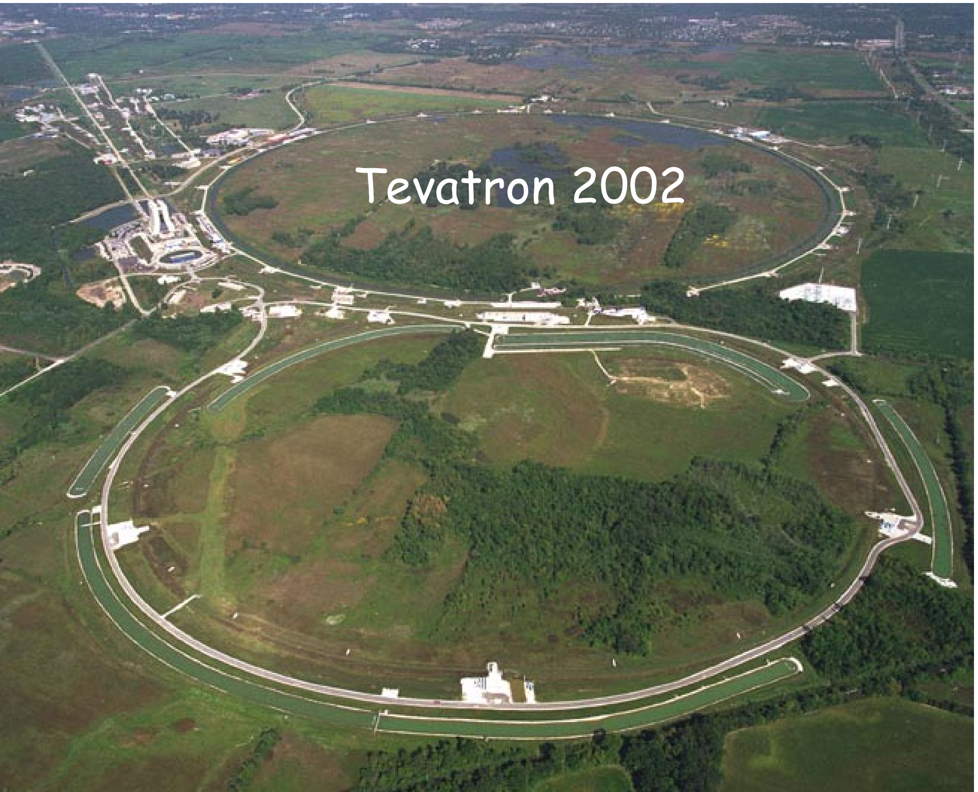
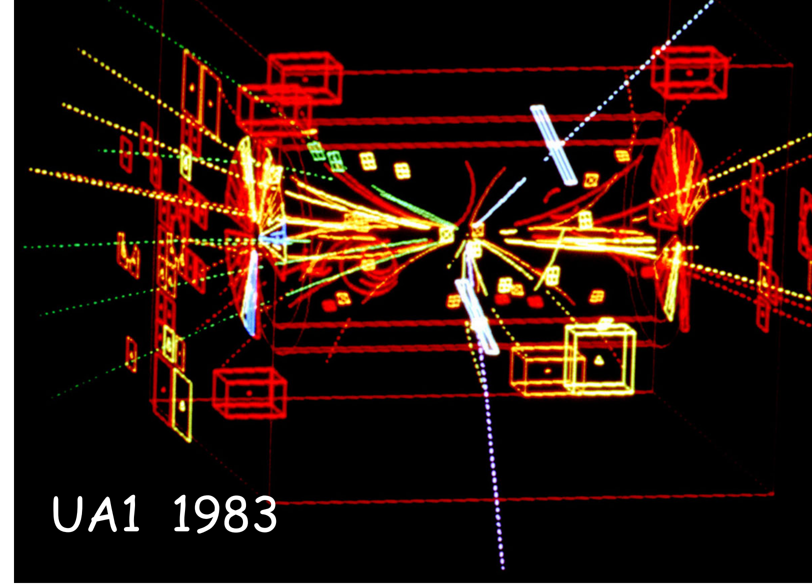
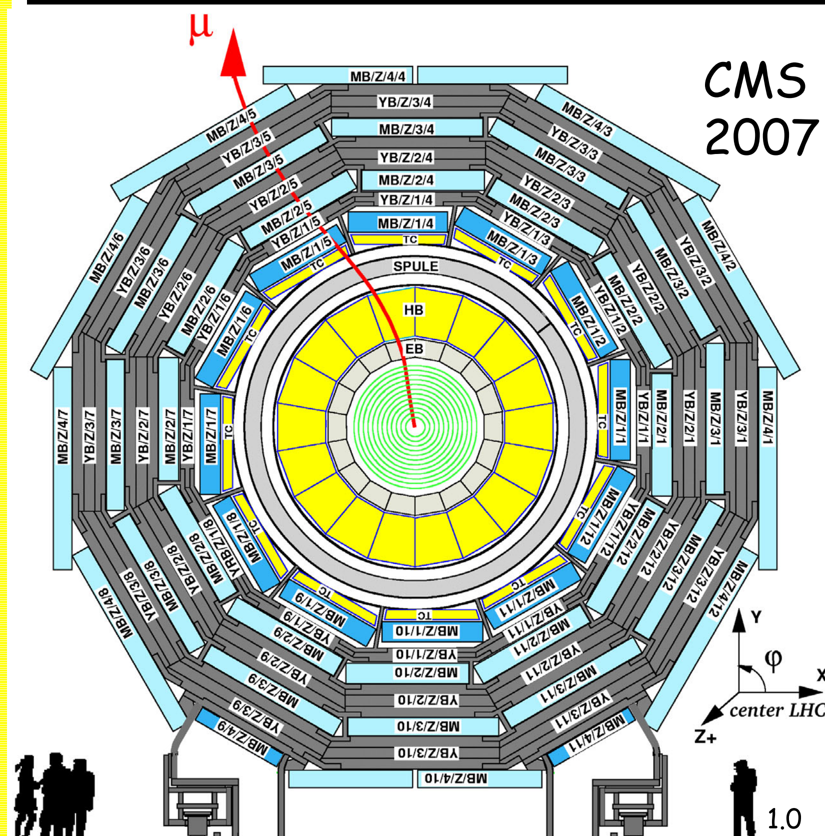
Thomas Hebbeker, RWTH Aachen
Belgian-Dutch-German school
September 2003

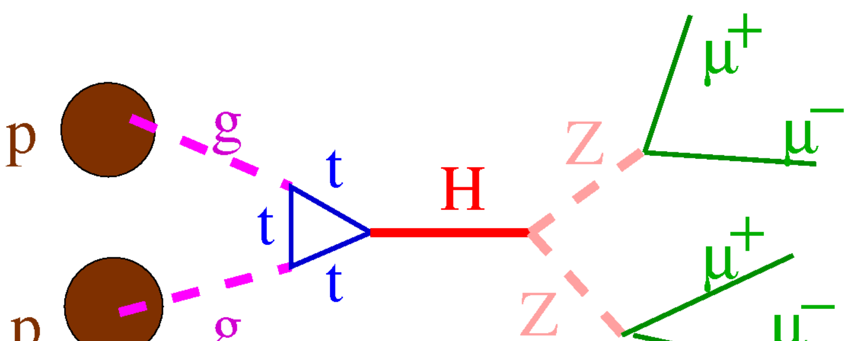
part II

# pp physics




LHC 2008 ?

p p physics

## Part I Introduction

## Part II Standard Model Physics

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

## Part III Higgs

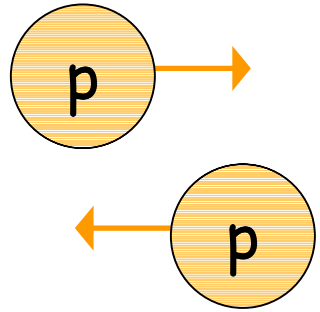
## Part IV New Phenomena

## References

# Cross Section

Elastic cross section

LUMINOSITY



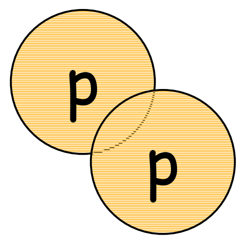

strong, electromagnetic

Xsection relatively small
scattering angle tiny

Total inelastic cross section

BACKGROUND

LUMINOSITY

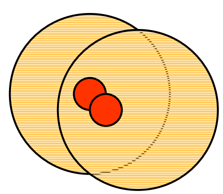



strong

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

Pointlike cross section

SIGNAL



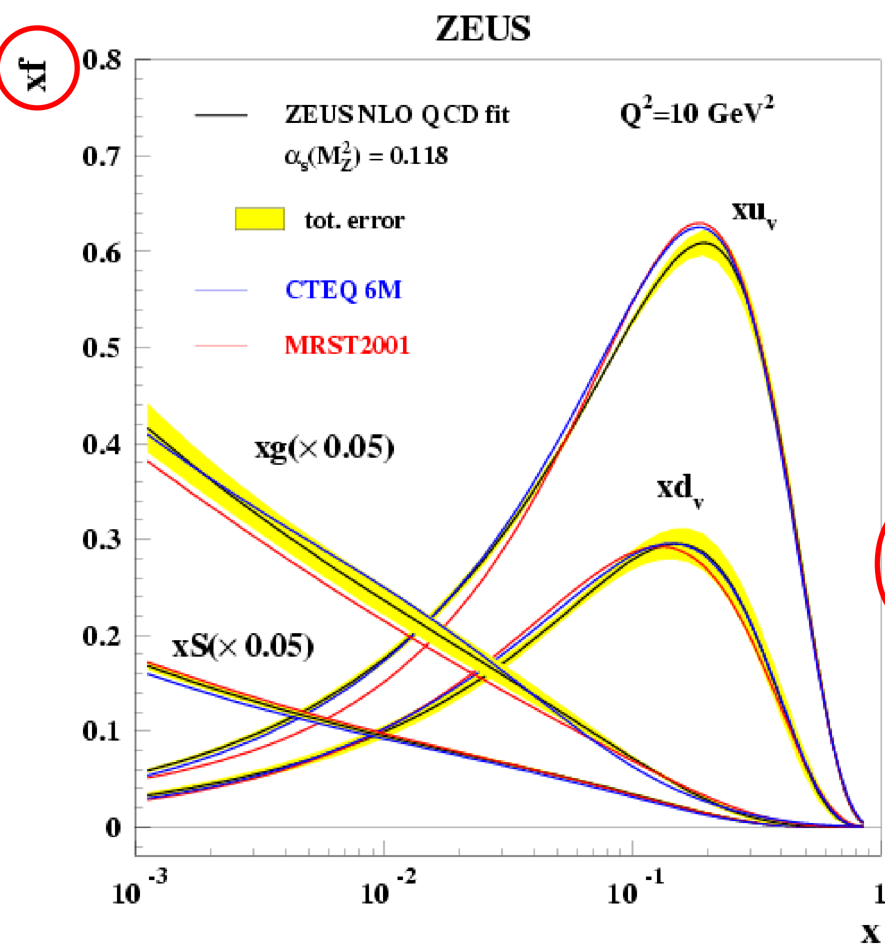
electroweak

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

LHC

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

# Structure Functions

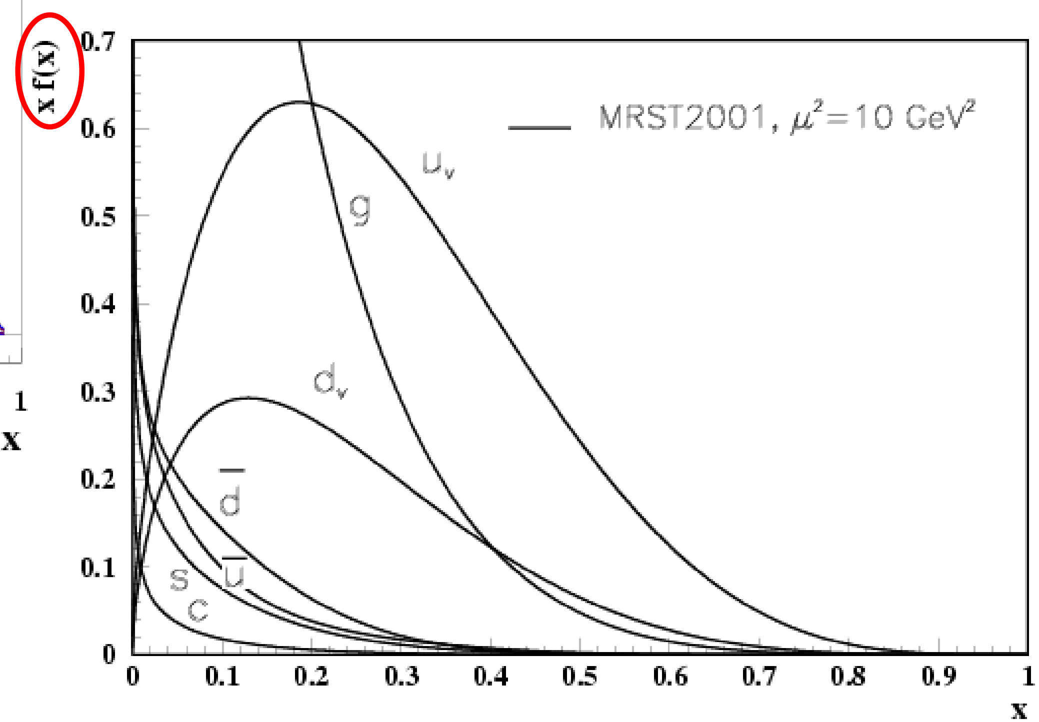



## Measurements:

$F_2$, $F_3$ ... in DIS

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

⇨ valence, sea, gluons...




## Fits/parametrisations:

- CTEQ
- MRST

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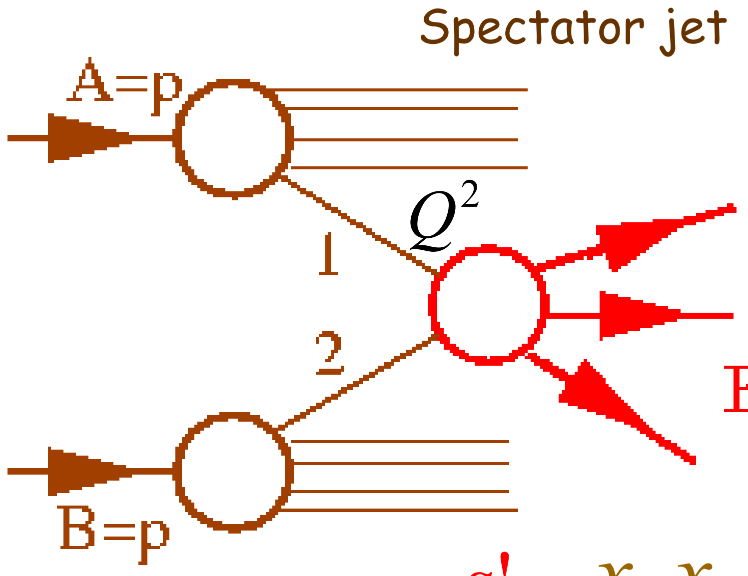
# Cross section calculation in pp

final state

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

kinematical variable




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

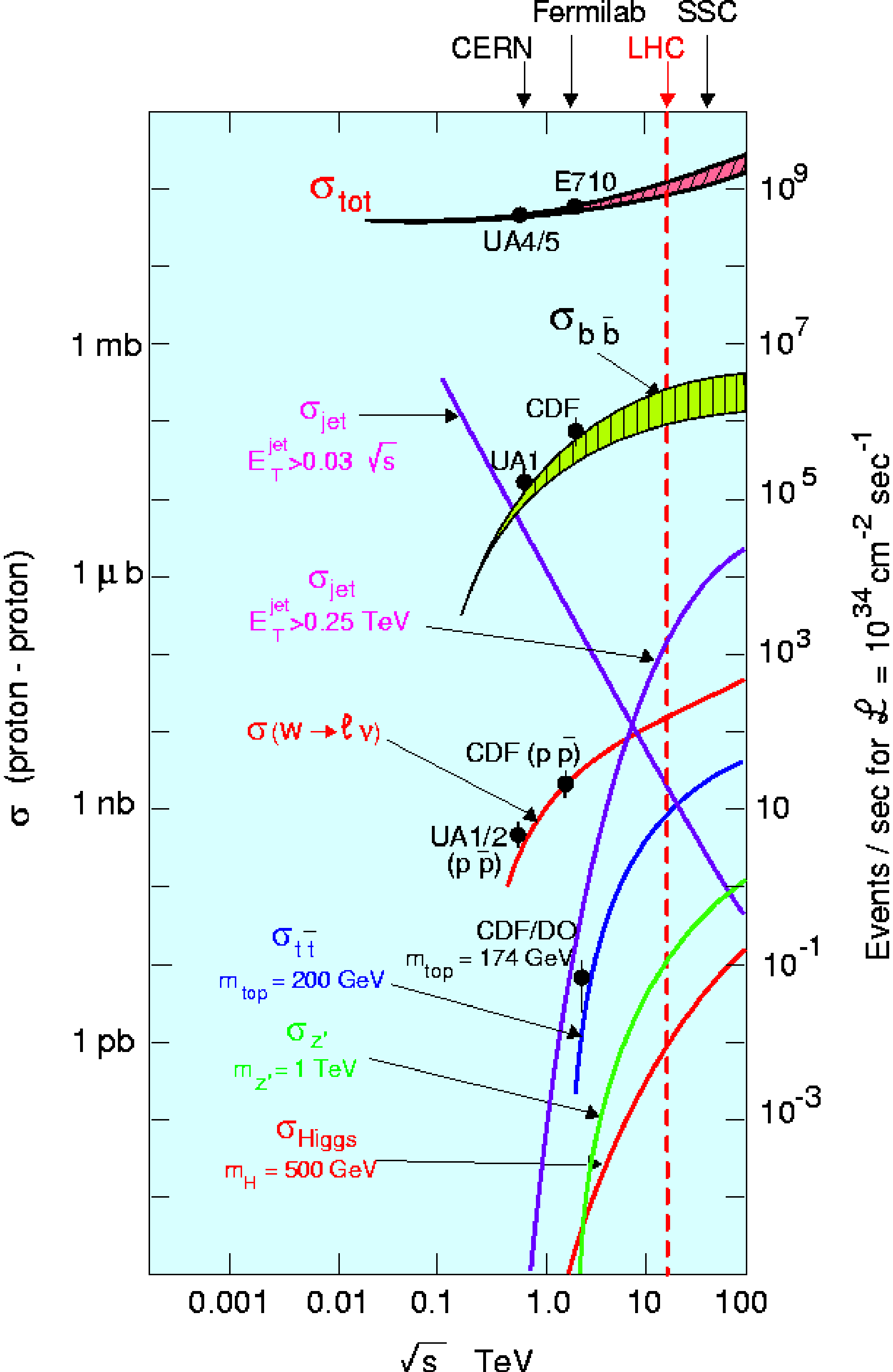
Known: $$f_i(x_i,Q^2)$$

$Q^2$ = („momentum transfer")$^2$

depends on final state

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

# Cross Sections at Hadron Colliders




Note:

may trade:

energy ↔ luminosity

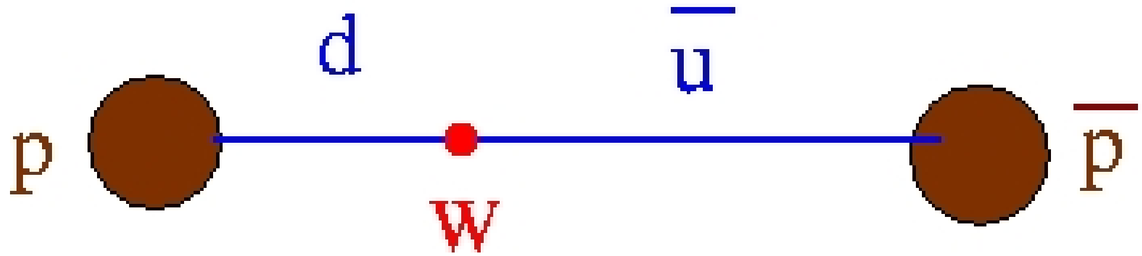
Example:

In principle top discovery at SPS !

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

**Ansatz:**

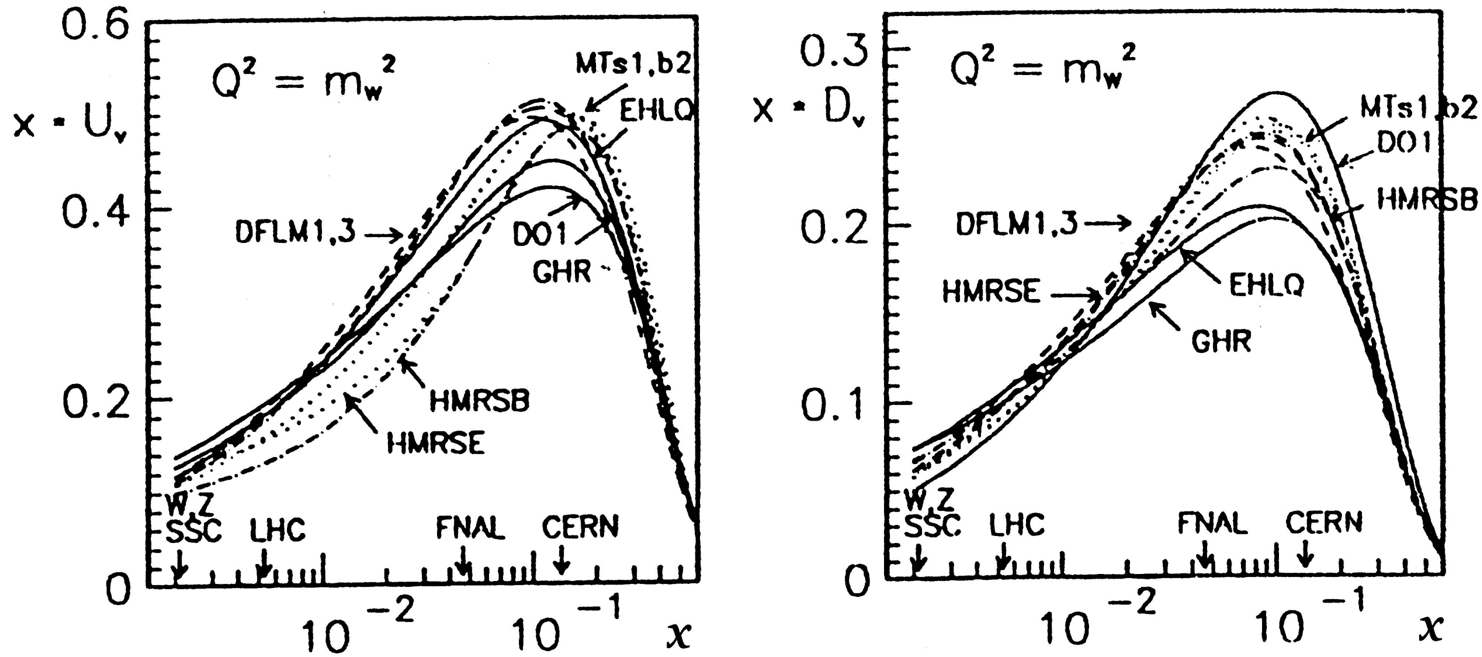
$$d\,\bar{u} \;\rightarrow\; W^- \qquad (valence \;\; quarks)$$




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

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

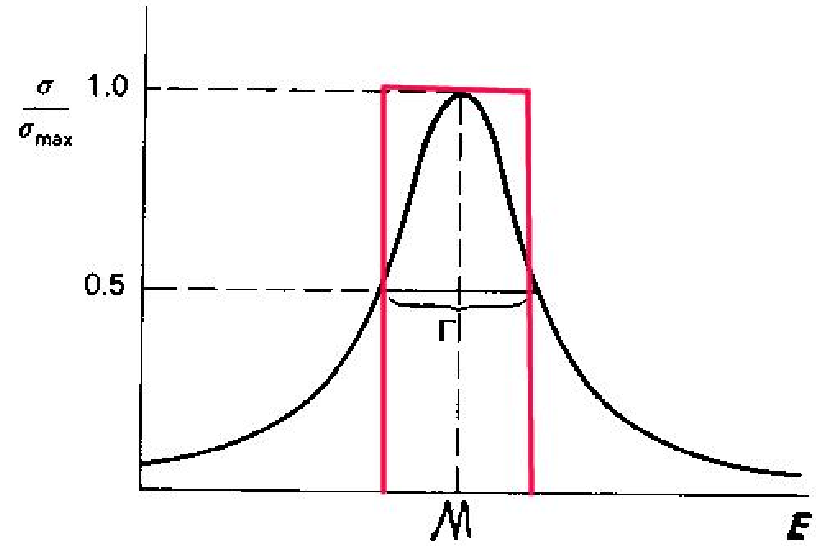
# Structure Functions:




Rough parametrisation:

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

## 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:**

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

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

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

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

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

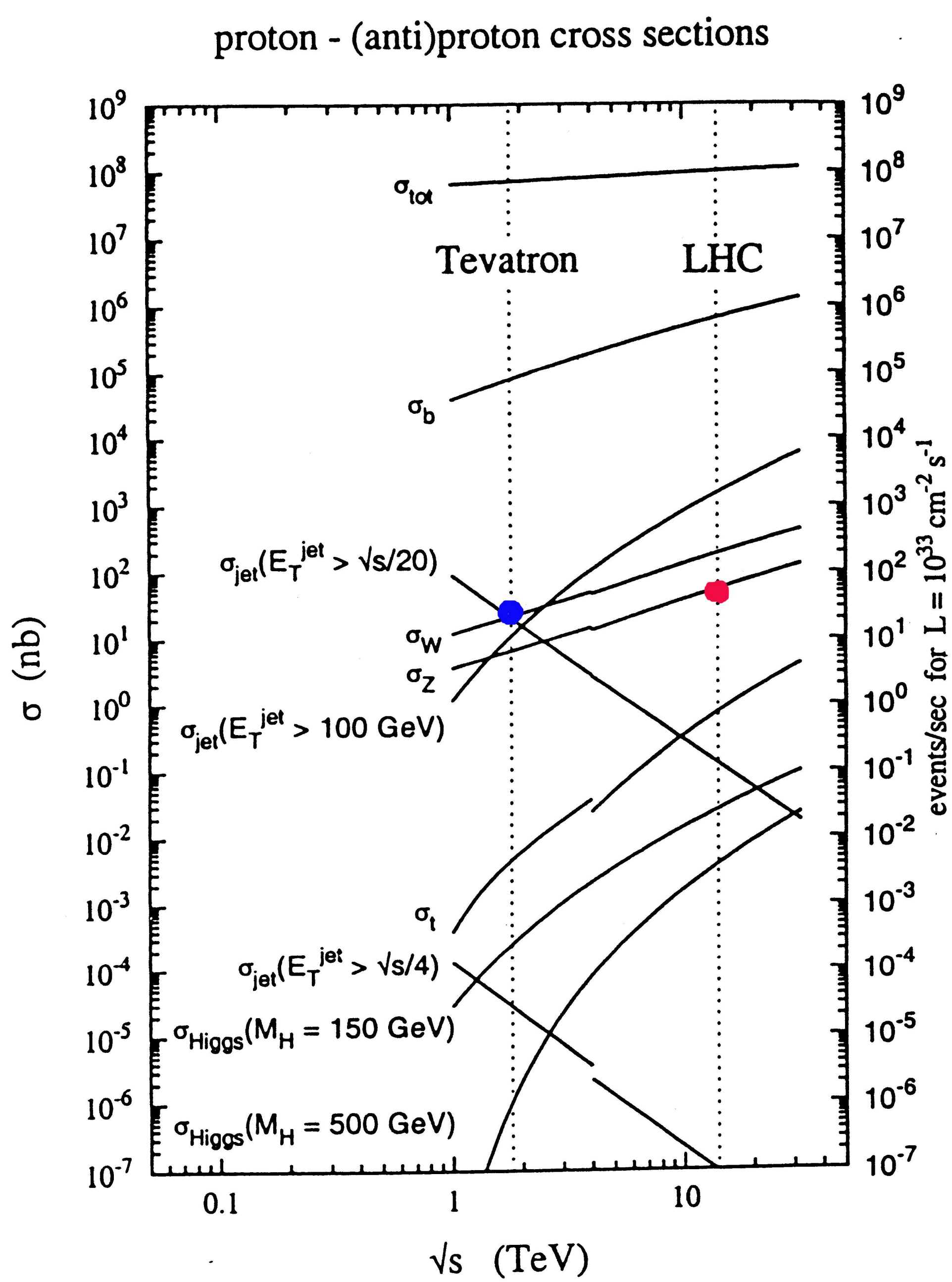
**Results:**

$$1/\mathrm{GeV} = 2 \cdot 10^{-16}\,\mathrm{m}^2$$
$$m_W = 80\,\mathrm{GeV}$$
$$\Gamma_W = 2\,\mathrm{GeV}$$

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

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

LHC(pp!) :
$$\sigma_p(\sqrt{s}) \approx 40\,\mathrm{nb}$$



# QCD = Quantum Chromodynamics

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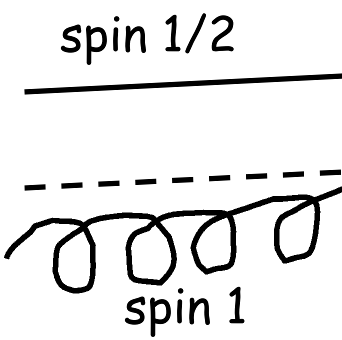
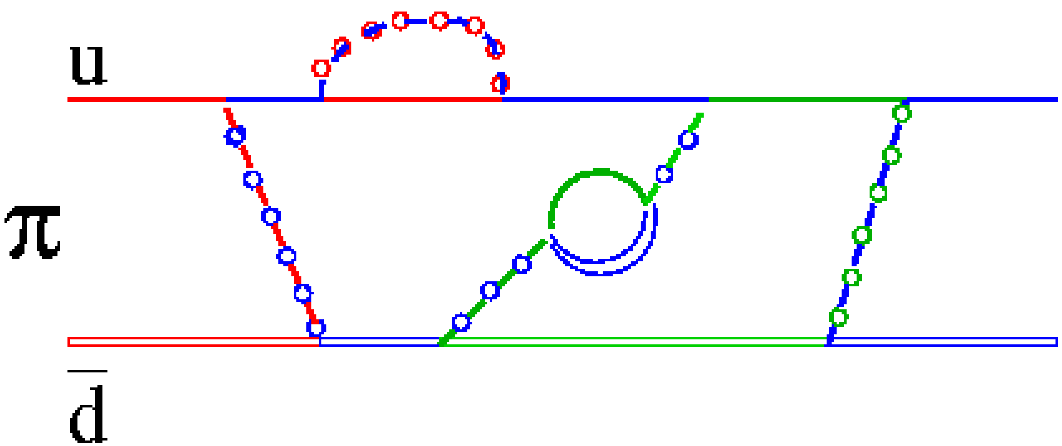
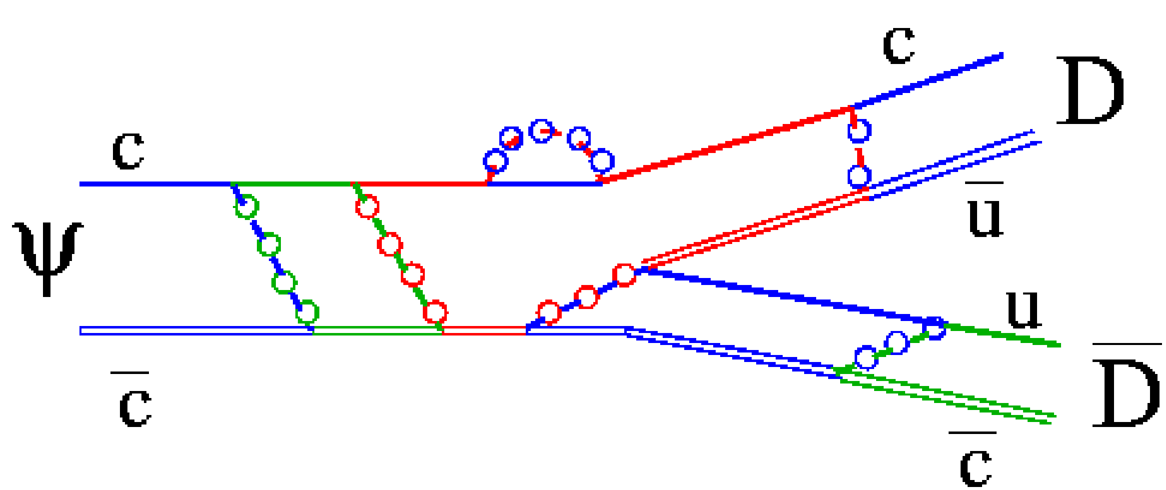



**Gauge theory:** • quarks with 3 colors (r,g,b)

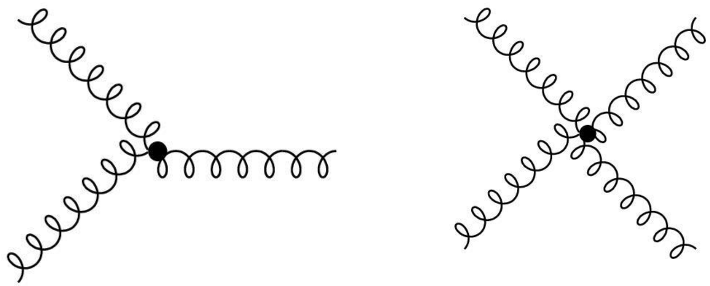
**SU(3)** • 8 gluons (color + anticolor $\bar{r}$,$\bar{g}$,$\bar{b}$)



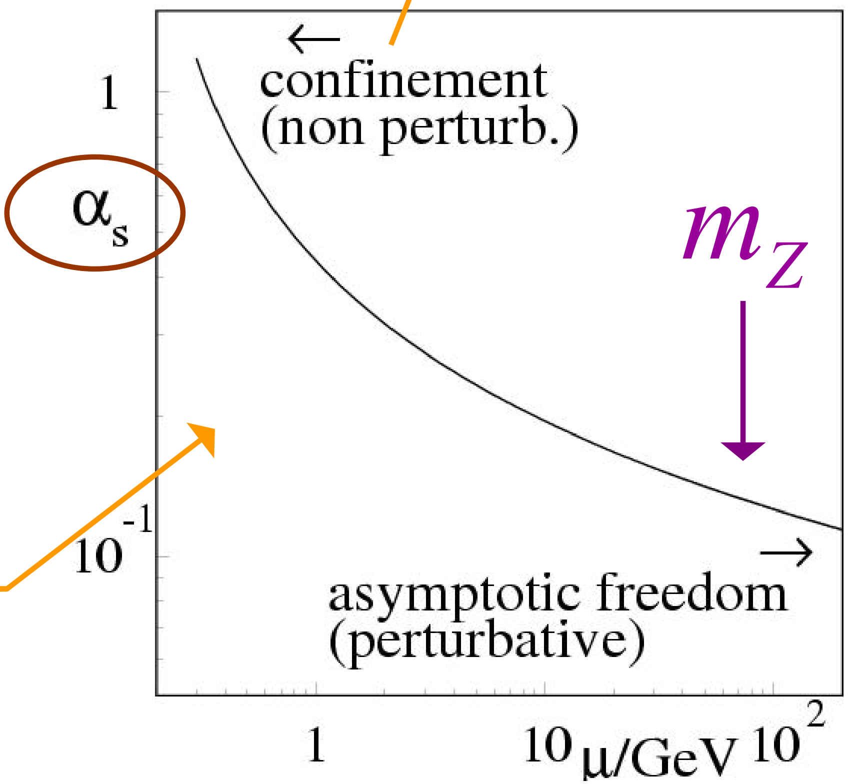
# self coupling, running, confinement

nonabelian:



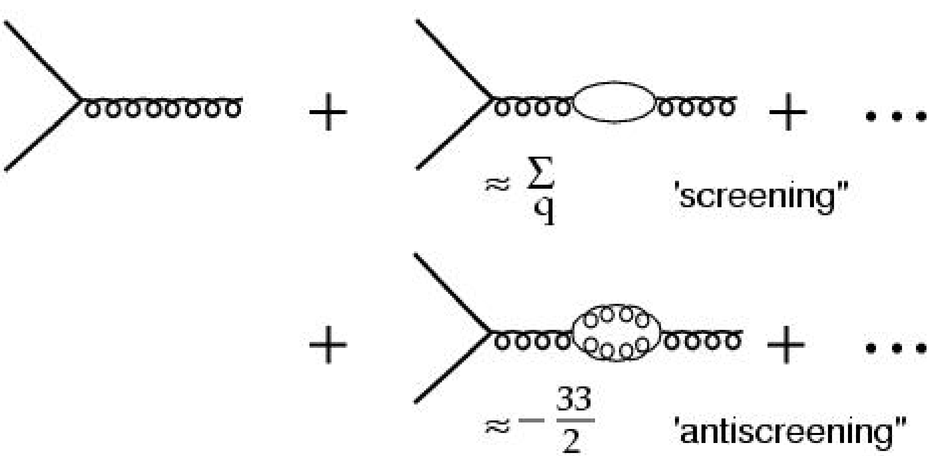
mesons and baryons „white":


strong coupling „constant"




~ 1/distance

„Running":



# Hadronization = Fragmentation

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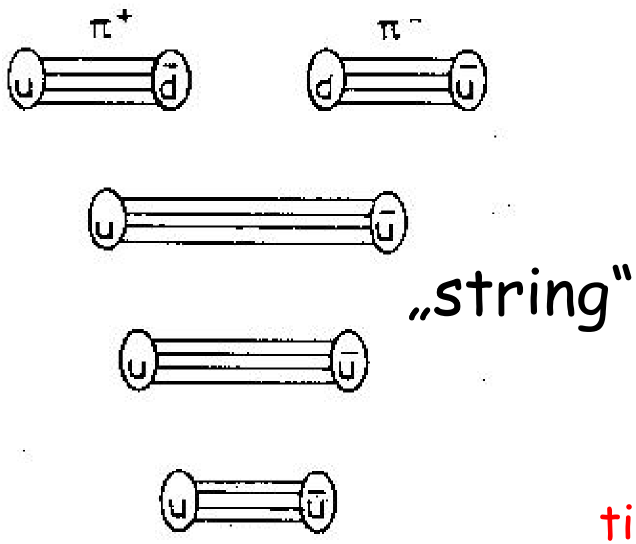
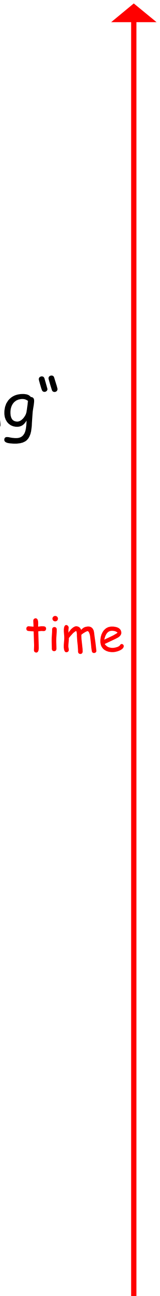
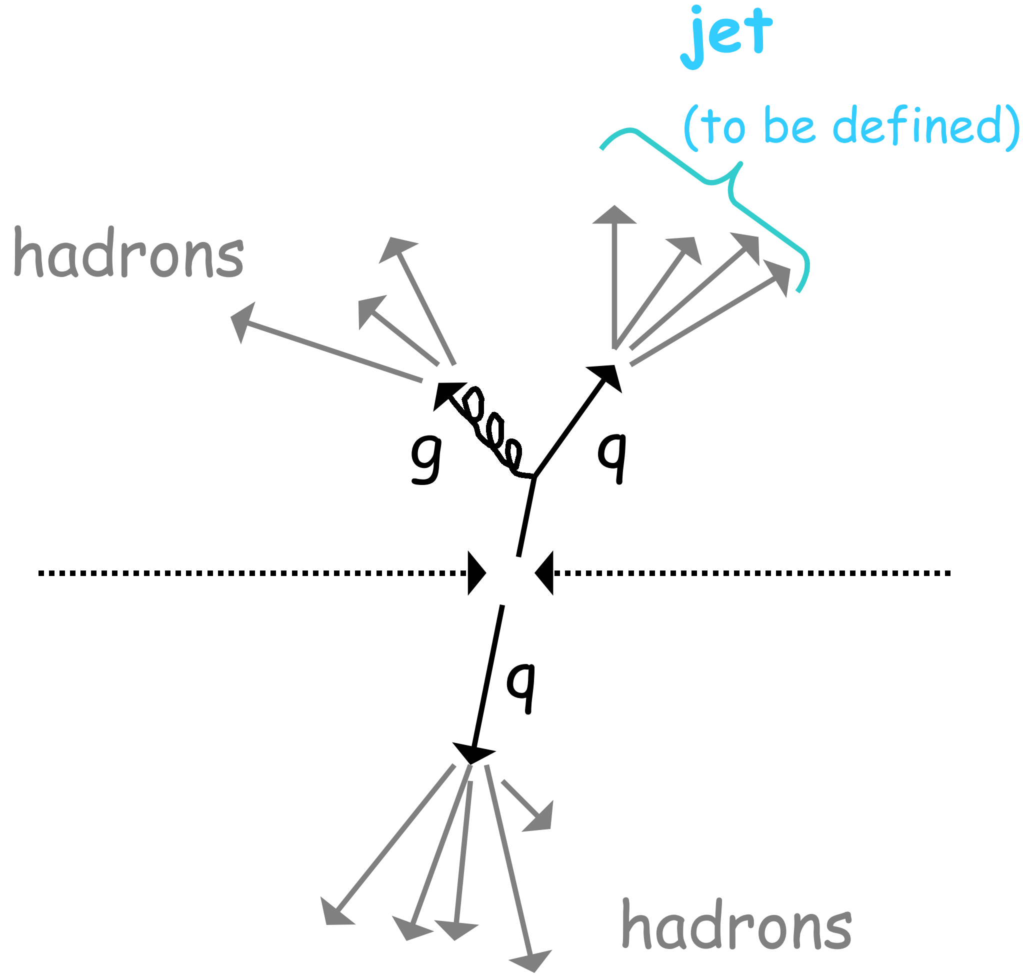
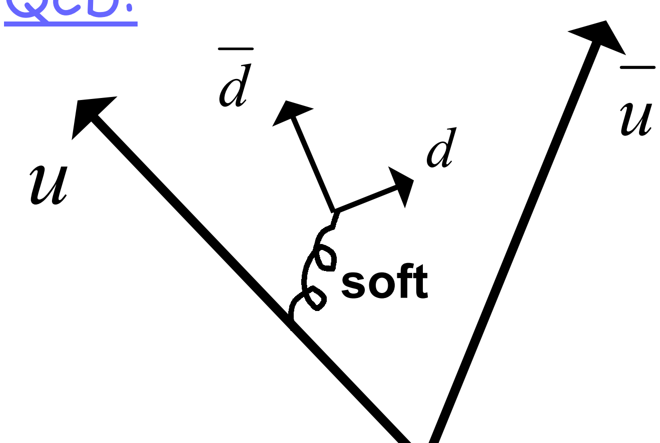
String model:




QCD:




Hadronization: non-perturbative

⇨ need models!

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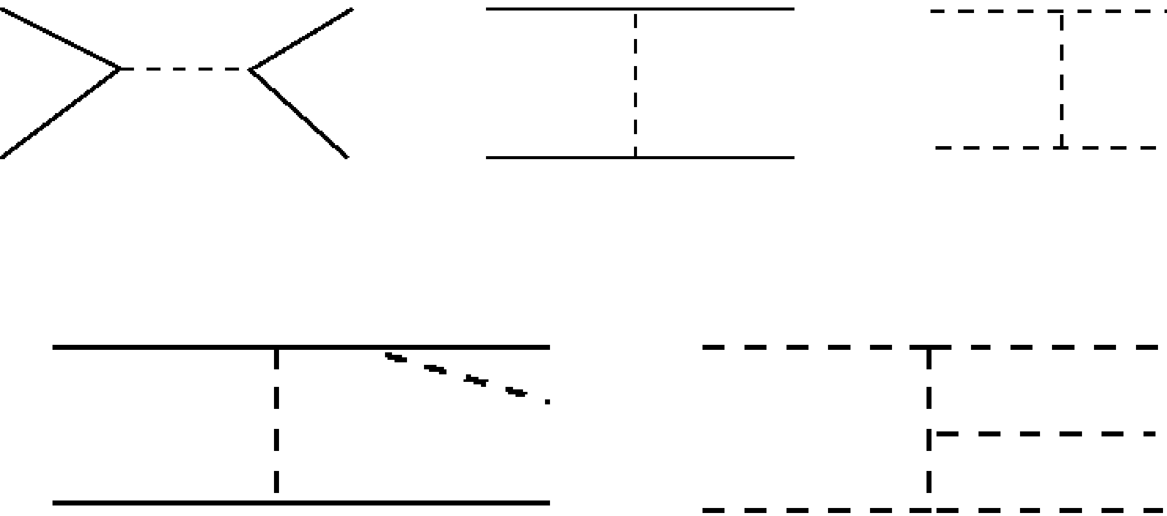
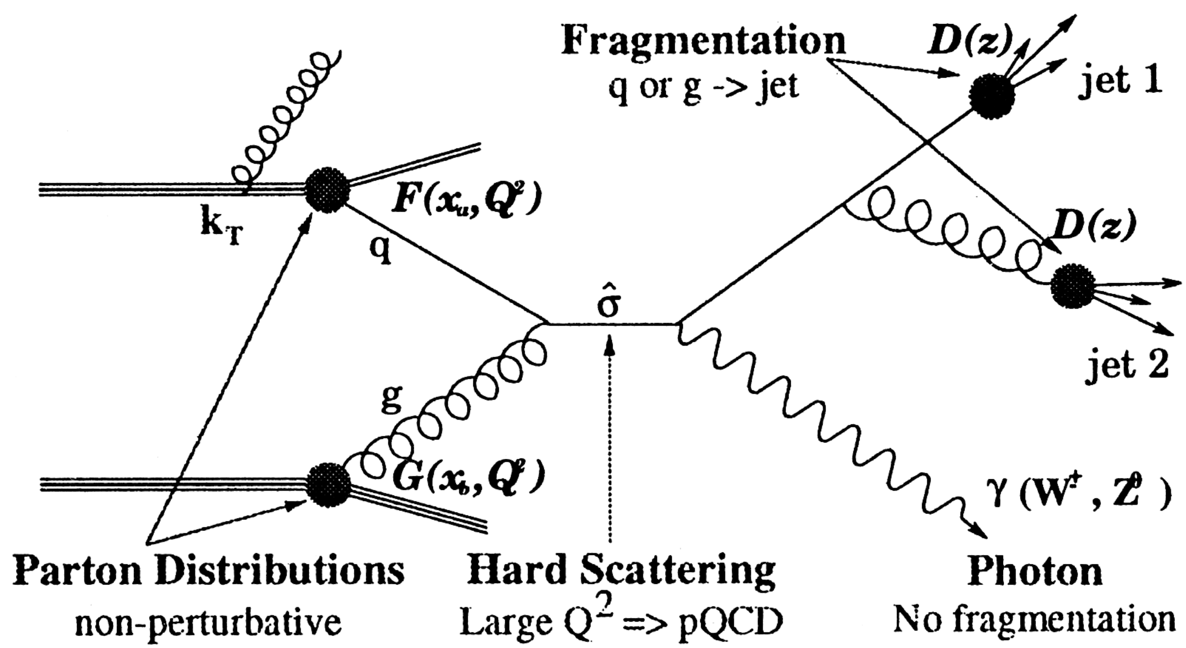
# Calculation of QCD processes



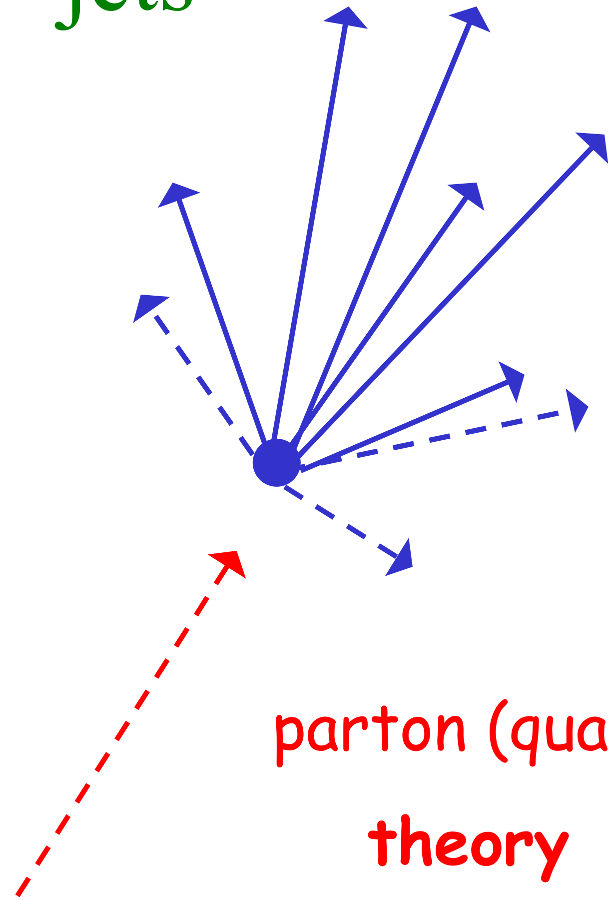


# jets

Typical: 100 particles total

(14 TeV)

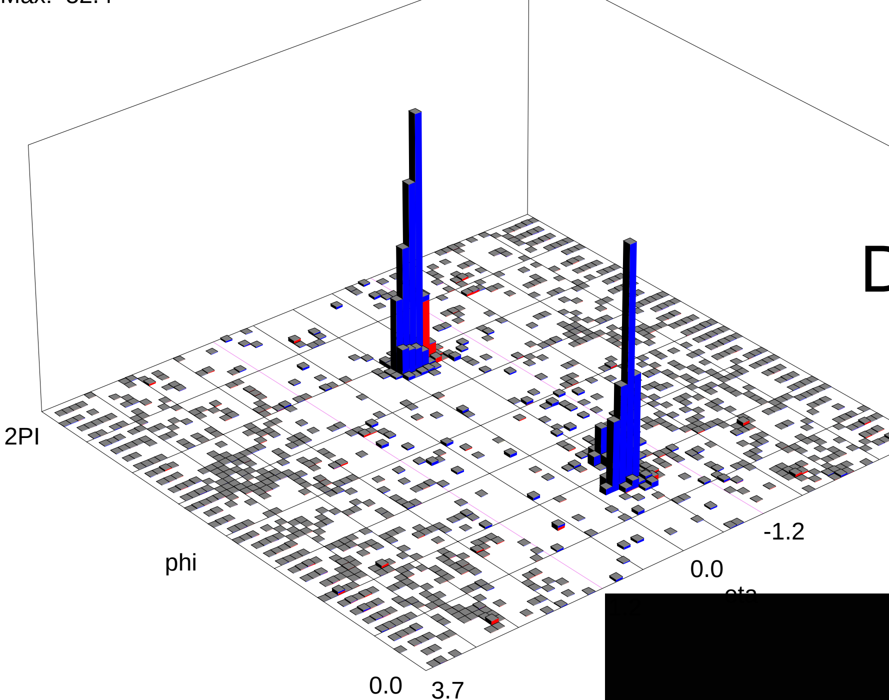
2-5 jets per event

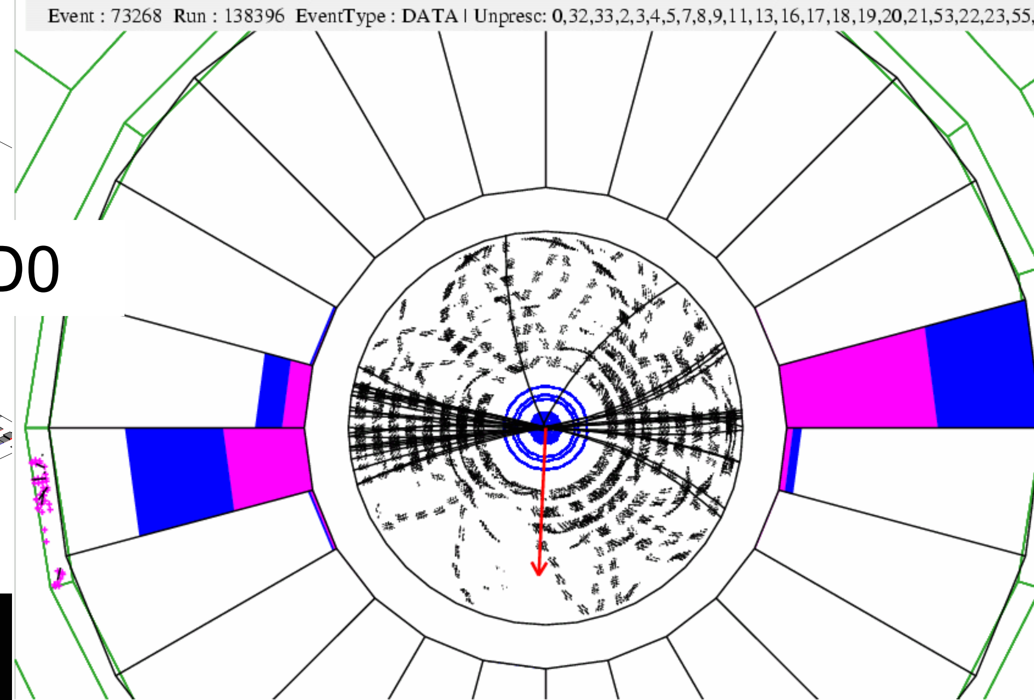


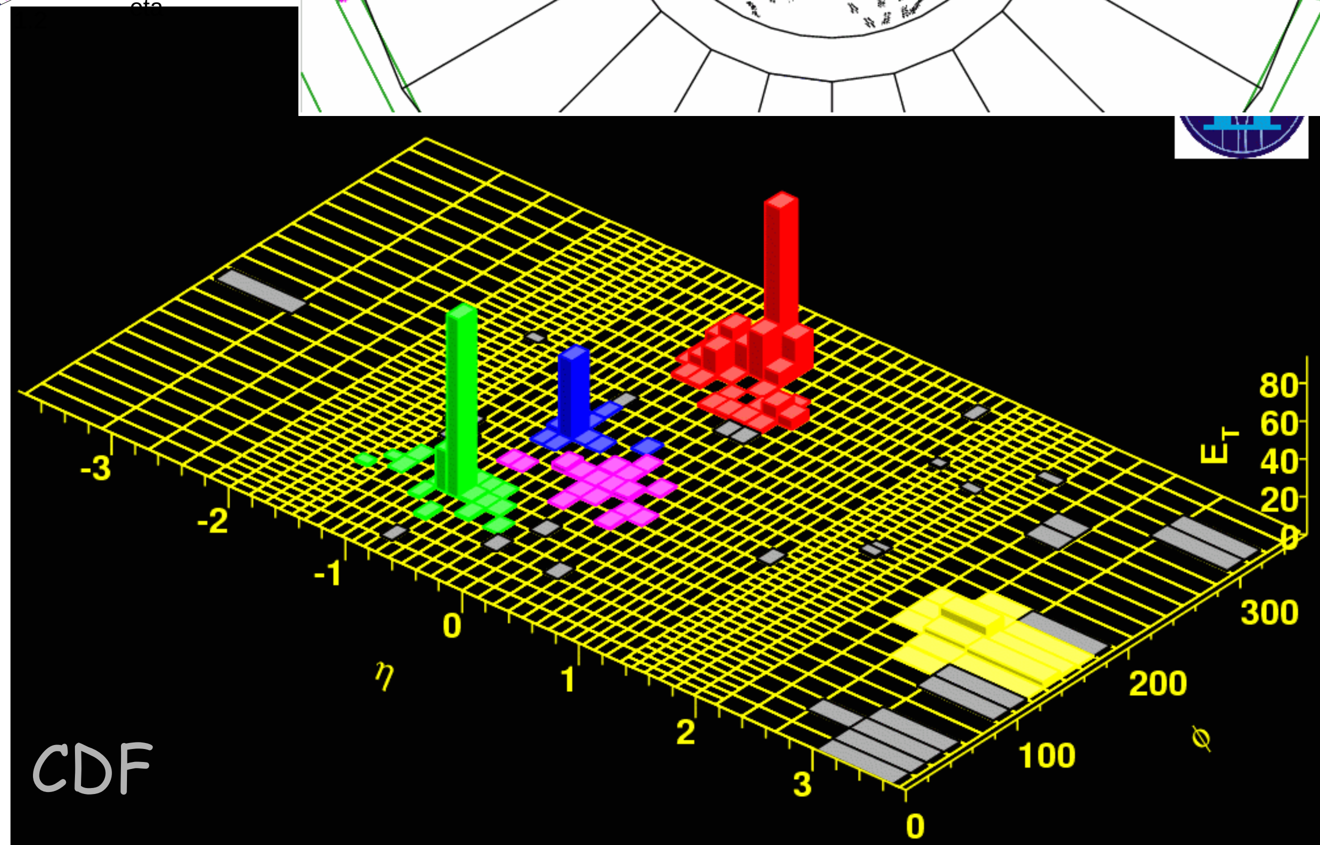

jets reveal hard processs (direction, energy)

experiment and theory must use the same language:

**jets need to be defined: „jet algorithm"**

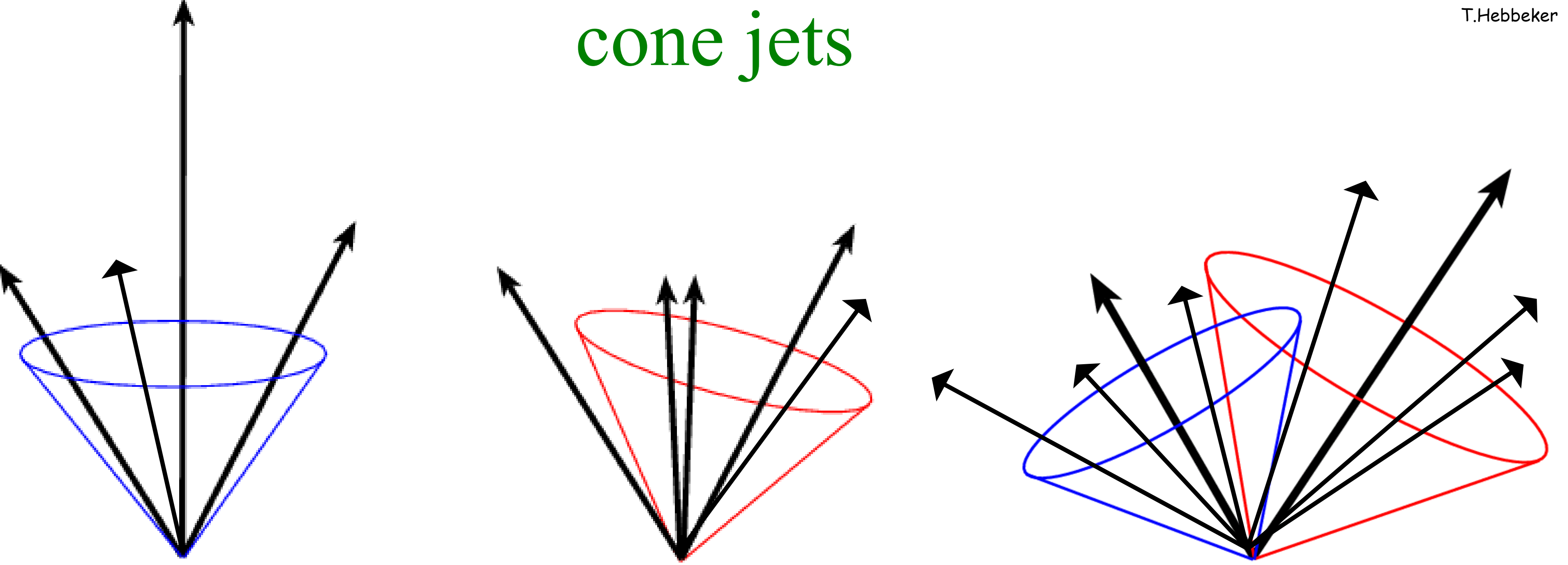

2PI
phi
-1.2
0.0
0.0
3.7


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


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

Jet events

# cone jets



Cone defined in $\eta, \varphi$ 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

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# kT jets

a) list of hadrons = clusters

b) each cluster:

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

each pair of clusters:

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

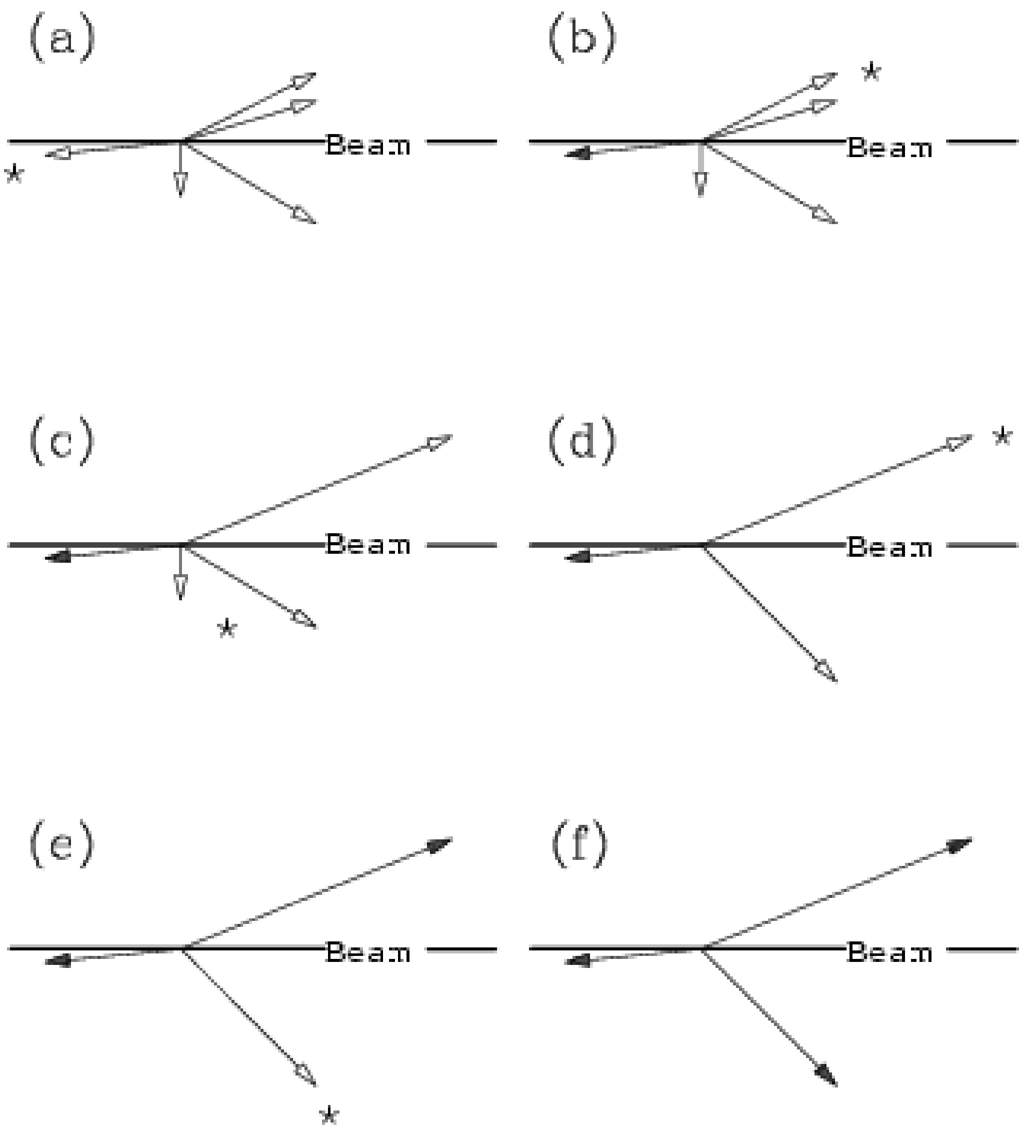
c) minimum of $d_{ij}, d_i$

→ combine or remove from list)

d) iterate: goto b)

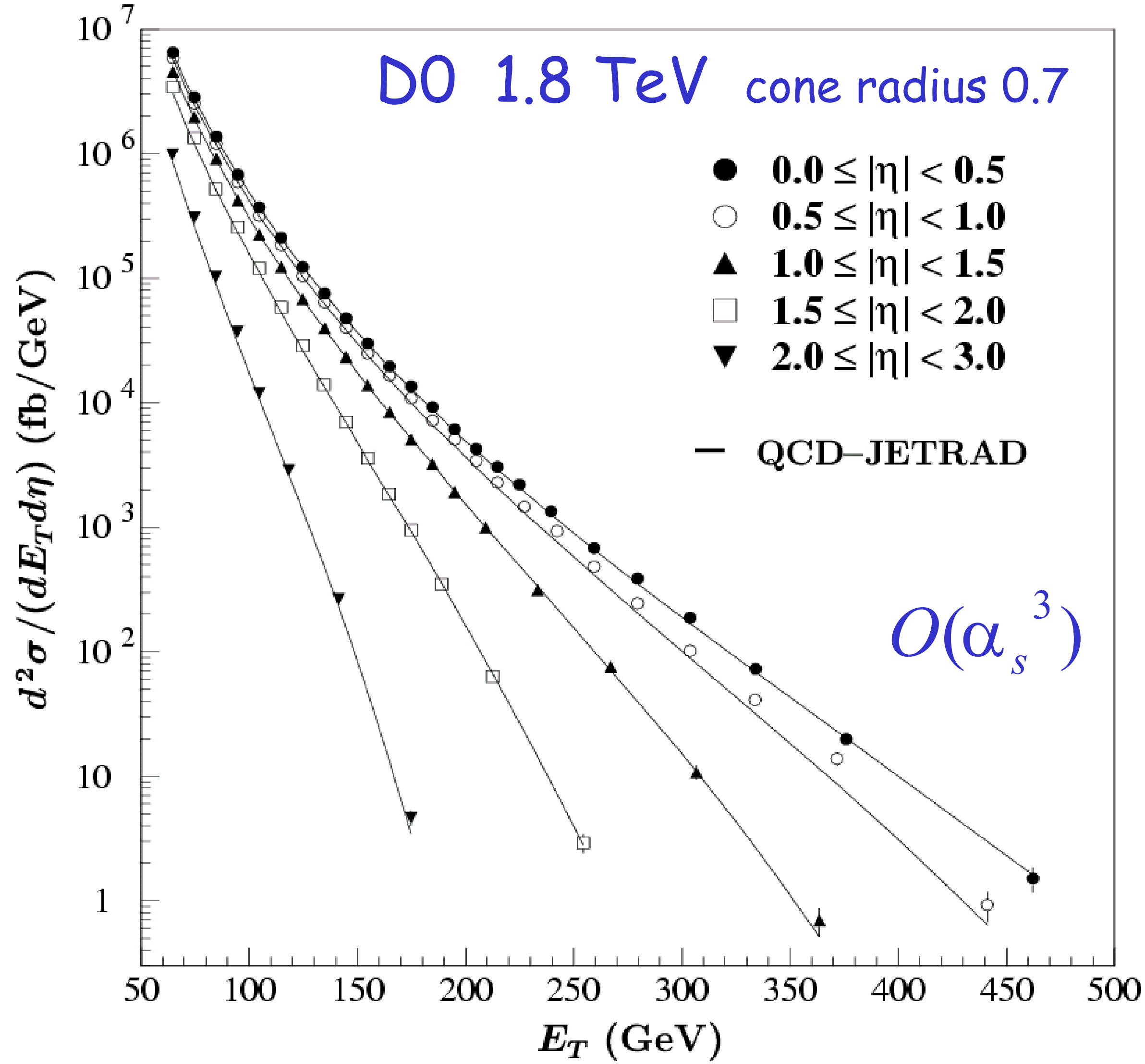
till list empty

Example:




... several variations exist

# Inclusive jet production



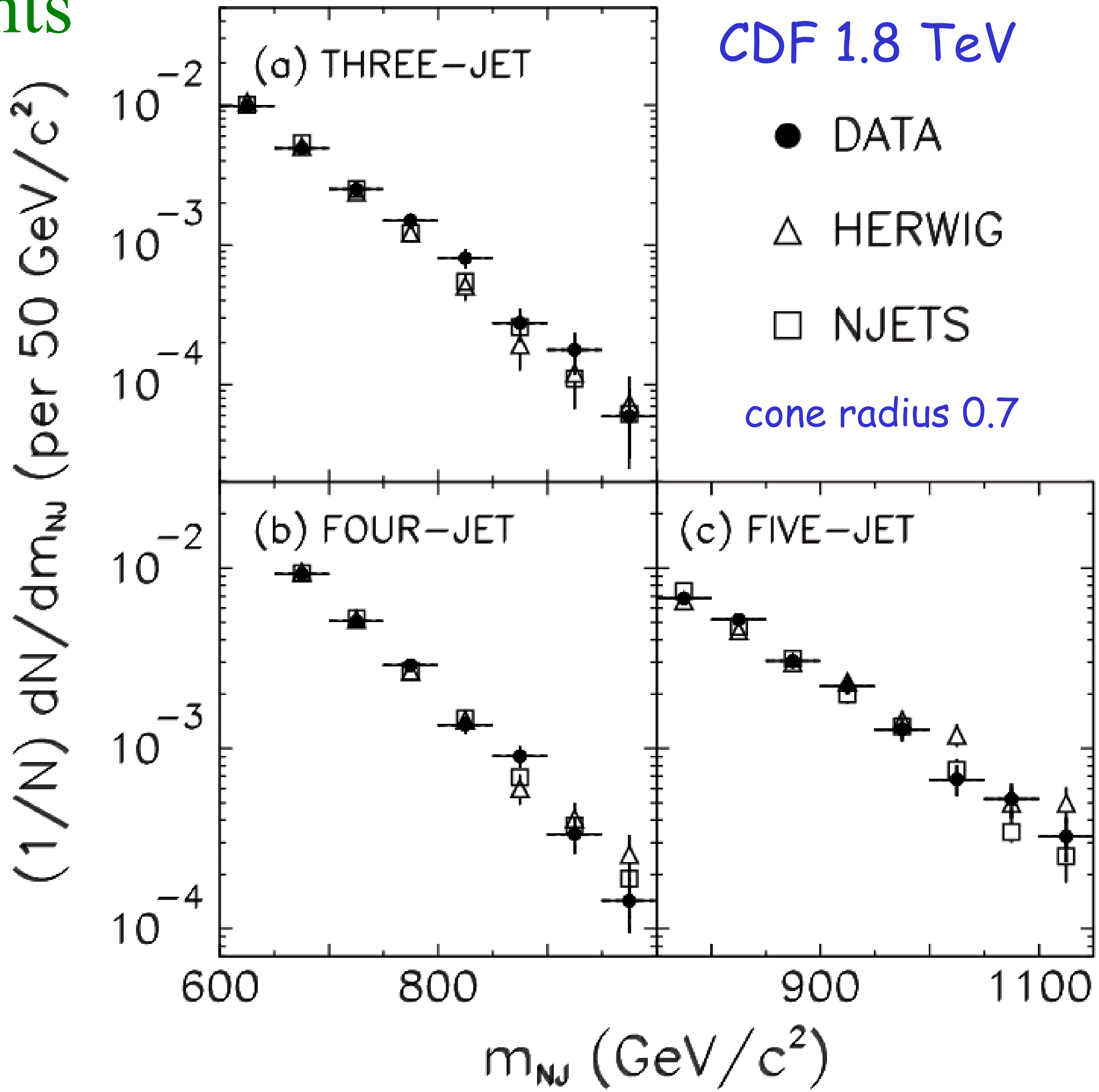

Conclusion: agreement with QCD over many orders of magnitude!

# multijet events



Test
QCD

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



# W and Z

measured at LEP
reference for W mass measurement

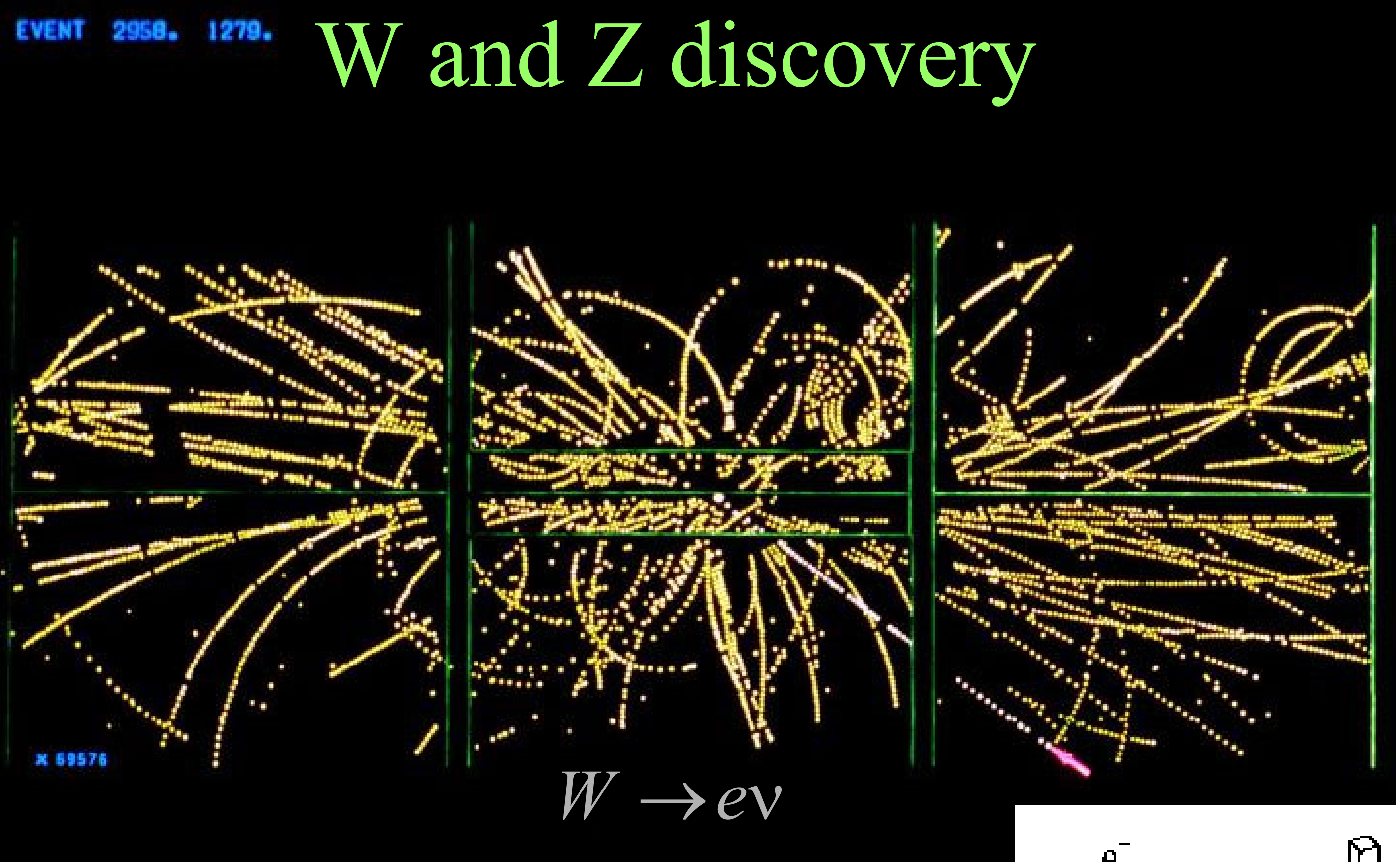
- production cross section
- decay modes
- W mass

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

Test of SM !

- W width
- ...

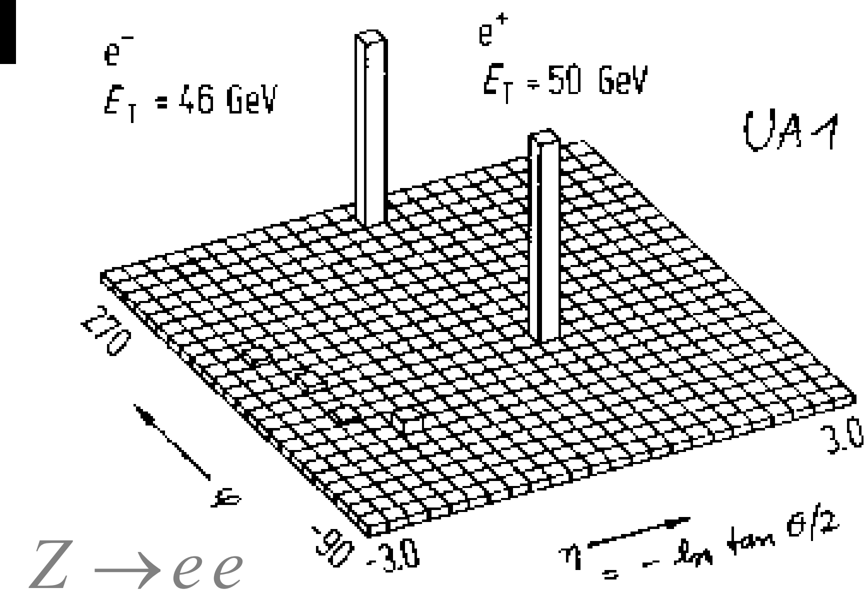
# W and Z discovery




Discovery:

UA1, UA2

(1983)

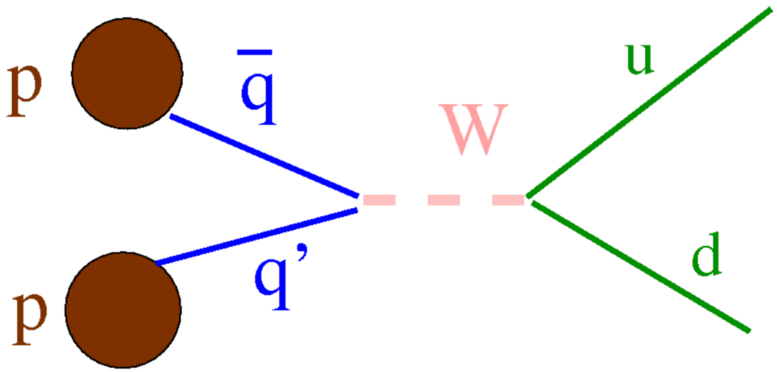


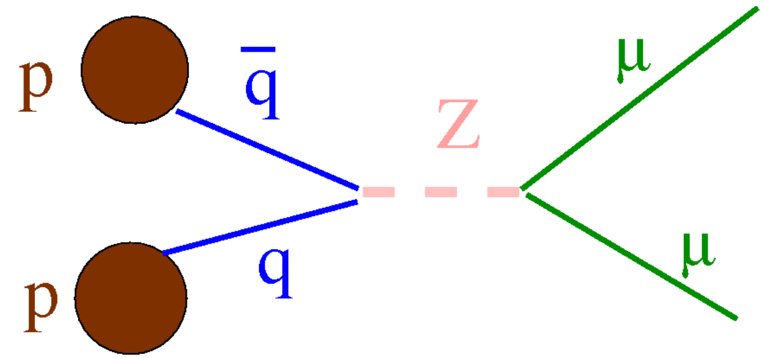

Precision measurement

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% |

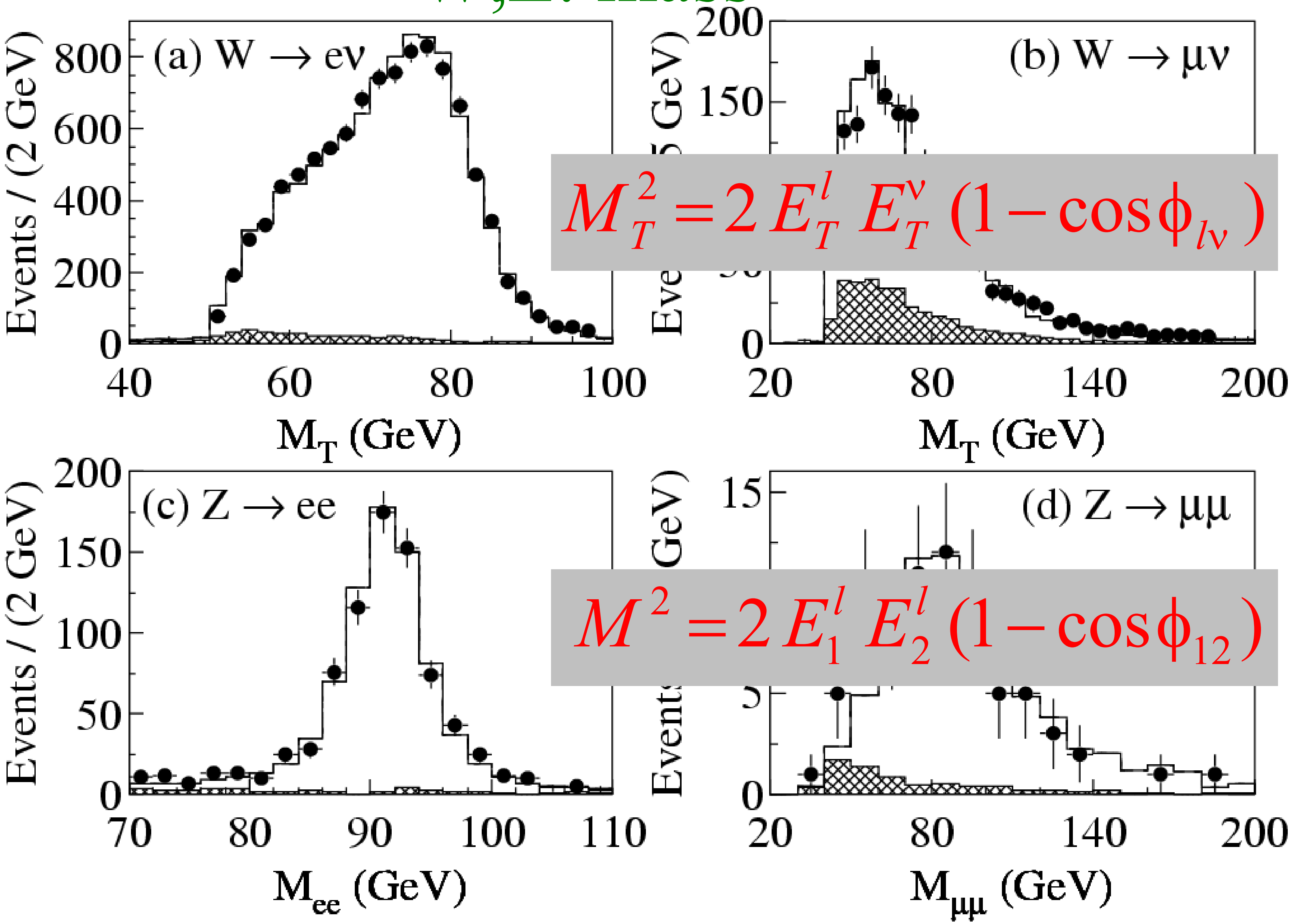
Clear signature

## 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

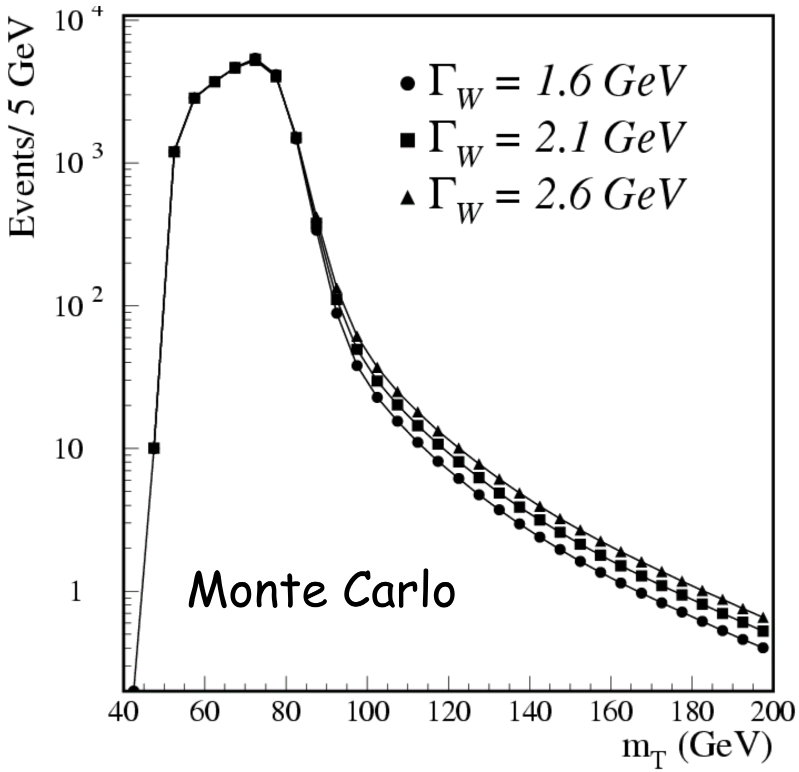
Tevatron combined: $80.456 \pm 0.059\,GeV$

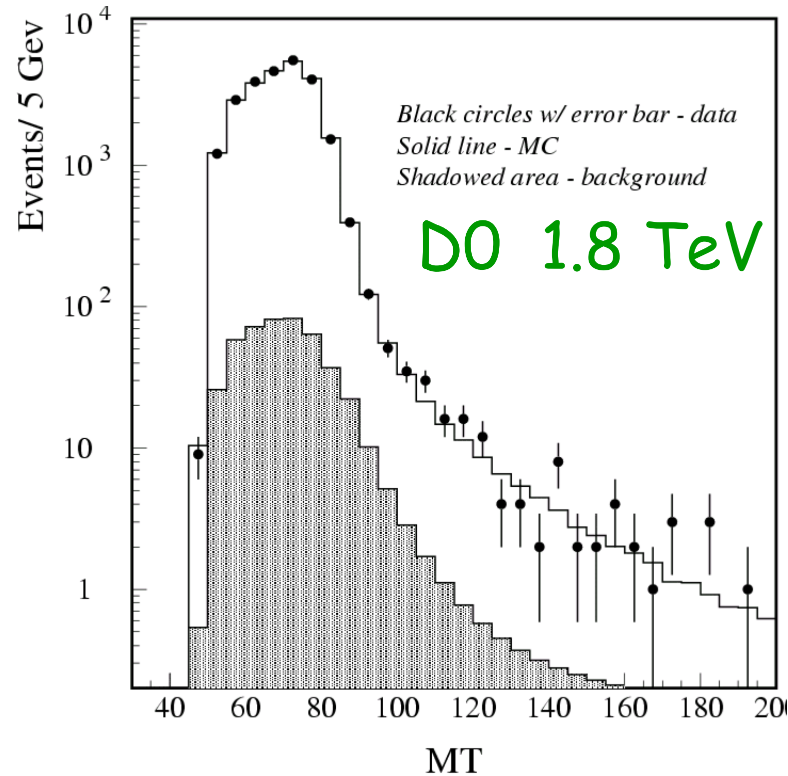
Run I

LEP: $\pm 0.042\,GeV$

LHC: $\pm 0.015\,GeV$

# W: width



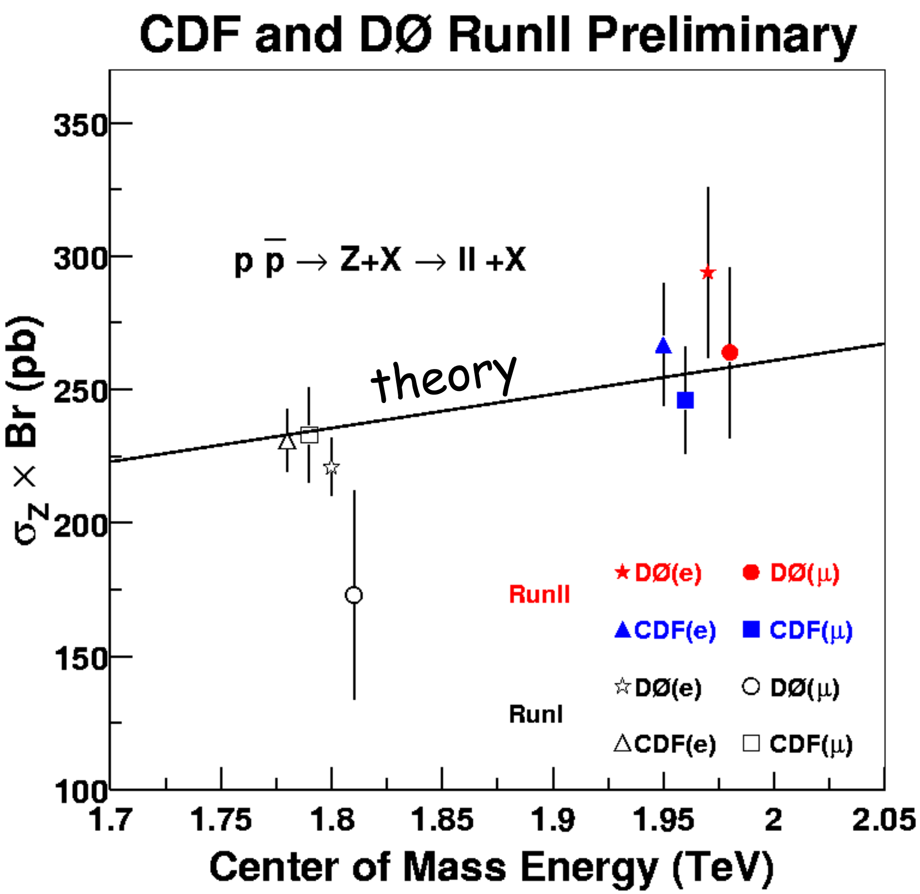



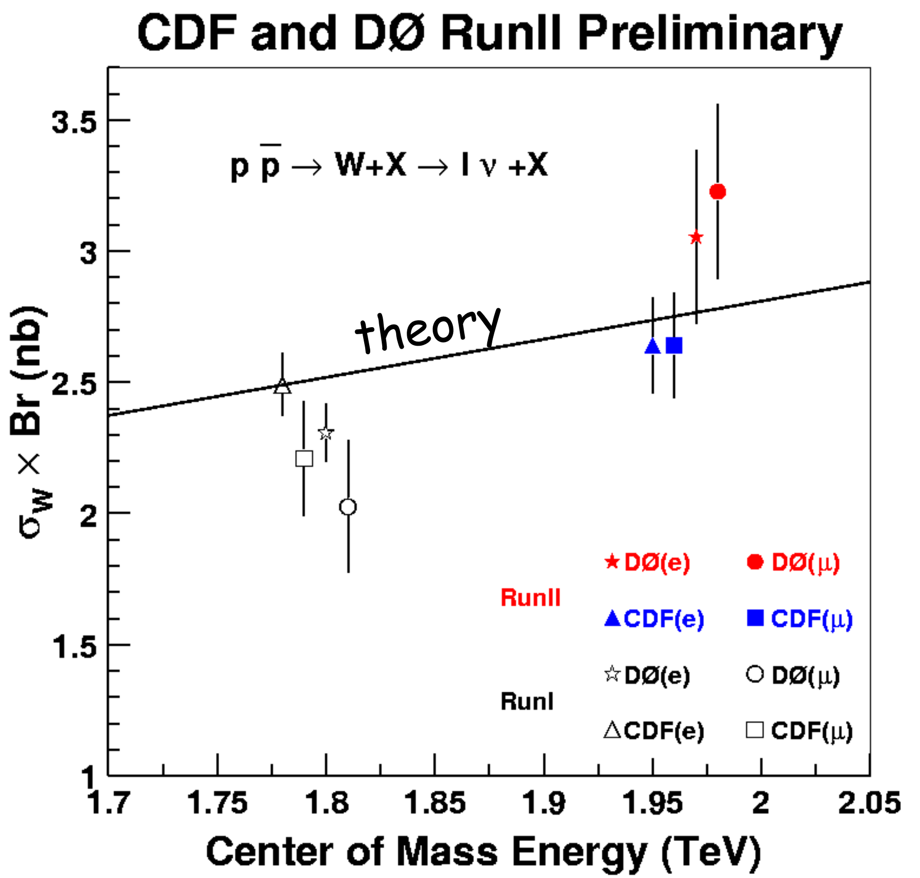

... difficult...

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

# W,Z: production cross section



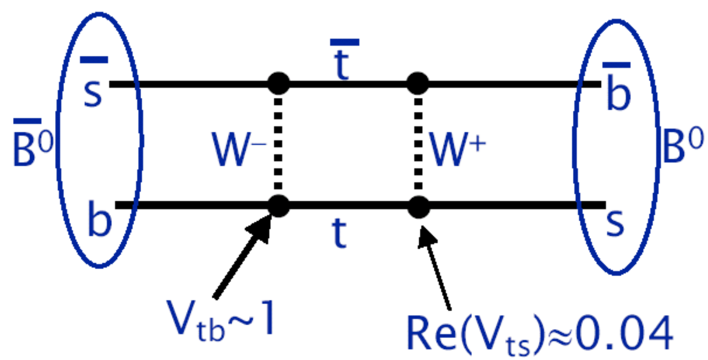


# pp-physics with charm and bottom

**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

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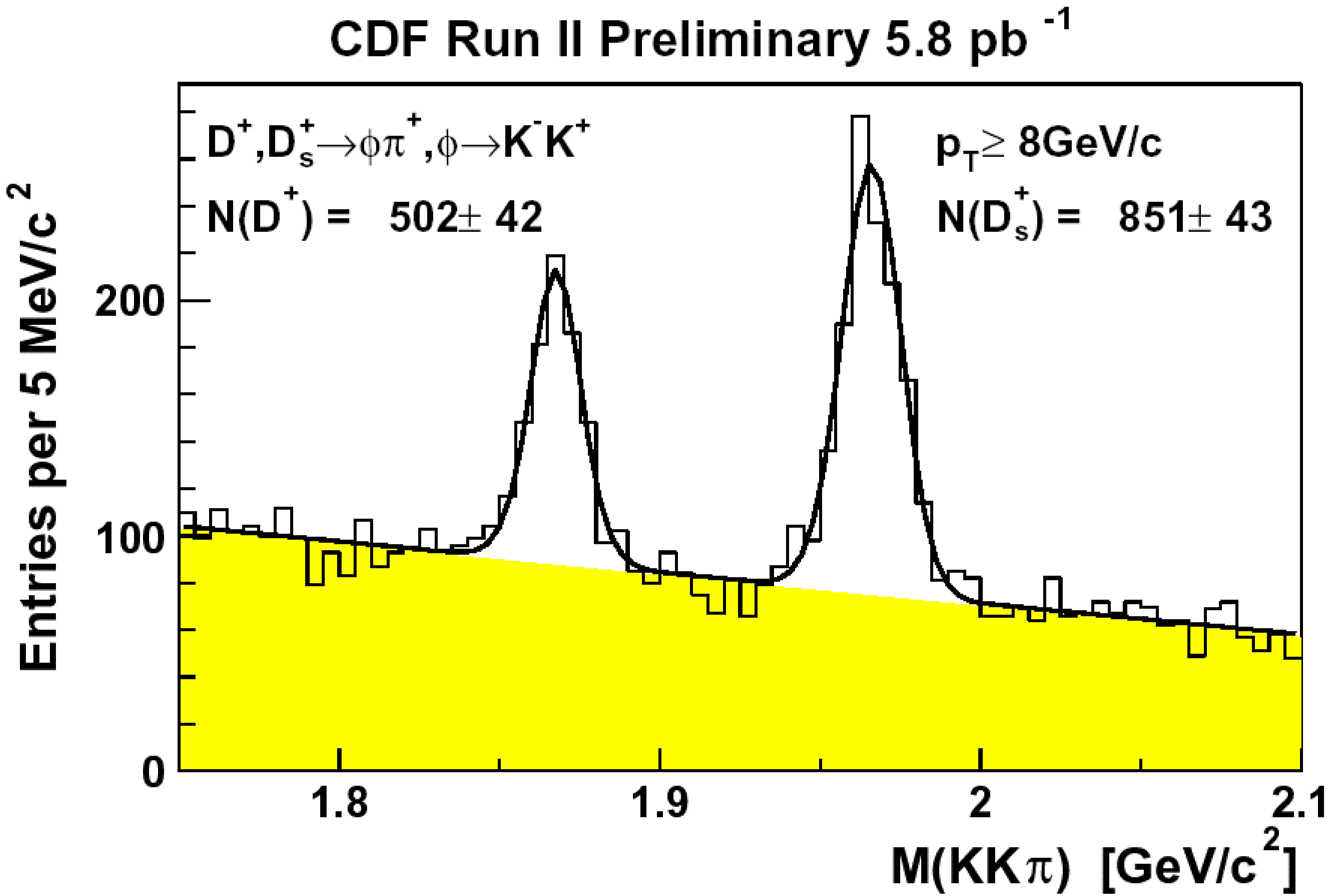
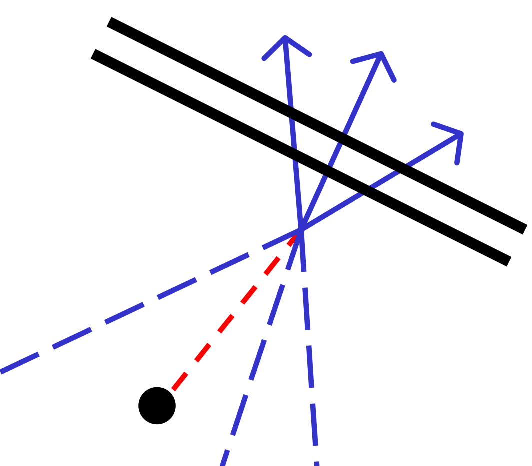
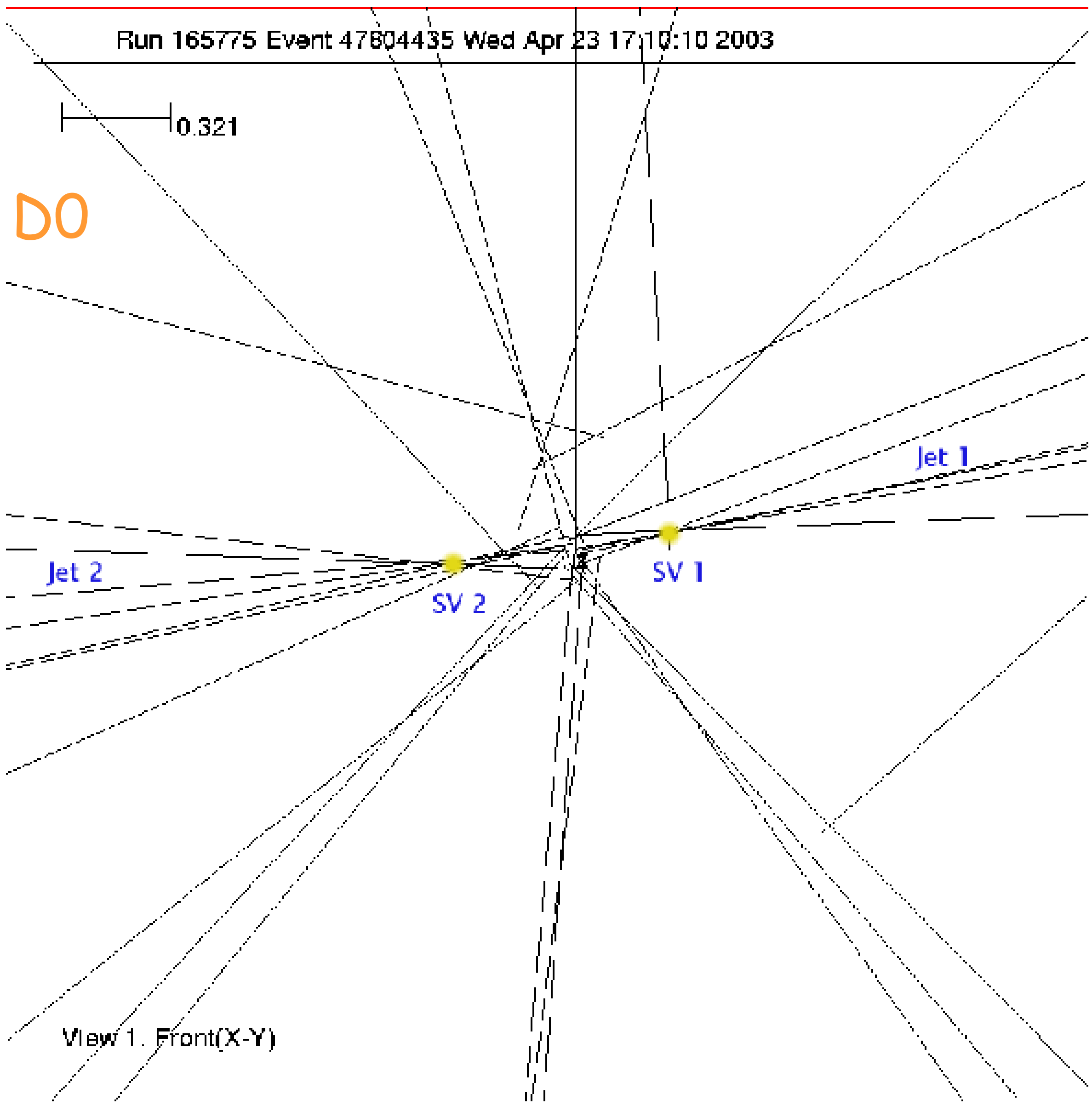


# Reconstruction of decay vertices

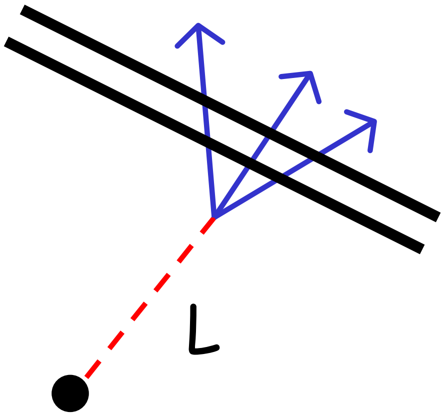


$$Z \to b\bar{b}$$





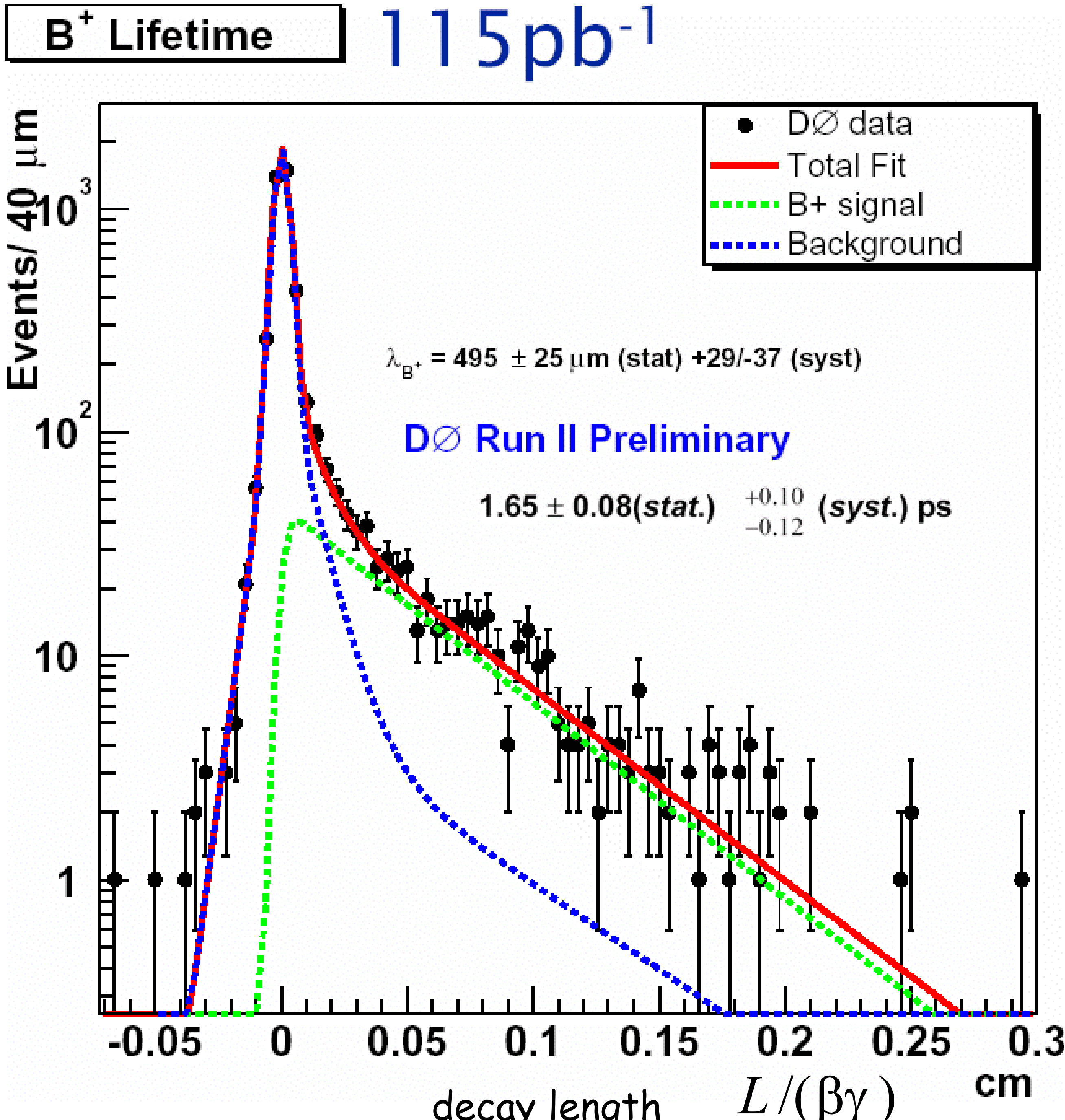
# Example:




decay length:

Lab frame:

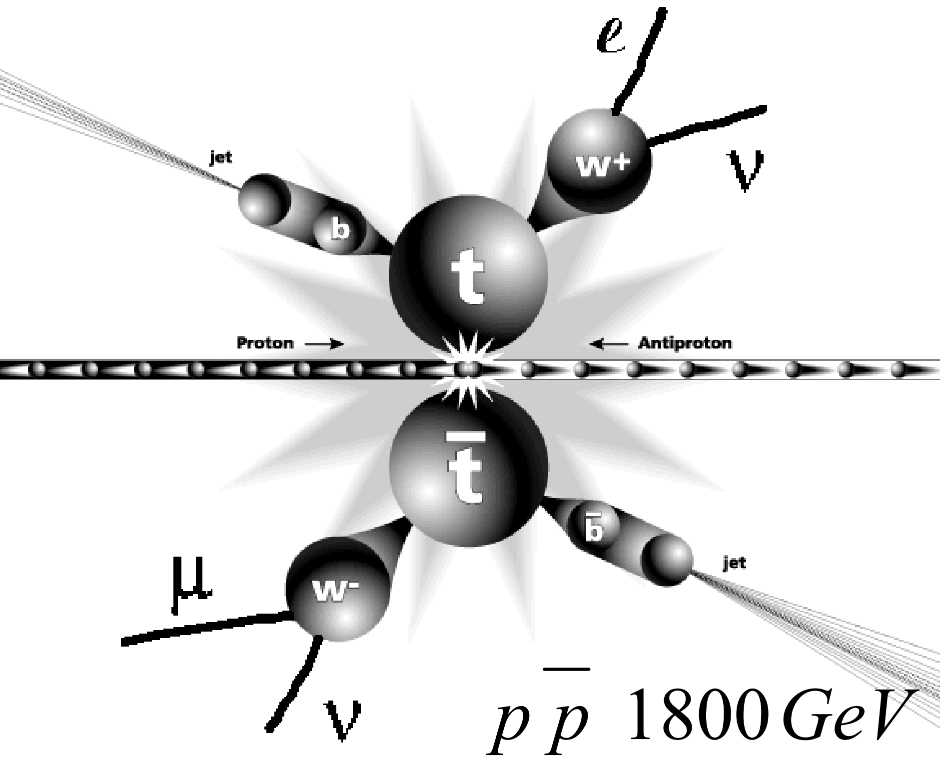
$$L = ct\,\beta\gamma$$

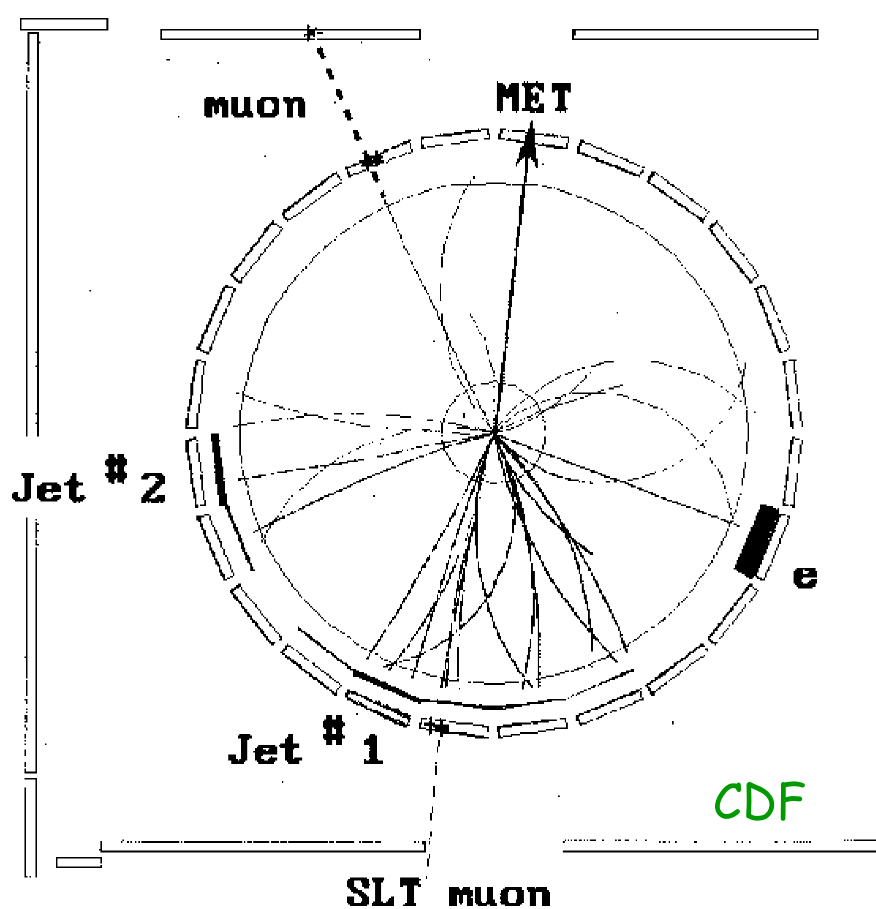


# Top Discovery

Fermilab, 1995

CDF, D0

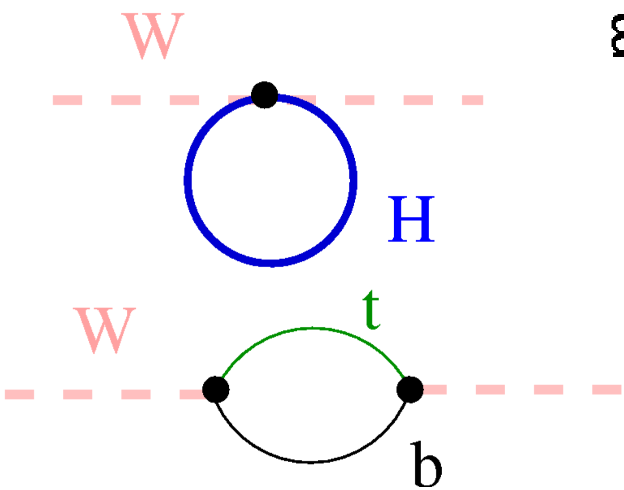


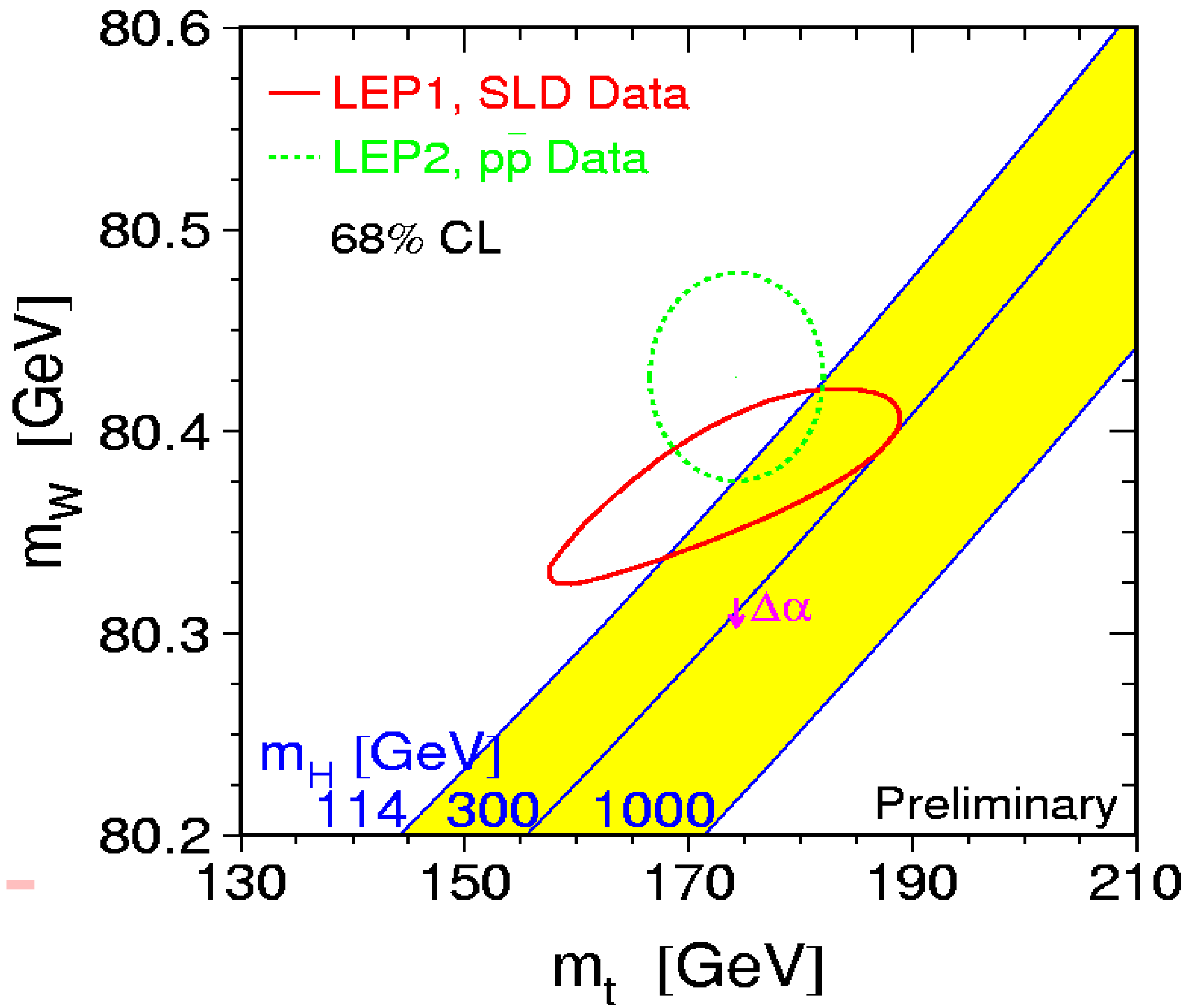




m ~ 175 GeV

# Top Physics

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




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

# Top Identification

cross section small (at 2 TeV)

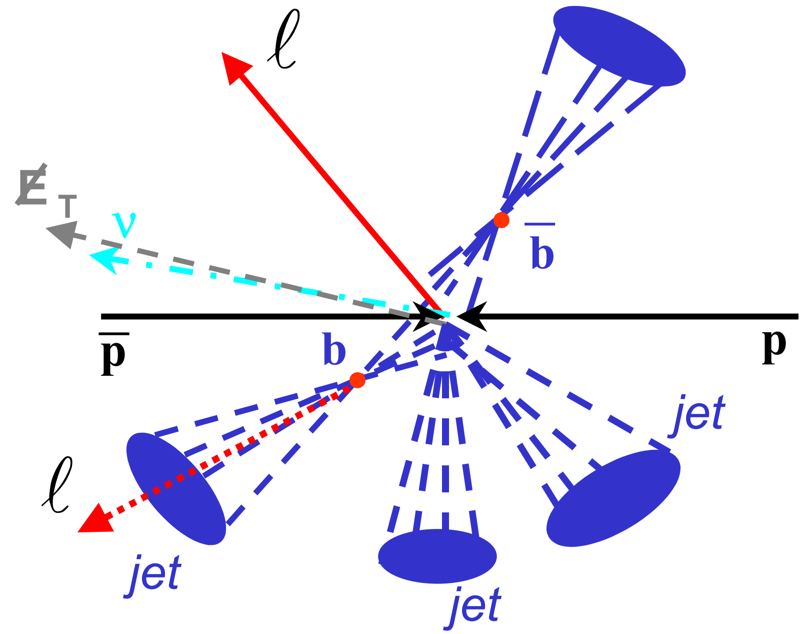
production:

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

decay:

$$t \rightarrow W\,b$$

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

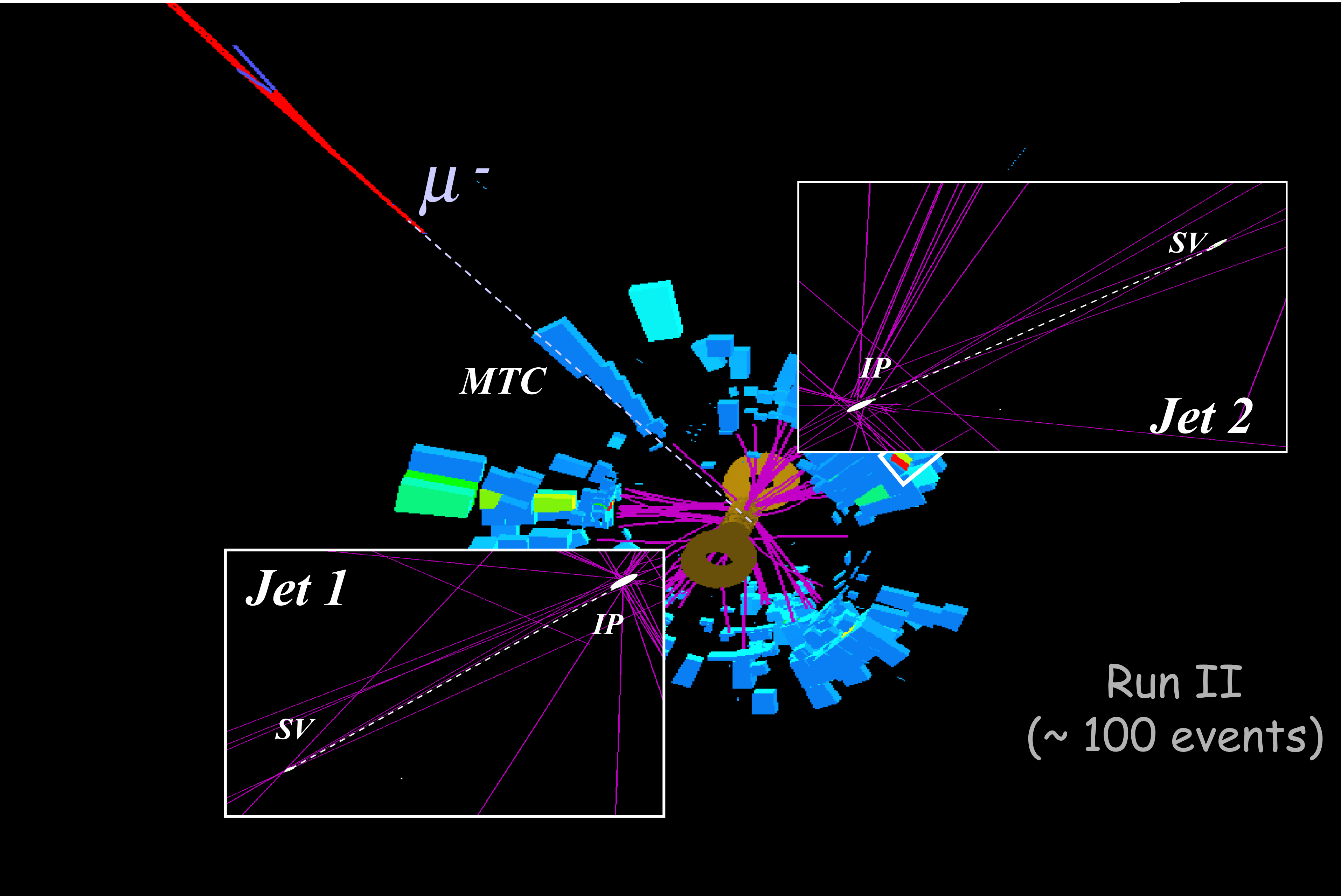



Signature:

2 b jets
+ leptons/jets/missing energy

# Top event in D0

T.Hebbeker

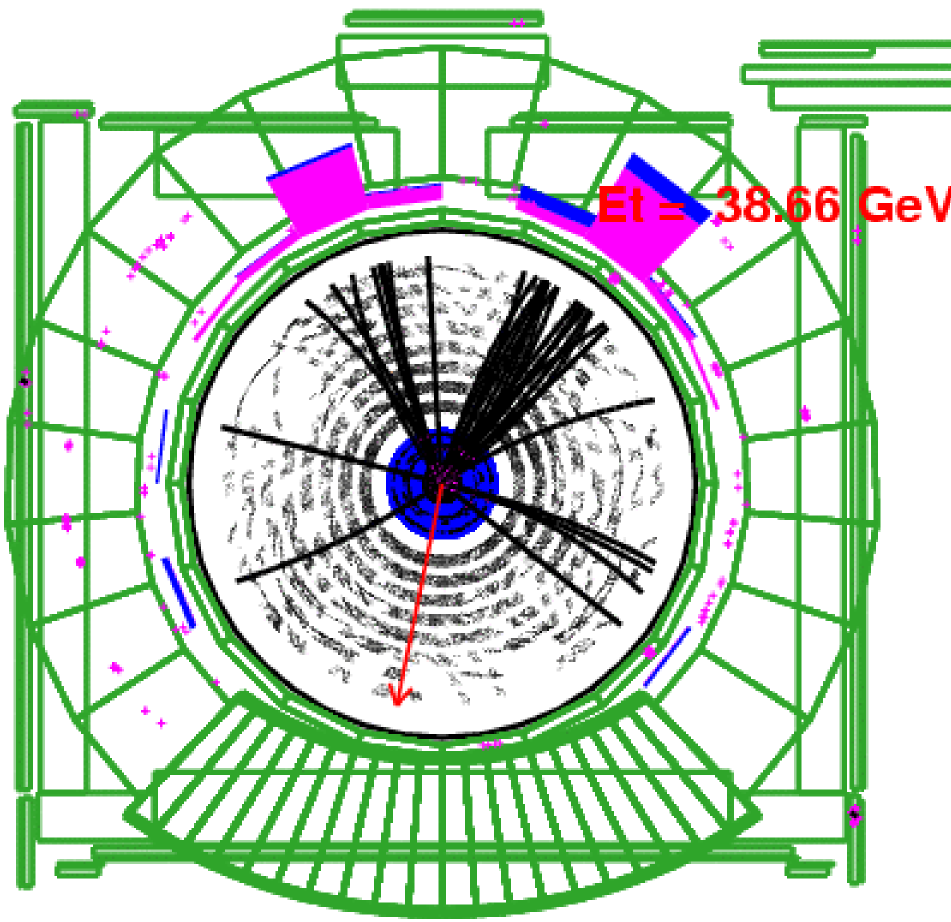


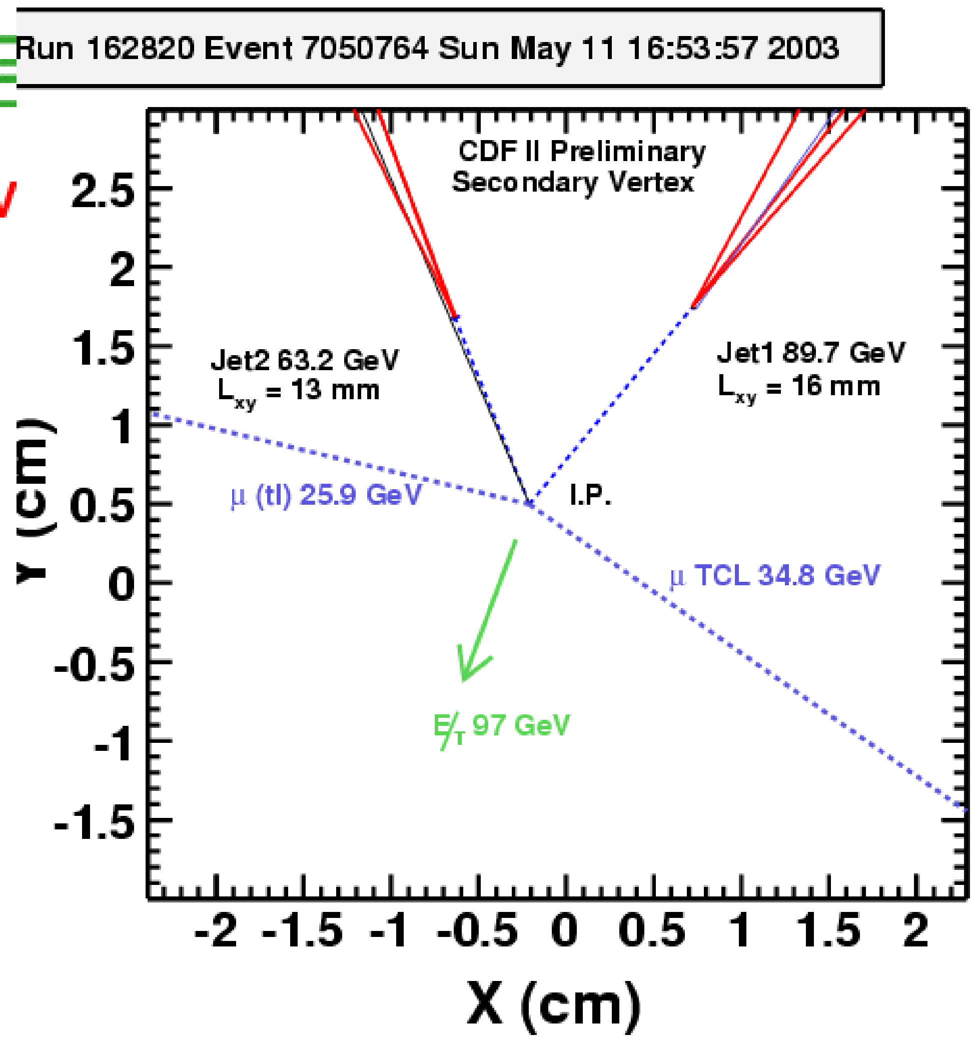

Run II
(~ 100 events)

# Top event in CDF

Run II

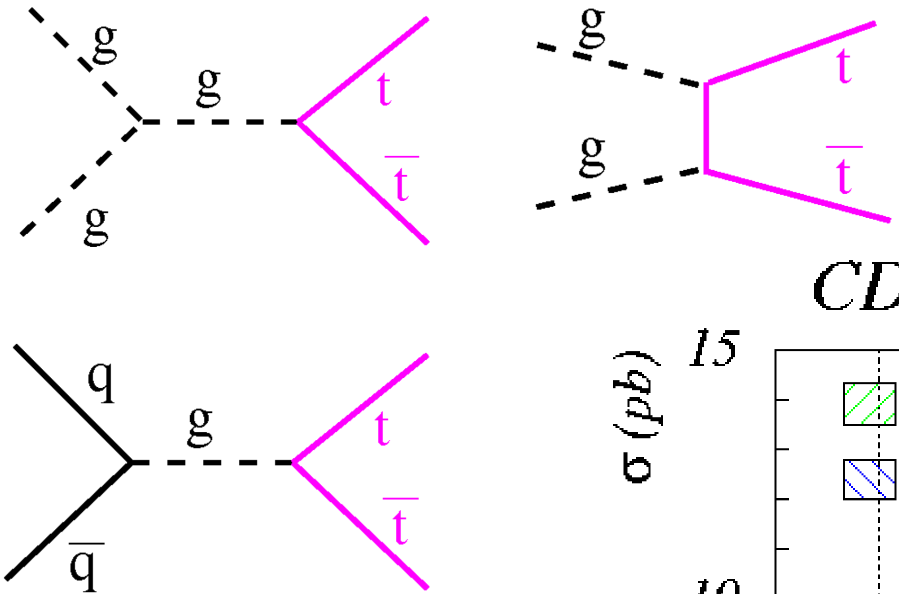
(~ 100 events)

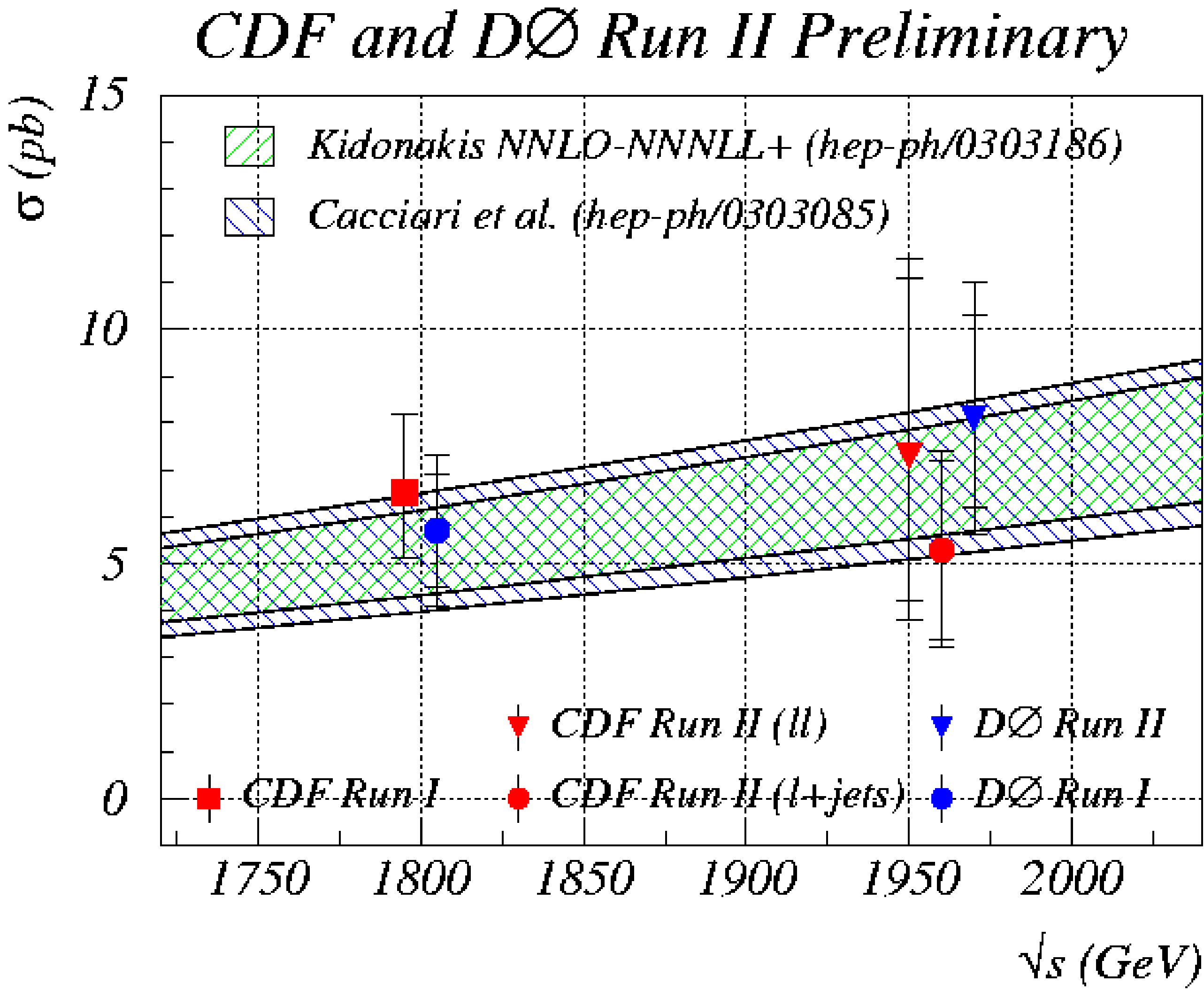


T.Hebbeker

# Top Pair Production

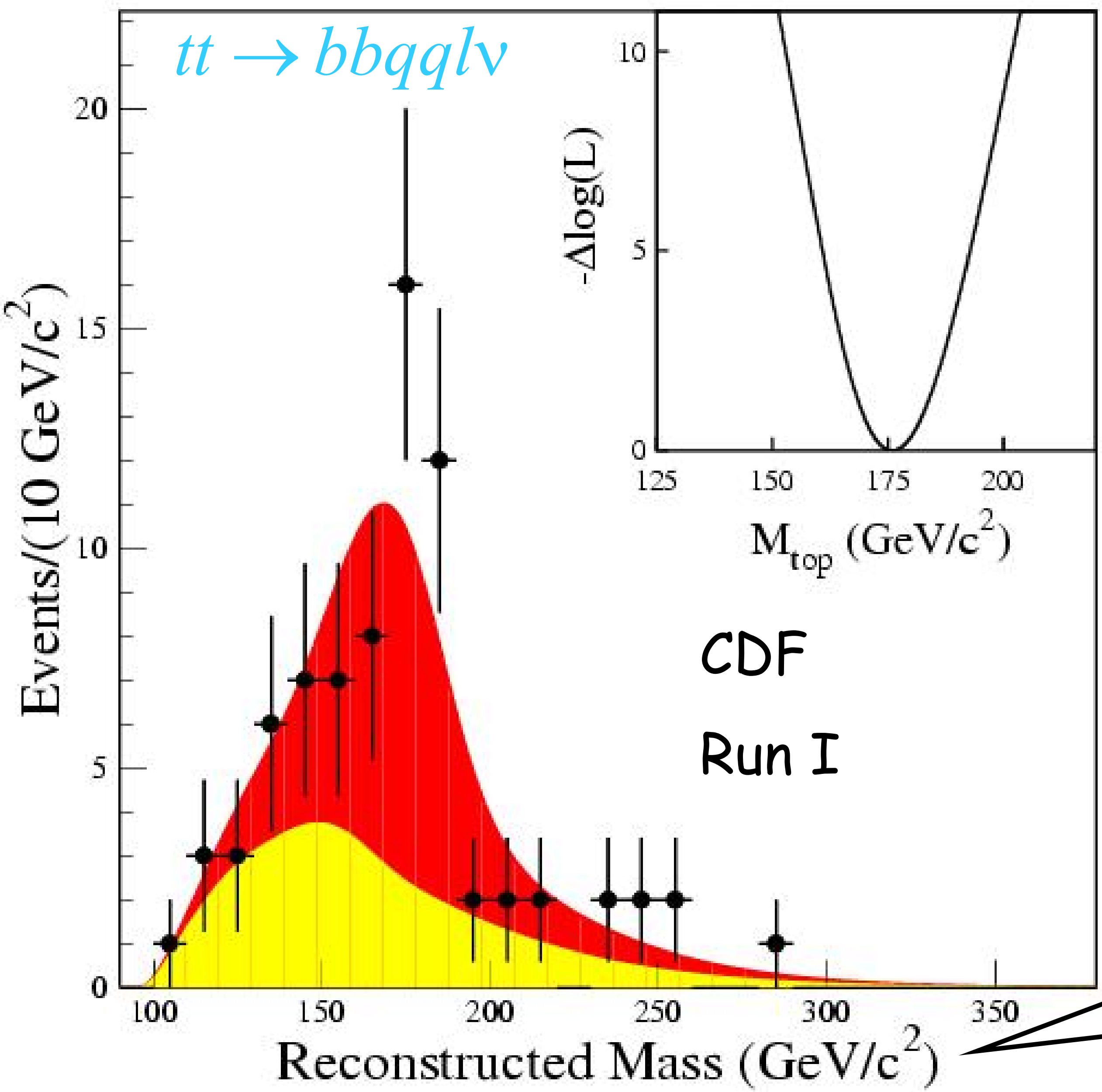



gg contributes

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

# Top Mass




Tevatron Run I

CDF + D0:

$$174.3 \pm 5.1 GeV$$

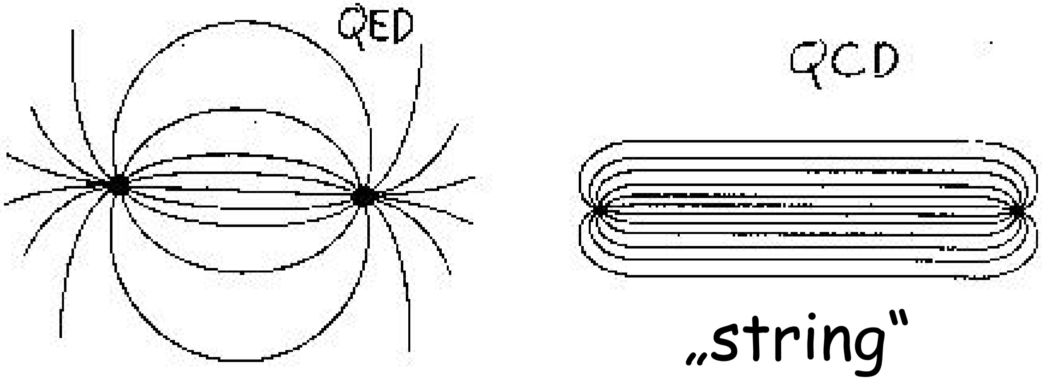
LHC: +- 1 GeV

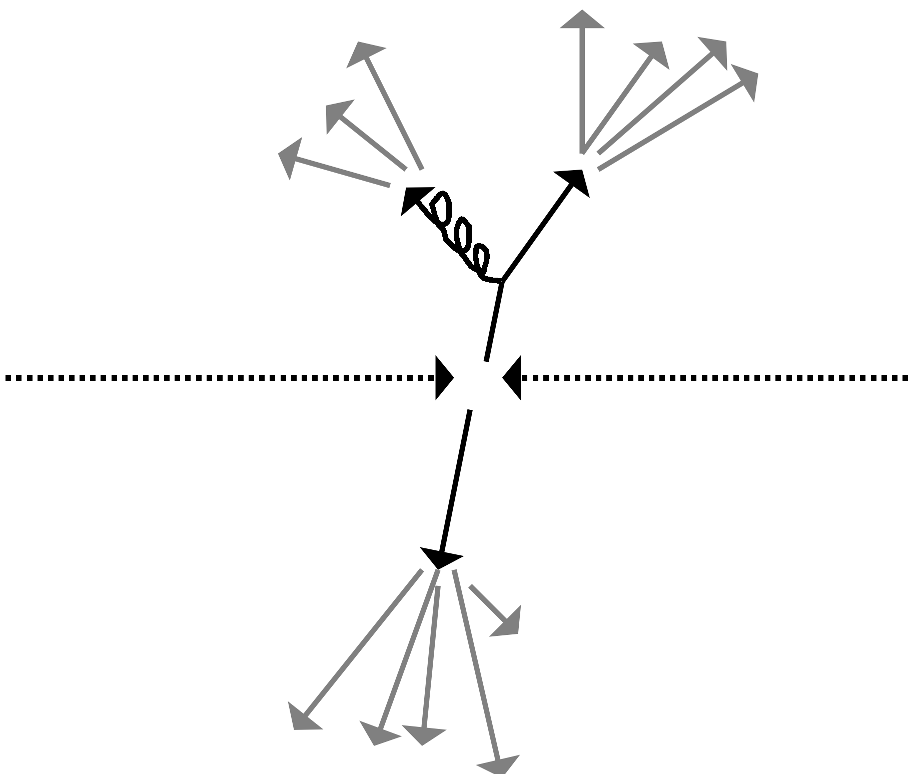
Using mass constraints $W \to l\nu$ ...

# Appendices

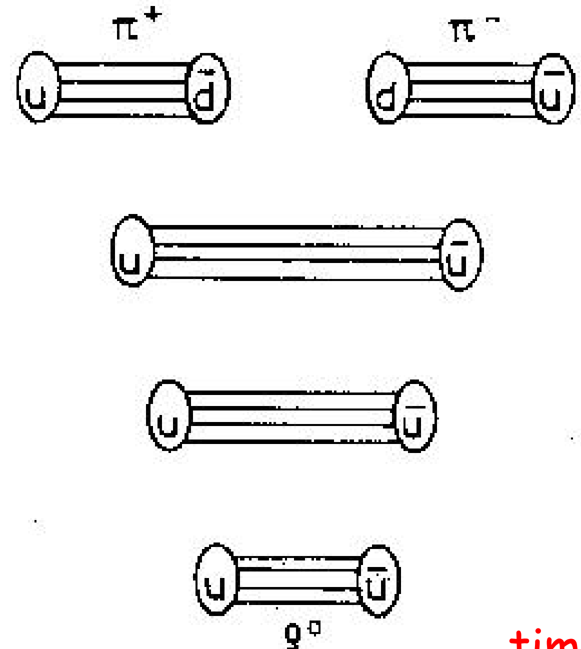
# Hadronization

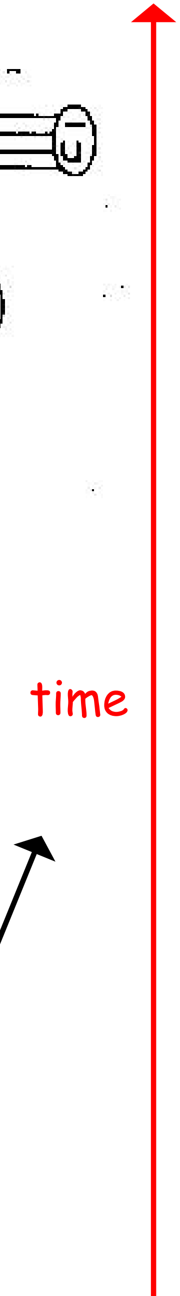
T.Hebbeker



## String model:




## QCD: