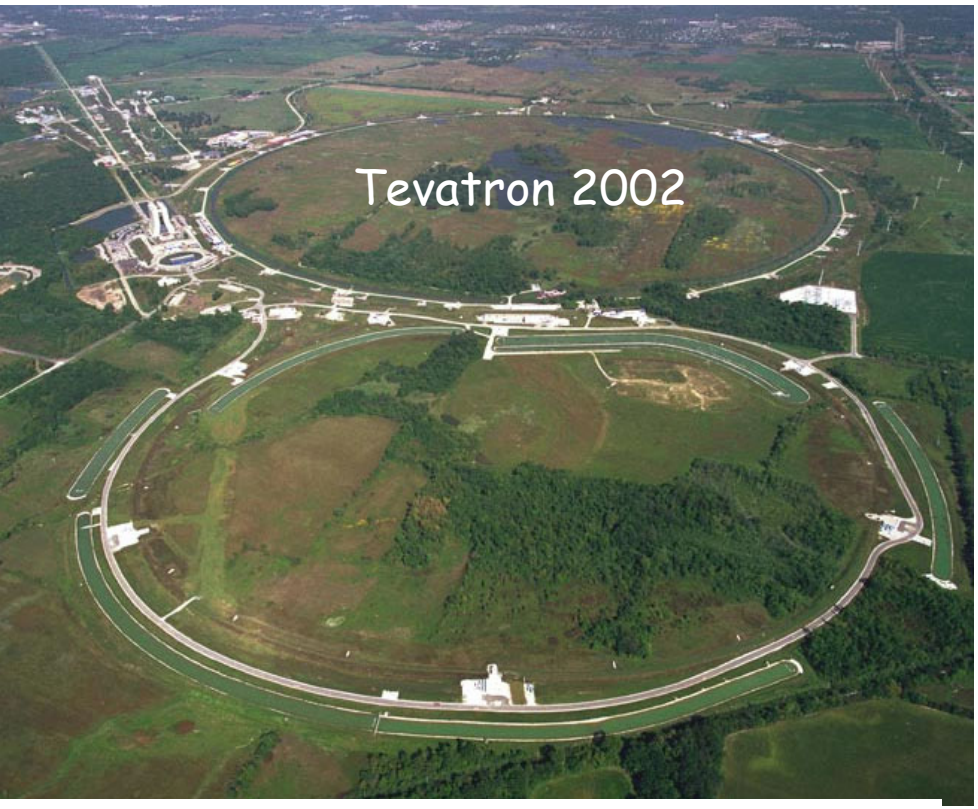
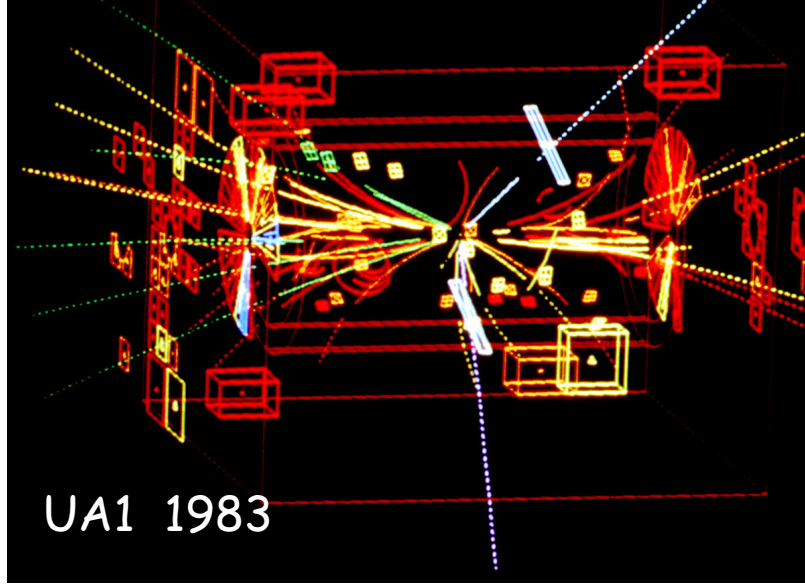
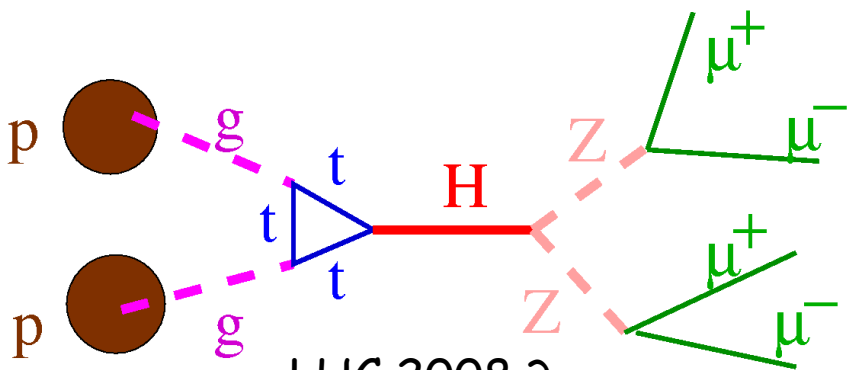
Thomas Hebbeker
RWTH
WS 2003/2004

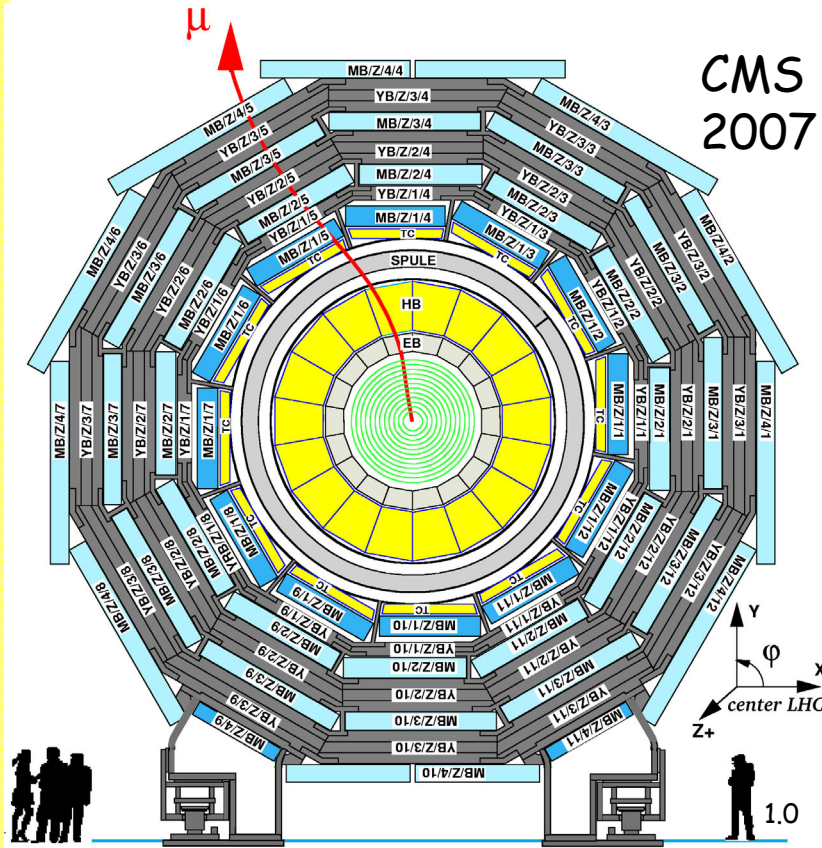
part II

pp physics









p p p h y s i c s

Part I Introduction

Part II Standard Model Physics

- cross section calculation
- QCD and jets
- W and Z
- charm and bottom
- top

Part III Higgs

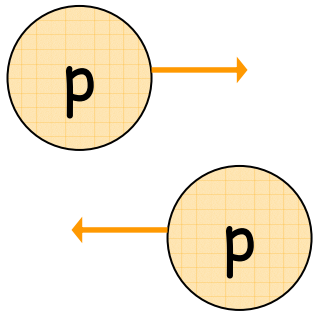
Part IV New Phenomena

References

Cross Section

LUMINOSITY

Elastic cross section

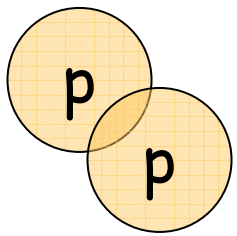


strong, electromagnetic

Xsection relatively small
scattering angle tiny

BACKGROUND
LUMINOSITY

Total inelastic cross section

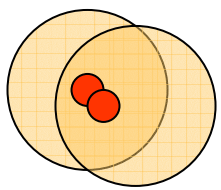


strong

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

SIGNAL

Pointlike cross section



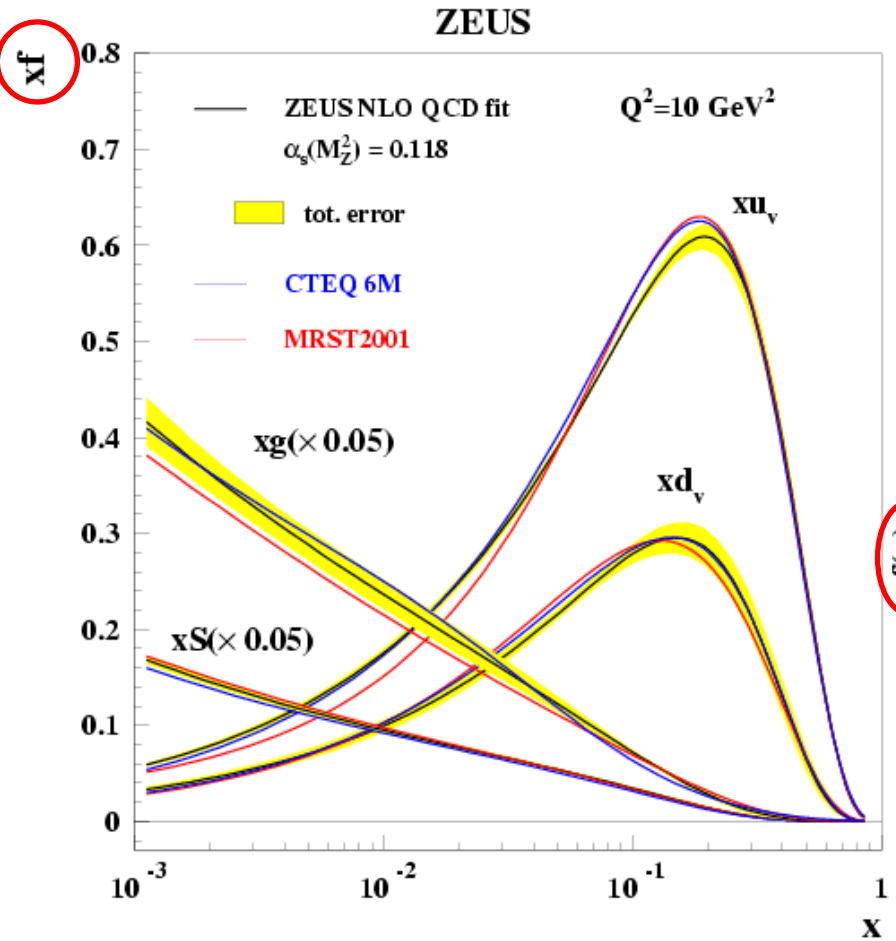
electroweak

$$\sigma \leq \frac{\alpha^2}{s} \approx 10^{-36}\, cm^2$$

LHC

Signal / Background $<10^{-11}$

Structure Functions

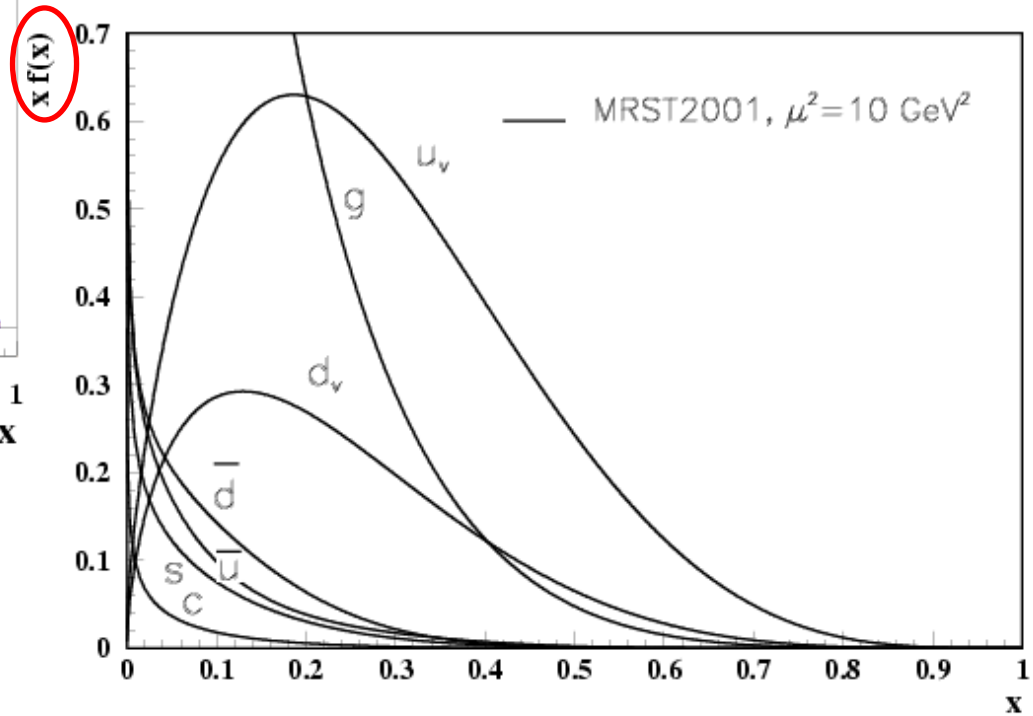


Measurements:

F_2 , F_3 ... in DIS

(n,p,elm.,weak, Q^2-depend.)

⇨ valence, sea, gluons...



Fits/parametrisations:

- CTEQ
- MRST

Cross section calculation in pp

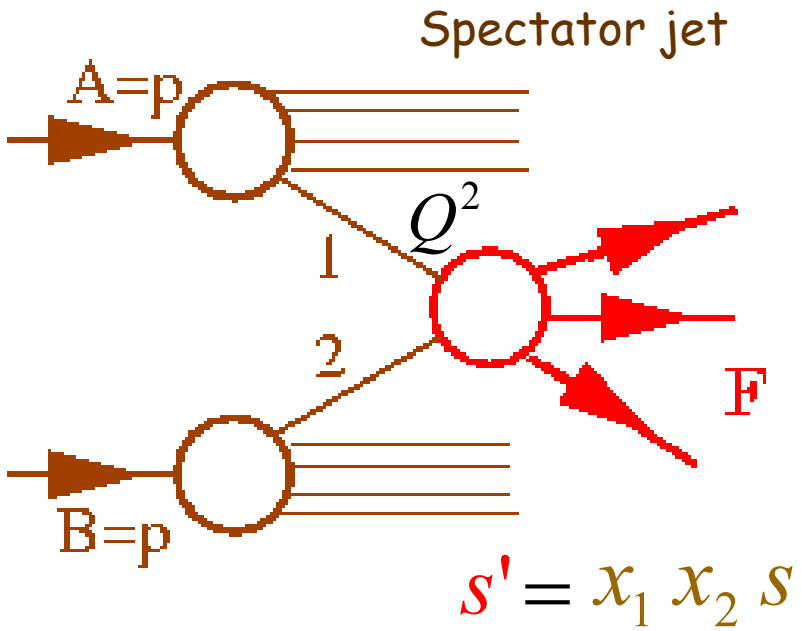
final state

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

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

Known: $f_i(x_i,Q^2)$ ← Q² = („momentum transfer")²

depends on final state



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

Cross Sections at Hadron Colliders

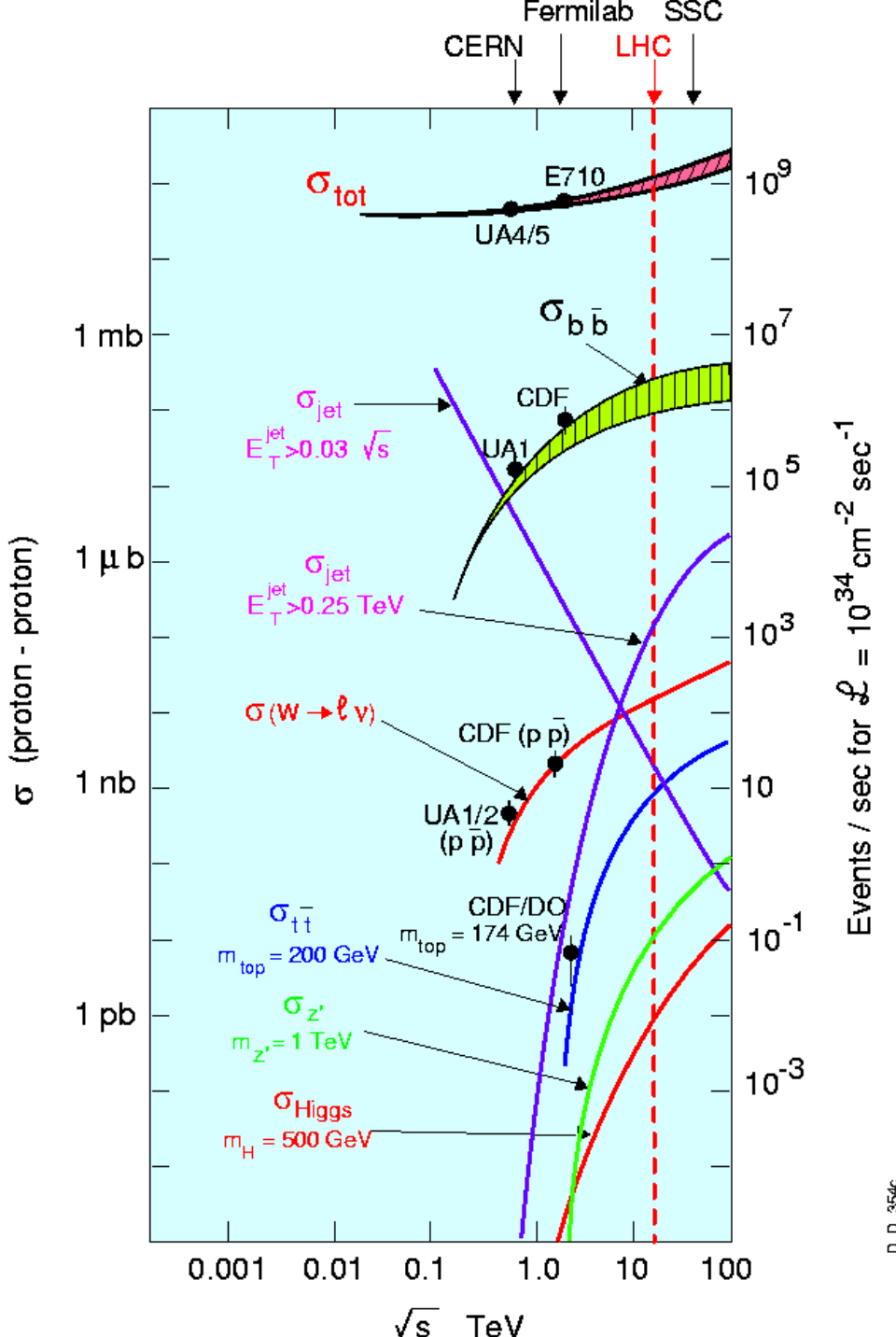
Note:

may trade:

energy ⟷ luminosity

Example:

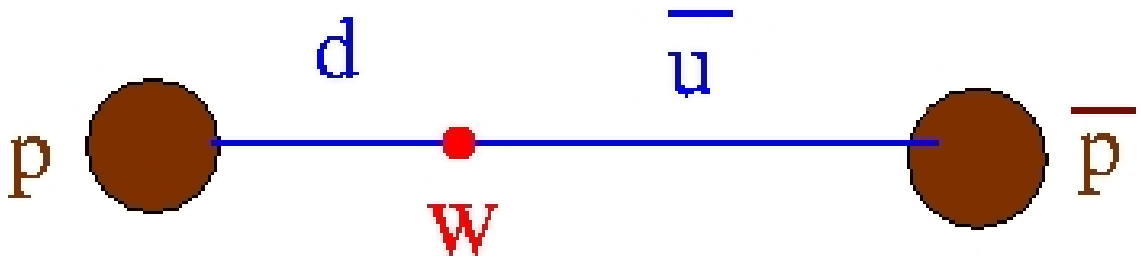
In principle top discovery at SPS !



Estimate of Xsection $p\,\bar{p} \longrightarrow W^- X$

Ansatz:

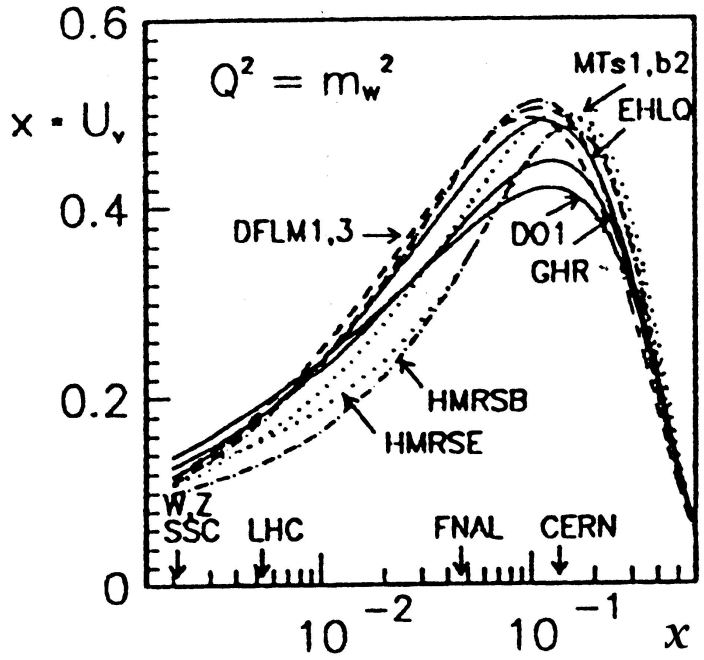
$$d\,\bar{u} \;\longrightarrow\; W^- \qquad (valence\;\; quarks)$$

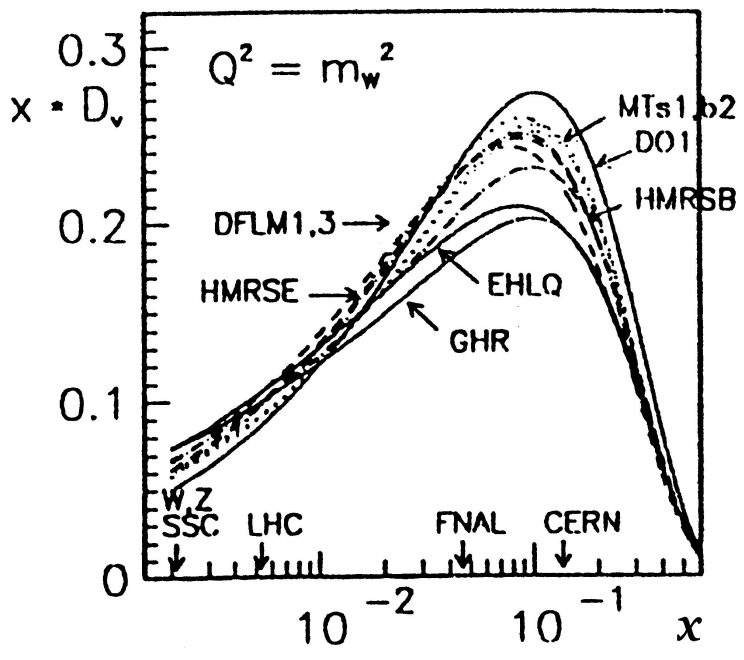


$$\sigma_W(\sqrt{s}) = \int\int f^d(x_1)\, f^{\bar{u}}(x_2)\, \sigma^{d\bar{u}}(\sqrt{s'})\, dx_1\, dx_2$$

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

Structure Functions:

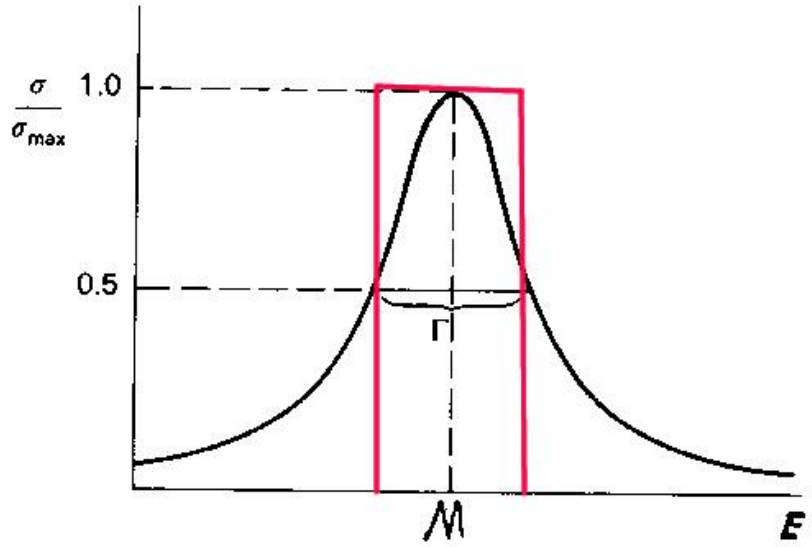




Rough parametrisation:

$$f_d(x) = \frac{0.2}{x} \qquad f_{\bar{u}}(x) = 2\, f_d(x)$$

Cross section (quark level):



$$\sigma^{d\bar{u}}(\sqrt{s}') = \sigma_0 \cdot \frac{s\,\Gamma_W^2}{(s' - m_W^2)^2 + m_W^2\Gamma_W^2}$$

$$\sigma_0 = \frac{12\pi}{m_W^2} \cdot \frac{\Gamma_{qq}}{\Gamma_W} \approx \frac{12\pi}{m_W^2} \cdot \frac{6}{9} \approx \frac{25}{m_W^2}$$

$$\sigma^{d\bar{u}}(\sqrt{s}') \approx \frac{25}{m_W^2} \cdot \begin{cases} 1 & m_W - \Gamma_W/2 < \sqrt{s'} < m_W + \Gamma_W/2 \\ 0 & \text{else} \end{cases}$$

Calculate:

$$\sigma_W(\sqrt{s}) = 25 \cdot 0.2 \cdot 0.4 \cdot \frac{1}{m_W^2} \cdot \int_{x_2^{min}}^{1} \frac{1}{x_2} \left[\int_{x_1^{min}}^{x_1^{max}} \frac{1}{x_1} dx_1 \right] dx_2$$

$$x_2^{min} \approx \frac{m_W^2}{s}$$

$$x_1^{min} = \frac{(m_W - \Gamma_W/2)^2}{x_2\, s} \qquad x_1^{max} = \frac{(m_W + \Gamma_W/2)^2}{x_2\, s}$$

$$\sigma_W(\sqrt{s}) \approx 25 \cdot 0.2 \cdot 0.4 \cdot \frac{1}{m_W^2} \cdot \int_{x_2^{min}}^{1} \frac{1}{x_2} \left[2\frac{\Gamma_W}{m_W} \right] dx_2$$

$$\sigma_W(\sqrt{s}) = -4 \cdot \frac{1}{m_W^2} \cdot \frac{\Gamma_W}{m_W} \cdot \ln \frac{m_W^2}{s}$$

Results:

$1/\mathrm{GeV} = 2 \cdot 10^{-16}\,\mathrm{m}$

$m_W = 80\,\mathrm{GeV}$

$\Gamma_W = 2\,\mathrm{GeV}$

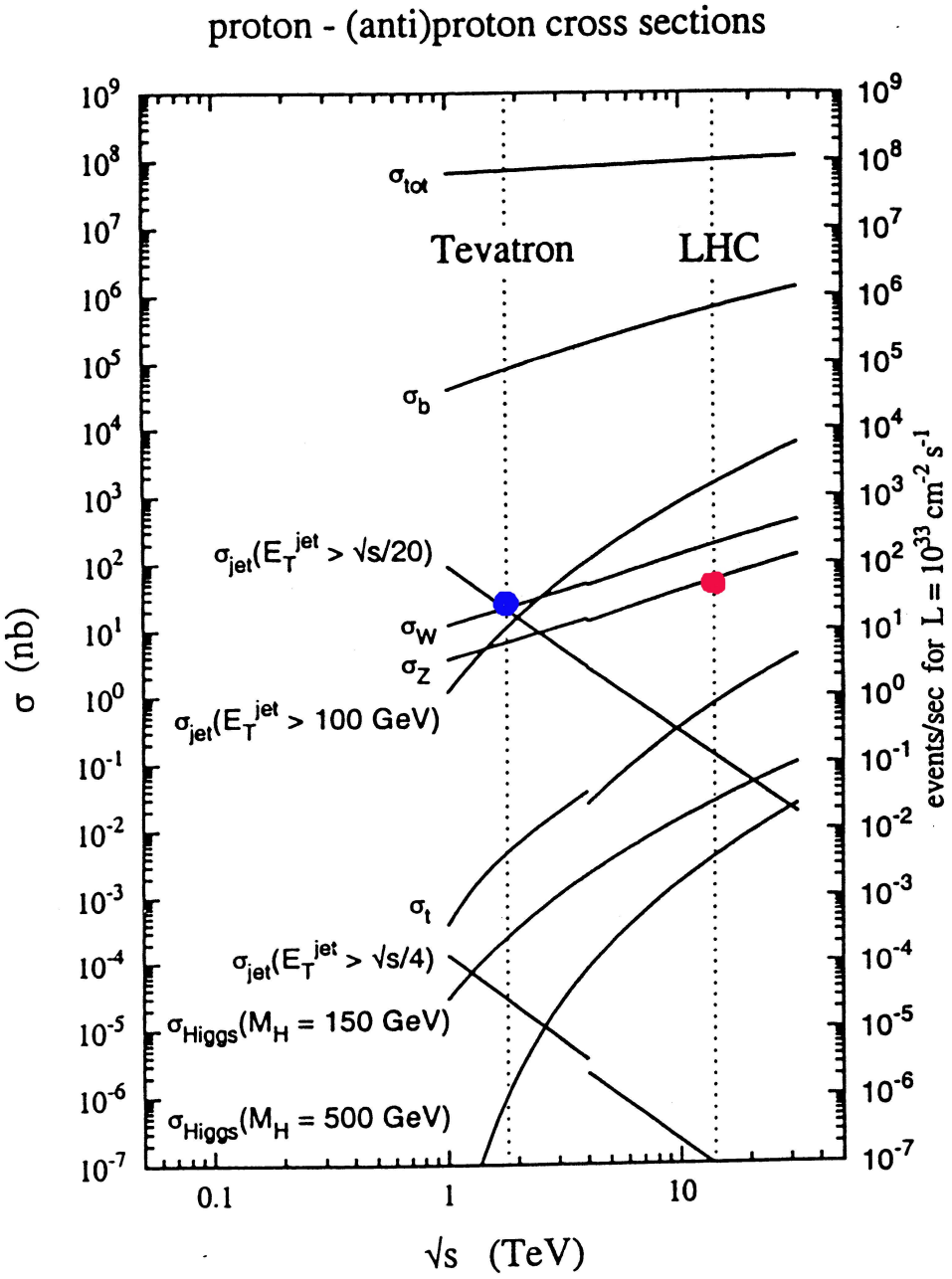
$\sigma_W(\sqrt{s}) \approx 4\,\mathrm{nb} \cdot \ln \frac{s}{m_W^2}$

FERMILAB :

$\sigma_p(\sqrt{s}) \approx 25\,\mathrm{nb}$

LHC(pp!) :

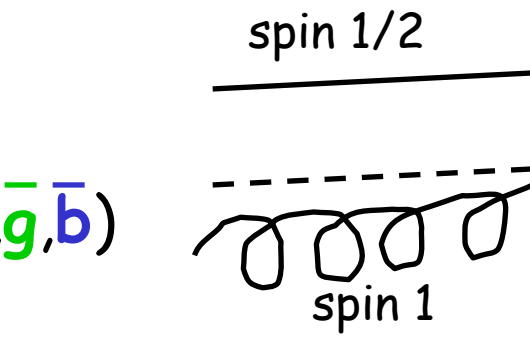
$\sigma_p(\sqrt{s}) \approx 40\,\mathrm{nb}$

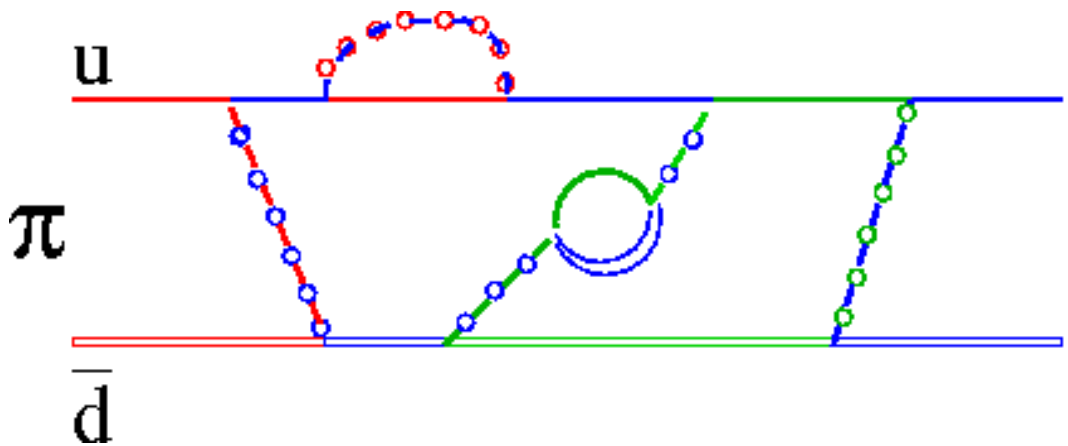


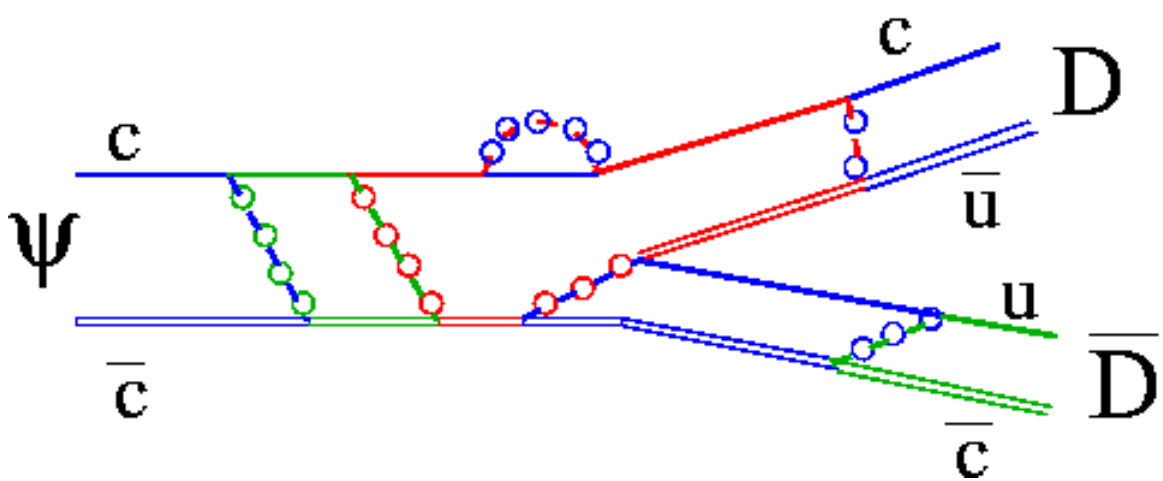
QCD = Quantum Chromodynamics

Gauge theory: • quarks with 3 colors (r,g,b)

SU(3) • 8 gluons (color + anticolor $\bar{r},\bar{g},\bar{b}$)

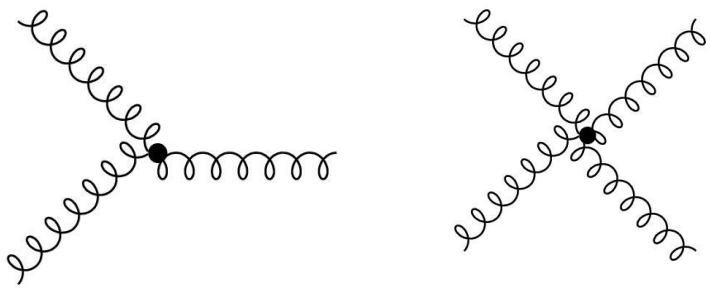






self coupling, running, confinement

nonabelian:



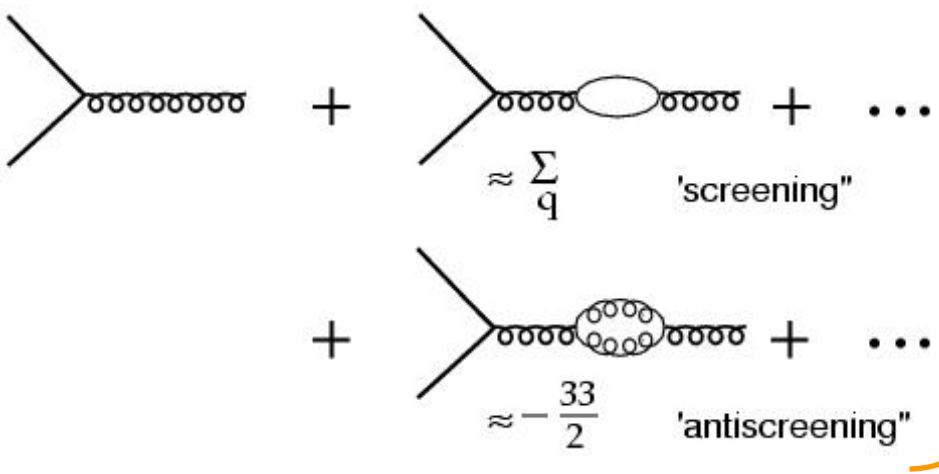
mesons and baryons „white“:

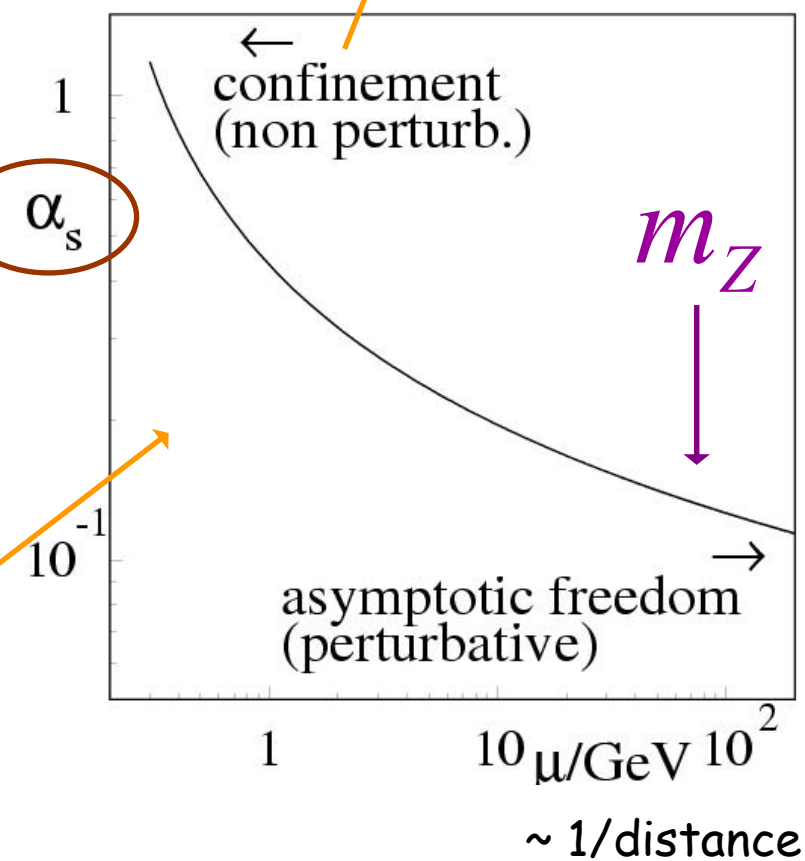
$q\bar{q}$ qqq

strong coupling „constant“

α_s

„Running“:

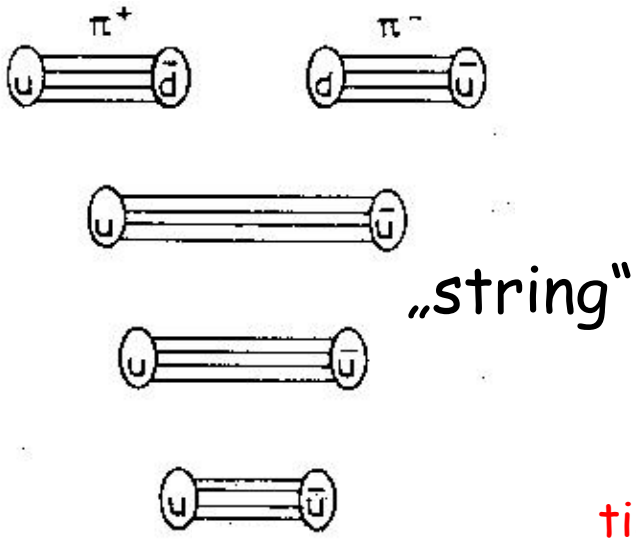




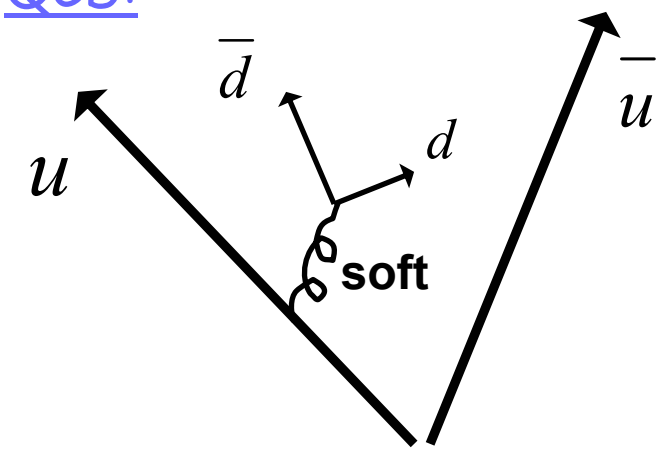
~ 1/distance

Hadronization = Fragmentation

String model:



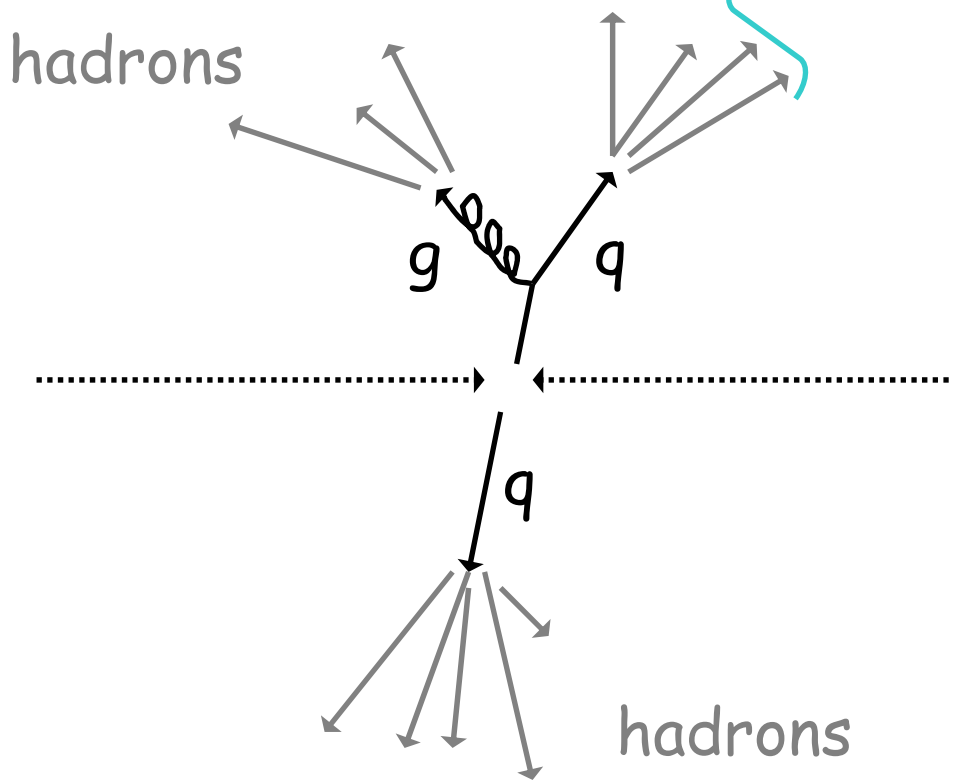
QCD:



time

jet

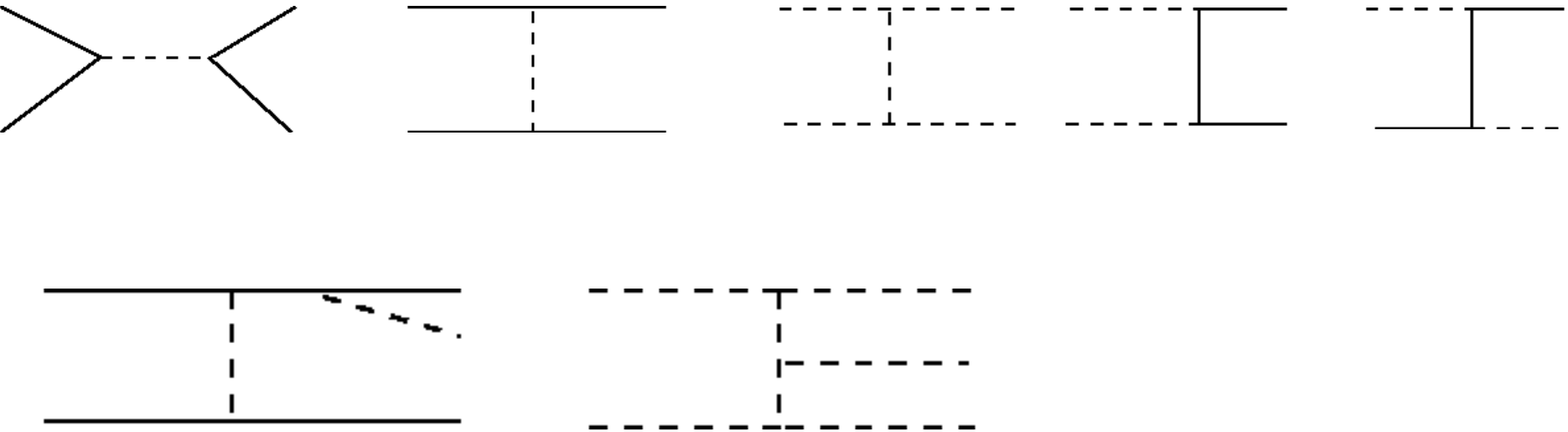
(to be defined)

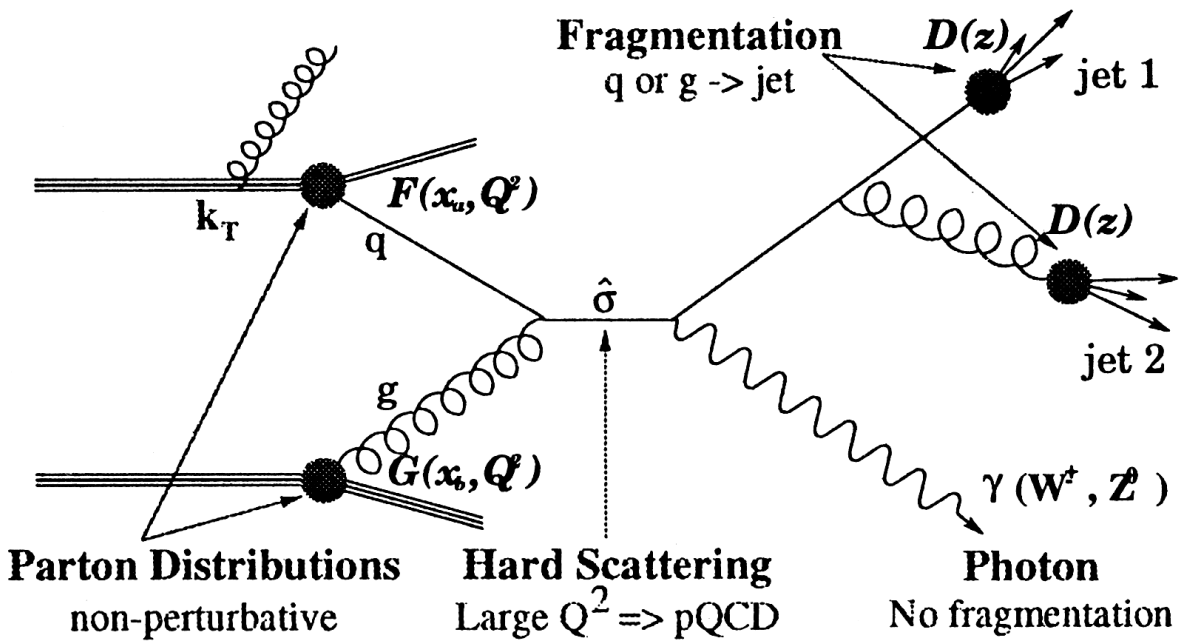


Hadronization: non-perturbative

⇨ need models!

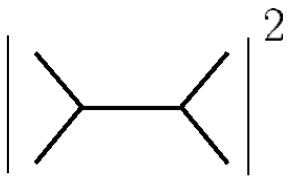
Calculation of QCD processes



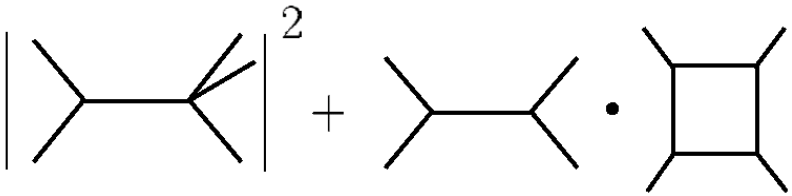


Higher Order Corrections

can be large in particular for QCD processes!



LO = Leading Order



NLO = Next to Leading Order

Difficulties for p p reactions:

- parton densities and fragmentation functions depend on order!
- factorization scale, renormalization scale, fragmentation scale

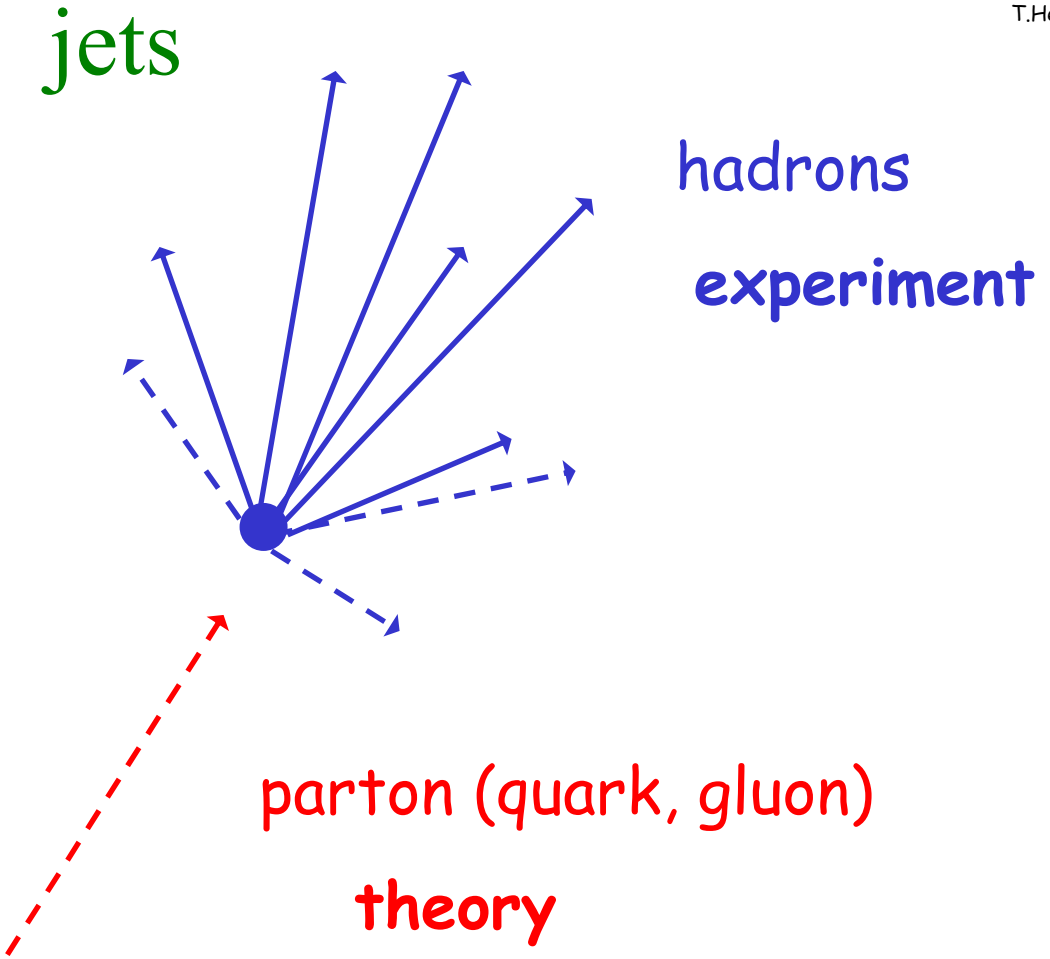
  (Q^2 parton density) (Q^2 hard process) ....

Often: higher order corrections to differential cross section modeled by LO prediction and „**K factor**" (typ. 1 ... 2)

Typical: 100 particles total

(14 TeV)

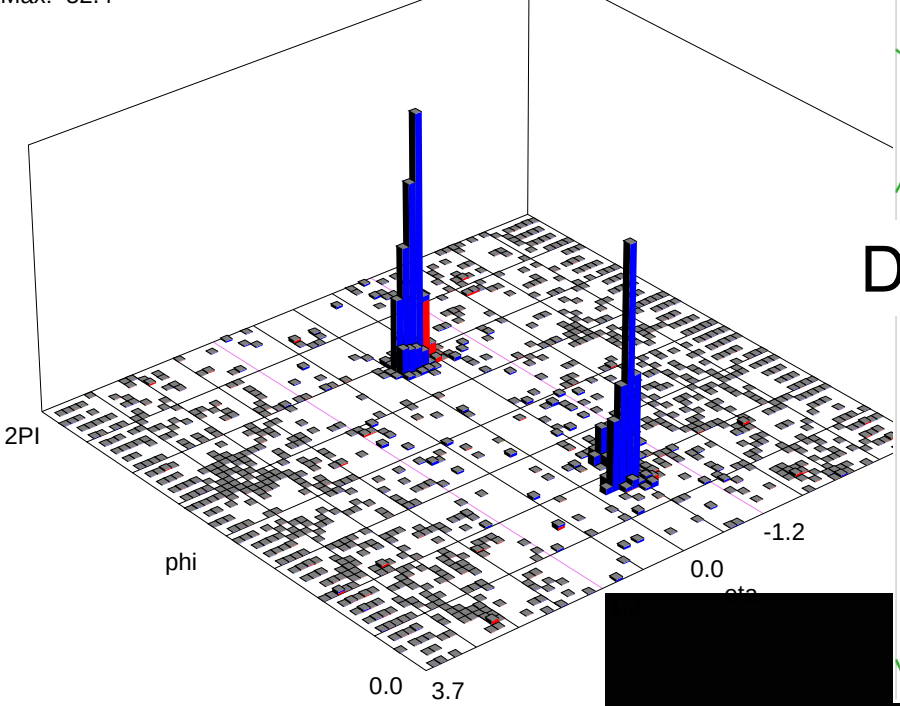
2-5 jets per event

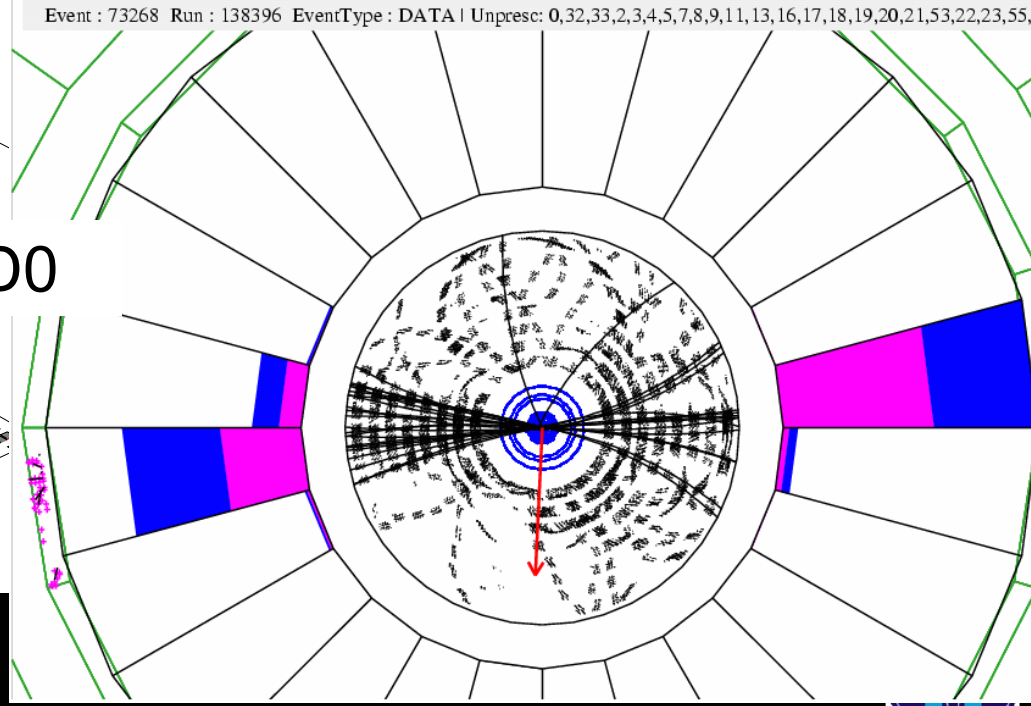


jets reveal hard processs (direction, energy)

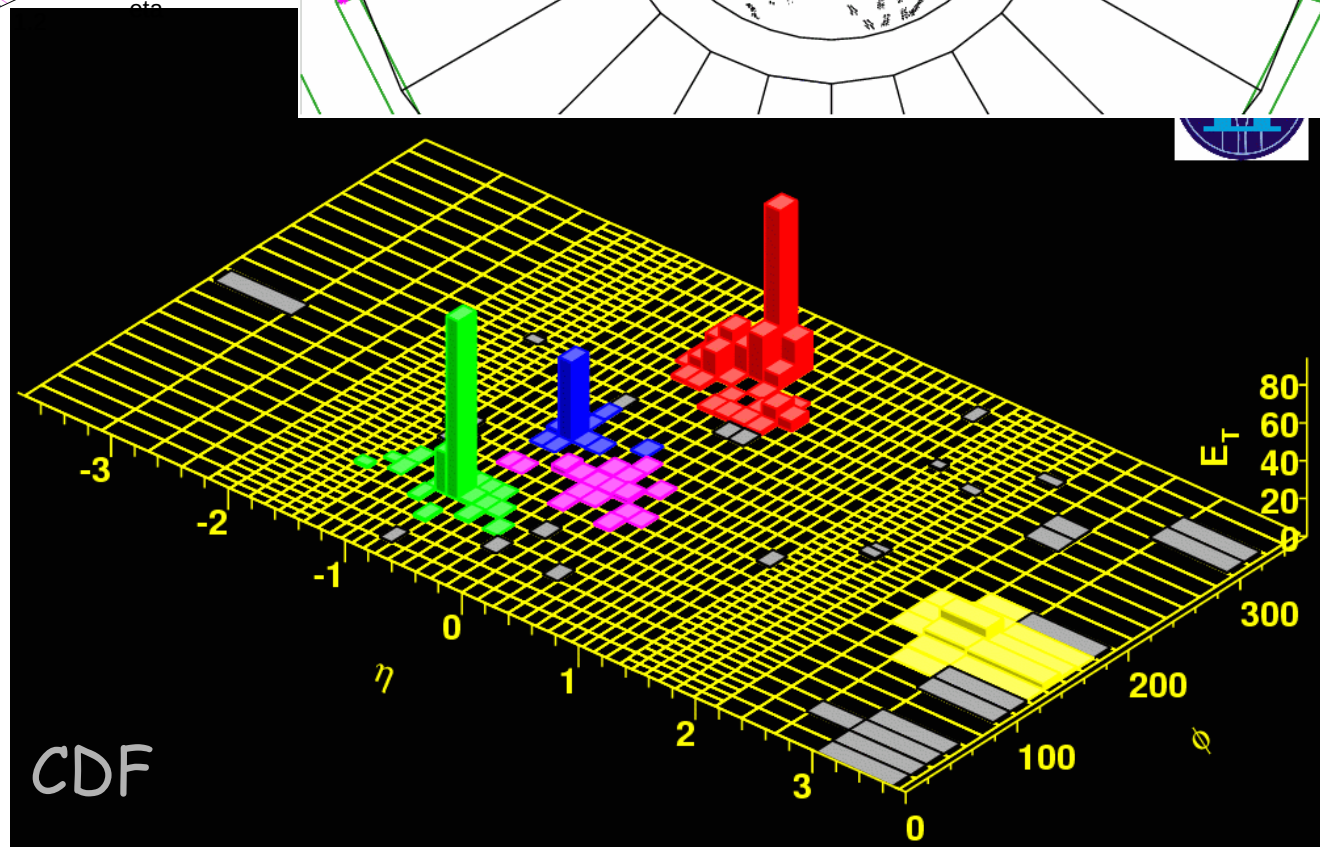
experiment and theory must use the same language:

jets need to be defined: „jet algorithm"



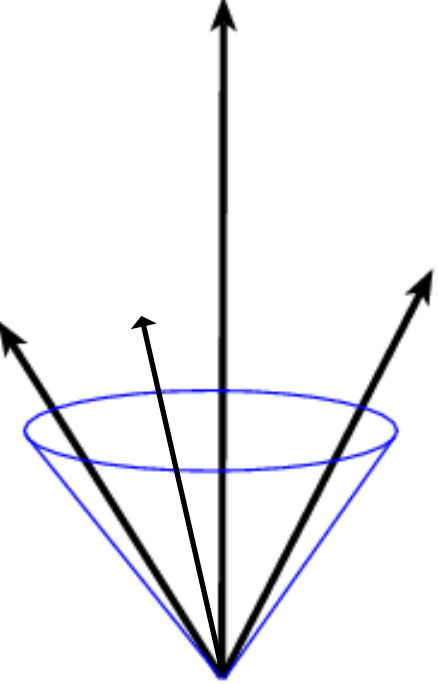


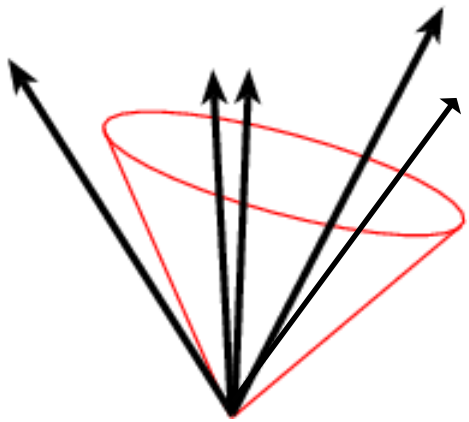
D0

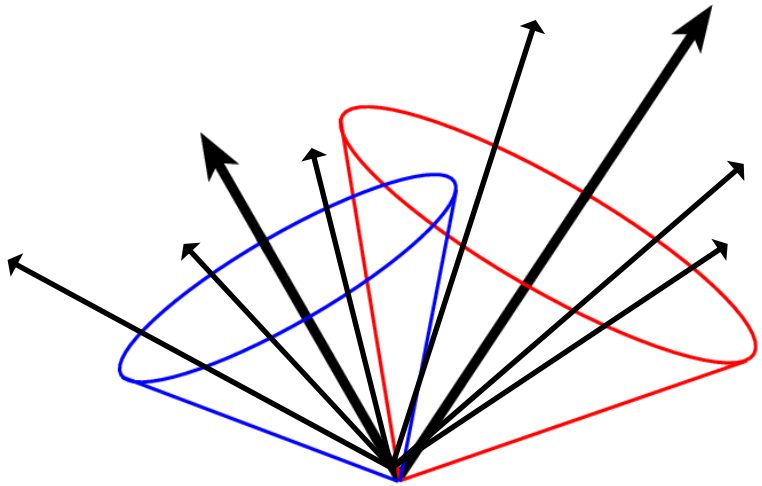


Jet events

cone jets







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

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

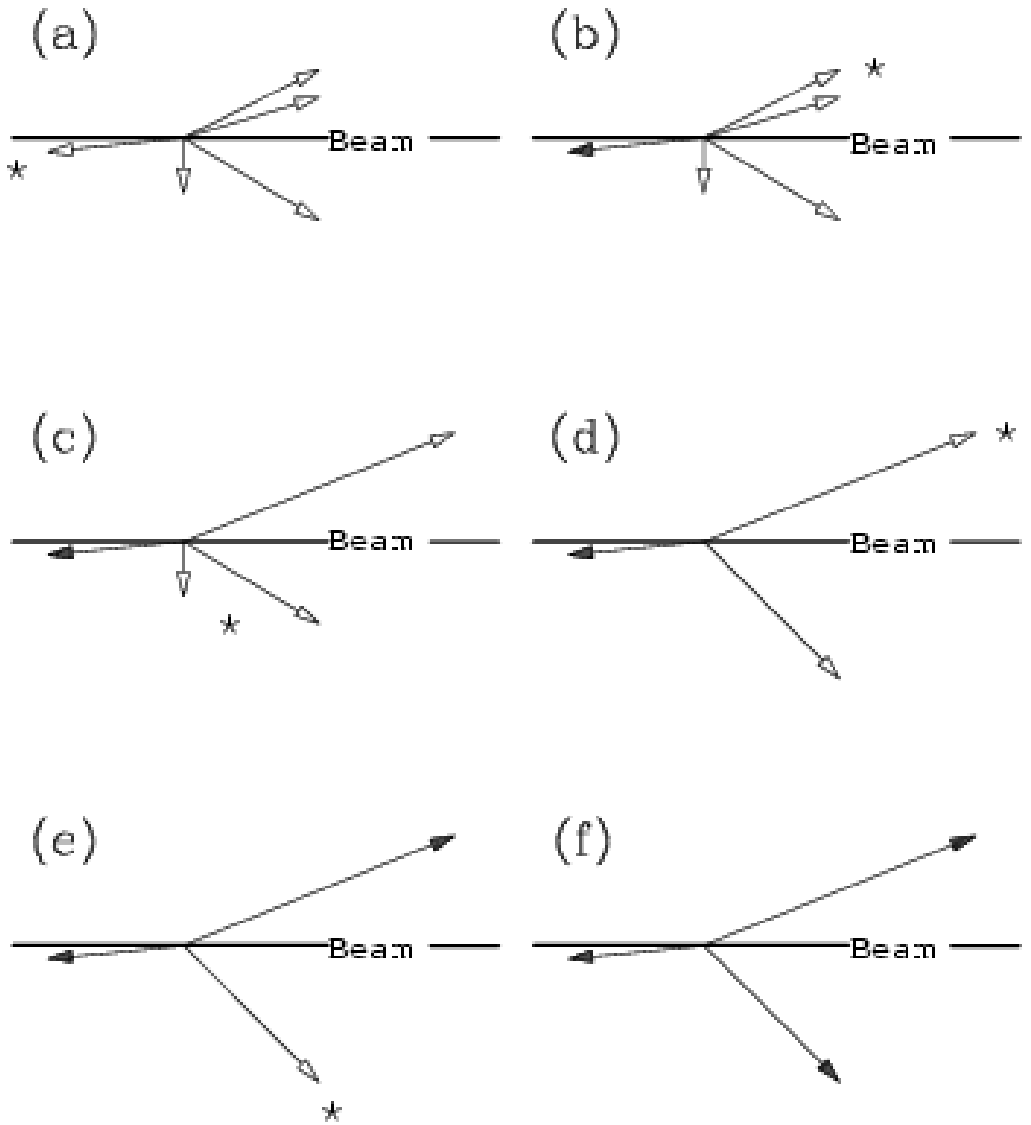
c) minimum of d_{ij} , d_i

→combine or remove from list)

d) iterate: goto b)

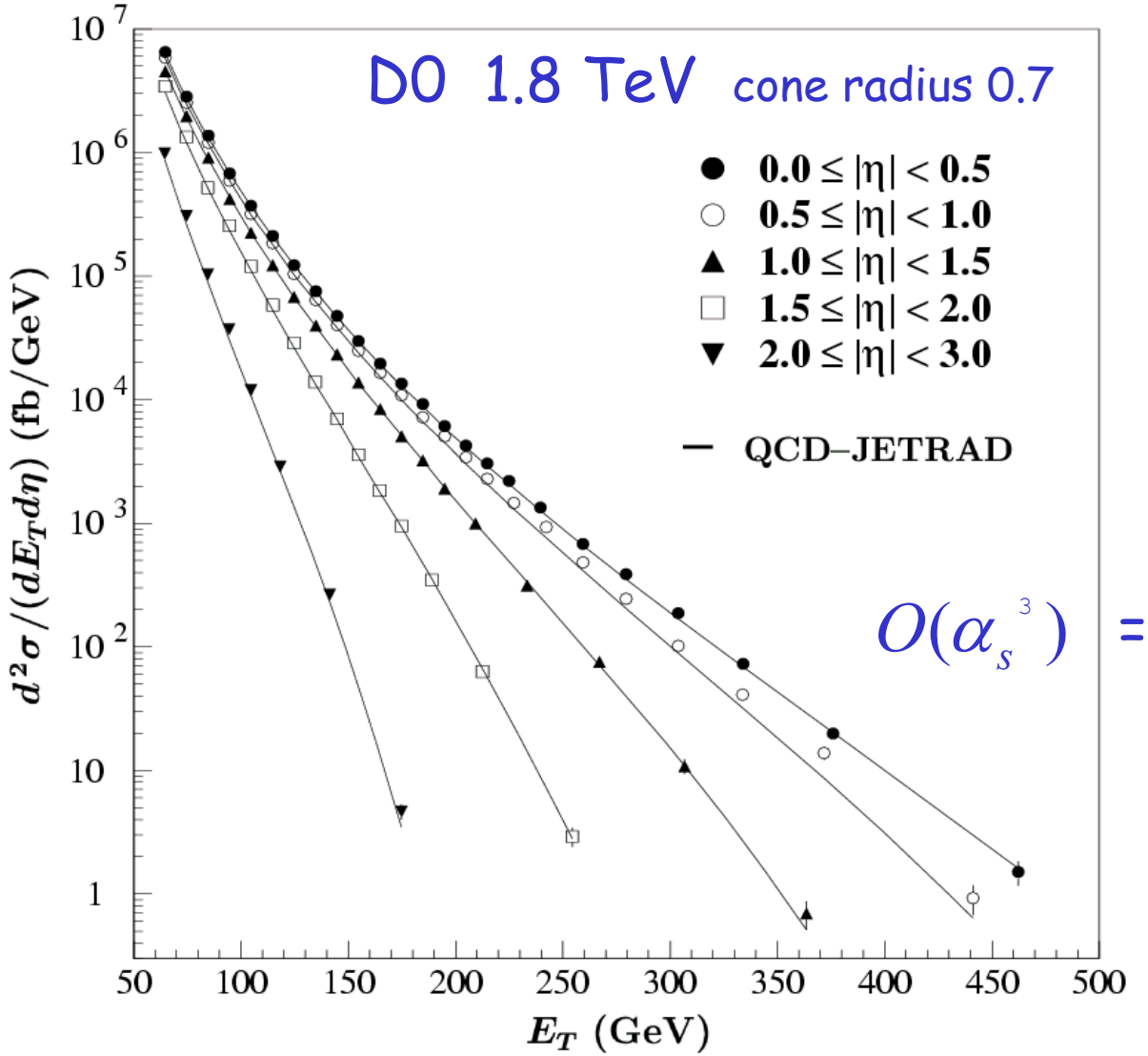
till list empty

Example:



... several variations exist

Inclusive jet production



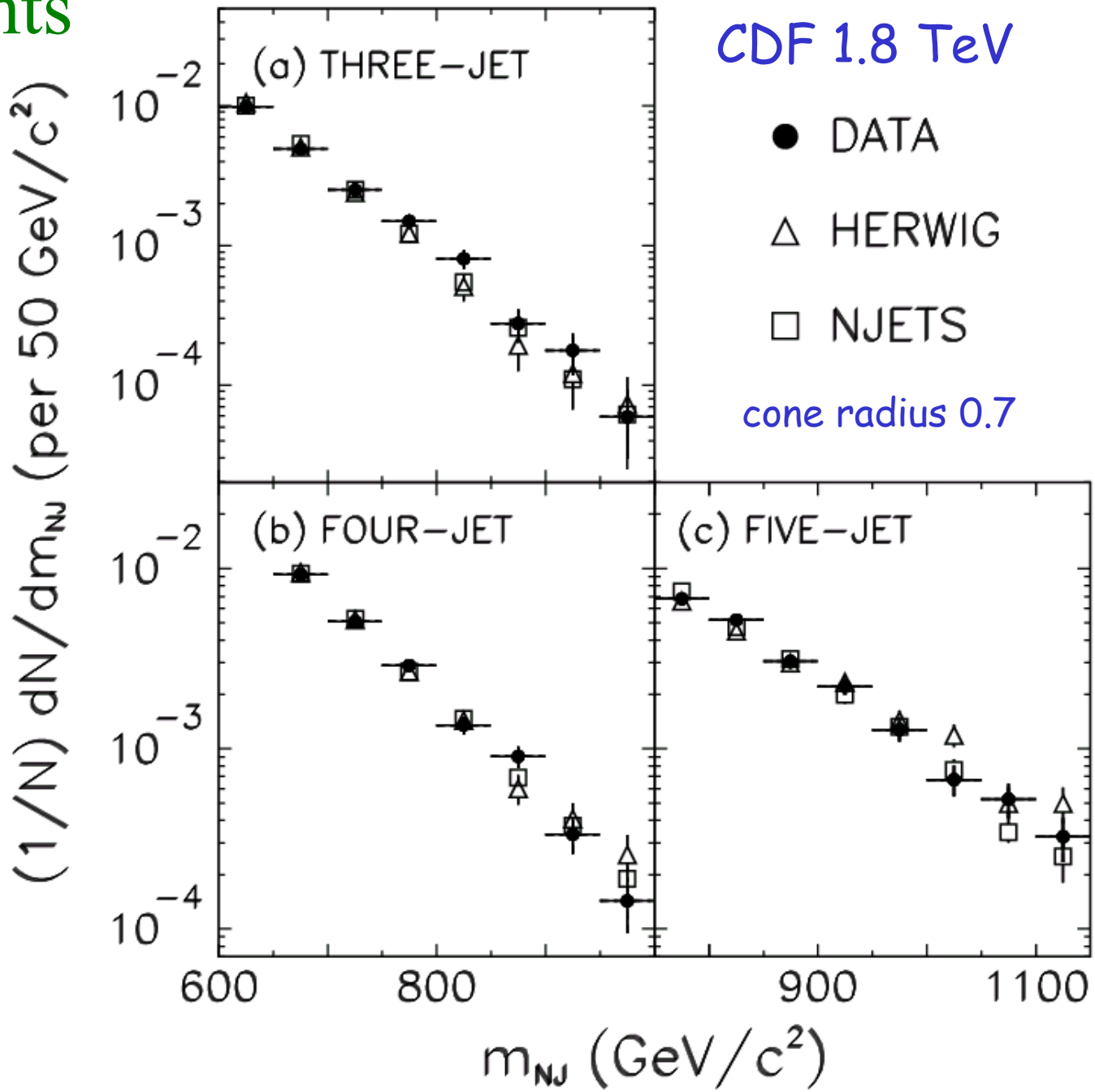
$O(\alpha_s^3)$ =NLO

Conclusion: agreement with QCD over many orders of magnitude!

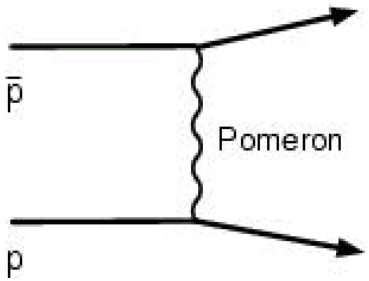
multijet events

Test QCD

Measure alphas from relative fraction of events with 2,3,... jets



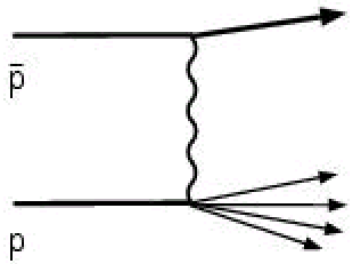
Soft hadronic processes (LHC)

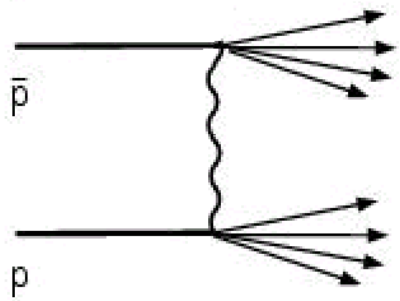


(zero quantum numbers!)

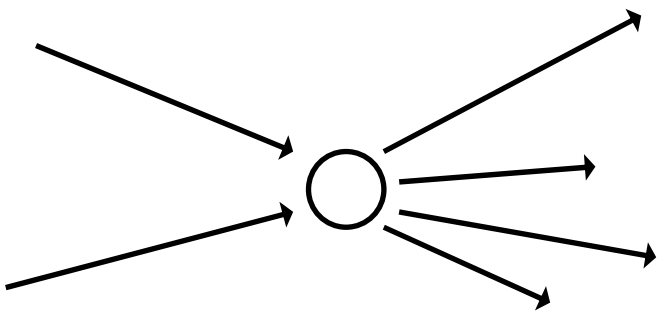
Elastic

(20 mb)





diffractive (25 nb)

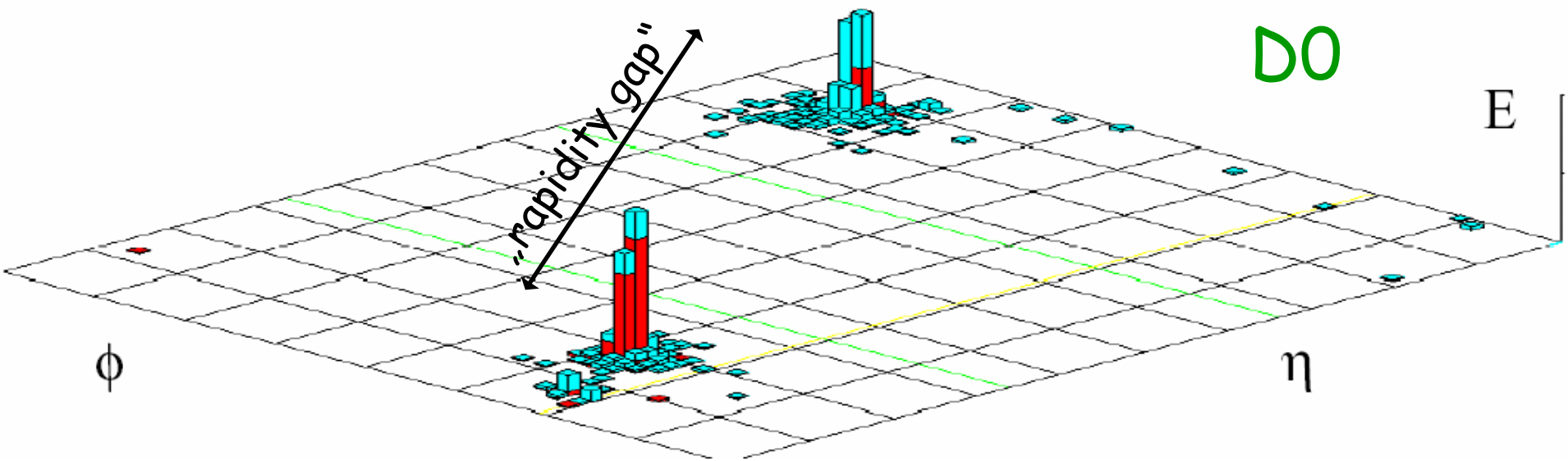


non-diffractive (55 nb)

Inelastic

(80 mb)

Double-Diffractive Event



W and Z

measured at LEP
reference for W mass measurement

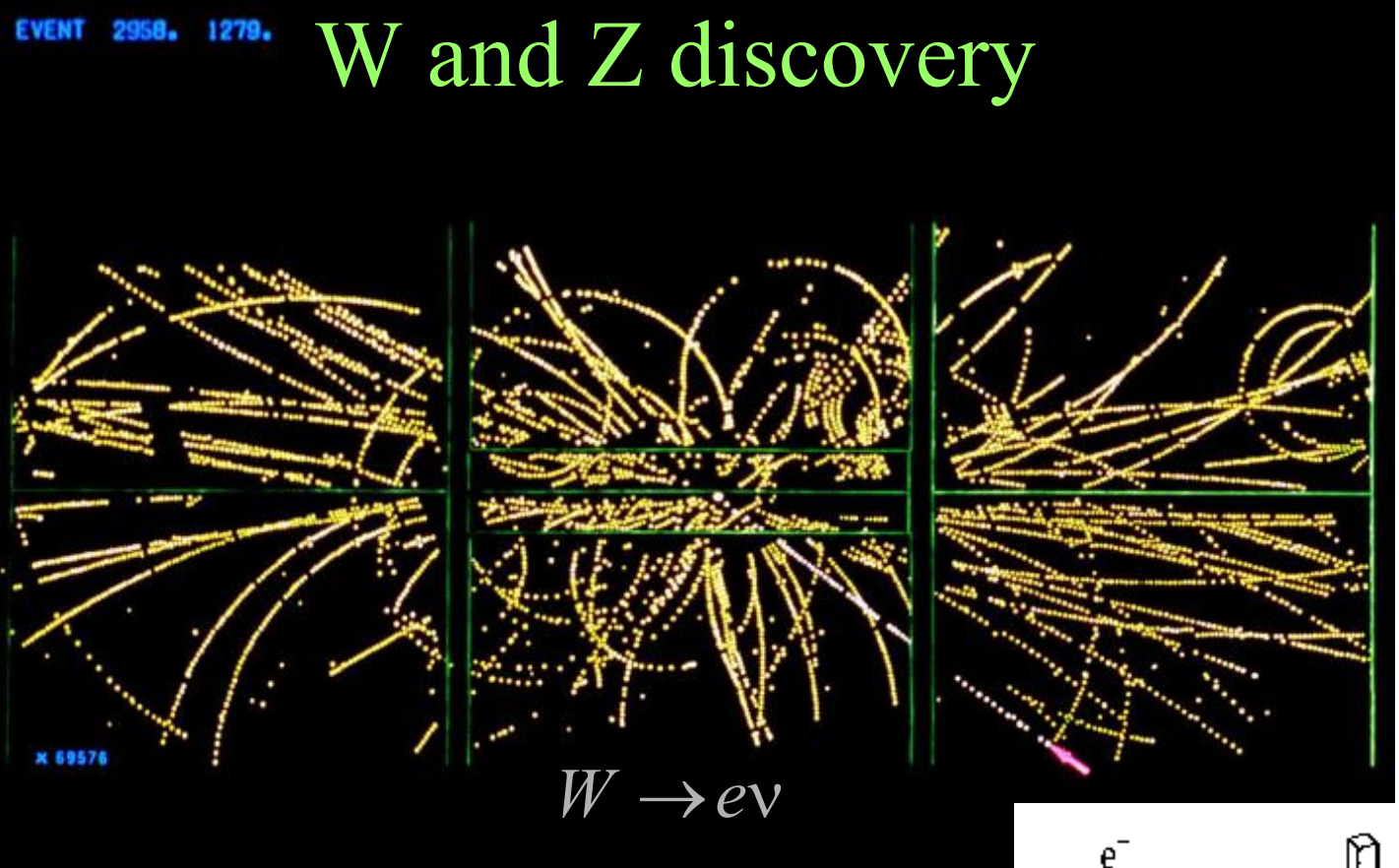
- production cross section
- decay modes
- W mass

$$\left(\frac{m_W}{m_Z}\right)^2 = \cos^2\theta_W = 1 - \sin^2\theta_W$$

Test of SM !

- W width
- (W polarization in top decays)
- ...

W and Z discovery

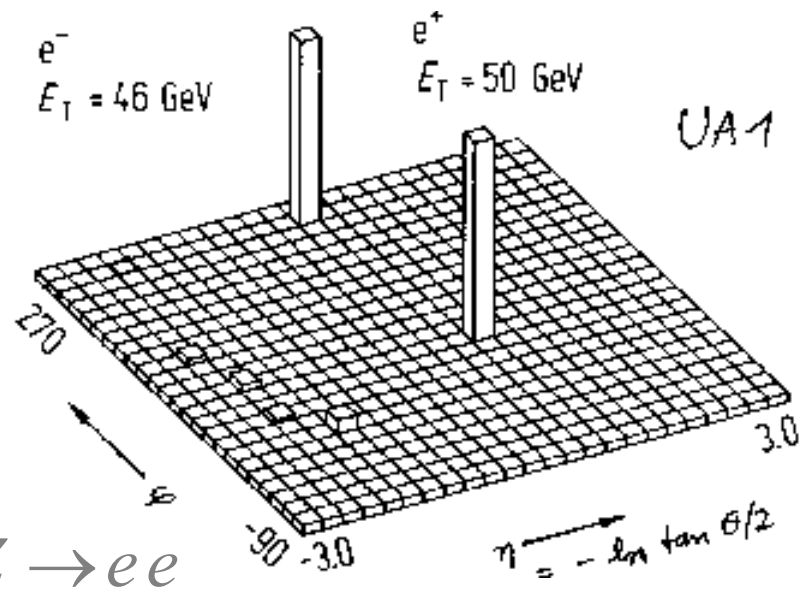


$W \rightarrow e\nu$

Discovery:

UA1, UA2

(1983)



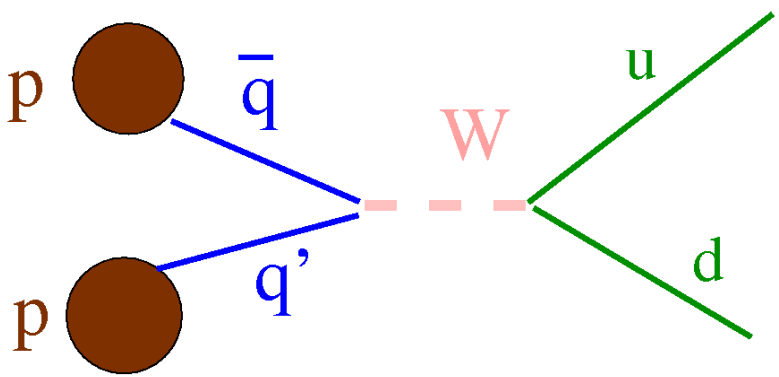
$Z \rightarrow ee$

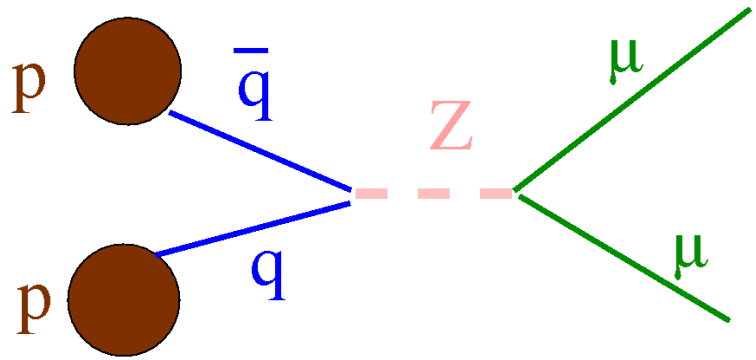
Precision measurement

Z mass at LEP:

91.1876 +- 0.0021 GeV

W,Z: production and decay





W decay probability:

$$Br \sim N_C$$

$e\nu$	11%
$\mu\nu$	11%
$\tau\nu$	11%
ud	33%
cs	33%

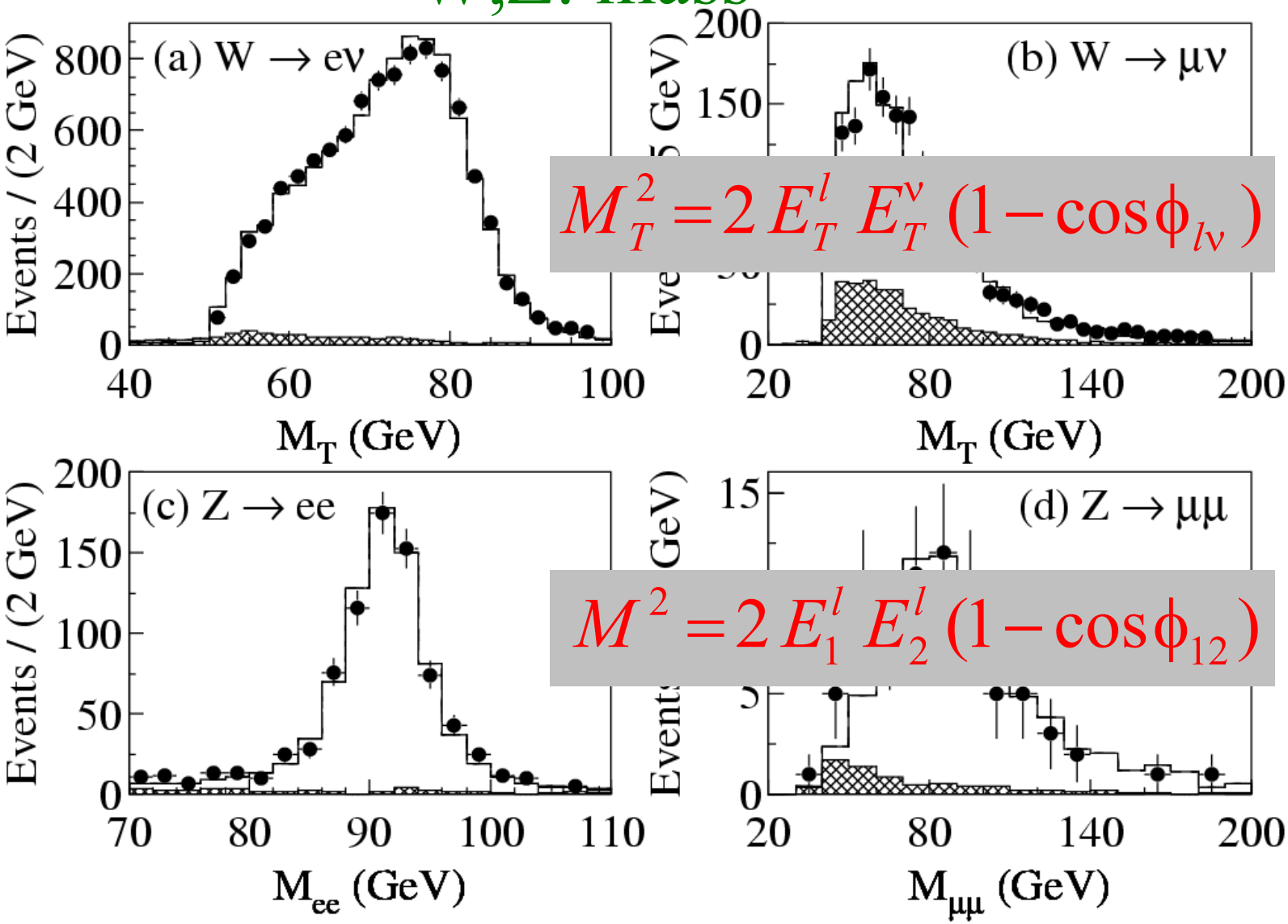
Clear signature

Z decay probability:

$$Br \sim N_C(g_V^2 + g_A^2)$$

$e\,e$	3%
$\mu\,\mu$	3%
$\tau\,\tau$	3%
$uu + dd + ss + cc + bb$	70%
$\nu\nu$	20%

W,Z: mass



$$M_T^2 = 2\,E_T^l\,E_T^\nu\,(1-\cos\phi_{l\nu})$$

$$M^2 = 2\,E_1^l\,E_2^l\,(1-\cos\phi_{12})$$

D0 1.8 TeV

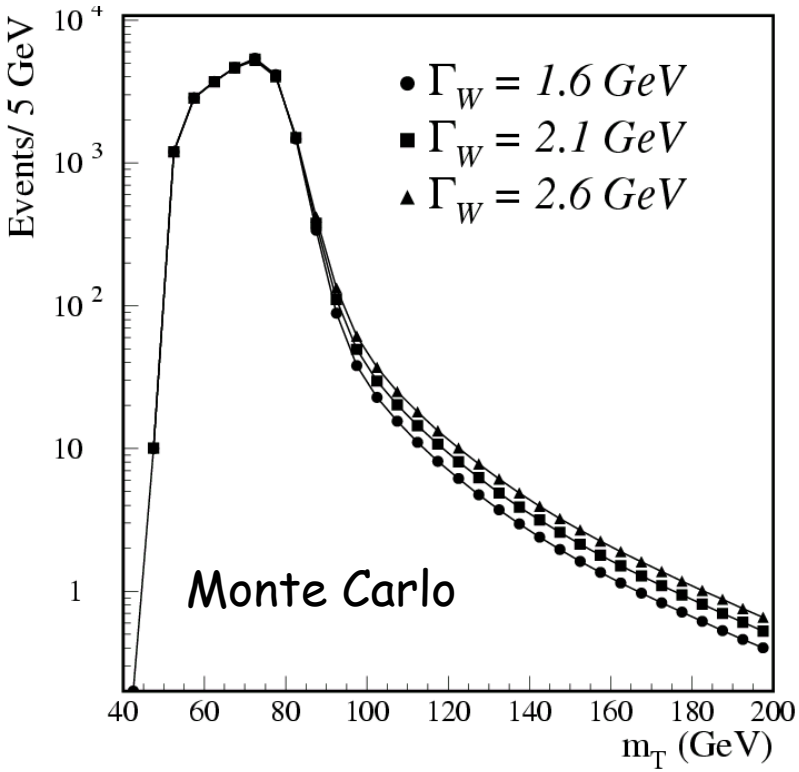
Tevatron combined: $80.456 \pm 0.059\,GeV$

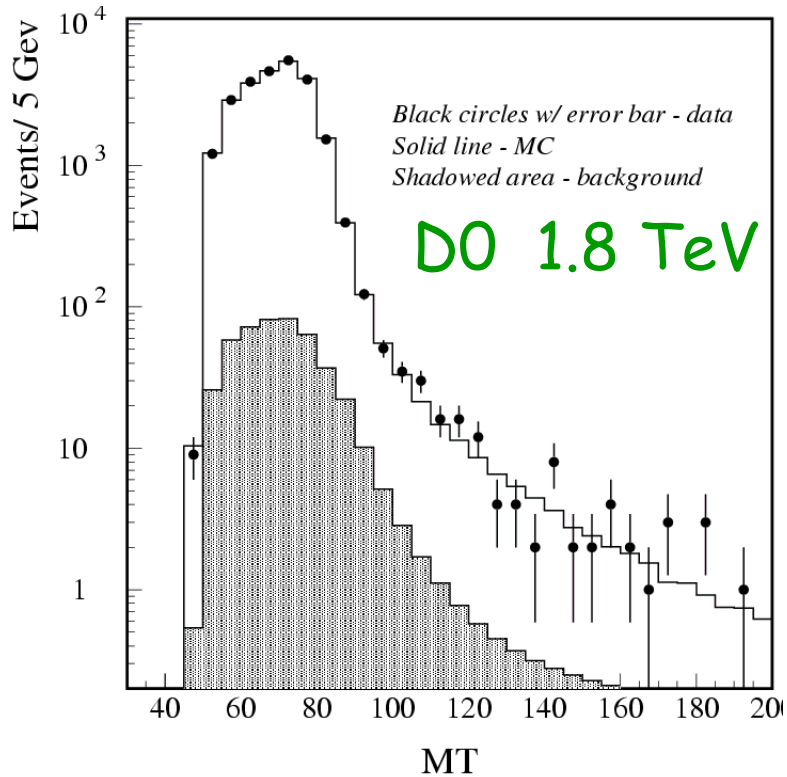
Run I

LEP: $\pm 0.042\,GeV$

LHC: $\pm 0.015\,GeV$

W: width

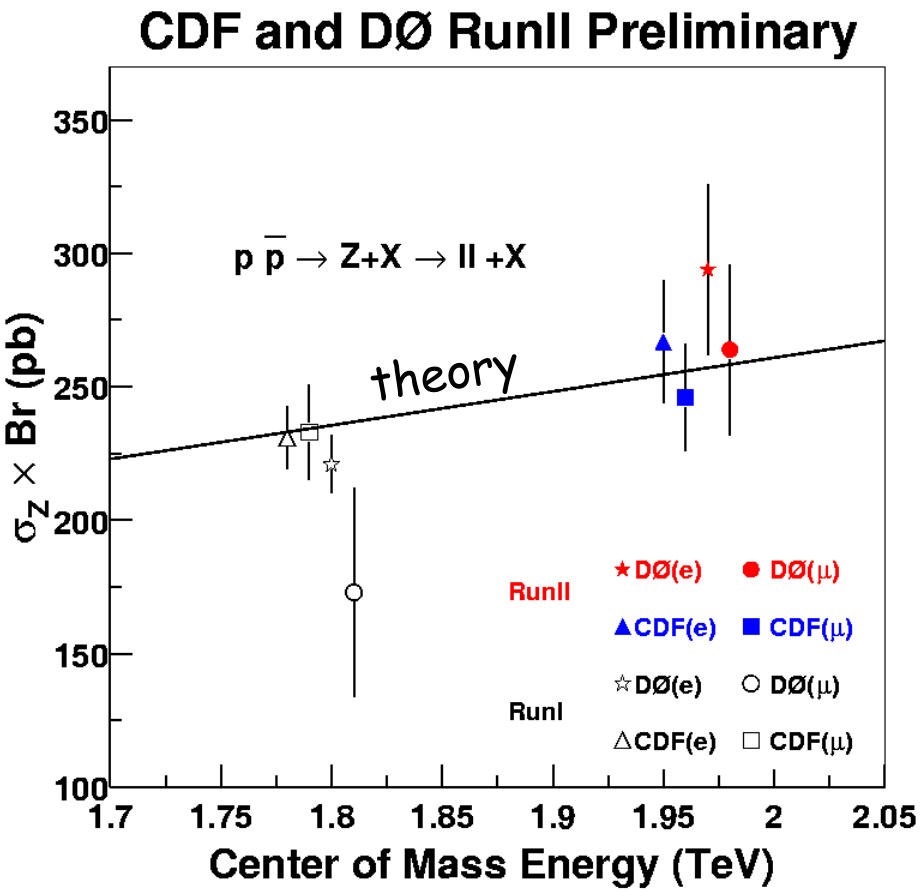


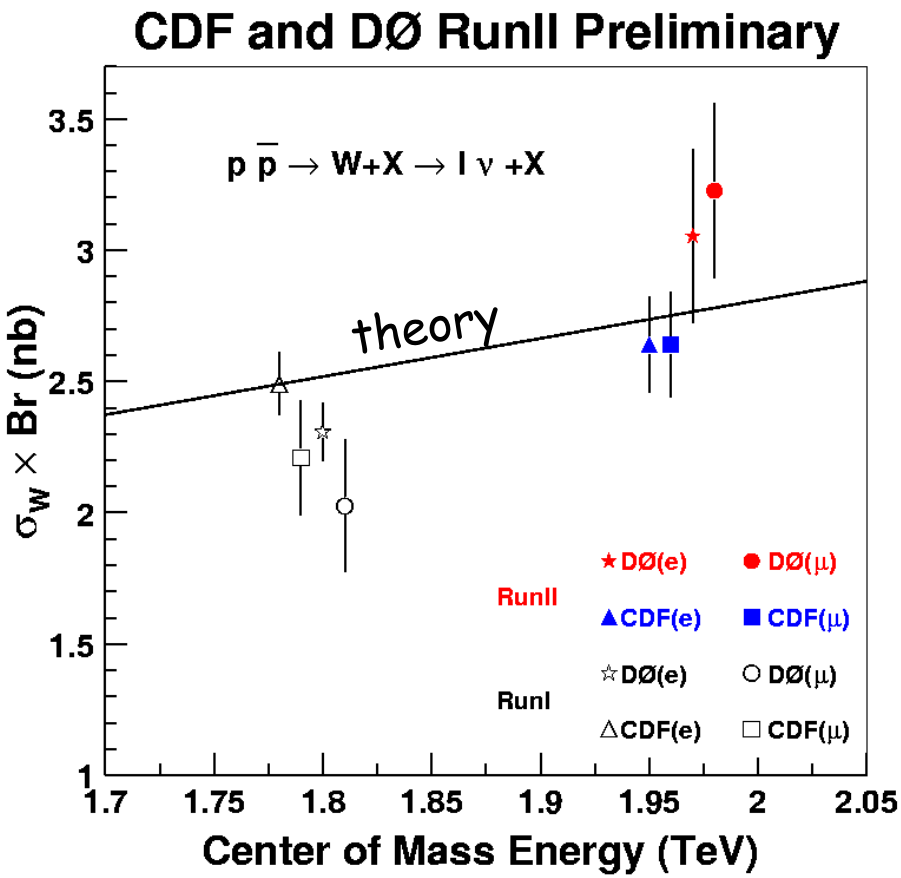


... difficult...

Tevatron combined: $2.160 \pm 0.047\ GeV$ (indirect+direct)

W,Z: production cross section

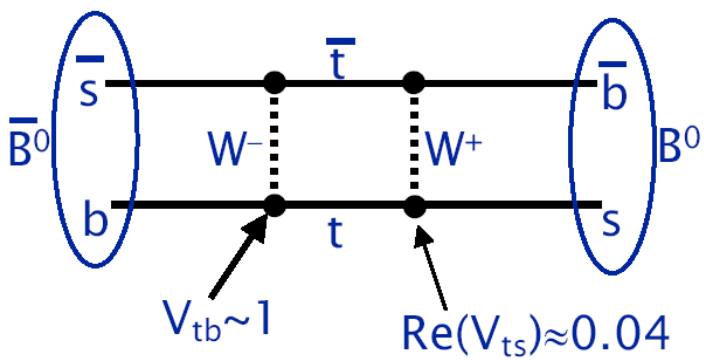




pp-physics with charm and bottom

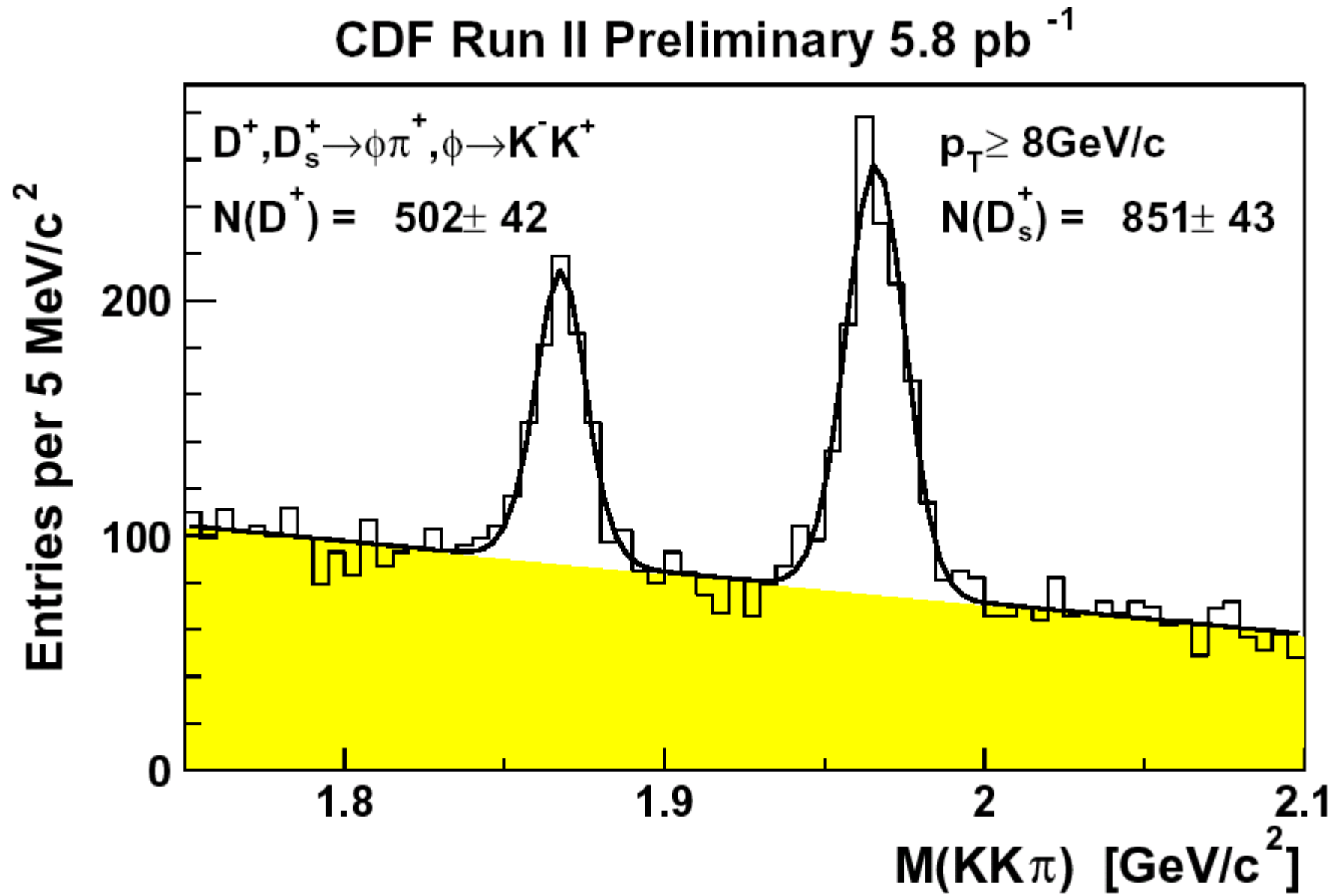
cross section huge !

- cross section
- new mesons/baryons/hybrids/... ?
- hadron masses
- hadron lifetimes
- branching fractions (rare decays ?)
- B_s^0 mixing



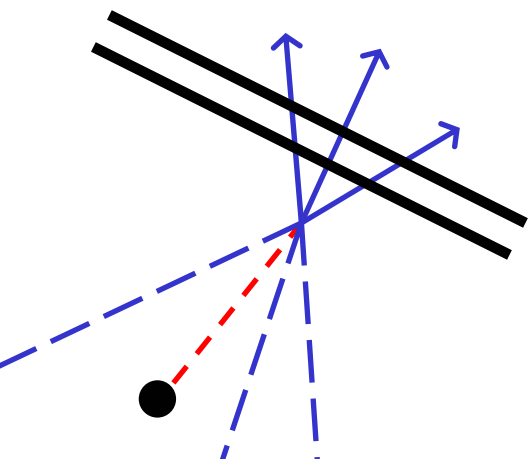
- CP violaton

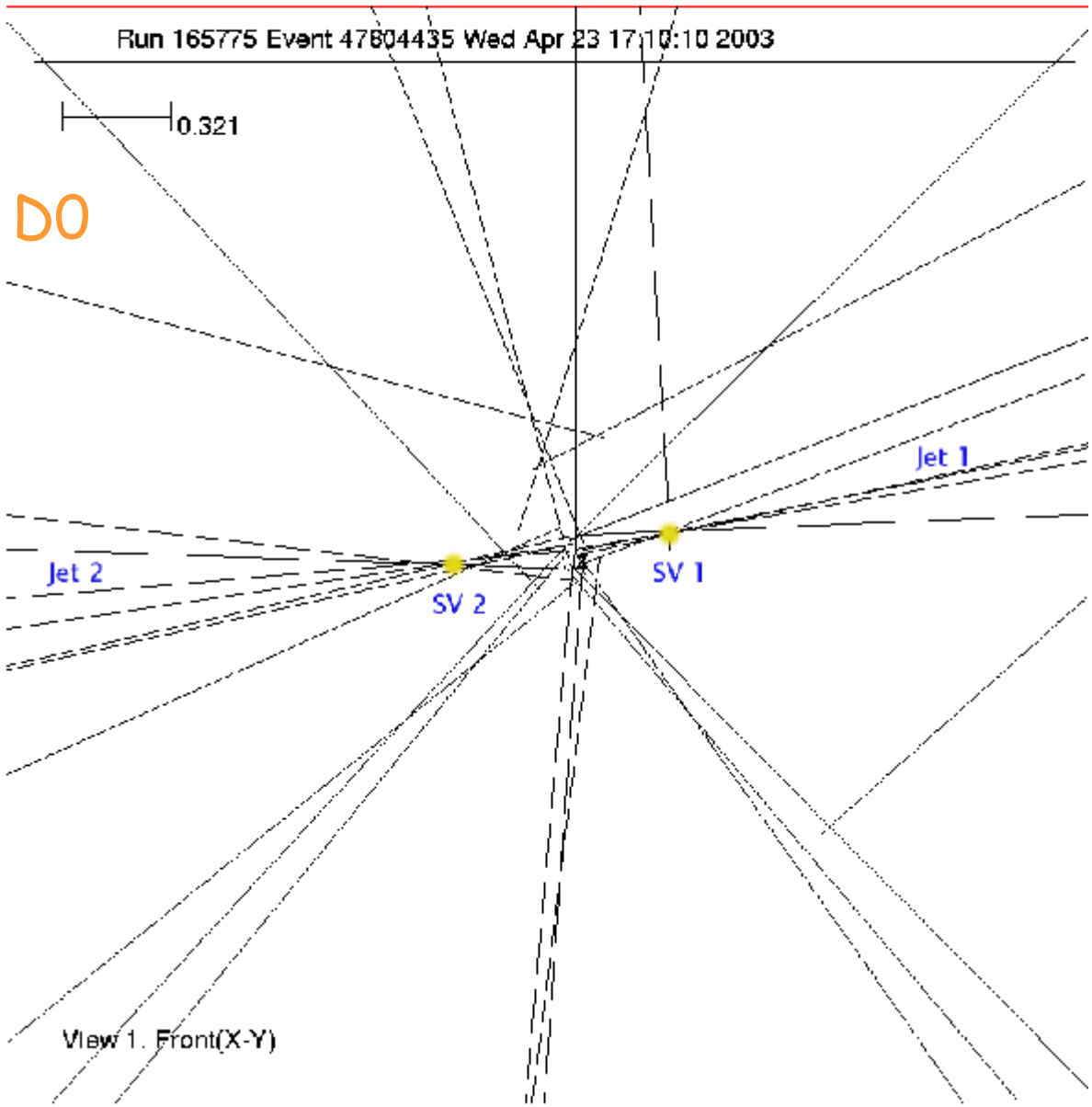
Example: D meson masses



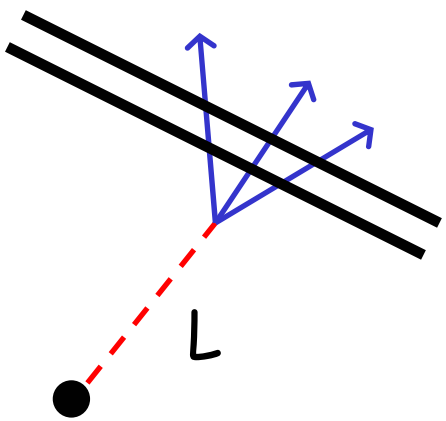
Reconstruction of decay vertices

$$Z \to b\bar{b}$$





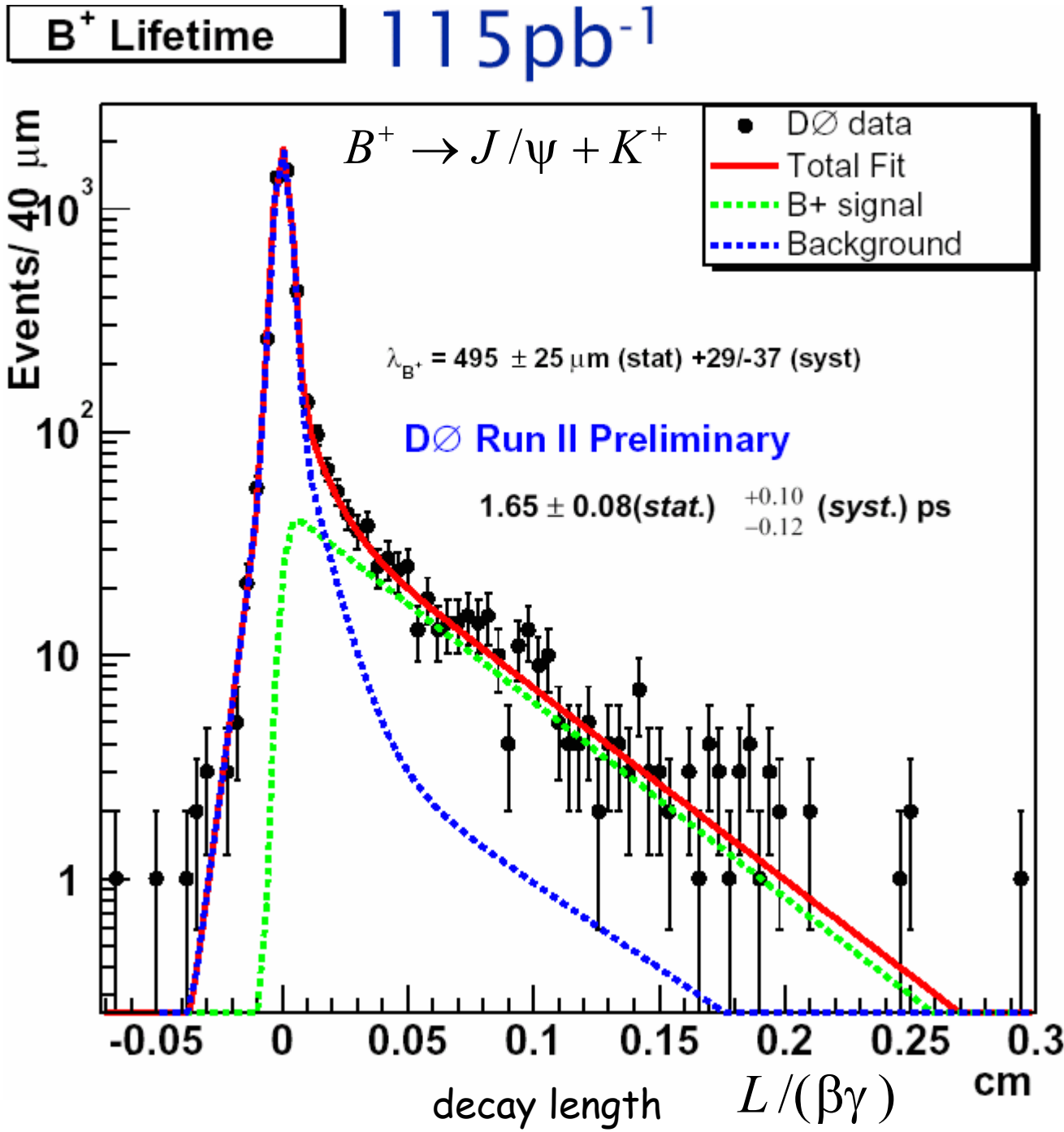
Example:



<u>decay length:</u>

Lab frame:

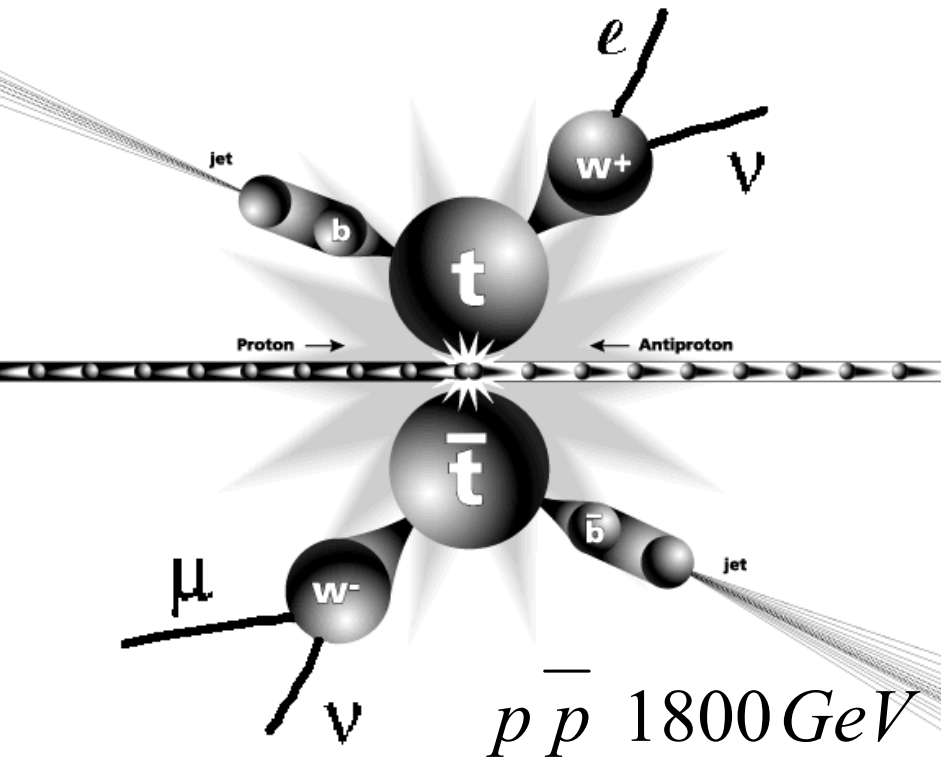
$$L = ct\,\beta\gamma$$



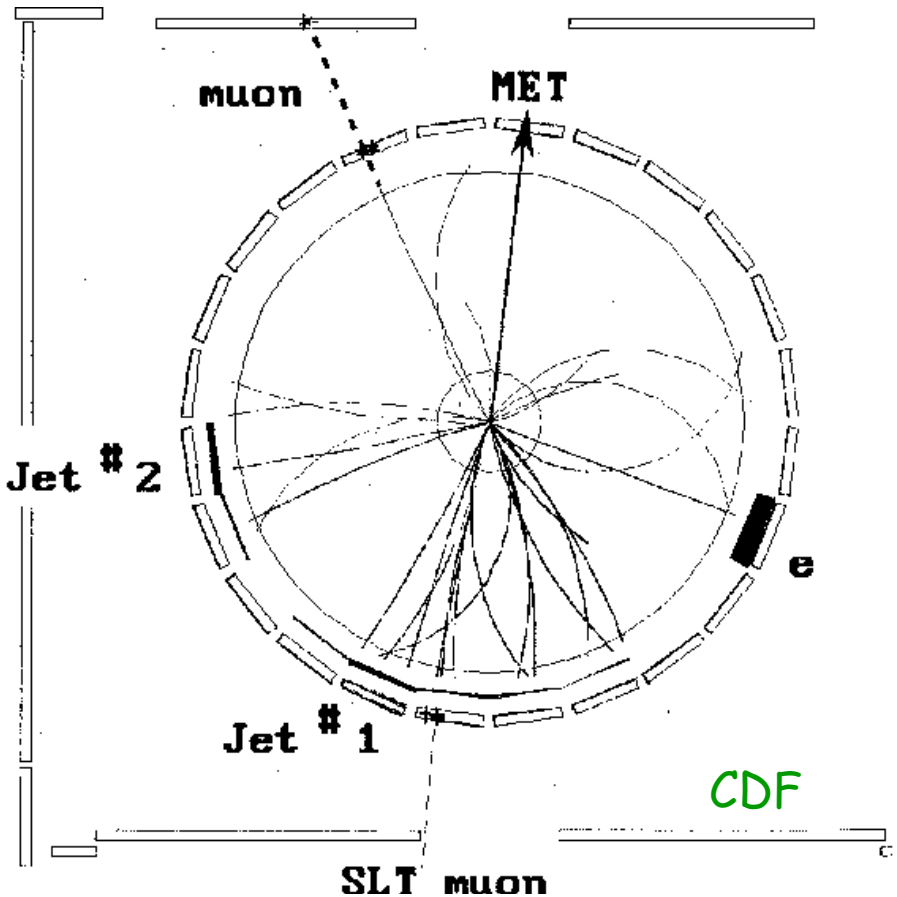
Top Discovery

Fermilab, 1995

CDF, D0



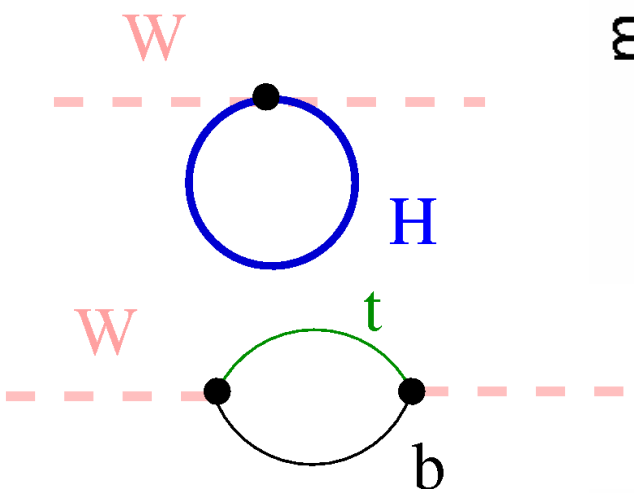
$p\bar{p}$ 1800 *GeV*

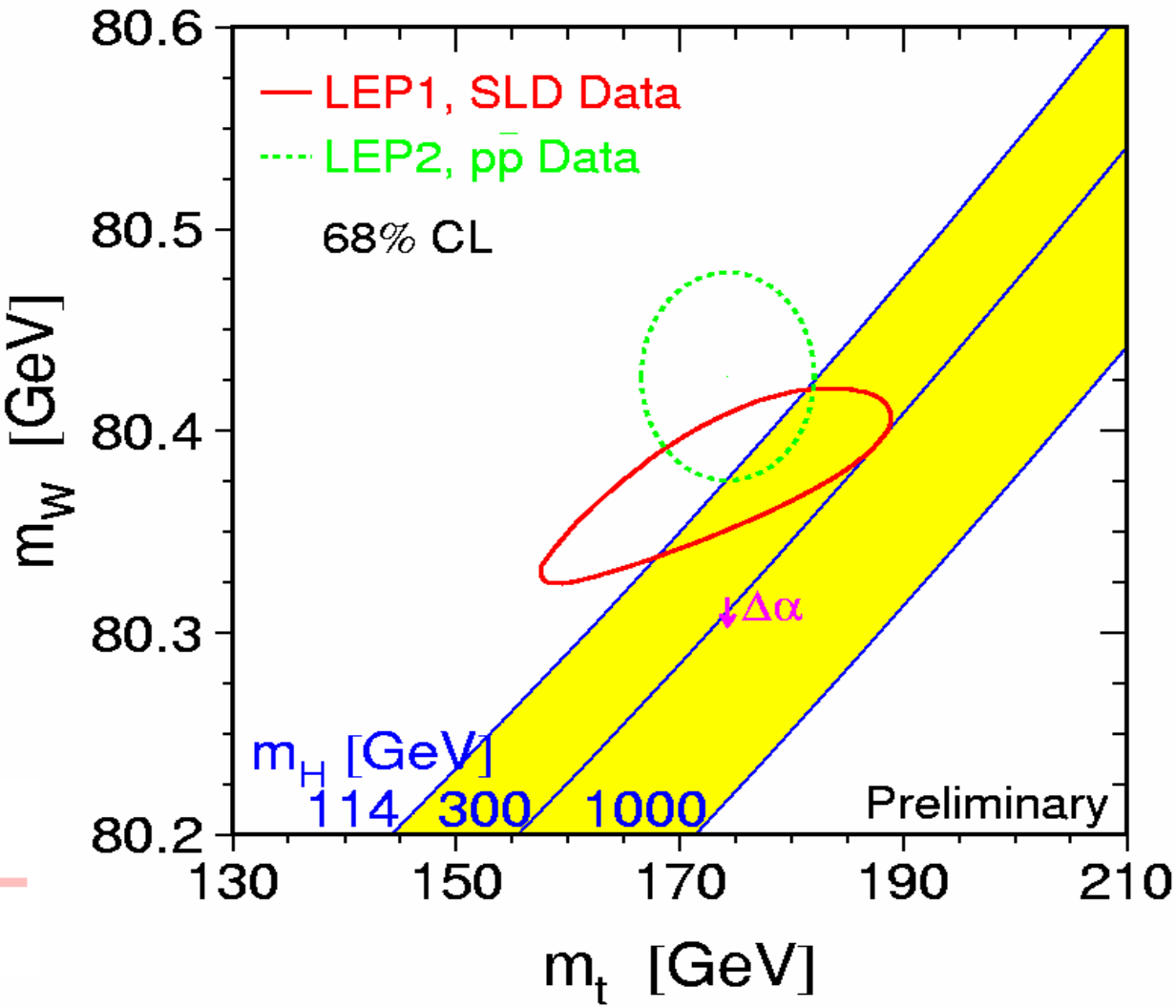


m ~ 175 GeV

Top Physics

- cross section
- decay modes
- top mass
- spin correlations
- ...





$$m_W = \left(\frac{\pi \alpha}{\sqrt{2} G_F} \right)^{1/2} \cdot \frac{1}{\sin\theta_W \sqrt{1 - \Delta r(m_t, \ln m_H)}}$$

Top Identification

cross section small (at 2 TeV)

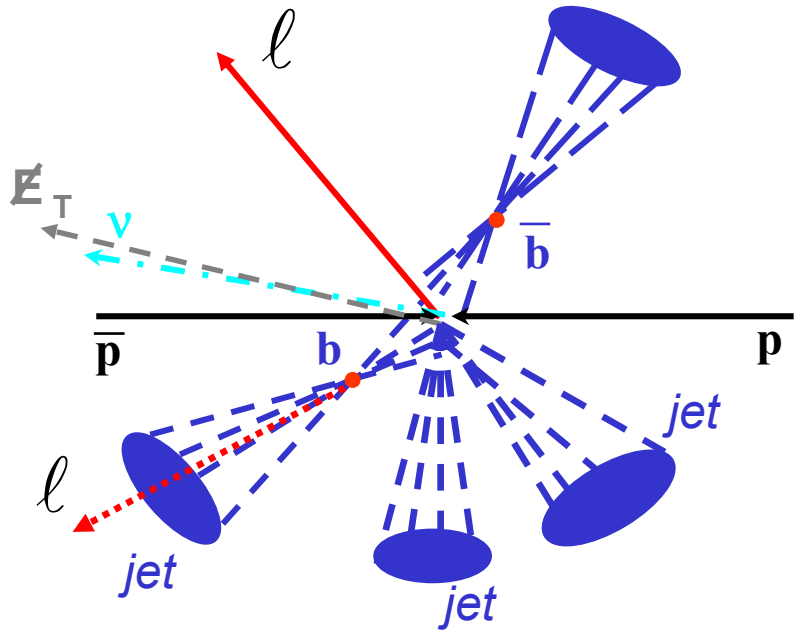
production:

$$p\,\bar{p} \rightarrow t\,\bar{t}$$

decay:

$$t \rightarrow W\,b$$

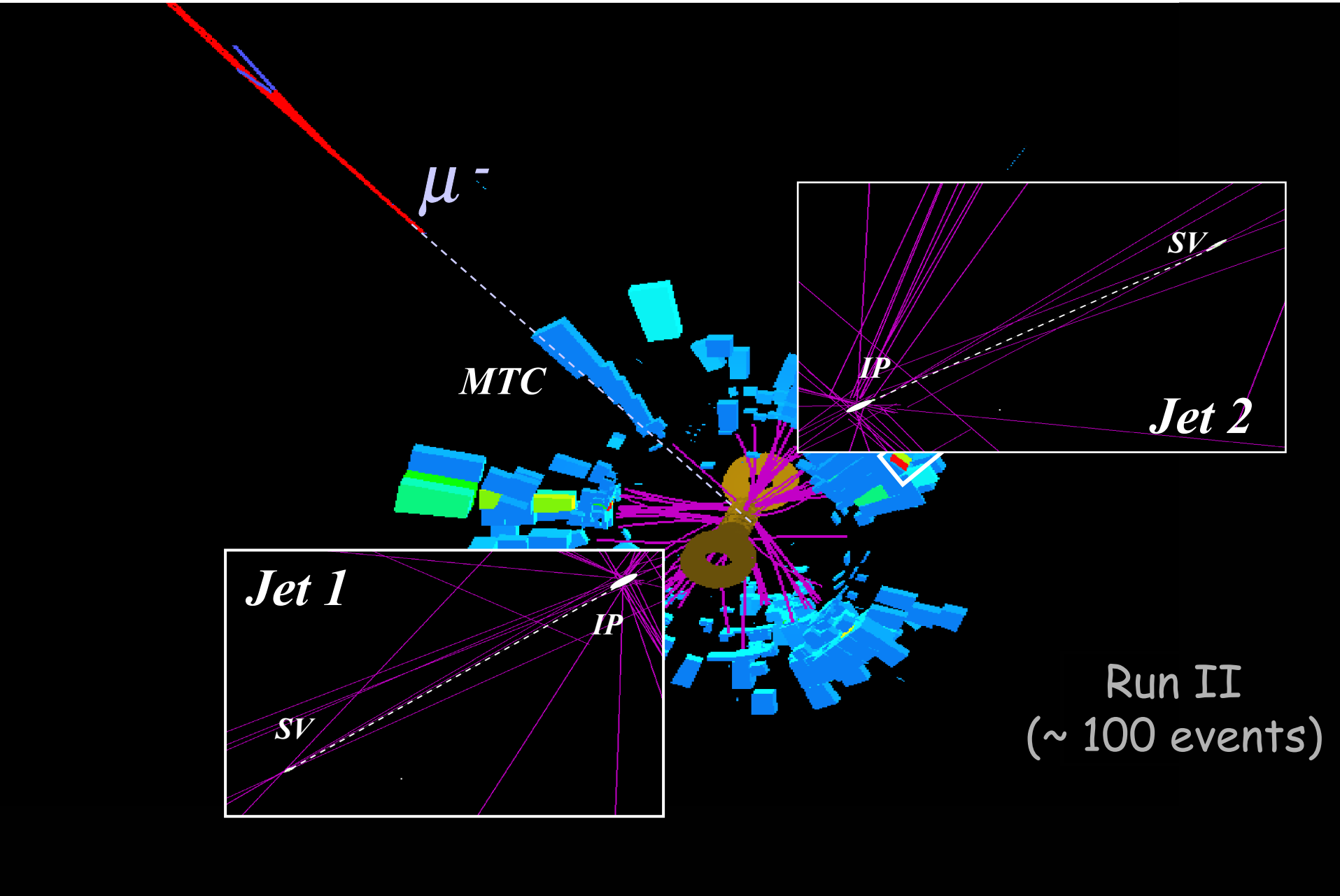
$$W \rightarrow q\,q, l\nu$$



Signature:

2 b jets
+ leptons/jets/missing energy

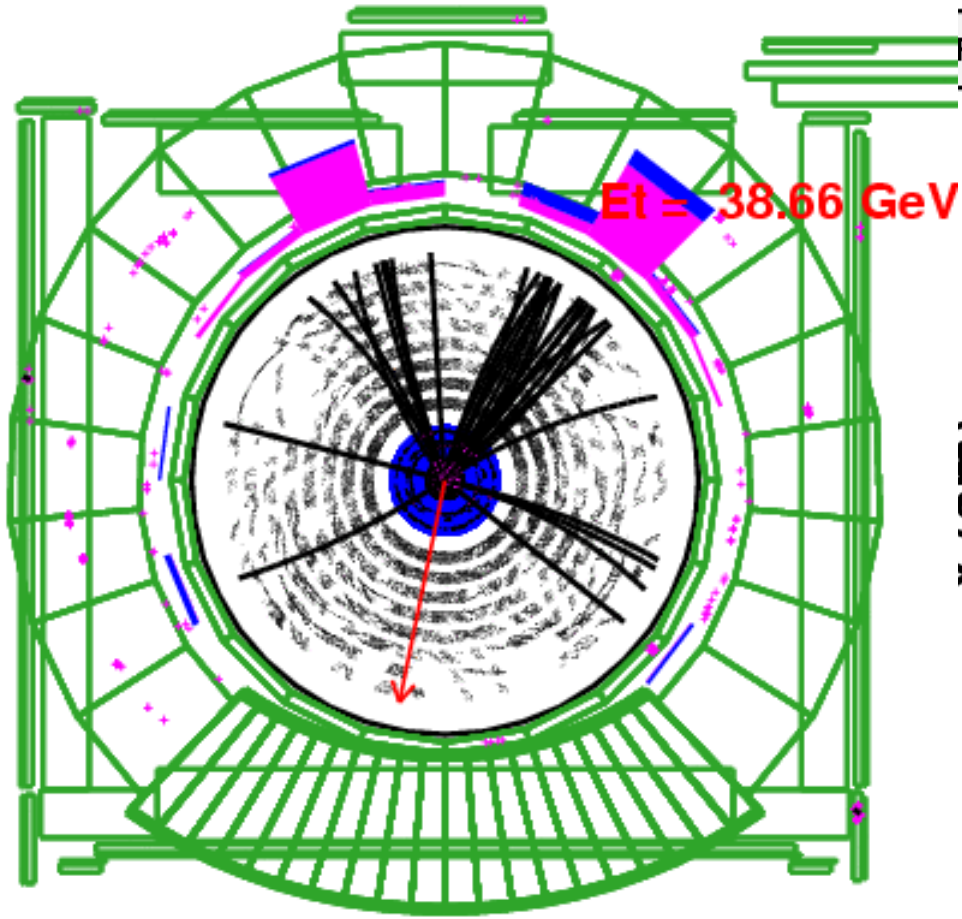
Top event in D0

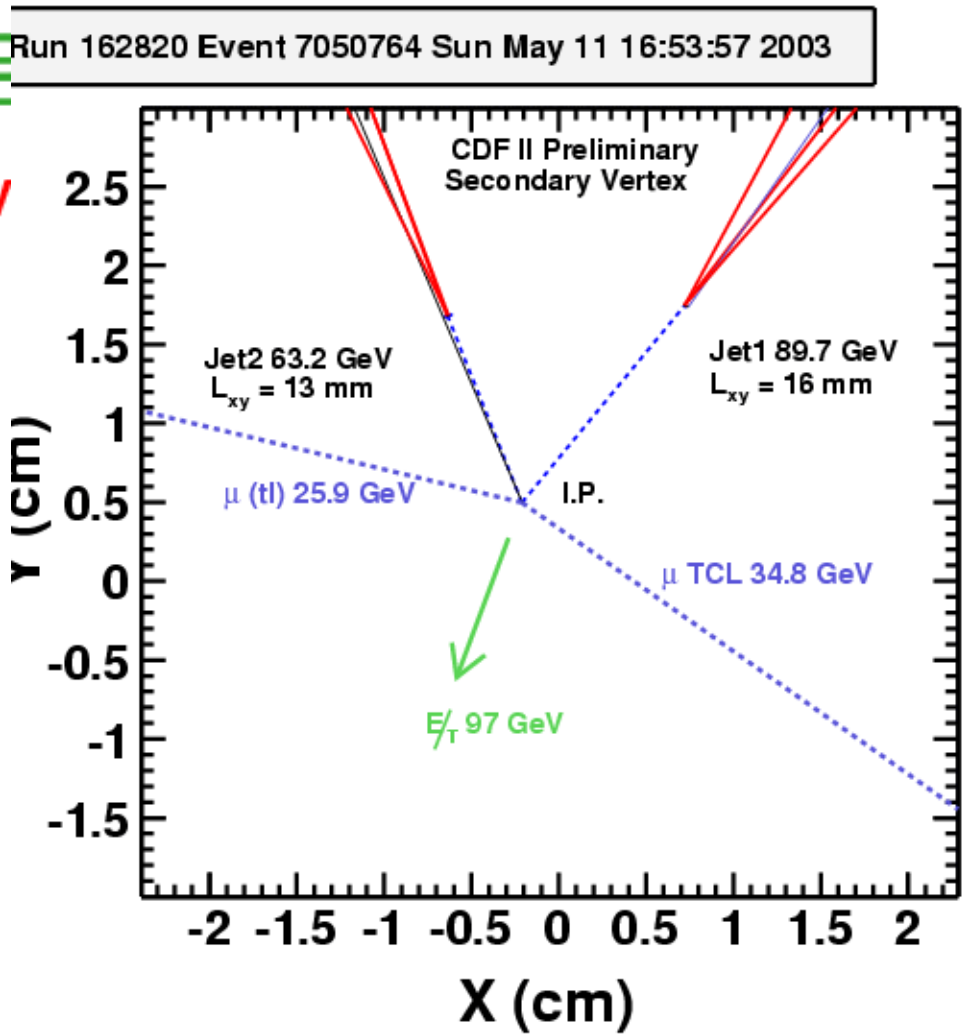


Top event in CDF

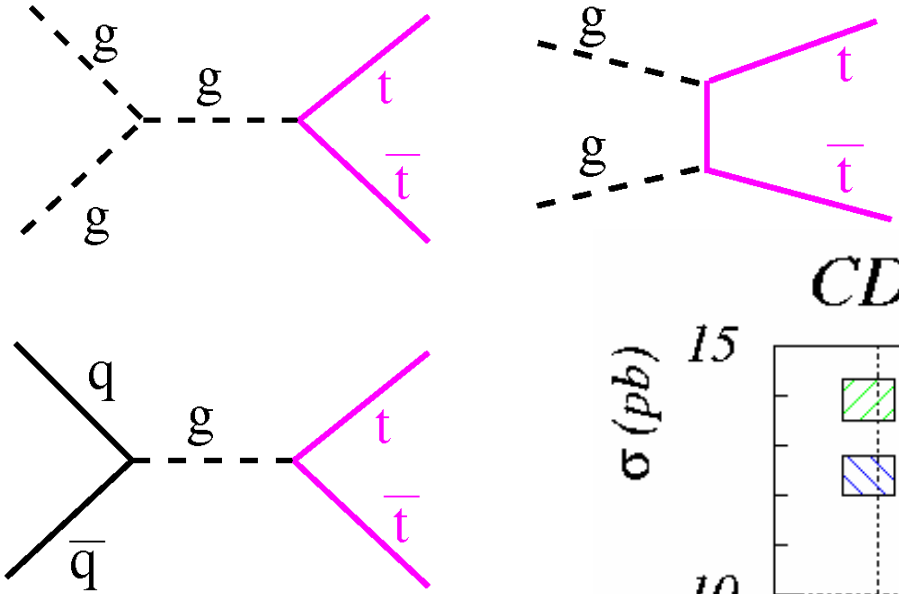
Run II

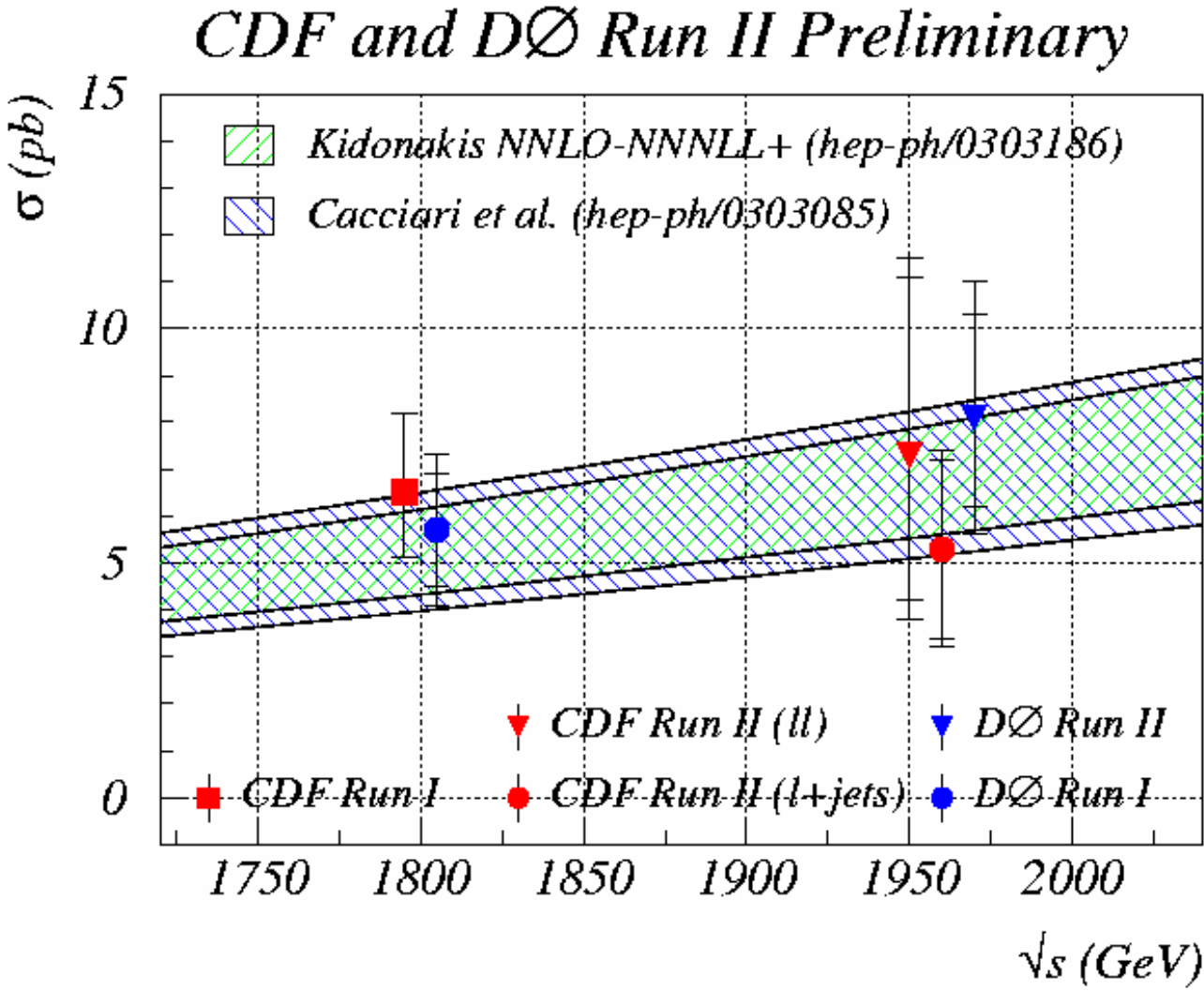
(~ 100 events)





Top Pair Production

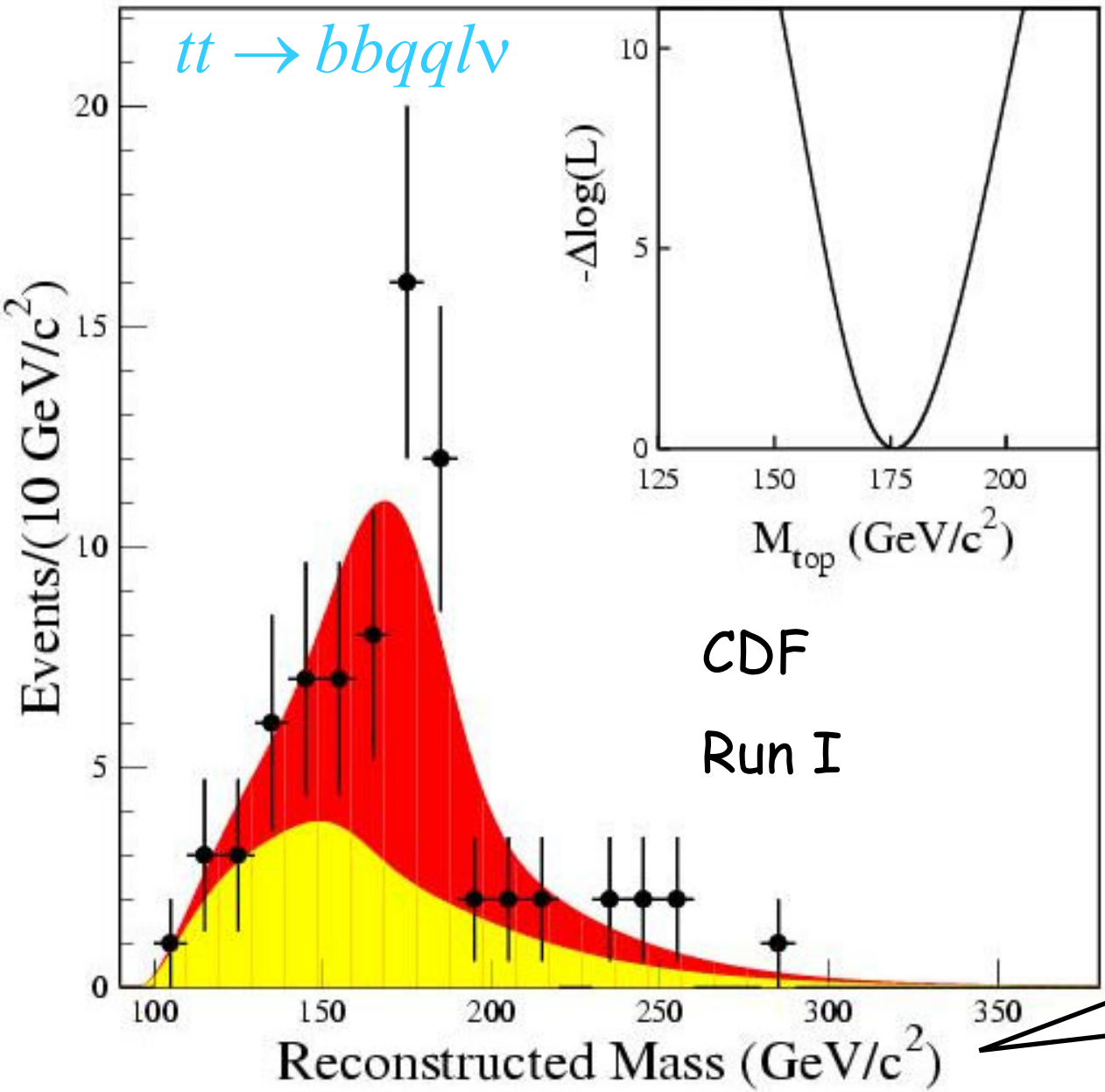




gg contributes

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

Top Mass



Tevatron Run I

CDF + D0:

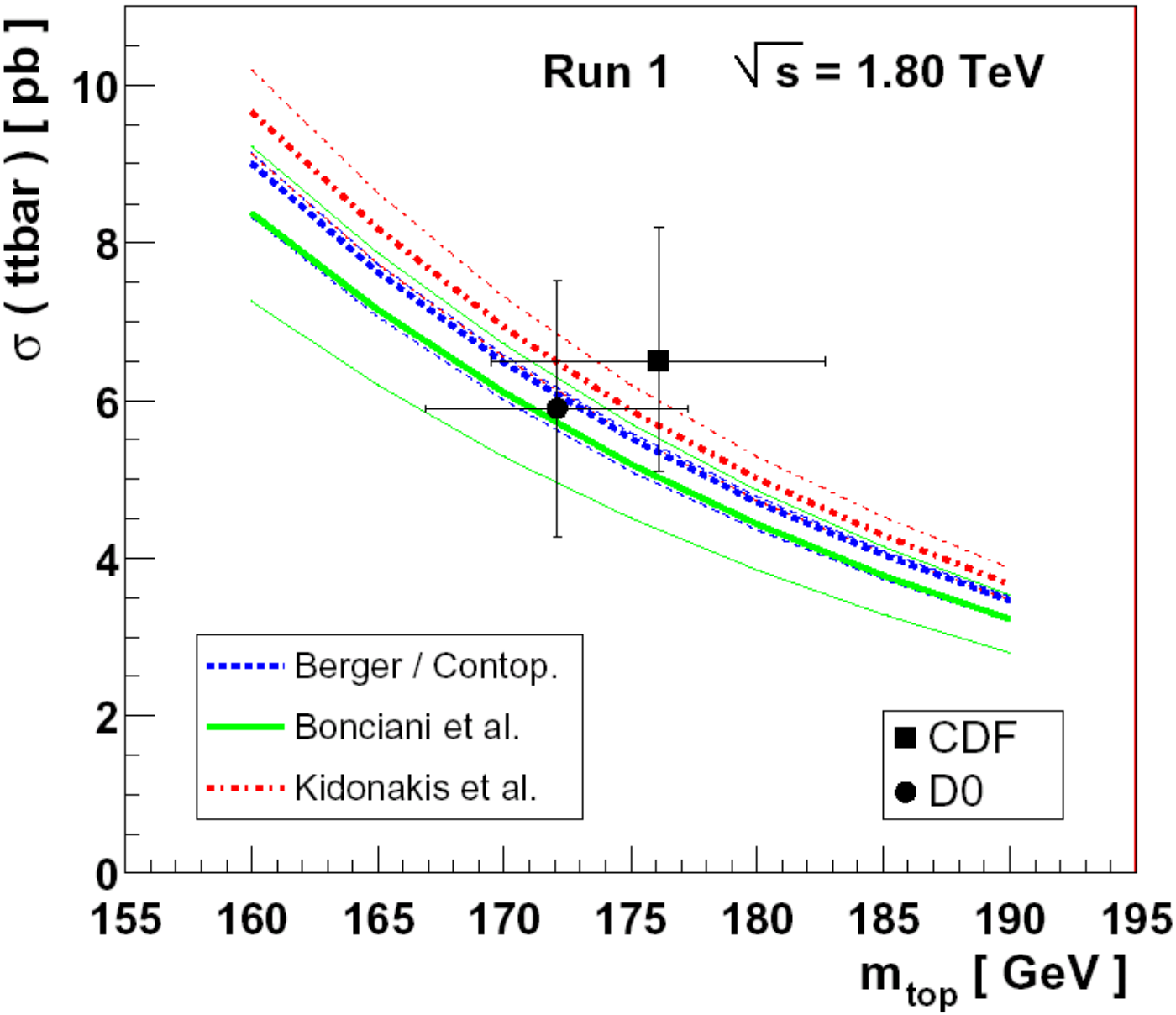
$$174.3 \pm 5.1\,GeV$$

LHC: +- 1 GeV

Using mass constraints

$W \to l\nu$ ...

Top Cross Section and Top Mass



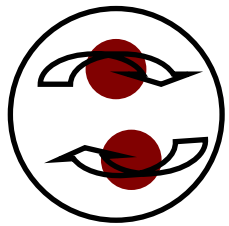
cross section measurement = indirect mass determination!

Spin Correlations - introduction

Top quark lifetime $$\tau_t \approx \frac{8\pi\sqrt{2}}{G_F^2 m_t^3} \approx 5 \cdot 10^{-25}\, s$$

much shorter than „hadron formation time"

$$\tau_h > 1\, fm/c \sim 3 \cdot 10^{-24}\, s$$



Spin of top related to lepton direction in

$$t \to bW \to b\nu\, l$$

due to parity violation!

If $t\,\bar{t}$ is produced in a certain spin state, e.g. $^1S_0$

spins of the two quarks are correlated!

Top Spin Correlations

in $q\bar{q} \to t\bar{t}$

mostly $^3S_1$

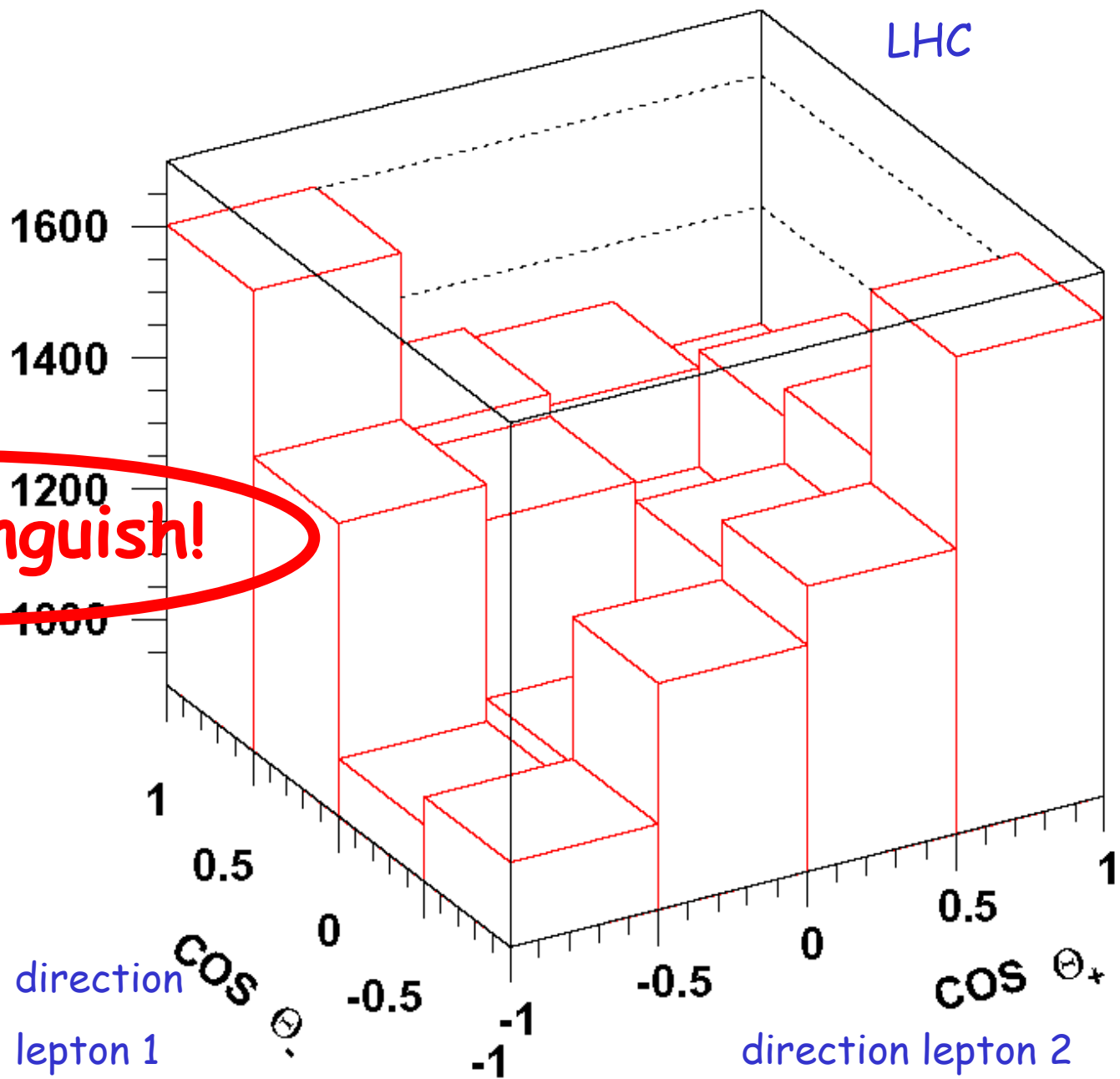
(Tevatron)

can distinguish!

in $gg \to t\bar{t}$

mostly $^1S_0$

(LHC)



p p p h y s i c s

Part I Introduction

Part II Standard Model Physics

- cross section calculation
- QCD and jets
- W and Z
- charm and bottom
- top

Part III Higgs

Part IV New Phenomena

References