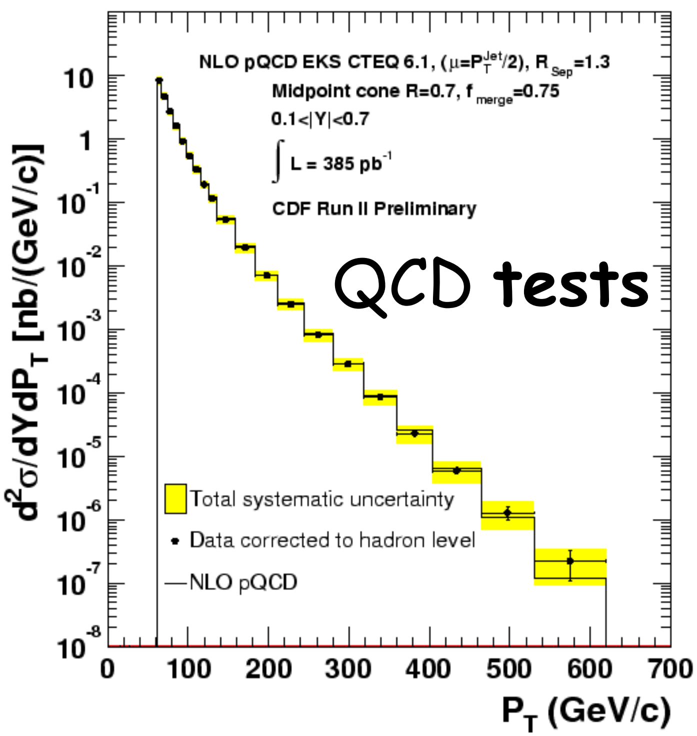
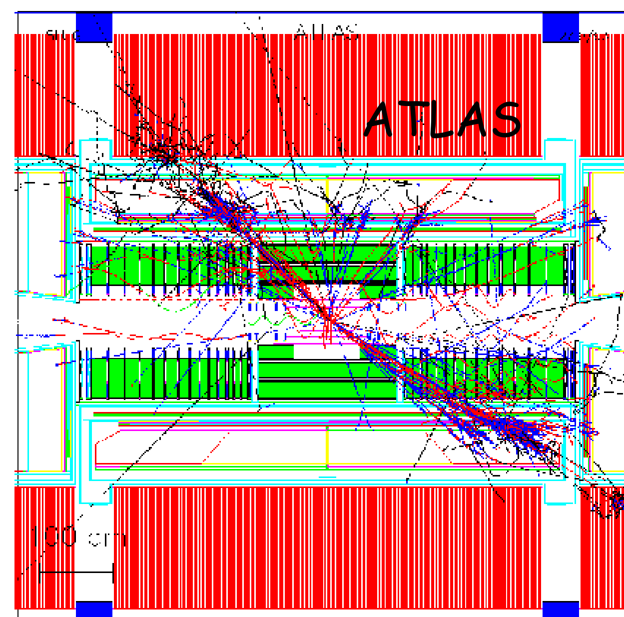
Summary







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

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

$$\begin{array}{rcl}
\alpha, \beta, \ldots = & 1,2,3,4 & \text{Dirac index} \\
\mu, \nu, \ldots = & 1,2,3,4 & \text{space time index} \\
a, b, \ldots = & 1, \ldots, N_{\mathrm{C}} = 3 & \text{quark color index} \\
r, s, \ldots = & 1, \ldots, N_{\mathrm{C}}^2 - 1 = 8 & \text{gluon color index} \\
j, k, \ldots = & 1, \ldots, N_{\mathrm{F}} & \text{flavor index} .
\end{array}$$

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

Missing transverse energy/momentum

a) energy = momentum (masses small)

b) $\vec{p}_T$ can be measured for all „visible" particles:

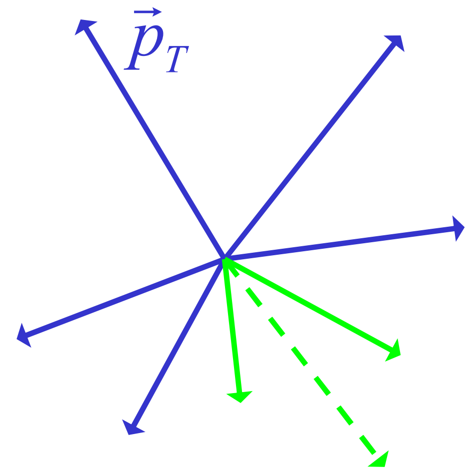
i) small angle to beam pipe: escapes but $\vec{p}_T$ small

ii) large angle: seen in detector

c) „invisible particles" (neutrinos, gravitons, ...):

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

plane perpendicular to beam:



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

(Example: $W \to \mu \, \nu$)

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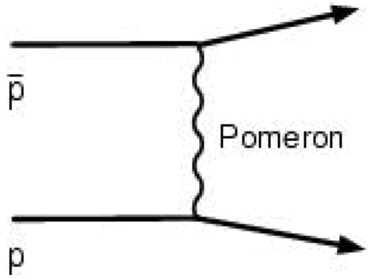
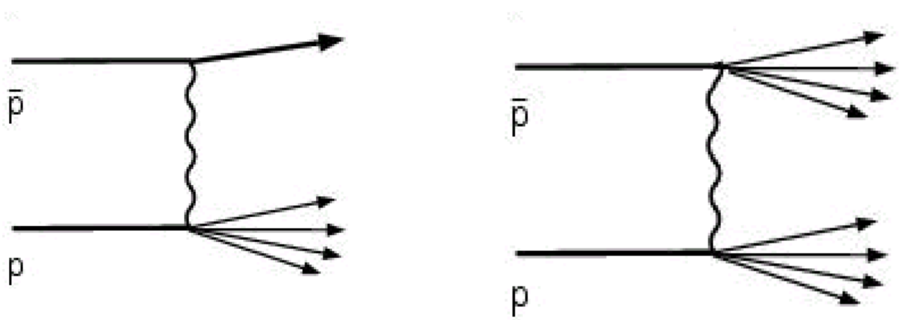
Soft hadronic processes (LHC)



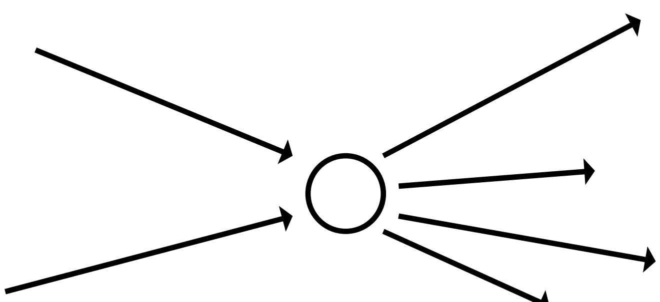
(zero quantum numbers!)

Elastic

(20 mb)



diffractive (25 nb)

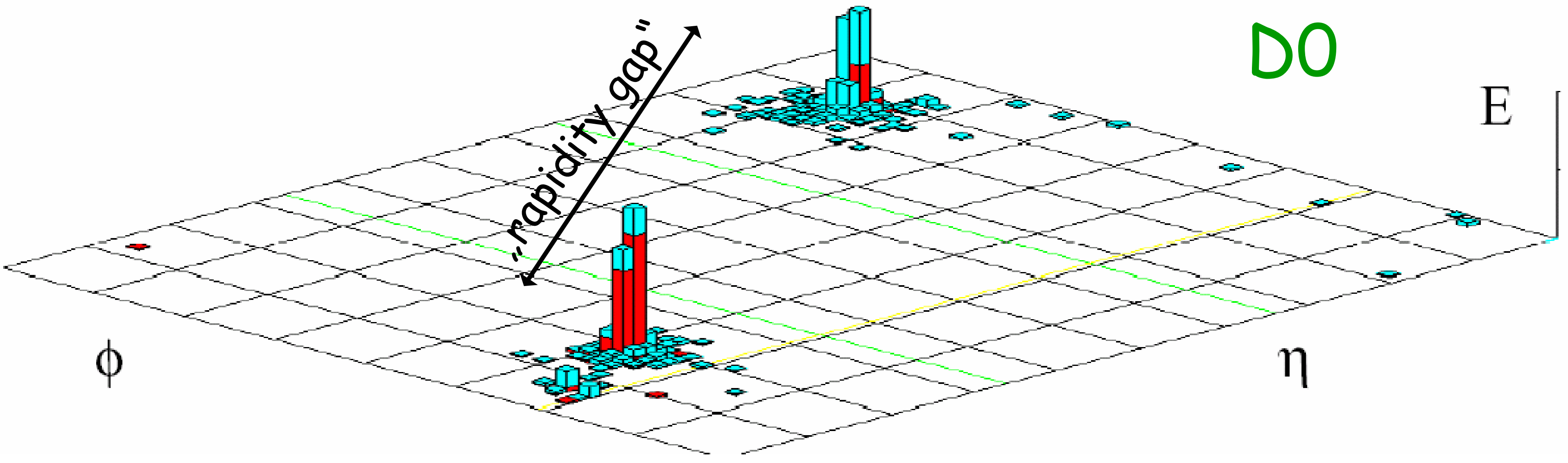


non-diffractive (55 nb)

Inelastic

(80 mb)

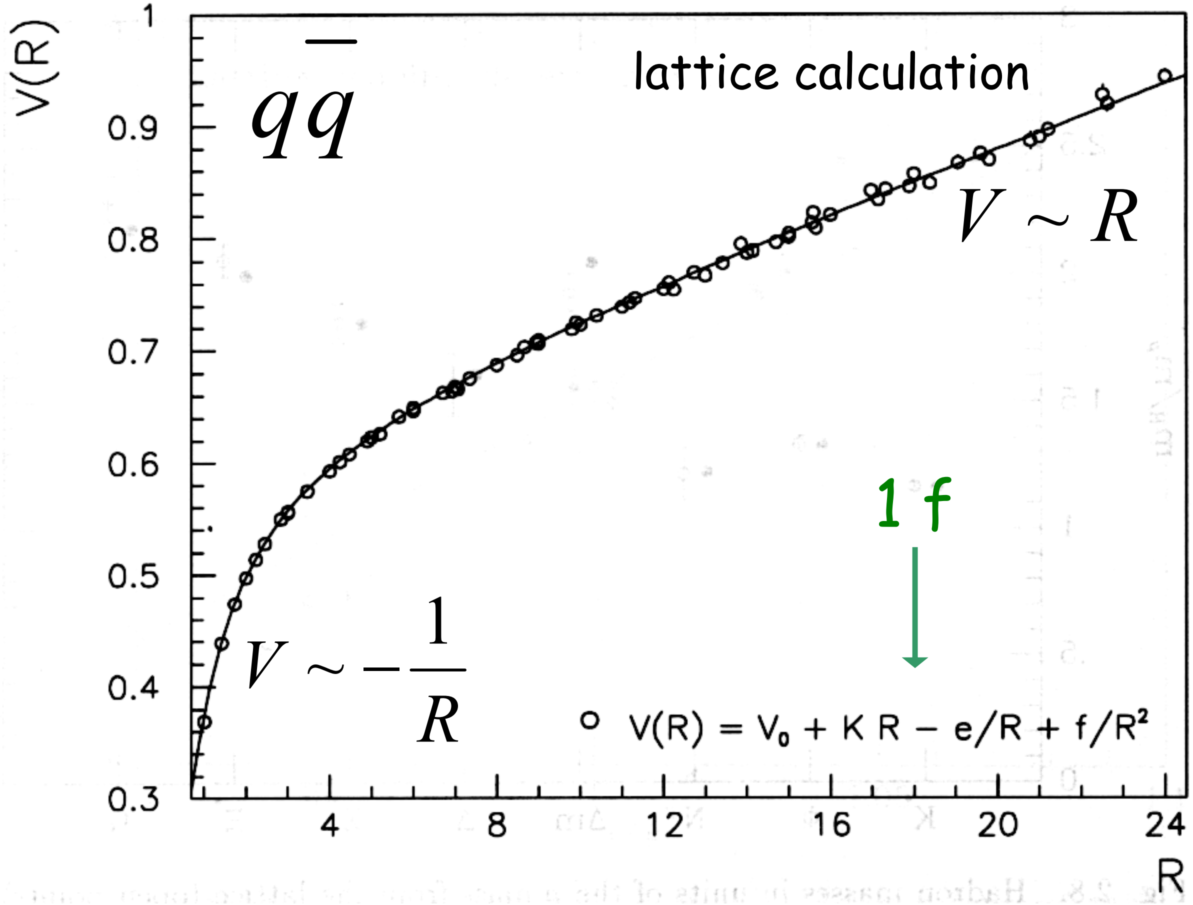
Double-Diffractive Event



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

QCD at large distances

quarks and gluons confined:



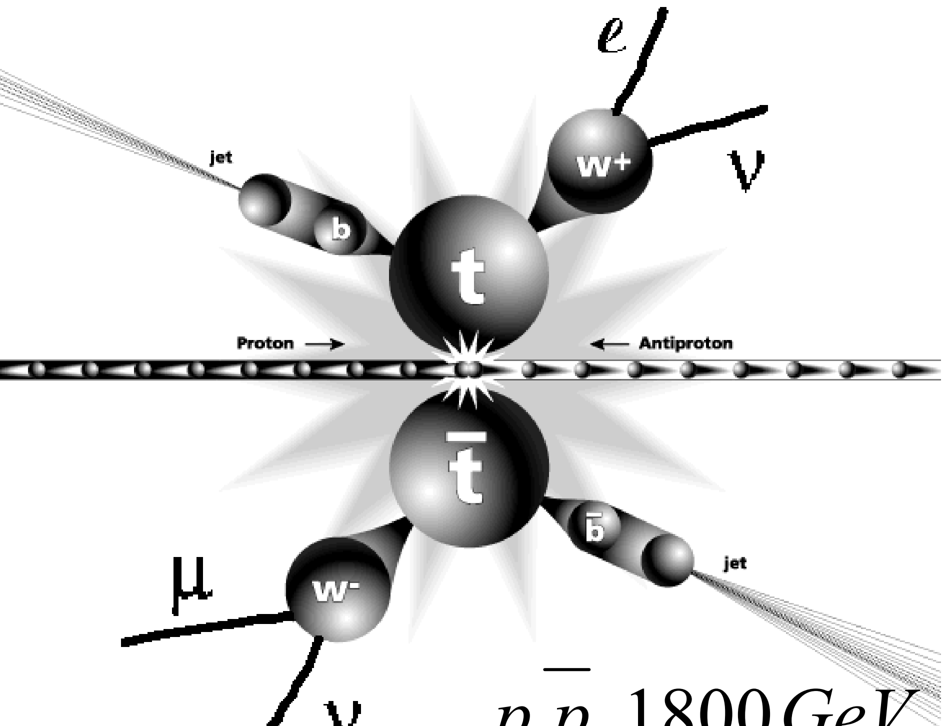
bound states

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

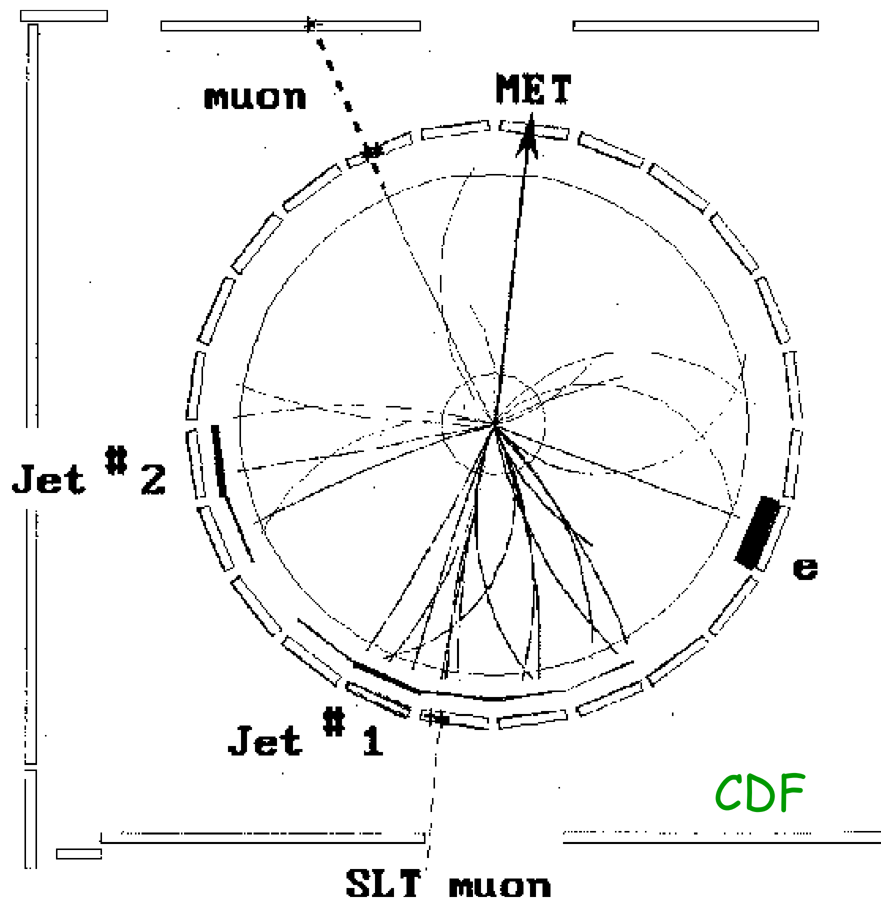
Top Discovery

Fermilab, 1995

CDF, D0



$p\,\bar{p}\;\; 1800\, GeV$

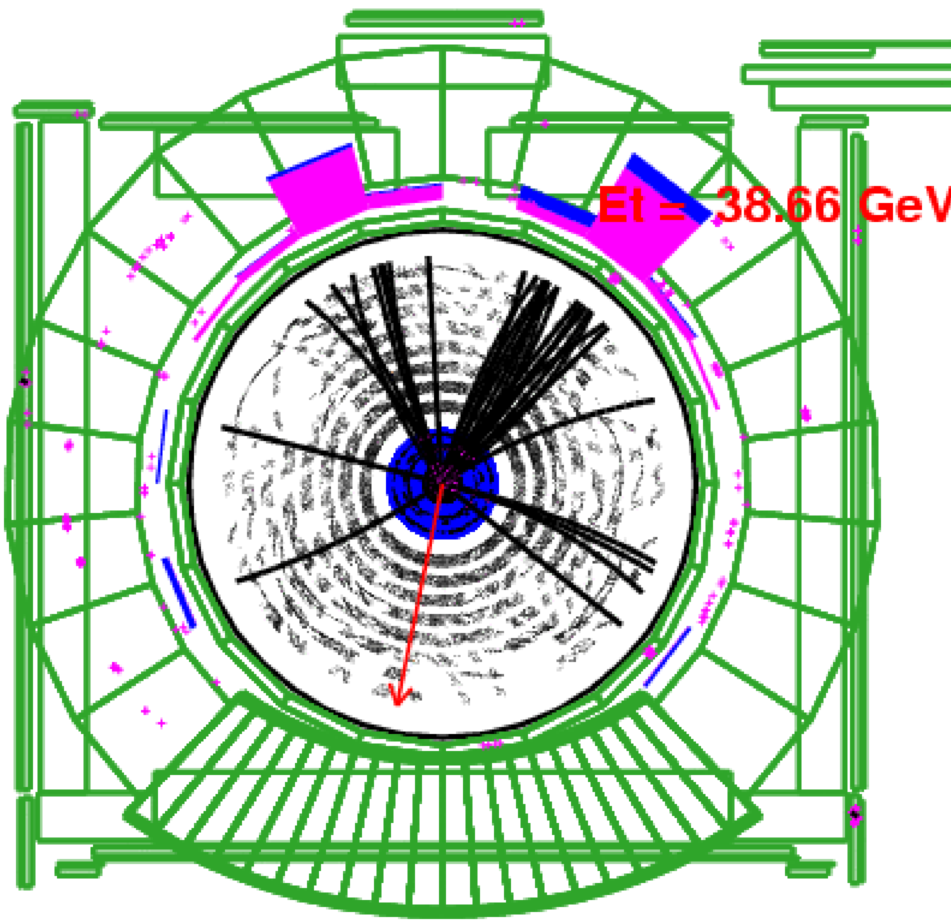


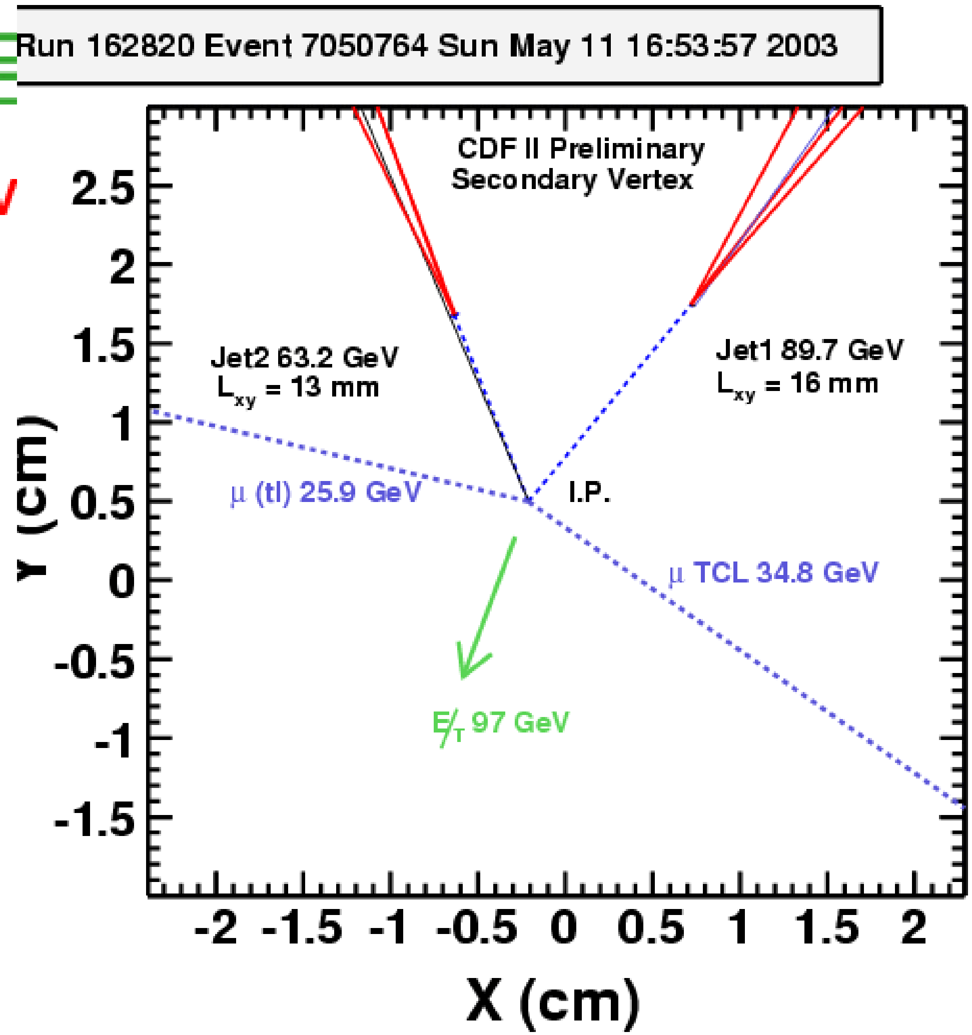
m ~ 175 GeV

Top event in CDF

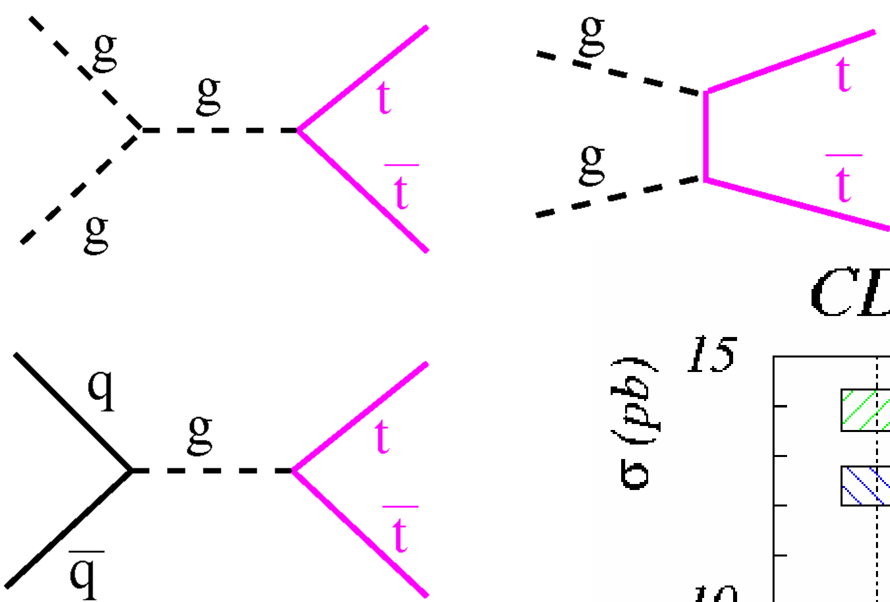
Run II

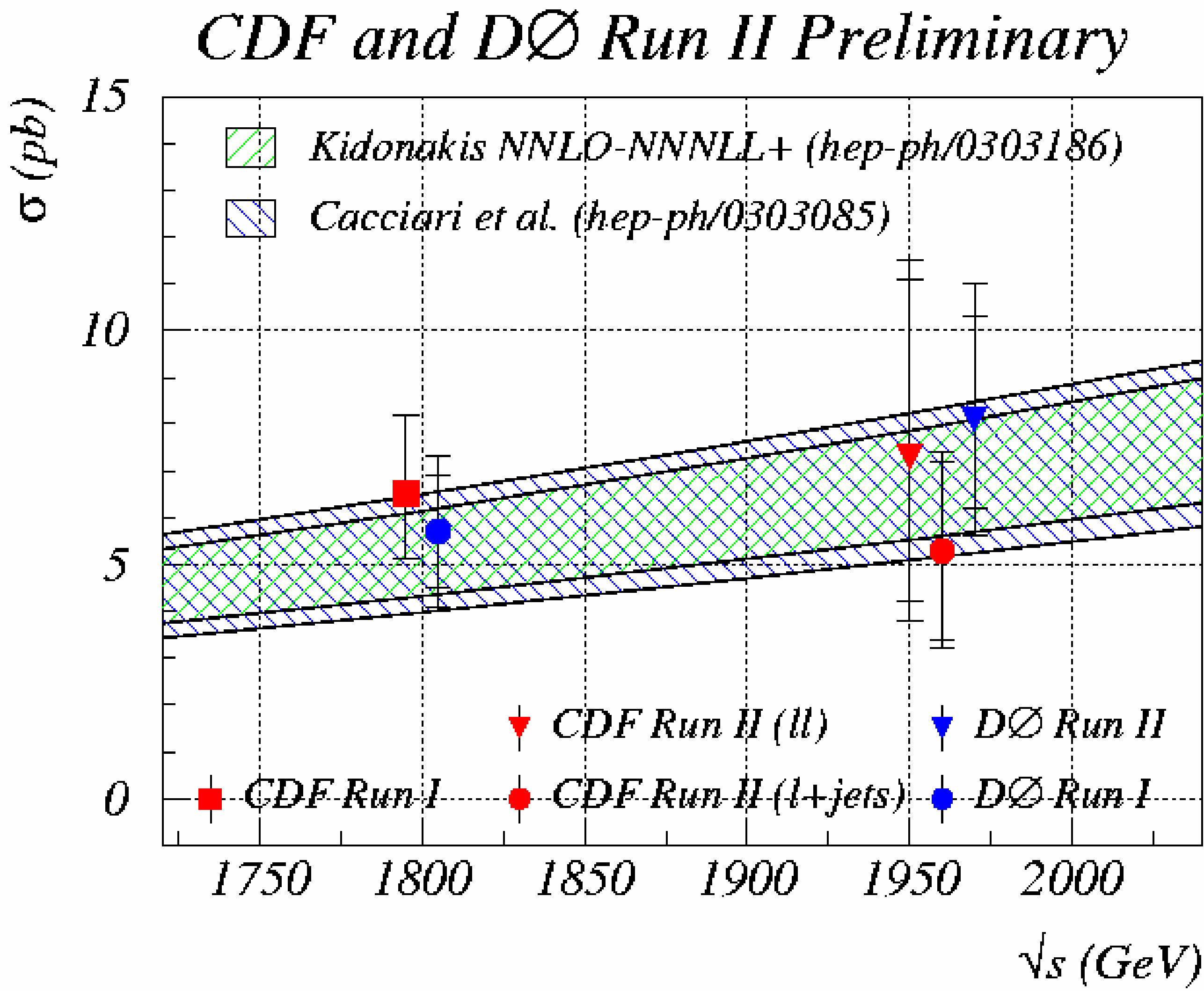
(~ 100 events)





Top Pair Production

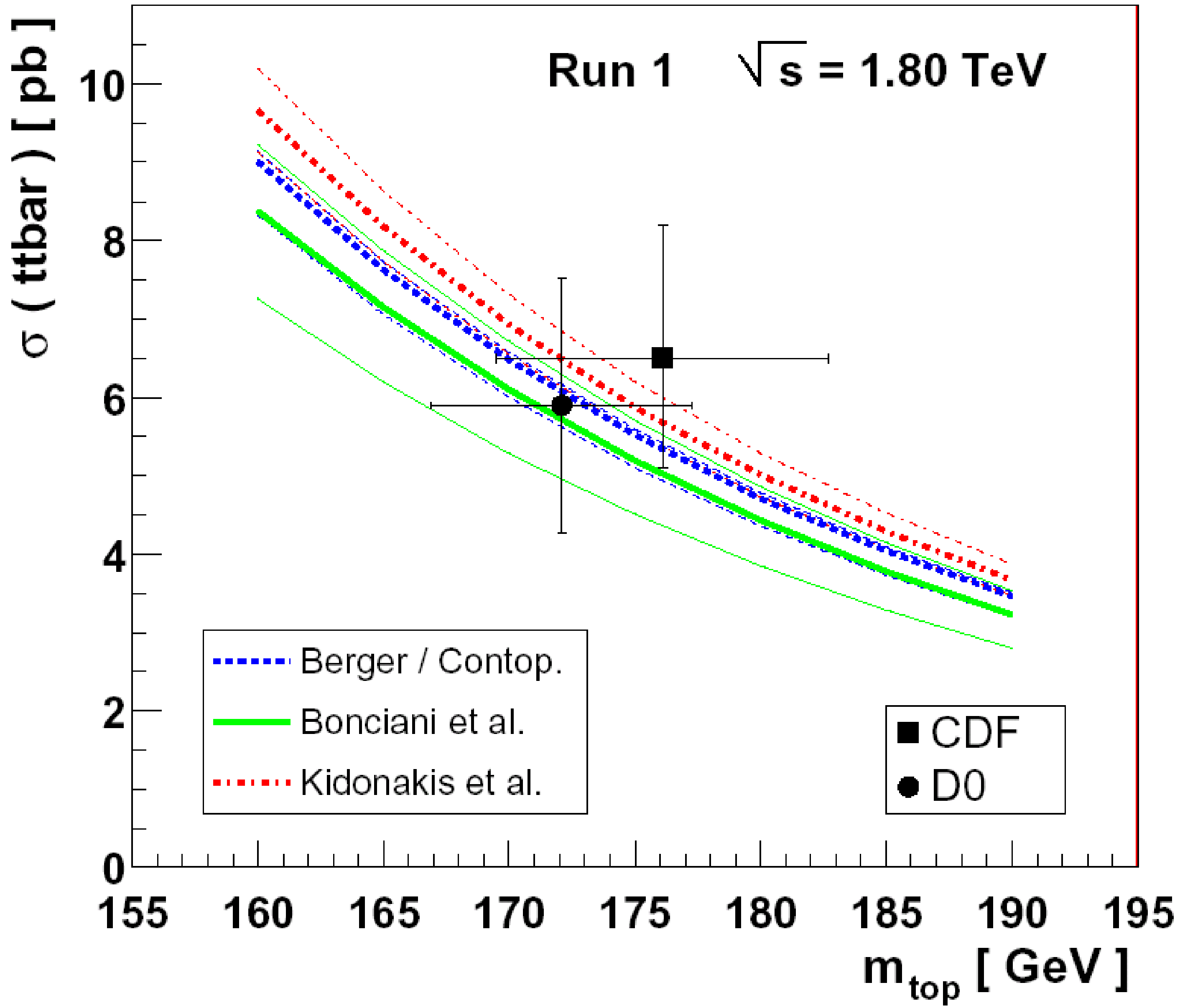




gg contributes

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

Top Cross Section and Top Mass



cross section measurement = indirect mass determination!

Rapidity distribution

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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:

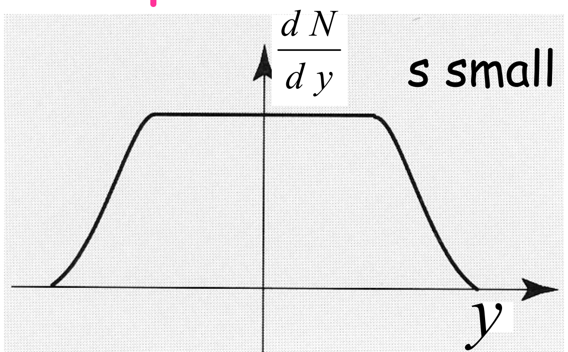
$$-\ln \frac{\sqrt{s'}}{m} \leq y \leq \ln \frac{\sqrt{s'}}{m}$$

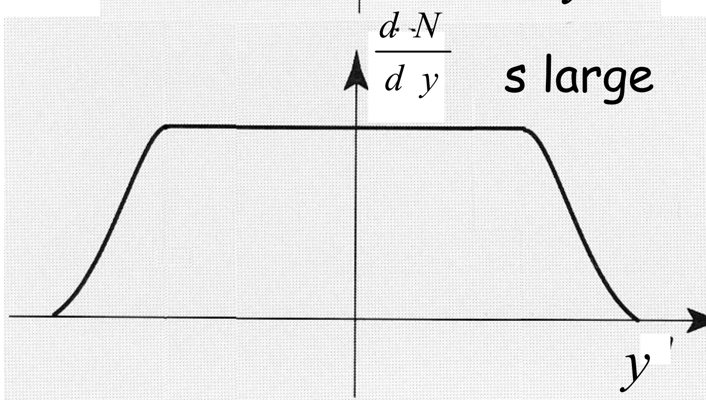
Empirical in pp collisions:

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

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

... „plateau"





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