QCD and Electroweak Physics at Hadron Colliders

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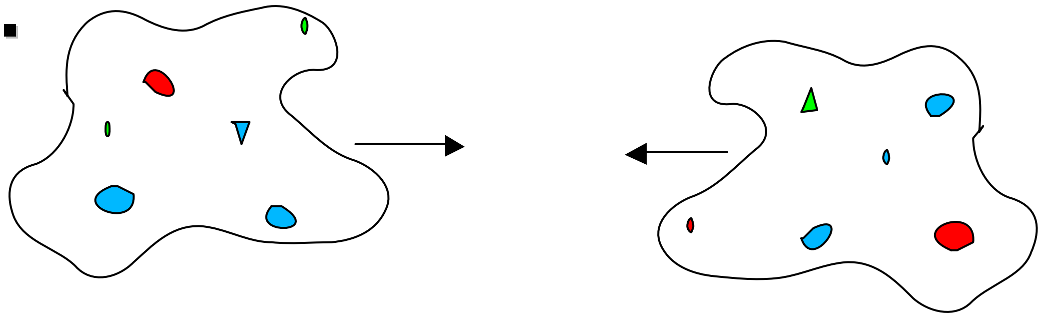
The Hadron Collider Idea

- Similar to a collision between two bags of rocks.



- Occasionally two stones or “partons” will collide.
- But you’ll never know which two collide and how much energy they carry.
- For the proton the “partons” are quarks and gluons.

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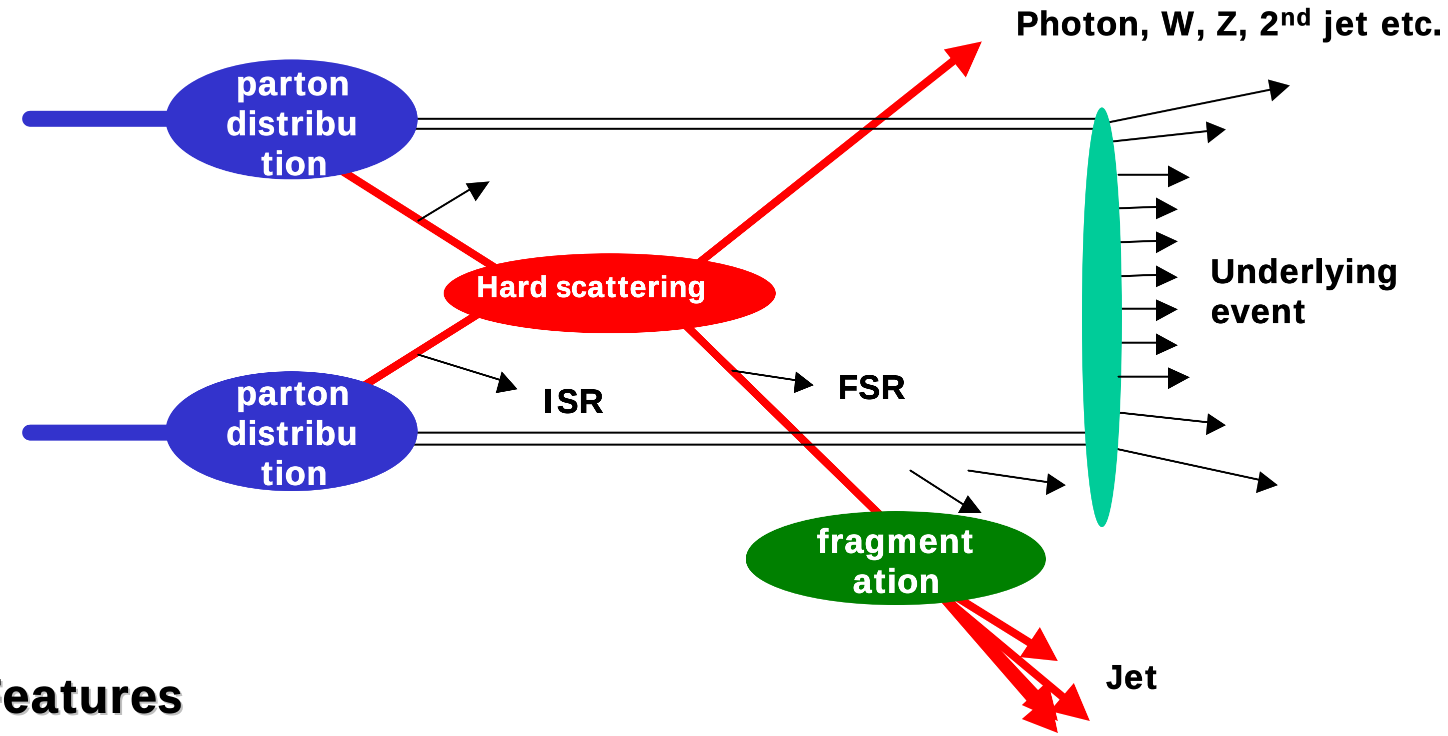
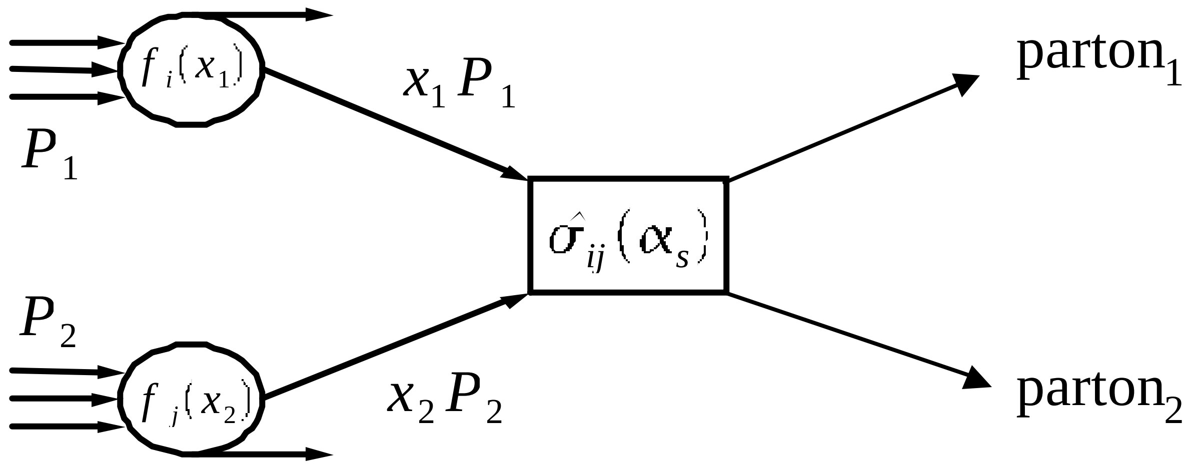
A Bit More Formal



- **Features**
  - The initial states are composed of quark and gluon distributions (absent for electron-electron machines)
  - As with Rutherford scattering the hard scatter can be described quite well
  - Particles can radiate form incoming and outgoing partons
  - The un-scattered partons form an "underlying" event (also absent for electron-electron machines)

Very Formal



$$\sigma = \sum_{ij} \int dx_1 dx_2\, f_i\left(x_1, \mu_F^2\right) f_j\left(x_2, \mu_F^2\right) \hat{\sigma}_{ij}\left(\alpha_s^m\left(\mu_R^2\right), x_1 P_1, x_2 P_2, \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

- *Sum over initial states*
- *Parton Distributions*
- *Factorization Scale*
- *Point Cross Section*
- *Order α_s^m*
- *Renormalization Scale*

QCD: Quantum ChromoDynamics

- A gauge theory (like electromagnetism)
  - describes fermions (quarks) which carry an SU(3) charge (color)
  - interact through the exchange of vector bosons (gluons)
- Interesting features:
  - gluons themselves have color
  - interactions are strong
  - coupling constant between quarks and gluons runs rapidly
  - weak at momentum transfers above a few GeV

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

- Q^2 is the momentum transfer between the partons related to Mandlestam variable $t^2 = (p_1 - p_3)^2$

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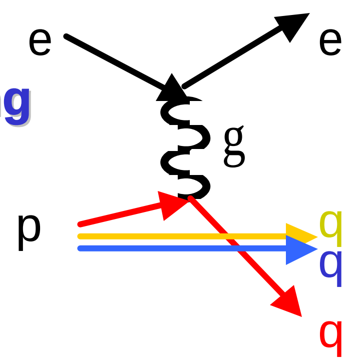
A Bit of Quark History

- **These features lead to a picture where quarks and gluons are bound inside hadrons if left to themselves**
- **Behave like "free" particles if probed at high momentum transfer: asymptotic freedom (This year's noble!)**
- **This is exactly what was seen in deep inelastic scattering experiments in the late 1960's which led to the genesis of QCD**
  - **electron beam scattered off nucleons in a target**
  - **electron scattered from point-like constituents inside the nucleon**
  - **~ $1/\sin^4(\theta/2)$ behaviour like Rutherford scattering**
  - **other (spectator) quarks do not participate**



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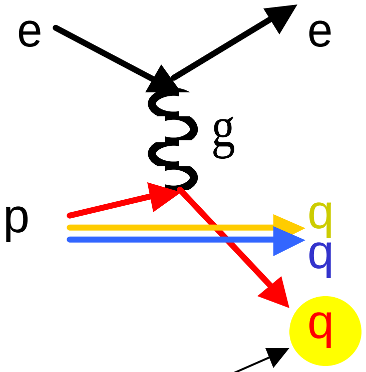
One More Ingredient: Fragmentation



So what happens to a quark that is knocked out of the proton?

α_s is large (large distances = low momentum scales)

- **Strong field = lots of gluon radiation between scattered quark and color-ed remnant of the nucleon**
- **Energy required for separation is large compared to pair production energy.**
- **Quarks and gluons produced in the "wake" of the outgoing quark recombine to form a "spray" of roughly collinear, colorless hadrons: a jet**
- **This process is known as: "fragmentation" or "hadronization**

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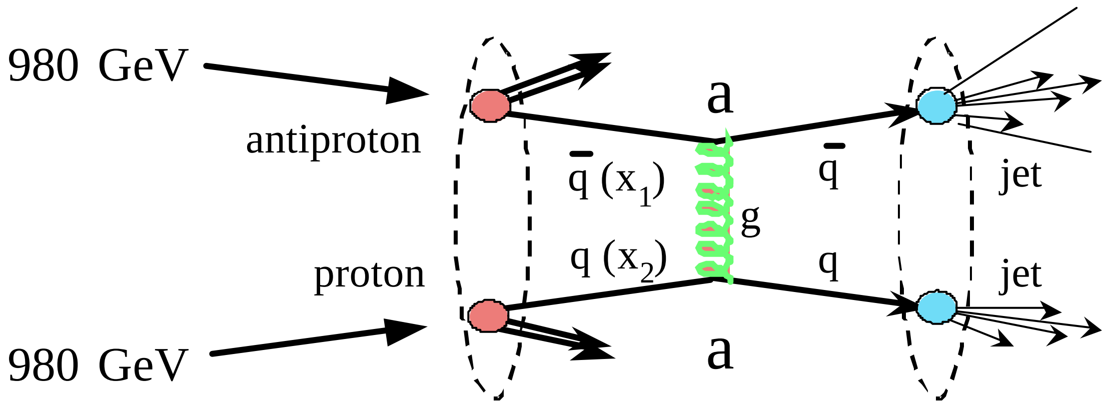
A Descriptive Example: Jet Production



- **Parton distribution functions determine incoming energy**
  - **Collider energy (center of mass) = 1.96 TeV**
  - **Parton energy (center of mass) = x_1x_2s**
- **Probability of gluon exchange dictated by full theory of QCD.**
- **Strength of parton scatter given by coupling constant, momentum transfer**
- **Final state requires fragmentation.**

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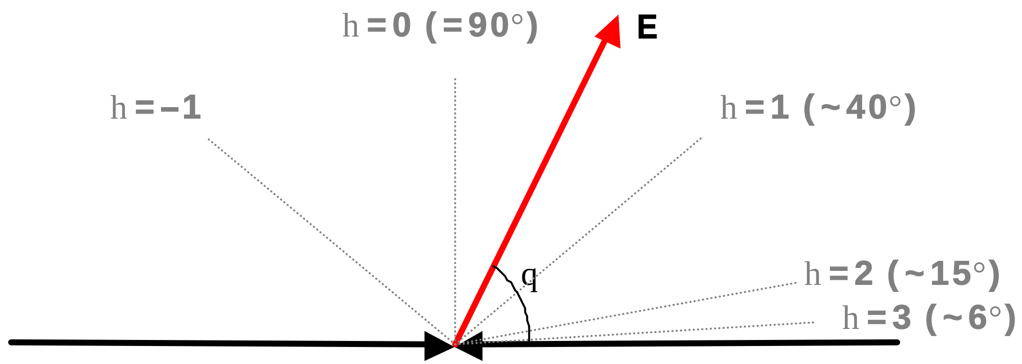
Hadron Collider Variables

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



- Focus on transverse variables
  - Transverse Energy E_T = E sin q (= p_T if mass = 0)
- And Longitudinally boost-invariant quantities
  - Pseudorapidity h = – log (tan q/2) particle production typically scales per unit rapidity

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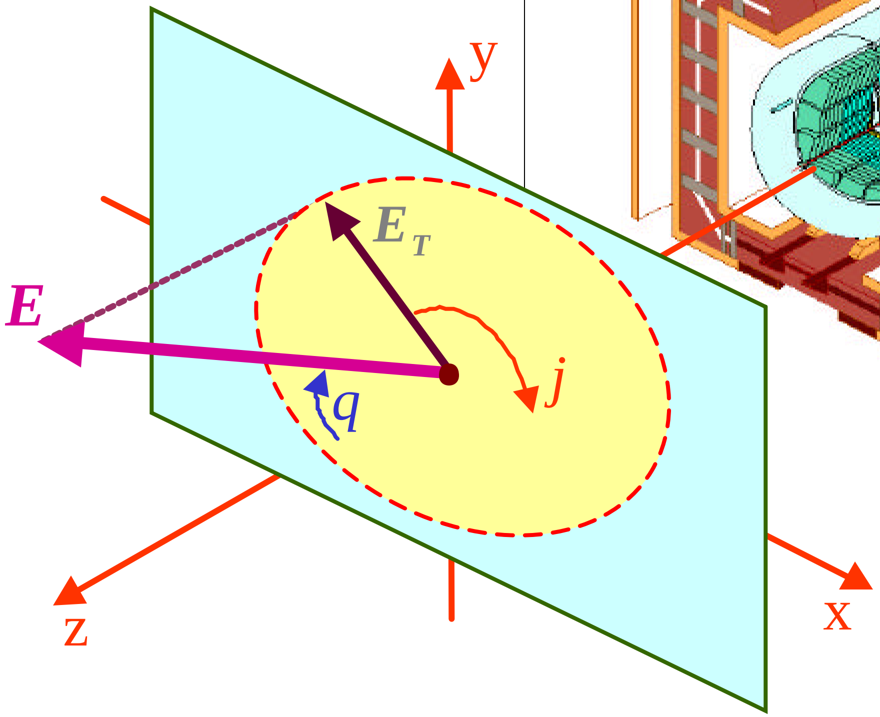
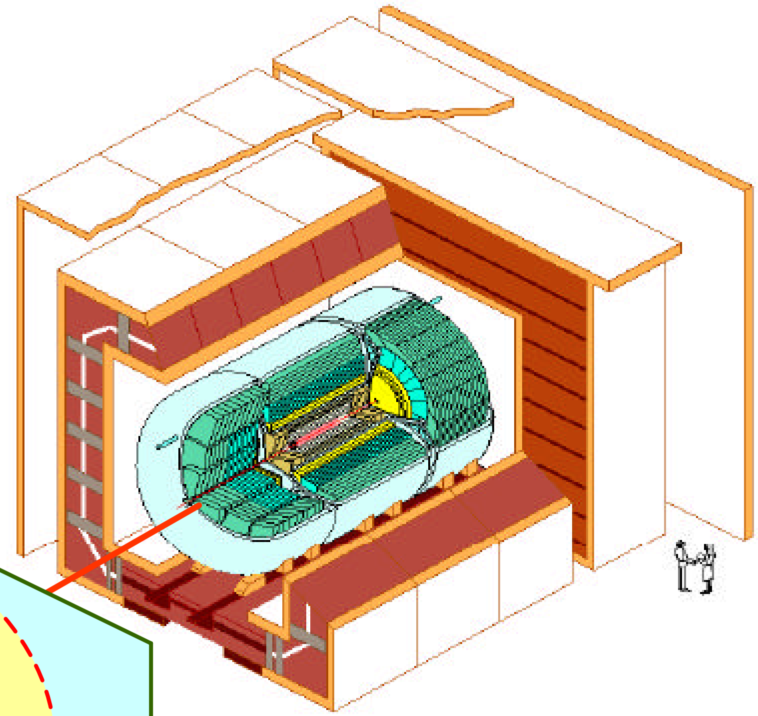
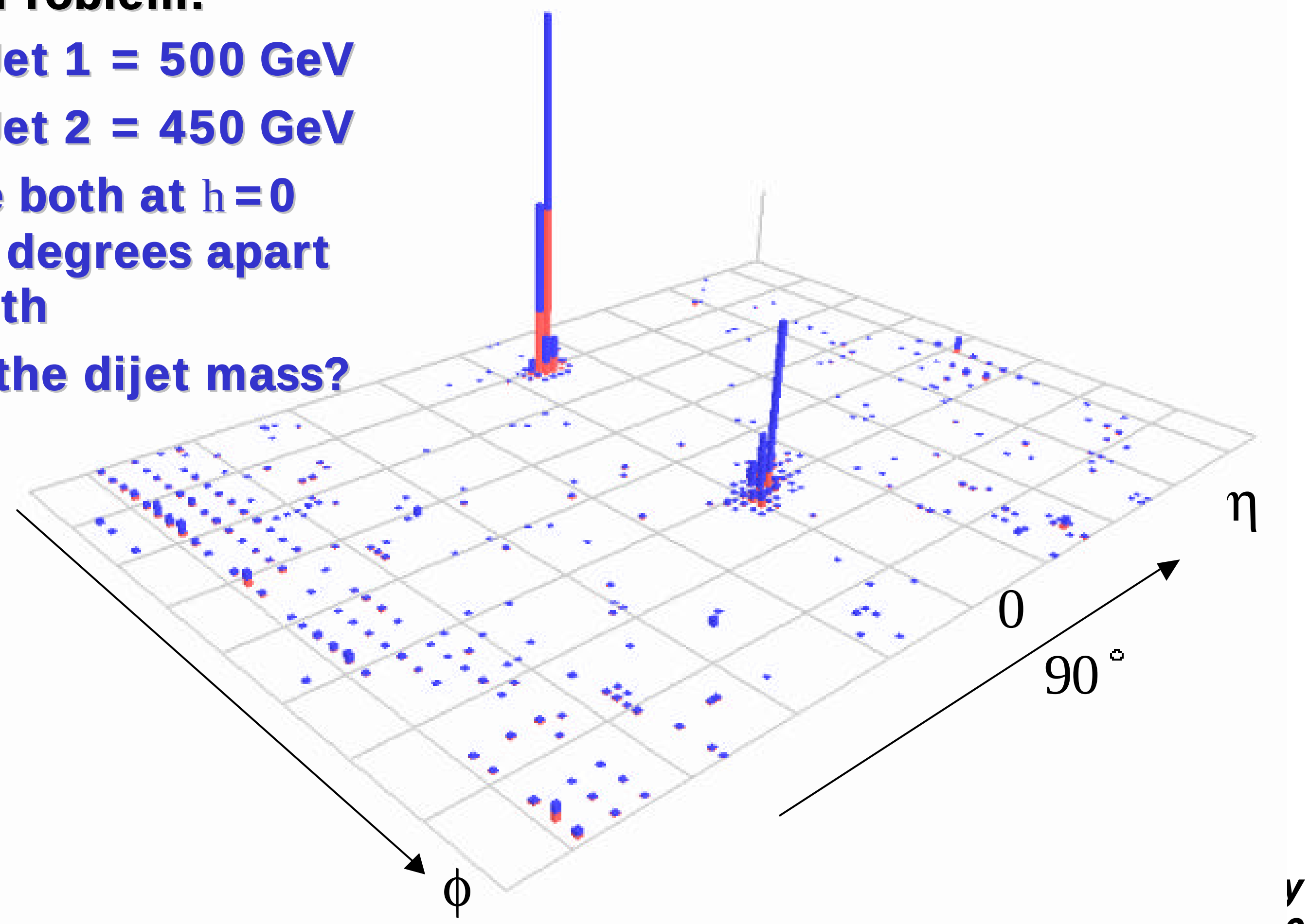
An Example:





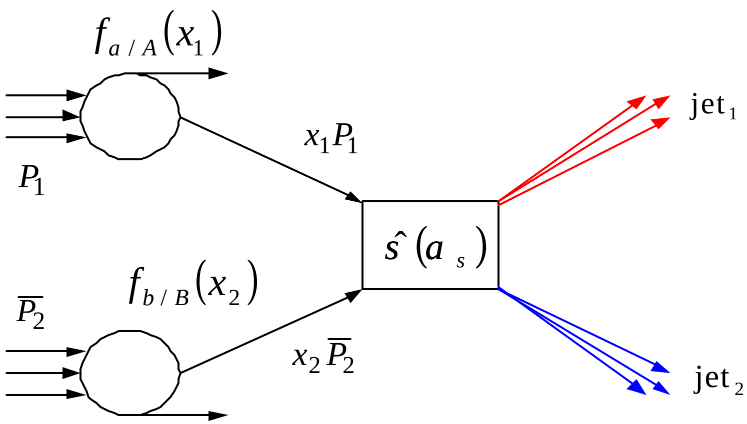
A Real Event !
(see Slide 8)

6. **Homework Problem:**
   - Energy Jet 1 = 500 GeV
   - Energy Jet 2 = 450 GeV
   - They are both at h=0 and 180 degrees apart in azimuth
   - What is the dijet mass?



Counting (q and g) Jets: Inclusive Jet Cross Section as a Test of the Standard Model (QCD)

Single Inclusive Jets: $p\bar{p} \rightarrow jet + X$



$$\sigma(p_1\bar{p}_2 \rightarrow 2\ jets) = \sum_{abcd} \int dx_1 dx_2\, f_{a/A}(x_1)\, f_{b/B}(x_2)\, \hat{\sigma}(ab \rightarrow cd)$$

$$\frac{1}{\Delta E_T \Delta\eta} \int\int d\eta\, dE_T \frac{d^2\sigma}{dE_T\, d\eta} \longrightarrow \frac{N_{jet}}{\Delta E_T \Delta\eta\, \varepsilon \int L dt} \text{ vs. } E_T$$

$\Delta E_T \rightarrow E_T$ *bin size*

$\Delta\eta \rightarrow \eta$ *bin size*

$N_{jet} \rightarrow$ *# of jets in the bin*

$\varepsilon \rightarrow$ *selection efficiency*

$L \rightarrow$ *inst. Luminosity*

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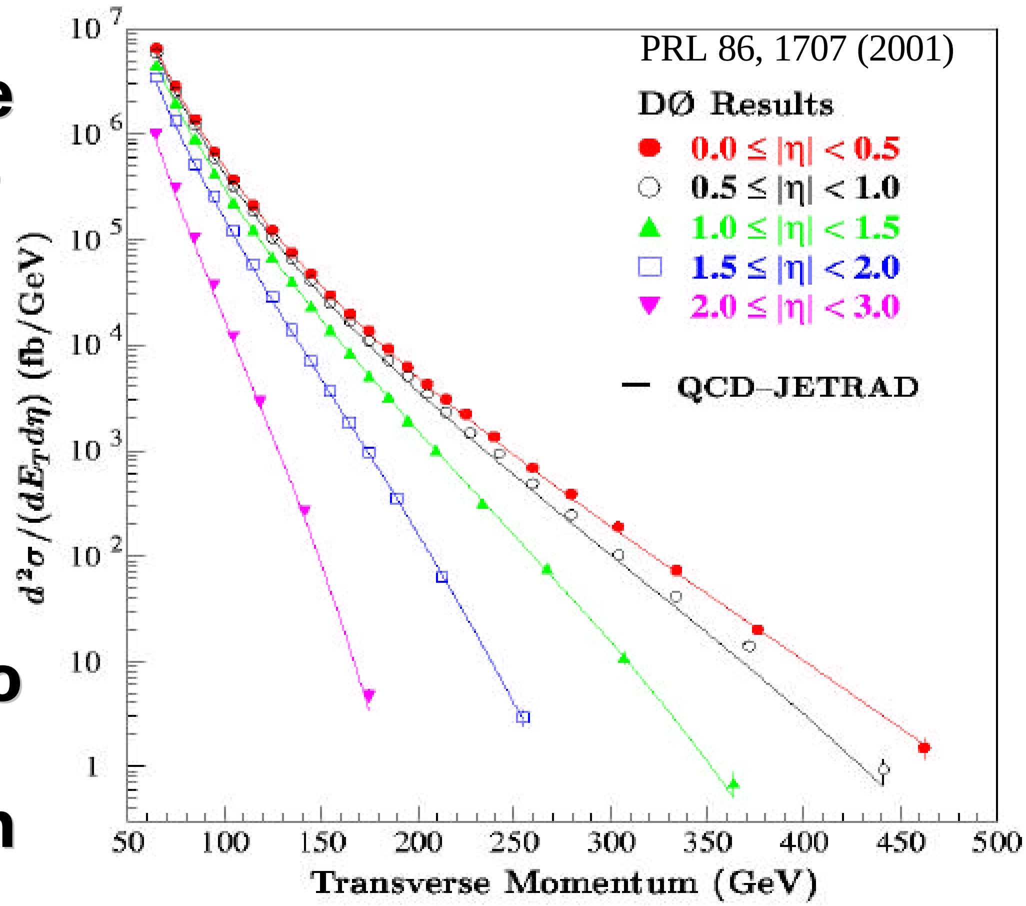
More Homework

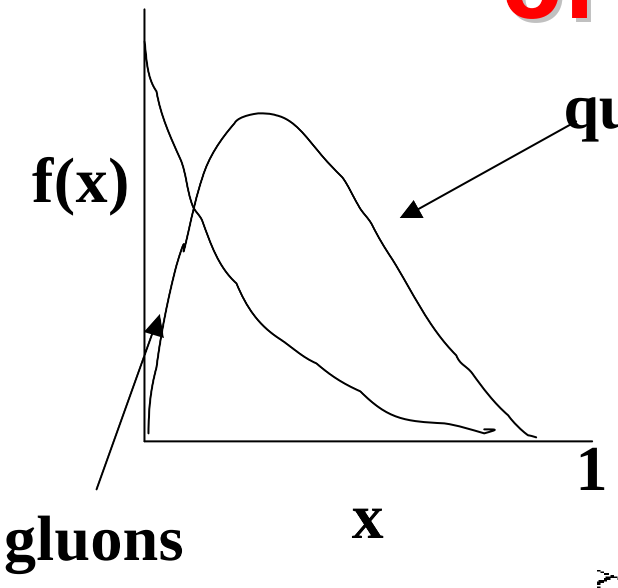
7. Calculate the central jet cross section for 900 jets observed with 90% efficiency in the range $295<ET<305$ GeV and $-0.5<h<0.5$ and produced with a luminosity of 0.3 fb^{-1}
8. What would be the statistical error?

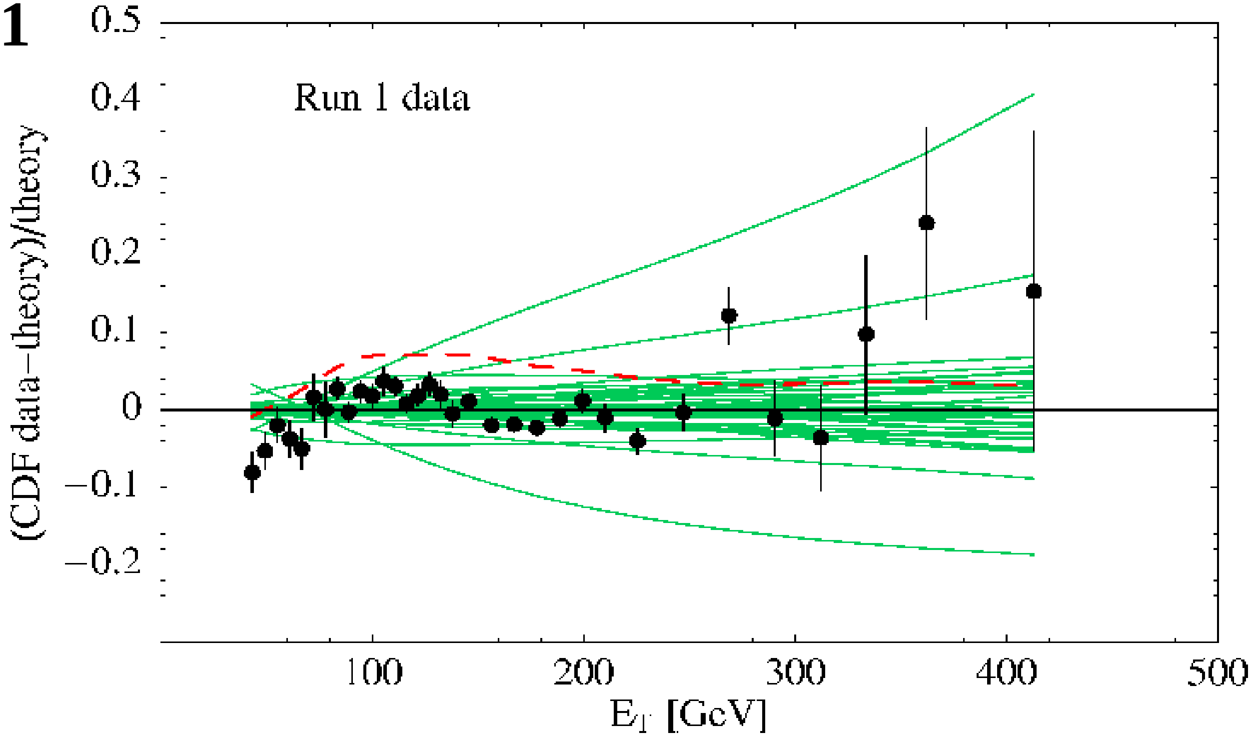
Inclusive Jet Cross Section

- ? Probes the hard interaction vertex over many decades in momentum exchange
- ? Probes for deviations from pQCD at small distance scales
- ? Sensitive to pdfs and running of a_s
- ? Cross section falls by seven orders of magnitude from 50 to 450 GeV
- ? Good agreement with QCD over the whole range



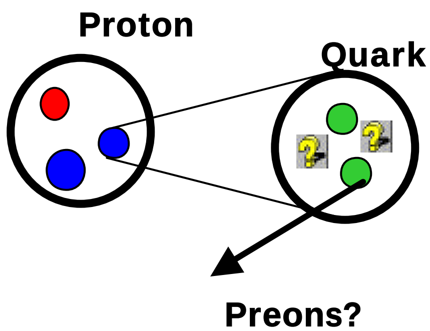
Data Consistent with a Number of Possible PDFs

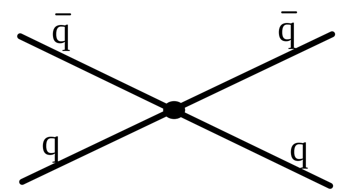


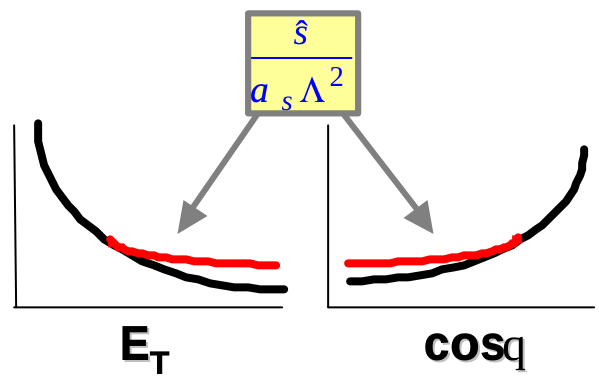


Jet Cross Sections Probe New Physics

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







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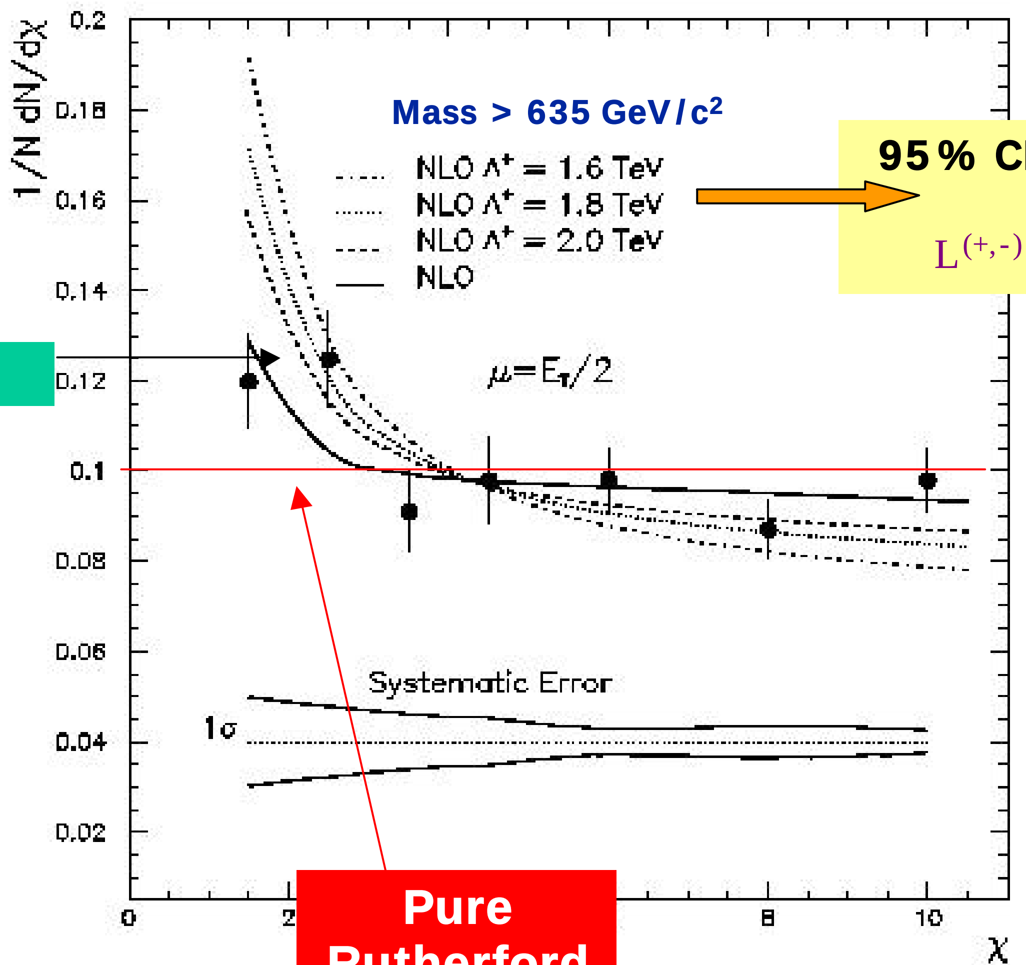
DØ Dijet Angular Distribution



95 % CL Compositeness Limit:

$L^{(+,-)}$ 3 **2.1 - 2.4 TeV**

QCD

Pure Rutherford scattering

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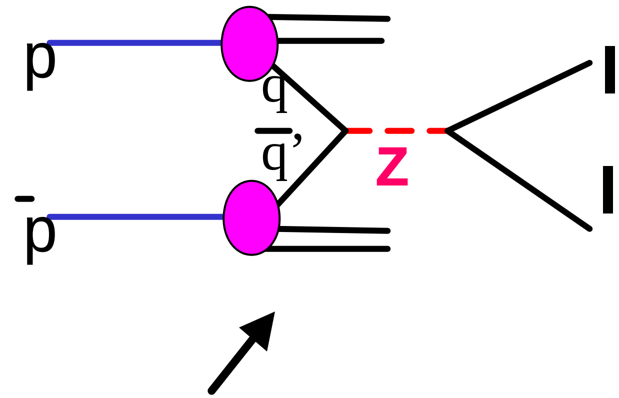
Electroweak Vector Boson Production



- **Recall our introductory lecture?**
- **Especially interesting physics as the bosons couple to both quarks and leptons.**
- **W and Z boson masses test electroweak theory**
- **Lepton signals experimentally distinct.**

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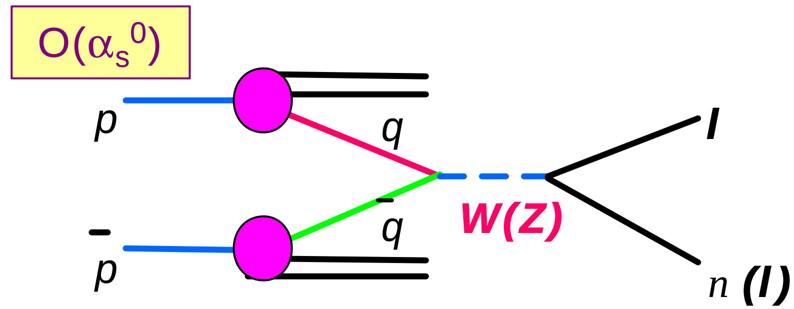
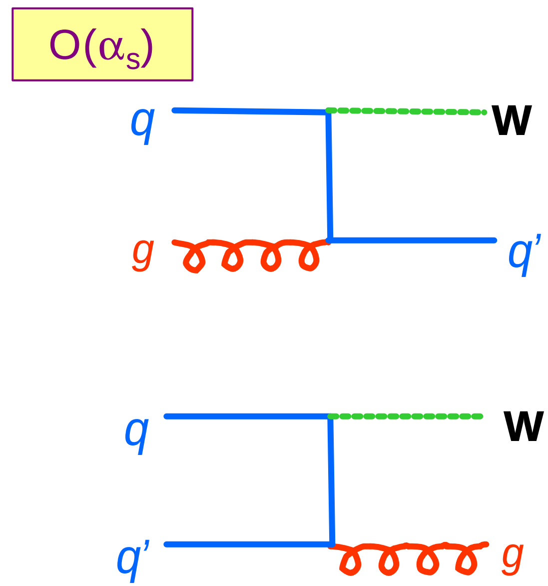
W / Z Production at Hadron Colliders

- **General Characteristics**
  - **Production dominated by`qq annihilation (~60% valence-sea, ~20% sea-sea)**
  - **Due to very large pp ® jj production, need to use leptonic decays to extract signal**



- **Higher order QCD corrections:**
  - **Boson produced with mean p_T ~ 10 GeV**
  - **Boson + jet events (W+jet ~ 7%, E_T^{jet} > 25 GeV)**



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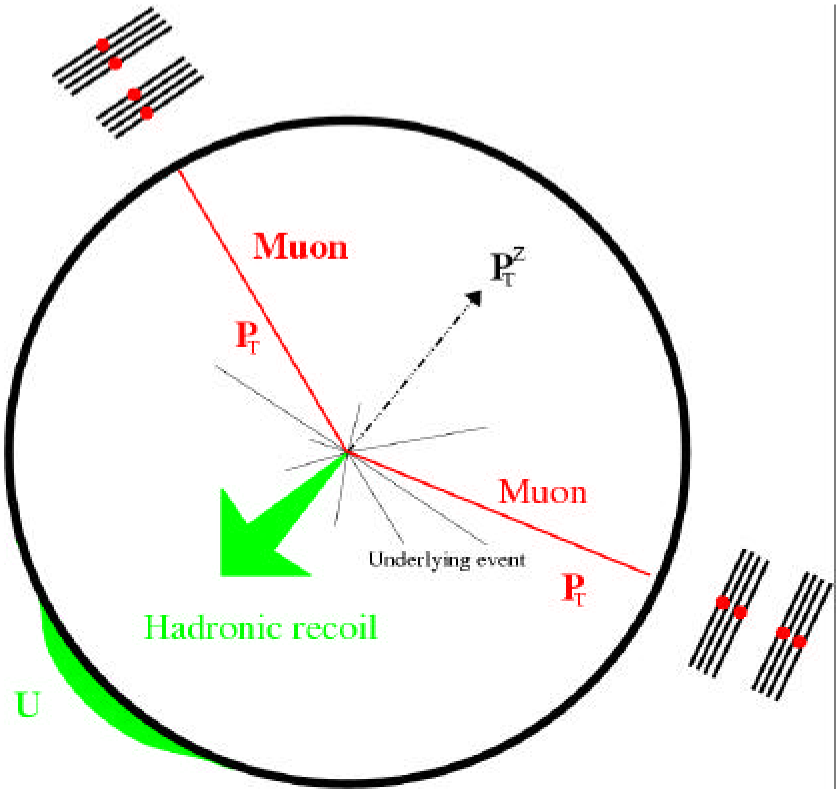
Experimental Signature: Z? m+m-

- **A pair of charged leptons:**
  - **high p_T**
  - **isolated**
  - **opposite-charge**
- **Redundancy in trigger and offline selection**
- **Low backgrounds**
- **Control of systematics**



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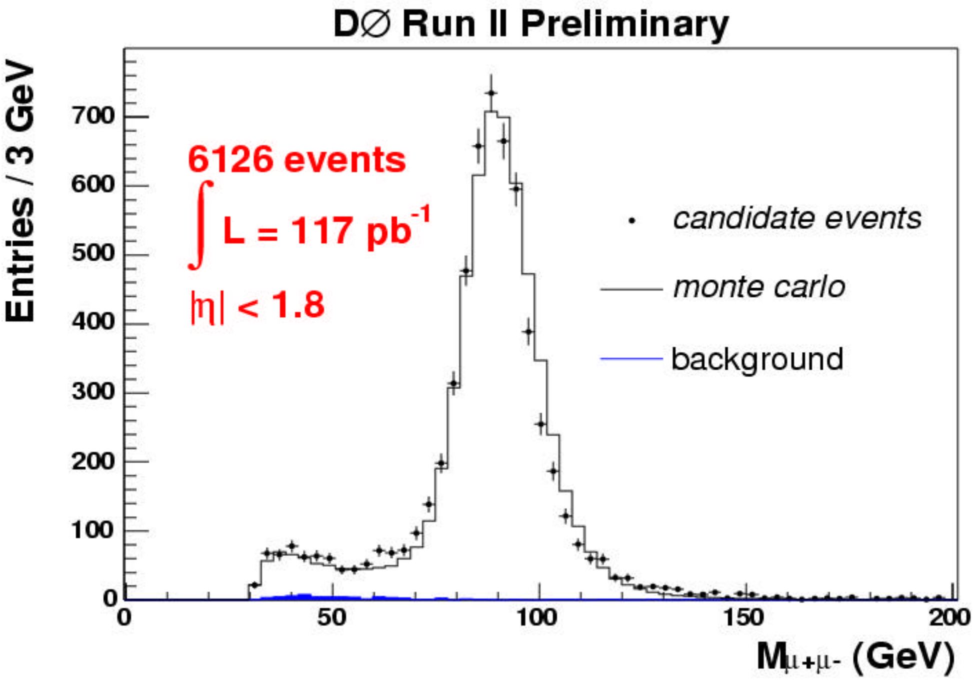
Select Events, Calculate Dilepton Mass, Calculate Cross Sections

- **Event selection:**
  - Two central tracks:
  - μ-id with p_T > 15 GeV
  - opposite charge
  - |?| < 1.8
  - More than 1 isolated μ

- **Calculate Cross Section:**
  - e_{total} = 19%
  - For $M_{\mu\mu}$ > 30 GeV
    N_{cand} = 6126
  - ? = 117 pb^{-1}



- **Homework 9:**
  - Calculate the Z→mm cross section for yourself!
  - From the figure can you tell why it's a few percent higher than the cross section on the next page?

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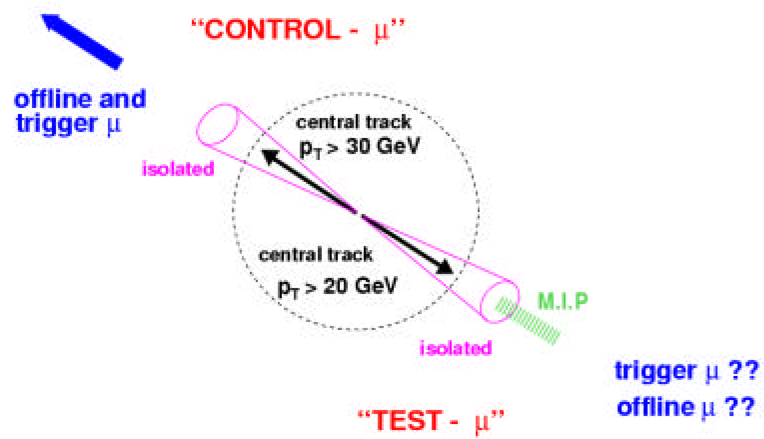
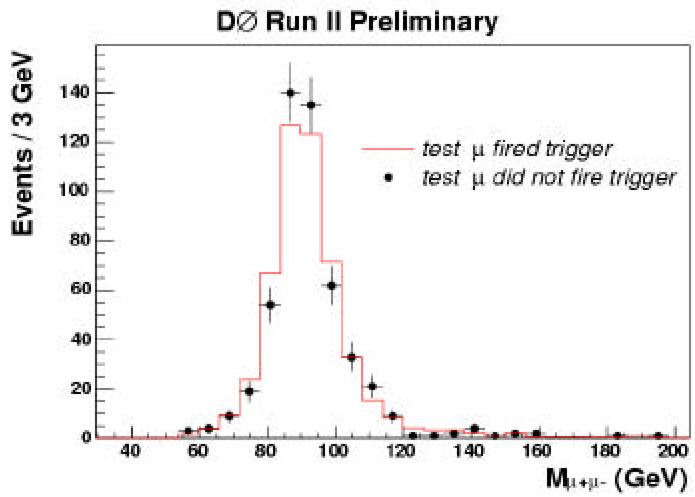
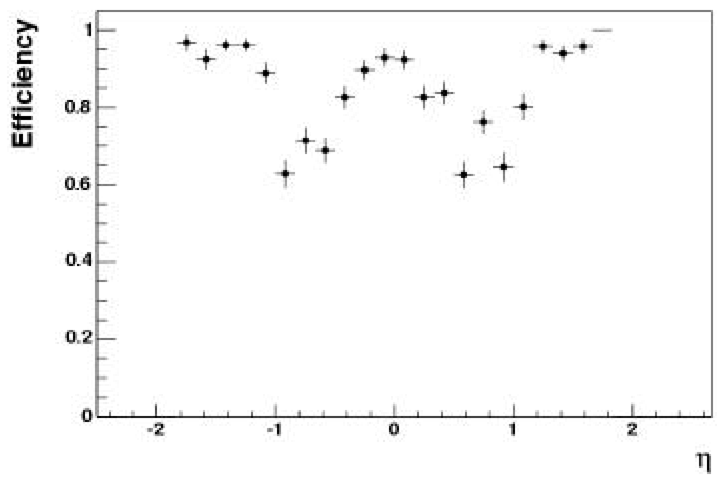
Measuring efficiencies using the Z? $\mu^+\mu^-$ data

- There are two μ's
- The backgrounds are low
- Can select pure Z sample with even looser cuts on one μ







$$s_Z \bullet Br(Z?\ \mu^+\mu^-) = 261.8 \pm 5.0 \pm 8.9 \pm 26.2 \text{ pb}$$

stat. syst. lumi.

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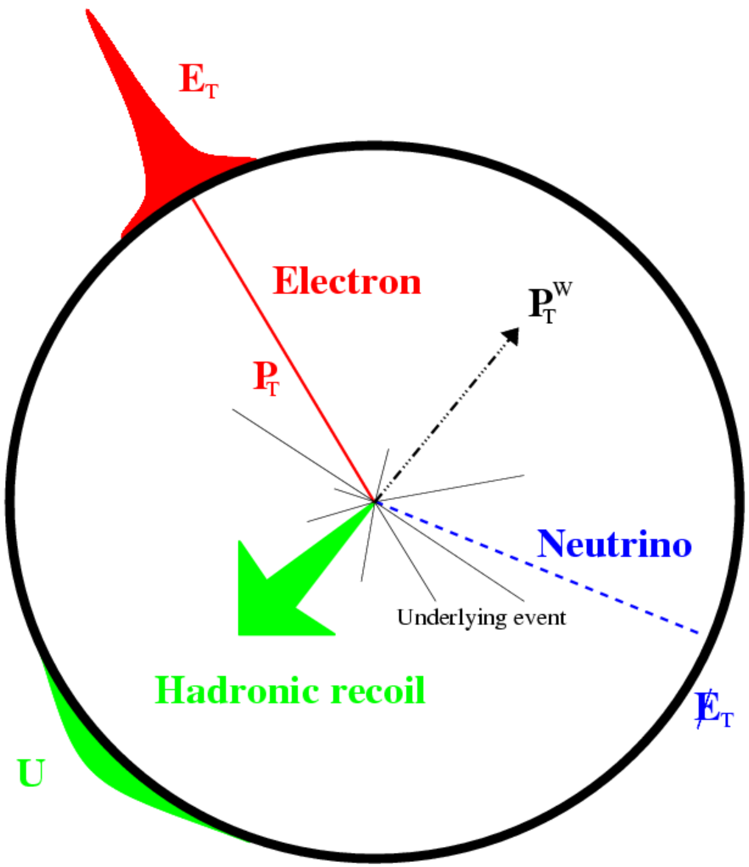
Experimental Signature: W? ln

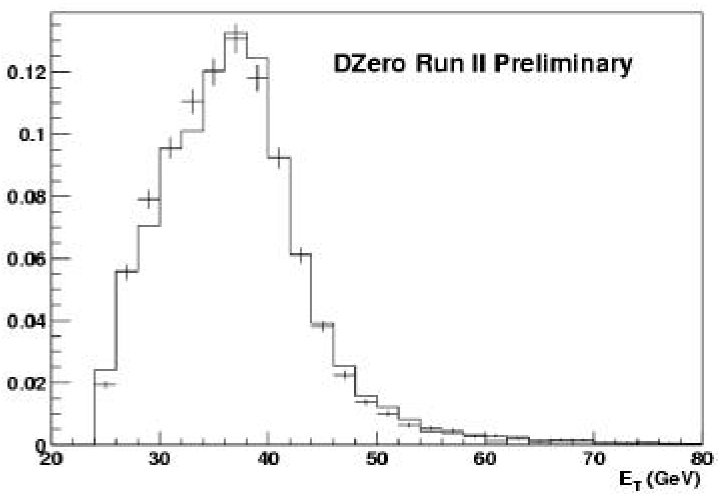


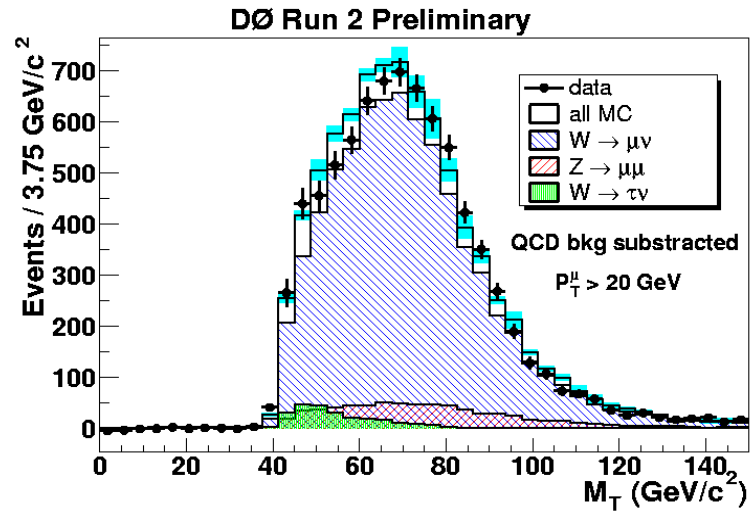
- Single charged lepton:
  - high p_T
  - isolated
- E_T^{miss} (from neutrino)
- Less redundancy in trigger and offline selection
- More difficult to control backgrounds and systematics
- need to understand hadronic recoil
- s •Br 10 times larger than Z

W? en and W? μn

- $p_T(e) > 25$ GeV
- $E_T^{miss} > 25$ GeV
- $N_{cand} = 27370$
- ?L = 42 pb^{-1}

- $p_T(\mu) > 20$ GeV
- $E_T^{miss} > 20$ GeV
- $N_{cand} = 8302$
- ?L = 17 pb^{-1}





$s_W \bullet Br(W?\ e\nu) = 2.884 \pm 0.021 \pm 0.128 \pm 0.284$ nb

$s_W \bullet Br(W?\ \mu\nu) = 3.226 \pm 0.128 \pm 0.100 \pm 0.322$ nb

stat. syst. lumi.

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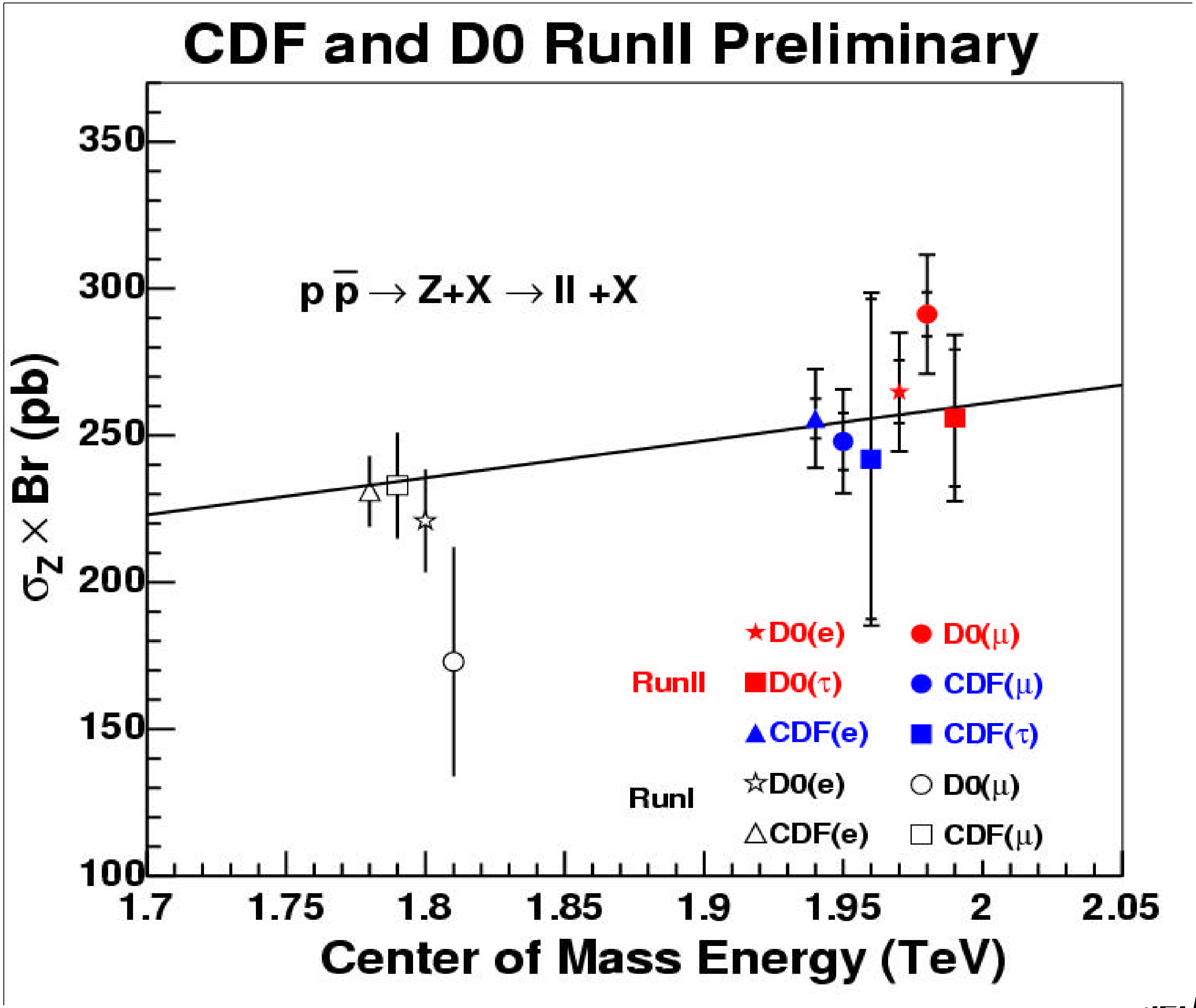
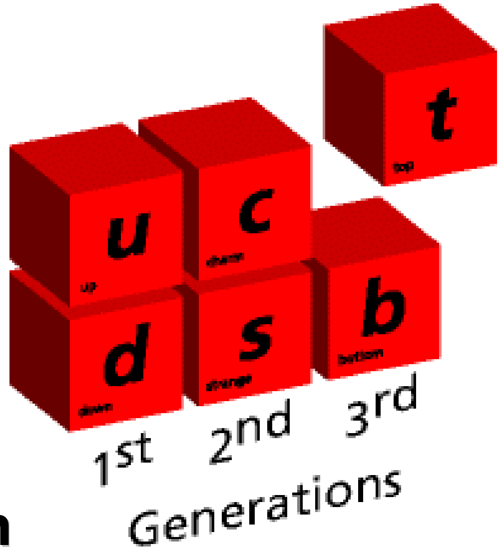


CDF and D0 RunII Preliminary
$p\bar{p} \rightarrow Z+X \rightarrow ll+X$
$\sigma_Z \times Br$ (pb)
Center of Mass Energy (TeV)
RunII
RunI
D0(e)
D0(μ)
D0(τ)
CDF(μ)
CDF(e)
CDF(τ)
D0(e)
D0(μ)
CDF(e)
CDF(μ)
350
300
250
200
150
100
1.7
1.75
1.8
1.85
1.9
1.95
2
2.05

The Last Quark: an Introduction

- **Top quark was expected in the Standard Model (SM) of electroweak interactions as a partner of b-quark for the third family of quarks**
  - **Evidence for top in 1994 (CDF)**
  - **Observation in 1995 (CDF&D0)**



- **In Run I statistical uncertainties dominated:**
  - **Overall consistency with the SM picture**
  - **but…still a few loose ends**

- **In anticipation of much increased statistics in Run II:**
  - **Rich physics menu**
  - **Increased luminosity → increased precision**
  - **Surprises?**

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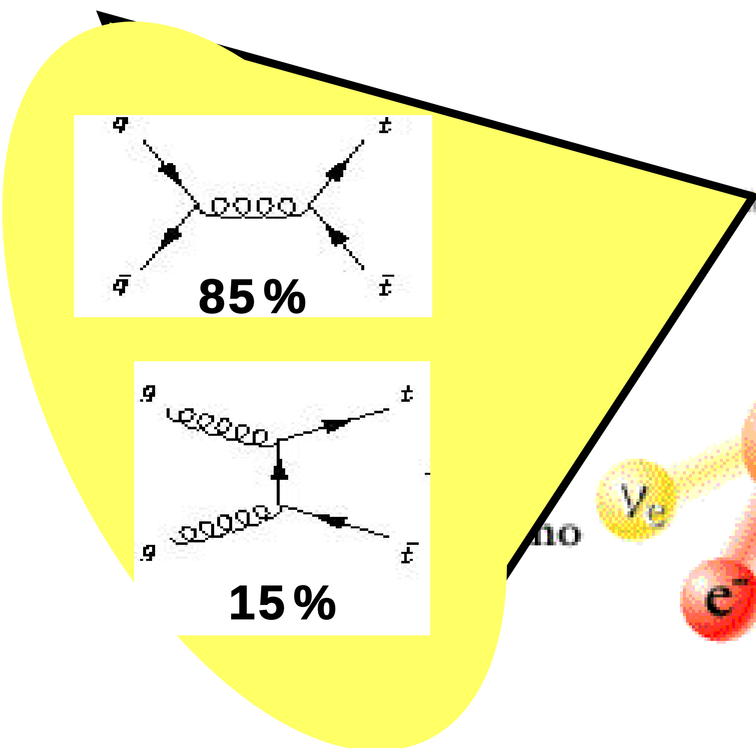
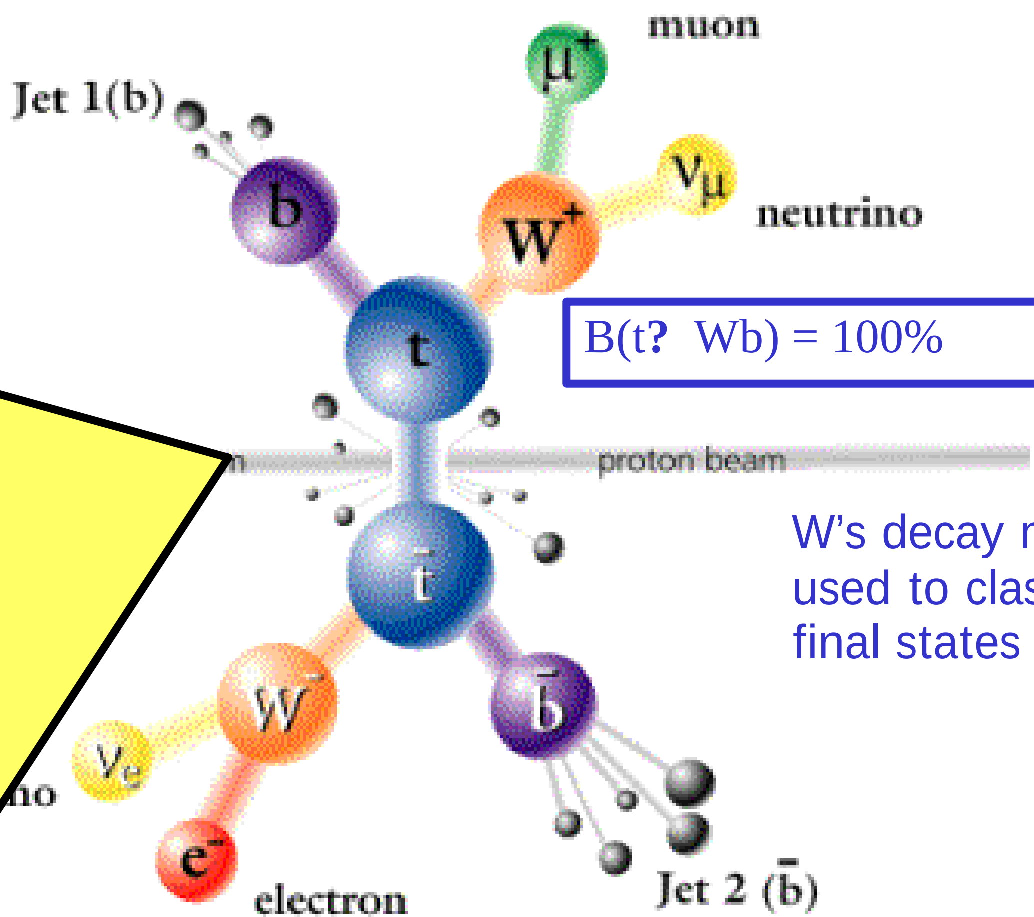
Top Quarks at the Tevatron

Pair production





W’s decay modes used to classify the final states

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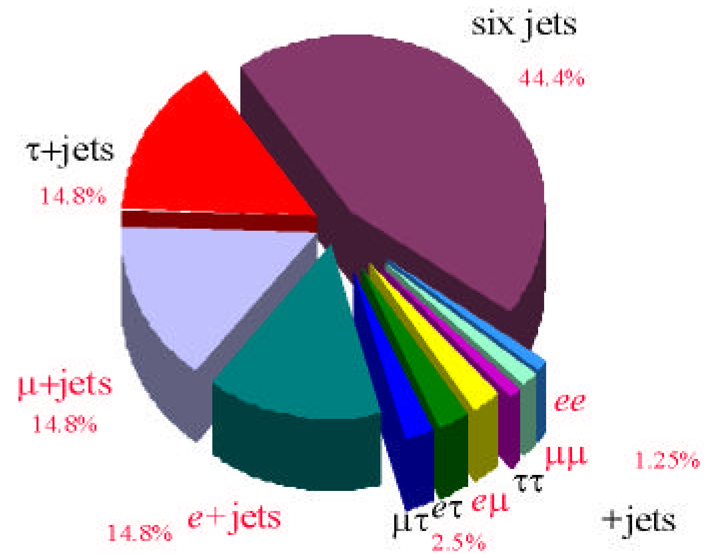
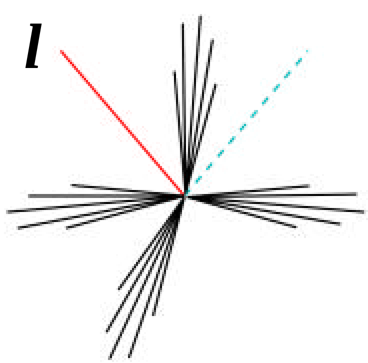
Cross Section

- **Why?**
  - **test of QCD predictions**
  - **Any discrepancy indicates possible new physics:**
    - **production via a high mass intermediate state**
    - **Non-Wb decay models**
- **How?**
  - **Measurement performed using various final states**
  - **Dilepton channels**
    - **ee, em, mm final states**
  - **Lepton + jets channels**
    - **e+jets, m+jets**
      - **topological analysis**
      - **b-tagging**
  - **All-jets channel**
    - **Use topological variables**
    - **exploit b-tagging using soft leptons**
      - **Combine them using a Neural network technique**

- **W and b-quark decays specify final states**
  - **Isolated high P_T leptons**
  - **Soft leptons in jets**
  - **detached vertices in jets**



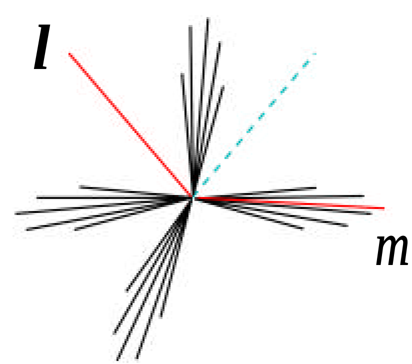
Lepton+jets
(topological)



e+jets, μ+jets

Br = 14.7%

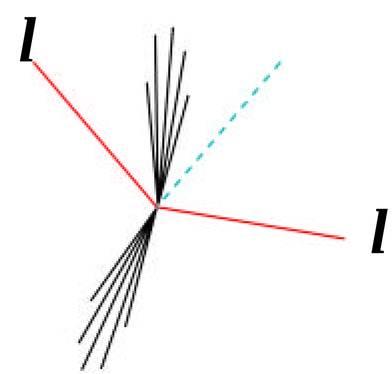
Lepton+jets
(soft muon tag)



e+jets/μ, μ+jets/μ

Br = 14.7%

Dileptons



eμ, ee, and μμ

Br = 2.5 and 1.2%

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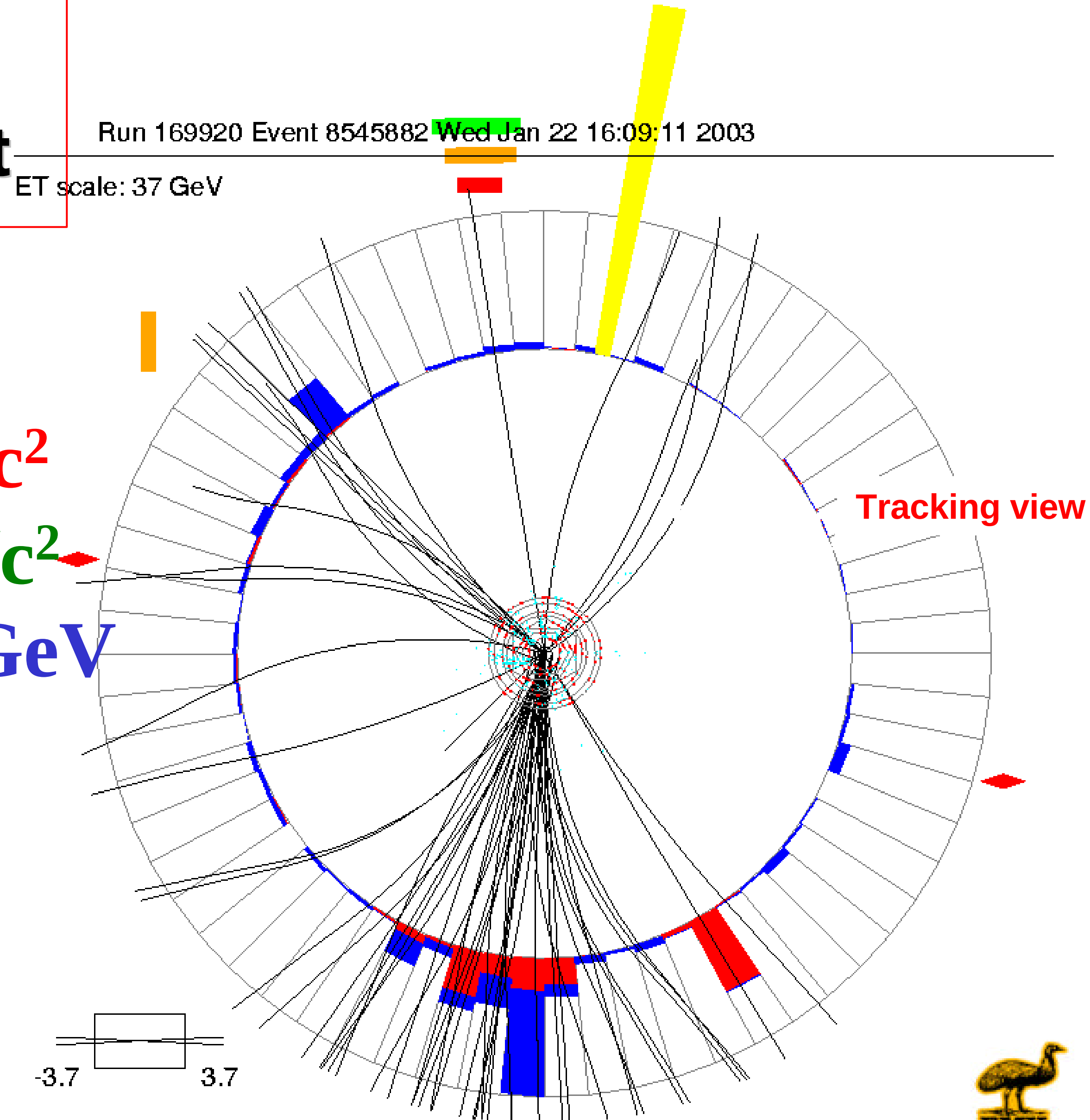
em + 2jet Candidate Event



$p_T(e) = 20.3$ GeV/c^2

$p_T(m) = 58.1$ GeV/c^2

$E_T^j = 141.0, 55.2$ GeV

$\not{E}_T = 91$ GeV

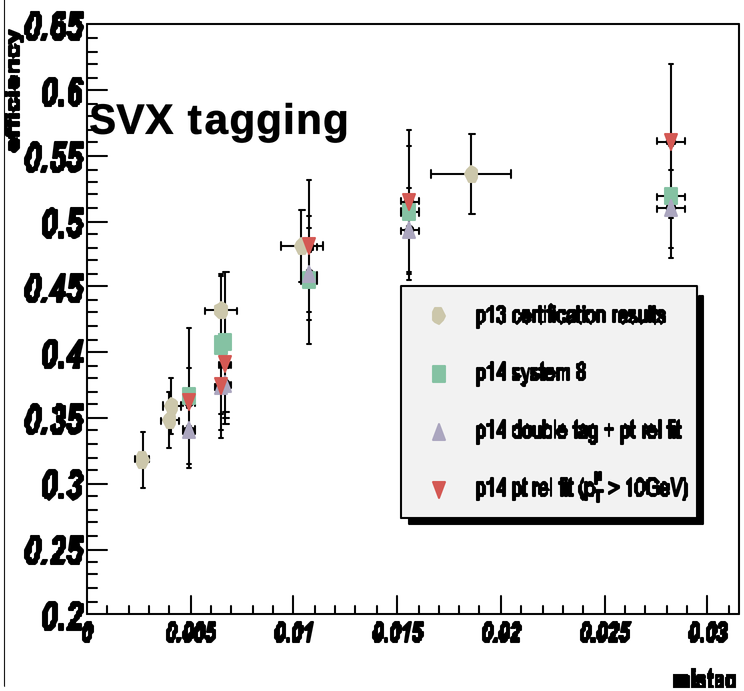
$H_T(e) = 216$ GeV

Lifetime b-tagging

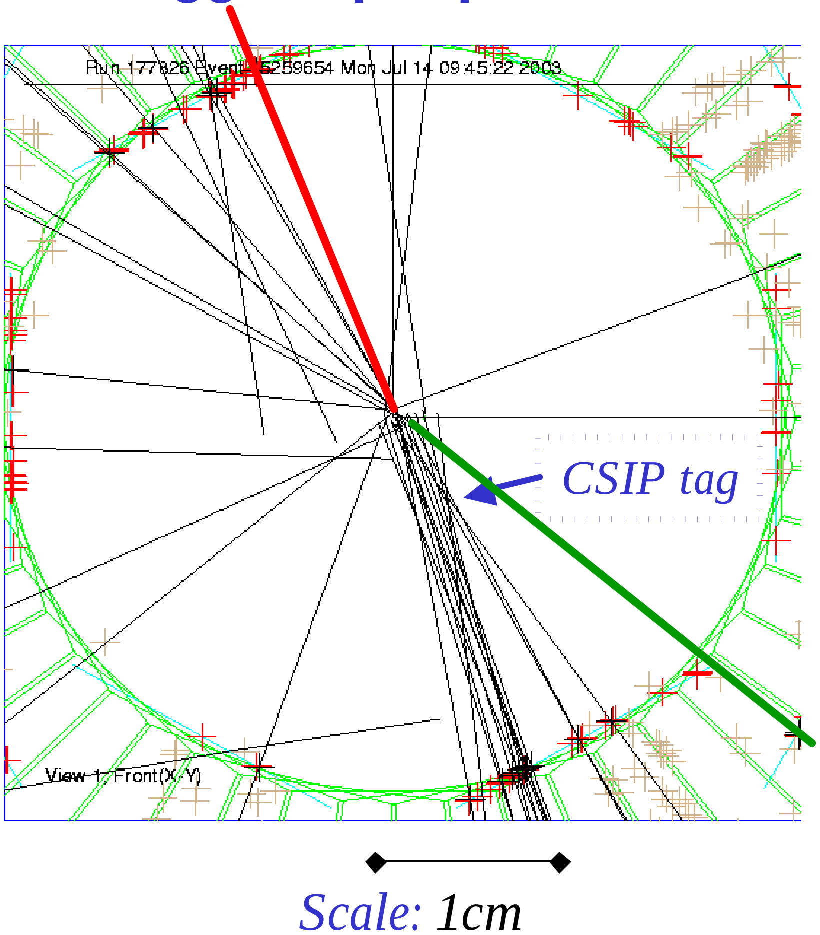
Three different tagging algorithms

- **One based on secondary vertices**
- **Two based on tracks with large IPs**

Multiple methods to measure efficiencies and fake rates



A tagged eμ top candidate



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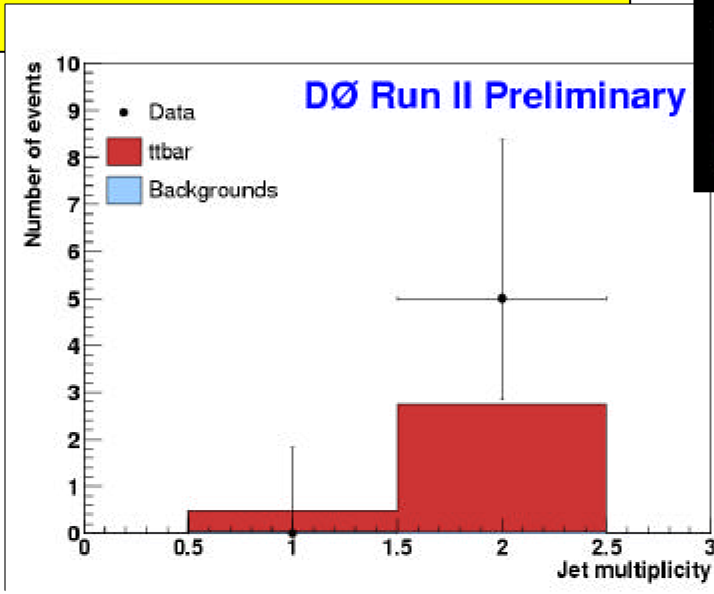
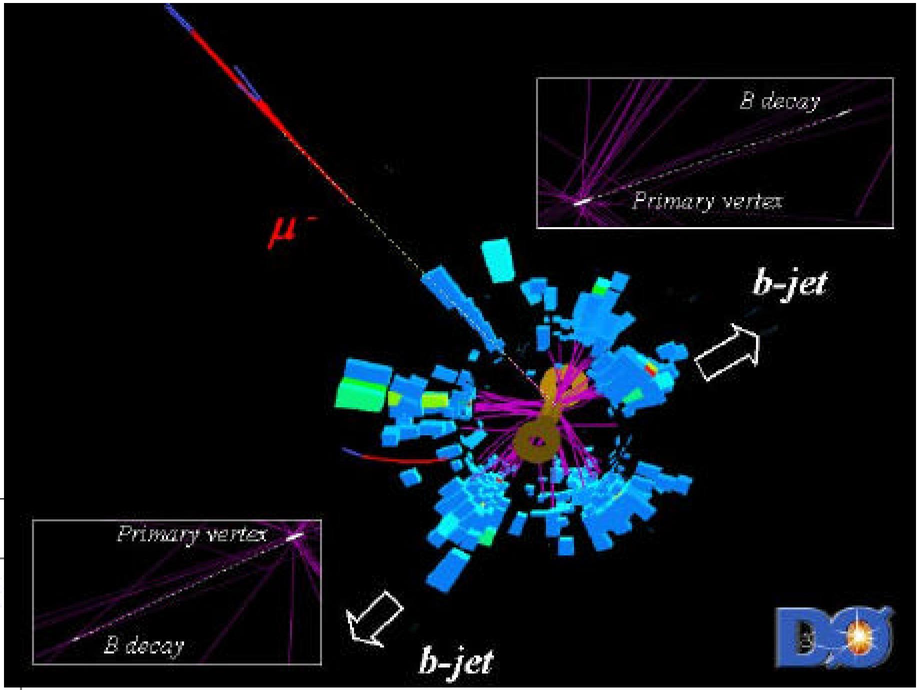
The Golden Doubly Tagged eu Channel

- Incredibly Clean
- Two leptons
- Two b-tags
- Signal / Noise > 70!





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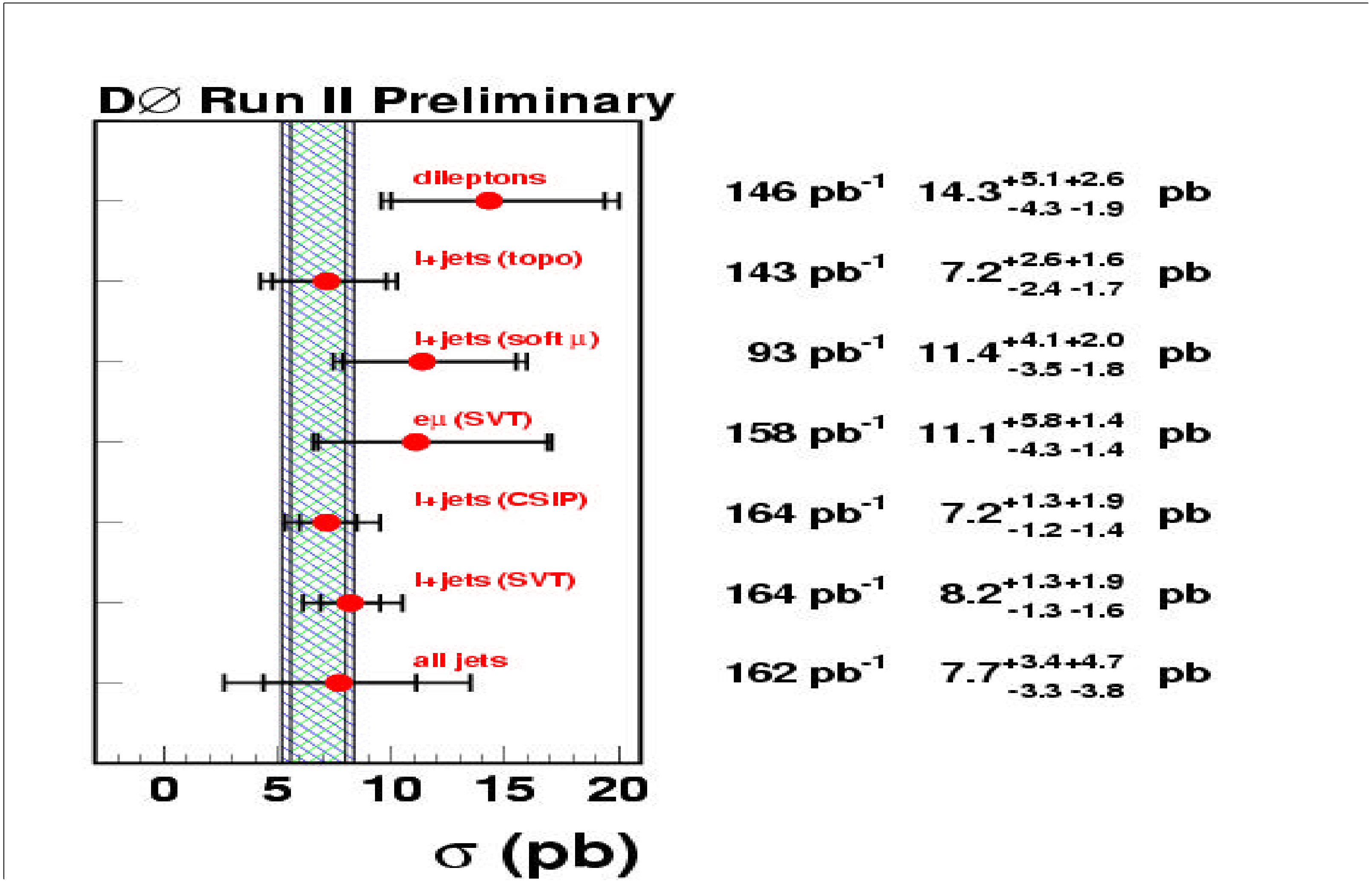
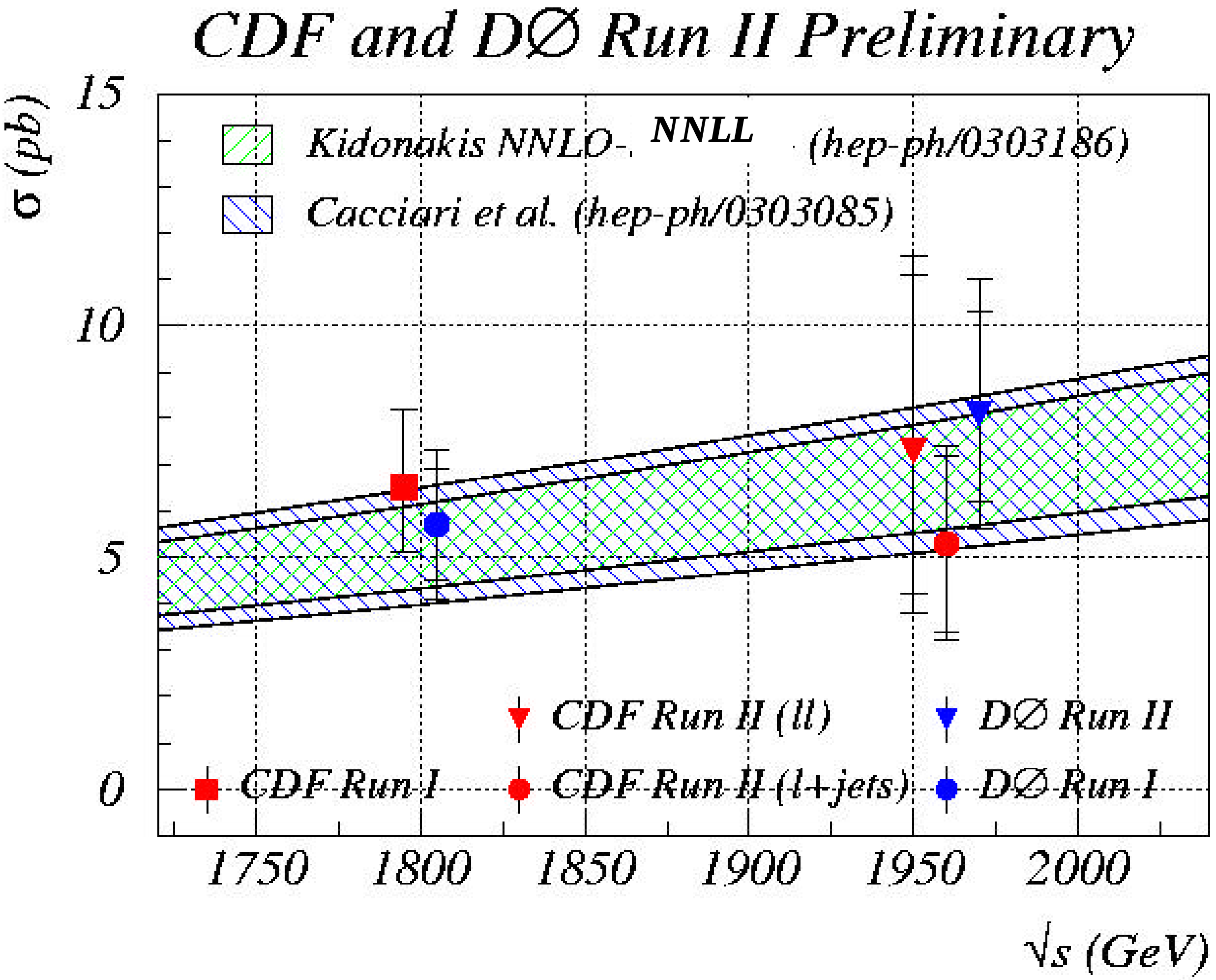
Top cross sections



Cross section Ös dependence



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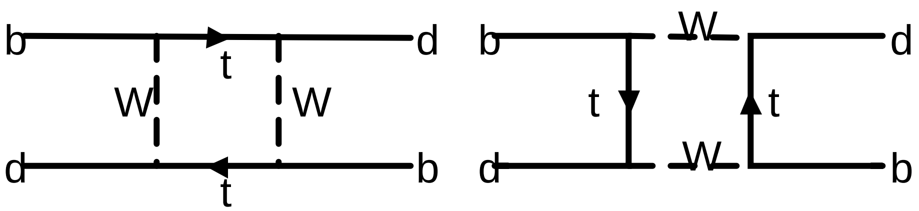
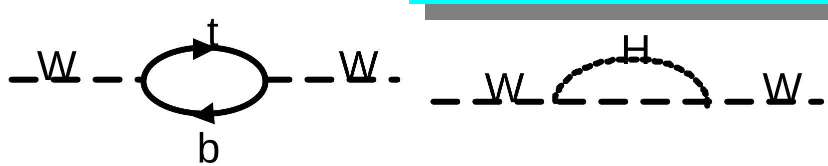
Equally Interesting: Top Quark Mass

- **Fundamental parameter of Standard Model (SM)**
- **Affects predictions of SM via radiative corrections:**
  - **BB mixing**



$$dM_W \propto m_t^2, \ln(M_H)$$

  - **W and Z mass**



  - **measurements of M_W, m_t constrain M_H**

- **Large mass of top quark**
  - **Yukawa coupling » 1**
  - **may provide clues about electroweak symmetry breaking**

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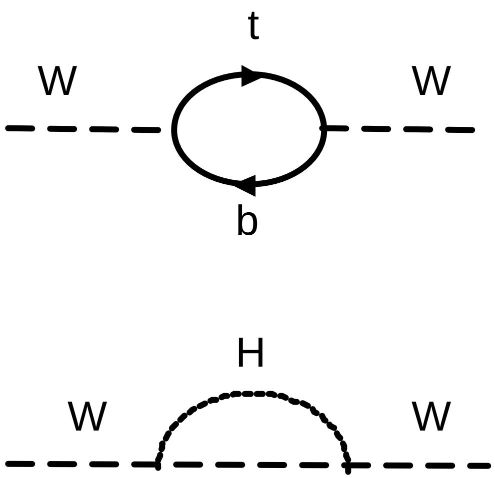
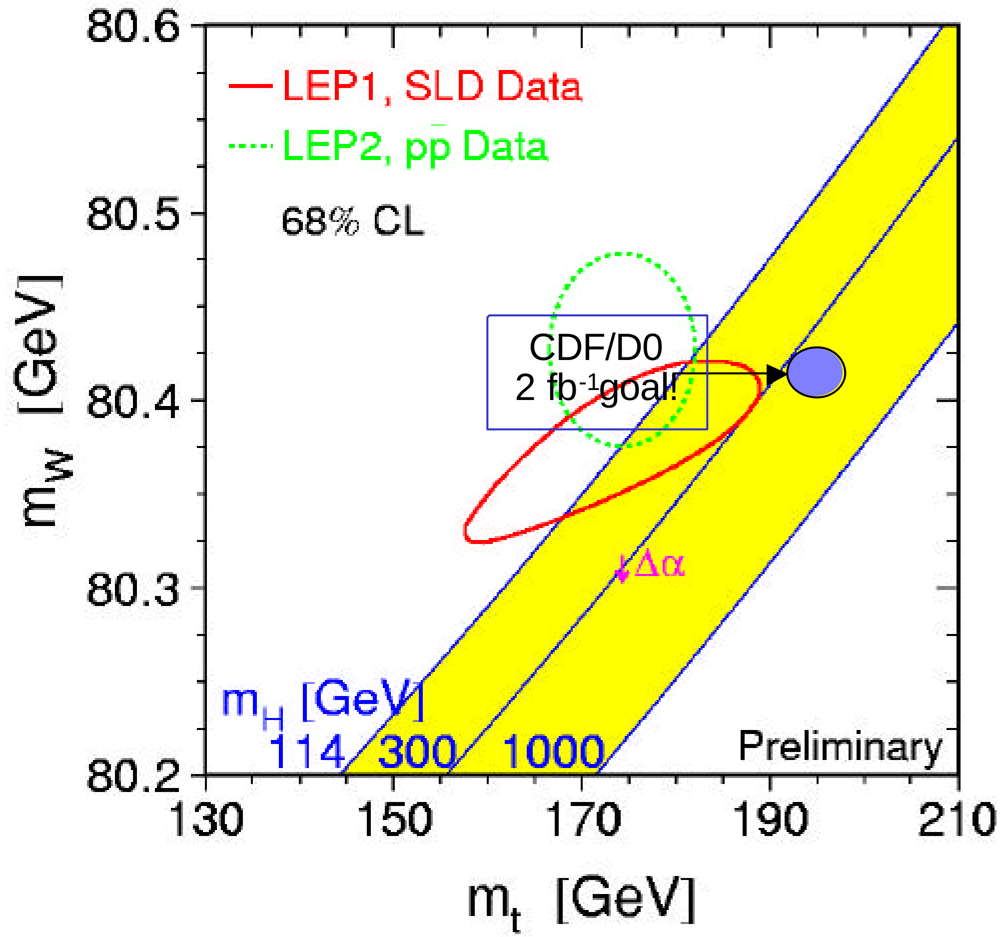
Top Mass Constrains the Higgs





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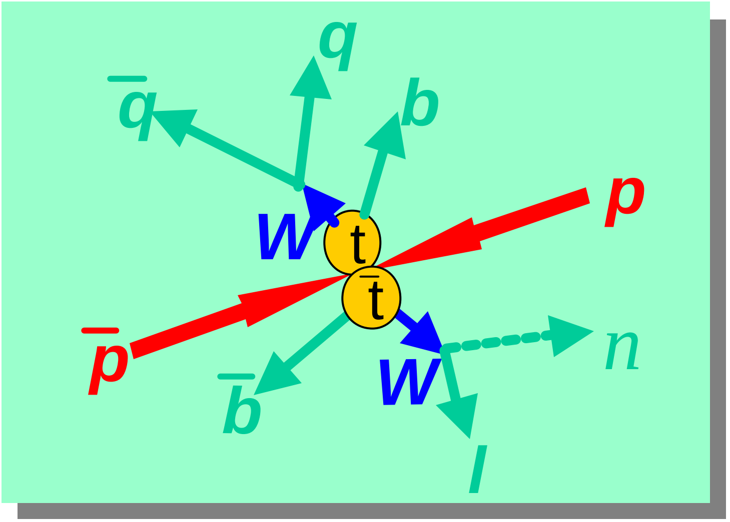
Mass: Lepton + Jets Channel
(there are other channels / methods)

$t\bar{t} \rightarrow l\nu b q\bar{q}\bar{b}$



- 1 unknown (p_z^{ν})
- 3 constraints
  - $m(l\nu) = m(qq) = m_W$
  - $m(l\nu b) = m(qqb)$
- 2-constraint kinematic fit
- up to 24-fold combinatoric ambiguity
- compare to MC to measure m_t

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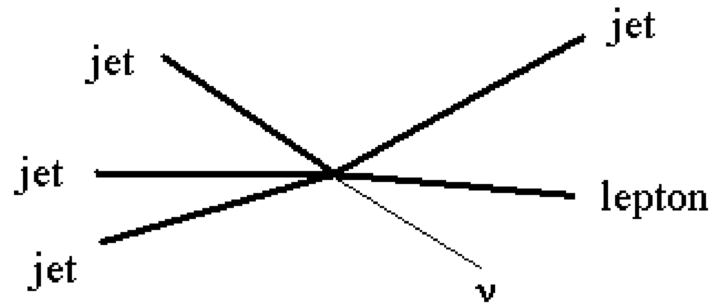
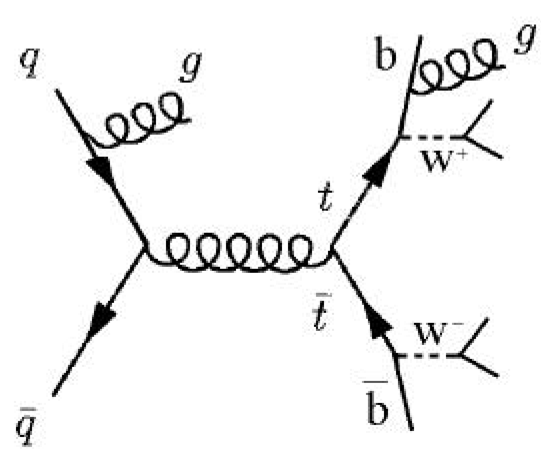
Mass: Complications

- **Combinatorics:**
  - 4 possible jlν pairings
  - there are 12 possible assignments of the 4 jets to the 4 quarks (bbqq)
    - only 6 if one of the jets is b-tagged
    - only 2 for events with double b-tagged jets
    - Homework 10:
      - Work out the possibilities.
      - Although the eμ channel would have fewer combinatoric choices, why would it have less precision than lepton+jet channel?
- **Gluon radiation can add extra jets**





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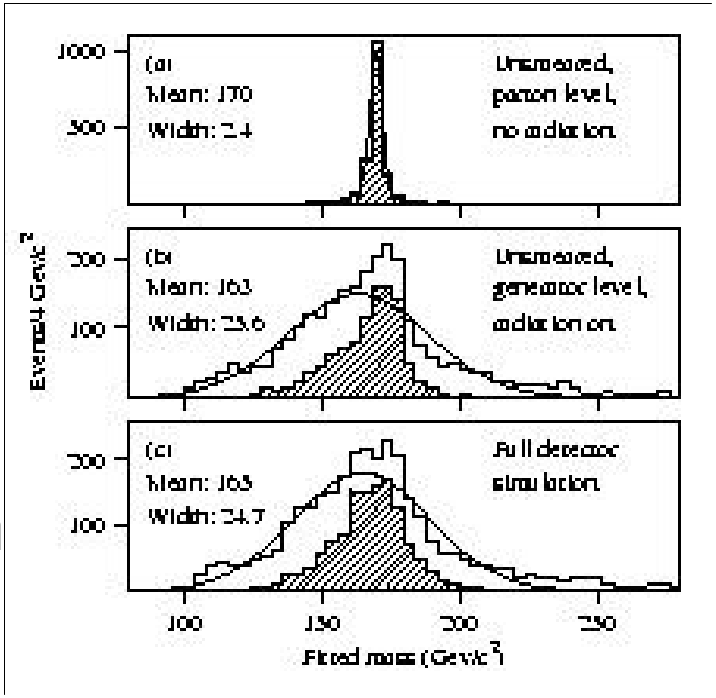
Mass: Combinatorics

- **Monte Carlo tests:**
  - **shaded plots show correct combinations (Herwig MC, m_t = 175 GeV)**
- **The width and shape of the fitted mass distribution is due primarily to**
  - **jet combinatorics**
  - **QCD radiation**



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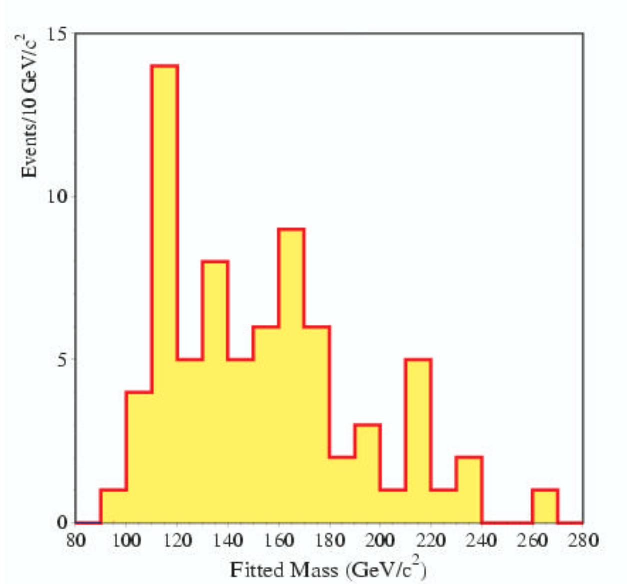
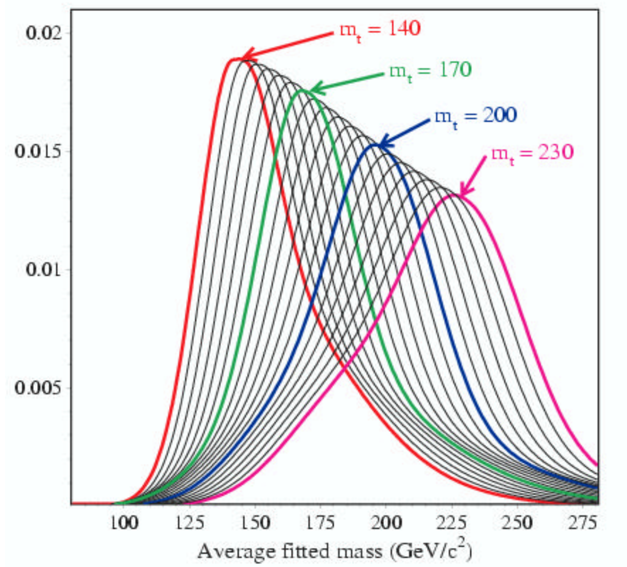
Mass: Basic Procedure

- In a sample of tt candidate events
  - For each candidate make a measurement of X = f(m_t), where X is a suitable estimator for the top mass
    - e.g. result of the kinematic fit
  - This distribution contains signal and background.

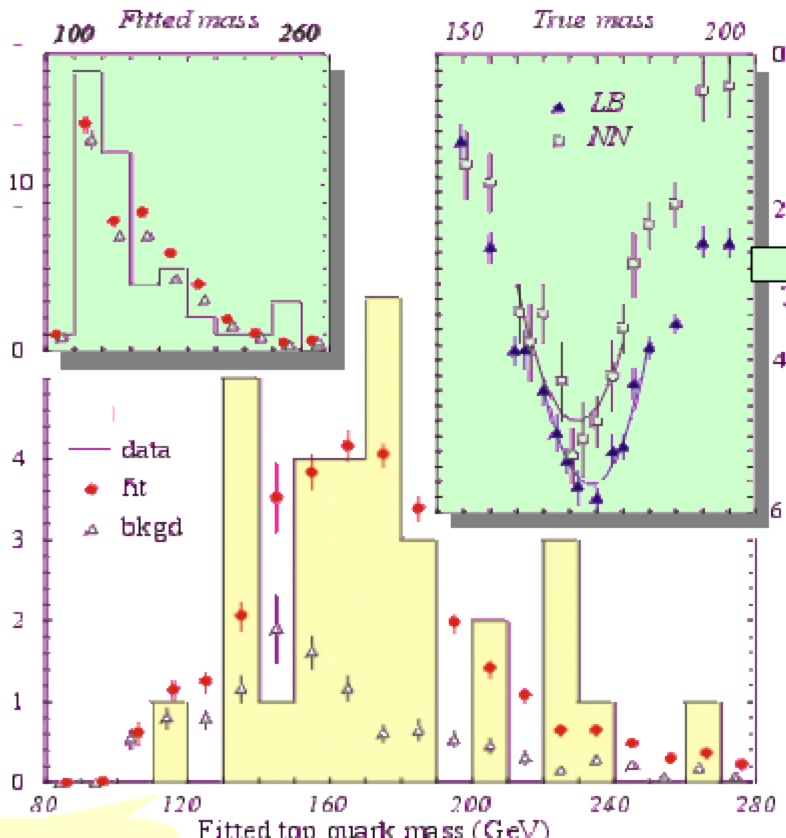
- From MC determine shape of X as a function of m_t
  - Determine shape of X for background (MC & data).
  - Add these together and compare with data





Lepton + Jets Channel (DØ)

Background-rich sample



Signal-rich sample

m_t = 173.3±5.6±5.5 GeV

largest systematics	
jet energy	4.0 GeV
MC generator	3.1 GeV
noise/pile-up	1.3 GeV

dominated by
jet energy scale and
gluon radiation

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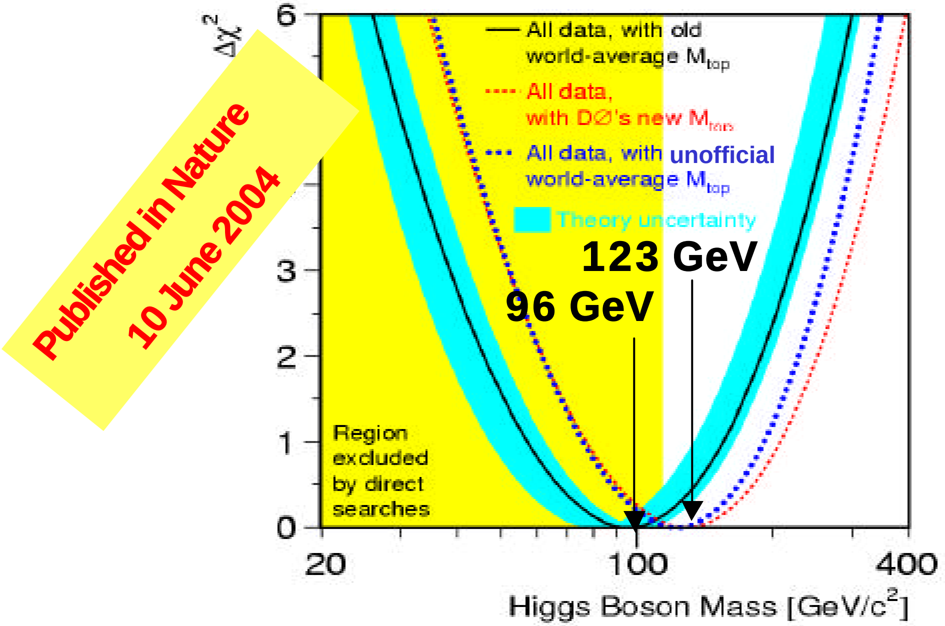
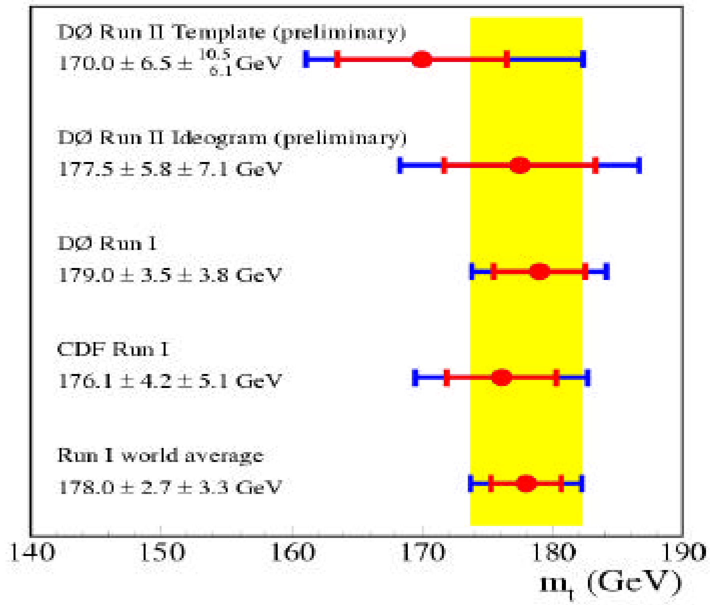
Run I and Run II Top mass

m_{top} = 179.0 ± 5.1 GeV (DØ combined)

m_{top} = 178.0 ± 4.3 GeV (official average)





First DZero Run II lepton + jets mass
160 pb-1

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A Disclaimer

- **We've looked at QCD, Vector Boson, and Top Production.**
- **Just a sample of interesting Standard Model topics**
- **Many others:**
  - **Heavy Flavor**
  - **Di-boson Production**
  - **Diffractive Physics**
  - **And more….**

Our Lecture Series

- ✓ Overview
- ✓ History, Accelerators, Detectors, & Cross Sections
- ✓ QCD and Electroweak Physics
- Searches for New Physics